Convocatorias 2015
Proyectos EXCELENCIA y Proyectos RETOS
Dirección General de Investigación Científica y Técnica
Subdirección General de Proyectos de Investigación

AVISO IMPORTANTE

En virtud del artículo 11 de la convocatoria **NO SE ACEPTARÁN NI SERÁN SUBSANABLES MEMORIAS CIENTÍFICO-TÉCNICAS** que no se presenten en este formato.

La parte C de la memoria no podrá exceder de 20 páginas.

Lea detenidamente las instrucciones para rellenar correctamente esta memoria, disponibles en la web de la convocatoria.

Parte A: RESUMEN DE LA PROPUESTA/SUMMARY OF THE PROPOSAL

INVESTIGADOR PRINCIPAL 1 (Nombre y apellidos)**:**

Martin Ménégoz

INVESTIGADOR PRINCIPAL 2 (Nombre y apellidos)**:**

No Investigador principal 2

TÍTULO DEL PROYECTO: Actividad de los Volcanoes en predicciones climáticas estacionales y decenales

ACRÓNIMO: VOLCADEC

RESUMEN Máximo 3500 caracteres (incluyendo espacios en blanco):

A una escala intermedia entre las predicciones meteorológicas y las predicciones climáticas, las predicciones estacionales y decenales aparecen como un reto que necesitamos de responder considerando a la vez su aspecto científico y sus aplicaciones sociales, especialmente para la agricultura y la producción y consumo de energía. El Institut Català de Ciències del Clima (IC3) es el único instituto español que está en condiciones de suministrar este tipo de predicciones, usando las fuentes de previsibilidad del clima y diseñando los mejores modelos de predicción. Durante los últimos años, el IC3 ha trabajado en la previsibilidad del clima asociada a la inicialización de los modelos de clima con las mejores observaciones disponibles, y se enfocó a la vez en la temperatura global y la variabilidad climática regional. Uno de los aspectos aún no considerados en esta actividad es la asociada con las partículas estratosféricas que influyen ampliamente en la variabilidad climática, a través de unas complejas respuestas dinámicas de la atmósfera al forzamiento radiativo de los aerosoles. La mayor parte de los aerosoles estratosféricos son emitidos por los volcanes. El proyecto VOLCADEC tiene como objetivo definir y estudiar cómo los sistemas de predicción climática deben tener en cuenta estas partículas. El proyecto se focaliza en tres objetivos principales: (1) Cómo las condiciones climáticas modulan la respuesta del clima a las grandes erupciones volcánicas (2) Cómo se puede predecir la respuesta del clima a una gran erupción volcánica (3) En qué medida los aerosoles estratosféricos influyen en la variabilidad climática fuera de los periodos de grandes erupciones volcánicas. El último objetivo de VOLCADEC es diseñar el protocolo óptimo que permita tener en cuenta los aerosoles estratosféricos en los sistemas de predicción del clima. Esta solución será muy útil a la hora de suministrar información sobre el clima a

escalas estacionales y decenales, especialmente en la región mediterránea, donde la variabilidad climática es muy dependiente de procesos influidos por los aerosoles estratosféricos.

PALABRAS CLAVE: Variabilidad climática, predicción estacionales y decenales, volcanes, aerosoles estratosféricos, Océano Atlántico Norte

TITLE OF THE PROJECT: Volcanic activity in seasonal to decadal climate forecasts

ACRONYM: VOLCADEC

SUMMARY Maximum 3500 characters (including spaces):

At the intermediate timescales between weather forecasts and climate predictions, seasonal to decadal forecast represents a challenge that needs to be risen both for increased scientific understanding and to develop societal applications, in particular for agriculture, and energy production and consumption. The Institut Català de Ciències del Clima (IC3) is the only Spanish institute that is currently able to provide such forecasts in a real-time context, using all available climate predictability sources and shaping forecast systems for services. Over the last years, IC3 illustrated the predictability associated with the initialisation of climate models with the best observations, which could be seen both in terms of global temperature and regional climate variability. An open aspect of this activity is linked to the role of the stratospheric particles that strongly impact the climate interannual variability through a complex dynamical response of the atmosphere to this aerosol forcing. A large part of those stratospheric particles are emitted by volcanic eruptions. This new project, named VOLCADEC aims at answering how forecast systems should take into account these particles. It focuses on three main challenges: (1) How the climate conditions modulate the climate response to large volcanic eruptions? (2) How can the climate response to a large volcanic eruption be predicted? (3) How the stratospheric aerosol burden affects the climate variability out of the period of major eruptions? The final goal of VOLCADEC is to design the optimal strategy to take into account stratospheric aerosols in climate forecast systems. Optimized systems will be very helpful to provide climate information, in particular in the Mediterranean region, where the climate variability is largely dependent on processes associated to stratospheric aerosols.

KEY WORDS: Climate variability, seasonal and decadal forecasts, volcanoes, stratospheric aerosols, North Atlantic climate

Parte B: INFORMACIÓN ESPECÍFICA DEL EQUIPO

B.1. RELACIÓN DE LAS PERSONAS NO DOCTORES QUE COMPONEN EL EQUIPO DE TRABAJO (se recuerda que los doctores del equipo de trabajo y los componentes del equipo de investigación no se solicitan aquí porque deberán incluirse en la aplicación informática de solicitud). Repita la siguiente secuencia tantas veces como precise.

Nombre y apellidos: Oriol Mula-Valls
Titulación: ingeniero
Tipo de contrato: técnico
Duración del contrato: temporal

B.2. FINANCIACIÓN PÚBLICA Y PRIVADA (PROYECTOS Y/O CONTRATOS DE I+D+I) DEL EQUIPO DE INVESTIGACIÓN (repita la secuencia tantas veces como se precise hasta un máximo de 10 proyectos y/o contratos).

