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Coral Salvador Tese de Doutoramento Effects of drought on daily mortality in Iberian Peninsula: risks and vulnerability 2020

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“Mención Internacional”

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Effects of drought on daily mortality in Iberian Peninsula: risks and vulnerability

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HACEN CONSTAR que el presente trabajo titulado "**Effects of drought on daily mortality in Iberian Peninsula: risks and vulnerability**", que presenta Dña. Coral Salvador Gimeno para la obtención del título de Doctora por la Universidad de Vigo con Mención de Doctorado Internacional, fue elaborado bajo nuestra dirección en el programa de doctorado "*Auga, sustentabilidade e desenvolvemento*" y que se presenta en este manuscrito bajo la modalidad por compendio de artículos de investigación.

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RESUMEN

La salud y el bienestar humano son extremadamente vulnerables a variaciones climáticas y particularmente a la incidencia de fenómenos extremos conexos al clima como las olas de calor, incendios forestales, sequías, tormentas de polvo, inundaciones, o ciclones, etc., que causan graves impactos en el medio ambiente, la economía y la sociedad, sobre todo cuando existe una combinación de ellos. Como consecuencia del cambio climático, se espera que estos fenómenos extremos ocurran con mayor frecuencia e intensidad en varias regiones del mundo a finales del siglo XXI, actuando éste como un factor multiplicador de la amenaza de la salud de la población, especialmente en regiones vulnerables con reducida capacidad de adaptación.

Entre todos estos fenómenos la sequía es uno de los peligros naturales más complejos, que afecta a un mayor número de personas en comparación con cualquier otro evento climático, causando una amplia gama de impactos en diversos sectores. La sequía tiene lugar cuando hay un déficit de precipitación y escasez de agua durante un periodo de tiempo prolongado, causando un desbalance hídrico. Otros factores climáticos (ej. temperaturas elevadas, vientos fuertes, baja humedad relativa) o antropológicos (deforestación y degradación del suelo, mala gestión del agua, o sobre-explotación de los recursos hídricos) pueden agravar el impacto de las sequías o promover su aparición. Probablemente este extremo climático sea a su vez el peligro natural menos entendido, que cuenta con unas características propias que le diferencian del resto por varios aspectos. En este contexto, aunque hay multitud de definiciones de sequía, no existe una definición universal, siendo éstas dependientes de la perspectiva disciplinaria a través de la cual se estudia o de los sectores afectados. Frecuentemente se distinguen diferentes tipos de sequía que se encuentran interrelacionados entre sí causando diversas consecuencias a lo largo del ciclo hidrológico a medida que las anomalías pluviométricas se propagan a través del mismo (sequía meteorológica, agrícola, hidrológica y socioeconómica, y más recientemente descritas la sequía subterránea y ecológica). Además, al tratarse de un fenómeno lento y progresivo, es difícil definir y establecer el comienzo y final de un evento de sequía y muchos de sus impactos son indirectos, acumulados en el tiempo y difusos, pudiendo extenderse por grandes áreas geográficas, dificultando todo ello su análisis. Así, diversos índices de sequía han sido diseñados,

siendo una herramienta fundamental para el monitoreo y caracterización de las sequías, así como para la estimación de los riesgos asociados. Sin embargo, hay una falta de consideración en evaluar cuáles de ellos son los mejores proxys para reflejar los impactos de la sequía en determinados aspectos de la salud humana y qué escalas temporales son las que mejor se ajustan para describir esos efectos.

En el campo de la salud pública, la ocurrencia de este extremo hidroclimático está cada vez más asociada a un mayor riesgo de morbilidad y mortalidad a través su impacto en el medio ambiente y los ecosistemas mediante la disminución de la disponibilidad y calidad del agua, la reducción en la producción de alimentos, reducción de la calidad del aire y aumento del riesgo de incendios forestales, especialmente bajo condiciones de altas temperaturas. Por lo tanto, los impactos de la sequía en la salud son indirectos y estos podrían verse incrementados con la aparición de otros eventos concurrentes o en cascada. Entre ellos se han descrito un mayor riesgo de enfermedades transmitidas por el agua y alimento, enfermedades trasmitidas por vectores, malnutrición e inseguridad alimentaria, exacerbación de enfermedades respiratorias y circulatorias asociadas a la reducción de la calidad del aire, así como graves impactos económicos, e importantes efectos en la salud mental. En último término dichos efectos podrían resultar en mayor mortalidad, especialmente en poblaciones vulnerables.

Mientras tanto, la vulnerabilidad está fundamentalmente determinada por factores ambientales, económicos y sociales, dependiendo en gran medida del grado de preparación y adaptación de la población, así como de su estado de salud previo. Particularmente, los países de bajos ingresos, trabajadores agrícolas cuya subsistencia dependa principalmente de la agricultura, refugiados, niños menores de cinco años, ancianos, personas con enfermedades crónicas preexistentes son los grupos más vulnerables y de mayor riesgo a los impactos de la sequía. Además, también se han descrito diferencias entre hombres y mujeres, siendo en particular las mujeres (especialmente embarazadas) las más vulnerables a los impactos de extremos climáticos como la sequía, sin embargo, la relación entre vulnerabilidad y género es compleja y hay una amplia variabilidad regional. Los países subdesarrollados son los más afectados y donde ocurre la mayor carga de mortalidad asociada a la ocurrencia de este peligro climático. Sin embargo, las sequías ocurren tanto en países en vías de desarrollo como en países desarrollados, y los países ricos también están notablemente impactados por la sequía, que resulta en severas pérdidas económicas cada año.

El objetivo principal de esta tesis de investigación es el análisis exhaustivo del impacto de diferentes condiciones de sequía medidas por dos índices estandarizados calculados a diferentes escalas temporales sobre la mortalidad diaria por causas naturales, circulatorias y respiratorias en la Península Ibérica. Para ese propósito, se tuvieron en cuenta variables como el género o la edad, en un estudio particular, así como el control de otros factores climáticos frecuentemente asociados a eventos de sequía como las temperaturas de ola de calor y la contaminación atmosférica.

La Península Ibérica es una región idónea para llevar a cabo este estudio, donde la sequía es descrita como un problema de gran relevancia. Además, existen diferentes patrones espaciales de sequía a lo largo del territorio, evidenciándose en general un marcado gradiente norte-sur. En términos de los mecanismos ambientales que podrían vincular la sequía con la salud, la Península Ibérica sufre de recurrentes olas de calor e incendios forestales, con fuertes impactos sobre la mortalidad por causas respiratorias y circulatorias, que además y debido a su localización geográfica se ve frecuentemente afectada por intrusiones de polvo del Sahara, con notables impactos en la salud. Por otro lado, en función de las características demográficas que podrían influenciar en un mayor impacto de la sequía sobre la mortalidad en la Península Ibérica, España y Portugal muestran una pirámide de población en forma de bulbo con un porcentaje de población envejecida (mayor 65 años) relativamente elevado. Es por esto que, además, este estudio de investigación está adicionalmente motivado por el hecho de que hasta la actualidad no existía ningún trabajo llevado a cabo en Europa que analice los detalles de la relación entre la sequía y diferentes causas de mortalidad, especialmente basado en el análisis comparativo de diferentes índices de sequía y escalas temporales para la identificación y cuantificación del impacto. Además, la Península Ibérica es una de las regiones del sur de Europa donde se prevé un notable incremento en la frecuencia y severidad de la sequía, constatando todo ello la importancia y necesidad de este trabajo.

Para llevar a cabo el propósito de esta tesis se propusieron varios objetivos particulares que fueron abordados individualmente en cinco trabajos, tres de ellos publicados y dos enviados, bajo revisión por pares, y que se presentan en este manuscrito de tesis como un compendio de los mismos.

El primero de ellos establece un marco conceptual de la relación entre las sequías y diversos aspectos de la salud humana, desde un punto de vista global, estableciendo una breve discusión de diversos desafíos para futuras investigaciones.

Posteriormente se llevó a cabo un análisis sobre los efectos de diferentes condiciones de sequía en la mortalidad diaria por causas naturales, circulatorias y respiratorias evaluando el rendimiento de diferentes índices de sequía obtenidos a diferentes escalas temporales desde una perspectiva regional, en las provincias de Galicia, extendiendo después el análisis a escala nacional para todas las provincias de la España peninsular y posteriormente realizando un estudio en el distrito de Lisboa, Portugal, para el cual los datos de mortalidad se pudieron segregar por edad y género.

Se llevaron a cabo estudios de series temporales para la cuantificación de los riesgos de mortalidad diaria asociados a eventos de sequía utilizando Modelos Lineales Generalizados (GLMs) con el link Poisson. Los periodos de estudio de cada trabajo variaron en función de la disponibilidad de los datos de mortalidad y/o contaminación atmosférica. La variable dependiente usada fue la mortalidad diaria por causas naturales (CIE10: A00-R99), circulatorias (I00-I99) y respiratorias (J00-J99), cuyos datos fueron proporcionados por los Institutos Nacionales de Estadística de España y Portugal.

Para el estudio regional de Galicia se utilizó la tasa de mortalidad diaria de cada provincia para el periodo 1983 a 2013, mientras que el número total diario fue el utilizado en el estudio llevado a cabo para todas las provincias de la España peninsular (referido al número de defunciones de la capital y de municipios con más de 10000 habitantes de cada provincia) para el periodo 2000-2009, y en el distrito de Lisboa para 1983-2016. En Lisboa se llevó a cabo un análisis adicional por género y grupos de edad (45-64, 65-74, >75).

Como variable independiente se utilizaron dos índices de sequía meteorológicos ampliamente utilizados para su identificación: el índice de Precipitación Estandarizada (SPI, de sus siglas en inglés), basado en datos de precipitación, y el índice de Precipitación Evapotranspiración Estandarizado (SPEI, de sus siglas en inglés), calculado a partir del procedimiento de cálculo de SPI e incorporando un balance hidroclimático (precipitación menos evapotranspiración). Ambos se basan en una variable normal estandarizada y tienen la ventaja de ser multiescalares, por lo que pueden ser comparables en espacio y tiempo. Las diferentes escalas temporales reflejan la cantidad de déficit hídrico durante diferentes periodos de acumulación, permitiendo identificar diferentes tipos de sequía. La nomenclatura utilizada en estos trabajos fue SPI-n/SPEI-n, siendo n la escala temporal. De acuerdo con las escalas de tiempo utilizadas en los diferentes estudios, SPEI y SPI se obtuvieron a corto (1 mes de acumulación) y a corto-medio plazo (3 meses de acumulación), y en Galicia, ambos índices fueron obtenidos también a medio (6 meses de acumulación) y largo plazo (9 meses de acumulación). Tanto SPEI como SPI pueden detectar condiciones húmedas (valores positivos de los índices) y secas (valores negativos). En particular para el estudio regional llevado a cabo en Galicia, las series fueron adicionalmente categorizadas en base a dos niveles de severidad (moderada y alta). La resolución de los índices de sequía suele presentarse a escala mensual, aunque últimamente diferentes estudios ajustan los datos mensuales a semanales, y dado que para los trabajos referentes a salud las series son diarias se construyeron series a esta última escala, asumiendo las mismas condiciones para cada intervalo de siete días.

Se incluyó el control adicional del efecto de las olas de calor y de la contaminación atmosférica (concentraciones medias de PM_{10}, NO_2, O_3 ($\mu g/m^3$)), para los periodos de contaminación disponibles (2000-2009 para todas las provincias de la España peninsular, y 2007-2016 para el distrito de Lisboa). Las temperaturas asociadas a las olas de calor fueron calculadas a partir de los datos de temperaturas máximas diarias (T*max*) y de la temperatura de disparo de la mortalidad asociada al calor (T*threshold*). Se utilizaron los valores de T*threshold* de cálculos ya disponibles en trabajos previos para cada provincia de la España peninsular, sin embargo para el distrito de Lisboa, y siguiendo la misma metodología de cálculo de los mismos, se obtuvo su valor haciendo uso de un modelo ARIMA, para obtener la serie de residuos de mortalidad por causas naturales. Estos valores de los residuos tienen la peculiaridad de no poseer ni tendencia ni estacionalidad, por lo que cualquier asociación observada se deberá a una relación real mortalidad-temperatura. Posteriormente, y a través de la representación de un diagrama de dispersión se determinó la temperatura umbral de mortalidad asociada al calor (34ºC), a partir de la cual la mortalidad comienza a incrementarse significativamente. En términos de su efecto sobre la mortalidad esta temperatura (T*hwave*) se determinó de la siguiente forma:

$$Thwave = Tmax - Tthreshold \qquad \text{si } Tmax > Tthreshold$$

$$Thwave = 0 \qquad \text{si } Tmax \leq Tthreshold$$

Por otro lado, a diferencia de PM_{10} (partículas con un tamaño aerodinámico de menos de 10µg/m^3) y NO_2 (dióxido de nitrógeno) que poseen una relación lineal con la mortalidad, el ozono (O_3) muestra una relación en forma de U similar a la observada con la temperatura. Por ello, una nueva variable fue creada (denominada O_{3a}) en función del valor umbral de la mortalidad asociada a concentraciones de ozono para el periodo de estudio pertinente (O_3*threshold*). En la España peninsular los valores de O_3*threshold* ya han sido previamente calculados y fueron tomados de estudios previos, mientras que para el distrito de Lisboa fue de nuevo determinado para éste mediante la elaboración de un diagrama de dispersión donde se representó en el eje de abscisas la concentración media diaria del ozono y en el eje de ordenadas la mortalidad media correspondiente a esas concentraciones de ozono. El valor umbral de la concentración diaria de ozono estadísticamente significativo correspondió al valor mínimo de la función cuadrática ajustada. A partir de 67 µg/m^3 la mortalidad incrementó significativamente asociada a incrementos en las concentraciones de este contaminante. La nueva variable parametrizada del ozono (O_{3a}) utilizada en los modelos estadísticos se calculó de la siguiente forma:

$$O_{3a} = O_3 - O_3threshold \qquad si\ O_3 > O_3threshold$$

$$O_{3a} = 0 \qquad si\ O_3 \leq O_3threshold$$

Como el impacto de las olas de calor y de la contaminación atmosférica puede no ser inmediato, se tuvieron en cuenta diferentes retardos diarios (lags): 1 a 4 días para la temperatura de ola de calor, 1 a 5 días para PM_{10} y NO_2, y 1 a 9 días para el ozono (O_{3a}).

Otras variables fueron también consideradas en los modelos estadísticos, como la tendencia de la serie, la estacionalidad y la naturaleza autorregresiva de la mortalidad diaria por cada causa analizada (autorregresivo de primer orden).

El proceso estadístico es similar para todos los análisis por provincia de la España peninsular y distrito de Lisboa, se basó en aplicar modelos Poisson independientes para cada índice de sequía (y para escala temporal), individualmente para cada causa de mortalidad. Primero se evaluó el efecto de la sequía sobre la mortalidad diaria y posteriormente se incluyeron en los modelos el control a corto plazo de la temperatura de ola de calor y contaminación atmosférica. Estos modelos permitieron el cálculo de los riesgos relativos (RR), calculados para cada unidad de incremento de la variable ambiental estadísticamente significativa (SPEI/SPI, T*hwave*, PM_{10}, NO_2, O_3a), y a partir de los valores de riesgo relativo vinculados al índice de sequía se calcularon los porcentajes de riesgo atribuible (RA), representando el porcentaje en el incremento en mortalidad diaria asociado con la sequía en la población expuesta a este factor ambiental de riesgo. Para determinar las variables significativas se llevó a cabo el procedimiento de "*backward-step*" (en español "paso atrás"), comenzando con un modelo que incorporó todas las variables explicativas, eliminando de forma individual y gradualmente aquellas con menor significación estadística, hasta obtener un modelo final con todas las variables estadísticamente significativas (con un nivel de confianza superior a un 95%), manteniéndose el control del autorregresivo. En el distrito de Lisboa estos modelos se realizaron de forma independiente para cada género y grupos de edad.

Para sintetizar e integrar los resultados de los estudios individuales por provincias de un modo global, en el caso de la España peninsular además se llevó a cabo un estudio cuantitativo de meta-análisis de efectos aleatorios. En este análisis se combinaron los riesgos relativos de mortalidad provinciales asociados a condiciones de sequía obtenidos en los modelos Poisson para obtener tanto un valor de riesgo a nivel nacional (para cada causa de mortalidad utilizando independiente cada tipo de índices de sequía y escala de 1 y 3 meses), como un valor de riesgo conjunto para diferentes categorías espaciales en base a diferentes criterios. España administrativamente está dividida en áreas territoriales intermedias (Comunidades Autónomas), es por esto que se realizó la combinación de riesgos relativos provinciales para cada una de ellas, que proporcionará información útil para las administraciones autonómicas de salud pública que se encuentran transferidas desde el Gobierno de España. Por otro lado, se combinaron los riesgos relativos en función del patrón espacial de distribución de la sequía para los índices SPEI y SPI obtenidos para escalas de tiempo de 1 y 3 meses. Finalmente, y a falta de datos de series de mortalidad segregadas por edad (como en el caso del distrito de Lisboa) se consideró la proporción de población de 65 años y mayor edad para categorizar las provincias de la España peninsular en cuatro grupos para estimar el impacto de la sequía en la mortalidad considerando indirectamente la edad, a través del nivel de envejecimiento de la población.

Particularmente en el estudio regional llevado a cabo en Galicia, para el periodo 1983 a 2013, los eventos de sequía medidos mediante los dos índices utilizados (SPEI y SPI) se asociaron significativamente a la mortalidad diaria por causas naturales, circulatorias y respiratorias, con especial impacto sobre las dos últimas. Sin embargo, hubo marcadas diferencias entre lo obtenido para las regiones del interior y las costeras. En las provincias de interior (Lugo y Ourense) el impacto en la mortalidad debido a las sequías fue mayor, tanto a corto, mediano como a largo plazo, mientras que sólo se detectó una asociación estadísticamente significativa entre la mortalidad por causas circulatorias bajo condiciones de sequía prolongada (9 meses) en la provincia costera de A Coruña. En Lugo (donde se contabilizó un mayor número de días con sequía, y de días de sequía severa y extrema) y en Ourense, los efectos en la mortalidad se manifestaron principalmente para escalas temporales más cortas (1 y 3 meses de acumulación). Además, en general el impacto se asoció principalmente a un nivel de severidad alto de sequía para estas provincias de interior. En contraste, en Pontevedra (litoral), donde se contabilizó el menor número de días de sequía, no se evidenció ninguna asociación estadísticamente significativa entre la ocurrencia de sequías y mortalidad diaria. Bajo el control adicional a corto plazo de las olas de calor y la contaminación atmosférica que suelen ir acompañando a los eventos de sequías, en Ourense el impacto de la sequía se explicó principalmente por el efecto de la contaminación atmosférica (en Lugo no había datos disponibles de contaminación). Los resultados obtenidos con SPEI y SPI fueron similares a lo largo de todo el estudio, por lo que en esta región ambos tipos de índices parecen ser igualmente válidos para la identificación del riesgo de mortalidad diaria asociada a la ocurrencia de sequías.

Se extendió de manera similar este análisis a todas las provincias de la España peninsular para el periodo 2000 a 2009, evaluando el impacto de la sequía medida a corto plazo (1 mes) sobre la mortalidad diaria. Se observó, en general un efecto significativo entre la ocurrencia de este extremo hidroclimático medido tanto por SPEI como por SPI y las diferentes causas de mortalidad analizadas, con un mayor impacto sobre la mortalidad por causas respiratorias. Sin embargo, la mortalidad por causas circulatorias fue la causa menos asociada a eventos de sequía. A lo largo del territorio se observó una clara heterogeneidad en términos de impacto, siendo las provincias ubicadas al Oeste las más afectadas. Por otro lado, cuando se controló el efecto de las olas de calor y la contaminación atmosférica en las provincias donde hubo una asociación significativa entre sequía y mortalidad previa, los principales resultaros indican que el impacto de la sequía se explicó principalmente por el efecto asociado a las mismas del aumento de la contaminación atmosférica (y en algunos casos también por el efecto de olas de calor) para un número considerable de provincias, mientras que para otras, la mortalidad diaria se mantuvo influenciada por la sequía, independientemente del control de la contaminación y las olas de calor.

El análisis comparativo de los resultados a nivel nacional, utilizando un estudio de meta-análisis, indica que usando tanto SPI como SPEI a 1 y 3 meses de acumulación, la sequía influyó significativamente en la mortalidad debido a las tres causas estudiadas en esta investigación. Los resultados obtenidos mostraron diferencias notables (aunque no significativas) en la magnitud de los riesgos de mortalidad en función de la escala temporal de la sequía utilizada, con un mayor impacto en las causas respiratorias a corto-medio plazo.

Los valores del riesgo relativo a nivel nacional mostraron una perspectiva general, pero el análisis a nivel provincial o por categorías territoriales intermedias reflejó una gran heterogeneidad. Comparando los resultados para sequías a corto y corto-medio plazo (1 y 3 meses, respectivamente) a nivel provincial en general se observaron valores de riesgos relativos vinculados a sequías medidas con SPI-3 y SPEI-3 más altos (o similares) que los obtenidos utilizando SPI-1 y SPEI-1. Sin embargo, el número de provincias donde se detectó una asociación estadísticamente significativa entre sequía y mortalidad varió en algunos casos. Así, se detectó un menor número de provincias afectadas con el uso de SPEI-3 (comparado con SPEI-1) para causas naturales, y un mayor número de provincias afectadas para causas circulatorias con el uso de SPI-3 (comparado con SPI-1).

Por otro lado, en base a los riesgos obtenidos para grupos territoriales más amplios se evidenció que, considerando una escala administrativa territorial intermedia (a nivel de autonómico), Galicia, Castilla y León y Extremadura fueron las Comunidades Autónomas más afectadas en términos de mortalidad por las diferentes causas, a diferencia de lo observado en Cataluña, Comunidad de Madrid y Principado de Asturias. Además en la Comunidad Valenciana y la Región de Murcia no hubo ninguna asociación significativa. Otras Comunidades Autónomas como Andalucía o País Vasco fueron también notablemente impactadas. En particular, Castilla y León mostró un incremento significativo del impacto sobre la mortalidad por causas respiratorias de eventos de sequía medidos con SPI-3, en comparación SPI-1.

Desde un punto de vista climático, y basada la clasificación regional en función de los diferentes patrones espaciales de la sequía, se observó que en el Noroeste, Centro y Sur las sequías tuvieron una mayor influencia en la mortalidad por todas las causas analizadas, en contraste con lo observado en el Este donde no se observa ninguna relación. Además, en el Noroeste, hubo un incremento significativo del impacto de la sequía sobre la mortalidad por causas respiratorias cuando ésta fue medida para escalas temporales a corto-medio plazo.

Desde un punto de vista demográfico, en las regiones con una mayor proporción de población envejecida se reflejó el mayor riesgo de mortalidad diaria vinculado a eventos de sequía. Además, de forma comparativa, el impacto fue mayor para la escala temporal de 3 meses siendo significativo a un nivel de confianza del 95% en el Noroeste para causas respiratorias con el uso de SPEI-3 y al borde de la significación con SPI-3.

Para completar el análisis peninsular se estudió el efecto de las sequías en la mortalidad diaria en el distrito de Lisboa, siendo esta la región más poblada de Portugal. Además, este estudio permitió analizar las diferencias de los riesgos en función de la edad y género, aportando un mayor detalle de los grupos de población afectada y por tanto más vulnerable a las sequías en términos de mortalidad. En el distrito de Lisboa, las sequías medidas a corto y corto-medio plazo también se asociaron a las causas naturales, circulatorias y respiratorias, siendo los adultos de mayor edad (>75 años) los más fuertemente impactados. A corto plazo, el impacto de la sequía se explicó por el efecto asociado de la contaminación atmosférica y las olas de calor. Sin embargo, cuando se consideró el análisis por género y edad, la mortalidad diaria permaneció significativamente influenciada por la sequía bajo el control del efecto de la contaminación atmosférica y olas de calor en grupos de la población total y masculina. . Además, hubo diferencias en el efecto de la sequía considerando el género, que variaron en función del periodo de estudio considerado. Para el periodo largo 1983-2016, para las mujeres se detectó influencia significativa de la sequía medida a corto plazo en la mortalidad diaria por causas circulatorias, no encontrada en hombres, mientras que para la población masculina la mayor afectación se observó para las causas respiratorias. Sin embargo para el periodo más corto de 2000-2009 en el que la disponibilidad de datos de contaminación permiten acoplarla a los efectos de la sequía, se observa que en general la sequía a corto plazo tuvo mayor influencia sobre la mortalidad por todas las causas analizadas en los hombres que las mujeres. En este contexto, en la población masculina los efectos fueron significativos para los grupos de edad de 65-74 años y mayores de 75, mientras que en las mujeres sólo para aquellas mayores de 75 años. Además, especialmente para la mortalidad por causas respiratorias no se encontró una asociación significativa entre sequías medidas a corto plazo y mortalidad en mujeres durante 2000 a 2009.

En el caso del distrito de Lisboa, los resultados indican que SPEI detecta mejor los riesgos debidos a la sequía en la mortalidad diaria de la población en comparación con SPI. Además, atendiendo a la escala temporal en términos comparativos se observó que la escala temporal de SPEI más corta reflejó un mayor número de asociaciones estadísticamente significativas entre sequía y mortalidad diaria entre los diferentes grupos de la población, mientras que para SPI esto se observó para la escala temporal de corto-medio plazo. Con esto, a diferencia de lo obtenido para la España peninsular, la inclusión de la evapotranspiración potencial en el cálculo de SPEI le convierte en un índice que asocia mejor el efecto de la sequía en la mortalidad diaria en la población de Lisboa.

Teniendo en cuenta la creciente amenaza de las sequías en consideración con proyecciones futuras de cambio climático, hace que la inclusión de resultados como los obtenidos en este trabajo de tesis sea recomendable en las estrategias de las administraciones públicas en términos de salud, para poder abordar los diferentes riesgos asociados en la salud de la población, mitigar sus efectos y reducir la vulnerabilidad, especialmente entre los grupos más susceptibles. En base a los principales hallazgos obtenidos en este estudio de investigación sería necesario elaborar un plan de acción proactivo integrado (tanto a nivel nacional como regional), a través de un enfoque que incluya sistemas de alerta y vigilancia de la salud pública contra diversos fenómenos extremos relacionados con el clima y que además pueden ser concurrentes como olas de calor, condiciones de sequía o episodios de contaminación, protegiendo la salud desde un punto de vista integral. Estos deben ser diseñados "ad hoc" y contextualizados en función de las características de la región y de los grupos de población. Además, es de crucial importancia la consideración de la edad y de la perspectiva de género en los planes de adaptación contra los efectos en la salud de fenómenos extremos.

La estructura de esta tesis de doctorado presentada en la modalidad por compendio de artículos de investigación, se compone de cinco capítulos en el orden que a continuación se describe: la **sección 1** refleja una introducción general en el que se indica el fundamento de este trabajo, incluyendo información sobre la descripción y métrica de la sequía y su vínculo sobre diversos aspectos de la salud humana; la **sección 2** indica el objetivo principal de la tesis y de las tareas llevadas a cabo a lo largo del periodo de investigación; la **sección 3** incluye una descripción detallada de la metodología empleada para la identificación de eventos de sequía y la cuantificación de su impacto en las diferentes causas de mortalidad analizadas en este estudio incluyendo una información detallada sobre los datos utilizados y las variables controladas en el proceso de análisis; la **sección 4** describe el compendio de los "cinco" manuscritos, tres de ellos publicados en revistas especializadas incluidas en la lista de *Journal Citation Reports (JCR)* y dos enviados bajo revisión; en la **sección 5** se exponen las principales conclusiones obtenidas, que junto con el material suplementario y la lista de referencias completan el presente documento.

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ACRONYMS

AEMET: Spanish National Meteorological Service (Agencia Estatal de Meteorología)

AR: Attributable Risk

CSIC: Spanish National Research Council (Consejo Superior de Investigaciones Científicas)

ECA&D: European Climate Assessment & Dataset Project

EEA: European Environment Agency

GLMs: Generalised linear models

ICD10: International Classification of Diseases, 10th revision

INE: National Statistics Institute (From Spain/Portugal: Instituto Nacional de Estadística/Estatística)

IPCC: Intergovernmental Panel on Climate Change

MAPAMA: Spanish Ministry of Agriculture and Fisheries, Food and Environment (Ministerio de Agricultura y Pesca, Alimentación y Medioambiente)

NNCDC CDO: National Oceanic Administration Agency's National Climate Data Center. Climatic Data Online

NO_2: Nitrogen dioxide

NUTS: Nomenclature of Territorial Units for Statistics

O_3: Ozone

O_{3a}: Ozone concentration in reference to the ozone effect on mortality

O*threshold*: Ozone threshold for daily mortality associated with ozone concentrations

PDSI: Palmer Drought Severity Index

P: Precipitation

PET: Potential Evapotranspiration

PM_{10}: Particulate matter with an aerodynamic diameter of less than 10 µm

RR: Relative risk

SCPDSI: Self-Calibrating Palmer Drought Severity Index

SPDI: Standardised Palmer Drought Index

SPEI: Standardised Precipitation Evapotranspiration Index

SPI: Standardised Precipitation Index

T*hwave*: Temperature for heatwave

T*max*: Maximum temperature

T*threshold*: Temperature threshold for daily mortality associated with heat

USA: United States of America

USDM: United States Drought Monitor

WHO: World Health Organization

WMO: World Meteorological Organization

1

INTRODUCTION

1.1. Overview of the climate change-drought-health nexus

Climate change is one of the most substantial environmental challenges worldwide (Ebi and Bowen, 2016; Tong and Ebi, 2019). The frequency and intensity of extreme climatic events and hazards, such as heatwaves, droughts, floods, cyclones, dust intrusions, or forest fires, can be increased as a consequence of climate change, thereby leading to far-reaching environmental, economic, and social effects (Watts et al., 2015; Bell et al., 2018; Gupta et al., 2019; Linares et al., 2020a), especially when a combination of these events occur (Raymond et al., 2020; Zscheischler et al., 2020).

Moreover, there is evidence indicating with a high level of confidence that both human health and well-being are extremely vulnerable to climatic modifications (McMichael and Lindgren, 2011; Patz et al., 2014; IPCC, 2019). In particular, the Lancet report (Watts et al., 2017) on climate and health, titled "The Lancet Countdown: tracking progress on health and climate change", begins with the phrase "*The World Health Organization (WHO) estimated that, in 2012, 12.6 million deaths (23% of all deaths worldwide) were attributable to modifiable environmental factors, many of which could be influenced by climate change or are related to the driving forces of climate change*". Moreover, the WHO's report in 2020 added that between 2030 and 2050, climate change is expected to cause approximately 250,000 additional deaths per year from malnutrition, malaria, diarrhoea, and heat stress alone. In addition, the direct costs of damage to health could be approximately 2–4 billion USD/year by 2030 (WHO, 2020a).

These WHO statistics verify that the study of the connection of climatic factors with health is essential for public health services, especially considering that observed and predicted climate change will act as a multiplying factor for health threats (Watts et al., 2017; 2019; WMO, 2020; Woetzel et al., 2020).

Among the different climatic extremes, drought is widely considered the most complex, costliest, and destructive natural hazard, which affects more people than any other climatic phenomenon and involves notable impacts on morbidity and mortality worldwide (Obasi, 1994; Wilhite, 2000; Kallis, 2008; IPCC, 2014; Watts et al., 2019). As much as 15% of natural disasters globally are caused by droughts, and the mortality related to droughts represents approximately 59% of the total deaths caused by extreme weather events (McCann et al., 2011). In addition, data from the Emergency Events Database also indicated that international droughts and the resulting famines have caused more deaths than any other climatic hazard (Bell et al., 2018). Meanwhile, according to the WHO, an estimated 55 million people globally are affected by droughts every year (WHO, 2020b). In particular, the recent report of the United Nations World Water Development indicated that between 2001 and 2018, approximately 1.26 billion people were affected by around 290 drought events worldwide (UNESCO, 2020). Moreover, under global warming, it is projected that the share of a decade spent in drought conditions will increase and reach up to 80% in some parts of the world by 2050, and be especially remarkable in parts of the Mediterranean, southern Africa, and Central and South America (Woetzel et al., 2020), which could involve increased threats to the environment and human health and well-being. In this context, it has been indicated that climate change (and population changes) could involve an increase of 1.4 billion people exposed to drought episodes per year by the end of this century (Watts et al., 2015).

Droughts occur both in developing and developed countries; however, the magnitude of the risks vary among different regions owing to social and economic inequities, with poor countries being the most affected (Kallis, 2008; Stanke et al., 2013; Quiring, 2015). Although the majority of drought-related fatalities (high burden of morbidity and mortality) occur in developing countries, resource-rich nations can also be affected by the negative impacts associated with the incidence of this type of hydrological extreme through heat stress or severe economic impacts (Keim, 2015; Luber and Lemery, 2015;

EEA, 2019; UNDRR, 2019). From a global point of view, Kallis (2008) pointed out that Asia is the continent where a greater number of people are affected and Africa is where more drought disasters and higher mortality occur, while economic effects have principally been reported in the West. Significant economic losses have been described in several regions such as the United States of America (USA), Europe, China, and Brazil owing to the occurrence of drought periods (Alpino et al., 2016). Meanwhile, the Intergovernmental Panel on Climate Change (IPCC) reports indicate that health impacts linked to extreme climatic events may be reduced but not eliminated, and there will be a heterogeneous response based on socioeconomic means, the adaptive capacity of the population, and the underlying health status of the population (IPCC, 2014; 2019).

The occurrence of drought events can be caused by different climatic and social factors. Principally, prolonged precipitation deficiency and water shortages over extended periods of time promote drought (McCann et al., 2011; Stanke et al., 2013; Quiring, 2015), and other climatic variables (e.g. high temperatures) can enhance the intensity and aggravate drought periods through the increase in evapotranspiration (Wilhite, 2000; Vicente-Serrano et al., 2014). Moreover, anthropological activities such as deforestation, soil degradation, and poor land and water management can increase drought susceptibility and induce or exacerbate the severity of droughts and their effects, and the consequences of these activities can be exacerbated by the occurrence of droughts as well (Quiring, 2015; Brüntrup and Tsegai, 2017; Gebremeskel et al., 2019). In addition, socioeconomic resources, infrastructure, water-intensive industries, and population growth and movement can also increase the consequences of drought and exacerbate its severity (e.g. through higher water demand under reduced water availability and quality conditions) (Smoyer-Tomic et al., 2004; Ebi and Bowen, 2016). Thus, the role of both the government and society in developing good measures of water management and promoting the responsible use of water are essential. This is particularly important with regard to future projections of climate change that indicate an increase in duration and intensity of droughts for the end of the 21st century in several regions worldwide such as Southern Europe, the Mediterranean region, Central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa, which are associated with reduced precipitation and/or increased evapotranspiration (Stanke et al., 2013; Yusa et al., 2015; Ebi and Bowen, 2016; IPCC, 2018). Moreover, a recent study has also indicated that drought frequency will be increased in many parts of the world, except for high latitudes in the Northern Hemisphere and Southeast Asia (Spinoni et al., 2020). In this context, it is expected that drought will become prevalent in the Mediterranean region, including the Iberian Peninsula, and that there will be a significant decrease in the surface water supply of more than 70% by 2050 in this region and others, such as the USA and Mexico, compared with that observed in 2018 (Woetzel et al., 2020). Drought is a recurrent feature of the European climate that markedly affects the population each year (EEA, 2020a). Moreover, an increase in heatwave days and drought conditions in southern Europe has been estimated for 2050 to 2100 in all scenarios of climate change, and in the high-impact scenario, future droughts could be up to 14 times worse than those observed in the last decades (Guerreiro et al., 2018). Furthermore, from a global point of view, approximately half of the world's population will live in conditions of water scarcity by 2025 (Bifulco and Ranieri, 2017); thus, health threats could increase in vulnerable regions, particularly if adequate mitigation and adaptation measures are not taken.

1.2. Complexity of drought phenomena

1.2.1. Difficulty in defining and characterising drought

Drought is a recurrent and slow extreme climatic event that results from a deficiency of precipitation over an extended period of time causing notable effects on a large number of environmental and social systems worldwide (Wilhite and Vanyarko, 2000; Quiring, 2015; Haile et al., 2020). Drought is the most complex and least understood natural hazard (Vicente-Serrano, 2016), as it is difficult to define and establish the beginning and end of each event (Kallis, 2008; Vicente-Serrano et al., 2020a). Despite more than 150 definitions, there is no consensus on a universally accepted concept, and many of the definitions depend on the different disciplinary perspectives, sectors, or systems in which it is analysed (Wilhite, 2000; Marcos Valiente, 2001; Mishra and Singh, 2010; Vicente-Serrano et al., 2012a; Bachmair et al., 2016). Thus, different types of droughts can be distinguished, thereby creating new challenges in the estimation of the different risks such as health effects due to each type of drought, which can affect health outcomes differently (Berman et al., 2017). Standard classifications (Table 1) measure droughts as a physical phenomenon, including meteorological, hydrological, and agricultural droughts; however, they can also include and track the effects of supply and demand of water for the population, which is a socioeconomic drought (Wilhite, 2000; Marcos Valiente, 2001; Dai, 2011; Stanke et al., 2013; MITECO, 2019). However, other types of droughts have recently been proposed, such as groundwater drought (Mishra and Singh, 2010) or ecological drought (Bachmair et al., 2016; Crausbay, 2017; Haile et al., 2020).

The different types of droughts are not independent; they are associated with and lead to different consequences through the hydrological cycle (Wilhite, 2000; Bachmair et al., 2016; Haile et al., 2020; Vicente-Serrano et al., 2020b) (Figure 1). The fact that drought is largely influenced by both environmental and human factors means that the drought concept should be understood in an interdisciplinary way as a socioenvironmental phenomenon, which is produced by mixtures of climatic, hydrological, environmental, socioeconomic, and cultural dimensions (Kallis, 2008; Quiring, 2015).

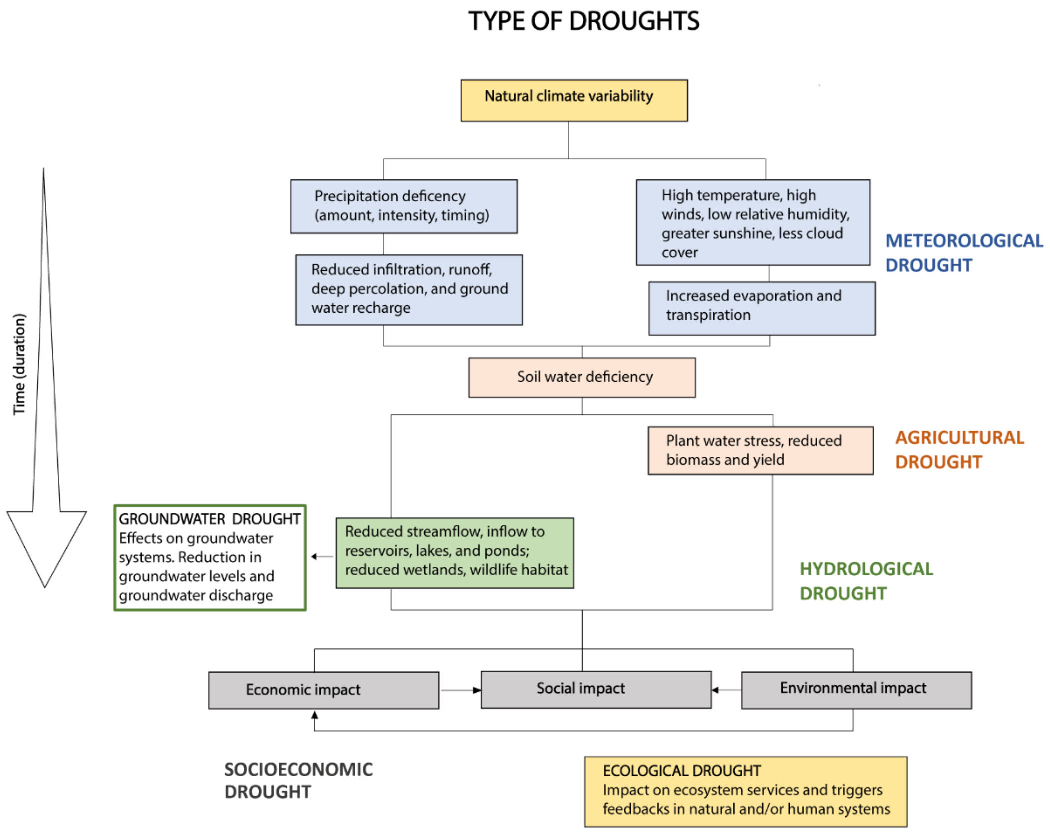

Figure 1. Types of drought and their effects and relationships. Adapted from Wilhite (2000).

1.2.2. Drought metric and estimation of risks: The role of drought indices

Droughts are widely considered to be slowly developing phenomena, and many of their effects are accumulated, indirect, diffuse, and often considered to be cascading impacts (Wilhite, 2000; Kallis, 2008; Mishra and Singh, 2010; Stanke et al., 2013; Ebi and Bowen, 2016; Spinoni et al., 2019). In addition, drought impacts vary both spatially and temporally and involve a wide variety of sectors (Wilhite et al., 2007; Dalezios et al., 2017), which makes it more difficult to quantify the drought effects on specific health aspects in comparison with those of other natural hazards, thereby making their assessment a great challenge.

Thus, drought indices are crucial for monitoring this hydrological extreme (characterising its severity, location, duration, and timing) as well as detecting, quantifying, and tracking the different impacts in order to obtain better knowledge and prepare to tackle drought risks (Vicente-Serrano et al., 2017). Multiple drought indices have been proposed for measuring different types of droughts (Keyantash and Dracup, 2002; Mishra and Singh, 2011; WMO and GWP, 2016), but there is a lack of studies that focus on examining the performance of different indices to determine which is the most accurate for measuring the type of drought with reference to its specific effects on particular systems, which is of critical importance (Bachmair et al., 2016).

An index commonly used is the Palmer Drought Severity Index (PDSI) (Palmer, 1965), which was a landmark in the development of other drought indices. It was developed to identify droughts in the USA agricultural regions, and is based on a soil water balance equation considering precipitation and temperature data within a two-layer soil model. This index can be used individually or in combination with other types of drought indicators to create new indices such as those used by the United States Drought Monitor (USDM), which was recently used to link drought conditions and the estimation of the risk of hospital admissions and mortality (Berman et al., 2017).

Table 1. Different definitions of drought based on its impacts on a specific sector or systems in which it is analysed.

Meteorological drought refers to the prolonged deficit of precipitation or an acute shortage of precipitation (below normal levels), and it can affect large areas. Its occurrence is determined by parameters such as the duration, severity, intensity, and periodicity, and it leads to other types of droughts. A meteorological drought occurs owing to multiple climatic causes, and high temperatures, strong winds, or low relative humidity are often associated with this type of drought, which can aggravate its severity (Wilhite, 2000). Moreover, meteorological drought is also linked to weather systems such as high-pressure systems and climate feedbacks that result in reduced precipitation (Haile et al., 2020).

Agricultural drought links the characteristics of meteorological or hydrological drought to agricultural impacts (e.g. reduced crop production and plant growth). It refers to a deficiency of soil moisture to satisfy particular crop needs (in any of its growth phases) (e.g. Marachi, 2000).

Hydrological drought is associated with the impacts of precipitation shortages on surface water or groundwater supplies (discharge deficit). This type of drought develops more slowly (e.g. Dai et al., 2011).

Groundwater drought occurs when groundwater systems are affected by water shortages (diminution of groundwater recharge, groundwater levels, and groundwater discharge over a prolonged period of several months or years) (e.g. Mishra and Sing, 2010). It can be treated as an additional category or be subsumed into hydrological drought (Bachmair et al., 2016).

Socioeconomic drought is based on the excess demand with respect to the supply for a specific economic good (e.g. water and hydroelectric power) as a consequence of a water shortage that affects people (e.g. Mishra and Sing, 2010; Haile et al., 2020).

Ecological drought refers to (and emphasises) the environmental consequences of episodes dominated by deficits of available water or moisture, thereby triggering feedbacks in natural and/or human systems (e.g. Crausbay, 2017).

The PDSI has been modified with several aims to create derived indices (Mishra and Singh, 2010; Vicente-Serrano et al., 2012a; WMO and GWP, 2016; NCEI, 2000), such as a) the Palmer Z Index, which responds to short-term drought conditions better than the PDSI; b) the Palmer Hydrological Drought Index (Karl, 1986), which measures long-term droughts reflecting hydrological effects; c) the modified PDSI (Heddinghaus and Sabol, 1991), which is an operational version of the PDSI; or d) the Self-Calibrating PDSI (SCPDSI) (Wells et al., 2004). Unlike the PDSI that was designed based on parameters applicable to USA regions, the SCPDSI calibrates the behaviour of the index in the function of the climatic regime of any place, thereby allowing spatial comparisons between different regions (Vicente-Serrano et al., 2012; WMO and GWP, 2016).

As different effects of droughts can vary in both space and time, several indices are widely used in the scientific literature, such as the Standardised Precipitation Index (SPI) (McKnee et al., 1993) and the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). The SPI is calculated from precipitation data, while the SPEI is based on precipitation and temperature data taking into account the atmospheric evaporative demand; both have the advantage of being able to be obtained at different timescales. The different scales reflect the quantity of water deficits during different periods of accumulation, which allows association with the different forms of droughts and thereby reflects the drought responses of different systems at the short, medium, and long term. One month of accumulation is used for meteorological droughts, 1 to 6 months is usually used for agricultural droughts, and 6 to 24 months or longer is used for hydrological droughts (Vicente-Serrano, 2016; Monteiro et al., 2019). Both indices are based on standardised normalised data; unlike the PDSI that has some limitations in spatial and temporal comparability, the SPEI and SPI are comparable in both space and time. However, a multiscalar SPDI has been also developed (Ma et al., 2014). There are other common drought indices such as the Soil Moisture Anomaly (Bachmair et al., 2016) or the Standardised Streamflow Index (Vicente-Serrano et al., 2012b), among others.

1.3. Drought effects on health and vulnerability

Droughts have far-reaching impacts across environmental, economic, and social sectors, which can have notable repercussions in public health; for instance, an exacerbation of existing chronic diseases, the increase in morbidity and mortality risk, or/and effects on human well-being (Sena et al., 2014; Quiring, 2015; Yusa et al., 2015; Alpino et al., 2016). These fingerprints can occur at different timescales; however, providing a clear classification of short and long-term effects is usually complex. Drought impacts can be direct, principally impacting the environment, or indirect, such as the majority of effects on human health. Both types are described in Section 1.3.1. and schematised in Figure 2.

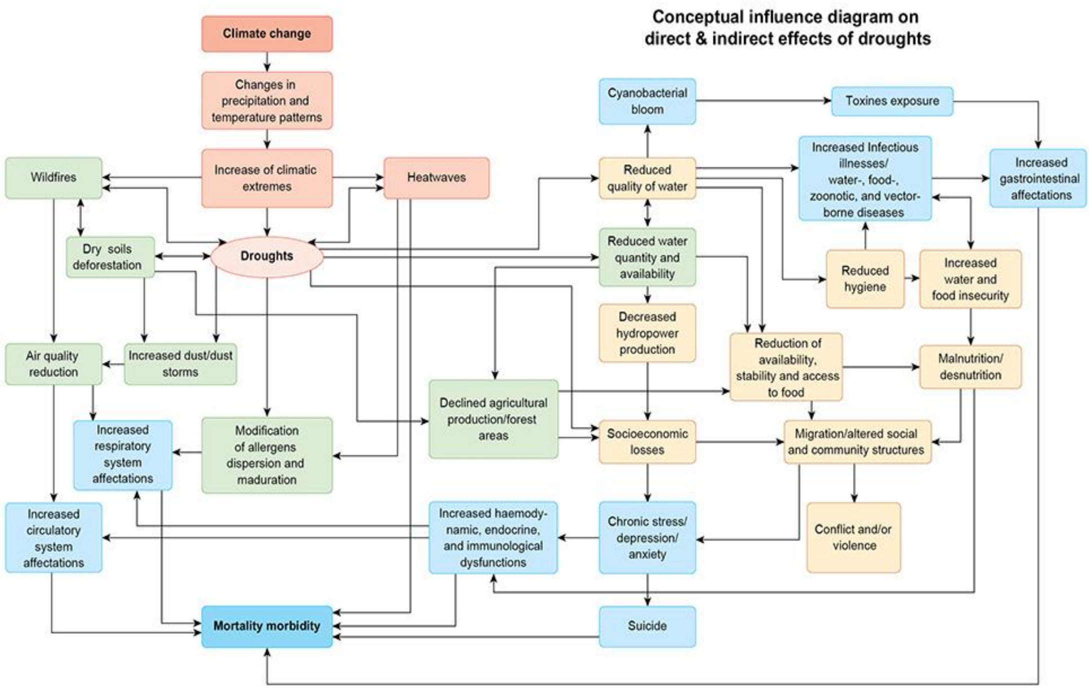

Figure 2. Conceptual influence diagram of the principal direct and indirect effects of droughts. From Salvador et al. (2020).

1.3.1. Vulnerability to drought

The risk and magnitude of the impacts of an extreme climatic event such as drought vary in relation to the exposure to the specific event in a given region (characterised by variables such as duration, severity, and intensity) and the vulnerability to the natural hazard (Wilhite, 2000; Handmer et al., 2012; Quiring, 2015; Alpino et al., 2016). Vulnerability is determined by different environmental, economic, and social factors, and can increase or decrease over time, so similar drought events can lead to different effects on the changes in population characteristics (Wilhite, 2000; Ebi and Bowen, 2016) (Figure 3). In particular, among these factors highlight the geographic location where the event occurs (which is characterised by specific local climatic and environmental conditions), demographic variables, health status, sensitivity, and adaptive capacity of the population, education, culture, social behaviours, science and technology, availability of healthcare, resource availability, and socioeconomic status (Kallis, 2008; Quiring, 2015; Ebi and Bowen, 2016). Several studies have shown that the negative effects of drought are in line with the level of development and degree of preparation of different countries in adapting to current and future climatic variability in different sectors (IPCC, 2014).

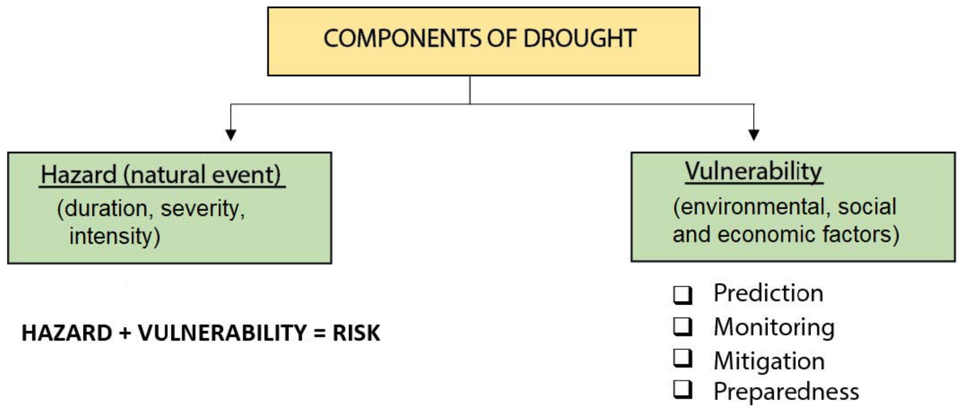

Figure 3. Components of drought. Adapted from Quiring (2015).

The geographic location is an important direct vulnerability factor. People that live in regions prone to drought or water shortages are especially vulnerable to health impacts attributable to this hydroclimatic extreme (Lohmann and Lechtenfeld, 2015). This is the case for arid or semiarid regions, such as the semiarid areas of Brazil where droughts are more frequent in comparison with the rest of the country and where people suffer greater repercussions in terms of health (Sena et al., 2014), or in African regions where the impacts can be exacerbated by the growth in population, as is expected for the next 30 years (Kraviz, 2017). In addition, droughts can cause heterogeneous health effects according to the climatic location, such as regions located in east vs. west, north vs. south, coastal vs. inland, or urban vs. rural areas (Obrien et al., 2014; Vins et al., 2015; Berman et al., 2017; Lynch et al., 2020).

Meanwhile, a comprehensive review conducted by Ebi and Bowen (2016) suggested the role of drought as a possible source of health vulnerability for subsequent hydrological extreme phenomena because an extreme event can alter vulnerability through changes in exposure degree or population susceptibility. If there is an inadequate recovery time for communities and an inadequate capacity of adaptive responses of the population and healthcare systems, then the vulnerability and health risks could increase. Berman et al. (2017) indicated a higher risk of mortality and cardiovascular hospital admissions among older adults in regions that previously suffered from a few drought events.

The literature indicates that agricultural workers and small producers (especially those whose subsistence depends on agriculture), destitute people such as refugees, pregnant women, children (particularly under 5 years old), elderly people, socially and economically disadvantaged communities, and people with chronic conditions are the groups most vulnerable to extreme events such as droughts (Edwards et al., 2015; Lohmann and Lechtenfeld, 2015; Yusa et al., 2015; Alpino et al., 2016). In addition, economic globalisation can also exacerbate their vulnerability (Kallis, 2008). Developing countries suffer from greater impacts of drought than developed countries. In this context, regions in Africa and southern Asia are the most vulnerable to food insecurity, diseases related to limited hygiene, and mortality during prolonged drought (Krishnamurthy et al., 2012; Bifulco and Ranieri, 2017). According to age, children are particularly affected by nutrition and mortality, thereby leading to negative repercussions during their adult life (Lohmann and Lechtenfeld, 2015). However, evidence shows heterogeneous differences between genders in terms of health impacts attributable to extreme climatic events such as extreme temperatures or drought, with women generally being the most affected. However, the relationship between vulnerability and gender is complex and a regional variability exists (IPCC, 2014; WHO, 2014; United Nations, 2019; Zhao et al., 2019). Race can also be a contributing factor to differences in the relationship between drought and mortality (Lynch et al., 2020).

1.3.2. Direct effects of drought: Environmental impacts

Droughts directly affect the environment and ecosystems through impacts on the quality, structure, and/or diversity of soil, air, vegetation, and water (Vicente-Serrano et al., 2020b). In particular, some environmental effects strongly associated with droughts are the reduction in water availability and quality, diminution of both soil and air quality, increase in wildfire occurrence, land degradation and desertification in semiarid regions, deterioration of forests, reduction in food production, and wildlife damage (Wilhite et al., 2007; IPCC, 2014; Vicente Serrano et al., 2020b). Droughts can also incorporate, or reflect, the effects of other related extreme climatic events, such as heatwaves and wildfires (Sutanto et al., 2020), and these concatenated effects can lead to feedbacks and accelerate the development of the drought, thereby increasing its severity or involving greater risks to human health when they are concurrent or cascading (Stanke et al., 2013; Bell et al., 2018). In this context, droughts and high temperatures frequently promote the occurrence of wildfires (He et al., 2014; IPCC, 2014; Franchini and Mannucci, 2015), which cause damaging effects on health (Finlay et al., 2012; Gasparrini et al., 2015a; 2015b; Black et al., 2017; Machado-Silva et al., 2020; Huber et al., 2020). Moreover, high temperatures have also been linked to cardiovascular and respiratory mortality (e.g. Díaz et al., 2015a, b; Cheng et al., 2019; Silveira et al., 2019). However, the mechanisms between these phenomena are complex, and they can occur even without the presence of a drought. Nevertheless, drought periods are frequently linked to the incidence of persistent atmospheric blocking and stagnant conditions (Vicente-Serrano et al., 2020b), which favour poor air quality (e.g. Pope et al., 2014; Russo et al., 2014; Ordoñez et al., 2017; Ormanova et al., 2020).

1.3.3. Indirect effects of drought: Health impacts

The health impacts associated with drought episodes are mainly indirect, and in extreme cases they can result in mortality, especially in vulnerable groups of people (Stanke et al., 2013; Sena et al., 2014; Yusa et al., 2015; Ebi and Bowen, 2016).

Health effects associated with the reduction in water quantity and quality

The most evident drought impacts derived from the reduction in water availability and quality (microbiological and chemical contamination) lead to an increased risk of infectious illness, particularly water, food, zoonotic, and vector-borne diseases (Hayes, 2002; Tirado-Blázquez, 2010; Yusa et al., 2015; Alpino et al., 2016; Grigoletto et al., 2016; Bell et al., 2018). Drought events cause stagnant water conditions that together with high temperatures can promote the increase in pathogens, thereby affecting population security (Bell et al., 2018). Moreover, the incidence of high temperatures and drought conditions can promote large blooms of toxin-producing cyanobacteria, thereby compromising health (Stanke et al., 2013; Yusa et al., 2015). Evidence has associated the occurrence of this hydrological extreme with water-borne diseases transmitted through faecal-oral pathways caused by bacteria and other pathogens (e.g. *Escherichia coli*, *Salmonella*, and *Vibrio cholerae*), thereby leading to diarrheal illness and gastrointestinal disorders (Bifulco and Ranieri, 2017; Bell et al., 2018). The decrease in water quality associated with drought can also be linked to higher chemical and pollutant levels, lower dissolved oxygen levels, and contamination of drinking freshwater sources with salt water in coastal regions, thereby threatening public health (Stanke et al., 2013; Bell et al., 2018; Vicente-Serrano et al., 2020b). Meanwhile, the limitation of water during drought periods can lead to poor hygiene and increase the risk of dermatological and parasitic infections and skin conditions (Yusa et al., 2015; Alpino et al., 2016; Grigoletto et al., 2016).

Vector-borne diseases

Another drought-related risk to health is the alteration of the ecology of vector-borne diseases. Although rainfall can substantially influence the risk of diseases transmitted by vectors, drought has also been associated with the higher risk of this type of diseases (Stanke et al., 2013; Alpino et al., 2016). In some extratropical regions across Europe and North America, vector-borne diseases can be promoted by climate change (increased temperatures and drier conditions) when climatic conditions are similar to those found in tropical regions where vector-borne diseases are endemic (particularly in territories close to affected regions) (López-Vélez and Molina-Moreno, 2005). A comprehensive review of the impact of drought on vector-borne diseases shows that drought can reduce predators and competitors of arthropod vectors and cause the increase in vector numbers following re-wetting conditions. In addition, mosquito vectors have the ability to rapidly adapt to climate variations, e.g. the exploration of additional aquatic habitats created during drought periods such as water storage containers in urban regions or the production of drought-resistant eggs (Brown et al., 2014). However, this review also indicated that tick vectors can be negatively affected by drought conditions because the majority of species depend largely on humidity and soil moisture. Furthermore, the impact of drought episodes on wildlife affects rodents and pests, which can spread to other territories in search of water sources, thereby leading to higher risks of contact with the human population and disease transmission (Hayes, 2002).

Reduction in food production and food insecurity

Droughts have been linked to food insecurity, malnutrition, and nutritional deficiencies (deficit of vitamins and micronutrients) as a result of the reduction in food production (e.g. livestock losses, fishing stock losses, and diminution of crop yields) and the quality and stability of food, which are influenced largely by the reduced availability and quality of water, land degradation, and limited hygiene (Krishnamurthy et al., 2012; Stanke et al., 2013; Lohmann and Lechtenfeld, 2015; Alpino et al., 2016; Grigoletto et al., 2016). Malnutrition, nutritional deficiencies, and diet changes can impair the immune system and lead to higher risks of morbidity and mortality, especially in vulnerable regions (Ebi and Bowen, 2010; 2016).

Respiratory and circulatory conditions linked to air quality

Droughts can also lead to the reduction in air quality (higher dust, ozone (O_3), or other pollutants such as particulate matter (PM)) through effects on atmospheric chemistry or increasing wildfire occurrence (Hayes, 2002; Wang et al., 2017; Vicente-Serrano et al., 2020b), which in turn has been associated with significant impacts on respiratory and circulatory systems, including mortality (e.g. Haikerwal et al., 2015; Linares et al., 2015; Reid et al., 2016; Bell et al., 2018; Linares et al., 2018a; Machado-Silva et al., 2020). Moreover, evidence exists indicating that wildfires and Saharan dust intrusions, which can occur mainly during the warmer season in Mediterranean areas (Faustini et al., 2015), also have significant impacts on variables related to pregnancy (number of births, low birth weight, and pre-term birth) not only through higher PM concentrations, but also owing to other factors linked to these phenomena, such as high temperatures or the increase in other pollutants such as nitrogen dioxide (NO_2) and O_3 (Moreira et al., 2020). Drought and high winds may produce windborne dust and suspended materials in the atmosphere (e.g. particulates or allergens) and transport them to other regions (Sena et al., 2015), thereby compromising the respiratory health of the population (IPCC, 2014). Thus, droughts can exacerbate respiratory disorders such as allergies, inflammation processes, bronchitis, and pneumonia, particularly in vulnerable people, e.g. people with common chronic pathologies (Grigoletto et al., 2016), and contribute to circulatory issues (Stanke et al., 2013; Bell et al., 2018). In addition, drought periods are usually associated with persistent anticyclonic situations and stagnant conditions that lead to higher atmospheric pollutant concentrations such as PM, O_3, or NO_2 (Thishan Dharshana et al., 2010; AIRPARIF, 2016; Ordoñez et al., 2017) with significant impacts on morbidity and/or mortality (Díaz and Linares, 2018; Hooper and Kaufman, 2018; Díaz and Linares, 2019).

In particular, a recent study conducted in the western USA assessed the impacts of drought (the first study linking a drought multiple index, those supported by the USDM, to human health) on the risk of mortality and respiratory and cardiovascular hospital admissions among older adults (Berman et al., 2017). This study showed a significant increase in mortality risk during high-severity worsening drought, but a decrease in respiratory hospital admissions, which was controversial with other studies such as those conducted by Smith et al. (2014), Yusa et al. (2015), or Alpino et al. (2016). These discrepancies corroborate the effect of local factors on different afflictions; for instance, another regional study conducted by Machado-Silva et al. (2020) showed a general increase in respiratory diseases during droughts in the Brazilian Amazon, but a decrease in the cases of asthma.

Economic and mental health repercussions

Prolonged droughts can cause large economic impacts worldwide through their effects on agriculture, businesses, industries, and communities, which are principally associated with the reduction in the quantity of water and power production, losses from timber production, diminution of food availability (e.g. losses to agricultural production and livestock production), and the subsequent increased price of food (Kallis, 2008; Goyal et al., 2017). In addition, drought can have serious effects on tourism (Handmer et al., 2012; Dalezios et al., 2017). Environmental and economic repercussions attributable to droughts have been associated with forced displacement of communities, and in several cases this resulted in emotional consequences and repercussions to human well-being, especially for farmers (Vins et al., 2015). All these effects can seriously affect mental health, such as chronic stress, worry, sleeplessness, generalised anxiety, depression, conflict, and violence (Grigoletto et al., 2016). In turn, it has been described that physiological stress can be associated with higher disease risk, such as cardiovascular and respiratory conditions (Hayes, 2002; Cohen et al., 2007). Moreover, in extreme cases, prolonged drought can contribute to higher suicide rates, mainly in rural populations (Hanigan et al., 2012; Alpino et al., 2016). These repercussions can be discussed regarding the role of drought as a contributing factor in civil conflicts, political instability, and crises (Selby et al., 2017; Bell et al., 2018).

1.4. Scope of the thesis

Drought is a complex and slowly developing phenomenon that leads to a wide range of effects on many systems, thereby affecting more people than any other natural hazard (Wilhite, 2000). Whereas the effects of drought in meteorological, agricultural, hydrological, or economic contexts are well analysed, there is a lack of studies that address the estimation of specific health impacts. In addition, the majority of research is focused on resource-poor countries and the effects on malnutrition or vector-borne diseases (Berman et al., 2017; Bifulco and Ranieri, 2017); however, the public health impacts of droughts should not be ignored in developed countries (Hayes, 2002).

To our knowledge, there are no studies in Europe that evaluate the details of the relationship between drought conditions measured by a specific index (or indices) and different causes of daily mortality. In addition, there have been few attempts to evaluate what measures and characteristics of droughts are the most predictive to identify and reflect the different drought impacts on health systems (Balbus, 2017; Salvador et al., 2020). There are no studies that compare the performance of different drought indices and the sensibility of different timescales to predict and estimate specific-cause mortality, particularly in consideration with the different types of droughts as well as the time periods in which these effects can be manifested.

The Iberian Peninsula is a region of southwest Europe that is vulnerable to climate change and prone to drought, where this hydrological extreme is described as the main hydroclimatic hazard (Pires et al., 2010; Páscoa et al., 2017). Several studies have shown an increase in the severity of drought in most of the region in the last few decades associated with a decrease in precipitation and increase in temperature (Vicente-Serrano et al., 2014; Spinoni et al., 2017), and the region will likely suffer an increase in drought frequency and severity throughout the 21st century (Spinoni et al., 2018). This territory has suffered an increase in temperature of approximately 1.5 °C annually and a decrease of approximately 15.6% in precipitation over the last five decades (Vicente-Serrano et al., 2014). The last report by the Spanish National Meteorological Service (AEMET) indicated an increase in the mean temperature during all seasons in Spain since 1971, and particularly during summer, as this hot season is approximately five weeks longer than those in the 1980s. The areas with a semi-arid climate in this region have also increased to nearly 6% (AEMET, 2019).

Moreover, the Iberian Peninsula also suffers from relatively high exposure to intense heatwaves and wildfires, which are phenomena significantly associated with greater mortality risk in the area (Trigo et al., 2009; Díaz et al., 2015a, b; Linares et al., 2018). The impact of heatwaves on hospital admissions and cardiorespiratory morbidity has also been described, but the impact on mortality is more remarkable and the results on morbidity are more heterogeneous (Cheng et al., 2019; Linares et al., 2020a).

Owing to its geographical position, the region is frequently affected by Saharan dust intrusions (which are often linked to high temperatures), which lead to higher PM concentrations with significant impacts on specific-cause morbi-mortality (Reyes et al., 2014; Basagaña et al., 2015; Stafoggia et al., 2016) and other pathologies such as pre-term birth, low birth weight (Díaz et al., 2012; 2017, Moreira et al., 2020), and neurodegenerative diseases such as Alzheimer's disease (Culqui et al., 2017).

Meanwhile, the majority of research focusing on the evaluation of climatic impacts on morbidity and mortality usually does not consider gender and age variables in the analysis. This confirms the need to improve the understanding of the details of the relationship between this phenomenon and specific health risks among different subgroups in the exposed population. This can be helpful for obtaining specific information on the structure of the population at risk, determining the most vulnerable groups, and developing specific and more effective mitigation measures as well as reducing population vulnerability.

Thus, in this study, the impact of different drought conditions on daily natural, circulatory, and respiratory mortality across the Iberian Peninsula were analysed using two standardised indices calculated at different timescales from an integrative point of view. For this purpose, variables such as gender, age, and the control of heatwaves and atmospheric pollution were additionally evaluated when they were available. This approach allows a comparative performance assessment of the different drought metrics to identify and quantify daily mortality effects as well as to obtain better understanding of the details of the relationship between drought and specific human health aspects. The existence of limited literature in this field as well as future climate change projections make this type of study essential.

2

OBJECTIVES

Future projections of climate change indicate more frequent and severe extreme climatic events such as drought in southwest Europe (Spinoni et al., 2018), which highlights the threat to health if adequate actions are not taken (Watts et al., 2017). The assessment of the details of the relationships between health aspects such as specific-cause mortality and drought conditions constitutes a great challenge in the 21st century owing to the significant number of affected people at both the regional and global level and the limited studies in the public health field (Bifulco and Ranieri, 2017). Vulnerability to drought is increasing in both developing and developed countries (Quiring, 2015), but studies focused on developed countries are limited. Moreover, the majority of existing analyses are conducted at a regional level, which manifests the need to conduct additional assessments nationwide. Particularly in European countries, there are no studies that have analysed the impact of drought episodes on natural, circulatory, and respiratory mortality. However, better understanding of the most vulnerable subgroups among the exposed population is also required, but the studies depend largely on mortality data availability. The integration of the main findings of this type of study could be helpful to develop or improve action plans for the mitigation of health effects and to reduce vulnerability among the population.

The main objective of this thesis is **to determine the impact of drought conditions on specific causes of daily mortality (natural, circulatory, and respiratory) in the Iberian Peninsula by addressing the performance of different drought indices for the estimation of the effects on the population**.

A set of specific objectives are proposed to successfully achieve the main objective of this work, which are as follows:

1. <u>Establish a conceptual framework of the relationship between droughts and human health.</u>

   1.1. From an international point of view, built a conceptual framework that relate the occurrence of climatic conditions associated with extreme variables to drought conditions and that involve a higher risk of specific causes of morbidity and mortality in vulnerable regions.

   1.2. Update knowledge on the current advances focused on the study of drought phenomena and details on the environmental and biological mechanisms through which drought episodes can affect health and vulnerability to drought.

   1.3. Conduct a brief discussion to establish future challenges and strategies that may be useful for public health systems.

This is addressed in the article titled "*Effects of droughts on health: Diagnosis, repercussion, and adaptation in vulnerable regions under climate change. Challenges for future research*" published in 2020 in Science of The Total Environment, 703, 134912, pp: 1–8, DOI: https://doi.org/10.1016/j.scitotenv.2019.134912.

2. <u>Assess the effects of different drought conditions on daily natural, circulatory, and respiratory causes of mortality at a regional level (Galicia, NW Spain) and evaluate the performance of different drought indices (and timescales) to quantify the risks.</u>

2.1. Conduct an ecological time series study regarding the impact of drought events on daily natural, circulatory, and respiratory causes of deaths in each province of Galicia through the use of different drought metrics.

2.2. Conduct a performance analysis of different types of drought indices and timescales to estimate drought effects on specific-cause mortality.

2.3. Monitor drought conditions by severity to determine their role in the risk estimation of different analysed causes of daily mortality.

2.4. In order to conduct a more exhaustive study, carry out an integrated assessment of the impact of drought conditions on mortality under the control of the effects of other environmental and climatic hazards that are often strongly associated with this type of extreme hydroclimatic phenomenon, namely heatwaves and air pollution.

2.5. Determine the relative and attributable risks (ARs) of specific-cause daily mortality associated with drought conditions and elaborate risk maps.

This objective is addressed in the article titled "*Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013*" published in Science of The Total Environment, 662, pp: 121–133, DOI: https://doi.org/10.1016/j.scitotenv.2019.01.217.

3. Extend the study at the national level for peninsular Spain.

3.1. Conduct a research study similar to that in Objective 2 quantifying the short-term effects of drought on the specific-cause mortality for each province of peninsular Spain in order to obtain broader knowledge.

3.2. Compare the performances of the different types of drought indices used.

3.3. Control the short-term effects of heatwaves and atmospheric pollution under drought conditions.

This objective is addressed in the article titled "*Short-term effects of drought on daily mortality in Spain from 2000 to 2009*" published in Environmental Research, 183, 109200, DOI: https://doi.org/10.1016/j.envres.2020.109200.

4. Create a comprehensive assessment of the effects of drought on daily natural, circulatory, and respiratory mortality in broader territorial categories and from a nationwide point of view across peninsular Spain.

4.1. Analyse the risks of daily specific-cause mortality associated with drought conditions at the short–medium term.

4.2. Combine the provincial relative risks (RRs) of daily mortality associated with drought conditions according to a higher administrative division using the autonomous region level.

4.3. Combine the provincial RRs of daily mortality according to the spatial distribution of drought.

4.4. Combine the provincial RRs based on the percentage of the elderly population.

4.5. Compare the capability of different types of drought indices and timescales to reflect and quantify the impact of drought conditions on the different causes of daily mortality and according to the different regionalisation levels.

This objective is addressed in the article titled "*Quantification of the global effects of droughts on daily mortality in Spain at different timescales: A meta-analysis" submitted to* International Journal of Environmental Research and Public Health

5. Conduct an exhaustive assessment including an analysis by gender and age in Lisbon district (Portugal) to analyse the structure of the population at risk and determine the most vulnerable subgroups to the impact of drought on daily mortality.

5.1. Conduct an ecological time series study to evaluate the effect of drought conditions measured by different types of indices and timescales on daily natural, circulatory, and respiratory deaths.

5.2. Assess the effect of drought on the daily specific-cause mortality considering different age groups.

5.3. Assess the effect of drought on the daily specific-cause mortality taking gender into account.

5.4. Assess the effect of drought on the daily specific-cause mortality controlling the effect of heatwaves and atmospheric pollution.

This objective is addressed in the article titled "*Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: Risks assessment by gender and age*" under review in Science of the Total Environment.

6. Based on the results obtained in this study, indicate recommendations to address the future challenges of climate change and climate-related events in the context of public health.

This objective is developed in Chapter 5 (Section 5.5) as the final conclusions.

3

DATA AND METHODOLOGY

3.1. Region of study: Iberian Peninsula

The location of the Iberian Peninsula (Figure 4) in the mid-latitudes of the Northern Hemisphere at the boundary between tropical and subtropical climates makes this territory interesting from a climatological point of view. Linked to its complex orography and geographic location, there is a significant heterogeneity in the precipitation and temperature patterns, and the climate is very diverse throughout the north and south as well as between the coastal and interior regions (Trigo and Dacamara, 2000; de Castro et al., 2005; Santos et al., 2011; AEMET, 2018; IGN, 2019). The climate largely depends on the influence of the circulation patterns and the origin of air masses (de Castro et al., 2005; Gimeno et al., 2010).

Owing to the location of the Iberian Peninsula, this region can suffer from South Saharan warm air intrusions, which transport dust several times with a marked seasonal cycle, showing higher (lower) inflows during summer (winter) and more frequent occurrence over the southern and central areas (Russo et al., 2020 and references therein). These intrusions are favoured under anticyclonic meteorological configurations, which usually have a subtropical ridge extending from northern Africa to the northern latitudes. The anticyclonic atmospheric configuration, which adds a low-pressure system over the eastern Atlantic Ocean, is also a key factor for the occurrence of heatwaves in southern Europe (Tomczyk et al., 2017; Sousa et al., 2018; 2019; Sanchez-Benítez et al., 2020).

The combination of both dust intrusions and heatwaves plays a critical role for health in the region (Trigo et al., 2009; Hernández-Ceballos et al., 2016; Díaz et al., 2017; Linares et al., 2017).

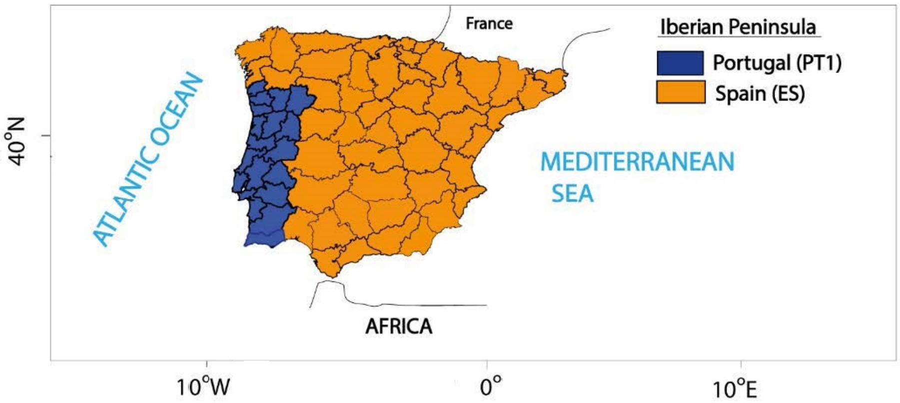

Figure 4. Map of the study region location (the Iberian Peninsula). Both mainland Spain (in orange) and Portugal (in blue) are indicated according to the Nomenclature of Territorial Units for Statistics at level 1 (NUTS1: ES and PT1, respectively).

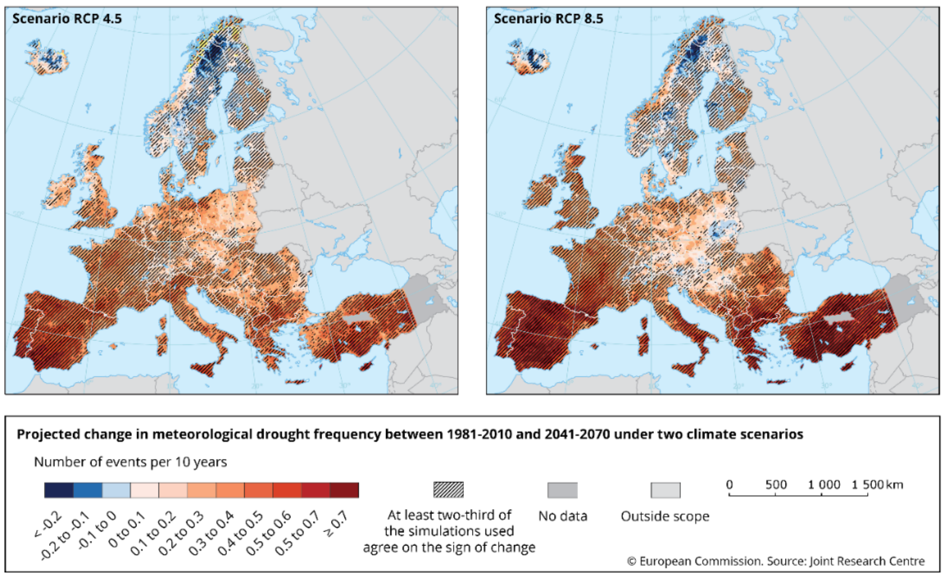

Figure 5. Projected change in the frequency of meteorological drought between 1981–2010 and 2041–2070 in Europe for RCP 4.5 (left map) and RCP 8.5 scenarios (right map). Similar changes in sign are represented by the lines. The figure is from the European Environment Agency (https://www.eea.europa.eu/data-and-maps/figures/projected-change-in-meteorological-drought, 2020b) and adapted from Boersma et al. (2017).

The Iberian Peninsula is considered to be a southern European region that is most likely to suffer from an increase in drought frequency (Figure 5) and severity in the coming years and decades (Vicente-Serrano et al., 2012a; Boersma et al., 2017) and where extreme climatic events such as prolonged dry conditions and heatwaves are recurrent (Rodríguez-Fonseca et al., 2017), which have also increased in magnitude and frequency, respectively, since 20th century (Padrón et al., 2020; Perkins-Kirkpatrick and Lewis, 2020).

Drought is a problem of great relevance and interest, and several studies have been conducted with different methodologies and indices. The Iberian Peninsula is a region that suffers from alternate dry and wet periods, but with variations in their intermittences. Being a relatively small territory, marked differences in the behaviour of these alternating dry/wet spells is observed. From south to north, three types of meteorological drought can be observed. The south is characterised by the occurrence of very long dry spells alternating with short wet events, the northern half is characterised by medium–long dry spells alternating with short wet events, while in the north, medium dry spells alternate with longer wet spells (Monjo et al., 2020). This spatial distribution of dry periods could become more marked in the near future as a consequence of climate change (Sánchez et al., 2012).

Other studies have indicated that in mainland Spain, droughts occur more frequently in the northern regions than in the southern regions; however, the average duration and magnitude of drought events in the central and southern areas are double those observed in the north. In addition, the number of drought episodes decreases for higher drought timescales (Domínguez-Castro et al., 2019). Furthermore, there are significant differences in the spatial pattern of drought evolution when different scales are analysed; at shorter timescales there are less patterns, while for longer timescales the patterns are more heterogeneous and complex (Vicente-Serrano, 2006). Meanwhile, Santos et al. (2011) found a similar distribution for mainland Portugal, with three well-defined spatial drought patterns with different temporal drought evolution (northern, central, and south Portugal), and droughts were also markedly more frequent in the south than in the north.

Spain has a geographical extent of almost 506 000 km^2, and the political and administrative division of peninsular Spain has taken shape in 47 provinces (Nomenclature of Territorial Units for Statistics (NUTS) level 3 or NUTS3) organised in fifteen Autonomous Communities (NUTS level 2 or NUTS2) (Figure 6).

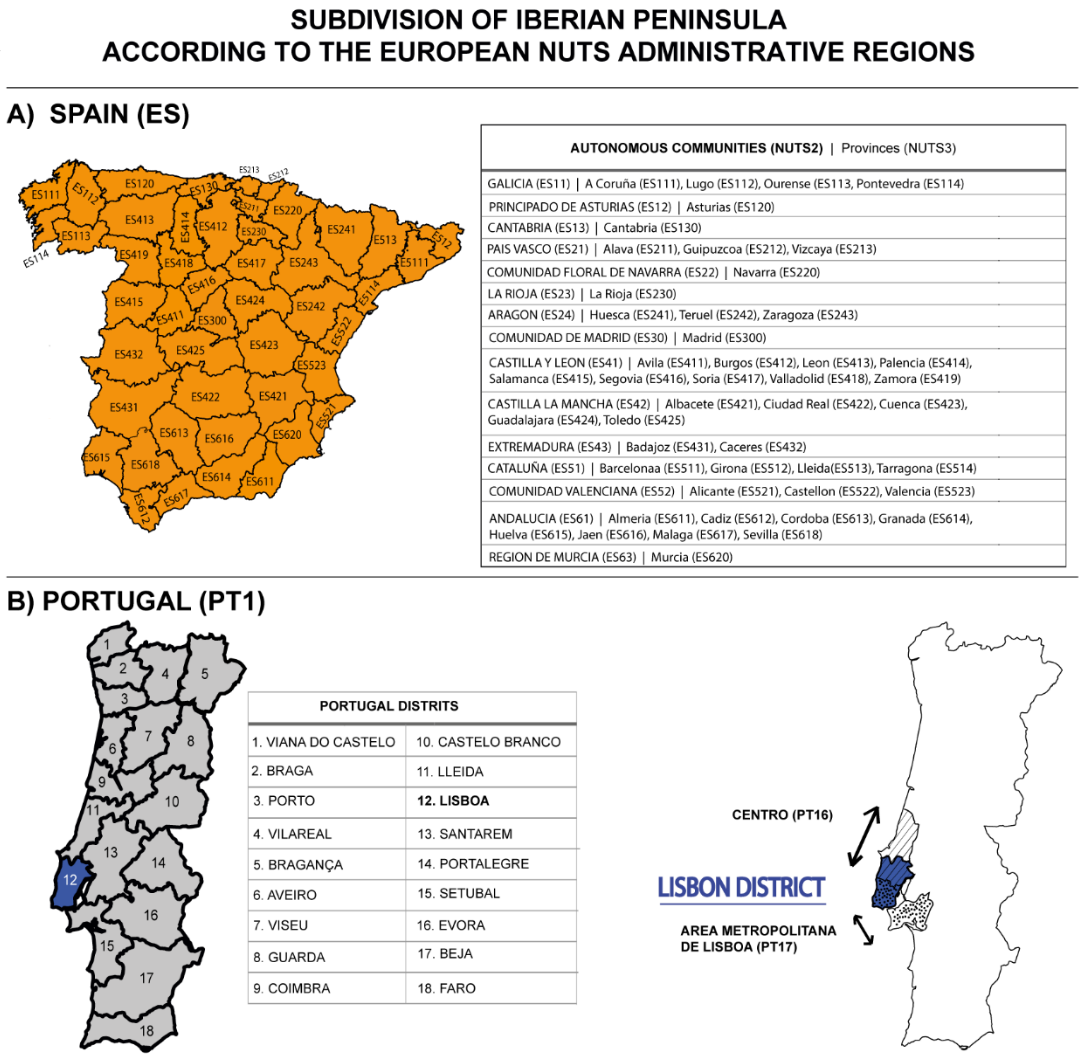

Figure 6. Geographic location of the Iberian Peninsula. According to the Nomenclature of Territorial Units for Statistics (NUTS1), ES and PT1 correspond to the countries of Spain and Portugal.

The Spanish National Statistics Institute (INE) reports a total population of approximately 47 026 208 residents. According to the INE (2020a), there was significant population growth during the study period of this research (2000–2009), highlighting Andalucía, Cataluña, Comunidad Valenciana, and Comunidad de Madrid are the most populated autonomous regions, followed by Galicia and Castilla-y-León. In contrast, La Rioja, Navarra, and Cantabria were the least populated regions (INE, 2020b). In addition, in terms of the factors that can influence the health risk differences linked to the occurrence of drought events among different regions, the greatest ageing population level based on the mean proportion of people over 65 years old was counted in Galicia and Castilla-y-León, unlike that observed in Andalucía, Madrid, and Valencia (INE, 2020c).

Portugal has a geographical extent of almost 92 226 km^2, with approximately 10 295 009 residents (data obtained from the INE of Portugal) (INE, 2020d). Mainland Portugal is organised into 18 districts (Figure 6). According to the NUTS of the European Commission, it is split into five regions (NUTS2: Norte, Algarve, Centro, metropolitan area of Lisbon, and Alentejo). The population density is principally concentrated in Norte, Lisbon metropolitan area, and Centro. Meanwhile, Lisbon district is part of central Portugal and the metropolitan area of Lisbon, and contains the homonymous capital of the country, which is the largest urban city of Portugal. According to recent national INE reports, the distribution of the Spanish and Portuguese population is very similar (regressive population pyramid or bulb-shaped), with greater differences between men aged 30–40 years and women aged 60–79 years. Moreover, Portugal is considered to be one of the European Union countries with the highest aging population (in 2018, 21.5% of its population was aged 65 years or older) (INE, 2019).

3.2. Variables

As this manuscript is composed of a compendium of several papers, the periods of data vary and are consistent within each article. The differences can be found along the next sub-chapters, and Tables 4 and 5.

3.2.1. Dependent variables: Daily specific-cause mortality

Daily natural (all causes of mortality, except for accidents), circulatory, and respiratory causes of deaths are the dependent variables used in this research. They are coded as A00-R99, I00-I99, and J00-J99, respectively, in the WHO International

Classification of Diseases in its 10th revision (ICD10; https://www.who.int/classifications/icd/icdonlineversions/en/). These daily mortality data were provided by both the Spanish and Portuguese INE, and are confidential, meaning that they cannot be used for any purpose other than the authorised research.

There are slight differences in the daily mortality data use and covered period for the three different studies for Galicia, peninsular Spain, and Portugal. In the case of peninsular Spain, the number of daily deaths include those that occur in the province capitals and in towns with over 10 000 inhabitants, but for different periods. From 1983 to 2013, the rate of mortality was used for the study in Galicia, and from 2000 to 2009, the total number of daily deaths in each province was used for the whole peninsular analysis.

Portuguese daily mortality data for Lisbon district cover the period of 1983 to 2016. In addition, for Lisbon district, the daily mortality series were provided by dividing the cases by gender (men vs. women) and age, which were accumulated in the following five age intervals: 0–9, 10–44, 45–64, 65–74, and >75 years old. Only adults with ages ranging from 45–64, 65–74, and >75 years old were considered in the statistical assessment because there were limited deaths among young people including children and adolescents in the descriptive analysis (see Chapter 4, the study entitled "*Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: Risk assessment by gender and age*").

3.2.2. Independent variables: Drought indices

Two meteorological drought indices widely used in the scientific literature to determine and quantify drought conditions were used in this thesis, namely the SPI developed by McKnee (1993) and the SPEI developed by Vicente-Serrano et al. (2010). Both drought indices are based on a standard normal variable and have the advantage of being multiscalar, so they can be compared in space and time (Vicente-Serrano, 2006; Vicente-Serrano et al., 2010). The fact that the SPI and SPEI can be obtained at different timescales allows the identification of different types of droughts and the reflection of the impact of drought on the availability of different water resources (Quiring, 2009; Stagge et al., 2015; Vicente-Serrano et al., 2012a), as commented in Chapter 1 (Section 1.2.2.).

The SPI is calculated from precipitation data and is based on the probability of precipitation for any specific timescale that is transformed to a standard norma distribution with an average of zero and a standard deviation of one. Similarly, the SPEI is based on the original SPI calculation procedure, but uses a climatic water balance considering temperature data, which makes it very useful for climate change studies. The SPEI is based on the difference between precipitation and potential evapotranspiration (P-PET), which can also be calculated at different timescales. Hereafter, the length (*n*) of the accumulated index is denoted following the index type as SPEI-*n* or SPI-*n* (*n* = 1, 3, 6, or 9 months of accumulation). The SPI and SPEI detect both dry and wet conditions (positive and negative values of the series, respectively). The onset of a drought event is commonly defined as when the drought index value falls below zero, and the episode ends when the index value returns to a positive value. In addition, the severity of drought can be quantified through the application of thresholds (based on a normal value). In the study conducted in Galicia, this categorisation of severity was also considered. Five severity groups can be established gradually from 0 (considered "no drought" conditions) to 5 ("extreme or exceptional" drought conditions) following the criteria of Agnew (2000) and Berman et al. (2017). Although negative SPI and SPEI values indicate dry conditions, their range is indicated in Table 2.

Table 2. Drought classification based on the Standardised Precipitation Evapotranspiration Index (SPEI)/Standardised Precipitation Index (SPI) thresholds following the criteria of Agnew (2000) and Berman et al. (2017).

