ERC Starting Grant 2017
Research proposal [Part B1]

Understanding **s**tratospheric **i**nfluence on tropospheric **d**ynamics for **i**mproving North Atlantic-European **s**easonal forecasts

SIDIS

Cover Page:
- Name of the Principal Investigator (PI): *Javier García-Serrano*
- Name of the PI's host institution for the project: *Barcelona Supercomputing Center (BSC)*
- Proposal duration in months: *48 months*

Seasonal climate forecasting is a field with enormous potential influence in different socio-economic sectors, such as water resources, agriculture, health, and energy. Yet, winter atmospheric circulation anomalies in the North Atlantic sector and the associated surface climate conditions in Europe still represent a hurdle to formulate skilful seasonal predictions. This project, SIDIS, aims to advance understanding of the simulation and prediction of the remote influence of two dominant tropical variability modes on the North Atlantic-European (NAE) region. These predictors are: El Niño-Southern Oscillation (ENSO) in the Pacific Ocean, the leading interannual variability mode in the tropical troposphere; and the quasi-biennial oscillation (QBO), the leading interannual variability mode in the tropical stratosphere. ENSO is highly predictable and constitutes the cornerstone of seasonal forecasting. The QBO is well constrained by initialization and has a long persistence, and is considered as the most promising source of seasonal forecast quality apart from ENSO. However, many scientific questions remain unresolved concerning their tropical-extratropical teleconnections, and model systematic errors only worsen the problem. SIDIS will focus on the stratospheric pathway of the ENSO/QBO teleconnections to NAE and pursue better representation of the stratospheric circulation as well as gaining insight into the dynamical mechanisms of the linkages. This goal will be undertaken by implementing targeted model developments with a hierarchy of climate models, by carrying out carefully designed atmosphere-only simulations, and by performing an unprecedented set of idealized seasonal forecast experiments. SIDIS is very timely in helping to reduce model biases in the relevant stratospheric processes and to increase current seasonal forecasting capabilities for the winter NAE surface climate.

Section a: Extended Synopsis of the scientific proposal (max. 5 pages)

This project has been designed to address one main scientific question: what is the impact of correctly representing stratospheric variability and dynamics, and its influence upon the troposphere, on the seasonal prediction skill of the winter Euro-Atlantic climate?

The aim is to improve seasonal forecasting capabilities, namely more accurate and more reliable seasonal predictions, of winter surface climate in the North Atlantic-European region by both better simulating stratospheric circulation and enhancing understanding of the stratospheric pathway involved in the dominant tropical-extratropical teleconnections at interannual time-scales.

This goal will be undertaken by implementing targeted model developments with a hierarchy of climate models and by performing an unprecedented set of sensitivity and seasonal forecast experiments.

Seasonal climate forecasting is a field with enormous potential influence in different socio-economic sectors, such as agriculture, health, water management, and energy. Given the chaotic nature of the climate system, one might question the feasibility of forecasting climate conditions months in advance. Yet, seasonal climate prediction is feasible because atmospheric variability on seasonal time-scales is modulated by slowly-varying boundary conditions, such as sea surface temperature (SST), and can retain memory from internal processes with very slow relaxation rates, such as those in the stratosphere. These fluctuations are not noticeable in day-to-day weather conditions but become evident in seasonal averages, e.g. two/three-month means (e.g. Shukla 1998). Seasonal climate prediction has progressed considerably in the last decade but the tropics remain the region where seasonal forecasts are most successful (see Doblas-Reyes et al. 2013 for review). This project, SIDIS, will focus on the two main modes of interannual variability at tropical latitudes, which are relatively well predicted and/or constrained by initialization (e.g. Tripathi et al. 2015; Butler et al. 2016), and for which tropical-extratropical teleconnections affecting the Euro-Atlantic sector have been robustly shown in observations (e.g. Smith et al. 2012; Anstey and Shepherd 2014): *El Niño-Southern Oscillation* (ENSO), the leading interannual variability mode in the tropical troposphere; and the *quasi-biennial oscillation* (QBO), the leading interannual variability mode in the tropical stratosphere.

In most of the extratropics, and in particular in the North Atlantic-European (NAE) region, the anomalies predicted by general circulation model (GCM)-based seasonal forecast systems have usually been weak and barely added valuable information over a forecast based on climatology or persistence. This can be explained by the high level of atmospheric internal variability, particularly during winter – the target season of SIDIS. Half of the winter NAE atmospheric variability is associated with the North Atlantic Oscillation (NAO), a meridional air-mass seesaw tied to the strength of the Azores High and Icelandic Low, which strongly influences European climate on interannual time-scales (see Hurrell et al. 2003 for review). The long-lasting problem in seasonal forecast systems over NAE is thought to be potentially alleviated by better representing stratospheric circulation and stratosphere-troposphere coupling in the models. The surface impact of extratropical stratospheric variability is actually very prominent in the Euro-Atlantic sector, projecting on the NAO pattern. This surface signature holds for both anomalies of the polar stratosphere (e.g. Hitchcock and Simpson 2014; Shaw et al. 2014) and tropical-extratropical stratospheric pathways (e.g. Anstey and Shepherd 2014; Calvo et al. 2016). The stratospheric influence on tropospheric variability has been largely detected and analysed, but not until recently have seasonal forecast systems started to explore the enhanced prediction skill provided by this connection. This potential effect on the forecast quality was long anticipated (e.g. Douville 2009), and the last generation of forecast systems have yielded traces of added skill via the stratosphere (Scaife et al. 2014a; Domeisen et al. 2015; Stockdale et al. 2015); however, the precise role of resolving the stratosphere and simulating stratospheric processes is unclear and needs to be properly assessed (Kang et al. 2014; Butler et al. 2016). As reviewed by Kidston et al. (2015), whether seasonal climate predictions can benefit from representing stratosphere-troposphere interactions remains to be tested. <u>SIDIS will tackle this challenge, and address the separate contribution of the tropical stratosphere and the polar stratosphere to the prediction skill of the winter NAE surface climate. The action will follow a hierarchical approach, performing the same set of idealized seasonal forecasts with suppressed variability in the two stratospheric regions, using both state-of-the-art and intermediate-complexity models</u>. *The completion of this research could represent a major breakthrough at international level for the climate forecasting community.*

The goal of SIDIS is not only to identify the key sources of predictability but also to improve understanding and simulation of the mechanisms responsible for that predictability. The project deals with the ENSO and QBO extratropical teleconnection to NAE, both of which projects on the NAO pattern (Fig. B1), thereby representing suitable phenomena that can enhance regional predictability. SIDIS will improve prediction of the ENSO/QBO-NAE teleconnections by gaining new insight into the stratospheric dynamics at play and by reducing model biases in the relevant stratospheric processes. *The former will be undertaken by performing comprehensive and novel atmosphere-only sensitivity experiments that will help to address some unresolved scientific questions related to the ENSO/QBO-NAE teleconnections* (see below). *The latter will be carried out by implementing cutting-edge parameterizations of non-orographic gravity waves specially designed for better representing tropical (QBO-like) and extratropical (i.e. Brewer-Dobson) stratospheric circulation and variability*, by explicitly taking into account the connection to their sources (Lott and Guez 2013; de la Cámara and Lott 2015; de la Cámara et al. 2016). These non-orographic gravity waves (NGWs) or buoyancy waves, linked to convection in the tropics and to fronts and jet imbalances in the extratropics, propagate upwards from the troposphere and are fundamental to accurately simulate atmospheric circulation near the tropopause and in the stratosphere. As such, climate models are starting to incorporate source-related parameterizations of NGWs to reduce biases (Berner et al. 2016). *SIDIS will additionally perform a pioneering activity by assessing the role of source-related NGW parameterizations in forecast mode*, which is not yet in the strategic/implementation plan of SPARC (Stratosphere-troposphere Processes and their Role in Climate; http://www.sparc-climate.org/). In particular, SIDIS will assess for the first time the impact of a source-based NGW parameterization on the forecast quality of the winter NAE surface climate.

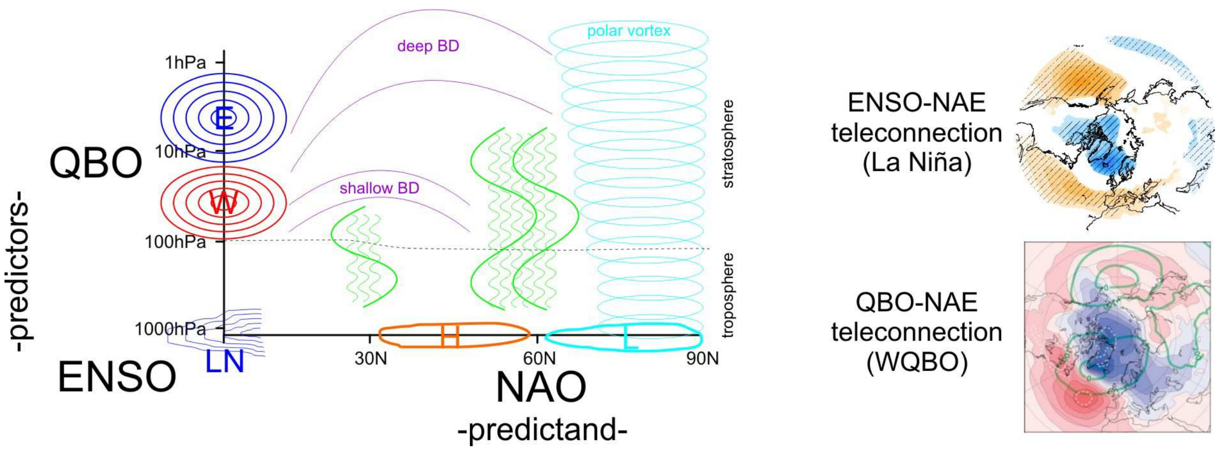

Figure B1: [left] Schematic of the key elements in SIDIS: ENSO, the QBO and the NAO; upward-propagating planetary (thick green) and non-orographic gravity (thin green) waves; the shallow and deep branches of the Brewer-Dobson circulation; and the stratospheric polar vortex, coupled to the NAO in the troposphere. [right] (top) Composite of January-February sea level pressure anomalies for La Niña winters (adapted from Iza et al. 2016). (bottom) Composite of January 1000hPa geopotential height anomalies for WQBO (adapted from Anstey and Shepherd 2014).

EL NIÑO-SOUTHERN OSCILLATION (ENSO)

ENSO can be characterized as a dipole in ocean heat content across the tropical Pacific, in which ocean-atmosphere coupled processes trigger anomalous warm (El Niño) or cold (La Niña) events over the central-eastern equatorial Pacific (e.g. Chang and Battisti 1998). The ENSO influence on the winter NAE atmospheric circulation has only recently been elucidated. The canonical ENSO teleconnection takes place in mid/late-winter (JFM), not in the conventional winter season (DJF), and consists of a dipolar pressure anomaly that resembles the NAO pattern (Fig. B1). As reviewed by Brönnimann (2007), this canonical ENSO-NAE teleconnection has been stationary and robust over the past 300 years and is linear for El Niño and La Niña events. SIDIS will maximize North Atlantic atmospheric predictability emanating from ENSO by using JFM as target season.

The underlying mechanisms of the ENSO-NAE teleconnection however, remain to be properly understood. Tropospheric and stratospheric pathways have been suggested to be at play in establishing the canonical NAO-like response but a unifying framework has been elusive to date. A national project – DANAE, in which García-Serrano is also the PI – will examine the tropospheric pathway by applying Rossby wave source and ray-tracing diagnostics to gain insight into the dynamics of the ENSO wavetrain response over the North Pacific-American sector and its propagation to NAE. Complementing DANAE, SIDIS will comprehensively focus on the stratospheric pathway of the ENSO-NAE teleconnection, with the aim of improving process understanding and isolating the stratospheric impact on the regional forecast skill. Additionally, SIDIS will clarify the time-dependent role of both pathways for the ENSO-NAE teleconnection by using sensitivity experiments with/without stratospheric variability.

There is evidence of a linear impact of ENSO on the tropical stratosphere via a modulation of the upwelling through the tropical tropopause (e.g. Randel et al. 2009; Calvo et al. 2010; Ábalos et al. 2015). The associated subtropical wave-forcing primarily affects the 'shallow branch' of the Brewer-Dobson (BD) circulation (Ábalos et al. 2014), which connects the tropics to middle latitudes in the lower stratosphere (see Fig. B1). SIDIS will assess for the first time the contribution of changes in the shallow-BD circulation to the timing of the ENSO-NAE teleconnection by means of sensitivity experiments supressing variability in the tropical-subtropical stratosphere. Concomitant with the ENSO signal in tropical stratospheric upwelling, there is an ENSO modulation of the downwelling in the polar stratosphere as part of the 'deep branch' of the BD circulation (see Fig. B1), which also tends to be linear (e.g. Randel et al. 2009; Calvo et al. 2010). This perturbation is associated with anomalies in the temperature and strength of the polar vortex. However, there is no agreement on the effective wave-forcing of this ENSO signal. Some studies suggest that it arises from the interference of the ENSO-forced wavetrain with the climatological wave over the Aleutian Low region (e.g. Garfinkel and Hartmann 2008), but the actual injection of ENSO-related wave-activity into the stratosphere occurs at latitudes poleward of about 60ºN (e.g. Taguchi and Hartmann 2006). SIDIS will explore the interference of the ENSO-forced wavetrain with the climatological wave at high latitudes over northern Canada-Alaska, which is where the ENSO signal penetrates deeper into the upper stratosphere, and quantify the contribution of changes in the deep-BD circulation to the timing of the ENSO-NAE teleconnection by means of sensitivity experiments supressing variability in the extratropical stratosphere.