1. **Investigador del equipo de investigación que participa en el proyecto/contrato:** Martin Ménégoz
   Referencia del proyecto: Acuerdo de subvención nº 308378
   Título: SPECS: Seasonal-to-decadal climate Prediction for the improvement of European Climate Services (http://www.specs-fp7.eu/)
   Investigador principal: Francisco Doblas-Reyes
   Entidad financiadora: European Commission under the Seventh Framework Programme (FP7)
   Duración: 01/11/2012-31/01/2017
   Financiación recibida: 1.615.305 euros
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

2. **Investigador del equipo de investigación que participa en el proyecto/contrato:** Martin Ménégoz
   Referencia del proyecto: ANR-13-SENV-0002 (http://www.agence-nationale-recherche.fr/?Project=ANR-13-SENV-0002)
   Título: MORDICUS
   Investigador principal: Christophe CASSOU
   Entidad financiadora: French National Agency for Research Funding (ANR)
   Duración: 01/01/2014-31/12/17
   Financiación recibida: 1 068 080 euros; IC3 no recibe dinero de este proyecto, excepto para financiar viajes de personal del IC3 en Francia
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

3. **Investigador del equipo de investigación que participa en el proyecto/contrato:** Nicola Cortesi
   Referencia del proyecto: Acuerdo de subvención nº 607085
   Título: EUCLEIA : European Climate and weather Events: Interpretation and Attribution
   Investigador principal: Francisco Doblas-Reyes
   Entidad financiadora: European Commission under the the Seventh Framework Programme (FP7)
   Duración: 01/01/2014-31/12/2016
   Financiación recibida: 138282,00 euros
   Relación con el proyecto que se presenta: está algo relacionado
   Estado del proyecto o contrato: concedido

4. **Investigador del equipo de investigación que participa en el proyecto/contrato:** Daniel Ortega
   Referencia del proyecto:CGL2013-41055-R
   Título: RESILIENCE-REFUERZO DE LA RED ENERGÉTICA EUROPEA CON EL USO DE SERVICIOS CLIMÁTICOS
   Investigador principal: Francisco Doblas-Reyes
   Entidad financiadora: MINECO
   Duración: 01/01/2014-31/12/2016
   Financiación recibida: 273.460,00euros
   Relación con el proyecto que se presenta: está algo relacionado
   Estado del proyecto o contrato: concedido

Parte C: DOCUMENTO CIENTÍFICO. Máximo 20 páginas.

C.1. PROPUESTA CIENTÍFICA

General context

The scientific knowledge of the climate system is now sufficient to demonstrate the link between the current global warming and the anthropogenic activities. Due to greenhouse gas emissions, surface temperature has increased over the last century, and this warming is expected to strengthen during the XXIst century, in a way more or less pronounced depending on the scenario followed by societal evolution (IPCC, 2013). Apart from human factors impacting the climate with a time of response of several decades, natural variability induces a strong inter-annual to decadal climate variability that is challenging to forecast (Hawkins et al., 2009). Natural variability is linked to both internal variability and natural forcings (Deser et al., 2012). Internal variability is driven by the interactions between the oceans, the continents and the atmosphere. Natural forcings refer to changes of solar energy and natural emissions of gases and aerosols. There is a strong need for a better understanding of natural variability to design models able to provide forecasts for the next years and decades. These models still need significant progress for successful operational applications at seasonal to decadal scales. Initialisation of climate models is fundamental to forecast temperature and precipitation at these timescales (Doblas-Reyes et al., 2013), but external radiative forcings play also a significant role: variations of greenhouse gases, human-made aerosols, volcanic particles, solar irradiance and land use changes consists in the main forcings that impact climate decadal variability (*e.g.* Hansen et al., 2011). Figure 1 shows the temperature anomalies induced by these forcings over the last century. Among them, volcanic aerosols have inter-annual variations whose impact is challenging to estimate because their representation in climate models is generally basic. As a consequence, it is therefore difficult to estimate the predictability associated to volcanic aerosols in seasonal to decadal forecasts.

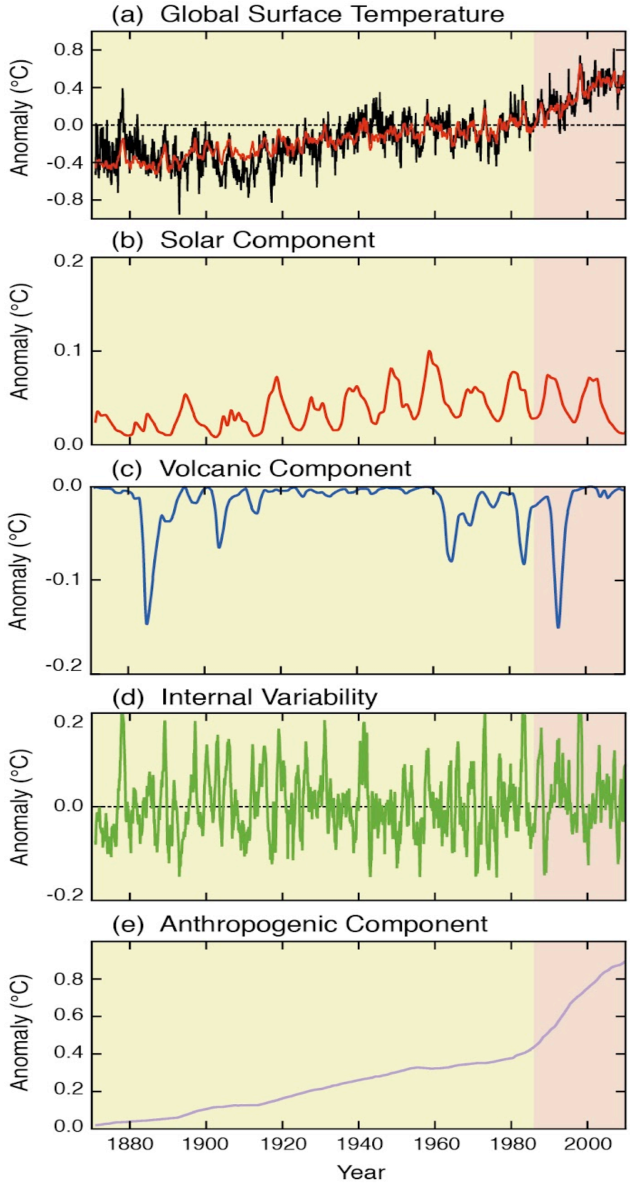

Figure 1: Global surface temperature anomalies from 1870 to 2010, and the natural and anthropogenic factors that influence them. (a) Global surface temperature record (1870–2010) relative to the average for 1961–1990 (black line). A model of global surface temperature change (a: red line) produced using the sum of the impacts on temperature of natural (b, c, d) and anthropogenic factors (e). (b) Estimated temperature response to solar forcing. (c) Estimated temperature response to volcanic eruptions. (d) Estimated temperature variability due to internal variability, here related to the El Niño-Southern Oscillation. (e) Estimated temperature response to anthropogenic forcing. From IPCC (2013).

