AGENCIA ESTATAL DE INVESTIGACIÓN - Convocatorias 2018
Proyectos de I+D de GENERACIÓN DE CONOCIMIENTO y Proyectos de I+D+i RETOS INVESTIGACIÓN

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IMPORTANT – The research proposal cannot exceed 20 pages. Instructions to fill this document are available in the website. If the project cost exceeds 100.000,00 €, this document must be filled in English.

IP 1 (Nombre y apellidos): Markus G. Donat

***TITLE OF THE PROJECT (ACRONYM)*:** Impact of Modeling imPROvements on the representation of variability and Near-Term prediction skill in north Atlantic climate (IMPRONTA)

TÍTULO DEL PROYECTO (ACRÓNIMO): Impacto de las mejoras en modelización en la representación de la variabilidad climática del Atlántico Norte y su predicción a corto plazo (IMPRONTA).

1. PROPUESTA CIENTÍFICA - *SCIENTIFIC PROPOSAL*

I. Introduction and state-of-the-art

Climatic conditions, and in particular extreme events (such as heat waves, cold snaps, drought or heavy precipitation), can affect a broad range of socio-economic sectors including energy production, agriculture, water management and health. Due to the prevailing westerly winds in northern hemisphere midlatitudes, European climate is largely controlled by the arrival of atmospheric systems coming from the North Atlantic. The arriving air masses are particularly warm due to the heat that they gain as they pass over the Gulfstream region, which thus explains the relatively mild conditions over Europe when compared to other regions of similar latitude.

The North Atlantic ocean is a major source of decadal variability known to induce decadal climate fluctuations in different regions of the Northern Hemisphere, from North America, to Africa and Europe. The underlying mechanism of these decadal variations is the Atlantic Meridional Overturning Circulation (AMOC), and is associated with deep water formation in the Labrador and Nordic Seas. The AMOC plays a prominent role in North Atlantic climate, not only controlling the poleward heat transport from the tropics, but also acting as a major sink of CO_2, which places it as key player of the global carbon cycle (Perez et al., 2013). The AMOC is also suspected to contribute substantially to the Atlantic Multidecadal Variability (AMV), a coherent pattern of slowly-varying sea surface temperature (SST) anomalies across the North Atlantic (Knight et al. 2005) that is related to widespread multidecadal climate impacts. This includes changes in the frequency of occurrence of hurricanes (Knight et al. 2006), modulations in the frequency of occurrence of El Niño and La Niña events (Ruprich-Robert et al. 2017), summer precipitation in southwestern North America and western Europe (Sutton and Hodson 2005), and drought conditions over Africa (Zhang and Delworth 2006). Previous studies also argued for the existence of a causal link between the warm phase of the AMV and warm conditions over Central Europe (Ghosh et al, 2017), dry conditions over the Mediterranean basin, and wet conditions over Northern Europe (Sutton and Dong, 2012), further impacting river streamflow and electricity production. The AMV can also modify the location and activity of the North Atlantic storm track and modulate the number of blocking events, and has been reported to induce climate extremes, such as heat waves over North America (Ruprich-Robert et al 2017), extreme daily rainfall in Mexico (Curtis, 2008) and the extremely severe and long lasting 70s-80s sahelian drought, responsible for 100,000 deaths.

Due to the AMV and the AMOC, the North Atlantic emerges as a key region for decadal prediction. Many decadal prediction systems with different climate models attest to the prominent predictive role of the North Atlantic in timescales ranging from years to a decade (García-Serrano and Doblas-Reyes, 2012), in stark contrast to the North Pacific, another region with important decadal oscillations but in which models do not generally show predictive skill (Guemas et al, 2012). Given the large variety of reported impacts in neighboring and remote areas, the predictive capacity over the North Atlantic has in theory the potential to reach these regions. However, to this date, the decadal predictability over the continents is still highly limited, which suggests that some of aspects of the key linking processes might be, at least partially, misrepresented by the models.

At shorter time-scales (monthly-to-seasonal), the Atlantic ocean is also known to drive a number of important climate impacts. For example, subtropical Atlantic SSTs are a well-known precursor of hurricane activity (via a link with the Intertropical Convergence Zone and its subsequent effect on the Tropics) and can provide predictive skill up to two months ahead (Klotzbach 2007, 2011). Likewise, anomalously high/low summer Tropical Atlantic SSTs have been shown to influence the Tropical Pacific and enhance/weaken El Niño Southern Oscillation (ENSO) activity in the following winter (Rodriguez-Fonseca et al, 2009), although its potential use for climate prediction has not yet been explored. The underlying mechanism involves a strengthening/weakening of the Walker circulation when the Tropical Atlantic is anomalously warm/cold. It's also important to note that ENSO can itself induce climate impacts over Europe, through a stratospheric teleconnection (Bell et al, 2009, Ineson and Scaife, 2009) that can influence the phase of the North Atlantic Oscillation (NAO), the major atmospheric driver of winter climate variability in the North Atlantic. In this sense, the skill that some seasonal predictions systems like GloSea5 show on the winter NAO has been traced back to the high predictive capacity of the Tropical Pacific (Scaife et al 2014). Other analyses, however, suggest that additional factors can also influence the winter NAO and determine part of its predictive skill. In particular, observations show that autumn sea ice reductions in the Barents–Kara Seas tend to be followed by a negative NAO phase in the next winter, a response that seems to be related to a Rossby wave train–like anomaly across Eurasia (García-Serrano et al, 2015). It remains to be determined to what extent these sea-ice atmosphere interactions are captured in the current seasonal forecast systems and whether they contribute significantly to their skill.

Given then the important role of the Atlantic region for climate prediction in the surrounding and remote regions (like the Tropical Pacific), it is crucial to guarantee that the newest generation of Coupled General Circulation Models (CGCMs) correctly represents the driving mechanisms in the ocean, as well as the atmospheric processes that provide the links with the continents and/or the other basins, including the specific regional aspects preconditioning the occurrence of extreme events. However, to date, the typical atmospheric and oceanic resolutions (~1º) used for global climate experimentation and in particular for climate prediction present important biases and shortcomings, compromising the representation of some key climate characteristics in their ocean, atmospheric and sea-ice components. In the atmosphere, for instance, typical biases affect the mean atmospheric flow resulting in an underestimation of blocking events (Scaife et al 2010), and also the latitude of storm tracks (Kidston and Gerber 2010), both thus providing erroneous bridging effects between the ocean and the land. Ocean features commonly misrepresented in the models are the Gulfstream Separation, deep water formation in the Labrador Sea, and Tropical Atlantic SSTs, which are generally too cold. It is also worth mentioning that due to the different model biases, CGCMs show a great diversity of AMOC behaviours in terms of their predominant timescales, latitudinal coherence, and underlying mechanisms. Historical simulations with CGCMs also seem to consistently underestimate the observed rate of Arctic sea-ice retreat, which suggests that they are missing some of the key sea-ice processes (Rosenblum and Eisenman, 2017). As a consequence, there is still no model consensus on when ice-free Arctic conditions will be reached. All these model shortcomings and uncertainties cast doubt on their capacity to predict correctly the upcoming future changes, and in particular the fate of the AMOC in a global warming context.

