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:	Dynamical and risk assessment analysis under future climate conditions of tropical cyclones impacting the eastern North Atlantic
Computer Project Account:	SPESMART
Principal Investigator(s):	MARÍA LUISA MARTÍN
Affiliation:	ESCUELA DE INGENIERÍA INFORMÁTICA. UNIVERSIDAD DE VALLADOLID
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Daniel Santos (DMI), Juan Jesús González-Alemán (AEMET), Mariano Sastre (UCM), Pedro Bolgiani (UCM), Javier Díaz (UCM), Francisco Valero (UCM), Ana Montoro (AEMET), Carlos Calvo (UVA), Jose Ignacio Farrán (UVA), Íñigo Gómara (UVA), Mauricio López-Reyes (UCM)
Start date of the project:	01/01/2025
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)	12000000	3883650	12000000	10534455
Data storage capacity	(Gbytes)	25000	25000	25000	25000

Summary of project objectives (10 lines max)

The main purpose of the current proposal consists of evaluating the genesis and evolution of anomalous African East Waves (AEWs) and tropical transitions (TTs) that may pose a threat to southwestern Europe, and how Anthropogenic Climate Change (ACC) could contribute to amplify this risk. This response will be studied via the Pseudo Global Warming (PGW) approach for high-resolution mesoscale atmospheric simulations [Schär et al., 1996; Mooney et al., 2020; González-Alemán et al., 2023; Martin et al., 2024]. To the knowledge of this research team, this proposal is the first application of this kind of methodology to AEWs and TTs over the eastern North Atlantic (eNATL) basin [cf. Haarsma et al., 2021]. WRF, HARMONIE-AROME and MPAS mesoscale atmospheric models will be considered for this purpose. These models will be evaluated in very-high resolution mode (500 m - 3 km) for a better adaptation to future weather forecasts.

Summary of problems encountered (10 lines max)

The first objective of this project "To establish a robust climatology of the atmospheric environments related to AEWs and TTs genesis and evolution over the eNATL under present and future climate conditions" is developed. The study of the environmental conditions that promote the development of AEWs and TTs over the eNATL under present climate is developing as well as the analysis of the simulations of several TTs with HARMONIE is now carrying out. Moreover, some severe weather events (such as the DANA of Valencia) has been simulated with WRF. However, we have several problems in simulating, at very high resolution, some of those selected systems in the previous tasks, mainly due to obtaining sub-hourly outputs when using the HARMONIE model.

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

Although some severe events have been simulated using the novel PWG methodology, the task associated at the simulation, at very high resolution, of cyclones with tropical characteristics and AEWs with anomalous northern trajectory in the vicinity of Spanish territory is carrying out. To do this, selected AEWs and TTs, picked up from the pool of events obtained in the Objective 1, will be studied under present and future climate conditions with HARMONIE, WRF and MPAS mesoscale atmospheric models. Additionally, the effect of the ACC conditions over the AEWs and TTs meteorological behavior will be analyzed with special emphasis on the dynamics and meteorological evolution of selected events and the possible threat to Spanish territory as well as the meteorological impacts (wind gusts, precipitation, etc.) of these events.

List of publications/reports from the project with complete references

Publications

- Díaz-Fernández, J., C. Calvo-Sancho, P. Bolgiani, M. Sastre, M. López-Reyes, S. Fernández-González, M.L. Martín (2025). Effect of complex orography on numerical simulations of a downburst event in Spain. Atmospheric Research, 314, 107821; https://doi.org/10.1016/j.atmosres.2024.107821.
- Calvo-Sancho, C., Díaz-Fernández, J., González-Alemán, J.J., Halifa-Marín, A., Miglietta, M.M., Azorín-Molina, C., Prein, A.F., Montoro-Mendoza, A., Bolgiani, P., Morata, A., & Martín, M.L. (2025). Climate change unleashed: physical-based attribution analysis proves human-induced amplification of Valencia's deadly flooding. DOI: 10.21203/rs.3.rs-6709965/v1
- Díaz-Fernández, J., Calvo-Sancho, C., Bolgiani, P., González-Alemán, J.J., Morata, A., Santos-Muñoz, D., & Martín, M.L. (2026). Case study of a supercell outbreak in Spain and cost-benefit analysis of the nesting approach in HARMONIE-AROME. Atmospheric Research. Atmospheric Research 334, 108774

