SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2021
Project Title:	REsolved orography impact on the mid-latitude FlOw with ECEarth (REFOrgE)
Computer Project Account:	spitdav2
Principal Investigator(s):	Paolo Davini
Affiliation:	Istituto di Scienza dell'Atmosfera e del Clima, Consiglio Nazionale delle Ricerche (CNR-ISAC)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr. Irina Sandu (ECMWF)
Start date of the project:	01/01/2019
Expected end date:	31/12/2021

Computer resources allocated/used for the current year and the previous one

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	40 millions	39.9 millions	10 millions	0.95 millions
Data storage capacity	(Gbytes)	55,000	70,000	75,000	70,000

Summary of project objectives (10 lines max)

Within REFORGE we aim at exploring the impact that resolved and sub-grid orography has on the flow using the EC-Earth3 global climate model. Making use of a set of atmosphere-only integrations at three different horizontal resolutions (~80 km, ~40 km and ~25 km) we will 1) explore the effect of resolved orography on the mid-latitude climate – with a special regard to recurrent weather patterns as atmospheric blocking –2) assess to what extent the current parametrizations of sub-grid orographic effects (which are unresolved at a standard climate model resolution, i.e. ~80 km) are able to reproduce the effects of the resolved orography, 3) explore ways of improving the simulation of circulation patterns in climate simulations improving the representation of the unresolved orography.

Summary of problems encountered (10 lines max)

In May 2020, a serious bug in EC-Earth3 has been encountered and this affected the original workplan. This unfortunately occurred after most of the CORE simulations has been run. The bug – that was causing unrealistic reading of SST forcing in December and January – has been fixed in July 2020 and changes have been included in EC-Earth3 code. However, this had serious consequences on a large set of experiments already run. A large part of the TL511 and TL799 simulations had to be re-run. This has been possible through a 10 million SBUs additional resources request and making use of a very conservative computing setup. The new integrations have been completely at the end of the year 2020, but due to the reduced available resources the TL799 integrations are now shorter (24 years instead of 31). This does not seem to have influenced the reliability of the results.

Summary of plans for the continuation of the project (10 lines max)

We are currently wrapping up the results from the CORE simulations – which provide more interesting material than expected – into a first publication. A second publication, more focused on the role of the orographic parametrizations, is planned in the upcoming months. In the remaining 6 months and with the remaining core hours we will pursuit the original goal of REFORGE operating extra simulations in the low-resolution configuration (TL255) playing with sub-grid orography aiming at improving the properties of the mid-latitude climate.

List of publications/reports from the project with complete references

A first publication is currently in preparation, with the following working title:

- Davini P., F. Fabiano and I. Sandu (2021). "Resolved orography vs. grid refinement: impacts of increasing atmospheric resolution on the winter mid-latitude circulation", to be submitted to Climate Dynamics.

A second one more focused on the role of parametrizations is envisaged.

Summary of results

In the last 12 months of the project (from June 2020 up to June 2021) the work has been divided in mainly two chunks: 1) a first technical part, carried out up to the end of the last year, where EC-Earth3 integrations have been completed, including the re-running of the bugged experiments and 2) a second part which took place in 2021, where we proceeded with the analysis of the simulations. After the re-running of the experiments, we have at disposal eight experiments, i.e. the CORE integrations: the EC-Earth3 default configuration (*rfgr-ctrl-param,* which corresponds to the version of EC-Earth3 used for the CMIP6 effort) plus the configuration where the sub-grid orography parametrizations are disabled (*rfrg-ctrl-noparam*) at three different horizontal resolutions (TL255, TL511, TL799, roughly 80km, 40km and 25km respectively). Then, other two experiments at TL511 and TL799 have been performed where the original mean orography has been swapped with the mean orography of the TL255 (*rfrg-orog255-noparam*). In such way it is possible to distinguish among the effect of increase in "pure" resolution (for example, what is done by better resolved transient eddies), the effect of better resolved mean orography and the effect of orographic parametrizations.
The parametrizations which have been disabled in the *noparam* integrations are the Turbulent Orographic Form Drag (TOFD) and the Subgrid Scale Orography (SSO). The former includes the

drag caused by the large-scale orography pattern (larger than 5km) while the second embeds the smaller scale feature (smaller than 5 km), due to both the gravity wave drag and to the blocking effect that orography exert on the flow at lower levels.

