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

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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:

$Thwave = Tmax - Tthreshold$ si $Tmax > Tthreshold$ $Thwave = 0$ 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:

$$O_{3a} = O_3 - O_3threshold \text{ si } O_3 > O_3threshold \quad O_{3a} = 0 \text{ si } O_3 \leq O_3threshold$$

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).

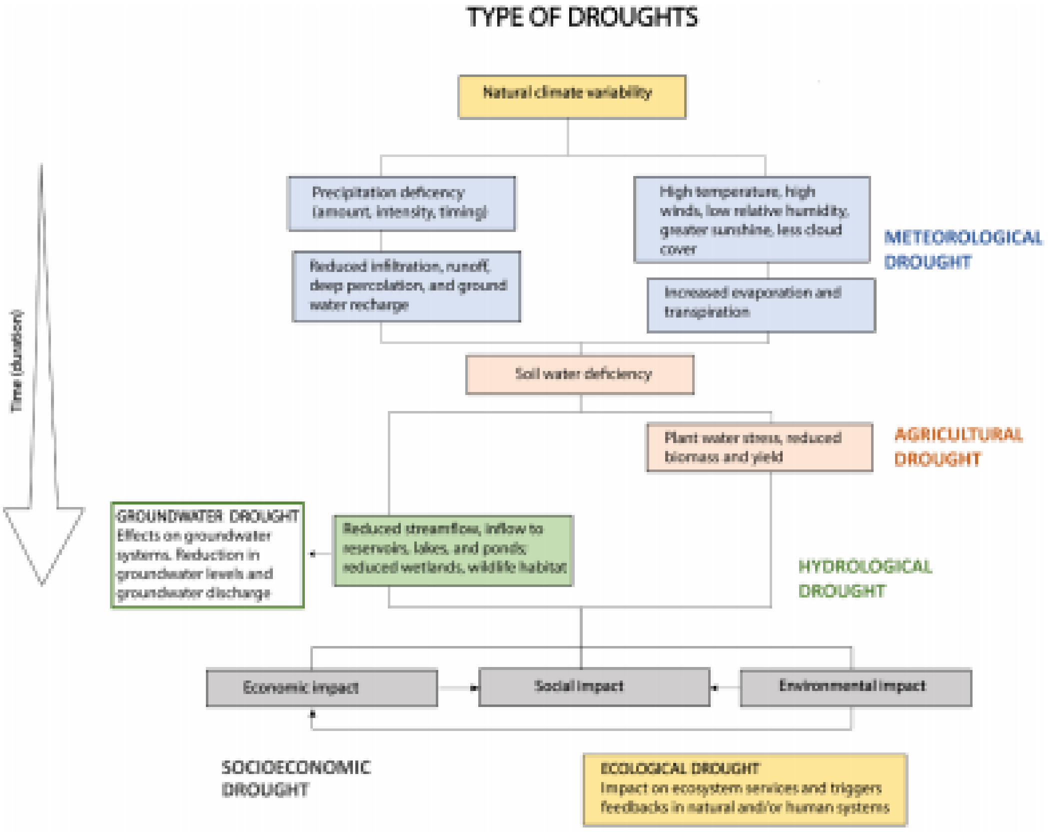


Figure 1. Types of drought and their effects and relationships. Adapted from Wilhite (2000).

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.