Noteworthy advances can be achieved by just increasing the model resolution. Among the most important improvements reported for the ocean, we highlight a better simulation of ENSO variability (Shaffrey et al. 2009, Masson et al. 2012) and the Gulf Stream and its influence on the atmosphere (Chassignet and Marshall 2008; Kuwano-Yoshida et al. 2010). Likewise, improved atmospheric features include the global water cycle (Demory et al. 2014), the position of the jet stream (Lu et al., 2015), the occurrence of Euro-Atlantic blockings (Jung et al 2012) and tropical cyclones (Zhao et al. 2009, Bengtsson et al. 2007), and tropical-extratropical interactions (Baatsen et al. 2014, Haarsma et al. 2013). Higher resolutions allow also for a better representation of sea ice drift and deformation (Zhang et al 1999; Gent et al, 2010), and can even lead to more realistic heat waves and droughts (Van Haren et al. 2015). It remains to be tested to what extent these improvements also lead to better predictive skill on the Atlantic region and its teleconnections.

The proposed research in IMPRONTA will explore pathways to improve climate models, specifically the simulation of North Atlantic climate variability, and how these improvements affect the ability to predict climate, including extremes, over land.

II. Project Objectives

This project is articulated to tackle three major and complementary objectives:

A. Explore a wide range of alternative approaches to improve the representation of North Atlantic mean climate and variability.

B. Evaluate the particular benefits of the model improvements, in particular resolution, on the associated teleconnections and impacts over the continents, with a special focus on the representation of extreme events.

C. Quantify the added-value of these different model developments on the predictive skill at seasonal and decadal scales.

III. Description of the Research Environment and Research Team

The **Barcelona Supercomputing Center** (BSC) combines unique high-performance computing facilities and in-house research departments on Computer, Life, and Earth sciences, counting more than 500 researchers and students from more than 45 different countries. BSC has been accredited as one of the first eight Severo Ochoa Centers of Excellence. This award is given by the Spanish Government as recognition for leading research centers in Spain that are internationally well known in their respective areas.

Within the BSC, the Department of **Earth Sciences** (BSC-ES) is a prolific group with multiple research areas of interest, from air quality and atmospheric composition modelling, to climate prediction and climate services in Europe. The department is currently composed of over 80 people, including technical and support staff, structured in four distinct but interacting research groups: Earth System Services, Atmospheric Composition, Climate Prediction and Computational Earth Sciences.

The BSC-ES mission is to perform research on and develop methods for environmental forecasting, with a particular focus on the atmosphere-ocean-biosphere system. This includes managing and transferring technology to support the main societal challenges through the use of models and data applications in high-performance computing (HPC). It also includes the dissemination of real-time air quality and climate information based on its research expertise in collaboration with both the Spanish authorities and the World Meteorological Organisation (WMO). It is a highly productive scientific entity that has published more than 180 research articles in peer-reviewed journals over the last five years (2014-2018), some of them in prestigious high-impact journals. A full list of publications is available here.

All the members of the research team are part of the **Climate Prediction** (CP) group. The Climate Prediction group aims at developing climate prediction capability for time scales ranging from a few weeks to a few decades (sub-seasonal to decadal climate prediction) and from regional to global scales. This objective relies on a deep analysis of the strengths and weaknesses of state-of-the-art climate forecast systems, via a thorough comparison with the most up-to-date observational datasets, and on exploiting these detailed analyses to refine the representation of processes relevant to climate in its forecast systems through new model parameterisations and components. The BSC-ES, through the activities of the CP group, is in the process of becoming a WMO-endorsed center for decadal prediction.

The workhorse of the group activities is the **EC-Earth** model (version 3), in whose development the BSC-ES participates actively. This is the model that will be used to perform the different experiments envisaged in IMPRONTA. The group relies heavily on the support from the Computational Earth Sciences group to perform and post-process the experiments and contributes to the their activities by testing the optimised code and tools they develop. The Climate Prediction group also feeds the Earth System Services group with high-quality climate predictions, and collaborates with that group on bias adjustment methodologies and climate diagnostics for the generation of user-tailored products. The Earth System Services group also looks to develop applications based on the latest results and data products originating from the Climate Prediction group.

Research Team

The research team combines expertise in ocean, sea-ice and atmospheric processes, advanced climate modelling techniques including nudging and high-resolution simulations, model evaluation and climate data analysis. This rich combination of expertise is essential for the different developments and analyses undertaken in the project, involving all the major components of the climate system.

Dr. Markus Donat is an expert in studying climate extremes and climate variability, mechanisms driving or amplifying extremes, and climate model evaluation focussing on their fidelity to simulate climate extremes. He has published more than 60 peer-reviewed journal articles since 2010, seven of these in *Nature*-family journals, and has contributed to the IPCC 5th Assessment Report. Markus Donat is now co-leader of the Climate Prediction group at the BSC and a new Ramon y Cajal fellow. Until recently, he was a scientist at the University of New South Wales in Sydney (Australia). As the PI of this project, he will lead and supervise the proposed research activities, equally contributing to each of the four work packages.

Dr. Thomas Arsouze is a research scientist in the Climate Prediction group at the BSC, with past activities as a postdoctoral researcher between 2009 and 2010 at Columbia University / LDEO (NY, USA), and as a research scientist between 2011 and 2017 at ENSTA-ParisTech (Paris, France), within the IPSL group. He acquired a strong background in regional modeling of the Mediterranean, with a focus on the influence of oceanic small scale structures on oceanic transport on one part, and on ocean-atmosphere interactions on the other part. He has 35 published and 3 submitted articles in international Q1 peer-reviewed journals, with a total of more than 1000 citations, an h-index of 15 and an i10-index of 20. He has led 3 national projects, contributed to 4 national scientific projects and 1 European project.

Dr. Eduardo Moreno has developed his scientific career at highly regarded international research institutions, first at the Max Planck Institute, where he obtained his PhD in 2016, then the MIT in 2016 and 2017, and finally, at the BSC since February, 2018. His main scientific interest is in the field of climate dynamics, specifically focused on the interactions between the ocean, atmosphere, and sea ice in the North Atlantic and Arctic. His extensive collaborations with numerous international institutions have resulted in six peer-reviewed articles so far, four as leading author and two as co-author (all in Q1 journals), and in a book chapter, with six more articles either currently in review or in preparation. He has presented his research at numerous international conferences, workshops, and seminars, on several occasions as invited speaker, as well as in outreach events for the general public.

