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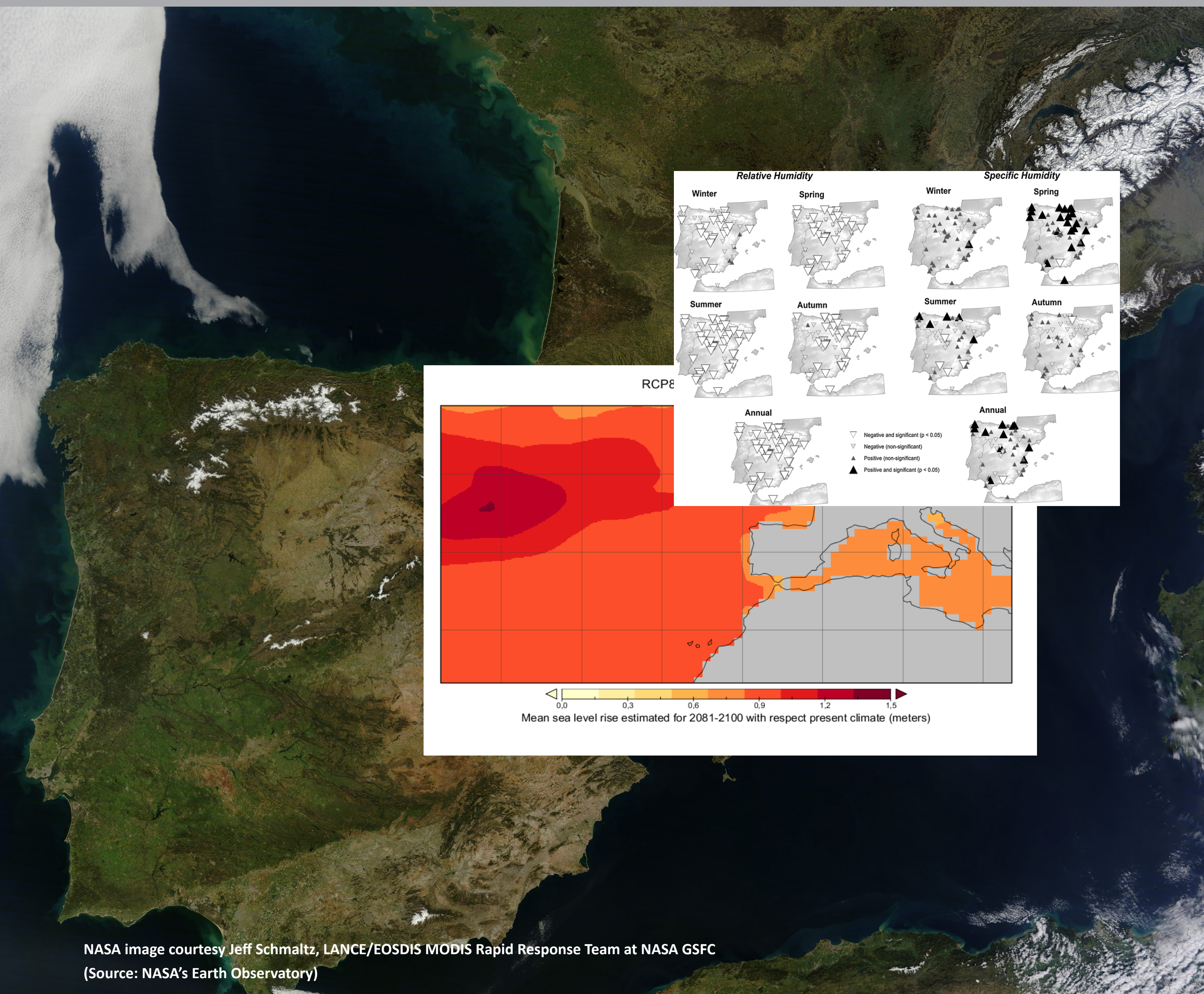

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CLIVAR Ocean and Climate: Variability, Predictability and Change is the World Climate Research Programme's core project on the Ocean-Atmosphere System

World Climate Research Programme

Progress in Detection and Projection of Climate Change in Spain since the 2010 CLIVAR-Spain regional climate change assessment report

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Introduction

The Iberian Peninsula region offers a challenging benchmark for climate variability studies for several reasons. It exhibits a wide variety of climatic regimes, ranging from wet Atlantic climates with annual precipitation around 2000 mm, to extensive semi-arid regions with severe hydrological stress, to even cold alpine environments in some isolated areas. This climatic diversity results from its latitudinal location at the northern edge of the subtropics, its complex topography punctuated by several important mountain chains, its peninsular nature, and the presence of two surrounding very different water masses: the Atlantic Ocean and the Mediterranean sea. The climate variety is reflected in large heterogeneities in the land-surface energy and water budgets and related exchanges with the atmosphere. Additionally, extreme events such as prolonged dry periods, heatwaves, heavy convective precipitation and floods are recurrent features. All these factors make comprehensive understanding and modelling of Iberian climate particularly challenging.

Like the rest of the Mediterranean region, and as stated in the last IPCC report (WG1AR5, Chapter 14, Christensen et al., 2013) the Iberian Peninsula is projected to be severely affected by large temperature increase and precipitation reduction, particularly in summer, and very likely more frequent heat waves. The prospect of strong negative impacts in an already vulnerable region emphasizes the need for thorough assessments of the current climate to better interpret climate projections, and increase our confidence in them.

Climate science developed slower in Spain if compared to some other European countries, but currently a large community of national researchers is involved in assessing the role of various processes, such as topography, natural modes of variability, teleconnections from the tropics, air-sea and land-sea interactions, in shaping those diverse regional climates and understanding how these may change under global warming. This task is aided by the existence of relatively long meteorological time-series and a dense network of stations — although regrettably not all data are publicly available to investigators.

Because many of the studies undertaken by the Spanish climate community fit in well with the main scientific objectives of the CLIVAR project, a network of scientists was created about 15 years ago with the goal of coordinating climate science in Spain, and increasing its international visibility. Roberta Boscolo at the time working for the International CLIVAR Project Office, was instrumental in promoting this effort. This led to the creation of the current CLIVAR-SPAIN scientific committee (www.clivar.es), that includes representatives from all the different fields related to CLIVAR science (meteorologists, atmospheric physicists, oceanographers and paleo scientists). The committee, with very little support from the national government, also strives to serve as a reference for the Spanish climate science community, a contact point with society and policy-makers, and a liaison with the international CLIVAR program.

The first tangible achievements of this committee were the organization of two national workshops in 2005 and 2009, both of which were followed by the publication of two assessment reports (available in English in the above webpage). While the first one, entitled "State of the art of the Spanish contribution to the Climate Variability and Predictability (CLIVAR) study", was intended to provide an overview of Spanish research groups involved in climate science, the second one, entitled "Climate in Spain: past, present and future. Regional climate change assessment report" was a comprehensive peer-reviewed regional climate assessment report, to which more than a hundred researchers contributed. It was the first coordinated effort to involve the entire Spanish climate community into a scientific endeavour to be made available nationally and internationally, as evidence of the vitality and relevance of Spanish climate science. We were proud to be able to present this report orally at the 18th session of the CLIVAR Scientific Steering Group in Paris (2011), and at the WCRP Open Science Conference held the same year in Denver via a cluster of posters.

After the publication of the last IPCC report in 2013, the CLIVAR-SPAIN committee decided that an update of that first regional assessment report was timely. With that in mind, a symposium was held in Tortosa in 2015 entitled "International Symposium CLIMATE-ES 2015: Progress on climate change detection and projections over Spain since the findings of the IPCC AR5" (http://www.climaes2015.urv.cat), with the support of various research institutions, including the Spanish Meteorological office (AEMET). The main goal of the symposium was to serve as a starting point for an updated assessment report. Subsequently, however, owing to lack of institutional funding, it was thought that a more viable option — and hopefully a more effective one — would be to present the results of the symposium via a special issue in CLIVAR Exchanges.

The following nine articles summarize the main findings presented at the Tortosa meeting. Each article deals with one of the topics of the symposium, namely: paleoclimate, climate time series, gridded datasets, atmospheric trends, teleconnections, oceanic variability, regional model assessment, regional atmospheric climate projections and oceanic projections (with projections for the Mediterranean and Atlantic treated separately). The structure resembles that of the first report but the emphasis is on updated results, advances in understanding, and new developments or research foci. The aim of this publication is to highlight the broad scope of ongoing national research focused on Spanish climate. For this reason, special attention has been paid to include as many research groups as possible, hoping that this issue may be used as a basis for finding Spanish scientists who specialize on particular topics.

Although the continued growth of Spanish climate science is evident, with an increasing number of contributions to international journals and individual participation in international projects and IPCC reports — a non-negligible feat in times of economic crisis and drastic science budget cuts —, we hope this special issue will also serve to demonstrate the capacity of the Spanish climate science community to work together in a coordinated effort. At the same time, we recognise that this special issue only partially describes national achievements of recent years.

We thank all the researchers that have contributed directly or indirectly to this issue, hoping that it will help to increase their international visibility and create awareness and recognition of their work. We also want to express our gratitude to all former members of the CLIVAR-SPAIN committee who, with their example and enthusiasm, paved the road and taught us that initiatives such as these are possible even without institutional support.

What follows is a brief summary of the main findings from each article.

1: Paleoclimate
The available marine and terrestrial climate reconstructions in the Iberian Peninsula for the last 2,000

years show the evidence of a complex spatial and temporal evolution for precipitation and temperature, with a pronounced spatial variability.

This replicates somehow the current climate variability in the Iberian Peninsula with a complex geography, led to a large presence of microclimates. However, the climate evolution of the Iberian Peninsula for the two last millennia can be divided in four main climate periods: the Roman Period, The Early Medieval Ages, the Medieval Climate Anomaly and the Little Ice Age, characterized by distinctive temperature and precipitation patterns. However, a larger effort must be conducted in order to obtain more robust and multiproxy climate reconstructions in areas where the geographical coverage is still low, such as the central Iberian Peninsula and northern marine areas. Furthermore, a better understanding of the decadal-to-centennial evolution of the main climate modes, specially the EA (Eastern Atlantic) and SCAND (Scandinavian), is of paramount importance, as well as their temporal interactions with each other, and with the total solar irradiance.

2-3: Instrumental reconstructions

In the last few years, a great effort has been carried out to improve the quality of the tools and atmospheric observations, including gridded datasets, used to analyse the climatic system from different points of view. In this sense, several initiatives and projects have emerged aiming to rescue and digitalize existing observational data, with special attention to regions with a poor spatial and/or temporal coverage, and to develop adequate tools and methods to elaborate high-quality datasets for climate analysis. Several regional and national gridded products have been developed in the last years for research purposes, covering a wide range of applications, resolutions, variables and time periods. However, the main shortcoming that should be pointed out is that most of the high-quality datasets developed at a local, regional or national scale in Spain are rarely shared in the climatological community leading to redundant analysis in many cases. On the other hand, there are not adequate intercomparison analyses between the different datasets developed.

4-5: Atmospheric variability and trends

Observations from the last decades reveal that there is a warmer and drier scenario in comparison to past decades, a finding that is compatible with observations in other Mediterranean areas. In particular there has been a strong solar radiation increase from the 1980s, in agreement with an increase in the atmospheric evaporative demand, mainly in summer months. Temperatures have showed strong increases since the 1960s. Nevertheless, no noticeable changes in surface wind speed have been found. Strong decrease in relative humidity with no significant changes in absolute humidity has been identified. Although strong spatial and seasonal variability in precipitation trends have been found, it may be in relation to changes in the global teleconnections. Average annual precipitation over Spain has showed a moderate decrease in the past five decades. Regarding teleconnections, relevant research has been developed in the last decades regarding predictability of NAO (North Atlantic Oscillation), showing increased skill with tropics and stratosphere. Future scenarios project an enhancement of the NAO along the seasonal cycle, with impacts also in sea level and upwelling (see articles on oceanic downscalling in this issue). Nevertheless, the spatial pattern of NAO has been found to be non-stationary, and dependent on the influence that ENSO (El Niño – Southern Oscillation) and the slowly variant oceanic background exert on the atmospheric variability. The Pacific and Atlantic Oceans, and the Mediterranean, the stratosphere, and tropical convection have been found to modulate teleconnection patterns affecting Europe. Taking into account this information, a great progress has been made in recent decades on the development of applications on seasonal to decadal (s2d) and subseasonal to seasonal (s2s) forecast. The availability of results from the Climate system Historical Forecasting Project (CHFP), and the Coupled Model Intercomparison Project (CMIP5), together with very active investigations in both operational and research communities, have improved our abilities to make skilful predictions and future projections.

The Barcelona Supercomputing Center and AEMET are the most important institutions leading this progress, and a significant step forward is being done by the Spanish research community in the context of the climate services.

6: Oceanic observations

Results confirm the impacts of global heating on the Ocean at the Iberian regional scale.

This report highlights the importance of routine water monitoring. Unfortunately, many financial sources have a limited time span, typically 3-4 years. It is also true, however, that many of the monitoring efforts on which the report is based, and that are currently maintained by the IEO (Instituto Español de Oceanografía) and other institutions (ports, universities, etc…), started through specific scientific projects. This is the case of IEO Observing System, and the Espartel monitoring station. Other monitoring stations started as voluntary initiatives at very low cost, e.g. the Hydrochanges network or some of the oldest coastal recording stations (Aquarium in San Sebastián or L'Estartit station). In all cases, their usefulness to follow the evolution of climate change in the years to come has already been proven, as well as for the study of the biological resources and their dependence on the physico-chemical variables, which are all crucial aspects to implement the EU Marine Framework Strategy.

Nevertheless, a more coordinated strategy that considers the overall capability of the observation system to detect climate change signals would be very welcome.

7-8: Atmospheric downscaling: present climate features and climate change projections

Many studies analysing regional climate models (RCMs) in present climate conditions on the Iberian Peninsula have been published since 2010. EURO- and Med-CORDEX or ENSEMBLES and ESCENA national project are the main ones during this period. The main conclusion of these studies is that RCMs over the Iberian Peninsula provide very valuable information, proving that RCMs enhance local spatial distribution of climate variables, mainly due to a better representation of orographic and surface features. RCMs are largely able to capture precipitation regimes, temperature and wind variability as well as extreme events. However, substantial biases are still observed, hindering the direct applicability of RCM outputs in sectorial applications (hydrology, agriculture and energy, for instance). This opens a controversial issue about RCM bias correction, or adjustment, and its impact on the climate change signal. Related to statistical downscaling procedures (SDM), these methods are shown to be a spatially consistent alternative to standard bias correction methods, although the limitation for extreme values should be taken with caution in applications where this aspect is relevant. Among the benefits of SDMs, it could be highlighted that they are less computationally demanding than the RCMs and allow downscaling non-meteorological variables.

Related to climate change regional atmospheric projections, from the large ensemble of downscaling methods shown in this issue of Exchanges, and taking into account all several uncertainties indicated, some global statements can be made. For precipitation, there is a general trend to decreasing average precipitation in all seasons, with an average decrease of 30% for RCM estimates. Regarding temperature, the largest increases are expected in summer and autumn, reaching close to 3^{o}C with respect to the 1971-2000 climatology in the upper end, and no less than 1^{o}C in the most conservative estimates. Some relevant issues are worth to be mentioned for regional climate change impact studies applications. Several bias correction/ adjustment methods have been developed in the past years, and several examples of specific usage and limitations which impacts studies over the region are shown. One current major focus of climate projections studies is the application of relevant climate change information for vulnerability, impact and adaptation research. Nevertheless, it is not already clear how to best proceed in order to select a subset of representative data for each particular study, since inconsistent or even conflicting information could be found. This is one of the key challenges considered in ongoing initiatives on climate change scientific research groups.

9: Oceanic downscaling: present climate features and climate change projections

A small reduction in the wave height and mean wave period has been found along both the Mediterranean and Atlantic coasts. In the Northeast Atlantic, sea level is projected to increase at a higher rate than the global mean value, although uncertainty is large. A temperature increase in the Atlantic is projected by all models although an AMOC (Atlantic Meridional Overturning Circulation) slowdown, also described in the article on Oceanic observations, may reduce heat advection towards the Northeast and modulate the warming. The projected general increase in upwelling will also affect the western margin of the Iberian Peninsula, counteracting the warming in a narrow band along the western Peninsula.

Concerning salinity, the increase in freshwater fluxes in high latitudes of the North Atlantic, and the increase in ice melting in Greenland, will likely result in a reduction in salinity in the Northeast Atlantic coast. Instead, evaporation-related freshwater loss will increase in the Mediterranean, causing an increase in salinity in this basin. However, injection of fresher waters from the Atlantic may partially counteract this process.

As for extreme events, although it is clear that the impact of marine storms will increase due to the general rise in the mean sea level, the evolution of storminess in southern Europe is not clear. Some results point towards a decrease in the overall number of storms but an increase in the most intense events, although the statistical significance of these changes is weak. The latest Intergovernmental Panel on Climate Change Assessment Report states that there is a high uncertainty associated with future winds and storms.

Concerning the sources of uncertainty of regional projections, the dominant factor in general is the Global Climate Model used to force the regional ocean model. Although temperature and sea-level scale linearly with increasing greenhouse gases concentrations, for salinity, storm surge and wind-waves the relation is not so robust.

A comprehensive overview of the last 2,000 years Iberian Peninsula climate history

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Introduction

The understanding of past multiannual-decadal climate variability in the Iberian Peninsula, and the long-term evolution of the main climate modes, can only be fully achieved if a large set of well resolved precipitation and temperature reconstructions are available. Such reconstructions can be obtained through a large array of proxies measured from different natural archives, like tree rings, lacustrine and marine sedimentary records, peatbog sequences and speleothems, among others. These climate reconstructions permit to characterize the main climate conditions and modes of climate variability at different geographical and time scales, and identify the stationary or non-stationary behaviour in the relationship of different climatic variables.

The Iberian Peninsula lies within two main climatic regions: Eurosiberian (north and northwest) characterized by wet and cold climate without a marked summer drought, and Mediterranean with a summer drought and relatively cool and wet winters. The complex geography of the Iberian Peninsula, with a central altiplano segmented and bounded by several mountain ranges exceeding 2,000 m of altitude and a relatively large coastal area, results in north-south and west-east gradient of decreasing precipitation and increasing temperature. Because of these interactions, multiple microclimatic regimes occur across the Iberian Peninsula with different spatial and temporal sensitivity to the main climate modes that rule its climate variability.

Multiannual-decadal evolution of the main Northern Hemisphere climate modes such as the North Atlantic Oscillation (NAO), Eastern Atlantic (EA) and Scandinavian (SCAND) is of paramount importance controlling the Iberian Peninsula climate, but the lack of long time view compromises our ability to forecast their evolution under the present global warming scenario. To reach this goal, we need robust and reliable datasets, obtained by both instrumental measurements and detailed Global Climate Models (GCM), but proxy records are our only measurements at long time-scales. Here, we present a comprehensive summary of the climate evolution of the Iberian Peninsula for the last 2,000 years through the integration of different sets of continental and marine climate reconstructions. Figure 1 shows the location of the main paleo-reconstructions available from the Iberian Peninsula for this time period, and those highlighted have been represented in Figure 2 as an example of the current available records. Climate fluctuations during the last two millennia represent the recent Holocene variability before the Global Warming (GW), and they include four main periods: the Roman Period (RP, ca. 250 BC – 500 CE), the Early Middle Ages (EMA, 500-900 CE), the Medieval Climate Anomaly (MCA, 900-1300 CE) and the Little Ice Age (LIA, 1300-1850 CE). In fact, the comparison of the RP and MCA with the GW period might provide a baseline to better evaluate the relative impact of both anthropogenic warming and the natural variability associated with the main climate modes by the end of the 21st century. Only well-dated sequences, with high temporal resolution and robust multi-proxy approaches can provide valuable information, but they need to cover complete latitudinal and altitudinal transects to fully capture the climate history of the multiple microclimatic regions in the Iberian Peninsula. A large number of continental and marine reconstructions are available, and several efforts have been carried out to summarize the climate evolution and trends in the Iberian Peninsula for the last two millennia with different temporal and spatial coverages (Morellón et al., 2012; Moreno et al., 2012; Cisneros et al., 2016; Sánchez-López et al., 2016; Abrantes et al., 2017) Nevertheless, there are still significant geographical gaps, such as the central areas of the Iberian Peninsula and the high-mountains, which hamper a more comprehensive picture of the climate evolution of the whole Iberian Peninsula during the last two millennia.

The Roman Period (ca. 250 BCE – 500 CE)

The available terrestrial and marine temperature reconstructions suggest relatively warm conditions during this period. Sea surface temperatures in records from both sides of the Iberian Peninsula, in the Atlantic margin and in the Balearic sector, show this as the

Figure 1: Map of the Iberian Peninsula (IP) with the location of the main records currently available for the last 2000 years. Blue dots indicate marine records, red dots represent lacustrine sequences, yellow dots are speleothems archives, and green dot corresponds to a peat bog. The location of the Figure 2 records are highlighted in bold and cursive.

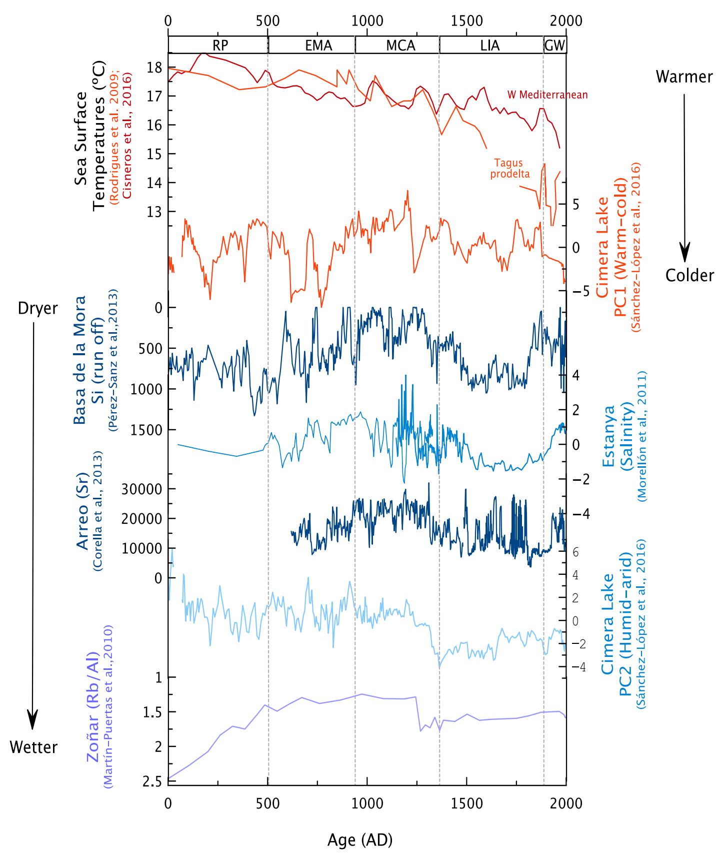

Figure 2: Selection of some of the available records that represent temperature and humidity changes along the IP. The source of the data is indicated in the figure

warmest interval of the last 2000 years (Abrantes et al. 2011, Cisneros et al., 2016). On land, a warming trend is detected on the Pyrenees (Pla and Catalan, 2005) whereas the central Iberian Peninsula was characterized by centennial-to-decadal scale alternation of cold and warm periods (Sánchez-López et al., 2016). In terms of humidity, the available records display a rather complex spatial pattern: while the northern Iberian Peninsula was dominated by arid conditions, the central Iberian Peninsula showed alternating humid and arid phases, and the more humid conditions prevailed in the southern Iberian Peninsula (Martín-Puertas et al., 2008; Morellón et al., 2012; Sánchez-López et al., 2016). Furthermore, the comparison between high-altitude and lowland sites underlines this complex hydrological pattern: high-altitude eastern Iberian Peninsula records reflect humid conditions, while western low-altitude sites indicate prevailing aridity (Morellón et al., 2011). These latitudinal and altitudinal humidity gradients might be related to regional precipitation variability, albeit the scarcity of records prevents the evaluation of the possible responsible climate processes.