- Montoro-Mendoza, A., Calvo-Sancho, C., González-Alemán, J.J., Díaz-Fernández, J., Bolgiani, P., & Martín, M.L. (2026). Strengthening of favorable environments for North Atlantic tropical cyclogenesis in midlatitudes in a warmer climate. npj Climate and Atmospheric Science volume 9, Article number: 45.
- López-Reyes, M., Martín, M.L., Calvo-Sancho, C. & González-Alemán, J.J. (2026). Dynamic forcing behind Hurricane Lidia's rapid intensification. Weather and Climate Dynamics. https://doi.org/10.5194/wcd-7-523-2026.
- García-Miguel, A., Díaz-Fernández, J., Calvo-Sancho, C., López-Reyes, M., Bolgiani, P., & Martín, M.L. (2026).). Projected changes in wind speed and power over Iberia and surrounding maritime areas using CMIP6 models. Wind energy, in review.
- Calvo-Sancho, C., Rotunno, R., Montoro-Mendoza, A., González-Alemán, J.J., Bolgiani, P., & Martín, M.L. (2026). The role of moist convection and mesoscale processes in achieving the final stage of a tropical transition: Hurricane Ophelia. In review.
- López-Reyes, M., Calvo-Sancho, C., León-Cruz, J. F., Meulenert, Á., Galvez, J. M., Díaz-Fernández, J., González-Alemán, J. J., & Martín, M. L. (2026). A multivariable approach to the regional calibration of the Gálvez–Davison Index across Mexico's climate regimes. Earth Systems and Environment. In review.
- Gómez-Plasencia, P., González-Alemán, J. J., Calvo-Sancho, C., Rodríguez-Acosta, E. J., Bolgiani, P., Díaz-Fernández, J., Montoro-Mendoza, A., Martín, M. L., & Gómara, I. (2026). Convective activity within a tropical cyclone undergoing extratropical transition over a warmer ocean: Tropical Storm Delta (2005). Weather and Climate Dynamics. In review.
- Rodríguez-Acosta, E. J., Gómez-Plasencia, P., Calvo-Sancho, C., González-Alemán, J. J., Bolgiani, P., Gómara, I., & Martín, M. L. (2026). Synoptic-scale environment of African Easterly Waves with anomalous northward trajectories. Weather and Climate Dynamics. In preparation.

Conferences/Meetings:

- Díaz-Fernández, J., Calvo-Sancho, C., Bolgiani, P., Farrán, J. I., Luna, M. Y., & Martín, M. L. (2025, 22–24 de enero). Proyecciones futuras de los precursores de ondas de montaña en la Sierra de Guadarrama utilizando modelos climáticos de CMIP6 [Comunicación oral]. XIII Congreso Internacional de la Asociación Española de Climatología, San Lorenzo del Escorial, España.
- Montoro-Mendoza, A., Calvo-Sancho, C., González-Alemán, J. J., Díaz-Fernández, J., Bolgiani, P., Sastre, M., & Martín, M. L. (2025, 22–24 de enero). Influencia del cambio climático antropogénico en ambientes favorables para el desarrollo de transiciones tropicales en el Atlántico Norte [Comunicación oral]. XIII Congreso Internacional de la Asociación Española de Climatología, San Lorenzo del Escorial, España.
- Calvo-Sancho, C., Rotunno, R., Montoro-Mendoza, A., González-Alemán, J. J., López-Reyes, M., & Martín, M. L. (2025, 22–24 de enero). Evolución del calentamiento en la transición tropical del huracán Ophelia [Comunicación oral]. XIII Congreso Internacional de la Asociación Española de Climatología, San Lorenzo del Escorial, España.
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- González-Alemán, J. J., Oltmanns, M., González-Herrero, S., Donat, M., Doblas-Reyes, F., Vitard, F., Riboldi, J., Álvarez-Castro, C., Barriopedro, D., & Jiménez-Esteve, B. (2025, 27 de abril–2 de mayo). From Greenland to the Mediterranean Sea: Unveiling a new cascade mechanism under anthropogenic warming? [Comunicación en congreso]. EGU General Assembly 2025, Viena, Austria.
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- Azorin-Molina, C., Calvo-Sancho, C., Martin-Barrio, A., Granell-Haro, F., Gomez-Reyes, J., Prein, A. F., González-Alemán, J. J., Vicente-Serrano, S. M., McVicar, T. R., Chen, D., Zeng, Z., Pirooz, A., Gimeno, L., Nieto, R., Martinez-Roig, M., Plaza-Martín, N. P., & Martín, M. L. (2025, 7–12 de septiembre). The DOWNBURST MXO: a real-time downburst monitoring service in eastern Spain [Póster]. EMS Annual Meeting 2025, EMS2025-446. https://doi.org/10.5194/ems2025-446. Liubliana, Eslovenia.
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- González-Alemán, J. J., Gómez-Plasencia, P., Calvo-Sancho, C., Gómara, I., & Martín, M. L. (2025, 17–21 de noviembre). Convective activity behaviour on tropical cyclones impacting Europe in a warmer world [Póster]. 12th European Conference on Severe Storms, ECSS2025-202. https://doi.org/10.5194/ecss2025-202. Utrecht, Países Bajos.
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- Rodríguez-Acosta, E. J., Gómez-Plasencia, P., González-Alemán, J. J., Calvo-Sancho, C., Bolgiani, P., Díaz-Fernández, J., Martín, M. L., & Gómara, I. (2026, 13–15 de enero). Climatological environments associated with African Easterly Waves with anomalous trajectories [Comunicación en congreso]. Workshop on Climate Change, Variability, Predictability, Impacts and Responses in West Africa (WA-CLIM), Dakar, Senegal.
- Gómara, I., Calvo-Miguélez, E., Rodríguez-Fonseca, B., Coll, M., & Ortega, P. (2026, 13–15 de enero). ENSO impacts on marine ecosystems and fisheries in the tropical and South Atlantic [Comunicación en congreso]. Workshop on Climate Change, Variability, Predictability, Impacts and Responses in West Africa (WA-CLIM), Dakar, Senegal.
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- Rodríguez-Acosta, E. J., Gómez-Plasencia, P., González-Alemán, J. J., Calvo-Sancho, C., Bolgiani, P., Díaz-Fernández, J., Morata, A., Montoro-Mendoza, A., Martín, M. L., & Gómara, I. (2026, 25–27 de febrero). Análisis sinóptico comparativo de dos sistemas tropicales con impacto en las Islas Canarias [Comunicación en congreso]. XXXVII Jornadas de la Asociación Meteorológica Española, Málaga, España.
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- Kushabaha, A., González-Alemán, J. J., Miglietta, M. M., Mastrangelo, D., & Panegrossi, G. (2026, 3–8 de mayo). Evaluation of a deep learning model to classify convective and stratiform precipitation patterns [Comunicación en congreso]. EGU General Assembly 2026, Viena, Austria.
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- González-Alemán, J. J., Oltmanns, M., González-Herrero, S., Vitard, F., Donat, M., Doblas-Reyes, F., Barriopedro, D., Riboldi, J., Calvo-Sancho, C., Jiménez-Esteve, B., Cos, P., & Wehner, M. (2026, 3–8 de mayo). Emerging evidence of Greenland Ice Sheet melt influence on recent Euro-Mediterranean record-breaking heat and convective storms [Comunicación en congreso]. EGU General Assembly 2026, Viena, Austria.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