Dr. Juan Camilo Acosta Navarro obtained a PhD in environmental science from Stockholm University in January of 2017. He has a background on atmospheric dynamics, cloud and aerosol microphysics and the link between remote climatic changes induced by regional radiative forcing with a particular emphasis on Arctic climate and its teleconnections. He is currently a scientific researcher at the Climate Prediction group where his work focuses on understanding drivers of sea ice variability and how it may affect climate locally and remotely. He has published ten scientific peer reviewed articles in first quartile journals, being first author in three of them (one in *Nature Geoscience*).

Dr. Eleftheria Exarchou is currently a postdoctoral scientist in the Climate Prediction group of the BSC-ES. She has a strong background in physical oceanography and in ocean and climate modeling. She has experience in seasonal/decadal forecasting and climate projections, with a particular focus on ocean dynamics. Her interests include investigation of model drift and biases and their impacts on climate predictability. She is also interested in high-resolution climate modeling and how the resolution impacts the representation of natural climate variability (the tropics in particular) and predictability.

Dr. Simon Wild obtained his Ph.D. from the University of Birmingham in July 2018. His research aims at understanding extreme climate events, their underlying atmospheric processes and their socioeconomic impacts. He specialises in extra-tropical cyclones and associated extreme wind speeds, their representation in climate models and their predictability at various time scales. He has been involved in EU projects such as EU FP6 ENSEMBLES and H2020 EUCP and collaborated with several risk model development companies in the insurance sector and has published seven scientific peer reviewed articles.

IV. Work Plan

This project will rely on the analysis of simulations run with different configurations and resolutions of the global general circulation model EC-Earth. More details about the specific configurations used for each study can be found in the respective work packages.

WP1: Improving the realism of Arctic processes and their linkages with the North Atlantic

Participants (% of the total dedication to the project):
Eduardo Moreno-Chamarro (100%)
Markus Donat (25%)

***Background**:* The Arctic is a key region to understand future climate change, as it is expected to experience the largest warming due to the effect of Polar Amplification (Bindoff et al. 2013). The unprecedented projected Arctic changes, including a drastic reduction on sea ice coverage and melting of Greenland ice sheet, can have a large impact on the climate of the mid-latitudes, either mediated by atmospheric-driven teleconnections triggered in response to surface heat flux changes, or via fresh-water discharges that impact the strength and variability of the Atlantic Meridional Overturning Circulation (AMOC). However, there are large discrepancies among current CGCMs regarding the rate of sea ice decline (Rosenblum and Eisenman, 2017). Besides, these models that do not usually include Greenland ice sheet components, and cannot therefore resolve their impacts. This suggests that improved representation of sea ice processes and the inclusion of refined estimations of regional Greenland models are essential to advance our understanding of the real predictability over the Arctic, the North Atlantic and in their neighbouring areas.

***Goals**:* The main goals of this work package are, first, to refine the representation of sea ice physical processes in the Arctic and their linkages with the mid-latitudes through the testing of different model parameterizations, and secondly, to evaluate the impact that realistic Greenland melt water fluxes have on the AMOC, and ultimately on the prediction skill.

Analyses: Task 1.1 will tackle the first goal through the analysis of a suite of different sensitivity experiments testing the impact of including active melt pond schemes and multiple sea ice categories on the variability of sea ice. All these experiments will be run with a forced ocean-sea ice configuration of the model at the standard resolution (TL255-ORCA1, that is ~80 km in the atmosphere and ~100 km in the ocean), driven over the period 1960-2015 by atmospheric heat, freshwater and momentum fluxes from the DRAKKAR forcing set DFS5.2 (Dussin et al, 2016). This will allow us to compare the major modes of sea ice variability with those from observational products, and thus estimate which particular configurations (i.e. melt pond scheme parameters, and total number of sea ice categories) lead to a better agreement with them. The impact of this improved sea ice representation on the large-scale ocean and atmosphere circulation will be also assessed.

Task 1.2 addresses the second goal by performing a set of groundbreaking real-time decadal climate predictions resulting from the combination of two different climate models: EC-Earth in standard resolution, which will produce a first set of the global near-term predictions for the period 2015-2045, and the Greenland ice sheet model GISM at the highest possible resolution of 1–2 km, that will be forced with EC-Earth atmospheric fields to produce compatible and refined estimates of the melting fluxes. The GISM experiments will thus provide updated meltwater fluxes to constrain a new set of refined predictions with EC-Earth over the same period. The comparison of both sets of global climate predictions will allow us to evaluate the benefits of including a more realistic estimation of Greenland melting, and in particular whether this helps inducing a stronger response of the AMOC or the subpolar gyre strength. To estimate the impact on the prediction skill, a similar set of predictions will be produced over the historical period 1985-2015, to maximize the overlap with the best satellite products. This task will be done in close collaboration with our partners Dr. Philippe Huybrechts from the Vrije Universiteit Brussel and Dr. Xavier Fettweis from the University of Liege, who will perform the simulations with the regional model within the context of the Belgian research project PARAMOUR.

Expected Outcomes

1. Research paper on the sensitivity of Arctic variability and related teleconnections to different sea ice model configuration
2. Research paper on the impacts of improved Greenland meltwater fluxes on North Atlantic prediction

WP2: Effect of bias reduction on the representation of key Atlantic teleconnections

Participants:

Markus Donat (25%)
Thomas Arsouze (100%)
Eleftheria Exarchou (100% from her 0.5 EDP)

***Background**:* The Atlantic ocean is a region where current CGCMs tend to develop important systematic biases (i.e. substantial differences with respect to observations), due to the misrepresentation of some important processes, like eddies and wave propagation. The origin of these biases varies depending on the specific subregion. For example, models tend to show a typical southward misplacement in the position of the Gulf Stream, a separation that is associated with a warm sea surface bias over the Mid Atlantic. Other regions, like the eastern Tropical Atlantic also exhibit warm biases but related to the unrealistic representation of coastal upwelling, due both to insufficient vertical ocean advection and an underestimation of the wind speed near the coast (Large and Danabasoglu 2006; Richter and Xie 2008; Toniazzo and Woolnough 2013). Some particular biases have been reported to impact other distant regions. For example, cold biases across the Northern Hemisphere have been traced back to unrealistically weak simulated AMOC states (Wang et al 2014), and SST biases along the Gulf Stream extension and North Atlantic Current have been reported to induce unrealistic responses in remote areas of the Northern Hemisphere, triggered via planetary Rossby waves and associated changes in the atmospheric circulation (Keely et al 2012, Lee et al 2018). Recent studies also demonstrate that systematic mean model biases in the Tropical Atlantic can hinder the correct representation of the climate variability over the region and erode its predictive skill (e.g. Dippe et al. 2018), a deterioration that might also affect the ability to predict over other regions like the Equatorial Pacific, given the well-established influence of the Atlantic Niños on ENSO activity (Rodriguez-Fonseca et al 2009). In this context, improving the simulation of regional Atlantic variability and reducing the local biases can enhance the overall model performance elsewhere.