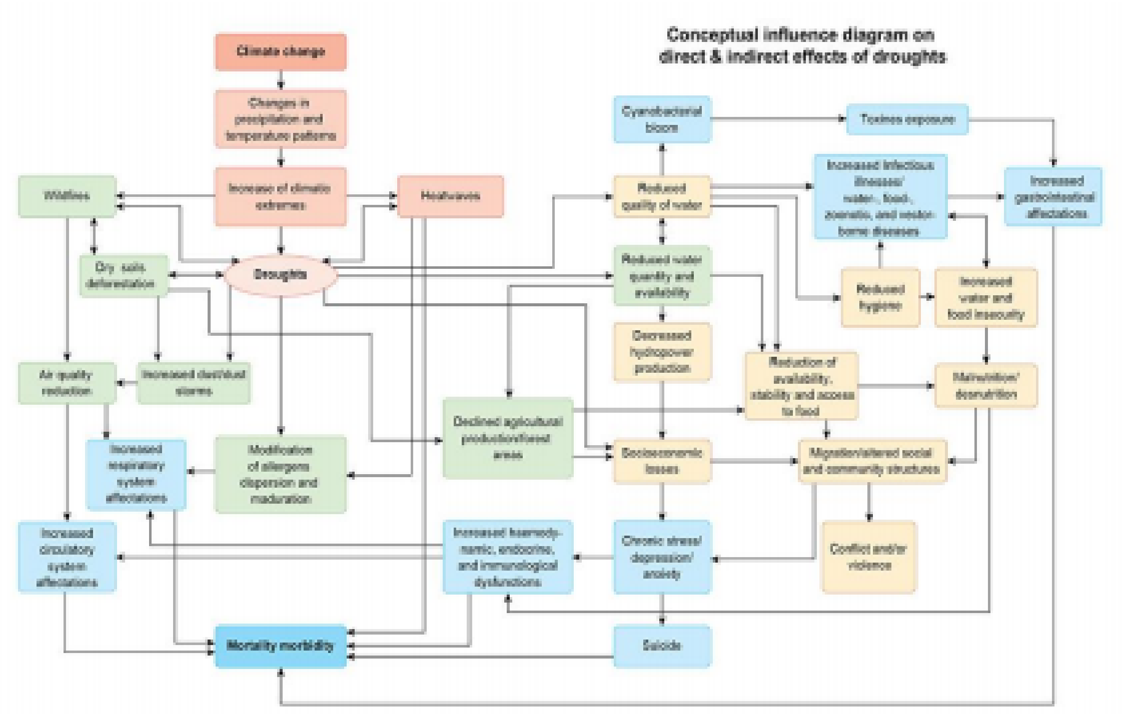


Figure 2. Conceptual influence diagram of the principal direct and indirect effects of droughts. From Salvador et al. (2020).

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).

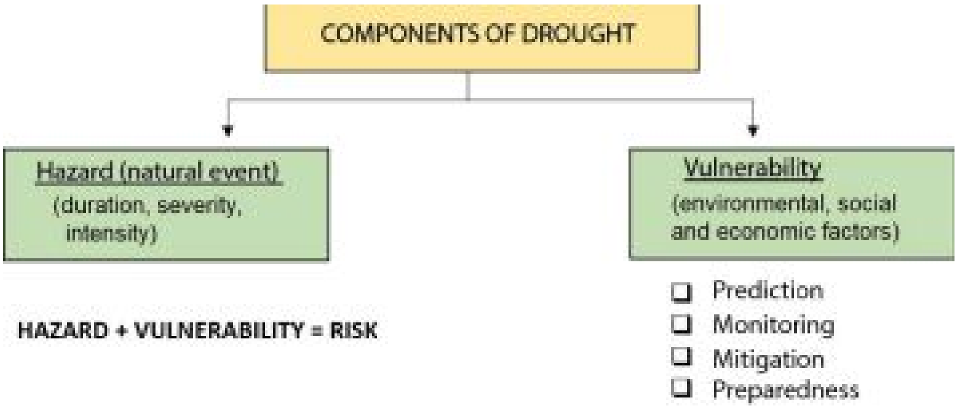


Figure 3. Components of drought. Adapted from Quiring (2015).

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. 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.

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).