QUASI-BIENNIAL OSCILLATION (QBO)

The QBO is the most prominent variability mode of tropical stratospheric zonal winds characterized by downward-propagating westerly (WQBO) and easterly (EQBO) regimes with a periodicity of approximately 28 months. The QBO wind regimes descend at about 1km/month until they are dissipated in the tropical tropopause (~100hPa). In mid-winter, the WQBO (EQBO) phase shows westerly (easterly) wind anomalies in the lower stratosphere and easterly (westerly) wind anomalies in the middle stratosphere (e.g. Randel et al. 1999; see Fig. B1). The QBO is mainly driven by upward-propagating, convectively-forced equatorial waves (i.e. Kelvin waves, mixed Rossby-gravity waves, and small-scale gravity waves) that break in the stratosphere and deposit momentum flux (e.g. Baldwin et al. 2001). Because the QBO has such a long time-scale and persistence, its evolution is expected to be predictable, thereby potentially useful for seasonal forecasting. The QBO is indeed the most promising potential source of seasonal prediction skill apart from ENSO (Smith et al.2012; Kidston et al. 2015; Butler et al. 2016); it is actually seen as a 'glimmer of hope' for seasonal forecasting (Hoskins 2013). However, the QBO has proved difficult to simulate accurately in climate models. As introduced above, SIDIS will implement a source-based NGW parameterization in order to better, and more realistically, simulate wave/mean-flow interaction in the tropical stratosphere.

Despite the lack of tropical stratospheric variability (i.e. QBO-like) in most of the climate models/forecast systems, their skill at capturing the evolution of tropical winds once initialized is quite high, even in low-top models (Butler et al. 2016). The forecast systems maintain the state of the initialized tropical winds, which is dominated by the state of the QBO, due to slow relaxation rates in the tropical lower stratosphere (Haynes 1998). The QBO-related, initialized tropical winds persist throughout the forecast winter (e.g. Marshall and Scaife 2009); hence the QBO still represents a potential source of extratropical predictability even if models themselves do not internally generate QBO-like variability. The QBO-NAE teleconnection (Fig. B1) appears to be mediated by the influence of the QBO on the stratospheric polar vortex (Garfinkel et al. 2011a, 2011b), which is called the Holton-Tan mechanism and relies on the modulation of upward-propagating planetary waves and the associated changes in the BD circulation. Yet, the simulation/prediction of this tropical-extratropical teleconnection remains a challenge for many climate models (Scaife et al. 2014b), both low-top and high-top (Butler et al. 2016). SIDIS will assess for the first time the impact of implementing a source-based NGW parameterization on the representation and skill of the QBO-NAE teleconnection. Likewise, the dynamics underlying the Holton-Tan mechanism are still not well understood (see Anstey and Shepherd 2014 for review). In particular, it is not established yet whether the QBO-related wind anomalies in the tropical upper (e.g. Pascoe et al. 2006) or lower (e.g. Garfinkel et al. 2012) stratosphere are key for the QBO-vortex relationship. SIDIS will investigate which tropical wind regime in the QBO vertical structure is more relevant for the QBO-NAE teleconnection by performing targeted atmosphere-only simulations.

---------- Work Plan ----------

The project is divided into five work-packages: four for research (WP1-4), which are described below, and one for management and dissemination (WP5). The main tools in SIDIS are: (i) the state-of-the-art climate model EC-EARTH3.2 [BSC is part of the EC-EARTH consortium] with IFS cy36r4 as atmosphere model at T255L91 (~80km horizontal resolution, 91 vertical levels – top 0.01hPa), and NEMO3.6 as ocean model in ORCA1L75 configuration; and (ii) the intermediate-complexity climate model SPEEDO [Kucharski et al. 2015] with SPEEDYv41 as atmosphere model at T30L8 (~400km horizontal resolution, 8 vertical levels – only two in the stratosphere, 100 and 30 hPa), and NEMO3.0 as ocean model in ORCA2L46 configuration.

WP1 – MODEL DEVELOPMENT

Task 1.1 – New parameterization of non-orographic gravity waves in EC-EARTH

[Postdoc1, 1 year; Collaborators: F. Lott (LMD, France), J. von Hardenberg (CNR, Italy)]

The current parameterization of NGWs in EC-EARTH/IFS, which was implemented by J. von Hardenberg and tuned for T255L91, follows a source-unrelated approach where the amplitude of the momentum flux is zonally-symmetric and prescribed as a function of latitude, thereby not representing the intermittent nature of the NGWs and leading to systematic errors (de la Cámara et al. 2016). SIDIS will upgrade the NGW parameterization in EC-EARTH/IFS by implementing the source-related parameterizations used in the atmospheric model LMDz for both convective waves (relevant for the tropical stratosphere; Lott and Guez 2013) and frontal waves (relevant for the extratropical stratosphere; de la Cámara and Lott 2015).

Task 1.2 – Implementation of stratospheric levels and non-orographic gravity waves in SPEEDO

[Postdoc2, 1.5 years; Collaborators: F. Kucharski (ICTP, Italy), R.J. Haarsma (KNMI, Holland), F. Lott]

SIDIS will develop a comprehensive and sustainable improvement by providing SPEEDY with a proper stratosphere; the outcome will be named strato-SPEEDY and double the layers in SPEEDY [adding the levels of 150, 70, 50, 20, 10, 5, 3, 2, and 1 hPa]. The implementation of strato-SPEEDY will rely on the parameterization devised by Polvani and Kushner (2002) plus a radiative forcing mimicking the shortwave radiation flux prescribed as a seasonally-varying profile of ozone concentration, as in the current stratospheric layers of SPEEDY (100 and 30 hPa; King et al. 2010). The new levels will be hard-coded individually and strongly tied to the adjusted parameterizations, with a damping scheme in the upper-most level that allows absorption of waves and prevents spurious reflection, as in the current version of SPEEDY. SIDIS will additionally implement in strato-SPEEDY the same source-related NGW parameterizations as in EC-EARTH/IFS (Task 1.1), with the aim of improving representation and minimizing biases in circulation and variability of both the tropical and extratropical stratosphere.

WP2 – TELECONNECTIONS

Task 2.1 – ENSO/QBO-NAE teleconnections in EC-EARTH, old vs new NGWs

[Postdoc1, 1 year; PhD, 6 months; PI, 1 year; Collaborators: H. Douville (CNRM, France), I. Bladé (UB)]

Two long control runs of 200 years (after spin-up) with EC-EARTH will be performed using fixed radiative forcing at year 2000, with both the current and the new source-based parameterizations. The comparison of both simulations in terms of teleconnection dynamics will allow estimating the impact of the NGW parameterization on the ENSO/QBO teleconnections to the polar vortex and NAE surface circulation.

Task 2.2 – Sensitivity experiments of ENSO/QBO-NAE teleconnections with EC-EARTH

[PI, 2 years; Collaborators: R.J. Haarsma, I. Bladé (UB, Spain)]

Four short transient runs of 3 months (JFM) with the atmospheric component of EC-EARTH (IFS) will be performed. The experimental protocol will be similar to the one used in García-Serrano and Haarsma (2016), namely control and perturbed transient runs, all consisting of a 200-member ensemble of integrations. The different initial conditions for January 1st are taken from each year of the simulation in Task 2.1. The control runs use SST climatology as boundary condition. In the perturbed runs, a SST anomaly will be prescribed in the tropical Pacific with climatology elsewhere ('ENSO'). The other two transient runs are similar to 'ENSO' but nudging the tropical ('ENSO-noTROP') or the polar ('ENSO-noPOL') stratosphere to model climatology from the simulation in Task 2.1. These experiments are constrained by relaxing the zonal-mean spectral component of the temperature, vorticity, and divergence fields to the corresponding climatology from 50hPa (in 'ENSO-noTROP') or 10hPa (in 'ENSO-noPOL') upwards, thus supressing variability.

Two additional transient runs of 3 months (JFM) will be performed to analyse which tropical wind regime in the QBO vertical structure is key for the QBO-NAE teleconnection. In this case, the 200-member ensembles of integrations use SST climatology as boundary condition, but differ in the atmospheric conditions. The perturbed runs are constrained by nudging the tropical lower stratosphere (30hPa-100hPa; 'QBOlower') or the full tropical stratosphere (3hPa-100hPa; 'QBOfull') to QBO composites from the simulation in Task 2.1.

<u>Task 2.3 – Sensitivity experiments of polar vortex-NAE coupling with strato-SPEEDO</u>

[PhD, 1.5 years; Collaborators: F. Kucharski, I. Bladé]

A comprehensive set of moderate (5K) and strong (10K) stratospheric temperature perturbation experiments will be performed with stratro-SPEEDY to assess the timing of the surface response to circulation changes in the polar stratosphere – typically in the range of ENSO/QBO-induced perturbations (e.g. Bell et al. 2009/Garfinkel and Hartmann 2011a). 200-member ensembles of 90-day integrations starting on January 1st will be carried out. The atmospheric initial conditions will be obtained from a 200-year integration with strato-SPEEDO (after spin-up) with fixed radiative forcing at year 2000. The control and perturbed transient runs will use SST climatology as boundary condition. The heating perturbation will be prescribed at the polar stratopause (1hPa), upper stratosphere (5hPa), middle stratosphere (10hPa), and lower stratosphere (50hPa).

WP3 – SEASONAL PREDICTION

The BSC is positioned at the cutting edge of climate forecasting research. It routinely performs seasonal hindcasts (i.e. retrospective forecasts), which ensures the successful completion of the tasks in WP3. The exercise follows a hierarchical approach, performing simultaneously the same suite of idealized seasonal hindcasts with EC-EARTH [<u>Task 3.1</u> – *Postdoc3, 3 years*] and strato-SPEEDO [<u>Task 3.2</u> – *Postdoc2, 2.5 years*]. Note that F.J. Doblas-Reyes (BSC) will co-advise the postdoctoral researchers.

Two kind of hindcasts will be considered: (i) *realistic hindcasts*, using observational estimates to initialize the forecast systems each January 1st over the period 1979-2016 (38 years); and (ii) *perfect-model hindcasts*, where the potential effect of the drift on the simulated dynamics is absent as the model remains in its own attractor, although at the expense of estimating not actual skill but model predictability. In the latter, 40 start dates, spacing five years, will be selected from the 200-year control runs (Task 2.1 for EC-EARTH; Task 2.3 for strato-SPEEDO). For each start date an ensemble of 30 members will be generated with singular vector perturbations (Buizza and Palmer 1994). In each kind, a suite of four hindcast experiments will be performed: (i) a control hindcast ('CTL') with the full ocean-atmosphere model, including the new NGW parameterization (WP1); (ii) a deteriorated-model hindcast ('OLD-NGW' in EC-EARTH, 'NO-NGW' in strato-SPEEDO); (iii) a hindcast similar to 'CTL' but nudging the tropical stratosphere to model climatology as in Task 2.2 ('noTROP'), thus supressing tropical stratospheric variability (the QBO); and (iv) a hindcast similar to 'CTL' but nudging the polar stratosphere to model climatology as in Task 2.2 ('noPOL'), thereby supressing variability associated with the polar vortex.

WP4 – MODEL BIASES

<u>Task 4.1 – Impact of NGW parameterization on model biases</u>

[PI, 6 months; Collaborators: F. Lott, J. von Hardenberg]

The comparison of the 200-year long control runs from EC-EARTH (Task 2.1) and strato-SPEEDO (Task 2.3), in terms of mean climate, will allow assessing the impact of NGW parameterization on model biases: (i) strength, position, and variability of the stratospheric jet and North Atlantic tropospheric jet; (ii) amplitude and phase of the climatological planetary waves; and (iii) the Brewer-Dobson circulation.

<u>Task 4.2 – Impact of resolving the stratosphere on model biases</u>

[PI, 6 months; Collaborators: F.J. Doblas-Reyes, J. von Hardenberg]

The comparison of the hindcasts 'CTL', 'noTROP' and 'noPOL' in WP3, in terms of mean climate, will allow assessing the impact of resolving the tropical and polar stratosphere on model biases (as in Task 4.1).

<u>Task 4.3 – Impact of resolving the polar stratosphere on model biases with sensitivity experiments</u>

[PhD, 2 years; Collaborators: F.J. Doblas-Reyes, I. Bladé]

Three additional 200-year control integrations of strato-SPEEDO (after spin-up; radiative forcing at year 2000) by nudging the polar stratosphere to model climatology from 5hPa, 10hPa, and 50hPa upwards will be performed to further assess the impact of resolving the polar stratosphere on model biases (as in Task 4.1).

