INFORME FINAL DE PROYECTOS DE I+D+i

Como paso previo a la realización del informe, se ruega lean detenidamente las instrucciones de elaboración de los informes de seguimiento científico-técnico de proyectos **disponible al final de este informe.**

Este informe debe reflejar las actividades desarrolladas **durante todo el proyecto** destacando las realizadas en este segundo periodo de ejecución del proyecto

Se recomienda leer atentamente la información solicitada en los distintos apartados del informe, revisar la memoria y el presupuesto solicitado inicialmente y justificar adecuadamente todas aquellas actividades o gastos que haya sido necesario realizar para la consecución de los objetivos y que no estuvieran previstos o suficientemente detallados en la memoria inicial.

Para completar la justificación final científico-técnica es indispensable rellenar el formulario de indicadores que se encuentra en la aplicación de justificación. Los datos introducidos en este informe deben coincidir con los aportados en el formulario.

En cada uno de los apartados, puede añadir tantas filas como necesite.

A. Datos del proyecto

Relacione los datos actuales del proyecto. *En caso de que haya alguna modificación, indíquelo en el apartado A2.*

A1. Datos del proyecto

Referencia proyecto	CGL2015-70177-R	
Título Proyecto	VOLCADEC	
Investigador Principal 1	Martin MÉNÉGOZ	
IP1	Researcher ID:	Código Orcid: orcid.org/0000-0001-7098-9270
Investigador Principal 2*	No investigador principal 2	
IP2	Researcher ID:	Código Orcid:
Entidad		
Centro	Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS)	
Fecha de inicio	01/01/2016	
Fecha final	31/12/2018	
Duración	3 años	
Total concedido (costes directos)	139.000€	

A2. Descripción de modificaciones en los datos iniciales del proyecto *(Cambio de IP, entidad, centro, modificación del periodo de ejecución…).*

During the project, two changes have been requested:

1.Change of the beneficiary institution:

The project started in the Climate Forecast Unit (CFU) at the Institut Catala de Ciences del Clima (IC3, Barcelona). **Martin Ménégoz**, PI of the project, and the CFU team joined the Barcelona Supercomputing Center - Centro nacional de Supercomputación (BSC-CNS) in 2016. This change was officially approved by the MINECO and the starting date of the project at BSC was on 1 March 2016. Therefore, the VOLCADEC project has been transferred from the IC3 to the BSC. Before the transfer of the project, the IC3 has transfer fully to BSC the first payment (21.864,70 €) made by the MINECO.

2. Modification of the research team:

Daniel Ortega left the project on 31 December 2015.

* Rellenar si procede

B. Personal activo en el proyecto

*Tiene que relacionar la situación de **todo** el personal de las entidades participantes que haya prestado servicio en el proyecto y cuyos costes (dietas, desplazamientos, etc.) se imputen al mismo.*

B.1. Equipo de investigación

Incluido en la solicitud original

	Nombre	NIF/NIE	Función en el proyecto	Fecha de baja	Observaciones
1	Nicola Cortesi	Y0752145J	Researcher		
2	Daniel Ortega	47236836B	Technical support	31/12/2015	

No incluido en la solicitud original

	Nombre	NIF/NIE	Función en el proyecto	Fecha de alta	Fecha de baja	Observaciones
1						
			Total personal en el equipo de investigación: 1			

B.2. Equipo de Trabajo

	Nombre	NIF/NIE	Función en el proyecto	Inicio	Fin	Observaciones
1	Oriol Mula-Valls	46359276Q	Ingeniero	01/10/2015	30/09/2016	Finalización de contrato en BSC
2	Roberto Bilbao	15430584E	Post Doctoral	01/11/2016	30/09/2018	
3	Xavier Yepes	47851858J	Developer	01/03/2016	31/08/2018	
4	Miquel Canal Esteve	39401479H	Junior Research engineer- soporte técnico	01/06/2018	31/08/2018	
5	Eneko Martin Martinez	45892982R	Junior Research engineer- soporte técnico	09/07/2018	31/01/2019	
			Total personal en el equipo de trabajo: 5			

La solicitud de “Altas” y “Bajas” de nuevos investigadores en el **equipo de investigación** ha debido ser tramitada de acuerdo con **las instrucciones de ejecución y justificación** expuestas en la página web de la convocatoria. La incorporación de personal que haya participado en el proyecto en el **equipo de trabajo** no necesita autorización por parte de la AEI, pero su actividad debe incluirse y justificarse en este informe.

C. Resumen del proyecto para difusión pública

Resuma *los principales avances y logros obtenidos del proyecto con una* ***extensión máxima de 30 líneas,*** *teniendo en cuenta su posible difusión pública (páginas webs institucionales).*

The VOLCADEC project has been conducted at the Barcelona Supercomputing Centre (BSC) from 2016 to 2018 to investigate how the climate system responds to volcanic eruptions. This research was based on the development, the use and the validation of climate models and in particular the EC-Earth model. The BSC is one of the operational centres using this model to produce seasonal to decadal forecasts for a wide range of societal applications. The predictability of forecast systems associated to the model initialisation with the best observations has been illustrated. The stratospheric particles, mainly emitted by volcanic eruptions also drive a part of the climate interannual variability. The VOLCADEC activity focused on this topic, allowing to quantify the magnitude of the volcanic signals compared to internal variability. Volcanic eruptions with a magnitude similar to the Pinatubo eruption in 1991 induce a significant warming of the stratosphere and a cooling of the troposphere during 3 to 5 years. Such eruptions also contract the Hadley cell and slow down the zonal circulation between 50°S and 50°N, whereas the sea ice grows at high latitudes. These changes are associated to dynamical responses evidenced in the observations, favouring a chain of El Niño – La Niña events and strengthening the Westerlies at middle to high latitudes. This signal occurring at middle latitude in the Northern Hemisphere does not project necessarily onto the typical seasonal pattern of the North Atlantic Oscillation (NAO) and its signature is model-dependant: some models simulate a positive NAO signal as a direct response to the volcanic forcing the first year after the eruption, whereas positive NAO signals only appear the third year, because of tropical-extratropical teleconnections and sea-ice extent growing that affect the atmospheric circulation. Overall, at the regional scale, the volcanic imprint of a Pinatubo-like eruption is small compared to internal variability that is the major driver of the interannual to decadal variability. The Tambora eruption, which is 4 to 6 times stronger than the Pinatubo in terms of sulphur compounds emissions induced a cooling during more than 10 years, and show a significant regional imprint: The probability to get a cooling during the three years after a Tambora-like eruption exceeds a probability of 90% in most areas of the globe, except in the central Pacific, where a strong El Niño event is triggered during 18 months, and in some areas where the strengthening of the Westerlies leads to a local warming both in the Northern and the Southern Hemispheres. The VOLCADEC project demonstrated that a significant part of the skill of forecast systems estimated from retrospective forecasts is related to the volcanic forcing. A model configuration has been set up to include any change of stratospheric aerosol forcing in climate simulations. This forecast system is ready to produce a forecast for the next future volcanic eruption.