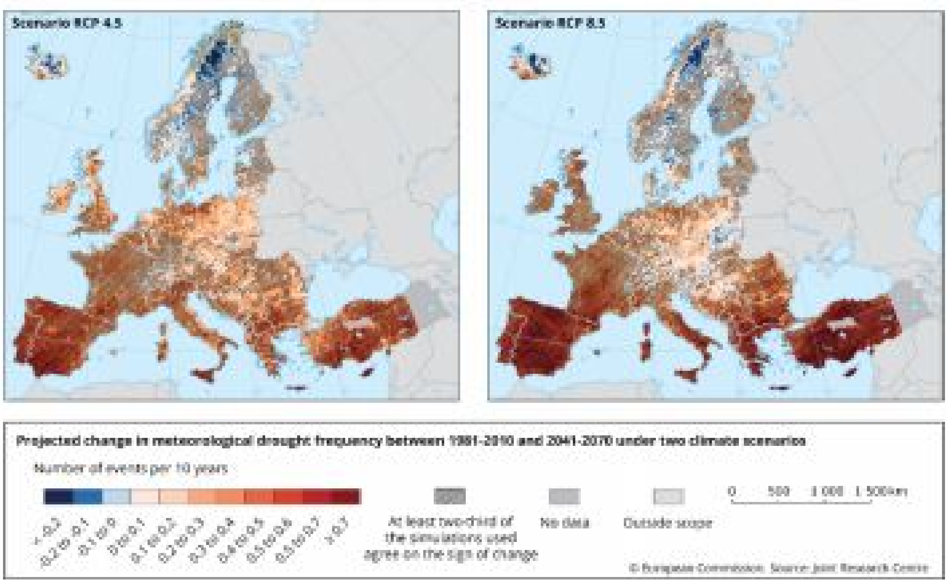


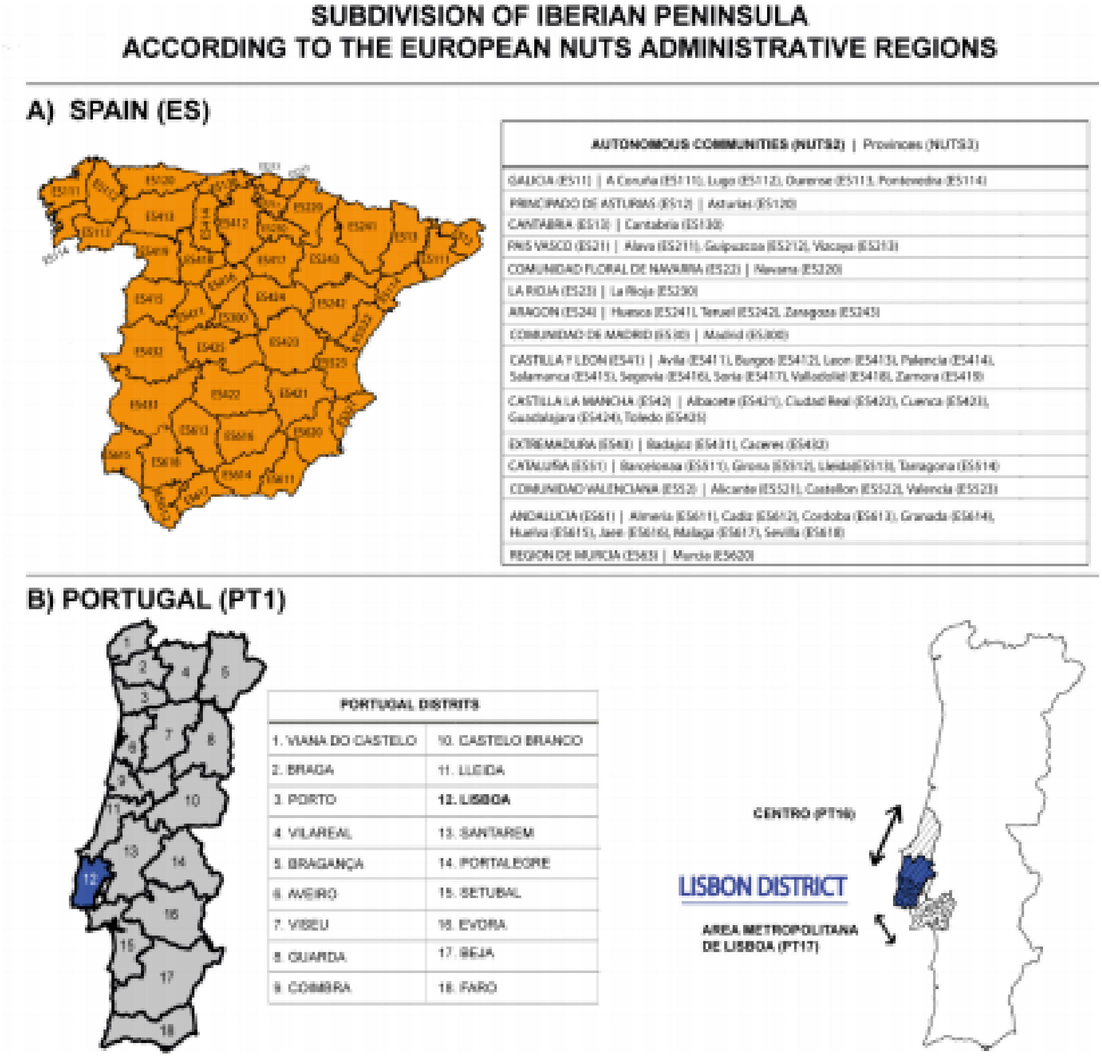
Figure 5. Projected change in the frequency of meteorological drought between 1981–2010 and 2041–2070 in Europe for RCP 4.5 (left map) and RCP 8.5 scenarios (right map). Similar changes in sign are represented by the lines. The figure is from the European Environment Agency (https://www.eea.europa.eu/data-and-maps/figures/projected-change-in-meteorological-droug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



