EMI R&D 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	2026
Project Title:	Mapping the continuum of cyclone dynamics in the phase space of diabatic and baroclinic forcing
Computer Project Account:	sprgflao
Principal Investigator(s):	Emmanouil Flaounas
Affiliation:	Hellenic Centre for Marine Research
Start date of the project:	1/1/2025
Expected end date:	31/12/2027

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)	8M	4.1M	12M	3.6M
Data storage capacity	(Gbytes)	25TB	25TB	50TB	50TB

Summary of project objectives (10 lines max)

Simulate ~500 Euro-Atlantic cyclones with WRF (30 km parent, 10 km moving nest), nudged to ERA5 tracks for consistent life cycles.

- Diagnose online PV tracers to partition PV into convective, diffusive, radiative and frictional contributions.
- Apply piecewise PV inversion to quantify each process's contribution to the low-level cyclonic circulation (850 hPa relative vorticity).
- Classify cyclones by dominant process, establishing the diabatic–baroclinic continuum.
- Track how dominant processes shift through intensification and tropical/extratropical transition.

Summary of problems encountered (10 lines max)

During the past period, storage limitations and refinements to the PV-tracer code implementation had to be addressed. These were resolved to ensure the consistency and continuity of the simulation dataset across all cyclone cases, although they caused the project to fall behind schedule.

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

We aim to continue the simulations through 2027 to further complete the inventory of cyclone cases, adding more systems to those already produced. This will increase the statistical sample and improve the representativeness of the different kinds of cyclones spanning the diabatic–baroclinic continuum. The larger dataset will strengthen the robustness of the process-based classification and allow us to better characterise rarer categories, such as cyclones undergoing tropical or extratropical transition. In parallel, we will complete the PV-tracer diagnostics and piecewise PV inversion across the full ensemble to quantify the relative contributions of convective, diffusive, radiative and frictional processes to cyclone development.

List of publications/reports from the project with complete references

Flaounas E., Gray S., 2026: A Potential Vorticity Budget Framework for Quantifying the Role of Competing and Synergistic Processes in Tropical Cyclone Development, 4-9 October 2026, 21st Cyclone Workshop, Bad Durkheim, Germany

Summary of results

1. Preliminary work on the preparation of simulations

In this project, we use a large set of cyclone tracks identified from the ERA5 reanalysis dataset (Hersbach et al., 2020). For each cyclone track, we perform a dedicated two-domain simulation. The parent domain is designed to closely encompass the entire path of the cyclone, while a nested square domain measuring 4,000 km on each side follows the cyclone center throughout its evolution. This nested domain is large enough to capture all key dynamical features of the cyclone, including tropical cyclone convective eyewalls, frontal structures, and the associated airstreams. The two domains are configured with different horizontal resolutions: the parent domain uses a resolution of 30 km, and the nested domain uses a finer resolution of 10 km. This higher resolution aligns with the anticipated capabilities of future Ensemble Prediction Systems (EPSs). The nested domain consists of roughly 400 x 400 grid points and includes about 61 vertical levels, allowing for detailed representation of the cyclone's vertical structure.

Fig. 1 Cyclone tracks in May 2020, simulated by WRF in the context of the current project

To ensure that the simulated cyclones follow realistic tracks and maintain life stages consistent with observations, the wind field in the parent domain is strongly nudged toward ERA5 data. This nudging constrains the large-scale atmospheric flow and helps reproduce cyclone behavior comparable to reanalysis. In contrast, the nested domain is intentionally left without nudging. This allows the model to resolve important fine-scale processes autonomously, such as mesoscale convective systems and intricate dynamical interactions within the cyclone core. This approach forces the Weather Research and Forecasting (WRF) model to simulate cyclones with similar tracks and life cycles to those in ERA5, while still capturing cyclone dynamics with "optimal skill" and effectively minimizing model errors in the large-scale circulation. Figure 1 illustrates an example of all the cyclone tracks selected for a one-month period in May 2020. These tracks span the entire Northern Hemisphere, reflecting the wide range of cyclone types included in this study. Our dataset covers a rich diversity of systems, including tropical cyclones, Mediterranean cyclones, polar lows, subtropical systems, mid-latitude storms, and other less commonly studied cyclones that develop over land.

