REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation:	Spain
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Project Title:	Perturbed parameter ensembles of gravity waves in subseasonal prediction of Sudden Stratospheric Warmings using OpenIFS 48r1.1

To make changes to an existing project please submit an amended version of the original form

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** …………..	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES ☐**X**	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	3,000,000	4,000,000	3,000,000
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	10,000	25,000	35,000

EWC resources required for project year:		**2027**	**2028**	**2029**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

Scientific motivation

The Northern Hemisphere stratospheric polar vortex (SPV) is a major source of subseasonal-to-seasonal (S2S) predictability during boreal winter due to its influence on extratropical circulation and surface weather extremes. Variations in the strength and structure of the SPV, including the major disruptions called sudden stratospheric warmings (SSWs), modulate the atmospheric circulation over the North Atlantic and Eurasian region, affecting cold-air outbreaks, storm tracks and precipitation patterns over Europe. Despite substantial progress in operational forecasting systems such as the Integrated Forecasting System (IFS), important uncertainties remain regarding the predictability of SPV variability and specially the representation of stratosphere-troposphere coupling processes and wave-mean flow interactions in numerical models.

The dynamical and thermal structure of the middle atmosphere is shaped by waves, which transport momentum upward from their tropospheric sources and deposit it in the stratosphere and mesosphere when breaking. Wave momentum deposition acts as a primary driver for the wintertime branch of the Brewer-Dobson circulation (Haynes et al., 1991) and regulates the strength of the SPV (Cullens and Thurairajah, 2021). Large-scale planetary waves are explicitly resolved by climate models, but both orographic and non-orographic gravity waves (GWs) can occur at spatial scales below standard grid resolutions and must be parametrised. Orographic GWs (OGWs) are generated by stably stratified flows over subgrid-scale topography, exerting drag on the atmosphere through a combination of low-level flow blocking (blocked-flow drag) and the absorption of vertically propagating GWs (GW drag). The OGW parametrisation in IFS is described in detail in Lott and Miller (1997). Non-Orographic GWs (NOGWs) are triggered by transient tropospheric sources such as convection, frontogenesis and jet stream instability (Fritts and Nastrom, 1980). Their vertical wavelengths vary from less than one to tens of kilometres and horizontal wavelengths vary from tens to hundreds of kilometres (Ern et al., 2004). Because their spatial scales are too small to be explicitly resolved in climate models, their simulation relies on parametrisation schemes (Orr et al. 2020).

Given that GW drag (GWD) controls the preconditioning of the SPV and supplies part of the necessary torque to break the SPV during SSWs (Cullens and Thurairajah, 2021; Zhang et al., 2025), the tuning parameters within these schemes represent a source of uncertainty in S2S forecasts. This project uses the OpenIFS model to systematically perturb key parameters governing the magnitude, launch pressure level and spatial distribution of both OGW and NOGW fluxes. By analyzing these sensitivity experiments, we aim to isolate how subgrid-scale gravity wave uncertainties propagate into the middle atmosphere and affect the predictability of SSWs.

Objectives

The main goal of this project is to assess the sensitivity of subseasonal SSW predictability to the inherent uncertainties in the parametrisations of OGWs and NOGWs. To achieve this goal, the project is structured around the following specific objectives:

1) Evaluate the sensitivity to Orographic Gravity Wave Drag (OGWD): We will quantify the role of subgrid OGWs by scaling the initial surface momentum flux using the model's tuning parameters.
2) Evaluate the sensitivity to Non-Orographic Gravity Wave Drag (NOGWD): We will systematically vary the baseline momentum flux, the launch pressure level and the latitudinal Gaussian distribution width of the NOGW spectrum.
3) Evaluate the sensitivity to NOGWD coupled to total precipitation: We will contrast the standard, Gaussian latitudinal distribution of NOGWs against a configuration where the launched momentum flux is weighted by the simulated grid-point total precipitation.