As it is abovementioned, the task related to find TTs and AEWs with anomalous tracks within the eNATL in ERA-5 reanalysis (1940-present) is completed. In a first analysis, to study cyclones developed from anomalous AEWs, trajectories in the Atlantic Ocean have been analysed using the HURTAD2 database (Landsea and Franklin, 2013) between the years 1979-2022. To select those cyclones coming from anomalous easterly waves, those that exceed the 90th percentile in latitude and longitude have been selected. To this end, firstly, a statistical analysis is carried out of all the points of the cyclone paths in the Atlantic region between longitudes 80 º W and 10 º W and latitudes 10 º N and 30 º N, in which the 90th percentile of both is calculated (Wilks, 2011).

In a first step, the longitudes are considered (Figure 1). Figure 1a shows the green dots corresponding to the points of the trajectories equal to or greater than the 90th percentile of length. Figure 1b also shows the histogram of all lengths, where the 90th percentile value is marked with a red line, leaving the new study group on the right.

a) b)

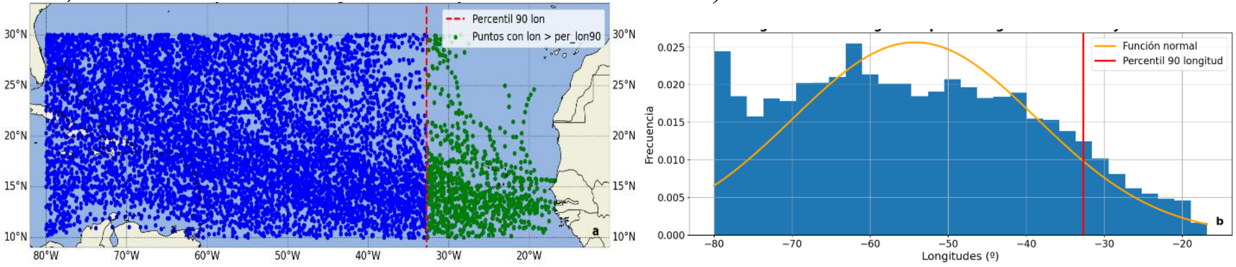

Figure 1: (a) Tracks of the cyclones selected according to the 90th percentile (represented by the red line) of the longitudes. (b) Distribution of cyclones selected in (a) with normal function (orange line) and 90th percentile value (red line).

Same analysis has been performed for latitudes (Fig. 2). As can be seen in Figure 2a, the points of the trajectories that have been selected with this methodology are those represented in green, above the black dashed line that represents the 90th percentile. After these analyses, the number of points will be reduced, which can be seen in the histogram of the frequencies of the latitudes present in Figure 2b where from the percentile value the values are extremely low.