D. Progreso y resultados del proyecto

Se debe reflejar el progreso de las actividades del proyecto y el cumplimiento de los objetivos propuestos

D1. Desarrollo de los objetivos planteados.

Describa *los objetivos y el grado de cumplimiento de los mismos (**porcentaje estimado respecto al objetivo planteado** y, en su caso, indique lo que queda por realizar en cada uno de ellos).*

Objetivo 1: **100%**	**Within the first objective of the project, the climate response to volcanic eruptions with different magnitudes has been investigated under different climate background conditions**. This work was divided in two different tasks: (1) The first one aimed at investigating the role of the Atlantic Multidecadal variability (AMV) in modulating the climate response to volcanic eruptions. Through collaboration with French researchers, a large set of numerical experiments has been built to answer this question, and the results are presented in an article published in the journal *Climate Dynamics* (Ménégoz et al., 2018a). These investigations are based on statistical concepts that have been published in a scientific journal during the first period of the project (Siegert et al., 2017). (2) The second objective aimed at investigating the climate response to volcanic eruptions under different background climate conditions (not only the AMV) and under different magnitudes of volcanic eruptions, focusing on the regional response as well as on two modes of climate variability: the ENSO and the NAO. This objective has been completed at the end of the project (Martin et al., in prep) and will serve as a base of future researches, in the framework of the international initiative VolMIP.
Objetivo 2: **100%**	**The second objective of the project has been completed with an assessment of the skill of AOGCMs to simulate the climate response to large eruptions in the application of decadal forecasts**. This work was divided in two tasks: (1) The first one aimed at evaluating the possibility to simulate the climate response with the current generation of climate models. These results have been synthetized in a review article (Swingedouw et al., 2017); (2) In a second task, the skill related to the volcanic forcing in retrospective predictions performed with the EC-Earth forecast system has been assessed. These results are described in an article published in *Environmental Research Letters* (Ménégoz et al., 2018b). This study includes an analysis of the ENSO response to volcanic eruptions.
Objetivo 3: **100%**	**The third objective of the project was to provide a way to define the stratospheric aerosol burden in climate models.** It was divided in three tasks: (1) The first one was based on retrospective forecast experiments using different protocols to take into account the forcing of volcanic aerosols. Two protocols have been tested, and the possibility to use them in real-time forecasts is described in Ménégoz et al., (2018b)*;* (2) A second task was devoted to the improvement of the realism of the stratospheric aerosol forcing in the EC-Earth climate model. This technical development has been completed and validated during the last year of the project and the new scheme is now included in the version of EC-Earth used for the CMIP6 project (Doesher et al., in prep). (3) A third task was devoted to the analysis of initialised forecasts including a volcanic eruption. Two parallel studies has been performed: first, a forecast initialised in the end of 2014/beginning of 2015 including a fictive Pinatubo eruption and covering the period 2015-2020 has been produced with 4 European models. Second, similar forecasts produced with the same models for three different eruptions (Agung, El Chichon and Pinatubo) have been used to investigate the response of modes of variability after such eruptions (Hermanson et al., to be submitted). These three tasks has been completed, one corresponding to a published article and the two others corresponding to publications that are under preparation.

D2. Actividades realizadas y resultados alcanzados.

Actividad 1: As described previously, the first activity is divided in two tasks.

(1) The first task is completed, with results described in Ménégoz et al. (2018). This study is based on a suite of large ensemble experiments using the CNRM-CM5 Coupled Global Circulation Model carried out by C. Cassou (Cerfacs, France). **M. Ménégoz** and N. Cortesi are contributing to the development of s2dverification (Manubens et al., 2018), an open-source package used in VOLCADEC. A fruitful collaboration between **M. Ménégoz,** C. Cassou and D. Swingedouw (CNRS, France) has been organised to set up physical and statistical approaches to investigate the modulation by the Atlantic Multidecadal Variability (AMV) of the dynamical response to a Pinatubo eruption in CNRM-CM5 experiments. In these simulations, a volcanic eruption induces a reduction and retraction of the Hadley cell during two years following the eruption and independently of the phase of the AMV. The mean extratropical westerly circulation simultaneously weakens throughout the entire atmospheric column, except at polar Northern latitudes where the zonal circulation is slightly strengthened. Yet, there are no changes of the North Atlantic Oscillation (NAO) during the first two winters after the eruption, whereas a significant modification of the atmospheric circulation appears in the North Atlantic sector during the third winter. Using clustering techniques, the atmospheric circulation can be decomposed into weather regimes. The occurrence of negative NAO-type of circulation in response to volcanic forcing drastically decreases the third winter after the eruption. This forced signal is amplified in cold AMV conditions and is related to sea-ice/atmosphere feedbacks and to tropical-extratropical teleconnections. This study demonstrated that large ensembles of simulations are required to make volcanic fingerprints emerge from climate noise at mid-latitudes. Using small size ensemble can easily lead to misleading conclusions especially those related to the extratropical dynamics, and specifically the NAO. This first activity is based on statistical concepts used to detect small signal-to-noise ratios, that are described in Siegert et al., (2017), a study involving **M. Ménégoz.**

(2) In a second task, E. Martin (Bachelor student at BSC), R. Bilbao (post-doc at BSC) and **M. Ménégoz** have investigated the climate response to volcanic forcing following a protocol slightly modified from those described in the initial proposal, because of the small magnitude of volcanic signal with respect to internal variability: A set of experiments has been run considering three configurations of the EC-Earth model: (i) a control experiment; (ii) a Pinatubo-like eruption; (iii) a Tambora-like eruption (~5 times larger than the Pinatubo eruption). The EVA module (Toohey et al., 2016) has been used to describe the forcing corresponding to the location/magnitude of any volcanic eruption. It has been used there to reproduce the forcing of the Pinatubo and the Tambora eruptions, and could be used also to forecast the climate response to a new volcanic eruption. The innovative results get from this research can be summarized in three points: (i) large volcanic eruptions cool the earth surface, mainly in the Tropics and over the continental surface at least during three years; at the regional scale, this cooling is largely overwhelmed by internal variability in the case of a Pinatubo eruption, whereas it very likely (probability>90%) to occur everywhere but in some high latitude areas in the case of a Tambora eruption (Figure 1); (ii) an ENSO signal is triggered by the volcanic forcing, with a chain of El-Niño and La Niña events that are stronger, longer and statistically more significant in the case of a Tambora eruption; A concomitant negative phase of the Southern Annular Mode is modelled during the El-Niño phase; (iii) the volcanic signal is more complex at middle to high latitude, with pronounced local cooling related to sea-ice increase, and local warming occurring in Northern Eurasia in relation with a strengthening of the westerly's. A scientific publication is under preparation (Martin et al., in prep) to describe these results, and these activities will be pursued in the framework of the VolMIP international project (http://volmip.org/).