Work over the reporting period advanced along two complementary lines: a detailed process-based analysis of the potential vorticity (PV) budget of tropical cyclones, used to establish and validate the diagnostic framework, and its extension to extratropical cyclones over the Euro-Atlantic domain.

2. Process-based PV budget of tropical cyclones (ongoing work)

Any cyclone can be conceptualised as a coherent mesoscale PV anomaly which, owing to the invertibility property of PV, may be inverted to yield the cyclonic circulation of the system. Since PV is materially conserved only under adiabatic and frictionless conditions, and since air masses continuously exchange heat and momentum with their environment, quantifying the relative contribution of different processes to the PV budget is equivalent to quantifying the role of these processes in cyclone dynamics. The PV-tracer framework makes this decomposition explicit: total PV is the sum of PV_{co}, PV_{diab} and PV_{mo}, plus a small residual. The online diagnostic module we developed and use in this project decomposes the total atmospheric PV at every model time step into three additive components: a conserved tracer (PV_{co}), representing the PV that pre-existed the cyclone or entered through the domain boundaries; a diabatic tracer (PV_{diab}), accumulating temperature tendencies from microphysics, radiation and the boundary layer; and a momentum tracer (PV_{mo}), accumulating the momentum forcing from frictional and turbulent processes.

Tropical cyclones (TCs) represent the purely diabatic end of the cyclone continuum targeted by this project and therefore provide an ideal testbed for the PV-tracer diagnostics. As an examplary case, we simulated typhoon Usagi (2013) and hurricane Katrina (2005) with WRF. Both tracks and intensity TC evoluations have been reproduced realistically, providing an adequate basis for a PV-based analysis of cyclone development. Our results show that during intensification, convection is the main source of PV production and hence the main driver of TC development. As the cyclone matures, the cloudless eye emerges as a dynamically distinct substructure, bounded by a baroclinic zone between the warm core and its colder surroundings (not shown). Within the lower part of the eye, longwave radiation generates negative PV_{diab} at the ocean surface, which is advected inwards, while the interaction of frictional forces with the strengthening baroclinic zone generates positive PV_{mo}. Both contributions are large in absolute value and mutually compensating, with the frictional contribution to PV (i.e. PV_{mo}) outweighing PV_{diab}. Decay commences when the accumulation of negative PV_{diab} within the eye can no longer be balanced, highlighting ocean-surface processes as critical to the TC life cycle.

Figure 1 summarizes these results through Hovmöller diagrams of PV averaged within a 100 km radius of the cyclone centre. Total PV (panels a, b) forms a coherent tower extending from the surface to the tropopause, with values exceeding 2 PVU appearing first between 5 and 12 km altitude at the time of most rapid deepening. The decomposition into PV_{diab} (panels c, d) and PV_{mo} (panels e, f) reveals a striking vertical discontinuity: negative PV_{diab} develops bottom-up close to the surface, while PV_{mo} remains positive throughout the column with maxima near the surface. The two components display similar structures with opposite signs, indicating interconnected processes of PV destruction and production, whose sum yields a net positive PV budget in the lower and upper troposphere. The MSLP evolution (panels g, h) confirms that these structural transitions coincide with the intensification, mature and decay stages of both cyclones. A manuscript presenting these results is in preparation for submission (Flaounas and Gray, in prep.) and results will be presented to the 21st cyclones workshop in October 2026.

