

REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: Greece

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Project Title: Understanding dynamics and impacts of cyclone systems through a comprehensive dataset of convection-permitting simulations

| | | |
|--|---|-----------------------------|
| If this is a continuation of an existing project, please state the computer project account assigned previously. | SP _____ | |
| Starting year: <small>(A project can have a duration of up to 3 years, agreed at the beginning of the project.)</small> | 2023 | |
| Would you accept support for 1 year only, if necessary? | YES <input checked="" type="checkbox"/> | NO <input type="checkbox"/> |

| | | | |
|---|-------------|-------------|-------------|
| Computer resources required for 2023-2025: <small>(To make changes to an existing project please submit an amended version of the original form.)</small> | 2023 | 2024 | 2025 |
|---|-------------|-------------|-------------|

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.

| | | | | |
|--|-------|-----------|------------|--------|
| High Performance Computing Facility | (SBU) | 8,000,000 | 12,000,000 | 0 |
| Accumulated data storage (total archive volume) ² | (GB) | 10,000 | 22,500 | 22,500 |

Continue overleaf

Principal Investigator: Emmanouil Flaounas

Project Title: Understanding dynamics and impacts of tropical and extratropical cyclones through a comprehensive dataset of convection-permitting simulations

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

Scientific Plan

Tropical, sub-tropical and midlatitude storms refer to systems of cyclonic circulation, undoubtedly among the most catastrophic ones. Indeed, cyclones are often responsible for floods, damaging wind gusts, storm surges, lightning activity and high sea waves. From the perspective of atmospheric dynamics, all cyclones are outcomes of similar atmospheric processes interacting however in "different portions". Disentangling the relative contribution of the processes involved to storms' development and quantifying their role in delivering socio-economic impacts has long been the cornerstone of community efforts. This project aims to substantially promote these efforts by making available and analyzing a unique comprehensive dataset of cyclone simulations in very high spatial resolutions that would allow for this assessment.

Cyclone dynamics refer to the combined effect of several interacting atmospheric processes that generate and develop low-pressure systems. The field of cyclone dynamics has been established for more than a century now (Emanuel 2018; Schultz et al. 2019), where tropical cyclones (TC) and extratropical cyclones (ETC) are traditionally regarded as two distinct categories of cyclone systems, each governed by distinct processes: TCs are diabatically driven systems where kinetic energy is drawn from latent heat release within a convective area around a well-defined low-pressure centre (Emanuel, 1986), while ETCs are formed through the conversion of atmospheric potential energy into kinetic energy due to baroclinic instability (Charney, 1947; Eady, 1949). These two simplistic and fundamentally different conceptual models of cyclone dynamics become intermingled when considering realistic atmospheric conditions. For instance, frictional deceleration, radiation cooling, latent heat release in clouds and baroclinic forcing are always involved in both cyclone types. These processes have a clear positive or negative contribution to wind vortices, e.g. latent heat release and radiative cooling or heating (Kuo et al. 1991; Wernli et al. 2002; Schäfer and Voigt, 2018, Papavasileiou et al. 2020), or an ambiguous effect, as frictional deceleration (Stoelinga, 1996; Flaounas et al. 2021). Regardless of the complexity of cyclone dynamics, the direct relationship between thermo-dynamical processes and cyclone wind circulation can be quantified by adopting specific diagnostics such as the potential vorticity (PV) framework or the surface pressure tendency framework. Indeed, PV diagnostics have been widely employed in atmospheric modelling to improve our understanding, e.g. of cyclogenesis, rapid intensification and formation of weather extremes (e.g. Joos and Wernli, 2012; Chagnon et al. 2015; Martínez-Alvarado et al. 2016; Büeler and Pfahl, 2017; Attinger et al. 2019). A process-based PV budget is thus proven to provide deep insights into the processes that turn cyclones into catastrophic storms. However, such an approach is demanding either on-line diagnostics which are difficult to acquire at post-treatment level, or atmospheric variables that are not usually available in model outputs or reanalysis. On the other hand, surface pressure tendency diagnostics have been previously applied in both modelling (Fita and Flaounas, 2018) and reanalysis (Fink et al. 2012, Papavasileiou et al. 2020) studies to decompose the relative contribution of both diabatic and dynamic processes and can be applied off-line in model output.

The complex 3D structures of the interacting processes are difficult to be captured by remote or in-situ observations and thus atmospheric modelling is still an important tool for the cyclones community. More than adopting adequate model frameworks, understanding cyclone processes is also a question of the models ability to resolve fine-scale processes. In fact, important fine-scale structures, e.g. convection in frontal areas, or airflow-mountains interaction, are playing an important role to cyclones development. Therefore, the finer the resolution the more detailed is the representation of such physical processes. A horizontal grid spacing of less than 4 km is generally considered as an important threshold

for omitting the use of convection parameterization (i.e., the largest part of convection is explicitly resolved) and therefore for reducing inherent model uncertainty involved in physical parameterizations. Also in terms of impacts, the representation of cyclone processes and structures responsible for delivering substantial impacts (e.g. sting jets) depend strongly on the ability of a model to resolve fine-scale dynamics (Riviere et al., 2020).