Drought values	**Category**		
-0.84<SPEI/SPI≤-0.00	Level 0	Usual conditions or mild drought	No drought
-1.28<SPEI/SPI≤-0.84	Level 1	20% probability that a similar drought could occur in 5 years	Moderate drought
-1.65<SPEI/SPI≤-1.28	Level 2	Reflects a return period of 10 years with a 10% probability	Severe drought
-2.06<SPEI/SPI≤-1.65	Level 3	Reflects a return period of 10 years with a 10% probability	
-2.33<SPEI/SPI≤-2.06	Level 4	Reflects a return period of 50 years with a 2% probability	Extreme drought
SPEI/SPI≤-2.33	Level 5	Reflects a period of 100 years with a 1% probability	

The SPEI and SPI uncategorised continuous annual series were considered in all the analyses. Two categorised series (low severity (level 1) and high severity (levels 2 to 5) were additionally considered in the study conducted in Galicia to determine the role of drought severity in the estimation of daily mortality RRs. Severe and extreme drought categories were grouped together in the high severity category because there were few extreme days.

In the case of all the studies conducted in peninsular Spain, the SPI-*n* and SPEI-*n* time series over each province capital were obtained from the Spanish National Research Council (CSIC), and are available from the following website: http://monitordesequia.csic.es. Vicente-Serrano et al. (2017) rigorously developed a high-resolution spatial (1.1 km) and temporal (weekly) drought dataset for the period of 1961–2018, from which the studied periods were extracted.

In the case of the study conducted in Lisbon district, the SPI-*n* and SPEI-*n* dataset series were not available online, and they were calculated through the use of the SPEI R library (Beguería et al., 2014) using the weekly data series of precipitation and temperature (maximum and minimum values) obtained from the daily ensemble gridded E-BSO data (Cornes et al., 2018) from the European Climate Assessment & Dataset project (ECA&D) available on a 0.1° regular grid from January 1950 to present (the database is continuously updated).

To compute the SPEI, it is necessary to calculate PET, which is usually based on an approximation method that is chosen as a function of the available meteorological data. For instance, the Thornthwaite method only requires monthly-mean temperature data, the Hargreaves method considers the minimum and maximum temperature, and the Penman-Monteith method is often recommended, but requires large amounts of input data that may not be available for longer time periods. It has been indicated that as the purpose of considering PET in the SPEI calculation is to obtain a relative temporal estimation, the method chosen is not critical (Vicente-Serrano et al., 2010). To estimate PET for the SPEI-*n* for Lisbon district, the Hargraves method was used, as it is recommended in Páscoa et al. (2017). In order to obtain the standardised series, several probability distributions can be used to obtain the SPI-*n* and SPEI-*n* series. Based on the original description of both indices, the recommendations of the World Meteorological

Organization, and the methodology used by Parsons et al. (2019) and Spinoni et al. (2018), a gamma distribution was used to compute the SPI (McKee, 1993; Vicente-Serrano et al., 2017; EDO, 2020) and a log-logistic distribution was used to compute the SPEI (Vicente-Serrano et al., 2010; 2012a) across the available data period from 1950 to 2017. Weekly SPEI-*n* and SPI-*n* series from the period of interest (1983 to 2016) for the analysis in Lisbon district were then selected.

According to the timescales used in the different studies, the SPEI-*n* and SPI-*n* were obtained at the short (1 month of accumulation) and short–medium term (3 months of accumulation), and in Galicia both indices were additionally obtained at the medium (6 months of accumulation) and long term (9 months of accumulation).

The temporal resolution of both types of indices is normally presented on a monthly or weekly scale; however, human health analyses are usually conducted on a daily scale. Thus, daily series assuming the same conditions for each 7 d interval were constructed from the weekly drought data to better control the acute daily confounding factors following similar criteria to those of Berman et al. (2017), who conducted the first study in the literature linking a drought index and daily mortality in the USA.

3.2.3. Control variables

Heatwave temperatures (T*hwave*) and atmospheric pollution (PM with an aerodynamic diameter of less than 10 µm (PM_{10}), NO_2, and O_3) were also included in the analysis because they are variables that are usually linked to drought periods (IPCC, 2014; Peterson et al., 2014) and strongly associated with an increased risk of natural, circulatory, and respiratory deaths in the Iberian Peninsula (e.g. Trigo et al., 2009; Díaz et al., 2015; Díaz et al., 2018; Linares et al., 2018b). Evidence indicates that in Europe, droughts play an important role in the occurrence of concurrent and cascading events such as heatwaves and fires (Akhtar, 2019; Sutanto et al., 2020).

Because the available pollution data were from 2000 to 2009 for all provinces of peninsular Spain and from 2007 to 2016 for Lisbon district, the control of the short-term effects of T*hwave* and pollution in the statistical analysis was conducted for these sub-periods of study.

Temperature of heatwave (T*hwave*)

The temperature shows a U-shaped relationship with mortality (Figure 7), where the left branch of the curve reflects the cold effect and the right branch represents the impact of heat (Alberdi et al., 1998). T*hwave* values were obtained using the daily maximum temperature (T*max*) and the specific maximum temperature threshold for daily mortality associated with heat (T*threshold*) from the available sub-periods of the study.

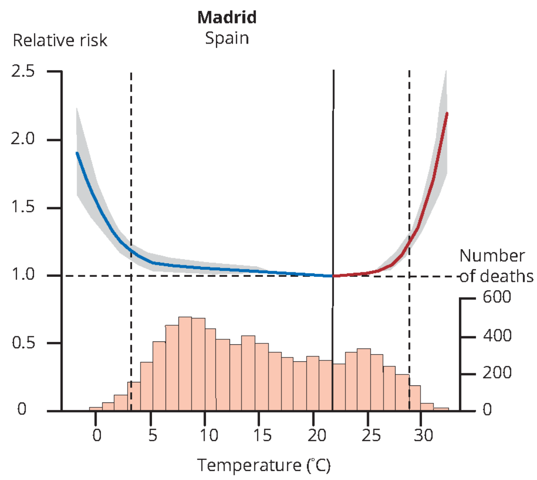

Figure 7. Upper part of the figure: relationship between mortality and temperature in Madrid, Spain (where the 95% confidence interval is shaded in grey) and the associated relative risk (RR). The solid grey vertical line marks the minimum mortality temperature. Bottom part of the figure: temperature distribution. The dashed grey vertical lines delineate the 2.5th and 97.5th percentile temperatures. The figure was obtained from the European Environment Agency (2020c) adapted from Gasparrini et al. (2015a).

i) In the case of all the provinces of peninsular Spain, the specific T*threshold* values for the period 2000–2009 were previously calculated by Díaz et al. (2015b) (Table 3). T*max* daily data series were collected at the meteorological observatories of reference, which were usually located in the provincial capital cities and provided by the AEMET.

ii) In the case of Lisbon district, the T*threshold* for 2007–2016 was calculated ad-hoc for this research following the same methodology as Díaz et al. (2015a, b) corresponding to 34 °C (93rd percentile). The daily T*max* series are the average from the data at the reference meteorological stations of the

Portuguese Institute for Sea and Atmosphere (IPMA) in Lisbon (namely Lisbon, Lisbon/Gago Coutinho, and Lisbon/Geophysics), which are available online from the National Oceanic Administration Agency's National Climate Data Center (NNCDC CDO, 2019).

T*hwave* calculation:

Following Díaz et al. (2015a; 2015b), to determine an authentic causal mortality-temperature relationship, a univariate autoregressive integrated moving average (ARIMA; Box et al., 1994) model was firstly created with daily natural-cause mortality as the dependent variable. The use of the residual series obtained from this model, instead of daily mortality, has the advantage that after modelling, they do not display trends or periodicities, so the associations that are found present an authentic causal mortality-temperature relationship from a statistical point of view ($p<0.05$). To determine the T*threshold*, the summer months were considered (when the highest temperatures occur). Subsequently, as shown in Figure 8, the daily mean value of the residuals from the ARIMA model (ordinate axis) were for each T*max* interval value grouped at 2 °C intervals (abscissa axis) with their 95% interval of confidence was represented. In the scatter plot, the parallel lines represent the 95% IC of the mean of the residuals for the entire study period. It can be seen that from a maximum daily temperature of 34 °C, the anomaly of the residuals with its IC does not touch the IC of the average of the residuals for the entire period, which clearly appears centred on zero. Therefore, from the T*max* of 34 °C, the mortality due to heatwaves begins to increase significantly. This temperature coincides with the 93rd percentile of the series of maximum daily temperatures of the summer months (June–September) in the considered period.

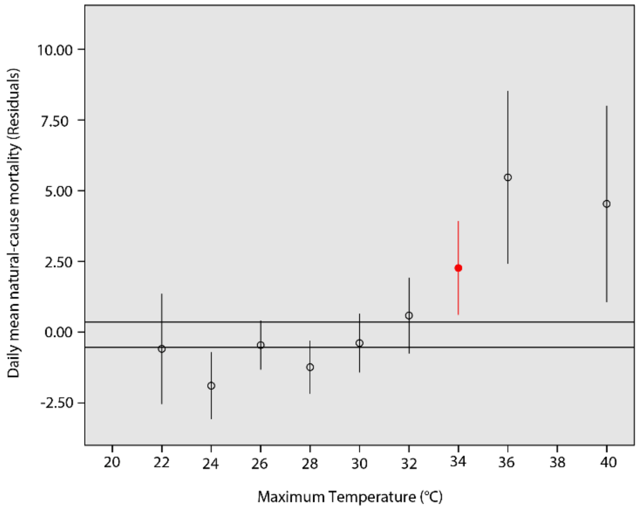

Figure 8. Scatter plot of the maximum daily temperature (T*max*) and daily mortality residuals for the definition of the heat trigger temperature (T*threshold*) in Lisbon district for the period of 2007–2016. T*max* of 34 °C marked in red.

In terms of its effects on mortality, the T*hwave* variable is defined as follows:

$$Thwave = Tmax - Tthreshold \quad if \quad Tmax > Tthreshold$$
$$Thwave = 0 \quad if \quad Tmax \leq Tthreshold$$

Daily atmospheric pollution (PM_{10}, NO_2, and O_3)

The daily mean concentrations (µg/m^3) of PM_{10}, NO_2, and O_3 were considered in the statistical models for the available study sub-periods in order to control the short-term effect of air quality on mortality under the assessment of drought conditions. Pollution data series in Spain were recorded at monitoring stations situated in each capital province, which were furnished by the Spanish Ministry of Agriculture and Fisheries, Food and Environment (*Ministerio de Agricultura y Pesca, Alimentación y Medioambiente*; MAPAMA). In the case of Lisbon district, pollutant series were obtained from the Portuguese Environmental Agency (available online) recorded at the principal and monitored stations from the air quality network of Lisbon and Tagus Valley (*Entrecampos, Avenida da Liberdade, Olivais, Alfragide/Amadora, Cascais-Mercado, Loures, Mem-Martins, Alverca*, and *Laranjeiro*, from QualAr (2019)). The daily pollution data from the different stations were averaged to provide a single concentration estimation for the whole district.

Both the PM_{10} and NO_2 concentrations have a linear relationship with mortality (Ortiz et al., 2017; Linares et al., 2018b). However, O_3 shows a U-shaped relationship with mortality that is very similar to that registered by temperature (Díaz et al., 2018), where the right branch of the curve shows the increase in mortality linked to the increase in O_3 concentrations. For this reason, for O_3, a new variable in the function of a threshold (O_{3a}) was calculated (as for temperature) to be used in the statistical models.

The new variable O_{3a} was created to estimate the effects of O_3 on natural, circulatory, and respiratory mortality, as follows:

$$O3a = O3 - O3threshold \quad if \;\; O3 > O3threshold$$

$$O3a = 0 \qquad\qquad\qquad if \;\; O3 \leq O3threshold$$

The O_3 mortality threshold values associated with mortality (O_3*threshold*) were determined as follows:

i) In peninsular Spain, the O_3*threshold* values for 2000 to 2009 were taken from the previous study conducted by Díaz et al. (2018) (Table 3).

ii) In the case of Lisbon district, the O_3*threshold* values for 2007 to 2016 were calculated following Díaz et al. (2018) through performing a scatter plot with the daily mean ozone concentrations plotted on the abscissa axis and the mean daily mortality corresponding to such ozone concentrations plotted in the ordinate axis. The minimum value of the quadratic function between the daily mean O_3 concentrations and mean daily natural mortality corresponded to the specific O_3*threshold* value (Figure 9). The O_3*threshold* was 67 µg/m^3 (which corresponds to the 72nd percentile).

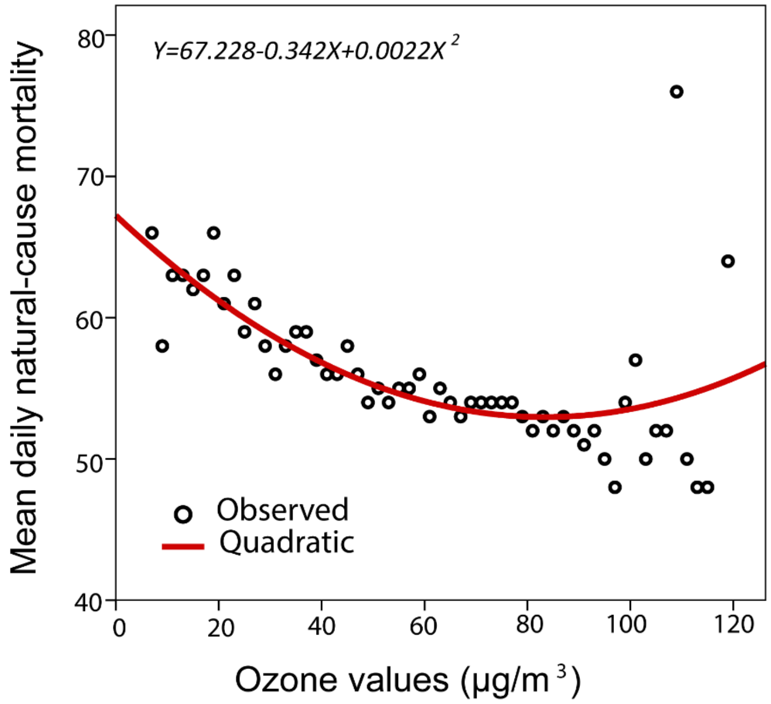

Figure 9. Scatter plot of the mean daily natural-mortality and mean daily O_3 concentrations to calculate the O_3*threshold* values in Lisbon district from 2007 to 2016.

Lagged variables

Lagged variables for T*hwave* and for each atmospheric pollutant were also calculated because the effects of temperature and pollution on mortality can occur immediately or with a delay of 4 days in the case of temperature (Guo et al., 2017; Martínez et al., 2018), 5 days for PM_{10} (Ortiz et al., 2017) and NO_2 (Linares et al., 2018b), and 9 days for O_3 (Díaz and Linares, 2018; Díaz et al., 2018). Thus, time lags were included in the statistical models. Lag 1 considers the effect of the environmental variable on the following day (day+1), lag 2 considers the effect 2 days later (day+2), and so on.

Table 3. Thresholds used for maximum temperature (Tthreshold; °C) and O3 and their percentiles (O3threshold; µg/m3) for daily mortality in each capital province of peninsular Spain from 2000to 2009. Values are taken from Díaz et al. (2015a) and Díaz et al. (2018), respectively. N.D.: No Data.

Autonomous community (code NUTS2)	**Province (code NUTS3)**	**T*threshold* (°C) by provincial capital**	**Ozone threshold (µg/m^3) by provincial capital (%)**
Galicia (ES11)	A Coruña (ES111)	26	71 (91%)
	Lugo (ES112)	34	
	Ourense (ES113)	36	
	Pontevedra (ES114)	30	
Principado de Asturias (ES12)	Asturias (ES120)	30	67 (60%)
Cantabria (ES13)	Cantabria (ES130)	32	
Pais Vasco (ES21)	Alava (ES211)	30	74 (72%)
	Guipuzcoa (ES212)	30	61 (75%)
	Vizcaya (ES213)	30	72 (78%)
Comunidad Foral de Navarra (ES22)	Navarra (ES220)	36	81 (74%)
La Rioja (ES23)	La Rioja (ES230)	36	125 (97%)
Aragon (ES24)	Huesca (ES241)	34	
	Teruel (ES242)	36	106 (70%)
	Zaragoza (ES243)	36	72 (89%)
Comunidad de Madrid (ES30)	Madrid (ES300)	34	60 (89%)
Castilla y Leon (ES41)	Avila (ES411)	32	67 (44%)
	Burgos (ES412)	34	86 (70%)
	Leon (ES413)	32	83 (85%)
	Palencia (ES414)	N.D.	N.D.
	Salamanca (ES415)	34	93 (76%)
	Segovia (ES416)	34	70 (50%)
	Soria (ES417)	34	82 (75%)
	Valladolid (ES418)	36	84 (73%)
	Zamora (ES419)	36	
Castilla la Mancha (ES42)	Albacete (ES421)	36	156 (99%)
	Ciudad Real (ES422)	38	
	Cuenca (ES423)	34	
	Guadalajara (ES424)	38	102 (67%)
	Toledo (ES425)	38	116 (80%)
Extremadura (ES43)	Badajoz (ES431)	38	
	Caceres (ES432)	38	

Cataluña (ES51)	Barcelona (ES511)	32	77 (92%)
	Girona (ES512)	36	
	Lleida (ES513)	36	133 (99%)
	Tarragona (ES514)	36	127 (97%)
Comunidad Valenciana (ES52)	Alicante (ES521)	32	
	Castellon (ES522)	32	113 (96)
	Valencia (ES523)	34	99 (99%)
Andalucia (ES61)	Almeria (ES611)	36	
	Cadiz (ES612)	32	108 (89%)
	Cordoba (ES613)	40	134 (97%)
	Granada (ES614)	38	138 (99%)
	Huelva (ES615)	36	97 (73%)
	Jaen (ES616)	36	128 (93%)
	Malaga (ES617)	40	
	Sevilla (ES618)	40	95 (92%)
Region de Murcia (ES62)	Murcia (ES620)	34	124 (95%)

Other control variables

Other variables were controlled throughout the studies, as in the study conducted by Martinez et al. (2018), as follows: i) the autoregressive nature of the dependent variable from the autoregression of the first order of daily mortality (AR1); ii) the seasonality of the series using the sine and cosine functions that correspond to these periodicities (e.g. annually (365-day), every 6 months (180 day), every 4 months (120-day), quarterly (90-day), and every 2 months (60-day)); and iii) the trend of the series, which was included by taking $n1 = 1$ for the first day of the series, $n1 = 2$ for the second day of the series, and so on to the end of the series.

3.2.4. Modelling process to quantify the impact of drought on daily mortality

Daily retrospective ecological time series studies were conducted. To identify and quantify the effects of drought on natural, circulatory, and respiratory deaths, Generalised Linear Models (GLMs) were used with the Poisson link. First, the assessment of drought indices (independent SPEI-*n* and SPI-*n* series) were taken into account individually in the Poisson models to estimate the effects of drought on the different analysed specific causes of mortality over all the regions, periods analysed (along the complete periods and again for the sub-periods when pollution data were available), and subgroups of gender and age if present (Table 4).

Hereafter, for the cases where there were statistically significant associations between drought and mortality, the control of the T*hwave* variable was considered in the statistical models. Finally, the control of pollution was included in the Poisson models in order to determine the risks of drought conditions on mortality while both the short-term impact of T*hwave* and atmospheric pollutants remained controlled.

This methodology allowed the calculation of the RRs of the statistically significant variables ($p<0.05$) from the estimator or coefficient values obtained in the Poisson models, which were calculated for each unit of increment of the independent variable used (Royo-Bordonada and Damián-Moreno, 2009), as follows:

$$RR = e^{|coefficient|}$$ (Absolute value for the coefficient of SPI-n/SPEI-n)

The absolute value of the coefficient in the previous exponential equation was used because the meaning of the sign of the estimator must first be interpreted. SPI and SPEI values below 0 indicate drought conditions; thus, negative coefficient values only represent higher mortality linked to drought conditions. The quantification of mortality risk linked to drought was then calculated through the exponential of the absolute value of the estimator.

The percentage of attributable risk (%AR) for mortality (Coste and Spira, 1991) for the population associated with different conditions of drought was calculated based on RR values, as follows:

$$\%\,AR = \left[\frac{(RR-1)}{RR}\right] \times 100$$

where $\%AR$ represents the percentage of the increase in the daily mortality effect associated with drought in the population exposed to this risk factor. In the case of atmospheric pollution, the calculated $\%AR$ represents the percentage of increased daily mortality per 1 μg/m^3 of each pollutant.

To determine the statistically significant variables, a "backward-step" process was conducted following the methodology used by Díaz and Linares (2018) and Martinez et al. (2018) beginning with a model that included all the explicative variables (both the independent and control variables and the respective lags for T*hwave*, PM_{10}, NO_2, and O_{3a}, considering individually SPEI-n and SPI-n for each couse of daily mortality). Subsequently, the variables that had lower statistical significance than a *p*-value of 0.05 were individually and gradually removed (retaining the control of the autoregressive nature of the mortality series). This process was repeated until obtaining a final model that included all the significant variables ($p<0.05$). In provinces where there were no O_{3a} values, O_3 was considered to have no effect on mortality (Díaz et al., 2018).

The statistical equation of the Poisson models used to estimate the risk of drought on specific-cause mortality by controlling the effect of heatwaves and atmospheric pollution is as follows:

$$Log\ E(Yt^r) = \alpha AR1 + \beta_t\, day_t + \gamma senX + \delta cosX + \cdots + \varepsilon\, (Thwave_t{}^r) + \vartheta \sum_{i=1}^{n=4} lagi\ Thwave_t{}^r + \mu\, (PM_{10_t}{}^r) + \pi \sum_{i=1}^{n=5} lagi\ PM_{10_t}{}^r + \rho\, (NO_{2_t}{}^r) + \sigma \sum_{i=1}^{n=5} lagi\ NO_{2_t}{}^r + \tau\, (O_{3a_t}{}^r) + \varphi \sum_{i=1}^{n=9} lagi\ O_{3a_t}{}^r + \omega drt_t{}^r + \theta\ cons$$

where Yt^r is the number of death outcomes on day *t* in the specific region (*r*). $\alpha AR1$ is the factor that controls the autoregressive nature of the dependent variable controlled from the autoregression of the first order of daily mortality, with α being the regression coefficient value. Both the trend of the series ($\beta_t\, day_t$) and the seasonality (represented using sine and cosine functions that correspond to the different periodicities; X = 360, 180, 120, 90, and 60) were analysed. β, γ , and δ correspond to the respective coefficients. ω is the magnitude of the coefficient or estimator for drought in region *r* using an annual continuous series of the SPI or SPEI (denoted as *drt*) obtained at a specific timescale ($drt_t{}^r$) for a specific region and study period. In the case of Galicia from 1983 to 2013, drought index series were additionally categorised by severity. For the complete Poisson models, both the short-term effect of heatwaves [$\varepsilon\, (Thwave_t{}^r)$] and atmospheric pollutants such as PM_{10} [$\mu\, (PM_{10_t}{}^r)$], NO_2 [$\rho\, (NO_{2_t}{}^r)$], and O_3 [$\tau\, (O_{3a_t}{}^r)$] were controlled. The lagged variables corresponding to high temperatures (lag = 1–4), PM_{10}, NO_2 (lag = 1–5), and O_{3a} (lag = 1–9) were also indicted in the equation. The constant of each model was also indicated ($\theta\ cons$).

The RR values obtained from the Poisson models using only drought indices calculated at the short and short–medium term (SPI-1,3/SPEI-1,3) for each province of Spain were combined by means of a random effects meta-analysis, which incorporated an estimation of inter-studio variability (heterogeneity) in the weighting (Sterne, 2009), thereby obtaining RR values (95% CI) in the autonomous regions, the climatic regions in terms of the drought indices, and those regions grouped in terms of the proportion of people aged 65 years old and over, and overall for all provinces that showed statistically significant results (at the national level).

All analyses were performed using IBM SPSS Statistics 22 and STATA v 14.1 software.

Datasets

Table 4. Summary of the data sets considered in the analyses and models for peninsular Spain.

STUDY REGION	DEPENDENT VARIABLES	INDEPENDENT VARIABLES	CONTROL VARIABLES Environmental control variables
SPAIN	<u>**Galicia (NW Spain)**</u> **Daily mortality rates*** for **natural** (ICD10: A00-R99), **circulatory** (ICD10: I00-I99), and **respiratory** (ICD10: J00-J99) causes of **mortality from 1983 to 2013** *Data of the capital and towns with over 10 000 inhabitants in each province	The **SPI** (McKee, 1993) The **SPEI** (Vicente-Serrano et al., 2010) Both calculated at **1, 3, 6, and 9 months of accumulation** Obtained from the CSIC (Vicente-Serrano et al., (2017))	From 2000 to 2009 (pollution data available) -**Daily maximum temperatures (T*max*)*** (supplied by the AEMET) -**Pollutants***: Mean daily concentrations ($\mu g/m^3$) of PM_{10}, NO_2, and O_3 (provided by MAPAMA) -**Transformed variables:** i) Non-linear control variables: thresholds of temperature and O_3 linked to mortality ("T*threshold* and O_3*thresold*") ii) Lagged variables: T*threshold* (1–4), PM_{10}, NO_2 (1–5), and O_{3a} (1–9) *Dates of provincial capitals as the reference
	<u>**Peninsular Spain**</u> Daily number of deaths* for natural (ICD10: A00-R99), circulatory (ICD10: I00-I99), and respiratory (ICD10: J00-J99) causes of mortality **from 2000 to 2009** *Data of the capital and towns with over 10 000 inhabitants in each province, which were provided by the INE of Spain	The **SPI** (McKee, 1993) The **SPEI** (Vicente-Serrano et al., 2010) Both calculated at **1 and 3 months of accumulation** Obtained from the CSIC (Vicente-Serrano et al., (2017))	

Table 5. Summary of the data sets considered in the analyses and models for Lisbon district, Portugal.

STUDY REGION	**DEPENDENT VARIABLES**	**INDEPENDENT VARIABLES**	**CONTROL VARIABLES**
			Environmental control variables
LISBON DISTRICT	**Lisbon district** Daily number of deaths for **natural** (ICD10: A00-R99), **circulatory** (ICD10: I00-I99), and **respiratory** (ICD10: J00-J99) causes of mortality from 1983 to 2016 Mortality data series were additionally divided by **gender** (women vs. men) and **age** (45–64, 65–74, and >75). Data were provided by the INE of Portugal.	The **SPI** (McKee, 1993) The **SPEI** (Vicente-Serrano et al., 2010) Both calculated at **1** and **3** months of accumulation Obtained through the SPEI R library using climatic variables calculated from gridded E-OBS data from the ECA&D	From the sub-period of 2007 to 2016 (pollution data available) -**Daily maximum temperatures (T*max*)** (supplied by NNDC CDO) -**Pollutants**: Mean daily concentrations (μg/m^3) of PM_{10}, NO_2, and O_3 (furnished by QualAr) **-Transformed variables:** i) Non-linear control variables: Thresholds of temperature and O_3 linked to mortality ("T*threshold* and O_3") ii) Lagged variables: T*threshold* (1–4), PM_{10}, NO_2 (1–5), and O_{3a} (1–9)

4

SET OF PUBLICATIONS

Future climatic previsions indicate that drought events will likely become more frequent and severe in southwestern Europe as a consequence of climate change, which could trigger greater repercussions on respiratory and circulatory health, including premature mortality, particularly in the most vulnerable groups. Drought effects on health in the Iberian Peninsula are uncertain; therefore, there is a need for an in-depth understanding of the relationship between the occurrence of this extreme hydroclimatic hazard and specific-cause mortality risks in order to conduct effective strategies for drought management, have better preparation, and create early responses to reduce the damaging effects on health associated with the occurrence of drought.

This chapter includes a total of three publications and two submitted papers addressing the assessment of drought conditions (measured by different metrics) on daily natural, circulatory, and respiratory mortality in vulnerable regions such as Spain and central Portugal. Table 6 provides a summary of information on each study, the authors, the year of publication (or in the case of unpublished studies, the year in which they were submitted to the journal), and details about the journal metrics (scientific impact factor, quartile, and the ISSN). The articles are not listed in order of publication, but in a coherent sequence. Moreover, the supplementary material linked to each article is presented in Appendix A.

According to Table 6, the first article is "*Effects of droughts on health: Diagnosis, repercussion, and adaptation in vulnerable regions under climate change. Challenges for future research*" conducted by **C. Salvador**, R. Nieto, C. Linares, J. Díaz, and L. Gimeno, which was published in Science of the Total Environment in 2020. This is a paper in which, following an update of knowledge in this field, a brief conceptual framework of the relationship between drought and health, including drought concepts and metrics, details on the mechanisms that link the occurrence of this natural hazard and specific health impacts, and vulnerability to drought are discussed. Moreover, the uncertainties about this topic are described and future lines of research are proposed to address current and future challenges.

The second article that forms part of this thesis is titled "*Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013*", which was conducted by **C. Salvador**, R. Nieto, C. Linares, J. Díaz, and L. Gimeno and published in the Science of the Total Environment in 2019. This is a regional retrospective ecological time series study that reports the first evidence of a relationship between exposure to different drought conditions and daily natural, circulatory, and respiratory mortality for each Galician province from 1983 to 2013 through the use of GLMs and mortality rate datasets. For this approach, drought was monitored using the SPI and SPEI obtained at short, short–medium, medium, and long-term periods, which allowed the comparison of the performance of different types of drought indices and the sensitivity of different timescales to reflect and quantify the mortality risks. The role of drought severity in the mortality risk estimation was also determined. Moreover, the short-term effects of heatwaves and atmospheric pollution were examined under the control of drought conditions measured at short-term periods in order to obtain more detailed and precise results.

The third article that forms this chapter is entitled "*Short-term effects of drought on daily mortality in Spain from 2000 to 2009*", which was conducted by **C. Salvador**, R. Nieto, C. Linares, J. Díaz, and L. Gimeno and published in Environmental Research in 2020. The principal aim of this study was to obtain broader conclusions across the country from 2000 to 2009 through the use of the SPEI and SPI obtained over a short-term period and number of deaths datasets. The impacts of drought conditions on daily natural, circulatory, and respiratory mortality of each province of peninsular Spain were also evaluated under the control of the effects of T*hwave* and atmospheric pollution.

Subsequently, the paper entitled "*Quantification of the global effects of droughts on daily mortality in Spain at different timescales: A meta-analysis*" was conducted by **C. Salvador**, R. Nieto, C. Linares, J. Díaz, and L. Gimeno and submitted to the

International Journal of Environmental Research and Public Health. Taking into account the previous cited study, an impact assessment of longer drought conditions on daily natural, circulatory, and respiratory mortality at the provincial level was conducted with the main objective of comparing the results with those of shorter drought periods. Thus, this study revealed for the first time for which drought accumulation period (1 or 3 months) the daily specific-cause mortality was mainly manifested for each province of peninsular Spain from 2000 to 2009 using two types of multi-scalar meteorological drought indices (SPEI and SPI). Moreover, through a meta-analysis combining the provincial RR values, the overall value was calculated for all of peninsular Spain. As Spain is administratively divided into intermediate territorial areas (autonomous regions), the RR levels were obtained for each area with the aim to provide useful information for public health administrations. The droughts were not similar along the territories, and in this way a meta-analysis was also performed for the different known spatial patterns. Finally, and in the absence of daily mortality data by age, a prospective study was conducted for the areas with different proportions of people aged 65 years and over.

This allows the illustration of a comprehensive view of the effects throughout the country.

Finally, the last study that makes up this section is entitled "*Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: Risks assessment by gender and age*", which was conducted by **C. Salvador**, R. Nieto, C. Linares, J. Díaz, C.A. Alves, and L. Gimeno and submitted to Science of the Total Environment in 2020. This is a comprehensive ecological time series study regarding the evaluation of daily natural, circulatory, and respiratory mortality risks linked to droughts measured by the SPEI and SPI calculated at the short term and short–medium term in Lisbon district in the context of climate change with an analysis by gender and age. The short-term effects of extremely high temperatures and atmospheric pollution were also evaluated. The principal objective was to obtain more precise and exhaustive information on the structure of the population at risk and to determine the most vulnerable groups. The inclusion of results obtained in this type of study is crucial in order to develop more effective measures of prevention, mitigation, and adaptation in specific groups of the population and to reduce vulnerability, especially considering future projections of climate change. Number of deaths datasets were used.

Table 6. List of publications.

TITLE	AUTHORS	YEAR	JOURNAL
Effects of droughts on health: Diagnosis, repercussion, and adaptation in vulnerable regions under climate change. Challenges for future research.	**C. Salvador**; R. Nieto; C. Linares; J. Díaz; L. Gimeno	**2020**	Science of the Total Environment. JCR abbrev: STOTEN
Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013.	**C. Salvador**; R. Nieto; C. Linares; J. Díaz; L. Gimeno	**2019**	Science of the Total Environment. JCR abbrev: STOTEN
Short-term effects of drought on daily mortality in Spain from 2000 to 2009.	**C. Salvador**; R. Nieto; C. Linares; J. Díaz; L. Gimeno	**2020**	Environmental Research. JCR abbrev: ER
Quantification of the global effects of droughts on daily mortality in Spain at different timescales: A meta-analysis.	**C. Salvador**; R. Nieto; C. Linares; J. Díaz; L. Gimeno	**2020**	Submitted. International Journal of Environmental Research and Public Health. JCR abbrev: IJERPH
Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: Risks assessment by gender and age.	**C. Salvador**; R. Nieto; C. Linares; J. Díaz; C.A. Alves; L. Gimeno	**2020**	Under review. Science of the Total Environment. JCR abbrev: STOTEN

Table 7. List of publications and summary of the impact and quality of the journal in which the papers are published or submitted. The data corresponds to the characteristics listed for 2019 (last year available at the date of preparation of this manuscript) in the Web of Science (JCR).

JOURNAL	DESCRIPTION	JOURNAL METRICS
Science of the Total Environment	An international journal for scientific research into the environment and its relationship with humankind. It is a multi-disciplinary journal for publication of novel, hypothesis-driven, and high-impact research on the total environment, which interfaces the atmosphere, lithosphere, hydrosphere, biosphere, and anthroposphere.	- Impact factor: 6.551 - 5 y impact factor: 6.419 - Quartile: Q1 in Environmental Science - ISSN: 0048-9697
Environmental Research	A multidisciplinary journal of environmental sciences and engineering publishing high-quality and novel information about anthropogenic issues of global relevance and applicability in a wide range of environmental disciplines and demonstrating environmental application in a real-world context.	- Impact factor: 5.715 - 5 y impact factor: 5.735 - Quartile: Q1 in Environmental Science - ISSN: 0013-9351
International Journal of Environmental Research and Public Health	A multidisciplinary peer-reviewed open access journal. It covers environmental sciences and engineering, public health, environmental health, occupational hygiene, health economic evaluation, and global health research. - Special issue "Human health implications of droughts".	- Impact factor: 2.849 - 5 y impact factor: 3.127 - Quartile: Q1 in Public, Environmental & Occupational Health (SSCI); Q2 in Environmental Sciences (SCIE) - ISSN: 1660-4601

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Effects of droughts on health: Diagnosis, repercussion, and adaptation in vulnerable regions under climate change. Challenges for future research

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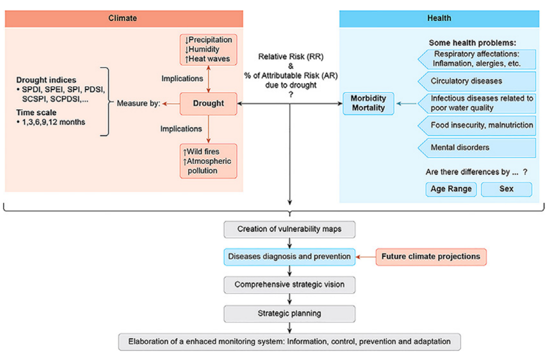
GRAPHICAL ABSTRACT



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ABSTRACT

There is little doubt about the effects of drought events on human health in the present climate. Projections of climate change indicate an increase in the occurrence and severity of droughts in the 21st century in a number of regions, thus it is likely that these types of hydrological extremes could have more of an impact if appropriate adaptation measures are not taken. The majority of studies on the effects of drought are focused on meteorological, agricultural, or hydrological contexts, but there are rather fewer assessments of the impacts of droughts on health. In particular, there have been hardly any attempts to compare different drought indices in order to identify and quantify the impacts of drought on health systems. In addition, rather better knowledge is needed on the mechanisms of vulnerability involved. In this paper, we attempt to describe the complexity of drought phenomena and the difficulty involved in quantifying the health risks linked to their occurrence. From an international perspective, we provide a brief review of the harmful effects of droughts on health in the context of climate change, as well as the vulnerability factors related to droughts. We make an assessment of aspects that have not yet been investigated, or which require further attention to be devoted to this topic. The principal aim of this paper is therefore to draw attention to the need to consider closely the relationship between drought indices and human health, in order to achieve a more fundamental understanding, and to propose specific courses or lines of action for future years, which could eventually be of use to healthcare providers and services.

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1. Difficulty in studying drought events and quantifying their risks on human health

1.1. Difficulty in defining and characterizing "drought"

Unlike other extreme phenomena, droughts are highly complex events that are difficult to define clearly and quantify (Vicente-Serrano et al., 2012; Quiring, 2015; Vicente-Serrano, 2016; Spinoni et al., 2019) because it is difficult to establish a beginning and an end of each event and many of the definitions depend on the different disciplinary perspectives or systems in which it is analysed (Wilhite, 2000; Valiente, 2001; Vicente-Serrano et al., 2012). Thus, different types of droughts can be distinguished, creating new challenges in the estimation of health risks because each type of drought can affect health outcomes in different ways (Berman et al., 2017). Standard classifications refer to meteorological, agricultural, hydrological, and socioeconomic droughts that include specific-sector impacts in their definitions (Wilhite, 2000; Mishra and Singh, 2010; Dai, 2011; Stanke et al., 2013; Sena et al., 2014; Ebi and Bowen, 2016; MINECO, 2019):

- **Meteorological drought** is a consequence of the prolonged deficit of precipitation or an acute shortage of precipitation, and it usually affects large areas. Its occurrence is determined by parameters such as the duration, severity, and intensity and it gives rise to other types of drought.
- **Hydrological drought** is associated with the impacts of precipitation shortages on surface water or groundwater supplies (discharge deficit).
- **Agricultural drought** links the characteristics of meteorological and hydrological drought to agricultural impacts. It refers to a deficiency in soil moisture to satisfice particular crop needs.
- **Socioeconomic drought** is based on the excess demand with respect to the supply for a specific economic good as a consequence of a water shortage that affects people.

The different types of droughts are not independent because they are associated with a deficiency in the hydrological variable characteristic; hence, drought concepts should be understood in an interdisciplinary pathway as socio-environmental phenomena that are produced by mixtures of climatic, hydrological, environmental, socioeconomic, and cultural factors (see Kallis, 2008). Particularly, we considered drought as a complex, recurrent and slow natural extreme climatic event that affects several environmental and society systems, whose effects depend on the vulnerability factors such as the magnitude of the events, geographical location of the affected region, socioeconomic and demographic aspects of exposed population as well as the sensibility and adaptive capacity of the communities, among others. This phenomenon acts in different spaces and time scales, and occurs as a consequence of a deficit in the amount of rainfall over a long period (several months to years) being largely influenced by the demands of human and environment use of water. The severity of the event depends on the duration, intensity and geographical extent and can be aggravated by the influence of other climatic factors such as high temperatures, strong winds or low relative humidity (Wilhite, 2000; Wilhite et al., 2007; Kallis, 2008; Quiring, 2015).

1.2. Metric of droughts and the estimation of risks. The crucial role of drought indices

Droughts are slow creeping phenomena, and many of their impacts are indirect, non-structural, diffuse, and often accumulate slowly over time and may linger after the end of an event, making it challenging to study as discrete events (Wilhite, 2000; Kallis, 2008; Mishra and Singh, 2010; Brüntrup and Tsegai, 2017; Spinoni et al., 2019). Furthermore, the different effects largely depend on the magnitude of drought events (Stanke et al., 2013; Ebi and Bowen, 2016). Drought indicators are essential in monitoring the hydrological extremes, as well as detecting and quantifying the direct and indirect risks associated with the occurrence of these hazards to obtain better knowledge and preparation to tackle drought impacts (Vicente-Serrano et al., 2017). Although numerous specialized indices have been proposed for measuring different forms of drought (Keyantash and Dracup, 2002; Bachmair et al., 2016; WMO and GWP, 2016), there is a lack of studies that focus on examining which index is the most accurate for measuring the type of drought with reference to its effects on health, which is of critical importance (Bachmair et al., 2016; Berman et al., 2017; Salvador et al., 2019), and there is no specific index designed specifically for address this purpose (Berman et al., 2017). As different effects of droughts can vary in both space and time (Wilhite et al., 2007; Salvador et al., 2019), several indices are widely used in the scientific literature, such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI), which have the advantage of being able to be used with different time scales. SPI is calculated based on precipitation data, while SPEI is based on precipitation and evapotranspiration data, taking into account the atmospheric evaporative demand (Vicente-Serrano et al., 2012). Another index commonly used in drought analysis is the Palmer Drought Severity Index (PDSI) (Palmer, 1965; Dai, 2011) that could be used individually or in combination with other different types of drought indicators to create new indices as those used by the United States Drought Monitor (USDM), which was recently used to monitoring drought conditions and estimating the risk of hospital admissions and mortality in USA (Berman et al., 2017). On the other hand, PDSI has been modified with serval aims into derived indicators as for instance the Standardized Palmer Drought Index (SPDI) (Ma et al., 2013), Self-Calibrating PDSI (SCPDSI, Wells et al. (2004)), or the modified Palmer Drought Severity Index (MPDSI, Yu et al., 2019). The different scales used for some of these indices reflect the quantity of water deficits during different periods of accumulation, which allows association with the different forms of droughts: one month of accumulation is used for meteorological droughts, one to six months is used for agricultural droughts, and six to 24 months or longer is used for hydrological droughts (Vicente Serrano, 2016; Monteiro et al., 2019), and used for the first time in Salvador et al. (2019) linked to health affectations.

2. Climate change-drought-health nexus: a global overview

Climate change is one of the most substantial environmental challenges worldwide and is in large part caused by anthropogenic activities, which increase greenhouse gas emissions that actively contribute to global warming (Franchini and Mannucci, 2015). It has been widely described that a consequence of climate change would be an increased frequency in extreme climatic events such as heatwaves, droughts, floods, cyclones, and forest fires that would have a higher intensity, leading to far-reaching effects on environmental and human systems (IPCC, 2014; Watts et al., 2015; Bell et al., 2018; Gupta et al., 2019).

Among the different climatic extremes, droughts are widely considered as the costliest, most complex and destructive phenomena, as well as the least understood event affecting more people than any other climatic hazard (Obasi, 1994; Wilhite, 2000; Kallis, 2008). There is a growing body of evidence to indicate that health is profoundly vulnerable to droughts (Stanke et al., 2013; IPCC, 2014), which affect several million people every year (Dai, 2011), and are responsible for widespread morbidity and mortality worldwide (Stanke et al., 2013). As much as 15% of natural disasters globally are caused by droughts and the mortality related to droughts represents around 59% of the total deaths caused by extreme weather events (McCann et al., 2011). In addition, it was described that 15 of the major droughts in 2003 to 2012 affected around 36.5 million people worldwide (Ebi and Bowen, 2016). There are differences in the repercussions and magnitude of drought impacts in the different continents because the resource-poor nations are where most of the drought-related morbidity and mortality occur, and the resource-rich nations have a mainly economic impact (Keim, 2015). A higher number of people are affected by droughts in Asia, while Africa is where more drought disasters and higher mortality occur, and the West suffers higher economic damages (Kallis, 2008). Droughts in the United States have caused mounting costs (an average of $6–8 billion has been reported) (Keyantash and Dracup, 2002). Furthermore, in Europe where occurs an increase in the number and severity of droughts since 1980, the cost is estimating in around €100 billion during the past 30 years (European Commission, 2010). A global analysis (Alpino et al., 2016) shows that from 659 droughts studied during 1900–2005, they resulted in 2.21 billion people affected and 11 million deaths in the world as well as in notable economic losses in several regions such as in China (around 2.4 billion dollars) or Brazil (around 11 billion dollars).

The continued deficiency of precipitation and water shortage over an extended period promotes the occurrence of drought events (McCann et al., 2011; Stanke et al., 2013; Quiring, 2015). However, other climatic factors can escalate the intensity and aggravate drought periods, such as the increase in temperatures (as a result of the loss of water by evapotranspiration) (Kallis, 2008; Vicente-Serrano et al., 2014), high winds, or low relative humidity (Wilhite, 2000; Quiring, 2015). Anthropological activities and inefficiencies in water distribution, planning, and management (eg. poor land management, deforestation, soil degradation, water mismanagement policies) can induce or potentially exacerbate the severity of droughts and their effects, whose consequences could be aggravated by the occurrence of droughts as well (Quiring, 2015; Brüntrup and Tsegai, 2017; Spinoni et al., 2018; Gebremeskel et al., 2019). In this aspect, although droughts are understood as natural phenomena, mismanagement of water resources can lead to increase in drought susceptibility, greater water scarcity intensification, drier soils, overexploitation of groundwater reservoirs, higher risk of forest fires occurrence, as well as other environmental and social costs, which in consequence can in turn to strengthen the negative effects associated to droughts (e.g. Brüntrup and Tsegai, 2017). Thus, is crucial importance that government systems pay particular attention to implement good measures of water management, and promote the establishment of good systems of surveillance being necessary a responsible use of water.

Droughts appear to be increasing in both developing and developed countries (Quiring, 2015) and the Intergovernmental Panel on Climate Change (IPCC) reports indicate that the health impacts of climatic extremes, such as droughts, may be reduced but not eliminated in more developed countries and there will be a heterogeneous response based on socioeconomic means and underlying health status (IPCC, 2014). In this context, future projections of climate change indicate that droughts will become more frequent and intense over the 21st century as a result of reduced precipitation and increased evapotranspiration in several regions in the world (WHO, 2018). This may especially impact Southern Europe, the Mediterranean region, Central Europe, Central North America, Central America and Mexico, northeast Brazil, and Southern Africa (Vicente-Serrano et al., 2011; Ebi and Bowen, 2016), which could further reinforce any dangers to public health, especially in vulnerable regions. Particularly, it has been estimated that about half of the world's population will live in conditions of water scarcity by 2025, which will compromise water quality; this is already evident in different parts of the world (Bifulco and Ranieri, 2017). Furthermore, a study conducted in Europe projected in the next decades an increase in the frequency of droughts mainly in spring and summer (especially over southern Europe) but also a decrease in the frequency of droughts over Northern Europe in winter (Spinoni et al., 2018).

3. Direct and indirect effects of drought on health and vulnerability

3.1. Direct and indirect effects of droughts

Droughts have far-reaching effects that are both short and long term across diverse sectors (environmental, economic and social). However, the classification of the effects in short or long term impacts is usually very complex (Wilhite, 2000; Hayes, 2002; Keyantash and Dracup, 2002; Wilhite et al., 2007; Alpino et al., 2016; Bachmair et al., 2016). In terms of health, several compressive reviews on health risks associated with droughts indicated that drought effects occur primarily through an indirect pathway (Stanke et al., 2013; Sena et al., 2014; Yusa et al., 2015; Ebi and Bowen, 2016).

In a direct pathway, droughts impact the environment and ecosystems through a reduction in water availability and quality, decrease of hydropower production, diminution of food production, or an increase in forest fires and wildlife damages (Wilhite et al., 2007; Stanke et al., 2013; IPCC, 2014; Bachmair et al., 2016; Bifulco and Ranieri, 2017). Droughts can also incorporate and reflect the effects of other associated extreme climatic events to negatively affect health when they take place in the same period because concurrent incidence can accelerate the development of droughts and increase indirect risks on health (Stanke et al., 2013; Bell et al., 2018; Salvador et al., 2019). During summer droughts may be strongly associated with the increase of heatwaves, and stagnation conditions (e.g. prolonged blocking of anticyclonic atmospheric conditions) (García-Herrera et al., 2010), which favour the increase in pollutant concentrations associated with stagnant conditions (e.g. Wang et al., 2017). In winter, it has been described that droughts can generate unfavourable dispersion conditions and much higher particulate matter (PM) with harmful effects on health (e.g. Hu et al., 2019). On the other hand, droughts can also induce extreme temperatures through variations in soil moisture (e.g. He et al., 2014). In addition, heatwaves may increase the severity of droughts, and both events may directly promote an increase in the frequency and intensity of wildfires that release toxic aerosols into the atmosphere (He et al., 2014; IPCC, 2014; Franchini and Mannucci, 2015). However, the mechanisms between these phenomena are complex and can occur without the presence of droughts.

In any way, the majority of health impacts that are linked to droughts are primarily indirect (Ebi and Bowen, 2016). In the case of the most visible impacts, a combination of drought events with extreme precipitation can compromise the availability and quality of water (microbiological and chemical contamination) and indirectly lead to an increased risk for infectious illnesses, particularly water-, food-, zoonotic-, and vector-borne diseases affecting the security of the population (Hayes, 2002; Tirado-Blazquez, 2010; Yusa et al., 2015; Alpino et al., 2016; Bell et al., 2018). Several studies have indicated an association between the incidence of droughts (as the reduction in water levels, streamflow, and the consequent stagnation) and various waterborne diseases transmitted through faecal-oral pathways caused by bacterium and other pathogens (e.g. *Escherichia coli, Salmonella, Vibrio cholerae*), triggering diarrheal illness and gastrointestinal disorders and other water-related diseases, which could threaten public he (Bifulco and Ranieri, 2017; Bell et al., 2018). In addition, the incidence of high temperatures and drought conditions could also promote massive blooms of toxin-producing cyanobacteria (Yusa et al., 2015; Lehman et al., 2016; Walter et al., 2018).

Droughts have also been strongly linked to food insecurity (undernutrition and malnutrition) (Watts et al., 2017) through a reduction in the quantity and stability of food, as well as through affectation of water quality and quantity, which lead to an increased risk of impairing the immune system (Lohmann and Lechtenfeld, 2015), as well as morbidity and mortality (Ebi et al., 2010; Stanke et al., 2013; IPCC, 2014; Ebi and Bowen, 2016).

Other drought-related risk on health is a rise in the incidence of vector-borne diseases (Brown et al., 2014; IPCC, 2014; Alpino et al., 2016). In some extratropical regions across Europe and North America, vector-borne diseases can be promoted by climate change (increased temperatures and drier conditions) because of their geographic location, when climatic conditions are similar to those found in tropical regions where vector-borne diseases are endemic (López-Vélez and Molina Moreno, 2005). In this context, droughts also have impacts from wildlife intrusion, rodents, and pests that may cause an increase of harmful affectations to the human population (Hayes, 2002).

As stated above, droughts have frequently been associated with drier soil, deforestation, an increase in airborne dust, wildfire smoke and poor air quality (increased toxic particles in the atmosphere), as well as alterations in the dispersion of allergens, which potentially compromise respiratory and circulatory health (Stanke et al., 2013; IPCC, 2014; Sena et al., 2014; Yusa et al., 2015; Berman et al., 2017; Wang et al., 2017; Bell et al., 2018). These affectations may result in mortality, especially among vulnerable populations such as the elderly and people with pre-existing chronic problems (Hayes, 2002; Watts et al., 2017; Bell et al., 2018; Salvador et al., 2019). A recent study conducted in the Western USA during 2000 to 2013 described that high-severity and worsening drought conditions increased the risk of mortality, but were also linked to a decrease in respiratory admissions among older adults (Berman et al., 2017), in contrast to evidence of other studies (Smith et al., 2014; Salvador et al., 2019). Furthermore, it was found more significant repercussions on the risk for cardiovascular diseases and mortality in those regions that had previously been less exposed to drought events (Berman et al., 2017). For the first time, a recent study conducted by Salvador et al. (2019) in NW Iberian Peninsula (Southern Europe) showed the significant association between the effect of droughts, measured by two daily drought indices (SPI and SPEI) at different accumulation periods and daily mortality (natural, respiratory, and circulatory causes) during a long period from 1983 to 2013. The main findings suggested that interior regions were the most affected principally for shorter droughts (in comparison with coastal areas), where impacts on daily mortality were mainly explained by the effects of atmospheric pollution, and the results for both indices used were very similar.

But, in this way, the study by Vicente-Serrano et al. (2012) shows that although SPEI and SPI showed similar results, SPEI is the best measure for detecting drought effects on hydrological, agricultural and ecological variables particularly in summer. So, and according to the global warming projections, SPEI could also provide a better estimation for droughts severity and health risks than SPI, for bigger areas, because the former considers both precipitation and evapotranspiration data for its calculation, while SPI only takes into account precipitation data.

Finally, the effects of droughts on mental health and wellbeing is a crucial and far-reaching issue. Prolonged droughts are associated with socioeconomic losses, forced displacement of communities (Wilhite et al., 2007; Alpino et al., 2016), which can lead to serious mental health problems and emotional consequences such as chronic stress, distress, worry, sleeplessness, generalized anxiety, depression, conflict and violence (Hayes, 2002; Sartore et al., 2007; Berry et al., 2010; Shukla, 2013; Stanke et al., 2013; Vins et al., 2015). Other studies have also indicated that, in extreme cases, prolonged droughts have been associated with an increase in the rate of mortality by suicide, mainly in rural populations (Shukla, 2013; IPCC, 2014; Obrien et al., 2014; Berman et al., 2017). Further, there are discussions about the role of extreme drought conditions as a contributing factor in civil conflicts (Selby et al., 2017), political instability and crises (Bell et al., 2018).

Many of these relationships were summarized in Fig. 1, trying to sum up the link between climate, droughts, human health, environmental, and socioeconomics problems.

3.2. Drought vulnerability climate change

Vulnerability mediates the hazards and impacts and is a function of drought exposure and the sensibility and adaptive capacity of the population (Kallis, 2008; Ebi and Bowen, 2016). The vulnerability is also determined by demographic characteristics, technologies, policies, and social behaviours (Quiring, 2015). Several studies indicated that the negative effects of droughts are in line to the level of development and degree of preparation of different countries in adapting their systems to current and future climatic variability in different sectors. Socioeconomic factors, the underlying health status of the population, geographical location, and the capacity of the government to respond are crucial predictors of vulnerability, any of which could aggravate the threats to human health (Stanke et al., 2013; IPCC, 2014). Thus, drought impacts will affect different countries at varying degrees depending on the region, and the affected populations (being the poor and other vulnerable people those that tend to suffer higher negative repercussions (Sena et al., 2014)).

Particularly, geographical location is an important direct factor of vulnerability because people who lives in regions more affected by droughts or in regions that are prone to droughts or water shortages are highly vulnerable to the harmful health effects of droughts (Lohmann and Lechtenfeld, 2015). That is the case of arid or semiarid regions (e.g. Sena et al., 2014; Ebi and Bowen, 2016), where these effects could be exacerbated by a growth in population, as is expected in the case of Africa for the next 30 years (Kravitz, 2014). In addition, different magnitudes of drought impacts on health can occur between coastal and interior areas (e.g. Berman et al., 2017; Salvador et al., 2019), or between rural and urban locations (e.g. OBrien et al., 2014; Vins et al., 2015; Lohmann and Lechtenfeld, 2015; Berman et al., 2017). In particular, Berman et al. (2017) described that in the interior counties of Western USA where droughts occurred less frequently (e.g. eastern Great Plains), the risk for cardiovascular diseases and mortality in older adults was higher during worsening drought conditions in contrast to coastal areas (such as California, and the southwest), where exits a higher frequency of drought conditions. This fact occurs may be due to possible population acclimatization.

However, a comprehensive international review showed that more frequent and intense droughts might be sources of health vulnerability themselves for subsequent droughts, or when they are followed by other extreme events, such as floods (mainly by alterations in the degree of exposure or changes in sensibility and susceptibility of exposed people). The role of the floods after drought periods are particularly interesting because floods are associated to deaths, exacerbation of chronic diseases, increase of water- and vector-borne diseases, rise of respiratory infections as well as increase of malnutrition, mental health diseases or adverse birth outcomes (Alderman et al., 2012). Thus, the magnitude and

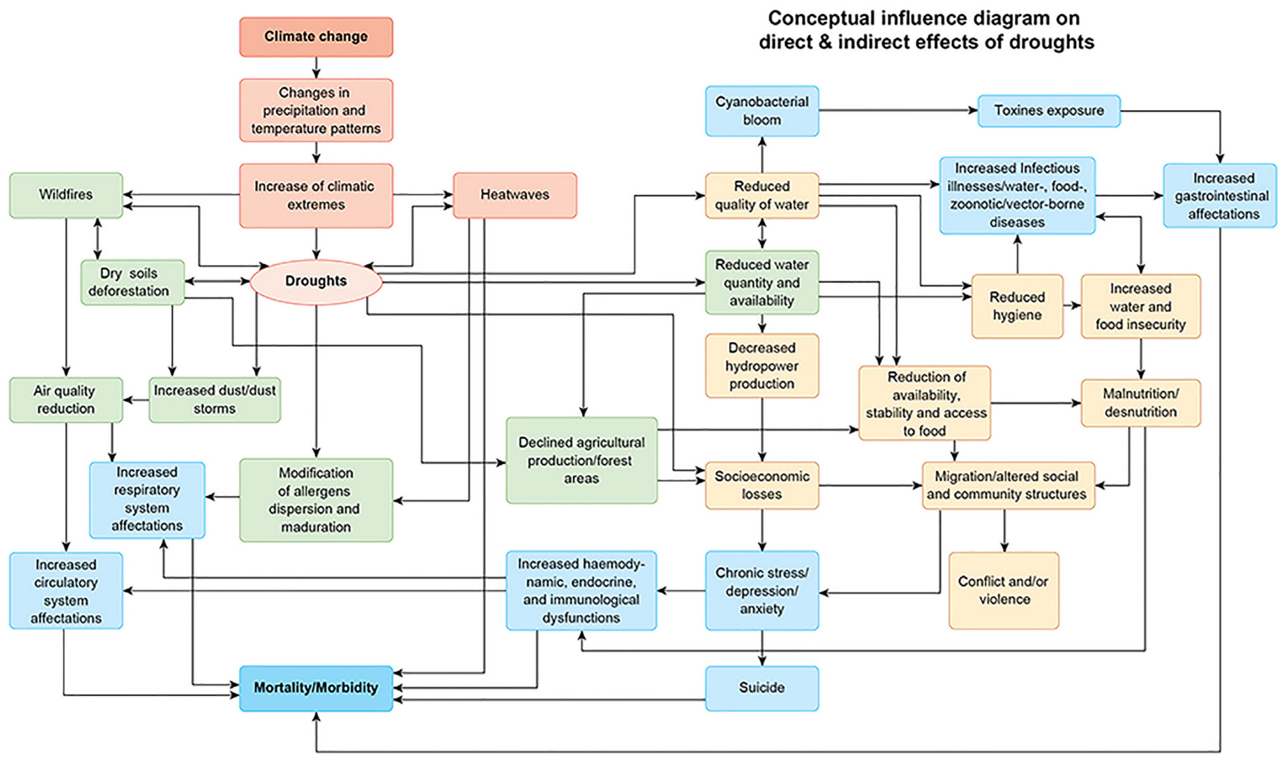

Fig. 1. Conceptual influence diagram on direct and indirect effects of droughts. The direct effects of droughts on environmental degradation and ecosystems modification were illustrated as well as the different processes and indirect pathways through which droughts impacts on society and human health in the context of climate change. Colour code: climatic, health, environmental and social aspects are represented in red, blue, green and yellow colours, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

health risk behaviour pattern could increase, especially if there is not adequate recover time of affected people between the different hydrological extreme events or if there is an inadequate adaptive capacity of the population (Ebi and Bowen, 2016).

Finally, it has been described that agricultural workers, smallholder producers, herders, and rural populations, whose economy and subsistence largely depend on agriculture, are the groups most vulnerable to drought hazards (Kallis, 2008; Edwards et al., 2014; Lohmann and Lechtenfeld, 2015). Destitute people, women (and particularly pregnant women), and groups that are physiologically more susceptible (e.g. children, older adults, and low socioeconomic status) have an increased vulnerability to the negative impacts of drought events (Kallis, 2008; Yusa et al., 2015). People with chronic conditions are also highly vulnerable to the negative health impacts associated with droughts because the occurrence of this hydrological extreme can exacerbate their conditions, making them less capable of facing other extreme climatic hazards (Yusa et al., 2015). In this aspect, regions such as West-, East-, and Southern Africa and Southern Asia are the most vulnerable regions to food insecurity (Krishnamurthy et al., 2014), where children are the most affected by malnutrition and mortality during droughts long term, which may have negative repercussions during their adult life (Lohmann and Lechtenfeld, 2015). On the other hand, reliable data from the World Health Organization (WHO) show heterogeneous differences between the different sexes related to the negative health impacts attributable to natural disasters (droughts, floods, and storms), with the highest levels of mortality generally being seen in women (IPCC, 2014). However, in rural populations of Australia (New South Wales) there was an increase in the incidence of suicide primarily in male farmers aged 30–49 associated with the incidence of drought events during 1970–2007 in contrast to the diminution the risk of suicide in females aged >30 years old during droughts (Hanigan et al., 2012).

4. Uncertainty

The study and characterization of droughts are very complex, and there are several uncertainties about the details of the relationship between the occurrence of these hydrological extremes and their effects on health, so more studies are necessary to understand the different mechanisms, in order to promote awareness of the risks and social and environmental vulnerabilities worldwide. The majority of studies have focused on the association between droughts and the effects on health through indirect mechanisms, and, although different hypotheses have been proposed, the biological mechanisms through which droughts affect health are not well understood (Berman et al., 2017). But, it is important to remark that there is a lack of systematic studies that tackle the following aspect that remains to be investigated: what measures and characteristics of droughts are the most predictive to reflect health effects (Balbus, 2017). To our knowledge, with the exception of Salvador et al. (2019), there are no studies that evaluate and compare the performance of different drought indicators (calculated as an index or indices) to quantifying the risks of this hydrological extreme on specific health effects particularly in consideration to the different forms of drought and periods of time in which these effects can be manifested. Thus, future studies that explore this relationship through the comparison of multiple drought exposure and models are needed.

In addition, a better understanding of the vulnerability associated with droughts as well as the mechanisms linked to this vulnerability is crucial, considering future negative climate change in order to reduced vulnerabilities. There are necessary more conclusive studies that evaluate different effects of drought (measured by different indices) in consideration to changing climate, conducting the control by sex and age groups of the population exposed in order to identify which index (or indices) are the best proxy for reflecting the health risks in different sectors of the population and determinate the most vulnerable groups. Furthermore, it is also essential to extend this type of analysis at large scales (eg. national level) toward obtaining broader conclusions than regional or local studies.

Therefore, it is necessary to implement global and regional strategies in prevention and adaptation plans to ensure mitigation of the different direct and indirect effects on environmental systems. In particular, human health should be considered, from the most immediate effects (e.g., water insecurity) to long-term effects (e.g., malnutrition), including the least visible (e.g., impairments in mental health), all with a focus on the most vulnerable groups in society.

This research initiative should be articulated via a set of primary objectives (as shown in Fig. 2):

- To exhaustive study the climatic conditions that affect different health parameters of the population in currently affected regions, with the objective of understanding patterns of behaviour. Health parameters should be related to the thresholds of environmental conditions (temperatures, precipitation, humidity, pollution) and the occurrence of droughts.
- To carry out systematic global and regional studies on health indicators attributable to different environmental conditions by quantifying Relative Risk (RR) and the percentage of Attributable Risk (AR) of different causes of daily morbidity and mortality linked with drought events measured by different indices using different statistical models). Variables should be mapped to assess geographical variations.
- To conduct an exhaustive systematic study that evaluates and quantifies the different repercussions (both direct and indirect impacts) monitoring drought conditions differentially by severity (mild, moderate, extreme and severe), intensity and frequency.
- To carry out methodological studies in which different types of indicators of droughts (and different accumulation periods) are evaluated, with the ultimate aim of identifying the optimal and most sensitive drought index (and time scale) to reflect and quantify the risks in terms of morbidity and mortality. In this way, it will be possible to establish a more precise classification of drought effects on health as short, medium or long term impacts.
- On the other hand, to obtain datasets of droughts at different temporal resolutions to conduct comparative studies on the quantification of health risks associated with droughts using daily, weekly, monthly and/or annual data series. This is important because in several regions of the word health data are not available in scales as precise as daily or weekly scales.
- To perform statistical models to control the effects of other extreme climatic phenomena associated with the occurrence of drought events, such as heatwaves, forest fires, and atmospheric pollution, as well as investigate the association between droughts and weather types. It is important to carry out a comparative study about the effects on health parameters only under drought periods and when this hydrological extreme occurs with other extreme climatic events in study regions. This fact allows evaluate direct and indirect impacts as well as analyse the synergic effects on health parameters.
- Other aspect that remain to be investigated is evaluate and compare changes in composition in particulate matter (eg. more toxicity) during droughts respect to no-droughts periods and analyse, in the case of this occur, if these lead to greater impacts. Although there are studies which reveal changes in particulate matter quantity associated to drought periods, as far as we know there is no evidence about changes in composition of toxic aerosols during drought conditions. In this context, Berman et al. (2017) discuss the possibility of changes in toxic-

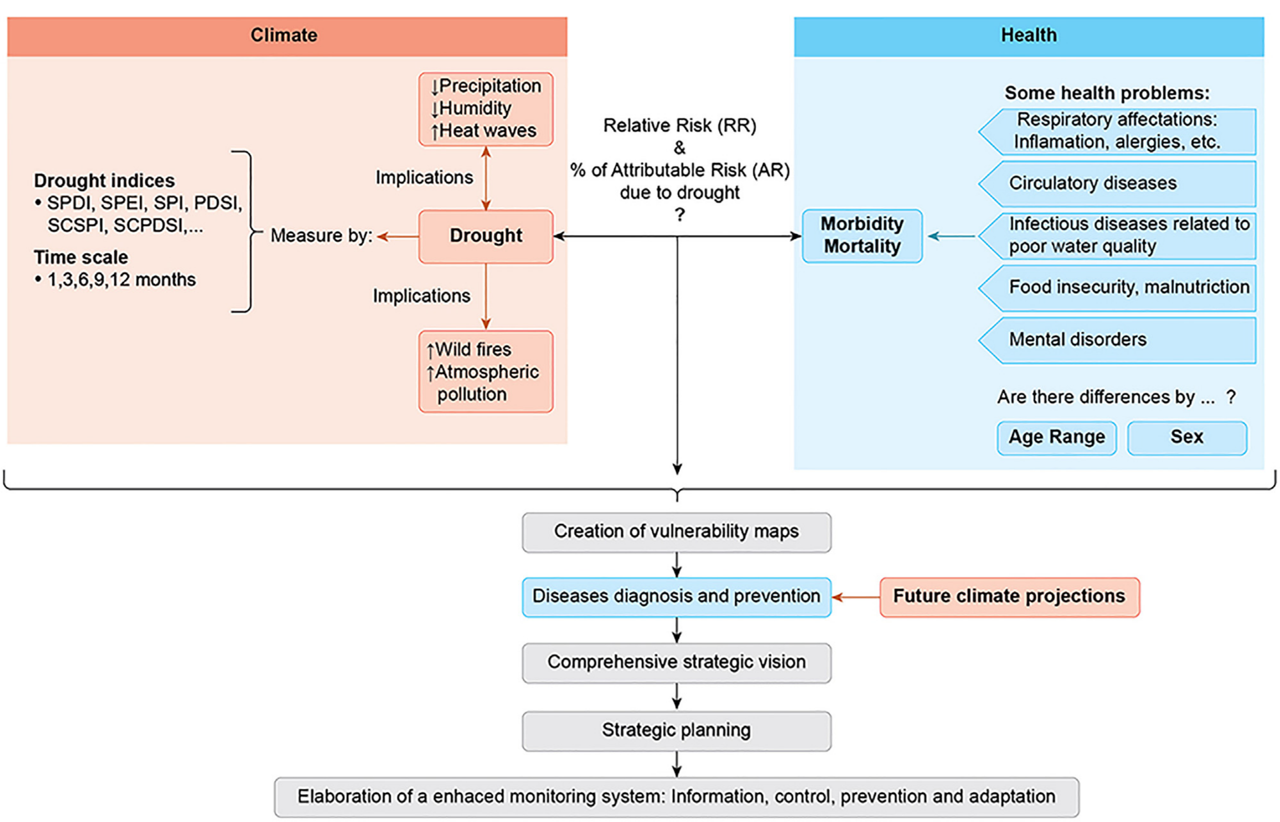

Fig. 2. Conceptual diagram of the methodological summary and protocol to follow for the here articulated research initiative for future years.

ity of PM2.5, however this fact was not tested.

- To carry out the quantification of different health risks (according to the diseases and causes of mortality described above) by age groups and gender for the population using statistical models, in order to identify the groups most vulnerable to the effects of droughts in terms of health. Also, to consider other vulnerability factors in statistical models and to compare the different health risks during different conditions (e.g. drought days and non-drought days in summer, spring, autumn, and winter months). For example, conduct comparative studies on the estimation of health risks associated to droughts in developed and developing countries under similar drought conditions to assess the role of socioeconomic factors and government measures as sources of vulnerability to drought impacts. On the other hand, to carry out differential analysis on drought effects taking into account seasonality will allow to know in a more precise way the different biological mechanism through which droughts specifically affect health.
- Estimating future scenarios and the probability of occurrence of the minimum, maximum, and mean climatic thresholds, as well as the incidence of extreme climatic events described in the previous points for different future climatic scenarios, making use of regional climate change projections (eg. RCP4.5 and RCP8.5 emissions scenarios). This will permit us to estimate the health risks associated with each of these future climatic conditions.
- To construct vulnerability maps for a better understanding of current and future risks associated with climate change, to improve monitoring, prevention, and adaptation systems.
- To investigate the potential of pre-operative seasonal and climatic as undertaken by the ECMWF (European Centre for Medium-Range Weather Forecasts) for the elaboration of an early warning system that could become operative and useful for the regional health services.
- To develop preventive and early-warning measures to achieve better adaptation plans that will allow for the mitigation of the possible harmful threats to human health in the near future, mainly focusing on the most vulnerable groups in order to reduce their vulnerability. Strengthen drought management measures of water and raise public awareness of possible future health risks of drought events.

Obtaining a complete understanding of the details on the link between the occurrence of different drought conditions and the different health effects is crucial to be able to take early measures of prevention and adaptation as well as reduce vulnerability in more susceptible groups, especially in consideration to future projections of climate change.

5. Conclusions

Droughts are complex socio-environmental hazards produced by mixtures of climatic, hydrological, environmental, socioeconomic, and cultural factors, and its study should be holistic by using different fields and institutions. Droughts are widely considered to be the costliest, most complex, most destructive, and the least understood phenomenon affecting more people than any other hazard. The definition and quantification of droughts are difficult and often uncertain. Droughts directly impact the environment and ecosystems through a reduction in both water availability and quality, reduced crops, and reduced forest yield back, as well as through an increase in the occurrence and intensity of fires. In addition, droughts may incorporate effects of other climatic extremes whose concurrent incidence may accelerate the development of droughts as well as increase the indirect risks on health. The majority of the effects on health are indirect and range from water-, food-, zoonotic-, and vector-borne diseases to malnutrition, socioeconomic impacts, migration, effects in mental health, morbidity, and mortality. The risks linked to droughts are heterogeneous and depend on the interaction between the regionś exposure to the events, and other vulnerability factors, such as previous vulnerability or the socioeconomic status of the population. In this discussion paper we want show that the study of effects of droughts on health is a topic of current concern, but there are some uncertainties about it, being necessary research that are focused on what characteristics of droughts as well as what measures (indexes of droughts and timescales) are the best proxy to identifying and estimating specific risk on human health systems. In addition, a better knowledge about the biological mechanisms through which drought conditions affect health as well as what mechanisms of vulnerability are involved are needed. More precise information will allow distinguish effects of droughts in short-, medium- and long- term impacts. Finally, a broader knowledge on this topic will be crucial to implement early prevention and adaptation measures, reduce vulnerabilities and to mitigate potential risks in future climate scenarios.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Author contributions

Conceptualization, C.S.; Writing—Original Draft Preparation, C. S.; Writing—Review & Editing, C.S. R.N, L.G., C.L. and J.D.; Figures C.S.; Funding Acquisition, R.N and L.G.

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Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013

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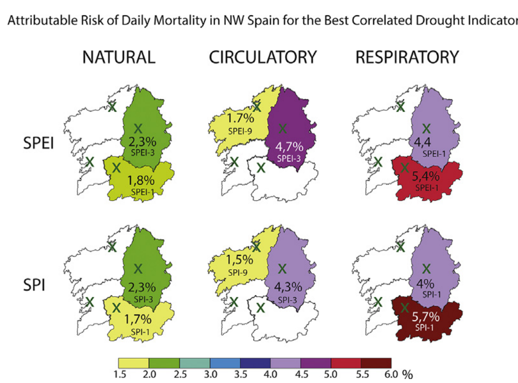
HIGHLIGHTS

- Drought periods had a greater influence on mortality in the interior provinces.
- Mortality was mainly manifested for longer timescales of SPEI/SPI in the Coastal.
- In short-term, the effect of droughts and heatwaves was observed in interior zones.
- In short-term, the drought effect on mortality was mainly explained by pollution.
- There are hardly differences between SPEI and SPI for the mortality risk estimation.

GRAPHICAL ABSTRACT



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SPI

ABSTRACT

Climate change scenarios indicate an increase in the intensity and frequency of droughts in several regions of the world in the 21st century, especially in Southern Europe, highlighting the threat to global health. For the first time, a time-series diagnostic study has been conducted regarding the impact of droughts in Galicia, a region in north-western Spain, on daily natural-cause mortality, daily circulatory-cause mortality, and daily respiratory-cause mortality, from 1983 to 2013. We analysed the drought periods over the area of interest using the daily Standardized Evapotranspiration-Precipitation Index (SPEI) and the daily Standardized Precipitation Index (SPI), obtained at various timescales (1, 3, 6, 9 months), to identify and classify the intensity of drought and non-drought periods. Generalized linear models with the Poisson regression link were used to calculate the Relative Risks (RRs) of different causes of mortality, and the percentage of Attributable Risk Mortality (%AR) was calculated based on RRs data. According to our findings, there were statistically significant ($p < 0.05$) associations between drought periods, measured by both the daily SPEI and SPI, and daily mortality in all provinces of Galicia (except Pontevedra) for different timescales. Furthermore, drought periods had a greater influence on daily mortality in the interior provinces of Galicia than in the coastal regions, with Lugo being the most affected. In short term, the effect of droughts (along with heatwaves) on daily mortality was observed in interior regions and was mainly explained by atmospheric pollution effect throughout 2000 to 2009 period in Ourense, being respiratory causes of mortality the group most strongly associated. The fact that droughts are likely to become increasingly frequent and intense in the context of climate change and the lack of studies that have considered the impact of droughts on specific causes of mortality make this type of analysis necessary.

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1. Introduction

1.1. Droughts and the risk to public health

Several studies have demonstrated the vulnerability and exposure of many human systems to the current climate variability, highlighted by the recent impact of climate related to extreme phenomena, such as heatwaves, droughts, floods, cyclones, and forest fires (e.g., McMichael and Lindgren, 2011; Handmer et al., 2012; Watts et al., 2017).

Furthermore, climate change scenarios indicate that hydrological extremes, like droughts or floods, will be more frequent and intense in the 21st century in several regions of the world (e.g., Stewart et al., 2015; Sapionini et al., 2017; Wang et al., 2018; WHO, 2018; Zhaoli et al., 2018), with important effects in Europe (e.g., Guerreiro et al., 2018). Specifically, in Southern Europe, a 15% decrease in precipitation and a large increase in temperature (e.g., Vicente-Serrano et al., 2011) have been predicted. Although there have been several studies regarding the effects of floods, there are much fewer on the effects of droughts despite their dangerous global impact, due to the complexity in assigning the beginning and end of the events and their accumulated effects over time. In addition, many of the effects of droughts are indirect (Vins et al., 2015; Ebi and Bowen, 2016; Berman et al., 2017). Every year droughts affect several million people and the most recent data available from the international disasters database (EMDAT) estimate that >50 million people around the world were affected by droughts in 2011 (Stanke et al., 2013). In addition, between 1960 and 2013, about 600 drought events resulted in 2.19 million deaths and 2.14 billion affected people (Sena et al., 2014). Moreover, the Lancet commission in 2015 indicated that a change in population from Shared Socioeconomic Pathway 2 (SSP2) and climate change could lead to 1.4 billion additional people exposed to drought events per year by the end of this century (Watts et al., 2015), what could be associate with greater morbidity and mortality (IPCC, 2014; Yusa et al., 2015; Berman et al., 2017). One of the most notable effects of drought is the decrease in air quality. Droughts often have secondary effects, such as dust storms and forest fires, leading to an increase in the concentration of fine particles (PM), dust, and smoke, and they are also associated with alteration of dispersion of allergens. All these events could lead to increased risk of respiratory tract and/or cardiovascular diseases, and could result in mortality (Sena et al., 2014; Yusa et al., 2015; Stanke et al., 2013; Berman et al., 2017; Watts et al., 2017; Bell et al., 2018).

Among the few studies on the effects of droughts on health is a recent study from the USA, which showed that in more severe drought conditions the risk of mortality increased in adults over 65 years, with the particularity that, those regions that had previously suffered fewer drought events had a higher risk of cardiovascular disease and mortality (Berman et al., 2017). This fact reflects the great importance in emphasizing the effects of droughts, which are projected to occur with greater intensity and duration in future climates, on global health. Although a decrease in respiratory hospital admissions during periods of drought is described in Berman´ study, Smith et al. (2014) showed for the Brazilian Amazon that drought events led to increased hospitalization for respiratory diseases of children under five years old.

On the other hand, droughts also have a long-term influence on the modification and degradation of the environment and ecosystems. Droughts are a growing threat to the increase the risk of malnutrition, infectious diseases, problems associated with mental health and human well-being disorders, and to changes in the ecology of vector borne diseases (e.g., Berry et al., 2010; Shukla, 2013; OBrien et al., 2014; Sena et al., 2014; Yusa et al., 2015; Vins et al., 2015; Bell et al., 2018; Berman et al., 2017).

All these effects will interact with the susceptibility and vulnerability of the reference population, socio-economic factors, adequate access to health infrastructure, and underlying demographics factors, whose combined influence can aggravate some of the existing threats, creating new challenges in health care (Stanke et al., 2013; IPCC, 2014; Ebi and Bowen, 2016).

1.2. The metric of droughts and the estimation of health effects: the crucial role of drought indicators

The impact on health largely depends on the severity of droughts (Stanke et al., 2013; Ebi and Bowen, 2016; Berman et al., 2017) and, in this sense, drought indices are essential measures for quantifying and identifying possible changes in the frequency and duration of the risks they measure. Drought indicators make it possible to obtain better knowledge and undergo preparation to tackle the drought effects on health (Vicente-Serrano et al., 2017). One difficulty in studying the different effects of droughts lies in their own definition, as they are classified into four categories: meteorological, hydrological, agricultural, and socioeconomic (Bachmair et al., 2016; Ortega-Gómez et al., 2018). In addition, droughts differ from other environmental phenomena in that they are a slow developing hazard (Bachmair et al., 2016). There are continually an increasing number of indicators, but there is no specific index designed to measure the type of drought in reference to its impact on health, so each index can differ in its estimation, and each type of drought can affect health outcomes in a different way (Berman et al., 2017).

1.3. The study region: Northwest of the Iberian Peninsula (Galicia)

The Iberian Peninsula is considered one of the southern European regions that is most likely to suffer an increase in drought severity during the 21st century (Vicente-Serrano et al., 2011). This study focuses on Galicia, in the northwest of the Iberian Peninsula (Fig. 1). Galicia is an ideal region for studying the relationships between droughts and health, including analysing the meteorological and biological mechanisms, because its climate is very unique and varied (Gómez-Gesteira et al., 2011). It is surrounded by the Atlantic Ocean with its coastal areas marked by a mild and rainy maritime climate and an inner area that has a much less rainy continental climate, very warm in summer and cold in winter. In terms of precipitation mechanisms, Galicia is located in the southernmost part of the Atlantic storm track (Dong et al., 2013), and its extremes of precipitation are strongly influenced by the occurrence of atmospheric rivers (Gimeno et al., 2014; Eiras-Barca et al., 2018). Furthermore, its climatic variability is closely linked to several and important teleconnection patterns as the North Atlantic Oscillation (Lorenzo et al., 2008). Concerning to weather conditions, a particular study in Galicia showed an increase in respiratory admissions associated with cold, dry weather, or anticyclonic types (Royé et al., 2016). In terms of the environmental mechanisms that link droughts and health, Galicia has one of the highest incidences of forest fires of all the regions in Europe (Fuentes-Santos et al., 2013). Galicia certainly is the region in Spain where more fires have occurred and more hectares have been burned. In 2017, there were 3249 forest fires and 62,000 ha that were burned (Mapama, 2017). In addition, Galicia has two coastal industrial poles, one in the North (A Coruña) and the other in the South (Vigo in Pontevedra) with strong emissions (García-Santiago et al., 2017), and has undergone intense heatwaves with potential effects on health (e.g. Decastro et al., 2011).

In this study, we report the first evidence of a relationship between drought exposure and the daily risk of specific causes of mortality in northwest Spain. With the exception of the Berman et al. (2017) study, few works have evaluated the effects of droughts on specific daily causes of mortality, so, analysis such as the work presented here in this paper are necessary to gain better understanding in adopting strategies of management and preparation as well as create early responses to reduce the negative health effects attributable to hydrological extremes.

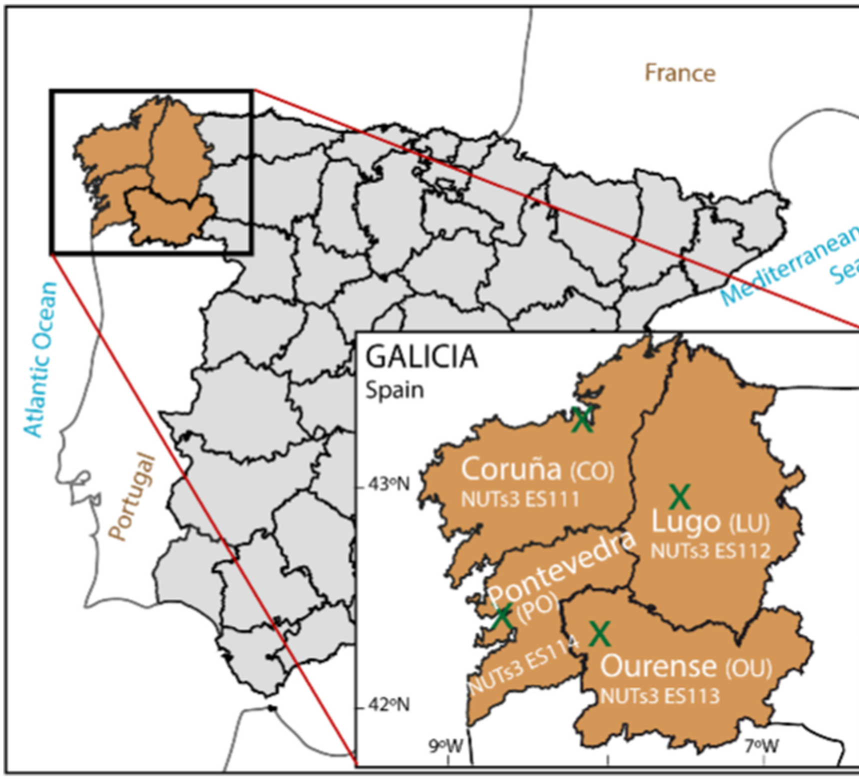

Fig. 1. Region under study. Our focus is on the Galicia region, situated in northwest Spain, during the period from 1983 to 2013. The subdivision (provinces) corresponds to the European NUTs3 administrative regions: Coruña (ES111), Lugo (ES112), Ourense (ES113), and Pontevedra (ES114). Green crosses denote the position of the capital of each province: A Coruña (43.36° N, −8.41° W), Lugo (43.01° N, −7.56° W), Ourense (42.34° N, −7.86° W), and Pontevedra (42.43° N, −8.65° W).

The main objective of this study is the evaluation of the impact of drought, measured by the Standardized Evapotranspiration-Precipitation Index (SPEI) and the Standardized Precipitation Index (SPI), on daily natural, circulatory and respiratory causes of mortality in Galicia, Spain, from 1983 to 2013. For its approach, we conducted the following aims:

I) Evaluation of the effect of this hydrological extreme on different causes of daily mortality using SPI and SPEI obtained for different timescales (1, 3, 6, and 9 months), throughout 1983 to 2013 period.
II) Integrated analysis to control the effect of heatwaves and pollution levels along with drought periods measured by short-term to determinate the effect of these strongly associated climatic variables on the different causes of mortality from 2000 to 2009.

2. Material and methods

We conducted a retrospective ecological study of daily time series to evaluate the impact of droughts on daily mortality from different causes in Galicia, at NW Spain, during the period from 1983 to 2013. The variables involved in the study are outlined below.

2.1.1. Dependent variables

The dependent variables include the daily natural-cause mortality classified according to the International Code Disease 10 (ICD10: A00-R99), daily circulatory-cause mortality (ICD10:I00-I99), and daily respiratory-cause mortality (ICD10: J00-J99). These mortality data refer to the daily mortality for the capital and towns over 10,000 inhabitants in each province of Galicia from 1983 to 2013. The provinces correspond to the following European NUTs3 (Nomenclature of Territorial Units for statistics level 3) administrative regions (Fig. 1): A Coruña (ES111), Lugo (ES112), Ourense (ES113), and Pontevedra (ES114). All mortality data were provided by the National Institute of Statistics (INE) of Spain.

2.1.2. Independent variables

To quantify the drought conditions in the four provinces of Galicia, we used two meteorological drought indices: the SPI (Standardized Precipitation Index), which is based on precipitation data, and the SPEI (Standardized Evapotranspiration-Precipitation Index), which incorporates precipitation and evapotranspiration data, to take into account the atmospheric evaporative demand. The SPEI and SPI time series were obtained from the Spanish Superior Council of Scientific Researches (CSIC) website: http://monitordesequia.csic.es (see Vicente-Serrano et al. (2017) for more details). The complete drought dataset is available with 1.1-km spatial resolution and a weekly time resolution (4 time-steps per month). Both indices could be obtained at various timescales (1, 3, 6, 9, 12, 36, and 48 months) that reflect the impact of drought on the availability of different water resources. The different timescales correspond to different accumulation periods, which are associated with different drought types, such as 1 month in length (short-term conditions) for meteorological droughts, 1–6 months (short- and medium-term conditions) for agricultural droughts, and 6–24 months or longer (medium- and long-term conditions) for hydrological drought. In this work, we select SPEI and SPI for the accumulated periods of 1, 3, 6, and 9 months to analyse the effects on health from meteorological, agricultural, and hydrological droughts. Hereafter, the length (n) of the accumulated index will be denoted following the index type as SPEI-n or SPI-n.

In our study, we selected weekly drought data from 1983 to 2013 over each capital city of Galician province (green crosses in Fig. 1) that they are the highly populated areas with high representation of the total population to construct the four time-series of SPEI-n and SPI-n for the same period as we have for the mortality data (ICD10: A00-R99, ICD10: I00-I99 and ICD10: J00-J99).

As the drought data are available weekly, we construct continuous daily series assuming the same conditions for each seven-day interval to obtain better control of acute daily confounding factors, following the criteria of Berman et al. (2017).

Commonly, the onset of a drought episode is defined when the index value falls below zero and the episode ends when the index returns a positive value; furthermore, its severity could be quantified applying some thresholds (based on a normal distribution). Following the criterion of Agnew (2000) and Berman et al. (2017), the drought conditions were ranged from 0 to 5, where 0 is 'no drought' and 5 is 'exceptional drought'. A drought period is classified as level 0, when index value is below 0 and higher than −0.84, and it is considered "usual" conditions or a "mild drought". Level 1, "moderate drought", corresponds to values between −0.84 and −1.27; this interval reflects a 20% probability that a similar drought could occur in 5 years. Levels 2 and 3, "severe drought", occur if values are between −1.28 to −1.64 (reflecting a return period of 10 years with a 10% probability) and between −1.65 to −2.05 (return period of 20 years with a 5% probability), respectively. Levels 4 and 5, "extreme drought", correspond to values between −2.06 to −2.33 (return period of 50 years with a 2% probability) and values less −2.33 (return period of 100 years with a 1% probability), respectively.

