MEMORIA CIENTÍFICO-TÉCNICA DE PROYECTOS INDIVIDUALES
Convocatoria 2021 - «Proyectos de Generación de Conocimiento»

AVISO IMPORTANTE - La memoria no podrá exceder de 20 páginas. Para rellenar correctamente esta memoria, lea detenidamente las instrucciones disponibles en la web de la convocatoria. Es obligatorio rellenarla en inglés si se solicita 100.000 € o más (en costes directos).

IMPORTANT – The research proposal cannot exceed 20 pages. Instructions to fill this document are available in the website. If the project cost is equal or greater than 100.000 €, this document must be filled in English.

1. DATOS DE LA PROPUESTA – *PROPOSAL DATA*

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TÍTULO DEL PROYECTO (ACRÓNIMO): *Evaluación en alta resolución del transporte de humedad en el Atlántico Norte en clima actual y en las proyecciones futuras del CMIP-6 (SETESTRELO)*

TITLE OF THE PROJECT (ACRONYM): *High-re**s**olution ass**e**ssmen**t** of North Atlantic moistur**e** tran**s**por**t** in cur**re**nt c**l**imate and CMIP-6 future pr**o**jections (SETESTRELO)*

2. ANTECEDENTES, ESTADO ACTUAL Y JUSTIFICACIÓN DE LA PROPUESTA - *BACKGROUND, CURRENT STATUS AND JUSTIFICATION OF THE PROPOSAL*

Each main component in hydrological cycle plays a major role in the global climate system (Peixoto & Oort, 1992). Thus, from a **climate change** perspective, it is important to obtain the best possible understanding of both *the intensity of the hydrological cycle and its evolution over time*. Indeed, this may represent *one of the most important challenges for geoscience research in this century*. Understanding the processes governing water evaporation from oceans (Yu & Weller, 2007) and the transport of atmospheric moisture (Trenberth et al., 2003) is particularly important, as is understanding the effects of these processes on the hydrological cycle (Bales, 2003) within the context of global climate change (Stocker et al., 2013). The **transport of moisture** from oceans to continents is the primary component of the atmospheric branch of the water cycle, linking evaporation from the ocean and precipitation over the continents (Gimeno et al., 2016). A detailed study of this transport provides a better understanding of any observed changes, physical evidence in support of the many available projections of future climates (e.g. Gimeno et al., 2010, 2012, 2013), and a better understanding of the role of anomalies in moisture transport in relation to extreme drought (Trigo et al., 2013) or intense precipitation (Stohl & James, 2004).

Based on the understanding of source-sink relationships, Gimeno et al. (2012) performed a characterisation using several related studies to assess how water from different moisture source regions influences continental regions. There has been a notable increase in studies on the origins of precipitation, identification of moisture sources, and establishment of climatologies of moisture source-sink relationships following Gimeno et al. (2012). The results provide new detailed insights regarding the role of synoptic-scale systems such as Low-Level Jets (LLJs; e.g. Algarra et al., 2019; Zhang et al., 2019), Atmospheric Rivers (ARs; e.g. Dettinger et al., 2015; Ralph et al., 2017a; Eiras-Barca et al., 2017), and monsoons (e.g. Ordoñez et al., 2019; Sorí et al., 2018; Pathak et al., 2017; Hu & Dominguez, 2015) on precipitation over different continental areas. Additionally, many studies have considered the role of moisture sources in diagnosing the occurrences of extreme hydroclimatic events (e.g., Drumond et al., 2019; Bohlinger & Sorteberg, 2018), even at multiple spatiotemporal scales (Herrera-Estrada et al., 2019). To this end, several authors have implemented classical Eulerian (Van der Ent & Savenije, 2011), Lagrangian (Stohl & James, 2004, 2005; Dominguez et al., 2006; Dirmeyer et al., 2014), and stable isotope approaches (Dansgaard, 1964), as well as new sophisticated and robust methods such as Eulerian mesoscale tracer tools (Insua-Costa & Miguez-Macho, 2018). The results of these studies have contributed to a deeper understanding of the functioning of the hydrological cycle on the planet and have provided support for socioeconomic planning.

As global warming continues in the short and long term (IPCC, 2021), the global climatological characteristics of the source-sink relationships of atmospheric moisture may be altered. As atmospheric temperature increases, so does its capacity to hold water according to the Clausius-Clapeyron relationship (Held & Soden, 2006). Accordingly, the thermodynamic response to idealised climate warming can be understood as a generalised mechanism of "dry gets drier and wet gets wetter", in which the greatest precipitation is enhanced the most from increased gross stratification of moisture (Chen et al., 2019). However, observational evidence shows discrepancies in the "dry gets drier and wet gets wetter" mechanism for the tropics, which results in an uneven increase of tropical precipitation in a warming climate (Zhang & Fueglistaler, 2019). Observational and modelling studies suggest that strong dependence of saturated vapour pressure on temperature will result in increased evaporation and precipitation, intensifying the water cycle (Gimeno et al., 2015). From the connections already established, changes in certain hotspot moisture source regions (Nieto et al., 2014) will be directly related to projected increases in the intensity of extreme precipitation events, probably of unprecedented magnitude, throughout the 21st century (Giorgi et al., 2019). Marked differences between latitudes and continents are expected (Madakumbura et al., 2019), collaterally affecting the availability of freshwater resources (Cosgrove & Loucks, 2015), which is a topic of worldwide concern. In a crowded world with rising populations and changing consumption patterns, humankind has not sufficiently managed or planned for water availability in the future (FAO, 2011). Changes in the hydrological cycle due to climate change severely compromise food security (Wheeler & Von Braun, 2013) and hydropower generation (Teotonio et al 2017). Hence, the impact of an altered hydrological cycle is likely to increase inequality (King & Harrington, 2018; Gazzotti et al., 2021).

Few studies have focused on moisture transport in future climates, partly because moisture flux data have not been readily available from past Coupled Model Intercomparison Project (CMIP) experiments. In an Eulerian framework and taking advantage of the new CMIP phase 6 (CMIP6) variables, the vertically integrated eastward and northward moisture transport or flux, Watterson et al. (2020) provided a multi-model assessment of the water vapour path in a not very realistic scenario of global warming ranged from 4.3 to 6.5°C finding among other things, an intensification in monsoonal regions. **With the exception of this preliminary work, at to our knowledge, there are not studies using CMIP6 models and their new emission scenarios (RCPs-SSPs) to study the projection of moisture transport in future climates in the North Atlantic region; no regionalisations exists that use dynamic downscaling experiments for this purpose, and even less Lagrangian studies have been conducted to identify future changes in the sources and sinks of moisture, which are the focus of this project.**

The proposal is included in the Spanish Science Strategic Plan 2021-2023 in the *Thematic Priority Lines devoted to "Climate, Energy and Sustainability"* (5th point) with special relevance to of the themes of *Climate Change and Decarbonisation.* The project also aligns with the 13th Sustainable Development Goal (SDG) of the 2030 Agenda for "Climate Action". Additionally, the projected changes in the precipitation patterns (related to droughts and floods) are linked to impacts that fall within the framework of the other SDGs as "15. Life on Land", "3. Good health and well-being ", and "6. Clean Water and Sanitation."

This project requires the computation of intermediate variables, including wind, which will be regionalised at high resolution for the first time using the CMIP6 dataset. These wind resources can be used for estimates related to wind energy, and therefore fit in the strategic lines of the Xunta de Galicia RIS3 2021-2027 within Challenge 1, Priority 1.3, for the diversification of the Galician energy sector to achieve a significant improvement in the efficient use of Galician natural resources that prioritises offshore wind energy (https://ris3galicia.es/wp-content/uploads/ESTRATEXIA-_REXIONAL_RIS3_GALICIA-1.pdf).

The **SETESTRELO** project is the continuation of an uninterrupted series of projects on moisture transport funded by the Ministry for Science in Spain since 2004: DINPRE (CGL2004-05187-C03-02), MSM (CGL2008-05968-C02-02), TRAMO (CGL2012-35485), EVOCAR (CGL2015-65141-R), and LAGRIMA (RTI2018-095772-B-I00), and is complemented by two projects funded by the Xunta de Galicia CHEGA (PGIDIT05PXIC38301PN) and THIS (CGL2012-35485), one European ACPCA (PRI-PIMERU-2011-1429) and another funded by the European State Agency (CCI + PHASE I-ECV WATER VAPOOR). Together, these projects have resulted in 108 SCI publications, some in very prestigious journals, such as *Nature Reviews Earth and Environment*, *Nature Communications, Reviews of Geophysics, Annual Reviews of Environmental Resources, Earth Science Reviews, WIRES Climate Change, WIRES Water,* or *npj Climate and Atmospheric Sciences* (https://ephyslab.uvigo.es/moisturetransport).