Large volcanic eruptions are one of the main sources of sulphate aerosols into the atmosphere. They significantly drive climate variability (Figure 1c) by injecting aerosols into the stratosphere (Dutton et al., 1993). Regional climate impacts of these eruptions are poorly known. Recent investigations showed that small eruptions also affect the stratospheric aerosol burden (Ridley et al., 2014), and could have explained part of the current slowdown of the global warming (Solomon et al., 2011). **This project aims at estimating the predictability related to volcanic aerosols in seasonal to decadal forecasts, by designing a new way to simulate volcanic forcing in operational forecasts systems**. This proposal is divided in the seven following sections:

1. *Climate and volcanoes: state of the art*
2. *Context of the proposal and main issues*
3. *Groups working on climate response to volcanoes and decadal forecasts*
4. *Description of the objectives, research methodology, approach and work plan*
5. *Planning*
6. *Detail of the workforce needed*
7. *Services and infrastructure available and needed for VOLCADEC*

1. Climate and volcanoes: state of the art

During explosive tropical eruptions (e.g. Agung, 1963, El Chichon, 1982, Pinatubo in 1991), large quantities of sulphur compounds reach the stratosphere, where sulphate particles stay from several months to a couple of years because of the limited efficiency of aerosol sinks above the tropopause. Strongly reflecting the solar radiation, these particles cool the troposphere, and absorbing the longwave radiation, they warm the stratosphere (Robock, 2000). This radiative balance induces a general cooling of the surface during one to two years after large eruptions. The cooling is stronger over the continents than over the oceans, particularly during the summer, where it can locally reach -1°C (Man et al., 2014). This radiative response can be associated to a dynamical summer signal, in particular in the Indian subcontinent, where eruptions are associated to a decrease of the monsoon circulation (Oman et al., 2005).

The winter response is more complex to understand, since it is mainly driven by the dynamical response of the atmosphere, and depends on the location of the volcano. Tropical eruptions induce a warming of the stratosphere that leads to an increase of the meridional temperature gradient, intensifying the polar vortex due to the thermal wind relation. In contrast, the meridional temperature gradient decreases close to the surface, leading to a decrease of the planetary wave activity, reinforcing also the polar vortex that is hence less perturbed (Robock, 2000). Regarding the major tropical eruptions over the last century, it has been observed that such an increase of the polar vortex was generally associated with an increase of both the frequency and the intensity of the positive phases of the North Atlantic Oscillation (NAO) during the two winters following the eruption (Stenchikov et al., 2002; Smith et al., 2014). This response is generally associated to particularly warm winter temperature over large areas of the Northern Hemisphere continents. This assumption is supported by proxy data analysis that shows also positive NAO anomalies the second and the third winter after eruptions for most of the volcanoes that erupted during the last millennium (Ortega et al., 2015). In contrast with tropical eruptions, particles emitted by high-latitude eruptions stay in the stratosphere only several months (IPCC, 2013), and affect generally only one hemisphere. In addition, high-latitude eruptions do not show any significant dynamical winter response in Northern continental areas (Oman et al., 2005).

The volcanic forcing appears to be significant when investigating drivers of the climate variability at short to medium timescales: the atmospheric response is clearly visible in the observations during the 1 to 5 years following the eruption. Iwi et al. (2012) modelled an oceanic response noticeable from 10 to 20 years after a large eruption, with a significant modification of the Atlantic Meridional Overturning Circulation (AMOC; Swingedouw et al., 2015).

2. Context of the proposal and main issues

Agung (1963), El Chichón (1982) and Pinatubo (1991) are the three last major eruptions with significant climatic impact, inducing a decrease of the global temperature by about 0.1°C (Figure 1c), strong enough to attenuate the anthropogenic signal during several years (IPCC, 2013). However, it is challenging to understand the regional climate response to these eruptions. The return period of such a Pinatubo eruption is about 30 years (IPCC, 2013). Due to the low number of observations of both the eruptions and their climate impacts, it is difficult to isolate its signal from the high natural variability of the climate system. In particular, positive phases of the El Niño Southern Oscillation (ENSO) have been suggested to strongly modulate the volcanic signal of these three past eruptions (Yang et al., 2001). No one could maintain if these positive phases of the ENSO have been triggered by the eruption themselves or not. One of the main modes of climate variability in the Northern Hemisphere is the North Atlantic Oscillation (NAO) that strongly drives temperature and precipitation rates, in particular in the Mediterranean area, both in summer (Bladé et al., 2011) and in winter (López-Moreno et al., 2011). As stated before, the dynamical climate response to recent volcanic eruption shows anomalies typical of the positive phase of the winter NAO. However considering the low number of these observations, it is difficult to say if such a response would occur during a future eruption.

The current generation of Atmosphere Ocean General Circulation Models (AOGCMs) are increasingly more efficient to simulate the radiative response to volcanic eruptions (e.g. Kirchner et al., 1999; Schneider et al., 2009; Man et al., 2014). However, Driscoll et al. (2012) found AOGCMs to reproduce very badly the dynamical winter response to tropical eruptions, with signals of temperature and pressure strongly under-estimated that show in some models an opposite sign to what is found in the observations. All the modelling experiments trying to reproduce the climate response to tropical eruptions highlighted the importance of the background conditions of the atmosphere that are not only superimposed to the variability caused by the volcanic particles but drive it partially (Zanchettin et al., 2013). For instance, the Quasi Biennial Oscillation (QBO) has been found in particular to largely drive how the polar vortex responds to an eruption (Thomas et al., 2009).

In front of the growing importance of seasonal to decadal forecasts for decision makers and industry, the community of climate scientists is focusing a large part of its research on these time scales. Within the fifth phase of the Coupled Model Intercomparison Project (CMIP5; http://cmip-pcmdi.llnl.gov/cmip5/; Taylor et al., 2012), a set of decadal prediction experiments has been performed with different AOGCMs to investigate how these models can reproduce the climate observations during one decade after being initialized from an observational state. However, all these experiments have been performed with observed anthropogenic and natural forcings. Therefore, they cannot be considered as “real forecasts”. If these experiments are very useful to test the ability of AOGCMs to simulate the near-term climate evolution after an initialisation, they cannot give an exact idea of how we can use such models in real forecasts, in a future period for which we do not know natural and anthropogenic forcings. Such a hypothesis is critical in particular regarding the volcanic forcing that is currently unpredictable and with a fast impact (Ammann et al., 2010). If a large volcanic eruption occurred today, these uncertainties on aerosols emissions added to the low skill of current AOGCMs would strongly limit our possibility to forecast its seasonal to decadal climatic impacts. In addition, recent minor eruptions have been observed to impact the stratospheric aerosol burden, with significant impacts on climate over the past 15 years that had been badly anticipated with current AOGCMs (Ridley et al., 2014). On a general way, there is a strong need to design AOGCMs able to forecast the climate response to stratospheric volcanic aerosols at seasonal to decadal timescales. This is the aim of the VOLCADEC proposal, which focuses on three major issues:

(1) Using an original approach to investigate the regional climate impacts of volcanic aerosols;

(2) Checking the ability of current AOGCMs to forecast the climate response to volcanic eruptions;

(3) Setting up new protocols to take into account stratospheric volcanic aerosols in climate forecast systems.