Actividad 2: The second activity included two tasks:

(1) The thermodynamical response to the volcanic forcing is well understood and correctly simulated by climate models, the volcanic aerosols inducing a direct cooling of the troposphere during one to three years depending on the magnitude of the eruption. The dynamical response of both the atmosphere and the ocean to volcanic eruptions is more complex to understand due to the few observations that are available and the difficulties in reproducing it with climate models. This is particularly true when considering the large internal variability that may overwhelm the volcanic signal (Ménégoz et al., 2018a). This question becomes even more complicated when considering that the first year climate response to volcanic eruptions does not seem to project exactly onto the internal modes of climate variability at the

seasonal scale (Barnes et al., 2016, Ménégoz et al., 2018a). Facing these uncertainties and the general weaknesses of modelling approaches based on ensemble experiments too small to detect any significant volcanic signals, we decided to not investigate potential NAO signals in CMIP5 hindcasts during periods of volcanic eruptions, as initially planned in the project. As a substitution, we merged a large set of millennium observations and model experiments to investigate the climate response to volcanic eruptions. Large volcanic eruptions are found to favour positive phases of the NAO and to increase the probability of El Niño events during respectively three and two years after large eruptions, whereas such a signal is less clear for eruptions with a medium magnitude (like the Pinatubo). Results were published in a review paper (Swingedouw et al., 2017; involving **M. Ménégoz**). This article includes forecasts performed with the EC-Earth model to highlight the difficulty to predict dynamical signal after volcanic eruptions.

(2) The second task is described in Ménégoz et al. (2018b) who quantified the skill of the EC-Earth model applied in retrospective decadal forecasts. Oriol Mula-Valls set up the HPC to run this model on the BSC infrastructures. The initialisation of the model is found to contribute to a large part of the skill for the first year of forecast, whereas the skill related to the volcanic forcing becomes significant and larger than those related to the initialisation from the third year of forecast (Figure 2). The skill related to the volcanic forcing is significant in the Western Pacific, the tropical Atlantic and the Indian Ocean. It is important to emphasize that the volcanic forcing used in retrospective forecast is issued from observations that are obviously not available for real-time forecasts. We have also demonstrated that the phase of ENSO can be predicted from 6 to 18 months in advance with the EC-Earth model, but with a negligible impact of the volcanic forcing when considering 5-member ensemble forecasts during periods of eruptions with a magnitude comparable with those of the Pinatubo. R. Bilbao undertook the investigations related to the ENSO signal.

Actividad 3: The progress of the 3 tasks of the third activity is described below.

(1) The first task was devoted to testing new protocols to take into account the volcanic forcing in real-time forecasts. They are described in Ménégoz et al. (2018b). The first protocol consists in applying a two-year exponential decay to the initial stratospheric aerosol load observed at the beginning of a forecast. This allows to simulate the aerosol forcing in the Tropics after volcanic eruptions, but induces forecast deficiencies at high latitudes. In terms of correlation skill, the contribution of such idealized volcanic forcing shows a similar pattern as for the observed volcanic forcing, which is smaller but statistically significant, in particular over the Western Pacific and over some areas of the Southern Ocean high latitudes (Figure 2c, 2f and 2i). The second protocol is based on the use of the forcing of a past eruption with a similar magnitude to forecast the climate response to a new eruption. This protocol is relevant on condition of checking that the new and the past eruptions are affecting the same hemisphere(s).
(2) Within the EC-Earth consortium, **M. Ménégoz**, X. Yepes and Miquel Canal developed in the EC-Earth model a representation of the stratospheric aerosol forcing that includes a dependency to the altitude and to the spectral wave bands. This task was required to implement the forcing dataset distributed by CMIP6, and it has been completed during the second period of VOLCADEC. The validation of this new scheme appears in Doesher et al. (in prep) that describes the EC-Earth version 3 used for the CMIP6 project.

(3) Under the SPECS European project and other European activities, the BSC and partners (MPI, IPSL, MetOffice) have developed an operational decadal forecast system. In the framework of these activities, R. Bilbao and M. Ménégoz with several European colleagues have investigated the impact of a Pinatubo-like eruption in a 5-years forecast initialised in 2014, produced with 4 different forecast systems (Ménégoz et al., in prep.). Concurrently, the forecasts of these models during the periods of the Agung, the El Chichon and the Pinatubo eruptions have been used to produce a large ensemble (135 members) to investigate dynamical signals occurring after such eruptions (Hermanson et al., in prep). Both of these approaches highlighted a general cooling occurring after such eruptions, with an increased probability for El-Niño and positive NAO-like signals during two and three years respectively. Overall, these investigations confirm that both the thermodynamical and the dynamical signals driven by the volcanic forcing are largely overwhelmed by internal variability in the case of volcanic eruptions with such a magnitude.

References:

Barnes, et al., 2016: Robust wind and precipitation responses to the Pinatubo eruption, as simulated in the CMIP5 models J Clim, 29(13), 4763-4778.
Manubens, N., […], **Ménégoz, M**. et al., 2018. An R package for climate forecast verification. *Environmental Modelling & Software*, *103*, pp.29-42.
Toohey M, et al., 2016, Easy Volcanic Aerosol (EVA v1.0): an idealized forcing generator for climate simulations Geosci. Model Dev. 9, 4049–70

D3. Problemas y cambios en el plan de trabajo.

Describa** las dificultades y/o problemas que hayan podido surgir durante el desarrollo del proyecto. Indique cualquier cambio que se haya producido respecto a los objetivos o el plan de trabajo inicialmente planteado, así como las soluciones propuestas para resolverlos.* ***Extensión máxima 1 página.

