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:	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
Data storage capacity	(Gbytes)			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 developing. The task related to find TTs and AEWs with anomalous tracks within the eNATL in ERA-5 reanalysis (1940-present) is completed. We have a pool with systems with tropical characteristics and anomalous tracks that will be studied. 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. 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)

The next task will be the application of the novel PWG methodology to simulate, at very high resolution, cyclones with tropical characteristics in the vicinity of Spanish territory. To do this selected AEWs and TTs 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.

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. Nature Communications. Under Review.

- Montoro-Mendoza, A., Calvo-Sancho, C., González-Alemán, J.J., Díaz-Fernández, J., Bolgiani, P., & Martín, M.L. (2025). Strengthening of favorable environments for North Atlantic tropical cyclogenesis in midlatitudes in a warmer climate. npj Climate and Atmospheric Science. Under Review.
- Díaz-Fernández, J., Calvo-Sancho, C., Bolgiani, P., González-Alemán, J.J., Morata, A., Santos-Muñoz, D., & Martín, M.L. (2025). Case study of a supercell outbreak in Spain and cost-benefit analysis of the nesting approach in HARMONIE-AROME. Atmospheric Research. Under Review.
- López-Reyes, M., Martín, M.L., Calvo-Sancho, C. & González-Alemán, J.J. (2025). The key role of trough-tropical cyclone interaction in the rapid intensification of Hurricane Lidia. Geophysical Research Letters. Under Review.
- García-Miguel, A., Díaz-Fernández, J., Calvo-Sancho, C., López-Reyes, M., Bolgiani, P., & Martín, M.L. (2025). Future changes in wind energy source in Spain. In preparation.
- Calvo-Sancho, C., Rotunno, R., Montoro-Mendoza, A., González-Alemán, J.J., Bolgiani, P., & Martín, M.L. (2025). The role of moist convection and mesoscale processes in achieving the final stage of a tropical transition: Hurricane Ophelia [2017]. In preparation.

Conferences/Meetings:

- Azorin-Molina, C., Granell, F., Gomez-Reyes, J., Calvo-Sancho, C., Barrio-Martín, A., Plaza-Martin, N.P., Prein, A.F., Vicente-Serrano, S.M., Gimeno, L., Nieto, R., Chen, D., McVicar, T.R., Zeng, Z., Pirooz, A., Martínez-Roig, M., González-Alemán, J.J., Martín. M.L.: The DOWNBURST MXO: a real-time downburst monitoring service in eastern Spain, 12th European Conference on Severe Storms, Utrecth, Netherlands, 17–21 November 2025, ECSS2025-55, https://doi.org/10.5194/ecss2025-55, 2025.

- 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., and Martín, M. L.: Storm Dynamics-based Attribution to the Valencia's deadly floods, 12th European Conference on Severe Storms, Utrecth, Netherlands, 17–21 November 2025, ECSS2025-54, https://doi.org/10.5194/ecss2025-54, 2025.

- Calvo-Sancho, C., Martín, Y., González-Alemán, J. J., Azorin-Molina, C., Martín, M. L.: Supercells and large hail in Spain, 12th European Conference on Severe Storms, Utrecth, Netherlands, 17–21 November 2025, ECSS2025-53, https://doi.org/10.5194/ecss2025-53, 2025.

- 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., and Martín, M. L.: Anthropogenic Climate Change Attribution to the Valencia's deadly floods, EMS Annual Meeting 2025, Ljubljana, Slovenia, 7–12 Sep 2025, EMS2025-504, https://doi.org/10.5194/ems2025-504, 2025.

- Calvo-Sancho, C. , Díaz-Fernández, J., González-Alemán, J. J., Azorín-Molina, C., Halifa-Marín, A., Montoro-Mendoza, A., Bolgiani, P., Beguería, S., Vicente-Serrano, S. M., Morata, A., and Martín, M. L.: Anthropogenic Climate Change Attribution to a Record-breaking Precipitation Event in October 2024 in Valencia, Spain , EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-15941, https://doi.org/10.5194/egusphere-egu25-15941, 2025.

