REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE:	Italy
Principal Investigator[1]:	Stefano Della Fera (itsf)
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Project Title:	Exploiting the spectral dimension of outgoing longwave radiation to open a new window on climate model evaluation

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.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☐	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	23,025,000		
Accumulated data storage (total archive volume)[2]	[GB]	71,750		

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]	0		
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special 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

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 10,000,000 SBU should be more detailed (3-5 pages).

Abstract

The Earth's energy imbalance, a crucial determinant of the climate system's warming rate, arises from anthropogenic greenhouse gases, aerosol emissions, natural forcers (e.g., volcanoes), and the Earth's outgoing radiation response to these forcings. Current climate models heavily depend on radiation measurements for validation, with most data being spectrally-integrated (e.g., CERES), providing only total outgoing longwave and shortwave radiation. However, spectrally resolved measurements offer deeper insights into climate model assessment by identifying biases across different spectral regions and understanding climate feedbacks on interannual and decadal scales.

Hyperspectral observations in the mid-infrared (MIR) region (667 to 2750 cm−1) have been available since the mid-2000s, and new missions like PREFIRE (2024) and FORUM (2027) will extend these measurements to the far-infrared (FIR) region (100 to 667 cm−1), closing current observational gaps. These measurements, containing spectral signatures of temperature, water vapour, clouds, and gas concentrations, can be leveraged to test General Circulation Models (GCMs), refine sub-grid process parameterizations, and monitor climate system evolution. In previous work, a simulator for IASI/FORUM instrument was integrated into the EC-Earth3 climate model. Analysis revealed significant biases in the model: a strong positive temperature bias (~3.5 K) in the stratosphere, a small negative bias (~1 K) in the troposphere, and an underestimation of upper tropospheric water vapour.

This project aims to use EC-Earth3 to explore the impact of spectral measurements on model tuning and climate feedback assessment. We will perturb key tuning parameters and assess spectral sensitivity, improving the model's representation of spectrally-resolved radiative fluxes. Furthermore, coupled atmosphere-ocean simulations will evaluate the potential of FORUM's future measurements to separate forcing and feedbacks from OLR observations. To this end, we will conduct historical and near-future simulations under the CMIP6 SSP3-7.0 scenario to assess the synthetic radiances' sensitivity to projected climate changes and explore the direct assessment of spectrally-resolved climate feedbacks.

Introduction

The Earth's energy imbalance is a key quantity determining the rate of warming of the climate system, which is at the core of the research on the climate system and its response to anthropogenic forcing. The imbalance is determined by the forcing imposed by anthropogenic greenhouse gases (GHG) and aerosol emissions, natural forcers (e.g. volcanoes) and by the concomitant change of the Earth's outgoing radiation in response to these forcings (the so called climate feedbacks). The climate modelling community relies strongly on radiation measurements for the verification, identification of biases and tuning of climate models. Most of these are spectrally-integrated measurements (i.e. CERES) that give information only on the total outgoing longwave (OLR) and shortwave (OSR) radiation. Spectrally resolved measurements of the OLR will allow further insight in the assessment of climate models, by separating biases in different spectral regions, and in the climate system understanding, potentially allowing a direct detection of spectrally-resolved climate feedbacks on interannual and decadal timescales.

Stable hyperspectral observations of the mid-infrared (MIR) region (667 to 2750 cm^{-1}) of the Earth's emitted radiance have been provided by different space-based sensors (IASI, AIRS, etc.) since the mid 2000s and today long-term dataset of spectrally resolved measurements are available for climate studies applications. In addition, new missions, such as PREFIRE (2024) and FORUM (from 2027), will provide for the first time from space unique spectrally resolved measurements extending down to the far-infrared (FIR) region (100 to 667 cm^{-1}), thus filling the current observational gap of the Earth's emission spectrum measured from space.

Since these measurements contain the spectral signatures of temperature, water vapour, clouds and gases concentration, they can be exploited to strictly test General Circulation Models (GCMs), to constrain the parametrizations of sub-grid processes and to monitor the evolution of the climate system.

Spectral biases

In a previous work (Della Fera et al., 2023), a IASI/FORUM simulator was implemented in EC-Earth3, a state-of-the-art climate model participating to CMIP6 (Coupled Model Intercomparison Project – Phase 6) and developed by a consortium of European research institutions (Doescher et al., 2023). A clear-sky climatology of synthetic radiances computed online in an historical atmosphere-only simulation from 2008 to 2016 was then compared to IASI climatology and used to assess spectral model biases. The spectral analysis has highlighted a strong positive temperature bias ($\approx$3.5 K) in the stratosphere of the EC-Earth climate model, a small ($\approx$1 K) negative temperature bias in the troposphere and an underestimation of the water vapour concentration in the upper troposphere of the model. These biases are consistent with those identified in a comparison performed between EC-Earth and ERA5 data over the same period.