Given the multiple scales of the processes involved in cyclones development, i.e. from baroclinic instability (large-scale dynamics) to latent-heat release (microphysical processes), the employment of high resolution simulations is indeed an important research element to be taken into consideration when analysing cyclone dynamics. On the other hand, the limitation imposed by computer resources when simulating a number of cyclones greater than few case studies becomes a considerable obstacle for comprehensive analysis. As a result, most detailed studies on cyclone dynamics are focusing on specific cyclone cases, while climatological approaches are mostly based on reanalysis and climate simulations at the expense of obtaining valuable diagnostics like physics tendencies or PV budget terms, or also at the expense of having fine scale cyclone structures resolved, like the ones leading to sting jets.

Motivation and objectives

Researchers working on cyclone dynamics, but also stakeholders interested in weather impacts, have a constantly increasing need to acquire climatological simulations and associated knowledge of cyclones at high resolutions. Such a climatological dataset would provide diagnostics about processes and impacts that cannot be explicitly resolved, or that are not available in reanalysis.

This project aims to address this increasing need by fulfilling a twofold objective:

- O1: to build a first-of-its-kind comprehensive dataset of cyclone simulations at convection-permitting scales;
- O2: to use this dataset for the ends of better understanding cyclone dynamics and impacts.

For these reasons, a large ensemble of simulations will be produced for a wide number of cyclones in the Euro-Atlantic domain, giving priority to cyclones making landfall in Europe. Therefore, this project is expected to substantially promote our understanding of cyclone dynamics and in parallel, to provide deeper insights into the link between atmospheric dynamics and the impacts delivered by precipitation, wind and the sea state.

Through the fulfilling of the large ensemble of simulations, we will produce a dataset which per-se will undeniably attract great interest from the cyclones community. Therefore the fulfilment of O1 will consist of a major contribution to the achievement of numerous research topics. Plans for safeguarding and making available the simulations as an open accessed dataset are already in progress. The O2 will be fulfilled by dedicated studies from the project participants. Several "one-paper projects" are foreseen to start after completing the simulations, namely:

Project 1: Use the ensemble of simulations to understand cyclone dynamics from the perspective of a process-based PV budget.

Project 2: Use the ensemble of simulations to understand cyclone-produced windstorms and heavy precipitation across resolutions.

Project 3: Use the ensemble of simulations to understand compound hazards due to cyclones.

Project 4: Analyse processes of extreme cyclones in complex geographical regions such as Eastern Europe and Black Sea

Project 5: Analyse windstorms and relationship to sting jets

Project 6: Diabatic contributions in developments towards flood conditions

Project 7: Determine how the size and location of the wind footprint and the intensity, timing and location of wind gusts

Project 8: Improve the understanding of the dynamics of explosive Mediterranean cyclones and medicanes

Project 9: Better understand the role of diabatic vs baroclinic forcing in the development of cyclones

Project 10: Compare dynamics and impacts of cyclones that develop in different regions: Polar and mid-latitude Atlantic Ocean, Tropics, Mediterranean basin, Black Sea.

Project 11: Use of the high-resolution dataset of simulated Mediterranean cyclones as ground truth of present climate for sake of comparison to corresponding pseudo-global warming simulations

Project 12: Use the ensemble to assess the relative importance of different diabatic processes for the cyclone evolution using the pressure tendency budget equation (PTE) as an off-line diagnostic tool.

The interest in undertaking these projects is already confirmed by the participants of this project. Reaching out to the cyclones community and especially to the MedCyclones COST Action (2020-2024), we expect the above projects to be joined by additional colleagues, but also we expect new "one-paper projects" to emerge.

Technical characteristics: WRF simulations in a moving nest configuration

A climatological dataset of cyclone tracks will be used for the purposes of this project. All cyclone tracks have been produced using ERA5 for the last 5 years (2018-2022) and will be provided by the PI in the context of previous projects. Among the thousands of tracks, we will select the ones that reach the deepest mean sea level pressure or which have the largest impacts and that capture all stages of cyclones development: from genesis and maturity until decay. Geographically we only consider tracks in the North Atlantic and Mediterranean region.