The continuous original SPI and SPEI series data were used to conduct the main statistical analyses, while the categorized series were used with a statistical purpose and to check the role of the severity when significant results were founded (see Table 2 in the supplementary appendix).

Fig. 2 shows SPEI-1 for Ourense from 2001 to 2013, as an example, of the continuity of the index (Fig. 2A) and the severity classification (Fig. 2B).

2.1.3. Analysis variables

We conducted two type of analysis in this study: Aim I) The analysis of the drought impact on natural, circulatory and respiratory causes of daily mortality from 1983 to 2003 period, and Aim II) The evaluation of the impact during 1-month drought accumulation (SPEI-1 and SPI-1) also being taken into account the combined effect with the heatwaves and pollution throughout a sub set of 10-years period from 2000 to 2009, when pollution data for A Coruña, Ourense and Pontevedra are available. We controlled these independent variables because they are strongly related with daily mortality at short-term.

2.1.3.1. Drought variables. We have used two daily SPI-n and SPEI-n indices with the goal to which of both is the better proxy for detecting the impact on daily mortality. As it was commented previously, SPEI is obtained mathematically in a similar way as SPI but it includes the temperature (Bachmair et al., 2016; Vicente-Serrano et al., 2010), facilitating the evaluation of any possible differences in the drought effects on daily mortality related to it.

As the objective of this study is to evaluate the impact of drought on daily mortality by the various described causes, the original continuous SPEI-n and SPIE-n values were retained in the analysis to measure the intensity of the event.

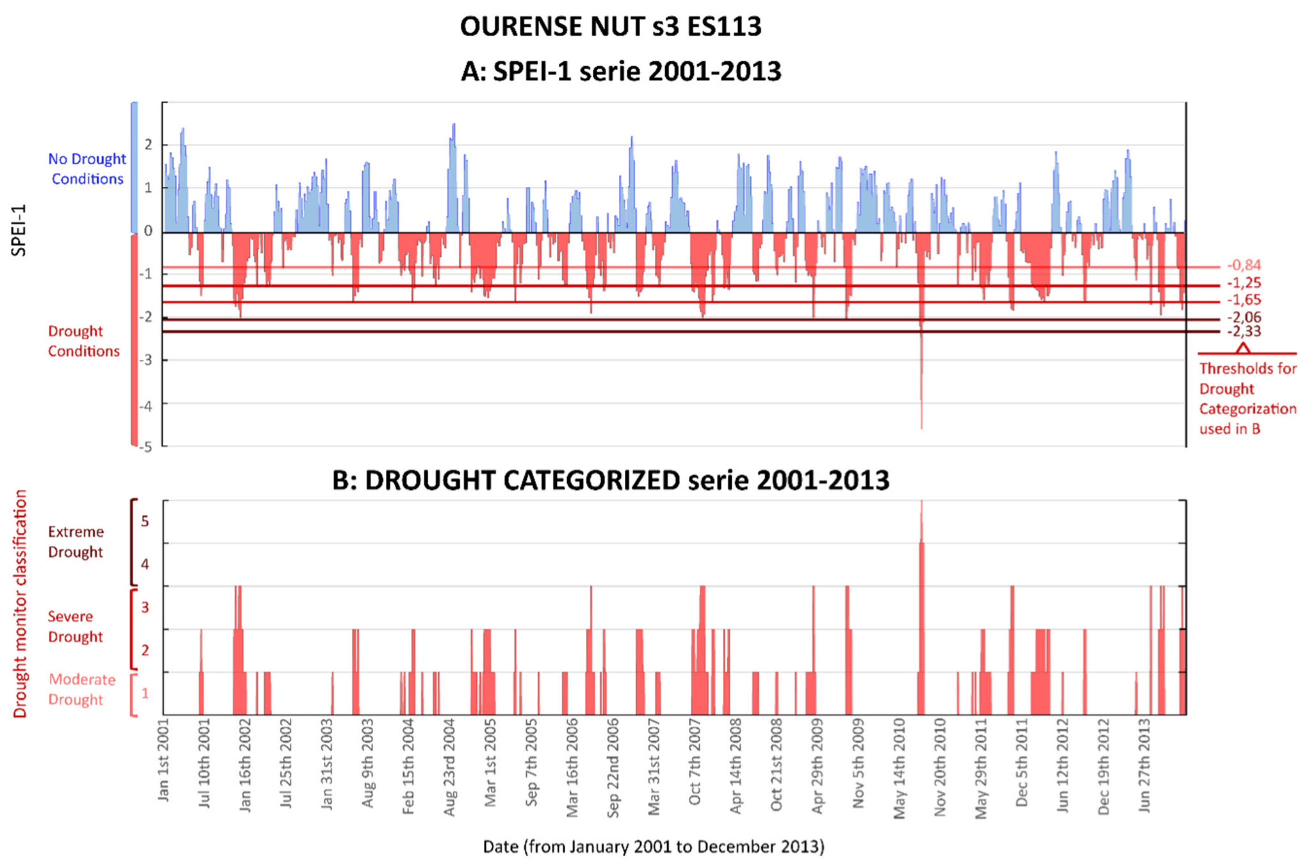

Fig. 2. Drought characterization measured by SPEI-1 for Ourense, Galicia, Spain (NUTs3 ES113) across 2001 to 2013. A) Time evolution of the SPEI-1 values. In blue days with no drought conditions, and in red the days with drought conditions. Horizontal continuous lines indicate the different thresholds that allow the classification in severity following Agnew (2000). B) Categorized drought measured by SPEI-1. Five different groups were distinguished gradually from 0 ("no drought") to 5 ("exceptional drought") as in Berman et al. (2017), and according to Agnew (2000) thresholds. SPEI-1 greater than −0.84 is considered "no drought conditions", and the SPEI-1 is set to 0. For SPEI-1 between −0.84 and −1.25, SPEI-1 is set to 1, considered as "moderate" drought conditions. For SPEI-1 between −1.25 and −1.65, SPEI-1 is categorized as 2; and for SPEI-1 between −1.65 and −2.06, SPEI-1 is set to 3. Both SPEI-1 = 2 and SPEI-1 = 3 are considered "severe" drought conditions. For SPEI-1 between −2.06 and −2.33, SPEI-1 is categorized as 4; and for SPEI-1 lower than −2.33, SPEI-1 is set to 5. Both SPEI-1 = 4 and SPEI-1 = 5 are considered "extreme" drought conditions.

In reference to the first aim, we used SPEI and SPI obtained at four different time scales (1, 3, 6, and 9 months) to evaluate the manifestation time for daily mortality due to drought. We used these time scales because they are the most common accumulation periods for meteorological indicators (Bachmair et al., 2016). In reference to the second aim, we only used droughts measured at short-term (SPEI-1 and SPI-1).

Other variables were controlled throughout the study, as in Sánchez Martinez et al. (2018): i) The trend of the series was introduced by taking n1 = 1 for day 01/01/1983, n1 = 2 for 02/01/1983, and so on to the end of the series (31/12/2013). ii) The autoregressive nature of the dependent variable was controlled from the autoregression of the first order of daily mortality. iii) We also categorized by seasonality of the series: annual (365-day), six-monthly (180-day), four-monthly (120-day), and quarterly (90-day), using the sine and cosine functions that correspond to these periodicities. In the second part of the study, to control the seasonality in summers, which are four months, we also controlled the seasonality of 60.

2.1.3.2. Heatwave and pollution variables. Additionally, we have controlled several independent variables to carry out the second aim of the study related with the heatwaves and pollution from 2000 to 2009.

To consider the effect of the *heatwaves* it was accounted the daily "temperature for heatwave" (T_{hwave}), as in Diaz et al. (2015), calculated as below:

$$T_{hwave} = Tmax - Tthreshold \quad \text{if } Tmax \geq Tthreshold$$

$$T_{hwave} = 0 \quad \text{if } Tmax < Tthreshold$$

where Tmax is the maximum temperature recorded at the reference observatories located in the provincial capital cities, and Threshold is the maximum temperature threshold for daily mortality attributable to heat calculated in Diaz et al. (2015). This threshold for A Coruña is 26 °C, for Lugo 34 °C, for Ourense 36 °C, and for Pontevedra 30 °C. Tmax data were supplied by the State Meteorological Agency (Agencia Estatal de Meteorología/AEMET). From a point of view of daily mortality impact, we have considered a heatwave day when Tmax surpasses the Tthreshold (Diaz et al., 2015).

We also use *pollution* as an independent variable. Specifically, we control daily mean O_3, PM_{10} and NO_2 concentrations (in μg/m^3) recorded at monitoring stations situated in each capital province. These data were furnished by the Ministry of Agriculture and Fisheries, Food and Environment (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, MAPAMA).

The effect of air pollution on mortality may not be immediate, and it can occur up to 5 days in case of PM_{10} and NO_2 (Ortiz et al., 2017; Diaz et al., 2018; Linares et al., 2018a) and up to 9 days in case of O_3 (Diaz et al., 2018). In the case of temperature, the effect on daily mortality can delayed up to 4 days (Diaz et al., 2015). For these reasons, only droughts in short-term were considered here, and in the statistical models we also controlled those known lags.

2.2. Process of analysis and models

In both parts of the study, the impact of drought conditions on daily mortality for each province of Galicia was quantified using generalized linear models (GLM) with the Poisson regression link. We used single models for independent SPI-n and SPEI-n series. This process was conducted individually for natural, circulatory, and respiratory causes of daily mortality.

Respect to the second part of this study, firstly, we evaluated the impact of drought combined with temperature on the different causes of daily mortality, and then we added pollution independent variable in the model.

Poisson modelling makes it possible to determine the relative risks (RRs) of mortality in respect of the variables which resulted statistically significant. Subsequently, RR of the variables in terms of drought was calculated from the value of the estimator obtained in each model ($e^{|coefficient|}$), calculated for each unit of increment for the indicator of the independent variable used (Royo-Bordonada and Damián-Moreno, 2009).

The p-value was determined using the step-back procedure, in which the complete model that included all the analysed explanatory variables was initially implemented, with those variables that individually showed less statistical significance gradually eliminated until concluding with a model that included just the statistically significant variables ($p < 0.05$).

The percentage of attributable mortality risk (%AR) for the population associated with a particular drought time was calculated based on RR, following the equation: $\%AR = [(RR-1)/RR] \times 100$ (Coste and Spira, 1991), representing the percentage of the increase in daily mortality effect associated with the drought in the population exposed to this risk factor.

All analyses were performed using the software IBM SPSS Statistics 22 and STATA v 14.1.

3. Results

3.1. Descriptive statistics of the episodes of drought in Galicia, NW Spain, and mortality causes

The descriptive environmental and mortality characteristics according to drought conditions in the provincial capital cities of Galicia, in the period 1983 to 2013, using SPEI and SPI metrics obtained for the time scales of 1, 3, 6 and 9 months were evaluated. The total number of daily deaths by different causes were tabulated, according to the categorization of days with drought for each provincial capital city of Galicia (see Table S1 in the supplementary material).

In terms of drought exposure, the percentage of total days with drought is between 18.36% and 28.17%, with the highest percentage in Lugo (24.19% to 28.17% using SPEI and 21.62% to 25.40% for SPI). In general, a higher percentage of total days with drought has been observed in the interior provincial capital cities of Galicia (Lugo and Ourense) than in the coastal ones (A Coruña and Pontevedra) for all timescales using either indicator, except for A Coruña in the long term where there was a greater number of days with total drought than in Ourense.

On the other hand, both indicators showed a higher percentage of total days with drought in all provinces for 9 months of accumulation: in A Coruña for SPEI-9 (SPI-9) there were 25.96% (22.93%) of days with drought, 28.17% (25.40%) in Lugo, 25.36% (21.01%) in Ourense, and 22.47% (19.58%) in Pontevedra.

There were differences between the number of drought days when the severity was taken into account between different regions and in terms of the drought timescale. In Lugo, for instance (where the maximum total days with drought were counted) for SPEI-9 it was obtained 47.02% of days with moderate drought, 51.57% with severe drought, and 1.4% with extreme drought. For SPI-9, the percentages were 44.25% days as moderate drought, 52.85% as severe, and 2.89% as extreme. However, SPI for shorter periods (SPI-1 and SPI-3) showed fewer days with drought than SPEI-9 and SPI-9 but more days with extreme severity, with 13.64% for SPI-1 in Lugo and 14.51% for SPI-3.

Finally, adding drought days categorized as severe and extreme, in general terms Lugo reached the highest values, while Pontevedra had the lowest.

3.2. The impact of droughts on the different causes of daily mortality

A complete statistical analysis using the Poisson GLMs was done trying to find the statistically significant relationship between the continuous daily SPEI-n and SPI-n drought indicators and daily mortality by different causes in each provincial capital city of Galicia, from 1983 to 2013. From the estimator values obtained from the Poisson models, the Relative Risk value (RR) for each cause of daily mortality related with extreme hydrological events was calculated.

3.2.1. Daily mortality causes under drought conditions during 1983–2013

Fig. 3 shows a graphic summary of the estimated relative risk (RR) of the different causes of daily mortality associated with droughts measured by both indices when a statistically significant relationship exists at a confidence level of 95% ($p < 0.05$). Table S2 included in the supplementary material describes the complete statistically significant p-values as well as the complete values of the RR, estimators and those of the 95% confidence intervals of estimators and RRs. The RR values are described in the following section.

The general results of this study (see Table S2) indicate a high variability for each province. Roughly, droughts had a greater influence on daily mortality in the interior areas (Lugo and Ourense) than in coastal ones (A Coruña and Pontevedra). According to these, in Lugo drought conditions, measured by both SPI and SPEI, were associated with a statistically significant increase in daily natural-cause mortality as well as an association with both specific circulatory and respiratory causes of daily mortality. In Ourense, an association between droughts periods measured by both indices and daily natural and respiratory causes of mortality was statistically significant, but there was not a direct relation with daily circulatory-cause mortality. However, in A Coruña there was only an association with daily circulatory-cause mortality attributable to drought conditions measured by both SPI and SPEI, while in Pontevedra there was not a statistically significant relationship between any of study variables.

3.2.1.1. Period in which the effects of droughts were manifested on natural, circulatory and respiratory cause mortality for SPEI n and SPI n at different months. The study also revealed that the statistically significant manifestation of the effects of the drought conditions periods (for all months of accumulation) in any daily cause of mortality was very similar SPEI or SPI for the four provinces (Fig. 3, Table S2) during 1983 to 2013.

Although the findings in daily mortality attributable to droughts measured by SPEI-n and SPI-n were equivalent, we can see subtle differences in Fig. 3 between both indicators in terms of the estimation of relative risk. In particular, the figure shows that in Ourense the association of daily natural-cause mortality with drought conditions was statistically significant only for the short term (1 month of accumulation) by both indices; while in Lugo the effect was also observed for the medium term (3 and 6 months) and long term (9 months). In the case of A Coruña and Pontevedra, no statistical significance was found between daily natural-cause mortality and either drought index. With respect to daily circulatory-cause mortality, in Ourense no statistically significant association was observed with droughts. On the contrary, in Lugo

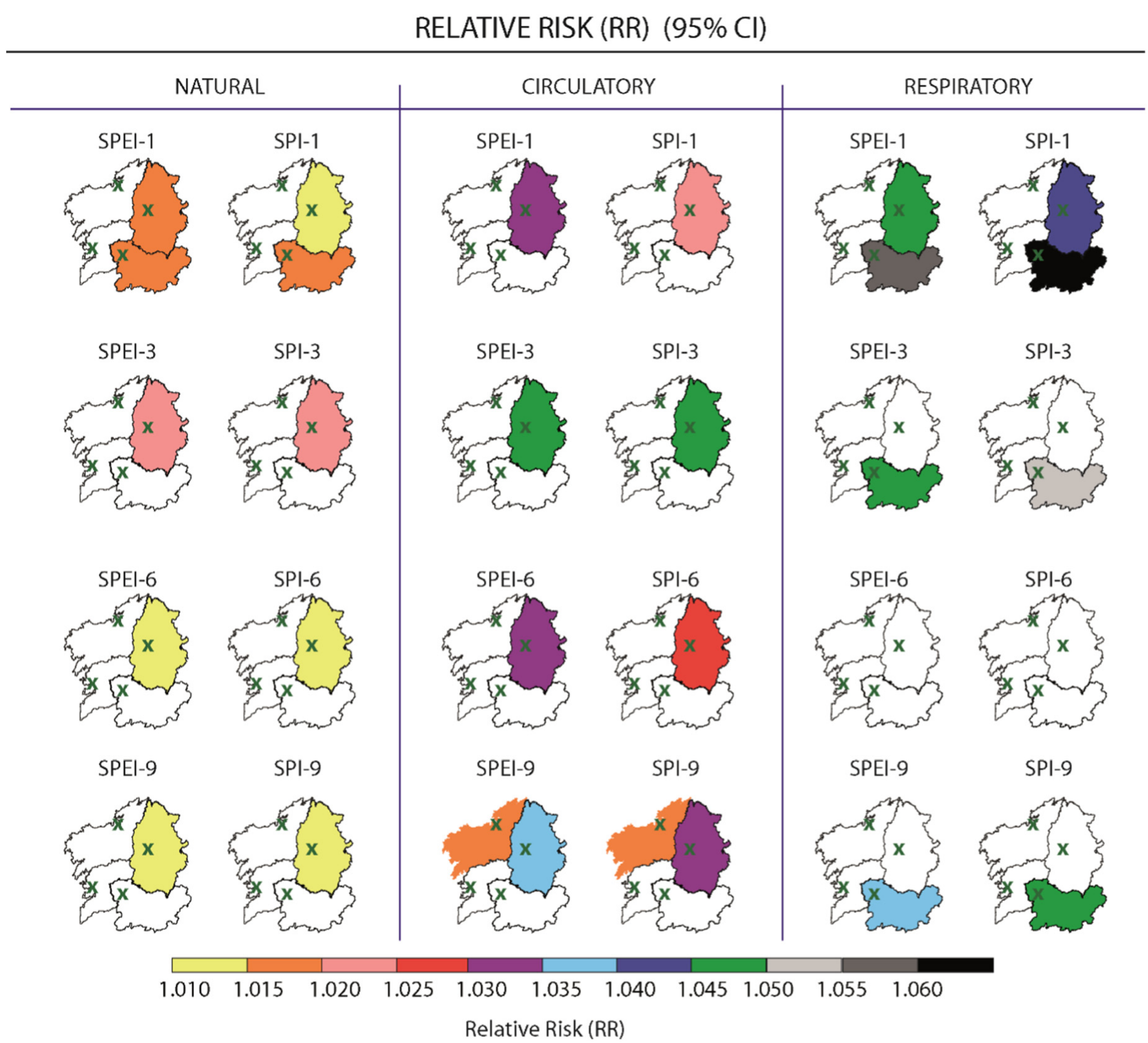

Fig. 3. Summary of representation of relative risk (RR) of natural, circulatory, and respiratory causes of daily mortality attributable to drought periods in northwest Spain during the period 1983 to 2013. The statistical significance of SPEI and SPI is shown for different timescales (1, 3, 6 and 9 months) in Poisson models ($p < 0.05$) for the period 1983 to 2013. Green crosses denote the position of the province capital.

the association with drought periods measured by SPEI and SPI was statistically significant for all accumulated months of study. In A Coruña, this effect was observed only when the droughts were measured for the long term (SPEI-9 and SPI-9). Finally, according to the impact of drought periods on daily respiratory-cause mortality, in Lugo this effect was exhibited with SPEI-1 and SPI-1, while in Ourense the relationship was statistically significant using both SPEI and SPI for the short term (1 month), medium term (3 months), and long term (9 months).

Fig. 4 represents the RRs as a function of the best indicator (SPEI-n and SPI-n), with a confidence level of 95% ($p < 0.05$) in the provincial capital cities of Galicia during the studied period of 1983 to 2013. According to it, in **Ourense**, there was greater statistical significance for the effect of drought for SPEI-1 and SPI-1 on daily natural- and respiratory-cause mortality. For SPEI-1, RR was 1.057 (95% CI: 1.020–1.095) for respiratory-cause mortality and 1.018 (95% CI: 1.006–1.030) for natural causes. For SPI-1, RR was 1.017 (95% CI: 1.005–1.028) for natural-cause mortality and 1.060 (95% CI: 1025–1096) for respiratory causes. In **Lugo**, daily respiratory-cause mortality attributable to drought was also more significant for the first month of accumulation, using both series of drought indicators (RR = 1.046 (95% CI: 1.007–1.087) for SPEI-1 and RR = 1.042 (95% CI: 1.005–1.080) for SPI-1). At the 3-month accumulation, RR = 1.023 (95% CI: 1.010, 1.037) for natural causes using both drought indices, and for circulatory-cause mortality RR was 1.049 (95% CI: 1.027, 1.071) using SPEI-3, and 1.045 (95% CI: 1.023, 1.066) using SPI-3. In the case of **A Coruña**, only daily circulatory-cause mortality associated with droughts was manifested when droughts were measured for the long-term, using both indicators as RR was 1.017 (95% CI: 1.004, 1.030) using SPEI-9 and 1.015 (95% CI: 1.003, 1.028) using SPI-9.

Fig. 5 shows the representation for the four provincial capital cities of Galicia of the percentage of attributable risk (%AR) that was only obtained from the RR value for those indices with the greatest statistical significance across 1983 to 2013. The increase in respiratory and circulatory causes of daily mortality attributable to drought periods compared to daily natural-cause mortality was notable. In Ourense, the increase in daily respiratory-cause mortality associated with drought periods were 5.4% and 5.7% when droughts were measured with SPEI1 and SPI1, respectively. Also remarkable is the %AR of respiratory and circulatory causes of daily mortality associated with droughts in Lugo (%AR: 4.4 using SPEI-1 and 4.0 using SPI-1 in relation with the daily respiratory-cause mortality and 4.7 using SPEI-3 and 4.3 using SPI-3 with respect to the daily cardiovascular-cause mortality). On the other hand, the value of %AR obtained in terms of daily natural-cause mortality associated with droughts was 2.3% in Lugo using both SPEI-3 and SPI-3, and 1.8% and 1.7% in Ourense using SPEI-1 and SPI-1, respectively. In addition, the increase in daily circulatory-cause mortality attributable to drought periods in A Coruña was 1.7% using SPEI-9 and 1.5% using SPI-9.

Additionally, we have checked the significance for the categorized SPEI-n and SPI-n series for the relations founded with the continuous ones. We have considered two categories of severity: moderate and high (comprising the severe and extreme groups jointly due that the extreme events only represent between 0.89% to 6.69%, and between 2.48% to 17.01% of days with drought using SPEI and SPI, respectively). According to this, in the interior regions of Galicia the mainly the effect on mortality is due to high severity drought events, while in the coastal area of A Coruña is mainly manifested for moderate severity at long time scale (see Table S3 of supplementary material).

3.2.2. Daily mortality causes under drought conditions merged with the effect of heat waves and pollution during 2000–2009

In this study, we have also studied the effect of droughts measured at short-term (1 month) across 2000 to 2009 to include in the analysis the evaluation of the effect of heat waves and pollution (mean O_3, NO_2, and PM_{10} concentrations). As the period with pollution data is shorter, we repeat the previous analysis for this "new" sub-period and only for SPEI-1 and SPI-1. According to our results (Table 1) only in interior regions of Galicia (Ourense and Lugo) there are statistically significant associations between different causes of daily mortality and drought conditions. In addition, the use of SPEI-1 or SPI-1 reveals are equivalent results. In both provinces all daily causes of mortality were significant associated with drought at short time, but with greater impact in daily respiratory-cause mortality. For Ourense, unlike for 1983–2013 results, it was observed a significant relationship with daily-circulatory cause mortality.

When we controlled drought indicators and heatwaves in Poisson models it has observed statistically significant results for both climatic variables in Lugo and Ourense at short-term, with the exception for Ourense in daily respiratory-cause mortality (only observed for SPEI-1 and

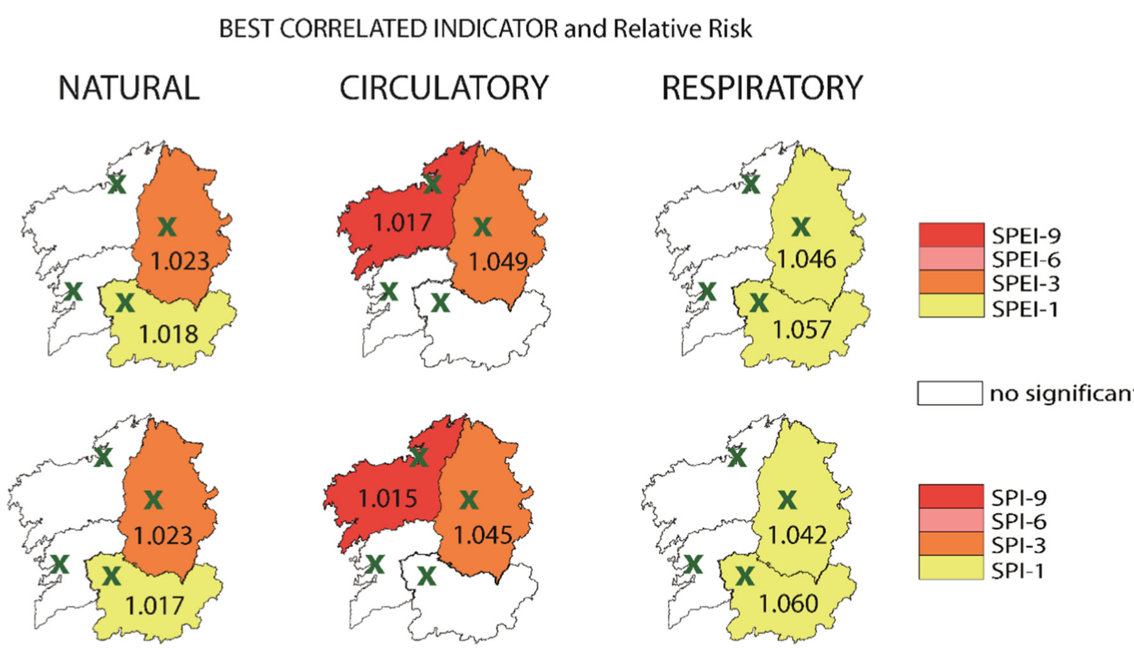

Fig. 4. Summary of the representation of relative risk (RR) of natural, circulatory, and respiratory causes of daily mortality attributable to drought periods in northwest Spain in the period 1983 to 2013. The relative risk of SPEI and SPI obtained by the most statistically significant timescale from the Poisson model ($p < 0.05$) throughout the period 1983 to 2013. Green crosses denote the position of the capital of each province.

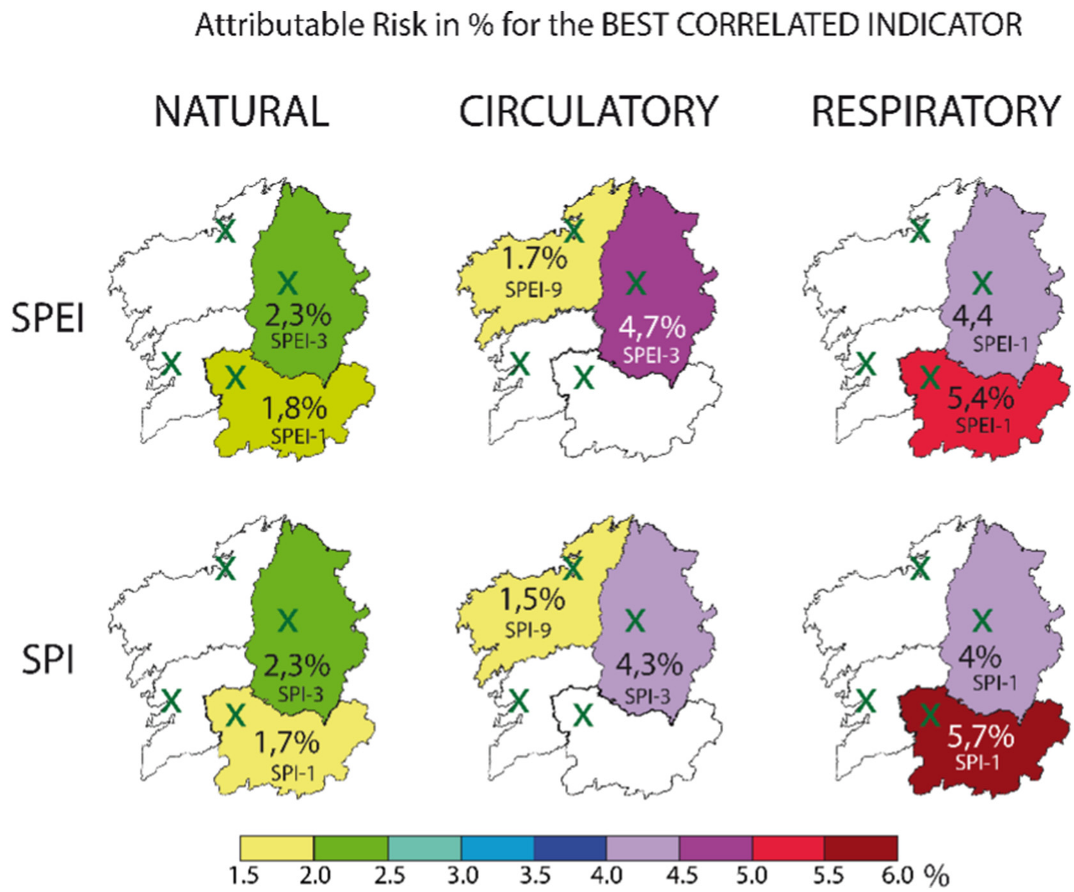

Fig. 5. Summary of the percentage of attributable risk (%AR) associated with natural, circulatory, and respiratory causes of daily mortality associated with droughts in northwest Spain, Galicia, during the period 1983 to 2013. The %AR in each province is shown where there was a relation between the different causes of mortality and drought conditions measured by the most statistically significant timescale between SPEI and SPI in the Poisson model ($p < 0.05$). Green crosses denote the position of the capital of each province.

SPI-1). In addition, the effect of drought on circulatory-cause mortality in Lugo only resulted significant for SPEI-1.

Furthermore, the effect of the heatwaves on daily mortality associated with drought events mainly occur up to one-day delay, except for Lugo with daily circulatory-cause mortality that was delayed up to four days, (Table 2).

On the other hand, besides to controlling drought and extreme temperatures, we controlled atmospheric pollution (daily mean O_3, NO_2 and PM_{10} concentrations levels) jointly in Ourense (Table 3) - due to there was no available pollutants data for Lugo -. According to the results, only NO_2 and PM_{10} were the variables statistically associated with daily natural and circulatory- causes mortality and only PM_{10} with respiratory-cause mortality, while drought indicators and heatwaves were no longer statistically significant. In any way, the strongest relation was observed between pollutants and daily respiratory-cause mortality.

Table 1

Summary of the statistically significant results obtained from Poisson modelling during 2000 to 2009 period. The table illustrates the statistically significant SPEI-1 and SPI-1 drought indicators ($p < 0.05$) that influence daily natural, circulatory, and respiratory-cause mortality for Ourense and Lugo in the period 2000–2009. The relative risk (RR) was calculated from the value of the estimator obtained in each model. The 95% confidence intervals of the estimator is displayed. Decreasing SPEI and SPI values of coefficient indicates worsening drought. Conf. Interval = Confidence Interval.

Ourense	p-Value	Coefficient	Coefficient [95% conf. interval]	Relative risk (RR)	RR [95% conf. interval]
Natural deaths	SPEI-1 p = 0.000	−0.04	(−0.064, −0.025)	1.046	(1.025, 1.066)
	SPI-1 p = 0.000	−0.045	(−0.064, −0.026)	1.046	(1.025, 1.066)
Circulatory deaths	SPEI-1 p = 0.000	−0.066	(−0.099, −0.034)	1.068	(1.035, 1.104)
	SPI-1 p = 0.000	−0.064	(−0.095, −0.032)	1.066	(1.032, 1.100)
Respiratory deaths	SPEI1 p = 0.001	−0.094	(−0.148, −0.040)	1.099	(1.041, 1.160)
	SPI1 p = 0.000	−0.094	(−0.146, −0.043)	1.099	(1.044, 1.157)
Lugo	**p-Value**	**Coefficient**	**Coefficient [95% conf. interval]**	**Relative risk (RR)**	**RR [95% conf. interval]**
Natural deaths	SPEI-1 p = 0.000	−0.043	(−0.066, −0.021)	1.044	(1.021, 1.068)
	SPI-1 p = 0.001	−0.038	(−0.060, −0.015)	1.039	(1.015, 1.062)
Circulatory deaths	SPEI-1 p = 0.003	−0.060	(−0.099, −0.021)	1.062	(1.021, 1.104)
	SPI-1 p = 0.017	−0.046	(−0.084, −0.008)	1.047	(1.008, 1.088)
Respiratory deaths	SPEI1 p = 0.001	−0.109	(−0.173, −0.045)	1.115	(1.046, 1.189)
	SPI1 p = 0.002	−0.097	(−0.157, −0.036)	1.102	(1.037, 1.170)

Table 2
Summary of the statistical significance results obtained from Poisson modelling taking into account the impact of the heatwaves during drought periods measured by SPEI-1 and SPI-1 during 2000 to 2009. The table shows the statistically significant results in Ourense (top) and in Lugo (bottom) using indicators of drought at short-term and daily extreme temperatures in Poisson models. The relative risk (RR) was calculated from the value of the estimator obtained in each model. The 95% confidence intervals of the estimator and of the RR are displayed. Conf. Interval = Confidence Interval.

Ourense	Indicator	Drought indicator + extreme temperatures (Thwave)					
		p-Value	Lag in days	Coefficient	Coefficient [95% conf. interval]	Relative risk (RR)	RR [95% conf. interval]
Natural deaths	SPEI-1	SPEI-1 p = 0.000		−0.043	(−0.063, −0.024)	1.013	(1.024, 1.065)
		Thwave p = 0.000	1	0.107	(0.061,0.153)	1.113	(1.063, 1.165)
	SPI-1	SPI-1 p = 0.000		−0.045	(−0.064, −0.026)	1.046	(1.026, 1.066)
		Thwave p = 0.000	1	0.110	(0.064, 0.155)	1.116	(1.066, 1.168)
Circulatory deaths	SPEI-1	SPEI-1 p = 0.000		−0.064	(−0.097, −0.031)	1.066	(1.031, 1.102)
		Thwave p = 0.000	1	0.149	(0.077, 0.221)	1.161	(1.080, 1.247)
	SPI-1	SPI-1 p = 0.000		−0.063	(−0.094, −0.031)	1.066	(1.031, 1.099)
		Thwave p = 0.000	1	0.153	(0.081, 0.225)	1.165	(1.084, 1.252)
Respiratory deaths	SPEI-1	SPEI1 p = 0.001		−0.094	(−0.148, −0.040)	1.099	(1.041, 1.160)
	SPI-1	SPI1 p = 0.000		−0.094	(−0.146, −0.043)	1.099	(1.044, 1.157)

Lugo	Indicator	Drought indicator + extreme temperatures (Thwave)					
		p-Value	Lag in days	Coefficient	Coefficient [95% conf. interval]	Relative risk (RR)	RR [95% conf. interval]
Natural deaths	SPEI-1	SPEI-1 p = 0.002		−0.038	(−0.062, −0.015)	1.039	(1.015, 1.064)
		Thwave p = 0.003	1	0.140	(0.048, 0.231)	1.150	(1.049, 1.260)
	SPI-1	SPI-1 p = 0.003		−0.036	(−0.060, −0.012)	1.037	(1.012, 1.062)
		Thwave p = 0.002	1	0.142	(0.051, 0.234)	1.153	(1.052, 1.264)
Circulatory deaths	SPEI-1	SPEI-1 p = 0.018		−0.049	(−0.090, −0.009)	1.050	(1.009, 1.094)
		Thwave p = 0.000	4	0.269	(0.141, 0.398)	1.309	(1.151, 1.489)
	SPI-1	Thwave p = 0.000	4	0.275	(0.146, 0.403)	1.309	(1.157, 1.496)
Respiratory deaths	SPEI-1	SPEI1 p = 0.003		−0.104	(−0.173, −0.036)	1.110	(1.037, 1.189)
		Thwave1 p = 0.027	1	0.263	(0.029, 0.496)	1.301	(1.029, 1.642)
	SPI-1	SPI1 p = 0.002		−0.106	(−0.174, −0.038)	1.112	(1.039, 1.190)
		Thwave p = 0.020	1	0.277	(0.043, 0.511)	1.319	(1.044, 1.667)

Mainly, the pollutants effect on natural and circulatory causes it has observed up to one day of delay, reaching 5 days for NO_2 on circulatory causes, and the effect is during the same day (lag = 0) for PM_{10} in respiratory causes of mortality (Table 3).

4. Discussion

This paper evaluates for the first time the effect of the droughts measured by SPEI and SPI on daily natural and specific (circulatory and respiratory) causes of mortality for each province of Galicia throughout the 1983 to 2013 period. In addition, droughts were measured for different timescales (1, 3, 6, and 9 months) to evaluate the periods of accumulation in which the different causes of daily mortality were manifested, comparing the results obtained by both indicators. Based on the results of this study and considering the values of the coefficients obtained using a GLM, the negative sign indicates an inverse relationship between both variables, so that the more intense the hydrological extreme, the greater its impact on daily mortality.

A greater impact on daily mortality has been observed in the interior provinces of Galicia than in the coastal areas. Specifically, Lugo, the region with the greatest number of days with drought and with the highest value of accumulating days with severe and extreme drought, was the most affected province in terms of health. There were statistically significant associations between the drought, using both SPEI and SPI, and the daily natural- and circulatory-cause mortality in the short, medium, and long term, while the association with daily respiratory-cause mortality appears only in short term. In Pontevedra, the region with the lowest number of days with drought and with the lowest value of accumulating days with severe and extreme drought, there was no a relationship observed between any studied variables (see Table S2 and Fig. 3). According to the best statistically significant timescales, in the interior regions of Galicia, the daily mortality associated with drought is mainly manifested for shorter periods of accumulation but with much higher impact than in the coastal regions. However, in A Coruña, it is necessary that the drought occurs for a long time (9 months) to observe a significant association with daily circulatory-cause mortality, obtaining less impact than the interior regions,

Table 3
Summary of the statistical significance results obtained from Poisson modelling taking into account the impact of the daily pollutant concentration during drought periods in Ourense measured by SPEI-1 and SPI-1 during 2000 to 2009. The table shows the statistically significant results in Ourense using indicators of drought at short-term, daily pollution variables (O_3, NO_2 and PM_{10} concentrations) and extreme temperatures in Poisson models. Data for Lugo is not available. The relative risk (RR) was calculated from the value of the estimator obtained in each model. The 95% confidence intervals of the estimator and of the RR are displayed. Conf. Interval = Confidence Interval.

Ourense	Indicator	Drought indicator + extreme temperatures (Thwave) + pollution (mean O_3, NO_2, PM_{10} concentrations)					
		p-Value	Lag in days	Coefficient	Coefficient [95% conf. interval]	Relative risk (RR)	RR [95% conf. interval]
Natural deaths	SPEI1	NO_2 (p = 0.001)	1	0.005	(0.002, 0.008)	1.005	(1.002, 1.008)
		PM_{10} (p = 0.000)	1	0.006	(0.003, 0.009)	1.006	(1.003, 1.009)
	SPI1	NO_2 (p = 0.001)	1	0.005	(0.002, 0.008)	1.005	(1.002, 1.008)
		PM_{10} (p = 0.000)	1	0.006	(0.003, 0.009)	1.006	(1.003, 1.009)
Circulatory deaths	SPEI1	NO_2 (p = 0.007)	5	0.006	(0.002, 0.011)	1.006	(1.002, 1.011)
		PM_{10} (p = 0.012)	1	0.007	(0.001, 0.012)	1.007	(1.001, 1.012)
	SPI1	NO_2 (p = 0.007)	5	0.006	(0.002, 0.011)	1.006	(1.002, 1.011)
		PM_{10} (p = 0.012)	1	0.007	(0.001, 0.012)	1.007	(1.001, 1.012)
Respiratory deaths	SPEI1	PM_{10} (p = 0.000)	0	0.014	(0.007, 0.021)	1.014	(1.007, 1.021)
	SPI1	PM_{10} (p = 0.000)	0	0.014	(0.007, 0.021)	1.014	(1.007, 1.021)

probably due to the presence of heavier droughts in the interior than in the coastal regions (see Figs. 4–5).

The variability of these findings could also be explained by other variables that could influence the impact of hydrological extremes on health (IPCC, 2014; Stanke et al., 2013; Ebi and Bowen, 2016). Although variables such as trend, seasonality, and the autoregressive nature of the series were controlled, we were unable to examine the individual socioeconomic status, the previous vulnerability, and health of the population or socioeconomic status and race, showing a limitation of this type of studies. In addition, differences in pollution levels and humidity between different regions could aggravate the effects of drought in interior areas compared to coastal regions.

There are evidences that associate drought conditions with an increased risk of morbidity and mortality (Hanigan et al., 2012; Stanke et al., 2013; Yusa et al., 2015; Berman et al., 2017). However, more conclusive studies are needed, specifically on respiratory- and circulatory-cause mortality. According to our results, daily respiratory- and circulatory-causes of mortality were the most related to drought periods conditions, with the higher RR and % RA (Figs. 4–5). Concretely, daily respiratory-cause mortality in Ourense was the study group most affected by droughts in the short-term (Fig. 5).

In this context, although the biological mechanisms through which droughts affect disease and death are not well-known, indirect effects of drought events have been described in respiratory and circulatory health, and in mortality (Berman et al., 2017). It is remarkable that drought is an indirect indicator that incorporates and reflects the effects of different environmental factors, which have been considered individually in several works, such as heatwaves, forest fires, and pollution, with great importance in mortality, especially in vulnerable populations. High temperatures are associated with the intensification of droughts (Bandyopadhyay et al., 2016; Sapionini et al., 2017), and both phenomena are related to drier soils, deforestation, increase the incidence and intensity of wildfires, dust storms as well as conditions that lead to increase in the reduction in air quality (Smoyer-Tomic et al., 2004; Westerling et al., 2006; IPCC, 2014; Patz et al., 2014; Smith et al., 2014; Yusa et al., 2015; Ebi and Bowen, 2016, Bell et al., 2018). All these events associated with droughts lead to an increase in dust, which can transport pathogens or PM, and a rise in the release of toxic aerosols in the atmosphere with potential effects in health (Smoyer-Tomic et al., 2004; Johnston et al., 2011; Finlay et al., 2012; Smith et al., 2014; Linares et al., 2017; Bell et al., 2018). In this point, it should be noted that although SPEI incorporates temperature data is difficult to use this type of indicator to disentangle the direct health effects of temperature from increased evapotranspiration and in the rise in drought severity that can imply.

For all these reasons, in the second part of this study we have analysed the effect of extreme temperatures (heatwaves) and mean O_3, NO_2 and PM_{10} concentrations associated to droughts on daily mortality in the short-term during 2000 to 2009. Only for interior provinces of Galicia there were statistically significant associations (Table 1).

When only droughts and heatwaves were considered it has observed that in the short-term, the effect on daily mortality was due to a synergic effect of both in Ourense and Lugo (with the exception to respiratory-cause mortality in Ourense that was only due to the effect of droughts) (Table 2). However, when pollutant were added as third climatic factor, in Ourense there was only a significant relationship between atmospheric pollution and the different causes of daily mortality in the short-term. In this case, the statistically association between drought, heatwave and daily mortality variables no longer observed when pollution was considered (Table 3). Thus, these findings suggest that in the short-term, the observable effect of droughts measured by SPEI-1 and SPI-1 and heatwaves on daily mortality across 2000 to 2009 was explained by the atmospheric pollution effect (higher PM and NO_2 concentrations).

Heatwaves and extremely high temperatures have been associated with natural, circulatory and respiratory causes of mortality in Spain in several longitudinal studies (Tobías et al., 2014; Linares et al., 2015b; Carmona et al., 2016; Linares et al., 2017). In Galicia as a whole, maximum temperature increase of 1 °C was more strongly associated with respiratory-cause mortality (RR: 1.14) than circulatory-cause mortality (RR: 1.06) (Diaz et al., 2015; Linares et al., 2017, and in addition, people over 65 years old were markedly more affected (Díaz et al., 2002; Linares and Diaz, 2008). These effects attributable to high temperatures will be conditioned by the physiological state and vulnerability of the individual (Linares et al., 2017). On the other hand, Díaz et al. (2012) showed that in Madrid (interior region of Spain) levels of PMs from anthropogenic origin can be strongly increase in days with Sahara dust intrusions, which occur more frequent in warmer months, when heatwaves usually take place. This fact can led to harmful effects on circulatory and respiratory health.

With respect to **high pollution levels**, Berman et al. (2017), in their study over USA for 2000–2013, indicated that drought periods were associated with an increase in daily concentrations of dust (PM with aerodynamic diameter of >2.5 μm and less than or equal to 10 μm or PM course), although also in decrease in $PM_{2.5}$. Several multicentre studies in the USA, Canada, and Europe strongly associated effects of short-term PM_{10} exposure with circulatory and respiratory causes of mortality (U.S. EPA, 2009).

In accordance with our findings, droughts in the short-term could be explaining under situations with maintained anticyclones. In the study by Ficher et al. (2007) about the heatwave occurred during summer 2003 the drought conditions probably amplified and lengthened the anticyclonic events. The anticyclones generate blocking situations, favoring the increase in pollutants such as PM_{10} and NO_2 associated with the stagnant conditions (Thishan Dharshana et al., 2010; AIRPARIF, 2016). The high mean concentrations of NO_2 suggest that probably the pollution was mainly of anthropogenic origin as it is a primary pollutant due to road traffic (Linares et al., 2018a).

PM can pass through the respiratory tract where is deposited exacerbating chronic respiratory and circulatory diseases due to local and systemic inflammation and the establishment of oxidative and nitrosative stress, as well as cellular toxicity due to PM inhalation. This results in cell damage and injury (Linares et al., 2018b; Jalava et al., 2006; Xia et al., 2007; U.S. EPA, 2009; Haikerwal et al., 2015; Ortiz et al., 2017). In the circulatory system, these events have been related to prothrombotic effects, endothelial dysfunction and acceleration of atherosclerotic processes, with consequent vessel obstruction and a decrease in blood flow. In addition, this can lead to atherosclerotic plaque rupture, myocardial infarction, and stroke (Pope 3rd et al., 2004; U.S. EPA, 2009; Haikerwal et al., 2015; Reid et al., 2016; Ortiz et al., 2017). PM has also been related to vessel reactivity affectation (U.S. EPA, 2009) and alteration of cardiac autonomic function, which can increase the risk of dysrhythmia, heart failure, and cardiac arrest (Pope 3rd et al., 2004).

A study on the evaluation of short-term mortality attributable to PM pollution in Spain (Ortiz et al., 2017) indicated a higher RR (1.026) for respiratory-cause mortality corresponding to increase of 10 $\mu g/m^3$ in PM_{10} concentrations than for natural- and circulatory-cause mortality ($RR = 1.009$ for both causes). In the case of NO_2 concentrations (Linares et al., 2018a) it was found a similar order for the RR of daily causes of mortality ($RR = 1.028$, $RR = 1.016$, and $RR = 1.012$, respectively for respiratory, circulatory, and natural mortality).

Although in this study we have not evaluated a direct relationship between droughts and wildfires, it should take into account that they are event strongly associated and can probably play an important role in specific causes of mortality in the short-term. Specifically, a study estimated that 339,000 premature deaths per year worldwide are attributable to pollution derived from forest fires, especially due to PM, which is the most prevalent air pollutant in the smoke of wildfires after the burning of biomass (Johnston et al., 2012). Linares et al. (2018b) showed the association between daily mortality and the increase in PM concentrations produced by biomass combustion from wildfires in Spain in regions where they were more frequent, including the northwest, throughout the 2004 to 2009 period (Linares et al., 2015a). In addition, daily-respiratory cause mortality is mainly the cause most related to this climatic extreme. Interior provinces of Galicia (Ourense and Lugo), which we had proved the most affected by drought events, are the most affected regions with the highest number of forest fires and the largest areas burned. In particular, during 2017, Ourense accounted for about 50% (30,000 ha) of the total burned area in Galicia (62,000 ha) (Mapama, 2017). However, it should be necessary conducted conclusive studies that analysing the association between droughts and wildfires.

The manifestation of daily mortality effects for prolonged timescales may be associated with mental health, especially in rural populations. Although we could not measure levels of stress in this retrospective study, there are several studies that have documented the association between droughts and psychological stress, psychological distress, generalized anxiety, and depression, that in extreme cases, could even be a contributing factor to mortality by suicide (Berry et al., 2010; Hanigan et al., 2012; Shukla, 2013; IPCC, 2014; OBrien et al., 2014; Sena et al., 2014; Yusa et al., 2015; Vins et al., 2015; Berman et al., 2017).

Chronic stress causes prolonged and persistent overactivation of the hypothalamic pituitary adrenal axis and the medullary adrenal sympathetic axis, which ultimately has direct effects on physiological processes and patterns of behaviour (Cohen et al., 2007; Vida et al., 2014). Murine models have shown that chronic stress and anxiety are related to the establishment of oxidative and inflammatory stress, which leads to the deterioration of the regulatory systems: nervous, immune, and endocrine, as well as the neuroimmunoendocrine communication. Ultimately, these events can lead to premature immunosenescence, decrease in homeostasis, dysfunction of an organism's systems, and therefore, a loss of good health and premature mortality (Vida et al., 2014). In particular, stress can be an important factor in respiratory tract infections and can promote cardiac pathogenic processes, such as myocardial ischemia and activation of inflammatory and coagulation mechanisms (Von Känel et al., 2001; Cohen et al., 2007). In any case, more exhaustive studies should be done to better understand the link of stress as a causal effector.

In addition, in this work is the first time that a comparison between the effects of periods of drought measured by the SPEI and SPI indices on daily mortality in a particular region of Europe was conducted, Galicia. The findings indicate that statistically significant differences between both types of indices hardly exist from the periods of study nor with respect to the timescales of both indicators (SPEI-n vs SPI-n). Thus, the indistinct use of either index could be valid to evaluate the risk of drought in terms of health in Galicia, probably due to precipitation is likely the most important variable when considering drought measurement. This is in concordance with a previous work by Vicente-Serrano et al. (2011) that analysed the evolution of drought severity on the NW Iberian Peninsula from 1930 to 2006 and no significant differences were found when it was measured by SPEI and SPI. However, according to warming projections of climate change (Patz et al., 2005; Carmona et al., 2016), SPEI could provide a better estimate of the severity of drought, as result of water by evapotranspiration (Beguería et al., 2014), and a better adjustment of the risk in health in the near future. Specifically in Spain an increase of between 3 and 5 °C and even 5–7 °C in the warmest months has been predicted to occur by the end of the 21st century (Morata-Gasca, 2014).

Finally, it should be noted that the findings obtained in this study include only the NW region of Spain, which implies a restriction in obtaining broader conclusions at the population level in Spain as a whole, showing a limitation of this study.

5. Conclusion

The main findings of this study are that daily mortality in the interior regions of Galicia are more affected by drought than in the coastal regions. In the interior provinces of Galicia, the effects on daily mortality suggest that they are associated with droughts mainly measured for shorter timescales. In the coastal province of A Coruña, the daily mortality is manifested with longer droughts. Moreover, there are hardly differences between SPEI and SPI, so both indicators are valid to assess the effects of droughts in terms of health. On the other hand, the results suggest that in short-term, the synergic effect of droughts measured by SPEI-1/SPI-1 and heatwaves on daily mortality observed in interior regions is mainly explained by atmospheric pollution effect in Ourense, during the 2000–2009 period. In addition, daily respiratory-cause mortality is the cause most associated to this extreme climatic event throughout all study. Taking into account the fact that many people are exposed to these extreme climatic events at a regional level, considering the future projections of climate change as well as the limited information on this issue in the scientific literature, these studies are crucial to public health, so that these serious effects attributable to drought periods can be minimized. The dichotomy seen in this study in reference to the behaviour of mortality and droughts between coastal and inland regions, as well as the different effects due to droughts in the short, medium or long term, will serve as an important point of departure in analysing the effect of droughts for different timescales for major regions such as the Iberian Peninsula.

Disclaimer

This paper reports independent results and research. The views expressed are those of the authors and not necessarily those of the Carlos III Institute of Health.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.01.217.

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Short-term effects of drought on daily mortality in Spain from 2000 to 2009

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ABSTRACT

Spain is a country of southern Europe that is prone to drought, and it is likely that this type of hydrological extreme will become substantially more frequent and intense in the 21st century, which could lead to greater health risks if adequate adaptive measures are not taken. For the first time, we calculated the relative risks (RRs) of daily natural (ICD10: A00–R99), circulatory (ICD10: I00–I99), and respiratory (ICD: J00–J99) mortality associated with drought events in each province of Spain from 2000 to 2009. For this purpose, we compared the performance of the Standardized Precipitation Index (SPI) and Standardized Precipitation- Evapotranspiration Index (SPEI) obtained at 1 month of accumulation (denoted as SPI-1/SPEI-1) to estimate the short-term risks of droughts on daily mortality using generalised linear models. Attributable risks were calculated from the RR data. The main findings of this study revealed statistically significant associations between the different causes of daily mortality and drought events for the different provinces of Spain, and clear spatial heterogeneity was observed across the country. Western Spain (northwest to southwest) was the region most affected, in contrast to northern and eastern Spain, and daily respiratory mortality was the group most strongly linked to the incidence of drought conditions. Moreover, for a considerable number of provinces, the effect of SPI-1 and SPEI-1 largely reflected the impact of atmospheric pollution and/or heatwaves; however, for other regions, the effect of drought conditions on daily mortality remained when these different climatic events were controlled in Poisson models. When the performances of the SPEI and SPI were compared to identify and estimate the risks of drought on daily mortality, the results were very similar, although there were slight differences in the specific causes of daily mortality.

1. Introduction

Human health is extremely vulnerable to variations in weather patterns and other aspects of climate change, and is particularly affected by the recent incidence of extreme climatic phenomena, such as heatwaves, droughts, floods, wildfires, and cyclones (IPCC et al., 2014; Franchini and Mannucci, 2015; Watts et al., 2017; Bell et al., 2018). In particular, drought is a slow hazard that is widely considered to be one of the most destructive and costly natural disasters worldwide, with serious effects on agriculture, water resources, ecology, and society. It generally affects a larger number of people compared with other extreme climatic phenomena. In addition, this climatic hazard is very complex because the determination of the beginning and end of the events as well as the evaluation and quantification of their effects are difficult; many of the effects are diffuse, indirect, and cumulative over time (Wilhite, 2000; Kallis, 2008; Bachmair et al., 2016; Berman et al., 2017; Vicente-Serrano et al., 2020). Droughts can be triggered by various climatic factors, occurring at different time scales and affecting different systems; this requires the differentiation of several types of droughts, namely, meteorological, hydrological, agricultural, and socioeconomic droughts, thereby making their study more difficult (Wilhite, 2000; Bachmair et al., 2016; Salvador et al., 2019a).

Health effects associated with drought episodes are principally indirect and include the increased risk of infectious diseases and diarrheal pathologies, malnutrition, changes in the ecology of vector-borne diseases, cardiorespiratory affectations, serious mental health repercussions and greater risk of mortality (Stanke et al., 2013; Yusa et al., 2015; Alpino et al., 2016; Berman et al., 2017; Bifulco and Ranieri, 2017). The vulnerability and drought risks vary depending on the level of the development and needs of each country (Stanke et al., 2013; Sena et al., 2014; Salvador et al., 2019a). While in developing countries (e.g. Eastern Africa or Asia regions) occur the most number of deaths, principally mediated by the impact on water and food insecurity or livelihood loss, among others (Alimullah Miyan, 2015; Gebremeskel Haile et al., 2019), in developed countries (e.g. Spain or USA) the impact of this type hydrological extreme could be principally focused on economic losses (United Nations, 2007; Kallis et al., 2008) or pollution exposures (Salvador et al., 2019b).

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Droughts are frequently associated with the occurrence of other climatic phenomena (e.g. heatwaves, wildfires, dust storms and atmospheric pollution (Stanke et al., 2013; Bell et al., 2018; Salvador et al., 2019a) which also cause higher risk of respiratory and circulatory mortality (Faustini et al., 2015; Ma et al., 2015; Díaz and Linares, 2018). The frequency and intensity of forest fires and dust storms can be increased by the incidence of this hydrological extreme. Moreover, droughts are also frequently associated with stagnant conditions and atmospheric blocking events characterised by a high concentration of atmospheric pollutants; all of this leads to an increase in airborne dust, wildfire smoke and reduction of air quality, thereby resulting in higher morbidity and mortality (Stanke et al., 2013; Berman et al., 2017; Salvador et al., 2019a; Bell et al., 2018). Blocking conditions in turn could contribute to the incidence and persistence of heatwaves, as was described in the critical review on the European summer heatwave of 2003 (García-Herrera et al., 2010). In addition, the co-occurrence of higher temperatures with droughts could influence the severity of the drought episodes as a result of the loss of water by evapotranspiration (Vicente-Serrano et al., 2014), increasing the risk of fires and thereby increasing threat on health systems (Salvador et al., 2019a). On the other hand, it has been also described that drought events are often linked to alterations in dispersion patterns of allergens, thereby compromising respiratory health (IPCC et al., 2014).

Meanwhile, future projections of climate change indicate that droughts will become substantially more frequent and intense in several regions of the world at the end of the 21st century, especially in southern Europe and the Mediterranean Basin, which could entail greater threats to health in vulnerable regions (Mishra and Singh, 2010; Ebi and Bowen, 2016; Guerreiro et al., 2018; Spinoni et al., 2018). Particularly, Iberian Peninsula (southwestern Europe) is an area prone to droughts, where this meteorological extreme is described as the main hydroclimatic hazard (Páscoa et al., 2017), and frequently this region undergoes extreme heat temperatures and wildfires, with potential implications on natural, circulatory and respiratory mortality of exposed population (Linares et al., 2017, Linares et al., 2018a; Turco et al., 2019). Several studies have revealed that the magnitude and frequency of droughts have increased during the last few decades in most of the area (Vicente-Serrano and Cuadrat-Prats, 2007; Vicente-Serrano et al., 2011; Páscoa et al., 2017), and it has been estimated that this region will likely suffer a rise in the severity of droughts throughout the 21st century, associated with a pronounced decrease in precipitation and an increase in temperature. Particularly, Iberian Peninsula has experienced a temperature increase of 1.5 °C annually and a decrease of 15.6% in precipitation over the last five decades (Vicente-Serrano et al., 2014). Moreover, the last State Meteorological Agency (AEMET) report published in 2019 showed an increase in the mean temperature during all seasons in Spain since 1971, with increases more clearly observed in spring and especially in summer. The report also described that at present, summers are approximately 5 weeks longer than those in the 1980s (AEMET, 2019). This report also showed the evolution of the Köppen climate classification for 1961–1990, 1971–2000, and 1981–2010, and the result was a clear increase (approximately 6%) in the extension of the semi-arid climate over Spain.

Only a regional study has been conducted on the effects of drought on daily mortality in Spain (Galicia, northwest Spain) (Salvador et al., 2019b), which revealed that in short-term, mortality was associated to the incidence of droughts and extreme heat temperatures in interior provinces, whose effects were mainly explained by pollution effect. However, the spatial patterns of droughts across the Iberian Peninsula are very complex (Vicente-Serrano, 2006), as there is a clear regionalisation of precipitation (strong spatial gradient of precipitation with significant seasonal characteristics) (Parracho et al., 2016). For this reason, and owing to the climatic and meteorological differences across the different geographical locations of the Spanish provinces, the conclusions obtained in Galicia cannot be extended to the rest of Spain. For the first time, we conducted a study at the national level in order to obtain broader knowledge on the short-term effects of droughts on specific causes of daily mortality across peninsular Spain from 2000 to 2009 and controlled the impact of heatwaves and atmospheric pollution during the study period. We also compared the performance of different drought indices to determine which proxy is better to estimate the different health risks.

2. Material and methods

In this retrospective ecological study of daily time series, we evaluated the short-term impact of droughts on daily natural, circulatory, and respiratory mortality across the provinces of peninsular Spain during the period from 2000 to 2009. The first aim of this study was to analyse the effect of droughts measured by the Standardized Precipitation-Evapotranspiration Index obtained at 1 month of accumulation (SPEI-1) and Standardized Precipitation Index obtained at 1 month of accumulation (SPI-1) on daily natural, circulatory and respiratory mortality. Meanwhile, the second aim was to evaluate the impact of drought conditions by controlling the effect of heat waves and atmospheric pollution on daily mortality. The variables involved in this study are described in the following subsections.

2.1. Study region: Spain

Spain (within the Iberian Peninsula) is one of the largest countries located in the southwest of Europe. It has a geographical extension of almost 506 000 km^2 (Instituto Geográfico Nacional IGN, 2019) and is divided into 50 provinces, with a total population of 46 658 447 (Instituto Nacional de Estadística, INE, 2019). Its location in the mid-latitudes of the Northern Hemisphere makes it interesting from a climatological point of view. Owing to the complex orography and geographic situation of the Iberian Peninsula, there is significant heterogeneity in the precipitation and temperature patterns, and the climate is extremely diverse throughout the north and south as well as between the coastal and interior regions (De Castro et al., 2005; AEMET, 2018; Instituto Geográfico Nacional IGN, 2019). The climate of the different territories of the Iberian Peninsula largely depends on the influence of the origin of air masses (Gimeno et al., 2010) and circulation patterns (De Castro et al., 2005). The study region was specifically peninsular Spain (Fig. S1).

2.2. Dependent variables

The dependent variable was the daily natural mortality, which incorporated all causes except for accidents (ICD10: A00–R99), as well as the daily circulatory mortality (ICD10: I00–I99) and daily respiratory mortality (ICD10: J00–J99). These mortality data were provided by the National Institute of Statistics of Spain and referred to the daily number of deaths for the capital city and towns with over 10 000 inhabitants in each province across peninsular Spain during 2000–2009.

2.3. Independent variables

2.3.1. Drought variables

We used two meteorological drought indicators for monitoring drought conditions in each province of Spain, namely the SPI and SPEI. The SPI incorporates the precipitation data, and the SPEI is based on the normalisation of the difference between precipitation and atmospheric evaporative demand (Vicente-Serrano et al., 2011). Vicente-Serrano et al. (2017) rigorously developed a high-resolution spatial (1.1 km) and temporal (weekly) dataset for Spain for the period of 1961–2018, which is available in the website: http://monitordesequia.csic.es (see Vicente Serrano et al. (2017)for more details). As the drought data are available weekly, we construct daily series assuming the same conditions for each seven-day interval, following the criteria of Berman et al. (2017) and Salvador et al. (2019b). Both types of drought indices have several advantages that makes them more capable to drought monitoring and to identify their risks in different systems in comparison with other indices also commonly used such as the Palmer Drought Severity Index (PSDI) (Palmer, 1965). Firstly, these type of drought indices are standardized based on normalized data, so they can be comparable in space and time and they are not affected by geographical or topographical differences (Vicente-Serrano, 2006; Vicente-Serrano et al., 2010). In addition, SPI and SPEI can be obtained at various timescales (1 month–48 months), which indicate different accumulation periods (Vicente-Serrano et al., 2012). These time scales reflect the different responses according to the availability of water resources in different systems, thereby making it possible to distinguish several types of droughts related to different accumulated precipitation deficits (Salvador et al., 2019a). The choice of the time scale will depend on the purpose of the study. Particularly, the main objective of this study was the assessment of the short-term effects of droughts on mortality so we have monitoring droughts for short periods of time (one month of accumulation) and we have compared the performance of the different types of droughts in order to determine which was the best proxy to reflect the impact of droughts on different causes of daily mortality.

The SPEI and SPI allow the quantification of both dry and wet periods. The onset of a drought event is frequently defined as when the indicator value becomes negative, and the episode ends when the index returns to a positive value (wet condition). Furthermore, the severity of drought periods can be classified according to the criteria of Agnew (2000) and Berman et al. (2017) (see Fig. 2 of Salvador et al. (2019b) for more details).

2.4. Control variables

Heatwaves and atmospheric pollution variables were also controlled in this study due to their harmful effects on health and because these climatic phenomena are frequently linked to drought phenomena. In Spain, circulatory and respiratory mortality are the causes most associated with heatwaves (Díaz et al., 2015). In addition, high atmospheric pollution events are also strongly linked to a clear increase in these specific causes of deaths for both nitrogen dioxide (NO_2) (Linares et al., 2018b) and particulate matter with an aerodynamic diameter of less than 10 μm (PM_{10}) (Ortiz et al., 2017). Moreover, in the case of the tropospheric ozone (O_3), the cardiorespiratory diseases are the most affected (Díaz et al., 2018). In the same way, the most related pathologies to days with Sahara dust advections (Díaz et al., 2017) or biomass combustion from wildfires (Linares et al., 2018a) are also the circulatory and respiratory.

2.4.1. Heat wave variable

To quantify the effect of heatwaves on daily mortality we calculated the daily temperature for heatwaves (T_{hwave}) based on the calculations conducted by Díaz et al. (2015). We used the maximum temperature ($Tmax$) recorded at the reference sites located in the provincial capital cities of peninsular Spain, data from the State Meteorological Agency (AEMET), and the maximum temperature threshold for daily mortality associated with heat ($Tthreshold$) for each province, as calculated by Díaz et al. (2015). We also considered heatwaves in terms of mortality effects when $Tmax$ surpassed $Tthreshold$ in the following manner:

$$T_{hwave} = Tmax - Tthreshold \quad \text{if } Tmax > Tthreshold$$
$$T_{hwave} = 0 \quad \text{if } Tmax \le Tthreshold$$

Given that the effect of heatwaves on mortality can be delayed by 0 days–4 days (Martinez et al., 2018), we included these lag times in the Poisson models.

2.4.2. Atmospheric pollution variables

We used daily mean O_3, PM_{10}, and NO_2 concentration (μg/m^3) data recorded at monitoring stations situated in each capital province, which were provided by the Ministry of Agriculture and Fisheries, Food and Environment. As the relationship between O_3 and mortality is non-linear (Díaz et al., 2018), this variable was parameterised, as was the described T_{hwave}. We used an O_3 concentration threshold calculated for the period of 2000–2009, above which mortality began to increase, associated with the increase in O_3 concentrations. We also created a new variable denominated O_3a to quantify the effect of O_3 on daily mortality according to the calculations by Díaz et al. (2018), as follows:

$$O_3a = O_3 - O_3threshold \quad \text{if } O_3 > O_3threshold$$
$$O_3a = 0 \quad \text{if } O_3 \le O_3threshold$$

In reference to the effects of atmospheric pollution on daily

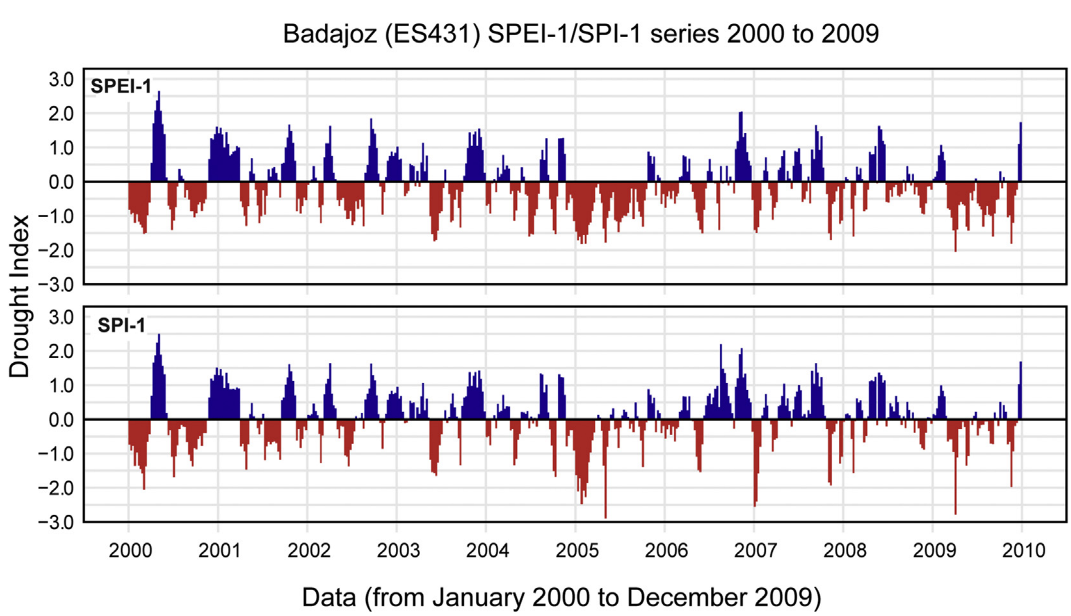

Fig. 1. Temporal evolution of the Standardized Precipitation-Evapotranspiration Index obtained at 1 month of accumulation (SPEI-1) (top)/Standardized Precipitation Index obtained at 1 month of accumulation (SPI-1) (bottom) values in Badajoz (ES431) from 2000 to 2009. Blue lines represent days with no droughts and in red represents days with drought conditions. Moreover, the more negative the SPEI-1/SPI-1 values, the greater the severity of the drought episodes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mortality, we considered different lag times in the statistical models, as described in the study of Galicia (Salvador et al., 2019b), namely, 0–5 days for PM_{10} and NO_2, and up to 9 days for O_3.

2.4.3. Other control variables

Other variables were analysed throughout the study, such as the trend of the series, the autoregressive nature of the dependent variable, and the seasonality of the series, which were controlled using the sine and cosine functions corresponding to the annual (365 days), 6 months (180 days), 4 months (120 days), quarterly (90 days), and 3 months (60 days) periodicities.

2.5. Analysis and models

We used generalised linear models with the Poisson link to evaluate the impact of drought conditions (as well as the effect of heatwaves and air pollution) on daily mortality for each province of peninsular Spain. In these models, we included the explicative independent and control variables as well as the respective lagged variables for T_{hwave}, O_3a, PM_{10}, and NO_2 (Section 2.4). For example, lag 1 took into account the effect of the climatic variable on day "d" on mortality 1 day later (d +1), whereas lag 2 took into account the effect of the climatic variable on day "d" on mortality 2 days later (d+2). In the provinces where O_3a value is not existing was deemed that this ozone has no effect on mortality in these provinces (Díaz et al., 2018).

This process was conducted individually for each daily cause of mortality and for the SPI-1 and SPEI-1 independently using single models. The process for determining the significant variables was the step-back procedure, in which the variables that had less statistical significance were gradually eliminated individually. This process was repeated until the complete model, including all the significant explanatory variables ($p < 0.05$), was obtained. First, we only controlled the drought indices in the Poisson models. Then, we included T_{hwave} in the statistical models and subsequently added the control of atmospheric pollution as the third climatic control variable in the modelling processes, because for several provinces, there were not no pollution data available.

We calculated the relative risks (RRs) of different causes of mortality from the value of the coefficients obtained in each Poisson model according to Salvador et al. (2019b). The RR value was calculated for each unit of increment for the indicator of the independent variable. In addition, we calculated the percentage of attributable mortality risk (%AR) by the following equation:. (Coste and Spira, 1991):.

$$\%AR = ((RR - 1)/RR) \times 100.$$

All analyses were performed using IBM SPSS Statistics 22 and STATA v. 14.1 software.

3. Results

3.1. Descriptive analysis

Table 1 shows the descriptive statistics corresponding to the daily natural, circulatory, and respiratory mortality for each province of Spain from 2000 to 2009, while Table 2 represents the descriptive statistics corresponding to annual T*max* and annual concentrations of atmospheric pollutants (PM_{10}, NO_2, and O_3 levels (µg/m^3)) for each province of Spain from 2000 to 2009. Fig. 1 illustrates the characterisation of droughts measured by the SPEI-1 (SPI-1) from 2000 to 2009, using Badajoz (Spain) as an example.

3.2. Evaluation of short-term impacts of droughts on daily natural, circulatory, and respiratory mortality during 2000–2009

Fig. 2 illustrates the estimated RRs of natural, circulatory, and respiratory causes of daily mortality associated with droughts measured by the SPEI-1 (SPI-1) in provinces of peninsular Spain when there was a statistically significant association at a confidence level of 95% ($p < 0.05$) (Fig. 2A). Fig. 2 also represents the RRs of daily mortality attributable to drought conditions when we controlled the effect of heatwaves and atmospheric pollution in the Poisson models (Fig. 2B). However, Fig. S2 included in supplementary appendix, describes the RRs when we only controlled drought indices and T_{hwave} variables. Particularly, Tables S1–S3 show the complete statistically significant *p*-values as well as the complete values of the coefficients, RRs, %ARs, and respective 95% confidence intervals for each province of Spain.

The results of this study revealed that with the use of both types of drought indices, there were notable significant relationships between daily natural mortality and the occurrence of drought events, especially for daily respiratory mortality, which was the most strongly linked to drought episodes because the highest RR values were obtained for this specific cause of death. In contrast, daily circulatory mortality was the group least associated with the incidence of this type of hydrological extreme because there were hardly any provinces where significant associations between the incidence of drought conditions and daily circulatory mortality were found in Spain across the analysed period (Fig. 2; Table S1). On the other hand, there was clear spatial variability in the drought effects on daily natural and specific causes of mortality between different regions of Spain. In this context, considering Spain as a whole, the greatest impact of drought events measured at the short-term scale on the different analysed causes of daily mortality was principally evidenced in the west during 2000–2009. Particularly, the impacts were focused in provinces located in northwest and southwest Spain as well as in the central regions of the country. In contrast, the observations in the north and east of Spain reveal no statistically significant association between the occurrence of drought periods and mortality (except in País Vasco and Navarra for natural and respiratory causes of death). However, some provinces in northeast Spain were affected by drought events in terms of daily mortality, particularly for daily natural and respiratory mortality (Fig. 2A). In addition, although the results obtained using the SPI-1 and SPEI-1 were very similar throughout the study, there were some subtle differences for circulatory and respiratory mortality in several provinces (Fig. 2A). It was observed that for daily circulatory mortality, the SPEI-1 was a slightly better proxy to detect statistically significant associations between droughts and this specific cause of daily mortality, whereas for daily respiratory mortality, the SPI-1 was slightly more sensitive in identifying the effects of droughts in Spain during 2000–2009.

3.3. Short-term impacts on daily natural, circulatory, and respiratory mortality under drought conditions when controlling the effects of heat waves and atmospheric pollution during 2000 to 2009

According to the second aim of this study, we analysed the short-term effects of droughts measured by the SPI-1 and SPEI-1 on daily mortality including the evaluation of both heatwaves and air pollution impacts in Spain during 2000–2009 under drought conditions.

First, we controlled the drought indices and heatwaves in the Poisson models because in several provinces there were no atmospheric pollutant data available (Table S2). The main findings suggested that the effect on daily mortality in Spain during 2000–2009 was linked to the occurrence of drought episodes and the incidence of extreme temperatures (except some cases where the statistically significance of SPEI-1/SPI-1 was lost when we included T_{hwave} variable in statistical models) (Table S2; Fig. S2). Moreover, the effect of heatwaves under drought conditions measured at the short-term scale on daily natural mortality occurred immediately (lag 0) and up to 4 days later (lag 4). Then, we included atmospheric pollution as the third climatic control variable in the modelling process (Fig. 2B; Table S3) and compared the RR values of daily natural, circulatory, and respiratory mortality associated with the drought periods between Fig. 2A (control of only drought indices) and Fig. 2B (control of all climatic phenomena). In

Table 1
Descriptive statistics corresponding to daily natural, circulatory, and respiratory mortality for each province of Spain across the period of 2000–2009. *Madrid (ES300) data corresponds with the period 2001 to 2009. Max: maximum; Min: minimum; SD: Standard Deviation. In Palencia there is no mortality data available during the study period.

Autonomus community	Province (code NUTS3)	Natural deaths				Circulatory deaths				Respiratory deaths			
		Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Galicia (ES11)	A Coruña (ES111)	31	7	12	59	11	4	1	29	4	2	0	15
	Lugo (ES112)	12	4	1	33	5	2	0	19	2	1	0	9
	Ourense (ES113)	12	4	1	28	4	2	0	16	2	1	0	9
	Pontevedra (ES114)	21	5	6	45	7	3	0	20	3	2	0	14
Principado de Asturias (ES12)	Asturias (ES120)	33	7	15	63	12	4	1	29	4	2	0	21
Cantabria (ES13)	Cantabria (ES130)	14	4	3	38	5	2	0	14	2	2	0	12
Pais Vasco (ES21)	Alava (ES211)	6	3	0	16	2	1	0	10	1	1	0	7
	Guipuzcoa (ES212)	16	5	4	36	5	2	0	16	2	2	0	14
	Vizcaya (ES213)	28	6	8	60	9	3	1	27	3	2	0	17
Comunidad Floral de Navarra (ES22)	Navarra (ES220)	13	4	3	31	4	2	0	15	2	1	0	12
La Rioja (ES23)	La Rioja (ES230)	7	3	0	19	2	2	0	10	1	1	0	6
Aragon (ES24)	Huesca (ES241)	6	3	0	15	2	1	0	9	1	1	0	6
	Teruel (ES242)	4	2	0	13	1	1	0	7	1	1	0	5
	Zaragoza (ES243)	24	6	7	54	8	3	0	21	3	2	0	14
Comunidad de Madrid (ES30)	Madrid (ES300)*	109	17	58	206	33	8	9	72	16	6	3	54
Castilla y Leon (ES41)	Avila (ES411)	5	2	0	15	2	1	0	8	1	1	0	6
	Burgos (ES412)	9	3	0	24	3	2	0	11	1	1	0	7
	Leon (ES413)	14	4	3	34	5	2	0	15	2	2	0	10
	Palencia (ES414)												
	Salamanca (ES415)	10	3	1	26	4	2	0	12	1	1	0	9
	Segovia (ES416)	4	2	0	12	1	1	0	8	0	1	0	4
	Soria (ES417)	3	2	0	12	1	1	0	6	0	1	0	6
	Valladolid (ES418)	12	4	2	29	4	2	0	14	1	1	0	10
	Zamora (ES419)	6	3	0	19	2	1	0	9	1	1	0	6
Castilla la Mancha (ES42)	Albacete (ES421)	9	3	1	22	3	2	0	12	1	1	0	9
	Ciudad Real (ES422)	13	4	1	32	4	2	0	14	2	1	0	14
	Cuenca (ES423)	5	2	0	14	2	1	0	8	1	1	0	5
	Guadalajara (ES424)	4	2	0	15	2	1	0	8	1	1	0	5
	Toledo (ES425)	14	4	1	34	5	2	0	17	2	1	0	12
Extremadura (ES43)	Badajoz (ES431)	17	5	3	38	6	3	0	20	2	2	0	10
	Caceres (ES432)	10	4	1	26	4	2	0	17	1	1	0	8
Cataluña (ES51)	Barcelona (ES511)	115	20	62	230	37	9	15	84	12	6	2	49
	Girona (ES512)	14	4	3	35	5	2	0	15	1	1	0	11
	Lleida (ES513)	10	4	1	29	4	2	0	14	1	1	0	9
	Tarragona (ES514)	16	4	4	39	2	1	0	9	5	2	0	17
Comunidad Valenciana (ES52)	Alicante (ES521)	35	8	13	72	13	4	2	32	4	2	0	15
	Castellon (ES522)	12	4	3	28	5	2	0	15	1	1	0	7
	Valencia (ES523)	57	11	30	114	20	6	4	47	7	3	0	26
Andalucia (ES61)	Almeria (ES611)	11	4	1	29	4	2	0	12	1	1	0	8
	Cadiz (ES612)	23	6	7	48	8	3	0	22	2	2	0	13
	Cordoba (ES613)	19	5	2	49	7	3	0	20	2	2	0	14
	Granada (ES614)	20	5	6	48	7	3	0	23	2	2	0	12
	Huelva (ES615)	11	4	1	28	4	2	0	15	1	1	0	8
	Jaen (ES616)	15	5	2	46	5	3	0	17	2	2	0	15
	Malaga (ES617)	30	7	9	58	12	4	0	30	3	2	0	14
	Sevilla (ES618)	38	9	14	81	16	5	3	40	4	2	0	16
Region de Murcia (ES62)	Murcia (ES620)	26	6	9	56	9	3	1	22	3	2	0	16

many provinces, either the statistically significant associations between droughts and daily mortality were lost when we included the different climatic factors in statistical models or the RR values were slightly lower, thereby resulting in statistically significant PM_{10}, NO_2, and O_3 (and/or T_{hwave}) variables (Table S3). For other provinces, the RRs of mortality associated with droughts remained very similar. In addition, respiratory mortality was the group most strongly affected by heatwaves and air pollution under drought conditions in consideration of the RR values (Table S3).

Considering the poor air quality linked to drought phenomena, it was observed that at a qualitative level, both NO_2 and O_3 were the atmospheric pollutants most associated with daily mortality in the largest number of provinces of Spain compared with PM_{10}. In addition, PM_{10} was specifically significant for natural and respiratory causes of daily mortality. At the quantitative level, in general, the RR associated with O_3 for any cause of daily mortality was slightly greater than that associated with NO_2 and greater than that associated with PM_{10}. Meanwhile, the air pollution effects linked with drought conditions on daily natural mortality occurred immediately (lag 0) and up to 5 days later (lag 5) for PM_{10} and NO_2, ranging from 0 d to 8 days later in the case of O_3. Considering the daily respiratory mortality, the effect of PM_{10} linked with drought was evidenced earlier (lag 1–lag 3), that for NO_2 ranged from 1 to 5 days, and that for O_3 ranged from 0 to 9 days. The delay of the impacts of NO_2 linked with drought events on daily circulatory mortality was similar to that for daily natural mortality, and that for O_3 was manifested with lag 0 and lag 4 (Table S3).

4. Discussion

Spain (within the Iberian Peninsula) is a region that is particularly prone to droughts, and it is likely that the occurrence of this type of hydrological extreme will become more frequent and intense by the end of the 21st century (Vicente-Serrano et al., 2014). From the national point of view, this study revealed the first evidence of links between the occurrence of drought measured at the short-term scale and specific causes of daily mortality across different provinces of peninsular Spain

Table 2
Descriptive analysis corresponding to annual data of maximum temperature (T*max*), particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) levels (µg/m^3) for each province of Spain from 2000 to 2009. Data was recorded at monitoring stations situated in each capital province. *Madrid (ES300) data corresponds with the period 2001 to 2009. Max: maximum; Min: minimum; SD: Standard Deviation. The empty cells indicate absence of valid values for a given pollutant.

Province (code NUTS3)	*Tmax*				PM_{10}				NO_2				O_3			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
A Coruña (ES111)	18.23	4.29	7.00	34.50	33.53	15.66	7.00	115.00					44.21	20.16	3.00	107.00
Lugo (ES112)	17.89	6.61	0.50	39.10												
Ourense (ES113)	21.80	7.55	2.40	42.00	21.76	13.89	3.00	104.00	35.53	15.33	10.00	108.00	53.13	26.18	1.00	129.00
Pontevedra (ES114)	19.13	5.76	5.10	39.50					26.66	12.02	0.00	73.00	52.57	22.31	2.00	137.00
Asturias (ES120)	17.59	5.64	0.80	35.60	48.16	22.74	7.58	137.00	45.02	14.71	9.00	105.31	59.32	23.01	11.00	149.50
Cantabria (ES130)	18.64	5.12	4.00	37.30	33.26	13.92	4.67	118.00	41.30	14.98	6.00	150.06	61.43	25.33	2.00	171.00
Alava (ES211)	17.51	7.74	−1.50	38.00	27.13	16.61	4.00	149.00	34.71	14.38	5.32	118.82	60.87	23.12	1.50	148.00
Guipuzcoa (ES212)	16.71	5.91	0.60	38.60	29.70	14.31	6.00	135.00	38.83	13.16	2.58	123.00	47.06	20.59	1.00	124.00
Vizcaya (ES213)	19.51	6.20	2.10	41.90	34.49	17.21	5.82	138.00	37.54	14.97	0.67	120.83	53.97	23.22	2.00	156.00
Navarra (ES22)	18.78	8.43	−2.80	39.80	32.49	15.03	2.00	160.96	27.72	16.08	2.00	117.48	63.73	27.08	2.00	158.00
La rioja (ES230)	19.99	8.51	−3.50	40.60	30.27	15.85	2.79	131.00	15.30	9.07	1.00	51.00	71.00	28.87	4.00	175.00
Huesca (ES241)	20.15	8.94	−4.40	41.30												
Teruel (ES242)	19.77	8.87	−4.80	38.80									85.22	26.12	10.00	167.00
Zaragoza (ES243)	21.48	8.91	−3.00	43.10	37.77	20.40	1.00	205.46	47.17	17.06	10.00	107.40	39.44	24.24	1.00	129.00
Madrid (ES300)*	20.23	8.76	1.00	38.60	32.47	16.10	0.00	149.50	59.39	17.88	17.56	142.00	35.71	18.06	3.74	89.39
Avila (ES411)	17.35	8.53	−3.50	37.40					37.56	16.21	1.26	143.08	72.46	28.59	4.00	171.00
Burgos (ES412)	17.35	8.77	−2.40	38.80	30.01	12.00	2.00	106.74	32.23	14.97	1.03	123.98	73.84	26.41	6.00	167.00
Leon (ES413)	16.84	8.16	−3.00	36.20	39.07	16.29	3.00	135.54	37.15	17.58	2.10	128.00	53.56	26.95	2.00	160.00
Palencia (ES414)																
Salamanca (ES415)	19.17	8.59	−1.00	39.00	31.44	14.92	6.00	129.21	25.04	11.50	1.00	88.48	72.47	28.24	1.00	168.00
Segovia (ES416)	18.14	8.83	−2.60	38.30	40.41	24.97	1.38	152.21	46.43	16.59	6.00	130.58	69.77	27.90	6.00	172.00
Soria (ES417)	17.59	8.70	−4.00	36.80	29.52	13.68	1.00	132.00	28.70	12.02	1.00	114.00	65.96	23.89	1.00	143.00
Valladolid (ES418)	18.84	8.99	−2.00	39.50	15.31	9.44	0.95	130.42	38.09	15.08	0.15	149.00	64.27	30.39	2.00	168.00
Zamora (ES419)	19.22	8.78	−2.60	39.20	31.23	11.69	7.71	92.25	42.39	14.79	6.04	132.33	64.69	25.85	5.00	161.00
Albacete (ES421)	21.31	8.94	−4.40	40.60	46.01	19.43	5.73	190.63	15.73	8.43	2.00	81.00	87.98	29.79	9.00	185.00
Ciudad Real (ES422)	22.09	9.24	−0.20	41.70					12.82	8.59	2.00	50.00	84.34	23.73	15.00	148.00
Cuenca (ES423)	19.86	8.78	0.00	38.40	30.89	16.74	6.00	139.00	21.87	10.52	3.00	66.00	73.73	27.50	3.00	134.00
Guadalajara (ES424)	21.05	8.96	0.10	40.70	29.58	17.76	2.95	247.25	27.33	14.87	2.00	95.68	84.31	35.94	2.00	192.00
Toledo (ES425)	22.48	9.09	−0.40	42.00	39.58	19.27	2.00	206.67	25.27	12.93	2.00	129.83	83.87	34.71	2.00	188.00
Badajoz (ES431)	24.09	8.30	5.40	44.80	18.42	10.86	3.00	126.00	11.46	7.42	2.00	60.78	89.26	24.51	14.00	162.00
Caceres (ES432)	22.17	8.55	3.60	42.60	18.98	9.66	1.00	83.51	12.04	7.69	1.45	57.00	89.81	32.06	2.00	198.00
Barcelona (ES511)	20.62	6.06	2.70	37.30					44.07	19.36	1.38	155.79	42.66	23.62	1.00	119.00
Girona (ES512)	21.30	7.10	2.90	41.20												
Lleida (ES513)	21.75	9.027	−5.80	40.80					25.56	12.91	1.00	108.60	65.16	31.74	2.00	154.00
Tarragona (ES514)	23.61	7.41	1.40	40.00					23.96	10.39	1.48	68.35	75.60	26.86	2.00	162.00
Alicante (ES521)	23.57	5.73	6.50	38.20					34.86	15.36	2.81	103.34	72.90	20.33	6.00	147.00
Castellon (ES522)	22.73	6.15	6.40	40.60					20.80	9.85	4.00	78.25	75.42	23.27	6.00	152.33
Valencia (ES523)	23.18	5.83	5.00	40.30	30.79	13.12	4.00	111.70	54.45	20.25	5.00	129.43	47.34	20.59	3.00	118.00
Almeria (ES611)	23.16	5.58	9.00	40.60	42.15	16.98	9.00	158.00	40.49	14.04	3.04	94.17	73.57	20.80	0.00	149.00
Cadiz (ES612)	21.80	4.96	7.60	38.00									82.30	21.34	19.00	175.00
Cordoba (ES613)	25.40	8.58	5.40	46.20	47.62	23.40	6.50	387.10	35.41	15.13	2.17	121.40	75.93	32.50	4.50	187.50
Granada (ES614)	22.80	8.64	3.00	42.10	42.58	21.69	8.00	338.63	45.02	17.88	7.08	144.33	72.88	30.98	7.00	155.01
Huelva (ES615)	24.14	6.58	7.60	43.80	32.69	15.07	6.00	233.00	20.09	8.44	4.00	69.13	80.68	26.15	11.00	184.00
Jaen (ES616)	21.68	8.48	1.60	41.20	40.29	23.16	5.00	446.13	29.69	14.48	4.58	112.25	86.38	29.44	7.00	173.00
Malaga (E617)	23.61	5.91	9.00	42.00	31.96	17.73	4.00	331.00	36.48	15.86	3.50	95.08	77.07	23.38	50.50	148.50
Sevilla (ES618)	25.74	7.84	6.70	45.20	40.06	16.99	6.00	202.00	47.69	16.66	9.00	139.67	57.99	24.42	4.00	129.00
Murcia (ES620)	22.24	5.19	7.20	40.80	29.40	12.71	7.70	92.00	35.75	15.60	5.00	95.13	77.41	32.17	4.00	153.00

from 2000 to 2009. We compared the performance of two types of drought indices in order to determine which was a better proxy to reflect and estimate the different short-term risks of daily mortality linked with drought episodes. Furthermore, we controlled the effects of climatic extremes strongly associated with droughts, such as heatwaves and atmospheric pollution, on mortality under the occurrence of drought events measured by the SPEI-1 and SPI-1.