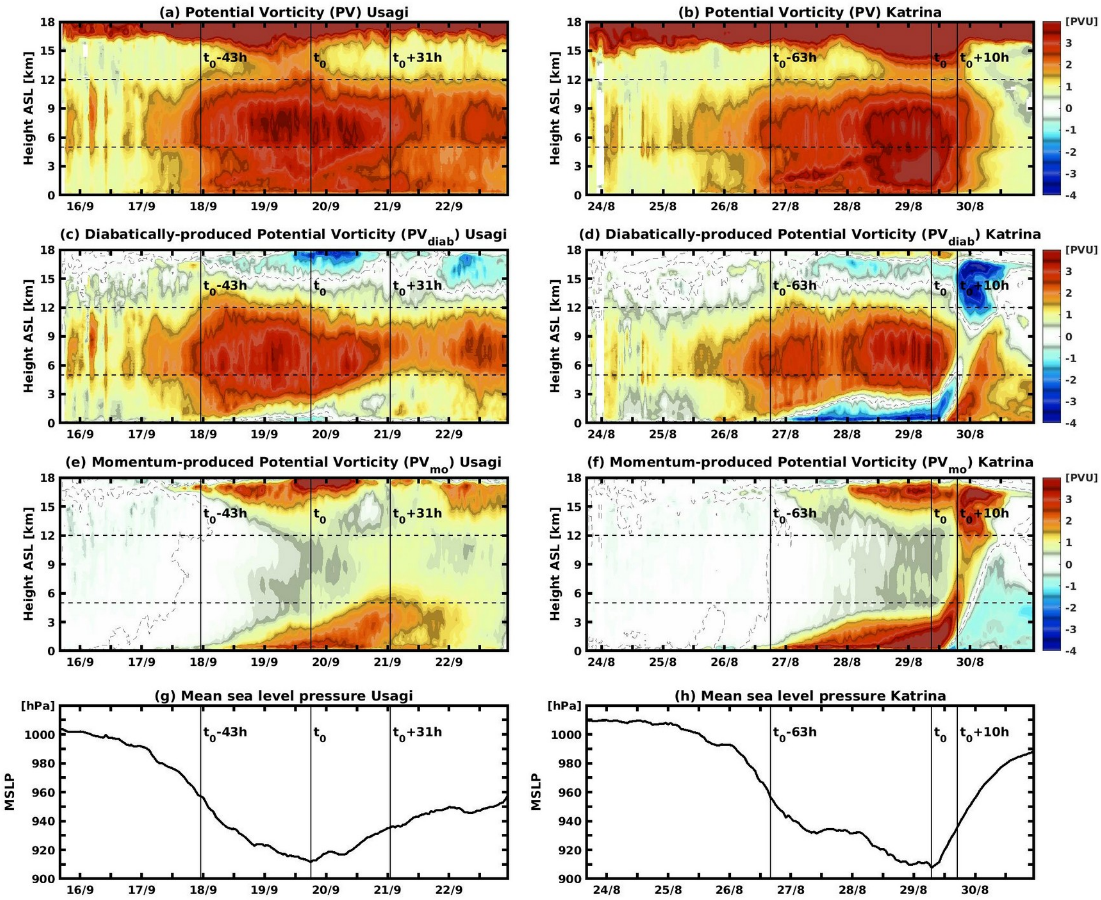

Fig. 1 *PV and MSLP evolution for TCs Usagi and Katrina.* ***(a)*** *Hovmöller diagram of total atmospheric PV (shading) averaged within 100 km around the centre of Usagi; the dashed contour depicts the 0 PVU isoline, horizontal dashed lines depict the levels of 5 and 12 km asl, and vertical solid lines depict different times with respect to the TC's maximum intensity (t_0).* ***(b)*** *as in* ***(a)****, but for Katrina.* ***(c)*** *and* ***(d)*** *as in* ***(a)*** *and* ***(b)****, but for PV_{diab} (shading);* ***(e)*** *and* ***(f)*** *as in* ***(a)*** *and* ***(b)****, but for PV_{mo}.* ***(g)*** *and* ***(h)*** *MSLP as a measure of the intensity of TCs Usagi and Katrina, respectively.*

3. Process-based decomposition of extratropical cyclones

Respect to a TC, an Extratropicasl cyclone (ETC) is expected to have also a strong baroclinic component affecting its intensity. Indeed, Figure 2 shows an example for an ETC over the North Atlantic Ocean on 21 May 2020. The top-left panel shows the total atmospheric PV, the top-right panel the diabatic component PV_{diab}, the bottom-left panel the conserved component PV_{co}, and the bottom-right panel the momentum component PV_{mo}; the three tracers add up to the total field. The decomposition shows that the PV anomaly collocated with the cyclone centre and along the frontal structures is largely diabatic in origin, while PV_{co} represents the smooth, large-scale environmental field advected into the domain — that is, the external baroclinic forcing on the resolved cyclone dynamics. PV_{mo} contributes a spatially confined but non-negligible positive anomaly close to the cyclone centre, consistent with the production of PV through the interaction of frictional forces with low-level baroclinicity. This example demonstrates the capability to decompose cyclones according to their driving processes and thereby to position each system along the diabatic–baroclinic continuum targeted by this project. Our analysis will continue with the systematic application of such decomposition to the full simulation ensemble and, most importantly, with piecewise PV inversion of the individual tracers, in order to quantify the actual contribution of each process to the low-level cyclonic circulation and hence to cyclone development.