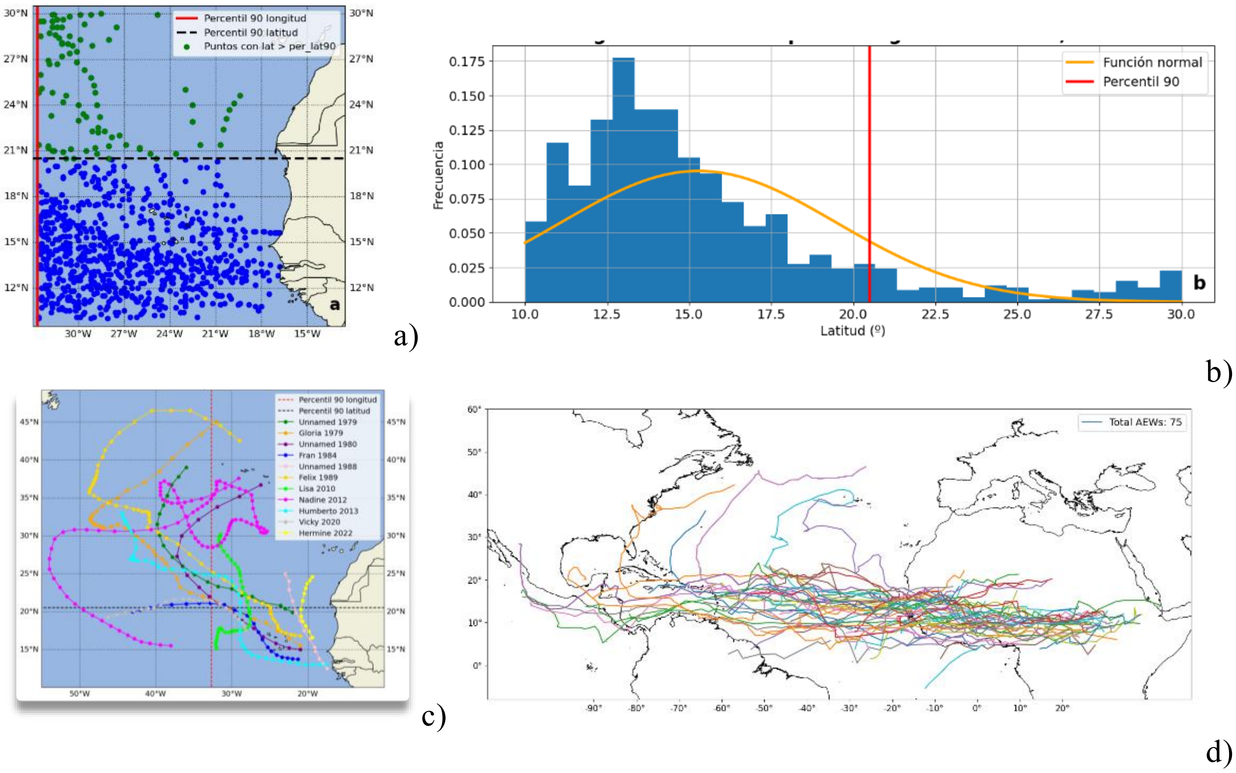

Figure 2: (a) Tracks of the cyclones selected according to the 90th percentile (represented by the red line) of the latitudes. (b) Wind distribution of cyclones selected in (a) with normal function (orange line) and 90th percentile value (red line). (c) Cyclones trajectories identified during the period 1979-2022 as those that have an anomalous trajectory and come from an EAWs. Dashed red line represents the 90th percentile of longitude and the dashed black line represents the 90th percentile of latitude. (d) EAWs identified during 2022 from ERA5.

We first selected (Fig. 2c) a pool of cyclones from AEWs with anomalous trajectories from 1979-2022. Right now, this database has been recently extended from 1940 to 2024 using ERA5. As an example, Figure 2d shows the AEWs obtained in 2022.

Moreover, the objectives related to comprehensively characterize the environmental conditions that promote the development of AEWs and TTs over the eNATL under present climate and future climate conditions are already achieved. Additionally, monthly climatologies of relevant variables for AEW/TT genesis and evolution in CMIP6 simulations are done (Montoro-Mendoza et al., 2026).

Results indicate that ACC is intensifying tropical cyclones and shifting them poleward, raising concerns for Europe. Projections suggest these cyclones will impact higher latitudes with increasing intensity, though uncertainties remain. We have studied the North Atlantic (NATL) basin's autumn climatology (SON), focusing on environments conducive to TT), as most cyclones affecting Europe originate from TTs during this season. Several CMIP6 climate models under the historical and SSP5-8.5 scenarios are used covering the 1981–2100, with the ERA5 reanalysis employed as a reference to support the results. Moreover, we have derived a novel metric for studying the TTs, named Tropical Transition Favorability Index (TTFI) that integrates key variables to quantify environmental favorability for TTs in the NATL. Findings indicate a progressive tropicalization of the NATL basin under SSP5-8.5, driven by increased sea surface temperatures and humidity, while dynamic constraints weaken. These changes suggest a higher likelihood of TTs, increasing the risk from these destructive systems.

