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	2025
Project Title:	Understanding dynamics and impacts of cyclone systems through a comprehensive dataset of convection-permitting simulations
Computer Project Account:	spgrflao
Principal Investigator(s):	Emmanouil Flaounas
Affiliation:	Hellenic Centre for Marine Research (HCMR)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	1 January 2023
Expected end date:	31 December 2025

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	8,000,000	8,000,000	12,000,000	12,000,000
Data storage capacity	(Gbytes)	50Tb	50Tb	50Tb	50Tb

Summary of project objectives (10 lines max)

Given the multiple scales of atmospheric processes involved in cyclones development, high resolution simulations are irreplaceable research means to address open questions in dynamics and impacts. This project aims to fulfil a twofold objective:

- to build a first-of-its-kind comprehensive dataset of cyclone simulations at convection-permitting scales;
- to use this dataset for the ends of better understanding cyclone dynamics and impacts through research projects which have been proposed by the community, especially in the context of the MedCyclones COST Action.

Summary of problems encountered (10 lines max)

The implementation of this project has encountered a series of challenges which are already resolved at large extent. From the technical perspective, much of the first year was devoted to the optimal configuration of the WRF model, the automation of simulations' production chain and the compilation options that make the model cost efficient. Additional challenges were related to the post processing of simulations, where two Lagrangian models are combined to provide air parcel trajectories for the needs of specific research projects. Storage issues have been resolved by saving 3-hourly file outputs.

The main challenge

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

The project estimates the production of a series of simulations. According to the resources consumed so far we estimate the production of about 200 simulations of Mediterranean cyclones and about 400 simulations of North Atlantic cyclones. Simulations are expected to use the entire allocated amount of SBUs for 2023 and 2024. In short term (within few months), we aim at completing post-processing and make available the simulations to the community. The project has no SBUs allocated for the third and final year.

List of publications/reports from the project with complete references

Hatzaki, M., and Coauthors, 2023: MedCyclones: Working Together toward Understanding Mediterranean Cyclones. Bull. Amer. Meteor. Soc., 104, E480–E487, https://doi.org/10.1175/BAMS-D-22-0280.1.

Ambrogio Volonté, Emmanouil Flaounas, (2024) Sting jets in Mediterranean cyclones? Working towards their identification using high-resolution simulations, 3rd MedCyclones Workshop & Training School, 15-19 July 2024 | ESA-ESRIN, Frascati (Rome), Italy

Christian Ferrarin, Marco Bajo, Emmanouil Flaounas (2024) The marine and coastal hazards of Mediterranean cyclones, 3rd MedCyclones Workshop & Training School, 15-19 July 2024 | ESA-ESRIN, Frascati (Rome), Italy

Flaounas, E., Meynadier, R., Rakotoarimanga, H., Diouf, A., and Mustafa, R.: Explicit risk modelling of sting-jet extratropical cyclones. , EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-15033, https://doi.org/10.5194/egusphere-egu25-15033, 2025.

Summary of results

Model setup

The simulations production chain is mainly composed by (1) the limited area model WRF, (2) the WRF pre-processing system (WPS), (3) the Read/interpolate/plot (RIP) program (a post-processing tool adapted to WRF outputs), and (4) the Lagrangian model LAGRANTO.

The operational chain for the production of simulations starts with a prescribed number of cyclone tracks from ERA5, produced by the method of Flaounas et al. (2014). Each track is provided as an input to a Fortran program that produces the size and coordinates of the parent domain (at 14 km of horizontal resolution). The parent domain tightly encompasses the cyclone track. Then the program calculates the size of the nested domain (2.8 km), the directions and times of its predefined movements to always follow the cyclone centre. WPS is provided with all this information to produce the necessary input fields for WRF. The model will eventually perform simulations for each cyclone track using two-way nesting. Spectral nudging is applied to the parent domain with a strength that increases linearly from the mid-troposphere to the model top at 50 hPa. Spectral nudging is necessary to force the cyclone in the parent domain not to diverge from the prescribed track from ERA5.

After the model integration is finished, we use the RIP (read/interpolate/plot) program to release 10,000 air mass trajectories every ~11 km (every 4 grid points) within the nested domain. Trajectories are released forward and backward in time for 48 hours in each time direction at 950, 850, 800, 700 and 600 hPa (so 50,000 trajectories in total per release time). If the time of maximum intensity of the cyclone (deepest MSLP according to ERA5) is set at t0, then release times are set at t0-24h, t0-12h, t0 and t0+12h. This makes a total of 4 datasets per cyclone. Each dataset includes a maximum of 50,000 trajectories where each trajectory runs for a maximum of 96 hours (we only retain trajectories that do not start below ground, and have tracked air parcels for at least 12 hours before leaving the domain). All trajectories eventually escape the nested domain. Therefore, we extend them in the parent domain using LAGRANTO backwards and forward in time for 48 hours. The change of model for the parent domain was necessary for computational reasons. Being adapted to WRF outputs, RIP takes into account that nested domains are moving in time. Nevertheless, RIP was found to have a rather slow performance and requires one release time per run. The latter issue is inconvenient when extending the trajectories in the parent domain since air parcels escape the nested domain in different times.