In these projects, sources and sinks of moisture were extensively studied in the present climate, as well as the contribution of these sources to average and extreme precipitation and their roles in drought and flood development. This was done for the Iberian Peninsula (DINPRE), for the Mediterranean region (MSM), for the Arctic (EVOCAR and ACPCA), and worldwide (TRAMO). In some of these projects, we also studied in depth the role of the main atmospheric moisture transport mechanisms such as ARs, LLJs, some extratropical cyclones, and more recently, tropical cyclones to determine how they affect drought and flood development from a moisture transport perspective. This was first partially done in TRAMO, for the Arctic in EVOCAR, and then globally and exhaustively in our most recent project, LAGRIMA. A local analysis was performed in CHEGA and THIS for Galicia, in EVOCAR for the Arctic Sea Ice, and in ACPCA for the Eurasian snow cover. Finally, global moisture transport was analysed to check the new global ESA atmospheric moisture database, which will be available in December 2021 on the CCI + PHASE I-ECV WATER VAPOOR web page.

All the above-mentioned studies were carried out in the present climate. **None of the studies addressed how moisture transport, its mechanisms, and its relationship with extremes of precipitation and droughts will change in the future climate.** This is due to enormous technical difficulties and the need for very intensive computation when using Lagrangian techniques (those used in our previous projects) in climate models. After many years of work and with the improvement of the computational resources available in our EPhysLab servers and in those of the Galician Supercomputing Centre, for the first time, we can address the fundamental scientific questions of **how sources and sinks are projected to change, how moisture transported by Atmospheric Rivers and Low-Level Jets will change, and if and how the dependence between moisture transport and precipitation extremes will change in the future climate**. Leveraging our increased knowledge, technical, and computational breakthroughs, the **new models of CMIP6 —which combine future forcing scenarios (RCPs) and shared socioeconomic pathways (SSPs)** and are the physical science basis for the 2021 IPCC Sixth Assessment Report, (AR6)]— and a much larger working team than in previous projects, we will be able to face the greatest scientific challenge we have undertaken since we started working on these projects.

3. OBJETIVOS, METODOLOGÍA Y PLAN DE TRABAJO - *OBJECTIVES, METHODOLOGY AND WORK PLAN*

3.1 Objectives and structure of the scientific proposal

The general objective of this project is a high-resolution assessment of the moisture transport in the North Atlantic for current and future climates using ERA5 reanalysis and CMIP6 outputs with increased resolution through dynamic models adjusted to regional meteorology.

The project is divided into **six working packages (WPs)** around the specific project objectives.

WP1 (Computation): The focus of this WP is to perform multiple **dynamic downscaling** experiments **using the regional Weather Research and Forecasting (WRF) model.** Simulations will be performed for **two regions, one centred on the North Atlantic Ocean and the other in Central America,** using **two nested domains of 30 and 10 km of spatial resolution**. WRF will be **forced with ERA5 reanalysis** (Hersbach et al., 2020) **and the outputs of three CMIP6 Global Climate Models** (CESM2, NorESM2-LM, and CNRM-ESM2-1), with **three sets of simulations: the historical climatic conditions** (1994-2014, also for ERA5), the **conditions for the middle and end of the century** (2040-2060 and 2080-2100), **and two of the new future greenhouse gas emission scenarios combining Shared Socioeconomic Pathways - SSP2-4.5 and SSP5-8.5-**. Then, the FLEXPART-WRFv3.3.2 Lagrangian model (Brioude et al., 2013) will be forced with 40 different sets of WRF outputs obtained to track the trajectory of atmospheric particles to calculate variations in specific humidity along their pathways at high horizontal resolution. Therefore, the **specific objective** of WP1 is to perform high-resolution simulations for current and future climates from ERA5 reanalysis and CMIP6 outputs using the WRF and FLEXPART-WRF models for two configurations centred on the North Atlantic Ocean and Central America.

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Specific **sub-objectives** of WP1 are as follows:

SO1.1 Obtain high-resolution WRF outputs for current (1994-2014) and future climates (2040-2060 and 2080-2100) and for two scenarios (SSP2-4.5 and SSP5-8.5) from the ERA5 and CMIP6 datasets - hereafter denoted **HR-ERA5** and **HR-CMIP6 datasets**- in two regions on both sides of the North Atlantic basin.

SO1.2: **Evaluation of the variables** necessary to determine the sources and sinks of moisture, transport mechanisms, and extreme events.

SO1.2: **Perform Lagrangian simulations using** the particle model **FLEXPART-WRF fed by** the complete set of obtained high-resolution WRF outputs, **HR-ERA5 and HR-CMIP6**.

WP2 (Sources and Sinks): The circulation of evaporated moisture through the atmosphere guarantees the connections between evaporation and precipitation by redistributing water on the planet. For this reason, the source-sink relationship of atmospheric moisture has been investigated at local, regional, and global scales using different methods and datasets. At the global scale, the major oceanic moisture sources for continental precipitation have been associated with areas of divergence over the oceans (Gimeno et al., 2010a); their contributions to precipitation have increased globally in the current climate (1980–2016) (Gimeno et al., 2020). There are three major sources in the North Atlantic region (Figure 1): the central Northern Atlantic Ocean (NATL), the Mediterranean (MED), and the Gulf of Mexico-Caribbean Sea (MEXCAR). NATL is the dominant source for winter precipitation to both sides of the North Atlantic basin (Gimeno et al., 2010a,b), while the MED and MEXCAR sources are the dominant moisture sources during summer in the Iberian Peninsula (Gimeno et al., 2010b) and Central America (Durán-Quesada et al, 2017), respectively.

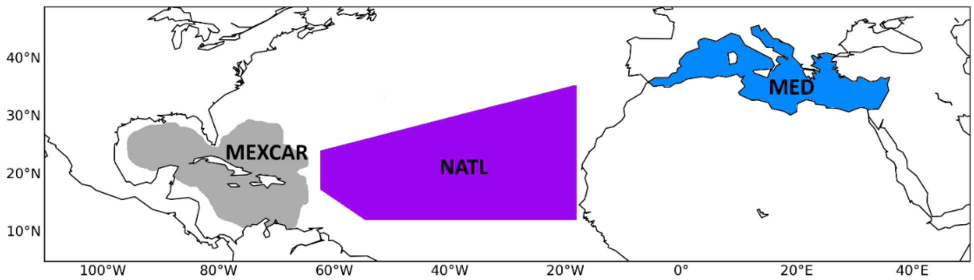

Figure 1: Major sources in the North Atlantic region: the central Northern Atlantic Ocean (NATL), the Mediterranean (MED), and the Gulf of Mexico-Caribbean Sea (MEXCAR), Gimeno et al. (2010a).

Any intensification or reduction in transported moisture results in precipitation anomalies including flooding and drought when the moisture content is high and low, respectively (Gimeno et al., 2016; Drumond et al., 2019; Liu et al., 2020). Thus, there is a significant direct link between the occurrence of extreme drought events in Europe and anomalies of moisture transported from the NATL (Sorí et al., 2020; García-Herrera et al., 2019; Stojanovic al., 2018a) and MED (Stojanovic et al., 2018b; Vautard et al., 2007). Reduced moisture contribution from MEXCAR appeared to be linked with the occurrence of drought events in Southern Mexico (Melgarejo et al., 2021). Recent studies performed on continental regions in the Northern Hemisphere continental regions (Herrera-Estrada and Diffenbaugh, 2020; Drumond et al., 2019) have also captured this relationship. Similar analyses have been performed to identify the roles of the NATL and MED in extreme precipitation occurrences in Europe (Insua-Costa et al., 2019; Tabari & Willems, 2018; Ciric et al., 2018; Cloux et al., 2021), as well as the MEXCAR moisture as a source for extreme precipitation in Central America and the Caribbean.

According to the IPCC (2021), floods and droughts are expected to become substantially more frequent under global warming conditions. However, no study to date has revealed the future variability of moisture sources under the influence of global warming and different socioeconomic and environmental scenarios. Consequently, the known information about future precipitation comes from estimates of models that reproduce the climate feedback processes under different forcing conditions (atmosphere, oceans), but not the associated mechanisms and origins of precipitation changes. Therefore, we will implement a new methodology to facilitate the **main WP2 objective** of **determining the historical and future extensions of major moisture sources located in the North Atlantic** (NATL, MEXCAR, and MED). The contributions of these moisture sources to precipitation (average and extremes) over the surrounding and remote continental regions considering a historical period and the new emission scenarios (RCP-SSPs) for different global warming conditions and the periods informed in WP1 will also be studied.

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Specific **sub-objectives** of WP2 are as follows:

SO2.1 Evaluate climatological characteristics (position, extension, etc.) **of the main moisture sources** in the North Atlantic Ocean (NATL, MEXCAR, and MED) **for historical and future periods using** high-resolution WRF outputs from the ERA5 and CMIP6 datasets (**HR-ERA5 and HR-CMIP6**) to confirm and improve current knowledge via the improved resolution and physics of the new WRF simulations.

SO2.2 Assess the **moisture sinks** (and their variabilities) **over the surrounding continental areas** of the North Atlantic basin **using the HR-WRF regionalised outputs** during the current climate and under different future climate scenarios from state-of-the-art CMIP6 CGCMs.