According to the main results of this research, negative values of the estimators obtained in the Poisson models indicated higher mortality linked to drought events, since SPEI-1 (SPI-1) values below 0 described drought conditions (Table S1). In agreement with this finding, Berman et al. (2017) described that high-severity worsening droughts measured by the US Drought Monitor from 2000 to 2013 increased the mortality risk in older adults in the western USA. Meanwhile, our results indicated that there was clear spatial heterogeneity in the behaviour patterns of drought events and their effects on daily mortality across Spain during the study period. The western provinces of Spain (northwest, central-west, and southwest) were the most strongly affected regions, as opposed to the provinces located in the north and east of Spain where there was hardly any statistically significant association between drought periods and daily mortality (Fig. 2A). These regional differences obtained in this study may be explained by different factors that could influence the magnitude of health outcomes, such as the geographical location or degree of exposure and intensity of the climatic extreme, because the more severe the drought, the more damage it is expected to cause (Wilhite, 2000; Wilhite et al., 2007; Stanke et al., 2013; Ebi and Bowen, 2016; Salvador et al., 2019b). A recent study conducted in Spain from 1961 to 2014 showed that the southern and central regions of Spain have a higher probability of suffering from extreme drought events compared with the northern and eastern regions of Spain (Domínguez-Castro et al., 2019); this could explain, in part, the greater risks of daily mortality linked to droughts in southern and central Spain. On the other hand, drought conditions in nearby areas can also cause marked differences in health outcomes, because

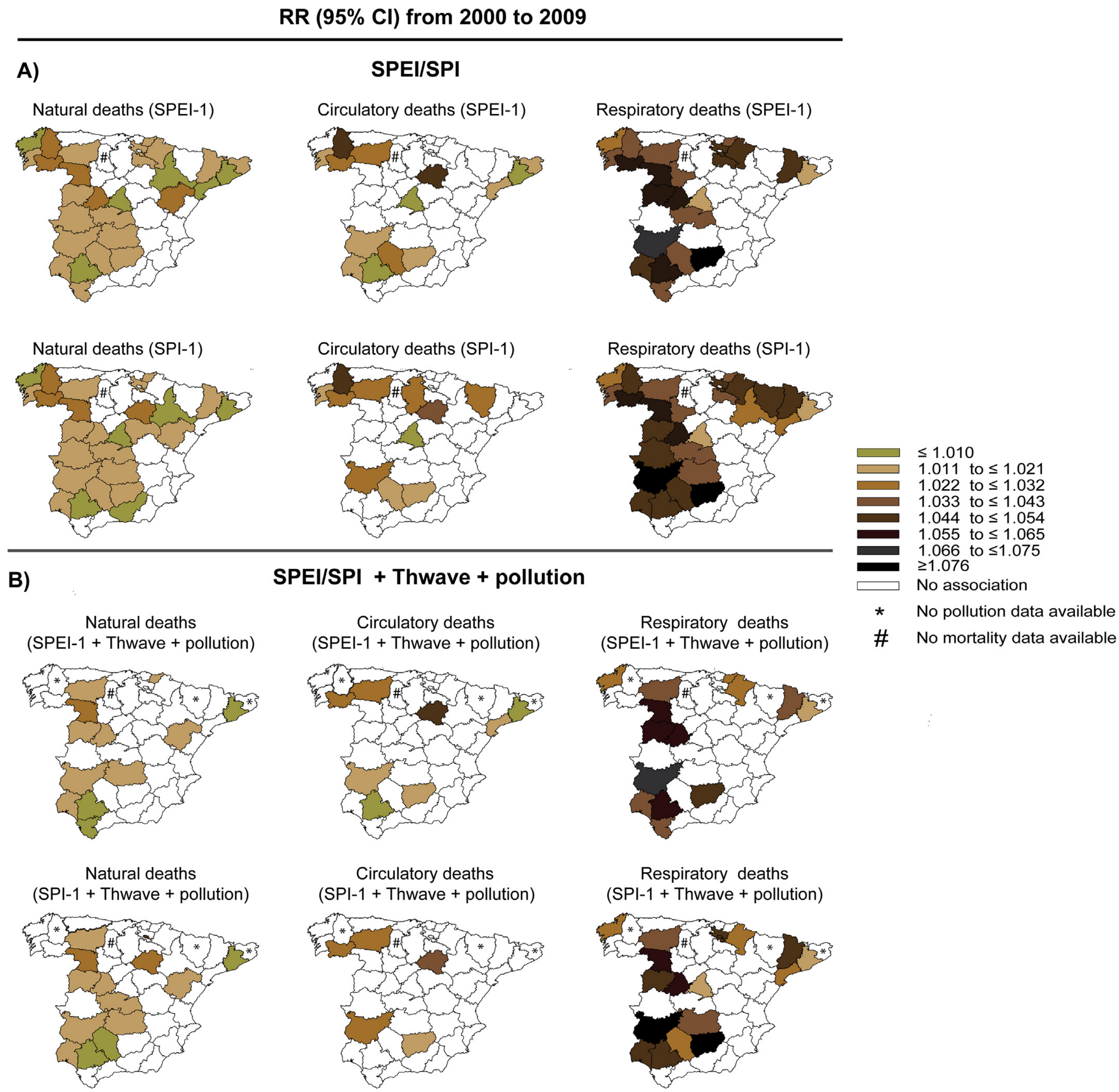

Fig. 2. Illustration of the estimated relative risks (RRs) of daily mortality associated with drought events measured by the Standardized Precipitation Index obtained at 1 month of accumulation (SPI-1) and Standardized Precipitation-Evapotranspiration Index obtained at 1 month of accumulation (SPEI-1) in provinces of peninsular Spain for statistically significant associations between both variables at a confidence level of 95% ($p < 0.05$). RRs of each cause of daily mortality linked to the occurrence of droughts: A) only when the SPI-1/SPEI-1 were considered in Poisson models, and B) when drought indices and both heatwaves and air pollution variables were included in the statistical models. Only provinces with valid values in any pollutants were showed. Provinces without pollution data available were marked with an asterisk (*) and in the case of Palencia, where there was no mortality data, was marked with a hash (#).

there are other factors that could exacerbate the severity of droughts and strengthen the risks related to the incidence of this type of hydrological extreme, such as the degree of sensitivity and adaptive capacity of the population; health status; sex; age; social, economic, and cultural factors; and availability and use of water. Nevertheless, we were unable to control them in this study (Wilhite, 2000; Wilhite et al., 2007; Kallis, 2008; Quiring, 2015; Ebi and Bowen et al., 2016; Salvador et al., 2019a).

The other main finding of this study was that short-term effects of drought events on daily mortality in Spain, as measured by referencing the RR values, were more statistically significant for daily respiratory mortality than for either natural or circulatory mortality during the period of 2000–2009. In addition, our results suggested that for many provinces, drought indices were indirect indicators that reflected the effect of other climatic events strongly associated with droughts, such as atmospheric pollution and/or extreme heat. This was due to the fact that for many provinces, controlling the impact of these climatic events in the Poisson models resulted in statistical significance for T*hwave* and/or atmospheric pollution however, the statistical significance of the SPEI-1 (SPI-1) that was observed previously when we only considered the drought indices in the statistical models, was lost (Fig. 2A and B). However, for other provinces, the statistical significance of drought indices was not lost and the effect of drought events remained similar.

4.1. Atmospheric pollution under drought conditions and the effects on mortality

In this context, droughts are strongly associated with poor air quality (Vicente-Serrano et al., 2020). A study conducted in USA revealed a strongly link between severe droughts and deterioration of air quality through natural processes (enhance of ozone and fine particulate matter with diameters less than 2.5 ($PM_{2.5}$) concentrations) in the growing season (March–October) during 1990–2014 (Wang et al., 2017). In this context, the incidence of this type of hydrological extreme is often accompanied by dust storms and frequently trigger greater occurrence and intensity of wildfires, especially when they occur with high temperatures (He et al., 2014; IPCC et al., 2014; Smith et al., 2014; Bell et al., 2018; Vicente-Serrano et al., 2020). The concurrence of these climatic phenomena can accelerate the development of drought or increase the indirect risks linked to it (Stanke et al., 2013; Salvador et al., 2019a). Dust storms and wildfires are conducive to the increase in toxic compound concentrations in the atmosphere, such as PM, which causes notable harmful effects on respiratory and circulatory health and can lead to premature mortality, especially in vulnerable people (e.g., children, the elderly, and people with pre-existing chronic diseases) (Johnston et al., 2011; IPCC et al., 2014; Reid et al., 2016; U.S. EPA, 2019). Under the conditions of our study, the effect of PM_{10} was specifically significant for daily natural and respiratory mortality (Table S3). It has been described that PM inhalation triggers local inflammation in the lungs, establishment of oxidative and nitrosative stress, as well as cellular toxicity, which can lead to higher risk of death (Ortiz et al., 2017). In Spain, the increased RR (IRR) of daily mortality per 10 μg/m^3 of PM_{10} linked to the biomass combustion of wildfires during 2000–2004 was significant in regions where wildfires were more frequent and were coincident with the most affected provinces in our study, namely, the northwest (IRR: 7.93), centre (IRR: 3.76), and southwest (IRR: 4.46) (Linares et al., 2018a). It should be noted that although the environmental mechanisms that connect forest fires with droughts are complex, several studies, such as some conducted in Spain and Portugal (Iberian Peninsula), showed a clear link between both extreme phenomena, especially when droughts were measured for shorter timescales (Bifulco et al., 2014; Russo et al., 2017; Parente et al., 2019). Parente et al. (2019) described that in Portugal from 1981 to 2017, a large percentage of wildfires occurred during drought episodes measured by the SPI (97%) and SPEI (95%), and the majority of wildfires occurred in a drought area measured by the SPI (SPEI) (Parente et al., 2019). In addition, Bifulco et al. (2014) indicated a statistically significant correlation between the wildfire-burned area in Portugal and drought events measured by the SPI obtained for 1, 3, and 6 months of accumulation.

Meanwhile, droughts have been linked to unfavourable dispersion conditions and persistent blocking situations, which are characterised by an increase in atmospheric pollution, thereby resulting in a higher risk of daily mortality (Hu et al., 2019; Salvador et al., 2019a). The severity of droughts is related to air quality (Wang et al., 2017), and this can be influenced by the occurrence of heatwaves (Vicente-Serrano et al., 2014). In Spain, several studies have shown statistically significant relationships between PM, NO_2, or O_3 and the different causes of mortality analysed during 2000–2009, with daily respiratory mortality being the group most strongly affected and O_3 being the most potentially harmful pollutant in consideration of the RR values (Ortiz et al., 2017; Díaz et al., 2018; Linares et al., 2018b), which was in agreement with our findings (Table S3). The mechanisms associated with the oxidative capacity of NO_2 as well as the cytotoxicity of O_3 are highly dangerous to health (Diaz and Linares., 2018).

4.2. Heatwaves, droughts, and the effects on daily mortality

Droughts can be associated with heatwaves in summer, especially when anticyclone conditions occur, which can exacerbate environmental and social impacts (Stanke et al., 2013). It has been described that 2003 European summer was strongly warmer and dryer, and antyciclonic weather types could have explained dry conditions over central Europe, particularly in spring and summer. This fact caused the reduction of soil moisture and loss of vegetation, which lead to surface conditions that frequently favour high temperatures (Fink et al., 2004). On the other hand, a recent study described that during July 2016 to June 2017 took place one of the most severe drought in Europe, strongly linked to blocking and subtropical ridges, and particularly in Southern European regions high temperatures had an important role in explaining drought and its notable severity. In addition, this heatwave was associated with forest fires in Iberia (García-Herrera et al., 2019). The short-term effects of extreme high temperatures on mortality are well documented (Trigo et al., 2009; Carmona et al., 2016; Bell et al., 2018). In Spain overall, an 11% increase in daily mortality for each degree that the T*max* exceeds the threshold temperature has been described, and high temperatures in the country are generally more strongly associated with daily respiratory mortality than with daily natural or circulatory mortality, being these impacts largely dependent on both the severity of the heat event and the physiological state of the individual (Linares et al., 2017; Bell et al., 2018). Moreover, high temperatures are linked to decreased air quality because they frequently trigger greater O_3 levels (Watts et al., 2017; Zhang et al., 2017), thereby leading to an increased risk of mortality for the exposed population (Filleul et al., 2006; Díaz and Linares, 2018). Meanwhile, due owing to the location of Spain, it can be affected by Saharan dust intrusions, which occur with more frequency during hot days, thereby leading to increased PM concentrations and, consequently, contributing to an increase in the risk of mortality (Díaz et al., 2012, 2017). However, a recent study conducted in the Iberian Peninsula described that Saharan air intrusions played a critical role in the incidence of heatwaves during August 2018 and June 2019, particularly for southern regions (Sousa et al., 2019).

4.3. Other effects of droughts on daily mortality

The impact of mortality attributable to droughts in the provinces where the statistically significant associations between the SPEI-1 (SPI-1) and different causes of death were stable with the control of the impact of T_{hwave} and air pollution could partly reflect other impacts linked to droughts that threaten health but were not controlled, such as impacts on mental health (e.g., psychological stress). In extreme cases, these impacts could result in dysfunction to homeostatic systems, higher risk of circulatory and respiratory diseases, or premature mortality (Berman et al., 2017; Salvador et al., 2019a).

4.4. Comparison of the performance of the SPI-1 (SPEI-1) to estimate the risk of mortality in Spain from 2000 to 2009

We also evaluated, for the first time, the performance of the SPEI and SPI to identify and quantify the risks of different causes of daily mortality in Spain from 2000 to 2009. The results obtained using the SPEI and SPI were generally similar, also observed when both indices were compared for monitoring drought conditions and evaluating the ecological, agricultural, and hydrological impacts linked to this type of hydrological extreme (Vicente-Serrano et al., 2012). However, our results suggested that the SPEI was a slightly better proxy than the SPI for daily circulatory mortality for some provinces, while the SPI was slightly more sensitive at reflecting the risks of droughts related to daily respiratory mortality (Fig. 2). Our hypothesis stated that the mechanisms that link drought events with circulatory and respiratory causes of daily mortality could can be different, and each type of drought index can better reflect certain characteristics that are more sensitive when identifying one type of effect on health. Thus, in future studies, we have proposed evaluating the performance of both types of drought indices considering only summer or winter periods in order to more thoroughly determine which index is a better proxy. Because the SPEI takes into account the temperature variable for its calculation, it might be more sensitive at detecting drought effects linked to warmer months and heatwaves, whereas the SPI could respond better to estimate the risks linked to droughts in other seasons. In future studies, we should also consider other periods of accumulation of the SPEI (SPI) in order to quantify the health risks in the medium- and long-term across different regions. In Spain differences in estimations of drought probability between both types of indices and timescales have been found (Domínguez-Castro et al., 2018), so it is important to evaluate the different response of different environmental and human systems in function to drought scales.

Finally, although we included control variables in the Poisson models, such as the trend, seasonality, and autoregressive nature of the temporal series, there were some limitations that are inherent in any ecological study. First, we could not extrapolate the results at the individual level, and the use of data of atmospheric pollutants that were averaged from various measurement stations signified that the measurements did not represent individual exposure. In addition, the atmospheric pollutant measurement stations were heterogeneous in nature. Meanwhile, there was a problem of misalignment, which was also described in other studies that evaluated the impact of air pollution on health (Gelfand, 2010; Barceló et al., 2016). On the other hand, we have been unable to examine some variables that could affect vulnerability to drought such as individual socioeconomic status, the previous health conditions and adaptive capacity of the population, sex, race and age (Salvador et al., 2019a), showing other limitations of this type of studies.

As has been mentioned throughout this study, there are several health effects associated to drought conditions, revealing the need to promote integrated and proactive measures based on the prevention, mitigation and adaption to drought in terms of reducing health risks. According to the main findings of this study, public health surveillance systems that incorporate indicators that reflect the existent interrelation between different health problems should be articulated. Thus, in the case of drought, action plans against heatwaves as well as against episodic pollution situations should be activated. It is particularly important to have an integrated drawn up action plan that includes strategies and actions that tend to minimize all impacts previously described. Obviously, these surveillance systems and their corresponding action plans, both at national and local levels, must be designed "ad hoc" and must be contextualized to the geographical location and public health characteristics inherent to each population.

In line of public health surveillance systems that integrate multiple factors in relation to climate change, the work of the Public Health Agency of Barcelona are developing a new surveillance system (still under review) on the basis of previous studies conducted in this city (Villalbí and Ventayol, 2016), which includes in the same system a large part of the problems that may affect health, especially in urban population in the current context (Marí et al., 2019).

5. Conclusions

This study revealed the first evidence of short-term risks of drought events on daily natural, circulatory, and respiratory mortality at the national level for Spain from 2000 to 2009, while the effect of other extreme events linked to droughts, such as heatwaves and atmospheric pollution, remained controlled. We also compared the performance of the SPEI and SPI to estimate the risks linked to the occurrence of droughts for the different causes of daily mortality for different situations. The main findings were as follows:

- There were statistically significant associations between the drought conditions measured by the SPEI-1 (SPI-1) and daily mortality in Spain from 2000 to 2009, and the daily respiratory mortality group was the most strongly affected.
- There was clear spatial variability in the magnitude of mortality risks linked to droughts throughout Spain; thus, an independent evaluation for each province was necessary. Generally, provinces located in western Spain (northwest to southwest) were the regions most affected by drought measured by SPEI-1 and SPI-1 in terms of daily mortality, in contrast with the observations in northern and eastern Spain.
- In a considerable number of provinces, drought was mainly an indirect indicator of the impacts of other extreme climatic events, such as atmospheric pollution and/or heatwaves. However, in other regions, the impact on mortality linked to drought conditions measured by the SPEI-1 (SPI-1) remained when we controlled T_{hwave} and pollution variables in the Poisson models.
- The results of this study were very similar when comparing the performance of the SPEI and SPI on the estimation of mortality risk. However, for several provinces the SPEI could be a better proxy for identifying the risks of daily circulatory mortality, while the SPI could better estimate the impacts associated with drought conditions on daily respiratory mortality.
- The introduction of these results as recommendations in public health is necessary to address the risks of droughts on health. In this context, it is necessary drawn up an integrated proactive action plan (at national and local levels) that includes public health surveillance systems against extreme heat temperatures and pollution episodes in terms of minimize the effects on circulatory and respiratory health, which be designed "ad hoc" and contextualized in function of the characteristics inherent to each region and population.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.109200.

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Quantification of the global effects of droughts on daily mortality in Spain at different timescales: A meta-analysis

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Abstract: A performance assessment of two different indices (the Standardised Precipitation Index [SPI] and the Standardised Precipitation Evapotranspiration Index [SPEI]) for monitoring short-term and short–medium term drought impacts on daily specific-cause mortality in Spain was conducted. To achieve a comprehensive, nationwide view, a meta-analysis was performed using a combination of provincial relative risks (RRs). Moreover, the subdivisions of Spain based on administrative, climatic, and demographic criteria to obtain the measures of combined risks were also taken into account. The results of the SPEI and SPI calculated at the same timescale were similar. Both showed that longer drought events produced greater RR values, for respiratory mortality. However, at the local administrative level, Galicia, Castilla-y-Leon, and Extremadura showed the greatest risk of daily mortality associated with drought episodes, with Andalucía, País Vasco, and other communities being notably impacted. Based on climatic regionalisation, Northwest, Central, and Southern Spain were the regions most affected by different drought conditions for all analysed causes of daily mortality, while the Mediterranean coastal region was less affected. Demographically, the regions with the highest proportion of people aged 65 years of age and over reflected the greatest risk of daily natural, circulatory, and respiratory mortality associated with drought episodes.

Keywords: drought; Standardised Precipitation Evapotranspiration Index; Standardised Precipitation Index; meta-analysis; mortality; Spain

1. Introduction

Drought is a complex phenomenon that occurs due to a deficiency of precipitation over an extended period of time. It can be promoted by an increase in evapotranspiration associated with the incidence of high temperatures, strong winds, or low humidity, causing a significant hydrological imbalance (Wilhite, 2000; Haile et al., 2020). It is among the most damaging types of natural disaster. Drought operates in different places and at different timescales, leading to notable impacts on diverse environmental and social sectors (Wilhite et al., 2007; Stagge et al., 2015; Vicente-Serrano et al., 2020) with significant effects on human health, including an increased risk of morbidity and mortality (Stanke et al., 2013; IPCC, 2014; Yusa et al., 2015; Berman et al., 2017; Bell et al., 2018; Watts et al., 2019). The response of environmental systems to the occurrence of this hydrologically extreme phenomenon can vary according to the time period in which it is measured. For this reason, evaluating the performance of different types of drought indices and the sensitivity of the response to different timescales is important for predicting and quantifying drought impacts on a specific system or sector, such as human health.

The Iberian Peninsula in southwestern Europe has particularly suffered from long and severe periods of drought in recent decades (Vicente-Serrano et al., 2020), causing forest reduction, crop yield failures, and severe impacts on the economy (Vicente-Serrano et al., 2017). In this area, drought is described as the main hydroclimatic hazard. According to future climate change projections, droughts in this region are likely to become more frequent and severe by the end of the 21st century (Boersma et al., 2017; Spinoni et al., 2018). Assessments of drought impacts at different timescales have been conducted on several systems in the Iberian Peninsula using variables such as streamflow and reservoir shortages (Vicente-Serrano and López Moreno, 2005; Lorenzo-Lacruz et al., 2013), groundwater level (Lorenzo-Lacruz et al., 2017), vegetation activity (Gouveia et al., 2017), crop productivity (Peña-Gallardo et al., 2019), forest growth (Pasho et al., 2011; Vicente-Serrano et al., 2014), and the occurrence of wildfires and areas burned by them (Bifulco et al., 2014; Russo et al., 2015; Parente et al., 2019). However, analysing the details of the relationship between drought characteristics and health impacts using different indices and different timescales is seldom considered.

At the national level, there is only one recent study, carried out in peninsular Spain from 2000 to 2009, in which the study of the short-term effects of drought conditions were measured. This was determined via the calculation of the relative risk (RR) of drought conditions, measured on a 1-month timescale using the Standardised Precipitation Index (SPI; based on precipitation data) and the Standardised Precipitation Evapotranspiration Index (SPEI; which additionally incorporates temperature data for its calculation, based on the difference between precipitation and evapotranspiration potential). Daily natural (all causes except accidents), circulatory, and respiratory mortality were assessed for each province in the study area (Salvador et al., 2020a). In a regional study conducted in Galicia (Northwest Spain), the first evidence of the relationship between drought and daily mortality rate was gathered using the SPI and the SPEI calculated at 1, 3, 6, and 9 months of drought accumulation (Salvador et al., 2019). In general, shorter timescales (1 and 3 months) reflected the highest drought effects on daily mortality in inland provinces, whereas for coastal provinces, a significant relationship between daily circulatory-caused mortality and drought measured was observed only at longer timescales. Moreover, slight differences were obtained when both types of indices were compared; however, qualitatively, there was variability in the risk magnitude of different causes of deaths linked to drought conditions measured at different timescales. This fact highlights the importance of carrying out a broader analysis, at least for shorter timescales, across Spain.

These previous works highlight that more than one period of accumulation is needed to measure drought, and that to observe and compare its effects, timescales longer than 1 month are required. Thus, considering that daily mortality was found to be mainly influenced by shorter timescales in the regional study of Galicia, the impacts of short–medium term droughts (i.e., those lasting around three 3-months) on daily natural, circulatory, and respiratory mortality were evaluated at the provincial level from 2000 to 2009 in this study. The main objective was to compare different findings to reveal which drought accumulation period had greater influence on the different causes of deaths in each of the 47 peninsular provinces of Spain (Figure 1). Moreover, the combination of the provincial RRs of daily mortality linked to drought, according to broader territorial spatial groups and overall for peninsular Spain, was also considered using a meta-analysis of random effects. This allows for attaining a comprehensive view of the effects for the entire the country.

In climatological terms and in terms of drought occurrence, the Iberian Peninsula is a region with marked spatial differences in the frequency, average duration, and magnitude of drought episodes, with strong north–south and west–east gradients. In general, drought frequency is higher in the North than in the South, whereas the average duration and magnitude of droughts are much higher in the Central and Southern regions (Domínguez-Castro et al., 2019a, b). Following Vicente-Serrano (2006), peninsular Spain was divided according to six different drought spatial patterns on shorter timescales (1 and 3 months) based on a principal component analysis. Monjo et al. (2020) recently characterised meteorological droughts from south to north as a function of the longitude of alternating dry and wet periods. The South is where long dry spells alternate with short wet events, and the North is where median dry spells alternate with longer wet spells. Furthermore, Northwest Spain shows the highest frequency of flash-droughts (i.e., drought events which develop rapidly). However, these events show a decreasing trend in this region over the last six decades. In contrast, the Central and

Southern regions show a lower frequency, but positive trends (Noguera et al., 2020). On the other hand, the spatial distribution of drought in the Iberian Peninsula varies in function according to the timescale used for its measurement, i.e., its complexity increases on longer timescales (Vicente-Serrano, 2006).

Furthermore, it is known that the distribution of demography in terms of age exacerbates the different causes of mortality and morbidity rates, including those linked to extreme climatic events such as droughts (e.g., IPCC, 2014). Spain presents a regressive or bulb-shaped population pyramid. The Northwest territories are where the highest proportion of ageing people are concentrated (INE, 2019).

Thus, the combination of criteria for the meta-analysis used in this study is based on three different motivations with diverse aims: i) to develop a perspective on the effects of drought at a higher administrative division than provinces, namely Autonomous Communities, which are needed as the basis for future decision making for public health policy across the country; ii) with a climatological aim, to quantify the combined relative risks of daily mortality taking into account the drought spatial patterns (Vicente-Serrano, 2006); and iii) to generate evidence of the influence of age on mortality due to droughts for those groups of provinces with a higher proportion of people aged 65 and over.

SUBDIVIDISION OF PENINSULAR SPAIN ACCORDING TO THE EUROPEAN NUTS ADMINISTRATIVE REGIONS

AUTONOMOUS COMMUNITIES (NUTS2)	Provinces (NUTS3)
GALICIA (ES11)	A Coruña (ES111), Lugo (ES112), Ourense (ES113, Pontevedra (ES114)
PRINCIPADO DE ASTURIAS (ES12)	Asturias (ES120)
CANTABRIA (ES13)	Cantabria (ES130)
PAIS VASCO (ES21)	Alava (ES211), Guipuzcoa (ES212), Vizcaya (ES213)
COMUNIDAD FORAL DE NAVARRA (ES22)	Navarra (ES220)
LA RIOJA (ES23)	La Rioja (ES230)
ARAGON (ES24)	Huesca (ES241), Teruel (ES242), Zaragoza (ES243)
COMUNIDAD DE MADRID (ES30)	Madrid (ES300)
CASTILLA Y LEON (ES41)	Avila (ES411), Burgos (ES412), Leon (ES413), Palencia (ES414), Salamanca (ES415), Segovia (ES416), Soria (ES417), Valladolid (ES418), Zamora (ES419)
CASTILLA LA MANCHA (ES42)	Albacete (ES421), Ciudad Real (ES422), Cuenca (ES423), Guadalajara (ES424), Toledo (ES425)
EXTREMADURA (ES43)	Badajoz (ES431), Caceres (ES432)
CATALUÑA (ES51)	Barcelonaa (ES511), Girona (ES512), Lleida(ES513), Tarragona (ES514)
COMUNIDAD VALENCIANA (ES52)	Alicante (ES521), Castellon (ES522), Valencia (ES523)
ANDALUCIA (ES61)	Almeria (ES611), Cadiz (ES612), Cordoba (ES613), Granada (ES614), Huelva (ES615), Jaen (ES616), Malaga (ES617), Sevilla (ES618)
REGION DE MURCIA (ES63)	Murcia (ES620)

Figure 1. Administrative subdivision of peninsular Spain. The provincial and autonomous communities used correspond to levels 2 (NUTS2) and 3 (NUTS3) of the European nomenclature of territorial units, respectively. The NUTS3 provinces are shown on the map, with their names and the names of the corresponding NUTS2 Autonomous Communities listed in the box on the right.

2. Material and methods

2.1. Variables

The dependent variables used corresponded to the daily natural (ICD10: A00-R99), circulatory (ICD10:I00-I99), and respiratory (ICD10: J00-J99) mortality for each province of peninsular Spain (Figure 1) from 2000 to 2009. ICD10 codes refer to the 10th revision of the International Statistical Classification of Diseases and Related Health Problems. Mortality is represented by the number of deaths in the capital city and towns with over 10,000 inhabitants, and it was provided by the National Institute of Statistics (INE) of Spain. No mortality data were available for Palencia province (NUT3 ES414) or Madrid (NUT3 ES300) for 2000.

The independent variables used were two multi-scalar drought meteorological indices: the SPI (McKee, 1993) and the SPEI (Vicente-Serrano et al., 2010). Drought conditions were identified by both indices as values less than 0; the change to a positive value indicated the end of the drought event. Data for both drought indices for 1-month (short-term) and 3-months (short-medium term) of accumulation (denoted as SPI-1/SPEI-1 and SPI-3/SPEI-3, respectively) were obtained from the Spanish National Research Council (CSIC) website http://monitordesequia.csic.es (see Vicente-Serrano et al., 2017), at a weekly resolution. These drought series are based on a standard normal variable; therefore, both can be compared in time and space across different timescales (Vicente-Serrano, 2010). Following the methodology developed in previous studies (Salvador et al., 2019, 2020a), we constructed daily series assuming the same conditions for each seven-day interval. Moreover, other control variables such as the trend (considering n1=1 for the first day of the series and n1=2 for the second day and so one to the end of the series), the autoregressive nature of the dependent variable, and the seasonality (through sine and cosine functions for the annual [360-day], half-yearly [180-day], four monthly [120-day], quarterly [90-day], and bimonthly [60-day] periodicities) were also taken into account.

2.2. Statistical analysis

The purpose of this meta-analysis study was to develop a broader view on the RRs of daily specific-cause mortality associated with different drought conditions beyond a provincial (i.e., relatively small) area effect and to compare the findings obtained to the use of different timescales for SPEI and SPI. The individual provincial RR results due to SPI-1/SPEI-1 for each province from 2000 to 2009 were published by Salvador et al. (2020a). Applying the same methodology, the RRs of mortality linked to drought over the short–medium term, measured by SPI-3/SPEI-3, were quantified based on generalised linear models with the Poisson regression link. As SPEI/SPI have negative values for the drought periods, the negative coefficients obtained in the Poisson models were those that were taken into consideration. Then, from the magnitude of these coefficients in absolute value, the RR of daily mortality was calculated for each unit of increment of both drought indices over the short- and short–medium timescales. Thus, the RR shows the increase in daily mortality risk associated with the increase in drought severity in the exposed population relative to the unexposed population.

To determine the significant variables, the “backward-step procedure” was carried out, beginning with the model that included all explanatory variables (independent and control variables), removing gradually and individually those that displayed least statistical significance until a model with only statistically significant variables at $p<0.05$ was obtained. Single models for independent SPEI-3/SPI-3 series and for the different causes of daily mortality were conducted.

Moreover, the RRs for each province yielded by the Poisson models were combined by means of a meta-analysis of random effects to obtain the overall value for peninsular Spain. A measure of the RRs (95% CI) according to the different criteria of spatial grouping (administrative, climatic, or demographic) was also obtained. This method incorporated an estimation of variability, namely inter-studio heterogeneity (Sterne, 2009).

3. Results and discussion

3.1. RR of mortality associated with droughts by Spanish administrative division

The RR values of daily mortality associated with the occurrence of drought, as measured by the different timescales for peninsular Spain as a whole from 2000 to 2009, are shown in Table 1. A significant relationship between drought episodes and all analysed causes of daily mortality, independent of the type of index (SPEI or SPI) and timescale (1 or 3 months), was found. The results obtained using both indices at the same timescale were generally very similar; moreover, differences in the magnitude of daily mortality risks associated with the use of the different timescales for SPEI and SPI were found, although the differences were not significant. The highest impact was found for respiratory deaths, especially from short–medium term drought events. Meanwhile, for circulatory deaths, the RR values were similar under different drought conditions, reflecting SPI-1 a higher RR value. In the case of natural deaths, greater RR values were obtained for short–medium term droughts. Figures S1-S9 in the Supplementary Material list all RR values with their respective 95% confidence intervals.

	SPEI-1	SPI-1	SPEI-3	SPI-3
Natural deaths	1.014 (1.012, 1.016)	1.014 (1.011, 1.016)	1.017 (1.014, 1.020)	1.017 (1.014, 1.020)
Circulatory deaths	1.019 (1.014, 1.025)	1.023 (1.016, 1.031)	1.021 (1.015, 1.027)	1.021 (1.015, 1.026)
Respiratory deaths	1.043 (1.035, 1.052)	1.041 (1.034, 1.048)	1.053 (1.043, 1.062)	1.054 (1.045, 1.063)

Table 1. Overall relative risk (RR) values and their respective 95% confidence intervals of daily specific-cause mortality associated with drought measured by the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI), calculated at 1 and 3 months of accumulation (SPEI-1/SPI-1 and SPEI-3/SPI-3, respectively) across peninsular Spain from 2000 to 2009.

Although the results obtained at a nationwide level show an overall perspective and reflect the main evidence, evaluation at the provincial and Autonomous Community levels identified additional differences and heterogeneity throughout the country. As mentioned previously, the RRs' for each province for 1-month of accumulation were calculated by Salvador et al. (2020a). Although the overall RRs values at 3-months were similar (SPEI-3 *vs* SPI-3), when a provincial analysis was conducted for 3-months of accumulation, some differences were found, namely that SPI was generally slightly better for detecting mortality risk for several provinces than SPEI. Figure 2 shows a comparison of the RRs for daily natural, circulatory, and respiratory mortality associated with drought conditions measured by SPEI/SPI and calculated at 1 and 3 months of accumulation. The highest impact of drought observed was on respiratory deaths. Moreover, in the majority of cases, the RR values were higher (or similar) under short–medium term drought conditions than under short-term conditions. Although the difference was not significant, this increase in risk is remarkable, especially for respiratory mortality in those provinces ocated in Western Spain. However, there were particularities where daily mortality was mainly manifested by one type of index (or timescale) rather than the other. For instance, in many provinces located in Northeast Spain, mortality was mainly influenced by short-term drought events because the significant relationship between drought and mortality was lost when this hydrological extreme was measured over the short–medium term. Meanwhile, it should be noted that although the overall RR value of natural and respiratory deaths was qualitatively greater under longer drought events, the number of statistically significant provinces was lower with the use of SPEI-3 for natural deaths and SPI-3 for respiratory deaths in comparison with that obtained via the use of SPEI-1 and SPI-1, respectively. However, in the case of circulatory mortality, an increase in the number of affected provinces was found, particularly for SPI-3.

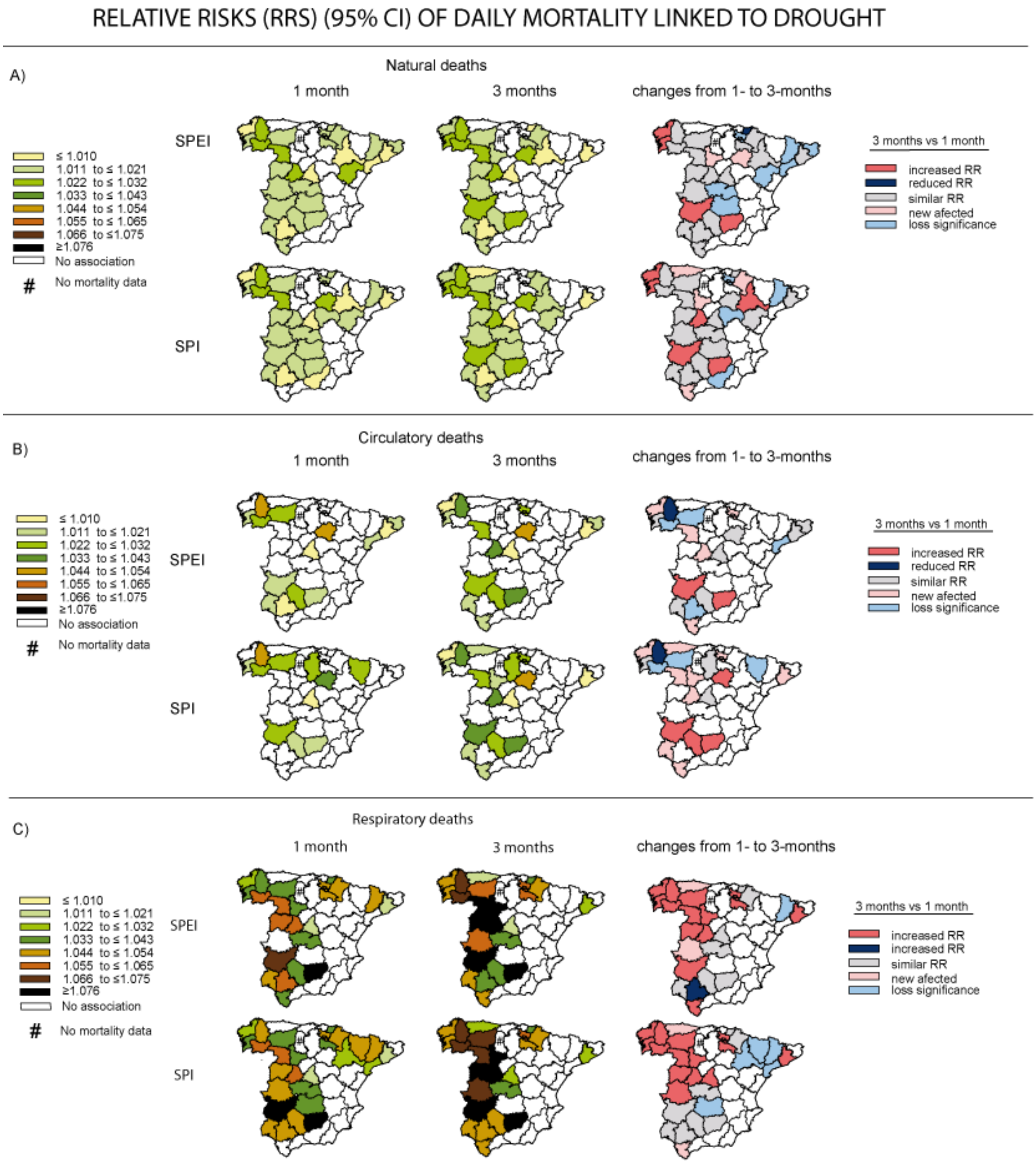

Figure 2. Relative risk (RR) values for daily specific-cause mortality linked to droughts measured by the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardised Precipitation Index (SPI) for natural, circulatory, and respiratory deaths calculated for short (1 month; left-hand column) and short–medium (3 months; central column) timescales. The right-hand column provides a comparison of the differences among them. RR values for SPEI-1 and SPI-1 are taken from Salvador et al. (2020a). Complete statistical information is provided in the Supplementary material (Tables S1–S3).

As Spain is administratively divided in intermediate territorial areas termed Autonomous Communities, the RRs levels were obtained for each. This will provide useful information for public health administrations as it is extremely important to know the mortality risk factors of the population in order to implement action plans and make appropriate management decisions.

As the management of public health has been delegated by the National Government to the Autonomous Communities, Figure 3 shows the combined provincial RR values for daily natural, circulatory, and respiratory mortality linked to different drought conditions at the Autonomous Community level. The main findings indicate that, in general, Galicia, Castilla-y-León, and Extremadura (northwest and west

Iberian Peninsula) show the greatest risk of daily mortality linked to drought conditions. All three have RR values above the overall value for the country, except Galicia for respiratory deaths when drought was measured over the short-term. Particularly, in Castilla-y-León, a significantly greater impact on respiratory deaths was observed for short–medium term droughts than for short-term droughts, as measured by SPI (SPI-3 vs SPI-1; Figure S3 in the Supplementary Material). Other autonomous communities such as País Vasco (principally for circulatory mortality associated with drought episodes measured in the short–medium term), Andalucía and Navarra (for respiratory deaths),and La Rioja (for respiratory mortality linked to short–medium term droughts) were also notably impacted. In contrast, the lowest RR values due to any analysed cause of death were found in the Comunidad de Madrid, Cataluña, and Principado de Asturias. Meanwhile, drought events were not found to have any influence on daily mortality in Cantabria, or Murcia or Comunidad Valenciana on the Mediterranean coast. It should be noted that there were differences (although not significant) in the magnitude of the risks in some of the Autonomous Communities according to the index, timescale, and cause of death analysed, particularly for circulatory and respiratory deaths. For instance, in Galicia, shorter droughts reflected a higher impact on circulatory mortality than short–medium term ones, contrary to what was observed for respiratory deaths. In Extremadura, the shortest timescale of SPEI (SPEI-1) showed a higher risk for respiratory deaths than SPEI-3. Conversely, the SPI-3 calculated greater impact on respiratory mortality than SPI-1 for this region.

3.2. RR of daily mortality associated with climatological spatial patterns of droughts

As previously mentioned, the behaviour of droughts varies according to region. For this reason, the known spatial distribution pattern of drought indices across Spain (Vicente-Serrano, 2006; Domínguez-Castro et al., 2019a) were additionally analysed to produce a climatological point of view of the RRs of daily mortality linked to drought. Figure 4 shows the combined provincial RR values of daily specific-cause mortality linked to the occurrence of droughts grouped according to the spatial distribution of drought indices described by Vicente-Serrano (2006) and obtained at shorter timescales. Figures S4-S6, in the supplementary material show the combined RRs of the different causes of daily mortality associated with drought by the climatic regionalization with their respective 95% confidence intervals. The provinces were grouped into six regions, which are the most similar to the six spatial patterns of drought across Spain The main findings demonstrate that droughts had a significant influence on daily mortality in all regions except East Spain, where there was no significant relationship between this phenomenon and any cause of mortality (no province in this region had a significant RR value). In contrast, Northwest, Centre, and South were the most affected regions under the different drought conditions. That is, in qualitative terms, the Northwest had a higher RR value than the RR value for peninsular Spain for natural and circulatory causes of mortality and the South had a higher value than that of peninsular Spain for respiratory deaths.

For natural deaths, the highest impact was observed in the Northwest (especially remarkable for three months of accumulation) and the South using both types of indices, followed by Centre when droughts were measured at the short–medium term. Contrarily, the Northeast was the region least affected.

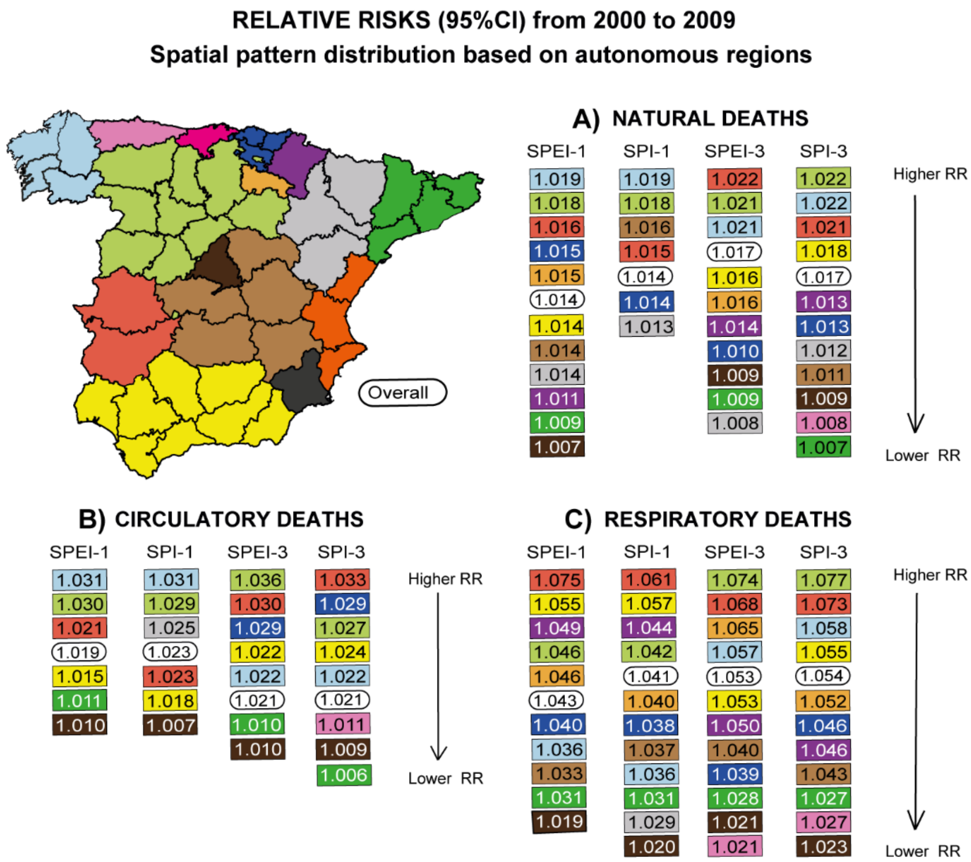

Figure 3. Combined provincial relative risk (RR) values of daily specific-cause mortality associated with drought for each Autonomous Community and overall for peninsular Spain from 2000 to 2009, as measured by the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardised Precipitation Index (SPI) calculated for short and short–medium timescales (1 and 3 months of accumulation, respectively). Complete statistical information is provided in the Supplementary material (Tables S1–S3).

For daily circulatory-caused mortality, the Northwest (mainly for short-term drought events) as well as Central and Southern regions (mainly for short-medium drought conditions) were the territories most affected. The lowest influence of drought on daily-circulatory deaths was evidenced in the Northeast and the North, except when drought episodes were measured by SPI-1 and SPEI-3, respectively. Meanwhile, the greatest RR values of daily respiratory mortality measured by SPEI-1 and SPI-1 were found in the South, North, and Northwest; whereas they were found in the Northwest, South, and Central regions for SPEI-3 and SPI-3. In addition, the RRs of respiratory mortality associated with drought episodes in the Northwest were significantly higher for short–medium-term droughts measured by both indices than for short-term droughts (Figure S6 in the Supplementary Material). Again, Northeast Spain was the region least impacted by droughts in terms of respiratory mortality risks.

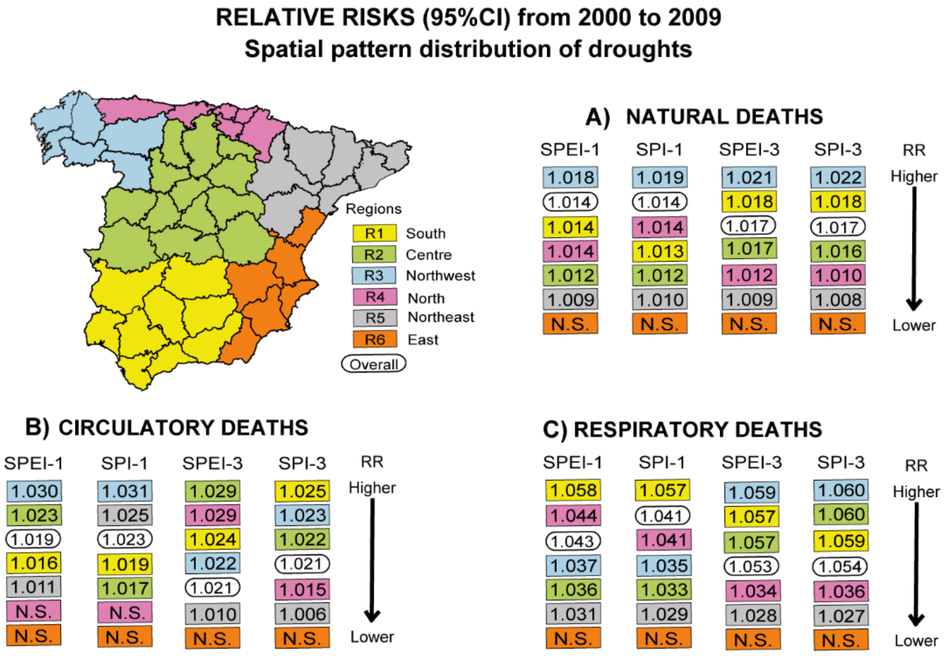

Figure 4. Combined provincial relative risk (RR) values of daily specific-cause mortality associated with drought for different spatial patterns of drought distribution and overall for peninsular Spain from 2000 to 2009, as measured by the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardised Precipitation Index (SPI) obtained for short and short—medium timescales (1 and 3 months of accumulation, respectively). Complete statistical information is provided in the Supplementary material (Tables S4—S6).

3.3. RR of daily mortality associated with droughts based on demography

Annual demographic data of the population of each province from 2000 to 2009 was obtained from the INE (INE, 2020). Each province was categorised into one of the following four groups according to whether the population aged 65 years old and over represented: (1) 11–15% of the population (8 provinces), (2) 16–19% of the population (23 provinces), (3) 20–23% of the population (9 provinces), or (4) 24–28% of the population (7 provinces; Figure 5). The combined RRs of the different analysed causes of mortality measured by both SPEI and SPI at short- and short–medium terms were then obtained according to the above defined groups (Figure 5 and Figures S7-S9). The main findings obtained indicate that the group of provinces with the highest proportion of people aged 65 years old and over had the greatest risk of mortality linked to the occurrence of drought episodes both at short- and short–medium timescales. The impacts were found to be higher for short–medium term drought events (being significant the difference at the 95% level of confidence using SPEI and with a significant trend using SPI for respiratory mortality). Moreover, in the areas with the lowest proportion of people aged 65 years old and over, the lowest RR values were generally observed (with some exceptions, principally for circulatory deaths). Those provinces with the lowest proportion of people aged 65 years old and over (e.g., Madrid, Murcia, Malaga) were the least affected. Meanwhile, the results obtained through the use of SPEI and SPI obtained at the same timescale were very similar. It is notable that some of the most drought-prone regions, which show the highest mortality, also coincide with the regions with ageing populations (e.g., Northwest Spain, where the majority of provinces have a high proportion of people over the age of 65). East Spain was the climatological region least affected in terms of mortality, and with fewer people aged 65 years or older. However, for Southern Spain as a whole, which also contained a majority of provinces with the lowest proportion of people aged 65 years or older, was a climatological region notably impacted by drought on mortality. It should be noted that this analysis considers age to be a factor that can influence drought risk on population health; thus, based on this first approach, more exhaustive and direct analyses that take into account different age groups should be conducted in the future.

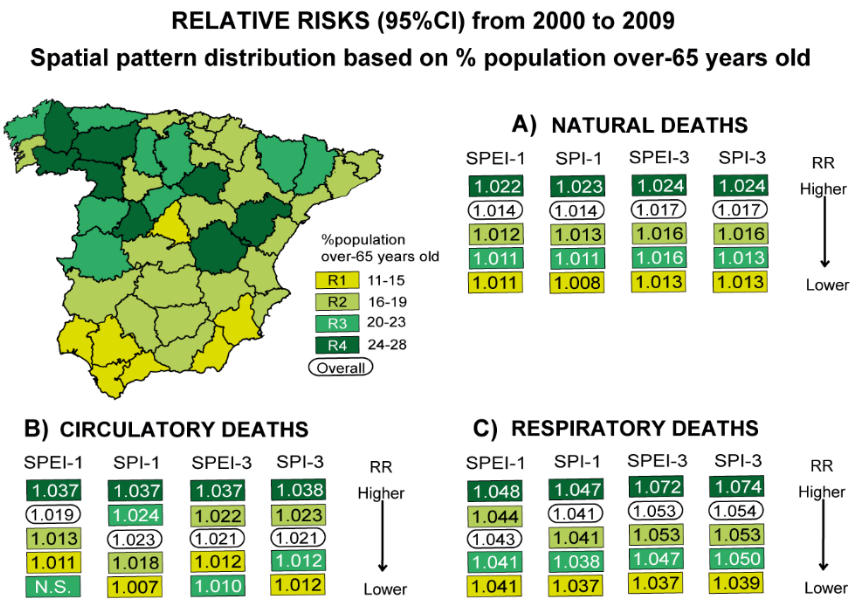

Figure 5. Combined provincial relative risk (RR) values of daily specific-cause mortality associated with drought in different territories based on the proportion of people aged 65 years and over from 2000 to 2009, measured by the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardised Precipitation Index (SPI) obtained for short and short–medium timescales (1 and 3 months of accumulation, respectively). Complete statistical information is provided in the Supplementary material (Tables S7–S9).

4. Conclusions

This study found that in peninsular Spain, drought events are associated with daily natural, circulatory, and respiratory causes of mortality, with the highest impact found on respiratory deaths. In the majority of cases, short–medium term drought events reflected higher (or similar) impacts more than short-term ones. Given that drought effects on cardiorespiratory conditions are principally indirect through reduced air quality (Stanke et al., 2013; Sena et al., 2015; Ebi and Bowen, 2016; Bell, 2018; Salvador et al., 2020b), this phenomenon could be exacerbated by longer drought conditions, reflecting greater impact on mortality than short-term droughts. Meanwhile, the overall RRs of the different causes of mortality analysed for peninsular Spain overall were similar when SPEI and SPI, calculated at the same timescale, were compared. This suggests that a deficiency in precipitation was the most influential variable in the estimation of drought effects on the different causes of deaths and the atmospheric evaporative demand had a minor role (the differences between the indices are reflected by the potential evapotranspiration). Therefore, for this region as a whole, either index can be used to measure links with the risk in daily mortality. Using either index, regional differences were observed, which could be associated with the specific characteristics of each region. This shows that an assessment at different regional levels is essential for this type of study.

The main findings obtained through the analysis from a public health point of view (at the administrative level) suggest that the Autonomous Communities located in Northwest and West Spain shown the greatest risk of daily mortality associated with the occurrence of drought conditions, followed by other Autonomous Communities such as Andalucia or Pais Vasco, which were also notably impacted. Based on the climatic regionalisation of peninsular Spain, the Northwest, Central, and Southern regions were most affected in contrast to that observed in the Mediterranean coastal regions. Differences in drought characteristics across peninsular Spain could account for the higher impact of drought on mortality in the previous cited regions. Meanwhile, from a demographic point of view, the region that included those provinces with the highest proportion of people aged 65 years and over showed the greatest risk of daily, natural, circulatory, and respiratory mortality associated with the occurrence of this hydroclimatic hazard. This may be linked to the fact that the elderly are particularly vulnerable to environmental stress, which makes them the a group of a greater risk of morbidity and mortality associated with the occurrence of extreme climatic events. These findings highlight the need to conduct further assessments considering more different age groups.

Acknowledgments

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Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: risks assessment by gender and age groups

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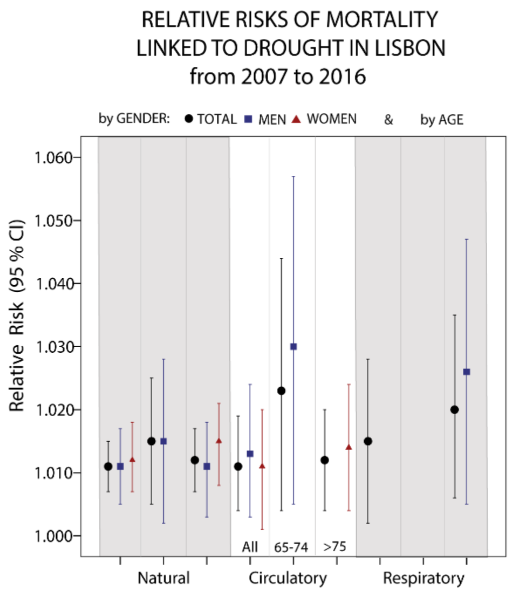
HIGHLIGHTS

- Drought had influence on daily mortality in Lisbon from 1983 to 2016 (and 2007-2016)
- SPEI showed an improved capability to reflect mortality risks as compared with SPI
- The oldest population groups had the highest risks of mortality linked to drought
- There were differences in mortality risks linked to drought between men and women
- Droughts largely reflected the effect of air pollution and heatwaves on mortality

Keywords

Drought
Lisbon
Daily specific-cause mortality
Age group
Gender assessment

GRAPHICAL ABSTRACT



ABSTRACT

Portugal (Southwestern Europe) experiences a high incidence of dry hazards such as drought, a phenomenon that entails a notable burden of morbidity and mortality worldwide. For the first time in the Lisbon district, a time-series study was conducted to evaluate the impact of drought measured by the Standardised Precipitation Index (SPI) and Standardised Precipitation-Evapotranspiration Index (SPEI) on the daily natural, circulatory, and respiratory mortality from 1983 to 2016. An assessment by gender and adult age population groups (45–64, 65–74, >75 years old) was included. To estimate the relative risks and attributable risks, generalised linear models with a Poisson link were used. Additionally, the influence of heatwaves and atmospheric pollution for the period from 2007 to 2016 (available period for pollution data) was considered. The main findings indicate statistically significant associations between drought conditions and all analysed causes of mortality. Moreover, SPEI shows an improved capability to reflect the different risks. People in the 45–64 year-old group did not indicate any significant influence in any of the cases, whereas the oldest groups had the highest risk. The drought effects on mortality among the population varied across the different study periods, and in general, the men population was affected more than the women population (except for the SPEI and circulatory mortality during the long study period). The short-term influence of droughts on mortality could be explained primarily by the effect of heatwaves and pollution; however, when both gender and age were considered in the Poisson models, the effect of drought also remained statistically significant when all climatic phenomena were included for specific groups of the total population and men. This type of study facilitates a better understanding of the population at risk and allows for the development of more effective measures to mitigate the drought effects of the population.

1. Introduction

In the Iberian Peninsula, drought is a common hydroclimatic extreme (Lorenzo-Lacruz et al., 2013; Coll et al., 2017; Vicente-Serrano et al., 2017) that has become more severe in recent decades (Vicente-Serrano et al., 2014; Andrade and Belo-Pereira, 2015); this will likely continue to increase in both frequency and severity with climate change (Mishra and Singh, 2010; Ebi and Bowen, 2016; Spinoni et al., 2018). This phenomenon impacts the environmental, economic, ecological, and social sectors at both the global and regional scale (Wilhite and Vanyarkho, 2000; Quiring, 2015) through negative effects on the quality, structure, and diversity of systems such as soil, air, vegetation, and water (Vicente-Serrano et al., 2020). This also negatively impacts public health, being responsible for a notable burden of morbidity and mortality worldwide (Yusa et al., 2015; Alpino et al., 2016 Watts et al.,2017; Salvador et al., 2020a). Although the majority of drought-related fatalities occur in developing countries, wealthy countries can also indirectly suffer the negative health effects of droughts associated with heat stress, atmospheric pollution, and economic impact, including cardiorespiratory diseases and mortality (UNDRR, 2019; Salvador et al., 2020a). However, the estimation of their consequences is difficult owing to the complexity in the quantification of drought severity, the determination of the beginning and end of the events, and because their effects are principally diffuse, indirect, and cumulative (Stanke et al., 2013; Salvador et al., 2020a; Sutanto et al., 2020; Vicente-Serrano et al., 2020). Moreover, different types of droughts can be distinguished (Marcos Valiente, 2001; Kallis, 2008; Mishra and Singh, 2010), which can affect human health differently.

Drought indices are crucial tools for monitoring and characterising this climatic extreme (Quiring, 2009) and quantifying the different impacts (Bachmair, 2016; Vicente-Serrano et al., 2012; Vicente-Serrano et al., 2017; Parsons et al., 2019). Thus, studies that are focused on the assessment of the capacity of different drought indices to quantify health effects, and the determination of which of these are the best proxies to reflect the occurrence of specific impacts in public health are needed (Salvador et al., 2020a). In Europe, and in particular in the Iberian Peninsula, only two recent studies conducted in Spain have attempted to evaluate the performance ability of two meteorological drought indices (the Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI)) to identify and quantify the impact on daily natural, circulatory, and respiratory mortality (Salvador et al., 2019; Salvador et al., 2020b). The main findings of these studies suggested small differences in the comparative performance of the SPI and SPEI; however, additional studies are required to obtain conclusive results worldwide. Specific differences were observed in terms of geographical distribution and higher risks of mortality, western Spain (northwest to southwest) being the most affected region. Moreover, in NW Spain, the mortality risk increased more strongly in the inland areas and was manifested primarily when droughts were measured by shorter accumulation periods (Salvador et al., 2019).

On the other hand, another recent study conducted in the Western USA indicated an association between drought severity and the increase of mortality risk in older people in the period from 2000 to 2013, and suggested that in countries that previously suffered a fewer number of drought events, the population had a greater risk of cardiovascular diseases and mortality. However, that study surprisingly indicated a reduction of respiratory hospital admissions associated with drought periods (Berman et al., 2017). Conversely, the recent study of Salvador et al. (2020b) evidenced the highest risk of drought events on daily respiratory-caused mortality compared to natural and circulatory mortality in peninsular Spain. Other studies have indicated negative respiratory repercussions associated with drought conditions (Smith et al., 2014; Yusa et al., 2015; Alpino et al., 2016). Machado-Silva et al. (2020) indicated an increase of respiratory hospital admissions during drought episodes, except for a decrease in asthma.

Portugal is a western region of the Iberian Peninsula prone to drought (Pires et al., 2010) that suffers from a high exposure to intense heatwaves; these are frequently the main factors contributing to a higher risk of wildfires (Parente et al., 2018), which are associated with the exacerbation of cardiovascular and respiratory diseases and premature mortality from wildfire smoke (Franchini and Mannucci, 2015; Black et al., 2017, Machado-Silva et al., 2020). Extreme heat temperatures have caused notable effects on mortality in this country (e.g., in the 2003 European heatwave, there was an estimated increase of 58% of the expected death, women and older adults being the most affected groups) (Trigo et al., 2009). In this context, different vulnerabilities to extreme climatic events among the exposed population have been suggested. Agricultural rural workers, children, older people, woman (particularly pregnant), and people with low economic status, with chronic diseases or cognitive constraints are considered the most susceptible groups (Alderman et al., 2012; Ebi and Bowen, 2016; Linares et al., 2017; Salvador et al., 2020a). However, it should be noted that the relationship between gender and vulnerability is complex, unclear, and describes a regional variability (IPCC, 2014).

In Portugal, the impact of drought on health remains unexplored. This study suggests the first detailed evidence of the link among drought phenomena measured over shorter time scales and specific-cause mortality in the district of Lisbon in a context of climate change, considering an assessment by gender and age groups of the population. This can be helpful to obtain specific information on the structure of the population at risk and determinate the most vulnerable groups. Subsequently, the control of the short-term effects of heatwaves and atmospheric pollution on daily mortality were also included under the control of drought conditions measured over the short term.

2. Material and methods

2.1. Region of study: district of Lisbon, Portugal

Continental Portugal is located in the western part of the Iberian Peninsula. In this territory there is a marked variability in the spatial distribution of mean annual precipitation between the north (rainier regions) and south (dryer regions) and between the inland and coastal areas (Trigo and Dacamara, 2000; Santos et al., 2011). The weather conditions in Portugal are strongly influenced by both the position and magnitude of the Azores anticyclone, the effect of the Atlantic Ocean, and the influence of the Mediterranean Sea and North Africa (Parente et al., 2018). Among the eighteen districts that form continental Portugal, the Lisbon district (central Portugal) is the region of this study (38.72 latitude, -9.14 longitude, with approximately 2,272,222 residents). This area was strategically chosen because it includes the homonymous capital city of the country, which is the largest urban city in Portugal, with the highest population density (over 507,220 inhabitants) (National Statistical Institute/Instituto Nacional de Estatística, INE, 2019). It frequently experiences high temperatures owing to the urban heat island and strong exposure to pollution, which cause negative effects on health (Alcoforado et al., 2005; Casimiro et al., 2006; Trigo et al., 2009; Alves et al., 2010; Russo et al., 2014).

2.2. Dependent variables

The number of daily natural (ICD10: A00-R99), circulatory (ICD10: I00-I99), and respiratory (ICD10:J00-J99) deaths were recorded in the district of Lisbon from 1983 to 2016; these were provided by the National Institute of Statistics in Portugal. Moreover, the daily mortality data series was divided by gender obtaining the following groups: *total* (referring to the total population), *men*, and *women*, which were additionally separated by age group (0–9, 10–44, 45–64, 65–74, and >75 years old).

2.3. Independent variable: drought indices

The SPI developed by McKee et al. (1993) and SPEI defined by Vicente-Serrano et al. (2010) were used to monitor the drought events. Both indices have the advantage of being multiscalar, allowing the identification of different types of droughts and reflecting the responses of different systems based on several water deficit accumulation periods (Quiring, 2009; Vicente-Serrano et al., 2012; Stagge et al., 2015). The SPI is calculated from precipitation data and is based on the probability of precipitation for a specified time scale that is transformed to a standard normal distribution, with an average of zero and a standard deviation of one. The SPEI is calculated in a similar manner to the SPI. However, it is based on the climatic water balance, considering both precipitation and temperature variables (through the difference between precipitation and potential evapotranspiration) (Vicente-Serrano et al., 2010; Vicente-Serrano et al., 2012; Parsons et al., 2019). Thus, these indices can identify both wet (positive values of the series) and dry (values of the series below zero) events. Furthermore, the more negative the values of the SPEI/SPI, the more severe the drought conditions.

The time resolution of both drought indices is normally presented on a monthly scale. However, following studies by Berman (2017) and Salvador (2019; 2020b) in this type of analysis, linking droughts and health effects, the scale used was weekly (each month was divided into four periods as in Vicente-Serrano et al. (2017). In this study, the weekly data series of precipitation, and maximum and minimum temperature of the Lisbon district were calculated using the daily ensemble gridded E-OBS data (Cornes et al. 2018) from the European Climate Assessment & Dataset project (ECA&D) available on a 0.1 degree regular grid from January 1950 to present (the database is continuously updated).

To calculate the SPEI and SPI, the SPEI R library was used (Begueria et al., 2014). To obtain the SPEI series, the potential evapotranspiration variable was first estimated based on the Hargreaves method, as recommended by Páscoa et al. (2017). Based on the original description of both indices and according to the methodology used by Parsons et al. (2019) and Spinoni et al. (2018), a gamma distribution was used to compute the SPI (McKee, 1993; EDO, 2020) and the log-logistic distribution to compute the SPEI (Vicente-Serrano et al., 2012) across the available period (1950 to 2017). We then selected weekly data from 1983 to 2016. Both indices were calculated for one month (and three months) of accumulation to quantify short (and short-medium) term droughts; hereafter, the length of the time scales, is denoted as SPEI-n or SPI-n, where n is equal to "1" or "3". Subsequently, we constructed a daily series assuming the same conditions for each seven-day interval during the study period, according to the criteria of Berman et al. (2017) and Salvador et al. (2019, 2020b).

2.4. Control variables

The control of heatwaves and air quality variables during the sub-period from 2007 to 2016 was included in the analysis, where there was pollution data available, as these climatic hazards are frequently associated (Peterson et al., 2014). It has been demonstrated that in Europe, the incidence of concurrent and cascading dry hazards such as droughts, heatwaves, and forest fires is evident (e.g., Sutanto et al., 2020). These are important drivers of deteriorating air quality, and both phenomena lead to harmful effects on respiratory and circulatory systems (IPCC, 2014; Watts et al., 2017). Furthermore, time lags for the heatwaves and atmospheric pollutants of this study were calculated. So, the fact that the short-term effects of extreme heat temperatures on mortality occur immediately to four days later was taken into account (Guo et al., 2017); in the case of the atmospheric pollution, this effect can be delayed up to five days for PM_{10} and NO_2, and in the case of O_3, the impact on mortality can lag up to nine days. Hence, these lags were included in the Poisson models (Ortiz et al., 2017; Díaz and Linares, 2018; Salvador et al., 2020b).

2.4.1. Temperature of heatwave (Thwave)

It has been demonstrated that temperature has a U-shaped relationship with mortality (Tobías and Díaz, 2014). The temperature for the heatwaves (T*hwave*) was calculated using the maximum daily temperatures (T*max*) and the specific maximum temperature threshold for daily mortality associated with heat (T*threshold*) in Lisbon for the available sub-period from 2007 to 2016, following Díaz et al. (2015). In terms of its effect on mortality, T*hwave* was considered when the T*max* exceeded the T*threshold* value, as follows:

$$T_{hwave} = Tmax - Tthreshold \qquad \text{if } Tmax > Tthreshold$$

$$T_{hwave} = 0 \qquad \text{if } Tmax \leq Tthreshold$$

The daily T*max* series was obtained through an average of the daily T*max* series recorded at the reference stations of the Portuguese Institute for Sea and Atmosphere (IPMA) located in Lisbon, available online from the NOAA´s National Climatic Data Center (NCDC) (NNDC CDO, 2019). The threshold value was 34 ºC, corresponding to the 93th percentile (see Figure S1 in supplementary material).

2.4.2 Daily atmospheric pollution (PM_{10}, NO_2, and O_3)

We also included the control of the short-term effect of air quality on the daily mortality in Lisbon from 2007 to 2016. For this purpose, the daily mean concentrations (μg/m^3) of particulate matter with an aerodynamic diameter of less than 10 μm (PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) were used.

From the air quality network of the Lisbon and Tagus valley, pollutant data recorded at main monitoring stations situated in the district of Lisbon for each pollutant (*Entrecampos, Avenida da Liberdade, Olivais, Alfragide/Amadora, Cascais-Mercado, Loures, Mem-Martins, Alverca*, and *Laranjeiro*) were obtained online from the Portuguese Environmental Agency (QualAr, 2019). The data from the different stations were averaged to provide a single estimation of the daily concentration of each pollutant.

It has been indicated that PM_{10} and NO_2 have a linear relationship with mortality (Ortiz et al., 2017; Linares et al., 2018); however, O_3 registers a U-shaped relationship with mortality (similar to that registered by temperature), where the right branch of the curve indicates the increase of mortality associated with the increase in O_3 concentrations. Thus, this variable was parametrised according to the methodology of Díaz et al. (2018), and a new variable named O_3a was created to estimate the risks of O_3 on daily mortality as:

$$O_3a = O_3 - O_3\text{threshold} \qquad \text{if } O_3 > O_3\text{threshold}$$

$$O_3a = 0 \qquad \text{if } O_3 \leq O_3\text{threshold}$$

The threshold ozone value of the Lisbon district from 2007 to 2016 was 67 (μg/m^3), corresponding to the 72th percentile (indicated in Figure S2 in supplementary material).

2.5 Modelling process to quantify impact of droughts on daily mortality

To estimate the effects of droughts, and then the heat wave and pollution, on daily natural, circulatory, and respiratory mortality general linear models (GLMs) with the Poisson link were used. First, the impact of droughts on each cause of daily mortality was evaluated conducting analyses of independent models for the SPEI-n and SPI-n from 1983 to 2016. For the sub-period 2007 to 2016, the control variables related to heatwaves and air quality and the considered lags were additionally included. Moreover, we also considered the trend of the series, the autoregressive nature of the dependent variable, and the seasonality of the series in the Poison model through the use of sine and cosine functions corresponding to the periodicities indicated below: annual (365 days), six months (180 days), four months (120 days) and quarterly (90 days).

This methodology allowed the calculation of the relative risk (RR) of the variables that resulted statistically significant ($p<0.05$) from the estimator value obtained in Poisson models. RR values were calculated for each unit of increment for the indicator of the independent variable used and from these values, the percent of attributable risk (%AR) were calculated using the following equation:

$$\%AR = [(RR - 1) / RR] \times 100 \qquad \text{(Coste and Spira, 1991)}$$

To determine the statistically significant variables, a "backward-step" process was conducted (e.g., Díaz and Linares (2018), Martinez et al. (2018), and Salvador et al., 2020b), beginning with a model that included all the explained variables and subsequently individually and gradually removing those that had the least statistical significance, obtaining a final model that included all significant variables ($p < 0.05$).

All analyses were conducted using the IBM SPSS Statistics and STATA v14.1 software.

3. Results and discussion

3.1. Descriptive analysis

The descriptive statistics of both the daily mortality by gender and age in the district of Lisbon across the period 1983 to 2016 is presented in Table 1; Table 2 displays the descriptive analysis of both maximum temperature and air quality in the district of Lisbon from the sub-period 2007 to 2016, for which atmospheric pollution variables were available.

3.2. Quantification of short-term effects of drought on specific-cause mortality in district of Lisbon during period 1983 to 2016

3.2.1. Risk assessment for total population and different age subgroups

The complete set of statistical values obtained in the Poisson models (coefficients, p-values, RRs, 95% confidence intervals of RRs, and %AR) are described in Table S1 (supplementary material). The negative coefficient values of the SPEI/SPI indicate a significant association between drought conditions and the different causes of mortality. Figure 1 displays the RR values (with 95% confidence intervals) of the natural, circulatory, and respiratory mortality associated with drought events measured by the SPEI-1/SPI-1 in the total population of Lisbon and in adults grouped by age (45–64, 65–74, >75 years old) from 1983 to 2016. We only considered adults because there were limited deaths among young people including children and adolescents (Table 1). A comparison with the SPEI-3/SPI-3 is displayed in the supplementary material (Figure S3).

PORTUGAL	POPULATION	Natural deaths					Circulatory deaths					Respiratory deaths				
		% Pp.	X	SD	m	M	%Pp.	X	SD	m	M	%Pp.	X	SD	Min	Max
DISTRICT OF LISBON	**TOTAL**	(665383) 100%	54	12	19	135	(286820) 43.11%	23	7.4	4	77	(59083) 8.89%	5	2.93	0	30
	0-9	(6776) 1,02%	1	0.8	0	7	(168) 0.06%	0.01	0.12	0	1	(479) 0.81%	0.04	0.21	0	3
	10-44	(29042) 4,36%	2	1.7	0	12	(4573) 1.59%	0.37	0.6	0	5	(1676) 2.84%	0.13	0.37	0	3
	45-64	(107186) 16.11%	9	3.2	0	27	(30271) 10.55%	2	1.8	0	10	(5212) 8.82%	0.42	0.67	0	5
	65-74	(136250) 20.48%	11	3.9	0	31	(53316) 18.59%	4	2.6	0	18	(9357) 15.84%	0.75	0.91	0	9
	>75	(386082) 58.02%	31	9.7	6	89	(198483) 69.20%	16	5.6	2	59	(42353) 71.68%	3	2.52	0	23
	MEN	**(333035)** 50.05%	27	6.8	6	61	(125845) 43.88%	10	4	0	31	(31922) 54.03%	3	1.9	0	19
	0-9	(3876) 1.16%	0.3	0.6	0	4	(95) 0.08%	0.01	0.09	0	1	(284) 0.89%	0.02	0.16	0	2
	10-44	(19428) 5.83%	2	1.4	0	9	(3107) 2.47%	0.25	0.51	0	4	(1170) 3.67%	0.09	0.31	0	3
	45-64	(70651) 21.21%	6	2.5	0	21	(21013) 16.70%	2	1.4	0	9	(3785) 11.86%	0.30	0.56	0	4
	65-74	(82366) 24.73%	7	2.8	0	20	(31131) 24.74%	3	1.8	0	13	(6256) 10.59%	1	0.73	0	6
	>75	(156683) 47.05%	13	5	1	45	(70494) 56.01%	6	2.8	0	21	(20424) 63.98%	2	1.51	0	13
	WOMEN	**(332347)** 49.95%	27	7.3	7	83	(160975) 56.12%	13	4.8	0	54	(27161) 45.97%	2	1.80	0	16
	0-9	(2899) 0.87%	0,2	0.5	0	5	(73) 0.05%	0.01	0.08	0	1	(195) 0.72%	0.02	0.13	0	2
	10-44	(9614) 2.89%	1	0.9	0	6	(1466) 0.91%	0.12	0.34	0	3	(506) 1.86%	0.04	0.21	0	3
	45-64	(36535) 10.99%	3	1.8	0	11	(9258) 5.75%	0.75	0.91	0	7	(1427) 5.25%	0.11	0.34	0	3
	65-74	(53884) 16.21%	4	2.3	0	17	(22185) 13.78%	2	1.52	0	11	(3101) 11.42%	0.25	0.52	0	4
	>75	(229399) 69.02%	18	6.3	3	62	(127989) 79.51%	10	4	0	47	(21929) 80.74%	2	1.63	0	15

Table 1. Descriptive statistics corresponding to annual daily natural, circulatory and respiratory mortality of total population and sub-groups categorised by gender (men/women) and age ranges (0-9, 10-44, 45-64, 65-74, >75 years old) in the district of Lisbon from 1983 to 2016. %Pp= percentage of deaths; X=mean; SD=Standard Deviation; m= minimum; M= maximum.

PORTUGAL	*Tmax*				PM_{10}				NO_2				O_3			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
DISTRICT OF LISBON	21.39	6.29	0	39.83	26.37	11.66	4.70	109.79	32.57	14.80	6.88	100.23	54.55	20.19	5.19	118.63

Table 2. Descriptive analysis corresponding to annual data of daily maximum temperature (T*max*), particulate matter with an aerodynamic diameter of less than 10 µm (PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3) levels (µg/m^3) for the district of Lisbon from 2007 to 2016. Max: maximum; Min: minimum; SD: Standard Deviation.

The main results from Figure 1 indicate a statistically significant association between short-term drought events and the different causes of daily mortality, with the highest RR values obtained on daily respiratory-caused mortality (the highest RR values obtained), which is in agreement with Salvador et al. (2019; 2020b) in Spain. This is in accordance with the fact that drought conditions (especially in urban areas) can cause an exacerbation of respiratory tract disorders (e.g., allergies, bronchitis, pneumonia) and result in respiratory mortality due to the accumulation of dust, allergens or pollutants, particularly in vulnerable people such as those with common chronic lung pathologies (Bernstein and Rice, 2013; Yusa et al., 2015; Alpino t al., 2016; Grigoletto et al., 2016; Bifulco and Ranieri, 2017). Moreover, the deterioration of air quality associated with drought conditions could also contribute to a higher risk of cardiovascular issues (Stanke et al., 2013; Bell et al., 2018; Salvador et al., 2020a).

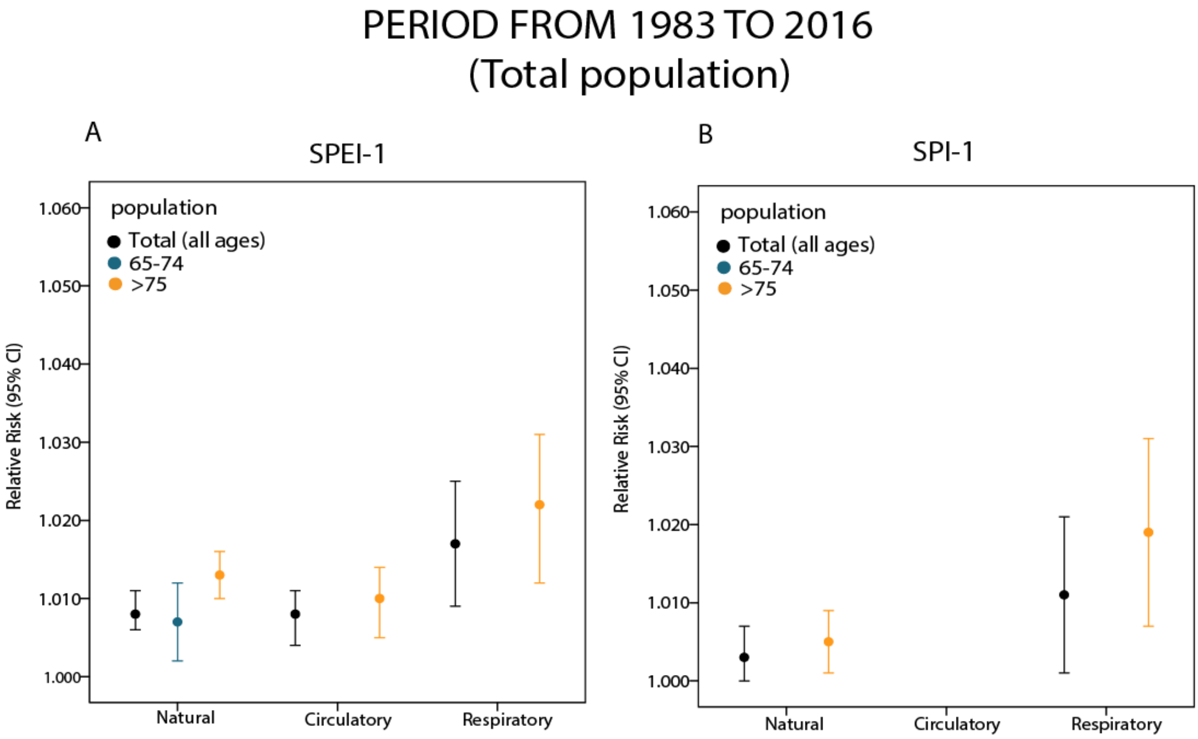


Figure 1. Significant Relative Risks (RRs) of daily natural, circulatory, and respiratory mortality of total population and adult age groups associated with drought events measured by: A) SPEI and B) SPI. Both indices were calculated for one month of accumulation (SPEI-1 and SPI-1). Upper and lower 95% confidence intervals are indicated with vertical bars.

Among the different age categories of the population, people over 75 years old were the highest risk group and no statistically significant relationship between daily mortality and drought conditions was found for people aged 45 to 64. Other research has indicated that the elderly are a subgroup particularly vulnerable to extreme events such as droughts, storms, or heatwaves, especially in terms of mortality. This is due to their mobility constraints and their weakened immune response to environmental stresses compared to younger adults (IPCC, 2014; Berman et al., 2017). Furthermore, it is known that the elderly has a reduced ability to restore homeostasis (Vida et al., 2014) and a higher prevalence of heart and lung chronic issues (Yazdanyar and Newman, 2009; Akgün et al., 2012; US EPA, 2019), which make them a highly vulnerable group. It has been indicated that people over 65 years old are at the greatest at risk of mortality associated with the occurrence of heatwaves (Linares and Díaz, 2008; deCastro et al., 2011; Linares et al., 2017) and with the effect of atmospheric pollution on natural, circulatory, and respiratory deaths (Gouveia, 2000). Moreover, elderly people are also a high-risk subgroup to the exacerbation of circulatory and respiratory diseases and mortality linked to wildfire smoke (Bell et al., 2018; US EPA, 2019).

Several differences were detected when the performance of the SPEI and SPI were compared. Only the SPEI-1 index reflected the impact of drought on circulatory mortality, indicating a greater number of statistically significant associations for natural mortality in the different age groups. Overall, the SPEI-1 (the shortest time scale) reflected the risks on mortality among the different groups (particularly for natural and circulatory deaths) better than the SPEI-3; conversely, the SPI-3 appeared to be more optimal than the SPI-1, particularly for daily natural deaths (Figure S3 in supplementary material).

3.2.2. Risks assessment by gender

When the population is categorised by gender, the results also indicate differences between the 65–74 and over-75 groups (Figure 2). In the supplementary material, Table S2 displays the significant statistic values obtained in the Poisson models. Figure S4 presents the comparative results using the SPEI-1/SPI-1 vs. SPEI-3/SPI-3. The findings indicate that both women and men were affected by the drought conditions in terms of mortality. The SPEI also resulted in a better index for the capture and estimation of the different risks on daily mortality. Moreover, when using the different time scales of the SPEI/SPI, similar findings were obtained in the gender analysis compared to those obtained for the total population (Figure S4).

Furthermore, a fluctuation of the drought risks on daily mortality between men and women was observed. Whereas the SPEI reflected a greater risk of droughts in women (especially in the over-75 group) for circulatory mortality (no significant association for men), the SPI indicated that men were the highest risk group, in principal, for natural and respiratory mortality (where there were limited significant associations in the case of women). Moreover, the affected people from the 65–74 group were men in all cases. The drought conditions measured by the SPEI did not identify gender differences in the risks of respiratory deaths (Figure 2; figure S4).

In this aspect, the risk associated with drought is defined by the product of the exposure to a specific event in a given region and the vulnerability of the population to this hazard (Wilhite, 2000, Quiring, 2015); however, the relationship between gender and vulnerability is complex. Several studies have indicated that in general terms, the mortality associated with extreme events is greater in women, yet with a regional variability (in specific regions, men are more affected) (IPCC, 2014). Gender differences in the structure of the population, social relationships, customs, and differences in the sensitivity and adaptation capability could influence the vulnerability and risks between males and females (Kallis, 2008; United Nations, 2019). Men and women differ in their roles, behaviour attitudes, and their means and strategies to respond to climatic phenomena (WHO, 2014). On the other hand, a recent report of United Nations of 2019 indicated that vulnerability differences to the effects of climate change between men and women depend principally on social factors, not on sex. Conversely, other studies have described that sex-linked differences (e.g., hormonal content) could influence the degree of susceptibility between males and females to environmental hazards (Clougherty, 2010; Van Steen et al., 2018), however this topic has not been sufficiently studied and still is not well known.

3.2.3. Short-term impact of drought on mortality under control of heatwaves and atmospheric pollution during sub-period 2007–2016

As the period with pollution data available was shorter, we first re-quantified the effect of droughts measured over the short term (SPEI-1/SPI-1) on the daily specific-cause mortality from the sub-period 2007–2016 (Tables 3–4). When only gender was considered in the analysis, differences in the risks of mortality linked to drought between men and women were hardly found (Table 3). However, when the population (total, men, and women) was categorised by adult age groups (Table 4), gender differences in the risk of mortality attributable to drought were particularly remarkable during this sub-period, men being more strongly affected than women.

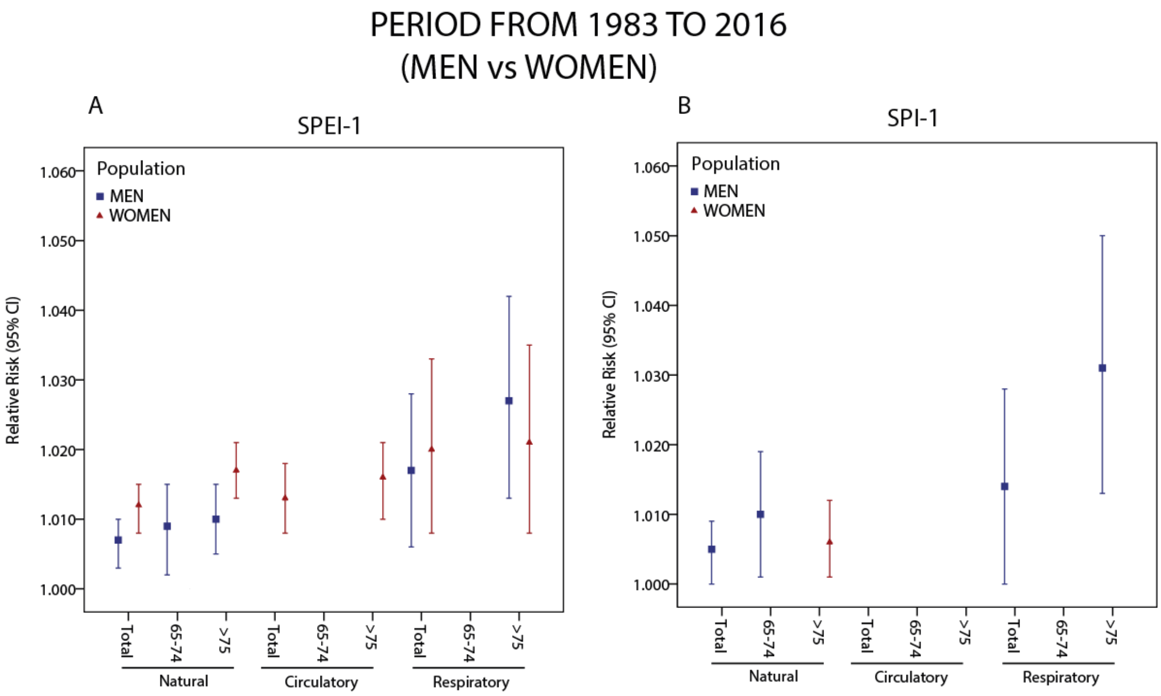


Figure 2. Significant Relative Risks (RRs) of daily natural, circulatory, and respiratory mortality across population separated by gender and categorised by advanced age group linked to occurrence of droughts conditions measured by: A) SPEI and B) SPI. Both indices were calculated for one month of accumulation (SPEI-1 and SPI-1). Upper and lower 95% confidence intervals are indicated with vertical bars.