Each simulation has been run for 31 years, and the last 30 years have been taken in consideration for analysis (in order to allow for a spin up of the land-surface). Furthermore, other two ensemble members starting from different initial conditions have been initially run at TL255 for the *rfrg-ctrl-noparam* to assess whether the chosen 30-year window is long enough to detect changes in the variability at the mid-latitudes. They showed that – as documented in the previous REFORGE report – given the highly idealized setup the internal variability is usually small over a 30-year window. Due to computational limitations, the TL799 runs are now 24-year long, so that only 23 years can be considered for the analysis. However, analysis on shorter time window – even of 20 years – showed that the results found are robust.
We performed again the analysis carried out last year with the new set of experiments, and the findings agree with what was previously found.

The analysis – which is part of the publication in preparation – has been mostly focused on the differences in the impact that the resolution increase "per se" have when compared to the increase in resolution of the mean resolved orography. On the same time, it has been possible to investigate the impact of the parametrizations at different resolutions (although this part is not going to be included in the first publication).

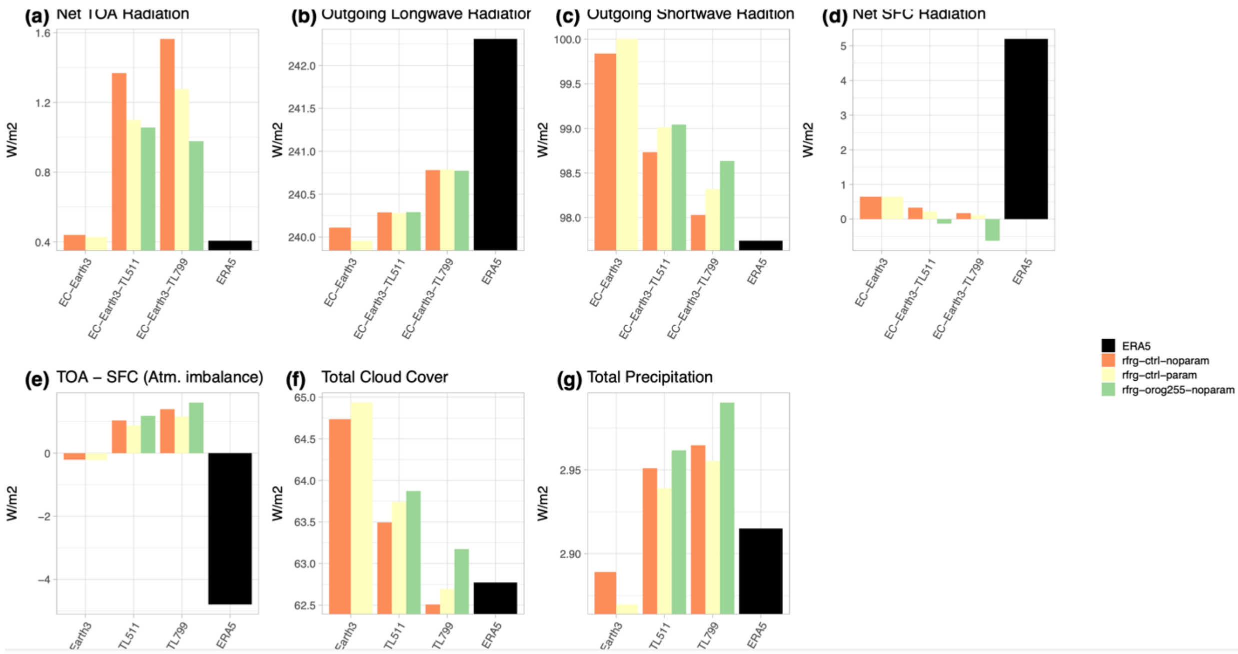

Figure 1: Global yearly average of a few selected radiative and dynamical fields for the different simulation and ERA5 reanalysis.

The first impact of modifying the model horizontal resolution is certainly seen in the global yearly-averaged radiative balance. This can be observed by looking at the results from Figure 1, which shows the changes in the top of atmosphere (TOA) radiation, in the outgoing longwave and shortwave radiation, in the net surface radiation, in the atmospheric imbalance (i.e., the heat source/sink generated by systematic biases in the energy and mass conservation of the model) and in total cloud cover and precipitation in the different experiments. All the changes (i.e., mean orography, grid refinement and parametrizations) have an evident impact on the radiative budget: however, for most variables, changes caused by mean orography are about half of the ones induced by the grid refinement. For others, as outgoing longwave radiation, the parametrizations activations and the mean orography have a negligible impact, and all the changes seems to be attributable to the change of the horizontal grid.