3. Groups working on climate response to volcanoes and seasonal to decadal forecasts

The VOLCADEC proposal aims at setting up the links between two main themes: "*Decadal to seasonal forecasts*" and "*climate response to volcanic eruptions*". Considering the first theme, the World Meteorological Organization (WMO) sponsored the Global Framework on Climate Services (GFCS) where the need for actionable climate information for periods from several months up to several years for economic, industrial and political planning has been expressed. Among the international groups involved in GFCS, a large group of European research and operational institutions organized the SPECS project to approach these issues (Seasonal to Decadal climate Predictions for the improvement of the European Climate Services, http://www.specs-fp7.eu/). This project is lead by the Institut Català de Ciències del Clima (IC3, http://www.ic3.cat) and brings together the 20 main European institutes investigating the climate predictability at these timescales. At the Spanish level, IC3 stands as the national reference in this research field. The VOLCADEC project submitted by IC3 will benefit from the strong experience of all the groups involved in SPECS, in particular KNMI (Netherlands), ECMWF and Met Office (UK), Météo-France and CERFACS (France) and SMHI (Sweden).

Under the sixth phase of the Coupled Model Intercomparison Project (CMIP6; http://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6) that will serve as a base for the next IPCC report, the "Model Intercomparison Project on the climatic response to Volcanic forcing to investigate the climate response to volcanic eruptions" (VolMIP) has been launched in 2015. It groups more than 70 scientists all over the world, mainly in North America and Europe. IC3 takes part in this exercise, a way to open collaborations with different partners that will be widely useful within the VOLCADEC project. Martin Ménégoz is responsible for the component of the VolMIP project that involves EC-Earth, a climate model developed by a large European consortium (http://www.ec-earth.org/). He is collaborating in particular with Myriam Khodri (IPSL, Paris, France) and Claudia Timmreck (MPI, Hamburg, Germany), co-chairs of the VolMIP component of CMIP6. Part of the investigations that will be performed within VolMIP will contribute also to the Decadal Climate Prediction Project (DCPP), the CMIP6 exercise that focuses on the predictability of the climate system at seasonal to decadal time scales.

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4. Description of the objectives, research methodology, approach and work plan

We will address the two main objectives of this project under **three work packages**: the first one aims at analysing the **dynamical response to a volcanic eruption in the current generation of AOGCMs**. It is based on the thorough analysis of a large number of simulations performed in the framework of national and international projects. The second work package aims at evaluating **the skill of AOGCMs used as seasonal to decadal forecast systems,** initialised from observations. The third work package aims at **defining the best way to take into account stratospheric volcanic aerosols in global forecast systems**, just after a large eruption has occurred, but also when the stratospheric aerosol burden is modified by a succession of small eruptions.

The VOLCADEC project will be carried out within the Climate Forecasting Unit (CFU, http://ic3.cat/wikicfu/index.php/Main_Page), involving Martin Ménégoz (PI of the project, with 14 publications focusing on climate variability and aerosols), Nicola Cortesi (expert in precipitation variability in Europe), Daniel Ortega (expert in climate analysis) and two new postdoctoral researchers that are requested for this project (who should have experience in atmospheric sciences and climate modelling). The VOLCADEC research will also be supported by the overall CFU team that makes a common effort to develop statistical tools (http://ic3.cat/wikicfu/index.php/Tools/s2dverification) and invests heavily in the development of the EC-Earth AOGCM (Hazeleger et al., 2010). The VOLCADEC team will include also two internationally recognized French researchers: Christophe Cassou (CERFACS, CNRS, France, expert in decadal climate variability, member of the DCPP panel) and Didier Swingedouw (University of Bordeaux, CNRS, France, expert in climate response to volcanoes with about 50 publications in the climate sciences).
The following sections describe the methodology planned to carry out the three work packages of this project. A Gantt chart describing the different tasks that will be performed over the three years of the project appear at the end of this section.

Work Package 1: Understanding and attributing the climate response to volcanoes

Months 1-18 *Martin Ménégoz (IC3) 30%*
Nicola Cortesi (IC3) 30%
Daniel Ortega (IC3) 20%
Post-Doc 1 (IC3) 50%
Post-Doc 2 (IC3) 30%
Christophe Cassou (CERFACS)
Didier Swingedouw (CNRS)

The proposing team is currently involved in different national and international projects that, among other objectives, are interested in solutions that allow the understanding of the global and regional climate impacts of volcanic eruptions. In this context, many simulations have been and will be performed and human resources is clearly needed to analyse this material. Two main sets of simulations will be considered in the Work Package 1 (WP1), each time addressing a specific scientific question:

Task 1.1: Investigating the climate response to large eruptions under different climate conditions. Months 1-12

The "Mechanisms for climate Oscillations and Retroactions at Decadal tImesCale: Uncertainties and Sensitivity" (MORDICUS) is a French project funded by the Agence National de la Recherche (http://www.agence-nationale-recherche.fr/en/anr-funded-project/?tx_lwmsuivibilan_pi2[CODE]=ANR-13-SENV-0002) where IC3 is an unfunded partner. The project is devoted to the analysis of the processes that drive the decadal climate variability. Christophe Cassou (CERFACS, Toulouse, France) coordinates this project that performed a large number of simulations in 2014 and 2015 to investigate both the internal and the externally forced climate variability at seasonal to decadal timescales. Apart from a 1,000-year control simulation with 13 ensemble members, specific sensitivity experiments were produced to investigate the climate response to volcanic eruptions under different climate conditions. Zanchettin et al. (2013) suggested that the background climate conditions are not only superimposed to the climate dynamical response to large eruptions, but drive also partially this response. Their work focused on climate simulations of the Tambora 1815 eruption. The El Chichon 1982 and the Pinatubo 1991 eruptions occurred during a cold phase of the Atlantic Multi-Decadal Oscillation (AMO; Knight et al 2005), a period with particularly low surface temperature in the Atlantic area. We do not know what would have been the climate response to these recent eruptions under a warm phase of the AMO. To answer this question, the coldest and the warmest phases of the AMO were extracted from the MORDICUS control run performed with the CNRM-CM5 model (Voldoire et al 2012), and a sensitivity experiment was performed simulating a Pinatubo-like eruption under these two extreme phases of the AMO. We will analyse these simulations to understand how the AMO state drives the dynamical response of the atmosphere to a large eruption, providing an estimate of the climate variations conditioned on the AMO phase after a specific eruption. Given the low number of observed response to volcanic eruptions, such sensitivity experiments will be key to increase our understanding of climatic response in different climatic conditions. In particular, most of the volcanic eruption during the instrumental era occurs during negative phase of the AMO, and this WP will crucially analyse if this may have an impact on dynamical response of the NAO for instance.