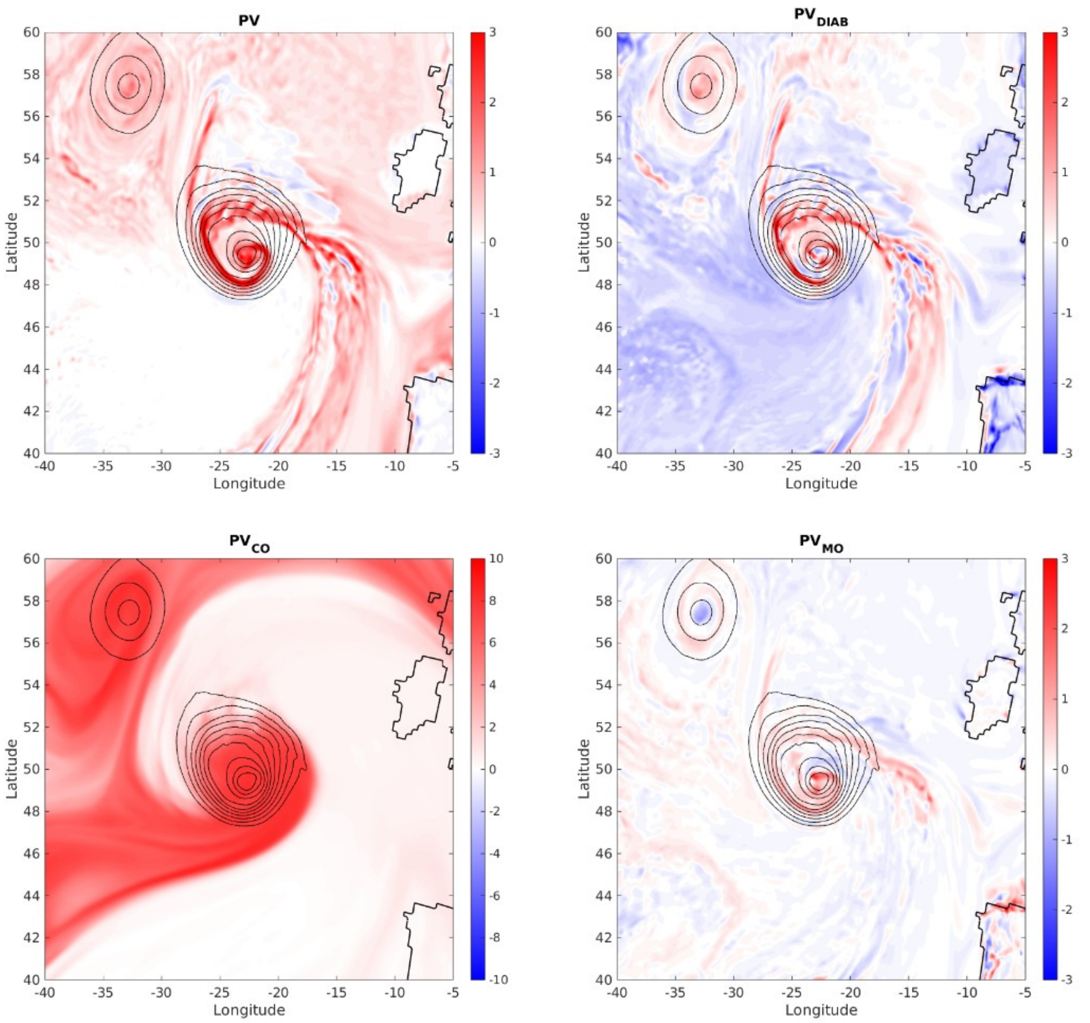

***Fig. 2** Decomposition of the PV field of a cyclone over the North Atlantic Ocean on 21 May 2020. Shading shows total atmospheric PV (top left), the diabatic PV tracer PV_{diab} (top right), the conserved PV tracer PV_{co} (bottom left) and the momentum PV tracer PV_{mo} (bottom right), in PVU. Black contours depict the sea level pressure field. Note the different colour scale used for PV_{co}. The three tracers add up to the total atmospheric PV.*