Section b: Curriculum Vitae (max. 2 pages)

PERSONAL INFORMATION

Family name: *García-Serrano*, First name: *Javier*
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Date of birth: 15-February-1980
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- **EDUCATION**

2010-May PhD 'Study of atmospheric teleconnections associated with oceanic forcings. Influence on the European climate'. Mark: distinction *Cum Laude* by unanimity.
Advisor: Belén Rodríguez-Fonseca.
Dept. Geophysics and Meteorology, Universidad Complutense Madrid (UCM), Spain
2007-Jun Master degree on Geophysics and Meteorology; Faculty of Sciences-Physics, UCM, Spain
2005-Feb Degree on Physics; Faculty of Sciences-Physics, UCM, Spain

- **CURRENT POSITION**

2015-Jun – Researcher – Marie Skłodowska-Curie Fellow (H2020-IF-EF)
Earth Sciences Dept., Barcelona Supercomputing Center (BSC-CNS), Spain

- **PREVIOUS POSITIONS**

2013 – 2015 Postdoc [with C. Frankignoul, professor emeritus]
LOCEAN/IPSL, Université Pierre et Marie Curie, Paris, France
2012/Mar-Nov Postdoc [with M. Kimoto, head of department]
Atmosphere and Ocean Research Institute (AORI), University of Tokyo, Japan
2010 – 2012 Postdoc [with F.J. Doblas-Reyes, head of Climate Forecasting Unit]
Institut Català de Ciències del Clima (IC3), Barcelona, Spain

- **SHORT STAYS**

2016/Jun-Aug CERFACS/CNRS, Toulouse, France [postdoctoral stay with C. Cassou]
2016/Mar-May CNRM-GMGEC, Météo-France, Toulouse, France [postdoctoral stay with H. Douville]
2009/Jul-Sep Global Climate Division/KNMI, De Bilt, The Netherlands [PhD stay with R.J. Haarsma]
2008/Feb-May Met Office-Hadley Centre, Exeter, UK [PhD stay with A. Arribas, A.A. Scaife]

- **FELLOWSHIPS**

2015 – 2017 Marie Skłodowska-Curie European Fellowship (H2020 grant 655339) for BSC-CNS
2015-Oct Severo Ochoa Mobility Grant to host Martin P. King (UniRes/BCCR, Norway) at BSC-CNS
2012/Mar-Nov CANON Foundation in Europe (grant N2011-062) for AORI, University of Tokyo, Japan
2009/Jul-Sep Spanish Ministry of Education (grant TME2008-00927) for KNMI, The Netherlands
2008/Feb-May European Science Foundation-MedCLIVAR (grant N2011-062) for Met Office, UK

- **SUPERVISION** [at Earth Sciences Dept., Barcelona Supercomputing Center (BSC-CNS), Spain]

2016 – 2019 PhD student (Bianca Mezzina, Italy) with a scholarship linked to the PI's national project DANAE, given in addition to the granted budget due to a highly-ranked evaluation
2016/Mar-Jul Master student (María Santolaria – University of Barcelona), internship and master thesis

- **TRAINING/TEACHING ACTIVITIES**

2015-Oct Lecturer – ‘Drivers/empirical predictors of mid-latitude seasonal forecasts’, *1st MedCOF Training Workshop on Seasonal Forecasting*, WMO/hosted by AEMET, Madrid, Spain
2011-Jul Lecturer – ‘Climate Variability in the Mediterranean’, *An ocean of resources and a global change scenario*, University of Barcelona International Summer School (UBISS), Spain
2006 Teacher Assistant – ‘Elements of Geophysics Fluids Dynamics’ in charge of C.R. Mechoso (UCLA, USA), Dept. Geophysics and Meteorology, UCM, Madrid, Spain

- **ORGANISATION OF SCIENTIFIC MEETINGS**

2016-Sep Convener of the session ‘Towards better understanding mid-latitude atmospheric teleconnections’ at 16th European Meteorological Society Annual Meeting, Trieste, Italy
2014-Dec Organising Committee of the WWRP/WCRP ‘International workshop on polar-lower latitude linkages and their role in weather and climate’, Barcelona, Spain
2010 – 2012 Co-convener of the session ‘Tropical Climate Variability and Teleconnections: past, present and future’ at the European Geosciences Union General Assembly, Vienna, Austria

- **COMMISSIONS OF TRUST**

[international] Contributing Author to the 5th IPCC Assessment Report *Chapter 11* (Kirtman et al. 2013): *Near-term climate change: projections and predictability*, in ‘Climate Change 2013: The Physical Science Basis’. Cambridge University Press, 953-1028.
[national] Contributing Author to *Chapter 4* (Rodríguez-Fonseca and Rodríguez-Puebla 2010): *Teleconnections affecting Iberian Peninsula climate variability: predictability and expected changes*, in ‘Climate in Spain: past, present and future’. Eds. FF Pérez and R. Boscolo – CLIVAR Spain, 53-67.
[regional] Co-author of *Chapter 5* (Calbó et al. 2016): *Climate projections and future scenarios*, in ‘Third Report on Climate Change in Catalonia’. Eds. A Queralt and J Martin-Vide – Consell Assessor per al Desenvolupament Sostenible, Generalitat de Catalunya (in press).

- Jury member of the PhD dissertation ‘Non-stationary ENSO influence on European and Mediterranean rainfall: dynamics and modulations’ by J. López-Parages, 2015-Nov, UCM, Madrid, Spain.
- Reviewer for *Journal of Climate* (Eds. T. DelSole, D.J. Vimont, J. Perlwitz), *Climate Dynamics* (Eds. J.-C. Duplessy, S. Corti, B. Kirtman, E.K. Schneider), *Geophys. Research Lett.* (Eds. N. Diffenbaugh, P. Williams), *Journal of Geophys. Research-Atmos.* (Ed. C. Zhang), *International J. of Climatology* (Eds. R. Huth, S. Gulev, G. McGregor), *Bull. Amer. Meteorol. Soc.* (Ed. B. Stevens).
- Reviewer for the Spanish Agency of Assessment and Planning (ANEP) to evaluate research projects.

- **MAJOR COLLABORATIONS**

- Ileana Bladé (atmospheric dynamics and teleconnections), University of Barcelona, Spain
- Reindert J. Haarsma (atmospheric dynamics and climate modelling), KNMI, The Netherlands
- Claude Frankignoul (climate variability) / Juliette Mignot (decadal prediction), LOCEAN/IPSL, France
- Martin P. King (polar-midlatitude teleconnections), UniRes/BCCR, Norway
- Hervé Douville (seasonal prediction and ENSO teleconnections), CNRM/Météo-France, France
- Christophe Cassou (air-sea interaction and ENSO teleconnections), CERFACS, France
- Daniela Matei (polar-midlatitude and ENSO teleconnections), MPI-M, Germany
- Álvaro de la Cámara (troposphere-stratosphere interaction and dynamics), NCAR, USA

Of particular relevance for SIDIS are: R.J. Haarsma, who contributed to the KNMI version of SPEEDO and contributes to developing EC-EARTH at KNMI [WPs1-3]; I. Bladé, leading researcher in atmospheric dynamics and multi-model assessment of climate variability [WP2,4]; and H. Douville, who led the development of a nudging strategy for the stratospheric polar vortex at CNRM [WPs2,3]. Thereby, existing collaborations will strongly support this research.

Finally, the PI is involved in the project QBOi of SPARC (Stratosphere-troposphere Processes And their Role in Climate), so that the results of SIDIS will inform and directly impact this community.

Appendix: All on-going and submitted grants and funding of the PI (Funding ID)

On-going Grants

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*[1]
DANAE ‘Dynamics and predictability of the ENSO teleconnection in the North Atlantic-European region’	Spanish Ministry of Economy and Competitiveness (MINECO)	146.410 + PhD funding	(3 years) 07/2016-06/2019	PI	Related, as DANAE deals with the tropospheric teleconnection pathway of ENSO to the winter Euro-Atlantic climate; but there is no overlap with SIDS as DANAE develops different diagnostics and employs data from operational forecast systems
DPETNA ‘Dynamics and predictability of the ENSO teleconnection to the tropical North Atlantic’	EU-H2020 MSCA-IF-EF	158.122	(2 years) 06/2015-05/2017	PI	No direct relationship, as DPETNA deals with the ENSO impact on the tropical-subtropical North Atlantic in spring; but common diagnostics are used
APPLICATE ‘Advanced prediction in polar regions and beyond: modelling, observing system and linkages associated with a changing Arctic climate’	EU-H2020 BG10-2016	667.375 (total budget 8.715.066)	(4 years) 11/2016-10/2020	Contributing researcher (WP3 ‘Atmospheric and oceanic linkages’)	No relationship, as WP3 deals with multi-model experiments to identify the response to Arctic climate change
PRIMAVERA ‘Process-based climate simulation: advances in high-resolution modelling and European climate risk assessment’	EU-H2020 SC5-2014	1.277.425 (total budget 11.000.000)	(4 years) 11/2015-10/2019	Contributing researcher (WP5 ‘Drivers of variability and change in European climate’)	No relationship, as WP5 deals with the influence of Arctic sea ice and Eurasian snow on decadal variability of European climate

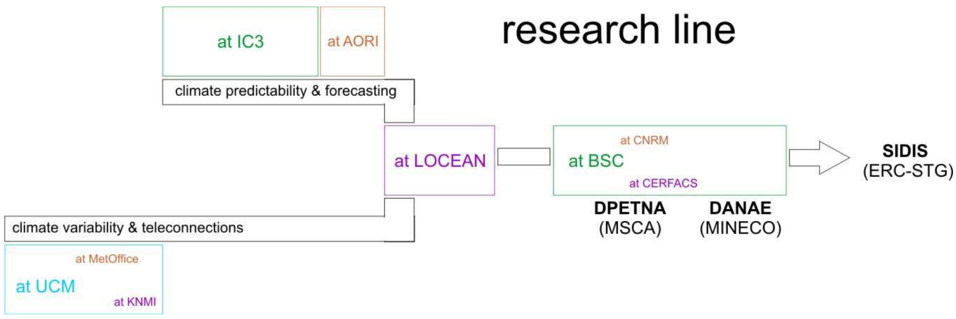
[1] Describe clearly any scientific overlap between your ERC application and the current research grant or on-going grant application.

Grant applications

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*[2]
MEDSCOPE ‘Mediterranean services chain based on climate predictions’	[submitted to] EU JPI-Climate ERA4CS-2016	[requested] 1.153.750 (total budget 5.372.198)	2017-2020	Co-PI at BSC and Task leader (T2.2 ‘Teleconnections with low-latitudes’)	Related, as T2.2 deals with the ENSO-NAE teleconnection (among other oceanic forcings, like the Atlantic and Indian basins); but there is no overlap with SIDIS as T2.2 would focus on the forecast quality assessment of hindcasts from operational forecast systems and the potential, derived climate services

Section c: Early achievements track-record (max. 2 pages)

During his scientific career, Dr. García-Serrano (the PI) has worked upon the fundamental initiative of exploring **teleconnection dynamics for climate prediction**. He has recently been able to tackle this challenge with autonomy thanks to an EU-funded H2020 Marie Skłodowska-Curie Action (MSCA), *DPETNA*, and a national project funded by the Spanish Ministry of Economy and Competitiveness (MINECO), *DANAE*. Obtaining these grants has been the reflection of the PI's solid and coherent career during his postdoctoral stage, thoroughly building a bridge between his theoretical background in atmospheric dynamics and the practical requirements of climate forecasting. These two research interests started to assemble into a single research line at LOCEAN (France) tackling the predictability of the North Atlantic Oscillation from Arctic sea-ice variability by assessing tropospheric and stratospheric teleconnection pathways [three publications in major journals have derived from this work: García-Serrano et al. 2015b, García-Serrano and Frankignoul 2016, García-Serrano et al. 2016]. Below is a diagram summarising the conception of his research line: *Teleconnections dynamics for climate prediction*. It also shows the institutions where the PI has been developing his scientific objectives, including those where he has carried out short stays thanks to his fund-raising capability (see Section b, CV).



During his PhD, the PI developed a deep understanding of the atmospheric dynamics associated with oceanic forcings, such as ENSO in the tropical Pacific (García-Serrano et al. 2011a [12 citations]), the Atlantic Niño in the tropical Atlantic (García-Serrano et al. 2011b), and temperature anomalies in the Mediterranean Sea (Fontaine et al. 2010 [26 citations]; García-Serrano et al. 2013b). His work on the tropical Atlantic variability led to a new statistical methodology to capture time-evolving covariability modes; which was named extended-maximum covariance analysis (EMCA) and was applied separately to time-varying predictors (Polo et al. 2008 [48 citations]) and time-varying predictands (García-Serrano et al. 2008 [17 citations]). This time it is also when his *most-cited paper* was published (Rodríguez-Fonseca et al. 2009 [73 citations]), where the hypothesis of the Atlantic Niño influence on ENSO was first formulated.

After completing his PhD, he moved from the diagnostic approach of climate variability into the prognostic approach of climate forecasting. He acquired an in-depth knowledge of the forecast quality of seasonal and decadal climate predictions; e.g. publishing pioneering work on the skill of the Atlantic multi-decadal variability (García-Serrano and Doblas-Reyes 2012 [28 citations]) and the Indian Ocean (Guemas et al. 2013 [16 citations]). He also brought his expertise to wider scopes, such as exploring strategies for ensemble generation (Du et al. 2012 [21 citations]) and applicability to climate-related infectious diseases (Rodó et al. 2013 [15 citations]). In García-Serrano et al. (2012 [11 citations], 2015a), a targeted procedure for quantitatively evaluating performance in different forecast systems was developed.

DPETNA and *DANAE* are helping the PI to strengthen and widen competences, like project management skills. The PI has fully demonstrated his proficiency and capability to deal successfully with a wide range of scientific challenges, achieving with quality all the required steps to pursue his career development. The fact that he has already revealed a high degree of responsibility guarantees the accurate implementation of *SIDIS*. The completion of this investigation could lead to worldwide cutting-edge results and will certainly contribute to the overall competitiveness and excellence of Europe in climate prediction.

<ins>Summary of achievements</ins>: author of 32 articles, 29 published - 3 under review, all in journals ranked in the first quartile (plus 2 in preparation); 458 total citations / H-index 12; 6 non peer-reviewed publications (e.g. CLIVAR Exchanges); 4 book chapters (e.g. CLIVAR-Spain); 21 oral contributions as first author (4 invited); participation in 5 European (FP6-FP7-H2020) and 8 national (total budget >1,2M€) projects; active collaboration with 11 international institutions; presence in the media; invited lecturer at workshops and summer schools; contributing author to the IPCC 5th Assessment Report.