One change of strategy (i) and one difficulty (ii) met during the project are described below:

(i) One change of strategy was adopted for the first task of the second activity (WP2). As described previously, it was originally planned to use the CMIP5 hindcast experiments available at the international level to investigate the possibility to forecast the atmospheric response to volcanic eruptions with the current generation of forecast systems, focusing on dynamical processes, and in particular on the NAO. In Ménégoz et al. (2018a), we found that the first-year climate response to a Pinatubo eruption does not project onto the internal modes of variability at the seasonal scale, and is partly overwhelmed by internal variability. This result is supported by Barnes et al. (2016) who get to the same conclusion using CMIP5 model outputs. Instead of reproducing the investigations described by Barnes et al (2016), we decided to investigate the dynamical response to volcanic eruptions in a review paper (Swingedouw et al., 2017), using a large set of observations and modelling experiments, including new experiments performed under the VOLCADEC project. This study was briefly summarized above (Activity n°2). Also in the first activity, we run additional experiments considering the Tambora eruption that is larger than those of the Pinatubo. This strategy evidenced with more confidence the dynamical signals related to the volcanic forcing.

(ii) Task 2 of WP3 relies on the possibility of using recent satellite observations of the stratospheric aerosol load in EC-Earth model experiments. The previous version of EC-Earth was including a simple scheme of the stratospheric aerosol forcing (only one vertical level and one wave band). **M. Ménégoz**, X. Yepes and Miquel Canal developed a representation of the stratospheric aerosol forcing that includes a dependency to the altitude and to the spectral wave bands. This task was a heavy technical development. Thanks to the involvement of the VOLCADEC team in the EC-Earth European consortium, and to the support of the BSC Computational Earth Science group, it has been completed and validated during the second period of the project.

D4. Colaboraciones con otros grupos de investigación directamente relacionadas con el proyecto.

***Relacione** las colaboraciones con otros grupos de investigación y el valor añadido que aportan al proyecto. Describa el acceso a equipamientos o infraestructuras de otros grupos o instituciones.*

The VOLCADEC Project has involved several international collaborations:

(1) M. Ménégoz completed the task 1 of WP1 in collaboration with D. Swingedouw (CNRS, France) and C. Cassou (Cerfacs, France). A large set of experiments has been produced by Cerfacs researchers, using their own infrastructures, and in particular a supercomputer that they share with Météo-France.

(2) A part of the statistical methods used in VOLCADEC has been developed in collaboration with Stefan Siegert (University of Exeter).

(3) A large part of the numerical experiments has been undertaken with the EC-Earth model, which is developed by the EC-Earth consortium, in which the BSC and in particular M. Ménégoz and R. Bilbao are widely involved. This consortium involves several European institutes, and in particular KNMI (Netherlands), SMHI (Sweden) and ECMWF (UK).

(4) Within the SPECS European FP7 project (completed at the beginning of 2017), Didier Swingedouw (CNRS, IPSL, France), Holger Pohlmann and Claudia Timmreck (MPI, Germany) and Leon Hermansonn (MetOffice, UK) performed and shared numerical experiments during the first period of the project. These experiments have been interpreted during the second period of the project.

(5) Finally, the VOLCADEC Project allowed to reinforce the involvement of the BSC team in the CMIP6 activities, trough the activities conducted with the EC-Earth consortium. The VOLCADEC activities contributed to the development of the version of the EC-Earth climate model that is now used for CMIP6. In addition, the BSC will pursue the investigations related to the climate response to volcanic eruptions in the context of VOLMIP (http://volmip.org/).

D5. Colaboraciones con empresas o sectores socioeconómicos directamente relacionados con el proyecto. *Relacione las colaboraciones con empresas o sectores socioeconómicos y el valor añadido que aportan al proyecto.*
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D6. Actividades de formación y movilidad de personal directamente relacionadas con el proyecto. ***Indique*** *las actividades de formación y movilidad de personal relacionadas con el desarrollo del proyecto. Describa, además, si procede, las actividades realizadas en colaboración con otros grupos o con actividades de formación en medianas o grandes instalaciones.*

	Nombre	Tipo de personal (*becario, técnico, contratado con cargo al proyecto, posdoctoral, otros*)	Descripción de las actividades de formación o motivo de la movilidad
1	-		

D7. Actividades de internacionalización y otras colaboraciones relacionadas con el proyecto.

***Indique** si ha colaborado con otros grupos internacionales. Consigne si ha concurrido, y con qué resultado, a alguna convocatoria de ayudas (proyectos, formación, infraestructuras, otros) de programas europeos y/o programas internacionales, en temáticas relacionadas con la de este proyecto. **Indique** el programa, socios, países y temática y, en su caso, financiación recibida.*

The international collaborations have been described previously (D4). These collaborations involve the following initiatives:

(1) The MORDICUS project was led by C. Cassou over 2014-2018 (http://www.agence-nationale-recherche.fr/?Projet=ANR-13-SENV-0002). In this project, a large set of numerical experiments have been performed to investigate the climate variability, and its sensitivity to external forcings. Martin Ménégoz contributed to this project by investigating the response on the climate system to volcanic eruptions, a common task between MORDICUS and VOLCADEC. The tasks planned and completed under VOLCADEC have been communicated during MORDICUS meetings (Paris, November 2015; and Toulouse, June 2017).

(2) VOLCADEC has been conducted in the context of larger European initiatives to develop climate services at the European scale, in particular within the SPECS FP7 project (http://www.specs-fp7.eu/) and EUCP (https://www.eucp-project.eu/). The protocols developed within VOLCADEC to forecast the climate response to volcanic eruptions as well as the evaluation of the forecast skill related to the volcanic forcing have been included in the SPECS final report that is available online: http://www.specs-fp7.eu/sites/default/files/u1/SPECS_D43_2.pdf. The VOLCADEC activities have been described during several SPECS meetings.

(3) Martin Ménégoz and Roberto Bilbao went to an international conference on the Atlantic Meridional Overturning Circulation (AMOC) in 2017 to present the results from the VOLCADEC and the MORDICUS projects. This conference was also fruitful in terms of collaboration, and several discussions were organised with Didier Swingedouw (EPOC, Bordeaux, France) and Juliette Mignot (IPSL, Paris, France) to set up the basis of the second part of the VOLCADEC project.

(4) Martin Ménégoz and Roberto Bilbao attended several international conferences to share the results of VOLCADEC, and in particular the EGU in 2016 and in 2018, as well as the Second International Conference on Seasonal to Decadal Prediction (S2D) in 2018 that took place at Boulder, USA.

(5) Martin Ménégoz, Roberto Bilbao and Xavier Yepes advertised the VOLCADEC research also during the meetings of the EC-Earth consortium, in particular to describe to new scheme developed to include the volcanic forcing in the atmospheric component of the EC-Earth model.

(6) Martin Ménégoz presented the VOLCADEC results at the Institute for Geosciences and Environmental Researches (IGE, Grenoble, France) in 2017, September, a group that he is joining in 2019 with a CNRS position.