For example, a step up in resolution from TL255 to TL511 brings almost a 1 W/m2 increase in the net TOA radiation entering the atmosphere, and this is limited by the presence of the orographic parametrizations which has an impact on the fluxes (Fig 1a): of course, since the model is forced by a fixed SST/SIC boundary condition, no increase in surface temperature is observed. Such TOA change is mainly associated with a reduction of the shortwave radiation reflected to space, which suggests an overall decrease in Earth's albedo (Fig 1c). This is only partially compensated by the increase in the outgoing longwave radiation: indeed, this field is not influenced at all by the mean orography (Fig 1b).
The total cloud cover decreases by 2% going up to TL511 and by 3% going up to TL799, suggesting that the reduced radiation scattered back to space is due to the decreased cloud amount (Fig 1f). Similarly, significant changes are observed for precipitation, showing increased rainfall at both TL511 and TL799 (Fig 1g). More in general, the changes seem to be quite linear, always putting the TL799 run farther from the TL255 ctrl run than the TL511 run.

A more detailed spatial analysis shows considerable changes in the tropical areas (not shown), with an overall moderate decrease in cloudiness in the tropical sectors, more evident over the Maritime Continent. However, the changes are very complex, associated with a redistribution of convection along the Equator: less precipitation and convection are observed over the Maritime Continent, while increased precipitation and convection are observed over Western Pacific, the Indian Ocean, and the Amazon. Surprisingly, a reduction of cloud cover is observed over the Peruvian coast, suggesting less stratocumulus there.

To simplify the discussion of the impact of the increase in resolution, the comparison of the eight experiments has been reduced to a simpler framework for the following figures.
Indeed, by comparing *rfrg-orog255-noparam* at different resolutions (TL511 and TL799) vs *TL255 rfrg-ctrl-noparam* it is possible to estimate the net impact of the increase in atmospheric resolution, keeping constant the mean resolved orography: this comparison will be here after defined as "Grid refinement". On the other hand, by comparing *rfrg-ctrl-noparam* vs *rfrg-orog255-noparam* (at both TL511 and TL799) it is possible to estimate the direct contribution of the resolved mean orography on the flow: this comparison will be defined as "Mean orography increase". Finally, by comparing the simulation with both the SSO and TOFD orographic parametrizations active at the three resolutions vs. the ones without (i.e., *rfrg-ctrl-param vs rfrg-ctrl-noparam)* it is possible to assess what is the impact of the parametrizations: this will be defined as “Orographic parametrization activation”.

For both the grid refinement and the mean orography increase, the average of the TL511 and TL799 response is shown in the figures. Of course, the signal for the TL799 experiments is on average larger than the ones found for TL511 experiments, but in most fields the two responses are consistent between each other. On the other hand, for the orographic parametrization activation we use the three resolutions available: here the response is usually stronger at lower resolution (i.e., TL255) where the parametrizations are most effectively perturbing the flow. Overall, this approach levels out eventual issues arising from the limited length of the simulations providing a more robust picture.