<u>Five relevant publications without PhD advisor</u> (B. Rodríguez-Fonseca, UCM, Spain):

- ***García-Serrano J.**, C. Frankignoul, G. Gastineau, A. de la Cámara (2015b): On the predictability of the winter Euro-Atlantic climate: lagged influence of autumn Arctic sea-ice. J. Clim., 28, 5195-5216.*
  [AMS/SCOPUS citation track] 7/3 citations, including Butler et al. (2016, *Q.J.R.Meteorol.Soc. 142:1413-1427*) – the last study assessing multi-model seasonal prediction skill in boreal winter. *García-Serrano et al. (2015b)* developed for the first time empirical predictions of interannual variability of the winter NAO and European surface climate based on Arctic sea-ice concentration, where a stratospheric pathway appears to be at play in the teleconnection dynamics.
  As example of this achievement the European Commission contacted him for a press interview in *HORIZON – The EU Research and Innovation Magazine* - to comment on the role played by Arctic sea-ice changes in European winter climate anomalies (http://horizon-magazine.eu/article/european-temperatures-likely-fall-due-arctic-vortex-us-thaws_en.html).
- *Doblas-Reyes F.J., I. Andreu-Burillo, Y. Chikamoto, **J. García-Serrano**, V. Guemas, M. Kimoto, T. Mochizuki, L.R.L. Rodrigues, G.J. van Oldenborgh (2013): Initialized near-term regional climate change prediction. Nature Comms., 4:1715, doi:10.1038/ncomms2704.*
  [SCOPUS] 65 citations – high impact. During his period as postdoctoral researcher working on the pioneering field of decadal climate prediction, first hired at IC3 and then via his own funding at the University of Tokyo (AORI), the PI was very productive, publishing 11 papers in major journals which contributed to internationalize his research activity. The effort culminated in the publication of this collaborative work in *Nature Comms.*, which e.g. showed for the first time that multi-annual predictions of land-surface precipitation in the Northern Hemisphere have skill.
- *Doblas-Reyes F.J., **J. García-Serrano**, F. Lienert, A. Pintó-Biescas, L.R.L. Rodrigues (2013): Seasonal climate predictability and forecasting: status and prospects. WIREs – Advanced Review, 4, 245-268.*
  [SCOPUS] 41 citations – strong impact in the field.
- ***García-Serrano J.**, F.J. Doblas-Reyes, R.J. Haarsma, I. Polo (2013a): Decadal prediction of the dominant West African monsoon rainfall modes. J. Geophys. Res. – Atmos., 118, 5260-5279.*
  [SCOPUS] 8 citations. This study offered for the first time the validation of decadal prediction systems upon the West African monsoon variability. Due to the novelty of the findings in *García-Serrano et al. (2013a)*, the work received support and publicising by the American Geophysical Union through the Research Spotlight "Can West African monsoon rainfall be predicted on decadal time scales?" in EOS, Transactions American Geophysical Union, vol. 94, no. 29, page 260 (2013).
- ***García-Serrano J.**, F.J. Doblas-Reyes (2012): On the assessment of near-surface global temperature and Atlantic multi-decadal variability in the ENSEMBLES decadal hindcast. Clim. Dyn., 39, 2025-2040.*
  [SCOPUS] 28 citations – strong impact in the field. This study discussed for the first time the effect of hindcast start-date frequency in the Atlantic Multi-decadal Oscillation (AMO) skill. It also evidenced AMO skill beyond the global-warming signal, thus opening the possibility of forecasting low-frequency climate variability related to the AMO. This work continued in García-Serrano et al. 2012 (*Understanding Atlantic multi-decadal variability prediction skill, Geophys. Res. Lett. 39:L18708* [11 citations]) and García-Serrano et al. 2015a (*Added-value from initialization in predictions of Atlantic multi-decadal variability, Clim. Dyn., 44, 2539-2555* [3 citations]).

Note that three recent publications do not involve either postdoc advisors or PhD advisor: García-Serrano J., R.J. Haarsma (2016, *Non-annular, hemispheric signature of the winter North Atlantic Oscillation, Clim. Dyn. doi:10.1007/s00382-016-3292-3*); King M.P., J. García-Serrano (2016, *Potential ocean-atmosphere preconditioning of late autumn Barents-Kara sea ice concentration anomaly, Tellus A, 68:28580*); Mignot J., J. García-Serrano, D. Swingedouw, A. Germe, S. Nguyen, P. Ortega, E. Guilyardi (2016, Decadal prediction skill in the ocean with surface nudging in the IPSL-CM5A-LR climate model, *Clim. Dyn.,47:1225-1246).*

<u>Invited presentations at international scientific events</u>:
- '*Polar-nonpolar atmospheric linkages: observations and model diversity*', in the EU/JPI-Climate InterDec Kick-Off Meeting. Hamburg, Germany, Nov-2016.
- '*Predictability of the Euro-Atlantic climate from Arctic sea ice variability*', in the WCRP "Workshop on understanding, modelling and predicting weather and climate extremes". Oslo, Norway, Oct-2015.
- '*Predictability and empirical predictions of the winter NAO*', in the EU/FP7 SPECS 2nd General Assembly. De Bilt, The Netherlands Oct-2013.
- '*Seasonal-to-decadal prediction of the West African monsoon*', in the EU/FP7 QWeCI Final Project Meeting. Barcelona, Spain, Jul-2013.

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ERC Starting Grant 2017

Understanding <u>**s**</u>tratospheric <u>**i**</u>nfluence on tropospheric <u>**d**</u>ynamics for <u>**i**</u>mproving North Atlantic-European <u>**s**</u>easonal forecasts - **SIDIS**

Part B2: *<u>The scientific proposal</u>* (max. 15 pages)

This project has been designed to address one main scientific question: what is the impact of correctly representing stratospheric variability and dynamics, and its influence upon the troposphere, on the seasonal prediction skill of the winter Euro-Atlantic climate?

The aim is to improve seasonal forecasting capabilities, namely more accurate and more reliable seasonal predictions, of winter surface climate in the North Atlantic-European region by both better simulating stratospheric circulation and enhancing understanding of the stratospheric pathway involved in the dominant tropical-extratropical teleconnections at interannual time-scales.

This goal will be undertaken by implementing targeted model developments with a hierarchy of climate models and by performing an unprecedented set of sensitivity and seasonal forecast experiments.

Section a. State-of-the-art and objectives

Given the chaotic nature of the climate system, one might question the feasibility of forecasting climate conditions months in advance. Yet, seasonal climate prediction is feasible because atmospheric variability on seasonal time-scales is modulated by slowly-varying boundary conditions, such as sea surface temperature (SST), and can retain memory from internal processes with very slow relaxation rates, such as those in the stratosphere. These fluctuations are not noticeable in day-to-day weather conditions but become evident in seasonal averages, e.g. two/three-month means (e.g. Shukla 1998). Seasonal climate prediction has progressed considerably in the last decade but the tropics remain the region where seasonal forecasts are most successful (see Doblas-Reyes et al. 2013 for review). This project, SIDIS, will focus on the two main modes of interannual variability at tropical latitudes, which are relatively well predicted and/or constrained by initialization (e.g. Barnston and Tippett 2013; Tripathi et al. 2015; Butler et al. 2016), and for which tropical-extratropical teleconnections affecting the Euro-Atlantic sector have been robustly shown in observations (e.g. Smith et al. 2012; Anstey and Shepherd 2014; ; Kidston et al. 2015): *El Niño-Southern Oscillation* (ENSO), the leading interannual variability mode in the tropical troposphere; and the *quasi-biennial oscillation* (QBO), the leading interannual variability mode in the tropical stratosphere. Note that intraseasonal phenomena, like the Madden-Julian Oscillation (MJO; e.g. Cassou 2008), are the subject of sub-seasonal forecasting.

In most of the extratropics, and in particular in the North Atlantic-European (NAE) region, the signals predicted by general circulation model (GCM)-based seasonal forecast systems have usually been weak and barely added valuable information over a climatological forecast. Boreal winter, the target season of SIDIS, represents the main hurdle in this scenario. The Euro-Atlantic winter stands for the season with the lowest prediction skill based on persistence, which can be explained by the high level of atmospheric internal variability. The winter in this region is also the season with the overall largest systematic error in dynamical forecasting, particularly for the pressure field, surface temperature and precipitation (e.g. Rodwell and Doblas-Reyes 2006; Doblas-Reyes et al. 2009, 2010). Even so, some traces of skill in Europe, for instance associated with ENSO and its stratospheric teleconnection (e.g. Scaife et al. 2014a; Domeisen et al. 2015; Butler et al. 2016), have been reported in the recent generation of seasonal forecast systems, which encourages further assessment and fosters targeted approaches.

Seasonal forecasting is a field with enormous potential influence in different climate-sensitive, socio-economic sectors, such as agriculture, health, water management, and energy. The relevance of making available trustworthy information at seasonal time-scales is indeed recognized by the WMO Global Framework for Climate Services. In the Euro-Atlantic sector, the winter North Atlantic Oscillation (NAO) dominates atmospheric variability and strongly influences surface climate on interannual time-scales, as it is associated with changes in the westerly flow reaching the continent from the ocean and latitudinal shifts of the North Atlantic storm-track (see Hurrell et al. 2003 for review). Thus, forecasting the NAO is of paramount importance for skilful predictions of European climate anomalies. The NAO pattern shows a meridional dipole between middle and high latitudes of the North Atlantic, with a strengthening of the Azores High (anticyclonic anomalies) and a deepening of the Icelandic Low (cyclonic anomalies) during its positive phase (Fig. B2.I). These anomalies are linked to warmer/wetter than average conditions over northern Europe and colder/dryer than average conditions over southern Europe. The reversed atmospheric anomalies and climate conditions occur during the negative phase of the NAO (e.g. Hurrell et al 2003). Interestingly, both the ENSO and QBO extratropical teleconnections project on the NAO pattern (Fig. B2.II), thereby representing suitable interannual phenomena that can enhance NAE seasonal predictability. One of the main goals of <u>SIDIS is to improve simulation and prediction of the ENSO/QBO-NAE teleconnections by enhancing understanding of their mechanisms</u>. Understanding the dynamical processes involved in predictability has been identified by the WMO World Climate Research Programme as one of the much-needed efforts in climate research.

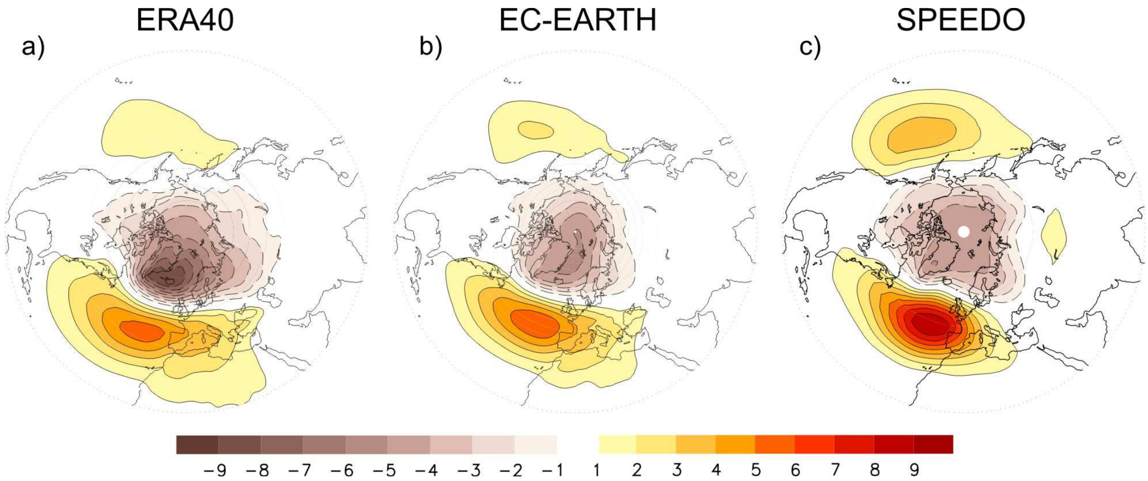

Figure B2.I: Hemispheric regression of mid-winter (January-February) sea level pressure anomalies [in hPa] onto the corresponding NAO index, obtained as standardized time-series associated with the leading EOF over the NAE region (90ºW-40ºE/20ºN-90ºN), in observational data (ERA40 reanalysis, a; adapted from García-Serrano et al. 2011), EC-EARTH3.1 (b; adapted from García-Serrano et al. 2017), and SPEEDO (SPEEDY-MICOM, c; adapted from García-Serrano and Haarsma 2016).

EL NIÑO-SOUTHERN OSCILLATION (ENSO)

ENSO can be characterized as a dipole in ocean heat content across the tropical Pacific, in which ocean-atmosphere coupled processes trigger anomalous warm (El Niño) or cold (La Niña) events over the central-eastern equatorial Pacific in conjunction with a zonal pressure seesaw (the Southern Oscillation) between eastern and western regions of the tropical basin (e.g. Chang and Battisti 1998). The main reason for the attention ENSO receives is that it affects weather/climate variability in large parts of the world, namely the ENSO teleconnections. This project focuses on the canonical ENSO phenomenon, characterized by SST anomalies with an arrowhead shape settling off the South American coastline, for which robust tropical-extratropical atmospheric teleconnections have been established (e.g. Trenberth et al. 1998; Alexander et al. 2002; Hoerling and Kumar 2002). A convenient measure of ENSO is the Niño3.4 index, defined as the anomaly of SST averaged over the region 5ºS-5ºN/170ºW-120ºW; the strength of an ENSO teleconnection is then defined as the linear regression coefficient of the field in question on the Niño3.4 time-series (e.g. Sterl et al. 2007; Yang and DelSole 2012).

ENSO is the most important source of predictability at seasonal time-scales (e.g. Doblas-Reyes et al. 2013). The ENSO influence on the North Pacific-American (NPA) sector is well known: the atmospheric response displays a wavetrain structure arching northeastward, whose centres of action are organized in the so-called Tropical-Northern Hemisphere (TNH) pattern, which is distinct from the internally-generated Pacific-North America (PNA) pattern (e.g. Robertson and Ghil 1999; Alexander et al. 2002; Straus and Shukla 2002;

DeWeaver and Nigam 2002; Nigam 2003; Bladé et al. 2008). The ENSO influence on the winter NAE atmospheric circulation has only recently been elucidated. The canonical ENSO signal takes place in mid/late-winter, namely January-to-March (JFM), not in the conventional winter season (December-to-February; DJF), and consists of a dipolar surface pressure anomaly that resembles the NAO pattern (e.g. Smith et al. 2012). As reviewed by Brönnimann (2007), this canonical ENSO-NAE teleconnection has been stationary and robust over the past 300 years and is linear for El Niño and La Niña events. SIDIS will maximize North Atlantic atmospheric predictability emanating from ENSO by using JFM as target season.

The underlying mechanisms of the ENSO-NAE teleconnection however, remain to be properly understood. Tropospheric and stratospheric pathways have been suggested to be at play in settling the canonical response but a unifying framework has been elusive to date.