The TTFI evolution throughout the XXI century is presented in Figure 3. Figure 3b shows that the maximum values are reached over the central and western part of the NATL basin, indicating that this region is particularly conducive to TTs development during SON. The TTFI range and pattern appreciated in Figure 3b closely match those from the ERA5 reanalysis (Fig. 3a), showing a high level of accuracy. This strong agreement suggests that the multi-model CMIP6 data used effectively captures the climatological characteristics of the TTFI. The TTFI calculated from the real TT cases during the 1979 – 2023 period presents values ranging from an approximate minimum of 4 TTFI units at the outer edges of the TTs composite to an approximate maximum of 33 TTFI units near the center of the systems composite (not shown). Given this threshold, areas in Figure 3b where the TTFI meets or exceeds 4 TTFI Units are marked with stripes, indicating regions where the minimum TTFI observed in real TT events is reached. This approach helps delineate zones that align with the most favorable TT environments.

Figures 3c, d reveal statistically significant positive anomaly values across the whole domain, with the most pronounced increases over the central – western NATL, especially in the far future period (Fig. 3d). This pattern is consistent with the results obtained from the analyzed variables, all of which suggest an intensified tropicalization of the NATL. The higher TTFI values in the central-western NATL, appreciated in Figure 3b, compared to the eastern part aligns with findings from Galarneau et al. (2015) and Calvo-Sancho et al. (2022), since they prove that the environmental conditions for TTs development have historically been less favourable in the eastern region.

However, under the influence of ACC, the TTFI undergoes a statistically significant increase, primarily in the central-western NATL, but also extending to northern and eastern parts of the NATL basin. It is important to note that the striped areas (TTFI $\geq$ 4 TTFI Units) expand substantially under the influence of the ACC in Figures 3c, d. The increase in the spatial extent of regions exceeding the 4 TTFI Units threshold indicates a broader area becoming conducive to TTs development. This expansion is particularly pronounced in the far future scenario (Fig. 3d), where high TTFI values extend further north-eastward. Such an intensification and expansion suggest that the eNATL, including its coastal regions, could experience an enhanced influence from TTs activity, potentially increasing the risk of TT-related impacts along the eNATL coast under the SSP5-8.5 scenario. As a result, the entire basin becomes more conducive to TTs formation, especially toward the latter part of the XXI century. It should be noted that the anomaly values reach up to +12 TTFI Units in the far future scenario (Fig. 3d), which nearly double the highest values obtained in the reference period (Fig. 3b).

These findings underscore the importance of continued monitoring and improved modelling of TTs development in the NATL, particularly under high-emission scenarios. An increased occurrence of TTs may have significant socio-economic implications for the NATL coastal regions.