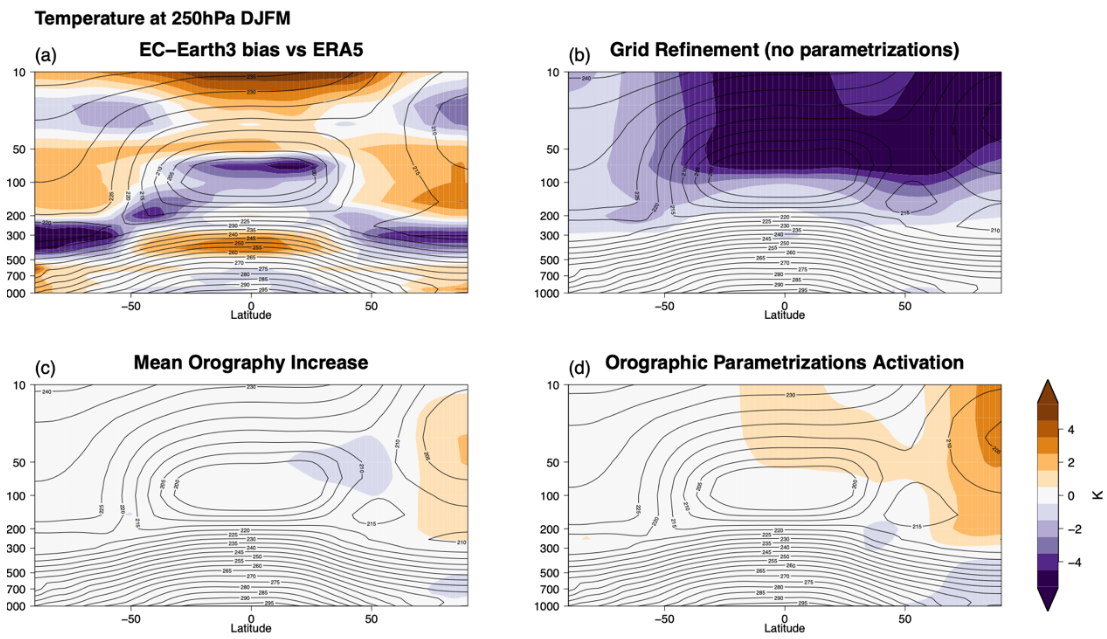

Figure 2: DJFM Zonal mean temperature for (a) EC-Earth3 bias compared to ERA5 (b) EC-Earth3 changes induced by grid refinement (c) EC-Earth3 changes induced by mean resolved orography increase (d) EC-Earth3 changes induced by orographic parametrization activation.

An example of this approach is provided in Figure 2, where the winter (DJFM) zonal mean temperature is shown. The EC-Earth3 model at TL255 has moderate biases: this is characterized by an overly intense temperature gradient at upper levels and by a too weak gradient at lower levels (Fig 2a), which is reflected by a strong jet stream, especially in the high troposphere, in both the hemispheres (not shown).
The impact of the grid refinement is completely different from the impact due to increased orography and of the orographic parametrizations. On the zonal average, the most impressive change is the cooling of the stratosphere following the grid refinement (Fig 2b), which is associated with an increase of the tropopause height, possibly caused by the previously discussed tropical convection changes. The changes in the tropospheric jets are however limited, mainly showing a small decrease of both the Northern and Southern jets (not shown). Conversely, the impact of the mean orography (Fig 2c) has a small impact on the tropical stratosphere but drives a warming of the polar stratosphere likely associated with a larger wave activity propagating upward. The activation of the orographic parametrizations (Fig 2d) has a similar but larger impact, which confirms the goodness of this numeric schemes in replicating the effect of the mean orography. Therefore, the jet streams are deflected in both cases (not shown), showing a poleward displacement in the Southern hemisphere and an equatorial displacement in the Northern hemisphere, which likely depends on the specific structure of the continental landmass in the two hemispheres: however, it goes in the direction of reducing the temperature and wind biases in both the hemispheres. The overall findings are in line with has been shown for weather forecast timescales by Kanehama et al. (2019).

A more detailed view on the mid-latitude climate variability can be observed in Figure 3. Here the blocking frequency over the winter period (DJFM) – based on the Davini et al. (2012) blocking index, a bidimensional extension of the most known Tibaldi and Molteni (1990) – is presented. Atmospheric blocking – given its highly non-linear behavior and the well-known issues that numerical models have in reproducing it (e.g., Davini and D'Andrea 2020) – is an ideal diagnostic to investigate the changes in the mid-latitude circulation.
Both grid refinement and increasing mean orography provide an increase in the blocking frequency over Europe, which goes into the direction of reducing the model bias. Over the Pacific sector, the impact of mean orography seems to have a clearer positive impact. The relevance of sub-grid orography parametrizations – which can almost double the modeled blocking frequency, from 5% to 10% approximately - was expected given the results of Pithan et al (2016), but in EC-Earth3 is

much more evident. This provides an interesting evidence that orographic parametrizations are fundamental for a correct simulation of the mid-latitude climate variability, especially over the North Atlantic sector.