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 FLORAL 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) | Barcelona (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 (ES62) | Murcia (ES620)

PORTUGAL DISTRITS	
1. VIANA DO CASTELO	10. CASTELO BRANCO
2. BRAGA	11. LLEIDA
3. PORTO	**12. LISBOA**
4. VILAREAL	13. SANTAREM
5. BRAGANÇA	14. PORTALEGRE
6. AVEIRO	15. SETUBAL
7. VISEU	16. EVORA
8. GUARDA	17. BEJA
9. COIMBRA	18. FARO

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	
SPEI/SPI≤-2.33	Level 5 Reflects a period of 100 years with a 1% probability	

Extreme drought

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.

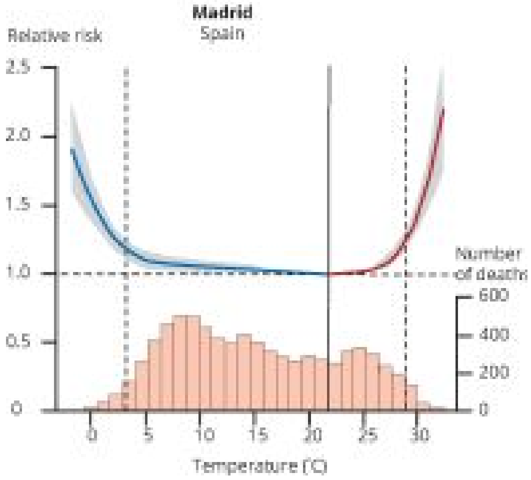


Figure 7. Upper part of the figure: relationship between mortality and temperature in Madrid, Spain (where the 95% confidence interval is shaded in grey) and the associated relative risk (RR). The solid grey vertical line marks the minimum mortality temperature. Bottom part of the figure: temperature 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.

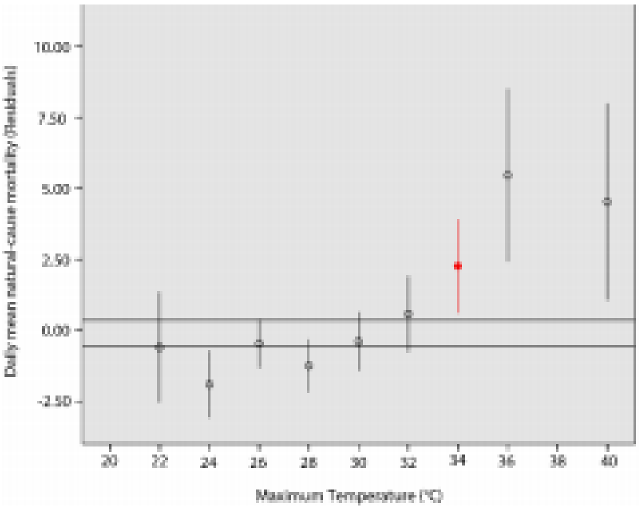


Figure 8. Scatter plot of the maximum daily temperature (T*max*) and daily mortality residuals for the definition of the heat trigger temperature (T*threshold*) in Lisbon district for the period of 2007–2016. T*max* of 34 °C marked in red.