All simulations will be performed by the Weather, Research and Forecasting model (WRF version 4.4; Skamarock et al. 2008) in a moving nest framework (Gopalakrishnan et al. 2006). In this framework, a two-domain simulation will be performed for each cyclone case study. A parent domain will tightly encompass a preselected cyclone track and a nested domain will be moving always following the cyclone centre. The displacements of the nested domain will be predefined, according to the cyclone tracks, taken from ERA5.

To assure that the simulated tracks will not diverge from the ones in ERA5, the wind fields in the parent domain will be strongly nudged at every grid point by the same reanalysis. Therefore, cyclones will be efficiently resolved (in terms of consistent tracks and life stages as in ERA5), as confirmed by a series of preliminary simulations, already performed by the PI of the project. The nested domain will not be nudged by ERA5 and thus the model will be free to resolve cyclone dynamics.

The advantage of this framework is its cost efficiency in computational time and storage when compared to simulations performed for single domains at high resolutions. More than that, this framework assures consistent reproduction of cyclone tracks with ERA5 and in parallel, a detailed description of cyclone dynamics in convection-permitting resolutions.

In all cases, the parent domain and the simulation duration will be always adapted to the duration and length of the selected tracks from ERA5. On the other hand, the nested domain will have a fixed square size with side-lengths of the order of 1,000 km. The resolution and time step ratio between the parent and nested domain will be equal to 3. Therefore a parent domain will use ~10 km of horizontal grid spacing with a time step of 60 sec and the nested domain will use a horizontal grid spacing of 3.3 km and a time step of 20 sec. As an example for the size of the domains, Fig. 1 (top panel) shows the parent domain and the cyclone track of TC Usagi (2013). The detail of the resolved scales can be visually deduced by comparing the PV component that has been produced by diabatic processes in the two panels of Fig. 1. High values (in blue colours) depict the convective eyewall of the cyclone.

The choice of specific physical parameterizations and the possible use of high resolution SST datasets will be defined prior to the massive simulations according to recent literature and following sensitivity tests on representative cases.

In addition to WRF, this project will be accompanied by the employment of the RIP tool (Read/Interpolate/Plot). RIP has been developed by NCAR and is configured to read directly WRF outputs and produce dedicated diagnostics. Most important, RIP incorporates a lagrangian model that operates directly on WRF outputs and produces air mass trajectories. Being able to identify moving grids, RIP is valuable for producing diagnostics in the moving nested domain about the development of important airstreams for cyclone dynamics such as sting-jets, dry air intrusions, as well as warm and cold conveyor belts.

Computer resources

One simulation will be performed for every cyclone case study using the same parameterizations. While the nested domain will have a fixed squared shape of 1000 km per side, the duration of the simulations and the size of the parent domain will depend on the cyclone track of each case study. Therefore, the computational time for all simulations will vary according to the case.

In a test that we performed for the TC in Fig. 1 (in a server other than the one of ECMWF), the simulation elapsed time was about 12 hours using Fortran Intel compiler and 100 cores. The duration of the simulation was about 9 days (1.2 hours per day of simulation). Table 1 shows the domain size in terms of grid points:

| | Horizontal resolution | Grid points | Vertical levels | Size of output (MB) |
|----------------------|------------------------------|--------------------|------------------------|----------------------------|
| Parent domain | 10 km | 380x210 | 50 | 380 |
| Nested domain | 3.3 km | 300x300 | 50 | 360 |