***Goals**:* This work package addresses two goals of rather distinct scope. The first is broader and seeks to quantify the overall improvements in mean state and variability over the whole North Atlantic region that can be achieved in EC-Earth with the eddy-permitting resolution (1/12º). The second, more specific, is to demonstrate the benefits in the predictive skill that can arise from a correct representation of Tropical Atlantic variability exclusively. This region is chosen due to the multiple teleconnections arising from its influences on both the Walker and Hadley circulation cells.

***Analyses**:* Task 2.1 addresses the first goal and will involve the performance and analysis of three separate sets of simulations run with increasing ocean/atmosphere resolution: standard (80 km in the atmosphere and 100 km in the ocean), high (40 km in the atmosphere and 25 km in the ocean) and very-high (15 km both in the atmosphere and ocean), which in the ocean corresponds to respectively, non-eddying, eddy-permitting and eddy-resolving resolutions. To allow for a more accurate characterisation of the model biases and their sensitivity to the resolution, all three sets of experiments will cover the observational period 1950-2015, using the historical radiative forcing factors from CMIP6. The analyses will focus on the impact of the resolution on the boundary currents, the AMOC and its drivers (e.g. deep water formation, overflows from the Arctic), the air-sea interactions, as well as the representation of atmospheric processes (storms and blocking events) that influence the continental climate, in particular over Europe. Special attention will be placed on the representation of extreme events over land areas.

The second goal will be addressed in Task 2.2 and will rely on the implementation and analysis of bias-corrected predictions. To correct for the local SST biases in the Tropical Atlantic, linked to overly weak coastal upwelling, we will perform a suite of retrospective predictions for the period 1980-2014 in which the 3-hourly reanalysed winds-stress from ERA-Interim are locally prescribed. Elsewhere, the wind will vary freely, following the coupled evolution of both the atmosphere and the ocean. This bias-corrected predictions will be compared with a conventional retrospective prediction system, covering the same period, and with no wind prescribed. Since the only difference between both sets of experiments comes down to the representation of surface winds in the Eastern Equatorial Atlantic and the subsequent improvements in the local mean state and variability, any difference in skill over the globe will be explained by it, in particular in the Tropical Pacific and the Euro-Atlantic sector. For the specific analysis of the influence on ENSO, we will collaborate with Dr. Belén Rodríguez Fonseca from the Universidad Complutense de Madrid, a recognised researcher in the field that performed the pioneering study linking the Atlantic with the Pacific Niños (Rodríguez-Fonseca et al, 2009). The experimental protocol put in place for this study was specifically conceived to identify the future benefits that can be obtained when Tropical Atlantic biases are overcome by the models. In parallel, we will pay special attention to the improvements over that region brought by the very-high resolution simulation in Task 2.1. Due to its high computational cost, this model version cannot be currently used for prediction purposes, but can give a hint of what future generations of prediction systems will be able to achieve.

Expected Outcomes

1. Research paper on the benefits that global simulations with eddy-resolving ocean provide in the North Atlantic
2. Research paper on the importance of Tropical Atlantic variability in the seasonal predictive skill

WP3: Impact of model resolution on the representation of North Atlantic climatic impacts

Participants:
Markus Donat (25%)
Simon Wild (50%)
Post-doc (75%)

Background*:* During the last century, the North Atlantic sea surface temperatures exhibited a long-term warming trend superimposed onto the multidecadal fluctuations of the AMV. The AMV has been identified as the source of marked climate anomalies and associated human impacts over many areas of the globe. However, there are several hints that the current generation of CGCMs (typically of 1° resolution) is missing key mechanisms to correctly simulate the observed AMV teleconnections / impacts. For example, if CGCMs tend to simulate a positive phase of the AMV some years after a strengthening of the northward oceanic heat transport (Ba et al. 2014), the tropical SST anomalies associated with this transport are weaker than the ones associated with the observed AMV (Medhaug and Furevik 2011). Since this tropical branch of the AMV is responsible of many of the AMV climate impacts (Peings and Magnusdottir 2015; Ruprich-Robert et al. 2017), its overly weak representation in climate models may partly explain the lack of AMV teleconnections in decadal predictions. Frontal oceanic regions such as Gulf Stream and its extension are also regions where important mechanisms related to eddy activity may be missing in current CGCMs due to their relatively coarse resolution. These fronts have been shown to shape both the local and the large scale atmospheric circulation characteristics (Chelton et al. 2001; Minobe et al. 2008), and therefore their misrepresentation in coarse models may also contribute to incorrect AMV teleconnections, in particular over Europe. It remains to be tested if increase in the model resolution leads to significant improvements in the representation of these AMV features and impacts.

The atmosphere is a key factor to explain the occurrence of climate extremes. In particular, recent works highlight the particular role that atmospheric wave dynamics played on the past severe European and Russian heatwaves (Hoskins & Woollings, 2015; Petoukhov et al, 2016). In these events, a key aspect was the propagation of Rossby waves (defined by north-south undulations on the westerly flow) along the atmospheric waveguides. Different factors can affect the background refractive index, and thus the preferred propagation pathways of Rossby waves. One avenue of recent research has focused on the possible importance of 'quasi-resonant amplification' (QRA) of Rossby waves in extreme weather events (e.g. Kornhuber et al. 2016; Mann et al. 2017). This occurs when synoptic-scale 'free' Rossby waves constructively interfere with 'forced' quasi-stationary Rossby waves from land-sea contrasts and orography, amplifying the quasi-stationary Rossby waves. It has been suggested that strong mid-latitude waveguides provide the conditions necessary for this quasi-resonant amplification to occur. The body of research provides evidence that waveguides may be important for extreme events, such as heat waves, cold snaps, droughts and blocking highs. However, current research does not examine the longitudinal geometry in the waveguides associated with these extreme events, nor does it look at how often such waveguide geometries exist without an extreme event occurring. The proposed research will address this gap, and in particular how important the model resolution is for their realistic representation.

***Goals**:* The goal of this WP is to evaluate the impact of changing resolution on North Atlantic climate impacts. More specifically, we aim to evaluate whether EC-Earth can capture the teleconnections linked to the AMV, in particular over Europe, and what is the impact of the model resolution on these teleconnections. We will also investigate the connection between extreme events and large-scale, slowly-varying (>5 day) background flow and how these connections are impacted by the climate model resolution.

***Analyses**:* To investigate the link between the AMV and the European climate, in Task 3.1 we will run experiments following the protocol established for the Decadal Climate Prediction Project (component C; DCPP-C) for the 6th phase of the Climate Model Intercomparison Project (CMIP6). Component C consists of targeted simulations intended to investigate the origins, mechanisms and predictability of long timescale variations in climate, and in particular the role of North Atlantic SSTs in the modulation of global surface temperature trends and in driving regional climate variations.