Proposed numerical experiments

We will execute a suite of numerical simulations using OpenIFS 48r1.1 at a standard climate resolution of T255L91. The common experimental setup is summarised in Table 1. We have selected three historical SSW events characterised by distinct morphological and predictability features:

1) January 2009: A major and highly abrupt vortex splitting event with very strong zonal wind deceleration ~10 days before the onset date (Harada et al., 2010; Taguchi, 2018). Previous studies suggest that GWs contributed significantly in the wave forcing during the prewarming of the SSW (Limpasuvan et al., 2011; Albers and Birner, 2014).
2) February 2018: A prolonged vortex split with preceding record-breaking extratropical wave activity, and long-lasting surface impacts over Eurasia (Karpechko et al., 2018; Ayarzagüena et al., 2018).
3) December 2001: A major vortex displacement event, predictable from at least 2 weeks in advance, but with high sensitivity to the initial conditions during the onset period (Mukouwaga et al., 2005).

For each historical event, we will first conduct an initialization sensitivity phase. This preliminary step consists of executing 10-member ensemble simulations with the default parameter values (corresponding to the control experiments described below) initialised at four different dates prior to the warming event (e.g. D-5, D-10, D-15 and D-20). This phase specifically targets the time when the forecast skill begins to degrade. The initialization date that best captures the onset of this predictability barrier will then be used as a reference to initialize the subsequent perturbed parameter simulations for that specific event.

Consequently, for each historical event and target parameter, a Perturbed Parameter Ensemble (PPE) will be generated with four initialization dates around the one previously selected. Each individual experiment will comprise a 10-member ensemble integrated for 60 days with a time step of 15 minutes (900 seconds; Table 1). This simulation length is chosen to capture the vortex preconditioning phase, the stratospheric warming onset and the subsequent downward propagation of anomalies into the troposphere.

Table 1. Experimental setup of the proposed simulations for each perturbed parameter.

Model version	OpenIFS 48r1.1
Resolution	T255L91
Time step	900 seconds = 15 minutes
Forecast length	60 days
Ensemble size (model uncertainties)	10 members
Output frequency	6-hourly

Because OpenIFS does not support perturbations in the initial conditions, members within each ensemble will share identical initial atmospheric conditions. Instead, uncertainties in subgrid-scale physical processes will be represented through the OpenIFS stochastic parametrisation schemes: the Stochastically Perturbed Parametrisation Tendency scheme (SPPT, Palmer et al., 2009; Buizza et al., 1999) and the Stochastic Kinetic Energy Backscatter scheme (SKEB, Berner et al., 2009; Shutts, 2005). SPPT represents the uncertainty from the subgrid-scale parametrisations by stochastically perturbing the net tendency from those schemes, whereas SKEB simulates the unresolved upscale transfer of energy from subgrid to the resolved scales.

Control experiments (Ctrl)

For each event, a control experiment (Ctrl) will be executed using all the default parameter values. This configuration will be used in the initialization sensitivity phase and will serve as the benchmark against which the perturbation experiments described below will be systematically evaluated. The default parameter values used in the Ctrl experiment are shown in Table 2.

Table 2. Default values of the perturbed parameters used in **Ctrl**.

GKDRAG	GFLUXLAUN	ZLAUNCHP	NGAUSS	GGAUSSA	GGAUSSB	GCOEFF
0.15	3.75 mPa	450 hPa	2	20°	-0.25	2,000

Set A: Orographic Gravity Wave Drag

In this set of experiments, we will evaluate the model's sensitivity to the magnitude of the subgrid mountain-induced wave forcing that propagates upward into the middle atmosphere. We will perturb the tuning constant **GKDRAG**, which directly scales the vertical profile of the subgrid-scale OGWD:

- Experiment A1 (**Low stratospheric drag**): GKDRAG reduced by 20% (0.12).
- Experiment A2 (**High stratospheric drag**): GKDRAG increased by 20% (0.18).