The Early Middle Ages (500 – 900 CE)

This period was also characterized by a complex spatial climate pattern. While colder and humid conditions prevailed in the northwestern Iberian Peninsula (Jambrina-Enríquez et al., 2014), the eastern Iberian Peninsula showed generally more arid conditions, although with a larger hydrological heterogeneity. Evaporation/precipitation (E-P) ratio decreased in the Minorca Mediterranean area (Cisneros et al., 2016), consistent with the drier trend recorded in the central Pyrenees (Morellón et al., 2011; Perez Sanz et al., 2013), but with a high variability also detected in the central and southern Iberian Peninsula (Nieto-Moreno et al., 2011; Sánchez-López et al., 2016). However, some Pyrenean sites suggest higher precipitation than during the previous RP (Corella et al., 2013). Therefore, in terms of humidity, Atlantic versus Mediterranean gradients seem to be present, although the scarcity of robust climate reconstructions covering the Iberian Peninsula hampers a more precise characterization of these gradients. On the other hand, the thermal conditions for this period were more homogeneous for the entire Iberian Peninsula. Marine and terrestrial records generally show colder climate conditions, and a temperature decrease of about 1-2^{o}C has been reconstructed in the Minorca Mediterranean area (Cisneros et al., 2016).

The Medieval Climate Anomaly (900 – 1300 CE)

The larger number of climate records spanning this period and their better spatial distribution has allowed a better reconstruction of main climate conditions for the MCA (Moreno et al., 2012). Marine records from the northwestern Iberian Peninsula suggest that the first half of the MCA was dominated by warmer winters and cooler springs-falls with large storms, while during the second half warmer springs-falls and drier conditions dominated (Abrantes et al., 2017). Overall drier conditions occurred in the Minorca Mediterranean (Cisneros et al., 2016) and in the Alboran Sea (Nieto-Moreno et al., 2011). On land, dry conditions have been documented in the northern (Martín-Chivelet et al., 2011; Morellón et al., 2012), central (Sánchez-López et al., 2016) and southern Iberian Peninsula (Martín-Puertas et al., 2008). Some climate reconstructions in the Pyrenees display more humid conditions (Pla-Rabes and Catalan, 2011) or increased storminess (Corella et al., 2014), possibly related to local factors such as geographical location and orientation. In terms of thermal conditions on land, almost all climate reconstructions suggest warmer conditions in the entire Iberian Peninsula.

The Little Ice Age (1300 – 1850 CE)

The LIA represents the last cold spell before the onset of anthropogenic warming. Marine and terrestrial records show colder and more humid conditions, with a double structure. Records in the Minorca area suggest that the first thermal stage was characterized by warmer average temperatures with large sea surface temperature (SST) oscillations, while the second half was characterized by colder average SST with short-time oscillations (Cisneros et al., 2016). Northern and central Atlantic marine records also show a transition from warmer to colder conditions along the LIA but with an intense cooling trend of about 3ºC along the LIA (Abrantes et al., 2017). Alboran marine records show overall humid conditions with a decadal oscillation pattern (Martín-Puertas et al., 2010; Nieto-Moreno et al., 2011). Terrestrial climate reconstructions highlight that the overall climate of the Iberian Peninsula for that period were dominated by cold and humid conditions with decadal oscillations. Terrestrial records from northeastern Iberian Peninsula show more humid and colder conditions during the LIA compared to the previous periods. However, the timing and intensity of the changes show clear regional differences (Morellón et al., 2012; Corella et al., 2013; Pérez-Sanz et al., 2013). Some records indicate a higher lake level, particularly during the mid to late 19th century (Morellón et al., 2011). In the Lake Moncortés record, the onset of the LIA is characterized by the largest increase in late spring-summer heavy rainfalls between 1372 and 1452 CE, suggesting an anomalous frequency of high elevation cold air arrivals towards southern latitudes during summer (Corella et al., 2016). Considering the diverse resolution of the age models, coherence between periods of higher lake level and lower solar activity suggest a climatic control of lake paleohydrology at centennial scales. In the Central (Sánchez-López et al., 2016) and Iberian Range (Barreiro-Lostres et al., 2015), the reconstructed LIA climate conditions were cold and humid with an increase of extreme events during the LIA (Moreno et al., 2008). The presence and intensity of these decadal oscillations most probably is linked to the temporal resolution and sensitivity of the reconstruction.

The Global Warming (1850 CE – present day)

Instrumental meteorological records clearly show that the last 150 years have been characterized by a long-term temperature increase and precipitation decrease as a consequence of the anthropogenic activities (Bladé et al., 2010). The long-term aridity increase is visible in most of the available continental records of the Iberian Peninsula, while the marine ones, specially those located in the southern Iberian Peninsula, display an increase in humidity (Nieto-Moreno et al., 2011). With respect to the temperature, the continental records located in the lowlands agree with the instrumental meteorological records, and a clear trend towards warmer and more arid conditions are commonly seen. However, some high-altitude lakes (Sánchez-López et al., 2016) and Mediterranean marine records (Cisneros et al., 2016) display a marked temperature decrease, although marine records for the Gulf of Lions capture the instrumental global warming (Sicre et al., 2016). The scarcity of well resolved proxy records, and the appearance of several interferences from human activities during this time interval, still prevents any solid instrument-proxy data comparison, although several efforts are currently in development to achieve this goal.

Climate-forcing mechanisms

Several forcings have been commonly invoked to explain the climate variability reconstructed in the Iberian Peninsula for the last 2,000 years, mainly climate mode fluctuations, insolation changes, and volcanic forcing. The variability in the main climate modes, such as the NAO, are frequently cited to explain the centennial to millennial trends, and the changes in summer and winter insolation as main forcings for abrupt climate fluctuations. However, Comas-Bru and McDermott (2014) have highlighted that besides the role of a given climate mode, the interactions between them, and the spatial and temporal evolution of these interactions, are of paramount importance to explain the observed climate variability. The coupling and uncoupling of the NAO with other climate modes, such as the EA and SCAND, can lead to shifts in winter temperature and precipitation spatial patterns (Comas-Bru and McDermott, 2014). It can also lead to homogeneous or heterogeneous spatial distributions of the climate parameters as a result of the interaction of the NAO and EA with the same or opposite sign (Comas-Bru and McDermott, 2014; Bastos et al., 2016).

These climate mode interactions also affect the Iberian Peninsula. Hernández et al. (2015) evidenced that the winter precipitation of the Iberian Peninsula is mainly controlled by the NAO, while EA is mainly responsible for winter and summer temperature variability. Dominance of the positive (negative) phase of the NAO leads to decreases (increases) in the winter precipitation, while positive (negative) phase of the EA can cause higher (lower) winter and summer temperatures. The interaction of both climate modes during periods of opposite/similar signs could explain the occurrence of periods with temperature and humidity changes of opposite trends.

Sánchez-López et al. (2016) suggested that the sign of these climate modes as well as their interaction could explain the observed spatial and temporal climate variability in the Iberian Peninsula for the last 2,000 years. The humidity gradients in the RP and EMA periods would be the consequence of the predominant interaction of the NAO and EA climate modes during opposite sign phases (NAO$^+$ - EA$^-$ and NAO$^-$ - EA$^+$), while the homogeneous precipitation distribution that occurred during the MCA and LIA periods might be attributed to the interaction of both climate modes in the same sign (NAO$^+$ - EA$^+$ and NAO$^-$ - EA$^-$). Therefore, the main RP climate conditions would correspond to the NAO$^-$ - EA$^+$ dominance which led to wet and warm winters and warm summers, and the EMA would be ruled by the predominance of the NAO$^+$ - EA$^-$ interactions with dry and cold winters, and cold summers. On the other hand, MCA would be marked by the predominance of the NAO$^+$ - EA$^+$ interaction where dry and warm winters and warm summers, whilst the LIA climate conditions would be the consequence of the NAO$^-$ - EA$^-$ interactions, with humid and cold winters, and cold summers. Marine records located offshore Portugal suggest that the MCA climate conditions would also be marked by changes in the total solar irradiance, and the SCAND climate mode that might explain the observed strong increase in precipitation in northern Portugal and low SST in the south (Abrantes et al., 2017).

Conclusions

The available marine and terrestrial climate reconstructions in the Iberian Peninsula for the last 2,000 years show a complex spatial and temporal evolution for precipitation and temperature. With a pronounced spatial variability, somehow replicating the current climate variability in the Iberian Peninsula with a complex geography, it leads to a large presence of microclimates. However, the climate evolution of the Iberian Peninsula for the last two millennia can be divided in four main climate periods: the Roman Period, The Early Medieval Ages, the Medieval Climate Anomaly and the Little Ice Age characterized by distinctive temperature and precipitation patterns. The dominant climate conditions would be the result of the interaction of the main climate modes (NAO, EA and SCAND), as well as long- and short-term fluctuations in the summer and winter total insolation. However, a larger effort must be conducted in order to obtain more robust and multiproxy climate reconstructions in areas where the geographical coverage is still low, such as the central Iberian Peninsula, and northern marine areas. Furthermore, a better understanding of the decadal-to-centennial evolution of the main climate modes, specially the EA and SCAND, is of paramount importance, as well as their temporal interactions with each other, and with the total solar irradiance.

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Atmospheric Climatic observations and instrumental reconstructions over the Iberian Peninsula I: development of high-quality climatic time series.

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Introduction

Observational series are the basis for climate variability studies. They provide the raw material used to analyse local climates, build gridded products to assess regional or global climates and their changes, and calibrate global climate models. Great efforts have been made in the last decades to increase the number and quality of the climate measurements, but the technologies and observing practices have suffered relevant changes since the beginning of the instrumental era (mid-19th century) which, jointly with relocations and changes in the surrounding of the observatories, altered the properties of the observational records. Therefore, statistical methodologies must be applied to the raw series in order to homogenize them, i.e., to identify and remove the artificial biases from the real climatic signal. International initiatives have grown in the last decades to improve homogenization methods, develop new techniques or adapt the existing ones to new variables. For example, in the years 2007-2011 the COST Action ES0601 "Advances in homogenisation methods of climate series: an integrated approach (HOME)" put together the main European research groups to "achieve a general method for homogenizing climate and environmental datasets" (Venema et al., 2012). Further improvements of these techniques have reached enough skill to reliably remove most significant biases in the monthly series.

However, daily series have much more variability than their monthly aggregates, hence limiting the power of detection of inhomogeneities. Therefore, more refined statistical methods are needed, including the study of parallel measurements to provide corrections based on metrological studies (MeteoMet project: Merlone et al., 2015) or on models simulating the physics of the phenomena producing biases (Auchmann and Brönnimann, 2012).

Development of high-quality time series

In order to study climate variability, climatologists would like to have long-term observational series, free of errors and inhomogeneities. Therefore, efforts are needed to obtain longer time series, particularly via digitalization of data in weather books (data rescue), and careful attention must be paid to control their quality and homogeneity.

Data Rescue (DARE)

Data rescue involves a great deal of work: discovering observations in old documents (logs, paper strips and climate summaries), scanning or photographing them, inventorying, and digitizing data. Yet the scarcity of staff in many National Meteorological Services prevents these tasks from progressing at the desired speed. Apart from limited data rescue activities in several universities and governmental institutions, it is worth mentioning the efforts on early instrumental data recovery conducted under framework of the Salvà-Sinobas project (Domínguez-Castro et al., 2014), which digitized more than 100,000 meteorological observations made between 1780 and 1850, a period in which only two series were previously available. This data set contains measurements of air temperature, atmospheric pressure, wind direction and weather state from 16 sites in mainland Spain and Balearic Islands, most of them at a daily resolution. García et al. (2014) reconstructed the 1933-2013 global solar radiation time series from the Izaña Atmospheric Observatory (Tenerife, Canary Is.).

On-going projects are currently recovering and digitizing monthly values of precipitation and average extreme temperatures prior to 1950. There are other isolated data rescue efforts focused on particular stations, as those completing the series of Maò (Carreras, 2009), Barcelona (Prohom et al., 2016) and Oviedo (Mora and González, 2017).

Quality control and homogenization

The quality control of observations is a multi-phase task since it must be performed from the first time data are registered to their final storage in the operational database. Moreover, climatologists normally apply further quality controls before analysing the series, checking their spatial and internal consistency. These procedures are often implemented in the same software used to detect and correct inhomogeneities.

As after the successful COST Action ES0601, several homogenization packages have improved their performance, and with new ones emerging, additional comparisons of their skill must be undertaken. One of these efforts is being financed by the Spanish Ministry of Economy and Competitiveness through the project MULTITEST, which aims at improving the comparative tests made by Guijarro (2011). Their results are available at http://www.climatol.eu/MULTITEST/index.html

Some international projects are currently trying to take advantage of current homogenization methodologies to build a global air temperature dataset with an unprecedented quality and density of stations, especially the International Surface Temperature Initiative (http://www.surfacetemperatures.org/).

One of the main concerns about series homogeneity is related to the changes from manual to automatic stations. As these are difficult to detect with relative homogenization methods when all or most of the instruments in a network are replaced in a short period of time, the Parallel Observations Science Team (POST) is compiling a database with parallel measurements, in order to assess the impact of this overall instrumental changes (http://www.surfacetemperatures.org/databank/parallel_measurements).

Among the first efforts to build a quality controlled and homogenized long dataset was the compilation of SDATS (Brunet et al., 2006), which contains 22 Spanish timeseries of daily air temperatures (mean, maximum and minimum) from 1850 to 2005. This dataset has recently been reassessed and updated to 2014. In addition to preparing datasets in gridded format (see Herrera et al. in this volume), quality control and homogenization tasks have also been undertaken as a previous step in several climate variability studies:

- Vicente-Serrano et al. (2010) constructed a daily precipitation database for Northeast Spain using data from 3106 stations along 1901-2002. Data gaps were filled using values from nearest neighbor stations, and the homogeneity of the series was checked using the Standard Normal Homogeneity Test (SNHT; Alexandersson, 1986) with the help of the AnClim package (Štepánek, 2008a).
- In the same area, El Kenawy et al. (2011 and 2013) compiled daily extreme air temperature data from 1583 stations spanning portions of the 1900-2006 period. After filling missing data by linear regression, the series homogeneity was assessed by applying SNHT, Two-Phase regression and the Vincent tests.
- González-Hidalgo et al. (2011 and 2015) built monthly precipitation (MOPREDAS, 1951-2010) and maximum and minimum temperature (MOTEDAS, 1949-2005) databases by using all available series (6821 and 1358 respectively) with a minimum of 10 years of observations in mainland Spain. Their homogenization was performed by means of the AnClim and ProclimDB software (Štepánek, 2008a, b).
- Luna et al. (2012) built a dataset integrated by 66 long monthly precipitation series, covering mainland Spain and the Balearic Islands, which was homogenized with the Climatol package (Guijarro, 2013a) using all available Spanish precipitation series as references.
- Martín et al. (2012) studied 36 selected stations from Tenerife (Canary Islands), using AnClim to homogenize them, while Máyer et al. (2017) selected 23 Canary precipitation series to study the trends of the Concentration Index.

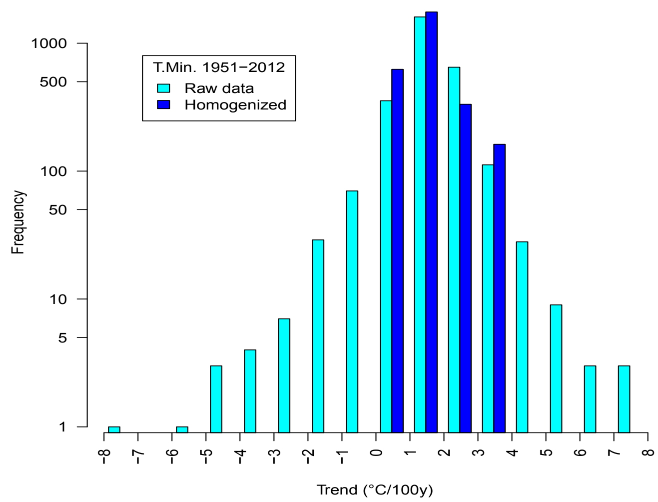

Figure 1: Trends of the Spanish minimum air temperatures before and after the homogenization of their series. Inhomogeneities in the raw observational data result in an abnormally high dispersion of the computed trends.

- Guijarro (2013b) homogenized mean maximum and minimum monthly air temperatures from 2856 Spanish series (including the Balearic and Canary archipelagos) with at least 10 years of observations by means of the Climatol package. An illustrative example of the benefits of the homogenization procedures before any variability test is made can be seen in Figure 1.
- Cuadrat et al. (2013) homogenized 49 long series of daily extreme temperatures using SNHT with the support of the ProClimDB software, to study the evolution of heat and cold waves in Spain.

- Sánchez-Lorenzo et al. (2013) developed a new dataset of surface solar radiation in Spain based on the longest series with records since the 1980s. Thirteen monthly series were selected, and their homogeneity was assessed by means of the SNHT. A similar approach was performed to study changes in cloudiness since the mid-19th century by considering 39 long-term Spanish series (Sanchez-Lorenzo et al., 2012).
- Sánchez-Lorenzo et al. (2014) built a dataset of evaporation in Spain based on long-term series of Piché and pan measurements. Piché evaporation data were gathered from 58 stations, beginning in the 1960s, while pan evaporation data from 21 observatories begin in 1984. This dataset was homogenized by means of the HOMER software.
- Azorin-Molina et al. (2014) compiled monthly wind speed series recorded at 67 stations across Spain and Portugal for 1961-2011, and applied the SNHT using the AnClim package with MM5 simulation output series as references.
- Azorin-Molina et al. (2016) assessed the variability of daily peak wind gusts of 80 series from Spain and Portugal for 1961-2014, also using MM5 outputs as references to homogenize them, this time by applying the Climatol package (Guijarro, 2013a).
- A recent PhD thesis (Serrano, 2017) compiles a new reconstruction of daily Spanish precipitation for the period 1951-2015.

Ongoing research within the MeteoMet project is being performed, and the Spanish IMPACTRON network is working towards improving our understanding of the impact of transitions such as (i) manual to automatic observation, (ii) relocations from cities to airports, and (iii) changes in thermometric screen types, on air temperature series.

Conclusion

Climatological studies developed in Spain along the last years have improved previous efforts focused on the production of quality controlled and homogeneous datasets, and have addressed the study of new climatic variables. These studies will need to be extended to other climatic variables and be updated regularly to include new incoming data. At the same time, forthcoming efforts will focus in the homogenization of daily series, which will allow a more refined assessment of the past and current climate variability, and at the same time will be useful to provide better future climate projections through downscaling of RCM forecasts.

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Climatic observations and instrumental reconstructions: development of high-quality climatic gridded products

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Introduction

Observations, studies of feedback processes, and model simulations are the basis of our knowledge and understanding of the climate system, as has been shown by the Working Group I of IPCC's Fifth Assessment Report (IPCC, 2013). In order to improve and adapt observational datasets to the actual needs of the scientific and impact studies communities, as well as to the needs of policy makers, many international programs have been setup to collect data and information used to study climate (e.g. Copernicus, formerly GMES: Global Monitoring for Environment and Security), and to provide climate services (e.g. Copernicus and GFCS: Global Framework for Climate Services). The main focus of some of these projects is to prepare and deliver climate information that meet users' needs (WMO, 2011). Within these initiatives, a set of Essential Climate Variables (ECVs) (GCOS, 2010a; Bojinski et al., 2014) have been identified, based on their relevance to characterize the climate system and its changes, feasibility and cost effectiveness. Also, guidance and best practices have been defined to obtain and support the generation of long-term, high-quality and traceable ECV datasets (GCOS, 2010b).

In this framework, several projects have grown in the last decade to improve the temporal and spatial coverage of our observational networks (e.g. EURO4M or UERRA Projects), process the raw measurements to isolate the climatic signal (e.g. Action Cost HOME or MeteoMet), develop products (e.g. gridded datasets) useful for the different communities, and include them in the assimilation process of the reanalysis products (e.g. UERRA Project). Despite the improvement of our observations and the development of very high quality observational datasets (see Guijarro et al., this volume, for more details), high-resolution gridded observational products that capture the temporal and spatial diversity of climatic variables are increasingly demanded by the climate analysis and impact communities. Several products have been developed within the activities of different national (e.g. Portugal: Belo-Pereira et al., 2011; Romania: Birsan and Dumitrescu, 2014; Dumitrescu and Birsan, 2015; the Alpine region: Isotta et al., 2014; or Germany: HYRAS precipitation database, Rauthe, 2013) or international (e.g. E-OBS, Haylock et al., 2008; van den Besselaar et al., 2011) projects by applying some interpolation process to the raw observations.

This work describes the main advances and initiatives since the previous CLIVAR-Spain assessment (Pérez and Boscolo, 2010) on the development of climatic gridded products emphasising the studies affecting the Iberian Peninsula.