With regard to tropospheric mechanisms, some modelling studies have suggested that transient-eddy activity in the North Atlantic basin generates a NAO-like signal in response to the downstream extension of the ENSO-forced wavetrain propagating across the NPA sector (e.g. Cassou and Terray 2001a, 2001b; Merkel and Latif 2002; Pohlmann and Latif 2005). However, no clear evidence has been found in observations supporting a link between ENSO and the NAO via this downstream effect (Brönnimann 2007). Some authors pointed to model biases as key to explain this apparent connection (Cassou and Terray 2001a, 2001b). An alternative and simpler view was proposed by García-Serrano et al. (2011), who interpreted the canonical NAO-like surface pattern as resulting from the westward tilt with height of the Rossby wavetrain triggered remotely from the tropical Pacific. This westward tilt is a characteristic feature of quasi-barotropic teleconnection patterns (e.g. Hsu and Wallace 1985). Their interpretation can explain the observed (Moron and Gouirand 2003; Brönnimann 2007; Fereday et al. 2008; Li and Lau 2012) and simulated (Gouirand et al. 2007) intraseasonal variation of the ENSO impact on the NAE atmospheric circulation from early-winter (November-December; ND) to mid-winter (January-February; JF), since the ENSO-forced wavetrain is not completely established until January (Wang and Fu 2000; Bladé et al. 2008). The intraseasonal timing in the development of the ENSO teleconnection to the NAE sector can be traced back to the NPA sector, in agreement with Livezey and Mo (1987) and Alexander et al. (2002), who also showed that the wavetrain response to ENSO is stronger in JF than in December. Bladé et al. (2008) used simple Rossby waveguide arguments to attribute the late timing of the extratropical NPA response to changes in the mean-flow, as a result of which the sensitivity of the NPA circulation to tropical forcing in the central-eastern Pacific is stronger in JF than in ND (Newman and Sardeshmukh 1998). They also pointed out that the subtropical jet is strongest in January and thus represents a stronger vorticity source. A national project – DANAE, in which García-Serrano is also de PI – will examine the tropospheric pathway by applying Rossby wave source and ray-tracing diagnostics to gain insight into the dynamics of the ENSO wavetrain response over the NPA and its propagation to NAE; this will be performed upon both observational data and operational forecast systems, i.e. the EUROSIP and NMME multi-models. Complementing DANAE, SIDIS will comprehensively focus on the stratospheric pathway of the ENSO-NAE teleconnection, with the aim of improving process understanding and isolating the stratospheric impact on the regional forecast skill.

The timing of the wavetrain response to ENSO might be fundamental when seeking a unifying framework of the ENSO-NAE teleconnection involving the stratosphere. It has been suggested both that ENSO has a strong and robust influence on the stratosphere (e.g. García-Herrera et al. 2006; Randel et al. 2009) and even that ENSO-induced stratospheric changes may dominate the ENSO impact on the NAE region (e.g. Ortiz Beviá et al. 2010; Butler et al. 2014). It is worth noting that, consistent with the establishment of the ENSO-forced wavetrain in January, most studies assessing the seasonal evolution of the zonal-mean ENSO temperature and zonal wind anomalies in the stratosphere show that the ENSO signal begins with maximum amplitude in January and propagates downwards thereafter (Manzini et al. 2006; Cagnazzo and Manzini 2009; Ineson and Scaife 2009; Bell et al. 2009; Free and Seidel 2009). Although all these studies agree that the downward influence of the ENSO-induced stratospheric anomalies on the troposphere is strongest in late-winter (February-March; FM), they differ in the interpretation of this result. For some, the downward-propagating signal is responsible for the ENSO-NAE teleconnection (Ineson and Scaife 2009), while for others it helps the NAE SLP anomaly to persist into early-spring (March; Cagnazzo and Manzini 2009). Given the results of García-Serrano et al. (2011), according to which the tropospheric ENSO-forced wavetrain alone can explain the NAO-like signature in JF, we speculate here that the tropospheric pathway dominates the ENSO-NAE relationship in mid-winter (JF), whereas the stratospheric pathway becomes dominant in late-winter (FM). SIDIS will clarify the time-dependent role of both pathways for the ENSO-NAE teleconnection by using sensitivity experiments with/without stratospheric variability.

Concerning the dynamics involved in the stratospheric pathway, prior upward propagation of ENSO-induced waves from the troposphere into the stratosphere is required (Manzini et al. 2006). There is evidence of a linear impact of ENSO on the tropical stratosphere (e.g. Randel et al. 2009): El Niño (La Niña) events are associated with a reinforcement (weakening) of the subtropical tropospheric jet, which then becomes more (less) effective at channelling resolved and gravity wave upward propagation (de la Cámara et al. 2014), whose dissipation and drag in the lower stratosphere intensify (damp) the Brewer-Dobson (BD) circulation, thus enhancing (inhibiting) the upwelling through the tropical tropopause (Randel et al. 2009; Calvo et al. 2010; Ábalos et al. 2015). This subtropical wave-forcing primarily affects the 'shallow branch' of the BD circulation (Ábalos et al. 2014), which connects the tropics to middle latitudes in the lower stratosphere (e.g. Birner and Bönisch 2011). SIDIS will assess for the first time the contribution of changes in the shallow-BD circulation to the timing of the ENSO-NAE teleconnection by means of sensitivity experiments supressing variability in the tropical-subtropical stratosphere.

Concomitant with the ENSO signal in tropical stratospheric upwelling, there is an ENSO modulation of the downwelling in the polar stratosphere as part of the 'deep branch' of the BD, which also tends to be linear (e.g. Randel et al. 2009; Calvo et al. 2010). This perturbation is associated with anomalies in the zonal-mean temperature and strength of the polar vortex strength (e.g. Manzini et al. 2006; Cagnazzo and Manzini 2009). However, there is no agreement on the effective wave-forcing of this ENSO signal. Some studies suggest that it arises from the interference of the tropospheric ENSO-forced wavetrain with the climatological stationary wave over the Aleutian Low region (e.g. Garfinkel and Hartmann 2008), but the actual injection of ENSO-related wave-activity into the stratosphere occurs at latitudes poleward of about 60ºN (e.g. Taguchi and Hartmann 2006). The discrepancies could be due to the different data period considered in those studies; for example, Garfinkel and Hartmann (2008) computed observational composites over NDJF, probably mixing in various signals, whereas Taguchi and Hartmann (2006) performed sensitivity experiments under perpetual January conditions, more likely isolating the ENSO signal when it is at its maximum. Note that the target of SIDIS is the mean seasonal stratospheric response to ENSO, which is approximately linear (e.g. Butler et al. 2014; Calvo et al. 2016; Iza et al. 2016), rather than disturbances on short timescales (days and weeks) associated with sudden stratospheric warmings, which may be internally generated within the atmosphere (e.g. Manzini et al. 2006). SIDIS will explore the interference of the ENSO-forced wavetrain with the climatological stationary wave at high latitudes over northern Canada-Alaska, which is where the ENSO signal penetrates deeper into the middle-upper stratosphere (Garfinkel and Hartmann 2008), and quantify the contribution of changes in the deep-BD circulation to the timing of the ENSO-NAE teleconnection by means of sensitivity experiments supressing variability in the extratropical stratosphere.

The comprehensive and systematic comparison that will be performed in SIDIS between the observed tropospheric/stratospheric dynamics linked to the canonical ENSO-NAE signal in mid/late-winter and the teleconnection mechanisms simulated in targeted atmosphere-only and seasonal hindcast experiments, apart from being unprecedented, could clarify the as-of-yet elusive unifying view of this remote relationship and provide insight into the sources of prediction skill for the Euro-Atlantic climate.

QUASI-BIENNIAL OSCILLATION (QBO)

The QBO is the most prominent variability mode of tropical stratospheric zonal winds characterized by downward-propagating westerly (WQBO) and easterly (EQBO) regimes with a periodicity of approximately 28 months. The QBO wind regimes descend at about 1km/month until they are dissipated in the tropical tropopause (~100hPa). In mid-winter, the WQBO phase shows westerly wind anomalies in the lower stratosphere and easterly wind anomalies in the middle stratosphere (Fig. B2.II-bottom); through one complete cycle, the EQBO phase depicts anomalies of opposite sign (e.g. Randel et al. 1999). The QBO is mainly driven by upward-propagating, convectively-forced equatorial waves (i.e. Kelvin waves, mixed Rossby-gravity waves, and small-scale gravity waves) that break in the stratosphere and deposit momentum flux (e.g. Baldwin et al. 2001). A standard diagnostic to define the QBO phase is based on the equatorial zonal-mean zonal wind at 50hPa, U_{EQ} (e.g. averaged over 2ºS-2ºN – Anstey and Shepherd 2014, or over 5ºS-5ºN – Butler et al. 2016); although, for instance, defining the QBO phase at 40hPa has been found to give the strongest correlation with the extratropics (Dunkerton and Baldwin 1991).

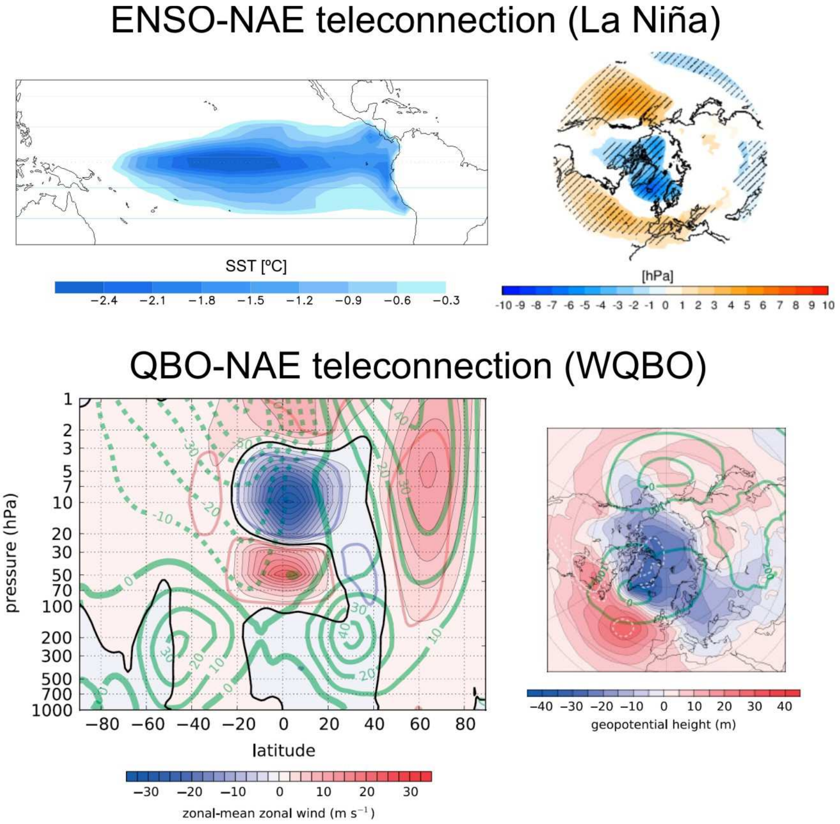

Figure B2.II: [top] (left) Forcing field for the atmosphere-only sensitivity experiments (La Niña) based on the regression of SST anomalies onto the Niño3.4 index in January-February, 1958-2002. (right) Composite of January-February sea level pressure anomalies for La Niña winters (adapted from Iza et al. 2016). [bottom] (left) Vertical-meridional structure of zonal-mean zonal wind anomalies and (right) polar projection of 1000hPa geopotential height anomalies in January for a WQBO-EQBO composite difference (adapted from Anstey and Shepherd 2014).

Because the QBO has such a long time-scale and persistence, its evolution is expected to be predictable, thereby potentially useful for seasonal forecasting. The QBO is indeed the most promising source of seasonal prediction skill apart from ENSO (Smith et al.2012; Kidston et al. 2015; Butler et al. 2016); it is actually seen as a ‘glimmer of hope’ for seasonal forecasting (Hoskins 2013). However, the QBO has proved difficult to simulate accurately in climate models. Rather than a high model top (beyond the stratopause ~1hPa), a fine vertical resolution in the stratosphere is thought to be important in simulating the vertical propagation of waves and momentum deposition that drive the QBO. But this condition alone might not be enough. Models that are able to internally simulate QBO-like variability employ a non-orographic gravity wave (NGW) drag parameterization. It has been shown that modelled winds in the tropical lower stratosphere remain almost constant if NGWs are not included/parameterized (Scaife et al. 2000). And, it is recognized that parameterized NGWs contribute as much as the resolved waves to forcing the QBO (Giorgetta et al. 2006; Richter et al. 2014). Among the high-top models participating in CMIP5, only those with a large number of vertical levels and NGW drag parameterization (MPI-ESM-MR, CMCC-CC, HadGEM2-CC, MIROC-ESM) simulate QBO-like variability (Lott et al. 2014). In current seasonal forecast systems, only half of the properly stratosphere-resolving models, with a high lid and good vertical resolution, do spontaneously generate QBO-like variability (MetOffice-GloSea5, ECMWF-S4, MPI-ESM-MR); these models have NGW schemes (Butler et al. 2016). Thus, it is possible that a NGW parameterization is key to accurately simulating the QBO. Along this line of reasoning, Dunkerton (1997) showed that the contribution of NGWs is necessary to generate a QBO with realistic period and amplitude. Recent theoretical and modelling efforts have successfully tried to understand the mechanisms triggering NGWs relevant for QBO-like variability and to parameterize the connection to their sources, namely tropical convection (e.g. Lott and Guez 2013; Bushell et al. 2015). From its hierarchical approach, SIDIS will implement a source-based NGW drag parameterization in both intermediate-complexity and state-of-the-art atmospheric models in order to better, and more realistically, simulate wave/mean-flow interaction in the tropical stratosphere.