(7) A large part of the VOLCADEC activities have been organised to reinforce the involvement of the BSC in the CMIP6 activities, and in particular in VolMIP (http://volmip.org/).

(8) Martin Ménégoz has been granted from a “Red Esañola de Supercomputacion (RES) project, referenced as “Volcanic activity in seasonal to decadal climate forecasts » (ref : AECT-2017-2-0009). This project corresponds to an amount of 536000 CPU hours to be used on the Marenostrum 4 HPC available at BSC. This HPC is the most powerful computer available in Spain (https://www.bsc.es/innovation-and-services/supercomputers-and-facilities/marenostrum). The hours have been used to complete the numerical experiments run for VOLCADEC applications.

E. Difusión de los resultados del proyecto

Relacione únicamente los resultados derivados de este proyecto.

E1. Publicaciones en revistas indexadas directamente relacionadas con los resultados del proyecto.

Indique autores, título, referencia de la publicación, año, factor de impacto de la publicación, cuartil….*

1.	Siegert, S., Bellprat, O., **Ménégoz, M.**, Stephenson, D., Doblas-Reyes, F., Detecting skill improvements in seasonal climate forecasts: Statistical tests and power analysis, 2017, *Monthly Weather Review, doi:10.1175/MWR-D-16-0037.1, open-access at: http://journals.ametsoc.org/doi/10.1175/MWR-D-16-0037.1*.
2.	Swingedouw, D., Mignot, J., Ortega, P., Khodri, M., **Ménégoz, M.**, Cassou, C., Hanquiez, V., 2017, Impact of explosive volcanic eruptions on the main climate variability modes, *Global and Planetary Change, Vol. 150, P. 24–45*, http://www.sciencedirect.com/science/article/pii/S0921818116300352.
3.	**Ménégoz, M.**, Cassou, C., Swingedouw, D., Bretonnière, P.-A., Doblas-Reyes, F*., 2017:* Role of the Atlantic Multidecadal Variability in modulating the climate response to a Pinatubo-like volcanic eruption, *Climate Dynamics*, 1-21, doi 10.1007/s00382-017-3986-1 open-access,
4.	**Ménégoz, M.**, Bilbao, R., Bellprat, O., Guemas, V., Doblas-Reyes, F.J., Forecasting the climate response to volcanic eruptions: prediction skill related to stratospheric aerosol forcing, 2018, Environ. Res. Lett.,13, 064022, open-access at http://iopscience.iop.org/article/10.1088/1748-9326/aac4db.
5.	Doesher, R., […], **Ménégoz, M.**, et al., The Community Earth System Model EC-Earth for collaborative climate research, in preparation.
6.	Hermanson, L., […], **Ménégoz, M**. et al., Impacts of volcanoes on climate modes from dedicated experiments with post-CMIP5 models, to be submitted.
7.	Martin, E., Bilbao, R., **Ménégoz, M**. et al., Thermodynamical and dynamical response to Pinatubo and Tambora eruptions: detecting volcanic signals with respect to internal variability, to be submitted.

*Resalte en negrita el/los IPs y miembros del equipo de investigación

Total publicaciones: 7
(4 publicadas, 3 en preparación)

E2. Otras publicaciones científico-técnicas directamente relacionadas con los resultados del proyecto.

Indique autores, título, referencia de la publicación, año…*

1.	**Ménégoz, M**., Forecasting the climate response to volcanic eruptions, deliverable included in the SPECS final report available online: http://www.specs-fp7.eu/sites/default/files/u1/SPECS_D43_2.pdf
2.	**Ménégoz, M**., Bilbao, R. et al., forecasting the climate response to a Pinatubo-like eruption occurring in 2015, BSC memorandum in preparation.

* Resalte en negrita el/los IPs y miembros del equipo de investigación

Total publicaciones: 2

E6. Asistencia a congresos, conferencias o workshops relacionados con el proyecto

13. Martin, E., Bilbao, R., **Ménégoz, M**. Ortega, P., Climate response to the Pinatubo and Tambora eruptions in EC-Earth3.2 (poster), CMIP6 Model Analysis Workshop, 25-28 March, Barcelona (Spain).

12. Bilbao, R., **Ménégoz, M.,** Ortega, P., Doblas-Reyes F.J., Forecasting the climate response to volcanic eruptions (poster), Second International Conference on Seasonal to Decadal Prediction (S2D), Boulder, USA, 17-21 September 2018.

11. Ménégoz, M.,, Cassou, C., Swingedouw, D., Bilbao R., Bellprat, O., Doblas-Reyes F.J., Understanding, modelling and forecasting the climate response to volcanic eruptions, Météo-France seminar, Toulouse, France, February 2018.

10. Bilbao, R., **Ménégoz, M.,** Bellprat, O., Guemas, V., Doblas-Reyes F.J., Forecasting the climate response to volcanic eruptions (poster), Geophysical Research Abstracts, Vol. 20, EGU2018-15208, 2018, EGU General Assembly 2018, Vienna.

9. Ménégoz, M.,, Cassou, C., Swingedouw, D., Bilbao R., Bellprat, O., Doblas-Reyes F.J., Understanding, modelling and forecasting the climate response to volcanic eruptions, IGE internal seminar, Grenoble, France, 2017.

8. Ménégoz, M., Cassou, C., Swingedouw, D., Doblas-Reyes F.J., Modulation of the climate response to a volcanic eruption by the Atlantic Multidecadal Variability, Observing and understanding the Atlantic Meridional Overturning Circulation, MORDICUS meeting, Cerfacs, Toulouse, France, 7 June 2017.

7. Ménégoz, M., Cassou, C. Swingedouw, D., Doblas-Reyes F.J., Modulation of the climate response to a volcanic eruption by the Atlantic Multidecadal Variability, Observing and understanding the Atlantic Meridional Overturning Circulation, Conference LEFE-IMAGO, Brest, France, 3-5 May 2017. Conference attended by R. Bilbao and M. Ménégoz.

6. Ménégoz, M., Cassou C., Swingedouw D., Bretonnière, P.A., Doblas-Reyes F.J., How do volcanic eruptions affect the North Atlantic Oscillation?, BSC internal seminar, April 2017.

5. Ménégoz, M.: Implementation of a 4D stratospheric aerosol forcing in the EC-Earth model, Presentation given at the 2016 EC-Earth annual meeting, ECMWF, Reading, 2-3 November 2016. Conference attended by R. Bilbao and M. Ménégoz.

4. Ménégoz, M.: Climate predictions for climate services, invited presentation for the European Climate Observations, Modelling and Services initiative (ECOMS), Met-office, Exeter, 5-7 October, 2016.