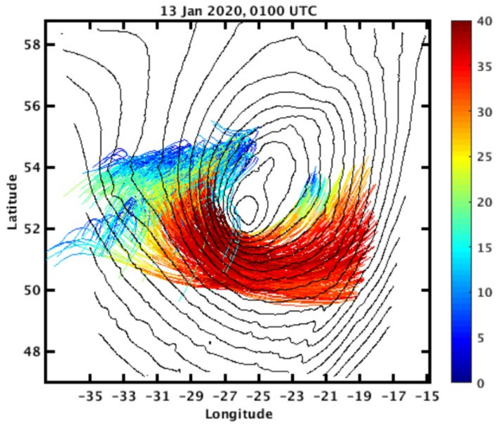

Fig. 1: *Air parcel trajectories that satisfy the condition of exceeding wind speed of 36 m s-1 below 700 hPa when they are close to the cyclone centre. We show only trajectory parts from 12 January 2020, 1900 UTC to 13 January 2020, 0700 UTC. Colorbar depicts wind speed in m s-1 and contour depicts the mean sea level pressure (cyclone centre is ~950 hPa).*

Windstorms due to Mediterranean and mid-latitude cyclones

In recent years, particular attention has been given to the production of results concerning high wind speeds in cyclone systems. In Volonté and Flaounas (2024), we identified specific Mediterranean storms exhibiting characteristics of extratropical cyclones that follow the Shapiro-Keyser lifecycle. For these storms, specific Lagrangian analyses were performed to identify the presence of sting jets. Our test case to verify that WRF is able to produce sting jets in cyclone systems has been done for storm Brendan (Fig. 1) that resulted in important socioeconomic impacts in the UK in January 2020. The nested WRF model domain at 2.8 km grid spacing, simulated maximum 850 hPa wind speeds exceeding 50 m/s at 03 UTC on 13 January, close to Brendan's center and in consistency with previous results on the same storm from Gray et al. (2021; Weather). The sting jets presented a typical structure, extending from the tip of the cloud head until the edge of the frontal-fracture region. Trajectory analyses for this event revealed air parcels undergoing descent and acceleration, features consistent with the dynamic signature of a sting jet.

Out of 200 Mediterranean cyclone simulations, we could identify a small fraction of system which seemed to develop sting jets during their mature stage. For a specific case on 26 March 1998, taking place in central Mediterranean, we identified in the WRF simulation, maximum winds exceeding 30 m/s west of the warm-core low center at 03 UTC. In this instance too, threshold-meeting trajectories exhibited ascent followed by descent and acceleration—again consistent with the kinetic definition of a sting jet. The most striking case however for sting jets in the Mediterranean region has been found for the cyclone system, developing on 6 February 2012. That system exhibited the development of a bent-back front, although the overall evolution was less reminiscent of a classic warm-seclusion extratropical cyclone and despite the presence of a clear warm core (Fig. 2). The cyclone has been a rapidly deepening system (23 hPa in 18 hours) that moved northward from the Gulf of Sidra to the Ionian Sea, showing features indicative of sting jet formation. In this event, the WRF model showed indeed warm seclusion formation as the cold front advanced eastward, with strong 850 hPa winds initially appearing south of the cyclone center and while the cyclone per-se remained nearly stationary (Fig. 2). Later, the most intense winds at 850 hPa developed on the northern flank of the cyclone center where trajectories showed a circular wrapping around it, not aligning with the behavior of a typical cold conveyor belt.