In the case of males, the daily natural and circulatory mortality attributable to droughts measured by the SPEI-1 was manifested for the 65–74 and over-75 groups; in the case of women, the mortality occurred for only the over-75 group. When the age groups were included in the Poisson models, it was observed that the respiratory mortality in men in the over-75 year old group was significantly affected by short-term droughts using both the SPEI-1 and SPI-1 (these were not observed at any statistically significant association in women). A possible explanatory hypothesis for these results is that the male groups could have been more engaged in activities where the health risk could increase through a greater degree of drought exposure (e.g., activities that involve more time outdoors), which could result in a greater vulnerability and contribute to greater risks (Yusa et al., 2015).

It is important to note that the differences in the mortality risk between the long and short periods could be influenced by differences in the population vulnerability. These could change over time and increase or decrease as a function of the response to changes in the population, rural to urban (or vice-versa) population shifts, demographic characteristics, or other social factors such as technology, policy, education, or social behaviours (Wilhite, 2000; Quiring, 2015).

REGION	Causes of mortality	Gender	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]	%AR [(RR-1)/RR] × 100
	Natural deaths	TOTAL	SPEI_1 (p=0.000)	-0.011	(-0.015, -0.007)	1.011	(1.007, 1.015)	1.088%
			SPI_1 (p=0.021)	-0.006	(-0.012, -0.001)	1.006	(1.001, 1.012)	0.60%
		MEN	SPEI-1 (p=0.000)	-0.011	(-0.017, -0.005)	1.011	(1.005, 1.017)	1.09%
			SPI-1 (p=0.037)	-0.008	(-0.016, -0.000)	1.008	(1.000, 1.016)	0.79%
		WOMEN	SPEI-1 (p=0.000)	-0.012	(-0.018, -0.007)	1.012	(1.007, 1.018)	1.19%
DISTRICT OF LISBON	Circulatory deaths	TOTAL	SPEI_1 (p=0.001)	-0.011	(-0.019, -0.004)	1.011	(1.004, 1.019)	1.088%
		MEN	SPEI-1 (p=0.015)	-0.013	(-0.024, -0.003)	1.013	(1.003, 1.024)	1.28%
		WOMEN	SPEI-1 (p=0.025)	-0.011	(-0.020, -0.001)	1.011	(1.001, 1.020)	1.09%
	Respiratory deaths	TOTAL	SPEI_1 (p=0.024)	-0.015	(-0.028, -0.002)	1.015	(1.002, 1.028)	1.48%
		MEN						
		WOMEN						

Table 3. Relative Risks (RRs) of daily natural, circulatory and respiratory mortality associated with drought events measured at short term (SPEI-1/SPI-1) among total and separated by gender population (men and women) of Lisbon district across the sub-period 2007 to 2016. The 95% confidence intervals were also shown. %AR= percentage of Attributable Risk. SPEI/SPI-1= Standardized Precipitation Evapotranspiration Index/ Standardized Precipitation Index, obtained at one month of accumulation.

SPEI-1/SPI-1								
REGION	Causes of mortality	Gender	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
	Natural deaths	TOTAL	SPEI-1	65-74 (p=0.004) >75 (p=0.000)	-0.015 -0.012	(-0.025, -0.005) (-0.017, -0.007)	1.015 1.012	(1.005, 1.025) (1.007, 1.017)
			SPI-1					
		MEN	SPEI-1	65-74 (p=0.026) >75 (p=0.008)	-0.015 -0.011	(-0.028, -0.002) (-0.018, -0.003)	1.015 1.011	(1.002, 1.028) (1.003, 1.018)
			SPI-1					
		WOMEN	SPEI-1	>75 (p=0.000)	-0.015	(-0.021, -0.008)	1.015	(1.008, 1.021)
			SPI-1					
DISTRICT OF LISBON	Circulatory deaths	TOTAL	SPEI-1	65-74 (p=0.021) >75 (p=0.003)	-0.023 -0.012	(-0.043, -0.004) (-0.020, -0.004)	1.023 1.012	(1.004, 1.044) (1.004, 1.020)
			SPI-1					
		MEN	SPEI-1	65-74 (p=0.018)	-0.030	(-0.055, -0.005)	1.030	(1.005, 1.057)
			SPI-1					
		WOMEN	SPEI-1	>75 (p=0.007)	-0.014	(-0.024, -0.004)	1.014	(1.004, 1.024)
			SPI-1					
	Respiratory deaths	TOTAL	SPEI-1	>75 (p=0.006)	-0.020	(-0.034, -0.006)	1.020	(1.006, 1.035)
			SPI-1	>75 (p=0.038)	-0.019	(-0.037, -0.001)	1.019	(1.001, 1.038)
		MEN	SPEI-1	>75 (p=0.013)	-0.026	(-0.046, -0.005)	1.026	(1.005, 1.047)
			SPI-1	>75 (p=0.016)	-0.032	(-0.059, -0.006)	1.033	(1.006, 1.061)
		WOMEN	SPEI-1					
			SPI-1					

Table 4. Short-term effects of specific-cause mortality associated with drought events measured at short term in total, men and women populations when were additionally split them by adult age groups in the district of Lisbon across the sub-period 2007 to 2016. P-value, coefficient values, relative risks (RRs) and the 95% confidence intervals of the coefficients and of the RRs were also displayed. SPEI-1/SPI-1= The Standardized Precipitation Evapotranspiration Index/The Standardized Precipitation Index obtained at one month of accumulation.

The improved capability of the SPEI to identify and quantify the different effects was more marked in the sub-period from 2007 to 2016. There were statistically significant associations between the droughts measured by the SPEI-1 and all analysed causes of mortality, whereas there were virtually no associations between the droughts and different causes of mortality using the SPI (Tables 3 and 4). This effect of the SPEI vs. SPI does not occur only in this mortality analysis; although the study of Vicente-Serrano et al. (2012) indicated small differences in the comparative performance of both indices, SPEI had superior capability to predict drought effects in streamflow, soil moisture, forest growth and crop yield (particularly in summer). In general, this also occur in another European study when drought impacts on agriculture, energy and industry, public water supply and freshwater ecosystem were evaluated (Stagge et al., 2015).

It was suggested that drought impact depends largely on the severity of the phenomenon (Stanke et al., 2013; Salvador et al., 2020a), and Berman et al. (2017) described a significant association between the severity of drought and increased mortality risk. The fact that the SPEI is obtained based on both precipitation and temperature data (whereas SPI only takes into account precipitation data) allows for identifying an increase of drought severity linked to higher water demand resulting from the influence of the potential evapotranspiration (Vicente-Serrano et al., 2010). This could make it more sensitive to detect specific effects linked to the occurrence of this hydroclimatic extreme, especially during periods with high temperatures. A pan-European study determined that, in southern Europe regions, the SPEI-3 identified drier conditions than the SPI-3 in the past decades, especially in summer and autumn (Spinoni et al., 2017).

3.4. Additional control of heatwaves and atmospheric pollution

First, we quantified the impact of droughts measured over the short term including the control of heatwaves in the statistical models (Table S3) for the significant groups in tables 3 and 4. The significant impact on mortality was explained by the effect of extreme heat temperatures and drought conditions, but in specific cases the statistically significance of drought index was lost when T*hwave* was controlled.

Subsequently, the impact of droughts were evaluated while both the effect of heatwaves and atmospheric pollution remained controlled in the Poisson models (see Table 5 and 6). Table 5 displays the results obtained across the population segregated by gender, without differentiation by age. It can be observed that the statistically significant signal of the SPEI-1 and SPI-1 previously obtained is lost when extreme heat temperatures and the effect of PM_{10}, NO_2, and O_3 are included in the Poisson models, only remaining T*hwave* and pollution variables statistically significant. Similar results were obtained in Spain for a considerabe number of provinces for the total population (Salvador et al., 2019, 2020b). Comparing the different pollutants, O_3 and NO_2 were the most strongly linked to mortality compared to PM_{10}, and qualitatively ozone was the pollutant associated with highest risk of death (the highest RR values). All pollutants had an effect on the natural mortality; NO_2 was mainly associated with daily circulatory-caused mortality, whereas O_3 was related particularly to respiratory issues.

Heatwaves, droughts, wildfires, and atmospheric pollution are phenomena frequently associated (Peterson et al., 2014; Bell et al., 2018; Salvador et al., 2020a). Several studies conducted in Portugal have described significant associations between them (Parente et al., 2018; Parente et al., 2019; Turco et al., 2019). Studies have indicated that droughts are linked to poor air quality (higher dust, ozone, and other pollutants) through their direct affectation on atmospheric chemistry or indirectly owing to their association with wildfires (Wang et al., 2017; Vicente-Serrano et al., 2020), which cause notable impact on natural, respiratory, and circulatory mortality owing to the exposure to wildfire smoke (Reid et al., 2016; Black et al., 2017). Moreover, drought events are associated with persistent high-pressure systems such as anticyclonic conditions characterised by high pollutant concentrations (Peterson et al., 2014; Vicente-Serrano et al., 2020). It has been demonstrated that PM_{10}, NO_2, and O_3 have serious effects on health, including natural, circulatory, and respiratory mortality, with the highest effect on respiratory mortality (especially O_3). The inhalation of atmospheric pollutants is associated with a reduction in lung function and exacerbation of respiratory diseases because it leads to higher inflammation, oxidative stress, and cytotoxicity. Poor air quality is also linked to a higher risk of hypertension, ischemic events, and heart failure (Du et al., 2106; Ortiz et al., 2017; Linares et al., 2018; Díaz and Linares, 2018). Moreover, heatwaves also have significant effects on mortality through direct and/or indirect effects (warmer temperatures are frequently linked to poor air quality with higher pollution levels such as ozone and PM) (IPCC, 2014; Peterson et al., 2014; Franchini and Mannuci, 2015; Díaz and Linares et al., 2018).

SPEI-1/SPI-1 + THWAVE + POLLUTION

REGION	Causes of mortality	Gender	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	TOTAL	SPEI-1	Thwave-1 (p=0.000)	0.035	(0.021, 0.049)	1.036	(1.021, 1.050)
				Thwave-2 (p=0.000)	0.031	(0.017, 0.045)	1.031	(1.017, 1.046)
				Thwave-4 (p=0.013)	0.015	(0.003, 0.028)	1.015	(1.003, 1.028)
				NO2-0 (p=0.002)	0.0006	(0.0002, 0.0009)	1.0006	(1.0002, 1.0009)
				NO2-3 (p=0.006)	0.0005	(0.0001, 0.0009)	1.0005	(1.0001, 1.0009)
				O3a-4 (p=0.028)	0.0008	(0.0001, 0.0015)	1.0008	(1.0001, 1.0015)
			SPI-1	Thwave-1 (p=0.000)	0.035	(0.021, 0.049)	1.036	(1.021, 1.050)
				Thwave-2 (p=0.000)	0.031	(0.017, 0.045)	1.031	(1.017, 1.046)
				Thwave-4 (p=0.013)	0.015	(0.003, 0.028)	1.015	(1.003, 1.028)
				NO2-0 (p=0.002)	0.0006	(0.0002, 0.0009)	1.0006	(1.0002, 1.0009)
				NO2-3 (p=0.006)	0.0005	(0.0001, 0.0009)	1.0005	(1.0001, 1.0009)
				O3a-4 (p=0.028)	0.0008	(0.0001, 0.0015)	1.0008	(1.0001, 1.0015)
		MEN	SPEI-1	Thwave-0 (p=0.022)	0.020	(0.003, 0.037)	1.020	(1.003, 1.038)
				Thwave-2 (p=0.000)	0.047	(0.031, 0.064)	1.048	(1.031, 1.066)
				PM10-0 (p=0.004)	0.0009	(0.0003, 0.0014)	1.0009	(1.0003, 1.0014)
				O3a-6 (p=0.015)	0.0012	(0.0002, 0.0022)	1.0012	(1.0002, 1.0022)
			SPI-1	Thwave-0 (p=0.022)	0.020	(0.003, 0.037)	1.020	(1.003, 1.038)
				Thwave-2 (p=0.000)	0.047	(0.031, 0.064)	1.048	(1.031, 1.066)
				PM10-0 (p=0.004)	0.0009	(0.0003, 0.0014)	1.0009	(1.0003, 1.0014)
				O3a-6 (p=0.015)	0.0012	(0.0002, 0.0022)	1.0012	(1.0002, 1.002)
		WOMEN	SPEI-1	Thwave-1 (p=0.000)	0.047	(0.028, 0.067)	1.048	(1.028, 1.069)
				Thwave-2 (p=0.001)	0.032	(0.012, 0.051)	1.033	(1.012, 1.052)
				Thwave-4 (p=0.006)	0.023	(0.007, 0.040)	1.023	(1.007, 1.041)
				NO2-3 (p=0.008)	0.0007	(0.0002, 0.0012)	1.0007	(1.0002, 1.0012)
				O3a-1 (p=0.036)	0.0011	(0.0001, 0.0021)	1.001	(1.0001, 1.0021)
			SPI-1					
	Circulatory deaths	TOTAL	SPEI-1	Thwave-1 (p=0.000)	0.045	(0.022, 0.068)	1.046	(1.022, 1.070)
				Thwave-2 (p=0.001)	0.038	(0.015, 0.062)	1.039	(1.015, 1.064)
				Thwave-4 (p=0.000)	0.040	(0.021, 0.060)	1.041	(1.021, 1.062)
				NO2-3 (p=0.001)	0.0010	(0.0004, 0.0016)	1.001	(1.0004, 1.0016)
			SPI-1					
		MEN	SPEI-1	Thwave-1 (p=0.001)	0.051	(0.022, 0.081)	1.052	(1.02, 1.084)
				Thwave-4 (p=0.001)	0.048	(0.019, 0.078)	1.049	(1.019, 1.081)
				NO2-3 (p=0.013)	0.0012	(0.0002, 0.0021)	1.0012	(1.0002, 1.0021)
			SPI-1					
		WOMEN	SPEI-1	Thwave-1 (p=0.001)	0.051	(0.021, 0.081)	1.052	(1.021, 1.084)
				Thwave-2 (p=0.006)	0.043	(0.012, 0.074)	1.044	(1.012, 1.077)
				Thwave-4 (p=0.001)	0.043	(0.018, 0.069)	1.044	(1.018, 1.071)
				NO2-2 (p=0.002)	0.0013	(0.0005, 0.002)	1.0013	(1.0005, 1.002)
			SPI-1					
	Respiratory deaths	TOTAL	SPEI-1	Thwave-0 (p=0.001)	0.064	(0.027, 1.000)	1.066	(1.027, 2.718)
				Thwave-3 (p=0.006)	0.051	(0.015, 0.088)	1.052	(1.015, 1.092)
				O3a-4 (p=0.002)	0.0035	(0.0012, 0.0057)	1.0035	(1.0012, 1.0057)
			SPI-1					
		MEN	SPEI-1					
			SPI-1					
		WOMEN	SPEI-1					
			SPI-1					

Table 5. Statistically significant effects of droughts measured at short term (1 month) on daily natural, circulatory and respiratory mortality of the total, men and women populations when the effect of heatwaves and atmospheric pollutants remained controlled in Poisson modelling in the district of Lisbon from the sub-period 2007 to 2016. P-value, coefficients, relative risks (RRs), the 95% confidence intervals of the coefficients and of the RRs were also displayed. SPEI-1= Standardized Precipitation Evapotranspiration data obtained at one month of accumulation; SPI= Standardized Precipitation Index obtained at one month of accumulation. "-n" after the Thwave and each pollutant correspond to the manifestation of the effects of these climatic phenomena on daily mortality, range from 0 "immediate" to 6 (lag 6).

SPEI-1/SPI-1 + THWAVE + POLLUTION (TOTAL POPULATION)

REGION	Causes of mortality	AGE RANGE	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	65-74	SPEI-1	SPEI-1 (p=0.017) Thwave-2 (p=0.013) O3a-3 (p=0.023)	-0.013 0.035 0.0020	(-0.023, -0.002) (0.007, 0.063) (0.0003, 0.0037)	1.013 1.036 1.002	(1.002, 1.023) (1.007, 1.065) (1.003, 1.038)
			SPI-1					
		>75	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.001) Thwave-4 (p=0.000) NO2-0 (p=0.002) NO2-3 (p=0.002) O3a-2 (p=0.039)	0.046 0.029 0.026 0.0007 0.0007 0.0009	(0.029, 0.062) (0.012, 0.047) (0.012, 0.041) (0.0003, 0.0012) (0.0003, 0.0012) (0.0000, 0.0018)	1.047 1.029 1.026 1.0007 1.0007 1.0009	(1.029, 1.064) (1.012, 1.048) (1.012, 1.042) (1.0003, 1.0012) (1.0003, 1.0012) (1.0000, 1.0018)
			SPI-1					
	Circulatory deaths	65-74	SPEI-1	SPEI-1 (p=0.047) Thwave-2 (p=0.027)	-0.020 0.059	(-0.040, -0.0003) (0.007, 0.111)	1.020 1.061	(1.0003, 1.041) (1.007, 1.117)
			SPI-1					
		>75	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.006) Thwave-4 (p=0.000) NO2-3 (p=0.001)	0.057 0.037 0.047 0.0011	(0.031, 0.083) (0.011, 0.064) (0.025, 0.070) (0.0004, 0.002)	1.059 1.038 1.048 1.0011	(1.031, 1.087) (1.011, 1.066) (1.025, 1.073) (1.0004, 1.002)
			SPI-1					
	Respiratory deaths	>75	SPEI-1	Thwave-1 (p=0.002) Thwave-3 (p=0.032) PM10-0 (p=0.033) O3a-4 (p=0.002)	0.063 0.044 0.0015 0.0039	(0.023, 0.104) (0.004, 0.085) (0.0001, 0.0028) (0.0014, 0.0063)	1.065 1.045 1.0015 1.0039	(1.023,1.110) (1.004, 1.089) (1.0001, 1.0028) (1.0014, 1.0063)
			SPI-1	Thwave-1 (p=0.002) Thwave-3 (p=0.032) PM10-0 (p=0.033) O3a-4 (p=0.002)	0.063 0.044 0.0015 0.0039	(0.023, 0.104) (0.004, 0.085) (0.0001, 0.0028) (0.0014, 0.0063)	1.065 1.045 1.0015 1.0039	(1.023, 1.110) (1.004, 1.089) (1.0001, 1.0028) (1.0014, 1.0063)

SPEI-1/SPI-1 + THWAVE + POLLUTION (MEN POPULATION)

REGION	Causes of mortality	AGE RANGE	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	65-74	SPEI-1	SPEI-1 (p=0.035) O3a-3 (p=0.003)	-0.014 0.0032	(-0.027, -0.001) (0.001, 0.005)	1.014 1.0032	(1.001, 1.027) (1.001, 1.005)
			SPI-1					
		>75	SPEI-1	Thwave-0 (p=0.019) Thwave-2 (p=0.000) PM10-0 (p=0.003)	0.027 0058 0.001	(0.005, 0.050) (0.036, 0.080) (0.0004, 0.0019)	1.027 1.060 1.001	(1.005, 1.051) (1.037, 1.083) (1.0004, 1.0019)
			SPI-1					
	Circulatory deaths	65-74	SPEI-1	SPEI-1 (p=0.018)	-0.030	(-0.055, -0.005)	1.030	(1.005, 1.057)
			SPI-1					
	Respiratory deaths	>75	SPEI-1	Thwave-0 (p=0.003) NO2-0 (p=0.029) O3a-4 (p=0.030)	0.084 0.002 0.004	(0.028, 0.140) (0.0002, 0.004) (0.0004, 0.007)	1.088 1.002 1.004	(1.028. 1.150) (1.0002, 1.004) (1,0004, 1,007)
			SPI-1	SPI-1 (p=0.026) Thwave-0 (p=0.001) O3a-4 (p=0.028)	-0.030 0.096 0.004	(-0.056, -0.004) (0.041, 0.150) (0.000, 0.007)	1.030 1.101 1.004	(1.004, 1.058) (1.042, 1.162) (1.000, 1.007)

SPEI-1/SPI-1 + THWAVE + POLLUTION (WOMEN POPULATION)

REGION	Causes of mortality	AGE RANGE	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	>75	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.007) Thwave-4 (p=0.000) NO2-0 (p=0.019) NO2-3 (p=0.002)	0.056 0.031 0.035 0.0007 0.0009	(0.034, 0.078) (0.008, 0.053) (0.017, 0.054) (0.0001, 0.0013) (0.0003, 0.0015)	1.058 1.031 1.036 1.0007 1.0009	(1.035, 1.081) (1.008, 1.054) (1.017, 1.055) (1.0001, 1.0013) (1.003, 1.0015)
			SPI-1					
	Circulatory deaths	>75	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.024) Thwave-4 (p=0.000) NO2-2 (p=0.000)	0.059 0.038 0.049 0.0017	(0.027, 0.091) (0.005, 0.071) (0.022, 0.076) (0.0009, 0.0026)	1.061 1.039 1.050 1.017	(1.027, 1.095) (1.005, 1.074) (1.022, 1.079) (1.0009, 1.0026)
			SPI-1					

Table 6. Statistically significant effects of droughts measured at short term on daily natural, circulatory and respiratory mortality of the exposed population separated by gender and age groups when the effect of heatwaves and atmospheric pollutants remained controlled in Poisson modelling in the district of Lisbon from 2007 to 2016. P-value, coefficients, relative risks (RRs), the 95% confidence intervals of the coefficients and of the RRs were also displayed. SPEI-1/SPI-1= The Standardized Precipitation Evapotranspiration Index/The Standardized Precipitation Index obtained at one month of accumulation. "-n" after the Thwave and each pollutant correspond to the manifestation of the effects of these climatic phenomena on daily mortality, range from 0 "immediate" to 4 (lag 4).

Finally, we carried out an assessment by adult age group (Table 6) to detect if the significance of drought indices remained statistically significant when the previous commented phenomena were included in Poisson models. In fact, there were notable differences. For example, the significance of drought indices remained in specific subgroups within the total and male populations. Moreover, the mortality in the male age subgroups was associated with the highest number of pollutants. These differences could contribute to the higher risk in elderly male groups compared to elderly female groups.

The effects of drought on mortality that remained statistically significant in specific subgroups of the total population and men could be linked to other impacts of droughts that have not been considered in this analysis, such as serious mental health issues (e.g., chronic stress, anxiety, and depression among others). These have been linked to pathogenic processes and could result in a higher risk of mortality, especially in vulnerable people such as farmers or farm workers and workers with pre-existing conditions (IPCC, 2014; Berman et al., 2017; Salvador et al., 2020a; Edwards et al., 2015). The World Health Organisation has indicated that prolonged droughts can increase the suicide risk in male farmers (WHO, 2014). In particular, in Australia, a study indicated differences in the affectation of droughts on mortality by suicide between rural men and women in the period from 1997 to 2007. An increase in suicide was observed in farmer and farmworkers, especially in rural male adults (30–49 years old), whereas a decrease in suicide during drought conditions was evidenced in women over 30 years old (Hanigan et al., 2012).

Our results are in concordance with previous studies that indicate different affectations between men and women to the effect of air pollution on mortality (Clougherty, 2000). Moreover, in the case of the impact of heatwaves on mortality, men in the 65–-74 year-old have higher impacts of heatwaves on daily mortality than women, although women over-75 years old were the most affected by extreme heat on circulatory-caused mortality (Díaz et al., 2002); however, this study includes the effect of drought in this relationship.

3. **Conclusions**

For first time, the effects of drought measured by the SPEI and SPI on specific-cause mortality including an assessment by gender and adult age group in the Lisbon district from 1983 to 2016 were evaluated. Additionally, the impact of short-term droughts when the control of heatwaves and atmospheric pollution remained in the Poisson models was analysed for the sub-period 2007 to 2016, which was the available period for the pollutant data. The main conclusions were the following:

- Droughts had a significant impact on daily natural, circulatory, and respiratory mortality across the population. Moreover, the SPEI was a better indicator than the SPI for reflecting the different risks of mortality attributable to the incidence of this hydrological extreme.
- Not all the study subgroups within the population were equally affected by the drought conditions in terms of daily mortality and the risks varied between long and short study periods.

- Considering the assessment by age group, there was no statistically significant association between drought events and mortality in people 45 to 64 years old. During the long study period, individuals over 75 years old were the most affected group; for the sub-period 2007 to 2016, both the 65–74 and over-75 age groups were notably impacted, being this last group the most affected.
- There were gender differences in the risks of mortality associated with the incidence of this hydroclimatic phenomena. These differences were more evident from the last period of study when we considered both gender and age in the analysis; the male population was more affected than the female population.
- The short-term impact of drought among the population could be explained primarily by the impact of heatwaves and atmospheric pollution. However, when the analysis by age group was considered in specific cases, the statistically significance of the SPEI/SPI remained some groups in the total and male populations.
- The integration of these results that consider the assessment by gender and age into public heath are crucial to the enhancement of action plans and the development of more effective measures to address the risks of these climatic extremes on health (mitigate the effects and reduce the vulnerability among the population subgroups). This is particularly important considering future projections of climate change that indicate more frequent and severe droughts in several regions of the world, including southwestern Europe.

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5

SUMMARY, CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

5.1. Summary and conclusions

Drought is widely considered to be the costliest, most complex, and destructive phenomenon affecting more people, including their health, than any other natural hazard. It impacts the environmental, ecological, economic, and social sectors at both the global and regional scale through decreased water availability and quality, reduced food production and food security, effects on air quality, increased occurrence of wildfires (especially when it occurs with heatwaves) and dust events, altered ecology of vector-borne diseases, significant economic losses, and mental health repercussions. Drought is increasingly associated with a higher risk of morbidity and mortality worldwide, and the magnitude of the risks depend largely on environmental, social, and economic factors. Moreover, drought effects are principally indirect and accumulated, and many are cascading impacts. Meanwhile, droughts may often incorporate impacts of other phenomena, such as extreme temperatures or atmospheric pollution, which can increase the health threats, including a higher risk of respiratory and circulatory mortality in the exposed population.

In this thesis, the relationship between drought occurrence and daily specific-cause mortality in a vulnerable region of the Iberian Peninsula was investigated.

These studies focused on the assessment of which types of drought indices and timescales are the best proxies to identify and reflect the impacts on particular aspects of human health, which are crucial to gain a better understanding of the mechanisms through which different drought conditions can affect health in a specific region. Vulnerability assessment among different groups of the population are also essential to obtain more precise information of the population at risk. These types of studies are essential to improve drought monitoring and management and to gain information that allows the development and implementation of more effective action plans in order to mitigate risks and reduce vulnerability among population subgroups, especially in the most susceptible groups.

The main findings from this thesis are presented below in the same sequence as the papers in Chapter 4.

In the **regional study in Galicia (NW Spain)** during the period from 1983 to 2013, drought events measured by both the SPEI and SPI were significantly associated with daily natural, circulatory, and respiratory mortality. The geographical characteristics of this region allow the inference of differences concerning the distance to the coast. Thus, greater impacts were found inland than in coastal provinces (Lugo and Ourense vs. A Coruña and Pontevedra, respectively). In general, the effects on mortality in interior regions were mainly associated with high-severity drought, while those in A Coruña were mainly associated with moderate-severity drought. Particularly, Lugo was the province most affected in terms of mortality (all types of mortality causes were influenced by the occurrence of this hydrological extreme, which was measured by both types of drought indices and calculated at the short, short-medium, medium, and long term). In addition, in this province, the highest number of days with drought conditions and with the highest value of accumulated days with severe and extreme drought were registered. Contrarily, in Pontevedra, there was no significant association between this phenomenon and daily mortality for any cause, and it showed the lowest number of days with drought conditions. Although in inland regions daily mortality attributable to drought was evidenced for different timescales of the SPEI and SPI, the main findings suggested that mortality was mainly manifested for shorter periods (1 and 3 months of accumulation) with the highest

RR values obtained. In the case of A Coruña, only the association between circulatory mortality and prolonged droughts (9 months of accumulation) measured by both the SPEI and SPI was found. Particularly, daily respiratory mortality in Ourense was the cause most strongly linked to drought episodes. In this province, the impact of short-term drought on mortality could be explained by the effects of atmospheric pollution.

An overall view shows that respiratory and circulatory mortality causes were the most affected by droughts, and the monitoring of the SPEI or SPI was equally valid to assess the effects in terms of the RR of drought on natural, circulatory, and respiratory mortality in Galicia.

In a **nationwide context for peninsular Spain** for the period of 2000 to 2009, the main findings showed a significant influence of the short-term droughts measured by both the SPI and SPEI calculated at 1 month of accumulation and daily natural, circulatory, and respiratory mortality. The greatest impact was found on respiratory deaths, and circulatory deaths were the causes of mortality least associated with drought. Moreover, clear spatial heterogeneity across the country in terms of the mortality magnitude attributable to drought was observed, and western Spain was the territory most strongly affected. In the northeast, there were also several provinces where the relationship between droughts measured at the short-term and daily mortality was significant. Meanwhile, the main results of this study suggest that for a notable number of provinces, the effects of short-term droughts could be explained by atmospheric pollution (and/or T*hwave* in some cases), whereas for other regions the impacts of droughts remained significant when all phenomena were controlled (both the SPEI or SPI, extreme heat temperatures and atmospheric pollution).

When the **short-medium-term effects of drought (3 months of accumulation) on daily mortality were analysed in peninsular Spain,** it was observed that daily mortality increased for daily natural and respiratory-cause mortality, with this increase being especially remarkable for respiratory deaths. Comparing the RRs measured with both indices at the same timescale (SPEI-1 vs. SPI-1 and SPEI-3 vs. SPI-3), it was found that the results were very similar.

It is important to note that although the overall RR of respiratory deaths associated with drought measured by the SPI was greater for short-medium-term drought than for short-term drought (1 month of accumulation), the number of affected provinces was lower. In the case of circulatory mortality, the global RR was similar for both time measures, but the number of provinces with a significant mortality-drought relationship increased notably at the short-medium-term for SPI. Although for the majority of provinces the use of both indices (SPEI and SPI) revealed similar results, there were some particular provinces where only one of both showed a significant influence of drought on a specific cause of death. This was also observed in relation to the timescales used.

Although the analysis at the national level showed an overall perspective reflecting the main evidence, the evaluation of other intermediate territorial groups showed additional differences and heterogeneity across the country.

The Spanish public health system is held by the Autonomous Communities, so for regional administrations it is extremely important to understand the factors that affect the risk of mortality for the population to make planning and management decisions. Galicia, Castilla y Leon, and Extremadura were the regions that showed the greatest risk of daily mortality associated with drought episodes. Other autonomous regions, such as Andalucía (principally for respiratory deaths) and País Vasco (principally for circulatory deaths linked to droughts measured at the short-medium-term), were also notably impacted. However, the least affected regions were the Comunidad de Madrid, Cataluña, and Asturias. Meanwhile, some differences in the magnitude of the risks according to the type of index, timescale used, and cause of mortality were found. In Castilla-y-León, significant greater impacts on respiratory deaths were observed for short-medium-term droughts than for short-term droughts measured by SPI.

The administrative divisions did not correspond to climatological criteria. Thus, it is necessary to compare the study to others in areas showing similar spatial behaviour of drought. The main findings indicated that drought events had a significant influence on daily mortality in all regions, except for in East Spain, with the northwest, southwest, and centre being the regions most affected. Particularly, the northwest and southern regions showed the greatest risk of natural deaths, especially for short-medium-term drought events, whereas for circulatory deaths the northwest (mainly for short drought episodes) and the centre and south Spain (principally for droughts measured at the short-medium-term) were the most impacted. In the case of respiratory deaths, the highest risk was observed in the south and northwest (for both drought timescales) as well as in the north (for the shorter timescale) or centre (for the longer timescale). Moreover, the lowest effect of drought on daily mortality was found in the northeast, except for circulatory deaths when it was measured at a shorter term by the SPI.

Elderly people are one of the most vulnerable groups to diverse external factors, and the risk of mortality increased significantly in several studies using other variables. The prospective analysis conducted in this research showed that the regions with the highest proportion of people over 65-year-old reflected the greatest risk of any analysed cause of mortality associated with drought events. Moreover, the impact of drought on daily mortality in this group was higher for short-medium-term droughts.

The analysis for the Iberian Peninsula was completed with the study of daily mortality conducted for the Lisbon district in Portugal. The available data allowed the control of both gender and age.

In **Lisbon district** from 1983 to 2016, daily natural, circulatory, and respiratory-cause mortality were significantly associated with drought events measured at the short and short-medium term. Moreover, not all the study subgroups within the population were equally affected. Among the different age groups included in the analysis (45–64, 65–74, and over 75 years old), the oldest were the most affected (possibly owing to their weakened immune response to environmental stress), whereas in the case of the 45–64 years old group no significant association between droughts and mortality was found.

Meanwhile, taking into account both gender and age, a fluctuation in the short-term drought risks on daily mortality between men and women was observed. In terms of the drought index, the SPEI reflected a greater mortality risk in women over 75 years old for circulatory mortality, while no significant association was found in the case of men. However, the SPI indicated that the male population was the highest risk group, especially for natural and respiratory deaths. In the short-term, the mortality risks varied between the long study period (1983 to 2016) and the sub-period (2007 to 2016) when pollution data were available. In the last (and shorter) study period, both people aged 65–74 and over 75 years old were notably impacted. In addition, gender differences were especially remarkable, with men more strongly affected by droughts than women. Short-term drought conditions were significantly associated with daily mortality in men from 65–74 and over 75 years old, whereas in the case of women it was only for over 75 years old. Moreover, drought only had a significant influence on respiratory mortality in men over 75 years old. Social factors and differences in both the degree of drought exposure and adaptive response between both genders could influence these results. Moreover, changes in the population vulnerability could contribute to the observed differences in the mortality risk between the long-term and short-term periods.

In Lisbon district, the short-term impact of drought among the population could be explained primarily by the impact of atmospheric pollution and heatwaves; however, when gender and age were considered in specific cases, the significant impacts of drought remained in the total and male populations when the additional control of heatwaves and pollution was conducted. Meanwhile, the SPEI was more capable than the SPI for reflecting the different risks of mortality attributable to the incidence of this hydrological extreme. Moreover, according to the timescale, the main findings suggest that the use of the SPEI calculated at the short-term (1 month of accumulation) reflected a higher number of statistically significant associations between drought and daily mortality than that in the short-medium-term (3 months of accumulation) among the different groups of the population for the 1983–2016 period, whereas the SPI at the short-medium-term appeared to be more optimal than the shortest timescale. Thus, unlike what was observed in Spain, the inclusion of the atmospheric evaporative demand in the calculation of the SPEI makes this index more optimal to reflect the health impacts associated with short-term drought conditions in Lisbon district.

5.2. Limitations

Although the autoregressive nature of the dependent variable, the seasonality, and the trend of the series were analysed, there are some limitations inherent in any ecological study that are important to know. Among them, the results are not extrapolated at an individual level. Moreover, the data of atmospheric pollutants (averaged from various measurement stations) do not represent individual exposure, as the pollutant measurement stations were heterogeneous in nature (similarly for temperature data). In addition, there was a problem of misalignment, which was also described in other studies that evaluated the impact of air pollution on health (Gelfand, 2000; Barceló et al., 2016). Other limitations of this type of research are the inability to examine some variables that could affect vulnerability to drought in terms of health impacts such as individual socioeconomic status, previous health conditions, or race.

5.3. Recommendations and future research

Drought is a growing threat to human health that is in need of more action. The introduction of the results of this study as recommendations for public health is necessary to address the risks of droughts on determinate aspects of human health. In this context, it is necessary to create an integrated proactive action plan (at national, regional, and local levels, as indicated in Linares et al. (2020b)) through an integrative approach that includes warning and public health surveillance systems against various climate-related extreme phenomena that can be concurrent, such as high temperatures, drought conditions, and pollution episodes (often associated), to minimise the effects (frequently interrelated) on circulatory and respiratory health and to reduce population vulnerability. Conducting adaptation measures and strategies attentive to possible synergies can help to minimise climate-related impacts on health more effectively than considering a single environmental indicator, thereby protecting human health from an integral point of view. These should be designed ad hoc and contextualised according to the function of the characteristics inherent to each region and population group. Moreover, the management of the health effects associated with drought and climate change requires inputs and cooperation of different government and society sectors. In this context, the Barcelona Public Health Agency planned an integrated surveillance system that integrates several climate-related factors based on previous studies conducted in this city (Villabí and Ventayol, 2016).

Linares et al. (2020b) have recently proposed an integrated action plan that could be conducted in the following four phases: i) the activation of different existing single-exposure prevention plans related to health impacts that can occur owing to certain circumstances, and when possible, adoption of corrective measures; ii) the assessment and quantification of health impacts expected by the event; iii) the activation of measures and actions to minimise the impact on health through population alerts and additional social and health services; and iv) the monitoring and evaluation of the plan through epidemiological surveillance.

Based on the recent draft of the national adaptation plan to climate change of Spain, it is of crucial importance to reinforce and promote coordinate adaptation (and prevention) action plans to reduce population vulnerability and minimise health risks and threats linked to climate change from a cross-sectional, multi-sectoral, and multi-level (different territorial scales) perspective. The characteristics that an effective adaptation plan should take into account to anticipate and minimise health risks linked to climate-related hazards and build social resilience are as follows: well-planned, flexible, coordination of different systems, international cooperation, inclusion of the human rights perspective, equity and social vulnerability, and integration of the gender perspective. It is important because the climate change effects vary among different groups within the population. Moreover, it is also important to promote surveillance systems and to update the information on the climatic change and the occurrence of extreme events and their implication in public health, and to reinforce its dissemination to enhance population awareness. In addition, the reinforcement of scientific research is crucial to obtain greater knowledge on the details of the risks of morbidity and mortality linked to the occurrence of extreme climatic events such as drought and other phenomena linked to climate change.

In consideration with the main findings of this study, some interesting perspectives and needs for future research are listed in the following statements.

- It is necessary to conduct an in-depth analysis by age and gender in order to gain better understanding of the possible factors that could influence greater vulnerability in determinate sub-groups of the population and develop more effective measures designed to minimise differences.

- A deeper seasonal analysis is required. During the summer, autumn, winter, and spring periods the climatological conditions are different, and droughts are associated with different meteorological synoptic patterns or associated with different effects on the environment and on human health. Thus, in order to gain more exhaustive knowledge on the mechanisms through which drought affects health, comparing the performance of different types of indices calculated at different timescales is required. Moreover, these analyses should control specific variables as a function of the season, e.g. cold wave temperatures or a flu epidemiology series in winter.

- The control of other climatic phenomena strongly linked to drought events, such as the incidence of wildfires and burned areas during drought periods, must be measured by different metrics.

- Although evidence indicates that there are higher PM levels during drought events, there is a lack of consideration in the analysis of possible changes in PM composition (e.g. more toxicity); thus, these possible changes during drought with respect to no-drought periods should be evaluated and compared to determine if they involve greater health impacts.

- It is recommended to investigate the association between drought episodes and local weather types and evaluate in more detail the possible environmental mechanisms that can link drought episodes with determinate health indicators.

- The behaviour during individual extreme droughts should be evaluated by province, or climatic areas, to analyse anomalies in the mortality after each event.

- An exhaustive study that considers the estimation of health risks linked to drought should be conducted taking into account different drought characteristics (severity, intensity, frequency, and duration).

- The impact of drought on aspects of human health not analysed in this study region should be evaluated, such as the specific causes of morbidity or mortality associated with gastrointestinal and nutritional pathologies and the impact of prolonged droughts on specific mental health repercussions. Moreover, different drought metrics should be used in order to obtain more information that allows the establishment of a more precise classification of drought effects on determinate health repercussions of short, medium, and long-term impacts.

- New methodological studies should be conducted that allow the exploration of the comparison of the results using other statistical models (e.g. distributed lag non-linear or DLNMs models) and other types of drought indices.

- Comparative studies that evaluate other vulnerability factors should be conducted, such as an analysis in developed vs. developing countries.

- Datasets of droughts at different temporal resolutions (weekly or monthly) should be obtained and used to analyse the effects of the occurrence of this hazard on health and compare the results obtained with daily series. This is important because in several regions of the world, health data (mortality or morbidity) are not available on daily or weekly scales.

- The health risks associated with the occurrence of drought conditions and high temperatures should be estimated under future scenarios of climate change through future trends of temperature and the SPEI/SPI.

- Preventive and early-warning measures must be developed to achieve better adaptation plans focusing on the most vulnerable groups in order to reduce their vulnerability. Drought management measures must also be strengthened.

A

SUPPLEMENTARY MATERIAL

In this section it is presented the supplementary material associated with each paper that conform the manuscript of this thesis. All this material is also published on-line if the article is published.

A.1. SUPPLEMENTARY APPENDIX

Supplement to: Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013.

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Equation S1. Statistical equation of Poisson models to estimate the risk of drought on daily mortality, controlling the effect of heatwaves and pollution.

$$\log E(Y_t^{\,p}) = \alpha AR1 + \beta_1^{\,p} drt_t^{\,p} + \gamma_1 sen_x + \gamma_2 \cos_x + \ldots + \delta_t day_t + \varepsilon\,(Thwave_t^{\,p}) + \sum_{x1\text{-}x4} \varepsilon_1\,(Lagx\ Thwave_t^{\,p}) +$$

$$+ \kappa\,(O3_t^{\,p}) + \sum_{x1\text{-}x9} \kappa_1\,(Lagx\ O3_t^{\,p}) + \lambda\,(PM10_t^{\,p}) + \sum_{x1\text{-}x5} \lambda_1\,(Lagx\ PM10_t^{\,p}) + \mu\,(NO2_t^{\,p}) + \sum_{x1\text{-}x5} \mu_1\,(Lagx\ NO2) + nconstant$$

where Y_t is the number of deaths outcomes on day t in province p.

α *AR1* is the factor that control the autorregresive nature of the dependent variable controlled from the autorregression of the first order of daily mortality, being α the regression coefficient value.

$\beta_1^{\,p}$ is the estimator or coefficient for drought in province p, and $drt_t^{\,p}$ is a continuous indicator SPEI or SPI for drought period in province p.

On the other hand, we adjusted for seasonal trends in the model, where γ_x is the regression coefficients for the following different statistical significant seasonality: annual (365-day), six-monthly (180-day), four-monthly (120-day), and quarterly (90-day), using the sine and cosine functions that correspond to these periodicities.

In the second part of the study to control the seasonality in summers, that they are four months, we controlled the seasonality of 120, 90 and also of 60.

We also adjusted for time trends ($\delta_t day_t$), and we controlled the extreme temperatures (heat wave) and several pollutants (mean O_3, NO_2 and *PM10* concentrations) as other independent variables.

On the other hand, we have also controlled the different lags of this independent variables associated to droughts (4 day delay for Thwave, 5 days delay for NO2, and PM10 variables until 9 days delay for O3 variable).

Finally, *nconstant* indicate the constant of each model. We used single models for independent SPI-n and SPEI-n series. This model was conducted individually for natural, circulatory, and respiratory causes of daily mortality.

Tables S1. Descriptive environmental and daily mortality characteristics in relation with droughts according to the different categorization, measured by SPEI and SPI obtained in time scales of 1, 3, 6, and 9 months, for each provincial capital cities of Galicia throughout 1983 to 2013 period.

Count of the total days with drought, and in function of the different categories of severity: "moderate", "severe" and "extreme", and the count of each different daily causes of mortality in relation with the different categories of this hydrological extreme in each provincial capital cities of Galicia.

SPEI - 1	**Drought assessment [1: "Moderate" ; 2,3: "Severe"; 4,5: "Extreme"]**											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2079 (18.36%)			2739 (24.19%)			2671 (23.59%)			2543 (22.46%)		
	1478	1181	50	1432	1241	66	1349	1260	62	1428	1065	50
Natural deaths	15495 (88169)			6161 (24641)			3593 (28460)			3972 (18109)		
	8301	6908	286	3269	2740	152	3421	3396	146	2204	1704	64
Circulatory deaths	5774 (30945)			2341 (9160)			2654 (10852)			1493 (6813)		
	3085	2596	93	1243	1043	55	1328	1271	55	809	668	16
Respiratory deaths	1765 (7006)			758 (2852)			861 (3212)			438 (1955)		
	914	818	33	394	341	23	440	410	11	247	183	8
Total deaths	23034 (126120)			9260 (36653)			10478 (42524)			5903 (26877)		
	12300	10322	412	4906	4124	230	5189	5077	212	3260	2555	88

SPEI - 3	**Drought assessment [1: "Moderate" ; 2,3: "Severe"; 4,5: "Extreme"]**											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2565 (22.65%)			2870 (25.35%)			2750 (24.29%)			2482 (21.92%)		
	1274	1213	78	1402	1420	48	1330	1322	53	1247	1213	22
Natural deaths	14833 (88169)			6383 (24641)			6856 (28460)			3903 (18109)		
	7304	7082	447	3102	3186	95	3423	3307	126	1975	1888	40
Circulatory deaths	5611 (30945)			2462 (9160)			2567 (10852)			1505 (6813)		
	2760	2690	161	1168	1255	39	1297	1224	46	767	725	13
Respiratory deaths	1691 (7006)			773 (2852)			821 (3212)			450 (1955)		
	840	800	51	386	372	15	404	401	16	234	195	21
Total deaths	22135 (126120)			9666 (36653)			10244 (42524)			5858 (26877)		
	10904	10572	659	4656	4813	197	5124	4932	188	2976	2808	74

SPEI - 6	Drought assessment [1: "Moderate" ; 2,3: "Severe"; 4,5: "Extreme"]											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2485 (21.95%)			3074 (27.15%)			2646 (23.37%)			2314 (20.44%)		
	1035	1322	128	1476	1478	120	1281	1188	177	1020	1146	148
Natural deaths	14125 (88169)			6845 (24641)			6337 (28460)			3687 (18109)		
	5885	7565	675	3256	3373	216	3202	3094	441	1691	1791	205
Circulatory deaths	5329 (30945)			2578 (9160)			2476 (10852)			1389 (6813)		
	2270	2789	270	1242	1253	83	1201	1099	176	639	663	87
Respiratory deaths	1536 (7006)			773 (2852)			754 (3212)			393 (1955)		
	646	829	61	352	388	33	368	334	52	180	192	21
Total deaths	20990 (126120)			10196 (36653)			9567 (42524)			5469 (26877)		
	8801	11183	1006	4850	5014	332	4771	4527	669	2510	2646	313

SPEI - 9	Drought assessment [1: "Moderate" ; 2,3: "Severe"; 4,5: "Extreme"]											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2939 (25.95%)			3190 (28.17%)			2871 (25.35%)			2544 (22.47%)		
	1431	1469	39	1500	1645	45	1303	1478	90	1236	1249	59
Natural deathss	16813 (88169)			7251 (24641)			7328 (28460)			4063 (18109)		
	8174	8402	237	3385	3773	93	3307	3863	158	2046	1945	72
Circulatory deaths	6356 (30945)			2722 (9160)			2681 (10852)			1478 (6813)		
	3192	3085	79	1266	1420	36	1228	1381	72	737	713	28
Respiratory deaths	1809 (7006)			874 (2852)			860 (3212)			448 (1955)		
	870	909	30	388	477	9	363	481	16	246	197	5
Total deaths	24980 (126120)			10847 (36653)			10869 (42524)			5989 (26877)		
	12236	12398	346	5039	5670	138	4898	5725	246	3029	2855	105

SPI - 1	Drought assessment [1: "Moderate" ; 2,3: "Severe"; 4,5: "Extreme"]											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2381 (21.03%)			2448 (21.62%)			2230 (19.69%)			2134 (18.85%)		
	1196	870	315	1118	996	334	898	967	365	841	946	347
Natural deaths	13652 (88169)			5511 (24641)			3593 (28460)			3390 (18109)		
	6769	5016	1867	2527	2263	721	1468	1707	418	1318	1523	549
Circulatory deaths	5128 (30945)			2100 (9160)			1283 (10852)			1281 (6813)		
	2516	1915	697	972	873	255	535	608	140	485	572	224
Respiratory deaths	1558 (7006)			695 (2852)			496 (3212)			374 (1955)		
	749	595	214	298	307	90	214	233	49	143	182	49
Total deaths	20338 (126120)			36653 (36653)			5372 (42524)			5045 (26877)		
	10034	7526	2778	3797	3443	1066	2217	2548	607	1946	2277	822

SPI - 3	Drought assessment [1: “Moderate” ; 2,3: “Severe”; 4,5: “Extreme”]											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2189 (19.33%)			2570 (22.70%)			2252 (19.89%)			2186 (19.31%)		
	985	845	359	1149	1048	373	1034	835	383	1057	796	333
Natural deaths	12557 (88169)			5737 (24641)			3232 (28460)			3443 (18109)		
	5462	4908	2187	2543	2333	861	1441	1302	489	1666	1271	506
Circulatory deaths	4787 (30945)			2231 (9160)			1124 (10852)			1342 (6813)		
	2100	1848	839	974	916	341	504	470	150	685	457	200
Respiratory deaths	1403 (7006)			710 (2852)			456 (3212)			382 (1955)		
	585	556	262	338	266	106	194	181	81	190	138	54
Total deaths	18747 (126120)			8678 (36653)			4912 (42524)			5167 (26877)		
	8147	7312	3288	3855	3515	1308	2139	1953	720	2541	1866	760

SPI - 6	Drought assessment [1: “Moderate” ; 2,3: “Severe”; 4,5: “Extreme”]											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2252 (19.89%)			2798 (24.71%)			2267 (20.02%)			2106 (18.60%)		
	879	1119	154	1236	1315	247	1033	989	245	886	990	230
Natural deaths	12803 (88169)			6233 (24641)			5834 (28460)			3330 (18109)		
	5091	6312	1400	2675	3028	530	2671	2535	628	1486	1535	309
Circulatory deaths	4835 (30945)			2348 (9160)			2167 (10852)			1260 (6813)		
	1957	2334	544	1013	1128	207	1014	914	239	558	570	132
Respiratory deaths	1416 (7006)			716 (2852)			659 (3212)			371 (1955)		
	585	690	141	291	364	61	290	290	79	165	178	28
Total deaths	19054 (126120)			9297 (36653)			8660 (42524)			4961 (26877)		
	7633	9336	2085	3979	4520	798	3975	3739	946	2209	2283	469

SPI - 9	Drought assessment [1: “Moderate” ; 2,3: “Severe”; 4,5: “Extreme”]											
provinces	A CORUÑA			LUGO			OURENSE			PONTEVEDRA		
Worsening drought periods stratified by severity	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme	Moderate	Severe	Extreme
TOTAL days with drought	2596 (22.93%)			2876 (25.40%)			2379 (21.01%)			2217 (19.58%)		
	1232	1283	81	1273	1520	83	1058	1262	59	1067	1015	135
Natural deaths	14948 (88169)			6538 (24641)			3900 (28460)			3553 (18109)		
	7104	7393	451	2843	3506	189	1551	2369	30	1791	1613	149
Circulatory deaths	5636 (30945)			2443 (9160)			1351 (10852)			1283 (6813)		
	2755	2714	167	1059	1310	74	532	812	7	617	598	68
Respiratory deaths	1618 (7006)			757 (2852)			503 (3212)			386 (1955)		
	746	829	43	322	416	19	175	322	6	209	168	9
Total deaths	22203 (126120)			9738 (36653)			5754 (42524)			5222 (26877)		
	10605	10937	661	4224	5232	282	2208	3503	43	2617	2379	226

Table S2. **Summary of the results of statistical significance obtained from Poisson modelling during 1983 to 2013 period.**

The table illustrates the statistically significant SPEI and SPI drought indicators ($p < 0.05$) that influence daily natural, circulatory, and respiratory-cause mortality at different timescales of drought accumulation (1, 3, 6, 9 months) for each provincial capital city of Galicia.

We have excluded those rows in which there were no statistically significant associations.

For Pontevedra there was not any statistically significant result.

The relative risk (RR) was calculated from the value of the estimator obtained in each model. The 95% confidence intervals (CI) of the estimator and of the RR are displayed.

Decreasing SPEI and SPI values of coefficient indicate worsening drought.

*The p-value=0.051 tend to be statistically significant.

REGION	Causes of mortality	p-value	Coefficients [95% CI]		RR [95% Conf. Interval]	
A Coruña	Circulatory deaths	**SPEI-9** (p=0.008)	-0.017	(-0.030, -0.004)	1.017	(1.004, 1.030)
		SPI-9 (p=0.018)	-0.015	(-0.028, -0.003)	1.015	(1.003, 1.028)
Lugo	Natural deaths	**SPEI-1** (p=0.007)	-0.018	(-0.031, -0.005)	1.018	(1.005, 1.031)
		SPEI-3 (p=0.001)	-0.023	(-0.036, -0.010)	1.023	(1.010, 1.037)
		SPEI-6 (p=0.040)	-0.014	(-0.026, -0.001)	1.014	(1.001, 1.026)
		SPEI-9 (p=0.037)	-0.014	(-0.027, -0.001)	1.014	(1.001, 1.027)
		SPI-1 (p=0.032)	-0.014	(-0.026, -0.001)	1.014	(1.001, 1.026)
		SPI-3 (p=0.001)	-0.023	(-0.036, -0.010)	1.023	(1.010, 1.037)
		SPI-6 (p=0.051)*	-0.013*	(-0.026, -0.000)*	1.013*	(1.000, 1.026)
		SPI-9 (p=0.048)	-0.013	(-0.027, -0.000)	1.013	(1.000, 1.027)
	Circulatory deaths	**SPEI-1** (p=0.006)	-0.030	(-0.051, -0.009)	1.030	(1.009, 1.052)
		SPEI-3 (p=0.000)	-0.048	(-0.069, -0.027)	1.049	(1.027, 1.071)
		SPEI-6 (p=0.002)	-0.033	(-0.055, -0.012)	1.034	(1.012, 1.056)
		SPEI-9 (p=0.002)	-0.034	(-0.056, -0.013)	1.035	(1.013, 1.057)
		SPI-1 (p=0.038)	-0.021	(-0.042, -0.001)	1.022	(1.001, 1.042)
		SPI-3 (p=0.000)	-0.044	(-0.064, -0.023)	1.045	(1.023, 1.066)
		SPI-6 (p=0.007)	-0.029	(-0.050, -0.008)	1.029	(1.008, 1.051)
		SPI-9 (p=0.003)	-0.034	(-0.055, -0.012)	1.034	(1.012, 1.057)
	Respiratory deaths	**SPEI-1** (p=0.021)	-0.045	(-0.084, -0.007)	1.046	(1.007, 1.087)
		SPI-1 (p=0.026)	-0.041	(-0.077, -0.005)	1.042	(1.005, 1.080)
Ourense	Natural deaths	**SPEI-1** (p=0.004)	-0.017	(-0.029, -0.006)	1.018	(1.006, 1.030)
		SPI-1 (p=0.004)	-0.016	(-0.028, -0.005)	1.017	(1.005, 1.028)
	Respiratory deaths	**SPEI-1** (p=0.002)	-0.055	(-0.091, -0.020)	1.057	(1.020, 1.095)
		SPEI-3 (p=0.011)	-0.045	(-0.080, -0.010)	1.046	(1.010, 1.083)
		SPEI-9 (p=0.030)	-0.037	(-0.071, -0.004)	1.038	(1.004, 1.074)
		SPI-1 (p=0.001)	-0.058	(-0.091, -0.025)	1.060	(1.025, 1.096)
		SPI-3 (p=0.003)	-0.051	(-0.085, -0.017)	1.052	(1.017, 1.089)
		SPI-9 (p=0.013)	-0.044	(-0.078, -0.009)	1.045	(1.009, 1.082)
Pontevedra	No statistically significant results					

Table S3. Summary of the results of statistical significance obtained from Poisson modeling during 1983 to 2013 in function to the severity: moderate and high severity.

The table illustrates the statistically significant categorized SPEI and SPI drought indicators ($p<0.005$) that influence daily natural, circulatory and respiratory-cause mortality at different timescales of drought accumulation (1, 3, 6 and 9 months).

It was categorized original series considering two groups: moderate severity and high severity (that comprises the severe and extreme groups (categorized as 2, 3, 4 and 5), because the extreme events only represent 0.89% to 6.69% and 2.48% to 17.01% of days with drought using SPEI and SPI, respectively; see Tables S1).

We have excluded those rows in which there were no statistical significant associations.

For Pontevedra there was not any statistical significant results.

REGION	Causes of mortality	p-value	Coefficients [95% CI]	
A Coruña	Circulatory deaths	**SPEI-9 moderate severity** (p=0.000)	0.071	(0.033,0.108)
		SPI-9 moderate severity (p=0.004)	0.059	(0.019,0.098)
Lugo	Natural deaths	**SPEI-9 moderate severity** (p=0.002)	0.057	(0.021,0.094)
		SPI-9 high severity (p=0.046)	0.036	(0.001,0.071)
	Circulatory deaths	**SPEI-3 high severity** (p=0.009)	0.079	(0.020,0.138)
		SPEI-6 moderate severity (p=0.032)	0.066	(0.006,0.126)
		SPEI-9 high severity (p=0.018)	0.068	(0.012,0.125)
		SPI-1 moderate severity (p=0.047)	0.068	(0.001,0.134)
		SPI-3 high severity (p=0.006)	0.084	(0.025,0.144)
		SPI-9 high severity (p=0.022)	0.067	(0.009,0.124)
	Respiratory deaths			
		SPI-1 high severity (p=0.025)	0.122	(0.015,0,229)
Ourense	Natural deaths	**SPEI-1 high severity** (p=0.000)	0.065	(0.029,0.100)
		SPI-1 high severity (p=0.000)	0.081	(0.046, 0.116)
	Respiratory deaths	**SPEI-1 moderate severity** (p=0.023)	0.117	(0.016, 0.218)
		SPEI-1 high severity (p=0.043)	0.107	(0.003, 0.210)
		SPEI-9 high severity (p=0.039)	0.102	(0.005, 0.198)
		SPI-1 moderate severity (p=0.014)	0.149	(0.030, 0.269)
		SPI-1 high severity (p=0.002)	0.159	(0.059, 0.259)
		SPI-3 high severity (p=0.034)	0.115	(0.009,0.221)
		SPI-9 high severity (p=0.031)	0.114	(0.010,0.218)
Pontevedra	No statistically significant results			

A.2. SUPPLEMENTARY APPENDIX

Supplement to: Short-term effects of drought on daily mortality in Spain from 2000 to 2009

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Figure S1. Region under study: Peninsular Spain. Each province of Spain is represented and named according to the European NUTs3 administrative nomenclature. The regional subdivision mainly corresponds to climatic characteristics (Northwest, North, Northeast, Center, East, Southwest and Southeast).

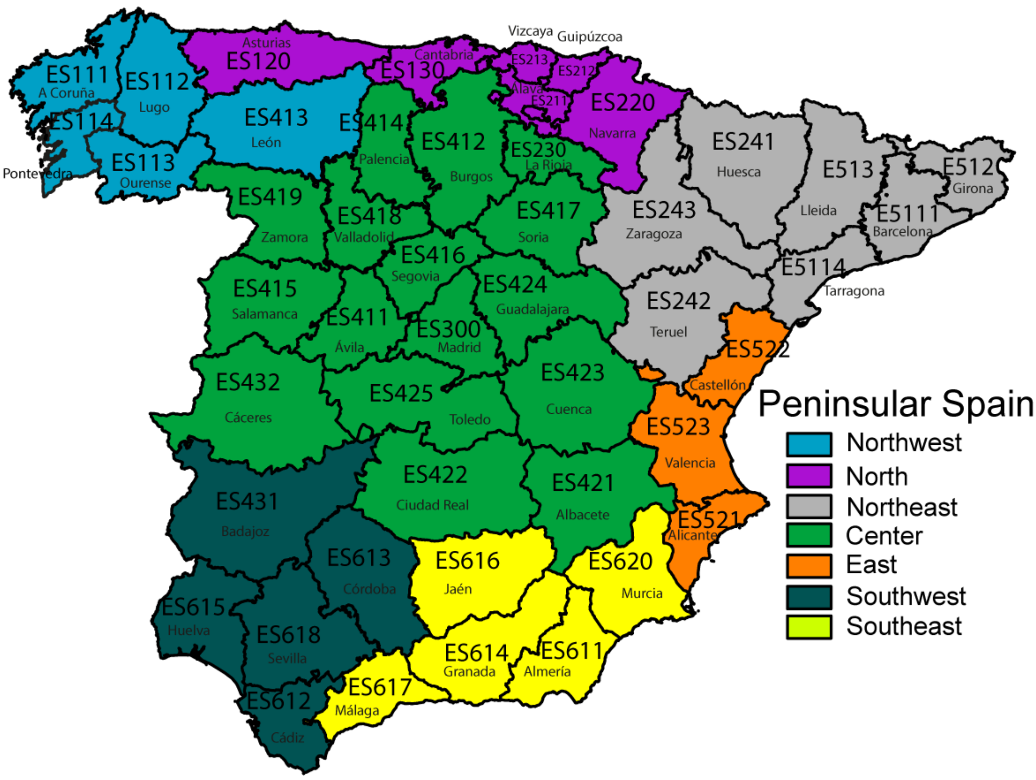

Fig. S2. Illustration of the RRs of daily mortality associated to droughts measured by the Standardized Precipitation Index obtained at 1 month of accumulation (SPI-1) and Standardized Precipitation-Evapotranspiration Index obtained at one month of accumulation (SPI-1) when the impact of heatwaves was controlled in Poisson modelling across Spain during 2000 to 2009. A) Relative Risks (RRs) of daily natural, circulatory and respiratory-cause mortality linked to occurrence of droughts only when the SPI-1/SPEI-1 climatic variables were considered. B) RRs of each cause of daily mortality linked to occurrence of droughts when Thwave variable was also controlled in statistical models. In Palencia there was no available mortality data during the study period.

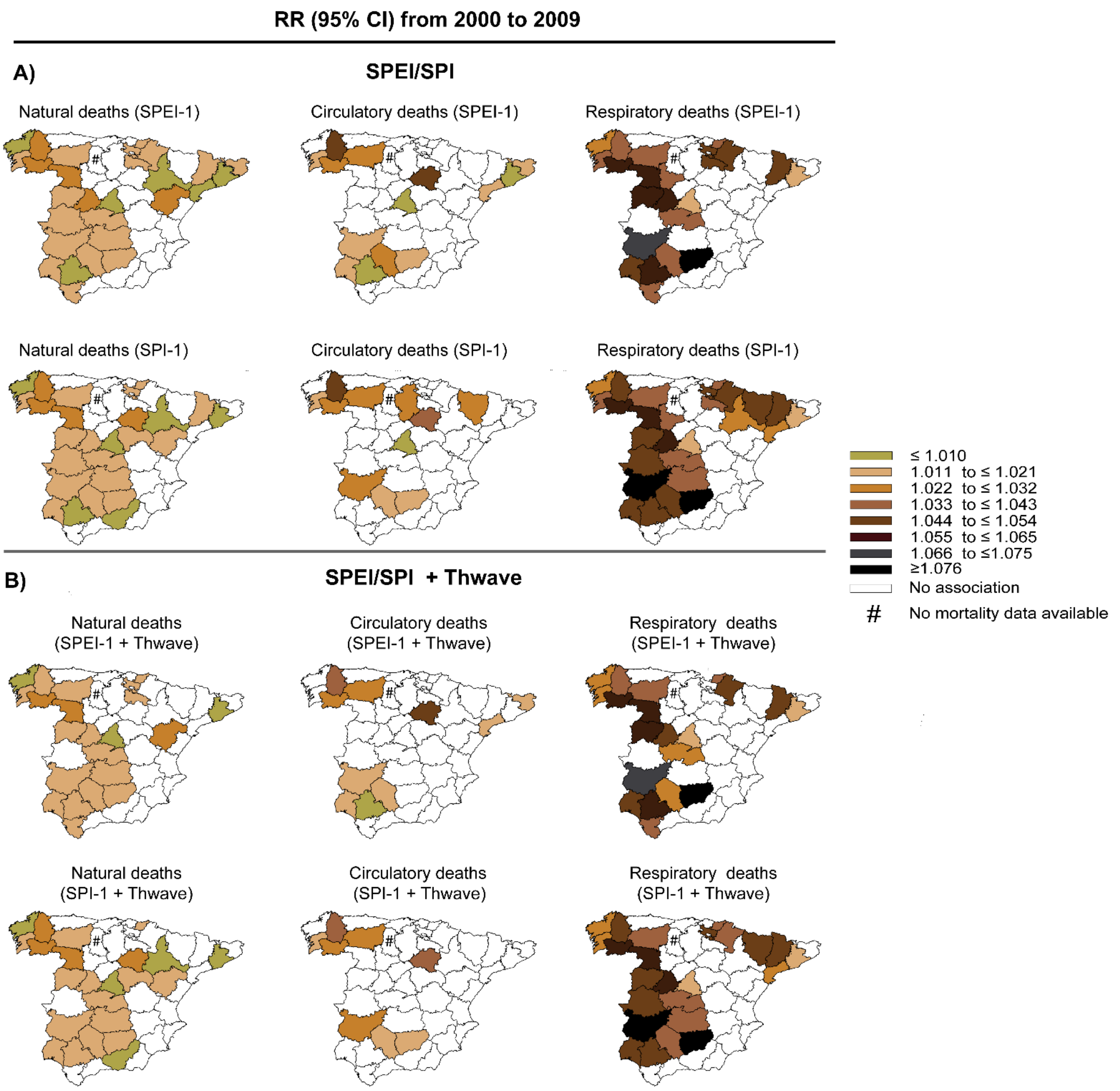

Table S1. Summary of the statistically significant results obtained from Poisson models when the effects on daily mortality of droughts measured by the Standardized Precipitation Index obtained at 1 month of accumulation (SPI-1) and Standardized Precipitation-Evapotranspiration Index obtained at one month of accumulation (SPEI-1) were evaluated across Spain during 2000 to 2009 period. The table shows the provinces of Spain where there was a statistical significance between SPEI-1/SPI-1 and daily natural, circulatory and respiratory-cause mortality during the studied period ($p<0.05$). Negative SPEI-1/SPI-1 values of the coefficients indicate higher mortality associated to droughts events because negative values of SPEI-1/SPI-1 describe drought conditions. In addition, decreasing values of indices indicate worsening drought. The relative risk (RR) was calculated from the value of the coefficient obtained in each model and the percentage of attributable risk (%AR = ((RR - 1)/RR) × 100) was obtained from RRs values. In addition, the 95% confidence intervals (CI) of the estimators and of the RRs are also displayed. *Madrid (ES300) data corresponds with the period 2001 to 2009. **The p-value = 0.050 or 0.051 tend to be statistically significant. In Palencia there was no mortality data available during the study period.

REGION	Causes of mortality	p-value	Coeff. [95% CI]		RR [95% CI]		%AR
A CORUÑA (ES111)	Natural deaths	**SPEI-1** (p=0.003)	-0.009	(-0.015, -0.003)	1.009	(1.003, 1.015)	0.89%
		SPI-1 (p=0.004)	-0.009	(-0.015, -0.003)	1.009	(1.003, 1.015)	0.89%
	Respiratory deaths	**SPEI-1** (p=0.002)	-0.027	(-0.043, -0.010)	1.027	(1.010, 1.044)	2.63%
		SPI-1 (p=0.004)	-0.024	(-0.041, -0.008)	1.024	(1.008 1.042)	2.34%
LUGO (ES112)	Natural deaths	**SPEI-1** (p=0.000)	-0.026	(-0.036, -0.016)	1.026	(1.016, 1.037)	2.53%
		SPI-1 (p=0.000)	-0.026	(-0.036, -0.017)	1.026	(1.017, 1.037)	2.53%
	Circulatory deaths	**SPEI-1** (p=0.000)	-0.048	(-0.064, -0.032)	1.049	(1.033, 1.066)	4.67%
		SPI-1 (p=0.000)	-0.047	(-0.062, -0.031)	1.048	(1.031, 1.064)	4.58%
	Respiratory deaths	**SPEI-1** (p=0.003)	-0.042	(-0.070, -0.014)	1.043	(1.014, 1.073)	4.12%
		SPI-1 (p=0.002)	-0.043	(-0.070, -0.016)	1.044	(1.016, 1.073)	4.21%
OURENSE (ES113)	Natural deaths	**SPEI-1** (p=0.000)	-0.026	(-0.035, -0.016)	1.026	(1.016, 1.036)	2.53%
		SPI-1 (p=0.000)	-0.025	(-0.035, -0.016)	1.025	(1.016, 1.036)	2.44%
	Circulatory deaths	**SPEI-1** (p=0.000)	-0.030	(-0.045, -0.014)	1.030	(1.014, 1.046)	2.91%
		SPI-1 (p=0.000)	-0.030	(-0.045, -0.016)	1.030	(1.016, 1.046)	2.91%
	Respiratory deaths	**SPEI-1** (p=0.000)	-0.054	(-0.080, -0.029)	1.055	(1.029, 1.083)	5.21%
		SPI-1 (p=0.000)	-0.054	(-0.079, -0.029)	1.055	(1.029, 1.082)	5.21%
PONTEVEDRA (ES114)	Natural deaths	**SPEI-1** (p=0.000)	-0.017	(-0.024, -0.010)	1.017	(1.010, 1.024)	1.67%
		SPI-1 (p=0.000)	-0.017	(-0.025, -0.010)	1.017	(1.010, 1.025)	1.67%
	Circulatory deaths	**SPEI-1** (p=0.022)	-0.014	(-0.026, -0.002)	1.014	(1.002, 1.025)	1.38%
		SPI-1 (p=0.008)	-0.016	(-0.028, -0.004)	1.016	(1.004, 1.028)	1.57%
	Respiratory deaths	**SPEI-1** (p=0.002)	-0.032	(-0.052, -0.012)	1.033	(1.012, 1.053)	3.19%
		SPI-1 (p=0.002)	-0.032	(-0.052, -0.012)	1.033	(1.012, 1.053)	3.19%
ALAVA (E211)	Natural deaths	**SPEI-1** (p=0.014)	-0.018	(-0.033, -0.004)	1.018	(1.004, 1.034)	1.77%
		SPI-1 (p=0.036)	-0.016	(-0.031, -0.001)	1.016	(1.001, 1.031)	1.57%
	Respiratory deaths	**SPEI-1** (p=0.030)	-0.052	(-0.099, -0.005)	1.053	(1.005, 1.104)	5.03%
		SPI-1 (p=0.033)	-0.051	(-0.097, -0.004)	1.052	(1.004, 1.102)	4.94%
GUIPUZCOA (ES212)	Natural deaths	**SPEI-1** (p=0.005)	-0.014	(-0.023, -0.004)	1.014	(1.004, 1.023)	1.38%
		SPI-1 (p=0.005)	-0.013	(-0.023, -0.004)	1.013	(1.004, 1.023)	1.28%
	Respiratory deaths	**SPEI-1** (p=0.020)	-0.034	(-0.062, -0.005)	1.035	(1.005, 1.064)	3.38%
		SPI-1 (p=0.021)	-0.033	(-0.062, -0.005)	1.034	(1.005, 1.064)	3.29%
NAVARRA (ES220)	Natural deaths	**SPEI-1** (p=0.027)	-0.011	(-0.021, -0.001)	1.011	(1.001, 1.021)	1.09%
	Respiratory deaths	**SPEI-1** (p=0.001)	-0.048	(-0.076, -0.021)	1.049	(1.021, 1.079)	4.67%
		SPI-1 (p=0.001)	-0.043	(-0.069, -0.017)	1.044	(1.017, 1.071)	4.21%
LA RIOJA (ES230)	Natural deaths	**SPEI-1** (p=0.022)	-0.015	(-0.028, -0.002)	1.015	(1.002, 1.028)	1.48%
	Respiratory deaths	**SPEI-1** (p=0.021)	-0.045	(-0.084, -0.007)	1.046	(1.007, 1.088)	4.40%
		SPI-1 (p=0.033)	-0.039	(-0.076, -0.003)	1.040	(1.003, 1.079)	3.85%
HUESCA (ES241)	Circulatory deaths						
		SPI-1 (p=0.036)	-0.025	(-0.048, -0.002)	1.025	(1.002, 1.049)	2.44%
	Respiratory deaths						
		SPI-1 (p=0.038)	-0.046	(-0.089, -0.003)	1.047	(1.003, 1.093)	4.49%

REGION	Causes of mortality	p-value	Coeff. [95% CI]		RR [95% CI]		%AR
TERUEL (ES242)	Natural deaths	**SPEI-1** (p=0.006)	-0.024	(-0.041, -0.007)	1.024	(1.007, 1.042)	2.34%
		SPI-1 (p=0.012)	-0.021	(-0.038, -0.005)	1.021	(1.005, 1.039)	2.06%
ZARAGOZA (ES243)	Natural deaths	**SPEI-1** (p=0.032)	-0.008	(-0.016, -0.001)	1.008	(1.002, 1.018)	0.79
		SPI-1 (p=0.009)	-0.010	(-0.018, -0.002)	1.010	(1.002, 1.018)	0.99
	Respiratory deaths						
		SPI-1 (p=0.040)	-0.024	(-0.046, -0.001)	1.024	(1.001, 1.047)	2.34
MADRID (ES300)* (2001-2009)	Natural deaths	**SPEI-1** (p=0.000)	-0.007	(-0.010, -0.003)	1.007	(1.003, 1.010)	0.70%
		SPI-1 (p=0.001)	-0.007	(-0.011, -0.003)	1.007	(1.003, 1.011)	0.70%
	Circulatory deaths	**SPEI-1** (p=0.005)	-0.010	(-0.017, -0.003)	1.010	(1.003, 1.017)	0.99%
		SPI-1 (p=0.039)	-0.007	(-0.014, -0.000)	1.007	(1.000, 1.014)	0.70%
	Respiratory deaths	**SPEI-1** (p=0.000)	-0.019	(-0.029, -0.009)	1.019	(1.009, 1.029)	1.86%
		SPI-1 (p=0.000)	-0.020	(-0.030, -0.010)	1.020	(1.010, 1.030)	1.96%
AVILA (ES411)	Natural deaths	**SPEI-1** (p=0.007)	-0.022	(-0.039, -0.006)	1.022	(1.006, 1.040)	2.15%
		SPI-1 (p=0.022)	-0.020	(-0.036, -0.003)	1.020	(1.003, 1.037)	1.96%
	Respiratory deaths	**SPEI-1** (p=0.013)	-0.060	(-0.107, -0.013)	1.062	(1.013, 1.113)	5.84%
		SPI-1 (p=0.016)	-0.059	(-0.107, -0.011)	1.061	(1.011, 1.113)	5.75%
BURGOS (ES412)	Circulatory deaths						
		SPI-1(p=0.051)**	-0.022	(-0.044, 0.000)	1.022	(1.000, 1.045)	2.15%
LEON (ES413)	Natural deaths	**SPEI-1** (p=0.006)	-0.013	(-0.023, -0.004)	1.013	(1.004, 1.023)	1.28%
		SPI-1 (p=0.001)	-0.016	(-0.026, -0.006)	1.016	(1.006, 1.026)	1.57%
	Circulatory deaths	**SPEI-1** (p=0.001)	-0.027	(-0.043, -0.011)	1.027	(1.011, 1.044)	2.63%
		SPI-1 (p=0.000)	-0.030	(-0.047, -0.014)	1.030	(1.014, 1.048)	2.91%
	Respiratory deaths	**SPEI-1** (p=0.008)	-0.035	(-0.062, -0.009)	1.036	(1.009, 1.064)	3.47%
		SPI-1 (p=0.021)	-0.032	(-0.059, -0.005)	1.033	(1.005, 1.061)	3.19%
SALAMANCA (ES414)	Natural deaths	**SPEI-1** (p=0.003)	-0.018	(-0.029, -0.006)	1.018	(1.006, 1.029)	1.77%
		SPI-1 (p=0.009)	-0.016	(-0.028, -0.004)	1.016	(1.004, 1.028)	1.57%
	Respiratory deaths	**SPEI-1** (p=0.001)	-0.060	(-0.096, -0.025)	1.062	(1.025, 1.101)	5.84%
		SPI-1 (p=0.005)	-0.052	(-0.090, -0.015)	1.053	(1.015, 1.094)	5.03%
SORIA (ES417)	Natural deaths						
		SPI-1 (p=0.040)	-0.022	(-0.043, -0.001)	1.022	(1.001, 1.044)	2.15%
	Circulatory deaths	**SPEI-1** (p=0.011)	-0.045	(-0.080, -0.010)	1.046	(1.010, 1.083)	4.40%
		SPI-1 (p=0.028)	-0.039	(-0.073, -0.004)	1.040	(1.004, 1.076)	3.85%
VALLADOLID (ES418)	Respiratory deaths	**SPEI-1** (p=0.040)	-0.034	(-0.067, -0.002)	1.035	(1.002, 1.069)	3.38%
		SPI-1 (p=0.041)	-0.033	(-0.065, -0.001)	1.034	(1.001, 1.067)	3.29%
ZAMORA (ES419)	Natural deaths	**SPEI-1** (p=0.002)	-0.024	(-0.039, -0.009)	1.024	(1.009, 1.040)	2.34%
		SPI-1 (p=0.002)	-0.025	(-0.040, -0.009)	1.025	(1.009 1.041)	2.44%
	Respiratory deaths	**SPEI-1** (p=0.008)	-0.060	(-0.105, -0.016)	1.062	(1.016, 1.111)	5.84%
		SPI-1 (p=0.021)	-0.054	(-0.101, -0.008)	1.055	(1.008, 1.106)	5.21%
CIUDAD REAL (ES422)	Natural deaths	**SPEI-1** (p=0.004)	-0.015	(-0.025, -0.005)	1.015	(1.005, 1.025)	1.48%
		SPI-1 (p=0.004)	-0.015	(-0.025, -0.005)	1.015	(1.005, 1.025)	1.48%
	Respiratory deaths						
		SPI-1 (p=0.019)	-0.033	(-0.061, -0.005)	1.034	(1.005, 1.063)	3.29%
GUADALAJARA (ES424)	Natural deaths						
		SPI-1 (p=0.043)	-0.017	(-0.034, -0.001)	1.017	(1.001, 1.035)	1.67%
TOLEDO (ES425)	Natural deaths	**SPEI-1** (p=0.012)	-0.013	(-0.023, 0.003)	1.013	(1.003, 1.023)	1.28%
		SPI-1 (p=0.004)	-0.016	(-0.027, -0.005)	1.016	(1.005, 1.027)	1.57%
	Respiratory deaths	**SPEI-1** (p=0.027)	-0.032	(-0.060, -0.004)	1.033	(1.004, 1.062)	3.19%
		SPI-1 (p=0.009)	-0.041	(-0.071, -0.010)	1.042	(1.010, 1.074)	4.03%
BADAJOZ (ES431)	Natural deaths	**SPEI-1** (p=0.000)	-0.019	(-0.028, -0.010)	1.019	(1.010, 1.028)	1.86%
		SPI-1 (p=0.000)	-0.017	(-0.026, -0.008)	1.017	(1.008, 1.026)	1.67%
	Circulatory deaths	**SPEI-1** (p=0.008)	-0.021	(-0.036, -0.005)	1.021	(1.005, 1.037)	2.06%
		SPI-1 (p=0.002)	-0.023	(-0.038, -0.008)	1.023	(1.008, 1.039)	2.25%
	Respiratory deaths	**SPEI-1** (p=0.000)	-0.072	(-0.099, -0.045)	1.075	(1.046, 1.104)	6.98%
		SPI-1 (p=0.000)	-0.073	(-0.100, -0.047)	1.076	(1.048, 1.105)	7.06%
CACERES (ES432)	Natural deaths	**SPEI-1** (p=0.050)**	-0.011	(-0.023, -0.000)	1.011	(1.000, 1.023)	1.09%
		SPI-1 (p=0.045)	-0.011	(-0.023, -0.000)	1.011	(1.000, 1.023)	1.09%
	Respiratory deaths						
		SPI-1 (p=0.005)	-0.043	(-0.074, -0.013)	1.044	(1.013, 1.077)	4.21%

REGION	Causes of mortality	p-value	Coeff. [95% CI]		RR [95% CI]		%AR
BARCELONA (ES511)	Natural deaths	**SPEI-1** (p=0.000)	-0.008	(-0.011, -0.005)	1.008	(1.005, 1.011)	0.79%
		SPI-1 (p=0.000)	-0.006	(-0.010, -0.003)	1.006	(1.003, 1.010)	0.60%
	Circulatory deaths	**SPEI-1** (p=0.003)	-0.009	(-0.014, -0.003)	1.009	(1.003, 1.014)	0.89%
	Respiratory deaths	**SPEI-1** (p=0.000)	-0.021	(-0.031, -0.011)	1.021	(1.011, 1.031)	2.06%
		SPI-1 (p=0.000)	-0.020	(-0.030, -0.009)	1.020	(1.009, 1.030)	1.96%
GIRONA (ES512)	Natural deaths	**SPEI-1** (p=0.013)	-0.012	(-0.021, -0.003)	1.012	(1.003, 1.021)	1.19%
	Circulatory deaths	**SPEI-1** (p=0.027)	-0.018	(-0.034, -0.002)	1.018	(1.002, 1.035)	1.77%
LLEIDA (ES513)	Natural deaths	**SPEI-1** (p=0.025)	-0.012	(-0.023, -0.001)	1.012	(1.001, 1.023)	1.19%
		SPI-1 (p=0.015)	-0.013	(-0.023, -0.003)	1.013	(1.003, 1.023)	1.28%
	Respiratory deaths	**SPEI-1** (p=0.002)	-0.047	(-0.077, -0.016)	1.048	(1.016, 1.080)	4.58%
		SPI-1 (p=0.000)	-0.053	(-0.083, -0.024)	1.054	(1.024, 1.087)	5.12%
TARRAGONA (ES514)	Natural deaths	**SPEI-1** (p=0.035)	-0.009	(-0.017, -0.001)	1.009	(1.001, 1.017)	0.89%
	Circulatory deaths	**SPEI-1** (p=0.045)	-0.015	(-0.029, -0.000)	1.015	(1.000, 1.02)	1.48%
	Respiratory deaths						
		SPI-1 (p=0.017)	-0.031	(-0.057, -0.006)	1.031	(1.006, 1.059)	3.01%
CADIZ (ES612)	Natural deaths	**SPEI-1** (p=0.001)	-0.013	(-0.021, -0.005)	1.013	(1.005, 1.021)	1.28%
	Respiratory deaths	**SPEI-1** (p=0.001)	-0.040	(-0.064, -0.016)	1.041	(1.016, 1.066)	3.94%
CORDOBA (ES613)	Natural deaths	**SPEI-1** (p=0.001)	-0.015	(-0.024, -0.007)	1.015	(1.007, 1.024)	1.48%
		SPI-1 (p=0.000)	-0.016	(-0.025, -0.008)	1.016	(1.008, 1.025)	1.57%
	Circulatory deaths	**SPEI-1** (p=0.003)	-0.022	(-0.036, -0.007)	1.022	(1.007, 1.037)	2.15%
		SPI-1 (p=0.013)	-0.018	(-0.032, -0.004)	1.018	(1.004, 1.033)	1.77%
	Respiratory deaths	**SPEI-1** (p=0.012)	-0.032	(-0.056, -0.007)	1.033	(1.007, 1.058)	3.19%
		SPI-1 (p=0.000)	-0.044	(-0.067, -0.020)	1.045	(1.020, 1.069)	4.31%
GRANADA (ES614)	Natural deaths						
		SPI-1 (p=0.036)	-0.008	(-0.016, -0.001)	1.008	(1.001, 1.016)	0.79%
HUELVA (ES615)	Natural deaths	**SPEI-1** (p=0.001)	-0.018	(-0.029, -0.008)	1.018	(1.008, 1.029)	1.77%
		SPI-1 (p=0.016)	-0.013	(-0.024, -0.002)	1.013	(1.002, 1.024)	1.28%
	Circulatory deaths	**SPEI-1** (p=0.026)	-0.019	(-0.036, -0.002)	1.019	(1.002, 1.037)	1.86%
	Respiratory deaths	**SPEI-1** (p=0.005)	-0.047	(-0.079, -0.014)	1.048	(1.014, 1.082)	4.58%
		SPI-1 (p=0.007)	-0.045	(-0.077, -0.012)	1.046	(1.012, 1.080)	4.40%
JAEN (ES616)	Natural deaths	**SPEI-1** (p=0.001)	-0.017	(-0.027, -0.008)	1.017	(1.008, 1.027)	1.67%
		SPI-1 (p=0.000)	-0.018	(-0.028, -0.009)	1.018	(1.009, 1.028)	1.77%
	Circulatory deaths	**SPEI-1** (p=0.048)	-0.016	(-0.033, -0.000)	1.016	(1.000, 1.034)	1.57%
		SPI-1 (p=0.032)	-0.017	(-0.033, -0.002)	1.017	(1.002, 1.034)	1.67%
	Respiratory deaths	**SPEI-1** (p=0.000)	-0.089	(-0.117, -0.061)	1.093	(1.063, 1.124)	8.51%
		SPI-1 (p=0.000)	-0.085	(-0.112, -0.058)	1.089	(1.060, 1.119)	8.17%
SEVILLA (ES618)	Natural deaths	**SPEI-1** (p=0.001)	-0.010	(-0.016, -0.004)	1.010	(1.004, 1.016)	0.99%
		SPI-1 (p=0.011)	-0.008	(-0.014, -0.002)	1.008	(1.002, 1.014)	0.79%
	Circulatory deaths	**SPEI-1** (p=0.040)	-0.010	(-0.019, -0.000)	1.010	(1.000, 1.019)	0.99%
	Respiratory deaths	**SPEI-1** (p=0.000)	-0.060	(-0.081, -0.040)	1.062	(1.041, 1.084)	5.84%
		SPI-1 (p=0.000)	-0.050	(-0.070, -0.030)	1.051	(1.030, 1.073)	4.85%

Table S2. Short-term effects of droughts on daily mortality when the effect of heatwaves was controlled in Poisson models across Spain during 2000 to 2009. The table shows the statistically significant results of the Relative Risks (RRs) and percentages of Attributable Risks (%ARs) of daily natural, circulatory and respiratory-mortality associated to droughts measured by SPEI-1/SPI-1 when also the impact of heatwaves was controlled. RRs were calculated from the value of the coefficient obtained in each model and the percentage of attributable risks (%AR = ((RR - 1)/RR) × 100)) were calculated from RRs values. In addition, the 95% confidence intervals (CI) of the estimators and of the RRs are also displayed. *Madrid (ES300) data corresponds with the period 2001 to 2009. **The p-value=0.052 tends to be statistically significant. In Palencia there was no available mortality data during the study period.