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

����h���������������� = ���������������� −
��������h������������h������������ ��������
���������������� >
��������h������������h������������

����h���������������� = 0 �������� ����������������
≤ ��������h������������h������������

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:

����3���� = ����3 −
����3����ℎ������������ℎ������������ ��������
����3 > ����3����ℎ������������ℎ������������

����3���� = 0 �������� ����3 ≤
����3����ℎ������������ℎ������������

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 $\mu g/m^3$ (which corresponds to the 72nd percentile).

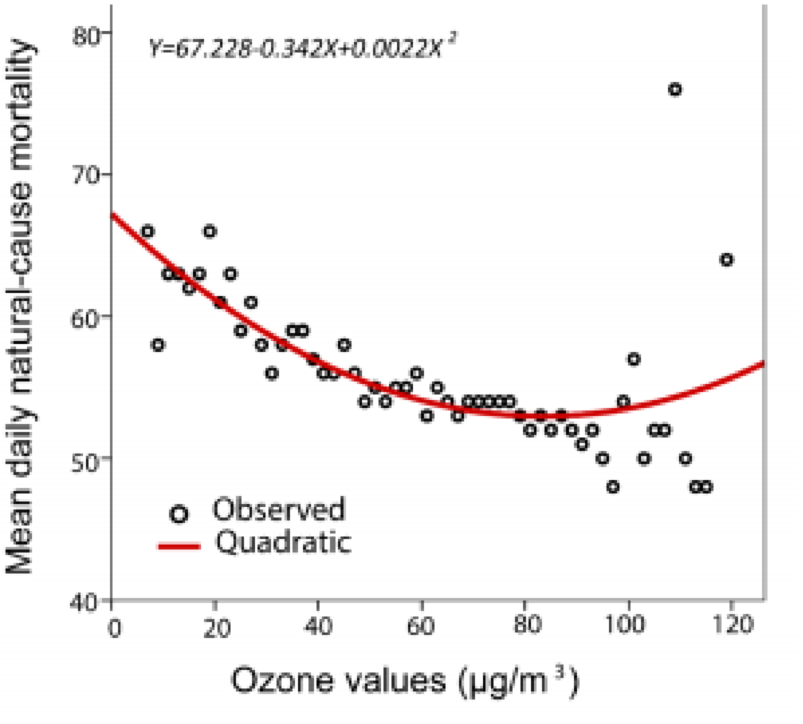


Figure 9. Scatter plot of the mean daily natural-mortality and mean daily O_3 concentrations to calculate the O_3*threshold* values in Lisbon district from 2007 to 2016.

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
Asturias (ES120) 30 67 (60%)

Principado de Asturias (ES12)
32
Cantabria (ES13)
Cantabria (ES130)

Pais Vasco (ES21) Alava (ES211) 30 74 (72%)
Guipuzcoa (ES212) 30 61 (75%)
Vizcaya (ES213) 30 72 (78%)
Navarra (ES220) 36 81 (74%)
Comunidad Foral de Navarra (ES22)

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) Burgos (ES412) 34 86 (70%)
Castilla y Leon (ES41) Leon (ES413) 32 83 (85%)
Madrid (ES300) 34 60 (89%) Palencia (ES414) N.D. N.D.