Task 1.2: Investigating the sensitivity of the climate response to volcanic forcing to the background climate conditions. Months 1-18

The MORDICUS simulations will be used to investigate the impact of the AMO state on the climate response to volcanic eruptions in the task 1.1. In the task 1.2, a new set of simulations will be performed with the EC-Earth model to estimate the response to volcanic forcing which may be comparable to the amplitude of the internal interannual variability. Following the VolMIP protocol, we plan to perform a five-year ensemble simulations that will use the same volcanic forcing recommended for the 1991 Pinatubo eruption in the context of the CMIP5 and CMIP6 historical simulations (Thomason et al., 2015). We will use a large ensemble size (a minimum of 25 members) by considering initial conditions typical for different states of the dominant modes of climate variability. These different states will be sampled from a long control simulation (at least 200 years) performed under pre-industrial conditions by the EC-Earth consortium for CMIP6. Then, we will extract from this control simulation the extreme phases (negative and positive) of ENSO, the AMOC, the QBO and the polar vortex with its associated NAO, that will be used to initialise the different members of this sensitivity experiment. This new set of simulations will consist in one of the experiment required for the unfunded VolMIP project (simulation VolShort20EQfull following the VolMIP experiment design). The large ensemble of these short-terms experiments will be used to estimate the climate response to eruptions under different background climate conditions. In addition, we will use it to check if the main modes of climate variability affect the climate response to large eruptions.

Milestones WP1: *M1.1: Report with the results of the MORDICUS simulation analysis (Month 12)*
M1.2: VolMIP experiments completed (Month 18)
Deliverable WP1: *D1.1: Publication investigating how the climate conditions influence the climate response to volcanoes (Month 15)*

Work Package 2: Evaluating the capability of AOGCMs to simulate the climate response to large eruptions in a decadal forecast system

Months 6-24 *Martin Ménégoz (IC3) 30%*
Nicola Cortesi (IC3) 30%
Daniel Ortega (IC3) 20%
Post-Doc 1 (IC3) 50%
Post-Doc 2 (IC3) 30%
Christophe Cassou (CERFACS)
Didier Swingedouw (CNRS)

Work Package 2 (WP2) will aim at evaluating the forecast quality of climate forecast systems to reproduce the observed climate response to the most recent eruptions. The first task is based on the use of the CMIP5 simulations, and the second one on new EC-Earth simulations.

Task 2.1: Analysis of the CMIP5 hindcasts. Months 6-18

The CMIP5 exercise provided a large number of simulations, including decadal forecasts that have not been fully exploited, in particular regarding the climate variations induced by volcanic activity. The direct response to the radiative perturbation following large eruptions is generally well reproduced by AOGCMs, with a significant cooling modelled at the surface (e.g. Man et al., 2014). At the decadal scale, Ding et al. (2014) suggested that large eruptions are likely to enhance the overturning circulation of the North Atlantic Ocean, pointing out that such response widely differs from one model to another. At seasonal to multi-annual timescales, Driscoll et al. (2012) pointed out the low performance of CMIP5 models to reproduce the observed dynamical response of the atmosphere, in particular during the winters following an eruption. Iles et al. (2014) found that the CMIP5 models reproduce well the general decrease of precipitation that follows large eruptions, with a wettening of the dry regions and a drying of the wet regions. However, all of these authors struggled to detect the volcanic signal due to the large internal climate variability. Generally, they excluded the internal variability by removing the ENSO signal with a simple statistical regression. Hence, they neglect the possible modulation of the climate response to volcanoes by the background climate conditions.
Here, we suggest to analyse the climate response to volcanoes in the CMIP5 decadal hindcasts (hindcasts are forecasts run for past periods) based on initialisations from estimates of the observed climate state. Using the hindcasts initialised around periods of large eruptions, we will check whether climate models reproduce the observed dynamical response of the atmosphere, in particular the winter intensification of the positive phases of the NAO. It will consist in a more strict evaluation of these models, to further estimate how we could use them for seasonal to decadal operational forecasting. Following the protocol of Guemas et al. (2013a), we will also estimate the skill of such forecast systems during periods of large eruptions.

Task 2.2: Differentiating the contribution of initialization and volcanic forcing in climate forecast quality. Months 12-24

The team is currently assessing the ability of EC-Earth to forecast the climate response to large eruptions in the SPECS project (http://www.specs-fp7.eu/). Preliminary results allowed distinguishing the contributions from both initialization and volcanic forcing to the surface temperature variations simulated in decadal forecasts (see Figure 2 for the first year temperature anomalies after an eruption). Such analysis aims at distinguishing the climate variability induced by internal variability from that induced by the volcanic forcing.

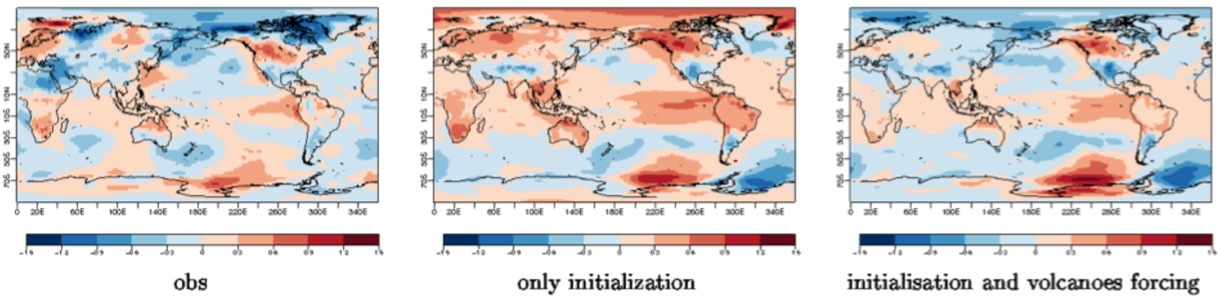

Figure 2: Composite of surface temperature anomalies the first year following the eruptions of Agung (1963), El Chichón (1982) and Pinatubo (1983). Left: Observations are an average of the annual ERA40 anomalies after the 3 eruptions. Simulations are 5-member averages after the 3 eruptions. The central panel shows anomalies in initialized hindcasts without aerosols emissions from large volcanoes, whereas the right panel corresponds to hindcasts performed both with initialization and volcanic forcing.