Development of gridded datasets

As described in the previous section, the high-quality observational datasets usually comprise of a limited number of time series non-homogeneously distributed, locally representative and, in most cases, spanning different time periods. However, datasets with different features are needed for different purposes, and some post-processing is needed to build adequate products. High-resolution gridded datasets built from quality controlled observational datasets are increasingly demanded for climate analysis and the impacts communities, and several products have been developed in the last few years in response to this demand (e.g. E-OBS in Europe or MOPREDAS, MOTEDAS, SAFRAN or Spain02, among others, in Spain).

Due to the high climatic variability and complex relief of Spain, the available international products (e.g. E-OBS, WATCH or WFDEI) are not able to reproduce properly the different Spanish climate regimes (Herrera et al., 2012; Herrera et al., 2015; Bedia et al., 2013). Many regional and national gridded datasets have been built in the last decade using different approaches according to the needs of the scientific and impact communities, leading to a wide range of products which will be summarized in this section.

Focusing on the spatial resolution, Ninyerola et al. (2007) developed a dataset with a 200-m spatial resolution for the Iberian Peninsula of monthly and annual climatologies of precipitation, radiation and temperatures, which has been extensively used in ecological modelling. Gonzalo et al. (2010) built a similar dataset to develop the phytoclimatic diagnosis of the Peninsular Spain, but using different interpolation method and explicative variables, and with lower spatial resolution (1 km).

At a regional scale, Vicente-Serrano et al. (2003, 2007 and 2010) built climatic maps of monthly precipitation, temperatures and fog in the Ebro Valley and Aragón at a 1 km spatial resolution, considering several interpolation methods. Garzón-Machado et al. (2014) built a climatophilous potential natural vegetation map with a spatial resolution of 25 m for La Palma Island, in the Canary Islands. Ruiz-Arias et al. (2011, 2015 and 2016) developed solar radiation gridded datasets for Andalusia (1km) and Peninsular Spain and Balearic Islands (10km), using this one to assess the solar radiation of the WRF Model. However, the aim of most of these studies was comparison between different interpolation methods and, as a result, most of these datasets are distributed only under request.

Despite the very high spatial resolution of the previous datasets, time series of monthly, daily or intra-daily data are necessary in many cases (e.g. for trend analysis). In this sense, González-Hidalgo et al. (2011 and 2015) developed monthly datasets of precipitation (MOPREDAS) and temperatures (MOTEDAS) for mainland Spain to be used for trend analysis, model validation and downscaling purposes, covering 1945-2005 and 1951-2010, respectively. Both datasets have a spatial resolution of 0.1º, and have made use of a dense observational network of 2670 stations for precipitation and 1358 for temperature from the Spanish Meteorological Agency (AEMET).

Herrera et al. (2011, 2012 and 2016) developed a series of high-resolution daily precipitation and temperature gridded datasets (Spain02) for the peninsular Spain and the Balearic Islands. To this aim, 2756 and 250 quality-controlled stations from the Spanish Meteorological Agency (AEMET) were used to build the different existing versions. In particular, version v2 (0.2º regular grid) is a gridded dataset with local representativeness, appropriate to local and extreme events analysis (Herrera et al., 2012), whilst version v4 includes three different resolutions matching Euro-CORDEX grids (0.11º, 0.22º and 0.44º in rotated coordinates). This version provides areal representative (AA) values (by averaging from an auxiliary 0.01º grid) in products AA-2D, AA-3D and AA-OK, following the notation used in Herrera et al. 2016, and it is an appropriate product to validate regional climate models (RCM). Point representative values are still provided in version v4 in product OK (Ordinary Kriging). Version v3 was built considering quality controlled stations with long time series of precipitation (at least 40 years with at most 10% of missing data per year) in order to obtain an appropriate dataset for trend analysis. The different versions of Spain02 are freely distributed for research purposes at the AEMET climate services portal. Version v2 is the reference dataset used in the development of the scenarios for the national program for regional climate change (PNACC-2012). Version v4 is one of the national gridded datasets considered in the framework of the COST Action VALUE (http://www.value-cost.eu/) used to validate regional climate models of Euro-CORDEX, the European branch of the CORDEX initiative.

In addition to the Spanish gridded datasets, Belo-Pereira et al. (2011) developed a dataset for Portugal (PT02) using 400 quality-controlled stations, and with the same interpolation technique and grid used in version v2 of Spain02. This has led the development of two equivalent datasets for a common period (1951-2003) that have been combined in recent studies to obtain the dataset IB02, a precipitation gridded dataset of daily precipitation for the Iberian Peninsula (Ramos et al., 2016; Sousa et al., 2016).

Recently, an extension of the SAFRAN analysis (Durand et al., 1993; 1999) has been applied to the mainland Spain and the Balearic Islands (Quintana-Seguí et al., 2016; 2017), leading to an hourly high-resolution (5 km) gridded dataset based on daily precipitation, and six-hourly temperature, wind speed, relative humidity and cloudiness. SAFRAN also provides modelled incoming visible and infra-red radiation. This way, it provides all the necessary variables to force, for instance, a Land-Surface Model (LSM) or any other physically based distributed hydrological model. The product covers the period 1979-2014, and is available for research purposes from the Mistrals-HyMex database (Quintana-Seguí, 2015).

On a regional scale, several high spatial resolution (~1 km) daily datasets have been developed in the last years within regional projects or specific analysis/needs of some research groups. Militino et al. (2015) defined and validated a spatio-temporal interpolation method to obtain a precipitation grid with a resolution of 1 km covering the Navarra region. Within the regional project "Escenarios Regionales Probabilísticos de Cambio Climático en Cantabria: Termopluviometría", Gutierrez et al. (2010) built a similar product for Cantabria, including precipitation and temperature, which was used to project the future climate change scenarios for the region by means of statistical downscaling. Miró Pérez et al. (2015) combined statistical downscaling and spatial interpolation to obtain a very-high resolution grid of daily maximum and minimum temperatures for the Valencia region considering ~300 stations from different institutions (AEMET, CEAM, SIAR and IIG) covering the period 1948-2011. This dataset is referred as SDSITVC in Miró et al. (2016), where it is proposed as a tool for estimating bioclimatic change already occurred in mountainous areas.

Summary and conclusions

In the last few years, a great effort has been carried out to improve the quality of the tools and products used to analyse the climatic system from different points of view. In this sense, several initiatives and projects have emerged aiming to rescue and digitalize existing observational data, with special attention to regions with a poor spatial and/or temporal coverage, and to develop adequate tools and methods to elaborate high-quality datasets for climate analysis.

The Spanish climatological community is involved in most of the current projects and initiatives related to the development of several tools and products (e.g., Climatol package for data analysis and homogenization, or the gridded datasets MOPREDAS, SAFRAN or Spain02), which are being presently used by the international community in many studies, and extending the analysis on data assimilation methods to different models, variables and processes.

In particular, as has been reflected in this article, several regional and national gridded products have been developed in the last years for research purposes covering a wide range of applications, resolutions, variables and time periods. However, the main shortcoming that should be pointed out is that most of the high-quality datasets developed at a local, regional or national scale in Spain are rarely shared with the climatological community, leading to redundant analysis in many cases. On the other hand, there are not adequate intercomparison analyses between the different datasets developed. Finally, recent changes made by the Spanish Meteorological Agency regarding its open data policy, along with the improvements of new or existing tools, could allow the publication of new and updated gridded climatological products in the near future.

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Observed atmospheric trends in the Iberian Peninsula

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State of the Art

Bladé and Castro-Diez (2010) provided a comprehensive review on climate trends in the Iberian Peninsula during the instrumental period, with a special focus on precipitation and air temperature. According to that review, Spain witnessed a general air temperature increase during the 20th century. That increase was more pronounced during the last decades of the 20th century, a finding that is consistent with other regions of Europe. The review of Bladé and Castro-Diez (2010) indicated a strong spatial, seasonal and inter-annual variability of precipitation over Spain, with a general negative trend between 1960 and 2010. Nevertheless, the authors did not include any updates on variability and changes of other essential atmospheric variables (e.g. relative humidity, wind speed, drought and atmospheric evaporative demand). Vicente-Serrano et al. (2017) published an update revision of the recent peer-reviewed articles that analysed changes in temperature and precipitation but also in solar radiation, near-surface wind speed, surface humidity and evapotranspiration. This article presents a summary of that study.

Changes in solar radiation

Sánchez-Lorenzo et al. (2013) showed a significant upward trend between 1985 and 2010 on the order of 3.9 $Wm^{-2}decade^{-1}$. Similar significant increases were observed in the mean seasonal series, with the highest rate of increase during summer (6.5 Wm^{-2} $decade^{-1}$) (Figure 1). Mateos et al. (2014) quantified the contribution of clouds and aerosols to "brightening" processes in Spain, indicating that clouds are the key factor responsible for explaining "brightening" trends, as they explain approximately 75% of the solar radiation changes.

Air temperature change

Del Río et al. (2011) analysed the evolution of mean air temperature using 473 meteorological stations between 1961 and 2006, and showed dominant positive trends, mainly in spring and summer months, suggesting an annual increase between 0.1 and 0.2°C $decade^{-1}$, which was statistically significant in the entire peninsular Spain. Del Río et al. (2012) analysed the evolution of maximum and minimum air temperatures for the same period and found an identical rate of increase (0.3°C $decade^{-1}$) for maximum and minimum temperatures, particularly in summer and spring months. The average of increase in maximum temperature was 0.37°C and 0.43°C $decade^{-1}$ during summer and spring, respectively. For minimum temperature, the warming rate was 0.34°C (summer) and 0.41°C $decade^{-1}$ (spring). Gonzalez-Hidalgo et al. (2015a; b)

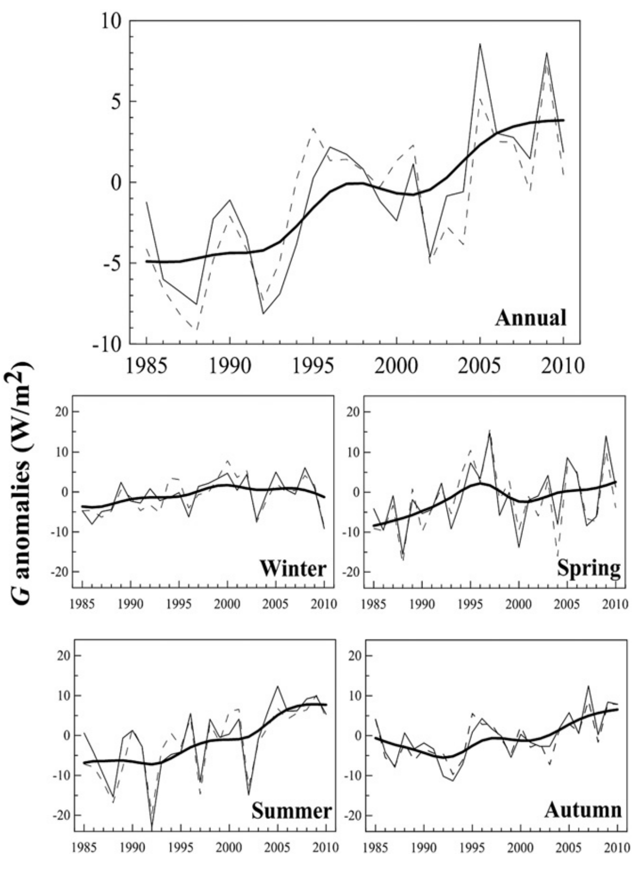

Figure 1: Mean annual and seasonal global radiation series (thin line) from 1985 to 2010 from the network of stations in Spain, plotted together with a 13-year Gaussian low-pass filter (thick line). The series are expressed as anomalies from the 1991–2010 mean. Dashed lines show the mean global radiation series obtained using the subset of 5 stations with collocated diffuse radiation records (From Sánchez-Lorenzo et al., 2013)

showed that maximum temperature has risen in late winter/early spring and summer, while minimum temperature has increased in summer, spring and autumn, especially in southern regions of Spain. Moreover, they showed that trends in the daily temperature range had a clear north–south gradient during summer, with positive trends in the north and negative trends in the south. The overall signal in maximum temperature showed a positive trend over more than 75% of land, and the strongest signal was detected in June, in which 87% of land exhibited a statistically significant positive trend (Figure 2).

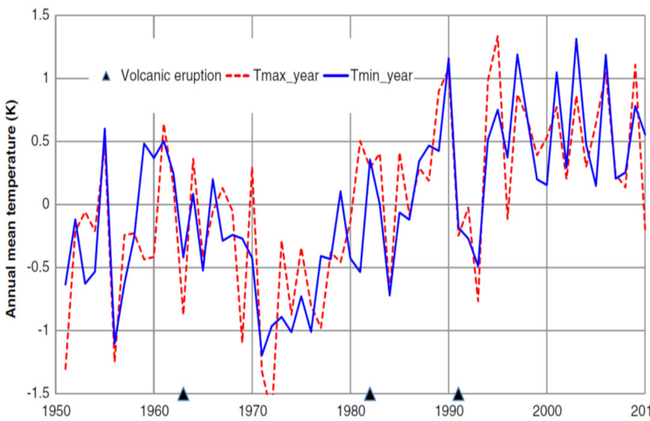

Figure 2: Annual mean of Tmax and Tmin value (1951–2010). Anomalies to base line period 1951–2010. Red line: Tmax; blue line: Tmin; triangles: volcanic eruptions (From González-Hidalgo et al., 2015b)

Regarding changes in daily temperatures over Spain, Rodríguez-Puebla et al. (2010) analysed changes in warm days and cold nights and indicated that warm days increased by 1.1% of decade^{-1} on average, while cold nights exhibited a decrease on the order of -1.3% decade^{-1}. The increase in the frequency of warm temperature extremes was continuous during the past two decades. Sánchez-Lorenzo et al. (2012) confirmed that the average frequency of tropical nights showed a continuous increase since the beginning of the 1970s, with the most extreme values recorded during the 2000s.

Changes in surface winds

Azorín-Molina et al. (2014) showed a generally slight downward trend for the period 1961–2011 (-0.016 ms^{-1} decade^{-1}). However, they found seasonal differences, with a declining trend in winter and spring and an increasing trend in summer and autumn. Over Spain, wind "stilling" affected almost 77.8% of the stations in winter and 66.7% in spring. Nonetheless, roughly 40% of the declining trends were statistically significant. On the contrary, increasing tendency appeared in 51.9% of the stations in summer and 57.4% in autumn.

Changes in surface humidity

Vicente-Serrano et al. (2014) showed a large decrease in relative humidity over mainland Spain from 1961 to 2011, which was more pronounced in spring and summer (-1.02% and -1.56% decade-1, respectively). On average, the decrease was on the order of -5.1% at the annual scale between 1961 and 2011. In contrast, there was no overall change in the specific humidity in this period, except in spring that exhibited an increase (Figure 3).

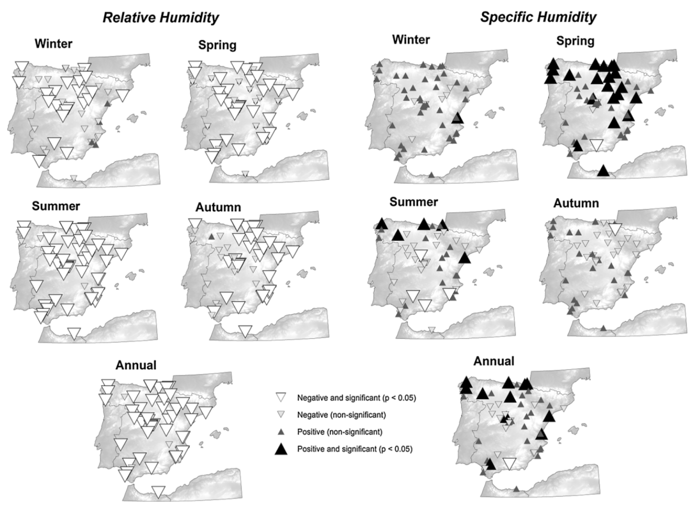

Figure 3: Spatial distribution of seasonal and annual trends in relative and specific humidity in Spain (1961–2011) (From Vicente-Serrano et al., 2014)

Changes in precipitation

González-Hidalgo et al. (2011) showed that monthly precipitation trends have high monthly variability, with coherent spatial trend patterns in March, June (both with a general and significant negative trend) and October (general positive trends). More localized trend patterns were noted in July, February and April. Del Río et al. (2011b) revealed a decrease in rainfall in more than 28% of the Spanish territory during summer and winter between 1961 and 2006. Although regional patterns of rainfall changes are complex, regional series over the whole Spain showed a precipitation decrease in winter and at the annual scale (Rodríguez-Puebla and Nieto, 2010; Vicente-Serrano et al., 2014). Gallego et al. (2011) analysed trends in frequency indices of daily precipitation during the last century (1903–2003), using data from 27 stations in Portugal and Spain, and found that the total number of rainy days and light (≥0.2 and <0.25 mm) rainfall increased at many observatories over the Iberian Peninsula for all seasons. Acero et al. (2011) who used a peaks-over-threshold approach showed that for a 2-yr return period yielded a large proportion of negative trends for the considered seasons: 58% for winter, 63% for spring, and 69% for autumn. Nevertheless, the parametric approach also revealed an increase in the area with positive trends for a 20-yr return level, relative to a 2-yr return period. This feature could give indications on certain increase of intense precipitation events. On the contrary, Rodrigo (2010) showed that the trend of the probability of daily rainfall less than the 5th percentile is positive but in contrast, the probability of daily rainfall higher than the 95th percentile is negative, which would suggest a decrease of rainfall intensity during this period.

The atmospheric evaporative demand (AED)

Vicente-Serrano et al. (2014b) found a strong increase (24.4 mm decade^{-1}) in the magnitude of AED at the annual scale across Spain, with the main increase in summer (12 mm decade^{-1}). This increase was mainly explained by the decrease in relative humidity and the increase in maximum temperature since the 1960s, particularly during summer months.

Concluding remarks

Although recent climate trends are determined by the used datasets and mostly the selected periods for analysis, it is possible to draw some concluding remarks for the different variables:

1. there is a strong solar radiation increase from the 1980s;
2. temperatures showed strong increases (around +0.3°C decade^{-1}) since the 1960s, which were stronger in summer months;
3. there are no noticeable changes in surface wind speed, with a slight downward trend recorded but not statistically significant;
4. strong decrease in relative humidity was recorded (-5% between 1961 and 2011). In contrast, no changes in absolute humidity were identified;
5. there is a strong spatial and seasonal variability in precipitation trends, maybe in relation with change in atmospheric teleconnections and the influence of ENSO (see Rodriguez et al., this issue), although average annual precipitation over Spain showed a moderate decrease in the past five decades;
6. the atmospheric evaporative demand increased in the past five decades (+24.4 mm decade^{-1}), mainly in summer months. Overall, the recent climate trends observed for Spain clearly suggest a warmer and drier scenario in comparison to past decades. This finding is compatible with observations in other Mediterranean areas, where there is a tendency toward a climate scenario characterized by lower water availability (García-Ruiz et al., 2011).

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Modes of Variability affecting southwestern Europe

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Introduction

Atmospheric variations may result from external forcing, but also naturally from internal interactions between components of the climate system. A closer inspection of the spatial structure of the atmospheric variability, in particular on seasonal and longer time-scales, shows that it occurs predominantly in preferred large-scale and geographically anchored spatial patterns, known as teleconnection patterns (TP). TP can vary in intensity and position at seasonal, interannual and decadal time scales (Wallace and Gutzler, 1981; Trenberth et al., 1998; Quadrelli and Wallace, 2004). They are regional in nature and shaped by wave processes, reflecting zonal mean anomalies and connections via other components of the climate system, especially the ocean (Liu and Alexander, 2007). Thus, TP are related to circulation types (Casado et al., 2008) and have an impact on other atmospheric surface variables such as temperature and precipitation.

Southwestern Europe, where the Iberian Peninsula is located, is mainly under the influence of the subtropical Azores high pressure system. This subtropical anticyclone exhibits meridional displacements along the seasonal cycle, inducing changes in the mean climatic conditions of this area.

The most important TP affecting the southwestern Europe is the North Atlantic Oscillation (NAO; Trigo et al., 2002), which is associated with changes in the meridional gradient between the subpolar and subtropical pressure systems. NAO explains a large part of the precipitation variability over Europe, mainly in winter, in such a way that positive phases of this oscillation are associated with an increase of precipitation over northern Europe and a decrease towards the south-western European continent. NAO also affects temperature, winds and other variables impacting climate and society. Apart from NAO, other TP affecting Europe are the East Atlantic/Western Russia (EA/WR), East Atlantic (EA) and Scandinavian (SCAND) patterns (García-Herrera and Barriopedro, 2017).

The atmosphere responds to other components of the climate system through excited Rossby waves and localized eddy–mean flow interactions, which can both result in regional teleconnection patterns (Liu and Alexander, 2007). Due to the large heat capacity of water when compared to the atmosphere, ocean subsurface can store energy for several months and release it later as latent and sensible heat fluxes which, in turn, can alter the global circulation of the atmosphere, triggering in this way, teleconnections. Sea surface temperature (SST) variability is used as a measure of the associated oceanic energy to be released. This is the basis of seasonal to decadal predictability (s2d). In particular, El Niño is the leading natural variability mode at global scale, determining most of the year-to-year global climate variability, including its impact on southwestern Europe (Brönnimann et al., 2007). Its Atlantic counterpart, with similar dynamics, is the Atlantic Niño, which is the main source of SST variability in the Tropical Atlantic at interannual time scales (Polo et al., 2008). Both, Atlantic and Pacific Niños are very much linked and cannot be considered as independent modes of variability (Rodriguez-Fonseca et al., 2009; Martín-Rey et al., 2014; Martín-Rey et al., 2015; Polo et al., 2015). Also, Tropical North Atlantic (TNA) variability cannot be isolated from ENSO (García-Serrano et al., 2017) and has a significant influence on the atmospheric circulation of the Atlantic-European sector and in particular in the Iberian Peninsula in both early winter and spring (Rodríguez-Fonseca et al., 2006).

Climate models are generally able to simulate the gross features of many of the modes of variability, and to provide useful tools for understanding how they might change in the future (Müller and Roeckner, 2008; Handorf and Dethloff, 2009). The most recent IPCC report includes a chapter devoted to the analysis of climate phenomena, in particular the main modes of variability, and their relationship with current and future regional climate (IPCC, AR5, Christensen et al., 2013).

In the former CLIVAR-Spain assessment, Rodríguez-Fonseca and Rodríguez-Puebla (2010) discussed the studies about atmospheric teleconnection patterns affecting the Iberian Peninsula, including possible predictability, with special emphasis in the NAO, and analyzing interactions with the ocean. Since then, a great progress has been made on the development of applications on subseasonal to decadal forecasts (s2s and s2d, Vitart et al., 2012). The availability of results from the Climate system Historical Forecasting Project (CHFP; Tompkins et al., 2017) and the Coupled Model Intercomparison Project (CMIP5), together with very active investigations in both operational and research communities, have improved and will continue to enhance our abilities to make skillful predictions and projections in the region. The present review collects most of the works dealing with TP affecting the Euro-Mediterranean region done from 2010, with special attention to internal vs. forced variability, predictability at different timescales and future projections.