- Halifa-Marín, A., Calvo-Sancho, C., Gil-Guallar, M., Royo-Aranda, A., Beguería, S., and Vicente-Serrano, S. M.: Reconstructing Extreme Weather Events in the Southeastern Iberian

Peninsula: Lessons from the Winter of 1944/45, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-18487, https://doi.org/10.5194/egusphere-egu25-18487, 2025.

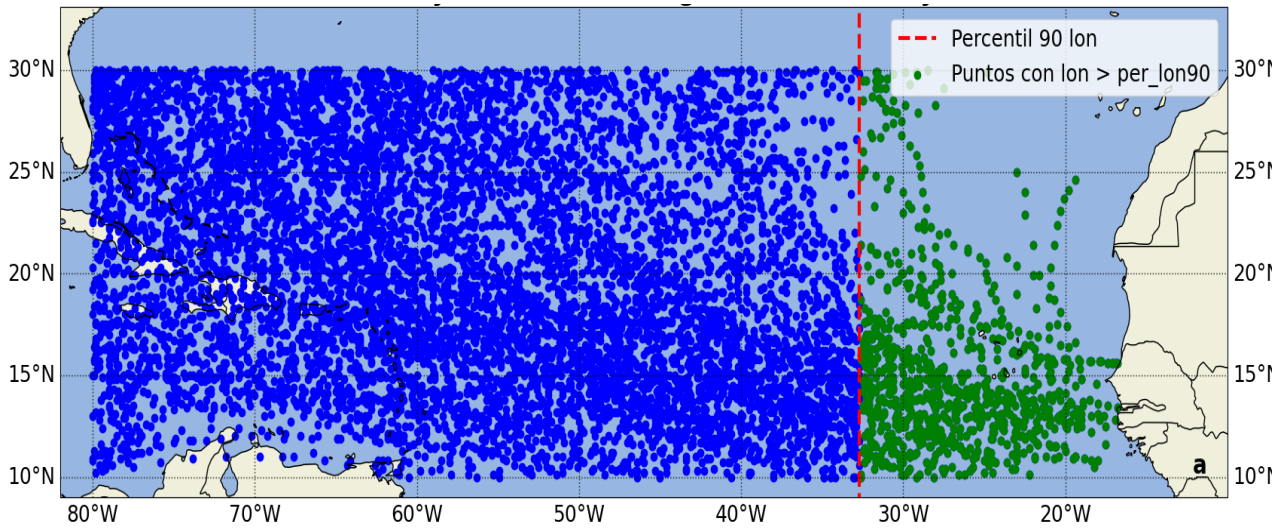
- González-Alemán,J.J., Gómez-Plasencia, P., Calvo-Sancho, C., Martín, M. L: Convective activity behaviour on tropical cyclones impacting Europe in a warmer world. 12th European Conference on Severe Storms, ECSS2025-202, Utrecht, Netherlands – 17 to 21 November 2025.

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 lengths 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, since the percentile value that has just been calculated will replace the westernmost value of the length of the region.