In this case, we will run 3 sets of experiments, each 10-year long and with a 25-member ensemble. Starting from a long control simulation (performed in WP2), we restore the North Atlantic SST of each of the 25 members to either i) climatology, ii) positive AMV anomalies or iii) negative AMV anomalies. By comparing these different experiments (in particular the extreme events), we hope to discover how the model responds to imposed SST anomalies in the Atlantic, the pathways through which the responses are expressed throughout the ocean and atmosphere and the extent to which we can attribute decadal climate anomalies at regional scales (particularly over land) to the patterns of AMV sea surface temperature. These experiments will be performed at both standard resolution and high resolution , thus providing information on the role of the resolution in resolving those teleconnections. This task will be performed in collaboration with Rym Msadek (CNRS/Cerfacs, France), who is a member of the DCPP panel and an expert in decadal predictions.

In Task 3.2, we will study, using the waveguide geometry indices, relationships between waveguide geometry and the frequency and intensity of heat waves, cold snaps, droughts, and blocking events, with a particular focus on the Euro-Atlantic region. This will be done first in reanalysis datasets, and then using the simulations performed in WP2 (Task 2.1). This will allow us to explore the impact of model spatial resolution on the relationships between waveguide geometry and extreme events. We will repeat all analysis on the model outputs at standard, high and very-high resolution. Comparison of results from the different resolutions will be interpreted relative to differences in mean state.

For both reanalyses and simulations, we will use the climatological definition of extreme temperature events as defined by the IPCC Special Report on Climate Extremes: the occurrence of temperatures above (or below) a given threshold percentile of its distribution. We will use different threshold percentiles, between 1-5% (and 95-99%) to determine the robustness of results to this parameter. Because we expect waveguide geometry to affect broad patterns of extreme events, not the frequency on grid-box scales, we will use clustering analysis to select larger regions over which we will average extreme event frequency. For each type of extremes, we will produce maps of the frequency of extreme event for individual months and seasons.

Correlation analysis of these extreme event frequency maps with the waveguide indices will be calculated to investigate whether particular waveguide geometries increase or decrease the probability of extreme events in different regions. We will also produce composite refractive index maps for seasons/months with extremes events or high blocking frequency, and compare to that time periods with no extremes, or low blocking frequency. This will identify patterns of refractive index associated with extreme events.

For waveguide indices or patterns strongly associated with extreme events, we will pick case studies of particular events to study. Lead-lag correlations will give some indication of causality. We will also make use of event-tracking software to study precipitation events. Identification of such anomalies associated with extreme events will allow us to study the propagation path of the anomaly (or anomalies) prior to the extreme event occurring, and compare this to theoretical pathways predicted by waveguide geometry. This task will be performed in collaboration with Rodrigo Caballero (Stockholm University, Sweden). Prof. Caballero is an expert in atmospheric dynamics and the relationship between Rossby wave patterns and extreme events.

Expected outcomes

1. Research paper on Rossby waves pathways and blocking and extreme temperature events
2. Research paper on the AMV, its impact over Europe and the role of model resolution
3. Research paper on the impact of model resolution on Rossby waves propagation and extreme events

WP4: Impact of model resolution on prediction skill over the Euro-Atlantic sector

Participants (% of the total dedication):
Markus Donat (25%)
Juan-Camilo Acosta (100%)
Simon Wild (50%)
Post-doc (25%)

Background*:* Increased horizontal resolution in the ocean and atmosphere has shown improvements in the seasonal skill of the North Atlantic Oscillation (NAO), winter storminess, and near-surface temperature and wind speed over Europe and North America (Scaife et al. 2014). Using EC-Earth in seasonal hindcasts, Prodhomme et al. (2016) reported improvement in the representation of the Gulf Stream together with a reduction in the summer warm bias in the North Atlantic in the higher resolution version of the model. Additionally, NAO skill and the representation of atmospheric blocking were also improved. For decadal forecasting (forecast ranging from 2-10 years), the benefit of increased resolution is less clear, but that is mainly due to the large amount of computer resources required for such experiments, which made them unaffordable until recently. However, as mentioned previously, there are several indications that the current generation of CGCM (~1° resolution) is missing key mechanisms to correctly simulate the observed oceanic–Europe teleconnections, therefore improvements can be expected if simulations at higher resolution better represent this key mechanisms.

Goals*:* Investigate the benefit of increasing model resolution in climate forecasting of extreme events, from seasonal to decadal timescales

Analyses*:* In Task 4.1, we will explore directly the impact on seasonal prediction skill of increasing horizontal resolution on the oceanic and atmospheric domains of the EC-Earth seasonal prediction system. Specifically, we will evaluate whether increases in the horizontal resolution of EC-Earth lead to better representation of the impacts of polar features on the large-scale atmospheric circulation in the mid-latitudes and to an improvement in seasonal forecast over Europe. To that end, two sets of retrospective seasonal predictions will be run at standard and high resolution, respectively. We expect that the increase in resolution will improve the representation of the sea ice edge, which should then impact the atmospheric response to sea ice changes and the forecasting of cold air outbreaks, polar cyclones and other atmospheric phenomena that also affect lower latitudes. Incidentally, the experiments will also include any impact stemming from the use of higher horizontal resolution initial conditions.

Using our results from WP3 on waveguide geometry and its impact on the frequency of extreme events, in Task 4.2 we will build empirical forecast systems for each type of extreme event studied in WP3 (heat waves, cold snaps, droughts, and blocking events). These systems will be compared to dynamical forecasts performed in Task 4.1, enabling us to determine whether EC-Earth has skill exceeding the empirical models in predicting these extreme events. We will also attempt to diagnose the origin of the skill and we will examine whether greater skill at modelling waveguide geometry leads to more successful seasonal prediction of extremes, and whether higher resolution leads to better forecasts.