Patterns affecting Southwestern Europe atmospheric variability and potential precursors

New studies have been done in the last years relating NAO with winter precipitation, winds and temperature, including extremes over the western Mediterranean region (Vicente-Serrano et al., 2009; Lorenzo et al., 2008; Jerez et al., 2013; Casanueva et al., 2014 Vicente-Serrano et al., 2009; Lorenzo et al., 2008). Also during this season, recent studies have found how positive phases of the NAO could act as precursors of explosive cyclones affecting Europe (Gómara et al., 2014).

Apart from NAO, recent studies point to combinations with other TP, as SCAND and EA, to explain climate variability in the region (Comas-Bru and MacDermott, 2014). From a more regional perspective, patterns such as the Mediterranean Oscillation (MO) and the Western Mediterranean Oscillation (WeMO) (Martin Vide and López-Bustins, 2006; Vicente-Serrano et al, 2009; Lana et al., 2016) are also important in the description of the atmospheric variability of the southwestern Europe. Together with the NAO, the westerly index (Barriopedro et al., 2014), a measure of the frequency of westerly winds over the English Channel, have been found to explain the drought variability across Europe (Vicente-Serrano et al. 2016).

In seasons other than winter, the NAO presents a less zonal structure due to the weakening of the extratropical jet, and other TP may be more influential on European climate (García-Herrera and Barriopedro, 2017). For example, during autumn, global atmospheric patterns project better on an EA-like pattern, whose structure and associated impacts depend on the background mean flow, therefore experiencing low-frequency oscillations. Thus, its annular structure has been active in the most recent decades, while a wave-4 pattern was dominant in the decades before (King et al., 2017). As compared to the winter NAO, the leading mode of variability in high-summer (July-August), also known as the summer NAO, is more regional and shifted northwards. Different to the winter NAO, its largest impacts over the Iberian Peninsula are detected, although weak, in maximum temperatures (Favà et al., 2016).

There is a clear non-stationary relationship between the winter NAO and European precipitation (Hertig et al., 2015). Several hypotheses have been formulated to explain this non-stationarity, including modifications in the meridional pressure gradient (Zveryaev, 2006), North Atlantic air-sea dynamics and variability in the Atlantic Meridional Overturning Circulation (AMOC) (Walter and Graf, 2002; Gómara et al., 2016), solar activity (Gimeno et al., 2003) and variability in the NAO pressure centers (Haylock et al., 2007; Vicente-Serrano and Lopez-Moreno, 2008).

In winter, the NAO is also modulated by ENSO, whose teleconnections over Europe might involve both a tropospheric pathway and a stratospheric one (Butler et al., 2014). The persistence of the wintertime ENSO signal in the stratosphere and air-sea interactions in the North Atlantic allow the winter ENSO signal to persist until the following spring (Herceg-Bullick et al., 2017). In this season, although El Niño influence on the North Atlantic has been related to a negative phase of the NAO (Brönnimann et al., 2007; Vicente Serrano et al., 2008, García-Serrano et al., 2011), this influence has been found to be non-stationary on time, depending on the slowly variant background of the ocean (Greatbach et al., 2004; Zanchettin et al., 2008; López-Parages and Rodriguez-Fonseca, 2012; López-Parages et al., 2015; López-Parages et al., 2016; King et al., 2017). In this way, the state of multidecadal variability of the north Atlantic SST determines the effectiveness of ENSO teleconnection. Moreover, two ENSO flavours have been reported, referred to as Eastern Pacific (EP) and Central Pacific (CP), with different winter teleconnections over Europe (Calvo et al., 2017). Their influence on southwestern Europe has also changed with time, being the EP warm events during negative Atlantic Multidecadal Oscillation (AMO) periods the combination with the largest impacts on European rainfall (López-Parages et al., 2016). Also, the Tropical North Atlantic region (TNA) has a significant influence on the atmospheric circulation in the Atlantic-European sector and in particular in the Iberian Peninsula in early winter and spring, also in relation to ENSO (Frankignoul et al., 2003; Rodríguez-Fonseca et al., 2016; King et al., 2017).

The impact of the Atlantic Niño decaying phase is mainly determined by the climatological jet stream's position and intensity, showing an arching pattern over the North Atlantic region during summer–autumn, and a zonally oriented wave train during autumn–winter (García-Serrano, 2011). Nevertheless, summer Atlantic Niño presents different impacts on summer Mediterranean climate depending on the state of the rest of the tropical oceans (Losada et al., 2012). Mediterranean SST anomalies also influence the Northern Hemisphere atmospheric circulation (García-Serrano et al., 2013; Sahin et al., 2015) affecting late summer temperatures.

Finally, at decadal time scales, the AMO (Ortiz Bevia et al., 2016; Zampieri et al., 2017) has been found to influence the length of the summer in southern Europe (Peña-Ortiz et al., 2015) and weather regimes at Mediterranean region in summer. Also, a coupling between Indian and southern European summer rainfall has been found after the late 1970s (Lin et al., 2017).

In addition to the ocean, other predictors are being defined for the better assessment of TP. The stratosphere (Scaife, 2005; Palmeiro et al., 2017), the Madden Julian Oscillation (Cassou, 2008; Schwartz et al., 2017), Eurasian snow cover (Orsollini et al., 2016), and the Arctic sea-ice extension (García-Serrano et al., 2015) have been pointed out to be determinant for the correct assessment of predictability in the Euro-Atlantic sector at subseasonal timescales.

Predictions and Future Projections

The evidence for potential seasonal predictions of the winter NAO has recently increased (Scaife et al., 2014; Athanasiadis et al., 2017), while a similar progress has not been achieved for other seasons or TP. Multiple studies have shown a potential for improved North Atlantic predictability at seasonal timescales based on two main predictors: ENSO and sudden stratospheric warming (SSW) events (Barriopedro and Calvo, 2014; Domeisen et al., 2015; Butler et al., 2016).

There are suggestions of extended skillful predictions of the NAO one year ahead with two sources of skill for the second-winter forecasts: the climate variability in the tropical Pacific region and the effect of solar forcing on the stratospheric polar vortex strength (Dunstone et al., 2016).

Multi-model decadal prediction exercises (Doblas-Reyes et al., 2013) have demonstrated the large potential for useful interannual-to-decadal prediction of European climate (Guemas et al., 2015; Lienert et al., 2017). The forecast information comes mainly from the warming trend in the case of temperature, but also from the AMO.

The Mediterranean is considered a 'hot spot' for climate change, due to the expected warming and drying of the region. While thermodynamically-induced changes due to greenhouse gases (GHG) forcing are robust, there are considerable uncertainties in the future projections of atmospheric circulation and variables related with dynamical processes, e.g., precipitation (Shepherd, 2014), so that large ensemble simulations are essential to estimate the probabilistic distribution. Regarding future projections of TP, Gonzalez-Reviriego et al. (2014) have found a positive trend for the NAO and a negative trend for the SCAND pattern under future SRES A1B climate change scenario. This result is in line with recent multi-model studies of NAO (Gillett and Fyfe, 2013) showing a small positive response of boreal winter NAO indices to GHG forcing. NAO will continue to influence precipitation and temperature in coming decades (López-Moreno et al., 2011), with the positive winter NAO trend in the future potentially leading to an increase in the frequency of dry conditions in the Iberian Peninsula. Moreover, as the simulations indicate a steady increase in temperature (see Serrano and Camino, this issue), winters classified as "cold" in the 21st century will be noticeably rarer compared with recent decades.

Bladé et al. (2012a, 2012b) examined the future summer NAO trend in CMIP3 models. They found an overall positive trend, albeit with a large spread in magnitude, which accounts for a large fraction of the projected multi-model mean precipitation reduction in northwest Europe. These changes should also lead to modest precipitation increases in the Iberian Peninsula, where the observed correlation between the SNAO and summer precipitation is weakly positive, partially offsetting some of the thermodynamically-induced drying in the region. However, this effect is not captured by the CMIP3 models, because those models do not correctly represent the surface signatures of the summer NAO.

Climate regime shifts are projected under future scenarios including a strengthening and eastward extension of the North Atlantic storm track towards western Europe (Feng et al., 2014). The atmosphere-ocean coupling shapes distinct responses of Atlantic Niño under GHG forcing (Mohino and Losada, 2015) with uncertainties in ocean circulation changes accounting for much of the projected spread in storm tracks (Woollings et al., 2012).

Regional future projections indicate a generalized increase of heatwaves and drought severity in the region (Jacob et al., 2014; Vicente-Serrano et al., 2014). Despite this, Atmospheric Rivers (ARs), which trigger intense precipitation and floods over continental areas, are projected to transport an increased amount of vertically integrated water vapor, producing extreme precipitation along the Atlantic European Coasts from the Iberian Peninsula to Scandinavia (Ramos et al., 2016). In relation to explosive cyclones, although most of them occur north of southwestern European region, abrupt southward shifts of the NAO, modulated by changes in the AMOC, could lead to more frequent events over the subtropical European regions (Gómara et al., 2016).

Similarly to the last decades, in the 21st century, multidecadal fluctuations of the oceans are expected to act as a switch for global teleconnections, enhancing predictability during certain decades (López-Parages et al., 2015). In this way, the decadal variability that will accompany the projected forced changes in the Mediterranean region should be considered in the development of future climate outlooks (Mariotti et al., 2015).

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Oceanic variability and sea level changes around the Iberian Peninsula, Balearic and Canary Islands

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Introduction

The ocean, with a heat capacity nearly 1200 times higher than the atmosphere, is the main component of the Earth climate system in terms of the energy budgets. One of the main objectives of CLIVAR is to get as much information as possible about the oceanic variability, including sea level changes, as an expression of the oceanic heat storage evolution. This information is currently being used to improve the understanding of interannual to decadal climate variability, assessing changes in the climate system and energy fluxes for model adjustments and tuning, and to improve decadal predictions and longer term projections of climate change. In a regional context, waters around the Iberian Peninsula (including the Balearic Islands) and around the Canary Islands are affected by the northeastern (NE) Atlantic and western Mediterranean variability, including the sills communicating both. In the previous CLIVAR-Spain assessment (2010), the basic knowledge of the oceanic variability and sea level changes in the region was analysed and discussed, based on long term in situ observations and satellite images. In that assessment, the whole recent evolution of the water characteristics (trends and scales of variability for temperature, salinity, heat content and sea level) was described from the first observations to the first decade of the present century.

Noticeable results of that report were, first, that surface waters in the whole Atlantic margin of the Iberian Peninsula showed alternating cold and warm periods since 1854. The last warm period started in 1974, with a warming trend extending to the upper 1000 m clearly detected in Bay of Biscay during the decade of the 1990s. The oceanic waters of the subtropical Atlantic around the Canary Islands presented both warming and increasing salinity trends at depths from 600 to 1800 m, probably associated with variations in the intensity of the dominant winds through their impact on vertical displacements of water masses. A strengthening of the coastal upwelling off northwestern (NW) Africa, or at least a weakening of the warming of the upwelling, was also reported, coherently with the progressive warming of surface waters in the whole tropical Atlantic region observed since 1967. In the western Mediterranean, the temperature and salinity of the deepest waters and the salinity of the intermediate waters were observed to increase since the middle of the 20th Century. However, the reported heat flux estimates in the Iberian region did not show any significant trend, only some alternating periods of higher (e.g. from 1958 to 1975) and lower (e.g. from 1975 to 2001) heat losses from the sea. A relevant feature highlighted in this context was the heavy heat loss in the winter of 2004/05, which caused the formation of very thick mixed layers everywhere in the region and an unprecedented exceptional generation of dense waters in the NW Mediterranean.

Regarding the long-term variability of mean sea-level, the reported observations indicated increasing trends of different magnitude. A relevant result was that from the 1960s to the 1990s, sea level did not increase in the western Mediterranean due to the forcing of atmospheric pressure. However, from that period on, sea level trends in the region reversed and followed the overall global positive trends. The long-term evolution and interannual variability of sea-level extremes were consistent with the behaviour of mean sea level, despite being the result of different processes such as the interaction between tides and storm surges. This resulted in indirect evidence that there were no relevant changes in the frequency or intensity of atmospheric disturbances near the Iberian Peninsula during the last decades of the 20th century.

This article covers new results obtained during the last ten years, most of them based on new data sets. The aim is to update and review previous results as well as to get a detailed view of the interannual changes occurred in the last decade. Most data come from the same monitoring programs used in the previous report:

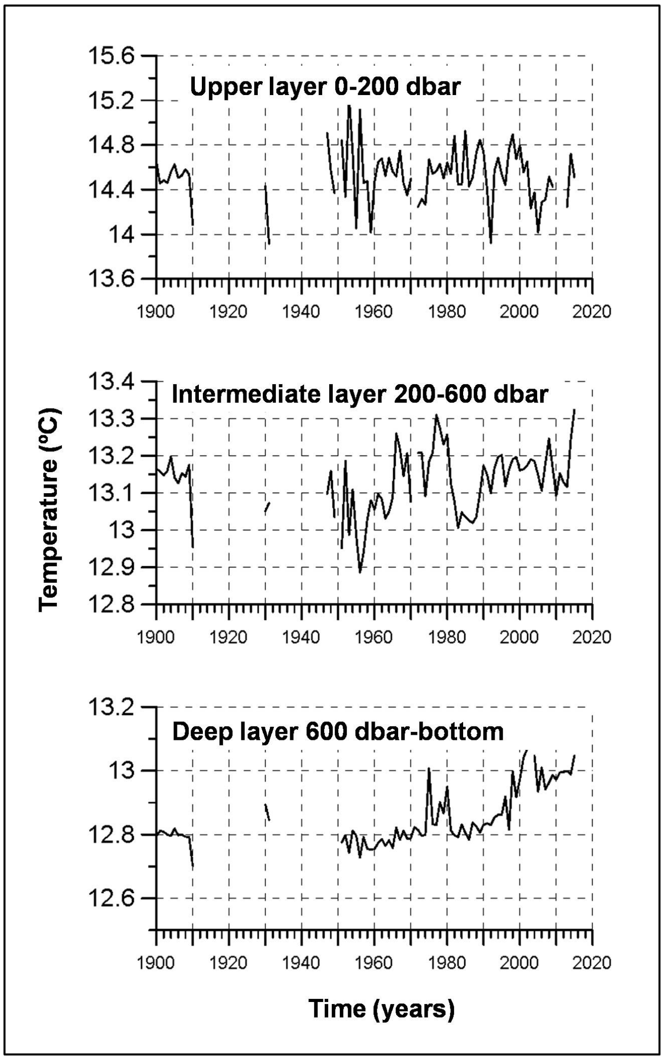

Figure 1: Mean annual temperature series at three layers, from 1900 to 2015 averaged for the Spanish western Mediterranean. Adapted from Vargas-Yáñez et al. (2017).

the network of sea-level gauges, repeated seasonal CTD sections and fixed stations, and moorings deployed at key points within the basins and at the Gibraltar sills. Sea surface temperature and sea level are also covered by remote sensing from satellites. Data from oceanographic cruises in the region, as well as some occasional fixed moorings, have also contributed to the results analysed in this article. Papers reviewed in this article also include data from sources such as gliders, instrumented drifting buoys and, especially, ARGO profilers, which have become essential (they were not used in the previous report because their expansion started few years ago). Finally, actual observations of heat fluxes, particularly of latent heat exchanges, although crucial for CLIVAR purposes, are still not available. Therefore, the results involving heat fluxes will still rely mostly on reanalyses or indirect estimations.

Results

Waters around the Iberian Peninsula, including the Balearic Islands

The analysed time series show a marked variability with sudden shifts in most of them, due to nonlinear responses of the ocean-atmosphere system. This does not contradict the existence of sustained long-term trends in hydrographic properties, but rather it reveals the regional heterogeneity of the responses. The most prominent feature is still the anomalous 2004/05 winter already mentioned in the previous report. Now with some more perspective, it can be confirmed as the coldest and one of the driest winters in southwestern (SW) Europe and Temperate NE Atlantic, in the last 60 years (Häkkinen et al., 2015). The atmospheric conditions in the winter of 2015 markedly affected the upper waters almost all around the Iberian Peninsula (Levitus et al., 2012). The exceptional heat loss through a large area increased the thickness of the surface mixed layer down to unprecedented depths in the NE Atlantic (Somavilla et al., 2009) and in the western Mediterranean basin, where the volume of newly formed Western Mediterranean Deep Water (WMDW) was much higher than average (Ulses et al., 2008; CIESM, 2009). The main shifts in the records associated with this episode have been obviously found in surface temperature and salinity (Goikoetxea et al., 2009; González et al., 2013), and in the characteristics of the water masses formed in the region: the Eastern North Atlantic Central Water (ENACW; Prieto et al., 2015) and the WMDW (López-Jurado et al., 2005; Font et al., 2007; Schroeder et al., 2016).

These changes also had a direct impact in the ocean heat content in the region, the most significant consequence being a redistribution of the heat to deeper layers (down to 800-1000 m in the NE Atlantic). Some consequent changes in the circulation patterns and seasonality were also detected, associated with changes in the thickness of isopycnal layers in the NE Atlantic (Somavilla et al., 2016). In the Mediterranean, the massive formation of new WMDW in 2005 had a direct impact on the structure of the deep layers, to the point that the event has been referred to as the Western Mediterranean Transient (WMT). Namely, the newly formed WMDW caused an upward displacement of the old resident WMDW and thus a decrease in the temperature and salinity of intermediate waters (Zunino et al., 2012), similarly to the event occurred in the Eastern Mediterranean in the late 1980s (Theocharis et al., 2002). The impact of the 2004/05 deep water formation (DWF) on the thermohaline structure of the western Mediterranean has some precedents, though of much smaller intensity (Lacombe et al., 1985), and could be recurrent (Puig et al., 2013). The temperature and salinity decrease at the intermediate layers post-WMT affected in particular the Mediterranean Outflow Water (MOW) observed at Gibraltar sill (Garcia-Lafuente et al., 2007). The hydrographical signatures of the MOW are however difficult to track across the spreading pathway of Mediterranean Water (MW) vein. Property swings observed in NW Iberia at the core of MW within the last 15 years have been interpreted as a regional advective response, linked to the expansion and contraction of subpolar and subtropical gyres (Prieto et al., 2015). In fact, the direct and indirect impacts of the winter 2005 anomaly produced a shift in most of the records at any level above ~1000 m in a large area of the north Atlantic. A relevant consequence is the contribution of the NE Atlantic Ocean to the so-called global warming hiatus through the heat and salt progressively gained by the upper ocean, and quickly transferred to deeper layers (Sullivan, 2016). According to Somavilla et al. (2016), "anomalous atmospheric patterns such as the one behind this shift [2005] are not unique to the last decade, although they may have been exacerbated under global warming". This suggests that new, relevant shifts in climatic time-series can be expected, but they can hardly be anticipated.

In addition to the major 2005 feature, and without any apparent relation, other relevant results to be mentioned are:

1. In 2014, the upper ENACW showed a marked freshening (down to 400 m) for the first time in about a decade (Larsen et al., 2016).
2. Significant changes have been detected at the transition level between MW and Labrador Sea Water (LSW), namely a transient shift towards colder and fresher conditions of the LSW from autumn 2008 to 2010 (Prieto et al., 2015). Later swings in the temperature and salinity of these intermediate waters appear to be related to the subpolar gyre expansion/contraction (Larsen et al., 2016).
3. Relevant DWF episodes in the NW Mediterranean occurred in 2006, 2009, 2010, 2012 and 2013 (Durrieu de Madron et al., 2013). In the last few years (2015 to 2017), no significant DWF episodes have been recorded in the NW Mediterranean (Durrieu de Madron et al., 2017).
4. The salinity of the WMDW formed after 2005 has been progressively increasing, especially when formed only by open sea convection (Borghini et al., 2014).
5. During the DWF episode of 2010, a huge amount of intermediate waters was produced (in addition to WMDW) along a much wider than usual area (Vargas-Yáñez et al., 2012).

The recent evolution of Mediterranean waters has also been documented in Sammartino et al. (2014) and Naranjo et al. (2015, 2017).

The Mediterranean outflow at the Espartel sill showed a slight, not significant decreasing trend from 2004 (Sammartino et al., 2014), and a seasonal cycle with maximum outflow in March-April, when the interface is roughly at its shallowest position. Salinity and particularly temperature of the MOW are rather sensitive to this seasonal cycle, and also to the intensity of the DWF in the western Mediterranean. A slight positive trend for both temperature (significant at the 95% confidence level) and salinity (not significant at this level) was detected from 2004 up to 2013, a trend which increased by almost a factor of 4 from 2013 onwards. This noticeable acceleration has been tentatively related

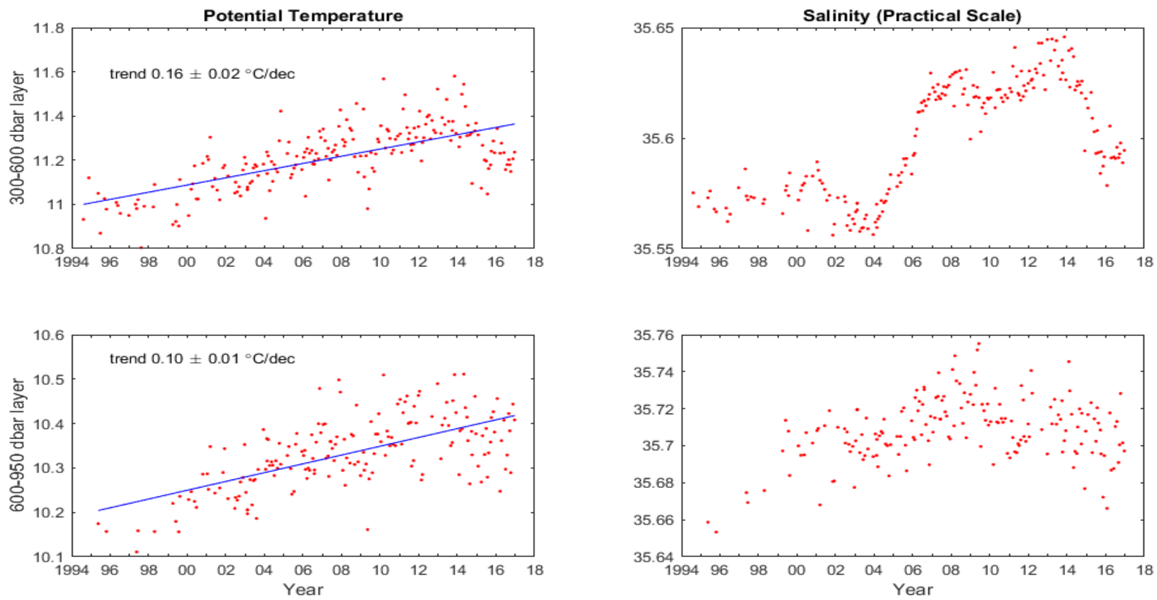

Figure 2: Series of temperature and salinity at intermediate levels (300 to 1000 m) from 1990 to 2016 at a station off Santander (Gulf of Biscay, 43° 48'N; 003° 47'W; 2400 m).

to the WMT, namely the "exhaustion" of the uplifted pre-2005 WMDW (Naranjo et al., 2017). In the eastern Gulf of Cadiz, the top 150 m of the water column exhibited significant cooling and freshening from 1996. At the MOW level (between 350-550 m depth) waters have warmed and salinity increased (International Council for the Exploration of the Sea (ICES) Working Group on Oceanic Hydrography - to be included in the 2017 ICES Report on Ocean Climate). These changes did not show any statistically relevant influence on the stratification of the water column.