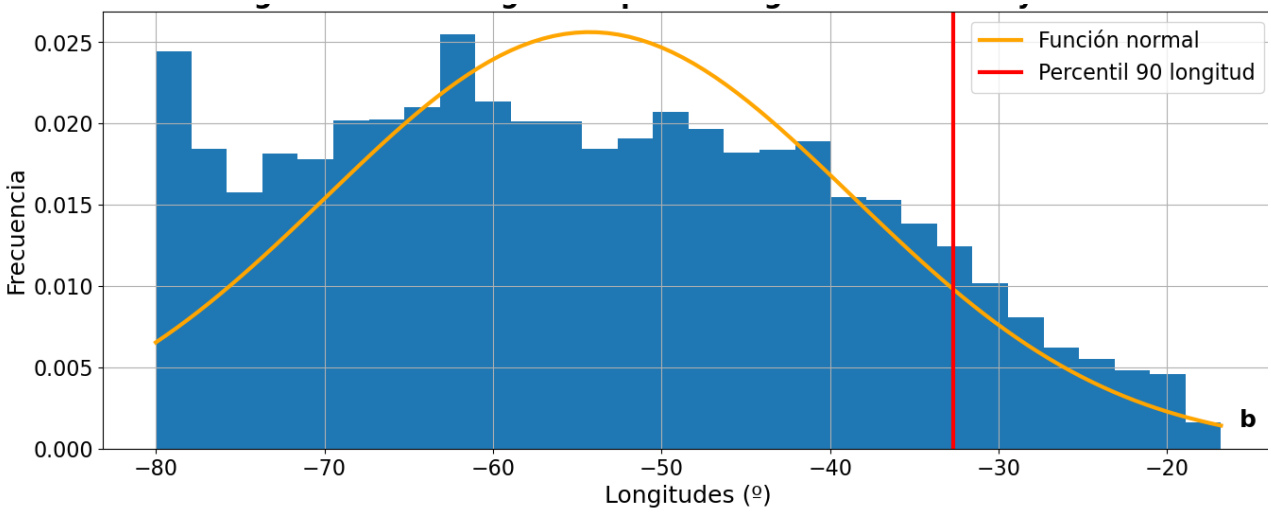
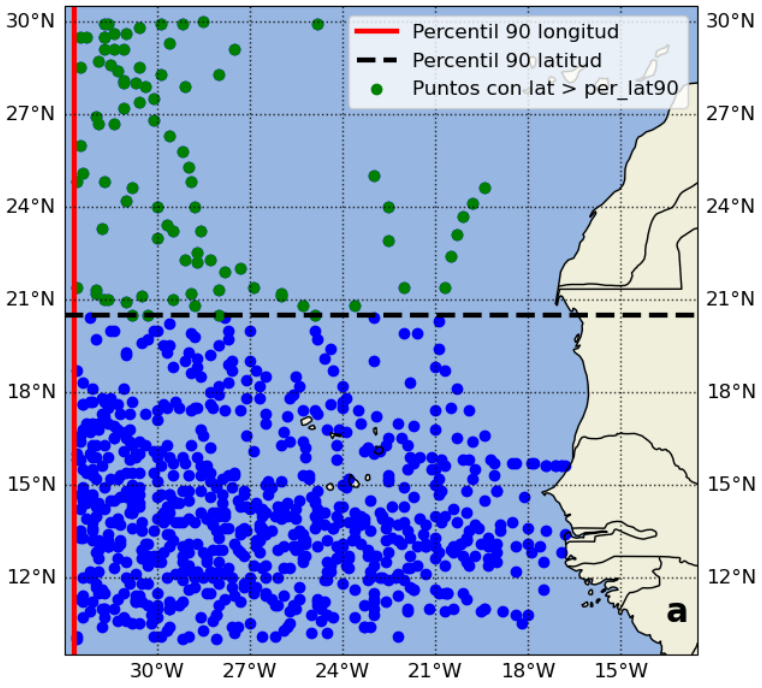


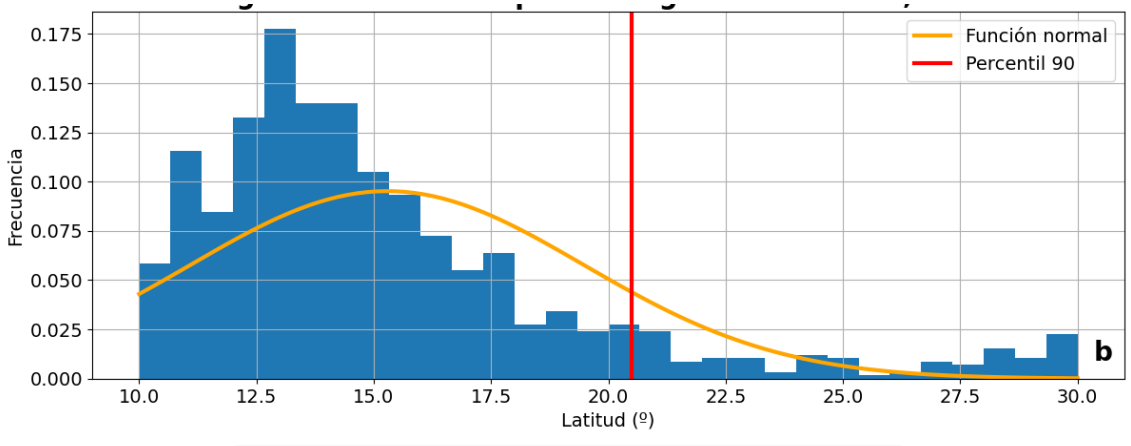
Figure 1: *(a) Tracks of the cyclones selected according to the 90th percentile (represented by the red line) of the longitudes. (b) Distribution of cyclones selected in (a) with normal function (orange line) and 90th percentile value (red line).*