A CORUÑA (ES111)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.016)		-0.007	(-0.013, -0.001)	1.007	(1.001, 1.013)	0.70%
		Thwave (p=0.000)	0	0.024	(0.011, 0.038)	1.024	(1.011, 1.039)	
		Thwave (p=0.032)	1	0.015	(0.001, 0.028)	1.015	(1.001, 1.028)	
		Thwave (p=0.000)	3	0.022	(0.010, 0.034)	1.022	(1.010, 1.035)	
	SPI-1	SPI-1 (p=0.011)		-0.008	(-0.014, -0.002)	1.008	(1.002, 1.014)	0.79%
		Thwave (p=0.000)	0	0.025	(0.011, 0.038)	1.025	(1.011, 1.039)	
		Thwave (p=0.030)	1	0.015	(0.001, 0.029)	1.015	(1.001, 1.029)	
		Thwave (p=0.000)	3	0.022	(0.010, 0.035)	1.022	(1.010, 1.036)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.005)		-0.024	(-0.040, -0.007)	1.024	(1.007, 1.041)	2.34%
		Thwave (p=0.000)	1	0.059	(0.027, 0.092)	1.061	(1.027, 1.096)	
		Thwave (p=0.001)	3	0.054	(0.021, 0.087)	1.055	(1.021, 1.091)	
	SPI-1	SPI-1 (p=0.007)		-0.022	(-0.039, -0.006)	1.022	(1.006, 1.040)	2.15%
		Thwave (p=0.000)	1	0.060	(0.027, 0.093)	1.062	(1.027, 1.097)	
		Thwave (p=0.001)	3	0.055	(0.022, 0.088)	1.057	(1.022, 1.092)	
LUGO (ES112)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.021	(-0.031, -0.010)	1.021	(1.010, 1.031)	2.06%
		Thwave (p=0.004)	1	0.067	(0.021, 0.113)	1.069	(1.021, 1.120)	
		Thwave (p=0.006)	3	0.065	(0.019, 0.112)	1.067	(1.019, 1.119)	
	SPI-1	SPI-1 (p=0.000)		-0.022	(-0.033, -0.012)	1.022	(1.012, 1.034)	2.15%
		Thwave (p=0.004)	1	0.068	(0.022, 0.114)	1.070	(1.022, 1.121)	
		Thwae (p=0.005)	3	0.066	(0.020, 0.113)	1.068	(1.020, 1.120)	
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.036	(-0.052, -0.019)	1.037	(1.019, 1.053)	3.57%
		Thwave (p=0.006)	0	0.100	(0.029, 0.171)	1.105	(1.029, 1.186)	
	SPI-1	SPI-1 (p=0.000)		-0.035	(-0.051, -0.018)	1.036	(1.018, 1.052)	3.47%
		Thwave (p=0.005)	0	0.101	(0.031, 0.172)	1.106	(1.031, 1.188)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.010)		-0.039	(-0.069, -0.009)	1.040	(1.009, 1.071)	3.85%
		Thwave (p=0.049)	2	0.127	(0.000, 0.253)	1.135	(1.000, 1.288)	
	SPI-1	SPI-1 (p=0.003)		-0.045	(-0.075, -0.015)	1.046	(1.015, 1.078)	4.40%
		Thwave (p=0.046)	2	0.129	(0.003, 0.256)	1.138	(1.003, 1.292)	
OURENSE (ES113)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.025	(-0.035, -0.015)	1.025	(1.015, 1.036)	2.44%
		Thwave (p=0.000)	1	0.054	(0.029 0.078)	1.055	(1.029, 1.081)	
	SPI-1	SPI-1 (p=0.000)		-0.025	(-0.034, -0.016)	1.025	(1.016, 1.035)	2.44%
		Thwave (p=0.000)	1	0.055	(0.030, 0.080)	1.057	(1.030, 1.083)	
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.029	(-0.044, -0.013)	1.029	(1.013, 1.045)	2.82%
		Thwave (p=0.000)	1	0.074	(0.035, 0.114)	1.077	(1.036, 1.121)	
	SPI-1	SPI-1 (p=0.000)		-0.030	(-0.045, -0.015)	1.030	(1.015, 1.046)	2.91%
		Thwave (p=0.000)	1	0.076	(0.037, 0.115)	1.079	(1.038, 1.122)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.054	(-0.080, -0.028)	1.055	(1.028, 1.083)	5.21%
		Thwave (p=0.002)	0	0.104	(0.038, 0.171)	1.110	(1.039, 1.186)	
	SPI-1	SPI-1 (p=0.000)		-0.054	(-0.079, -0.029)	1.055	(1.029, 1.082)	5.21%
		Thwave (p=0.002)	0	0.107	(0.041, 0.174)	1.113	(1.042, 1.190)	

PONTEVEDRA (ES114)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000) Thwave (p=0.000) Thwave (p=0.000)	 1 3	-0.015 0.030 0.029	(-0.022, -0.008) (0.030, 0.006) (0.029, 0.006)	1.015 1.030 1.029	(1.008, 1.022) (1.030, 1.006) (1.029, 1.006)	1.48%
	SPI-1	SPI-1 (p=0.000) Thwave (p=0.000) Thwave (p=0.000)	 1 3	-0.016 0.031 0.030	(-0.023, -0.009) (0.019, 0.042) (0.018, 0.041)	1.016 1.031 1.030	(1.009, 1.023) (1.019, 1.043) (1.018, 1.042)	1.57%
Circulatory deaths	**SPEI-1**	Thwave (p=0.006) Thwave (p=0.000)	1 3	0.029 0.038	(0.008, 0.049) (0.018, 0.058)	1.029 1.039	(1.008, 1.050) (1.018, 1.060)	
	SPI-1	SPI-1 (p=0.023) Thwave (p=0.000) Thwave (p=0.000)	 1 3	-0.014 0.028 0.037	(-0.026, -0.002) (0.007, 0.048) (0.017, 0.057)	1.014 1.028 1.038	(1.002, 1.026) (1.007, 1.049) (1.017, 1.059)	1.38%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.009) Thwave (p=0.006) Thwave (p=0.000)	 1 3	-0.027 0.046 0.068	(-0.047, -0.007) (0.013, 0.079) (0.036, 0.100)	1.027 1.047 1.070	(1.007, 1.048) (1.013, 1.082) (1.037, 1.105)	2.63%
	SPI-1	SPI-1 (p=0.005) Thwave (p=0.005) Thwave (p=0.000)	 1 3	-0.029 0.047 0.069	(-0.048, -0.009) (0.014, 0.080) (0.037, 0.101)	1.029 1.048 1.071	(1.009, 1.049) (1.014, 1.083) (1.038, 1.106)	2.82%
ALAVA (ES211		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.039) Thwave (p=0.000)	 1	-0.016 0.110	(-0.030, -0.001) (0.057, 0.163)	1.016 1.116	(1.001, 1.030)	1.57%
	SPI-1	Thwave (p=0.000)	1	0.115	(0.062, 0.168)	1.122	(1.064, 1.183)	
Respiratory deaths	**SPEI-1**	Thwave (p=0.002)	1	0.230	(0.082, 0.378)	1.259	(1.085, 1.459)	
	SPI-1	SPI-1 (p=0.052)** Thwave (p=0.002)	 1	-0.046 0.234	(-0.093, 0.000) (0.086, 0.382)	1.047 1.264	(1.000, 1.097) (1.090, 1.465)	4.49%
GUIPUZCOA (ES212)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.010) Thwave (p=0.001) Thwave (p=0.003)	 1 4	-0.012 0.033 0.031	(-0.022,-0.003) (0.013, 0.054) (0.011, 0.052)	1.012 1.034 1.031	(1.003, 1.022) (1.013, 1.055) (1.011, 1.053)	1.19%
	SPI-1	SPI-1 (p=0.009) Thwave (p=0.001) Thwave (p=0.002)	 1 4	-0.013 0.034 0.032	(-0.022, -0.003) (0.014, 0.054) (0.011, 0.052)	1.013 1.035 1.033	(1.003, 1.022) (1.014, 1.055) (1.011, 1.053)	1.28%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.031) Thwave (p=0.002)	 0	-0.032 0.087	(-0.060, -0.003) (0.031, 0.143)	1.033 1.091	(1.003, 1.062) (1.031, 1.154)	3.19%
	SPI-1	SPI-1 (p=0.024) Thwave (p=0.002) Thwave (p=0.048)	 0 2	-0.033 0.091 0.061	(-0.061, -0.004) (0.034, 0.147) (0.000, 0.122)	1.034 1.095 1.063	(1.004, 1.063) (1.035, 1.158) (1.000, 1.130)	3.29%
NAVARRA (ES220)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000) Thwave (p=0.005)	1 4	0.096 0.059	(0.056, 0.136) (0.018, 0.101)	1.101 1.061	(1.058, 1.146) (1.018, 1.106)	
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p0.003) Thwave (p=0.000)	 3	-0.043 0.265	(-0.070, -0.015) (0.172, 0.358)	1.044 1.303	(1.015, 1.073) (1.188, 1.430)	4.21%
	SPI-1	SPI-1 (p0.002) Thwave (p=0.000)	 3	-0.041 0.273	(-0.067, -0.015) (0.180, 0.365)	1.042 1.314	(1.015, 1.069) (1.197 1.441)	4.03%
LA RIOJA (ES230)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.030) Thwave (p=0.006)	 4	-0.014 0.066	(-0.027, -0.001) (0.019, 0.114)	1.014 1.068	(1.001, 1.027) (1.019, 1.121)	1.38%
	SPI-1							
Respiratory deaths	**SPEI-1**	Thwave (p=0.039) Thwave (p=0.015)	1 4	0.143 0.168	(0.007, 0.278) (0.033, 0.304)	1.154 1.183	(1.007, 1.320) (1.034, 1.355)	
	SPI-1	Thwave (p=0.039) Thwave (p=0.015)	1 4	0.143 0.168	(0.007, 0.278) (0.033, 0.304)	1.154 1.183	(1.007, 1.320) (1.034, 1.355)	

HUESCA (ES241)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Circulatory deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.026)	3	0.055	(0.007, 0.104)	1.057	(1.007, 1.110)	
Respiratory Deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.026)		-0.052	(-0.098, -0.006)	1.053	(1.006, 1.103)	5.03%
		Thwave (p=0.001)	4	0.139	(0.057, 0.222)	1.149	(1.059, 1.249)	
TERUEL (ES242)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural Deaths	**SPEI-1**	SPEI-1 (p=0.006)		-0.024	(-0.041, -0.007)	1.024	(1.007, 1.042)	2.34%
	SPI-1	SPI-1 (P=0.012)		-0.021	(-0.038, -0.005)	1.021	(1.005, 1.039)	2.06%
ZARAGOZA (ES243)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural Deaths	**SPEI-1**	Thwave (p=0.005)	1	0.047	(0.030, 0.063)	1.048	(1.030, 1.065)	
		Thwave (p=0.000)	4	0.024	(0.007, 0.041)	1.024	(1.007, 1.042)	
	SPI-1	SPI-1 (p=0.015)		-0.009	(-0.017, -0.002)	1.009	(1.002,1.017)	0.90%
		Thwave (p=0.000)	1	0.046	(0.029, 0.062)	1.047	(1.029, 1.064)	
		Thwave (p=0.015)	4	0.023	(0.006, 0.040)	1.023	(1.006, 1.041)	
Respiratory Deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.001)	1	0.084	(0.032, 0.135)	1.088	(1.033, 1.145)	
MADRID (ES300)*		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural Deaths	**SPEI-1**	SPEI-1 (p=0.012)		-0.005	(-0.009, -0.001)	1.005	(1.001, 1.009)	0.50%
		Thwave (p=0.048)	0	0.010	(0.000, 0.020)	1.010	(1.000, 1.020)	
		Thwave (p=0.000)	1	0.024	(0.012, 0.036)	1.024	(1.012, 1.037)	
		Thwave (p=0.015)	2	0.015	(0.003, 0.026)	1.015	(1.003, 1.026)	
		Thwave (p=0.004)	3	0.015	(0.005, 0.025)	1.015	(1.005, 1.025)	
	SPI-1	SPI-1 (p=0.001)		-0.006	(-0.010, -0.002)	1.006	(1.002, 1.010)	0.60%
		Thwave (p=0.042)	0	0.010	(0.000, 0.020)	1.010	(1.000, 1.020)	
		Thwave (p=0.000)	1	0.024	(0.013, 0.036)	1.024	(1.013, 1.037)	
		Thwave (p=0.014)	2	0.015	(0.003, 0.026)	1.015	(1.003, 1.026)	
		Thwave (p=0.003)	3	0.015	(0.005, 0.025)	1.015	(1.005, 1.025)	
Circulatory Deaths	**SPEI-1**	Thwave (p=0.000)	1	0.036	(0.017, 0.054)	1.037	(1.017, 1.055)	
		Thwave (p=0.031)	2	0.022	(0.002, 0.041)	1.022	(1.002, 1.042)	
		Thwave (p=0.015)	4	0.020	(0.004, 0.036)	1.020	(1.004, 1.037)	
	SPI-1	Thwave (p=0.000)	1	0.036	(0.017, 0.054)	1.037	(1.017, 1.055)	
		Thwave (p=0.031)	2	0.022	(0.002, 0.041)	1.022	(1.002, 1.042)	
		Thwave (p=0.015)	4	0.020	(0.004, 0.036)	1.020	(1.004, 1.037)	
Respiratory Deaths	**SPEI-1**	SPEI-1 (p=0.001)		-0.016	(-0.026, -0.006)	1.016	(1.006, 1.026)	1.57%
		Thwave (p=0.000)	1	0.064	(0.044, 0.084)	1.066	(1.045, 1.088)	
		Thwave (p=0.002)	4	0.033	(0.012, 0.053)	1.034	(1.012, 1.054)	
	SPI-1	SPI-1 (p=0.000)		-0.020	(-0.030, -0.010)	1.020	(1.010, 1.030)	1.96%
		Thwave (p=0.000)	1	0.065	(0.045,0.085)	1.067	(1.046, 1.089)	
		Thwave (p=0.001)	4	0.035	(0.014, 0.055)	1.036	(1.014, 1.057)	
AVILA (ES411)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural Deaths	**SPEI-1**	SPEI-1 (p=0.012)		-0.021	(-0.038, -0.005)	1.021	(1.005, 1039)	2.06%
		Thwave (p=0.004)	1	0.063	(0.020, 0.107)	1.065	(1.020, 1.113)	
		Thwave (p=0.018)	3	0.053	(0.009, 0.097)	1.054	(1.009, 1.102)	
	SPI-1	SPI-1 (p=0.017)		-0.020	(-0.037, -0.004)	1.020	(1.0041.038)	1.96%
		Thwave (p=0.003)	1	0.065	(0.022, 0.109)	1.067	(1.022, 1.115)	
		Thwave (p=0.015)	3	0.055	(0.011, 0.099)	1.057	(1.011, 1.104)	
Respiratory Deaths	**SPEI-1**	SPEI-1 (p=0.029)		-0.053	(-0.101, -0.005)	1.054	(1.005, 1.106)	5.12%
		Thwave (p=0.000)	0	0.210	(0.106, 0.315)	1.234	(1.112, 1.370)	
		Thwave (p=0.010)	4	0.148	(0.036, 0.261)	1.160	(1.037, 1.298)	
	SPI-1	SPI-1 (p=0.013)		-0.061	(-0.109, -0.013)	1.063	(1.013, 1.115)	5.93%
		Thwave (p=0.000)	0	0.216	(0.111, 0.320)	1.241	(1.117, 1.377)	
		Thwave (p=0.010)	4	0.154	(0.042, 0.267)	1.166	(1.043, 1.306)	

BURGOS (ES412)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Circulatory Deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.000)	3	0.116	(0.052, 0.180)	1.123	(1.053, 1.197)	
LEON (ES413)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural Deaths	**SPEI-1**	SPEI-1 (p=0.008) Thwave (p=0.000)	 1	-0.013 0.075	(-0.023, -0.003) (0.039, 0.112)	1.013 1.078	(1.003, 1.023) (1.040, 1.119)	1.28%
	SPI-1	SPI-1 (p=0.001) Thwave (p=0.016)	 1	-0.016 0.078	(-0.026, -0.006) (0.041, 0.114)	1.016 1.081	(1.006, 1.026) (1.042, 1.121)	1.57%
Circulatory Deaths	**SPEI-1**	SPEI-1 (p=0.002) Thwave (p=0.001)	 1	-0.026 0.102	(-0.042, -0.010) (0.041, 0.163)	1.026 1.107	(1.010, 1.043) (1.042, 1.177)	2.53%
	SPI-1	SPI-1 (p=0.001) Thwave (p=0.000)	 1	-0.029 0.109	(-0.046, -0.012) (0.048, 0.170)	1.029 1.115	(1.012, 1.047) (1.049, 1.185)	2.82%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.008)		-0.035	(-0.062, -0.009)	1.036	(1.009, 1.064)	3.47%
	SPI-1	SPI-1 (p=0.021) Thwave (p=0.042)	 2	-0.032 0.114	(-0.059, -0.005) (0.004, 0.225)	1.033 1.121	(1.005, 1.061) (1.004, 1.252)	3.19%
SALAMANCA (ES415)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.005) Thwave (p=0.002) Thwave (p=0.023)	 1 2	-0.017 0.059 0.043	(-0.028, -0.005) (0.022, 0.096) (0.006, 0.080)	1.017 1.061 1.044	(1.005, 1.028) (1.022, 1.101) (1.006, 1.083)	1.67%
	SPI-1	SPI-1 (p=0.012) Thwave (p=0.002) Thwave (p=0.030)	 1 2	-0.016 0.057 0.041	(-0.028, -0.003) (0.020, 0.094) (0.004, 0.079)	1.016 1.060 1.042	(1.003, 1.028) (1.020, 1.099) (1.004, 1.082)	1.57%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.002) Thwave (p=0.000)	 2	-0.058 0.175	(-0.094, -0.022) (0.084, 0.266)	1.060 1.191	(1.022, 1.099) (1.088, 1.311)	5.66%
	SPI-1	SPI-1 (p=0.006) Thwave (p=0.000)	 2	-0.052 0.180	(-0.089, -0.015) (0.089, 0.271)	1.053 1.197	(1.015, 1.093) (1.093, 1.311)	5.03%
SORIA (ES417)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.040)		-0.022	(-0.043, -0.001)	1.022	(1.001, 1.044)	2.15%
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.011)		-0.045	(-0.080, -0.010)	1.046	(1.010, 1.083)	4.40%
	SPI-1	SPI-1 (p=0.028)		-0.039	(-0.073, -0.004)	1.040	(1.004, 1.076)	3.85%
VALLADOLID (ES418)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Respiratory deaths	**SPEI-1**	Thwave (p=0.020) Thwave (p=0.024)	2 3	0.226 0.218	(0.035, 0.417) (0.028, 0.409)	1.254 1.244	(1.036, 1.517) (1.028, 1.505)	
	SPI-1	Thwave (p=0.020) Thwave (p=0.024)	2 3	0.226 0.218	(0.035, 0.417) (0.028, 0.409)	1.254 1.244	(1.036, 1.517) (1.028, 1.505)	
ZAMORA (ES419)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.004) Thwave (p=0.031) Thwave (p=0.007)	 0 3	-0.022 0.097 0.120	(-0.037, -0.007) (0.009, 0.186) (0.032, 0.207)	1.022	(1.007, 1.038)	2.15%
	SPI-1	SPI-1 (p=0.003) Thwave (p=0.027) Thwave (p=0.006)	 0 3	-0.023 0.099 0.122	(-0.039, -0.008) (0.011, 0.188) (0.035, 0.209)	1.023	(1.008, 1.040)	2.25%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.009) Thwave (p=0.019)	 2	-0.060 0.274	(-0.104, -0.015) (0.045, 0.502)	1.062 1.315	(1.015, 1.110) (1.046, 1.652)	5.84%
	SPI-1	SPI-1 (p=0.021) Thwave (p=0.016)	 2	-0.054 0.280	(-0.101, -0.008) (0.052, 0.509)	1.055 1.323	(1.008, 1.106) (1.053, 1.664)	5.21%

CIUDAD REAL (ES422)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.005)		-0.015	(-0.025, -0.005)	1.015	(1.005, 1.025)	1.48%
		Thwave (p=0.030)	1	0.050	(0.005, 0.094)	1.051	(1.005, 1.099)	
		Thwave (p=0.034)	2	0.049	(0.004, 0.095)	1.050	(1.004, 1.100)	
		Thwave (p=0.044)	4	0.041	(0.001, 0.080)	1.042	(1.001, 1.083)	
	SPI-1	SPI-1 (p=0.002)		-0.016	(-0.027, -0.006)	1.016	(1.006, 1.027)	1.57%
		Thwave (p=0.024)	1	0.052	(0.007, 0.096)	1.053	(1.007, 1.101)	
		Thwave (p=0.029)	2	0.051	(0.005, 0.096)	1.052	(1.005, 1.101)	
		Thwave (p=0.033)	4	0.043	(0.003, 0.083)	1.044	(1.003, 1.087)	
Respiratory deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.018)		-0.034	(-0.062, -0.006)	1.035	(1.006, 1.064)	3.38%
		Thwave (p=0.022)	4	0.123	(0.017, 0.228)	1.131	(1.017, 1.256)	
GUADALAJARA (ES424)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.045)		-0.017	(-0.034 -0.000)	1.017	(1.000, 1.035)	1.73%
		Thwave (p=0.019)	0	0.136	(0.022, 0.249)	1.146	(1.022, 1.283)	
TOLEDO (ES425)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.015)		-0.012	(-0.022, -0.002)	1.012	(1.002, 1.022)	1.19%
		Thwave (p=0.000)	2	0.063	(0.029, 0.097)	1.065	(1.029, 1.102)	
		Thwave (p=0.012)	4	0.044	(0.009, 0.078)	1.045	(1.009, 1.081)	
	SPI-1	SPI-1 (p=0.007)		-0.015	(-0.026, -0.004)	1.015	(1.004, 1.026)	1.48%
		Thwave (p=0.000)	2	0.062	(0.028, 0.095)	1.064	(1.028, 1.100)	
		Thwave (p=0.017)	4	0.042	(0.008, 0.076)	1.043	(1.008, 1.079)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.042)		-0.029	(-0.057, -0.001)	1.029	(1.001, 1.059)	2.82%
		Thwave (p=0.032)	4	0.102	(0.009, 0.100)	1.107	(1.009, 1.105)	
	SPI-1	SPI-1 (p=0.011)		-0.040	(-0.070, -0.009)	1.041	(1.009,1.073)	3.94%
		Thwave (p=0.024)	4	0.107	(0.014, 0.200)	1.113	(1.014, 1.221)	
BADAJOZ (ES431)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.017	(-0.027, -0.008)	1.017	(1.008, 1.027)	1.67%
		Thwave (p=0.000)	1	0.044	(0.025, 0.064)	1.045	(1.025, 1.066)	
		Thwave (p=0.000)	4	0.039	(0.020, 0.059)	1.040	(1.020, 1.061)	
	SPI-1	SPI-1 (p=0.000)		-0.018	(-0.027, -0.009)	1.018	(1.009, 1.027)	1.77%
		Thwave (p=0.000)	1	0.045	(0.026, 0.065)	1.046	(1.026, 1.067)	
		Thwave (p=0.000)	4	0.041	(0.022, 0.061)	1.042	(1.022, 1.063)	
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.015)		-0.019	(-0.034, -0.004)	1.019	(1.004, 1.035)	1.86%
		Thwave (p=0.000)	4	0.063	(0.032, 0.095)	1.065	(1.033, 1.100)	
	SPI-1	SPI-1 (p=0.002)		-0.023	(-0.038, -0.008)	1.023	(1.008, 1.039)	2.25%
		Thwave (p=0.000)	4	0.066	(0.034, 0.097)	1.068	(1.035, 1.102)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.071	(-0.098, -0.044)	1.074	(1.103, 1.045)	6.89%
		Thwave (p=0.003)	2	0.083	(0.028, 0.137)	1.087	(1.028, 1.147)	
	SPI-1	SPI-1 (p=0.000)		-0.074	(-0.100, -0.048)	1.077	(1.049, 1.105)	7.15%
		Twave (p=0.001)	2	0.090	(0.036, 0.144)	1.094	(1.037, 1.155)	
CACERES (ES432)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	0	0.084	(0.042, 0.127)	1.088	(1.043, 1.135)	
		Thwave (p=0.000)	2	0.087	(0.042, 0.131)	1.091	(1.043, 1.140)	
		Thwave (p=0.004)	4	0.064	(0.021, 0.108)	1.066	(1.021, 1.114)	
	SPI-1	Thwave (p=0.000)	0	0.084	(0.042, 0.127)	1.088	(1.043, 1.135)	
		Thwave (p=0.000)	2	0.087	(0.042, 0.131)	1.091	(1.043, 1.140)	
		Thwave (p=0.004)	4	0.064	(0.021, 0.108)	1.066	(1.021, 1.114)	
Respiratory deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.006)		-0.043	(-0.074, -0.013)	1.044	(1.013, 1.077)	4.21%
		Thwave (p=0.002)	1	0.169	(0.060, 0.278)	1.184	(1.062, 1.320)	
		Thwave (p=0.008)	4	0.152	(0.040 0.263)	1.164	(1.041, 1.301)	

BARCELONA (ES511)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.003)		-0.005	(-0.008, -0.002)	1.005	(1.002, 1.008)	0.50%
		Thwave (p=0.000)	0	0.030	(0.015, 0.046)	1.030	(1.015, 1.047)	
		Thwave (p=0.000)	1	0.030	(0.013, 0.047)	1.030	(1.013, 1.048)	
		Thwave (p=0.000)	2	0.030	(0.015, 0.046)	1.030	(1.015, 1.047)	
		Thwave (p=0.000)	4	0.033	(0.019, 0.047)	1.034	(1.019, 1.048)	
	SPI-1	SPI-1 (p=0.032)		-0.004	(-0.007, -0.000)	1004	(1.000, 1.007)	0.40%
		Thwave (p=0.000)	0	0.031	(0.015, 0.046)	1.031	(1.015, 1.047)	
		Thwave (p=0.000)	1	0.031	(0.014, 0.048)	1.031	(1.014, 1.049)	
		Thwave (p=0.000)	2	0.031	(0.015, 0.046)	1.031	(1.015, 1.047)	
		Thwave (p=0.000)	4	0.033	(0.019, 0.047)	1.034	(1.019, 1.048)	
Circulatory deaths	**SPEI-1**	Thwave (p=0.000)		0.063	(0.038, 0.088)	1.065	(1.039, 1.092)	
		Thwave (p=0.000)	2	0.047	(0.021, 0.074)	1.048	(1.021, 1.077)	
		Thwave (p=0.017)	4	0.032	(0.006, 0.058)	1.033	(1.006, 1.060)	
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.004)		-0.015	(-0.025, -0.005)	1.015	(1.005, 1.025)	1.48%
		Thwave (p=0.000)	1	0.103	(0.064, 0.142)	1.108	(1.066, 1.153)	
		Thwave (p=0.000)	4	0.093	(0.053, 0.133)	1.097	(1.054, 1.042)	
	SPI-1	SPI-1 (p=0.005)		-0.015	(-0.026, -0.005)	1.015	(1.005, 1.026)	1.48%
		Thwave (p=0.000)	1	0105	(0.066, 0.143)	1.111	(1.068, 1.154)	
		Thwave (p=0.000)	4	0.094	(0.054, 0.134)	1.099	(1.055, 1.143)	
GIRONA (ES512)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	1	0.087	(0.051, 0.124)	1.091	(1.052, 1.132)	
	SPI-1							
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.027)		-0.018	(-0.034, -0.002)	1.018	(1.002, 1.035)	1.77%
	SPI-1							
LLEIDA (ES513)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	1	0.071	(0.037, 0.105)	1.074	(1.038, 1.111)	
		Thwave (p=0.001)	4	0.061	(0.026, 0.095)	1.063	(1.026, 1.100)	
	SPI-1	Thwave (p=0.000)	1	0.071	(0.037, 0.105)	1.074	(1.038, 1.111)	
		Thwave (p=0.001)	4	0.061	(0.026, 0.095)	1.063	(1.026, 1.100)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.006)		-0.043	(-0.073, -0.012)	1.044	(1.012, 1.076)	4.12%
		Thwave (p=0.002)	1	0.151	(0.054, 0.247)	1.163	(1.055, 1.280)	
	SPI-1	SPI-1 (p=0.001)		-0.050	(-0.080, -0.021)	1.051	(1.021, 1.083)	4.85%
		Thwave (p=0.002)	1	0.152	(0.056, 0.248)	1.164	(1.058, 1.281)	
TARRAGONA (ES514)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	0	0.071	(0.035, 0.107)	1.074	(1.036, 1.113)	
		Thwave (p=0.000)	4	0.066	(0.029, 0.102)	1.068	(1.029, 1.107)	
	SPI-1							
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.045)		-0.015	(-0.029, -0.000)	1.015	(1.000, 1.029)	1.48%
	SPI-1							
Respiratory deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.028)		-0.029	(-0.054, -0.003)	1.029	(1.003, 1.055)	2.82%
		Thwave (p=0.024)	3	0.128	(0.017, 0.239)	1.137	(1.017, 1.270)	
CADIZ (ES612)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.002)		-0.012	(0.033, 0.074)	1.012	(1.034, 1.077)	1.19%
		Thwave (p=0.000)	2	0.053	(0.033, 0.074)	1.054	(1.034, 1.077)	
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.002)		-0.039	(-0.064, -0.015)	1.040	(1.015, 1.066)	3.85%
		Thwave (p=0.000)	2	0.113	(0.050, 0.175)	1.120	(1.051, 1.191)	
		Thwave (p=0.021)	4	0.078	(0.012, 0.144)	1.081	(1.012, 1.155)	
	SPI-1							

CORDOBA (ES613)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.001)		-0.015	(-0.023, -0.006)	1.015	(1.006, 1.023)	1.48%
		Thwave (p=0.000)	1	0.058	(0.034, 0.082)	1.060	(1.035, 1.085)	
		Thwave (p=0.000)	3	0.050	(0.026, 0.075)	1.051	(1.026, 1.078)	
	SPI-1	SPI-1 (p=0.000)		-0.016	(-0.024, -0.007)	1.016	(1.007, 1.024)	1.57%
		Thwave (p=0.000)	1	0.058	(0.033, 0.082)	1.060	(1.034, 1.085)	
		Thwave (p=0.000)	3	0.051	(0.026, 0.075)	1.052	(1.026, 1.078)	
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.010)		-0.019	(-0.033, -0.004)	1.019	(1.004, 1.034)	1.86%
		Thwave (p=0.001)	1	0.066	(0.026, 0.107)	1.068	(1.026, 1.113)	
		Thwave (p=0.000)	3	0.077	(0.037, 0.117)	1.080	(1.038, 1.194)	
	SPI-1	SPI-1 (p=0.010)		-0.018	(-0.032, -0.004)	1.018	(1.004, 1.033)	1.77%
		Thwave (p=0.001)	1	0.066	(0.026, 0.106)	1.068	(1.026, 1.112)	
		Thwave (p=0.000)	3	0.078	(0.038, 0.118)	1.081	(1.039, 1.125)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.018)		-0.030	(-0.054, -0.005)	1.030	(1.005, 1.055)	2.91%
		Thwave (p=0.006)	0	0.095	(0.027, 0.163)	1.100	(1.027, 1.177)	
		Thwave (p=0.004)	2	0.100	(0.032, 0.169)	1.105	(1.033, 1.184)	
		Thwave (p=0.023)	4	0.079	(0.011, 0.147)	1.082	(1.011, 1.158)	
	SPI-1	SPI-1 (p=0.001)		-0.042	(-0.065, -0.018)	1.043	(1.018, 1.067)	4.12%
		Thwave (p=0.007)	0	0.093	(0.025, 0.161)	1.097	(1.025, 1.175)	
		Thwave (p=0.004)	2	0.100	(0.031, 0.168)	1.105	(1.031, 1.183)	
		Thwave (p=0.019)	4	0.081	(0.013, 0.148)	1.084	(1.013, 1.160)	
GRANADA (ES614)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.042)		-0.008	(-0.016, -0.000)	1.008	(1.000, 1.016)	0.79%
		Thwave (p=0.000)	1	0.063	(0.029, 0.098)	1.065	(1.029, 1.103)	
		Thwave (p=0.019)	3	0.042	(0.007, 0.077)	1.043	(1.007, 1.080)	
HUELVA (ES615)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.002)		-0.017	(-0.027, -0.006)	1.017	(1.006, 1.027)	1.67%
		Thwave (p=0.000)	1	0.054	(0.035, 0.074)	1.055	(1.036, 1.077)	
		Thwave (p=0.000)	4	0.041	(0.021, 0.061)	1.042	(1.021, 1.063)	
	SPI-1	SPI-1 (p=0.007)		-0.015	(-0.026, -0.004)	1.015	(0.004, 1.026)	1.48%
		Thwave (p=0.000)	1	0.056	(0.037, 0.076)	1.058	(1.038, 1.079)	
		Thwave (p=0.000)	4	0.043	(0.023, 0.063)	1.044	(1.023, 1.065)	
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.036)		-0.018	(-0.035, -0.001)	1.018	(1.001, 1.036)	1.77%
		Thwave (p=0.000)	1	0.077	(0.046, 0.107)	1.080	(1.047, 1.113)	
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.008)		-0.044	(-0.076, -0.011)	1.045	(1.011, 1.079)	4.31%
		Thwave (p=0.000)	2	0.112	(0.059, 0.165)	1.119	(1.061, 1.179)	
	SPI-1	SPI-1 (p=0.005)		-0.046	(-0.079, -0.014)	1.047	(1.014, 1.082)	4.49%
		Thwave (p=0.000)	2	0.117	(0.064, 0.170)	1.124	(1.066, 1.185)	
JAEN (ES616)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.002)		-0.016	(-0.026, -0.006)	1.016	(1.006, 1.026)	1.57%
		Thwave (p=0.000)	2	0.061	(0.061, 0.013)	1.063	(1.063, 1.013)	
		Thwave (p=0.045)	4	0.027	(0.027, 0.014)	1.027	(1.027, 1.014)	
	SPI-1	SPI-1 (p=0.000)		-0.018	(-0.028, -0.009)	1.018	(1.009, 1.028)	1.77%
		Thwave (p=0.000)	2	0.062	(0.036, 0.088)	1.064	(1.037, 1.092)	
		Thwave (p=0.034)	4	0.029	(0.002, 0.055)	1.029	(1.002, 1.057)	
Circulatory deaths	**SPEI-1**	Thwave (p=0.000)	2	0.088	(0.048, 0.129)	1.092	(1.049, 1.138)	
	SPI-1	SPI-1 (p=0.031)		-0.017	(-0.033, -0.002)	1.017	(1.002, 1.034)	1.67%
		Thwave (p=0.000)	2	0.088	(0.048, 0.129)	1.092	(1.049, 1.138)	
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.089	(-0.117, -0.061)	1.093	(1.063, 1.124)	8.51%
		Thwave (p=0.005)	2	0.103	(0.032, 0.175)	1.108	(1.033, 1.191)	
	SPI-1	SPI-1 (p=0.000)		-0.085	(-0.112, -0.058)	1.089	(1.060, 1.119)	8.17%
		Thwave (p=0.002)	2	0.112	(0.041, 0.183)	1.119	(1.042, 1.201)	

SEVILLA (ES616)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave)						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% CI]**		**% AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.011	(-0.017, -0.005)	1.011	(1.005, 1.017)	1.09%
		Thwave (p=0.000)	0	0.069	(0.047, 0.091)	1.071	(1.048, 1.095)	
		Thwave (p=0.000)	2	0.073	(0.050, 0.096)	1.076	(1.051, 1.101)	
		Thwave (p=0.001)	4	0.039	(0.016, 0.062)	1.040	(1.016, 1.064)	
	SPI-1	SPI-1 (p=0.001)		-0.011	(-0.017, -0.005)	1.011	(1.005, 1.017)	1.09%
		Thwave (p=0.000)	0	0.070	(0.048, 0.093)	1.073	(1.049, 1.097)	
		Thwave (p=0.000)	2	0.074	(0.051, 0.097)	1.077	(1.052, 1.102)	
		Thwave (p=0.001)	4	0.040	(0.017, 0.063)	1.041	(1.017, 1.065)	
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.027)		-0.010	(-0.020, -0.001)	1.010	(1.001, 1.020)	0.99%
		Thwave (p=0.000)	0	0.088	(0.054, 0.122)	1.092	(1.055, 1.130)	
		Thwave (p=0.000)	2	0.100	(0.066, 0.134)	1.105	(1.068, 1.143)	
		Thwave (p=0.000)	4	0.076	(0.042, 0.110)	1.079	(1.043, 1.116)	
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.060	(-0.080, -0.039)	1.062	(1.040, 1.083)	5.84%
		Thwave (p=0.000)	2	0.156	(0.091, 0.222)	1.169	(1.095, 1.249)	
	SPI-1	SPI-1 (p=0.000)		-0.053	(-0.073, -0.033)	1.054	(1.034, 1.076)	5.12%
		Thwave (p=0.000)	2	0.166	(0.100, 0.231)	1.181	(1.105, 1.260)	

Table S3. Short-term effects of droughts on daily mortality when both the effects of heatwaves and atmospheric pollution were additionally controlled in Poisson modelling in Spain during 2000 to 2009 period. The table shows the statistically significant results of the Relative Risks (RRs) and percentage of Attributable Risks (%AR = ((RR - 1)/RR) × 100)) of daily natural, circulatory and respiratory-mortality statistically associated to droughts measured by SPEI-1/SPI-1 when the impact of both heatwaves and atmospheric pollution was controlled. RRs were calculated from the value of the coefficients obtained in each model and the %ARs were calculated from RRs values. In addition, the 95% confidence intervals (CI) of the estimators and of the RRs are also displayed. *Madrid (ES300) data corresponds with the period 2001 to 2009. **The p-value=0.051 tend to be statistically significant. In Lugo, Huesca and Girona there were no pollution data available, and in the case of Palencia there was no mortality data available.

A CORUÑA (ES111)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000) Thwave (p=0.004)	0 1	0.024 0.019	(0.011, 0.037) (0.006, 0.033)			
	SPI-1	Thwave (p=0.000) Thwave (p=0.004)	0 1	0.024 0.019	(0.011, 0.037) (0.006, 0.033)			
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.001) Thwave (p=0.003) O3a (p=0.030)	 2 1	-0.028 0.051 0.007	(-0.044 -0.011) (0.018, 0.085) (0.001, 0.014)	1.028	(1.011, 1.045)	2.72%
	SPI-1	SPI-1 (p=0.004) Thwave (p=0.002) O3a (p=0.024)	 2 1	-0.024 0.053 0.008	(-0.040, -0.007) (0.019, 0.086) (0.001, 0.014)	1.024	(1.007, 1.041)	2.34%
OURENSE (ES113)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	NO2 (p=0.009)	1	0.002	(0.0005, 0.004)			
	SPI-1	NO2 (p=0.009)	1	0.002	(0.001, 0.004)			
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.000) Thwave (p=0.000)	 1	-0.029 0.074	(-0.044, -0.013) (0.035, 0.114)	1.029	(1.013, 1.045)	2.82%
	SPI-1	SPI-1 (p=0.000) Thwave (p=0.000)	 1	-0.030 0.076	(-0.045, -0.015) (0.037, 0.115)	1.030	(1.015, 1.046)	2.91%
Respiratory deaths	**SPEI-1**	Thwave (p=0.003)	2	0.104	(0.036, 0.171)			
	SPI-1	Thwave (p=0.003)	2	0.104	(0.036, 0.171)			
PONTEVEDRA (ES114)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.018) NO2 (p=0.018)	1 4	0.061 0.002	(0.010, 0.111) (0.000, 0.003)			
	SPI-1	Thwave (p=0.018) NO2 (p=0.018)	1 4	0.061 0.002	(0.010, 0.111) (0.000, 0.003)			
Circulatory deaths	**SPEI-1**	Thwave (p=0.000)	1	0.038	(0.019, 0.058)			
	SPI-1	Thwave (p=0.000)	1	0.038	(0.019, 0.058)			
Respiratory deaths	**SPEI-1**	NO2 (p=0.037)	3	0.004	(0.000, 0.008)			
	SPI-1	NO2 (p=0.037)	3	0.004	(0.000, 0.008)			
ALAVA (ES411)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000) PM10 (p=0.036)	1	0.109 0.001	(0.055, 0.163) (0.000, 0.002)			
	SPI-1	Thwave (p=0.000) NO2 (p=0.009)	1 3	0.114 0.001	(0.061, 0.167) (0.000, 0.002)			
Respiratory deaths	**SPEI-1**	Tcal (p=0.001)	1	0.246	(0.099, 0.394)			
	SPI-1	SPI (p=0.052) Thwave (p=0.002)	 1	-0.046 0.234	(-0.093, 0.000) (0.086, 0.382)	1.047	(1.000, 1.097)	4.49%

GUIPUZCOA (ES212)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.014) Thwave (p=0.023) O3a (p=0.002) O3a (p=0.013) O3a (p=0.038) PM10 (p=0.000)	 4 0 2 8 0	-0.013 0.024 0.002 0.002 0.001 0.0016	(-0.023, -0.003) (0.003, 0.045) (0.001, 0.004) (0.000, 0.003) (0.000, 0.003) (0.001, 0.002)	1.013	(1.003, 1.023)	1.28%
	SPI-1	Thwave (p=0.037) O3a (p=0.001) O3a (p=0.009) O3a (p=0.028) PM10 (0.000) PM10 (p=0.032)	4 0 2 8 0 4	0.022 0.002 0.002 0.002 0.002 0.0007	(0.001, 0.043) (0.001, 0.004) (0.000, 0.003) (0.000, 0.003) (0.001, 0.002) (0.000, 0.001)			
Respiratory Deaths	**SPEI-1**	SPEI-1 (p=0.043) Thwave (p=0.005) PM10 (p=0.001) O3a (p=0.003)	 0 2 2	-0.031 0.082 0.003 0.006	(-0.062, -0.001) (0.025, 0.139) (0.001, 0.005) (0.002, 0.010)	1.031	(1.001, 1.064)	3.01%
	SPI-1	Thwave (p=0.004) PM10 (p=0.000) O3a (p=0.000)	0 2 2	0.084 0.003 0.007	(0.028, 0.141) (0.001, 0.005) (0.003, 0.011)			
NAVARRA (ES220)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000) NO2 (p=0.008) NO2 (p=0.046) O3a (p=0.031) O3a (p=0.000) PM10 (p=0.006)	1 0 4 0 5 2	0.077 0.0009 0.0007 0.001 0.002 0.0009	(0.037, 0.117) (0.000, 0.002) (0.000, 0.001) (0.000, 0.002) (0.001, 0.003) (0.000, 0.001)			
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.035) Thwave (p=0.000) NO2 (p=0.001) NO2 (p=0.009) O3a (p=0.001)	 3 0 5 4	-0.031 0.215 0.003 0.002 0.005	(-0.060, -0.002) (0.113, 0.316) (0.001, 0.005) (0.001, 0.004) (0.002, 0.008)	1.031	(1.002, 1.062)	3.01%
	SPI-1	SPI-1 (p=0.032) Thwave (p=0.000) NO2 (p=0.001) NO2 (p=0.009) O3a (p=0.001)	 3 0 5 4	-0.029 0.220 0.003 0.002 0.005	(-0.056, -0.003) (0.119, 0.321) (0.001, 0.005) (0.001, 0.004) (0.002, 0.008)	1.029	(1.003, 1.058)	2.82%
LA RIOJA (ES230)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	NO2 (p=0.004) O3a (p=0.033)	2 2	0.005 0.035	(0.002, 0.008) (0.003, 0.066)			
	SPI-1							
Respiratory deaths	**SPEI-1**	NO2 (p=0.019)	5	0.012	(0.002, 0.021)			
	SPI-1	NO2 (p=0.019)	5	0.012	(0.002, 0.021)			
TERUEL (ES242)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.013) O3a (p=0.002)	 4	-0.021 0.0036	(-0.038, -0,005) (0.0013, 0.006)	1.021	(1.005, 1.039)	2.06%
	SPI-1	SPI-1 (p=0.017) O3a (p=0.002)	 4	-0.020 0.0037	(-0,037, -0.004) (0.0014, 0,006)	1.020	(1.004, 1.038)	1.96%

ZARAGOZA (ES243)	INDICATOR	DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	1	0.044	(0.027, 0.061)			
		Thwave (p=0.006)	4	0.024	(0.007, 0.041)			
		PM10 (p=0.003)	0	0.0005	(0.000, 0.001)			
	SPI-1	Thwave (p=0.000)	1	0.044	(0.027, 0.061)			
		Thwave (p=0.006)	4	0.024	(0.007, 0.041)			
		PM10 (p=0.003)	0	0.0005	(0.000, 0.001)			
Respiratory deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.001)	1	0.084	(0.032, 0.135)			
MADRID* (ES300)	**INDICATOR**	**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	1	0.024	(0.014, 0.034)			
		Thwave (p=0.014)	2	0.015	(0.003, 0.026)			
		Thwave (p=0.005)	3	0.014	(0.004, 0.024)			
		PM10 (p=0.000)	0	0.0005	(0.000, 0.001)			
		NO2 (p=0.000)	1	0.0006	(0.000, 0.001)			
		NO2 (p=0.041)	5	0.0002	(8.47e-06, 0.0004)			
		O3a (p=0.011)	2	0.002	(0.0004, 0.003)			
	SPI-1	Thwave (p=0.000)	1	0.024	(0.014, 0.034)			
		Thwave (p=0.014)	2	0.015	(0.003, 0.026)			
		Thwave (p=0.005)	3	0.014	(0.004, 0.024)			
		PM10 (p=0.000)	0	0.0005	(0.000, 0.001)			
		NO2 (p=0.000)	1	0.0006	(0.000, 0.001)			
		NO2 (p=0.041)	5	0.0002	(8.47e-06, 0.0004)			
		O3a (p=0.011)	2	0.002	(0.0004, 0.003)			
Circulatory deaths	**SPEI-1**	Thwave (p=0.001)	1	0.032	(0.013, 0.051)			
		Thwave (p=0.037)	2	0.021	(0.001, 0.040)			
		Thwave (p=0.026)	4	0.018	(0.002, 0.034)			
		NO2 (p=0.000)	1	0.0007	(0.0004, 0.001)			
		NO2 (p=0.015)	5	0.0004	(0.0001, 0.001)			
	SPI-1	Thwave (p=0.001)	1	0.032	(0.013, 0.051)			
		Thwave (p=0.037)	2	0.021	(0.001, 0.040)			
		Thwave (p=0.026)	4	0.018	(0.002, 0.034)			
		NO2 (p=0.000)	1	0.0007	(0.0004, 0.001)			
		NO2 (p=0.015)	5	0.0004	(0.0001, 0.001)			
Respiratory deaths	**SPEI-1**	Thwave (p=0.000)	1	0.055	(0.035, 0.076)			
		Thwave (p=0.007)	4	0.029	(0.008, 0.049)			
		PM10 (p=0.000)	1	0.002	(0.001, 0.002)			
		NO2 (p=0.009)	4	0.0007	(0.000, 0.001)			
		O3a (p=0.032)	1	0.004	0.000, 0.007			
	SPI-1	SPI-1 (p=0.017)		-0.013	(-0.023, -0.002)	1.013	(1.002, 1.023)	1.28%
		Thwave (p=0.000)	1	0.055	(0.008, 0.049)			
		Thwave (p=0.008)	4	0.028	(0.008, 0.049)			
		PM10 (p=0.000)	1	0.002	(0.001, 0.002)			
		NO2 (p=0.024)	4	0.0006	(0.0001, 0.001)			
		O3a (p=0.034)	1	0.004	(0.000, 0.007)			
AVILA (ES411)	**INDICATOR**	**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.011)		-0.021	(-0.038, -0.005)	1.021	(1.005, 1.039)	2.06%
		Thwave (p=0.014)	1	0.055	(0.011, 0.099)			
		Thwave (p=0.046)	3	0.045	(0.001, 0.089)			
		O3a (p=0.003)	1	0.002	(0.001, 0.003)			
	SPI-1	SPI-1 (p=0.019)		-0.020	(-0.037, -0.003)	1.020	(1.003, 1.038)	1.96%
		Thwave (p=0.011)	1	0.057	(0.013, 0.101)			
		Thwave (p=0.037)	3	0.047	(0.003, 0.091)			
		O3a (p=0.004)	1	0.002	(0.000, 0.003)			
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.013)		-0.059	(-0.107, -0.012)	1.061	(1.012, 1.113)	5.75%
		Thwave (p=0.000)	0	0.196	(0.089, 0.304)			
		Thwave (p=0.017)	4	0.138	(0.025, 0.252)			
		O3a (p=0.023)	0	0.004	(0.000, 0.007)			
	SPI-1	SPI-1 (p=0.015)		-0.060	(-0.108, -0.011)	1.062	(1.011, 1.114)	5.84%
		Thwave (p=0.000)	0	0.195	(0.087, 0.302)			
		Thwave (p=0.016)	4	0.140	(0.026, 0.253)			
		O3a (p=.037)	0	0.003	(0.000, 0.006)			

BURGOS (ES41)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Circulatory deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.001) NO2 (p=0.015)	3 5	0.112 0.002	(0.048, 0.176) (0.000, 0.003)			
LEON (ES413)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.008) Thwave (0.000)	 1	-0.013 0.075	(-0.023, -0.003) (0.039, 0.112)	1.013	(1.003, 1.023)	1.28%
	SPI-1	SPI-1 (p=0.001) Thwave (p=0.000)	 1	-0.016 0.078	(-0.026, -0.006) (0.041, 0.114)	1.016	(1.006, 1.026)	1.57%
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.007) Thwave (p=0.015) O3a (p=0.017)	 1 0	-0.023 0.080 0.003	(-0.039, -0.006) (0.015, 0.145) (0.000, 0.005)	1.023	(1.006, 1.040)	2.25%
	SPI-1	SPI-1 (p=0.001) Thwave (p=0.016) O3a (p=0.010)	 1 0	-0.030 0.079 0.003	(-0.046, -0.013) (0.015, 0.144) (0.001, 0.005)	1.030	(1.013, 1.047)	2.91%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.012) O3a (p=0.015)	 4	-0.034 0.005	(-0.060, -0.007) (0.001, 0.008)	1.035	(1.007, 1.062)	3.38%
	SPI-1	SPI-1 (p=0.014) O3a (p=0.012)	 4	-0.034 0.005	(-0.060, -0.007) (0.001, 0.009)	1.035	(1.007, 1.062)	3.29%
SALAMANCA (ES415)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.005) Thwave (p=0.002) Thwave (p=0.023)	 1 2	-0.017 0.059 0.043	(-0.028, -0.005) (0.022, 0.096) (0.006, 0.080)	1.017	(1.005, 1.028)	1.67%
	SPI-1	SPI-1 (p=0.044) Thwave (p=0.002) Thwave (p=0.025) PM10 (p=0.011) O3a (p=0.031)	 1 2 1 8	-0.013 0.058 0.043 0.001 0.001	(-0.025, -0.000) (0.021, 0.094) (0.005, 0.080) (0.000, 0.002) (0.000, 0.003)	1.013	(1.000, 1.025)	1.28%
Respiratory Deaths	**SPEI-1**	SPEI-1 (p=0.002) Thwave (p=0.000)	 2	-0.058 0.175	(-0.094, -0.022) (0.084, 0.266)	1.060	(1.022, 1.099)	5.66%
	SPI-1	SPI-1 (p=0.006) Thwave (p=0.000)	 2	-0.052 0.180	(-0.089, -0.015) (0.089, 0.271)	1.053	(1.015, 1.093)	5.03%
SORIA (ES417)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.040)		-0.022	(-0.043, -0.001)	1.022	(1.001, 1.044)	2.15%
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.011)		-0.045	(-0.080, -0.010)	1.046	(1.010, 1.083)	4.40%
	SPI-1	SPI-1 (p=0.028)		-0.039	(-0.073, -0.004)	1.040	(1.004, 1.076)	3.85%
VALLADOLID (ES418)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Respiratory Deaths	**SPEI-1**	Thwave (p=0.022) Thwave (p=0.017)	2 3	0.222 0.231	(0.032, 0.412) (0.041, 0.422)			
	SPI-1	Thwave (p=0.022) Thwave (p=0.017)	2 3	0.222 0.231	(0.032, 0.412) (0.041, 0.422)			
ZAMORA (ES419)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural Deaths	**SPEI-1**	SPEI-1 (p=0.004) Thwave (p=0.031) Thwave (p=0.007)	 0 3	-0.022 0.097 0.012	(-0.037, -0.007) (0.009, 0.186) (0.032, 0.207)	1.022	(1.007, 1.038)	2.15%
	SPI-1	SPI-1 (p=0.003) Thwave (p=0.027) Thwave (p=0.006)	 0 3	-0.023 0.099 0.122	(-0.039, -0.008) (0.011, 0.188) (0.035, 0.209)	1.023	(1.008, 1.040)	2.25%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.009) Thwave (p=0.019)	 2	-0.060 0.274	(-0.104, -0.015) (0.045, 0.502)	1.062	(1.015, 1.110)	5.84%
	SPI-1	SPI-1 (p=0.021) Thwave (p=0.016)	 2	-0.054 0.280	(-0.101, -0.008) (0.052, 0.509)	1.055	(1.008, 1.106)	4.94%

CIUDAD REAL (ES422)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.005) Thwave (p=0.030) Thwave (p=0.034) Thwave (p=0.044)	 1 2 4	-0.015 0.050 0.049 0.041	(-0.025, -0.005) (0.005, 0.094) (0.004, 0.095) (0.001, 0.080)	1.015	(1.005, 1.025)	1.48%
	SPI-1	SPI-1 (p=0.002) Thwave (p=0.024) Thwave (p=0.029) Thwave (p=0.033)	 1 2 4	-0.016 0.052 0.051 0.043	(-0.027, -0.006) (0.007, 0.096) (0.005, 0.096) (0.003, 0.083)	1.016	(1.006, 1.027)	1.57%
Respiratory deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.019)		-0.033	(-0.061, -0.005)	1.034	(1.005, 1.063)	3.29%
GUADALAJARA (ES424)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.033) PM10 (p=0.000) PM10 (p=0.016)	0 0 4	0.125 0.002 0.001	(0.010, 0.239) (0.001, 0.0025) (0.000, 0.002)			
TOLEDO (ES425)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000) PM10 (p=0.005) O3a (p=0.016)	2 3 1	0.065 0.0007 0.002	(0.032, 00.098) (0.000, 0.001) (0.000, 0.003)			
	SPI-1	SPI-1 (p=0.006) Thwave (p=0.001) Thwave (p=0.010) O3a (p=0.015)	 2 4 3	-0.015 0.057 0.045 0.002	(-0.026, -0.004) (0.023, 0.092) (0.011, 0.079) (0.000, 0.003)	1.015	(1.004, 1.026)	1.48%
Respiratory deaths	**SPEI-1**	PM10 (p=0.001) O3a (p=0.011) O3a (p=0.014)	2 1 5	0.002 0.005 0.005	(0.001, 0.004) (0.001, 0.009) (0.001, 0.008)			
	SPI-1	PM10 (p=0.001) O3a (p=0.011) O3a (p=0.024)	3 1 5	0.003 0.005 0.004	(0.001, 0.004) (0.001, 0.009) (0.001, 0.008)			
BADAJOZ (ES431)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000) Thwave (p=0.000) Thwave (p=0.000)	 1 4	-0.019 0.044 0.039	(-0.028, -0.010) (0.025, 0.064) (0.019, 0.059)	1.019	(1.010, 1.028)	1.86%
	SPI-1	SPI-1 (p=0.000) Thwave (p=0.000) Thwave (p=0.000)	 1 4	-0.018 0.045 0.041	(-0.027, -0.009) (0.045 0.010) (0.041, 0.010)	1.018	(1.009, 1.027)	1.77%
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.015) Thwave (p=0.000)	 4	-0.019 0.063	(-0.034, -0.004) (0.032, 0.095)	1.019	(1.004, 1.035)	1.86%
	SPI-1	SPI-1 (p=0.002) Thwave (p=0.000)	 4	-0.023 0.066	(-0.038, -0.008) (0.034, 0.097)	1.023	(1.008, 1.039)	2.25%
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.000) Thwave (p=0.002)	 2	-0.069 0.087	(-0.096, -0.042) (0.032, 0.141)	1.071	(1.043, 1.101)	6.63%
	SPI-1	SPI-1 (p=0.000) Thwave (p=0.001)	 2	-0.074 0.094	(-0.100, -0.048) (0.039, 0.148)	1.077	(1.049, 1.105)	7.15%
CACERES (ES432)	**INDICATOR**	**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000) Thwave (p=0.000) Thwave (p=0.005) NO2 (p=0.004)	0 2 4 2	0.084 0.086 0.065 0.002				
	SPI-1	Thwave (p=0.000) Thwave (p=0.000) Thwave (p=0.005) NO2 (p=0.004)	0 2 4 2	0.084 0.086 0.065 0.002				
Respiratory deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.001) Thwave (p=0.004)	1 4	0.185 0.162	(0.076, 0.295) (0.051, 0.274)			

BARCELONA (ES511)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.006	(-0.009, -0.003)	1.006	(1.003, 1.009)	0.60%
		Thwave (p=0.001)	0	0.027	(0.011, 0.042)			
		Thwave (p=0.001)	1	0.028	(0.011, 0.045)			
		Thwave (p=0.000)	2	0.033	(0.017, 0.048)			
		Thwave (p=0.000)	4	0.036	(0.022, 0.050)			
		NO2 (p=0.000)	0	0.001	(0.0003, 0.0007)			
		NO2 (p=0.000)	1	0.0004	(0.0002, 0.0007)			
		O3a (p=0.033)	4	0.0008	(0.0001, 0.002)			
	SPI-1	SPI-1 (p=0.001)		-0.006	(-0.009, -0.002)	1.006	(1.002, 1.003)	0.60%
		Thwave (p=0.001)	0	0.027	(0.012, 0.043)			
		Thwave (p=0.001)	1	0.028	(0.011, 0.045)			
		Thwave (p=0.000)	2	0.033	(0.017, 0.049)			
		Thwave (p=0.000)	4	0.036	(0.022, 0.050)			
		NO2 (p=0.000)	0	0.0005	(0.0003, 0.0007)			
		NO2 (p=0.000)	1	0.0004	(0.0002, 0.0007)			
		O3a (p=0.034)	4	0.0008	(0.000,0.002)			
Circulatory deaths	**SPEI-1**	SPEI-1(p=0.045)		-0.006	(-0.012, -0.0000)	1.006	(1.000, 1.012)	0.60%
		Thwave (p=0.000)	0	0.059	(0.034, 0.084)			
		Thwave (p=0.000)	2	0.048	(0.022, 0.074)			
		Thwave (p=0.033)	4	0.029	(0.002, 0.055)			
		NO2 (p=0.001)	0	0.0005	(0.000, 0.001)			
		NO2 (p=0.006)	4	0.0004	(0.000, 0.001)			
		O3a (p=0.006)	4	0.002	(0.001, 0.003)			
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.002)		-0.016	(-0.026, -0.006)	1.016	(1.006, 1.026)	1.57%
		Thwave (p=0.000)	1	0.101	(0.063, 0.140)			
		Thwave (p=0.000)	4	0.093	(0.053, 0.133)			
		NO2 (p=0.000)	1	0.001	(0.001, 0.002)			
		NO2 (p=0.001)	5	0.0009	(0.000, 0.001)			
		O3a (p=0.037)	9	0.003	(0.000, 0.005)			
	SPI-1	SPI-1 (p=0.001)		-0.018	(-0.029, -0.007)	1.018	(1.007, 1.029)	1.77%
		Thwave (p=0.000)	1	0.103	(0.064 0.141)			
		Thwave (p=0.000)	4	0.095	(0.055, 0.135)			
		NO2 (p=0.000)	1	0.001	(0.0006, 0.002)			
		NO2 (p=0.001)	5	0.001	(0.0004, 0.001)			
		O3a (p=0.037)	9	0.003	(0.0002, 0.005)			
LLEIDA (ES513)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	1	0.071	(0.037, 0.105)			
		Thwave (p=0.001)	4	0.061	(0.026, 0.095)			
	SPI-1	Thwave (p=0.000)	1	0.071	(0.037, 0.105)			
		Thwave (p=0.001)	4	0.061	(0.026, 0.095)			
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.016)		-0.039	(-0.070, -0.007)	1.040	(1.007, 1.073)	3.85%
		Thwave (p=0.003)	1	0.149	(0.050, 0.248)			
		NO2 (p=0.016)	1	0.003	(0.000, 0.005)			
	SPI-1	SPI- 1 (p=0.003)		-0.047	(-0.077, -0.016)	1.048	(1.016, 1.080)	4.58%
		Thwave (p=0.003)	1	0.149	(0.050, 0.248)			
		NO2 (p=0.002)	1	0.003	(0.001, 0.005)			
TARRAGONA (ES514)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	0	0.064	(0.028, 0.101)			
		Thwave (p=0.000)	4	0.067	(0.030, 0.103)			
		NO2 (p=0.000)	1	0.002	(0.001, 0.003)			
	SPI-1							
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.044)		-0.015	(-0.029, -0.000)	1.015	(1.000, 1.029)	1.48%
		NO2 (p=0.007)	0	0.002	(0.001, 0.003)			
	SPI-1							
Respiratory deaths	**SPEI-1**							
	SPI-1	SPI-1 (p=0.027)		-0.029	(-0.054, -0.003)	1.029	(1.003, 1.055)	2.82%
		Thwave (p=0.024)	3	0.129	(0.017, 0.240)			
		NO2 (p=0.022)	1	0.003	(0.000, 0.005)			
		O3a (p=0.005)	6	0.023	(0.007, 0.038)			

CADIZ (ES612)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.023)		-0.009	(-0.017, -0.001)	1.009	(1.001, 1.017)	0.89%
		Thwave (p=0.000)	2	0.046	(0.025, 0.067)			
		O3a (p=0.000)	1	0.004	(0.002, 0.005)			
		O3a (p=0.039)	6	0.002	(0.000, 0.003)			
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.005)		-0.035	(-0.060, -0.011)	1.036	(1.011, 1.062)	3.47%
		Thwave (p=0.002)	2	0.102	(0.038, 0.165)			
		Thwave (p=0.048)	4	0.067	(0.001, 0.134)			
		O3a (p=0.010)	1	0.007	(0.002, 0.012)			
		O3a (p=0.026)	6	0.006	(0.001, 0.011)			
	SPI-1							
CORDOBA (ES613)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	1	0.054	(0.029, 0.078)			
		Thwave (p=0.001)	3	0.043	(0.018, 0.068)			
		PM10 (p=0.012)	0	0.0005	(0.000, 0.001)			
		PM10 (p=0.037)	5	0.0004	(0.000, 0.001)			
		NO2 (p=0.001)	1	0.001	(0.0005, 0.002)			
		NO2 (p=0.002)	4	0.001	(0.0005, 0.002)			
		O3a (p=0.004)	3	0.005	(0.002, 0.009)			
	SPI-1	SPI-1 (p=0.039)		-0.009	(-0.000, -0.018)	1.009	(1.000, 1.018)	0.89%
		Thwave (p=0.000)	1	0.052	(0.028, 0.077)			
		Thwave (p=0.001)	3	0.043	(0.018, 0.068)			
		PM10 (p=0.004)	1	0.0006	(0.000, 0.001)			
		NO2 (p=0.006)	1	0.001	(0.000, 0.002)			
		NO2 (p=0.001)	4	0.001	(0.0005, 0.002)			
		O3a (p=0.004)	3	0.005	(0.002, 0.009)			
Circulatory deaths	**SPEI-1**	Thwave (p=0.001)	1	0.069	(0.029, 0.109)			
		Thwave (p=0.001)	3	0.066	(0.026, 0.106)			
		NO2 (p=0.000)	3	0.003	(0.002, 0.004)			
		O3a (p=0.009)	4	0.008	(0.002, 0.014)			
	SPI-1	Thwave (p=0.001)	1	0.069	(0.029, 0.109)			
		Thwave (p=0.001)	3	0.066	(0.026, 0.106)			
		NO2 (p=0.000)	3	0.003	(0.002, 0.004)			
		O3a (p=0.009)	4	0.008	(0.002, 0.014)			
Respiratory deaths	**SPEI-1**	Thwave (p=0.026)	0	0.078	(0.009, 0.147)			
		Thwave (p=0.026)	2	0.080	(0.010, 0.151)			
		Thwave (p=0.038)	4	0.073	(0.004, 0.141)			
		PM10 (p=0.007)	1	0.001	(0.000, 0.003)			
		NO2 (p=0.010)	1	0.003	(0.001, 0.005)			
		NO2 (p=0.020)	5	0.002	(0.000, 0.004)			
		O3a (p=0.004)	1	0.014	(0.004, 0.023)			
		O3a (p=0.005)	3	0.014	(0.004, 0.023)			
		O3a (p=0.011)	7	0.013	(0.003, 0.023)			
	SPI-1	SPI-1 (p=0.015)		-0.030	(-0.055, -0.006)	1.030	(1.006, 1.057)	2.91%
		Thwave (p=0.014)	0	0.086	(0.017, 0.154)			
		Thwave (p=0.026)	2	0.080	(0.010, 0.151)			
		Thwave (p=0.014)	4	0.085	(0.017, 0.154)			
		PM10 (p=0.009)	1	0.001	(0.000, 0.002)			
		NO2 (p=0.009)	2	0.003	(0.001, 0.005)			
		O3a (p=0.004)	1	0.014	(0.004, 0.023)			
		O3a (p=0.006)	3	0.013	(0.004, 0.022)			
		O3a (p=0.008)	7	0.013	(0.003, 0.23)			
GRANADA (ES14)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**							
	SPI-1	Thwave (p=0.001)	1	0.059	(0.025, 0.093)			
		Thwave (p=0.037)	3	0.037	(0.002, 0.072)			
		NO2 (p=0.000)	2	0.0012	(0.001, 0.002)			

HUELVA (ES615)		DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.016)		-0.013	(-0.024, -0.002)	1.013	(1.002, 1.024)	1.28%
		Thwave (p=0.000)	1	0.048	(0.028, 0.068)			
		Thwave (p=0.000)	4	0.036	(0.016, 0.057)			
		NO2 (p=0.024)	2	0.002	(0.000, 0.003)			
		O3a (p=0.007)	0	0.001	(0.000, 0.003)			
		O3a (p=0.007)	5	0.001	(0.000, 0.003)			
	SPI-1	SPI-1 (p=0.023)		-0.013	(-0.024, -0.002)	1.013	(1.002, 1.024)	1.28%
		Thwave (p=0.000)	1	0.049	(0.030, 0.069)			
		Thwave (p=0.000)	4	0.038	(0.017, 0.058)			
		NO2 (p=0.022)	2	0.002	(0.000, 0.003)			
		O3a (p=0.006)	0	0.002	(0.000, 0.003)			
		O3a (p=0.006)	5	0.002	(0.000, 0.003)			
Circulatory deaths	**SPEI-1**	Thwave (p=0.000)	1	0.072	(0.041, 0.102)			
		O3a (p=0.020)	0	0.002	(0.000, 0.004)			
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.018)		-0.039	(-0.072, -0.007)	1.040	(1.007, 1.075)	3.85%
		Thwave (p=0.003)	2	0.085	(0.030, 0.140)			
		O3a (p=0.014)	1	0.004	(0.001, 0.008)			
		O3a (p=0.004)	3	0.005	(0.002, 0.008)			
	SPI-1	SPI-1 (p=0.006)		-0.045	(-0.078, -0.013)	1.046	(1.013, 1.081)	4.40%
		Thwave (p=0.001)	2	0.090	(0.035, 0.145)			
		O3a (p=0.012)	1	0.004	(0.001, 0.008)			
		O3a (p=0.003)	3	0.005	(0.002, 0.008)			
JAEN (ES616)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	Thwave (p=0.000)	2	0.069	(0.042, 0.096)			
		NO2 (p=0.000)	1	0.002	(0.001, 0.003)			
		O3a (p=0.002)	0	0.006	(0.002, 0.009)			
	SPI-1	Thwave (p=0.000)	2	0.069	(0.042, 0.096)			
		NO2 (p=0.000)	1	0.002	(0.001, 0.003)			
		O3a (p=0.002)	0	0.006	(0.002, 0.009)			
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.028)		-0.018	(-0.034, -0.002)	1.018	(1.002, 1.035)	1.77%
		Thwave (p=0.000)	2	0.093	(0.053, 0.133)			
	SPI-1	SPI-1 (p=0.013)		-0.020	(-0.036, -0.004)	1.020	(1.004, 1.037)	1.96%
		Thwave (p=0.000)	2	0.095	(0.055, 0.135)			
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.004)		-0.052	(-0.088, -0.017)	1.053	(1.017, 1.092)	5.03%
		Thwave(p=0.051)**	2	0.076	(-0.000, 0.152)			
		NO2 (p=0.029)	3	0.0025	(0.000, 0.005)			
	SPI-1	SPI-1 (p=0.000)		-0.082	(-0.109, -0.055)	1.085	(1.057, 1.115)	7.83%
		Thwave (p=0.008)	2	0.096	(0.025, 0.166)			
SEVILLA (ES618)		**DROUGHT INDICATOR +EXTREME TEMPERATURES (Thwave) + POLLUTION**						
		P-value	**Lag in days**	**Coeff. [95% CI]**		**RR [95% Conf. Interval]**		**%AR**
Natural deaths	**SPEI-1**	SPEI-1 (p=0.001)		-0.010	(-0.016, -0.004)	1.010	(1.004, 1.016)	0.99%
		Thwave (p=0.000)	0	0.067	(0.045, 0.090)			
		Thwave (p=0.000)	2	0.072	(0.049, 0.095)			
		Thwave (p=0.001)	4	0.039	(0.016, 0.062)			
		NO2 (p=0.000)	1	0.0007	(0.000, 0.001)			
	SPI-1	SPI-1 (p=0.002)		-0.010	(-0.016, -0.004)	1.010	(1.004, 1.016)	0.99%
		Thwave (p=0.000)	0	0.069	(0.046, 0.091)			
		Thwave (p=0.000)	2	0.073	(0.050, 0.096)			
		Thwave (p=0.000)	4	0.041	(0.018, 0.064)			
		NO2 (p=0.000)	1	0.0007	(0.000, 0.001)			
Circulatory deaths	**SPEI-1**	SPEI-1 (p=0.027)		-0.010	(-0.020, -0.001)	1.010	(1.001, 1.020)	0.99%
		Thwave (p=0.000)	0	0.088	(0.054, 0.122)			
		Thwave (p=0.000)	2	0.100	(0.066, 0.134)			
		Thwave (p=0.000)	4	0.076	(0.042, 0.110)			
	SPI-1							
Respiratory deaths	**SPEI-1**	SPEI-1 (p=0.000)		-0.059	(-0.079, -0.038)	1.061	(1.039, 1.082)	5.75%
		Thwave (p=0.000)	2	0.143	(0.077, 0.210)			
		NO2 (P=0.017)	4	0.002	(0.000, 0.003)			
		O3a (P=0.030)	3	0.006	(0.001, 0.012)			
	SPI-1	SPI-1 (p=0.000)		-0.052	(-0.072, -0.032)	1.053	(1.033, 1.075)	5.03%
		Thwave (p=0.000)	2	0.152	(0.085, 0.219)			
		NO2 (P=0.024)	4	0.001	(0.000, 0.003)			
		O3a (P=0.021)	3	0.006	(0.001, 0.012)			

A.3. SUPPLEMENTARY APPENDIX

Supplement to: Quantification of the global effects of droughts on daily mortality in Spain at different timescales: A meta-analysis

Salvador, C.[1], Nieto, R.[1], Linares, C.[2], Díaz, J.[2], Gimeno, L.[1]

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[2] Department of Epidemiology and Biostatistics. National School of Public Health. Carlos III National Institute of Health (Instituto de Salud Carlos III/ISCIII), Madrid, Spain.

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Figure S1-A.

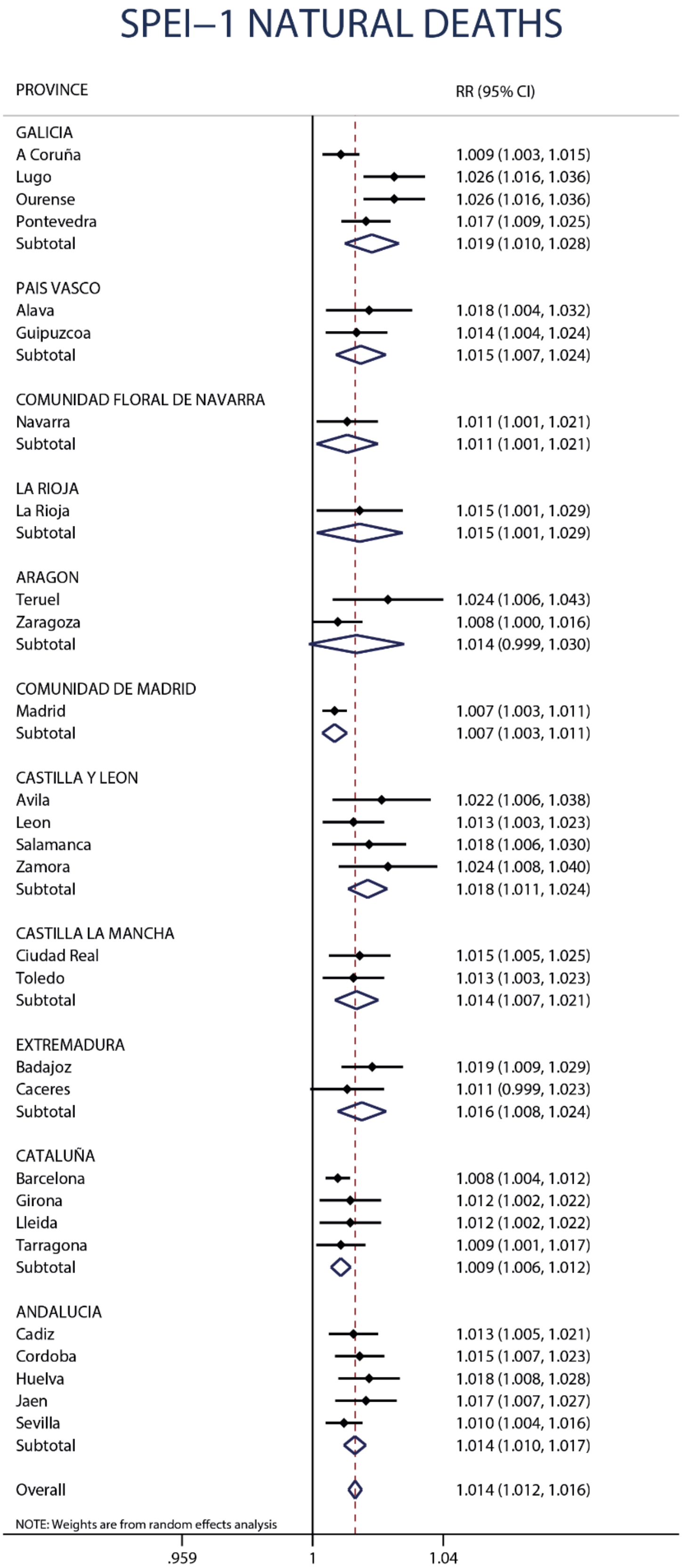

SPEI–1 NATURAL DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.009 (1.003, 1.015)
Lugo 1.026 (1.016, 1.036)
Ourense 1.026 (1.016, 1.036)
Pontevedra 1.017 (1.009, 1.025)
Subtotal 1.019 (1.010, 1.028)
PAIS VASCO
Alava 1.018 (1.004, 1.032)
Guipuzcoa 1.014 (1.004, 1.024)
Subtotal 1.015 (1.007, 1.024)
COMUNIDAD FLORAL DE NAVARRA
Navarra 1.011 (1.001, 1.021)
Subtotal 1.011 (1.001, 1.021)
LA RIOJA
La Rioja 1.015 (1.001, 1.029)
Subtotal 1.015 (1.001, 1.029)
ARAGON
Teruel 1.024 (1.006, 1.043)
Zaragoza 1.008 (1.000, 1.016)
Subtotal 1.014 (0.999, 1.030)
COMUNIDAD DE MADRID
Madrid 1.007 (1.003, 1.011)
Subtotal 1.007 (1.003, 1.011)
CASTILLA Y LEON
Avila 1.022 (1.006, 1.038)
Leon 1.013 (1.003, 1.023)
Salamanca 1.018 (1.006, 1.030)
Zamora 1.024 (1.008, 1.040)
Subtotal 1.018 (1.011, 1.024)
CASTILLA LA MANCHA
Ciudad Real 1.015 (1.005, 1.025)
Toledo 1.013 (1.003, 1.023)
Subtotal 1.014 (1.007, 1.021)
EXTREMADURA
Badajoz 1.019 (1.009, 1.029)
Caceres 1.011 (0.999, 1.023)
Subtotal 1.016 (1.008, 1.024)
CATALUÑA
Barcelona 1.008 (1.004, 1.012)
Girona 1.012 (1.002, 1.022)
Lleida 1.012 (1.002, 1.022)
Tarragona 1.009 (1.001, 1.017)
Subtotal 1.009 (1.006, 1.012)
ANDALUCIA
Cadiz 1.013 (1.005, 1.021)
Cordoba 1.015 (1.007, 1.023)
Huelva 1.018 (1.008, 1.028)
Jaen 1.017 (1.007, 1.027)
Sevilla 1.010 (1.004, 1.016)
Subtotal 1.014 (1.010, 1.017)
Overall 1.014 (1.012, 1.016)
NOTE: Weights are from random effects analysis
.959
1
1.04

Figure S1-B.

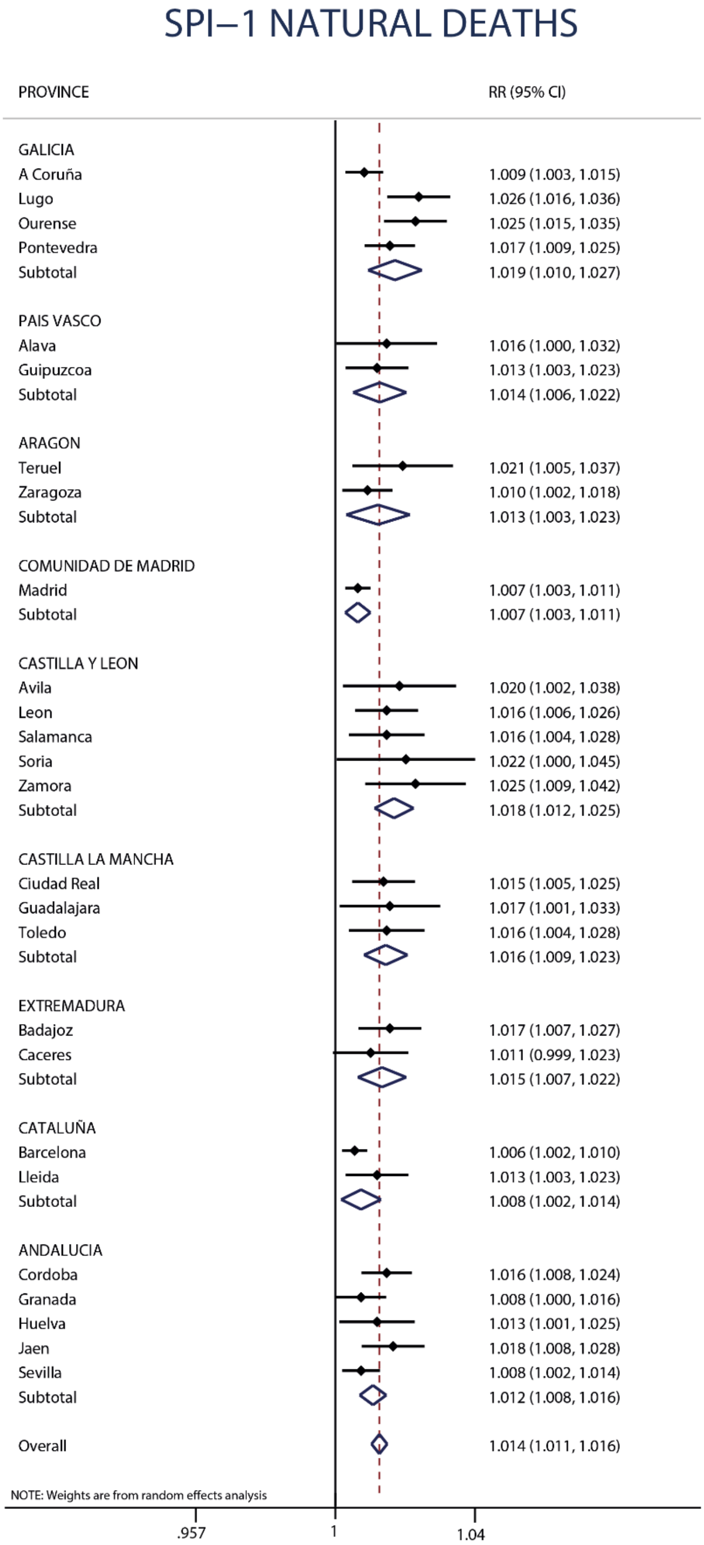
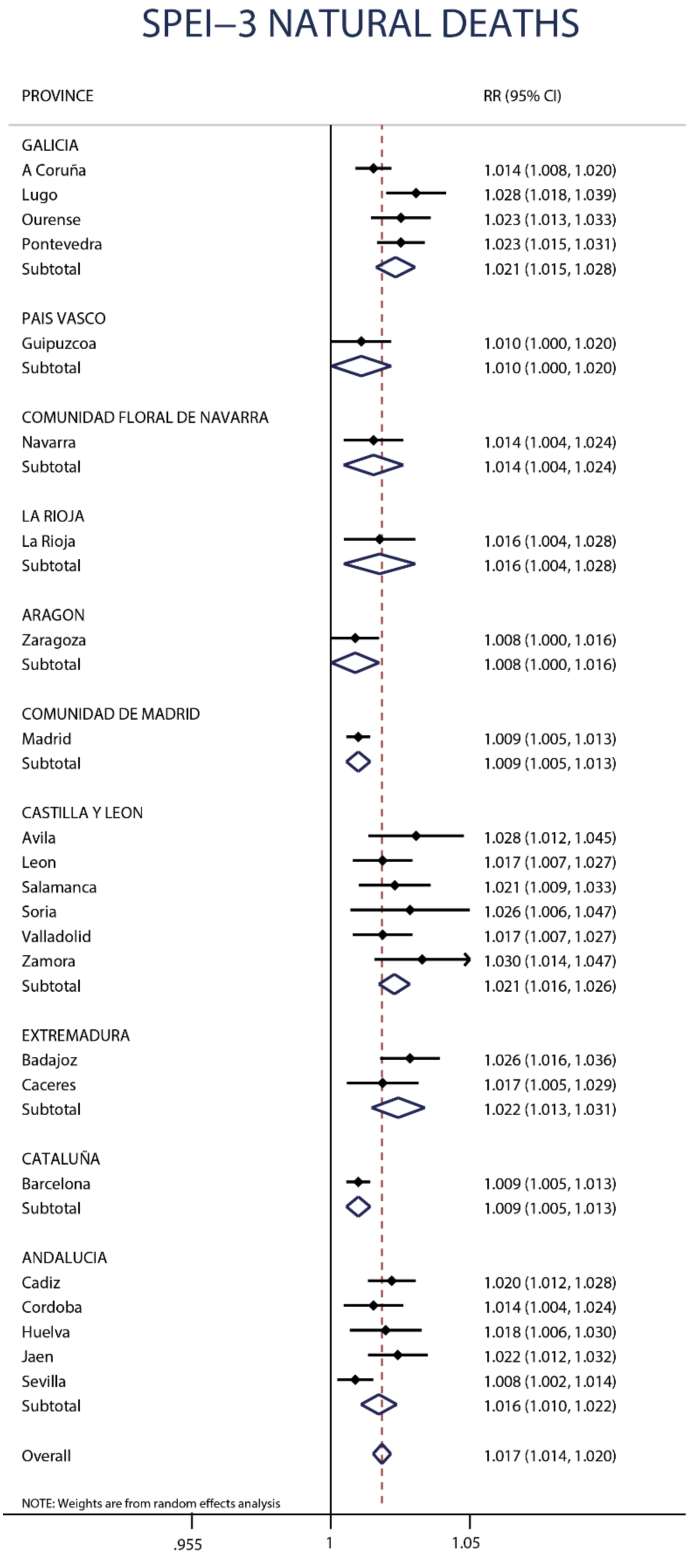

SPI–1 NATURAL DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.009 (1.003, 1.015)
Lugo 1.026 (1.016, 1.036)
Ourense 1.025 (1.015, 1.035)
Pontevedra 1.017 (1.009, 1.025)
Subtotal 1.019 (1.010, 1.027)
PAIS VASCO
Alava 1.016 (1.000, 1.032)
Guipuzcoa 1.013 (1.003, 1.023)
Subtotal 1.014 (1.006, 1.022)
ARAGON
Teruel 1.021 (1.005, 1.037)
Zaragoza 1.010 (1.002, 1.018)
Subtotal 1.013 (1.003, 1.023)
COMUNIDAD DE MADRID
Madrid 1.007 (1.003, 1.011)
Subtotal 1.007 (1.003, 1.011)
CASTILLA Y LEON
Avila 1.020 (1.002, 1.038)
Leon 1.016 (1.006, 1.026)
Salamanca 1.016 (1.004, 1.028)
Soria 1.022 (1.000, 1.045)
Zamora 1.025 (1.009, 1.042)
Subtotal 1.018 (1.012, 1.025)
CASTILLA LA MANCHA
Ciudad Real 1.015 (1.005, 1.025)
Guadalajara 1.017 (1.001, 1.033)
Toledo 1.016 (1.004, 1.028)
Subtotal 1.016 (1.009, 1.023)
EXTREMADURA
Badajoz 1.017 (1.007, 1.027)
Caceres 1.011 (0.999, 1.023)
Subtotal 1.015 (1.007, 1.022)
CATALUÑA
Barcelona 1.006 (1.002, 1.010)
Lleida 1.013 (1.003, 1.023)
Subtotal 1.008 (1.002, 1.014)
ANDALUCIA
Cordoba 1.016 (1.008, 1.024)
Granada 1.008 (1.000, 1.016)
Huelva 1.013 (1.001, 1.025)
Jaen 1.018 (1.008, 1.028)
Sevilla 1.008 (1.002, 1.014)
Subtotal 1.012 (1.008, 1.016)
Overall 1.014 (1.011, 1.016)
NOTE: Weights are from random effects analysis
.957
1
1.04

Figure S1-C.



SPEI–3 NATURAL DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.014 (1.008, 1.020)
Lugo 1.028 (1.018, 1.039)
Ourense 1.023 (1.013, 1.033)
Pontevedra 1.023 (1.015, 1.031)
Subtotal 1.021 (1.015, 1.028)
PAIS VASCO
Guipuzcoa 1.010 (1.000, 1.020)
Subtotal 1.010 (1.000, 1.020)
COMUNIDAD FLORAL DE NAVARRA
Navarra 1.014 (1.004, 1.024)
Subtotal 1.014 (1.004, 1.024)
LA RIOJA
La Rioja 1.016 (1.004, 1.028)
Subtotal 1.016 (1.004, 1.028)
ARAGON
Zaragoza 1.008 (1.000, 1.016)
Subtotal 1.008 (1.000, 1.016)
COMUNIDAD DE MADRID
Madrid 1.009 (1.005, 1.013)
Subtotal 1.009 (1.005, 1.013)
CASTILLA Y LEON
Avila 1.028 (1.012, 1.045)
Leon 1.017 (1.007, 1.027)
Salamanca 1.021 (1.009, 1.033)
Soria 1.026 (1.006, 1.047)
Valladolid 1.017 (1.007, 1.027)
Zamora 1.030 (1.014, 1.047)
Subtotal 1.021 (1.016, 1.026)
EXTREMADURA
Badajoz 1.026 (1.016, 1.036)
Caceres 1.017 (1.005, 1.029)
Subtotal 1.022 (1.013, 1.031)
CATALUÑA
Barcelona 1.009 (1.005, 1.013)
Subtotal 1.009 (1.005, 1.013)
ANDALUCIA
Cadiz 1.020 (1.012, 1.028)
Cordoba 1.014 (1.004, 1.024)
Huelva 1.018 (1.006, 1.030)
Jaen 1.022 (1.012, 1.032)
Sevilla 1.008 (1.002, 1.014)
Subtotal 1.016 (1.010, 1.022)
Overall 1.017 (1.014, 1.020)
NOTE: Weights are from random effects analysis
.955
1
1.05

Figure S1-D.