Subtropical Atlantic waters around the Canary Islands

The transatlantic hydrographic section along 24°30' N carried out in 1992 was repeated in 2011. The comparison between the two sections shows an increase in the southward transport of Upper North Atlantic Deep Water (NADW) compensated by a decrease in the transport of Lower NADW. A descent in the upper limit of the Antarctic Bottom Water (AABW) from 1992 to 2011 is also inferred. The northward flow of Antarctic Intermediate Water (AAIW) has also decreased significantly during these 20 years. Altogether, the heat transport across the parallel 24°30' N was not significantly different from 1992 to 2011 (Vélez-Belchí et al, 2010; Hernández-Guerra et al., 2014).

Records of sea surface temperature around the Canary Islands show a mean warming trend of 0.28°C decade-1 for the period 1982-2013, but with a large spatial variability. At the continental margin, the trends range from nearly zero in the upwelling region (Western Sahara) to more than 0.5°C decade-1 in the downwelling zone between Cape Verde and Cape Blanc. Hydrographic observations in the oceanic region of the coastal transition zone during the period 1997-2017 indicate that the trends are similar to those observed above the permanent thermocline (200-600 dbar). Hydrographic observations in the upper waters (50-150 dbar) of the upwelling region indicate that during the last 20 years there has been a decrease in temperature and salinity coherent with the global warming effect on the upwelling. In terms of density, the warming rate of the upper layers is compensated by an increase in salinity of 0.02 decade-1. Neither the intermediate waters nor the upper deep waters show any statistically significant trend. Conversely, the deep waters (2600-3600 m) north of the Canary Islands show cooling and freshening at rates of 0.01°C and 0.002 decade-1 respectively (Vélez-Belchí et al., 2015).

Sea-level

Sea level observations come basically from two sources: tide gauge records and satellite altimetry. During the last decade, both datasets have showed significant changes that have improved the knowledge on sea level variability and trends.

Regarding satellite altimetry, the main improvement has come from an extension of the records, which are nearly 25 years long at present, altogether with ongoing efforts to improve data corrections and processing. This has allowed an updating of present sea level rise rates that had been previously based on shorter records. In the Mediterranean Sea, for instance, satellite altimetry shows an average increase in absolute (geocentric) sea level of 2.6±0.2 mm/yr during the period 1993-2015 (Marcos et al., 2016). Linear trends at particular locations range from -4 to +6 mm/yr, but the most marked positive and negative trends are associated with ocean circulation variability rather than with long term, persistent structures. In the NE Atlantic the trend values are mostly positive (between 1.0 mm/yr and 4.5 mm/yr (Pérez-Gómez et al., 2015; Ablain et al, 2017), consistent with those observed within the Mediterranean basin. The spatial pattern of the trends shows the fingerprint of mesoscale and large-scale dynamics.

Regarding tide gauge records, a major improvement has come from the estimation of Vertical Land Movements (VLM) of the Earth's crust at gauge locations that has allowed the separation of the non-climatic linear trends from the ocean contribution. Subtracting the VLM signal from tide gauge records has resulted in a larger spatial coherence and hence in a better understanding of the processes underlying sea level variability at the coast (Wöppelmann and Marcos, 2012). In addition, the removal of the VLM is a key issue when comparing relative coastal sea level trends from gauges with altimetry geocentric observations. Further information from long term coastal sea level trends has come from the digitalization and quality control of long tide gauge records, and from the intercomparison with independent sea level measurement, e.g. the Tenerife record (Marcos et al., 2013). During the last decade, new improved regional reconstructions of sea level fields based on the combination of altimetry and tide gauge records have also been produced, e.g. for the Mediterranean Sea (Calafat and Jordà, 2011).

During the last decade, there has also been a significant improvement in the understanding of the processes underlying sea level variability. A relevant advance has been for instance the study of the coupling between Mediterranean and NE Atlantic sea level variability (Calafat et al., 2012). These authors have demonstrated that, besides the barotropic response of local atmospheric pressure and winds, coastal sea level variations on the eastern boundary of the North Atlantic (those driving Mediterranean sea level) also display a baroclinic response to longshore winds. Another advance has been the formulation of the role of salinity in sea level variability (Jordà and Gomis, 2013), which has been crucial to correct previous estimates of Mediterranean Sea level trends. These authors have shown that in semi-enclosed seas, salinity not only contributes negatively to the steric component of sea level, but it also contributes positively to the mass component, and that both contributions virtually cancel each other.

Lastly, there have also been some advances in the field of regional modelling (see the two Jordà et al. articles, this issue). Detecting sea level from Global Climate Models (GCMs) is not a problem. However, global models do not have enough resolution to resolve crucial features in marginal seas such as the Mediterranean. In those domains, Regional Climate Models (RCMs) nested with GCMs are required. The problem is that boundary conditions are usually set up in a way that prevents a correct detection of sea level within the regional domain (Adloff et al., 2105). This is nowadays acknowledged (Slangen et al., 2017) and it will be hopefully corrected in the next generation of climate runs.

Conclusions and final remarks

The reported results confirm the impacts of global heating on the ocean at the Iberian regional scale. These observed impacts often appear abruptly and stepwise, instead of following uniform trends. Such a behaviour is relevant, and sometimes unnoticed, since it can increase uncertainties of predictions. This article highlights the importance of routine water monitoring. Unfortunately, many financial sources have a limited time span, typically 3-4 years. It is also true, however, that many of the monitoring efforts on which the report is based and that are currently maintained by the IEO and other institutions (Puertos del Estado, Universities, etc), started through specific scientific projects. This is the case of IEO Observing System (Tel et al., 2016) and the Espartel monitoring station. Other monitoring stations started as voluntary initiatives at very low cost, e.g. the Hydrochanges network or some of the oldest coastal recording stations (Aquarium in San Sebastián or L'Estartit station). In all cases, their usefulness to follow the evolution of climate change in the years to come has already been proven, as well as for the study of the biological resources and their dependence on the physico-chemical variables (which are all crucial aspects to implement the EU Marine Framework Strategy). Nevertheless, a more coordinated strategy that considers the overall capability of the observing system to detect climate change signals (in line of the study of Llasses et al., 2015) would be very welcome.

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Regional climate projections over Spain: Atmosphere. Present climate evaluation

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Introduction

Projections for future climate change are primarily based on simulations with global circulation models (GCMs) forced by future greenhouse gases concentration scenarios. Their relative coarse horizontal resolution limits the atmospheric processes relevant for regional climate which can be realistically modelled. Moreover, their outputs do not have the spatial resolution often needed for impact and adaptation studies. In order to overcome these problems, two main downscaling approaches are commonly followed: 1) dynamical downscaling, based on Regional Climate Models (RCMs) driven at the boundaries by the outputs of the GCMs, and 2) statistical downscaling methods (SDMs), based on statistical links established between the GCM large-scale circulation and the regional/local observed climate. In this context, the Iberian Peninsula is a perfect candidate for downscaling due to its complex orography and its position with respect to the storm track, yielding a high spatial heterogeneity of climate conditions. The first step when applying a downscaling technique is to check its ability to reproduce the observed climate. This is a fundamental step, since it provides confidence when the method/model is applied to climate change scenarios (Sánchez et al., 2011, among many others), past climate (Gómez-Navarro et al., 2011), or the generation of a pseudo-observational database (regional hindcast) for a multitude of applications (Sotillo et al., 2005; Jerez et al., 2013c). In addition, the assessment of the added value with respect to the driving model is also important, because the extra step of downscaling in climate studies only makes sense if some extra and valuable information is provided (Sánchez et al., 2011; Jiménez-Guerrero et al., 2013; Lorente-Plazas et al., 2015). Present climate evaluation of downscaling techniques can be performed under two different perspectives, depending on the driving conditions employed. On the one hand, the use of quasi-observational driving data (reanalysis or analysis) permits assessing the performance of the RCM alone. On the other hand, GCM driving data (historical projections in present conditions) allows assessing the performance of particular GCM-RCM couplings. This is crucial for climate change applications, since any deficiency in a particular coupling may affect the credibility of future changes (Turco et al., 2013). The assessment is typically performed comparing climate statistics (such as mean, standard deviation or particular indices) of simulated and reference observed data. For reanalysis-driven simulations, the day-to-day correspondence with observations at the boundaries has been used in some cases to assess temporal aspects of the simulations (see Maraun et al., 2015, for more details).

In this article, we provide a summary of recent progress regarding the evaluation of dynamical and statistical downscaling over Spain. The aim is to update the results of the previous Spanish CLIVAR-Spain assessment (Sánchez and Miguez-Macho, 2010), which was based mostly on results from the European PRUDENCE project. The studies reported in this article relied on data from subsequent international regionalization initiatives such as ENSEMBLES (Déqué et al., 2012), VALUE (Maraun et al., 2015) and CORDEX (Jacob et al., 2014), as well as the Spanish strategic actions for the coordinated generation of regional projections using dynamical (ESCENA project) and statistical (ESTCENA project) methods. These projects provide regional climate simulations with resolution ranging from 0.44º to 0.11º (while the typical resolution of the GCMs is around 2º).

Dynamical Downscaling

Many studies analysing RCMs in present climate conditions on the Iberian Peninsula have been published since 2010. Some examples are international initiatives and projects such as EURO- and Med-CORDEX or ENSEMBLES and the national ESCENA project. These can be split in two groups: those that focus on the Iberian Peninsula or Spain (Herrera et al., 2010; Jiménez-Guerrero et al., 2013; Jerez et al., 2013b, among many others), and those where the Iberian

Peninsula is only a part of the analysis area (Vautard et al., 2013; Kotlarski et al., 2014; Katragkou et al., 2015, among many others).

Most studies evaluating RCMs usually focus on near-surface temperature and precipitation (Herrera et al., 2010; Jerez et al., 2013b; Gómez-Navarro et al., 2013), although some others have focused on wind (Jiménez et al., 2010; Lorente-Plazas et al., 2015; Gómez et al., 2016), snow (Pons et al., 2016), radiation (Ruiz-Arias et al., 2013), or soil-atmosphere fluxes (Knist et al., 2017). The evaluation of several variables involved in a process is highly recommended in order to identify and avoid possible error compensation (García-Díez et al., 2015b). It is important to focus on target processes instead of target variables. Even if interested in precipitation, or precipitation change, the process of precipitation (how/when does it rain? Is cloud cover realistic? partition between stratiform and convective rainfall, etc.) should be evaluated to build trust in the model. The potential of process evaluation is one of the main advantages of RCMs with respect to ESD. Another dimension to evaluate a process is by evaluating different climate regimes: assessing the capability to reproduce the mean climate (annual cycle and temporal variability) (Fernández et al., 2007; Argüeso et al., 2011; Jiménez-Guerrero et al., 2013; López-Franca et al., 2013) along with more extreme regimes (Argüeso et al., 2012; Domínguez et al., 2013; Vautard et al., 2013; López-Franca et al., 2015).

The main conclusion of those studies is that RCMs over the Iberian Peninsula provide very valuable information, proving that RCMs enhance local spatial distribution of climate variables, mainly due to a better representation of orographic and surface features. RCMs are largely able to capture precipitation regimes, temperature and wind variability as well as extreme events. However, substantial biases are still observed, hindering the direct applicability of RCM outputs in sectorial applications (hydrology, agriculture, energy, etc.). This opens a controversial issue about RCM bias correction, or adjustment, and its impact on the climate change signal (Casanueva et al., 2017; Turco et al., 2017). Moreover, the benefits of increasing RCM resolution are not clear (e.g. from 0.44º to 0.11º). While some studies claim clear benefits (Prein et al., 2016), others (García-Díez et al., 2015a) suggest that, as model resolution increases, traditional skill scores could not be appropriate, or even that there is not a clear improvement, e.g. in model biases (Casanueva et al., 2016b). Model formulation could be more important for the proper simulation of some processes (Gaertner et al., 2016).

Observational data (and the lack of them) play a key role in model evaluation. There are two main sources of observational data: raw meteorological data (point stations, soundings, satellite data, etc.) and gridded products based on them, which are most commonly used for RCM evaluation. There are several gridded databases available over Spain, such as E-OBS, CRU and Spain02 (Herrera et al., 2016), obtained using different sets of original meteorological stations as well as different interpolation methods. This leads to important differences between them, which makes model evaluation database-dependent (Gómez-Navarro et al., 2012). Therefore, observational databases are an important source of uncertainty in model evaluation. Various methodologies have been applied for comparing modelled and observed data: direct comparison and regionalization of data. The first one consist of comparing the observed value with the model data interpolated at such location (Fernández et al., 2007; Jiménez-Guerrero et al., 2013). Here, some controversy emerges, since results can depend on the interpolation method selected. The second one is based on the generation of spatial regions with similar climate variability for comparison (Herrera et al., 2010; Argüeso et al., 2011; Lorente-Plazas et al., 2015; Argüeso et al., 2011). This technique seems to be more robust since local effects that RCMs are unable to explain are filtered out but, on the other hand, the loss of regional detail could mask the added value of high resolution experiments.

Dynamical downscaling brings inherently a number of uncertainties related to virtually any change in the model: dynamical core, physical parameterizations, domain size and position, and initial conditions. These uncertainties are usually explored using ensembles of simulations. Several studies have analysed the uncertainty introduced by many of these factors, being multi-model ensembles the most common one (Herrera et al., 2010; Jiménez-Guerrero et al., 2013; Domínguez et al., 2013; Vautard et al., 2013). Over the Iberian Peninsula there have been also a remarkable number of studies dealing with multi-physics ensembles (Fernández et al., 2007; Argüeso et al., 2011; Argüeso et al., 2012; García-Díez et al., 2013; Jerez et al., 2013b; Katragkou et al., 2015). The latter provides the advantage of perturbing a single component of the model (microphysics, convection, radiation, etc.), thus linking the response to specific processes. In this way, the contribution of the different components to total uncertainty can be assessed, and also potential changes in their role in the future climate (Jerez et al., 2013a).

In most cases, ensemble mean properties show a great improvement in temporal variability and representation of the spatial patterns of the climatic variables with respect to the individual members, and very often the large ensemble spread covers the observational data. Multi-physics ensembles show spread of comparable magnitude to that obtained in multi-model ensembles, suggesting that multi-model ensemble spread can largely be attributed to the different physics of individual models. Another recurrent result is that no single multi-physics or multi-model ensemble member outperforms the others in every situation (time and space), and that biases are independent of the skill in reproducing the temporal variability. Nevertheless, some particular schemes or models display an overall better performance, while others use to present the worst results. In addition, the analysis of long periods (climatological) when evaluating models or physical parameterizations concluded that short-term studies should be used with caution. This opens the door to the distillation problem, i.e. to decide how conflicting messages from different models, configurations or experiments should be weighted to provide actionable information. In the last few years, the RCM community is incorporating more complexity to their models (mainly atmospheric component) by coupling them to models of other components of the climate system at regional scale. Some examples are sensitivity studies on the role of land surface models (Jerez et al., 2010; Jerez et al., 2012; Knist et al., 2017) or coupling to regional ocean models (Gaertner et al., 2016), and chemistry models (Palacios-Peña et al., 2017). While it is proved that the role of a land surface model is crucial for a right climate simulation, specially in areas with a transitional regime in land-atmosphere feedback, there are no clear works presenting a remarkable impact of coupling RCMs to regional ocean models. The enhancement of climate simulations by coupling RCMs to chemistry models has not been fully experimented, although there are some promising results (Baró et al., 2017).

Statistical Downscaling

Two fundamentally different approaches can be followed for statistical downscaling. Under the Perfect Prog (PP) approach, the statistical relationships are calibrated considering observations for both predictands (historical observations) and predictors (reanalysis data), whereas model predictions (from GCMs or RCMs) are used for the latter under the Model Output Statistics (MOS) approach. The typical predictor in MOS is directly the variable of interest, which is calibrated against the local observed counterpart. In the climate change context, this is typically done using distribution (e.g. mean- or quantile-mapping) corrections, which is usually referred to as (distributional) bias correction (BC) in the literature. It is important to note that the reanalysis choice is an additional source of uncertainty for PP methods, although it does not play an important role over the IP (Brands et al., 2012).

Gutiérrez et al. (2013) and San-Martin et al. (2017) evaluated the performance of several standard PP methods over Spain, including different implementations of analogs, weather types and regression techniques. After a screening process analysing different domains and considering commonly used predictors, they found that results are more sensitive to the predictor choice than to the geographical domain, although better results are generally obtained with smaller domains covering the Iberian Peninsula. The best configuration of predictors is formed by sea level pressure and 2-meter temperature (for temperatures) and sea level pressure and temperature and specific humidity at 850hPa (for precipitation). These large-scale predictors were shown to be well simulated by CMIP5 GCMs (Brands et al., 2013). Other PP downscaling methods have been tested over the Iberian Peninsula, including a two-step analog method (Ribalaygua et al., 2013) and a weather-typing technique (Osca et al., 2013). These studies were undertaken in the framework of the ESTCENA project, feeding the Spanish national plan for regional scenarios. Casanueva et al. (2016b) analysed the biases of the EURO-CORDEX RCMs over the Iberian Peninsula and the effect of simple BC methods based on linear scaling. More sophisticated BC techniques have been analysed specifically over the Iberian Peninsula (Amengual et al., 2011) as well as in the context of continental-scale studies (Dosio and Paruolo, 2011). Turco et al. (2011) and Turco et al. (2017) analysed the potential for downscaling and bias correction of generic MOS methods (based on analogs), building on the marginal day-to-day correspondence exhibited by reanalysis-driven RCM simulations. These methods are shown to be a spatially consistent alternative to standard bias correction methods, although the limitation for extreme values should be taken with caution in applications where this aspect is relevant. Among the benefits of SDMs, it could be highlighted that they are less computationally demanding than the RCMs and allow downscaling non-meteorological variables, such as wind power (García-Bustamante et al., 2013) or climate impact indices (Casanueva et al., 2014). The main limitation of the SDMs is that they rely on the available observed time series for the training/calibration phase. Also, they may suffer from non-stationarities or lack of extrapolation capability when applied in climate change applications. An example of this limitation is reported in Gutiérrez et al. (2013) for analog-based methods over the Iberian Peninsula. Finally, there have been several studies comparing statistical and dynamical downscaling over the Iberian Peninsula (Casanueva et al., 2013; San-Martín et al., 2017). However, for a fair comparison, special care must be taken in order to use suitable indices not directly calibrated by any of the two methodologies (Casanueva et al., 2016a).

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Regional Climate Projections over Spain: Atmosphere. Future Climate Projections

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Introduction

Regional climate information is increasingly being demanded by vulnerability, impact and adaptation (VIA) research communities. This information is required to feed impact models for specific sectors (health, energy, food availability, risk management, water resources) and for decision-making processes at different levels. Different global and regional climate change projections for the 21st century have been produced over the last decades using both dynamical regional climate models (RCMs) and statistical downscaling methods (SDMs) in a series of international and national initiatives. As a result, large ensembles of future global (e.g. CMIP3, CMIP5) and regional (e.g. ENSEMBLES, CORDEX) climate projections are available, sampling most of the uncertainties affecting climate change. Nowadays, users are confronted with the technical and ethical (distillation) dilemma of deciding which information out of the large amount of available data is best suited for their application, in order to address the different sources of uncertainty for their specific region/problem (Hewitson, 2013).

Regional Climate Change Scenarios for Spain

The Earth System Grid Federation (ESGF, https://esgf.llnl.gov) infrastructure provides standardized access to the last-generation climate change model output data (from CMIP5 and CORDEX). However, the direct use of ESGF is still complex and slow for an average user and therefore there are still several portals providing scenario data (e.g. for a particular region), as well as sector-specific derived indices (Hewitson et al., 2017).

In Spain, the main sources of regional climate change information have been collected by the Escenarios-PNACC initiative. The first dataset (Escenarios-PNACC, 2012) was based on CMIP3 projections from global circulation models (using B1, A1B and A2 greenhouse gases emission scenarios), and provided information for temperature and precipitation and several derived indices (e.g. percentiles). Besides the European-wide dynamical regional climate change projections provided by the EU-funded ENSEMBLES project (Déqué et al., 2012), and the contribution from AEMET (statistical downscaling methods), this initiative was fed with the outcomes of two strategic actions (ESCENA and ESTCENA, for dynamical and statistical downscaling, respectively) undertaken by the Spanish scientific community on regional climate change projection in the framework of the Spanish R+D 2008–2011 Program. The dynamical simulations complemented those produced in ENSEMBLES, focusing on a domain centered in the Iberian Peninsula (Fernández et al. 2012; Jiménez-Guerrero et al. 2013, Domínguez et al., 2013). The statistical downscaling scenarios were produced with different analog- and regression-based downscaling methods (Gutiérrez et al. 2012). The observational data set was based on a selection of stations provided by AEMET and on the gridded observations provided by Spain02 v2.1 (regular grids, at a 20 km resolution; see Herrera et al. 2012). More information and links to access data are described in Escenarios-PNACC (2012).