Despite the lack of tropical stratospheric variability (i.e. QBO-like) in most of the climate models/forecast systems, their skill at capturing the evolution of tropical winds once initialized is quite high, even in low-top models (Butler et al. 2016). The forecast systems maintain the state of the initialized tropical winds, which is dominated by the state of the QBO, due to slow relaxation rates in the tropical lower stratosphere (Haynes 1998). The QBO-related, initialized tropical winds persist throughout the forecast winter (Boer and Hamilton 2008; Marshall and Scaife 2009; Scaife et al. 2014b; Butler et al. 2016) before the winds converge towards model climatology; hence the QBO still represents a potential source of extratropical predictability even if models themselves do not internally generate QBO-like variability. The QBO-NAE teleconnection appears to be mediated by the influence of the QBO on the stratospheric polar vortex, thus on the NAO (Garfinkel et al. 2011a, 2011b). Yet, the simulation/prediction of this tropical-extratropical teleconnection remains a challenge for many climate models (Scaife et al. 2014b), both low-top and high-top (Butler et al. 2016). Interestingly, Marshall and Scaife (2009) showed that the low- (L38 up to ~3hPa) and high- (L60 up to ~0.004hPa) top versions of HadGEM1, with the same horizontal resolution and vertical levels in the troposphere, were able to reproduce the QBO impact on the polar vortex as well as on surface European climate; both versions having the same NGW drag parameterization. The dynamics through which the QBO affects the extratropical stratospheric circulation appears to be internal to the stratosphere, by means of modulating the upward propagation of tropospheric waves, mainly planetary Rossby waves (see Anstey and Shepherd 2014 for review). Observational (Randel et al. 1999) and modelling (Garfinkel et al. 2012) studies have shown that this QBO modulation translates into changes in the shallow and deep branches of the Brewer-Dobson (BD) circulation. On the other hand, the aspect of the extratropical circulation most sensitive to a source-based NGW drag parameterization is actually the BD circulation (de la Cámara et al. 2016). In this case, the sources of NGWs are mid-latitude fronts, jet instabilities and storm-tracks (Plougonven and Zhang 2014; de la Cámara and Lott 2015). Thus, it is conceivable that a better representation of the BD circulation thanks to a more realistic representation of the vertical distribution of the NGW drag could lead to improved simulation and prediction of the extratropical QBO signature. Complementary to the effect on the tropical stratosphere, SIDIS will assess for the first time the impact of implementing a source-based NGW parameterization on the representation and skill of the QBO-NAE teleconnection in seasonal hindcasts, both to the polar vortex and at surface.

The goal of this project is not only to improve predictions but also to improve understanding of the mechanisms providing predictability. Concerning the QBO-NAE teleconnection, it remains unclear which levels or vertical structure of the tropical QBO most strongly influence the winter polar vortex (Anstey and Shepherd 2014). SIDIS will tackle this question with a comprehensive set of sensitivity experiments. As introduced above, the most accepted explanation for the QBO influence is based on its modulation of upward-propagating planetary waves, which is called the Holton-Tan mechanism (Holton and Tan 1980). By modulating the latitudinal extent of the winter westerlies (waves cannot propagate through easterly winds), the QBO may guide planetary wave activity towards high latitudes or into the tropics; increased extratropical confinement of wave activity, corresponding to a poleward shift of the zero-wind line associated with the EQBO phase, is expected to weaken the vortex, while the opposite situation during the WQBO phase is expected to strengthen the vortex. However, the dynamics responsible for this coupling between low and high latitudes is still not well understood (see Anstey and Shepherd 2014 for review). In particular, it is not established yet whether the QBO-related wind anomalies in the tropical upper (e.g. Pascoe et al. 2006) or lower (e.g. Garfinkel et al. 2012) stratosphere are key for the Holton-Tan mechanism, thereby for the QBO-vortex relationship. SIDIS will investigate which tropical wind regime in the QBO vertical structure is more relevant for the QBO-NAE teleconnection by performing targeted atmosphere-only simulations.

It also remains unresolved how the QBO-vortex relationship interacts with the stratospheric effects of ENSO (e.g. Tripathi et al. 2015; Butler et al. 2016). Although there is no clear mechanism by which the phase of ENSO and the phase of the QBO would be linearly related (Anstey and Shepherd 2014), previous studies have been inconclusive due to the concurrence of El Niño (La Niña) events with EQBO (WQBO) winters. The interaction between ENSO and QBO is expected to be non-linear (e.g. Calvo et al. 2009), but the observational record is unfortunately too short to adequately separate the two influences. Complementary to both the atmosphere-only sensitivity experiments to ENSO-related SSTs and QBO-related tropical winds, SIDIS will analyse the ENSO/QBO-NAE teleconnections in long coupled runs, which contain a large number of ENSO and QBO cycles, and are able to provide statistically discriminant sampling and robustness to assess their potential link.

The suite of climate simulations and model improvements that will be carried out in SIDIS facing the accurate representation and skilful prediction of the QBO and its remote influence on the polar vortex and the Euro-Atlantic tropospheric circulation, in addition to be novel and timely, could certainly improve modelling the stratospheric dynamics involved, gain insight into the mechanisms at play, and help understanding the regional predictability forced by the tropical QBO.

MODEL SYSTEMATIC ERRORS

The impact of ENSO/QBO on the extratropical stratosphere is conceivably sensitive to the stratospheric representation of the model. SIDIS will assess the ENSO/QBO teleconnections in parallel upon two climate models from a hierarchical approach, with intermediate-complexity and state-of-the-art atmospheres, respectively, in order to obtain robust model-independent conclusions.

Prospects for seasonal forecasting are encouraging, since improved process understanding may translate into improved predictions. This exercise requires an appropriate assessment of the obtained skill for subsequent comparison with model improvements in terms of forecast quality. But ideally this assessment needs to be complemented with the identification of GCM biases, ultimately working towards their elimination. Limitations in forecasting planetary waves, which are precursors of stratospheric anomalies, and stratospheric model biases have been identified as hindering factors in this context (see Tripathi et al. 2015 for review). Likewise, the potential lack of wave-driven momentum convergence in the modelled extratropical stratosphere could explain the weak reproducibility of teleconnections from the tropics to NAO-like variability (Molteni et al. 2016), in agreement with the weak teleconnectivity from ENSO/QBO to the North Atlantic shown in current forecast systems (e.g. Butler et al. 2016). SIDIS will improve representation of both the stratosphere and the stratospheric processes relevant for the ENSO/QBO-NAE teleconnections. Firstly, the implementation of a source-based NGW parameterization aims at reducing biases in the stratosphere (e.g. de la Cámara and Lott 2015). Secondly, as both ENSO and the QBO influence the shallow and deep branches of the Brewer-Dobson (BD) circulation, the implementation of such an interactive NGW drag parameterization, with a significant impact on the annual cycle of the BD circulation (de la Cámara et al. 2016), provides a clue to improve simulation of the teleconnection dynamics. Thirdly, adding stratospheric levels in the intermediate-complexity atmospheric model presumably allows a better representation of wave processes and thus a better representation of the stratospheric circulation (Charlton-Perez et al. 2013), which markedly influences NAE atmospheric variability (e.g. Lott et al. 2005; Scaife et al. 2005, 2015; Douville 2009). Finally, it has been shown that a biased polar stratosphere leads to a biased North Atlantic eddy-driven jet (Shaw et al. 2014), so improving the former could help improving the latter.

This project offers a suitable scenario for improving the predictability of the winter surface climate in the North Atlantic-European region by means of better representing stratospheric circulation and variability as well as better understanding the dynamics involved in the ENSO/QBO extratropical teleconnections. The set of simulations and sensitivity experiments that will be conducted in SIDIS, being comprehensive and cutting-edge, will point out aspects that need to be considered in seasonal forecast systems to enhance their prediction skill and improve confidence in actual forecasts over the Euro-Atlantic sector.

Following the identification of all the issues above, a list of concrete objectives has been designed:

- To quantify the impact of the tropical and polar stratosphere on the NAE seasonal prediction skill.
- To improve process understanding of the stratospheric pathway in the ENSO/QBO-NAE teleconnections.
- To identify the most influential layer in the polar stratosphere (upper, middle, lower) in setting the timing of the NAE response to stratospheric vortex anomalies.
- To achieve a more realistic simulation of tropical (QBO) and extratropical (BD) stratospheric variability.
- To assess the role of resolving the polar stratosphere on model biases over the North Atlantic.
- To explore the link between model systematic errors and the success/lack of prediction skill over NAE.

Section b. Methodology

To achieve the objectives mentioned above, the following set of tasks has been considered. The project is divided into five work-packages (WPs): four for research (WP1-4) and one for management and dissemination (WP5). Further details follow below. The schedule of activities and the human resources required to successfully execute them are summarised in the following chronogram.

	yr1	**yr2**	**yr3**	**yr4**	**HHRR**
EC-EARTH	old NGW	GWs	exp. ENSO + QBO	hind.	PI
	new NGW	new NGW			Postdoc1
		perfect-model + realistic hindcasts			Postdoc3
SPEEDO	strato-SPEEDY + NGW	perfect-model + realistic hindcasts			Postdoc2
	obs / biases	exp. biases + hind.	exp. coupling		PhD

WP1 – *Model development* **WP2** – *Teleconnections*

WP3 – *Seasonal prediction* **WP4** – *Model biases*

WP1 – MODEL DEVELOPMENT

The efforts to be undertaken in SIDIS on model development are key for the success and scope of the project since there is a strong aim at improving representation and prediction of the stratospheric processes involved in the ENSO/QBO-NAE teleconnections. Thus, in addition to rely on the expertise of two experienced researchers (Postdoc 1,2), the project will count with the guidance and support of François Lott (LMD/IPSL, France) on the implementation of a source-based NGW drag parameterization and of Fred Kucharski (ICTP, Italy) on the implementation of stratospheric levels in the atmospheric component of SPEEDO, as well as with regular interaction with relevant senior scientists – Jost von Hardenberg (CNR, Italy) and Reindert J. Haarsma (KNMI, The Netherlands).

<u>Task 1.1 – New parameterization of non-orographic gravity waves in EC-EARTH</u>

Personnel: Postdoc1 [1 year, 50%] *Collaborators: F. Lott [guidance, discussion]*

J. García-Serrano [5%; advisor] *J. von Hardenberg [discussion]*

GW parameterizations control the mean-state and variability of the troposphere and stratosphere in current climate models; orographic GWs were first introduced to reduce biases in the upper troposphere and lower stratosphere, while NGWs have been incorporated afterwards to reduce large biases in the stratosphere and mesosphere (de la Cámara et al. 2016). Contrarily to orographic GWs, for which the source mechanisms are relatively well understood, the mechanisms exciting NGWs are less evident; for this reason, early parameterizations of NGWs have no relation with their sources (e.g. Lott et al. 2005). The current parameterization of NGWs in the last version of EC-EARTH (EC-EARTH3.2), which was implemented by J. von Hardenberg and tuned for the configuration T255L91 in the atmospheric component (IFS, Integrated Forecasting System) – approx. 80km horizontal resolution and top at 0.01hPa, follows a source-unrelated approach. In particular, the amplitude of the momentum flux associated with NGWs is zonally symmetric and prescribed as a function of latitude (green line in Fig. B2.IIIa). This parameterization is inspired by the one in the previous version of the model, EC-EARTH3.1, which has the same atmospheric component as in EC-EARTH3.2 and the ECMWF System4 (IFS cycle 36r4) (red line in Fig. B2.IIIa).

The absence of sources in NGW parameterizations limit their potential calibration with the growing number of in-situ and satellite observations, and is a cause of systematic errors (de la Cámara et al. 2016). A source-based parameterization, where the amplitude of NGWs depends on the resolved dynamics in the model (Fig. B2.IIIb), may additionally favour a framework for resolution-independent tuning. SIDIS will upgrade the NGW drag parameterization in EC-EARTH, to be implemented in version 3.2 and carried over to the coming versions, following the recent insights gained into the mechanisms generating NGWs. Particularly, SIDIS will implement in EC-EARTH (namely, in IFS) the source-related NGW drag parameterizations used in the atmospheric model LMDz. For convective waves, relevant for the tropical stratosphere, the Lott and Guez (2013) scheme translates grid-scale precipitation into subgrid-scale GW stress. For frontal waves (associated also with fluctuations in the jets), relevant for the extratropical stratosphere, the de la Cámara and Lott (2015) scheme translates grid-scale vorticity and stability conditions into subgrid-scale GW stress.

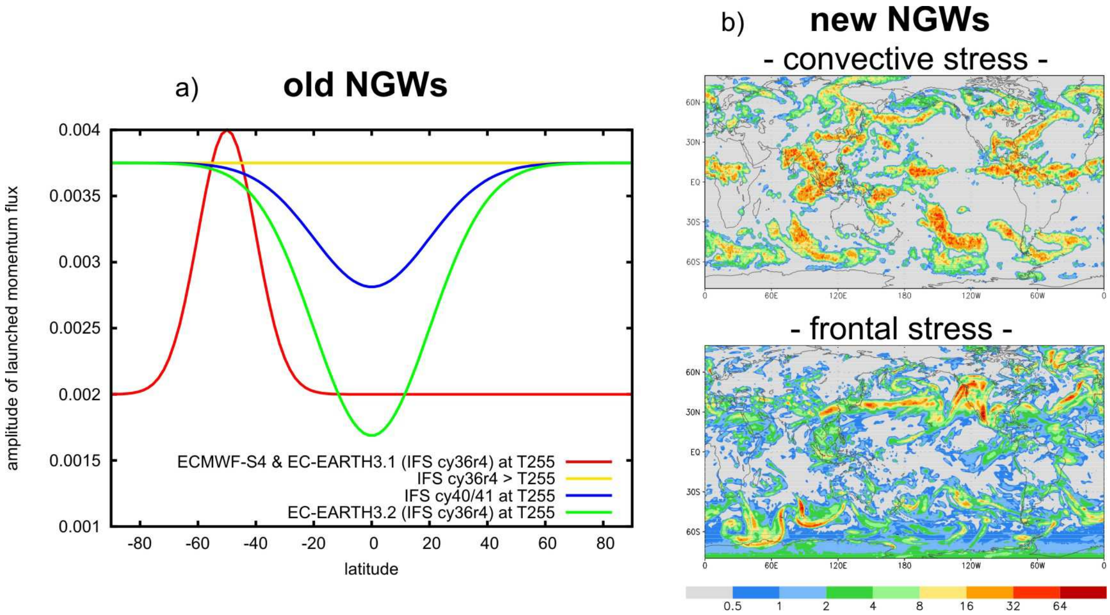

Figure B2.III: (a) Current parameterization of NGWs in EC-EARTH3, dependent on the model version and resolution (courtesy of J. von Hardenberg). (b) Examples of launched GW stress (mPa) for [top] convective waves (after Lott and Guez 2013; courtesy of A. de la Cámara) and [bottom] frontal waves (adapted from de la Cámara and Lott 2015).