SO3.3 Detect changes in related **extreme patterns over continents**, such as changes in the occurrence, severity, and duration of extreme precipitation events, floods, and droughts, under global warming conditions.

WP3 (Mechanisms): One of the most robust signs of climate change is the relentless rise in global mean surface temperature (IPCC, 2021), which is closely related to the water-holding capacity of the atmosphere. A wetter atmosphere will lead to increased moisture transport; therefore, it is important to study changes in the two main planetary-scale meteorological structures in moisture transport (Figure 2): the *Atmospheric Rivers* (ARs) and the *Low-Level Jets* (LLJ) (e.g. Gimeno et al., 2020). Several studies have analysed changes in the ARs in future climates (e.g. Ramos et al., 2016; Payne et al., 2020; O'Brien et al., 2021)), as well as future projections in the climatology of global LLJs (Torres-Alavez et al., 2021). However, a comprehensive analysis relating the enhanced moisture transport due to changes in ARs and LLJs activity has not yet been attempted using state-of-the-art AR6 climate models for the North Atlantic domain. Thus, changes in moisture transport in future climate scenarios can be attributed to the different key features that cause it. **The specific objective of WP3 is to determine changes in future climates of ARs and LLJs occurrence and characteristics linked to the moisture transported by these systems**

IP in charge: *L Gimeno.*

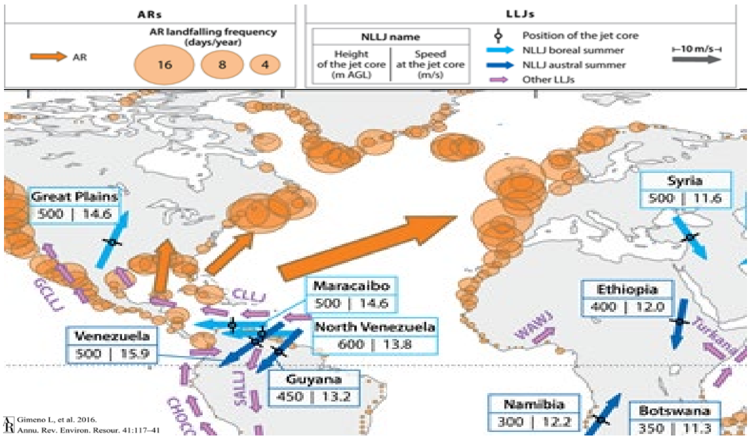


Figure 2: The geographical position of atmospheric rivers (ARs) and low-level jets (LLJs) in the North Atlantic surroundings. ARs are shown by the orange arrows. Each arrow denotes the direction of flow. Orange circles denote the frequency (days/year) of AR landfalling. Blue and purple arrows show the locations of LLJs. Colored boxes next to blue arrows inform about the name of the jet, its typical height (bottom-left; in m AGL), and its typical speed (bottom-right; in m/s) at the jet core. LLJs with high climatic relevance are also denoted: the Great Plains LLJ (GPLLJ), Gulf of California LLJ (GCLLJ), Caribbean LLJ (CLLJ), CHOCO-LLJ, South American LLJ (SALLJ), West African Westerly jet (WAWJ), Turkana LLJ. Figure adapted from Gimeno et al. (2016).

Specific **sub-objectives** of WP3 are as follows:

SO3.1 Assess ARs and LLJ variability under different future climate scenarios from state-of-the-art CGCMs from HR-CMIP6.

SO3.2 Study **how changes in the ARs and LLJs influence changes in the moisture transport** corridors and assess the nature of this relationship when compared with the present climate.

SO3.3 Detect differences in the main characteristics of future transport mechanisms, such as changes in geometry, or the atmospheric mechanisms involved.

SO3.4 Analyse the most relevant changes in the position and importance of the main moisture sources for these mechanisms.

WP4 (IVT-extreme precipitation dependence): The role of moisture transport is even more important in extreme precipitation than its average value. According to a simple approximation, extreme precipitation scales with moisture content and with some indicators of atmospheric instability, being much more sensitive to the former (Emori & Brown, 2005; Nie et al., 2018). *Extreme precipitation* requires a certain threshold of atmospheric instability; once it is reached the value of extreme precipitation increases as the water vapour content increases (Emori & Brown, 2005; Kunkel et al., 2020). To maintain high moisture in the atmospheric column a constant supply of humidity from the outside, in other words, high moisture transport, is required. It has been shown that *vertically integrated water vapour transport (IVT)*, a local measure of the moisture advected horizontally in the atmosphere, is a strong predictor of precipitation (Lavers & Villarini, 2015; Rutz et al., 2014) and its spatial extent is more strongly correlated with precipitation than with the total water vapour column over land. Furthermore, Lavers et al. (2014) found that large-scale horizontal moisture transport was more predictable than precipitation and could be used to extend the forecast time of extreme precipitation by up to three days in some parts of Europe. The relationship between moisture transport, moisture content, and extreme precipitation must therefore be intense and of great importance, not just in hydro-meteorological terms as well as in terms of climate change because the three parameters scale approximately with temperature following a thermodynamic constraint imposed by the Clausius-Clapeyron equation (Held & Soden, 2006; Bao et al., 2017). If moisture transport is quantified as *IVT*, there must be a dependence between the extremes of IVT and precipitation at the grid-scale. This relationship must be spatially and temporally heterogeneous throughout the world because most moisture is transported via two major mechanisms of atmospheric moisture transport (LLJs) in tropical and subtropical regions and ARs in subtropical and extratropical areas (Gimeno et al., 2016). Therefore, Gimeno-Sotelo & Gimeno (2021) found that AR occurrence accounts for most of the concurrent extreme days of precipitation and IVT (Figure 3a), with marked regional and seasonal differences, and that the role of ARs as drivers of extremal dependence between precipitation and IVT is not the same for the two sub-periods of the study, one earlier and another more recent (warmer) period. The general tendency is a decrease in recent (warmer) periods, which is especially apparent over the Pacific and Atlantic North American coasts during winter. However, this study is limited by the resolution of the reanalysis. As suggested by Zscheischler et al. (2021), studies based on reanalysis should be compared with others using higher resolution models when compound precipitation and wind (in our case, IVT) extremes are studied over complex terrain. This is the reason behind using a WRF simulation to study precipitation and IVT dependence for current and future climates at a 10 km resolution for Western European coasts and Atlantic American coasts—two regions of high AR occurrence. **The specific objective of WP4 is to provide a high-resolution assessment of the current and future dependence between daily precipitation and IVT to determine whether the probability of their concurrent extremes will change and how those changes are affected by major modes of atmospheric moisture transport (ARs and LLJs).**

IP in charge: *L Gimeno*

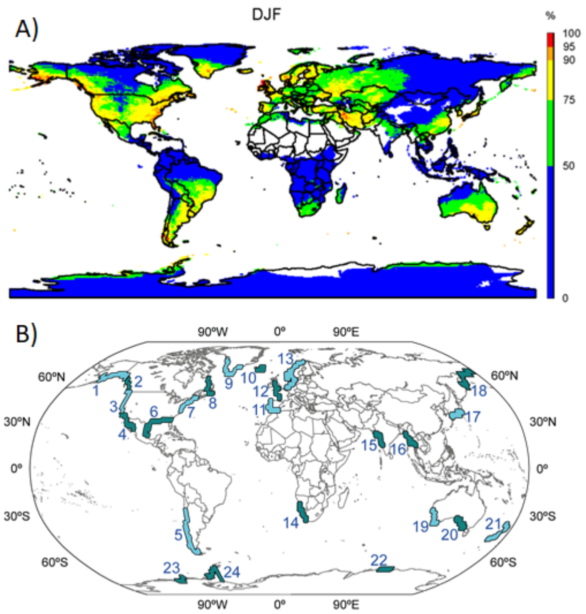


Figure 3: a) Percentage of wintertime concurrent extreme days of IVT and precipitation that coincide with the occurrence of ARs, for December-January-February, for the whole period 1981-2017 from ERA-5 data taken from Gimeno-Sotelo & Gimeno (2021). b) Regions of maximum occurrence of landfalling ARs adapted from Fig. 1 in Algarra et al. (2020).

Specific **sub-objectives** of WP4 are as follows:

SO4.1 To **analyse the dependence structure of precipitation and IVT** in the **current climate** in two regions with high occurrence of ARs and LLJs with enhanced physics and resolution.

SO4.2 To **analyse changes in the dependence structure** of precipitation and IVT **in future climates**.

SO4.3 To **study how climate change influences the role of ARs and LLJs in the occurrence of concurrent extreme events** of atmospheric moisture transport and precipitation.