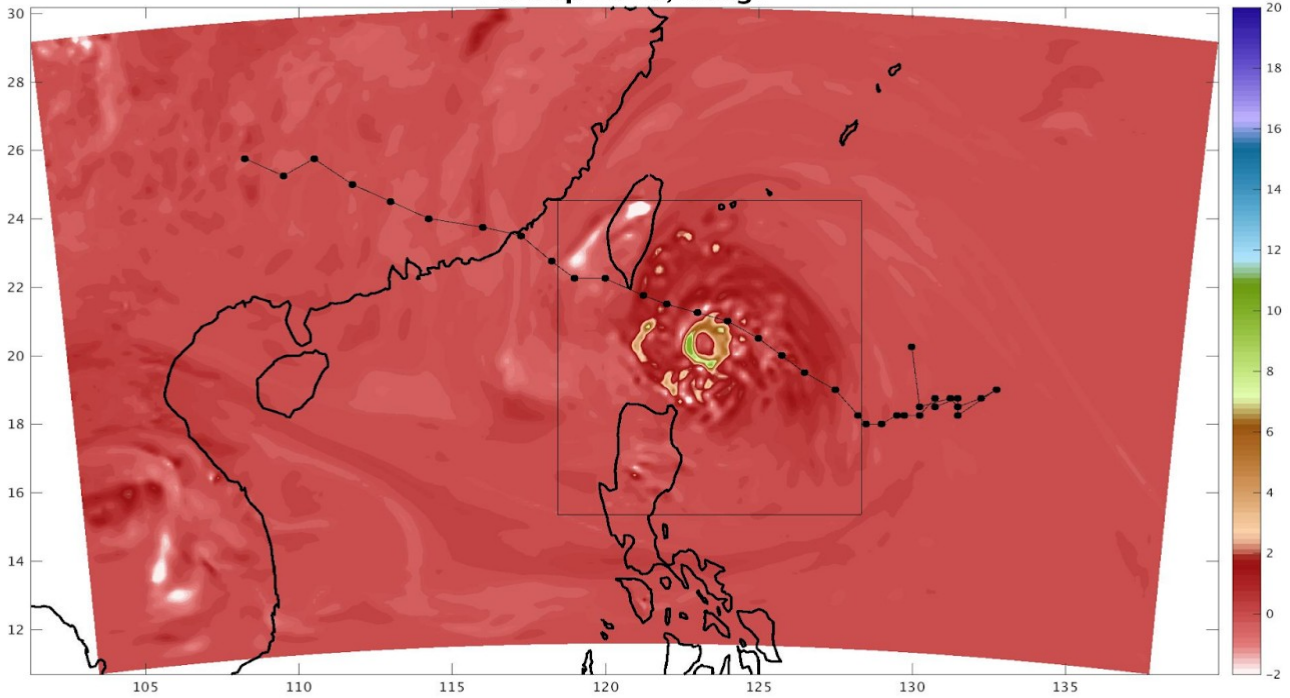
A 9-days simulation as the one shown in Fig. 1 is falling within the range of extreme duration of cyclone tracks (Neu et al., 2013). Therefore the grand majority of simulations are expected to be significantly cheaper in terms of computational time. Considering an average of 5 days, the elapsed time would be of the order of ~6 hours per simulation (using 100 processors). This yields about 11,484.62 SBUs per simulation.

- Our Objective is to perform at least 1,500+ simulations. This accounts for about 20,000,000 SBUs.

-Assuming that we will save 3-hourly outputs for selected 3D fields and hourly outputs for selected 2D fields, we estimate about 10-15GBs per simulation. This yields a total amount for the simulations of the order of 22.5 TBs.

In the 3-year duration of the project, we estimate several sensitivity tests to take place in the beginning of the first year and the core of the simulations to take place in year two. Our objective is to store the simulations in a local server however this will be the objective of future projects of the participants. Therefore, we expect the datasets to be stored in ECMWF servers until they can be relocated. It is highly probable that the demanded storage will be no longer needed in year three of the project.

20 Sep 2013, Usagi



20 Sep 2013, Usagi

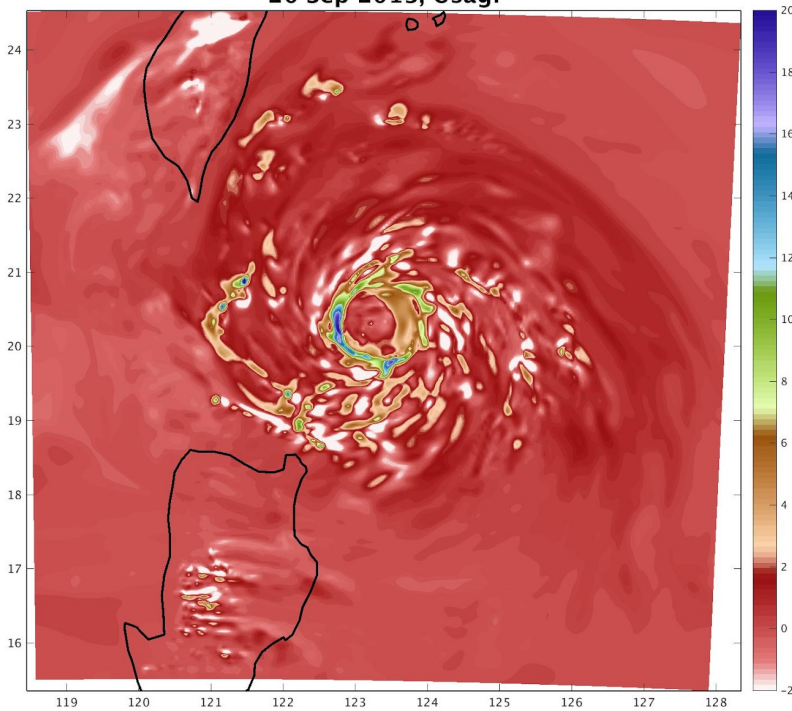


Figure 1 Parent domain (Top panel) and nested domain (Bottom panel) of a simulation for the case of TC Usagi (2013). Coloured fields show PV at the 8th model level, solely produced by diabatic processes (in color). In the topleft panel, the cyclone track and the nested domain size are shown sin black line and square, respectively.

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