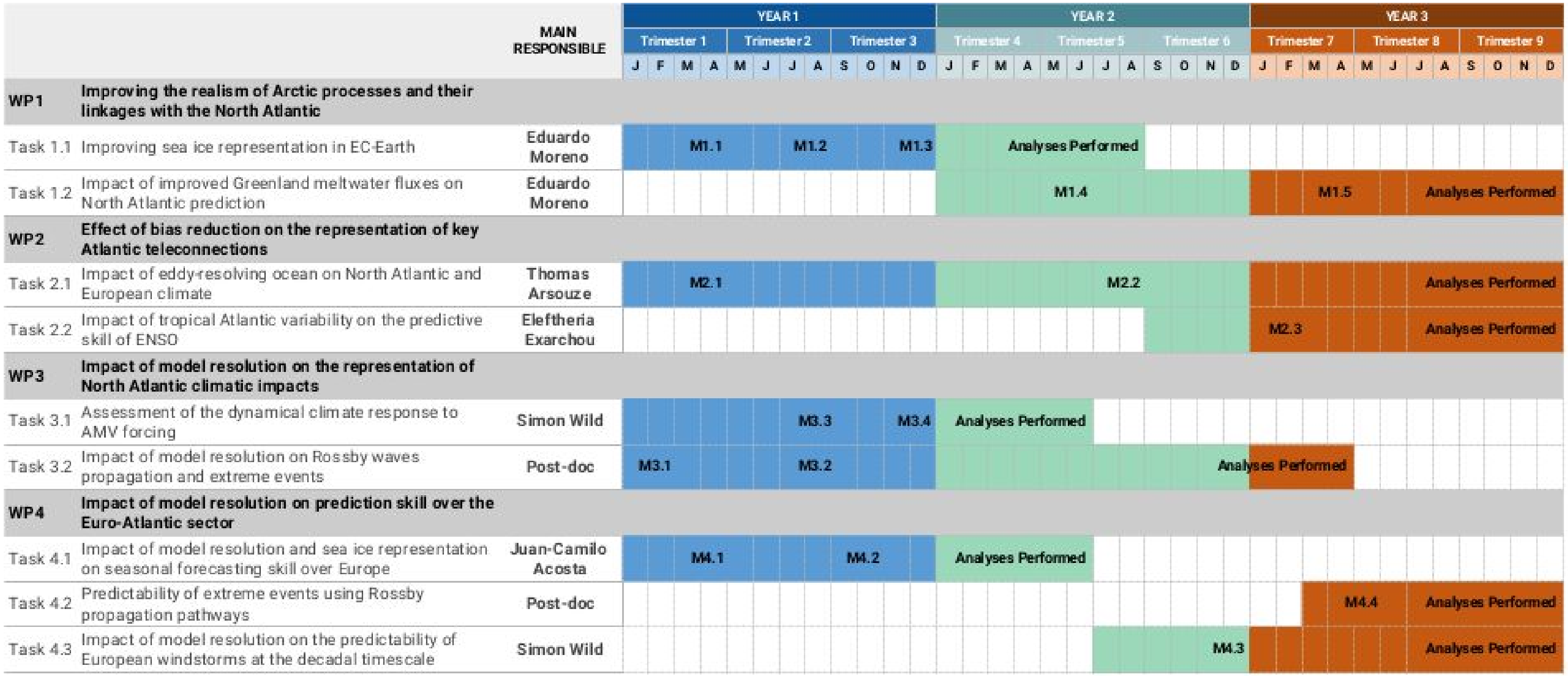
The North Atlantic basin has been shown as the most predictable region of the world at multi-year to decadal time scales. As mentioned above, North Atlantic SST exhibit multidecadal variations referred to as the AMV, which has been shown to modulate anomalies of the NAO and influence the location and activity of the North Atlantic storm tracks. Despite the high impact of windstorms over Europe, no efforts have been made so far in analysing decadal prediction skill of windstorm frequency or intensity. In Task 4.3, we will evaluate the skill of decadal hindcasts performed with EC-Earth at predicting European windstorms. The experiments used for this analysis will follow the protocol established by the Decadal Climate Prediction Project (DCPP), which is part of the sixth Climate Model Intercomparison Project (CMIP6) and which will be run at BSC as part of the MEIC project CLINSA. This set of simulations will be performed at standard EC-Earth resolution. We will then investigate the impact of increasing resolution on the skill by comparing the result of this first set of experiment with a second set of experiment which follow the same protocol, but performed at higher resolution. In both sets of experiments, windstorm frequency and intensity will be analysed using an objective identification and tracking algorithm as well as a storm severity index.

Expected outcomes

1. Research paper on the impact of model resolution and sea ice initialization on seasonal forecasting skill over Europe
2. Research paper on predictability of extreme events using Rossby propagation pathways
3. Research paper on the impact of model resolution on the predictability of European windstorms at the decadal timescale

V. Implementation

As envisaged from its conception, IMPRONTA has been designed with the aim of tailoring the research team's background and the facilities of the host institution, in order to ensure its successful completion. A Gantt chart detailing the time table of the project, with milestones, is provided below.



		MAIN RESPONSIBLE	YEAR 1												YEAR 2												YEAR 3											
			Trimester 1				Trimester 2				Trimester 3				Trimester 4				Trimester 5				Trimester 6				Trimester 7				Trimester 8				Trimester 9			
			J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
WP1	**Improving the realism of Arctic processes and their linkages with the North Atlantic**																																					
Task 1.1	Improving sea ice representation in EC-Earth	Eduardo Moreno	🟦	🟦	🟦	🟦 M1.1	🟦	🟦	🟦	🟦 M1.2	🟦	🟦	🟦	🟦 M1.3	🟩	🟩	🟩	🟩	🟩	🟩 Analyses Performed	🟩	🟩																
Task 1.2	Impact of improved Greenland meltwater fluxes on North Atlantic prediction	Eduardo Moreno													🟩	🟩	🟩	🟩	🟩	🟩 M1.4	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧 M1.5	🟧	🟧	🟧	🟧	🟧	🟧 Analyses Performed	🟧	🟧
WP2	**Effect of bias reduction on the representation of key Atlantic teleconnections**																																					
Task 2.1	Impact of eddy-resolving ocean on North Atlantic and European climate	Thomas Arsouze	🟦	🟦	🟦	🟦 M2.1	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 M2.2	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 Analyses Performed	🟧	🟧
Task 2.2	Impact of tropical Atlantic variability on the predictive skill of ENSO	Eleftheria Exarchou																					🟩	🟩	🟩	🟩	🟧	🟧 M2.3	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 Analyses Performed	🟧	🟧
WP3	**Impact of model resolution on the representation of North Atlantic climatic impacts**																																					
Task 3.1	Assessment of the dynamical climate response to AMV forcing	Simon Wild	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦 M3.3	🟦	🟦	🟦	🟦 M3.4	🟩	🟩	🟩	🟩 Analyses Performed	🟩	🟩																		
Task 3.2	Impact of model resolution on Rossby waves propagation and extreme events	Post-doc	🟦	🟦 M3.1	🟦	🟦	🟦	🟦	🟦	🟦 M3.2	🟦	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧 Analyses Performed	🟧	🟧								
WP4	**Impact of model resolution on prediction skill over the Euro-Atlantic sector**																																					
Task 4.1	Impact of model resolution and sea ice representation on seasonal forecasting skill over Europe	Juan-Camilo Acosta	🟦	🟦	🟦	🟦 M4.1	🟦	🟦	🟦	🟦	🟦	🟦 M4.2	🟦	🟦	🟩	🟩	🟩	🟩 Analyses Performed	🟩	🟩																		
Task 4.2	Predictability of extreme events using Rossby propagation pathways	Post-doc																											🟧	🟧	🟧 M4.4	🟧	🟧	🟧	🟧	🟧 Analyses Performed	🟧	🟧
Task 4.3	Impact of model resolution on the predictability of European windstorms at the decadal timescale	Simon Wild																			🟩	🟩	🟩	🟩	🟩	🟩 M4.3	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 Analyses Performed	🟧	🟧