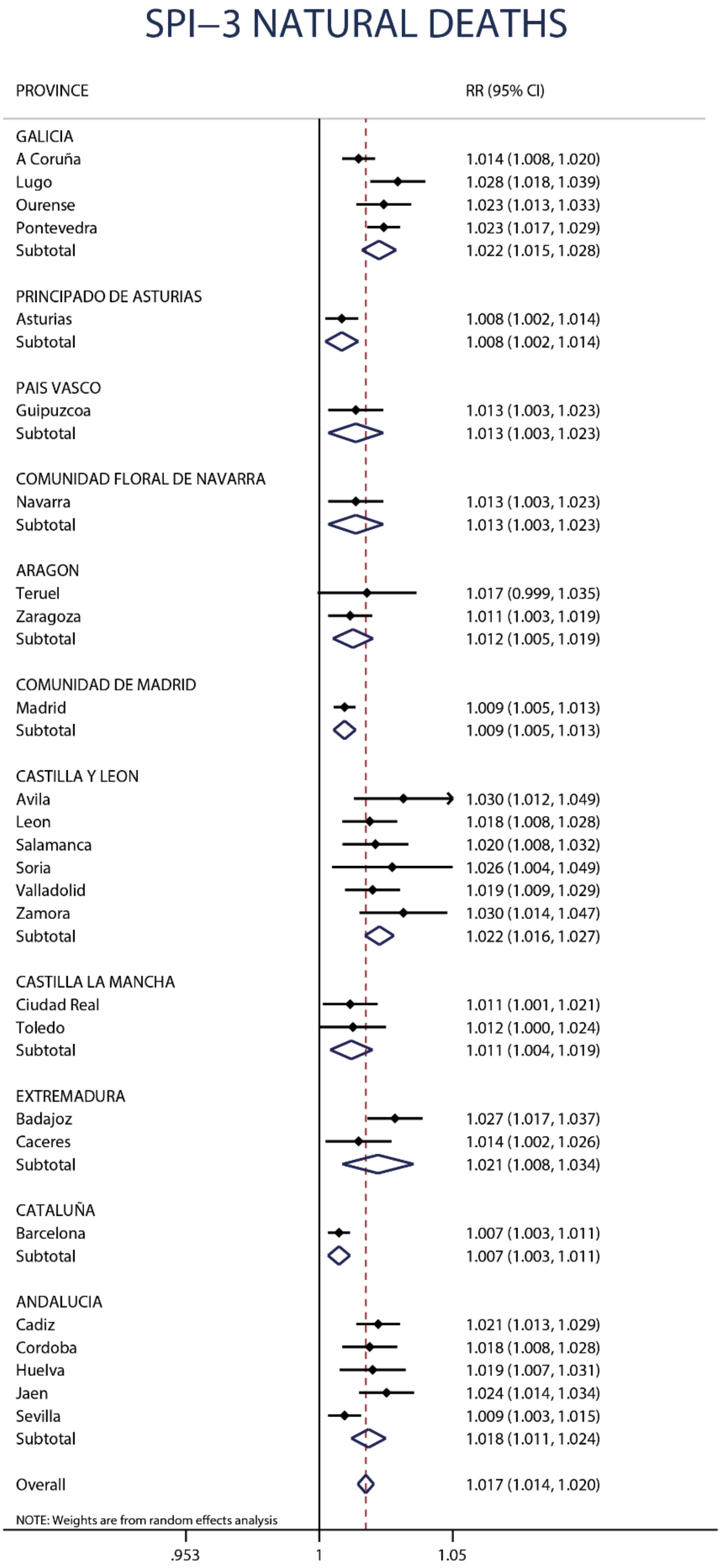

SPI–3 NATURAL DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.014 (1.008, 1.020)
Lugo 1.028 (1.018, 1.039)
Ourense 1.023 (1.013, 1.033)
Pontevedra 1.023 (1.017, 1.029)
Subtotal 1.022 (1.015, 1.028)
PRINCIPADO DE ASTURIAS
Asturias 1.008 (1.002, 1.014)
Subtotal 1.008 (1.002, 1.014)
PAIS VASCO
Guipuzcoa 1.013 (1.003, 1.023)
Subtotal 1.013 (1.003, 1.023)
COMUNIDAD FLORAL DE NAVARRA
Navarra 1.013 (1.003, 1.023)
Subtotal 1.013 (1.003, 1.023)
ARAGON
Teruel 1.017 (0.999, 1.035)
Zaragoza 1.011 (1.003, 1.019)
Subtotal 1.012 (1.005, 1.019)
COMUNIDAD DE MADRID
Madrid 1.009 (1.005, 1.013)
Subtotal 1.009 (1.005, 1.013)
CASTILLA Y LEON
Avila 1.030 (1.012, 1.049)
Leon 1.018 (1.008, 1.028)
Salamanca 1.020 (1.008, 1.032)
Soria 1.026 (1.004, 1.049)
Valladolid 1.019 (1.009, 1.029)
Zamora 1.030 (1.014, 1.047)
Subtotal 1.022 (1.016, 1.027)
CASTILLA LA MANCHA
Ciudad Real 1.011 (1.001, 1.021)
Toledo 1.012 (1.000, 1.024)
Subtotal 1.011 (1.004, 1.019)
EXTREMADURA
Badajoz 1.027 (1.017, 1.037)
Caceres 1.014 (1.002, 1.026)
Subtotal 1.021 (1.008, 1.034)
CATALUÑA
Barcelona 1.007 (1.003, 1.011)
Subtotal 1.007 (1.003, 1.011)
ANDALUCIA
Cadiz 1.021 (1.013, 1.029)
Cordoba 1.018 (1.008, 1.028)
Huelva 1.019 (1.007, 1.031)
Jaen 1.024 (1.014, 1.034)
Sevilla 1.009 (1.003, 1.015)
Subtotal 1.018 (1.011, 1.024)
Overall 1.017 (1.014, 1.020)
NOTE: Weights are from random effects analysis
.953
1
1.05

Figure S2-A.

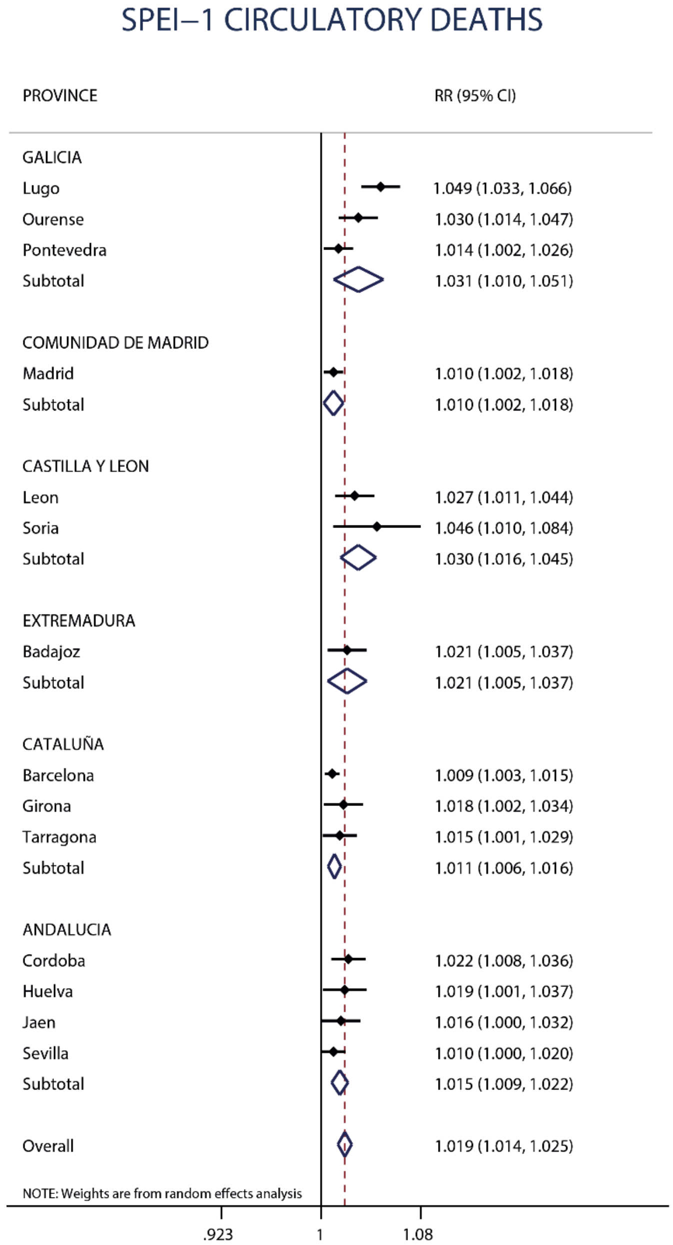

SPEI−1 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
Lugo
1.049 (1.033, 1.066)
Ourense
1.030 (1.014, 1.047)
Pontevedra
1.014 (1.002, 1.026)
Subtotal
1.031 (1.010, 1.051)
COMUNIDAD DE MADRID
Madrid
1.010 (1.002, 1.018)
Subtotal
1.010 (1.002, 1.018)
CASTILLA Y LEON
Leon
1.027 (1.011, 1.044)
Soria
1.046 (1.010, 1.084)
Subtotal
1.030 (1.016, 1.045)
EXTREMADURA
Badajoz
1.021 (1.005, 1.037)
Subtotal
1.021 (1.005, 1.037)
CATALUÑA
Barcelona
1.009 (1.003, 1.015)
Girona
1.018 (1.002, 1.034)
Tarragona
1.015 (1.001, 1.029)
Subtotal
1.011 (1.006, 1.016)
ANDALUCIA
Cordoba
1.022 (1.008, 1.036)
Huelva
1.019 (1.001, 1.037)
Jaen
1.016 (1.000, 1.032)
Sevilla
1.010 (1.000, 1.020)
Subtotal
1.015 (1.009, 1.022)
Overall
1.019 (1.014, 1.025)
NOTE: Weights are from random effects analysis
.923
1
1.08

Figure S2-B.

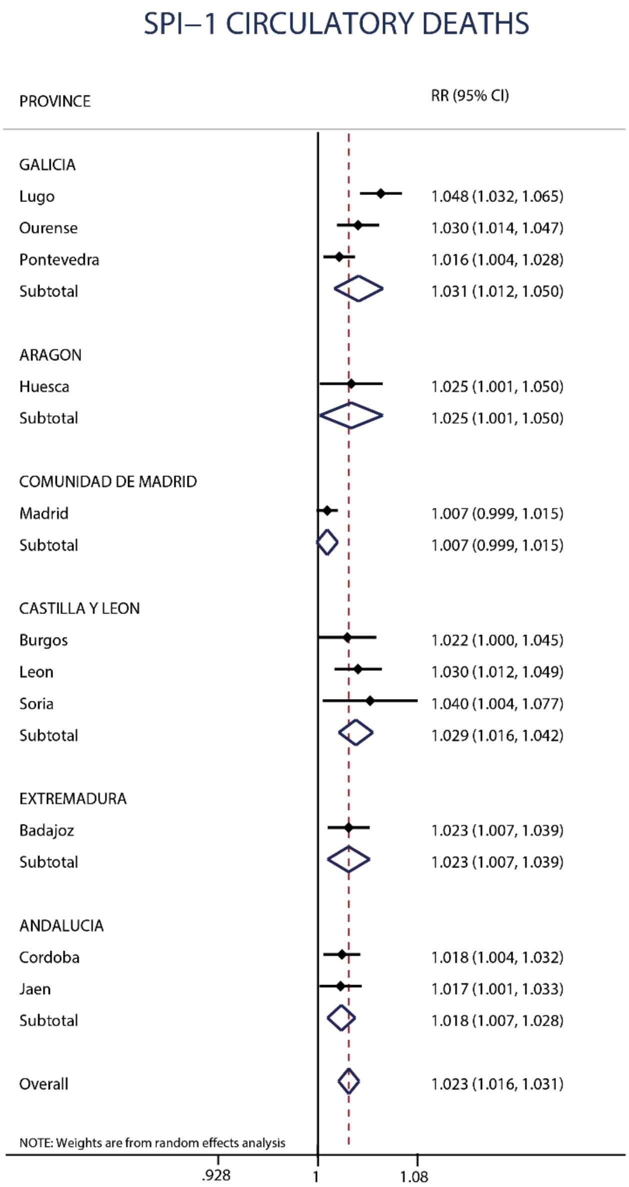

SPI–1 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
Lugo
1.048 (1.032, 1.065)
Ourense
1.030 (1.014, 1.047)
Pontevedra
1.016 (1.004, 1.028)
Subtotal
1.031 (1.012, 1.050)
ARAGON
Huesca
1.025 (1.001, 1.050)
Subtotal
1.025 (1.001, 1.050)
COMUNIDAD DE MADRID
Madrid
1.007 (0.999, 1.015)
Subtotal
1.007 (0.999, 1.015)
CASTILLA Y LEON
Burgos
1.022 (1.000, 1.045)
Leon
1.030 (1.012, 1.049)
Soria
1.040 (1.004, 1.077)
Subtotal
1.029 (1.016, 1.042)
EXTREMADURA
Badajoz
1.023 (1.007, 1.039)
Subtotal
1.023 (1.007, 1.039)
ANDALUCIA
Cordoba
1.018 (1.004, 1.032)
Jaen
1.017 (1.001, 1.033)
Subtotal
1.018 (1.007, 1.028)
Overall
1.023 (1.016, 1.031)
NOTE: Weights are from random effects analysis
.928
1
1.08

Figure S2-C.

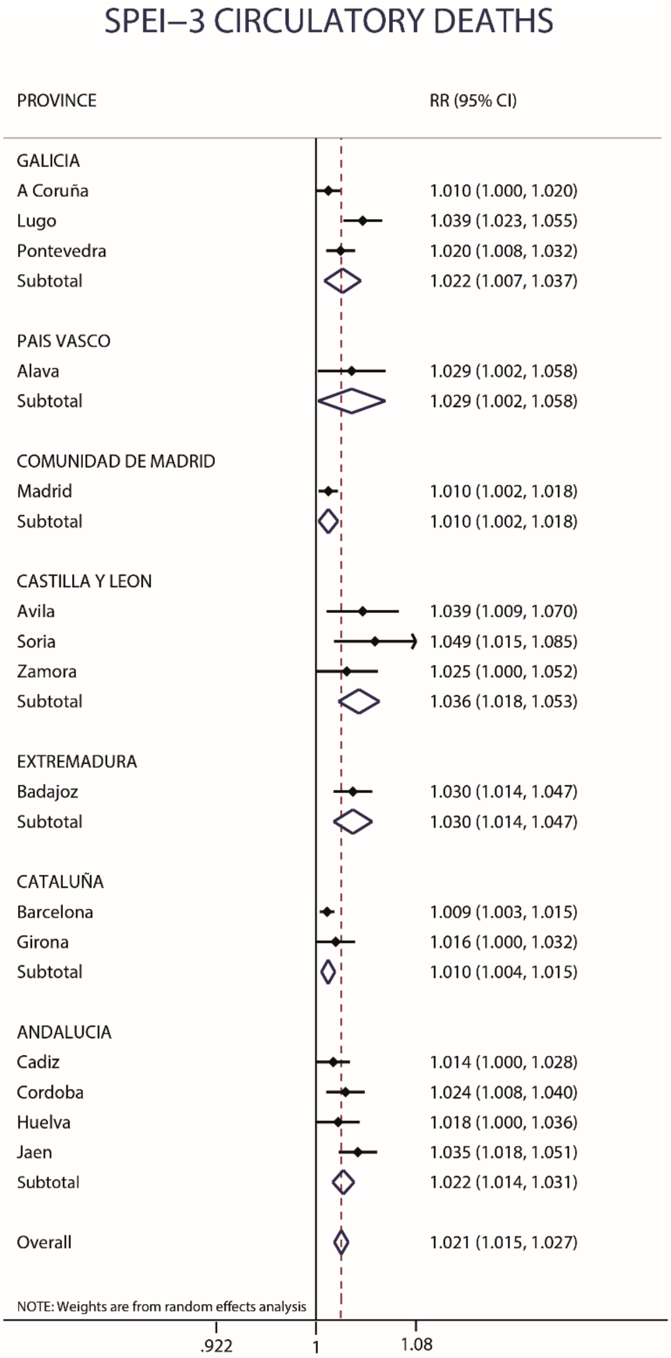

SPEI–3 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña
1.010 (1.000, 1.020)
Lugo
1.039 (1.023, 1.055)
Pontevedra
1.020 (1.008, 1.032)
Subtotal
1.022 (1.007, 1.037)
PAIS VASCO
Alava
1.029 (1.002, 1.058)
Subtotal
1.029 (1.002, 1.058)
COMUNIDAD DE MADRID
Madrid
1.010 (1.002, 1.018)
Subtotal
1.010 (1.002, 1.018)
CASTILLA Y LEON
Avila
1.039 (1.009, 1.070)
Soria
1.049 (1.015, 1.085)
Zamora
1.025 (1.000, 1.052)
Subtotal
1.036 (1.018, 1.053)
EXTREMADURA
Badajoz
1.030 (1.014, 1.047)
Subtotal
1.030 (1.014, 1.047)
CATALUÑA
Barcelona
1.009 (1.003, 1.015)
Girona
1.016 (1.000, 1.032)
Subtotal
1.010 (1.004, 1.015)
ANDALUCIA
Cadiz
1.014 (1.000, 1.028)
Cordoba
1.024 (1.008, 1.040)
Huelva
1.018 (1.000, 1.036)
Jaen
1.035 (1.018, 1.051)
Subtotal
1.022 (1.014, 1.031)
Overall
1.021 (1.015, 1.027)
NOTE: Weights are from random effects analysis
.922
1
1.08

Figure S2-D.

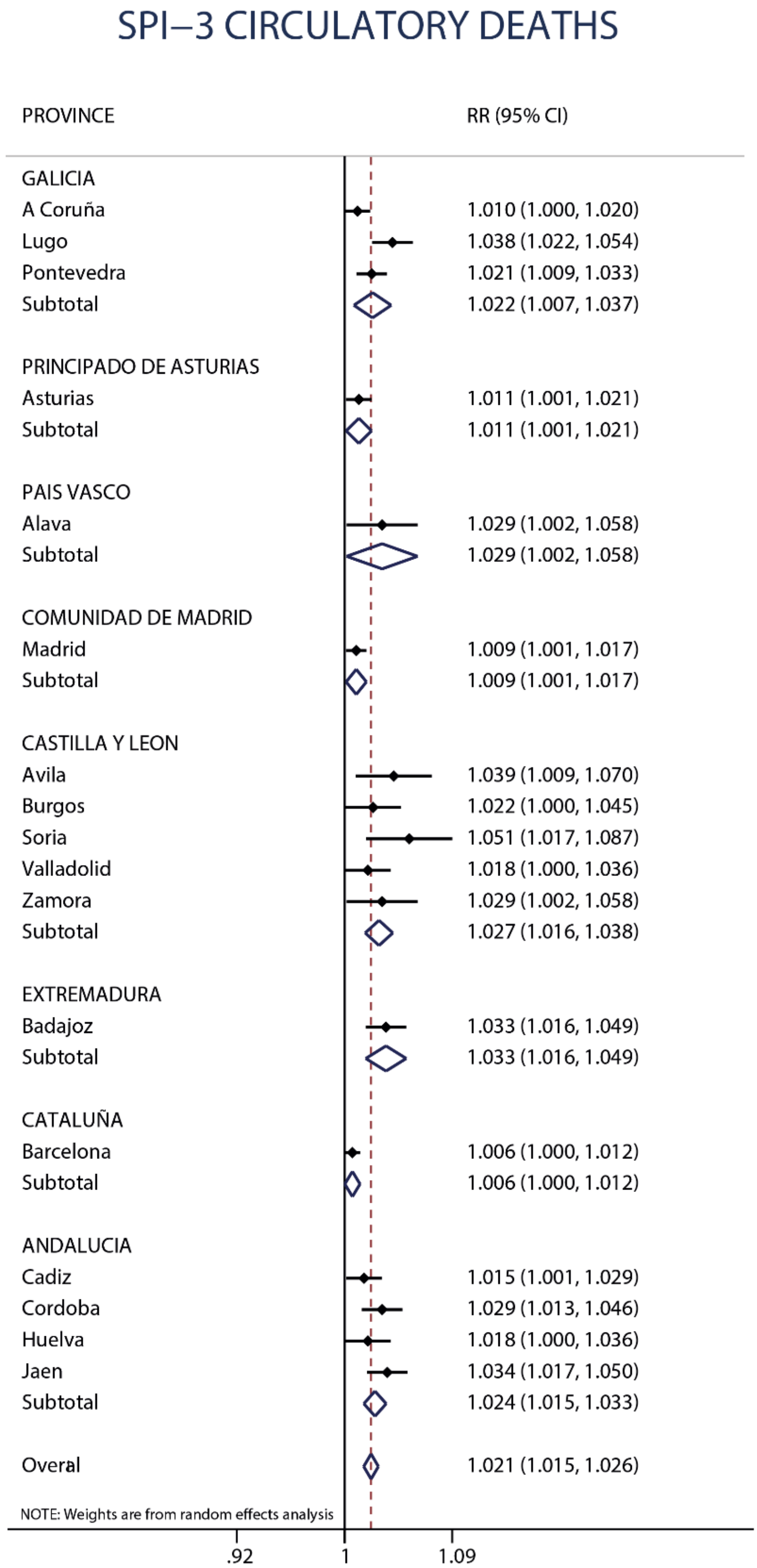

SPI–3 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.010 (1.000, 1.020)
Lugo 1.038 (1.022, 1.054)
Pontevedra 1.021 (1.009, 1.033)
Subtotal 1.022 (1.007, 1.037)
PRINCIPADO DE ASTURIAS
Asturias 1.011 (1.001, 1.021)
Subtotal 1.011 (1.001, 1.021)
PAIS VASCO
Alava 1.029 (1.002, 1.058)
Subtotal 1.029 (1.002, 1.058)
COMUNIDAD DE MADRID
Madrid 1.009 (1.001, 1.017)
Subtotal 1.009 (1.001, 1.017)
CASTILLA Y LEON
Avila 1.039 (1.009, 1.070)
Burgos 1.022 (1.000, 1.045)
Soria 1.051 (1.017, 1.087)
Valladolid 1.018 (1.000, 1.036)
Zamora 1.029 (1.002, 1.058)
Subtotal 1.027 (1.016, 1.038)
EXTREMADURA
Badajoz 1.033 (1.016, 1.049)
Subtotal 1.033 (1.016, 1.049)
CATALUÑA
Barcelona 1.006 (1.000, 1.012)
Subtotal 1.006 (1.000, 1.012)
ANDALUCIA
Cadiz 1.015 (1.001, 1.029)
Cordoba 1.029 (1.013, 1.046)
Huelva 1.018 (1.000, 1.036)
Jaen 1.034 (1.017, 1.050)
Subtotal 1.024 (1.015, 1.033)
Overal 1.021 (1.015, 1.026)
NOTE: Weights are from random effects analysis
.92
1
1.09

Figure S3-A.

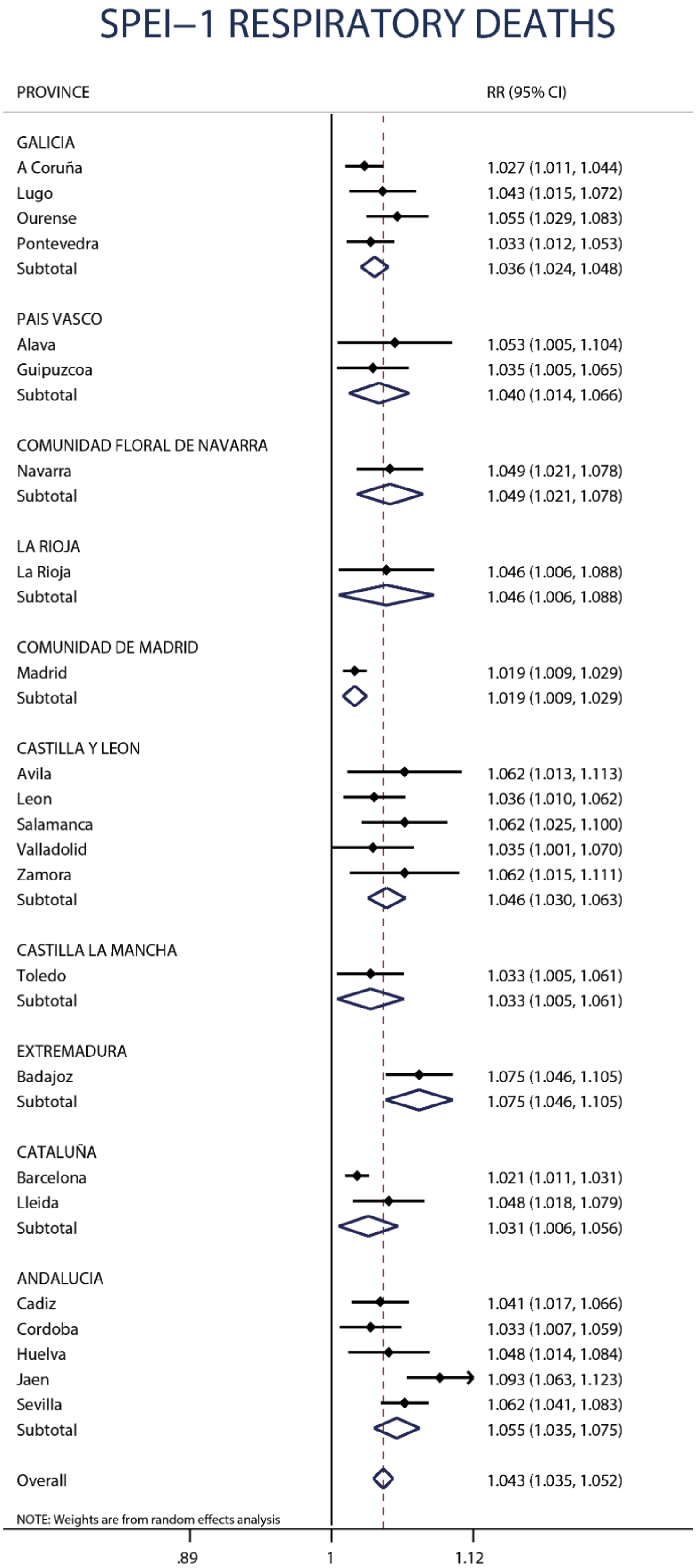

SPEI–1 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña
1.027 (1.011, 1.044)
Lugo
1.043 (1.015, 1.072)
Ourense
1.055 (1.029, 1.083)
Pontevedra
1.033 (1.012, 1.053)
Subtotal
1.036 (1.024, 1.048)
PAIS VASCO
Alava
1.053 (1.005, 1.104)
Guipuzcoa
1.035 (1.005, 1.065)
Subtotal
1.040 (1.014, 1.066)
COMUNIDAD FLORAL DE NAVARRA
Navarra
1.049 (1.021, 1.078)
Subtotal
1.049 (1.021, 1.078)
LA RIOJA
La Rioja
1.046 (1.006, 1.088)
Subtotal
1.046 (1.006, 1.088)
COMUNIDAD DE MADRID
Madrid
1.019 (1.009, 1.029)
Subtotal
1.019 (1.009, 1.029)
CASTILLA Y LEON
Avila
1.062 (1.013, 1.113)
Leon
1.036 (1.010, 1.062)
Salamanca
1.062 (1.025, 1.100)
Valladolid
1.035 (1.001, 1.070)
Zamora
1.062 (1.015, 1.111)
Subtotal
1.046 (1.030, 1.063)
CASTILLA LA MANCHA
Toledo
1.033 (1.005, 1.061)
Subtotal
1.033 (1.005, 1.061)
EXTREMADURA
Badajoz
1.075 (1.046, 1.105)
Subtotal
1.075 (1.046, 1.105)
CATALUÑA
Barcelona
1.021 (1.011, 1.031)
Lleida
1.048 (1.018, 1.079)
Subtotal
1.031 (1.006, 1.056)
ANDALUCIA
Cadiz
1.041 (1.017, 1.066)
Cordoba
1.033 (1.007, 1.059)
Huelva
1.048 (1.014, 1.084)
Jaen
1.093 (1.063, 1.123)
Sevilla
1.062 (1.041, 1.083)
Subtotal
1.055 (1.035, 1.075)
Overall
1.043 (1.035, 1.052)
NOTE: Weights are from random effects analysis
.89
1
1.12

Figure S3-B.

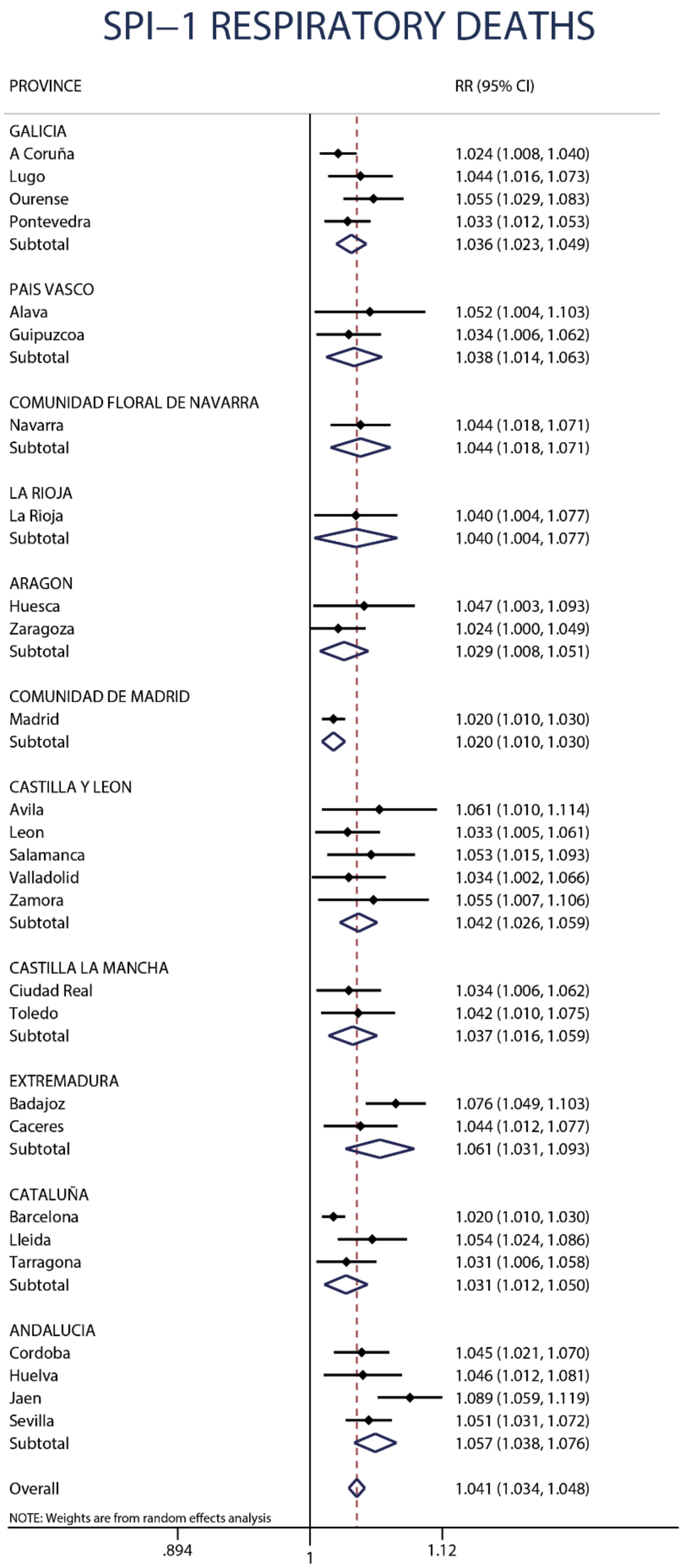
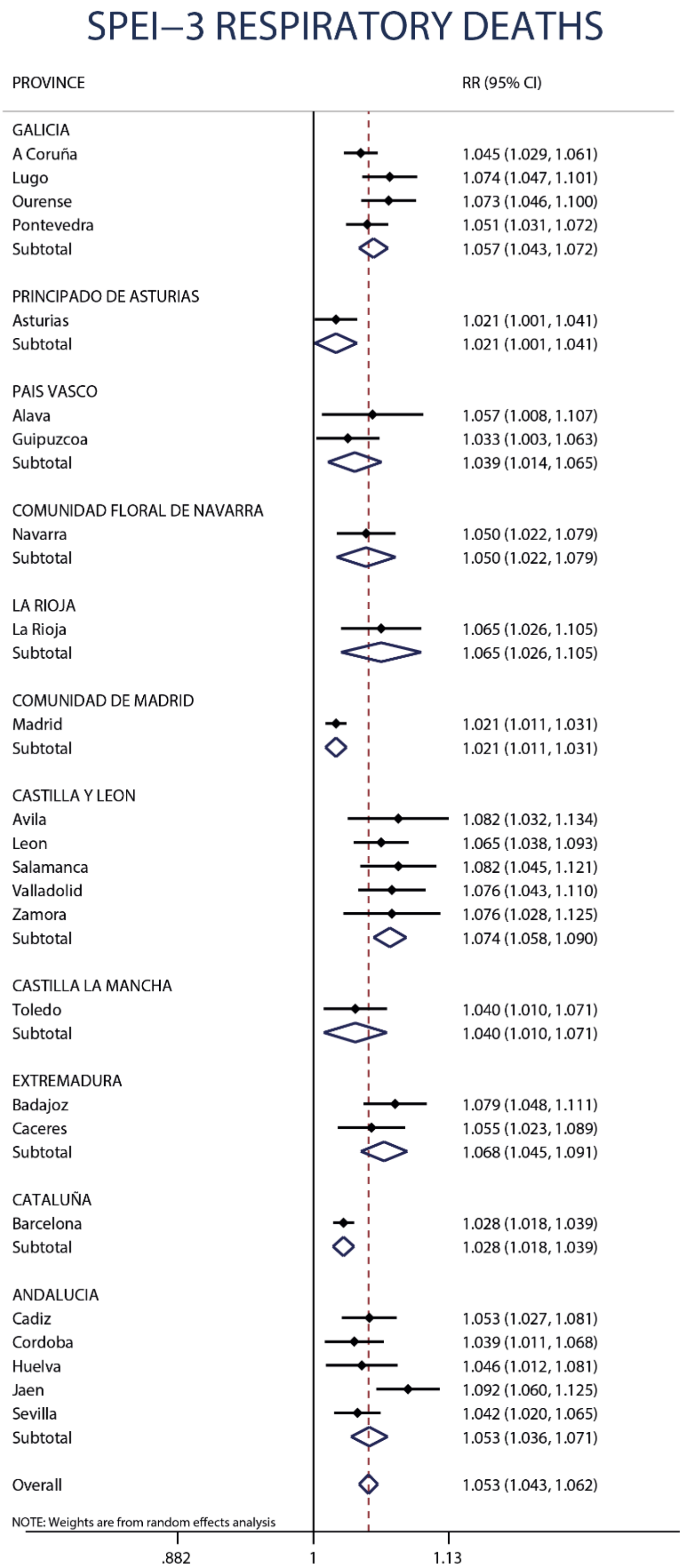

SPI–1 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.024 (1.008, 1.040)
Lugo 1.044 (1.016, 1.073)
Ourense 1.055 (1.029, 1.083)
Pontevedra 1.033 (1.012, 1.053)
Subtotal 1.036 (1.023, 1.049)
PAIS VASCO
Alava 1.052 (1.004, 1.103)
Guipuzcoa 1.034 (1.006, 1.062)
Subtotal 1.038 (1.014, 1.063)
COMUNIDAD FLORAL DE NAVARRA
Navarra 1.044 (1.018, 1.071)
Subtotal 1.044 (1.018, 1.071)
LA RIOJA
La Rioja 1.040 (1.004, 1.077)
Subtotal 1.040 (1.004, 1.077)
ARAGON
Huesca 1.047 (1.003, 1.093)
Zaragoza 1.024 (1.000, 1.049)
Subtotal 1.029 (1.008, 1.051)
COMUNIDAD DE MADRID
Madrid 1.020 (1.010, 1.030)
Subtotal 1.020 (1.010, 1.030)
CASTILLA Y LEON
Avila 1.061 (1.010, 1.114)
Leon 1.033 (1.005, 1.061)
Salamanca 1.053 (1.015, 1.093)
Valladolid 1.034 (1.002, 1.066)
Zamora 1.055 (1.007, 1.106)
Subtotal 1.042 (1.026, 1.059)
CASTILLA LA MANCHA
Ciudad Real 1.034 (1.006, 1.062)
Toledo 1.042 (1.010, 1.075)
Subtotal 1.037 (1.016, 1.059)
EXTREMADURA
Badajoz 1.076 (1.049, 1.103)
Caceres 1.044 (1.012, 1.077)
Subtotal 1.061 (1.031, 1.093)
CATALUÑA
Barcelona 1.020 (1.010, 1.030)
Lleida 1.054 (1.024, 1.086)
Tarragona 1.031 (1.006, 1.058)
Subtotal 1.031 (1.012, 1.050)
ANDALUCIA
Cordoba 1.045 (1.021, 1.070)
Huelva 1.046 (1.012, 1.081)
Jaen 1.089 (1.059, 1.119)
Sevilla 1.051 (1.031, 1.072)
Subtotal 1.057 (1.038, 1.076)
Overall 1.041 (1.034, 1.048)
NOTE: Weights are from random effects analysis
.894
1
1.12

Figure S3-C.



SPEI–3 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.045 (1.029, 1.061)
Lugo 1.074 (1.047, 1.101)
Ourense 1.073 (1.046, 1.100)
Pontevedra 1.051 (1.031, 1.072)
Subtotal 1.057 (1.043, 1.072)
PRINCIPADO DE ASTURIAS
Asturias 1.021 (1.001, 1.041)
Subtotal 1.021 (1.001, 1.041)
PAIS VASCO
Alava 1.057 (1.008, 1.107)
Guipuzcoa 1.033 (1.003, 1.063)
Subtotal 1.039 (1.014, 1.065)
COMUNIDAD FLORAL DE NAVARRA
Navarra 1.050 (1.022, 1.079)
Subtotal 1.050 (1.022, 1.079)
LA RIOJA
La Rioja 1.065 (1.026, 1.105)
Subtotal 1.065 (1.026, 1.105)
COMUNIDAD DE MADRID
Madrid 1.021 (1.011, 1.031)
Subtotal 1.021 (1.011, 1.031)
CASTILLA Y LEON
Avila 1.082 (1.032, 1.134)
Leon 1.065 (1.038, 1.093)
Salamanca 1.082 (1.045, 1.121)
Valladolid 1.076 (1.043, 1.110)
Zamora 1.076 (1.028, 1.125)
Subtotal 1.074 (1.058, 1.090)
CASTILLA LA MANCHA
Toledo 1.040 (1.010, 1.071)
Subtotal 1.040 (1.010, 1.071)
EXTREMADURA
Badajoz 1.079 (1.048, 1.111)
Caceres 1.055 (1.023, 1.089)
Subtotal 1.068 (1.045, 1.091)
CATALUÑA
Barcelona 1.028 (1.018, 1.039)
Subtotal 1.028 (1.018, 1.039)
ANDALUCIA
Cadiz 1.053 (1.027, 1.081)
Cordoba 1.039 (1.011, 1.068)
Huelva 1.046 (1.012, 1.081)
Jaen 1.092 (1.060, 1.125)
Sevilla 1.042 (1.020, 1.065)
Subtotal 1.053 (1.036, 1.071)
Overall 1.053 (1.043, 1.062)
NOTE: Weights are from random effects analysis
.882
1
1.13

Figure S3-D.

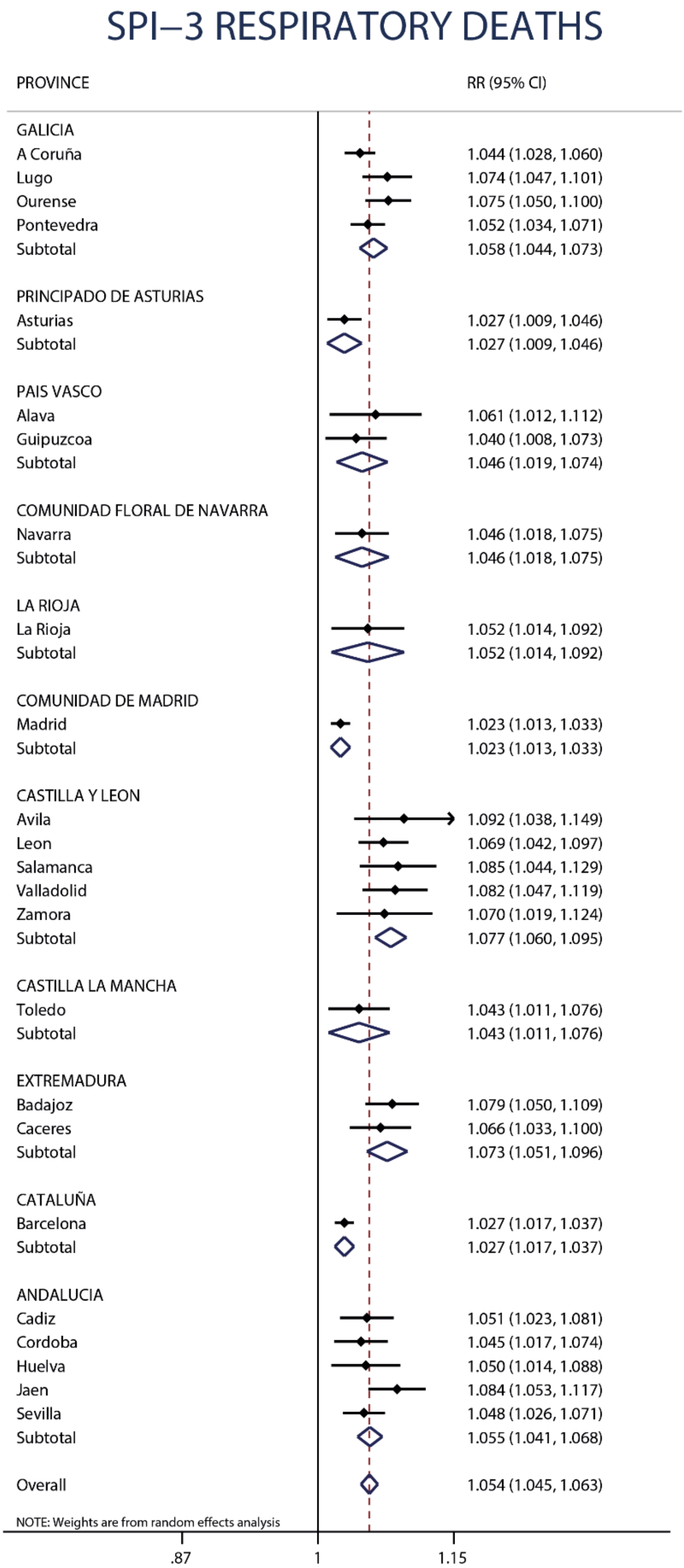

SPI–3 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
GALICIA
A Coruña 1.044 (1.028, 1.060)
Lugo 1.074 (1.047, 1.101)
Ourense 1.075 (1.050, 1.100)
Pontevedra 1.052 (1.034, 1.071)
Subtotal 1.058 (1.044, 1.073)
PRINCIPADO DE ASTURIAS
Asturias 1.027 (1.009, 1.046)
Subtotal 1.027 (1.009, 1.046)
PAIS VASCO
Alava 1.061 (1.012, 1.112)
Guipuzcoa 1.040 (1.008, 1.073)
Subtotal 1.046 (1.019, 1.074)
COMUNIDAD FLORAL DE NAVARRA
Navarra 1.046 (1.018, 1.075)
Subtotal 1.046 (1.018, 1.075)
LA RIOJA
La Rioja 1.052 (1.014, 1.092)
Subtotal 1.052 (1.014, 1.092)
COMUNIDAD DE MADRID
Madrid 1.023 (1.013, 1.033)
Subtotal 1.023 (1.013, 1.033)
CASTILLA Y LEON
Avila 1.092 (1.038, 1.149)
Leon 1.069 (1.042, 1.097)
Salamanca 1.085 (1.044, 1.129)
Valladolid 1.082 (1.047, 1.119)
Zamora 1.070 (1.019, 1.124)
Subtotal 1.077 (1.060, 1.095)
CASTILLA LA MANCHA
Toledo 1.043 (1.011, 1.076)
Subtotal 1.043 (1.011, 1.076)
EXTREMADURA
Badajoz 1.079 (1.050, 1.109)
Caceres 1.066 (1.033, 1.100)
Subtotal 1.073 (1.051, 1.096)
CATALUÑA
Barcelona 1.027 (1.017, 1.037)
Subtotal 1.027 (1.017, 1.037)
ANDALUCIA
Cadiz 1.051 (1.023, 1.081)
Cordoba 1.045 (1.017, 1.074)
Huelva 1.050 (1.014, 1.088)
Jaen 1.084 (1.053, 1.117)
Sevilla 1.048 (1.026, 1.071)
Subtotal 1.055 (1.041, 1.068)
Overall 1.054 (1.045, 1.063)
NOTE: Weights are from random effects analysis
.87
1
1.15

Figure S4-A.

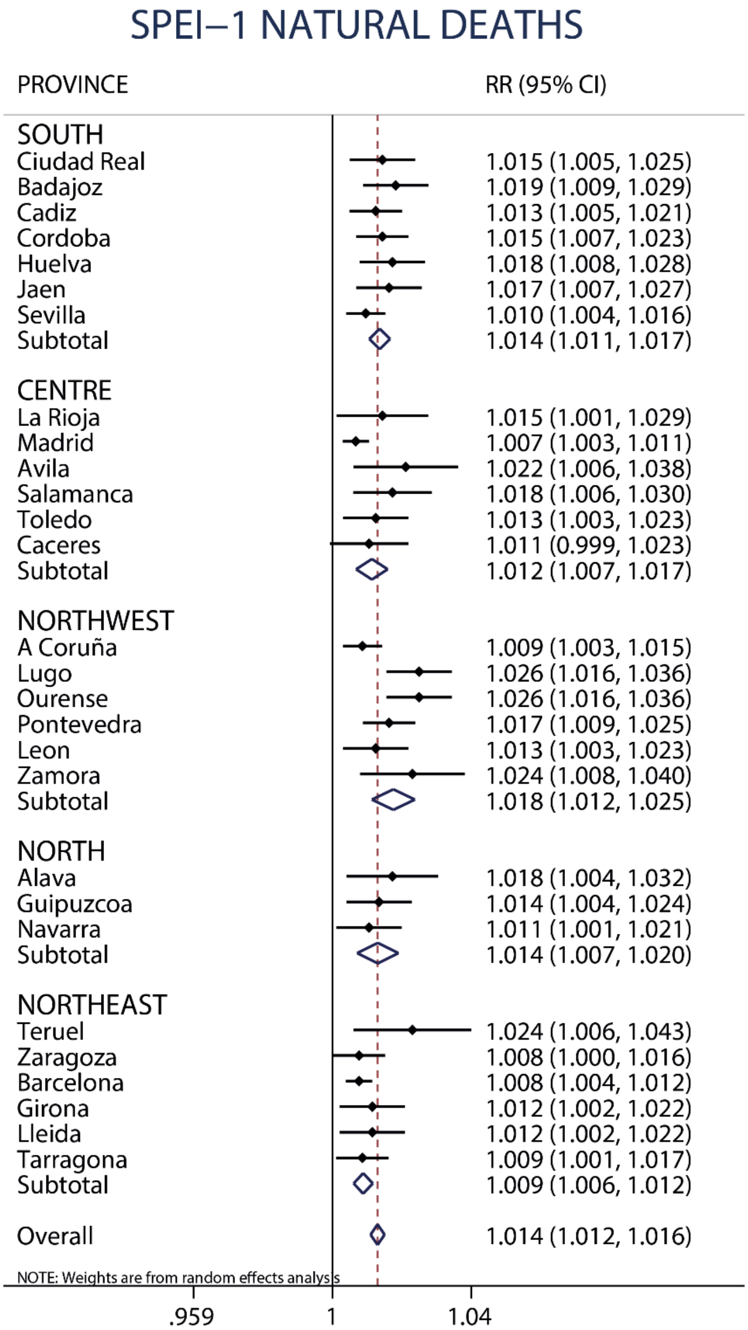

SPEI–1 NATURAL DEATHS
PROVINCE
RR (95% CI)
SOUTH
Ciudad Real 1.015 (1.005, 1.025)
Badajoz 1.019 (1.009, 1.029)
Cadiz 1.013 (1.005, 1.021)
Cordoba 1.015 (1.007, 1.023)
Huelva 1.018 (1.008, 1.028)
Jaen 1.017 (1.007, 1.027)
Sevilla 1.010 (1.004, 1.016)
Subtotal 1.014 (1.011, 1.017)
CENTRE
La Rioja 1.015 (1.001, 1.029)
Madrid 1.007 (1.003, 1.011)
Avila 1.022 (1.006, 1.038)
Salamanca 1.018 (1.006, 1.030)
Toledo 1.013 (1.003, 1.023)
Caceres 1.011 (0.999, 1.023)
Subtotal 1.012 (1.007, 1.017)
NORTHWEST
A Coruña 1.009 (1.003, 1.015)
Lugo 1.026 (1.016, 1.036)
Ourense 1.026 (1.016, 1.036)
Pontevedra 1.017 (1.009, 1.025)
Leon 1.013 (1.003, 1.023)
Zamora 1.024 (1.008, 1.040)
Subtotal 1.018 (1.012, 1.025)
NORTH
Alava 1.018 (1.004, 1.032)
Guipuzcoa 1.014 (1.004, 1.024)
Navarra 1.011 (1.001, 1.021)
Subtotal 1.014 (1.007, 1.020)
NORTHEAST
Teruel 1.024 (1.006, 1.043)
Zaragoza 1.008 (1.000, 1.016)
Barcelona 1.008 (1.004, 1.012)
Girona 1.012 (1.002, 1.022)
Lleida 1.012 (1.002, 1.022)
Tarragona 1.009 (1.001, 1.017)
Subtotal 1.009 (1.006, 1.012)
Overall 1.014 (1.012, 1.016)
NOTE: Weights are from random effects analysis
.959
1
1.04

Figure S4-B.

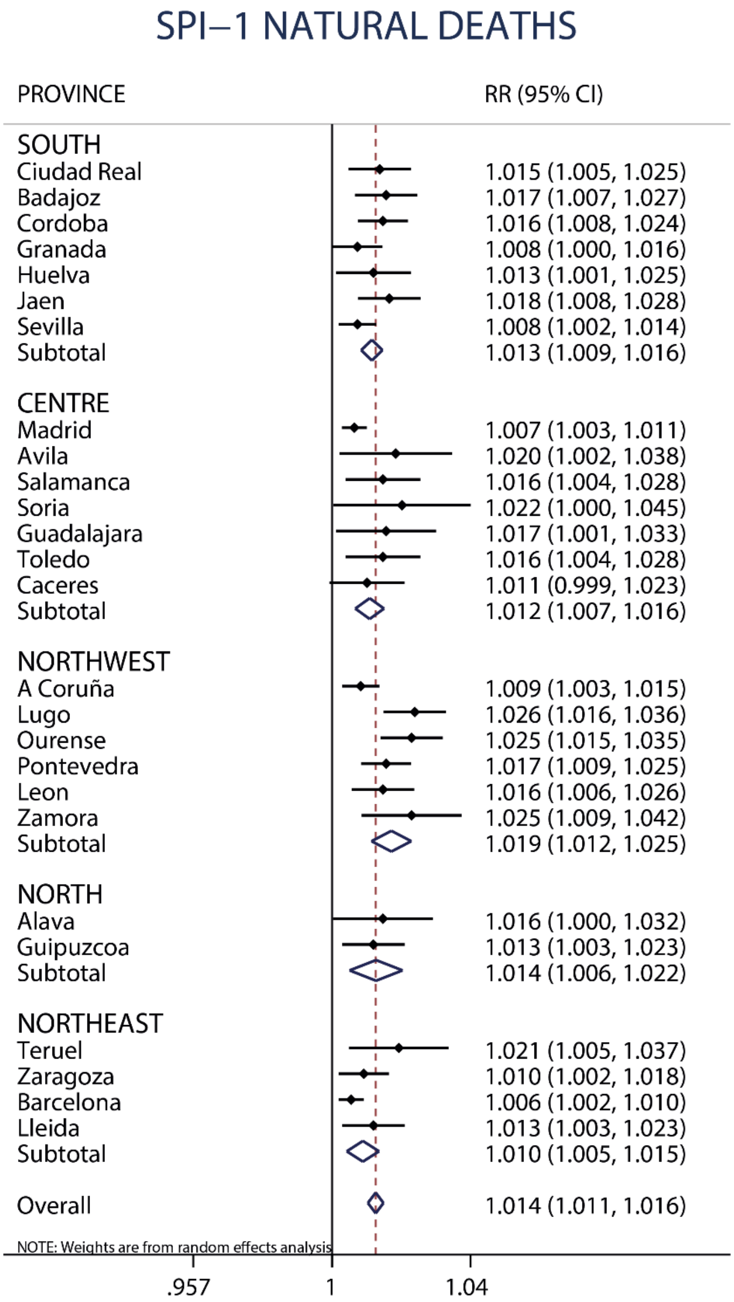

SPI−1 NATURAL DEATHS
PROVINCE
RR (95% CI)
SOUTH
Ciudad Real 1.015 (1.005, 1.025)
Badajoz 1.017 (1.007, 1.027)
Cordoba 1.016 (1.008, 1.024)
Granada 1.008 (1.000, 1.016)
Huelva 1.013 (1.001, 1.025)
Jaen 1.018 (1.008, 1.028)
Sevilla 1.008 (1.002, 1.014)
Subtotal 1.013 (1.009, 1.016)
CENTRE
Madrid 1.007 (1.003, 1.011)
Avila 1.020 (1.002, 1.038)
Salamanca 1.016 (1.004, 1.028)
Soria 1.022 (1.000, 1.045)
Guadalajara 1.017 (1.001, 1.033)
Toledo 1.016 (1.004, 1.028)
Caceres 1.011 (0.999, 1.023)
Subtotal 1.012 (1.007, 1.016)
NORTHWEST
A Coruña 1.009 (1.003, 1.015)
Lugo 1.026 (1.016, 1.036)
Ourense 1.025 (1.015, 1.035)
Pontevedra 1.017 (1.009, 1.025)
Leon 1.016 (1.006, 1.026)
Zamora 1.025 (1.009, 1.042)
Subtotal 1.019 (1.012, 1.025)
NORTH
Alava 1.016 (1.000, 1.032)
Guipuzcoa 1.013 (1.003, 1.023)
Subtotal 1.014 (1.006, 1.022)
NORTHEAST
Teruel 1.021 (1.005, 1.037)
Zaragoza 1.010 (1.002, 1.018)
Barcelona 1.006 (1.002, 1.010)
Lleida 1.013 (1.003, 1.023)
Subtotal 1.010 (1.005, 1.015)
Overall 1.014 (1.011, 1.016)
NOTE: Weights are from random effects analysis
.957
1
1.04

Figure S4-C.

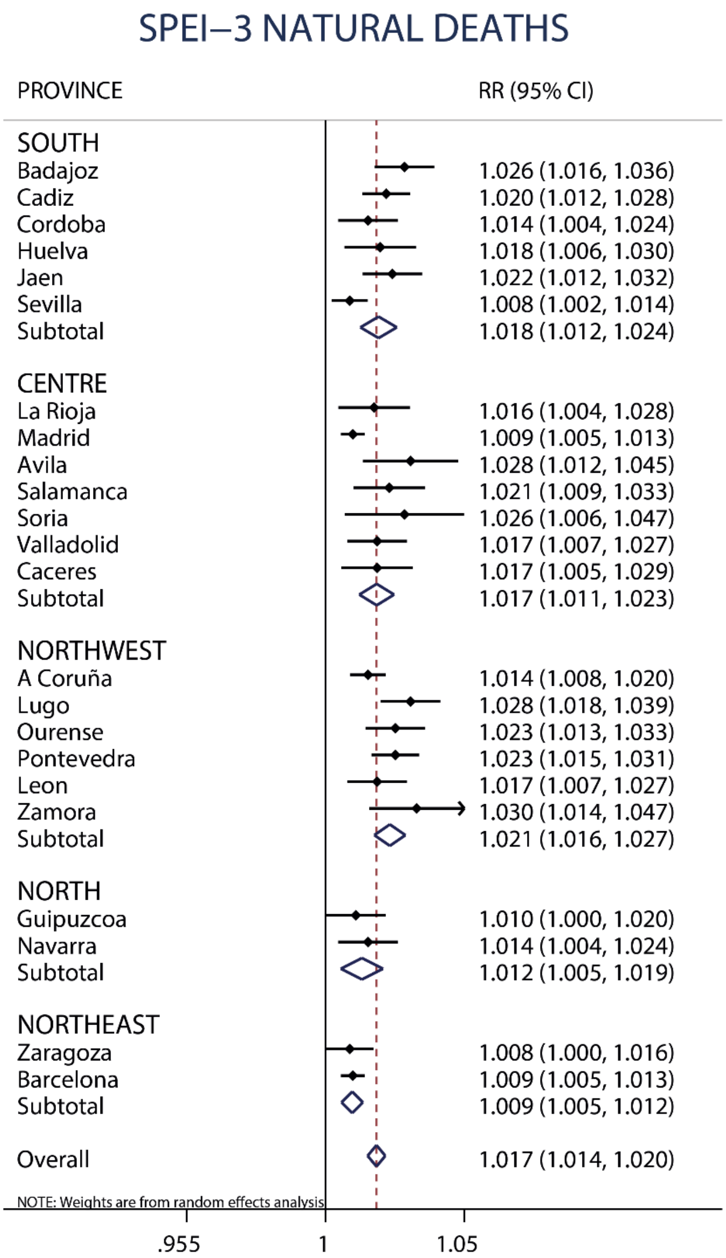

SPEI–3 NATURAL DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.026 (1.016, 1.036)
Cadiz 1.020 (1.012, 1.028)
Cordoba 1.014 (1.004, 1.024)
Huelva 1.018 (1.006, 1.030)
Jaen 1.022 (1.012, 1.032)
Sevilla 1.008 (1.002, 1.014)
Subtotal 1.018 (1.012, 1.024)
CENTRE
La Rioja 1.016 (1.004, 1.028)
Madrid 1.009 (1.005, 1.013)
Avila 1.028 (1.012, 1.045)
Salamanca 1.021 (1.009, 1.033)
Soria 1.026 (1.006, 1.047)
Valladolid 1.017 (1.007, 1.027)
Caceres 1.017 (1.005, 1.029)
Subtotal 1.017 (1.011, 1.023)
NORTHWEST
A Coruña 1.014 (1.008, 1.020)
Lugo 1.028 (1.018, 1.039)
Ourense 1.023 (1.013, 1.033)
Pontevedra 1.023 (1.015, 1.031)
Leon 1.017 (1.007, 1.027)
Zamora 1.030 (1.014, 1.047)
Subtotal 1.021 (1.016, 1.027)
NORTH
Guipuzcoa 1.010 (1.000, 1.020)
Navarra 1.014 (1.004, 1.024)
Subtotal 1.012 (1.005, 1.019)
NORTHEAST
Zaragoza 1.008 (1.000, 1.016)
Barcelona 1.009 (1.005, 1.013)
Subtotal 1.009 (1.005, 1.012)
Overall 1.017 (1.014, 1.020)
NOTE: Weights are from random effects analysis
.955
1
1.05

Figure S4-D.

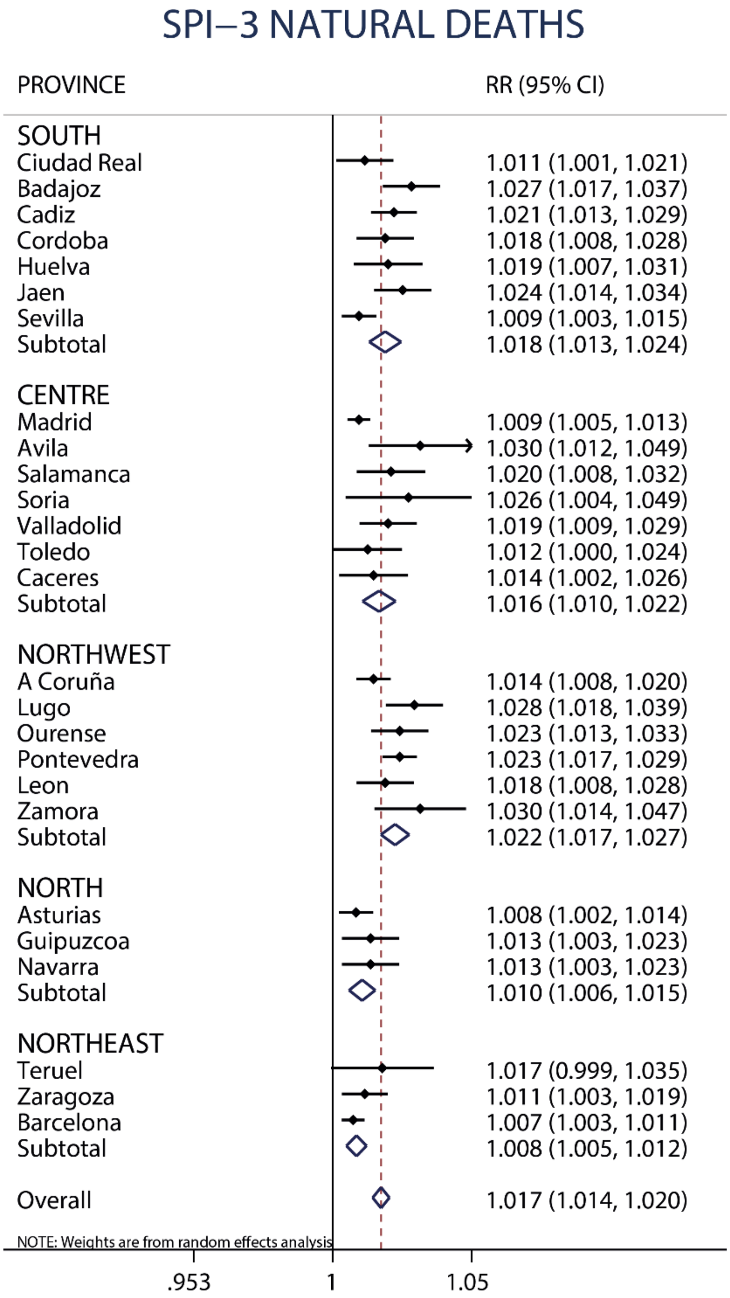
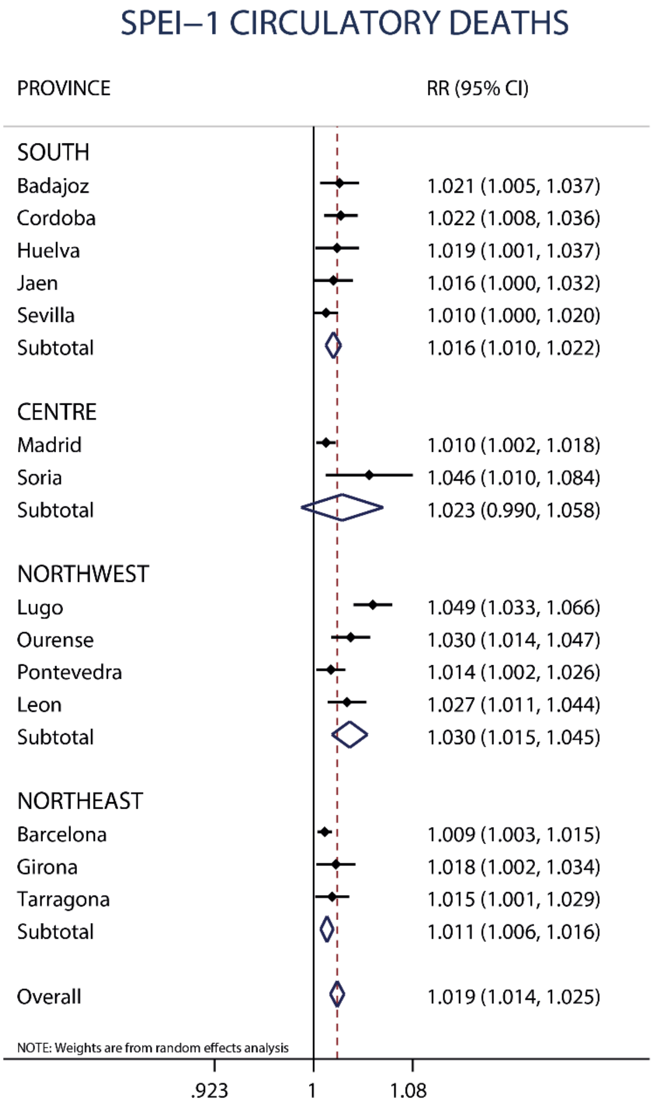

SPI–3 NATURAL DEATHS
PROVINCE
RR (95% CI)
SOUTH
Ciudad Real 1.011 (1.001, 1.021)
Badajoz 1.027 (1.017, 1.037)
Cadiz 1.021 (1.013, 1.029)
Cordoba 1.018 (1.008, 1.028)
Huelva 1.019 (1.007, 1.031)
Jaen 1.024 (1.014, 1.034)
Sevilla 1.009 (1.003, 1.015)
Subtotal 1.018 (1.013, 1.024)
CENTRE
Madrid 1.009 (1.005, 1.013)
Avila 1.030 (1.012, 1.049)
Salamanca 1.020 (1.008, 1.032)
Soria 1.026 (1.004, 1.049)
Valladolid 1.019 (1.009, 1.029)
Toledo 1.012 (1.000, 1.024)
Caceres 1.014 (1.002, 1.026)
Subtotal 1.016 (1.010, 1.022)
NORTHWEST
A Coruña 1.014 (1.008, 1.020)
Lugo 1.028 (1.018, 1.039)
Ourense 1.023 (1.013, 1.033)
Pontevedra 1.023 (1.017, 1.029)
Leon 1.018 (1.008, 1.028)
Zamora 1.030 (1.014, 1.047)
Subtotal 1.022 (1.017, 1.027)
NORTH
Asturias 1.008 (1.002, 1.014)
Guipuzcoa 1.013 (1.003, 1.023)
Navarra 1.013 (1.003, 1.023)
Subtotal 1.010 (1.006, 1.015)
NORTHEAST
Teruel 1.017 (0.999, 1.035)
Zaragoza 1.011 (1.003, 1.019)
Barcelona 1.007 (1.003, 1.011)
Subtotal 1.008 (1.005, 1.012)
Overall 1.017 (1.014, 1.020)
NOTE: Weights are from random effects analysis
.953
1
1.05

Figure S5-A.



SPEI–1 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.021 (1.005, 1.037)
Cordoba 1.022 (1.008, 1.036)
Huelva 1.019 (1.001, 1.037)
Jaen 1.016 (1.000, 1.032)
Sevilla 1.010 (1.000, 1.020)
Subtotal 1.016 (1.010, 1.022)
CENTRE
Madrid 1.010 (1.002, 1.018)
Soria 1.046 (1.010, 1.084)
Subtotal 1.023 (0.990, 1.058)
NORTHWEST
Lugo 1.049 (1.033, 1.066)
Ourense 1.030 (1.014, 1.047)
Pontevedra 1.014 (1.002, 1.026)
Leon 1.027 (1.011, 1.044)
Subtotal 1.030 (1.015, 1.045)
NORTHEAST
Barcelona 1.009 (1.003, 1.015)
Girona 1.018 (1.002, 1.034)
Tarragona 1.015 (1.001, 1.029)
Subtotal 1.011 (1.006, 1.016)
Overall 1.019 (1.014, 1.025)
NOTE: Weights are from random effects analysis
.923
1
1.08

Figure S5-B.

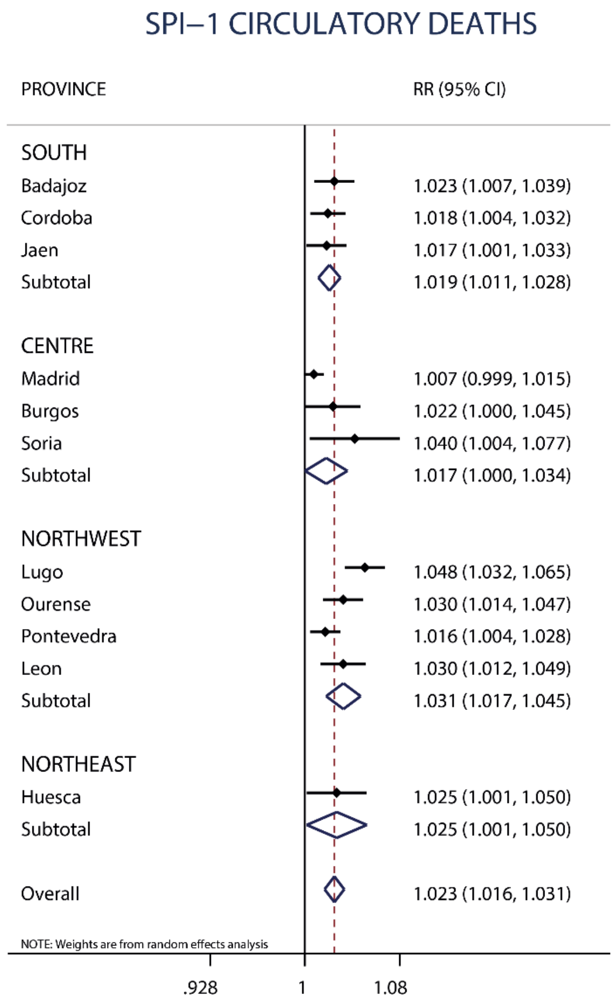

SPI–1 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz
1.023 (1.007, 1.039)
Cordoba
1.018 (1.004, 1.032)
Jaen
1.017 (1.001, 1.033)
Subtotal
1.019 (1.011, 1.028)
CENTRE
Madrid
1.007 (0.999, 1.015)
Burgos
1.022 (1.000, 1.045)
Soria
1.040 (1.004, 1.077)
Subtotal
1.017 (1.000, 1.034)
NORTHWEST
Lugo
1.048 (1.032, 1.065)
Ourense
1.030 (1.014, 1.047)
Pontevedra
1.016 (1.004, 1.028)
Leon
1.030 (1.012, 1.049)
Subtotal
1.031 (1.017, 1.045)
NORTHEAST
Huesca
1.025 (1.001, 1.050)
Subtotal
1.025 (1.001, 1.050)
Overall
1.023 (1.016, 1.031)
NOTE: Weights are from random effects analysis
.928
1
1.08

Figure S5-C.

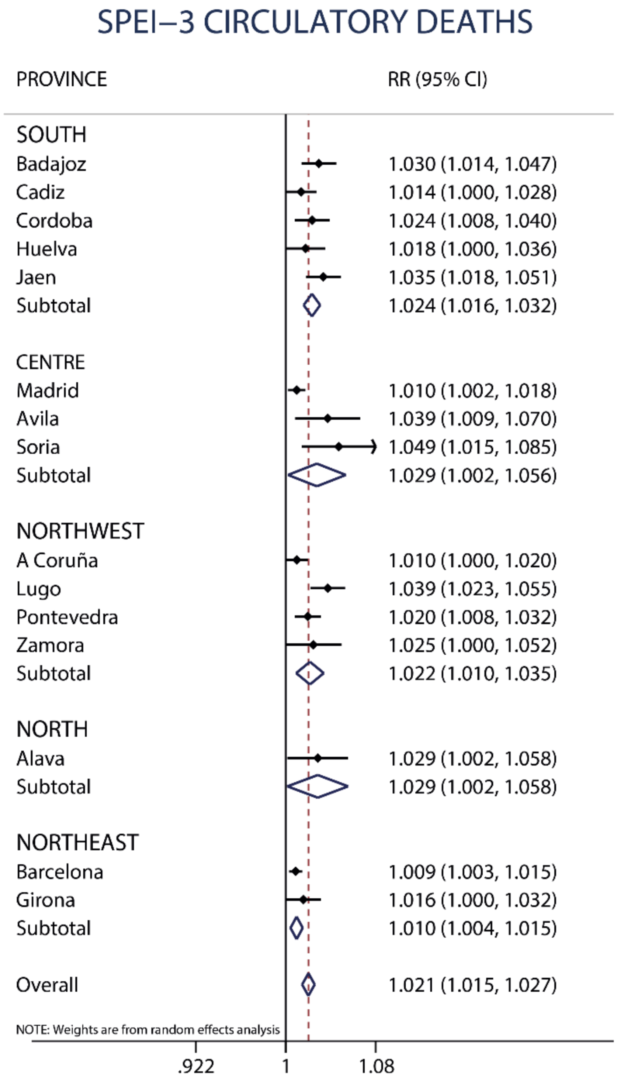

SPEI–3 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.030 (1.014, 1.047)
Cadiz 1.014 (1.000, 1.028)
Cordoba 1.024 (1.008, 1.040)
Huelva 1.018 (1.000, 1.036)
Jaen 1.035 (1.018, 1.051)
Subtotal 1.024 (1.016, 1.032)
CENTRE
Madrid 1.010 (1.002, 1.018)
Avila 1.039 (1.009, 1.070)
Soria 1.049 (1.015, 1.085)
Subtotal 1.029 (1.002, 1.056)
NORTHWEST
A Coruña 1.010 (1.000, 1.020)
Lugo 1.039 (1.023, 1.055)
Pontevedra 1.020 (1.008, 1.032)
Zamora 1.025 (1.000, 1.052)
Subtotal 1.022 (1.010, 1.035)
NORTH
Alava 1.029 (1.002, 1.058)
Subtotal 1.029 (1.002, 1.058)
NORTHEAST
Barcelona 1.009 (1.003, 1.015)
Girona 1.016 (1.000, 1.032)
Subtotal 1.010 (1.004, 1.015)
Overall 1.021 (1.015, 1.027)
NOTE: Weights are from random effects analysis
.922
1
1.08

Figure S5-D.

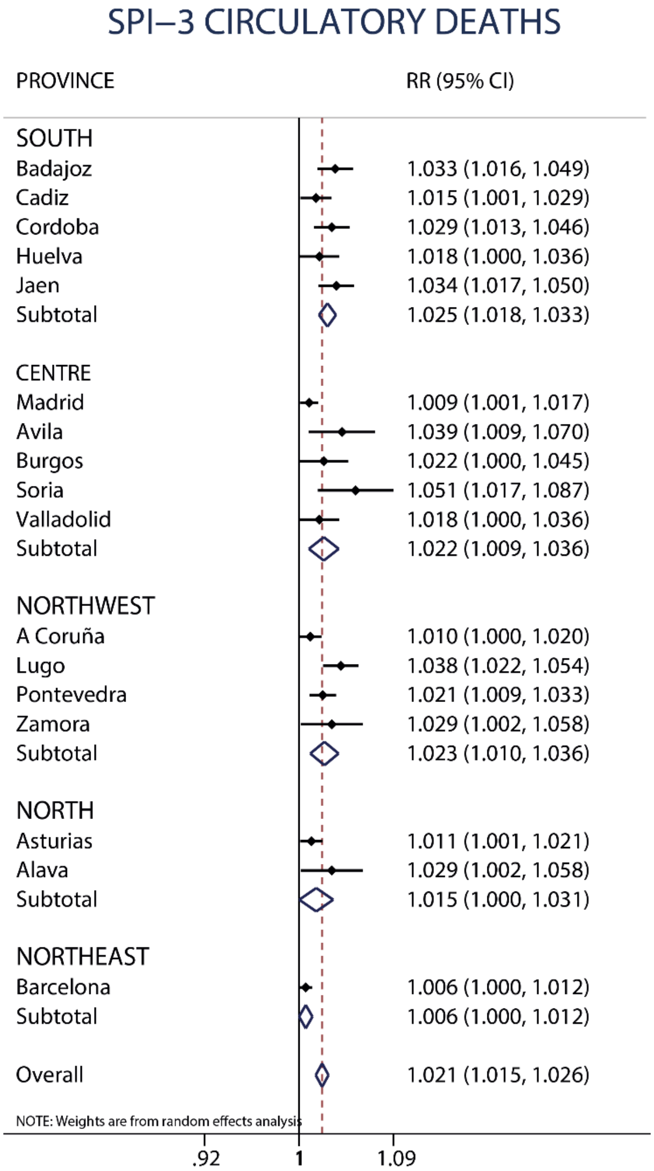

SPI–3 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.033 (1.016, 1.049)
Cadiz 1.015 (1.001, 1.029)
Cordoba 1.029 (1.013, 1.046)
Huelva 1.018 (1.000, 1.036)
Jaen 1.034 (1.017, 1.050)
Subtotal 1.025 (1.018, 1.033)
CENTRE
Madrid 1.009 (1.001, 1.017)
Avila 1.039 (1.009, 1.070)
Burgos 1.022 (1.000, 1.045)
Soria 1.051 (1.017, 1.087)
Valladolid 1.018 (1.000, 1.036)
Subtotal 1.022 (1.009, 1.036)
NORTHWEST
A Coruña 1.010 (1.000, 1.020)
Lugo 1.038 (1.022, 1.054)
Pontevedra 1.021 (1.009, 1.033)
Zamora 1.029 (1.002, 1.058)
Subtotal 1.023 (1.010, 1.036)
NORTH
Asturias 1.011 (1.001, 1.021)
Alava 1.029 (1.002, 1.058)
Subtotal 1.015 (1.000, 1.031)
NORTHEAST
Barcelona 1.006 (1.000, 1.012)
Subtotal 1.006 (1.000, 1.012)
Overall 1.021 (1.015, 1.026)
NOTE: Weights are from random effects analysis
.92
1
1.09

Figure S6-A.

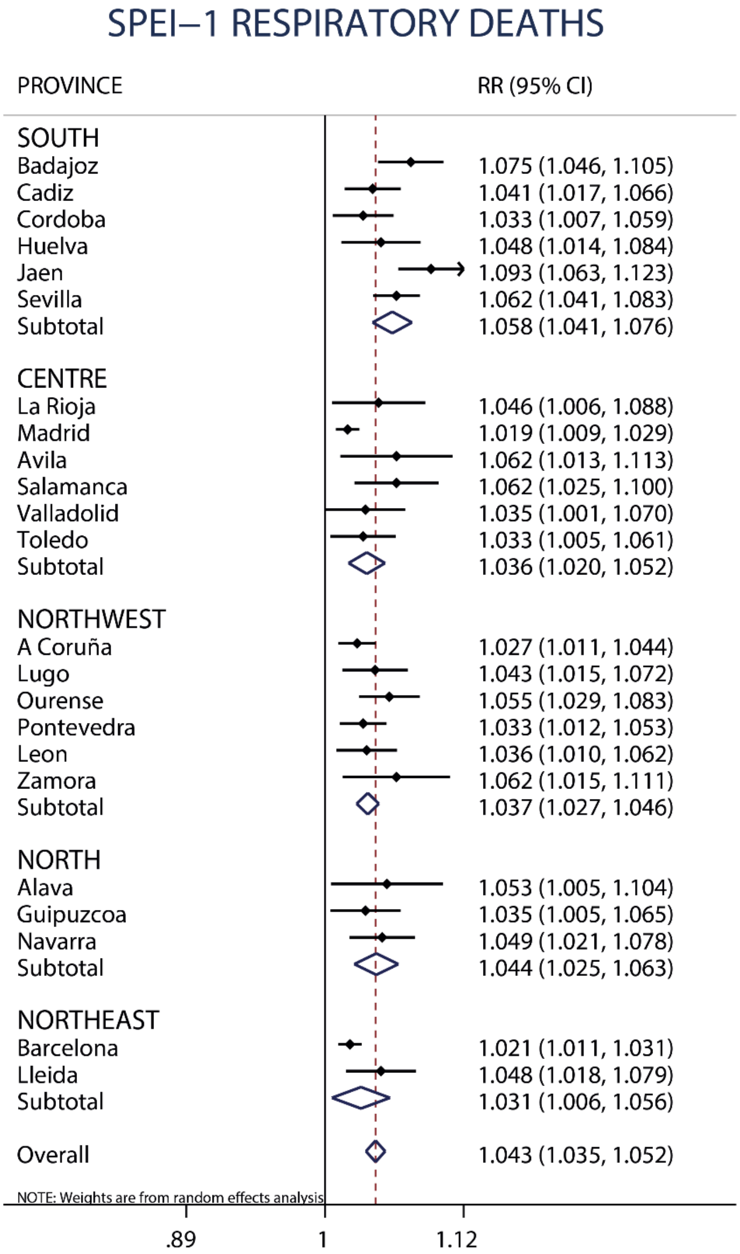
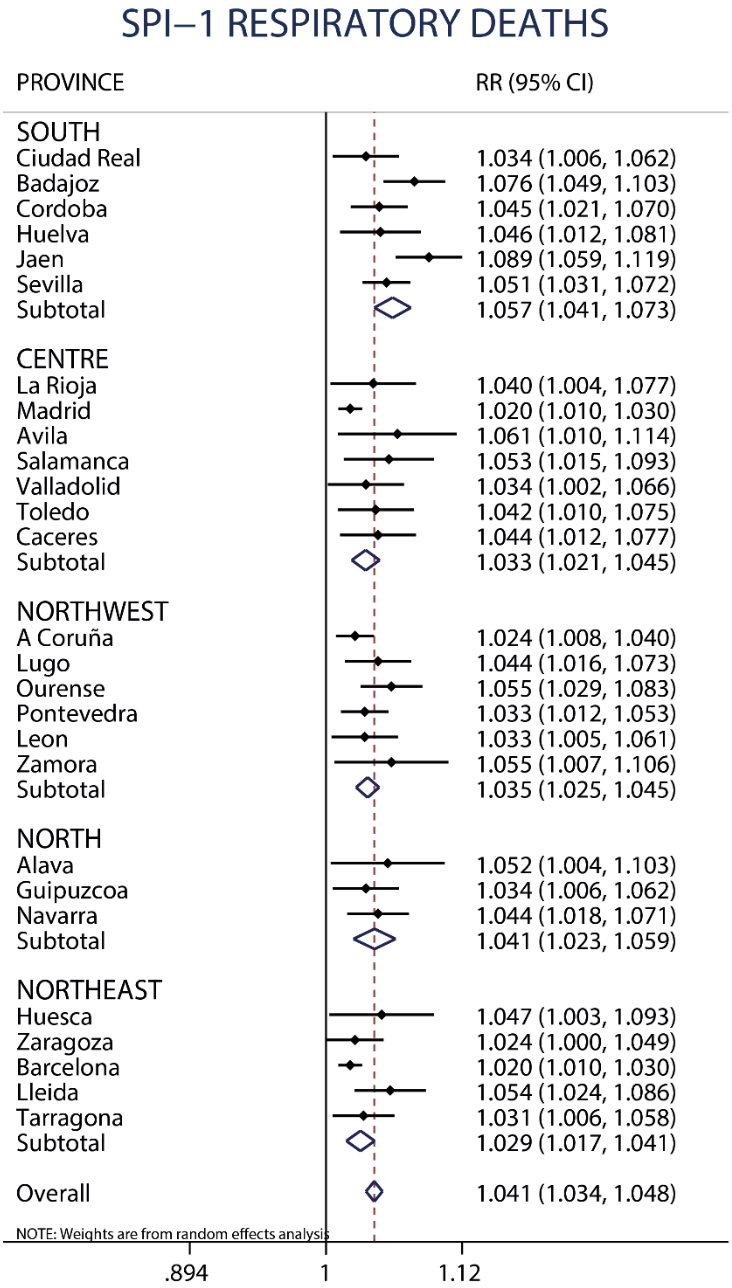

SPEI–1 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.075 (1.046, 1.105)
Cadiz 1.041 (1.017, 1.066)
Cordoba 1.033 (1.007, 1.059)
Huelva 1.048 (1.014, 1.084)
Jaen 1.093 (1.063, 1.123)
Sevilla 1.062 (1.041, 1.083)
Subtotal 1.058 (1.041, 1.076)
CENTRE
La Rioja 1.046 (1.006, 1.088)
Madrid 1.019 (1.009, 1.029)
Avila 1.062 (1.013, 1.113)
Salamanca 1.062 (1.025, 1.100)
Valladolid 1.035 (1.001, 1.070)
Toledo 1.033 (1.005, 1.061)
Subtotal 1.036 (1.020, 1.052)
NORTHWEST
A Coruña 1.027 (1.011, 1.044)
Lugo 1.043 (1.015, 1.072)
Ourense 1.055 (1.029, 1.083)
Pontevedra 1.033 (1.012, 1.053)
Leon 1.036 (1.010, 1.062)
Zamora 1.062 (1.015, 1.111)
Subtotal 1.037 (1.027, 1.046)
NORTH
Alava 1.053 (1.005, 1.104)
Guipuzcoa 1.035 (1.005, 1.065)
Navarra 1.049 (1.021, 1.078)
Subtotal 1.044 (1.025, 1.063)
NORTHEAST
Barcelona 1.021 (1.011, 1.031)
Lleida 1.048 (1.018, 1.079)
Subtotal 1.031 (1.006, 1.056)
Overall 1.043 (1.035, 1.052)
NOTE: Weights are from random effects analysis
.89
1
1.12

Figure S6-B.



SPI−1 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Ciudad Real 1.034 (1.006, 1.062)
Badajoz 1.076 (1.049, 1.103)
Cordoba 1.045 (1.021, 1.070)
Huelva 1.046 (1.012, 1.081)
Jaen 1.089 (1.059, 1.119)
Sevilla 1.051 (1.031, 1.072)
Subtotal 1.057 (1.041, 1.073)
CENTRE
La Rioja 1.040 (1.004, 1.077)
Madrid 1.020 (1.010, 1.030)
Avila 1.061 (1.010, 1.114)
Salamanca 1.053 (1.015, 1.093)
Valladolid 1.034 (1.002, 1.066)
Toledo 1.042 (1.010, 1.075)
Caceres 1.044 (1.012, 1.077)
Subtotal 1.033 (1.021, 1.045)
NORTHWEST
A Coruña 1.024 (1.008, 1.040)
Lugo 1.044 (1.016, 1.073)
Ourense 1.055 (1.029, 1.083)
Pontevedra 1.033 (1.012, 1.053)
Leon 1.033 (1.005, 1.061)
Zamora 1.055 (1.007, 1.106)
Subtotal 1.035 (1.025, 1.045)
NORTH
Alava 1.052 (1.004, 1.103)
Guipuzcoa 1.034 (1.006, 1.062)
Navarra 1.044 (1.018, 1.071)
Subtotal 1.041 (1.023, 1.059)
NORTHEAST
Huesca 1.047 (1.003, 1.093)
Zaragoza 1.024 (1.000, 1.049)
Barcelona 1.020 (1.010, 1.030)
Lleida 1.054 (1.024, 1.086)
Tarragona 1.031 (1.006, 1.058)
Subtotal 1.029 (1.017, 1.041)
Overall 1.041 (1.034, 1.048)
NOTE: Weights are from random effects analysis
.894
1
1.12

Figure S6-C.

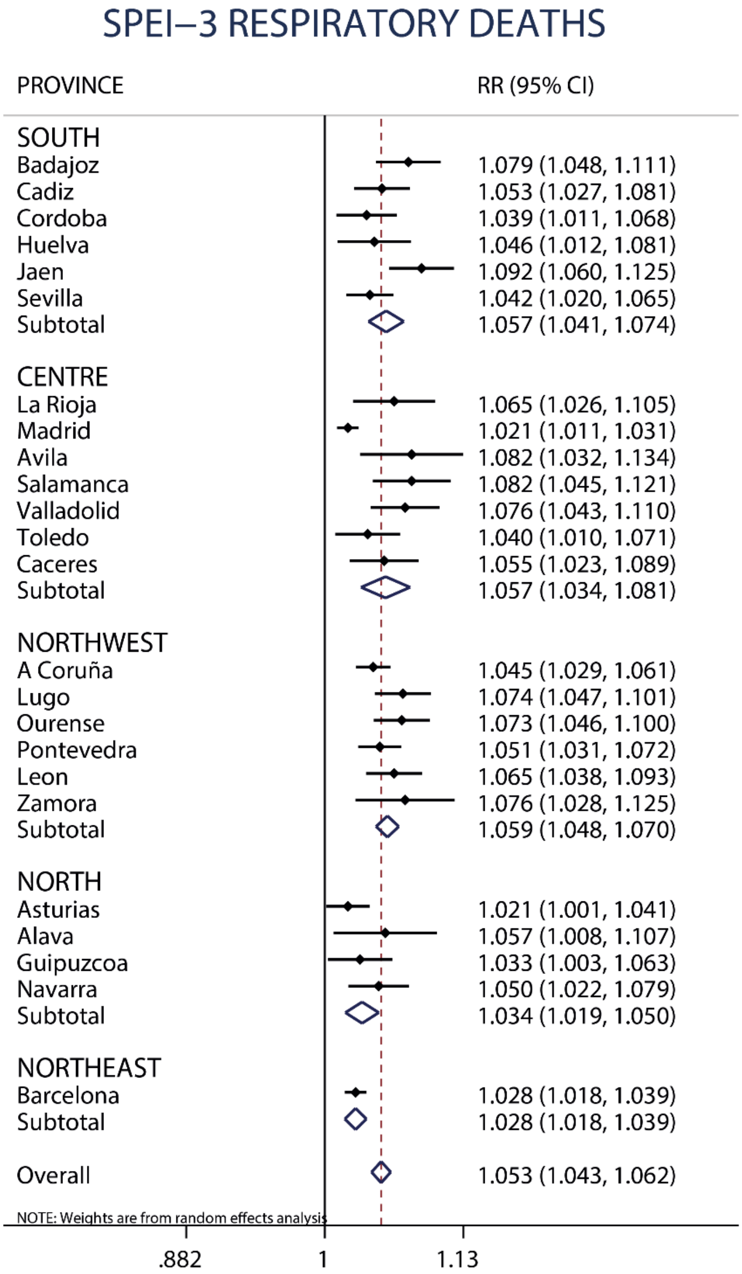

SPEI–3 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.079 (1.048, 1.111)
Cadiz 1.053 (1.027, 1.081)
Cordoba 1.039 (1.011, 1.068)
Huelva 1.046 (1.012, 1.081)
Jaen 1.092 (1.060, 1.125)
Sevilla 1.042 (1.020, 1.065)
Subtotal 1.057 (1.041, 1.074)
CENTRE
La Rioja 1.065 (1.026, 1.105)
Madrid 1.021 (1.011, 1.031)
Avila 1.082 (1.032, 1.134)
Salamanca 1.082 (1.045, 1.121)
Valladolid 1.076 (1.043, 1.110)
Toledo 1.040 (1.010, 1.071)
Caceres 1.055 (1.023, 1.089)
Subtotal 1.057 (1.034, 1.081)
NORTHWEST
A Coruña 1.045 (1.029, 1.061)
Lugo 1.074 (1.047, 1.101)
Ourense 1.073 (1.046, 1.100)
Pontevedra 1.051 (1.031, 1.072)
Leon 1.065 (1.038, 1.093)
Zamora 1.076 (1.028, 1.125)
Subtotal 1.059 (1.048, 1.070)
NORTH
Asturias 1.021 (1.001, 1.041)
Alava 1.057 (1.008, 1.107)
Guipuzcoa 1.033 (1.003, 1.063)
Navarra 1.050 (1.022, 1.079)
Subtotal 1.034 (1.019, 1.050)
NORTHEAST
Barcelona 1.028 (1.018, 1.039)
Subtotal 1.028 (1.018, 1.039)
Overall 1.053 (1.043, 1.062)
NOTE: Weights are from random effects analysis
.882
1
1.13

Figure S6-D.