There have been a number of studies analysing these results and assessing the limitations of the different datasets forming Escenarios-PNACC 2012, focusing mainly on temperature and precipitation. For instance, Turco et al. (2015) analysed the ENSEMBLES regional projections for daily maximum temperature and precipitation over Spain, and found consistent changes up to 2050 (A1B scenario) among the different members, generally indicating a decrease in precipitation (between -5 and -25 %) and an increase in maximum temperature (between 1 and 2.5°C, depending on the season/area). Gutiérrez et al. (2013) reported a limitation of generic analog based methods to extrapolate future temperatures for the last decades of the century. Therefore, those results should be used with caution for studies sensitive to this fact. Moreover, San-Martín et al. (2017) found a good agreement between dynamical (ENSEMBLES) and statistical (ESTCENA) regional projections for precipitation over Spain, although during summer and autumn the statistical methods exhibited a large uncertainty for different families (regression vs. analog methods).

There have been also some studies analysing additional variables such as snow, wind speed or dry spells. For instance, Pons et al. (2016) reported a decreasing trend in annual snowfall frequency (measured as the annual number of snowfall days) from the ENSEMBLES regional projections, with member values ranging from −3.7 to −0.5 days decade^{-1} (−2.0 day decade^{-1} for the ensemble mean). These future trends are similar to the historical observed ones since 1970 (−2.2 days decade^{-1}), and are mainly determined by the increasing temperatures. Gómez et al. (2016) analysed wind speed using ENSEMBLES data and found that the wind speed for 2031–2050 is reduced up to 5% compared to the 1980–1999 control period for all models. The models also agree on the time evolution of spatially averaged wind speed in each region, showing a negative trend for all of them. López-Franca (2015) analysed dry spells over Spain and found an increase of the probability of occurrence of long dry spells together with a decrease in the shorter ones.

The uncertainty of regional climate projections due to model physics has been also addressed for the specific case of the Iberian Peninsula. For instance, Jerez et al. (2013) showed that the spread of multi-physics ensembles are of the same order of magnitude that multi-model ensembles, and that model projections intensity does not depend on bias at present simulations. However, the spread could depend on the synoptic conditions that are usually different in future climates. In addition, Jerez et al. (2012) assesses the influence of the land-surface processes simulation, particularly the contribution of soil moisture modelling in perturbed climates, and its great importance on transitional climate zones.

These studies provide comprehensive information on the Escenarios-PNACC dataset, although further research is needed to understand the methodological and practical limitations of regional projections, particularly the extrapolation capability of the different methods, i.e. the robustness of the stationarity assumption.

Besides the PNACC activities, there have been also a series of studies of regional climate change projections in Spain, which are also valuable for regional studies. For instance, Osca et al. (2013) describes the application of a weather-type technique for precipitation over Spain. Ribalaygua et al. (2013) describes the results of a two-step analog method for regional projection in Aragón. Gómez-Navarro et al. (2010) presents the results of long dynamical projections for Spain with the MM5 model. Pérez (2014) and Gonçalves (2014) describe dynamical downscaling results using WRF over the Canary Islands and Mediterranean Spain, respectively. Ramos et al. (2013) analysed CMIP3 precipitation projections with a SDM.

An update of Escenarios-PNACC is being prepared, based on the new information produced using CMIP5 global projections (focused on the RCP2.6, RCP4.5 and RCP8.5 scenarios). The new edition (Escenarios-PNACC 2017) is based on the research done by Spanish groups in the framework of the EU VALUE SDM intercomparison project (Maraun et al., 2015), and the RCM projections produced in the context of the EURO-CORDEX (Jacob et al., 2014) and MED-CORDEX (Ruti et al., 2016) initiatives. The update of the observational dataset is Spain02 v5 (at 10km resolution, both regular and rotated grids). Most of this information is already available (with daily temporal resolution) at http://www.aemet.es/es/serviciosclimaticos/cambio_climat and http://www.meteo.unican.es/escenarios-pnacc

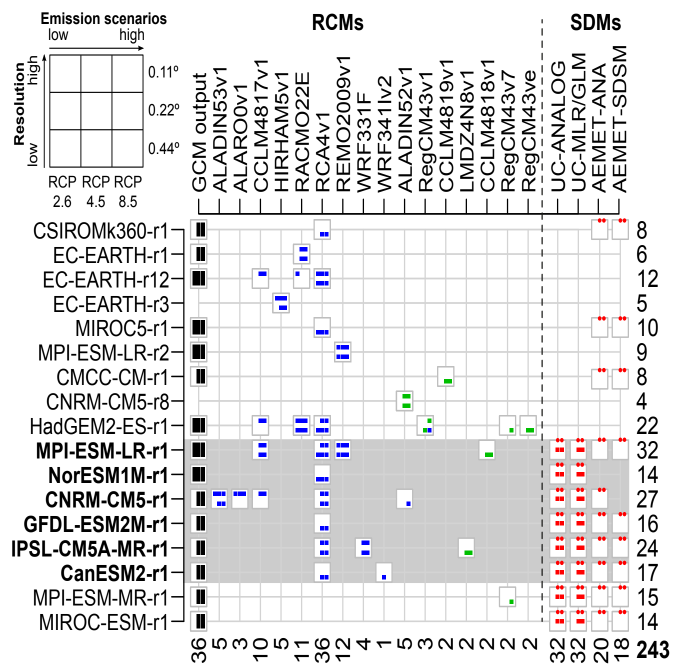

Figure 1: GCM-RCM matrix for the dynamical (blue from EURO-CORDEX, green from MED-CORDEX) and statistical (red) ensemble of regional projections from CMIP5 data available as of April 30th, 2017. Numbers show the number of ensemble members (marginal frequencies) for a given GCM (rows) or RCM/SDM (columns). The available projections comprise simulations at three resolutions (0.11º, 0.22º and 0.44º) and for three RCP scenarios (RCP 2.6, 4.5 and 8.5), as displayed in the matrix shown in the upper-left corner. Note that statistical downscaling methods provide local (station-based) information (denoted by the points over the square boxes) and, in some cases, also areal grid-box information (downscaled from Spain02 v5). Additionally, AEMET statistical downscaling point estimates are also available for 14 other CMIP5 GCMs for ANA and 10 for SDSM, not shown in this table.

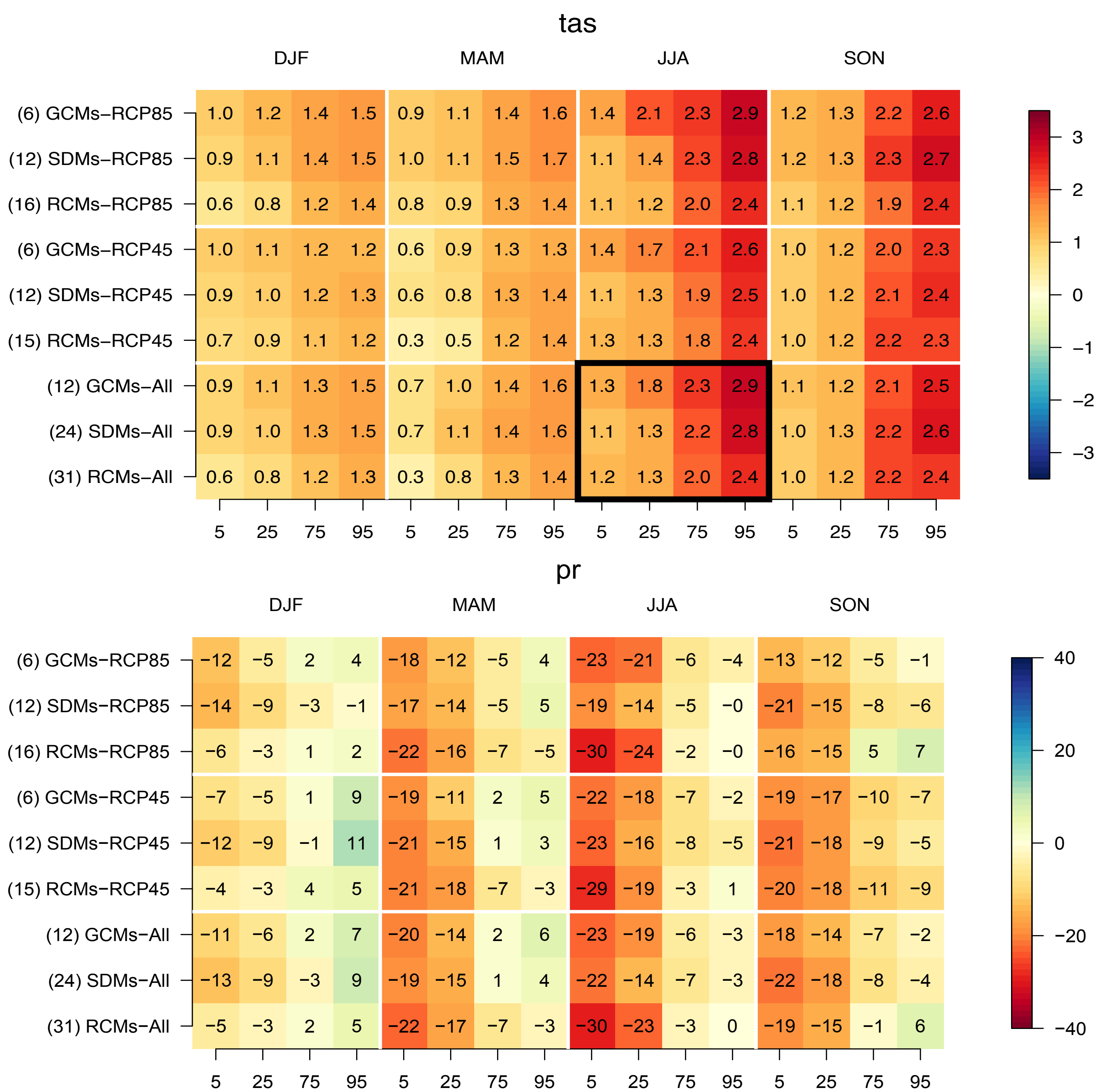

Figure 2: Projected changes for seasonal temperature (ºC, top) and precipitation (%, bottom) by 2021- 2050, with respect to the average of the 1971-2000 period, on average for continental Spain and the Balearic Islands for two different forcing scenarios (RCP8.5, RCP4.5 and both "All") considering the GCM, SDM, or RCM projections (in different rows for each scenario). In order to provide comprehensive information about the ensemble uncertainty in the climate change signal, different percentiles (5, 25, 75 and 95) are given for each case. The range 25-75 is the typical value used to characterize the ensemble spread, whereas 5th and 95th values characterize the extreme signals within the ensemble

Figure 1 shows the information already available from Escenarios-PNACC 2017, with a GCM-RCM/SDM matrix for the multi-project ensemble considered in this study and publicly available as of April 30th, 2017. The numbers show the marginal contribution to the ensemble for each particular GCM (in rows) and RCM/SDM (in columns). These include different forcing scenarios and RCM resolutions (see figure caption). For each GCM-RCM/SDM couple, boxes indicate the available spatial resolutions (0.11º, 0.22º and 0.44º) and RCP scenarios (RCP 2.6, 4.5 and 8.5). Note that, besides the two spatial resolutions, SDMs also provide local (station based) projections for a number of stations (over 2300 selected by AEMET). This makes a total of 255 regional projections available, forming a large multi-model multi-downscaling ensemble sampling the regional uncertainty for climate change projections over Spain. This dataset will be the basis for future regional climate change studies in Spain.

Figure 2 shows projected temperature and precipitation changes by 2021-2050 averaged over continental Spain and the Balearic Islands. It includes only the set of GCMs downscaled by dynamical and statistical models for the same RCP and spatial resolution, thus forming a balanced ensemble representative of regional uncertainties (grey shadow in Figure 1). Projected changes are presented as central 50% and 90% ranges (obtained from the 25th-75th and 5th-95th percentiles of the ensemble), estimated by different sub-ensembles, and for different seasons. For precipitation, there is a general trend to decreasing average precipitation in all seasons, although the expected range of change is only completely on the drier side during summer, reaching an average decrease of -30% for RCM estimates. Regarding temperature, the largest increases are expected in summer and autumn, reaching close to 3^{o}C with respect to the 1971-2000 climatology in the upper end, and no less than 1^{o}C in the most conservative estimates. GCMs tend to provide warmer estimates, which are matched in the upper end by SDMs. These, however, show larger spread and colder lower ends. RCMs provide, in general, colder estimates.

A description of the EURO-CORDEX projections at European level is given in Jacob et al. (2014), which also presents a comparison of the results with the previous ENSEMBLES scenarios. Some statistical downscaling studies building on CMIP5 data have been recently published analysing different aspects of climate change projections in Spain. For extremes, Monjo et al. (2016) applied a two-step analogue/regression downscaling statistical downscaling using CMIP5 predictors over Spain, and analysed 50 and 100-year return values for precipitation. They found that the projected changes were in general smaller than the natural variability. Future changes in extremes such as tropical-like cyclones phenomena (known as "medicanes" when located over the Mediterranean sea) in oceanic regions around the Iberian Peninsula have been studied with CMIP5 models (Romero and Emanuel, 2017) or ENSEMBLES RCMs (Romera et al., 2017)

Impact Studies and Bias Correction

There have been also a number of studies analysing the impact of climate change projections in different sectors using climate-related indices building on regional climate information. For instance, Bedia et al. (2013, 2014) analysed fire danger projections over Spain using the Fire Weather Index (FWI), and statistical/dynamical projections with CMIP3/ENSEMBLES data, respectively. Resco et al. (2015) and Lorenzo et al. (2016) analysed winegrowing in Spain using different bioclimatic indices and ENSEMBLES data. Jerez et al. (2015) analysed photovoltaic power generation in Europe using EURO-CORDEX data. Esteve-Selma (2012) studied the future distribution of Tetraclinis articulata (an endemic Mediterranean tree). Bafaluy (2014) investigated a number of climate indices relevant for tourism using ENSEMBLES data. Casanueva et al. (2014) introduced the direct application of statistical downscaling to multi-variate climate indices for fire danger and tourism.

One of the main problems found in impact studies when analysing climate-derived indices using RCM data is the effects introduced by model biases. Casanueva et al. (2016) provides a detailed analysis of EURO-CORDEX biases over Spain. This has motivated a huge research activity over the last two decades in order to find suitable bias adjustment methods, able to correct model biases against a reference high-resolution climatology. An intercomparison of different bias adjustment methods over Europe, using ENSEMBLES data, is provided in Dosio et al. (2012). Several impact studies have explored the use of these techniques. For instance, Ruiz-Ramos (2016) analysed the application of several bias correction methods for improving crop impact projections in the Iberian Peninsula for 21st century. Gabaldon-Leal (2015) used bias corrected ENSEMBLES data to analyse summer crops in the southern Iberian Peninsula, focusing on the impacts of rising temperatures, and of higher frequency of extreme events on irrigated maize, and to evaluate some adaptation strategies.

Further research on bias correction methods include the work by Romero et al. (2011), presenting a new parametric trend-preserving bias correction method, and by Turco et al. (2017), introducing a new methodology for correcting and downscaling RCM data based on an analog technique.

Distillation of global and regional scenario results

VIA research communities are usually advised to consider an ensemble of model projections, or at least a selection of members spanning the ensemble uncertainty, in order to propagate the uncertainty arising from different greenhouse gases emission scenarios and (global and regional) climate models. However, the distillation of information out of the large amount of available data is a technical and ethical challenge (Hewitson et al., 2013). It is still not clear how to best proceed in order to select a subset of representative data (out from the large ensemble available) for a particular study (Cannon, 2015). Moreover, different datasets could provide inconsistent or even conflicting information making this process even harder. This is one of the key challenges considered in ongoing initiatives (e.g. the "distillation of climate information" work package within EURO-CORDEX), and further advances are expected in the coming years.

In order to illustrate this problem, we will see that the simple summary of ensemble members in percentile ranges shown in Figure 2 is misleading. Ensemble

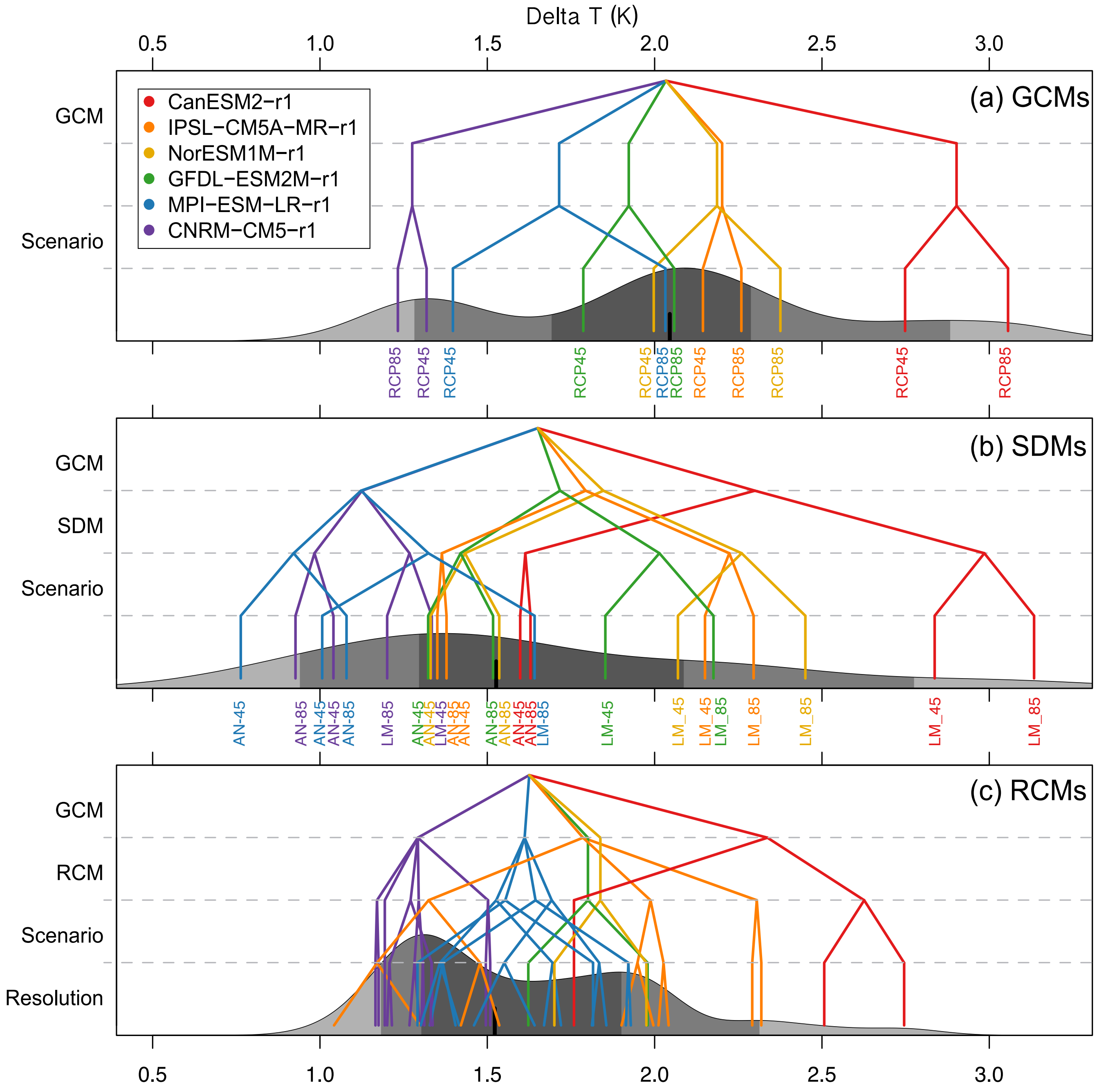

Figure 3: Summer (JJA) temperature deltas (2021-2050 vs 1971-2000) averaged over continental Spain and the Balearic Islands. The 255 ensemble members considered in this work have been split into sub-ensembles considering only (a) GCMs, (b) SDMs and (c) RCMs. In each case, the lines at the bottom depict all sub-ensemble member deltas and are averaged at the joints as the plot progresses upward to the upper joint representing the sub-ensemble mean. Probability density functions are estimated for each sub-ensemble and 50% and 90% central range estimates are depicted as shades. See Fernández et al. (2017) for more information.

members are not independent and specific features of downscaling methods, and (lack of) ensemble design, are behind the different climate change ranges shown. As an example, we focus on summer temperature change (squared in Figure 2) and show individual results (Figure 3) for the three sources of future projections (GCMs, SDMs and RCMs). Individual delta change estimates at the bottom are coloured by the driving GCM, which is the largest source of uncertainty (spread). There are GCMs, such as CanESM2, ranking in the upper end of the temperature change (Figure 3a), while others (e.g. CNRM-CM5, MPI-ESM) tend to project smaller changes. This trend is essentially preserved by downscaling methods (Figure 3b,c) with some particularities. In SDMs, the statistical method used (linear model -LM- or analogues -AN-) is a large source of spread, with analogue methods ranking clearly at the lower end due to their inability to extrapolate temperatures beyond the observed range. On the other hand, the RCMs, which are more physically based, are computationally very expensive, and the available GCM population has been very unevenly sampled. In this example, RCMs have favoured two of the GCMs projecting the smallest delta changes (CNRM and MPI models). This fact, along with a genuine tendency by the RCMs to project smaller delta changes (potential added value) results in a narrower range and smaller mean temperature change than projected by GCMs.

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Regional marine climate projections over Spain

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Introduction

Changes in marine climate due to global warming can potentially have dramatic consequences for a country like Spain where the ocean plays a key role in the country's socioeconomics. In Spain, a large fraction of the population lives in or close to coastal areas, and the national economy strongly relies on tourism, fisheries and marine transport activities (Kersting, 2016). Global warming would impact on the marine environment in different ways. The increase of global temperatures implies an increase in the ocean temperature which in turn implies an increase of sea level through the thermal expansion of the water column. Also, the warming induces larger rates of the terrestrial ice melting which also contribute to increase the sea level. Such increase would translate in an increase of coastal floodings, salinization of aquifers or the enhancement of the damages associated to sea storms (Nicholls and Cazenave, 2010). Another potential effect of global warming is the modification of the atmospheric circulation systems (e.g. wind fields, sea level pressure anomalies), which translates into a modification of the sea surface dynamics (basically storm surge and sea surface waves) due to meteorological drivers. Changes in the intensity, direction or period of the wind-waves can alter (i) the morphodynamics of coastal areas (e.g. beach erosion, shoreline retreat), and (ii) increase damages due to marine storms (Field, 2012). Finally, global warming can also induce changes in the ocean currents and the redistribution of salt and heat. Alterations in the temperature and salinity fields can have profound impacts on certain marine ecosystems through increases of the mortality, displacement of ecological niches or enhancement of invasive species (e.g. Marbà et al., 2015).