M1.1	Implementation of melt pond scheme in EC-Earth
M1.2	Implementation of multiple sea ice categories in EC-Earth
M1.3	Sensitivity experiments completed
M1.4	Standard climate predictions completed
M1.5	Climate predictions with meltwater fluxes completed
M2.1	Standard- and high-resolution simulations completed
M2.2	Very high-resolution simulations completed
M2.3	Retrospective forecasts with bias-corrected equatorial winds completed
M3.1	Selection of indices describing waveguide geometry
M3.2	Selection of cases studies
M3.3	Standard-resolution AMV experiments completed
M3.4	High-resolution AMV experiments completed
M4.1	Standard-resolution retrospective forecasts completed
M4.2	High-resolution retrospective forecasts completed
M4.3	Implementation of tracking algorithm completed
M4.4	Development of empirical models completed

T2.1 provides experiments for T3.1 and T3.2

T4.1 provides experiments for T4.2

VI. Technical Resources

[see requested budget for details]

Since its creation in 2006, the BSC has hosted outstanding high-performance computing facilities, which are made available to all its research groups through a bag of non-competitive computing time. These internal resources are thus a solid basis to support the execution of the experiments envisaged in IMPRONTA if application for other resources do not prove successful. For the main bulk of the experiments, we will demand computing time to the competitive programs from the Red Española de Supercomputación (RES) and the Partnership for Advanced Computing in Europe (PRACE), submissions with which the BSC-ES is usually successful.

The current supercomputer is MareNostrum IV was installed in June 2017 and is one of the 7 Tier-0 Systems currently available through PRACE. Technical characteristics of MN4 to highlight are:

- A peak power of 11.15 Petaflops, that enables it to perform more than eleven thousand trillion operations per second, ten times more than the MareNostrum 3, which was installed between 2012 and 2013.
- A disk storage capacity of 14 Petabytes that is connected to the Big Data infrastructures of BSC-CNS, which have a total capacity of 24.6 Petabytes.

The latest version of the EC-Earth model (v3.2.3), the same that will be used for the different IMPRONTA simulations, has already been ported on MN4, and all the different setups have been tested and are currently functional. This will allow us to produce the different experiments in a timely fashion and without major delays that could compromise the successful completion of the project.

All scientists have desktops with multi-core processors that are available through the local network and share exactly the same software stack and modules, offering a seamless environment to perform in a reproducible way all sorts of diagnostics that do not require the large memory available in the fat nodes. However, due to the unusually large outputs that the super-high resolution experiments produce in Task 2.2, we will require of additional local storage. To this end, a suite of five disks of 4TB HDD each has been included in the proposal (see requested budget for further details). We have also budgeted two workstations (PCs), one for the postdoc that we are planning to hire, and another for the Ph.D. student that we have requested. Also, to facilitate an efficient execution/development of the activities in missions outside the host institution, e.g. attendance to meetings and visits to our collaborators, we would require a laptop with an UNIX-based OS.

VII. Human Resources

The post-doctoral researcher requested will be in charge of investigating the impact of model resolution on Rossby waves propagation and extreme events (Task 3.2) and incorporating and investigating the use of this methodology in a seasonal forecasting context (Task 4.2). Under the supervision of the PI, he/she will investigate the connection between extreme events and large-scale, slowly-varying background flow and how these connections are represented in EC-Earth and how this connection is impacted by the climate model resolution. He/she will be also encouraged to learn how to set up and perform climate prediction experiments. Should the results look promising from a user perspective, the researcher will also interact with members of the Earth System Service group to exploit and disseminate the improvement in predictive skill of extreme events deriving from this innovative methodology. At the same time, this person will benefit from the vast experience accumulated in the Department, helping to train the new generation of climate services scientists that the society is increasingly demanding.

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2. IMPACTO ESPERADO DE LOS RESULTADOS - *EXPECTED RESULTS IMPACT*

Scientific Impact

Modelling and predicting the climate is a challenging task, and although current climate models have been proven useful to study a number of aspects in the climate system, their ability to simulate and predict some particular regional climate features can be compromised by current model shortcomings (e.g. misrepresented processes, inefficient parameterizations). These shortcomings add uncertainty to predictions on seasonal and decadal time scales, and projections of long-term climate change.

This proposal will explore several pathways to improve climate simulations, focussing on climate variability in the Atlantic and its effects on predicting climate conditions over land, with a special focus on Europe. This cutting-edge research will improve the understanding of sea-ice and ocean dynamics, their interactions and linkages with the atmospheric circulation and climate extremes. These coupled aspects in the climate system are currently subject to substantial uncertainties, and these uncertainties inhibit more accurate climate predictions. Improving the understanding of these coupled climate processes will therefore help to improve climate models in general, not just the EC-Earth model. The results are therefore anticipated to have substantial impact in the international climate modelling and climate prediction communities. In particular, many of the proposed activities also link with the interests of several H2020 projects in which the research group currently participates (these are: APPLICATE: grant no. 727862, developing enhanced predictive capacity for weather and climate in the Arctic and beyond; PRIMAVERA: grant no. 641727, developing and evaluating high-resolution climate models; EUCP: grant no.776613, developing a European climate prediction system for timescales from seasons to decades). These international collaborations will provide excellent channels to share and discuss our scientific results with other European partners and the wider scientific community.

Internationally, the World Climate Research Programme (WCRP) has identified seven Grand Challenges; these are areas of emphasis in scientific research, modelling, analysis and observations for WCRP and its affiliate projects in the coming decade. The research proposed here responds to two of the WCRP Grand Challenges, namely 'Near-term Climate Prediction' and 'Understanding and Predicting Weather and Climate Extremes', indicating that this research project is highly topical and relevant. This proposal therefore helps Spain to make world-class contributions to WCRP research priorities.

Impact on Societal Challenges

Climate conditions, including extreme events such as heat waves, cold snaps, drought or heavy precipitation, can affect a range of socio-economic sectors including energy, agriculture, insurance and health. In contrast with the use of weather information, few tools are in place to minimise climate-related risks. This implies that users are constantly operating in reactive mode whereby risks have to be dealt with, likely at high costs. By assessing the likelihood of climate risks and their impact several weeks or months in advance, some decisions can be modified in time to adapt operational strategies, avoid possible financial penalties and increase the resilience of the systems as a whole.

Numerical climate models are the primary tools to make climate predictions on seasonal, decadal and centennial time scales. These models, however, are not perfect and have characteristic weaknesses in the representation of climate features, in particular at the regional scale. This project will explore several pathways of how the state-of-the-art climate models could be improved in their ability to more realistically simulate typical climatological characteristics, including climate extremes and climate variability. Specific focus will be on improvements in simulating Atlantic climate variability, and how these affect simulated climate over land areas including Europe and Spain. Improved climate models will eventually allow for more accurate predictions of potential climatic risks, and thereby help users from a range of sectors to be prepared, potentially saving millions of Euros.