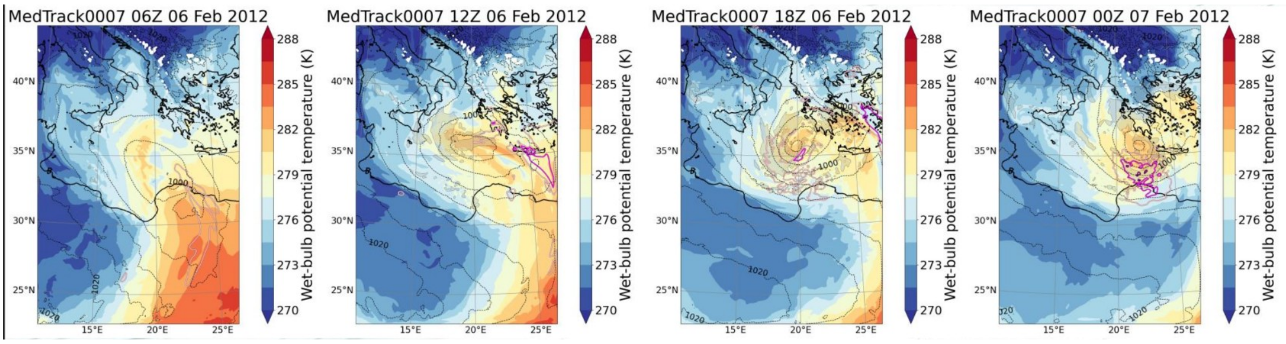

Fig 2: *Wet-bulb temperature at 850 hPa (in color) along with mean sea level pressure (in black contours) and high wind speed at 850 hPa (in magenta contours).*

Figure 3 shows air parcel trajectories associated with sting jets of the Mediterranean cyclone. These sting jets exhibit a marked descent, accompanied by increasing wind speeds and decreasing relative humidity as the parcels exit the cyclone's cloud head. These features are consistent with those expected from extratropical cyclones over the Atlantic Ocean that develop sting jets. Our results contribute to the growing evidence of "sting jet-like" (SJ-like) airstreams associated with strong near-surface winds in convection-permitting simulations of Mediterranean cyclones. However, relevant observational data still need to be investigated to assess how realistic these model outputs are. Further analysis is also required to better understand the underlying dynamics of these airstreams and to compare or contrast them with the more typical sting jets observed in mid-latitude cyclones taking place over the open oceans. Eventually however, the key issue is not one of terminology or "labeling", but of recognizing and understanding potentially uncommon, but significant pathways through which damaging surface winds can develop in Mediterranean cyclones.

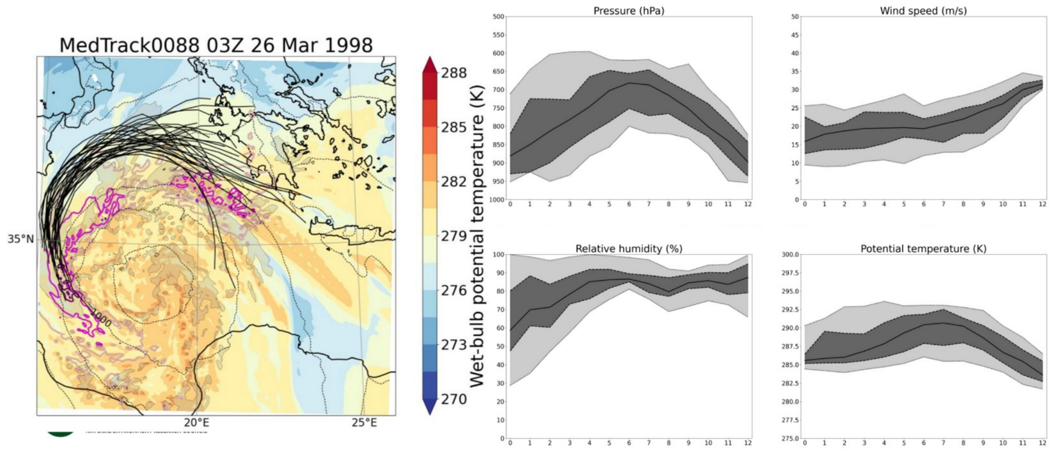

Fig 3: *(left panel) Wet-bulb temperature at 850 hPa (in color), high wind speed at 850 hPa (in magenta contours) and air parcel trajectories corresponding to stin jets. (right panel). Pressure level, Relative humidity, Wind speed and Potential temperature of sting jet air parcels (as shown in left panel).*

In this context, the same Mediterranean cyclone has also been examined by Ferrarin et al. (2024) in the context of sea-state related impacts. In their study, the wave model SHYFEM-WW3 was forced separately with ERA5 reanalysis and the higher-resolution WRF output. During the period associated with sting jet development, a striking difference emerged between the two simulations in terms of significant wave height (Fig. 4). The WRF-forced simulation produced more realistic and substantially higher wave heights and sea levels, particularly at observation stations in Crete, compared to the ERA5-forced simulation. These findings suggest a critical sensitivity of wave modeling to atmospheric forcing resolution and are currently the subject of ongoing investigation.