Task 1.2 – Implementation of stratospheric levels and non-orographic gravity waves in SPEEDO

Personnel: Postdoc2 [1.5 years, 40%] *Collaborators: F. Kucharski [guidance, discussion]*

J. García-Serrano [7.5%; advisor] *F. Lott [guidance, discussion]*

R.J. Haarsma [discussion]

The atmospheric component of SPEEDO is the Simplified Parameterizations primitivE-Equation Dynamics (SPEEDY) model. It is an intermediate-complexity AGCM based on a spectral primitive equation core and a set of simplified parameterization schemes, which were especially designed to work in models with just a few vertical levels but are similar to those adopted in state-of-the-art AGCMs (Molteni 2003). The standard configuration of SPEEDY has a triangular spectral truncation at total wavenumber 30 (T30) – approx. 400km horizontal resolution. The KNMI version of SPEEDY has a vertical resolution of seven layers (L7), with the levels corresponding to 925, 850, 700, 500, 300, 200, and 100 hPa (e.g. Haarsma and Hazeleger 2007; García-Serrano and Haarsma 2016); while the ICTP version has a vertical resolution of eight layers (L8), adding the level of 30hPa to L7 (e.g. King et al. 2010; Kucharski et al. 2013; see blue levels in SPEEDO of Fig. B2.IV). The coupled model SPEEDO (SPEEDY-Ocean), was configured for the Atlantic basin using the Miami Isopycnic Coordinate Ocean Model (MICOM) version 2.7 (e.g. Hazeleger and Haarsma 2005), but currently can be configured globally by coupling SPEEDY to the Nucleus for European Modelling of the Ocean (NEMO) model version 3.0, using the OASIS3 coupler, with the tripolar set-up ORCA2 – 2º nominal horizontal resolution and a tropical refinement to 0.5º (Kucharski et al. 2015). In the following, SPEEDO refers to SPEEDY-NEMO/ORCA2.

The goal of SPEEDY is to achieve computational efficiency while maintaining characteristics similar to state-of-the-art AGCMs with complex physics. SPEEDY can be used even with limited computational resources (it can be run on any conventional multi-core workstation), making it a very relevant tool for researchers in developing countries (i.e. ICTP's mission) and for graduate students, who gain better scientific and software insights allowed by a simple model than might be possible with state-of-the-art models (like EC-EARTH/IFS). The objective of SIDIS is to develop a comprehensive and sustainable improvement by providing SPEEDY with a proper stratosphere; the outcome will be named strato-SPEEDY, which will supply an intermediate-complexity climate model, strato-SPEEDO, resolving the atmosphere up to the stratopause (1hPa) and coupled to a global ocean model (NEMO/ORCA2). Strato-SPEEDY will double the layers in SPEEDY (L8), to eventually have 17 (L17; see green levels in Fig. B2.IV), with an increased vertical resolution around the tropopause and in the lower stratosphere [adding the levels of 150, 70, and 50 hPa], which allows a better representation of wave processes and thus a better representation of the troposphere-stratosphere interaction, and having six additional layers above the current top in SPEEDY (30hPa) – 20, 10, 5, 3, 2, and 1 hPa. The implementation of strato-SPEEDY will rely on the parameterization following Polvani and Kushner (2002) plus a radiative forcing mimicking the shortwave radiation flux prescribed as a zonally-symmetric, seasonally-varying profile of ozone concentration, as in the current stratospheric layers of SPEEDY (100 and 30 hPa; King et al. 2010); the new levels will be hard-coded individually and strongly tied to the adjusted parameterizations, with a damping scheme in the upper-most level that allows absorption of waves and prevents spurious reflection, as in the current version of SPEEDY.

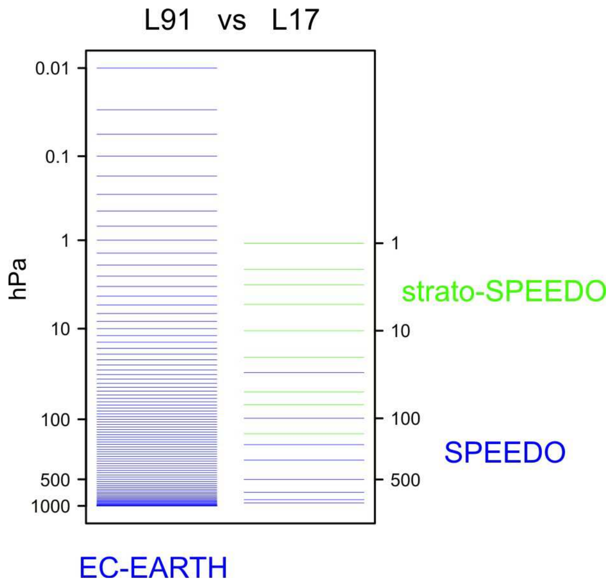

Figure B2.IV: Illustration of the vertical levels in the atmospheric component of EC-EARTH (IFS with L91; left) and SPEEDO (SPEEDY with L8; right, blue) together with the improvement for strato-SPEEDO (L17; right, blue+green).

SPEEDY includes basic components of physical parameterizations used in more complex AGCMs, such as convection, large-scale condensation, clouds, surface fluxes of momentum and energy, and vertical diffusion. SPEEDY has a drag parameterization for orographic GWs but not for NGWs. SIDIS will implement the same NGW parameterization as in EC-EARTH/IFS (Task 1.1) but upon strato-SPEEDY, with the aim of improving representation and minimizing biases in circulation and variability of both the tropical and extratropical stratosphere. Likewise, SIDIS will tackle the challenge of tuning the parameterized NGW drag to try to obtain spontaneously-generated QBO-like variability in strato-SPEEDY, being aware that simulating QBO-like variability in such an intermediate-complexity model would be a major success.

WP2 – TELECONNECTIONS

Process understanding is a crucial aspect of SIDIS, since it aims at improving simulation and prediction of the ENSO/QBO-NAE teleconnections not only by better representing the stratospheric processes involved (WP1's objective) but also by gaining insight into the dynamical mechanisms that underlay these elements and their interaction. The execution of this WP will benefit from the interaction with senior scientists with a large experience in teleconnection dynamics, whom the PI already collaborates with: Ileana Bladé (UB, Spain), Hervé Douville (CNRM/Météo-France, France), R.J. Haarsma (KNMI, The Netherlands), and Fred Kucharski (ICTP, Italy); note that additionally, I. Bladé will co-advise the PhD student.

<u>Task 2.1 – ENSO/QBO-NAE teleconnections in EC-EARTH, old vs new NGWs</u>

Personnel: Postdoc1 [1 year, 50%] *Collaborators: H. Douville [discussion]*

PhD student [6 months, 12.5%] *I. Bladé [discussion; co-advisor]*

J. García-Serrano [1 year, 15%; advisor]

Two long control runs of 200 years minimum (after spin-up) with EC-EARTH3.2 will be performed using fixed present-day climate conditions (radiative forcing) observed during the year 2000, with both the current (‘old NGW’; Fig. B2.IIIa) and the source-based (‘new NGW’; Task 1.1) parameterization of NGWs. The comparison of both simulations in terms of teleconnection dynamics will allow estimating the impact of the NGW drag parameterization on the ENSO/QBO teleconnections to the polar vortex and NAE surface circulation. It will also set a benchmark of the modelled variability and timing of the dominant processes involved in the ENSO/QBO teleconnections for the atmosphere-only (Task 2.2) and seasonal hindcast (Task 3.1) experiments. A set of diagnostics will be applied to characterize the model performance, and will be compared to two reanalysis products (in turn, to estimate observational uncertainty): ECMWF ERA-Interim (Dee et al. 2011), and NASA MERRA (Rienecker et al. 2011). The diagnostics to be applied include, but are not limited to, monthly regression analysis onto the winter (DJF) Niño3.4 index [ENSO] and January U_{EQ} at 50hPa [QBO] of (i) vertical cross-sections of zonal-mean zonal wind and temperature; (ii) geopotential height at 1000hPa (surface), 300hPa (upper troposphere), 50hPa (lower stratosphere) and 10hPa (middle stratosphere); (iii) Eliassen-Palm flux computed from daily data (e.g. Vallis 2006); (iv) residual meridional circulation in the Transformed Eulerian Mean formalism computed from daily data (e.g. Abalos et al. 2014).

Note that 200 years of simulation include approximately 80 complete QBO cycles, which allow assessing the potential link between ENSO, the QBO, and their teleconnections. Correlation and composite analyses will be used to address this issue, which is not feasible using observations due to the shortness of the record. Depending on results, these control simulations may be extended to 500 years to testing robustness.

<u>Task 2.2 – Sensitivity experiments of ENSO/QBO-NAE teleconnections with EC-EARTH</u>

Personnel: J. García-Serrano [2 years, 30%] *Collaborators: R.J. Haarsma [discussion]*

I. Bladé [discussion]

Four short transient runs of 3 months (JFM) with the atmospheric component of EC-EARTH3.2 (IFS) will be performed to identify the key mechanisms involved in the ENSO-NAE teleconnection. The experimental protocol will be similar to the one used in García-Serrano and Haarsma (2016), namely control (‘CTL_sst’) and perturbed transient runs, all consisting of a 200-member ensemble of integrations. The different initial conditions for January 1st are taken from each year of the long control run in Task 2.1, so that the starting conditions are different for each ensemble member but remain within the intrinsic variability of the model. The ‘CTL_sst’ runs use SST climatology as boundary condition. In the perturbed runs, a SST anomaly will be prescribed in the tropical Pacific with climatology elsewhere. To partially separate results from the model framework, and for ease of comparison, observational SSTs (ERSST; Smith et al. 2008) will be used to define the anomalous forcing fields, which correspond to the regression of ERSST January-February anomalies onto the Niño3.4 index in DJF; this will set El Niño runs – multiplying the regression by -1 will set the forcing field for La Niña runs (Fig. B2.II-top). El Niño and La Niña experiments are carried out to assess potential non-linearities in the atmospheric response; this pair of experiments are collectively called ‘ENSO’ runs. The amplitude of the SST regression map is amplified to reach a maximum of 2.5ºC at the equator, similar to previous studies (e.g. Taguchi and Hartmann 2006), in order to compensate for the damping in surface heat fluxes that results from considering the ocean as an infinite reservoir of heat capacity. The other two pair of transient runs are similar to ‘ENSO’ but nudging the tropical (‘ENSO-noTROP’) or the polar (‘ENSO-noPOL’) stratosphere to the model climatology from the long control run in Task 2.1. These experiments are constrained by relaxing the zonal-mean spectral component of the temperature, vorticity, and divergence fields to the corresponding climatology from 50hPa (in ‘ENSO-noTROP’) or 10hPa (in ‘ENSO-noPOL’) upwards, thus supressing stratospheric variability in the target region, associated with tropical upwelling and polar downwelling/polar vortex, respectively. The same diagnostics as in Task 2.1 will be applied to these simulations.

Three transient runs of 5 months (NDJFM) with the atmospheric component of EC-EARTH3.2 (IFS) will be performed to analyse which tropical wind regime in the QBO vertical structure is key for the QBO-NAE teleconnection, a scientific question that is still unresolved (Anstey and Shepherd 2014), and to assess the timing of the extratropical response along the seasonal cycle. In this case, the three 200-member ensemble integrations use SST climatology as boundary condition, but differ in the atmospheric conditions – all starting each ensemble member on November 1st from each year of the long control run in Task 2.1. The control runs ('CTL_atm') employ actual initial conditions in the whole depth of the atmosphere. The perturbed runs are constrained by nudging the tropical lower stratosphere (30hPa-100hPa; 'QBO_lower') or the full tropical stratosphere (3hPa-100hPa; 'QBO_full') to the EQBO and WQBO composites in Task 2.1 during the complete integration, on top of the initial conditions in the tropical troposphere and extratropical atmosphere. The nudging in the tropical stratosphere is restricted to 30ºS-30ºN. EQBO and WQBO experiments are carried out to assess potential non-linearities in the atmospheric response. The same diagnostics as in Task 2.1 will be applied to these simulations.

Task 2.3 – Sensitivity experiments of polar vortex-NAE coupling with strato-SPEEDO

Personnel: PhD student [1.5 years, 37.5%] *Collaborators: I. Bladé [discussion; co-advisor]*

J. García-Serrano [5%; advisor] *F. Kucharski [discussion]*

A comprehensive set of moderate (5K) and strong (10K) stratospheric temperature perturbation experiments will be performed with stratro-SPEEDY to assess the timing of the tropospheric-surface response to circulation changes associated with a warming/cooling of the polar stratosphere – typically in the range of the ENSO/QBO-induced perturbations (e.g. Bell et al. 2009/Garfinkel and Hartmann 2011a). The aim is to evaluate the hypothesis of Hitchcock and Simpson (2014) that the most relevant aspect is not the wind reversal in the middle stratosphere but the anomalies in the lower stratosphere, immediately above the tropopause. As in Task 2.2, transient runs will be considered because (i) the transient response allows investigating the causality more cleanly, and (ii) the response in observations will probably never reach equilibrium, implying that the transient response is more relevant to interpret the observed anomalies. 200-member ensembles of 60-day integrations starting on January 1st will be carried out with both signs (warming, cooling) of the heating perturbations in order to assess potential non-linearities in the atmospheric response. The atmospheric initial conditions will be obtained from a 200-year integration with strato-SPEEDO (after spin-up) with fixed radiative forcing at year 2000. The control and perturbed transient runs will use SST climatology as boundary condition. The heating perturbation will be prescribed at the stratopause (1hPa), upper stratosphere (5hPa), middle stratosphere (10hPa), and lower stratosphere (50hPa). The perturbation will be uniform over 60ºN-90ºN. The same diagnostics as in Task 2.1 will be applied to these simulations. Depending on results, both the control simulation and the ensemble size of the sensitivity experiments may be extended to 500 years/members (or even 1000 due to the computational efficiency of strato-SPEEDO/Y) to testing robustness.