These analyses will be followed by an evaluation of the predictability associated with the volcanic forcing considering different modes of climate variability in several regions: the NAO (Hurrell, 1995), the Southern Indian Ocean Dipole (SIOD; Behera et al., 2001), the El Niño Southern Oscillation, (ENSO; Trenberth et al., 1997) and the Southern Annular Mode (SAM; Limpasuvan et al., 1999). We will investigate the potential increase of forecast quality in seasonal-to-decadal predictions to reproduce these oscillations when including volcanic aerosols. In addition, we will also look for the increase in forecast quality related to the oceanic circulation, considering in particular the AMOC predictability. These analyses will be based on different sets of simulations that have been performed with and without volcanic forcings during the SPECS project.

Milestones WP2: *M2.1: Report with CMIP5 hindcasts analysis (Month 18)*
M2.2: Report with SPECS hindcasts analysis (Month 24)
Deliverable WP2: *D2.1: Publication evaluating the skill of forecast systems related to volcanic forcing (Month 21)*

<u>Work Package 3: Accounting for stratospheric aerosols in forecast systems</u>

Months 12-36 *Martin Ménégoz (IC3) 40%*
Nicola Cortesi (IC3) 20%
Daniel Ortega (IC3) 10%
Post-Doc 2 (IC3) 40%
Christophe Cassou (CERFACS)

Work Package 3 (WP3) aims at improving the representation of stratospheric volcanic aerosols in climate forecast systems. WP3 will require new sets of model experiments that will be performed with the EC-Earth climate forecast system. Different configurations of this system will be tested within three main tasks devoted to (1) the design of an optimal volcanic forcing that should be used when forecasting the climate response to a large eruption, (2) the improvement of the description of the stratospheric background level of aerosols in AOGCMs, and (3) the assessment of an optimised forecast system to simulate a Pinatubo-like eruption that would occur in 2015.

Task 3.1: Defining future volcanic large eruption forcing in forecast systems. Months 12-24

Two ways can be used to consider the volcanic forcing in seasonal to decadal forecast systems: The first one is to launch an AOGCM simulation considering the satellite-observed stratospheric aerosol concentration at the beginning of the simulation, and thereafter applying an exponential decay of this concentration that would reach the background value after some years. Such idealised protocol could be used to forecast the climate response just after a new large eruption for which we cannot evaluate the future concentration of stratospheric particles. Note that such protocol is classically used in different European forecast systems but has never been evaluated. Here, it will be tested thanks to sets of five-member hindcasts for the three last explosive tropical eruptions (Agung, El Chichón, Pinatubo) that will be compared to the hindcasts performed using estimates of the actual volcanic forcing. Comparing the forecast skill in the two sets of experiments will allow evaluating such idealised protocol.
Under a new large eruption, another way to forecast its climate impacts is to use an estimate of the forcing from a past large eruption, assuming that this past forcing is more realistic than the idealized forcing tested previously. An additional five-member set of hindcasts will be performed over the three last eruptions, but inverting the volcanic forcing between the different experiments. Again, a forecast quality assessment will be undertaken to evaluate the suitability of such a protocol.
The first task of WP3 will be concluded by providing recommendations of the optimal way to consider volcanic forcing in forecast systems after large eruptions. It is also a unique method to test AOGCMs under a specific forcing, with the final goal to improve its performance.

Task 3.2: Defining the stratospheric aerosol burden in forecast systems. Months 18-36

There are still many open questions about the small eruptions that clearly impact the climate variability at decadal timescales by injecting aerosols in the lower stratosphere (Santer et al., 2014). If the current hiatus of global warming has probably been triggered by ocean-atmosphere interactions (Guemas et al., 2013b), it is likely that it has been enhanced by a recent increase of small volcanic eruptions (Solomon et al., 2011). Such an increase of the aerosol burden in the lower stratosphere has never been taken into account in forecast systems, in particular because aerosol optical depth (AOD) used in models is based on satellite observations that underestimate the low stratospheric aerosol burden (Ridley et al., 2014). Here, we plan to implement in our EC-Earth simulations the Ridley et al. (2014) aerosol stratospheric burden estimated from lidar observations for the period 1995-2015. With such improvements, we will investigate if our AOGCMs hindcasts are more coherent with observations of the current hiatus of the global surface temperature by performing five-member hindcasts that will be compared to the CMIP5 hindcasts. We will also test different stratospheric aerosol background levels (upper and lower bounds of the estimations based on observations) in further hindcasts that will be performed to estimate the uncertainties associated to this forcing. The final goal of this task is to define how stratospheric AOD should be specified in operational forecast systems, both during periods of small or large volcanic activity.

Task 3.3: Forecasting the climate response to a new eruption. Months 24-36

The third task of WP3 will focus on the scenario of a Pinatubo-like eruption that would occur in 2015. Considering the same forcing as the 1991 eruption, we will investigate the potential effects of a volcanic eruption on a forecast of the coming decade. This experiment will be part of the VolMIP-DCPP joined effort to investigate the sensitivity of the volcanic response to the state of the climate system (simulation VolShort20EQini in the VolMIP experiment design, with 5 to 10 members). Considering together the possible climate responses to volcanic eruptions and the current climate conditions, we will use this forecast to provide detailed information to the society on what could be the consequences of a new large volcanic eruption in the short term.

Milestones WP3: *M3.1: Hindcasts including idealised volcanic forcing (Month 24)*
M3.2: Hindcasts sensitivity to stratospheric aerosol background (Month 30)
M3.3: Forecast of a hypothetical eruption occurring in 2015 (Month 30)

Deliverable WP3: *D3.1: Publication describing the design of the idealized forcing for large eruptions (Month 27)*
D3.2: Publication investigating the sensitivity of the climate system to the background level of stratospheric aerosol (Month 33)

5. Planning

The timeline of the VOLCADEC project is detailed in the following Gantt chart.