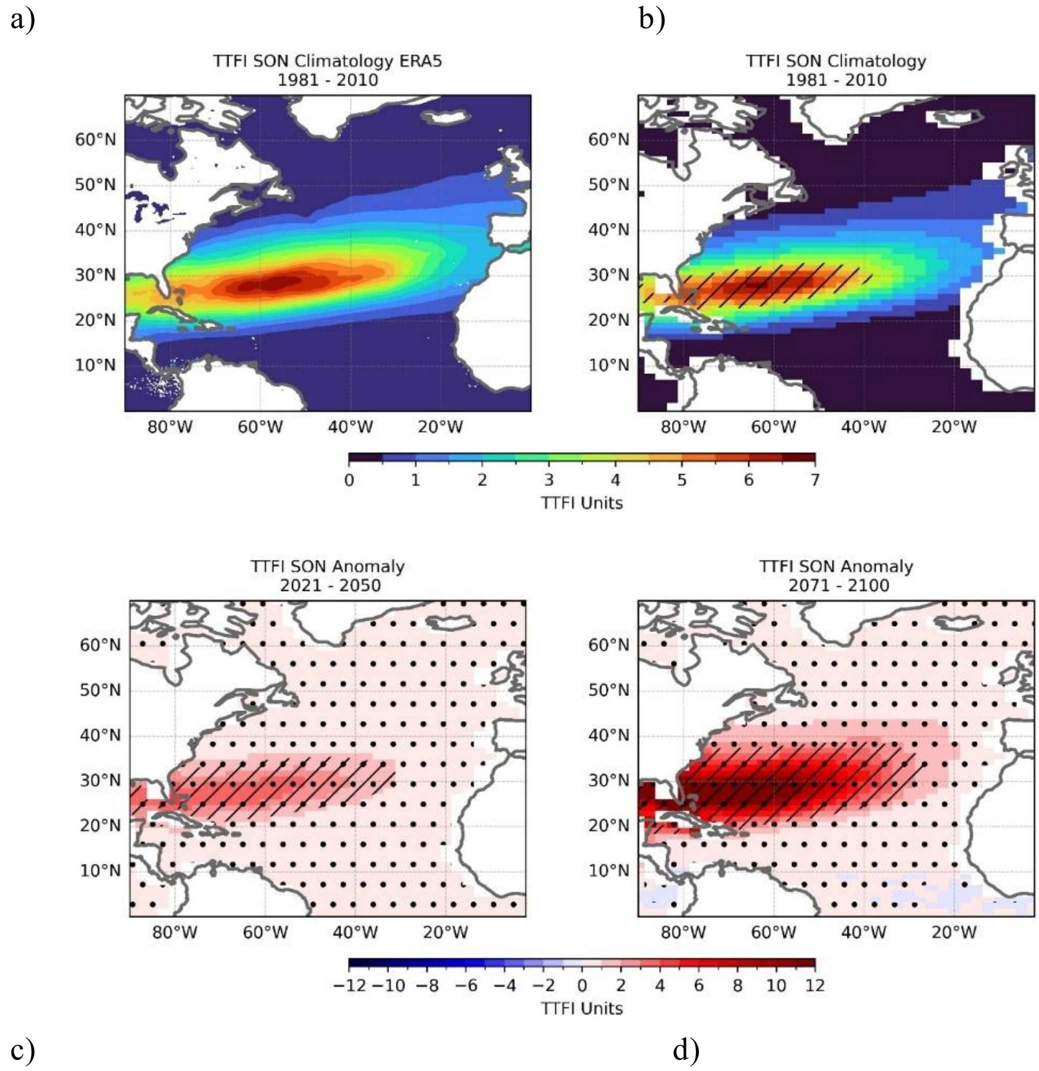

Figure 3: SON historical climatology of the TTFI (TTFI Units) from a) the ERA5 reanalysis dataset, b) the multi-model CMIP6 composite. SON anomaly values with respect to b) for the c) near future period and d) far future period. Black dots indicate statistically significant anomalies based on the Mann–Whitney U test (α=0.05). Striped regions in b) indicate where the TTFI value is higher or equal to 4 TTFI Units; in c) and d) indicate where the TTFI value is higher or equal to 4 TTFI Units adding the anomaly value to the b) field.

On the other hand, the influence of warmer sea surface temperatures (SSTs), expected in future climates, is studied in the convective activity of Tropical Storm Delta. Delta, which caused strong damage over the Canary Islands (Spain) in November 2005, is representative of a tropical cyclone (TC) experiencing an extratropical transition (ET) on its path to western Europe (Beven, 2006). Two simulations of the storm were performed with the high-resolution atmospheric numerical model HARMONIE-AROME: a control simulation with initial and boundary conditions from the ERA5 reanalysis, and a warm simulation where a uniform perturbation of +2 ºC was added to the SSTs surrounding the cyclone. The convective activity was analysed only in the convective cells near the cyclone's centre, employing the cloud tracking package Tobac, based on brightness temperature.

Figure 4 shows the trajectory and evolution of minimum SLP and maximum sustW10 in the Control Simulation (CSIM) and the perturbed + 2 ºC simulation (+2SIM). Here, the trajectory of the cyclone is shifted to the south in +2SIM in comparison CSIM, approaching to the Canary Islands. This displacement could have increased the impacts over the archipelago.

The minimum SLP evolution (Fig. 4b) shows that HURDAT observations depict a notable drop followed by a steady increase until the final dissipation of the cyclone. CSIM shows a similar behaviour, although the minimum SLP drop is much less pronounced. The minimum SLP in +2SIM dropped notably in comparison to CSIM, depicting pressure values typical of hurricanes belonging to CAT. 2 (Simpson, 1974) from 27 November 03:00 UTC until 28 November 09:00 UTC.

+2SIM shows higher maximum sustW10 and lower minimum SLP than CSIM which reflects a more intense cyclone. Specifically, Delta exhibits hurricane status maximum sustW10 values for two complete days from 27 November 04:00 UTC, peaking on 28 November 21:00 UTC with CAT. 3 wind speeds (183 km h^{-1}). The highest wind gust, 220 km h^{-1} (not shown), occurs when Delta is closest to the Canary Islands. This is relevant due to the increase in the socioeconomic impact in the islands in a future warmer scenario.