Avila (ES411) 32 67 (44%)
Salamanca (ES415) 34 93 (76%)

Segovia (ES416) 34 70 (50%) Soria (ES417) 34 82 (75%)

Valladolid (ES418) 36 84 (73%)

Zamora (ES419) 36

Albacete (ES421) 36 156 (99%)

Castilla la Mancha (ES42) Ciudad Real (ES422) 38

Cuenca (ES423) 34

Guadalajara (ES424) 38 102 (67%)

Extremadura (ES43)

Toledo (ES425) 38 116 (80%)

Badajoz (ES431) 38

Caceres (ES432) 38

39

Cataluña (ES51) Barcelona (ES511) 32 77 (92%)

Girona (ES512) 36

Lleida (ES513) 36 133 (99%)

Tarragona (ES514) 36 127 (97%)

Alicante (ES521) 32
Castellon (ES522) 32 113 (96)
Valencia (ES523) 34 99 (99%)
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%)
Murcia (ES620) 34 124 (95%)

Comunidad
Valenciana (ES52)

Andalucia
(ES61)

Region de Murcia (ES62)

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 *n*1 = 1 for the first day of the series, *n*1 = 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:

��������� =
����|���| (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:

$$\% ����_{����} = �(�������� - 1)$$

$$�������� ^{�} \times 100$$

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).

42

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:

$$������������ ����(��������^{����}) = ������������1 +$$

$$����_{����} ������������_{����} + �������������������� +$$

$$�������������������� + \cdots + ����$$

$$(����h���������������_{����}{}^{����})$$

$$����=4 \quad ����������_{�} \quad ����=5$$

$$+ ����� \; ����=1 \quad ���^{����} + ���� \quad �����������$$

$$����=5$$

$$����������� \; ���������^{10} \; �����$$

$$����� \quad ����^{����}� + \quad ��������^{10}$$

$$����h������ \quad ����� \; ����=1 \quad ��$$

�� ���� ����=9 ��������� ���� �����3����
+ ���� + ���� �����
���������2�� ���������� ���� ����� +
����� ����� ����=1
�� ����� + ���� ���������� ����������
� ����=1 ����� �����
+ ��������2��� ����3���� ��
����������� � ���� + ���� �� ����

where ����������� is the number of death outcomes on day *t* in the specific region (*r*). ������������1 is the factor that controlsthe 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 (������������������������) and the seasonality (represented using sine and cosine functions that correspond to the different periodicities; *X* = 360, 180, 120, 90, and 60) were analysed. ����, ���� , and ���� correspond to the respective coefficients. ���� 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 (��������������������) 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 [���� (����h����������������������������)] an d atmo sphe ric

pollutants such as PM_{10} [���� ���������10��������], NO_2 [����

���������2��������], and O_3 [���� �����3��������������]

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 (���� 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**
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))	Environmental control variables From 2000 to 2009 (pollution data available) -**Daily maximum temperatures (T*max*)*** (supplied by the AEMET) -**Pollutants***: Mean daily concentrations (µg/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**
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

CONTROL VARIABLES

Environmental control variables

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)

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
		2020	Science of the Total Environment. JCR abbrev: STOTEN

future research.

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

2019 Science of the Total

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

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

Environment.
JCR abbrev:
STOTEN

2020 Environmental

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;
L. Gimeno

Science of the Total Environment.
JCR abbrev:
STOTEN

C. Salvador; R. Nieto;
C. Linares; J. Díaz;
L. Gimeno

Research.
JCR abbrev: ER

C. Salvador; R. Nieto;
C. Linares; J. Díaz;
L. Gimeno

2020 Submitted.
International Journal of Environmental Research and Public Health.
JCR abbrev: IJERPH

C. Salvador; R. Nieto;
C. Linares; J. Díaz;
L. Gimeno

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

C. Salvador; R. Nieto;
C. Linares; J. Díaz;
C.A. Alves; L. Gimeno

2020 Under review.

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	about anthropogenic issues of global relevance and applicability in a wide range of environmental disciplines and demonstrating environmental application in a real-world context.	Environmental & Occupational Health (SSCI); Q2 in Environmental Sciences (SCIE) - ISSN: 1660-4601
Environmental Research	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: 6.551 - 5 y impact factor: 6.419 - Quartile: Q1 in Environmental Science - ISSN: 0048-9697	
International Journal of Environmental Research and Public Health 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: 5.715 - 5 y impact factor: 5.735 - Quartile: Q1 in Environmental Science - ISSN: 0013-9351	
A multidisciplinary journal of environmental sciences and engineering publishing high quality and novel information	- Impact factor: 2.849 - 5 y impact factor: 3.127 - Quartile: Q1 in Public,	