Several studies have analysed the potential impact of climate change on the Spanish marine environment. For instance, Losada et al. (2014) and Sánchez-Arcilla et al. (2016) analysed the potential coastal impacts, Gomis and Álvarez-Fanjul (2016) focused on the atmosphere and ocean variables trends for the last decades and 21st century in areas surrounding the Spanish harbours, and Kersting (2016) reported the impacts and vulnerability over the marine ecosystems. They found that sea level and wind waves, for physical ocean dynamics, and salinity and temperature for chemical conditions, are the main marine climate drivers. However, an updated review of the projected impacts of global warming on the physical variables around the Spanish coasts is still required. In the last CLIVAR-Spain report (Pérez-Fiz et al., 2013), Vargas-Yáñez et al. reviewed the signs of the on-going changes in the marine climate around the Spanish coasts. Nevertheless, the issue of regional marine projections was not addressed because at that time few studies were available. The goal of this article is to show the progress made by several studies, which allow us to draw an overall picture of what will be the impact of global warming on the Spanish marine environment.

The article will adress first the Mediterranean and then the Atlantic side of Spain. This distinction is required for physical reasons. Both regions behave very differently and the mechanisms that drive the evolution of the marine climate in each region are quite independent. Thus, it makes more sense to separate both regions in the analysis. It has also to be noted that, probably because of the singularity of the Mediterranean basin, there are much more regional studies focusing on the Mediterranean than on the NE Atlantic. Here we have tried to compensate for this imbalance analysing also global studies that shed some light into the evolution of the NE Atlantic. For each section we study different variables: wind waves, sea level, temperature and salinity. The analysis of currents is not included because of the lack of studies focusing on this variable. Finally, it is worth mentioning that at present there are few regional studies based on the RCP scenarios (Moss et al., 2010) which are those used in the last IPCC report (AR5; Collins et al., 2013). The reason is that ocean projections are always delayed with respect to global climate simulations. Regional ocean models require high resolution atmospheric forcing (i.e. downscalings from global models) which in turn require some time to be produced after the apparition of global climate projections. In consequence, here we will review studies using both RCP and SRES (i.e. IPCC-

AR4 report) scenarios. It should be noted that global warming projected under the RCP scenarios shares some similarities with to the one projected under SRES scenarios, so both sets of scenarios can be assimilated.

A. Mediterranean Region

A.1 Wind waves

The wave climate on the Spanish Mediterranean coast is milder than in the Atlantic with smaller mean wave heights (1-1.5 m) and shorter periods (5-6 s), and presents an important spatial variability. Seasonal wave climate variations show a different behaviour with respect to the winter-summer pattern of the Atlantic coast, with a strong semi-annual pattern (Menéndez et al., 2014) defined by maxima wave heights in spring and autumn, due to the more powerful cyclones that result from increased air-sea interactions during that period.

The evolution of the wind wave climate is strongly determined by the future evolution of the storm tracks. Although most projections show an increase of wind intensity north of 45ºN (Donat et al., 2011; Nikulin et al., 2011), the poleward shift location is subject to debate (Scaife et al., 2012). In addition, and despite not being the predominant factor, extratropical cyclones are also affected by concentration of water vapour in the atmosphere, which enhances their intensity, and by sea surface temperature (SST) gradients, which affects their position and activity (Bengtsson et al., 2006). Because of these factors, most studies concur that there will be a decrease in the number of Mediterranean cyclones. However, there is a lack of consensus on whether the number of intense cyclones will increase or decrease (Pinto et al., 2007).

These changes also determine the wind-wave projections. Lionello et al. (2008) ran a regional wave model for the whole Mediterranean under scenarios A2 and B2. They found that the mean significant wave height (Hs) over large fraction of the Mediterranean Sea would be lower during all seasons at the end of the 21st century, with a larger reduction during winter (about -20 cm) under scenario A2. These changes are similar, though smaller and less significant, in the B2 scenario, except during winter in the northwestern Mediterranean Sea, when the B2 mean Hs field would be higher than at present. Regarding extreme events, these authors also found smaller values in future scenarios than in the present climate. Also, they showed that, in general, changes of Hs, wind speed and atmospheric circulation were consistent. Casas-Prat and Sierra (2013) ran a regional wave model of the Western Mediterranean forced under scenario A1b by 5 different atmospheric downscalings. Their results show an increase in the northwestern winds and waves over the Gulf of Lion, which translates into a greater future predominance of wind-sea states in that region. These authors found projected height changes around ~ 10% for mean conditions (median Hs), ~ 20% for extreme climate (50-year return level), and small changes in the frequency of occurrence of waves from different directions (~ 5%). In their results, the spatial patterns of change are complex, and results of models forced by different global climate models (GCMs) do not agree. Finally, in a work based on statistical downscaling, Pérez et al. (2015) projected a decrease in Hs (Tm) of -5 cm (-0.1 s) under scenario RCP8.5, -3 cm (-0.2 s) under scenario RCP4.5, and no change under scenario RCP 2.6. These results agree with the above-mentioned studies, and point towards a larger decrease in the wave height under higher emission scenarios. Nevertheless, it is important to keep in mind the large uncertainties associated to these projections.

A.2 Sea Level

Modelling sea level variability in the Mediterranean Sea is not straightforward. On one hand, GCMs do not have enough spatial resolution to reproduce the main mechanisms that control the regional dynamics (Calafat et al., 2012a). For instance, the heat redistribution inside the basin is strongly biased if a too coarse resolution is used (Llasses et al., 2016). This has a strong impact on the reliability of the temperature projections in the Mediterranean, and consequently on the thermal expansion. On the other hand, at low frequencies the variability of the Mediterranean sea level is strongly influenced by changes in the nearby Atlantic (Calafat et al., 2012b), which is usually not included in regional climate models (RCMs) so making it impossible for them to estimate long term trends of total sea level (Calafat et al., 2012a).

Up to now, regional studies on projections of the Mediterranean sea level have focused on one of the components of sea level variability: the steric component (i.e. linked to changes in the density of the water column). However, due to the complexity of the basin dynamics, it has been shown that projections based only on the steric component should be carefully considered (Jordà and Gomis, 2013). Carillo et al. (2012) computed the evolution of the steric component in the Mediterranean until 2050, using two simulations forced by ECHAM5 model under the scenario A1b. Their results show a thermal expansion of ~5 cm in 2050. They also concluded that differences in the temperature of Atlantic waters flowing into the Mediterranean have little effect on the thermal evolution of the basin. Gualdi et al. (2013) used an ensemble of five regional coupled atmosphere-ocean models to estimate the evolution of the steric component until 2050 under the scenario A1b. Their results showed an increase in that component of ~15 cm, although it should be noted that this is not completely representative of total sea level as the salinity effects are not filtered out. Adloff et al. (2015) used an ensemble of regional ocean models to produce projections of the thermosteric component and to perform different sensitivity experiments. Their results project a basin average thermal expansion at the end of the 21st century ranging from +34 to +49 cm under scenario A2. Those discrepancies are mainly due to the conditions prescribed for the Atlantic forcing, thus somehow in disagreement with Carillo et al. (2012), which did not find significant sensitivity to the Atlantic forcing. Also, Adloff et al. (2015) showed that similar results were obtained by forcing the model under scenario A1b. Finally, Somot et al. (2016) followed a different approach combining information from global models with results of regional models to infer a more complete view of future Mediterranean Sea projections. From their results, it can be seen that the Mediterranean Sea level will basically follow the global mean sea level changes because of the combination of two factors. First, circulation changes in the northeastern Atlantic will translate in to an increase of Mediterranean sea level larger than the global average. Second, the fingerprints of continental ice melting will result in changes lower than the global average. Those two changes will roughly cancel out. In the end, the total sea level change for the Mediterranean has been projected to range between 4 and 100 cm (Figure 1a). Also, Somot et al. (2016) showed that regional differences inside the basin could differ up to ~ 15 cm from the basin average (Figure 1b).

Regarding extreme sea level events, Marcos et al. (2011) used a storm surge model forced by a regional atmospheric model under scenarios B2, A1b and A2 in order to characterize their evolution in a changing climate. Their results point towards a reduction on the average number of positive surges, whereas negative surges will increase throughout the 21st century. Such changes in the magnitude of extreme events can be partially attributed to the negative trend of the mean atmospherically-induced sea level projected for the future (Jordà et al., 2012a), with changes in winter up to -8 cm under scenario A2. Overall, the results indicate small changes in comparison with their present day magnitude (reduction of -10%). Jordà et al. (2012a) also found that some events in the scenario simulations were especially strong, thus suggesting that fewer cyclones can be expected, with an increase in the strength for some of them. Conte and Lionello (2013) performed an ensemble of a seven-member storm surge simulations until 2050, forced under the A1b scenario. They found an overall decrease of approximately 5% in the magnitude of positive surges with changes up to -10% in some locations along the Mediterranean coasts. They showed large differences among simulations and results not spatially coherent. In a more recent work, Lionello et al. (2016) found consistent results. In other words, projections of extreme sea level events in the Mediterranean are very sensitive to the choice of the atmospheric forcing.

A.3 Temperature and salinity

The evolution of hydrographic properties of the Mediterranean is closely linked to the evolution of water and heat fluxes through the sea surface. GCM projections

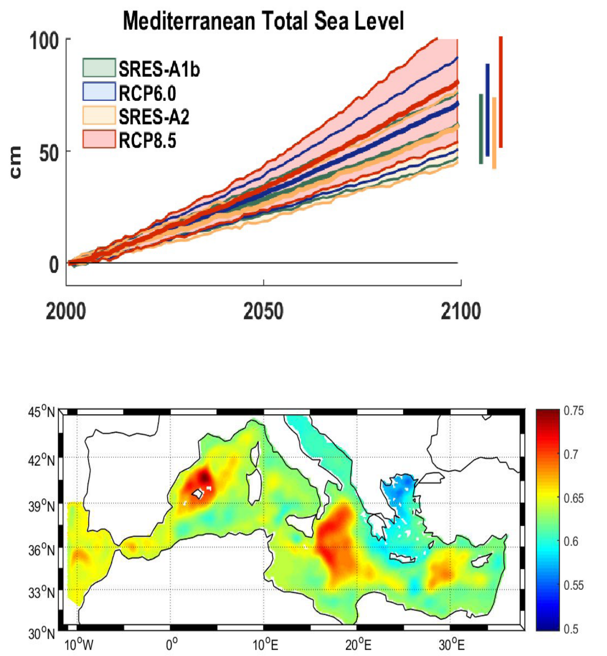

Figure 1: (Top), projections of basin average Mediterranean sea level (in cm, adapted from Somot et al., 2016). **(Bottom),** spatial distribution of Mediterranean sea level projection (in m) for 2100 under a moderate scenario (RCP4.5 or A1b).

for the Mediterranean region suggest a decrease of surface heat loss and an increase of surface water flux towards the atmosphere (Collins et al., 2013). Sánchez-Gómez et al. (2009) analysed the outputs from 12 RCMs forced by 6 different GCMs under the A1b scenario. Their results show that the Mediterranean water budget is likely to be significantly altered at the end of 21st century. Specifically, the regional projections show a 12% increase in the evaporation, a 16% reduction in precipitation, a 24% reduction in the rivers runoff, and a 40% reduction in the contribution from the Black Sea. All these changes result in an increase of 40% of water losses. The response of the hydrological variables to global warming starts to be statistically significant after 2050, though some alterations are already observed before 2050. Dubois et al. (2012), using a small ensemble of atmosphere-ocean coupled regional climate models (AORCMs), showed similar results. Moreover, those simulations project an increase of the surface heat loss for the period 2020-2050 ranging from -1.8 to -5.5 W/m^2.

Those changes in the surface fluxes have a direct impact on the evolution of the temperature and salinity in the Mediterranean (Figure 2). GCMs under scenario A1B project an increase of the mean temperature of 2.8^{o}C at the end of the 21st century, with an ensemble spread of 1.0^{o}C (Jordà et al., 2012b). Other studies solely based on RCMs provide very similar results. Gualdi et al. (2013) using an ensemble of five AORCMs showed a projection of basin averaged SST for 2050 ranging between 1.2^{o}C and 2ºC. Adloff et al. (2015), in an ensemble of forced ocean RCMs, obtained increases of basin average SST ranging from +1.7 to +3.0 °C for the period 2070-2099. Concerning sea surface salinity (SSS), Adloff et al. (2015) showed anomalies that spread from +0.48 to +0.89 in the period 2070-2099. Their results suggest that the choice of the near-Atlantic surface water evolution, which is very uncertain in GCMs, has a large impact on the evolution of the Mediterranean water masses. They also highlighted that the SSS increase would be highly heterogeneous with regional changes that could exceed 1 psu, mainly because of changes in the rivers runoff.

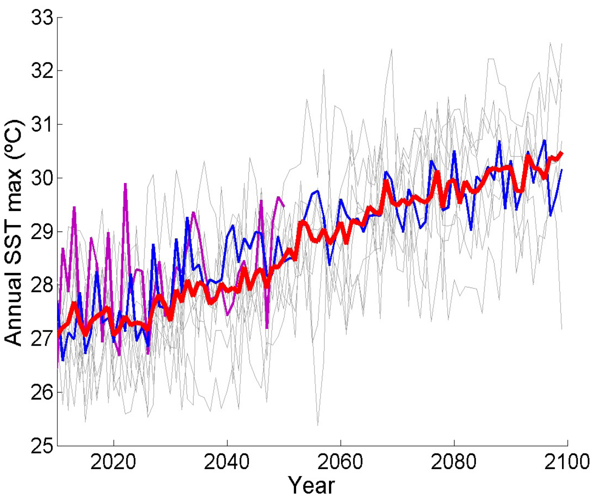

Figure 2: Projections of maximum annual sea surface temperature (ºC) for the western Mediterranean from a set of GCMs (thin grey lines) and two ocean RCMs (purple and blue lines). The ensemble average is shown in red (adapted from Jordà et al., 2012b)

Changes in temperature and salinity would also be felt at deeper layers. Most of the warming would occur in the layers 0-100, 100-600 and 600-bottom (+0.6ºC, 0.5ºC and 0.4ºC, respectively, in 2050), and similarly in eastern and western basins (Carillo et al., 2012; Adloff et al., 2015). Concerning salinity, both studies projections showed an increase of +0.3-0.5 in the whole water column for the same period. From a sensitivity analysis, they have suggested that the choice of the Atlantic boundary conditions has a large impact on the evolution of the whole water column temperature and salinity, while the choice of the scenarios have much less impact than for the surface variables. They also showed that the penetration of the heat and salt anomalies from surface to depth varies according to the simulation and depends on the changes in the convective areas, which are influenced by the historical state of the vertical stratification and the associated Mediterranean thermohaline circulation.

B. Atlantic Region

B.1 Wind waves

Atlantic Spanish coasts include different regional areas: the Biscay Gulf, the Cantabrian Sea, the Gulf of Cadiz and the Canary Islands. Overall, the strength and direction of the westerly winds and storm tracks are the main climatic drivers of the northeast Atlantic waves. The characteristics of the offshore wind climate vary significantly along the Spanish Atlantic margins (Menéndez et al., 2014). The Northern coasts are those showing the more intense wave storms (energetic swells) generated over the whole northeast Atlantic basin (Pérez et al., 2014), with averaged wave heights of 2-2.5m, and a mean peak period of approximately 10s. In the Gulf of Cadiz and the Canary Islands the effects of the swell generated at high latitudes in the North Atlantic are less intense (Izaguirre et al., 2010) being the average wave height around 1-1.5 m and the mean peak period 7-8s. Also, the wave characteristics have a strong temporal variability, both at seasonal and interannual scales. A large fraction of the wave energy along the Spanish Atlantic coast can be associated to large scale atmospheric circulation patterns, mainly North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and East Atlantic (EA) patterns (e.g. Izaguirre et al., 2010; Espejo et al., 2014; Martínez-Asensio et al., 2015).

Concerning dynamical projections of wind-wave climate, the global study of Hemer et al. (2013a) is noticeable since it provides an integrated investigation from five independent studies under the Coordinated Ocean Wave Climate Project (COWCLIP). Their results suggest that for the NE Atlantic at the end of the XXI century there will be a general decrease in Hs (5-10%) and mean period (Tm), and that those changes would be concentrated in the winter season. These results are in line with the conclusions of other studies based on single simulations using one climate model realization as forcing (Semedo et al., 2013; Hemer et al., 2013b). Complementary there are some studies based on regional models, which used higher resolution for the atmospheric forcing and the wave models. Charles et al. (2012) projected very similar winter wave height decreases over the Bay of Biscay using the ARPEGE-Climat GCM under three different future climate scenarios (B1, A1B, A2). In particular, they showed a reduction of -5/-10% in Hs depending on the season. A similar study was conducted by Gomis et al. (2016) using four different parent global climate models (GCMs) under the scenario A1b. In all cases the projected changes were modest (less than 10% reduction at the end of 21st century in all variables), and they found that the choice of the GCM which drives the regional atmospheric model can lead to significant changes in the results.

The statistical projections provide an interesting complement to the dynamical simulations of Atlantic wave climate. Wang et al. (2014) used statistical downscaling based on sea level pressure (SLP) as predictor under the scenarios RCP4.5 and RCP8.5. Their results suggest a statistically significant decrease of -10/-15cm of average Hs in the NE Atlantic, and a reduction of -50/-60 cm in

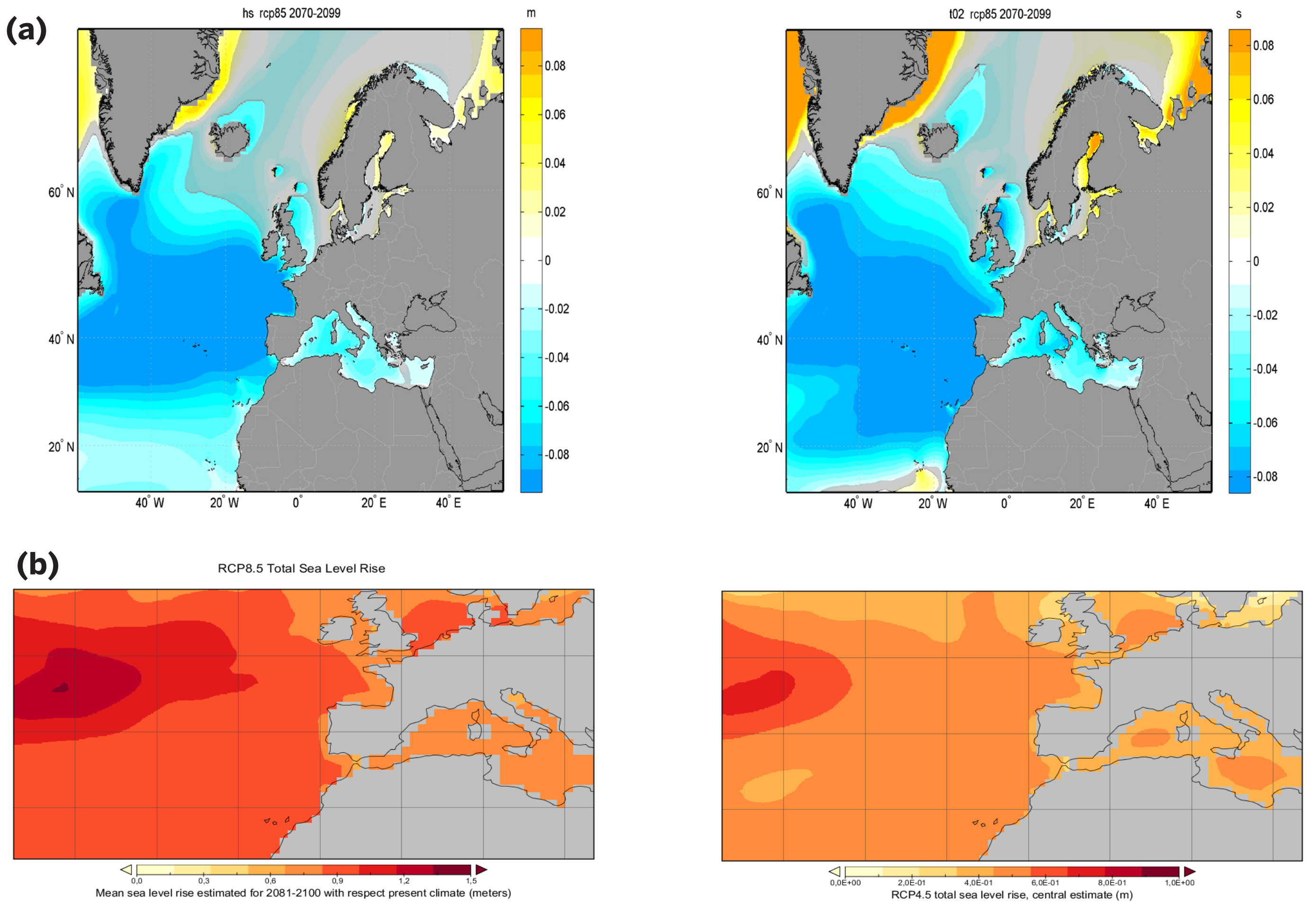

Figure 3: (a) Significant wave height **(left)** and mean period **(right)** projected under scenario RCP8.5 for the period 2070-2100 and expressed as anomalies with respect to the 1970-2000 period (adapted from Pérez et al., 2015). **(b)** Mean sea level rise projected under scenario RCP 8.5 **(left)** and RCP4.5 **(right)** for the 20-yr period 2081-2100 and expressed as anomalies with respect to the 1986-2005 period (adapted from Church et al., 2013)

the maximum height. Also, they did not find significant differences between the results obtained using the CMIP5 GCMs (IPCC-AR5) or the older CMIP3 GCMs (IPCC-AR4). Perez et al. (2016) developed a regional multi-model wave climate projection study focused on the European coast. They analysed the performance of the climate models over the North Atlantic (Perez et al., 2014), and finally used 17 atmospheric climate models from CMIP5 to build the ensemble. They applied a statistical downscaling based on weather type classification using SLP as a predictor. Their results suggest that around the Iberian Atlantic coasts the projected change in Hs (Tm) is -10 cm, -5 cm and -2 cm (-0.08s, -0.06s and -0.02s) for scenarios RCP8.5, RCP4.5 and RCP2.6, respectively (see Figure 3). An important outcome from that study is the robust conclusion that moderate scenarios of emissions lead to moderate changes in the wave height. Their results also show that more than 80% of the simulations agree on the sign of change around the Spanish coasts. Similar conclusions have been obtained by Martínez-Asensio et al. (2016).