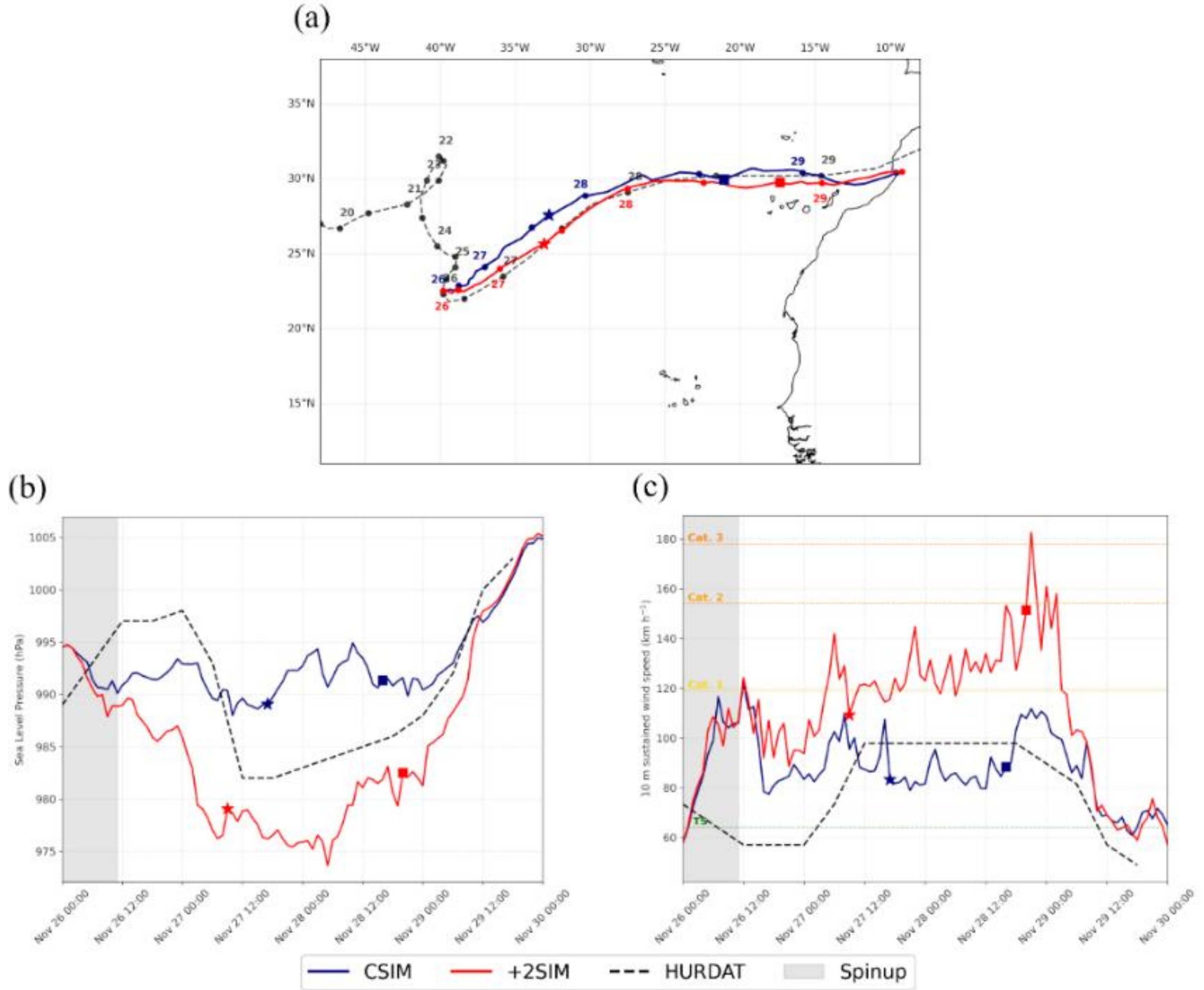

Figure 4: Comparison of different aspects of Delta in both simulations: (a) Trajectory, (b) minimum SLP, (c) maximum sustW10. In (a), dots indicate positions at 00:00 and 12:00 UTC, while day numbers are plotted at 00:00 UTC. Dotted black lines refer to the best track for Delta from HURDAT. The grey window indicates the first timesteps of the simulations, still influenced by the spinup. Horizontal dotted coloured lines in (c) indicate the thresholds for different TC categories in the Saffir-Simpson scale (The Saffir-Simpson Team et al., 2012). Stars and squares denote the beginning and the end of the ET, respectively, in both scenarios.

Delta's CPS (Hart, 2003) reveals differences between the two scenarios (Fig. 5). Regarding the thermal wind (V_T^U and V_T^L), CSIM exhibits a warm low-level core combined with a cold upper-level core (Fig. 5b), -i.e., a shallow warm core- a hybrid structure typical of subtropical cyclones (González-Alemán et al., 2015; Quitián-Hernández et al., 2021). In contrast, in +2SIM Delta develops a deep warm core, turning into a more tropical system. This is produced by the enhanced convection in the warmer scenario (see more in Gómez-Plasencia et al. (2026)), which promotes heating in higher levels in the troposphere, while the latent heat release in the control scenario is more reduced.

In +2SIM the cyclone starts to lose notably its horizontal symmetry on 27 November 09:00 UTC, while in CSIM Delta experiences this process about 8 h later (Fig. 5a). This highlights that the

ET begins earlier in the warmer scenario. This is produced due to Delta being a more intense and vertically extended cyclone, which interacts earlier and more efficiently with the upper-level trough (not shown) and the vertical wind shear. However, this earlier start of the ET is not in line with what Ribberink et al. (2026) found when simulating Hurricane Ophelia (2017) with different perturbations in the atmospheric temperatures and the SSTs, where a larger warm-up resulted in a later ET beginning. The difference between results of Ribberink et al. (2026) and these may be in the asymmetric convective structure displayed by Delta (Fig. 5c) due to the dry intrusion produced by a mesoscale tropopause depression, while Ophelia kept an axisymmetric convection.