3. Ménégoz, M., Doblas-Reyes, F., Muhammad, A, Prodhomme, C.: Volcanic forcing in decadal forecasts of surface temperature (poster), Geophysical Research Abstracts, Vol. 18, EGU2016-8041, EGU General Assembly 2016, Vienna, Austria.

2. Ménégoz, M.,VOLCADEC: Volcanic activity in seasonal to decadal climate forecasts, project description, BSC, April 2016.

1. Ménégoz, M., Cassou C, Swingedouw D, Doblas-Reyes FJ.: The Pinatubo eruption simulated under extreme phases of the Atlantic Multidecadal Oscillation. MORDICUS project meeting, IPSL, Paris, France, November, 2015.

* Resalte en negrita el/los IPs y miembros del equipo de investigación

Total congresos nacionales: 3

Total congresos internacionales: 3

Total conferencia/ workshop: 6

E7. Tesis doctorales relacionadas con el proyecto.

Indique si están (en marcha) o finalizadas

Nombre, Director, Título, Organismo:

Total tesis en marcha:

Total tesis finalizadas:

F. Impacto de los resultados del proyecto

Indicar el impacto científico-técnico, económico y social de los resultados de la investigación identificando el principal impacto científico-técnico derivado del proyecto de acuerdo con lo indicado en la solicitud y posibles impactos no previstos, el sector o sectores sobre los que tendrán impacto los resultados y actividades realizadas en el proyecto que puedan dar lugar a transferencia de conocimiento.

F1. Principal impacto derivado en el proyecto

The VOLCADEC research activities have two major impacts for the scientific community:

1/ First, the results get during the VOLCADEC project allowed to quantify the magnitude of the volcanic signals compared to internal variability. We confirmed that volcanic eruptions with a magnitude similar than the Pinatubo in 1991 show a clear signal in terms of global temperature of the troposphere. We also demonstrate that such eruptions also affect the Hadley cell, strengthen the zonal circulation, and induce a sea ice extent at high latitudes. These changes are associated to dynamical responses, favouring in particular a chain of El Niño – La Niña events. A strengthening the Westerlies occurs at middle to high latitudes that can be viewed as NAO like signals in the Northern Hemisphere, even if such response does not project necessarily onto the typical seasonal NAO pattern. Nevertheless, at the regional scale, the volcanic imprint of a Pinatubo-like eruption is small compared to internal variability that is the major driver of the interannual to decadal variability. For stronger eruptions, like the Tambora (4 to 6 times stronger than the Pinatubo in terms of amount of sulphur compounds emitted in the atmosphere), the regional imprint is more clear, and the probability to get a cooling during one to three years exceeds a probability of 90% in many areas of the globe, except in the central Pacific, where a strong El Niño event is triggered during 18 months, and in some areas where the strengthening of the westerlies leads to a local warming. These results are presented in several articles published and to be submitted, and have been communicated trough international project meetings and conferences. They will help the community to understand the climate response to previous volcanic eruptions and to produce a forecast for the next one.

2/ Second, the VOLCADEC research demonstrated that a significant part of the skill of seasonal to decadal forecasts estimated from retrospective forecasts is related to the volcanic forcing considered in climate models. Any information related to future volcanic eruption is obviously not available. Within VOLCADEC, several protocols to include the volcanic forcing in seasonal to decadal forecasts has been suggested, that could be used both in the case of a new eruption and out of periods of volcanic activity.

F2. Impacto no previsto derivado del proyecto

The community benefits now from detailed observations of the stratospheric aerosol load, and also from spectrally and altitudinal resolved estimations of the aerosol optical depth of volcanic particles. The previous version of EC-Earth was including a simple scheme of the stratospheric aerosol forcing (only one vertical level and one wave band). The VOLCADEC team developed in the EC-Earth model a representation of the stratospheric aerosol forcing that includes a dependency to the altitude and to the spectral wave bands. This task was a heavy technical development that has been completed thanks to the VOLCACEC activities for the EC-Earth European consortium. The new scheme is now part of the model version that is used for the CMIP6 activities, and in particular the VolMIP project. Another development concerns the use of the EVA module provided by Matthew Toohey (Max Planck Institute for Meteorology, Hamburg, Germany) to produce idealized volcanic forcing as input for EC-Earth experiments, and in particular simulations of past eruptions or forecast including a new eruption.

These developments contributed to the forecast system based on the EC-Earth model that the BSC is using to produce quasi-operational forecasts at seasonal to decadal timescales.

F3. Sector de Impacto de los resultados del proyecto: industria, administración, política, aumento del conocimiento, salud, medioambiente….

First, the scientific community investigating the variability of the climate system will benefit from the VOLCADEC researches. Second, this project will have societal impacts considering the large number of applications related to the seasonal to decadal forecasts. In particular, the BSC has been designated by the World Meteorological Organisation as one of the European Centres able to provide seasonal to decadal forecasts (https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/wmolc-adcp). These forecasts are produced for an increasing number of users, in many sectors as the renewable energy, the agriculture production and the forecast of summer fires among other applications.

F4. ¿Cuenta con socios que puedan explotar los resultados?

In addition to the whole Earth Department group at BSC, the EC-Earth consortium (http://www.ec-earth.org/) is benefiting directly from the VOLCADEC results, as well other European partners involved in the production of seasonal and decadal forecasts. The scientific community investigating the climate response to volcanic eruptions, in particular with the VolMIP project (http://volmip.org/) is also benefiting from the VOLCADEC results that are directly in line with these research activities.

F5. ¿Qué actividades del proyecto pueden generar valorización y transferencia del conocimiento?

See sections F3 and F4.

G. Gastos realizados durante la ejecución del proyecto

*Debe cumplimentarse este apartado **independientemente** de la justificación económica anual enviada por la entidad. Se deben incluir los principales conceptos de gastos con su importe, no el desglose de las facturas del proyecto, para valorar su adecuación a los objetivos y actividades realizadas en el proyecto.*

*Es **indispensable** especificar si el gasto estaba previsto en la solicitud original.*

Cree tantas filas como necesite

G1. Gastos de personal

Indique número de personas, situación laboral y función desempeñada

	Nombre	**Situación laboral**	**Función desempeñada**	**Importe**	**Previsto en la sol. original (S/N)**
1	Roberto Bilbao	Contratado	Post doctoral	78539.45€	S
2	Xavier Yepes	Contratado	Research engineer-soporte técnico	39272.25€	N
3	Miquel Canal Esteve	Contratado	Junior Research engineer-soporte técnico	4240.13€	N
4	Eneko Martin Martinez	Contratado	Junior Research engineer-soporte técnico	9300.32€	N
Total gastos de personal:				**131352.15 €**	