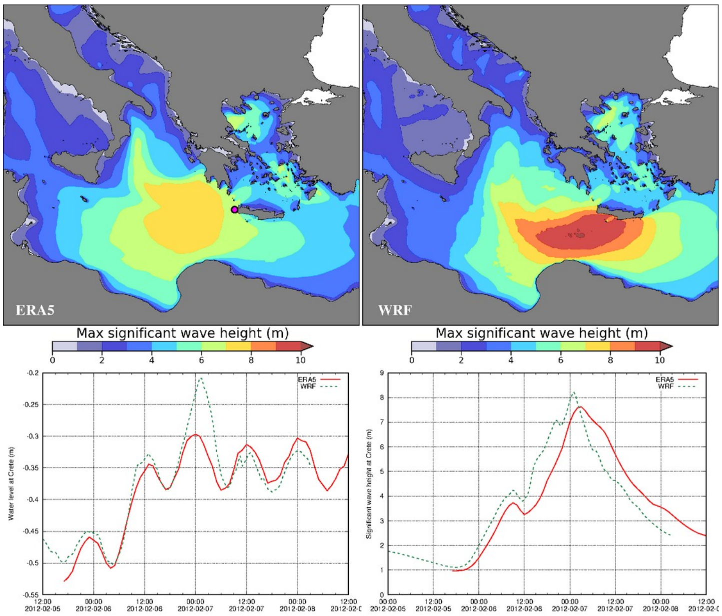

Fig 4: *(Top panels) max significant wave height on 7 Feb 2012 for SHYFEM-WW3, forced by ERA5 and WRF (in colour) along with (bottom panels) their time series at the location of western Crete.*

Analysis of the simulations is still ongoing, with a particular focus on high-impact cyclones over the Atlantic Ocean and their severe consequences across Europe. About 300 simulations have been performed for cyclones over the Euro-Atlantic domain, where about 100 cyclones present sting jets. Preliminary results (Flaounas et al., 2025) highlight the significant contribution of explicitly resolved sting jets to localized wind gusts, emphasizing the value of high-resolution modeling in capturing these hazardous features. Indeed, in a recent study, we simulated the expected losses that could be caused by severe storms. To quantify the added value of our high-resolution simulations, we utilized both parent and nested model domains at 14 km and 2.8 km scales. During collaborative work with AXA, we leveraged AXA's exposure portfolios across several European countries, including Ireland, the United Kingdom, France, Germany, and Belgium. By combining these exposure datasets with our in-house damage functions, we were able to simulate storm-related losses at the site level for each individual event. The loss model requires wind gust footprints as input—specifically, the maximum wind speeds recorded during the lifetime of each cyclone. For example, Figure 5 illustrates the wind gust footprint for Storm Eunice, which made landfall in Europe in 2022. The two simulations, at 14 km and 2.8 km resolutions, display broadly similar wind patterns with comparable peak gust magnitudes. However, the higher-resolution simulation reveals stronger wind speeds, particularly in areas impacted by a Sting Jet (highlighted in red on the left panel of Figure 5). This difference in resolution (and therefore on wind gust intensity) has a significant impact on the estimation of economic losses, resulting in an average of up to 20% relative increase among 46 intense storms which have been known about their impacts (not shown).

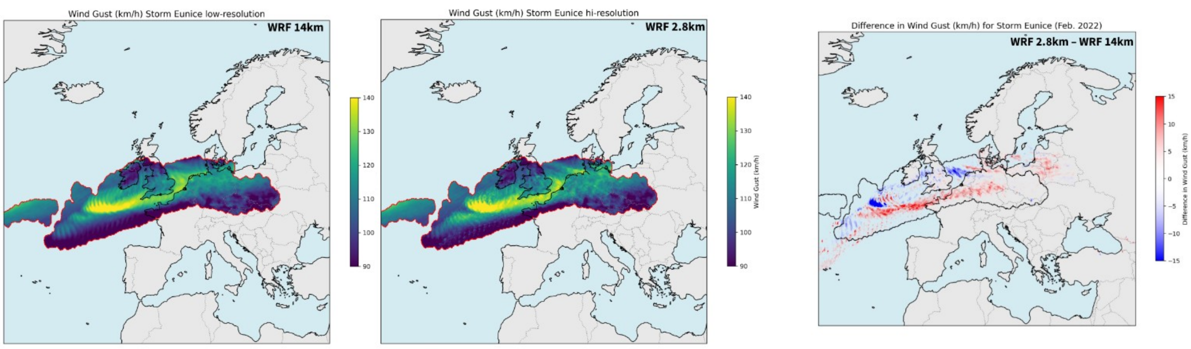

Fig 5: *(Left panels) wind gust footprint for storm Eunice (Feb 2022) from the parent and nested domain, at 14 and 2.8 km, respectively. (right panel) Difference of wind gust footprints between the two simulation domains.*

This study is still ongoing and aims at fully evaluating the added value of more accurate capturing of wind gust patterns associated with catastrophic cyclone airstreams like Sting Jets, which can significantly affect loss estimates. Our findings point to a meaningful physical footprint of sting jets in shaping windstorm damage patterns, which are often underestimated in coarser models. Furthermore, the effort to systematically explore the connection between the Atlantic and Mediterranean storm tracks is fostering valuable interdisciplinary collaboration between communities that traditionally have had limited interactions so far.

June 2025