WP5 (residence times) The residence time of water vapour in the atmosphere (water vapour residence time, WVRT) is a fundamental, if not yet fully resolved, diagnostic of our understanding of the hydrological cycle, and is an essential indicator of how the hydrological cycle is altered by dynamic and thermodynamic processes related to climate change (Trenberth, 1998). WVRT changes as a result of variations in the atmospheric circulation and is highly sensitive to surface evaporation and evapotranspiration as well as to the development of synoptic scale systems. The advection of moisture from the surface (oceanic and continental) to the atmosphere is dependent on the WVRT. Furthermore, in the atmosphere, the occurrence of precipitation alters the WVRT by means of processes such as the evaporation of precipitation. As WVRT is intrinsically linked to the modulation of moisture advection and transport processes, understanding the mechanisms that dominate WVRT at different scales is key to better understand how the local, regional and global scales of moisture transport interact. Changes in the WVRT can provide information on characteristic conditions during the development of extreme precipitation events as drier and wetter conditions feature different WVRT conditions. From the physical point of view, WVRT enables the advancement in the understanding of the connectivity of temporal and time scales within the hydrological cycle.

This WP focused on analysing changes in the WVRT for present and future climate conditions, the relationships between those changes and the impact of warming on large-scale circulation, and the impacts of such changes on the sources of moisture for precipitation and the modulation of moisture conveyors. Gimeno et al. (2021) presented a detailed discussion on the relevance of the regional scale for the interpretation of WVRT. A study accounting for regional estimation of WVRT changes requires high resolution, which will be enabled by the dataset generated by the dynamic downscaling experiment proposed for this project. Changes in the WVRT provide information on climate sensitivity and novel insights into the impact of a warming climate on storm tracks and extreme precipitation events in the Atlantic Ocean and surrounding continental and insular regions. The **specific objective of WP5** is to **determine how changes in the water vapour residence time influenced by changes in the large-scale circulation patterns modulate moisture transport and associated precipitation extremes in climate change hotspots** in the North Atlantic and Central America**.**

IP in charge: *L Gimeno.*

Specific **sub-objectives** of WP5 are as follows:

SO5.1 Estimate water vapour residence time (**WVRT**) based on the FLEXPART-WRF outputs (**HR-ERA5 and HR-CMIP6**) for the historical and projected climate.

SO5.2 Determine significant changes and trends in the estimates **for WVRT**, and identify hotspots for residence time changes.

SO5.3 Identify linkages between changes in WVRT and changes in large-scale circulations (e.g. Walker circulation) that may be associated with the modulation of extreme precipitation events.

SO5.4 Evaluate the impact of changes in large-scale circulation on the dynamics of the **main moisture transport mechanisms** (ARs and LLJs).

SO5.5 Analyse the impacts of changes in the WVRT and moisture sources (oceanic and continental) **on precipitation extremes** in climate change hotspots.

WP6 (Diffusion and Formation): The **objective of this WP is threefold,** focusing on **dissemination activities that engage in traditional scientific communication channels,** dissemination **through media closer to the general population and for policymakers**, and **a specific plan for the training of the PhD student.** A full description of these goals can be found in Sections 4 (scientific-technical impact), 5 (social and economic impact), and 6 (training capacity and FPI formation) of this report, following the instructions for writing this report.

IP in charge: *R Nieto*

3.2 Methodology and work plan

WP1 (Computation): The dynamic downscaling experiment uses the WRF v3.8.1 model (Skamarock et al., 2008), which is forced with the output of the CMIP6 GCMs with three sets of simulations of the historical climatic conditions (1994-2014) and the conditions for the middle and end of the century (2040-2060 and 2080-2100). The climate models CESM2, NorESM2-LM, and CNRM-ESM2-1 (Eyring et al. 2016 for a review of models performance) will be used as input data for the WRF model. In addition, the current conditions will be simulated using WRF forces with the reanalysis of ERA5 (Hersbach et al., 2020). Simulations will be performed for two configurations, the first centred on the North Atlantic Ocean and the second in Central America using two nested domains of 30 and 10 km of spatial resolution (see Figure 4a,c). The high-resolution outputs of the CMIP6 GCMs (HR-CMIP6) will be evaluated to compare the results with those of the HR-ERA5 reanalysis. This analysis will be for the variables involved in moisture transport, such as zonal and meridional wind, humidity, and water content in the vertical column for the two study regions. Subsequently, we will apply bias correction to the HR-CMIP6 mean states to HR-ERA5 using the methodology proposed by Bruyere et al. (2015).

Moreover, the parameterisations used in the WRF-ARW (ARW dynamic core) configuration for the domain over the North Atlantic are as follows: the WSM6 microphysics scheme (Hong & Lim, 2006), the Yonsei University PBL scheme (Hong et al., 2006), the Revised MM5 surface layer scheme (Jimenez et al., 2012), the United Noah Land Surface Model (Tewari et al., 2004), the RRTMG shortwave and longwave schemes (Iacono et al., 2008), and the Kain-Fritsch Ensemble cumulus scheme (Kain, 2004). For the Central American domain, the same surface layer, land surface, PBL, and cumulus schemes will be used as for the previous domain. However, the WSM3 microphysics (Hong et al., 2004) scheme will be used, and for shortwave and longwave Goddard (Tao & Simpson) and RRTM (Mlawer et al., 1997) will be used, respectively. Spectral nudging of waves longer than approximately 1000 km is activated to avoid distortion of the large-scale circulation within the regional model domain because of the interaction between the model's solution and the lateral boundary conditions (Miguez-Macho et al., 2004). For the WRF-ARW simulations, a three-month spin-up will be performed before the period to be simulated, and then the restart mode will be used when the WRF-ARW stops.

Likewise, the FLEXPART-WRF model (Version 3.3.2; Brioude et al., 2013) will be forced with the WRF-ARW output (HR-ERA5 and HR-CMIP6) every 6 h. We will use Hanna's scheme for turbulence parameterisation with the convection scheme activated. This scheme is based on boundary layer parameters PBL height, Monin–Obukhov length, convective velocity scale, roughness length, and friction velocity (Brioude et al., 2013). We assumed a skewed rather than Gaussian turbulence in the convective planetary boundary layer. The FLEXPART-WRF domains (~ 10 km) for each study region are shown in red in Figure 4a,c.

This dynamic downscaling methodology can be carried out considering the current computational requirements of the CESGA. Two tests were conducted for a month for the two nested domains; these are presented in Figure 4a,c with the SSP5-8.5 scenario and historical data for 2014. The main moisture sources for the Iberian Peninsula (IP) and Central America were correctly represented (see Figure 4b,d). In this example, the CESM2 climate model was used. Currently, historical period simulations are being carried out for both configurations and will be ready before the beginning of the project. Once the project has started, the simulations will be carried out using climatic scenarios for the North Atlantic region, then for Central America region. Additionally, the calculation time required for a year was evaluated for a different number of calculation nodes (24 CPUs per node): 12 (~ 8.5 days) and 20 (~ 6 days). Importantly, to complete all the proposed periods, simulations of 10 years will be carried out at the same time in the current accounts that we have at CESGA. Based on this approach, **144 computing days** are required to perform the simulations for each region. It is important to note that it is necessary to store the outputs of both configurations for all periods that will be used at approximately **480 T**.

The specific working plan proposed for WP1 is distributed in **nine tasks (T)** as follows:

T1.1 Perform high-resolution simulations with the WRF model for the current climate from ERA5 reanalysis for two configurations centred on the North Atlantic Ocean and Central America. **T1.2** Perform simulations with the FLEXPART-WRF model using the HR-ERA5 WRF outputs from T1.1.

T1.3 Evaluate the three CMIP6 CGCMs to be used to force the WRF model with respect to the ERA5 reanalysis for the variables involved in moisture transport (zonal and meridional wind, humidity, and vertical water content) in the two study regions. **T1.4** Apply a bias correction of the mean states of the CMIP6 CGCMs to ERA5. **T1.5** Generate the CESM2 intermediate files that will be used as the initial and boundary conditions to force the WRF. **T1.6** Perform high-resolution simulations with the WRF model using CMIP6 outputs for the historical period. **T1.7** Idem as T1.6, but for CMIP6, future scenarios and periods. **T1.8** Perform simulations with the FLEXPART-WRF model using the HR-CMIP6 WRF outputs with input data from T1.6 **T1.9** Idem as T.1.8. but for data from T1.7

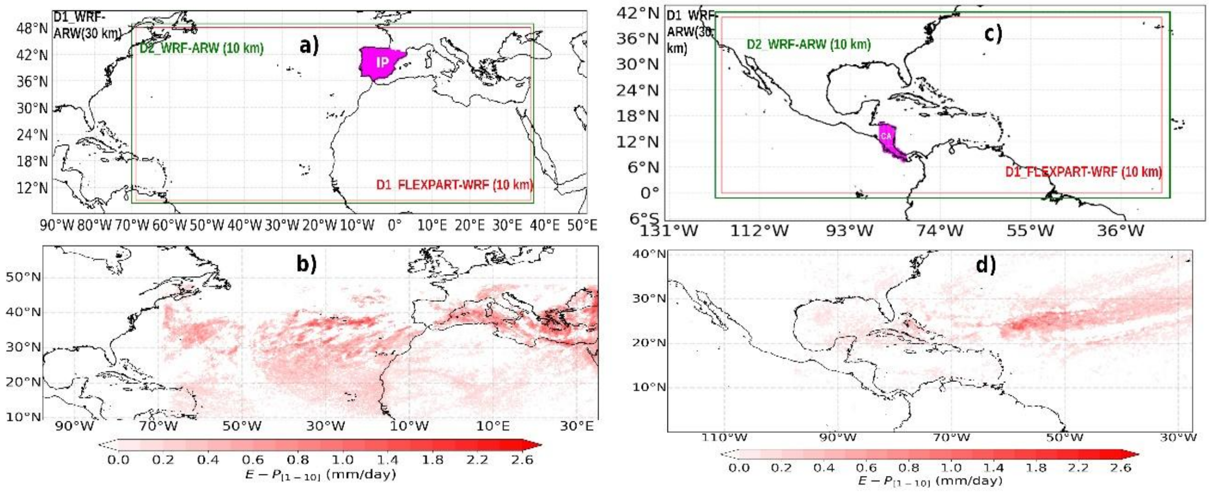


Figure 4. a,c) Domains for WRF-ARW [30 (10) km] and FLEXPART-WRF (10 km) corresponding to the areas of (a) the North Atlantic, and (c) Central America. b,d) Moisture sources (E-P>0 field, see methodology WP2) for 2014 using our high-resolution WRF-ARW outpus HR-CMIP6 CESM2 for b) the Iberian Peninsula (IP, in magenta), and for Central America (CA, in magenta) determined from backward tracking by FLEXPART-WRF.