	Year 1				Year 2				Year 3			
Months	M3	M6	M9	M12	M15	M18	M21	M24	M27	M30	M33	M36
WP 1	T1.1: MORDICUS											
	T1.2: VolMIP experiments											
WP2			T2.1: CMIP5 analysis									
					T2.2: SPECS experiments							
WP3					T3.1: Idealized forcing							
							T3.2: Stratospheric background levels					
									T3.3: A 2015 eruption			
Milestones				M1.1		M1.2 M2.1		M2.1 M3.1		M3.2 M3.3		
Deliverables					D1.1		D2.1		D3.1		D3.2	

Gantt chart of the VOLCADEC project: *Each column spans a three-month period with its last month indicated in the second row. T denotes the different tasks of the WPs, appearing in orange when referring to the analysis of existing simulations (Postdoc 1) and in blue when based on new model experiments (Postdoc 2).*

6. Detail of the workforce needed (Two postdoctoral positions)

Postdoc 1 (24PM): Given the large amount of data to be analysed during this project, a substantial increase in the human resources of the research group is highly desirable. The first post-doctoral researcher requested will contribute to the analysis of a large set of simulations available at IC3. She/he will focus on the analysis of the uninitialised simulations performed under the MORDICUS project (WP1/T1.1) to investigate the impact of the AMO state on the climate response to volcanoes. Then, she/he will identify the forecast systems skill related to the volcanic forcing considering two sets of simulations available at IC3: the CMIP5 (WP2/T2.1) and initialised simulations performed within the SPECS European project (WP2/T2.2). Its contribution will significantly help our understanding of the links between the main modes of variability and the climate response to volcanic eruptions.

Postdoc 2 (36PM): Given the large amount of experiments to be produced, sufficient workforce beyond what the research group can provide is essential to the success of the project. The second post-doctoral researcher requested will be the main person in charge of the generation of the decadal prediction experiments under the three WPs. She/he will perform a large set of members of non-initialised simulations under pre-industrial conditions following the VolMIP protocol (WP1/T1.2), to assess the links between ENSO, QBO, NAO and climate response to volcanic eruptions. This work will be carried out in close collaboration with the Postdoc 1. Then, the Postdoc 2 will work on the optimisation of a climate forecast system, by designing an idealised volcanic forcing that could reproduce the impact of large eruptions (WP3/T3.1). With the same model, she/he will investigate the climate sensitivity to the stratospheric aerosol background level, focusing in particular on the role of the small eruptions on the current hiatus of the global warming. Her/his work will serve as a base to improve the forecast system used at IC3. Finally, the postdoc 2 will launch a decadal forecast starting in 2015, with two scenarios of stratospheric aerosols: one keeping the most realistic aerosol background levels, and another one considering a new Pinatubo-like eruption.

7. Services and infrastructure available and needed for VOLCADEC

The VOLCADEC project will be carried out within the Climate Forecasting Unit (CFU) of the Institut Català de Ciències del Clima (IC3) which undertakes innovative and challenging research that ensures the development of cutting-edge climate services at seasonal to decadal timescales. The CFU has been a pioneer in this field, participating in the first European projects devoted to the calibration of scientific approaches to practical applications of decadal forecasts, in particular in the energy sector. The CFU is made of a core team of 1 senior scientist, Prof. Doblas-Reyes, 4 junior scientists including Martin Ménégoz, 5 postdocs, 1 PhD student, 2 master students, 1 project manager, 4 climate services officers, 5 software engineers, 1 system administrator and 1 secretary. The software engineers work on supercomputing over different platforms. They have a highly qualified technical expertise to deal with complex parallelised codes such as the ones that will be used within this proposal. Besides, the CFU members work with freely available softwares developing post-processing and diagnostic tools that are openly shared under GNU licenses with the rest of the community, strengthening the efficiency and the impact of their work. They also maintain a common data repository competitive with what is available in the leading climate research institutions to ensure that the research carried out makes use of the latest, highest quality observational datasets. Thanks to the host infrastructures (detailed below) and unique human resources (with a ratio of one technician for every two researchers), the CFU can run state-of-art global seasonal-to-decadal ensemble climate prediction system.

Local HPC: The continuous increase of computing needs of the scientific community motivated the deployment of a High Performance Computing (HPC) cluster at IC3. The IC3 cluster is made of 48 homogeneous server blades. Each server blade has two "quadcore" processors, 48 GB main memory, 146 GB disk space and fast network interconnect (Infiniband). In order to share data (model code, input data and output data) among computing nodes, there is an I/O node that comprises 48 disks of 1TB each. In short, the computing cluster has 384 cores, 8.81 TB memory (RAM) and 55 TB of shared disk capacity. Moreover, the cluster has 97.2 TB tape backup capacity. The IC3 computing cluster is installed within a CPD of 17 m2.

Competitive computing resources obtained to date: Thanks to many national and international partnerships with high-performance computing centres, the CFU is able to run state-of-the art climate models with a large number of ensemble members. Available computing time worth more than 1 million euros per year just in electricity costs have been obtained on the following institutions and programs: 1) Red Española de Supercomputación (RES), 2) PRACE Tier 0 and 1 (using platforms in Sweden, Spain and the UK), 3) European Centre for Medium-Range Weather Forecasts (ECMWF), and 4) INCITE (US DoE's programme, offering computing time on Titan). The remaining resources are obtained from the IC3 cluster, which provides around 10% of the total computing time used.

Local Storage: A local data storage with 1.5 PB of capacity with high availability and replication is also available, as well as a set of associated computing nodes for post-processing (fat nodes). The local storage hosts at this stage a unique set of global climate predictions performed by IC3 in research mode and operationally by global producing centres around the world. A comprehensive dataset including observations and re-analyses is also available to the CFU members. All these datasets are kept up to date.

Fat nodes: Two computing nodes to post-process model outputs and preprocess initial conditions to perform climate simulations are available. One of them has 8 cores and 144 GB memory (RAM), and the other one has 12 cores and 256 GB memory (RAM). Both are accessible through ssh and can be used through schedulers that have been fine tuned for the kind of work the CFU carries out.

Desktops: All scientists have desktops with multi-core processors that are available through the local network and share exactly the same software and environment, offering a seamless environment to perform all sorts of diagnostics that do not require the large memory of the fat nodes.

Equipment, consumables: To store all the climate simulation outputs that will be produced during the VOLCADEC, the storage system of the department will have to be expanded. For the amount of data that the project is expected to generate, we need around 40 TB of raw space. That will require the acquisition of 20 4TB disks, which cost about 4000 euros. Two desktop computers (2200 euros) will be needed for the new postdocs, and two additional laptops (4000 euros) that will be used when visiting the French collaborators. It makes a total of new equipment that reaches **6,200 euros**.

Publications: As described in the different WPs, four publications will be submitted during the project. At an average cost of 2,000 euros, it makes a total of about **8,000 euros**.

Travels: An average of three travels per year are planned for Martin Ménégoz, Nicola Cortesi and the two postdocs to attend international workshops or conferences such as the European Geosciences Union Annual Meeting or others more focused on climate variability and predictability on decadal timescales or volcanic aerosols. A part of these travels will be used to visit the French collaborators of the VOLCADEC project in Toulouse (France). One additional travel per year is planned for Daniel Ortega to attend workshops on big data processing. This makes a total of about 40 travels for the whole duration of the VOLCADEC project and for the whole team with a total cost of about **40,000 euros**.