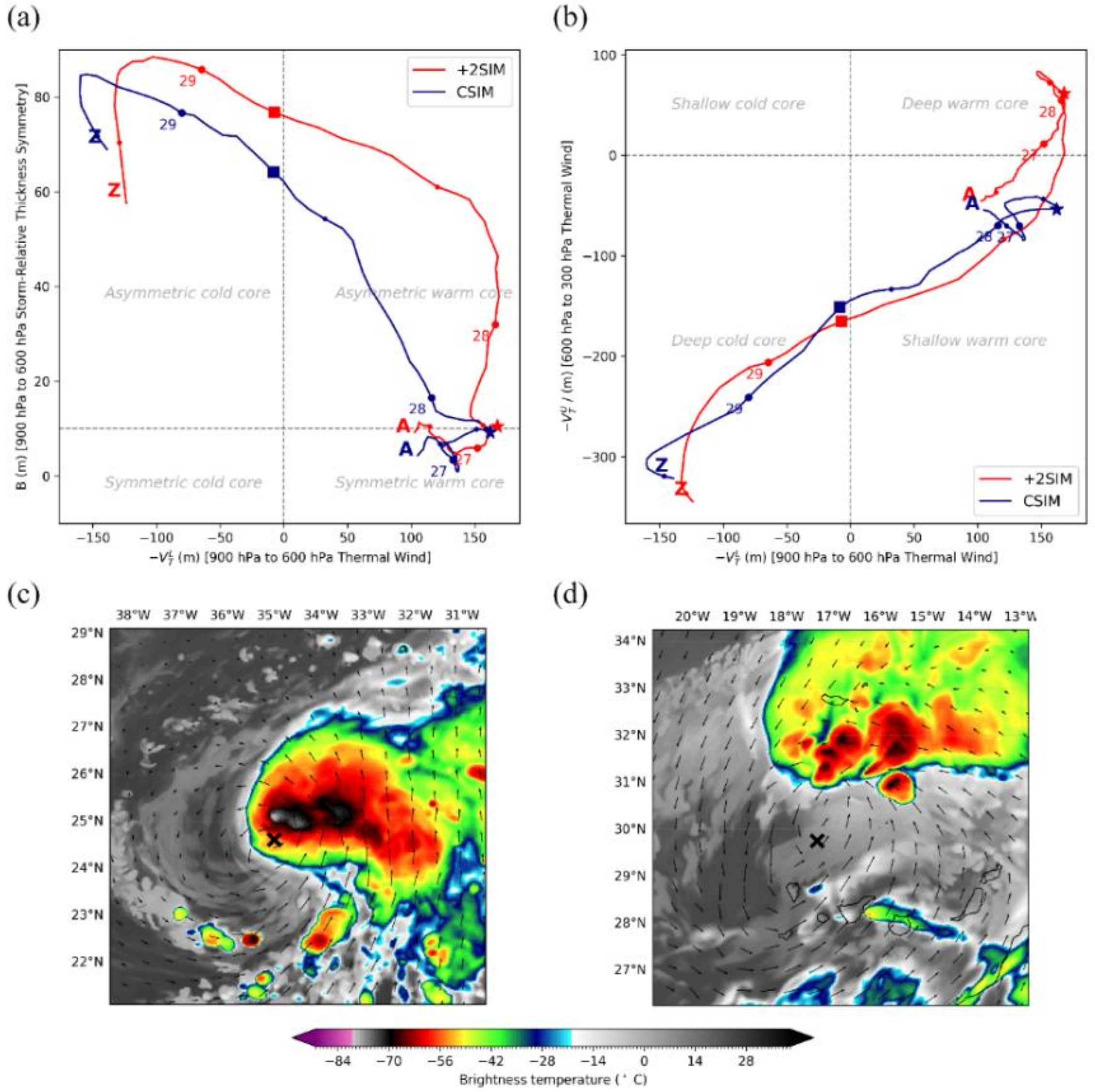

Figure 5: CPS diagrams for Delta in both simulations: (a) low-troposphere thermal wind vs thickness asymmetry, (b) low-troposphere thermal wind vs upper-troposphere thermal wind. Dots indicate positions in the CPS at 00:00 and 12:00 UTC, while day numbers are plotted at 00:00 UTC. A and Z mark initial and final positions, and stars and squares denote the beginning and the end of the ET, respectively. BT field at: (c) 04:00 UTC 27 November 2005, and (d) 20:00 UTC 28 November 2005, for +2SIM. Black arrows indicate 925 hPa wind vectors, and the black cross marks the cyclone's centre.

From the analysis of additional variables, the results show that increases in low-level water vapor flux, together with lower LCL and LFC levels and increased CAPE, create an environment more favourable for the development of deep moist convection in the warmer ocean simulation. These thermodynamic changes lead to more frequent intense moist updrafts and a larger number of convective cells associated with the cyclone, with greater vertical extent and higher precipitation rates. Consequently, Delta becomes a more intense and deeper TC, driven by latent heat release, reaching hurricane status. Later, Delta's ET starts earlier and gets extended over time, while turning notably more severe too. These results may contribute to a better understanding of the behaviour of convection within cyclones with tropical characteristics affecting the Macaronesia and Western Europe under future climates. More information can be found in Gómez-Plasencia et al. (2026).

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