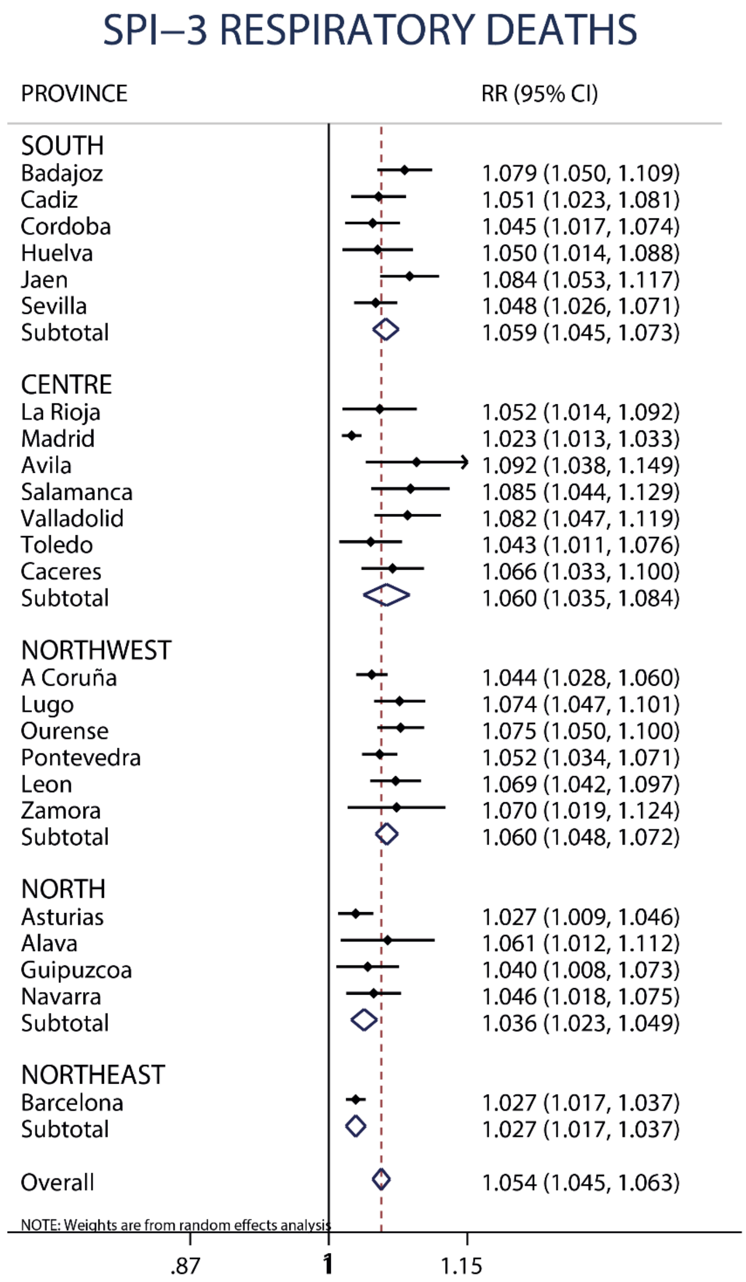

SPI–3 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
SOUTH
Badajoz 1.079 (1.050, 1.109)
Cadiz 1.051 (1.023, 1.081)
Cordoba 1.045 (1.017, 1.074)
Huelva 1.050 (1.014, 1.088)
Jaen 1.084 (1.053, 1.117)
Sevilla 1.048 (1.026, 1.071)
Subtotal 1.059 (1.045, 1.073)
CENTRE
La Rioja 1.052 (1.014, 1.092)
Madrid 1.023 (1.013, 1.033)
Avila 1.092 (1.038, 1.149)
Salamanca 1.085 (1.044, 1.129)
Valladolid 1.082 (1.047, 1.119)
Toledo 1.043 (1.011, 1.076)
Caceres 1.066 (1.033, 1.100)
Subtotal 1.060 (1.035, 1.084)
NORTHWEST
A Coruña 1.044 (1.028, 1.060)
Lugo 1.074 (1.047, 1.101)
Ourense 1.075 (1.050, 1.100)
Pontevedra 1.052 (1.034, 1.071)
Leon 1.069 (1.042, 1.097)
Zamora 1.070 (1.019, 1.124)
Subtotal 1.060 (1.048, 1.072)
NORTH
Asturias 1.027 (1.009, 1.046)
Alava 1.061 (1.012, 1.112)
Guipuzcoa 1.040 (1.008, 1.073)
Navarra 1.046 (1.018, 1.075)
Subtotal 1.036 (1.023, 1.049)
NORTHEAST
Barcelona 1.027 (1.017, 1.037)
Subtotal 1.027 (1.017, 1.037)
Overall 1.054 (1.045, 1.063)
NOTE: Weights are from random effects analysis
.87
1
1.15

Figure S7-A.

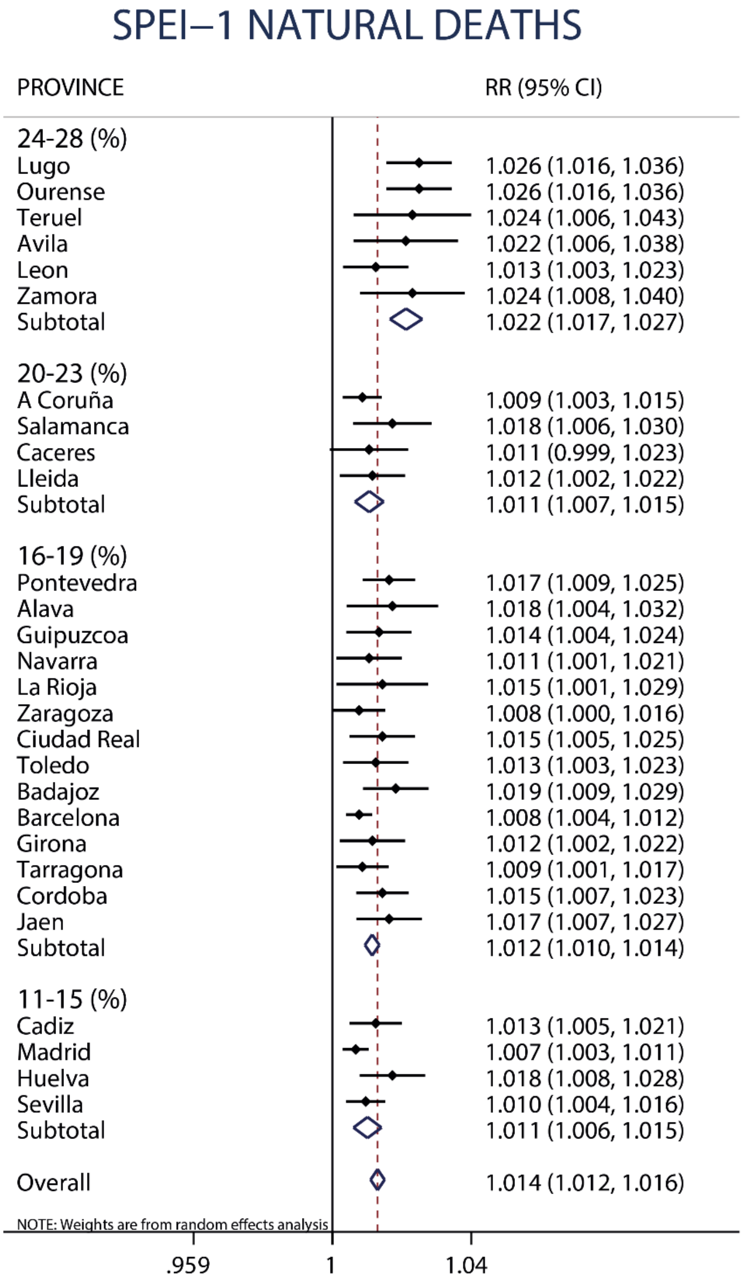

SPEI–1 NATURAL DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.026 (1.016, 1.036)
Ourense 1.026 (1.016, 1.036)
Teruel 1.024 (1.006, 1.043)
Avila 1.022 (1.006, 1.038)
Leon 1.013 (1.003, 1.023)
Zamora 1.024 (1.008, 1.040)
Subtotal 1.022 (1.017, 1.027)
20-23 (%)
A Coruña 1.009 (1.003, 1.015)
Salamanca 1.018 (1.006, 1.030)
Caceres 1.011 (0.999, 1.023)
Lleida 1.012 (1.002, 1.022)
Subtotal 1.011 (1.007, 1.015)
16-19 (%)
Pontevedra 1.017 (1.009, 1.025)
Alava 1.018 (1.004, 1.032)
Guipuzcoa 1.014 (1.004, 1.024)
Navarra 1.011 (1.001, 1.021)
La Rioja 1.015 (1.001, 1.029)
Zaragoza 1.008 (1.000, 1.016)
Ciudad Real 1.015 (1.005, 1.025)
Toledo 1.013 (1.003, 1.023)
Badajoz 1.019 (1.009, 1.029)
Barcelona 1.008 (1.004, 1.012)
Girona 1.012 (1.002, 1.022)
Tarragona 1.009 (1.001, 1.017)
Cordoba 1.015 (1.007, 1.023)
Jaen 1.017 (1.007, 1.027)
Subtotal 1.012 (1.010, 1.014)
11-15 (%)
Cadiz 1.013 (1.005, 1.021)
Madrid 1.007 (1.003, 1.011)
Huelva 1.018 (1.008, 1.028)
Sevilla 1.010 (1.004, 1.016)
Subtotal 1.011 (1.006, 1.015)
Overall 1.014 (1.012, 1.016)
NOTE: Weights are from random effects analysis
.959
1
1.04

Figure S7-B.

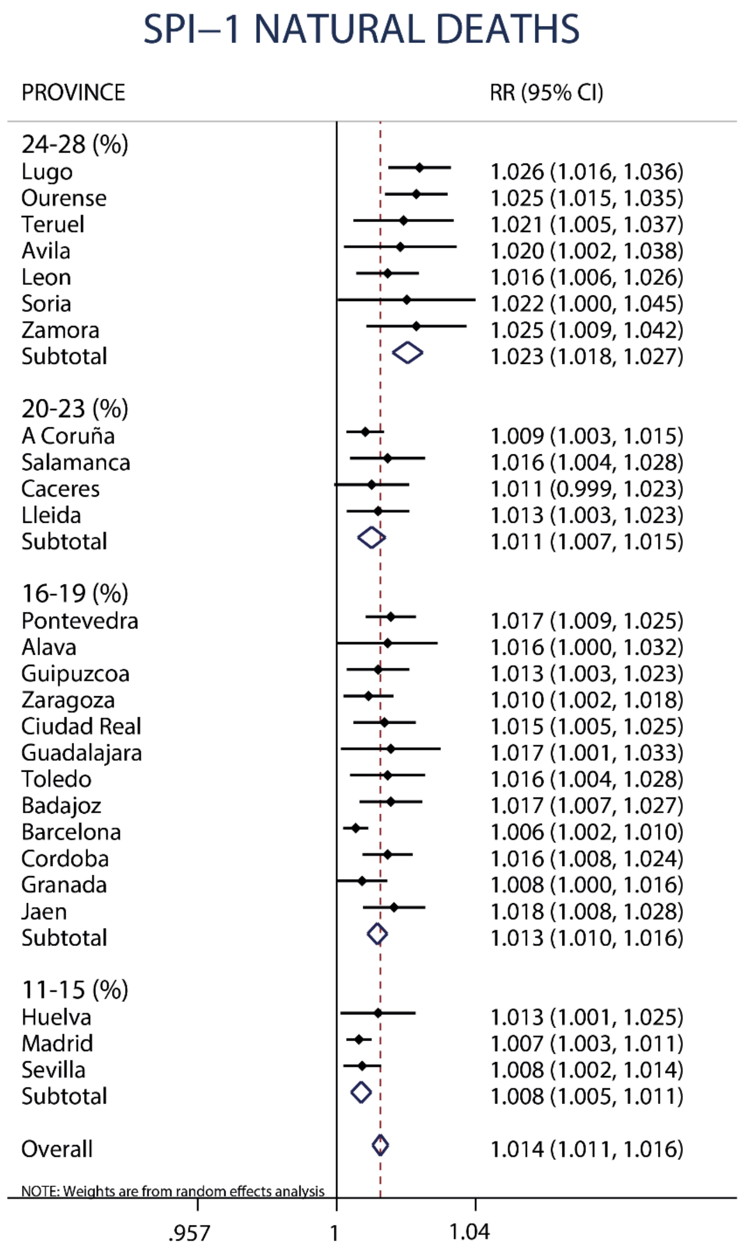

SPI–1 NATURAL DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.026 (1.016, 1.036)
Ourense 1.025 (1.015, 1.035)
Teruel 1.021 (1.005, 1.037)
Avila 1.020 (1.002, 1.038)
Leon 1.016 (1.006, 1.026)
Soria 1.022 (1.000, 1.045)
Zamora 1.025 (1.009, 1.042)
Subtotal 1.023 (1.018, 1.027)
20-23 (%)
A Coruña 1.009 (1.003, 1.015)
Salamanca 1.016 (1.004, 1.028)
Caceres 1.011 (0.999, 1.023)
Lleida 1.013 (1.003, 1.023)
Subtotal 1.011 (1.007, 1.015)
16-19 (%)
Pontevedra 1.017 (1.009, 1.025)
Alava 1.016 (1.000, 1.032)
Guipuzcoa 1.013 (1.003, 1.023)
Zaragoza 1.010 (1.002, 1.018)
Ciudad Real 1.015 (1.005, 1.025)
Guadalajara 1.017 (1.001, 1.033)
Toledo 1.016 (1.004, 1.028)
Badajoz 1.017 (1.007, 1.027)
Barcelona 1.006 (1.002, 1.010)
Cordoba 1.016 (1.008, 1.024)
Granada 1.008 (1.000, 1.016)
Jaen 1.018 (1.008, 1.028)
Subtotal 1.013 (1.010, 1.016)
11-15 (%)
Huelva 1.013 (1.001, 1.025)
Madrid 1.007 (1.003, 1.011)
Sevilla 1.008 (1.002, 1.014)
Subtotal 1.008 (1.005, 1.011)
Overall 1.014 (1.011, 1.016)
NOTE: Weights are from random effects analysis
.957
1
1.04

Figure S7-C.

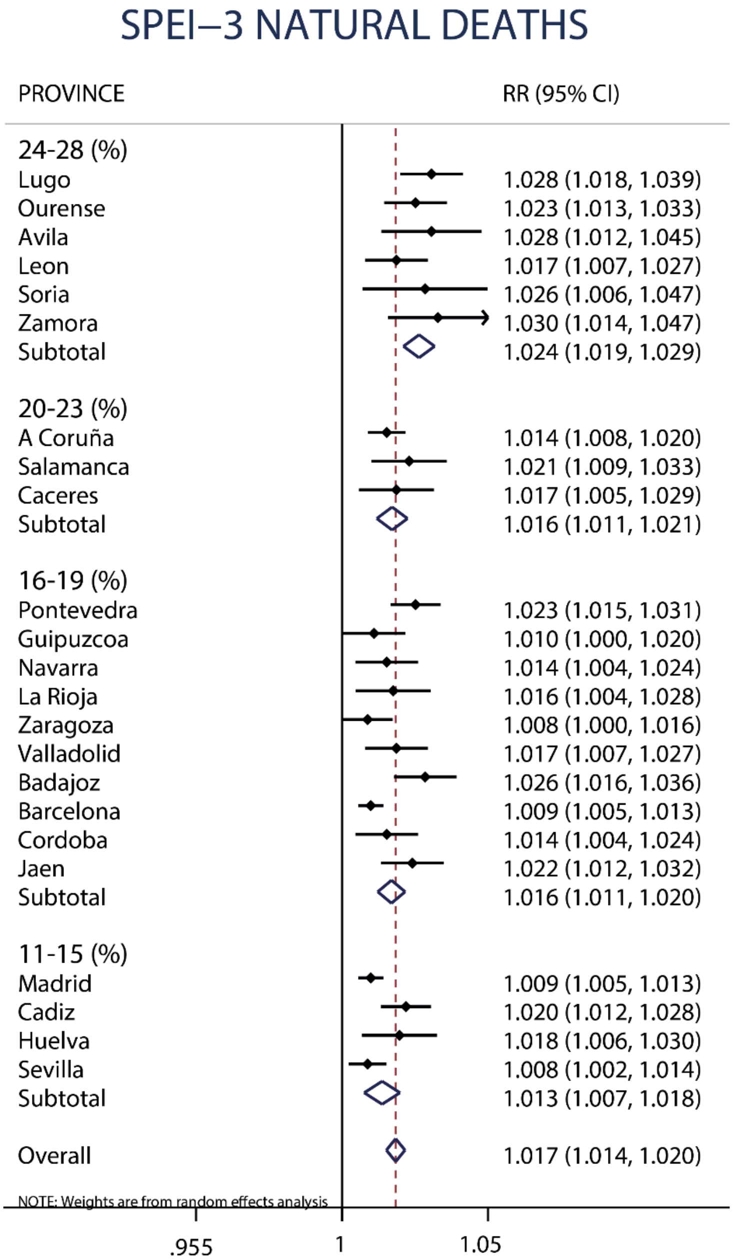

SPEI–3 NATURAL DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.028 (1.018, 1.039)
Ourense 1.023 (1.013, 1.033)
Avila 1.028 (1.012, 1.045)
Leon 1.017 (1.007, 1.027)
Soria 1.026 (1.006, 1.047)
Zamora 1.030 (1.014, 1.047)
Subtotal 1.024 (1.019, 1.029)
20-23 (%)
A Coruña 1.014 (1.008, 1.020)
Salamanca 1.021 (1.009, 1.033)
Caceres 1.017 (1.005, 1.029)
Subtotal 1.016 (1.011, 1.021)
16-19 (%)
Pontevedra 1.023 (1.015, 1.031)
Guipuzcoa 1.010 (1.000, 1.020)
Navarra 1.014 (1.004, 1.024)
La Rioja 1.016 (1.004, 1.028)
Zaragoza 1.008 (1.000, 1.016)
Valladolid 1.017 (1.007, 1.027)
Badajoz 1.026 (1.016, 1.036)
Barcelona 1.009 (1.005, 1.013)
Cordoba 1.014 (1.004, 1.024)
Jaen 1.022 (1.012, 1.032)
Subtotal 1.016 (1.011, 1.020)
11-15 (%)
Madrid 1.009 (1.005, 1.013)
Cadiz 1.020 (1.012, 1.028)
Huelva 1.018 (1.006, 1.030)
Sevilla 1.008 (1.002, 1.014)
Subtotal 1.013 (1.007, 1.018)
Overall 1.017 (1.014, 1.020)
NOTE: Weights are from random effects analysis
.955
1
1.05

Figure S7-D

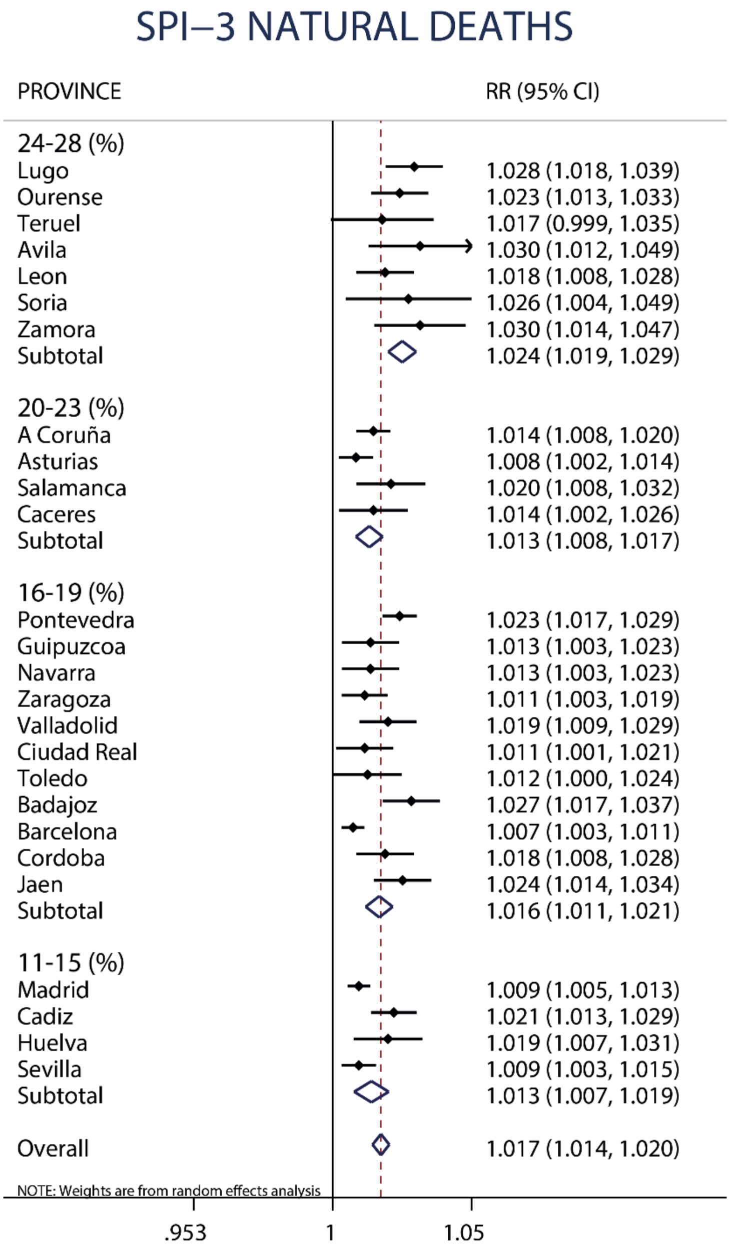

SPI–3 NATURAL DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.028 (1.018, 1.039)
Ourense 1.023 (1.013, 1.033)
Teruel 1.017 (0.999, 1.035)
Avila 1.030 (1.012, 1.049)
Leon 1.018 (1.008, 1.028)
Soria 1.026 (1.004, 1.049)
Zamora 1.030 (1.014, 1.047)
Subtotal 1.024 (1.019, 1.029)
20-23 (%)
A Coruña 1.014 (1.008, 1.020)
Asturias 1.008 (1.002, 1.014)
Salamanca 1.020 (1.008, 1.032)
Caceres 1.014 (1.002, 1.026)
Subtotal 1.013 (1.008, 1.017)
16-19 (%)
Pontevedra 1.023 (1.017, 1.029)
Guipuzcoa 1.013 (1.003, 1.023)
Navarra 1.013 (1.003, 1.023)
Zaragoza 1.011 (1.003, 1.019)
Valladolid 1.019 (1.009, 1.029)
Ciudad Real 1.011 (1.001, 1.021)
Toledo 1.012 (1.000, 1.024)
Badajoz 1.027 (1.017, 1.037)
Barcelona 1.007 (1.003, 1.011)
Cordoba 1.018 (1.008, 1.028)
Jaen 1.024 (1.014, 1.034)
Subtotal 1.016 (1.011, 1.021)
11-15 (%)
Madrid 1.009 (1.005, 1.013)
Cadiz 1.021 (1.013, 1.029)
Huelva 1.019 (1.007, 1.031)
Sevilla 1.009 (1.003, 1.015)
Subtotal 1.013 (1.007, 1.019)
Overall 1.017 (1.014, 1.020)
NOTE: Weights are from random effects analysis
.953
1
1.05

Figure S8-A.

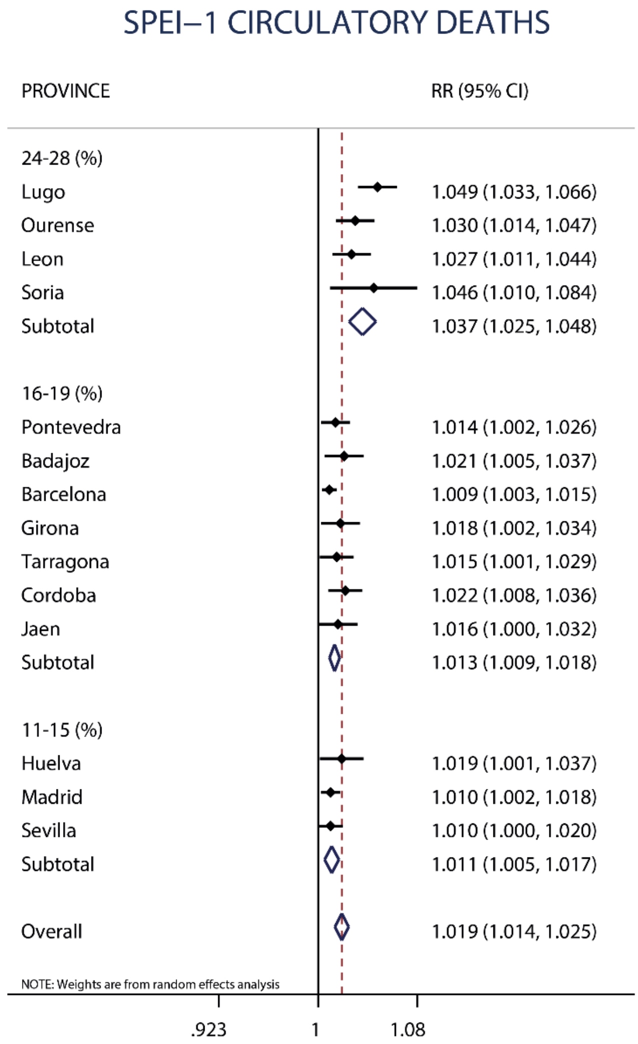

SPEI−1 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo
1.049 (1.033, 1.066)
Ourense
1.030 (1.014, 1.047)
Leon
1.027 (1.011, 1.044)
Soria
1.046 (1.010, 1.084)
Subtotal
1.037 (1.025, 1.048)
16-19 (%)
Pontevedra
1.014 (1.002, 1.026)
Badajoz
1.021 (1.005, 1.037)
Barcelona
1.009 (1.003, 1.015)
Girona
1.018 (1.002, 1.034)
Tarragona
1.015 (1.001, 1.029)
Cordoba
1.022 (1.008, 1.036)
Jaen
1.016 (1.000, 1.032)
Subtotal
1.013 (1.009, 1.018)
11-15 (%)
Huelva
1.019 (1.001, 1.037)
Madrid
1.010 (1.002, 1.018)
Sevilla
1.010 (1.000, 1.020)
Subtotal
1.011 (1.005, 1.017)
Overall
1.019 (1.014, 1.025)
NOTE: Weights are from random effects analysis
.923
1
1.08

Figure S8-B.

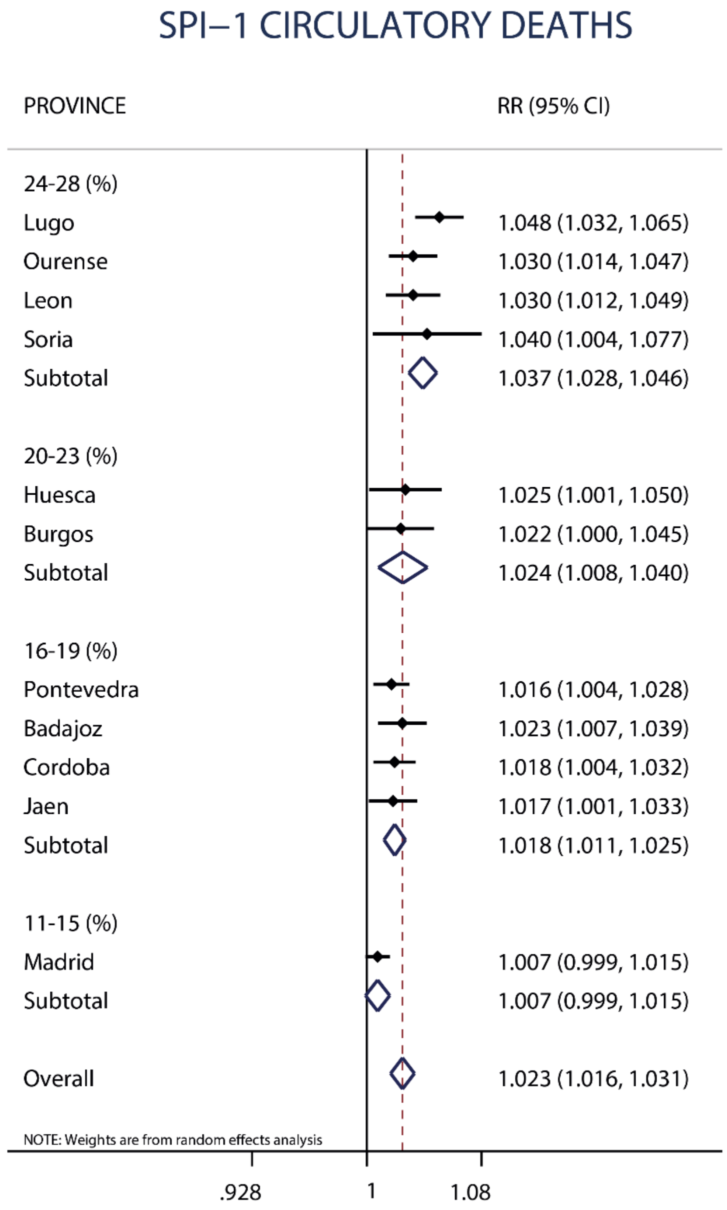

SPI–1 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo
1.048 (1.032, 1.065)
Ourense
1.030 (1.014, 1.047)
Leon
1.030 (1.012, 1.049)
Soria
1.040 (1.004, 1.077)
Subtotal
1.037 (1.028, 1.046)
20-23 (%)
Huesca
1.025 (1.001, 1.050)
Burgos
1.022 (1.000, 1.045)
Subtotal
1.024 (1.008, 1.040)
16-19 (%)
Pontevedra
1.016 (1.004, 1.028)
Badajoz
1.023 (1.007, 1.039)
Cordoba
1.018 (1.004, 1.032)
Jaen
1.017 (1.001, 1.033)
Subtotal
1.018 (1.011, 1.025)
11-15 (%)
Madrid
1.007 (0.999, 1.015)
Subtotal
1.007 (0.999, 1.015)
Overall
1.023 (1.016, 1.031)
NOTE: Weights are from random effects analysis
.928
1
1.08

Figure S8-C.

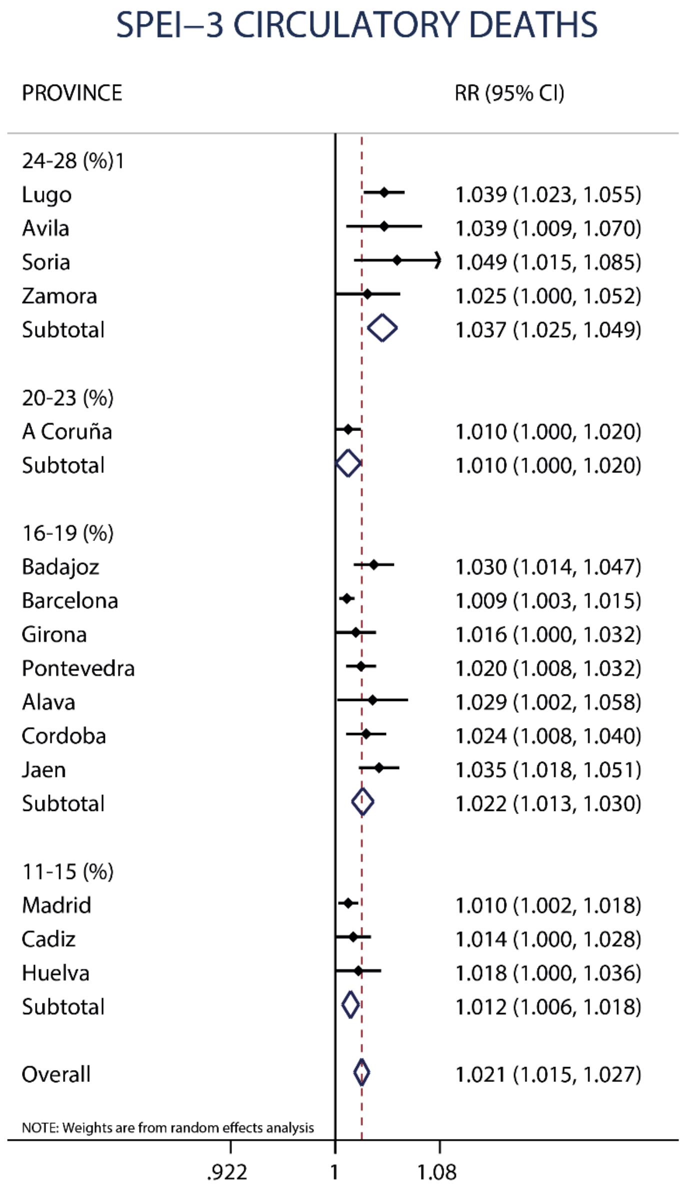

SPEI–3 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)1
Lugo
1.039 (1.023, 1.055)
Avila
1.039 (1.009, 1.070)
Soria
1.049 (1.015, 1.085)
Zamora
1.025 (1.000, 1.052)
Subtotal
1.037 (1.025, 1.049)
20-23 (%)
A Coruña
1.010 (1.000, 1.020)
Subtotal
1.010 (1.000, 1.020)
16-19 (%)
Badajoz
1.030 (1.014, 1.047)
Barcelona
1.009 (1.003, 1.015)
Girona
1.016 (1.000, 1.032)
Pontevedra
1.020 (1.008, 1.032)
Alava
1.029 (1.002, 1.058)
Cordoba
1.024 (1.008, 1.040)
Jaen
1.035 (1.018, 1.051)
Subtotal
1.022 (1.013, 1.030)
11-15 (%)
Madrid
1.010 (1.002, 1.018)
Cadiz
1.014 (1.000, 1.028)
Huelva
1.018 (1.000, 1.036)
Subtotal
1.012 (1.006, 1.018)
Overall
1.021 (1.015, 1.027)
NOTE: Weights are from random effects analysis
.922
1
1.08

Figure S8-D.

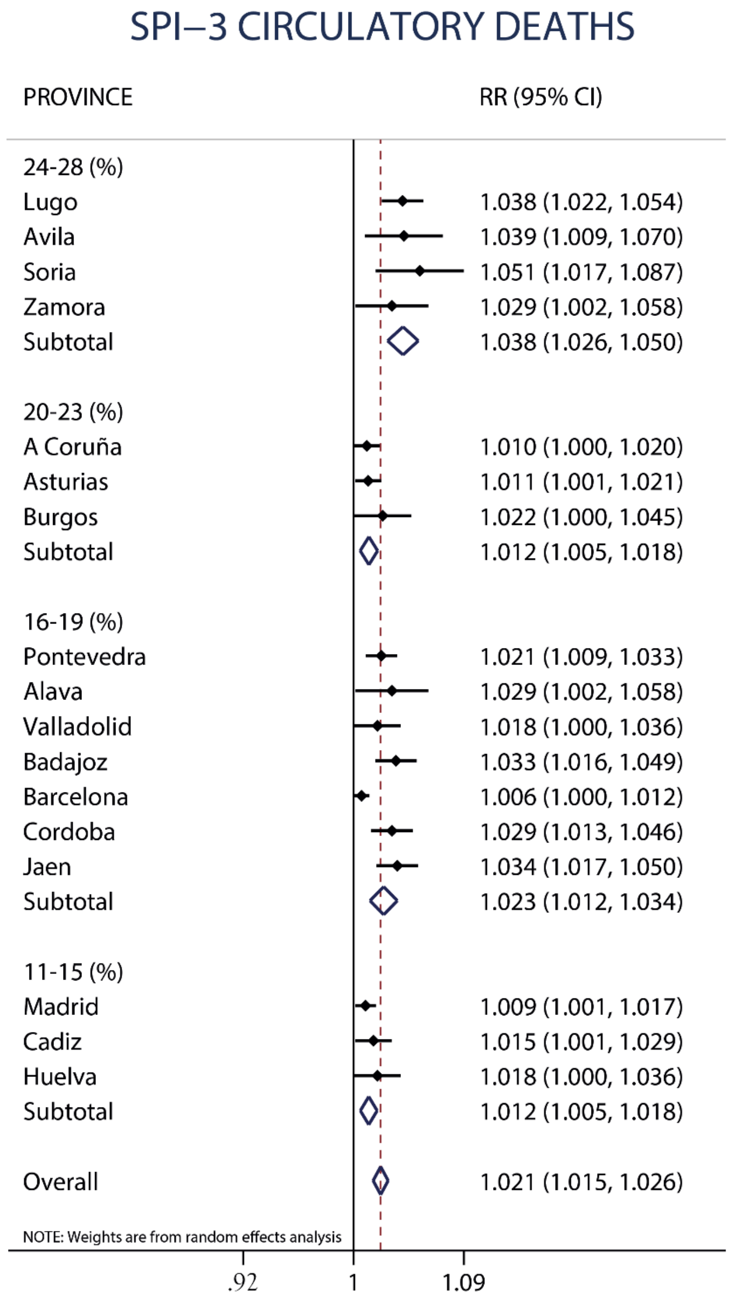

SPI–3 CIRCULATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo
1.038 (1.022, 1.054)
Avila
1.039 (1.009, 1.070)
Soria
1.051 (1.017, 1.087)
Zamora
1.029 (1.002, 1.058)
Subtotal
1.038 (1.026, 1.050)
20-23 (%)
A Coruña
1.010 (1.000, 1.020)
Asturias
1.011 (1.001, 1.021)
Burgos
1.022 (1.000, 1.045)
Subtotal
1.012 (1.005, 1.018)
16-19 (%)
Pontevedra
1.021 (1.009, 1.033)
Alava
1.029 (1.002, 1.058)
Valladolid
1.018 (1.000, 1.036)
Badajoz
1.033 (1.016, 1.049)
Barcelona
1.006 (1.000, 1.012)
Cordoba
1.029 (1.013, 1.046)
Jaen
1.034 (1.017, 1.050)
Subtotal
1.023 (1.012, 1.034)
11-15 (%)
Madrid
1.009 (1.001, 1.017)
Cadiz
1.015 (1.001, 1.029)
Huelva
1.018 (1.000, 1.036)
Subtotal
1.012 (1.005, 1.018)
Overall
1.021 (1.015, 1.026)
NOTE: Weights are from random effects analysis
.92
1
1.09

Figure S9-A.

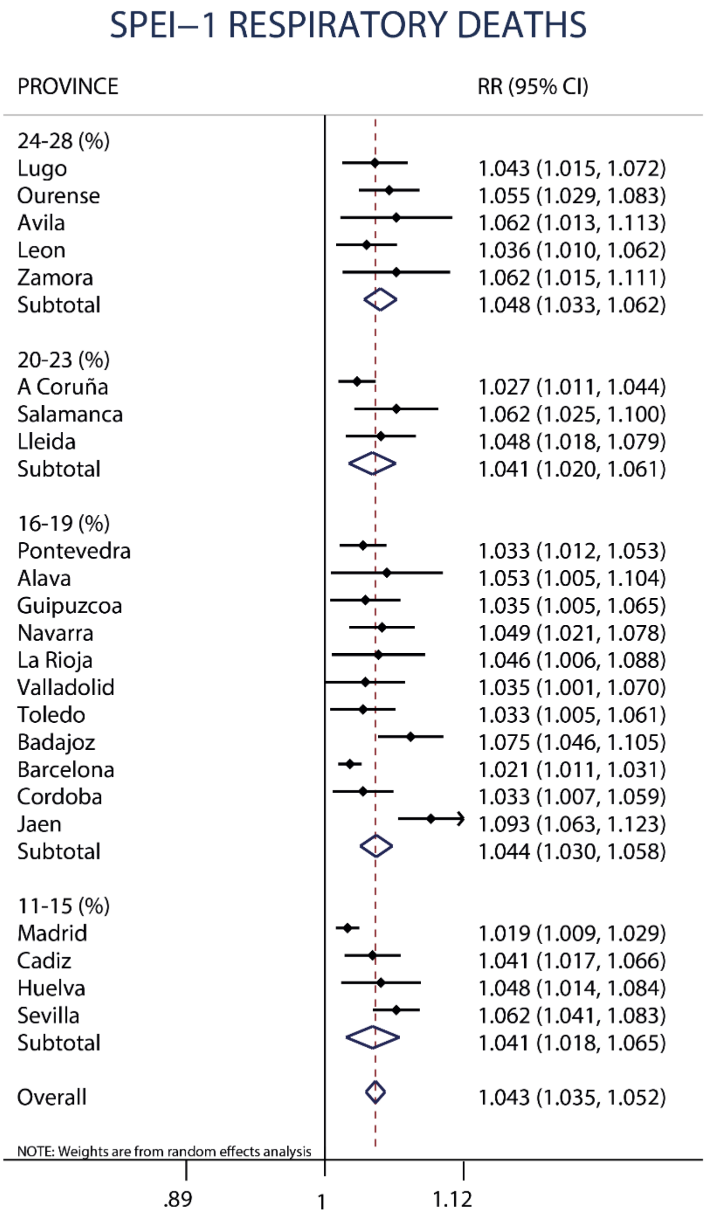

SPEI–1 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.043 (1.015, 1.072)
Ourense 1.055 (1.029, 1.083)
Avila 1.062 (1.013, 1.113)
Leon 1.036 (1.010, 1.062)
Zamora 1.062 (1.015, 1.111)
Subtotal 1.048 (1.033, 1.062)
20-23 (%)
A Coruña 1.027 (1.011, 1.044)
Salamanca 1.062 (1.025, 1.100)
Lleida 1.048 (1.018, 1.079)
Subtotal 1.041 (1.020, 1.061)
16-19 (%)
Pontevedra 1.033 (1.012, 1.053)
Alava 1.053 (1.005, 1.104)
Guipuzcoa 1.035 (1.005, 1.065)
Navarra 1.049 (1.021, 1.078)
La Rioja 1.046 (1.006, 1.088)
Valladolid 1.035 (1.001, 1.070)
Toledo 1.033 (1.005, 1.061)
Badajoz 1.075 (1.046, 1.105)
Barcelona 1.021 (1.011, 1.031)
Cordoba 1.033 (1.007, 1.059)
Jaen 1.093 (1.063, 1.123)
Subtotal 1.044 (1.030, 1.058)
11-15 (%)
Madrid 1.019 (1.009, 1.029)
Cadiz 1.041 (1.017, 1.066)
Huelva 1.048 (1.014, 1.084)
Sevilla 1.062 (1.041, 1.083)
Subtotal 1.041 (1.018, 1.065)
Overall 1.043 (1.035, 1.052)
NOTE: Weights are from random effects analysis
.89
1
1.12

Figure S9-B.

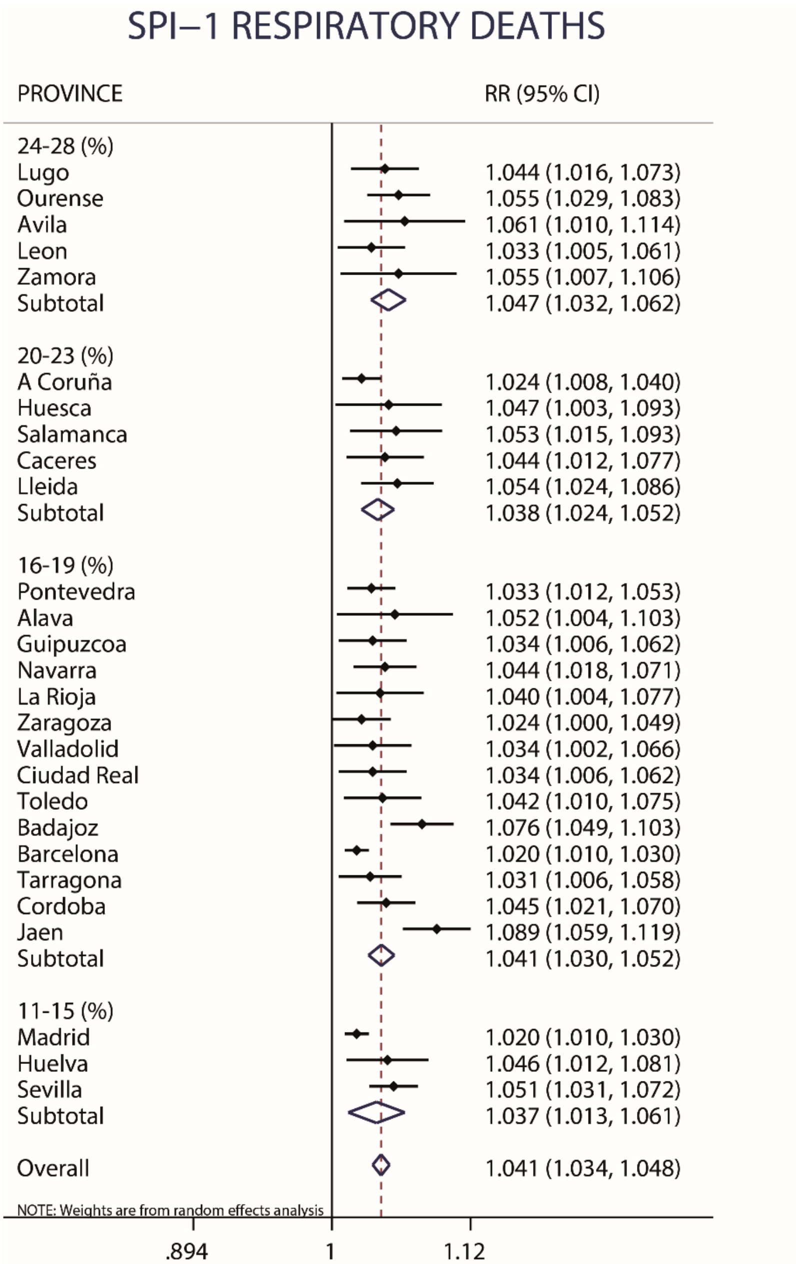

SPI–1 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.044 (1.016, 1.073)
Ourense 1.055 (1.029, 1.083)
Avila 1.061 (1.010, 1.114)
Leon 1.033 (1.005, 1.061)
Zamora 1.055 (1.007, 1.106)
Subtotal 1.047 (1.032, 1.062)
20-23 (%)
A Coruña 1.024 (1.008, 1.040)
Huesca 1.047 (1.003, 1.093)
Salamanca 1.053 (1.015, 1.093)
Caceres 1.044 (1.012, 1.077)
Lleida 1.054 (1.024, 1.086)
Subtotal 1.038 (1.024, 1.052)
16-19 (%)
Pontevedra 1.033 (1.012, 1.053)
Alava 1.052 (1.004, 1.103)
Guipuzcoa 1.034 (1.006, 1.062)
Navarra 1.044 (1.018, 1.071)
La Rioja 1.040 (1.004, 1.077)
Zaragoza 1.024 (1.000, 1.049)
Valladolid 1.034 (1.002, 1.066)
Ciudad Real 1.034 (1.006, 1.062)
Toledo 1.042 (1.010, 1.075)
Badajoz 1.076 (1.049, 1.103)
Barcelona 1.020 (1.010, 1.030)
Tarragona 1.031 (1.006, 1.058)
Cordoba 1.045 (1.021, 1.070)
Jaen 1.089 (1.059, 1.119)
Subtotal 1.041 (1.030, 1.052)
11-15 (%)
Madrid 1.020 (1.010, 1.030)
Huelva 1.046 (1.012, 1.081)
Sevilla 1.051 (1.031, 1.072)
Subtotal 1.037 (1.013, 1.061)
Overall 1.041 (1.034, 1.048)
NOTE: Weights are from random effects analysis
.894
1
1.12

Figure S9-C.

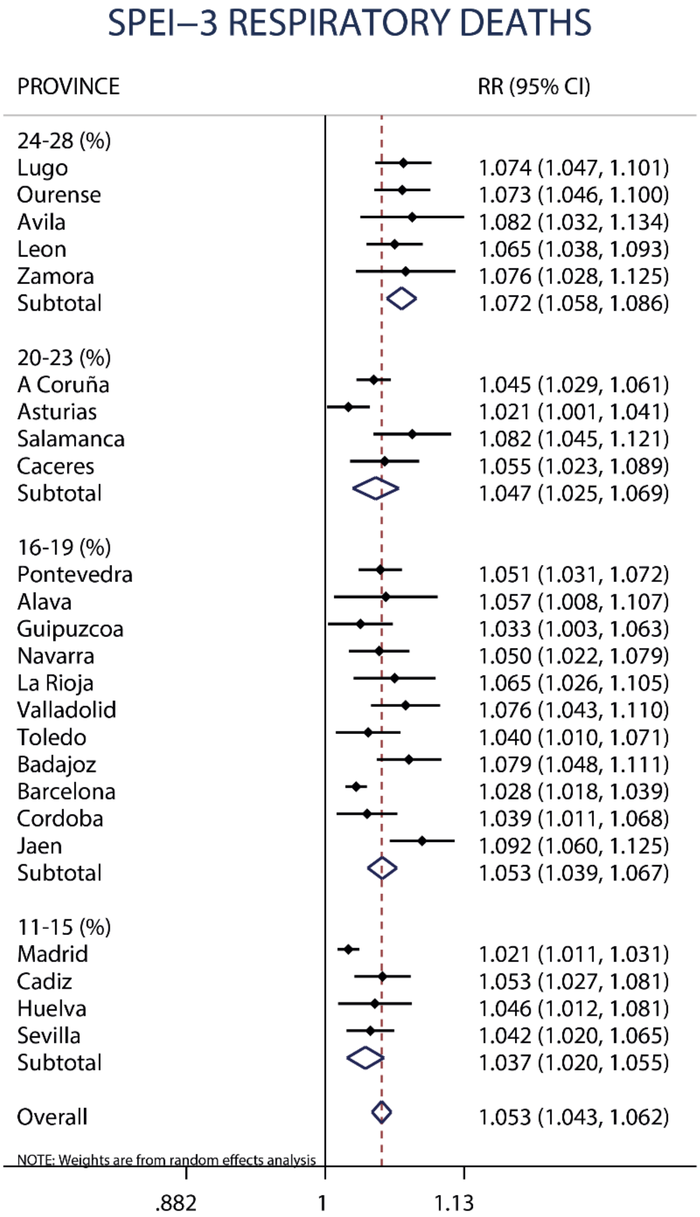
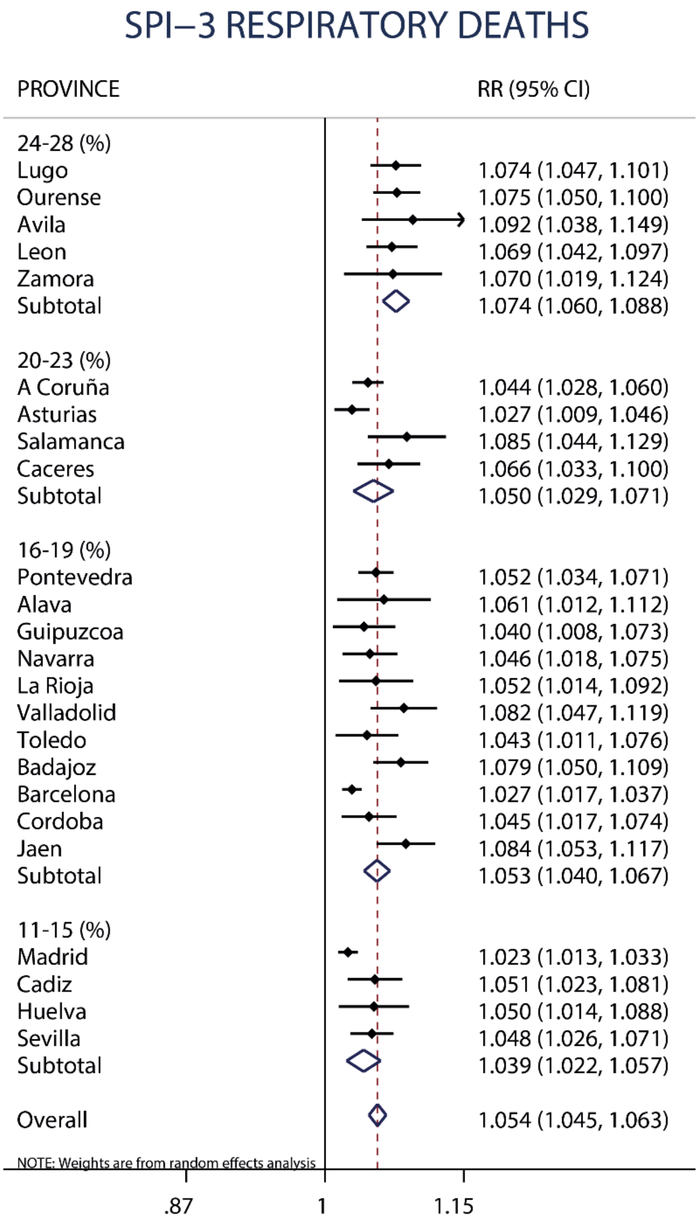

SPEI–3 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.074 (1.047, 1.101)
Ourense 1.073 (1.046, 1.100)
Avila 1.082 (1.032, 1.134)
Leon 1.065 (1.038, 1.093)
Zamora 1.076 (1.028, 1.125)
Subtotal 1.072 (1.058, 1.086)
20-23 (%)
A Coruña 1.045 (1.029, 1.061)
Asturias 1.021 (1.001, 1.041)
Salamanca 1.082 (1.045, 1.121)
Caceres 1.055 (1.023, 1.089)
Subtotal 1.047 (1.025, 1.069)
16-19 (%)
Pontevedra 1.051 (1.031, 1.072)
Alava 1.057 (1.008, 1.107)
Guipuzcoa 1.033 (1.003, 1.063)
Navarra 1.050 (1.022, 1.079)
La Rioja 1.065 (1.026, 1.105)
Valladolid 1.076 (1.043, 1.110)
Toledo 1.040 (1.010, 1.071)
Badajoz 1.079 (1.048, 1.111)
Barcelona 1.028 (1.018, 1.039)
Cordoba 1.039 (1.011, 1.068)
Jaen 1.092 (1.060, 1.125)
Subtotal 1.053 (1.039, 1.067)
11-15 (%)
Madrid 1.021 (1.011, 1.031)
Cadiz 1.053 (1.027, 1.081)
Huelva 1.046 (1.012, 1.081)
Sevilla 1.042 (1.020, 1.065)
Subtotal 1.037 (1.020, 1.055)
Overall 1.053 (1.043, 1.062)
NOTE: Weights are from random effects analysis
.882
1
1.13

Figure S9-D.


SPI–3 RESPIRATORY DEATHS
PROVINCE
RR (95% CI)
24-28 (%)
Lugo 1.074 (1.047, 1.101)
Ourense 1.075 (1.050, 1.100)
Avila 1.092 (1.038, 1.149)
Leon 1.069 (1.042, 1.097)
Zamora 1.070 (1.019, 1.124)
Subtotal 1.074 (1.060, 1.088)
20-23 (%)
A Coruña 1.044 (1.028, 1.060)
Asturias 1.027 (1.009, 1.046)
Salamanca 1.085 (1.044, 1.129)
Caceres 1.066 (1.033, 1.100)
Subtotal 1.050 (1.029, 1.071)
16-19 (%)
Pontevedra 1.052 (1.034, 1.071)
Alava 1.061 (1.012, 1.112)
Guipuzcoa 1.040 (1.008, 1.073)
Navarra 1.046 (1.018, 1.075)
La Rioja 1.052 (1.014, 1.092)
Valladolid 1.082 (1.047, 1.119)
Toledo 1.043 (1.011, 1.076)
Badajoz 1.079 (1.050, 1.109)
Barcelona 1.027 (1.017, 1.037)
Cordoba 1.045 (1.017, 1.074)
Jaen 1.084 (1.053, 1.117)
Subtotal 1.053 (1.040, 1.067)
11-15 (%)
Madrid 1.023 (1.013, 1.033)
Cadiz 1.051 (1.023, 1.081)
Huelva 1.050 (1.014, 1.088)
Sevilla 1.048 (1.026, 1.071)
Subtotal 1.039 (1.022, 1.057)
Overall 1.054 (1.045, 1.063)
NOTE: Weights are from random effects analysis
.87
1
1.15

A.4. SUPPLEMENTARY APPENDIX

Supplement to: Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: risks assessment by gender and age groups

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[2] Department of Epidemiology and Biostatistics. National School of Public Health. Carlos III National Institute of Health (Instituto de Salud Carlos III/ISCIII), Madrid, Spain.
[3] Centre for Environmental and Marine Studies (CESAM). Department of Environment and Planning, Univ of Aveiro, Portugal.

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Supplementary Methods:

Method S1: Determination of the temperature threshold for daily mortality in Lisbon district from 2007 to 2016.

According to the methodology of Díaz et al. (2015), we fit an univariate autorregresive integrated moving average (ARIMA) model for daily natural mortality as dependent variable to obtain the residuals series, which after modelling to display neither trend nor periodicities, so any associations found represent an authentic causal mortality-temperature relationship. Subsequently, T*threshold* was determined through the representation of a scatter plot, from which the mortality residual anomaly (and the 95% confidence intervals) increase significantly in relation to the residual mean (represented as two horizontal lines).

Method S2: Determination of the Ozone threshold for daily mortality in Lisbon district from 2007 to 2016.

According to the methodology of Díaz et al. (2018), we carried out a scatter plot diagram between daily mean ozone concentrations (abscissa axis) and mean daily natural mortality corresponding such as ozone concentrations (ordinate axis) across the period 2007 to 2016 to determine the minimum value of the quadratic function, corresponding to the specific threshold of O_3 concentrations.

References:

Díaz, J., Carmona, R., Linares, C., 2015. Temperaturas umbrales de disparo de la mortalidad atribuible al calor en España en el periodo 2000–2009. Instituto de Salud Carlos III, Escuela Nacional de Sanidad, Madrid.

Díaz, J., Ortiz, C., Falcón, I., Salvador, C., Linares, C., 2018. Short-term effect of tropospheric ozone on daily mortality in Spain. Atmospheric Environment 187, 107-116. https://doi.org/10.1016/j.atmosenv.2018.05.059

Supplementary Tables and Figures:

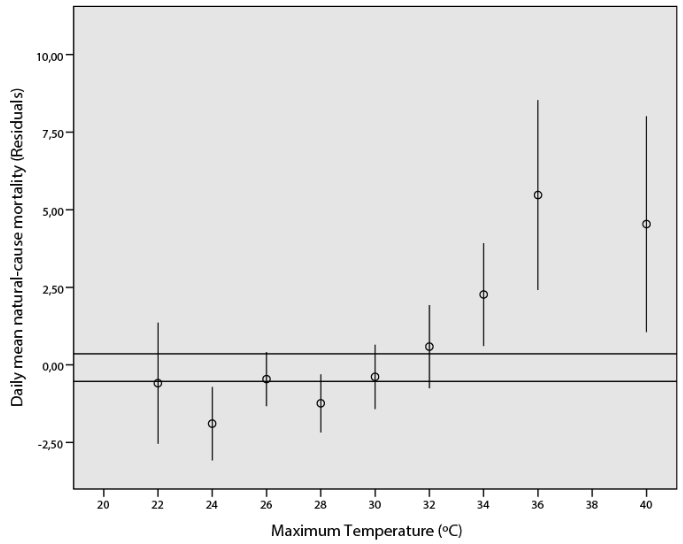

Figure S1. Scatter plot for the mortality threshold temperature (T*threshold*) associated with high temperatures in Lisbon district from 2007 to 2016. Mean residuals of daily natural-cause mortality (Y-axis) and the daily maximum temperatures (ºC) (joint to the respective 95% confidence intervals) (X-axis) were represented. In addition, upper and lower limits of the 95% confidence interval of mean residuals for the period 2007 to 2016 was represented through two straight parallel lines. T*threshold*= 34ºC

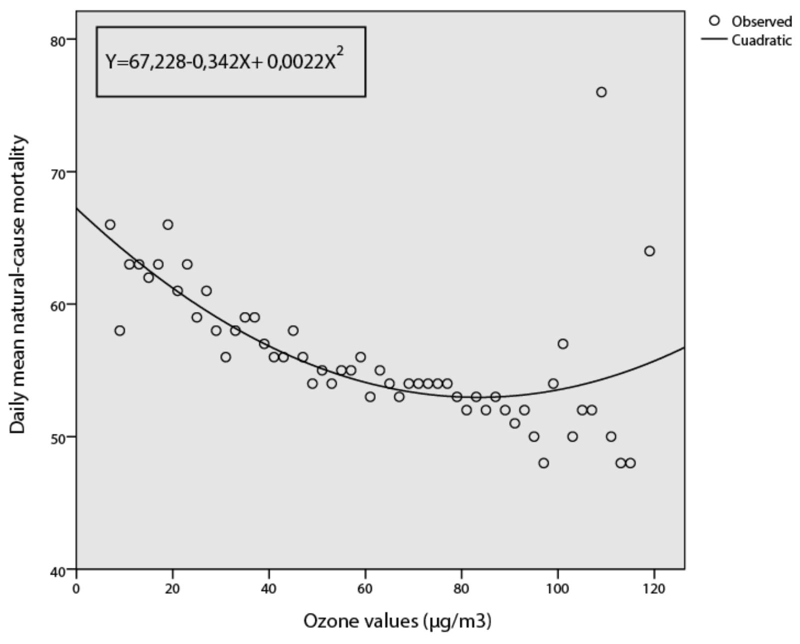

Figure S2. Scatter plot for the mortality threshold associated with ozone (O*threshold*) in Lisbon district from 2007 to 2016. The relationship between mean daily mortality (Y-axis) and mean daily ozone concentrations (µg/m^3) in Lisbon district from 2007 to 2016. Ozone threshold=67 µg/m^3.

Table S1. Summary of the complete statistically significant results obtained from Poisson models when the effects of drought on daily specific-cause mortality was evaluated for total population (all ages and adult age groups) in Lisbon district for the 1983 to 2016 period, using the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). Negative coefficient values of SPEI-n and SPI-n calculated at one and three months of accumulation (being n=1 or 3), indicate higher mortality associated with drought, because negative values of both indices represent drought conditions. Moreover, the 95% confidence intervals of the estimators and of the Relative Risks (RRs) are also displayed. Conf. = confidence; %AR=Attributable Risk.

Total population	Causes of mortality	Drought Index	p-value	Coefficients	Coefficients [95% conf. Interval]	RR	RR [95% conf. Interval]	%AR [(RR-1)/RR] × 100
DISTRICT OF LISBON	Natural deaths	SPEI-1	All ages (p= 0.000) 65-74 (p=0.012) >75 (p=0.000)	-0.008 -0.007 -0.013	(-0.011, -0.006) (-0.012, -0.002) (-0.016, -0.010)	1.008 1.007 1.013	(1.006, 1.011) (1.002, 1.012) (1.010, 1.016)	0.8% 0.7% 1.28%
		SPI-1	All ages (p=0.034) >75 (p=0.027)	-0.003 -0.005	(-0.007, -0.000) (-0.009, -0.001)	1.003 1.005	(1.000, 1.007) (1.001, 1.009)	0.3% 0.5%
	Circulatory deaths	SPEI-1	All ages (p=0.000) >75 (p=0.000)	-0.008 -0.010	(-0.011, -0.004) (-0.014, -0.005)	1.008 1.010	(1.004, 1.011) (1.005, 1.014)	0.8% 1.00%
		SPI-1						
	Respiratory deaths	SPEI-1	All ages (p=0.000) >75 (p=0.000)	-0.017 -0.022	(-0.025, -0.009) (-0.031, -0.012)	1.017 1.022	(1.009, 1.025) (1.012, 1.031)	1.67% 2.15%
		SPI-1	All ages (p=0.040) >75 (p=0.002)	-0.011 -0.019	(-0.021, -0.001) (-0.031, -0.007)	1.011 1.019	(1.001, 1.021) (1.007, 1.031)	1.09% 1.86%
Total population	**Causes of mortality**	**Type of drought Index**	**p-value**	**Coefficients**	**Coefficients [95% conf. Interval]**	**RR**	**RR [95% conf. Interval]**	**%AR [(RR-1)/RR] × 100**
DISTRICT OF LISBON	Natural deaths	SPEI-3	All ages (p=0.000) >75 (p=0.000)	-0.005 -0.009	(-0.007, -0.002) (-0.012, -0.006)	1.005 1.009	(1.002, 1.007) (1.006, 1.012)	0.5% 0.89%
		SPI-3	All ages (p=0.000) 65-74 (p=0.033) >75 (p=0.000)	-0.004 -0.006 -0.006	(-0.007, -0.002) (-0.012, -0.000) (-0.010, -0.003)	1.004 1.006 1.006	(1.002, 1.007) (1.000, 1.012) (1.003,1.010)	0.4% 0.6% 0.6%
	Circulatory deaths	SPEI-3	>75 (p=0.041)	-0.005	(-0.009, -0.000)	1.005	(1.000, 1.009)	0.5%
		SPI-3						
	Respiratory deaths	SPEI-3	All ages (p=0.000) >75 (p=0.000)	-0.018 -0.022	(-0.026, -0.010) (-0.032, -0.013)	1.018 1.022	(1.010, 1.026) (1.013, 1.033)	1.77% 2.15%
		SPI-3	All ages (p=0.000) >75 (p=0.000)	-0.015 -0.020	(-0.023, -0.007) (-0.030, -0.011)	1.015 1.020	(1.007, 1.023) (1.011, 1.030)	1.57% 1.96%

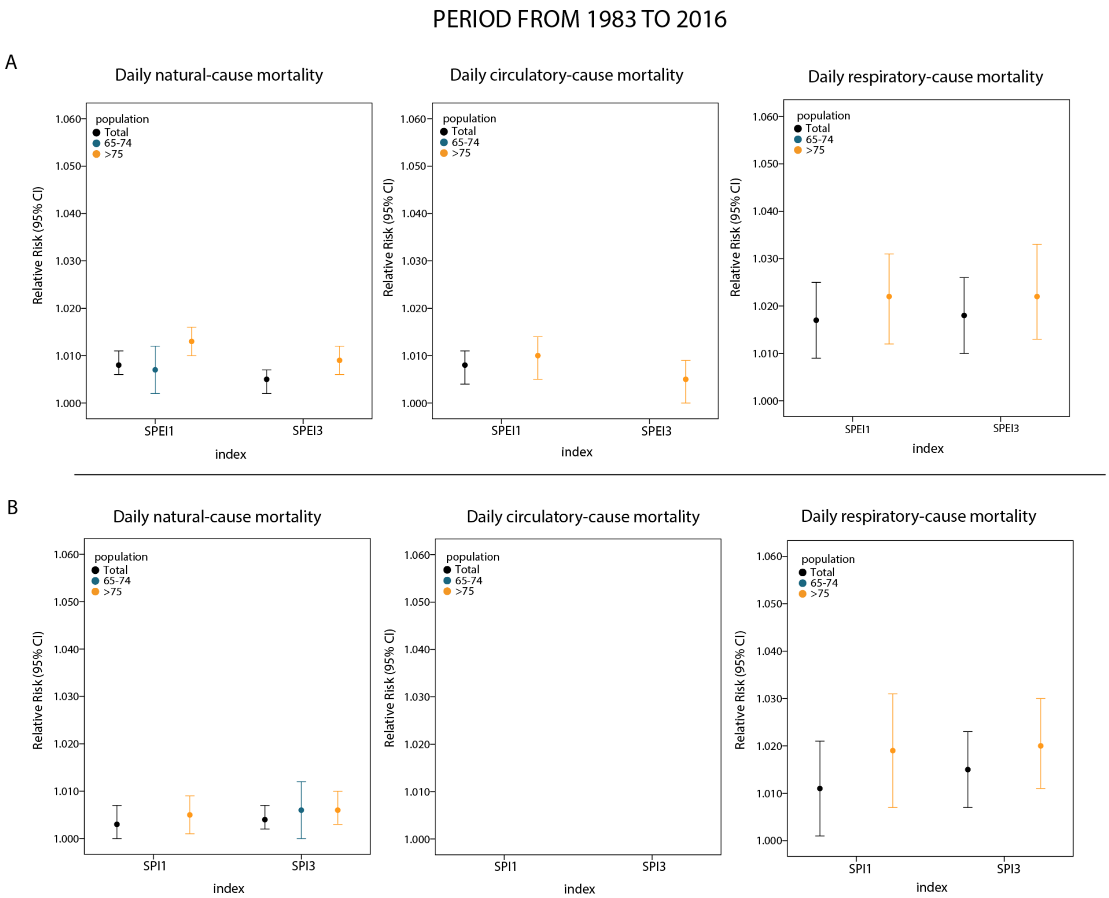

Figure S3. Comparative graphs of drought risks on specific-cause mortality of total population in Lisbon district from 1983 to 2016 with the use of A) The Standardized Precipitation Evapotranspiration Index and B) The Standardized Precipitation Index obtained at one (SPEI-1/SPI-1) and three (SPEI-3/SPI-3) months of accumulation.

Table S2. Summary of the complete statistically significant results obtained from Poisson models when the effects of drought on daily specific-cause mortality were assessed by gender and subsequently by adult age groups in Lisbon district from 1983 to 2016, using the Standardized Precipitation Evapotranspiration Index (SPEI) and The Standardized Precipitation Index (SPI). *p=0.051 trends to be statistically significant.

SPEI-1/SPI-1

REGION	Causes of mortality	Gender	Drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]	%AR [(RR-1)/RR] × 100
DISTRICT OF LISBON	Natural deaths	MEN	SPEI-1	All ages (p=0.000)	-0.007	(-0.010, -0.003)	1.007	(1.003, 1.010)	0.7%
				65-74 (p=0.016)	-0.009	(-0.015, -0.002)	1.009	(1.002, 1.015)	0.89%
				>75 (p=0.000)	-0.010	(-0.015, -0.005)	1.010	(1.005, 1.015)	1.00%
			SPI-1	All ages (p=0.047)	-0.005	(-0.009, -0.000)	1.005	(1.000, 1.009)	0.5%
				65-74 (p=0.028)	-0.010	(-0.019, -0.001)	1.010	(1.001, 1.019)	1.00%
		WOMEN	SPEI-1	All ages (p=0.000)	-0.012	(-0.015, -0.008)	1.012	(1.008, 1.015)	1.19%
				>75 (p=0.000)	-0.017	(-0.021, -0.013)	1.017	(1.013, 1.021)	1.67%
			SPI-1	>75 (p=0.021)	-0.006	(-0.012, -0.001)	1.006	(1.001, 1.012)	0.6%
	Circulatory deaths	MEN	SPEI-1						
			SPI-1						
		WOMEN	SPEI-1	All ages (p=0.000)	-0.013	(-0.018, -0.008)	1.013	(1.008, 1.018)	1.28%
				>75 (p=0.000)	-0.016	(-0.021, -0.010)	1.016	(1.010, 1.021)	1.57%
			SPI-1						
	Respiratory deaths	MEN	SPEI-1	All ages (p=0.002)	-0.017	(-0.028, -0.006)	1.017	(1.006, 1.028)	1.67%
				>75 (p=0.000)	-0.027	(-0.041, -0.013)	1.027	(1.013, 1.042)	2.63%
			SPI-1	All ages (p=0.049)	-0.014	(-0.028, -0.000)	1.014	(1.000, 1.028)	1.38%
				>75 (p=0.001)	-0.031	(-0.049, -0.013)	1.031	(1.013, 1.050)	3.01%
		WOMEN	SPEI-1	All ages (p=0.001)	-0.020	(-0.032, -0.008)	1.020	(1.008, 1.033)	1.96%
				>75 (p=0.002)	-0.021	(-0.034, -0.008)	1.021	(1.008, 1.035)	2.06%
			SPI-1						

SPEI-3/SPI-3

REGION	Causes of mortality	Gender	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]	%AR [(RR-1)/RR] × 100
DISTRICT OF LISBON	Natural deaths	MEN	SPEI-3	>75 (p=0.002)	-0.008	(-0.013, -0.003)	1.008	(1.003, 1.013)	0.79%
			SPI-3	All ages (p=0.005)	-0.005	(-0.009, -0.002)	1.005	(1.002, 1.009)	0.5%
				65-74 (p=0.020)	-0.008	(-0.016, -0.001)	1.008	(1.001, 1.016)	0.79%
				>75 (p=0.007)	-0.007	(-0.012, -0.002)	1.007	(1.002, 1.012)	0.7%
		WOMEN	SPEI-3	All ages (p=0.000)	-0.008	(-0.011, -0.005)	1.008	(1.005, 1.011)	0.79%
				>75 (p=0.000)	-0.012	(-0.016, -0.008)	1.012	(1.008, 1.016)	1.19%
			SPI-3	All ages (p=0.001)	-0.006	(-0.009, -0.002)	1.006	(1.002, 1.009)	0.6%
				>75 (p=0.000)	-0.008	(-0.012, -0.004)	1.008	(1.004, 1.012)	0.79%
	Circulatory deaths	MEN	SPEI-3						
			SPI-3						
		WOMEN	SPEI-3	All ages (p=0.021)	-0.006	(-0.011, -0.001)	1.006	(1.001, 1.011)	0.6%
				>75 (p=0.004)	-0.008	(-0.014, -0.003)	1.008	(1.003, 1.014)	0.79%
			SPI-3						
	Respiratory deaths	MEN	SPEI-3	All ages (p=0.001)	-0.018	(-0.029, -0.007)	1.018	(1.007, 1.029)	1.77%
				>75 (p=0.000)	-0.025	(-0.039, -0.012)	1.025	(1.012, 1.040)	2.44%
			SPI-3	All ages (p=0.001)	-0.018	(-0.029, -0.007)	1.018	(1.007, 1.029)	1.77%
				65-74 (p=0.051)*	-0.025	(-0.051, 0.000)	1.025	(1.000, 1.052)	2.44%
				>75 (p=0.000)	-0.027	(-0.041, -0.014)	1.027	(1.014, 1.042)	
		WOMEN	SPEI-3	All ages (p=0.000)	-0.023	(-0.035, -0.011)	1.023	(1.011, 1.036)	2.25%
				>75 (p=0.000)	-0.025	(-0.038, -0.012)	1.025	(1.012, 1.039)	2.44%
			SPI-3	All ages (p=0.007)	-0.017	(-0.029, -0.005)	1.017	(1.005, 1.029)	1.67%
				>75 (p=0.003)	-0.020	(-0.033, 0.007)	1.020	(1.007, 1.034)	1.96%

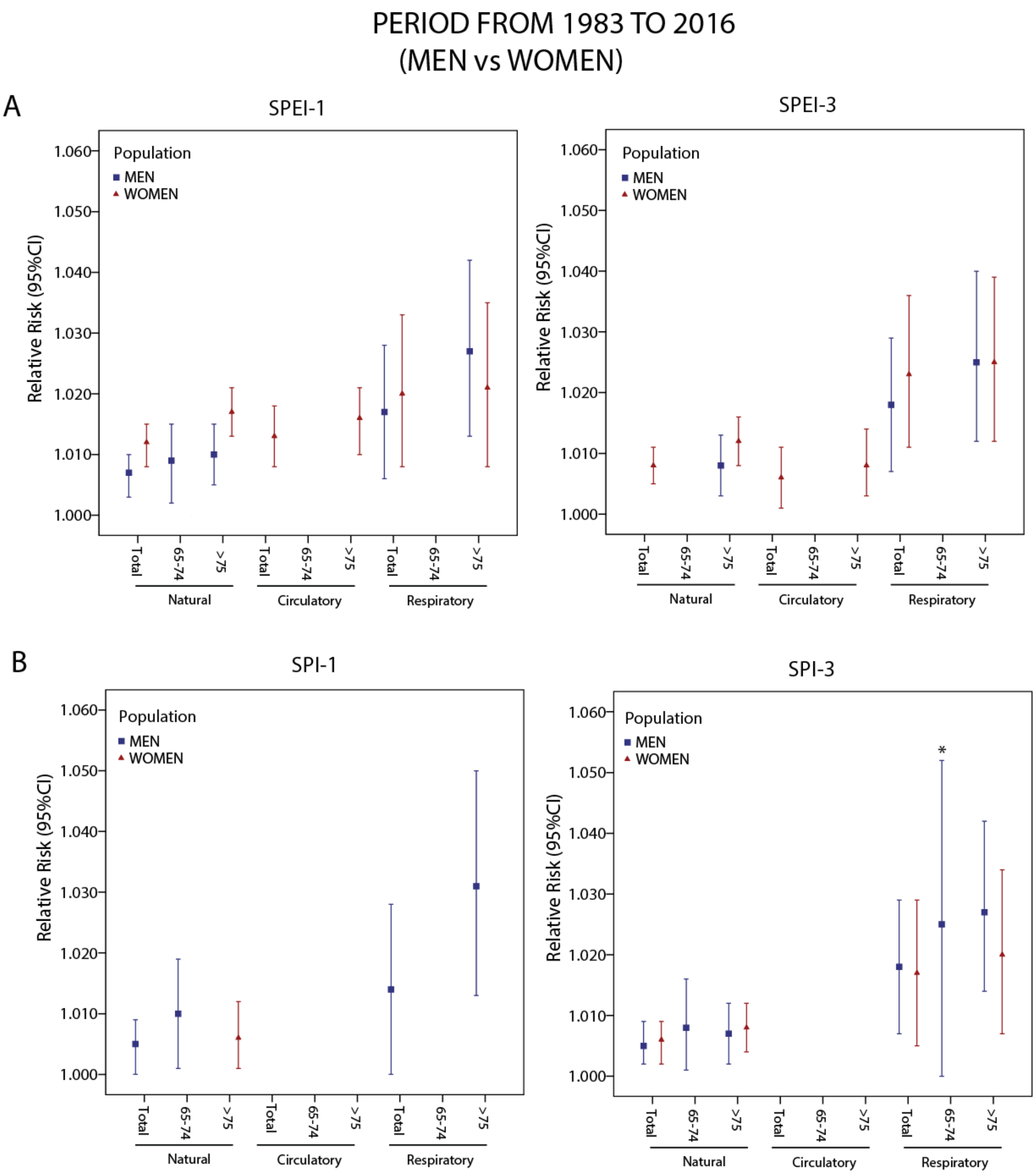

Figure S4. **Comparative graphs of the drought risks on specific-cause mortality of men and women populations (all ages and adult age groups) in Lisbon district from 1983 to 2016 with the use of A) The Standardized Precipitation Evapotranspiration Index and B) The Standardized Precipitation Index obtained at one (SPEI-1/SPI-1) and three (SPEI-3/SPI-3) months of accumulation.** *p=0.051 trends to be statistically significant.

Tables S3. Relative Risks of daily mortality associated with droughts measured by the Standardized Precipitation Index and the Standardized Precipitation-Evapotranspiration Index obtained at 1 month of accumulation (SPI-1/ SPEI-1) when the impact of heatwaves was controlled in Poisson modelling in Lisbon district during 2007 to 2016 for total, women and men populations. "-n" after the T*hwave* and each pollutant corresponds to the manifestation of the effects of these climatic phenomena on daily mortality, ranging from 0 "immediate" to 4 (lag 4).

TOTAL AND GENDER POPULATIONS (WITHOUT CONSIDERING AGE)								
SPEI-1/SPI-1 + THWAVE								
REGION	**Causes of mortality**	**Gender**	**Type of drought Index**	**p-value**	**Coefficients**	**Coef. [95% conf. Interval]**	**RR**	**RR [95% conf. Interval]**
DISTRICT OF LISBON	Natural deaths	TOTAL	SPEI-1	SPEI-1 (p=0.001) Thwave-1 (p=0.000) Thwave-2 (p=0.000) Thwave-4 (p=0.001)	-0.007 0.034 0.032 0.020	(-0.011, -0.003) (0.021, 0.048) (0.018, 0.046) (0.008, 0.032)	1.007 1.035 1.033 1.020	(1.003, 1.011) (1.021, 1.049) (1.018, 1.047) (1.008, 1.033)
			SPI-1	SPI-1 (p=0.024) Thwave-1 (p=0.000) Thwave-2 (p=0.000) Thwave-4 (p=0.000)	-0.006 0.037 0.033 0.021	(-0.012, -0.001) (0.023, 0.050) (0.019, 0.047) (0.009, 0.033)	1.006 1.038 1.034 1.021	(1.001, 1.012) (1.023, 1.051) (1.019, 1.048) (1.009, 1.034)
		MEN	SPEI-1	SPEI-1 (p=0.012) Thwave-0 (p=0.017) Thwave-2 (p=0.000)	-0.008 0.021 0.047	(-0.014, -0.002) (0.004, 0.038) (0.031, 0.063)	1.008 1.021 1.048	(1.002, 1.014) (1.004, 1.039) (1.031, 1.065)
			SPI-1	SPI-1 (p=0.042) Thwave-0 (p=0.006) Thwave-2 (p=0.000) Thwave-4 (p=0.043)	-0.008 0.024 0.045 0.017	(-0.016, -0.0003) (0.007, 0.040) (0.028, 0.062) (0.0005, 0.034)	1.008 1.024 1.046 1.017	(1.0003, 1.016) (1.007, 1.041) (1.028, 1.064) (1.0005, 1.035)
		WOMEN	SPEI-1	SPEI-1 (p=0.016) Thwave-1 (p=0.000) Thwave-2 (p=0.001) Thwave-4 (p=0.002)	-0.007 0.047 0.034 0.026	(-0.013, -0.0013) (0.028, 0.066) (0.014, 0.053) (0.010, 0.043)	1.007 1.048 1.035 1.026	(1.0013, 1.013) (1.028, 1.068) (1.014, 1.054) (1.010, 1.044)
			SPI-1					
	Circulatory deaths	TOTAL	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.001) Thwave-4 (p=0.000)	0.045 0.041 0.045	(0.022, 0.068) (0.018, 0.065) (0.026, 0.065)	1.046 1.042 1.046	(1.022, 1.070) (1.018, 1.067) (1.026, 1.067)
			SPI-1					
		MEN	SPEI-1	Thwave-2 (p=0.000) Thwave-4 (p=0.002)	0.054 0.047	(0.024, 0.084) (0.017, 0.077)	1.055 1.048	(1.024, 1.088) (1.017, 1.080)
			SPI-1					
		WOMEN	SPEI-1	Thwave-1 (p=0.001) Thwave-2 (p=0.001) Thwave-4 (p=0.000)	0.051 0.050 0.046	(0.021, 0.081) (0.020, 0.081) (0.020, 0.071)	1.052 1.051 1.047	(1.021, 1.084) (1.020, 1.084) (1.020, 1.074)
			SPI-1					
	Respiratory deaths	TOTAL	SPEI-1	Thwave-0 (p=0.001) Thwave-3 (p=0.001)	0.061 0.059	(0.025, 0.097) (0.022, 0.095)	1.063 1.061	(1.025, 1.102) (1.022, 1.100)
			SPI-1					
		MEN	SPEI-1					
			SPI-1					
		WOMEN	SPEI-1					
			SPI-1					

TOTAL AND GENDER POPULATIONS (CONSIDERING AGE ASSESSMENT)

SPEI-1/SPI-1 + THWAVE (TOTAL POPULATION)

REGION	Causes of mortality	AGE RANGE	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	65-74	SPEI-1	SPEI-1 (p=0.014) Thwave-2 (p=0.005)	-0.013 0.039	(-0.023, -0.003) (0.012, 0.067)	1.013 1.040	(1.003, 1.023) (1.012, 1.069)
			SPI-1					
		>75	SPEI-1	SPEI-1 (p=0.008) Thwave-1 (p=0.000) Thwave-2 (p=0.000) Thwave-4 (p=0.000)	-0.007 0.047 0.033 0.031	(-0.012, -0.002) (0.030, 0.064) (0.015, 0.050) (0.017, 0.045)	1.007 1.048 1.034 1.031	(1.002, 1.012) (1.030, 1.066) (1.015, 1.051) (1.017, 1.046)
			SPI-1					
	Circulatory deaths	65-74	SPEI-1	SPEI-1 (p=0.047) Thwave-2 (p=0.027)	-0.020 0.059	(-0.040, -0.0003) (0.007, 0.111)	1.020 1.061	(1.0003, 1.041) (1.007, 1.117)
			SPI-1					
		>75	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.003) Thwave-4 (p=0.000)	0.057 0.040 0.053	(0.031, 0.083) (0.014, 0.067) (0.031, 0.075)	1.059 1.041 1.054	(1.031, 1.087) (1.014, 1.069) (1.031, 1.078)
			SPI-1					
	Respiratory deaths	>75	SPEI-1	SPEI-1 (p=0.042) Thwave-1 (p=0.003) Thwave-3 (p=0.048)	-0.015 0.062 0.042	(-0.029, -0.0005) (0.021, 0.103) (0.0003, 0.084)	1.015 1.064 1.043	(1.0005, 1.029) (1.021, 1.108) (1.0003,1.088)
			SPI-1	SPI-1 (p=0.046) Thwave-0 (p=0.001) Thwave-3 (p=0.007)	-0.019 0.067 0.055	(-0.037, -0.0004) (0.027, 0.107) (0.015, 0.095)	1.019 1.069 1.057	(1.0004, 1.038) (1.027, 1.113) (1.015, 1.100)

SPEI-1/SPI-1 + THWAVE (MEN POPULATION)

REGION	Causes of mortality	AGE RANGE	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	65-74	SPEI-1	SPEI-1 (p=0.026)	-0.015	(-0.028, -0.002)	1.015	(1.002, 1.028)
			SPI-1					
		>75	SPEI-1	Thwave-0 (p=0.004) Thwave-2 (p=0.000) Thwave-4 (p=0.048)	0.032 0.056 0.023	(0.010, 0.055) (0.034, 0.078) (0.0002, 0.046)	1.033 1.058 1.023	(1.010, 1.057) (1.035, 1.081) (1.0002, 1.047)
			SPI-1					
	Circulatory deaths	65-74	SPEI-1	SPEI-1 (p=0.018)	-0.030	(-0.055, -0.005)	1.030	(1.005, 1.057)
			SPI-1					
	Respiratory deaths	>75	SPEI-1	SPEI-1 (p=0.046) Thwave-0 (p=0.003)	-0.021 0.085	(-0.042, -0.0004) (0.030, 0.140)	1.021 1.089	(1.0004, 1.043) (1.030, 1.150)
			SPI-1	SPI-1 (p=0.017) Thwave-0 (p=0.001)	-0.032 0.093	(-0.058, -0.006) (0.039, 0.148)	1.033 1.097	(1.006, 1.060) (1.040, 1.160)

SPEI-1/SPI-1 + THWAVE (WOMEN POPULATION)

REGION	Causes of mortality	AGE RANGE	Type of drought Index	p-value	Coefficients	Coef. [95% conf. Interval]	RR	RR [95% conf. Interval]
DISTRICT OF LISBON	Natural deaths	>75	SPEI-1	SPEI-1 (p=0.011) Thwave-1 (p=0.000) Thwave-2 (p=0.006) Thwave-4 (p=0.000)	-0.009 0.056 0.031 0.039	(-0.016, -0.002) (0.034, 0.078) (0.009, 0.054) (0.020, 0.058)	1.009 1.058 1.031 1.040	(1.002, 1.016) (1.035, 1.081) (1.009, 1.055) (1.020, 1.060)
			SPI-1					
	Circulatory deaths	>75	SPEI-1	Thwave-1 (p=0.000) Thwave-2 (p=0.004) Thwave-4 (p=0.000)	0.059 0.047 0.052	(0.027, 0.091) (0.015, 0.080) (0.025, 0.079)	1.061 1.048 1.053	(1.027, 1.095) (1.015, 1.083) (1.025, 1.082)
			SPI-1					

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