The logical switch **LDIAG_STRATO** will be activated across all simulations to output stratospheric wave fluxes, allowing a direct physical evaluation of the torque variations of the SPV due to OGWs. The low-level mountain blocking parameter (**GKWAKE**) will be kept at its default value (3.0).

Set B: Non-Orographic Gravity Wave Drag

This set of experiments targets the standard Gaussian distribution of the NOGW parametrisation (configured via **NGAUSS = 2**, the default value). We will systematically perturb three different geometric and energetic properties of the launched wave momentum flux (Figure 1a):

1. Extratropical launch momentum flux (**GFLUXLAUN**; default value 3.75 mPa):
    - Perturbations: ±20 % (3.0 mPa and 4.5 mPa; blue and red lines in Figure 1a, respectively).
    - Justification: Altering the baseline momentum flux injected into the midlatitude troposphere at **ZLAUNCHP** directly affects the wave forcing available to decelerate the SPV.
2. Launch pressure level (**ZLAUNCHP**; default value = 450 hPa):
    - Perturbations: 200 hPa (upper troposphere) and 700 hPa (lower troposphere).
    - Justification: Shifting the launch pressure level modifies the background winds and the wave filtering experience by the wave spectrum immediately after generation.
3. Gaussian distribution half-width (**GGAUSSA**; default value 20°):

- Perturbations: 10° (narrower tropical region; red line in Figure 1b) and 30° (wider tropical region; blue line in Figure 1b).
- Justification: Changing the half-width of the Gaussian distribution modifies the latitudinal blending between tropical and extratropical wave regimes.

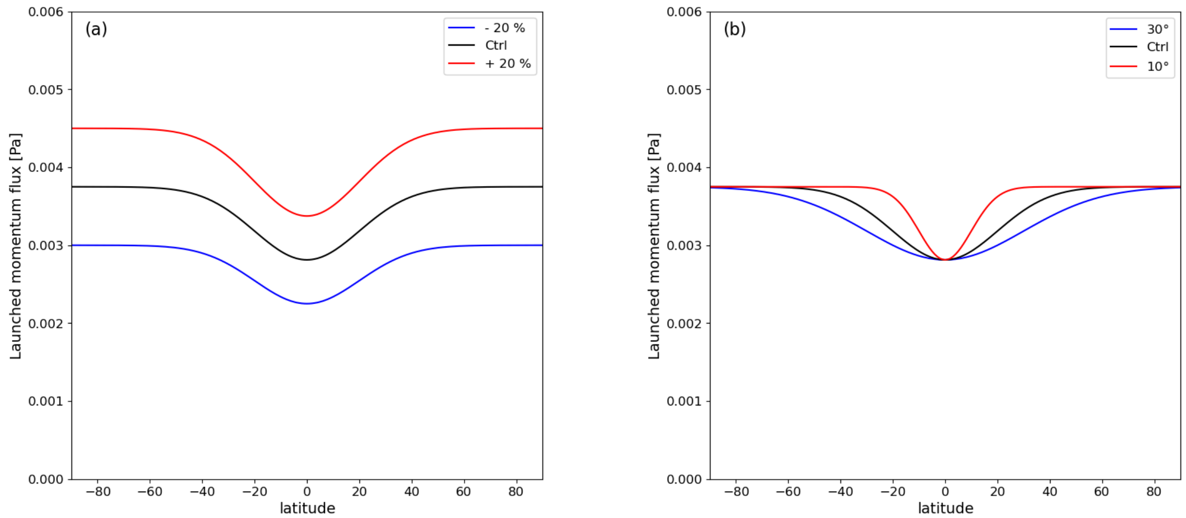

Figure 1. Latitudinal Gaussian distribution of the launched momentum flux [Pa] with **GGAUSSB=-0.25**. (a) In black, the default value of **GFLUXLAUN**=**3.75 mPa**; in blue, the +20% perturbation (4.5 mPa); and in red, the -20% perturbation (3 mPa). (b) In black, the default value of the half-width **GGAUSSA=20°**; in blue, the wider tropical region GGAUSSA=30°; and in red, the narrower tropical region GGAUSSA=10°.