B.2 Sea Level

The most updated projections of global mean sea level (GMSL) based on process-based models indicate that at the end of the 21st century GMSL would be significantly higher than what it was at the end of the 20th century. The results suggest that the rise would likely be in the range of 0.29–0.55m for RCP2.6, 0.36–0.63m for RCP4.5, 0.37–0.64m for RCP6.0, and 0.48–0.82m for RCP8.5 (Church et al., 2013). Projections based on semi-empirical models suggest even a larger rise, from 1 to 2 m (Rahmstorf et al., 2007). However, it is well known that the rise would not be homogeneous and that large regional differences should be expected (Pardaens et al., 2011). To our knowledge, only the study of Gomis et al. (2016) have used a regional ocean model to generate projections of sea level rise along the Spanish Atlantic coasts. They worked under the scenario A1b, considered only the effects of thermal expansion and the circulation changes, and their temporal horizon was 2050. Their results suggest that the rate of sea level rise would be 1.36 ± 0.27 mm/yr and 2.18 ± 0.54 mm/yr in the NE Atlantic depending on the GCM used to provide the boundary conditions (ECHAM5

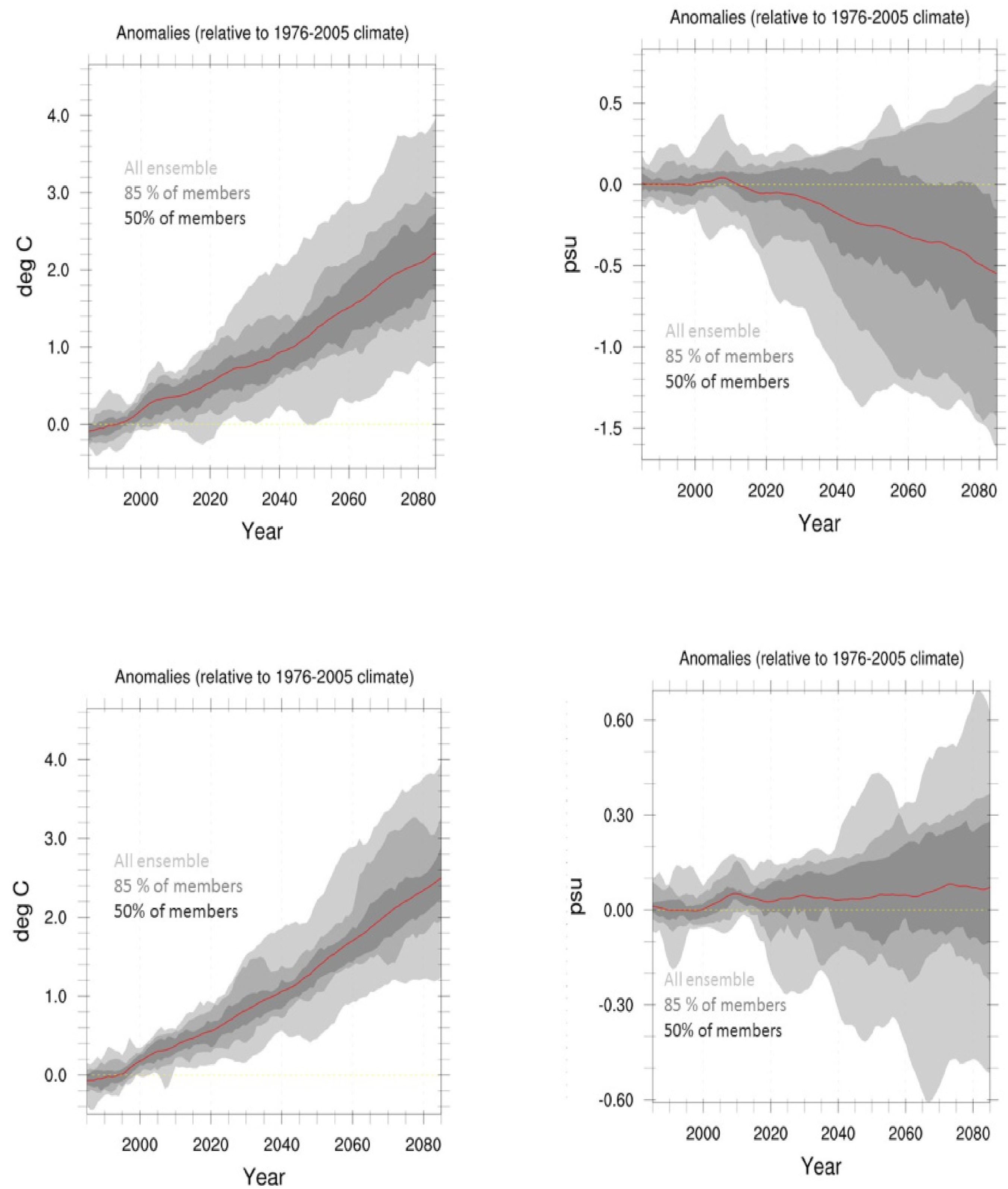

Figure 4: Sea surface temperature **(SST, left)** and sea surface salinity **(SSS, right)** evolution in the CMIP5 ensemble of GCMs under the RCP8.5 scenario. The results are shown for the Iberian Atlantic coast **(top)** and the Canary Island region **(bottom)**. The red line represents the ensemble mean and the different shades of gray indicate the spread of the ensemble when considering a given % of the members. Note the different vertical axis in each figure.

or HADCM3low). A more complete overview of regional sea level rise has been provided by Slangen et al. (2017), which updates previous studies on the same issue. They have analysed different components of regional sea level rise using 21 CMIP5 climate model projections with model- and observation-based regional contributions of land ice, groundwater depletion and glacial isostatic adjustment, including gravitational effects due to mass redistribution. Their results for the NE Atlantic under scenarios RCP4.5/RCP8.5 are that total sea level would rise 45/70cm at the end of the 21st century (Figure 3b). From that total, 8/12cm would be due to land ice melting, 25/40cm due to changes in ocean dynamics, 15cm due to dynamic ice sheet, 5cm due to terrestrial water storage, and 2cm due to GIA.

Complementary to the evolution of the mean sea level is the analysis of extreme events. In particular, positive extreme events caused by low atmospheric pressures and onshore winds (i.e. storm surges) piling the water along the coast are responsible for the largest damages in coastal infrastructures. Marcos et al. (2011) and Jordà et al. (2012a) have analysed those effects using a regional storm surge model forced by the regional ARPEGE atmospheric model under the B2, A1b and A2 scenarios. Their results show that the 50-year return level would decrease between 5 and 1cm at the end of the 21st century depending on the chosen scenario. Also, the largest changes are expected in the Bay of Biscay. This reduction is associated to a decrease in the number of positive extreme events (approximately 2 events/yr less at the end of the century), and to an increase in the mean atmospheric pressure in winter (i.e. the period where most extreme events occur) which translates into a reduction of approximately 4cm in the Bay of Biscay at the end of the century. Gomis et al. (2016) used the same model configuration but forced by other GCMs. Their results are not conclusive as far as the simulations forced by ECHAM5 and HADCM3low showed a slightly positive (around 10cm) change in the 50-year return level, while those forced by HADCM3red and HADCM3high show exactly the opposite. This suggests the absence of clear trends in the storminess of the region. That is, extreme sea levels will be higher in the 21st century because of the increase in mean sea level, not due to a significant increase in the storminess.

B.3 Temperature and salinity

There are few studies analysing the evolution of temperature and salinity around the Spanish Atlantic coasts, and most of them are based on the outputs of GCMs (Chust et al., 2010; Villarino et al. 2015). Figure 4 shows the time evolution of the ensemble of CMIP5 SST and SSS projections for the Atlantic Iberian coasts and for the Canary Islands region. SST is projected to increase around 2.2^{o}C and 2.4^{o}C, respectively at the end of the century, with the highest rate of increase found after 2050. The difference between both regions is found on the spread of the ensemble. In the Iberian coasts, 50% of the ensemble members project an increase ranging from 1.8 to 2.6^{o}C while in the Canary region the increase ranges from 2.2 to 2.8^{o}C. For SSS, the differences between regions are larger. Projections show a freshening of the Iberian marginand a slight salinization of the Canary region (projected changes being -0.5 and +0.1, respectively). Again, the ensemble spread is larger for the Iberian margins (from -0.9 to -0.1) than for the Canary region (from -0.1 to + 0.3).

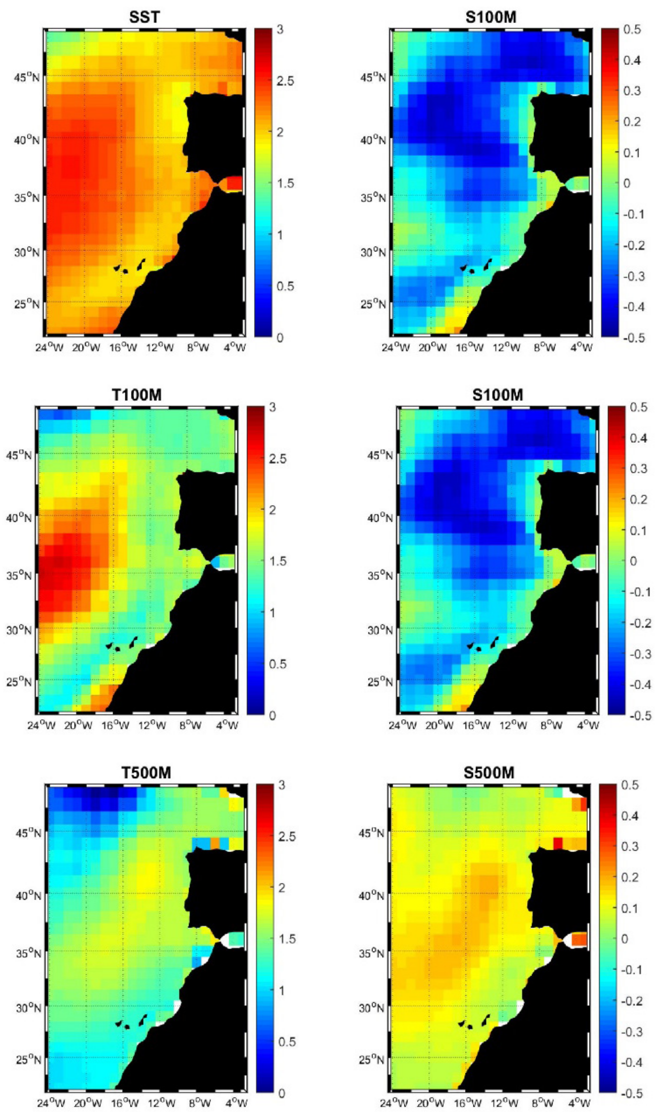

Figure 5: CMIP5 ensemble mean anomaly for the period (2050-2099) with respect to (1956-2005). The maps are shown for temperature in ºC (left) and salinity in psu (right) at surface (top), 100 m (middle) and 500 m (bottom).

At different depths (Figure 5) under scenario RCP8.5, a warming in the whole water column is observed. The average increase along the Spanish Atlantic coasts for the second half of the 21st century is 2-2.5^{o}C (surface), 1-1.5^{o}C (100m), and 1-1.6^{o}C (500m). Concerning salinity, results are a bit different. While surface salinity is expected to decrease around 0.3, changes at 100m and 500m along the Spanish coasts are barely significant. With regards to the open ocean, salinity is expected to decrease also at 100m, while it would increase at 500m. Concerning the vertical stratification, results point towards an increase in the stratification of the water column (higher temperatures and lower salinities in the upper layers), which could have implications for the coastal ecosystems.

The GCMs show a somehow distinct behaviour along the Iberian margin compared to the open sea. Their spatial resolution is too coarse to be reliable, and therefore regional projections should be preferred to that fine scale analysis. Using a regional circulation model, Gomis et al. (2016) show results that are highly consistent with the general picture provided by GCMs. Nevertheless, the higher resolution of their model has allowed to draw a more complex picture about the processes that would have influence over the evolution of temperature (Figure 6) and salinity in the region. In particular, they found that near the continental margin, the global temperature rise could be counteracted by an enhancement of the seasonal upwelling. Notably the enhanced upwelling could be strong enough to result in negative temperature trends along the Iberian coasts, while along the African coast it would only result in a reduction of the positive temperature trends. Concerning salinity, results suggest that the eventual salinity increase derived from a more intense upwelling would not be enough to counteract the above-mentioned freshening.

Discussion and conclusions

In this article, we have reviewed the current knowledge of how global warming will affect the Spanish marine environment during the next decades. Concerning wind wave climate, projections based on numerical and statistical models suggest a small reduction (less than 10%) in the wave height and mean period both in the Atlantic and Mediterranean Spanish coasts.

Regarding sea level, the Mediterranean and NE Atlantic values are expected to follow the global mean sea level positive trend. The overall result is a significant increase of the mean sea level at the end of the 21st century, ranging between 45 and 100cm in the Mediterranean, and between 35 and 70cm in the NE Atlantic, depending on the scenario, with an uncertainty associated to those projections of roughly ~ 40 cm.

Concerning temperature, all models project a temperature increase in the Spanish Mediterranean and Atlantic waters, consistent with the expected increase in surface heat flux. Nevertheless, the magnitude of the Atlantic Meridional Overturning Circulation (AMOC) slowdown, which is uncertain, can modulate that warming in the Atlantic region. In particular, a decrease in the AMOC transport would imply less heat advected towards the NE Atlantic. Thus, depending on the characteristics of the AMOC, we should expect a different rate of warming along the Spanish Iberian coasts. Those effects would also be noticed in the Canary region, but to a lesser extent. Additionally, some regional studies have suggested that the projected increase in the upwelling favourable winds can also trigger enhanced upwelling in the western margin of the Iberian Peninsula. The increase of the

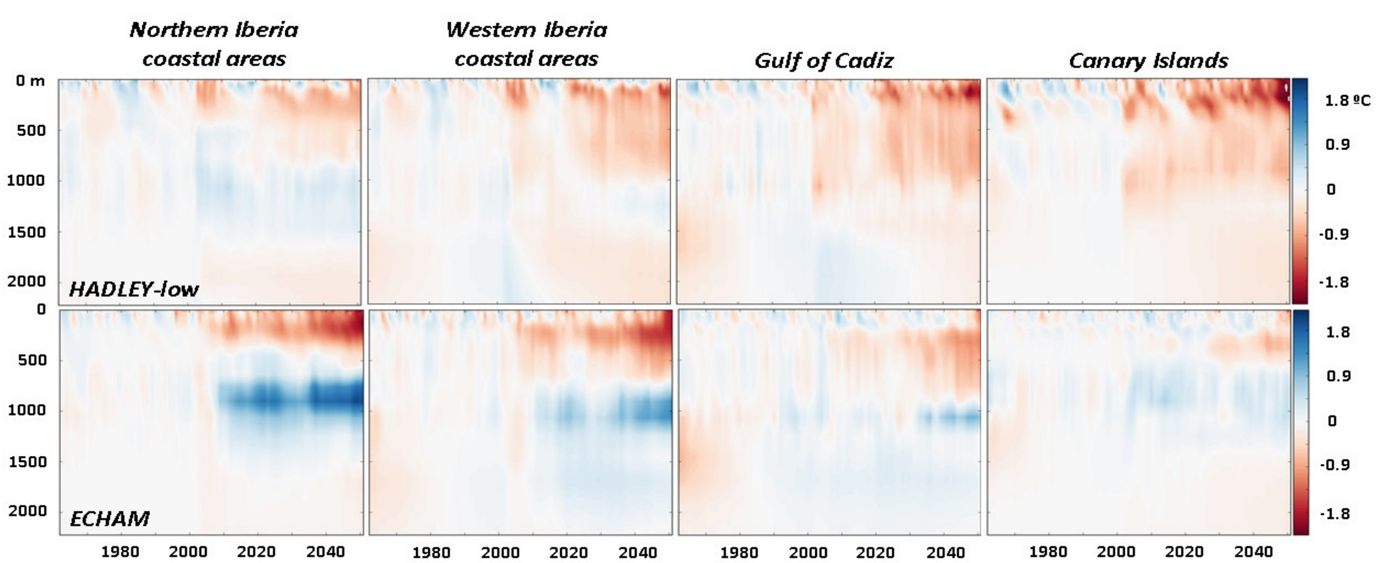

Figure 6: Hovmöller diagrams: evolution of temperature anomalies profiles (in ºC, with respect to 1971-2000 mean) averaged for Northern and Western Iberia coastal areas, Gulf of Cadiz and Canary Islands. Data correspond to an ocean RCM forced with A1B scenario from HADLEY-low and ECHAM GCMs.

amount of upwelled waters can, at least partially, counteract the open sea warming in a narrow band along the western Iberian coast.

As for salinity, the increase of freshwater fluxes in high latitudes of the North Atlantic and/or the increase of ice melting in Greenland would bring fresher waters towards the NE Atlantic coasts. On the other hand, it is expected that freshwater loss will increase in the Mediterranean inducing a gain in salinity for the basin, although the advection of fresher waters from the Atlantic can partially counteract this process. Regarding extreme events, although it is clear that the impact of future marine storms will increase due to the rise of the mean sea level, the evolution of the storminess in southern Europe is not clear. Some results point towards a decrease in the number of storms but also to an increase of the most intense events, although the statistical significance of those results is weak. IPCC's 5th Assessment Report states that there is a high uncertainty associated with future winds and storms (Collins et al., 2013).

Besides the evolution of the mean regime, the characterization of the evolution of extreme events is very important for coastal impacts. Some studies have addressed projections of extreme wave and sea level events but their results were not conclusive. The most consistent results from the majority of the current generation of models are a poleward shift of north hemisphere storm tracks in a future warmer climate. However, that shift depends on the polar surface and upper tropical troposphere warming together with different levels of change of the AMOC. Discrepancies in how GCMs project the evolution of those factors determine the uncertainties in the details of the poleward shift of the storm track.

An important result of this review is that we have found relatively few studies addressing regional marine climate change in southern Europe. This is especially problematic in the Atlantic side where the number of studies is extremely limited, and most of those which are related to hydrography and sea level are based on global climate models. This is a serious drawback since GCMs were not designed to address the particularities of that region and often miss basic mechanisms that can affect regional projections. In the Mediterranean, the number of regional studies is larger but still small preventing accurate analysis of the uncertainty. Finally, it must be noted that in all cases the large majority of studies are based on SRES scenarios (IPPC AR4), so not considering the more recent results from the IPCC-AR5.

Concerning the sources of uncertainty of the regional projections, the most determinant factor in general is the GCM used to force the regional models (atmospheric and ocean). Although GCMs may agree in the large scale, they can be very different in the projected small-scale changes, and this in turn has a strong impact on the spread of regional projections. For instance, most GCMs project a decline of the AMOC, but they do not agree on the amount of its slowdown. Therefore, the path of the north Atlantic fresh waters towards the NE Atlantic is very different among models, so it is the salinity evolution in the Iberian Spanish coasts. Similarly, most GCMs project a northward shift of the storm track but the exact location is uncertain. As consequence, projections of wind climate over the Mediterranean (and hence of storm surge or wind waves) are very dependent on the GCM chosen to force the regional modelling system. Concerning the emission scenario, results point towards stronger changes in the most pessimistic scenarios. This is clear for sea level and temperature. However, for salinity, storm surgeand wind-waves the relation is not so robust. Unfortunately, the number of regional simulations is too small to be able to produce an accurate estimate of the uncertainty budget. In this sense, it is important to point out that studies based on single models should be considered with caution. Uncertainties in projections are large, so conclusions based on a small number of simulations, or even a single one, can be misleading. A way to overcome this limitation is to try to understand the physical mechanism behind the changes, and to analyse its robustness.

The projected changes in temperature and sea level for the next decades are the most robust results we have found. Temperature increase in the whole water column and the rise of sea level around all the Spanish coasts are very likely to happen during this century. Details of the spatial heterogeneities and the exact value of those increases are subject to uncertainties linked to the emission scenario, the modelling uncertainties, and the natural variability. Nevertheless, those uncertainties are relatively small compared to the average projected change. So, the projected rise in temperature and sea level has to be considered as a serious threat. Thus, there is a pressing need to start developing adaptation strategies to protect coastal infrastructures and natural environments. Although some work has been done from a theoretical perspective, there has been no specific plans to transfer those adaptation ideas to the real world. This should be addressed by the administrations as soon as possible.

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No. 73 September, 2017

Progress in Detection and Projection of Climate Change in Spain since the 2010 CLIVAR-Spain regional climate change assessment report
Enrique Sánchez, Belén Rodríguez, Ileana Bladé, Manola Brunet, Roland Aznar, Isabel Cacho, María Jesús Casado, Luis Gimeno, Jose Manuel Gutiérrez, Gabriel Jordá, Alicia Lavín, Jose Antonio López, Jordi Salat, Blas Valero........ 1

A comprehensive overview of the last 2,000 years Iberian Peninsula climate history
Santiago Giralt, Ana Moreno, Isabel Cacho, Blas Valero-Garcés........ 5

Atmospheric Climatic observations and instrumental reconstructions over the Iberian Peninsula I: development of high-quality climatic time series
José Antonio Guijarro, Cesar Azorin-Molina, José Carlos González-Hidalgo, Arturo Sanchez-Lorenzo, Sixto Herrera, José Antonio López........ 11

Climatic observations and instrumental reconstructions: development of high-quality climatic gridded products
Sixto Herrera, Juan Javier Miró Pérez, Pere Quintana-Seguí, Julián Gonzalo, José Antonio Ruiz-Arias, Jose Carlos González-Hidalgo, José Antonio Guijarro, Jose Antonio López........ 15

Observed atmospheric trends in the Iberian Peninsula
Sergio M. Vicente Serrano, Ernesto Rodríguez Camino........ 20

Modes of Variability affecting southwestern Europe
Belén Rodríguez-Fonseca, María Jesús Casado, David Barriopedro........ 24

Oceanic variability and sea level changes around the Iberian Peninsula, Balearic and Canary Islands
Jordi Salat, Alicia Lavín, César Gonzalez-Pola, Pedro Vélez-Belchí, Ricardo Sánchez, Manolo Vargas-Yáñez, Jesús García-Lafuente, Marta Marcos, Damià Gois........ 32

Regional climate projections over Spain: Atmosphere. Present climate evaluation
Jordi Salat, Alicia Lavín, César Gonzalez-Pola, Pedro Vélez-Belchí, Ricardo Sánchez, Manolo Vargas-Yáñez, Jesús García-Lafuente, Marta Marcos, Damià Gomis........ 39

Regional Climate Projections over Spain: Atmosphere. Future Climate Projections
Juan Pedro Montávez, Jesús Fernández, Ana Casanueva, José Manuel Gutiérrez, Enrique Sánchez........ 45

Regional marine climate projections over Spain
Gabriel Jordà, Melisa Menéndez, Roland Aznar, Agustín Sánchez-Arcilla........ 53

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