G2. Material inventariable (describa el material adquirido)				
	Equipo	**Descripción del equipo**	**Importe**	**Previsto en la sol. original (S/N)**
1	Dos ordenadores	1 x optiplex 7040 formato pequeño 1 x dell 22 monitor p2217h+1 x dell optiplex 7040SFF 1 x monitor dell profesional p2217h	2021.11€	S
Total gastos material inventariable			**2021.11€**	

G4. Viajes y dietas

Describa la actividad del gasto realizado y ***las personas que han realizado la actividad****. Debe incluir aquí los gastos derivados de la asistencia a congresos, conferencias, colaboraciones, reuniones de preparación de propuestas relacionados con este proyecto, etc.*

	Concepto	**Relación con el proyecto**	**Importe**	**Nombre del participante**	**Previsto en la sol. original (S/N)**
1	Asistencia al *EC-EARTH MEETING* el 2-3 de noviembre 2016 en Reading	Los temas de esta conferencia están relacionados con el modelo EC-Earth utilizado en el desarrollo de las actividades de este proyecto.	535.45	Roberto Alejandro Bilbao	S
2	Asistencia a la LEFE CONFERENCE del 2-5 mayo de 2017 en Plouzané (Francia)	Los temas de esta conferencia están relacionados con AMOC (Atlantic Meridional Overturning Circulation) estudiado en WP1 y WP2.	1543.73€	Martin Ménégoz y Roberto Alejandro Bilbao	S
3	Asistencia *2nd International Conference on Subseasonal to Decadal Prediction* del 17-21 de septiembre de 2018 en Boulder (USA)	Los temas de esta conferencia están relacionados con la actividad desarrollada en este proyecto.	2277.39€	Roberto Alejandro Bilbao	S
4	Asistencia a *European Geosciences Union General Assembly 2018* del 8–13 de abril 2018, Viena	Los temas de esta conferencia están relacionados con la actividad desarrollada en este proyecto.	1384.64€	Roberto Alejandro Bilbao	S
5	Asistencia al *2018 NEMO Users meeting* el 11-12 octubre de 2018 en Toulouse	Los temas de esta conferencia están relacionados con la actividad desarrollada en este proyecto en particular con NEMO *(Nucleus for European Modelling of the*	42.63€	Roberto Alejandro Bilbao	S

		Ocean)			
6	Asistencia a la reunión de revisión del Proyecto el 21 de junio de 2018	Jornadas de seguimiento presenciales 2018 de Proyectos del programa de biodiversidad, ciencias De la tierra y cambio global/atmosfera, clima y Cambio (CGL/CLI)	465.68€	Martin Ménégoz	S
7	Seminario y trabajo en el CNMR del 1 al 5 de febrero de 2018 en Grenoble (Francia)	Presentacion de los resultados de Volcadec; Trabajo con otros investigadores en la representación de los aerosoles estratosféricos en los modelos.	143.40€	Martin Ménégoz	S
Total viajes y dietas			**6392.93€**		

G5. Otros gastos

Describa la actividad del gasto por concepto, y si procede, las personas que han realizado la actividad.

	Concepto	Relación con el proyecto	Importe	Nombre del participante	Previsto en la sol. original (S/N)
1	Gastos de publicación	Título*: Forecasting the climate response to volcanic eruptions: prediction skill related to stratospheric aerosol forcing.* Environ. Res. Lett.13(2018) 064022https://doi.org/10.1088/1748-9326/aac4db	1497.6€	Martin Ménégoz	S
Total otros gastos			**1497.6€**		

H. Descripción de gastos no contemplados en la solicitud original

*Si ha realizado algún gasto no contemplado en la solicitud original, **justifique** la necesidad de su ejecución en este apartado*

Gasto	justificación
Costes de personal para soporte técnico (Xavier Yepes, Miquel Canal Esteve, Eneko Martin Martinez)	La contratación de personal de soporte técnico se justifica por la trabajo necesario para el desarrollo del modelo.

I. Resumen de gastos realizados durante la ejecución del proyecto	
Desglose los gastos por conceptos (*costes directos únicamente*)**:**	**Importe:**
Personal:	**131352.15 €**
Inventariable:	**2021.11€**
Fungible:	**-**
Viajes y dietas:	**6392.93 €**
Otros gastos:	**1497.6€**
Importe total ejecutado (costes directos únicamente):	**141263.79 €**
Importe total concedido:	**139000€**