WP2 (Sources and Sinks): To identify and analyse the moisture sources and sinks for the North Atlantic domains, the FLEXPART-WRF model (Brioude et al., 2013) will be used fed by HR-ERA5 and HR-CMIP6 datasets. The FLEXPART-WRF model allows the retention of the particles' positions along their trajectories, as well as their specific humidity (q) (Stohl and James, 2004; 2005). From these data, it is possible to address the moisture variation suffered by each particle using the equation $e\text{-}p = m\, dq/dt$, where e and p are the evaporation and precipitation processes, q is the specific humidity, m is particle mass, and t is time. The first step in this WP is to characterise the sources and sinks for specific regions in the North Atlantic region. This will be performed for the historical period (1994-2014) and for different emission scenarios described in WP1 for the periods 2040-2060 and 2080-2100. To find the sources and sinks for a selected target region, the moisture contribution (e-p) from all the particles over each grid cell (with a horizontal resolution of 0.5°) will be added to obtain the total atmospheric moisture budget (E-P) where E and P are the rates of evaporation and precipitation, respectively. The model has two different modes which allow the trajectories to be followed backward and forward in time to identify sources (E-P>0 values) and sinks (E-P<0 values), respectively. Good examples with further explanations of the method to identify sources and sinks can be found in Gimeno et al. (2010a, 2010b).

The second methodological block is analysing extreme precipitation events associated with the different emission scenarios. For this, both deficit and excess precipitation will be analysed. Excess precipitation events will be defined by considering some of the extreme indices defined by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (Peterson, 2005). Some of the indices used in this WP account heavy/very-heavy precipitation days (precipitation > 10/20 mm/day) or precipitation fraction due to very/extremely wet days (> 95/99th percentile). On the other hand, the deficit of precipitation (droughts) events will be defined considering the Standardised Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) and/or the Standardised Precipitation Index (SPI) (McKee et al., 1993). SPI is a simplified index that only considers precipitation in its computation; however, it allows to consider the different timescales and the spatial scale at which drought occurs and propagates. As an advantage over the SPI, the SPEI also considers the atmospheric evaporative demand for the estimation of dry conditions, which combined with the multiscalar nature of the index, allows for the assessment of the drought response of different ecological, hydrological, and agricultural systems. Both methodologies have been widely used for drought characterisation in different studies (e.g. Li et al., 2020). The extreme precipitation events over the North Atlantic sector will be defined by the methodologies previously described, and the influence of the moisture sources on their occurrence, as well as the variation for the different emission scenarios, will be analysed.

The specific working plan proposed for WP2 is distributed in **eight tasks (T)** as follows:

T2.1 Computation of the climatological characteristics (position, extension, etc.) of the major moisture sources in the North Atlantic Ocean (NATL, MEXCAR, and MED) for the HR-ERA5 current period from WRF simulations from WP1 T1.1. **T2.2** Idem as T2.1 using data obtained in WP1 T1.6 for the historical period of HR-CMIP6 future climate models. **T2.3** Evaluation of the differences between the sources in T2.1 and T2.2 **T2.4** Determination of the NATL, MEXCAR, and MED moisture contribution for precipitation over surrounding continental areas (e.g. North America, Central America, the Caribbean region, and Europe) using FLEXPART-WRF simulations from WP1 T1.2 in the current period. **T2.5** Idem as Task 2.4 but for the historical data from WP1 T1.8 **T2.6** Idem as T2.5, but for HR future climate data from WP1 T1.9 **T2.7** Evaluation of changes in the role of moisture transport in the occurrence and intensity of extreme precipitation events and floods in the continental regions found in T2.1. **T2.8** Idem as T2.7, but for drought events (analysing changes in occurrence, severity, and duration).

WP3 (Mechanisms): ARs and LLJs can be detected using automated algorithms. In WP3, we will use two different detection algorithms—one for ARs and one for the LLJs—to detect both systems over our region of study for the largest time period available. The first step is the selection of algorithms that will best fulfil their function. These algorithms will be selected from among those available in the literature (e.g. Shields et al., 2018; Algarra et al., 2019) based on efficiency criteria. Once the detection algorithms have been selected, they will be computed on present and future climate data with a 6h time resolution.

The detection algorithms will also be applied to HR-ERA5 to gain a better understanding of the present climate in terms of intensity, frequency, phenomenological characteristics, and the identification of the atmospheric dynamics and physical mechanisms controlling the life cycle of ARs and LLJs in the present climate. The detection algorithms will also be used in the historical runs from our HR-CMIP6 outputs, and the results will be compared to those obtained from HR-ERA5. This methodology will provide us with information on the ability of HR-CMIP6 simulations to detect the main characteristics of ARs and LLJs, such as frequency, intensity, geometry, and seasonal variability.

These results will then be compared with those obtained for the future climate using the HR-CMIP6 outputs for different scenarios. In particular, we will detect changes in intensity, frequency, seasonality, or regions of higher incidence.

The specific working plan proposed for WP3 is distributed in **six tasks (T)** as follows:

T3.1 Objective selection of detection algorithms. **T3.2** Application of the algorithms to HR-ERA5 outputs. **T3.3** Application of the algorithm to HR-CMIP6 historical outputs **T3.4** Objective statistical intercomparison between the results obtained from T3.2 and T3.3. **T3.5** Application of the algorithms to HR-CMIP6 future climate output outputs under different scenarios. **T3.6** Objective statistical intercomparison between the results obtained from T3.4 and T3.5.

WP4 (IVT-extreme precipitation dependence): Daily Precipitation and IVT data will be obtained at 10 km resolution from the simulations described in WP1 for historical climatic conditions (1994-2014) and the conditions for the middle and end of the century (2040-2060 and 2080-2100). The dependence between daily precipitation and IVT for different periods and scenarios will be assessed using a copula approach. Copulas are very popular for modelling the dependence structure of a pair of environmental variables (e.g. Cong & Brady, 2012; Reddy & Ganguli, 2012; Zscheischler & Seneviratne, 2017; Lazoglou & Anagnostopoulou, 2019). A comprehensive description of this theory is provided by Nelsen (2006). Our analysis will be carried out at each point on a global grid separately for each season. Several copula models will be fitted to model the joint distribution of the pair (precipitation, IVT). At each analysed point, the best copula model will be used to estimate the probability of a concurrent extreme of the two variables. Furthermore, within the sample of observed concurrent extremes for each period and scenario, the proportion of days with ARs and LLJs (as estimated in WP3) will also be calculated.

Next, we will use copulas to carefully analyse the dependence between daily precipitation and IVT averaged over the main regions of landfalling ARs (Figure 3b) and moisture sinks of major LLJs, using means of three metrics: **a)** The estimated probability of achieving a concurrent extreme of precipitation and IVT, **b)** The estimated conditional probability of precipitation exceeding its corresponding 90th percentile, for a value of IVT equal to 250 kg m^{-1}. This value represents a threshold commonly used to identify ARs (e.g., Ralph et al., 2019; Eiras-Barca et al., 2021), **c)** The estimated value of IVT for which the probability of precipitation exceeding its corresponding 90th percentile equals 0.5.

The specific working plan proposed for WP4 is distributed in **nine tasks (T)** as follows:

T4.1 IVT-P copula fit for HR-ERA5 outputs. **T4.2** Estimation of the probability IVT-P concurrent extremes for HR-ERA5 outputs **T4.3** Estimation of the three metrics described below for HR-ERA5 outputs **T4.4** IVT-P copula fit for historical HR-CMIP6 outputs. **T4.5** Estimation of the probability of IVT-P concurrent extremes for historical HR-CMIP6 outputs **T4.6** Estimation of the three metrics described below for historical HR-CMIP6 outputs. **T4.7** IVT-P copula fit for the different scenarios considered in the HR-CMIP6 outputs. **T4.8** Estimation of the probability of IVT-P concurrent extremes for the different scenarios considered in the HR-CMIP6 outputs. **T4.9** Estimation of the three metrics described below for the different scenarios considered in the HR-CMIP6 outputs.