Spectral trends/feedbacks

The integrated OLR measurements (e.g. CERES) inform about the net radiative flux at the top of the atmosphere (TOA) of the planet, but mix up contributions from the different spectral bands, making it very difficult to disentangle forcing and feedbacks. The spectral dimension contains more information and could potentially allow unique insights into the response of the climate system to anthropogenic forcing, by separating it into different spectral bands or individual channels (Huang et al., 2010; Huang et al., 2014). This leads to the concept of spectral climate feedback, which can be determined directly from spectral observations, either exploiting the signal contained in the interannual variability (Roemer et al., 2023) or analyzing decadal trends in specific spectral channels (Raghuraman et al., 2023; Whitburn et al., 2021).

Scientific project

In this project, we plan to use EC-Earth3 (Doescher et al., 2023) to investigate the impact of spectral measurements on model tuning and on the assessment of climate feedbacks. EC-Earth3 is a state-of-the-art coupled general circulation model and includes advanced, robust and validated components for the atmosphere (the ECMWF IFS model cy36r4) the ocean (NEMO 3.6; Madec 2008), sea ice (LIM3; Fichefet and Morales Maqueda 1997) and land processes (H-Tessel; Balsamo et al. 2009). The model will be run in both atmospheric-only and coupled mode, with the IASI/FORUM simulator activated (Della Fera et al., 2023).

The IASI/FORUM simulator developed in Della Fera et al. (2023) has been recently extended to cloudy atmospheres. Since the model grid is far wider than IASI/FORUM field-of-view, this step requires a careful treatment of model grid subcolumns, in order to avoid biases coming from an overly smoothed cloud field. With the inclusion of clouds, the simulator now produces reliable synthetic measurements to perform sensitivity studies.

Spectral tuning

Tuning of parameters involved in model parameterizations is a crucial activity in model development, fundamental in achieving a reliable representation of the climate and radiative fluxes (Hourdin et al., 2017). However, such activity usually focusses only on integrated radiative fluxes at TOA and global surface temperature, thus making error compensation possible. Considering spectrally-resolved radiative fluxes and focusing on spectral biases would allow a more in-depth analysis of the sensitivity of the climate model to tuning parameters.

We plan here to investigate this new approach by performing a set of present-day atmosphere-only simulations with EC-Earth3 with the FORUM simulator activated and assess the spectral sensitivity to model tuning parameters. Tuning parameters for IFS typically regard the microphysics module, involving cloud and precipitation processes (e.g. rate of cloud to rain conversion, organised entrainment in deep convection, autoconversion critical radius, ..).
Simulations will use observed climatological sea surface temperature (SST) and sea-ice cover fields as boundary conditions. These atmosphere-only runs will be used to develop a spectral tuning simulator and adjust the parameters to best match the observed spectral OLR.

To this end, we will explore the sensitivity to 5 tuning parameters which have been previously identified (Doescher et al. 2023) chosen among those particularly relevant for long-wave radiances: each parameter will be perturbed in 2 directions (increased/decreased by e.g. 20%) and each sensitivity run will last 5 years with prescribed climatological SSTs and sea ice.

Spectral feedbacks

On the other side, we will investigate the potential of future FORUM's measurements to disentangle forcing and feedbacks from OLR observations.

For this, we plan to produce a set of coupled atmosphere-ocean simulations with EC-Earth3, with the FORUM simulator activated, to:

- assess the sensitivity of the synthetic radiances to the projected changes in various climate variables (e.g. surface temperature/tropospheric temperature/water vapour/clouds);
- explore the potential for directly assessing spectrally-resolved climate feedbacks through FORUM's measurements, comparing calculations on synthetic radiances to results obtained with classical variational methods.

With this goal, we will perform:

- a 3-member ensemble of coupled historical simulations for the recent historical period (2000-2014);
- a 3-member ensemble of coupled simulations for the near-future (2015-2049), assuming the CMIP6 SSP3-7.0 scenario.

Justification of the computer resources requested

Experiment	Configuration	set-up	SBU	Storage
spectral tuning	atmosphere-only	5 params x 2 directions x 5 years + control = 55 years	5,775,000 SBU	19,250 GB
recent historical	coupled	3 ens members x 15 years	5,175,000 SBU	15,750 GB
near-term future	coupled	3 ens members x 35 years	12,075,000 SBU	36,750 GB
total			23,025,000 SBU	71,750 GB

The cost of a single model year of EC-Earth3 with activated FORUM simulator for cloudy atmospheres has been estimated on HPC2020 as 105000 SBU / model year for AMIP runs and 115000 SBU/model year for coupled runs.

The model output size is dominated by the spectral radiance output (due to the large number of channels saved) and corresponds to about 350 GB / year (both for AMIP and coupled runs).

References

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