WP3 – SEASONAL PREDICTION

Incorporating a well-resolved stratosphere into seasonal forecast systems and representing relevant stratospheric processes in their teleconnections are promising ways to enhance prediction skill (e.g. Folland et al. 2012; Smith et al. 2012; Kidston et al. 2015). In this WP, SIDIS will assess the impact of simulating stratospheric variability and stratospheric pathways on the forecast quality of a set of targeted seasonal hindcasts performed with EC-EARTH3.2 and strato-SPEEDO. The Climate Prediction group at BSC, the host of the PI, is positioned at the cutting-edge of climate forecasting research, developing forecasting capabilities for time-scales ranging from a few weeks (e.g. Prodhomme et al. 2016) to a few decades (e.g. Du et al. 2012) into the future. It routinely performs seasonal hindcasts and forecasts (e.g. Guemas et al. 2016). This ensures the successful completion of the tasks undertaken in WP3. Note that F.J. Doblas-Reyes (BSC, Spain) will co-advise the postdoctoral researchers in WP3.

In particular, SIDIS aims at addressing the contribution of the tropical stratosphere, the polar stratosphere, and the ENSO/QBO extratropical teleconnections to the prediction skill of the winter NAE surface circulation and climate. The exercise follows a hierarchical approach, performing simultaneously the same suite of idealized seasonal hindcasts with the state-of-the-art EC-EARTH and the intermediate-complexity strato-SPEEDO models. The objective is twofold, namely identifying the key sources of predictability and understanding the dynamics responsible for that predictability.

Two kind of hindcasts will be considered: (i) *realistic hindcasts*, using ECMWF ERA-Interim for atmospheric conditions and ORA-S4 (Balmaseda et al. 2013) for oceanic conditions to initialize the forecast systems on the standard start-date for winter forecasts – each November 1st – over the period 1979-2016 (38 years); and (ii) *perfect-model hindcasts*, where the potential effect of the drift on the simulated dynamics is absent as the model remains on its own attractor, although at the expense of estimating not actual skill but model predictability. As predictability changes with mean climate (e.g. DelSole et al. 2014), the perfect-model hindcasts are conducted with radiative forcing fixed at present-day conditions. 40 start dates, spacing five years, will be selected from the 200-year control runs (Task 2.1 for EC-EARTH; Task 2.3 for strato-SPEEDO). For each start date an ensemble of 30 members will be generated with singular vector perturbations (Buizza and Palmer 1994).

In each kind, a suite of four 5-month long (NDJF) hindcast experiments will be performed: (i) a control hindcast ('CTL') with the full ocean-atmosphere model, including the new source-based NGW parameterization (WP1); (ii) a deteriorated-model hindcast ('OLD-NGW' in EC-EARTH, 'NO-NGW' in strato-SPEEDO) with the previous/absent NGW parameterization, respectively; (iii) a hindcast similar to 'CTL' but nudging the tropical stratosphere to model climatology as in Task 2.2 ('noTROP'), thus supressing tropical stratospheric variability (i.e. the QBO); and (iv) a hindcast similar to 'CTL' but nudging the polar stratosphere to model climatology as in Task 2.2 ('noPOL'), thereby supressing variability associated with the polar vortex. In addition to the diagnostics described in Task 2.1, deterministic and probabilistic skill scores will be used.

Task 3.1 – Seasonal hindcasts with EC-EARTH

Personnel: Postdoc3 [3 years, 100%]
J. García-Serrano [7.5%; advisor]

Collaborators: F.J. Doblas-Reyes [guidance; co-advisor]
R.J. Haarsma [discussion]
H. Douville [discussion]

Task 3.2 – Seasonal hindcasts with strato-SPEEDO

Personnel: Postdoc2 [2.5 years, 60%]
J. García-Serrano [6.5%; advisor]

Collaborators: F.J. Doblas-Reyes [guidance; co-advisor]
R.J. Haarsma [discussion]
H. Douville [discussion]

WP4 – MODEL BIASES

To better understand the performance of the two forecast systems, i.e. relative merits and deficiencies, their systematic errors in the course of the forecast time will be identified. Likewise, the link between these model systematic errors and the success/lack of prediction skill over the NAE region will be explored. The purpose is to lay the foundation for reducing bias-related uncertainties and improving the simulation and prediction of the NAE surface climate and ENSO/QBO teleconnections in future seasonal hindcast/forecast experiments.

Task 4.1 – Impact of NGW parameterization on model biases

Personnel: J. García-Serrano [6 months, 7.5%]

Collaborators: F. Lott [discussion]
J. von Hardenberg [discussion]

The comparison of the two long control runs 'old NGW' and 'new NGW' from Task 2.1, in terms of mean climate, will allow assessing the impact of the NGW drag parameterization on the EC-EARTH3.2 biases. In particular, SIDIS will evaluate (i) strength, position, and variability of the stratospheric jet and North Atlantic tropospheric jet; (ii) standard deviation and leading variability modes of geopotential height north of 20ºN, using Principal Component Analysis, at 1000hPa (surface), 300hPa (upper troposphere), 50hPa (lower stratosphere) and 10hPa (middle stratosphere); (iii) amplitude and phase of the climatological planetary waves; (iv) zonal-eddy heat flux at 100hPa; and (v) the Brewer-Dobson circulation.

Task 4.2 – Impact of resolving the stratosphere on model biases

Personnel: J. García-Serrano [6 months, 7.5%] Collaborators: F.J. Doblas-Reyes [discussion]

J. von Hardenberg [discussion]

The comparison of the realistic and perfect-model hindcasts 'CTL', 'noTROP' and 'noPOL' from Task 3.1, in terms of mean climate, will allow assessing the impact of resolving the tropical and polar stratosphere on the EC-EARTH3.2 biases. The same metrics as in Task 4.1 will be applied.

Task 4.3 – Impact of resolving the polar stratosphere on model biases with sensitivity experiments

Personnel: PhD student [2 years, 50%] Collaborators: I. Bladé [discussion; co-advisor]

J. García-Serrano [5%; advisor] F.J. Doblas-Reyes [discussion]

A similar approach to Task 4.2 will be followed for strato-SPEEDO, but only the 'CTL' and 'noPOL' perfect-model hindcasts (from Task 3.2) will be analysed to remain in the model framework and avoid drift effects, for ease of comparison with the sensitivity experiments.

SPEEDO underestimates the amplitude of the NAO-related centre of action at high latitudes, as compared to observations and EC-EARTH (Fig. B2.I), as well as fails to reproduce the amplitude and orientation of the North Atlantic jet, likely linked to the fact that SPEEDY does not have a proper, active stratosphere (García-Serrano and Haarsma 2016). Following the identification of the main biases in SPEEDY and strato-SPEEDY, applying most of the metrics in Task 4.1 to two separate 200-year integrations with climatological SSTs, a set of sensitivity experiments will be performed to further assess the impact of resolving the polar stratosphere on model biases over the NAE region. Three additional 200-year integrations of strato-SPEEDY with climatological SSTs but nudging the polar stratosphere to model climatology from 5hPa (upper stratosphere), 10hPa (middle stratosphere; to be consistent with 'noPOL'), and 50hPa (lower stratosphere) upwards will be carried out. The same metrics as in Task 4.1 will be applied. Depending on results, these sensitivity experiments may be extended to 500 years (or even 1000 years due to the computational efficiency of strato-SPEEDOY) to testing robustness.

WP5 – PROJECT MANAGEMENT AND DISSEMINATION

Personnel: J. García-Serrano [4 years, 3.5%]

This work-package will ensure the appropriate implementation of the project and widely disseminate the outputs throughout its duration. It is feasible thanks to the strong administrative support at BSC (i.e. Project Management Office, Transfer and Communication Office, and Outreach Group). WP5 will monitor the progress of the project, ensure timely preparation of scientific reports, facilitate communication among the collaborators' institutions (BSC, CNR, CNRM/Météo-France, ICTP, KNMI, LMD/IPSL, UB), and organize the project meetings. The latter consist of three meetings to ensure that action items are under way, and will be hosted by BSC [project month 13, 30, 46]; note that there is no kick-off meeting. These project meetings are not intended to be internal symposia but open conferences, in which researchers not directly involved in SIDIS, e.g. from other groups in Spain (N. Calvo - UCM) or Europe (N. Keenlyside - UiB/BCCR, F. Molteni / T. Stockdale - ECMWF, S. Osprey - U.Oxford), will be invited. In addition to the official collaborators described above, SIDIS will be supported by an External Expert Board (EEB), which comprises two internationally recognised experts in the field of stratosphere-troposphere dynamics and predictability: Elisa Manzini (MPI-M, Germany) and Adam A. Scaife (MetOffice, UK), who will provide their expert opinion and feedback during the project development. The EEB will be invited to the project meetings and regularly updated by the PI via teleconferences and electronic communication. The results of SIDIS will be publicized at the meetings of the projects DynVar and QBOi of SPARC (Stratosphere-troposphere Processes And their Role in Climate) where the EEB members are strongly involved. WP5 will prepare a 6-month report with major advances for the ECMWF, with which BSC/EC-EARTH shares the atmospheric model (i.e. IFS); and deliver a yearly brochure summarising results and achievements for research centres producing operational seasonal forecasts (e.g. those contributing to NMME and EUROSIP). Under WP5, the project will also undertake a final report that, in addition to summarizing the scientific goals, will identify priority research lines to enhance skill of the NAE climate by advancing the impact of model improvements on prediction and their potential to reduce uncertainties in seasonal forecasting.

Section c. Resources (including project costs)

Personnel: Salary for the PI (48 months – 249.050€); Experienced researcher starting in year 1 / Postdoc1 – Tasks 1.1, 2,1 (24 months – 120.000€); Experienced researcher starting in year 1 / Postdoc2 – Tasks 1.2, 3.2 (48 months – 240.000€); Young researcher starting in year 2 / Postdoc3 – Task 3.1 (36 months – 135.000€); PhD student – Tasks 2.1, 2.3, 4.3 (48 months – 104.000€).

Equipment: BSC has hosted outstanding high performance computing (HPC) facilities since its inception in 2006; and all the computational resources will be available for SIDIS [i.e. MareNostrum III, 48896 cores / 1017TFlops, where all simulations will be performed]. However, additional equipment is required for a successful implementation of the work plan. Due to the unusually large number of seasonal hindcasts and sensitivity experiments that will be performed and the output frequency (daily), a particular infrastructure will be needed for post-processing and storage: 1 large-memory FatNode [IntelXeon E5-2600v3, 6 core 1.6GHz / 16x32GB] 8.334€ + 30 HPC disks of storage x 3TB [disk cabinet, IBM 7200rpm / 6Gbps] 7.830€. Four workstations (for Postdoc1-2-3, PhD) will be needed to work in autonomy [Dell OptiPlex 9020 / i7-4790 3.6GHz / RAM 8GB] 4.402€.

Travels – SIDIS personnel: 4 European Geosciences Union, annual assembly [4x410€ registration, 4x140€ return ticket, 4x375€ accommodation] 3.700€; 2 American Geophysical Union, fall meeting [2x410€ registration, 2x850€ return ticket, 2x670€ accommodation] 3.860€; 4 SPARC workshops [4x300€ return ticket, 4x360€ accommodation] 2.640€; 4 European project meetings [similar budget as before] 2.640€.

Publications: It is intended to produce a minimum of 7 articles in major journals (e.g. 3 Journal of Climate, 3x2.700=8.100€; 2 Climate Dynamics, 2x2.200=4.400€; 2 Geophysical Research Letters, 2x1.800=3.600€) plus 1 high-impact publication (e.g. Nature Comms. 3.700€); all in open-access.

Other – Hosting: Three 1-month visits at BSC – F. Kucharski (Task 1.2, project month 2/strato-SPEEDO and 10/NGWs) and F. Lott (Task 1.1, project month 3/NGWs in EC-EARTH) [3x300€ return ticket, 3x1.710€ BSC Residence, 3x43€ local transport] 6.159€.

Other – SIDIS meetings: (see WP5) Three meetings with 7 people from abroad – 3 SIDIS collaborators + 2 EEB members + 2 invited researchers [3x7x395€ (including flight, Residence, transport, catering)] 8.295€.

Other – CFC: Costs for mandatory audit certificates [Certified Financial Consultant] 1.546€.

Cost Category			**Total in Euro**
Direct Costs	**Personnel**	PI	249.050€
		Senior Staff	0€
		Experienced Postdocs	360.000€
		Young Postdoc	135.000€
		PhD Student	104.000€
	i. Total Direct Costs for Personnel (in Euro)		848.050€
	Travel		12.840€
	Equipment		20.566€
	Other goods and services	Consumables	0€
		Publications (including Open Access fees)	19.800€
		Other (Hosting + SIDIS meetings + CFC)	16.000€
	ii. Total Other Direct Costs (in Euro)		69.206€
A – Total Direct Costs (i + ii) (in Euro)			917.256€
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)			229.314€
C1 – Subcontracting Costs (no overheads) (in Euro)			0€
C2 – Other Direct Costs with no overheads (in Euro)			0€
Total Estimated Eligible Costs (A + B + C) (in Euro)			1,146.570€
Total Requested EU Contribution (in Euro)			1,146.570€

Please indicate the duration of the project in months:	**48**
Please indicate the % of working time the PI dedicates to the project over the period of the grant:	**85%**

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