WP5 (residence times): Different metrics of WVRT will be used according to the box below (Box 1) taken from Gimeno et al. (2021). In this work, we will estimate the *Depletion time constants (DTC)*, using an Eulerian approach, and *Lifetimes (LT)* and *Lifetime distribution (LTD)*, using a Lagrangian approach following the methodology described by Läderach & Sodemann (2016). The calculations will be carried out for both the historical series of the HR-CMIP6 and for the available period of HR-ERA5. This methodology will allow the determination of the capacity of the HR-CMIP6 CGCMs to correctly estimate WVRT based on different metrics. Subsequently, the metrics will be applied to HR-CMIP6 future climate data, allowing us to project changes in WVRT both globally and regionally, for the different scenarios considered.

The specific working plan proposed for WP5 is distributed in **five tasks (T)** as follows:

T5.1 Estimation of DTC, LT, and LTD for ERA5 outputs. **T5.2** Estimation of DTC, LT, and LTD for historical CMIP6 outputs. **T5.3** Objective intercomparison between the results obtained from T5.1 and T5.2. **T5.4** Estimation of DTC, LT, and LTD for different scenarios considered in the CMIP6 outputs. **T5.5** Objective intercomparison between results obtained in T5.3 and T5.4.

Box 1 | Defining water vapor residence time (WVRT)

The quantification of water vapour residence time has traditionally relied on different metrics that can result in contrasting estimates. The most common metrics used are:

Turnover time (TUT): bulk mean age of the outflow from a reservoir. For the atmosphere, TUT equals the global average mean age of precipitation. It can be calculated as TUT = W/P, where W is precipitable water (or water vapor) and P is precipitation.
Depletion time constant (DTC): the local calculation of W/P. Values might vary substantially from TUT, but the global precipitation weighted average is equal to TUT.
AGE: the average age of water in the atmosphere since evaporation, which can differ from precipitation age. There are indications that heterogeneity causes the global average storage weighted AGE to be slightly higher than TUT.
Backward transit time (BTT) or lifetime: the time that a precipitated water particle spends in the atmosphere.
Lifetime distribution (LTD): the probability density function of all lifetimes of BTT in a specific region globally. The global precipitation weighted average of LTD is equal to TUT.
Forward transit time (FTT): the time that an evaporated water particle will spend in the atmosphere. In principle, BTT of a water particle at the sink locations is the same as FTT of that water particle at the source location. Hence, FTT is, on average, identical to BTT or lifetime, but with different regional patterns. FTT is heavily influenced by the type of land use.

WP6 (Diffusion and Formation): The specific working plan proposed for WP6 is distributed in **nine tasks (T)** as follows:

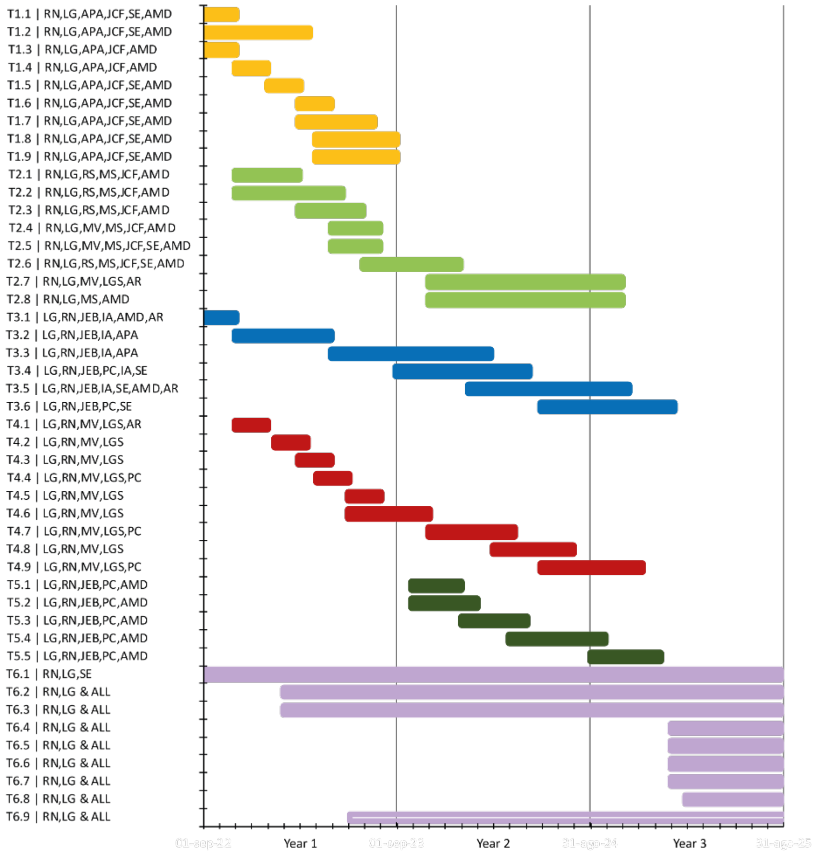
T6.1 Elaboration and maintenance of a project web page. **T6.2** Presentation of results in international conferences **T6.3** Publication of results in SCI journals. **T6.4** Workshop and summary book or review paper **T6.5** Elaboration of material and its dissemination to school or high school students as well as to the public more generally. **T6.7** Elaboration and dissemination of materials for different socioeconomic users **T6.8** Writing a report for policymakers. **T6.9** Supervision of the PhD work linked to the project.

3.3 Chronogram and tasks distribution by participant

The team is multidisciplinary (Meteorology and Hydrology) composed of **two leading professors** (PIs): **Raquel Nieto** (RN) and **Luis Gimeno** (LG) who will lead WPs and their associated Tasks; and 8 researchers who are added in the WPs: 4 post-doct researchers: **J Eiras-Barca** (JEB), **M Vázquez** (MV), **R Sorí** (RS) and **M Stojanovic** (MS)), and 4 pre-doct students: **A. Perez-Alarcón** (APA), **JC Fernandez** (JCF), **L Gimeno-Sotelo** (LGS) and **P Coll** (PC), all of whom belong to the UVigo with extensive research experience, having published over 200 papers in SCI journals in the last 15 years, including invited papers on the topic (see page 2). The team will have the support of **international experts** in different themes related to the project: two meteorologist and climatologist, **Ana M Durán-Quesada** (AMD, Univ. Costa Rica) and **Alexandre M. Ramos** (AR, Univ. Lisbon), who are experts in tropical dynamics and moisture transport, and in extreme events and ARs, respectively, and they will help in the WP.

Expertise and complementarity of the research team: Role (and need) of the people to contract:
Technical staff (SE): The project will use a high volume of data and models, and the tech. staff will be responsible for handling the large amount of data that will be generated and for the installation of the necessary software that will arise during the project. Software adaptation and the management of sophisticated visualisation tools require qualified and dedicated personnel. Articles in multidisciplinary

journals require the use of very high-level figures. The use of these high-level outputs will be one of the strong points of a successful submission.



***RN: Raquel Nieto** -> leading WP1, WP2 & WP6 with associated Tasks*

***LG: Luis Gimeno** -> leading WP3, WP4 & WP5 with associated Tasks*

3.4 Available resources

The **EphysLab-UVigo** research group **has the basic infrastructure to develop simulations and store part of the data** used and generated during the project. There is a data processing centre (monkey-island) where the necessary programs to process data and perform statistical analysis are installed (IDL, MatLab, R, Python, C++). Additional programs can be installed if required throughout the project.

The Monkey-Island has the following characteristics: **GPU servers:** - Supermicro 7047; CPU: 2x Intel Xeon E5-2640 at 2GHz (16 cores); GPU: 4x Nvidia Titan (6GB); RAM: 64GB; Storage: 9TB. - Supermicro 7046GT-TRF; CPU: 2x Intel Xeon E5620 at 2.4GHz (8 cores); GPU: 3x Nvidia Titan (6GB) 1x Nvidia Tesla K20 (5GB); RAM: 16GB; Storage: 15TB. - Supermicro 6016GT-TF-TM2; CPU: 2x Intel X5550 at 2.66GHz (8 cores); GPU: 1x Nvidia Tesla M1060 (4GB) 1x Nvidia GTX480 (1.5GB); RAM: 8GB; Storage: 3TB. **CPU servers:** - Supermicro AS2042G-6RF; CPU: 4x AMD Opteron 6174 at 2.2GHz (48 cores); RAM: 64GB; Storage: 16TB. - Supermicro 1012g-mtf; CPU: 2x AMD Opteron 6128; RAM: 8GB; Storage: 3TB. - 2x HP Proliant DL180G5; CPU: 2x IntelXeonE5405 2GHz (8 cores); RAM: 8GB; Storage: 1.5TB. - SGI Altix450; CPU: 4x Intel Itanium 9140 1.66GHz (8 cores); RAM:64GB; Storage: 16TB. - HP BladeSystem c7000 (2x blades); CPU: 1x Intel Xeon E5320 at 1.86GHz (4 cores); RAM: 6GB; Storage: 64GB + 1.5TB (Shared). **Backup system:** -Tape loader: HP StorageWorks 18 G2 (LTO-4). **Additional resources:** - UPS: APC SURT8000RMXLI RT (8KVA); Refrigeration system: Hitachi RAS-60 YHS (6.5KW).