Invitation of our collaborators: Each of our collaborators at CERFACS (Toulouse, France) and U. Bordeaux (France) will be invited for a one-week stay at least once during the VOLCADEC project to visit IC3. This makes a total of about 2 travels at an average cost of 1,000 euros, i.e. a total of **2,000 euros.**

C.2. IMPACTO ESPERADO DE LOS RESULTADOS

The impact of this project will be visible through four main axes: (1) The implication of new research on international research activities through international initiatives like CMIP6, (2) the publication of the original results in international peer-review journals and their dissemination in international conferences, (3) a new protocol designed to simulate the volcanic stratospheric aerosols in AOGCMs to be distributed to European operational climate forecast teams, and (4) the transfer of new results to AEMET and the IC3 climate services to provide climate information to public and private groups. These four points are detailed here:

1. International research activities

IC3 is involved in the MORDICUS French project, lead by a team that has already performed large sets of simulations to investigate internal and externally forced climate variability. The French colleagues involved in the project focus their investigations on the internal variability of climate that is largely driven by ocean-atmosphere interactions. They rely on IC3 to bring the expertise needed to better understand the external variability that is, to a certain extent, associated to volcanic activity. With a full understanding of both internal and external variability, we will be able to provide the information needed by our society to anticipate some aspects of the climate change in the next years.

IC3 is coordinating the SPECS European project that has been launched in 2012 and will be completed in 2017. This substantial effort will serve as a basis to exchange and promote the VOLCADEC results between the main European centres involved in seasonal to decadal forecasting. The initial research performed within SPECS highlighted the need to improve the way stratospheric aerosols are taken into account in operational forecast systems. This issue will be appropriately tackled for the first time in Europe thanks to the VOLCADEC project. In return, the experts involved in SPECS will provide a framework to discuss our results, and will help to disseminate our findings to the whole European community.

IC3 is arguably the main Spanish institution likely to be involved in CMIP6. IC3 will base a large part of its implication in CMIP6 on activities similar to the ones proposed in VOLCADEC, especially on the VolMIP and the DCPP components. The VOLCADEC project plays therefore a strategic role of the first order for IC3, but also for the whole spanish community involved in climate research. The research planned here will be of particularly interest for the VolMIP community, as it will bring information on background stratospheric aerosol burden, a well-known weakness in the understanding of volcanic impacts on climate. It will also reinforce the IC3 involvement in the "Stratosphere-troposphere Processes and their role in climate", a project of the "World Climate Research Program" (SPARC, WCRP, http://www.sparc-climate.org/), one of the WCRP core projects in which IC3 still does not play an important role.

2. Expected publications

Four main publications will be submitted under VOLCADEC: (1) The first one will focus on the modulation of the climate response to volcanoes by the Atlantic Multidecadal Oscillation (AMO), since the three last major eruptions occurred under a cold phase of the AMO. This new publication should help the community to forecast the impact of a new major eruption that would occur under the current warm AMO conditions. (2) The second paper will aim at understanding the dynamical atmospheric response to large volcanic eruptions in the CMIP5 hindcasts and SPECS initialised experiments. (3) The third paper will describe the design of idealized volcanic forcing that could be used in real-time climate forecasts. (4) The fourth paper will focus on the role of stratospheric aerosols on the current hiatus of the global warming. It will help our community to estimate how long the current hiatus could last for. The participation in other publications can be expected thanks to our international collaborations. We will be involved in particular in a paper lead by our French colleagues reviewing the climate impacts of volcanoes using one of the French global models.
The SPECS project is an efficient platform to diffuse information to European partners that will be used here to publish a fact sheet reviewing the climate impacts of volcanoes. The VOLCADEC results will also be presented to the scientific community when attending international conferences.

3. Thorough testing and distribution of a volcanic aerosol protocol for operational forecast systems

By completing the VOLCADEC project we hope to bring the optimal way to consider stratospheric aerosols in global climate predictions. A new experimental set up describing the forcing of these aerosols will be provided to other forecast centres, through the strong implication of the CFU team in the European community. In the last decades, the prediction at near-term time scales has received less attention than weather forecasting and long-term climate change projections. However, the World Meteorological Organization (WMO) has expressed in clear terms the increasing need for robust climate information covering future periods ranging from several months up to several years for economic, industrial and political planning. The answering to the open questions around the climate impact of volcanoes and their simulation in operational forecast systems is a critical point regarding these societal issues, especially in the framework of the development of operational climate services. Designing optimised forecast systems, we will be able to provide useful climate information, in particular in the Mediterranean region where the climate variability is highly dependent on dynamical atmospheric processes themselves largely affected by stratospheric aerosols.

4. Disseminating new results with the IC3 climate services to partners in the sectors of climate information and renewable energy

Climate services is a growing topic at IC3 that aims at providing useful, action-oriented climate information to both public and private partners. Any result with potential operational use and the associated technical expertise will be transferred to both the Agencia Española de Meteorología (AEMET) and the ECMWF. The project deliverables will be shared with the AEMET, which is the natural user of the climate forecast information at the Spanish level, to keep them informed about the progress of this sort of predictions. Being the body with competences on operational climate forecasting and a natural user of the Spanish climate research, AEMET will benefit from and take over the technological developments carried out throughout this project to improve climate prediction capability.

IC3 is also involved in close collaborations with several partners in the energy sector. All the results obtained within VOLCADEC will be disseminated through the IC3 climate service. We will inform the IC3 partners about the possible impacts of volcanoes on their activity through climate modifications. As an example, wind farm stakeholders from the private sector are interested in the impact of climate variability on their production rates. VOLCADEC will also help our team to take part in a recent European project that has been launched to provide real-time, multi-model seasonal to decadal forecasts (Smith et al., 2013), reinforcing the IC3 implication in this task with strong implications for both social and economic sectors. Overall, IC3 is the only group that can be expected to develop a real-time climate forecasting capability in Spain in a near future. Funding VOLCADEC will help IC3 to create an efficient forecast systems in Spain, competitive with the main ones in Europe, with clear applications in many socio-economical sectors and in general in all the European countries, and with the ability to transfer this technological development to the agency with operational competences in the field.

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C.3. CAPACIDAD FORMATIVA DEL EQUIPO SOLICITANTE

Not applicable.

C.4. IMPLICACIONES ÉTICAS Y/O DE BIOSEGURIDAD

Nothing to declare.