Within the Earth Sciences department at BSC, the Earth System Services group has established long-lasting and ongoing links with national and international companies in the energy (e.g. Iberdrola), agriculture (e.g. DeCOOP), wine production (e.g. Codorniu) and insurance sectors (e.g. AXA). Through the years, they have worked to understand their needs and tailor climate prediction information in a way that is both useful and accessible to them. The interest of these groups in our investigations may be representative of the issues that their communities have to face, both in Spain and worldwide, and help demonstrate what climate services can do for them. In addition, compared to climate-change projections, the shorter, near-term operational time scale of the decadal climate predictions is expected to be useful to design adaptation and mitigation strategies. By improving the predictions we will make sure that the climate information reaching the users through different European initiatives and projects in which the BSC-ES and those companies participate is of the greatest quality and reliability, thus allowing them to make better informed decisions.

Communication/Dissemination/Exploitation

The BSC counts on a communication and technology transfer team that allows reaching out to external actors from both public and private sectors. There is also a communication group in the Department that ensures that some of the outreach targets the weather, climate and air quality sectors. This is expressed via the services platform in which the department makes publicly available its operational products and scientific results of interest for a range of sectors. The communication team ensures that any relevant finding performed at the BSC is disseminated in a timely manner, but also to expand the number of users of the climate service that will be developed. The BSC also takes advantage of an exceptional set of meeting rooms available to the BSC staff that allows organising meetings with stakeholders, other scientists (in the form of workshops and conferences) and the public in general, as well as a series of webinars. For instance, the department has organised four international workshops and conferences in the last two years.

3. CAPACIDAD FORMATIVA - *TRAINING CAPACITY*

The Earth Sciences Department of BSC offers the opportunity for prospective Ph.D. students to work in an international multidisciplinary scientific environment. In the context of this project, we would like to recruit and enroll a Ph.D. student in the doctoral program of the Technical University of Catalonia (UPC), which was recognized with MEC Excellence Mention from 2004 to 2013 (MCD2004-00394, MEE2011-0335), and it is currently registered in the VERIFICA process of the ANECA evaluation agency (RUCT: 5600080).

The Ph.D. project proposed aims at furthering our understanding of European extreme events, their drivers and conditioning factors, exploiting the comprehensive sets of simulations that IMPRONTA will produce, and also some additional experiments. This will be achieved through three main activities:

1. In-depth analysis of European extreme events in the very-high resolution historical experiments and the best quality observational products available, with a special focus on the similarities/differences in terms of spatial distribution, frequency of occurrence, and dominant atmospheric circulation conditions. The analysis will be later extended to the experiments with high and standard resolution for comparison.
2. Assessment of the ability of the seasonal forecasts performed in Task 4.1 to predict some selected extreme episodes, chosen beforehand for the preconditioning role of the North Atlantic.
3. Explore the changes in the distribution of extreme events to be expected with future global warming conditions. This analysis will be based on the future projections experiments that the BSC-ES will produce within the context of CMIP6.

The Earth Sciences Department has a long record of supervising Ph.D. theses in the Environmental Engineering program of the UPC. In the last 10 years, 14 Ph.D. theses were completed and 7 are currently ongoing within the Department. Additionally, BSC has a specialized Education and Training Team, dedicated to establish a curriculum based on cutting-edge scientific research on software tools for HPC and application areas. BSC offers a personalized professional development plan to each member, according to their profile and objectives. Thanks to this approach, BSC has been awarded with the Human Resources Excellence in Research, recognizing the alignment of its human resources policies to the principles set out in the EU Charter and Code for Research.

The Ph.D. student will count on the direct supervision and advice of the PI of the project, who will guide him/her to develop a Research and Training Plan within the first academic year, considering both the training goals and the student needs. The training plan will be oriented towards the acquisition of competences in climate modeling and analysis of extreme events. The student will be involved in the research group activities, including periodical internal and external seminars and invited speaker conferences held at BSC. In addition, he/she will have the opportunity to share the results of his/her research in different national and international scientific forums and he/she will be encouraged to co-author scientific research articles of high impact. Complementary skills required for efficient research execution and communication will be fostered through the student participation on multiple training activities offered by BSC.

As stated above, the Ph.D. advisor for this project will be Dr. Markus Donat (PI), who is an expert in climate extremes and the representation of extremes in climate models. He has successfully supervised 2 Ph.D. students to completion up to now and has solid experience in mentoring M.Sc. and B.Sc. students. He is currently the supervisor of 3 ongoing Ph.D. students, while as co-leader of the Climate Prediction Group, he also supervises 10 postdoctoral scientists, including two Marie Curie fellows (Yohan Ruprich-Robert, Rachel White). Although at the postdoctoral level, the Marie Curie grants have an important training component, which is regulated in the Department to ensure that their work is monitored and that the grantees receive adequate support and feedback.

The team involved in the project has participated in the mentoring of 6 Ph.D. students:

1. Oliver Angélil (August 2016-April 2018) has submitted his PhD thesis entitled "Uncertainty Around Probabilistic Event Attribution Statements for Extreme Weather Events" on 23 April 2018 at UNSW Sydney. Ph.D. advisor: Markus Donat. Oliver now works as a data scientist for a private consultancy.
2. Elisabeth Vogel (September 2015-October 2018) has submitted her Ph.D. thesis entitled "Climate Extremes Impacts on Agricultural Crops" on 01 October 2018 at University of Melbourne. Ph.D. co-advisor: Markus Donat (primary advisor: Malte Meinshausen). Elisabeth currently works with the Bureau of Meteorology in Melbourne, Australia.
3. Steefan Contractor (February 2015-) is currently finishing his Ph.D. thesis entitled "Global changes in daily rainfall distributions" at UNSW Sydney, and will submit in November 2018. Ph.D. advisor: Markus Donat.
4. Mia Gross (August 2015-) is in the process of completing her Ph.D. thesis entitled "Are temperature distributions becoming more variable or more extreme?", to be submitted in February 2019. Ph.D. advisor: Markus Donat.
5. Yiling Liu (February 2016-) is in the process of completing her Ph.D. thesis entitled "Perfect-Model Decadal Prediction Benchmarks for Temperature and Precipitation Extremes", to be submitted in 2020 (Yiling will be on maternity leave from October 2018 to May 2019). Ph.D. advisor: Markus Donat.
6. Trung Nguyen (October 2013-) is currently finishing his Ph.D. entitled "Impact of riverine freshwater inflow on the Mediterranean Sea circulation" at the Ecole Polytechnique - Paris-Saclay. Ph.D. advisor: Thomas Arsouze.

While the rest of the team has not been involved in the supervision of Ph.D. students, many of the scientists have been supervising students at the B.Sc. and M.Sc. level. Juan Camilo Acosta has supervised two M.Sc. theses (Stockholm University), Simon Wild has been co-supervising 5 M.Sc. and 3 B.Sc dissertations (University of Birmingham and Freie

Universität Berlin), Thomas Arsouze has co-supervised 2 M.Sc. and 3 B.Sc dissertations, and Eleftheria Exarchou has co-supervised 1 M.Sc.

4. IMPLICACIONES ÉTICAS Y/O DE BIOSEGURIDAD - *ETHICAL AND/OR BIOSAFETY IMPLICATIONS*

Not applicable.