Additionally, researchers from **EPhysLab have access to the Galicia Supercomputing Center (CESGA),** the so-called **Finis Terrae II**, where version 3.8.1 of the Weather Research and Forecasting (WRF) model is installed, as well as the necessary post-processing programs based on Python and NCL (NCAR Command Language). The CESGA has advanced infrastructures destined to increase the research and technological capacity of the scientific community, with **computing servers** of different architectures to allow the researcher to always choose the architecture most suitable for their calculation needs. Notably, the CESGA allows us to perform the simulations, but the outputs of the simulations must be stored on the EPhysLab servers due to limited storage capacity. Few details about its characteristics: Finis Terrae II is a computing system based on Intel Haswell processors and interconnected by

Infiniband network with a peak performance of 328 Tflops and sustained in Linpack of 213 Tflops. It is composed of three types of computing nodes: - 306 CPU nodes "Thin": 2 CPUs Haswell 2680v3, 24 cores; RAM: 128 GB; Storage: 1 TB. - 4 GPU nodes: 2 GPUs NVIDIA Tesla K80; 2 CPUs Haswell 2680v3, 24 cores; RAM: 128 GB; Storage: 2 HDD of 1 TB. - 1 GPU node: 1 GPUs NVIDIA Tesla V100 PCIe; 2 CPUs Haswell 2680v3, 24 cores; RAM: 128 GB; Storage: 2 HDD of 1 TB.

3.4 Contingency Plan

The project was designed to be carried out with currently available computational resources; therefore, no deviations from the planned objectives and times are expected. However, if negative or positive situations occur, we may act as follows:

Negative Scenario: If more computation time than the estimate is required to perform the simulations, some technical problems occur in the CESGA cluster or the project is not fully funded to acquire the storage capacity needed to save the models outputs, making it unfeasible to perform the experiments as previously described, we would proceed as follows. FIRST: Simulations will be carried out first for the SSP5-8.5 scenario in the 2080-2100 period and then for the 2040-2060 period. SECOND: The simulations for the SSP2-4.5 scenario will be carried out for the end (2080-2100) and the middle of the century (2040-2060). THIRD: Similarly, the simulations were prioritised using the CESM2 model as the WRF input, the NorESM2-LM, and finally the CNRM-ESM2-1.

Positive scenario: We will apply for the 2022 call for proposal "RES Data Management Services," demanding both computing time and storage. If the proposal is granted, we will extend the research to other three or five CMIP-6 GCMs. The models that will be used IPSL-CM6A-LR, MRI-ESM2-0, IPSL-CM6A-LR, CNRM-CM6-1, and IPSL-CM6A-LR.

4. IMPACTO CIENTÍFICO-TÉCNICO – *SCIENTIFIC-TECHNICAL IMPACT*

The chapter 8 "Water Cycle Changes" of the new IPCC AR6 WGI report (Douville et al, 2021) concludes, concerning projections:

1. Without large-scale reduction in greenhouse gas emissions, global warming is projected to **cause substantial changes in the water cycle** at both global and regional scales (*high confidence*).

2. **Water cycle** variability and **extremes are projected to increase faster than average changes** in most regions of the world and under all emission scenarios (*high confidence).*

3. **Precipitation** associated with extratropical storms and **atmospheric rivers will increase** in the future in most regions (*high confidence*). **North American monsoon precipitation** is projected to **decrease** (*medium confidence*).

4. The representation of key physical processes has improved in GCMs, but they are still limited in their abilities to simulate all aspects of the present-day water cycle and to agree on future changes (*high confidence*). **Climate change studies benefit** from sampling the full distribution of model outputs when considering **future projections at regional scales**.

Furthermore, concerning **the role of moisture transport,** the report concludes:

1. At regional scales smaller than ~4000 km, **water cycle changes become dominated by the transport of moisture** (*high confidence*).

2. Human-caused global warming has led to an **overall increase** in water vapour and **moisture transport** throughout the troposphere since the mid-1990s (*high confidence*).

3. While projections of water vapour are well understood owing to the constraints of the Clausius-Clapeyron relationship**, projections of water vapour transport are complicated regionally** by the role of changes in the wind field, which is influenced by a wide variety of factors.

4. There has been relatively little general evaluation of moisture transport in models. In the CMIP5 models, both the mean and variability of vertically integrated **moisture transport are projected to increase**, largely due to increases in water vapour with substantial regional differences.

5. In general, there will be increases in moisture transport into storm systems, monsoons, and high latitudes (*medium confidence*).

In summary, *the report identifies moisture transport as the dominant factor for changes in the hydrological cycle, with higher impacts on extremes rather than on averages; moisture transport has increased with climate change and is expected to further increase in this century; this increase is mainly linked to major modes of moisture transport such as atmospheric rivers; global climate models are limited and need regional modelling.* **These objectives are outlined in our proposal.**

This section will also summarises the **dissemination activities** for disclosure of the project results, including scientific and communication activities. Scientific dissemination will be carried out to disclose the results of the project through traditional communication channels, such as the *publication of articles in professional journals (mainly open-access), presentations at related international conferences and seminars, and attendance at workshops.* The plan is to publish the results in high-impact journals in the fields of hydrology, meteorology, and climate research, such as WRR, Climate Change, GRL, J. Climate, or JGR, as is usual for the applicant group. The most relevant and important results will be submitted for publication in high-impact multidisciplinary journals, such as Nature or Science. To ensure the visibility and awareness of the results outside the project members, the team will be in communication with other research teams and special attention will be paid to the transfer of our results to other international collaborative projects. Short-term institutional visits will be made to exchange project results in European and global research networks. We will attend several international conferences, such as the annual meeting of AGU, EGU, or AMS to share our results internationally. A *final workshop and a book* by a prestigious editor (Elsevier, Springer, Cambridge University Press) will serve as a summary of the project. A *dedicated web page* will be devoted to updates on activities, results, and interface with data and software.

5. IMPACTO SOCIAL Y ECONÓMICO - *SOCIAL AND ECONOMIC IMPACT*

The study of moisture transport provides a fundamental understanding of observed changes in average and extreme precipitation, with physical evidence to support the many available projections of future climates. Thus, **moisture transport is key to understanding the occurrence of precipitation extremes and droughts** (Gimeno et al., 2016; IPCC, 2021). The central objective of this project is to assess the moisture transport for future climates using CMIP6 outputs with increased resolution through dynamic models adjusted to the meteorology of the North Atlantic region. Changes in both extreme precipitation and droughts have tremendous impacts on ecosystems, large forests, agricultural practices, hydroelectric energy production, and even human health, largely impacting regional economies.

There is no doubt that the **risk of precipitation extremes is likely to increase with climate change**. The observed and projected frequency and intensity of extreme precipitation in some regions greatly influence the social economy. Many studies have quantified the socioeconomic impact of the increase in extreme precipitation, including the new IPCC report (2021), including its impact on vulnerable cities, ecosystems, large forests, agricultural practices, and hydroelectric energy production, but perhaps the most studied is its impact on leading to more intense and more frequent river floods. It is estimated that ***river flooding*** *would affect 250,000–400,000 additional people per year in Europe by the 2080s, with an increase in direct damage from river floods in the* ***2080s ranging from €7.7 billion to €15 billion***, more than doubling the annual average damage during the period 1961–1990.

Drought is considered one of the most far-reaching natural disasters, affecting approximately 55 million people every year and **causing severe socioeconomic and environmental impacts** (Vicente-Serrano et al., 2019), including more deaths and human displacements than any other natural hazard

(Salvador et al., 2020; UNDRR, 2021). The impact of drought episodes can be **even higher in future climates**. As an example, in a recent paper published in Nature Climate Change by the EU Joint Research Center it is shown that in Europe, ”in *the absence of climate action (4 °C in 2100 and no adaptation),* ***annual drought losses*** *in the European Union and United Kingdom combined are projected to rise to* ***more than €65 billion per year*** *compared with €9 billion per year currently, or two times larger when expressed relative to the size of the economy. Drought losses show the strongest rise in southern and western parts of Europe, where drought conditions at 4 °C could reduce regional agricultural economic output by 10%. With high warming, drought impacts will become a fraction of the current impacts in the northern and northeastern regions. Keeping global warming well below 2 °C would avoid most impacts in affected regions."*

These known impacts and their consequences, which severely affect society and its economy, and in the face of predictions under a changing climate, demand better knowledge of the behaviour of precipitation and drought extremes as well as the mechanisms that generate this vulnerability. More precise information will make it possible to distinguish the effects of impacts in the short, medium, and long term, and will be crucial for implementing early prevention and adaptation measures, reducing vulnerabilities, and mitigating potential risks.