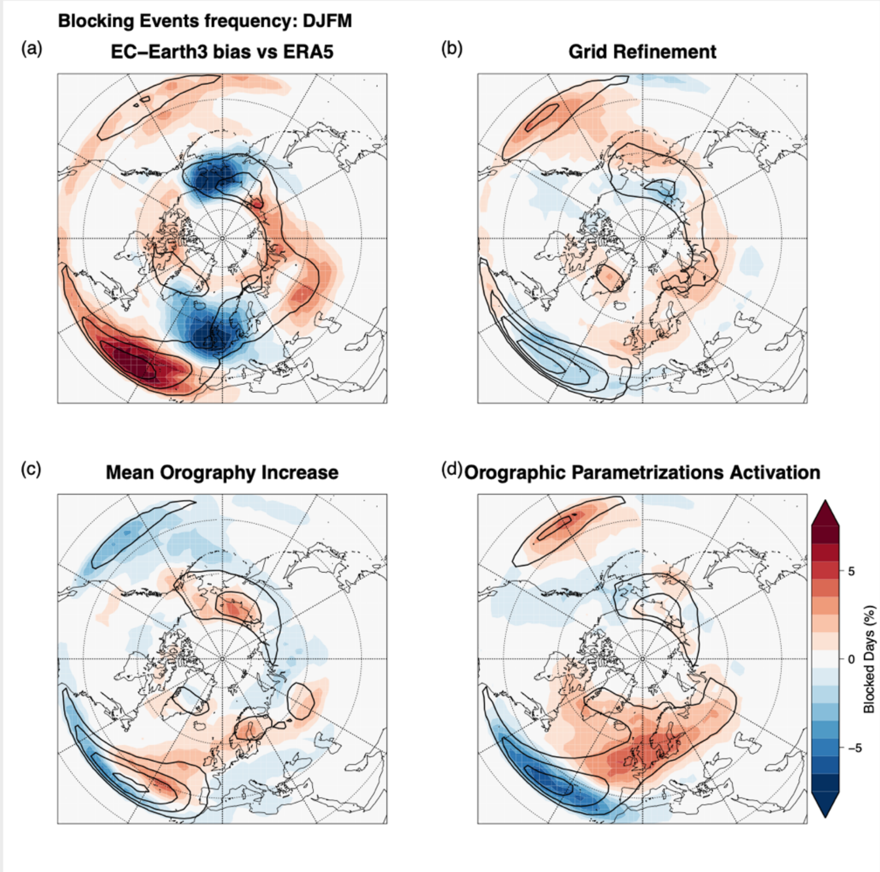

Figure 3: DJFM blocking events frequency for (a) EC-Earth3 bias compared to ERA5 (b) EC-Earth3 changes induced by grid refinement (c) EC-Earth3 changes induced by mean resolved orography increase (d) EC-Earth3 changes induced by orographic parametrization activation.

One important consequence of this analysis – that will be stressed out in the upcoming publication - is that the grid refinement “per se” can easily lead controversial improvement – likely due to the incorrect radiative balance which is achieved when changing fundamental numerical properties as the grid size or the timestep. On the other hand, mean orography and orographic parametrizations always provide a bias reduction, in almost all the diagnostic here analyzed. This points to the need of proper model tuning at high resolution, which otherwise is exposed to the risk of losing all the benefits which are provided by the increase in mean orography.

References

- Davini, P., Cagnazzo, C., Gualdi, S., & Navarra, A. (2012). Bidimensional diagnostics, variability and trends of Northern hemisphere blocking. Journal of Climate, 25(19), 6996–6509.
- Davini, P., & D’Andrea, F. (2020). From CMIP3 to CMIP6: Northern Hemisphere Atmospheric Blocking Simulation in Present and Future Climate, Journal of Climate, 33(23), 10021-10038.
- Kanehama, T., Sandu, I., Beljaars, A., van Niekerk, A., Lott, F. (2019). Which orographic scales matter most for medium-range forecast skill in the Northern Hemisphere winter? Journal ofAdvances in Modeling Earth Systems.
- Pithan, F., Shepherd, T. G., Zappa, G., & Sandu, I. (2016). Climate model biases in jet streams, blocking and storm tracks resulting from missing orographic drag. Geophysical Research Letters, 43, 7231–7240.
- Tibaldi, S., & Molteni, F. (1990). On the operational predictability of blocking. Tellus, Series A, 42, 343–365