Set C: Sensitivity to total precipitation

This set of experiments evaluates the sensitivity of the NOWG parametrisation to tropospheric meteorology via precipitation. By configuring NGAUSS=1, the Gaussian distribution is replaced, and the launched momentum flux is weighted by the grid-point total precipitation multiplied by a sensitivity coefficient (**GCOEFF**):

- Experiment C1 (**Precipitation baseline**): Default value of 2000.
- Experiment C2 (**Low precipitation sensitivity**): GCOEFF reduced by 20 % (1600).
- Experiment C3 (**High precipitation sensitivity**): GCOEFF increased by 20 % (2400).

We are aware that the precipitation-related flux amplification is bounded by an internal safety upper threshold (MIN(**0.5**,GCOEFF*PPRECIP)) to maintain numerical stability in the middle and upper atmosphere.

Computational resources

- Number of target events: 3 events.
- Initialization dates tested per event (initialization sensitivity phase): 4 dates.
- Initialization dates per event and parameter (PPE phase): 4 dates.
- Parameter configurations (12 different setups):
  - 1 control run with all the default parameters.
  - Set A (OGW): 2 perturbations (±20 %)
  - Set B (NOGW): 6 perturbations (3 parameters x 2 perturbations)
  - Set C (precipitation): 3 configurations (baseline, low and high sensitivity)
- Ensemble size per configuration: 10 members.
- Simulation length per run: 60 days

Total simulated time calculations:

- Initialization sensitivity phase: 3 events x 4 dates x 10 member = 120 runs (x60days = 7,200 days)
- PPE phase: 3 events x 4 dates x 12 configurations x 10 members = 1440 runs (x 60 days = 86,400 days)
- Total simulated time: 120 + 1440 = 1560 runs (x 60 days = 93,600 days ≅ 257 years)

Estimated computational resources: the OpenIFS team performed a test run with the standard, publicly available Storm Karl case, using TL255L91 resolution for 60 days with a model time step of 900s and standard OpenIFS model output writing every 6 hours. This run used ~4,000 SBUs. To account for the 1560 runs (4,000 SBUs x 1560 = 6,240,000 SBUs) and to include a contingency buffer for extra SBUs due to ensemble generation, initial test cases, potential job resubmissions and post-processing steps, we request **total computational resources of 10,000,000 SBUs.**

Data output and storage

To perform diagnostic budget calculations and evaluate the physical mechanisms of stratosphere-troposphere coupling and wave-mean flow interactions, specific three-dimensional (3D) atmospheric fields and physical tendencies will be stored at a 6-hourly temporal resolution.

A. Standard meteorological fields (3D spectral): to analyze the state and variability of the SPV.
    - Zonal wind component (u)
    - Meridional wind component (v)
    - Temperature (t)
    - Geopotential (z)
    - Relative vorticity (vo)
    - Omega velocity (ω)
B. Dynamic and parametrised tendencies (3D): to isolate the exact impact of each parametrised process (PEXTRA or LBUD23 model output).
    - Zonal wind tendency from resolved explicit dynamics.
    - Zonal wind tendency from vertical diffusion + GWD + surf processes.
    - Zonal wind tendency from GWD (OGWD + NOGWD).
    - Zonal wind tendency from convection.
C. Zonal-mean momentum diagnostics (2D): if possible, to diagnose wave-mean flow interactions using the Transformed Eulerian Mean (TEM) framework.
    - Eliassen-Palm (EP) flux components and the zonal wind tendency due to EP flux divergence.
    - TEM circulation components ($\overline{w}*, \overline{v}*$).

Estimated storage: Based on the T255L91 resolution, storing 12 3D variables on 40 pressure levels at a 6-hourly frequency yields approximately 20.0 GB per 60-day simulation. For the entire suite of 1560 individual simulations, the total volume of post-processed data is approximately 31.2 TB. To accommodate raw model outputs and temporary scratch workspace, we request a **total storage allocation of 35.0 TB.**

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