The results of the project will be extended to society, potential stakeholders, and policymakers. For dissemination to be effective, it will be designed to target key audiences, which must evolve in parallel with the development of the project, covering its entire duration, and all partners will be involved. It will be done through a public project website, workshops, and training courses, writing reports, press releases, and complemented by online activities based around the project website, and through the main social platforms.

6. CAPACIDAD FORMATIVA - *TRAINING CAPACITY*

The FPI fellow will join the **Doctorate Program on Water, Sustainability and Development** (https://www.uvigo.gal/cursos/es/doctorado-del-agua/informacion/), an international PhD program linked to the **Campus of International Excellence of Water at Ourense**, coordinated by the UVigo, whose partners are the Polytechnic Institute of Porto (IPP) and the Univ. de Trás-os-Montes e Alto-Douro (UTAD) in Portugal. This program has a high-level training scheme and includes methodological courses by distinguished foreign researchers and theoretical and practical training. The program has three thematic research blocks: WATER, SUSTAINABILITY, and DEVELOPMENT. The FPI´s line will be "**Sustainability"** on **"Climate change and water resources"**. The topic of this project and the FPI research lines are clearly framed in the described PhD program. In this PhD program, candidates must meet certain training requirements to complete a total of 500 h of work in different activities, which can be carried out at UVigo or at external universities or research centres.

Formation: We will develop activities related to the project topic focused on FPI training as well as informative training courses for a less specialised audience. In addition to the development of the doctoral thesis, a doctoral candidate is requested to complete a series of training activities related to the PhD level. In addition to completion of the doctoral thesis, the training activities of the *PhD Programme in Water, Sustainability, and Development* will include the fulfilment of specific and cross-curricular training activities for a minimum of 500 h. Several cross-curricular training activities may be covered through courses offered by the International School of Doctorate (EIDO). However, the student can apply for the recognition of specific training activities related to the development of the doctoral thesis: published papers, participation in congresses or conferences, participation in research projects, research methodologies, and stays in other universities.

Examples of **TRAINING ACTIVITIES** that the FPI may attend are as follows: **1.- Water PhD Program Training activities related to the project topic:** Fundamentals of the hydrological cycle, Research methods in the diagnosis and modelling of the hydrological cycle. **2.- Scientific computer courses** [Python by CESGA, R course by CSIC, IDL and FLEXPART courses by EPhysLab], **3.- UVigo International Doctoral School courses:** www.uvigo.gal/uvigo_gl/centros/vigo/eido, **4.-International Schools and**

Seminars [among others, for example, the specialised course on Earth System Physics (ESP) of the ICTP in Trieste, Italy; COPERNICUS workshops (Europe's eyes on Earth); Summer Schools by the Bolin Centre], **5.- International congresses** (one or two per year, EGU, AGU, EMS, Hymex).**6.- International Research Stays (one per year):** The structure of the project, with several foreign research centres involved, will facilitate stays. The FPI is intended to carry out his/her PhD work linked transversely to all project activities, implying comprehensive and multidisciplinary training. For this purpose, one of the proposed mechanisms may be chosen, such as the ARs or LLJs, modifications in the transport of humidity linked to different climate change models, and the implications for continental precipitation. Two or three international stays of approximately two months each are planned, with

· **Dr. Alexandre Ramos** at **IDL University of Lisbon (Portugal)**: Climatologist. His work is focused on climate and meteorological diagnosis tools, especially on ARs and cyclones. The research by the FPI will focus on understanding the role of ARs in moisture transport under different configurations of climate change models and the consequences of precipitation patterns over climatological moisture sinks. Personal web: http://idl.campus.ciencias.ulisboa.pt/alexandre-ramos.

· **Dr. Ana María Durán-Quesada** at the **University of Costa Rica (Costa Rica)**: Climatologist. Her work focuses on understanding the role of surface processes play in modulating the thermodynamic profiles controlling energy transfer between the surface and the atmosphere as a key process for understanding climatic variability and change. The research by the FPI will focus on understanding the role of LLJ-associated moisture flow, interaction with complex surfaces, and the role of surface conditions in this interaction that lead to either drier or wetter conditions, combining modelling, observations, and physical proxies. Personal web: https://www.cigefi.ucr.ac.cr/es/node/44.

· **Dr. Francina Domínguez** from **Illinois University, USA:** Hydroclimatologist. Her work is focused on land-atmosphere interactions, and more specifically, on changes in hydrology and climate due to human modification of the land surface and greenhouse gas emissions. The two primary lines of her research look at land-atmosphere interaction from two perspectives: 1) the effect of climate variability and change, primarily extreme events, on surface hydrology and 2) the effect of changes in surface hydrology on climate. On the other hand, she is an expert in ARs, and Co-IP project of "ARs and Changing Flood Risk in the Pacific Coast Region of the Western USA" by NASA. Personal web: https://www.atmos.illinois.edu/people/francina/home.

The decompensation in project time and the scholarship would allow the **FPI student** to incorporate much of the software and data already processed, which would be an advance for his/her PhD work and would also allow him/her a post-project period in which the work could be expanded to analyses that arise in the development of the project that may not be described here. Thus, the **FPI student** would have a **work plan** similar to that detailed below (open to certain modifications) to analyse the mechanisms of moisture transport and to conduct an in-depth study of the consequences and response to climate change.

PhDs carried out (last 10 years) or in progress, and a brief description of their scientific/professional development:

[12] C. Salvador 2021 "Effects of drought on daily mortality in Iberian Peninsula: risks and vulnerability" by RNieto & CLinares. International PhD. Xunta Postdoc// **[11]** I. Algarra 2021 "Moisture transport associated with ARs and LLJs at global scale" by LGimeno & RNieto. International PhD. FPI & Margarita Salas// **[10]** S. Salvador 2019 "The Influence of International, EU, National and Regional Legislation in the Development of Offshore Wind Farms. The Case of Galicia (Spain)" by LGimeno & Sanz-Larruga. International PhD. Xunta Postdoc// **[9]** D. Ciric 2019 "Atmospheric moisture transport in major extreme precipitation episodes" by LGimeno & RNieto. Quality Engineer at Badin Soft, Serbia// **[8]** M. Stojanovic 2019 "The role of Atmospheric moisture transport in major drought episodes" by LGimeno & ADrumond. Xunta Postdoc// **[7]** R. Sorí 2018 "Atmospheric moisture transport and extremes in major river basins" by LGimeno & RNieto. International PhD. Xunta Postdoc// **[6]** M. Vázquez, 2018 "Oceanic Sources of precipitation: New research goals and directions from a Lagrangian approach" by LGimeno & RNieto. Xunta Postdoc// **[5]** AP. Ferreira 2018 "Water vapour stratification and dynamical warming behind the sharpness of the Earth's mid-latitude tropopause" by LGimeno & JHCastanheira.

UVigo Postdoc// **[4]** R. Castillo 2015 "Fuentes globales de humedad: caracterización y estudio de su variabilidad" by RNieto & LGimeno. Associate professor Univ. Costa Rica// **[3]** MM Gómez 2014 "Análisis de las fuentes de humedad en la cuenca Mediterránea en el periodo 1980-2000" by LGimeno & RGarcía-Herrera. Meteorologist Eltiempo.es// **[2]** AM Durán-Quesada 2012 "Sources of moisture for Central America based on a Lagrangian approach: variability, contributions to precipitation and transport mechanisms" by LGimeno & JAmador. International PhD. Full professor Univ. Costa Rica// **[1]** AM Ramos 2012 "Improving circulation weather type classification using a 3D framework: relationship with climate variability and projections for future climates" by LGimeno & NLorenzo. International PhD. Senior Postdoc Researcher Univ. Lisbon

PhD in course: **[5]** P Coll-Hidalgo 2024 "High-resolution modeling of extratropical storms that affected the Iberian Peninsula and their effect on offshore wind potential and extreme rainfall" by LGimeno & RNieto// **[4]** L Gimeno-Sotelo 2024 "Statistical dependence structures in the global hydrological cycle" by LGimeno// **[3]** JC Fernández-Álvarez 2023 "Study of the wind field seasonal coupling with the SST and the cryosphere using numerical simulations: implications for moisture transport, extreme precipitation and wind energy" by LGimeno & RNieto. International PhD. Predoc Xunta// **[2]** A Gonçalves 2022 "Variability of extreme weather events and influence on the renewable energy sector in Iberian Peninsula: wind energy" by RNieto & MLiberato. International PhD. Predoc FCT, Portugal// **[1]** A Perez-Alarcón 2022 "Modeling of moisture transport associated with tropical cyclones'' by LGimeno & RNieto. International PhD. Predoc UVigo.

7. CONDICIONES ESPECÍFICAS PARA LA EJECUCIÓN DE DETERMINADOS PROYECTOS – *SPECIFIC CONDITIONS FOR THE EXECUTION OF CERTAIN PROJECTS*

Not applicable

8. REFERENCES

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