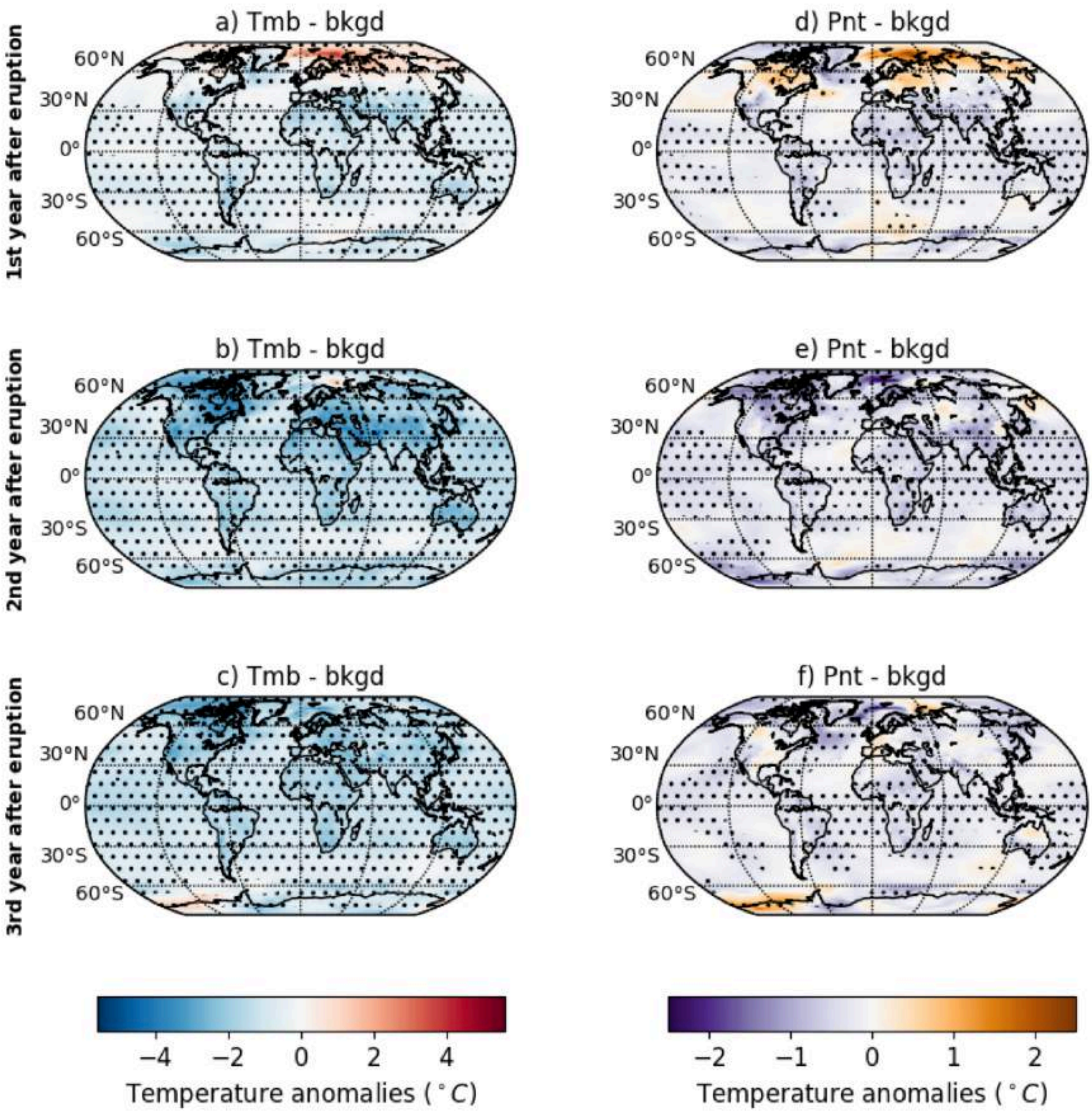

Figure 1: *2m temperature anomalies in Tambora-EVA (abc) and in Pinatubo-EVA (def) experiments with respect to the background experiment, for the first (ad) second (be) and third (cf) year after the eruption. The black dots denote the anomalies that are significant at the 95% confidence level computed with a bootstrap resampling (1000 times). The spatial correlation between Pinatubo and Tambora signals is 0.76 (ad), 0.50 (be) and 0.55 (cf) respectively for the first, second and third years after the eruption.*

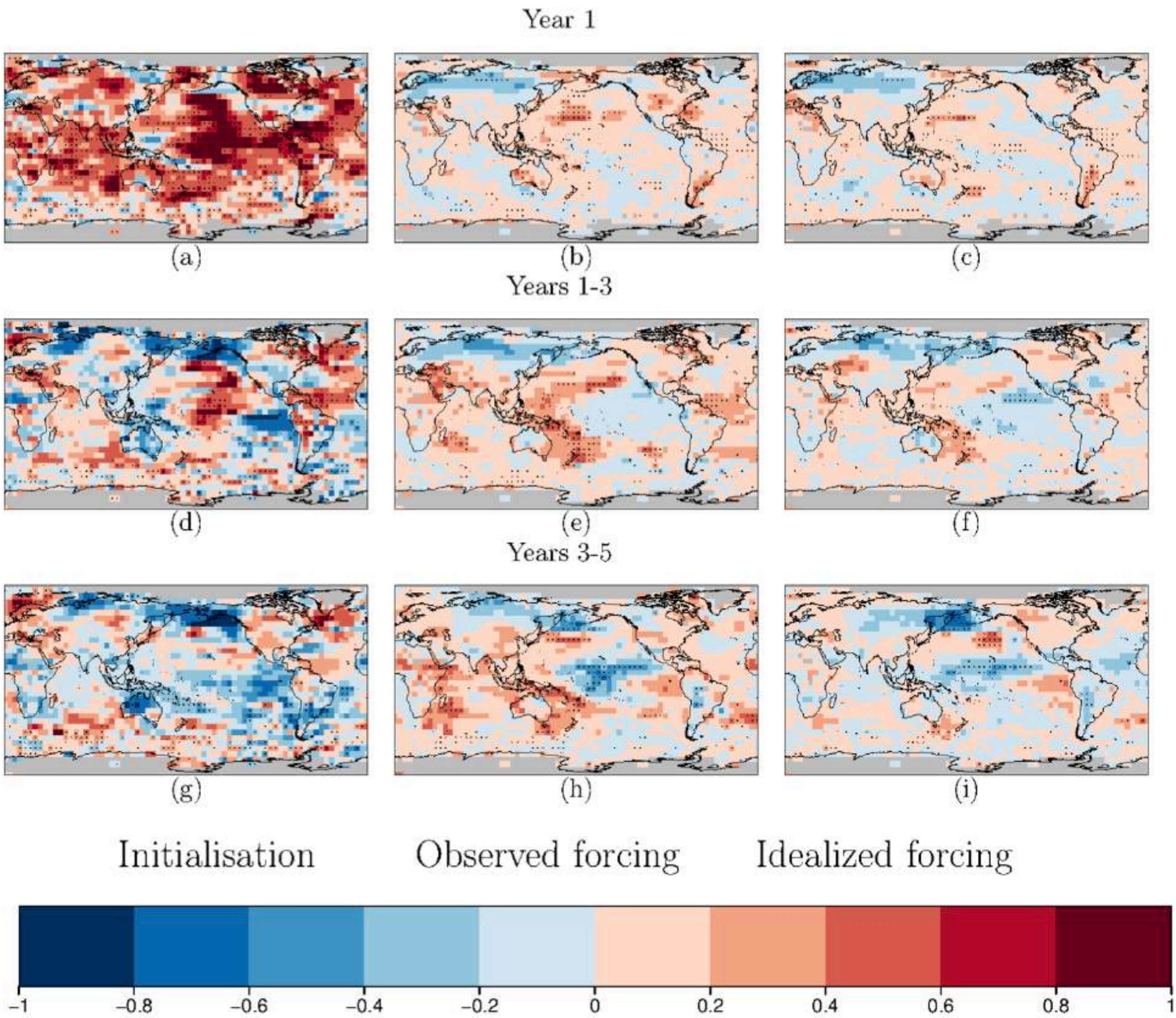

Figure 2: Contribution to the anomaly correlation for the first forecast year (Year 1, top), the average of the three first forecast years (Years 1-3, middle) and the average of the third, fourth and fifth forecast years (Years 3-5, bottom): from the initialisation (a,d and g), from the volcanic forcing based on observations, and from the idealized volcanic forcing based on a 2-year exponential decay (g, h and i). The correlation increase is significant in the dotted areas. The grey areas correspond to regions where the observational data (Hadcrut4, Morice et al. 2012) is missing for more than 25% of the total number of years. The correlation is computed between the observations and EC-Earth forecasts over the period 1961-2001.

Reference: Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset, *J. Geophys. Res.*, 117, D08101, doi:10.1029/2011JD017187.