Same analysis has been performed for latitudes (Figure 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, 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.

We first selected (Figure 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 EAWs obtained in 2022.



a)



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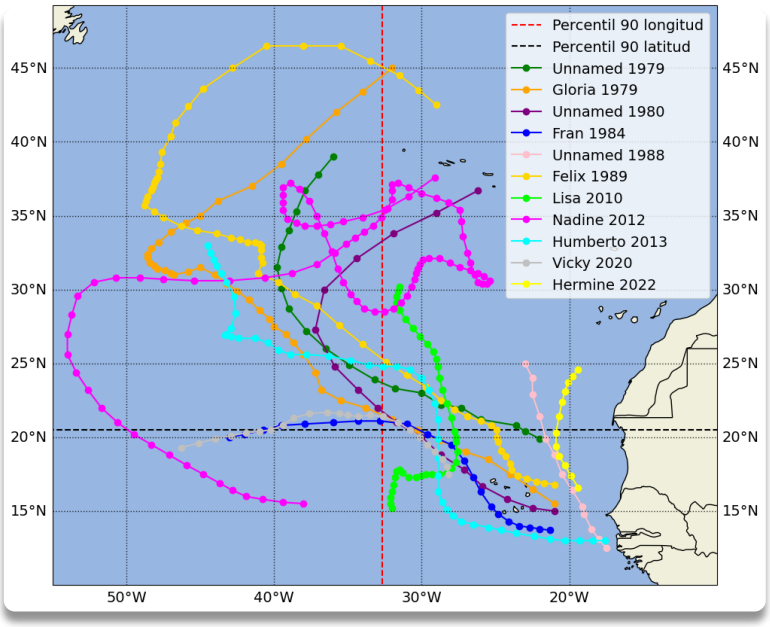
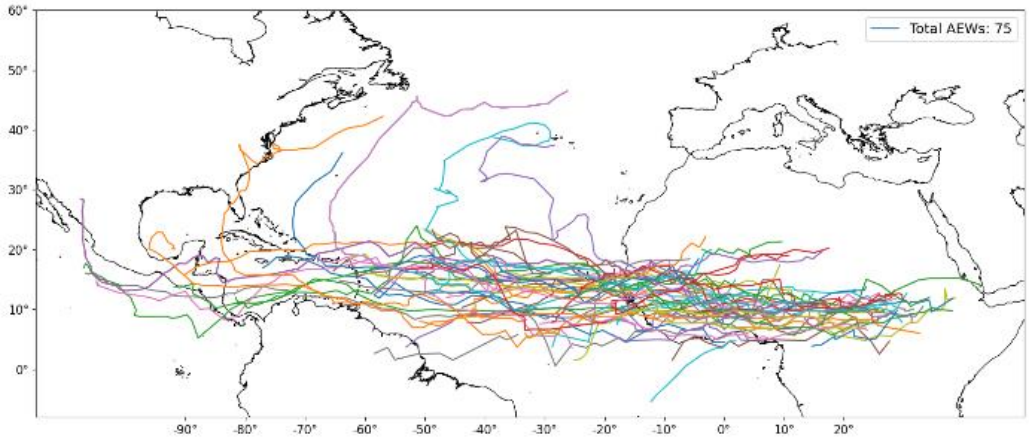


c)



d)

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.

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., 2025).

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. It should be noted that 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, reinforcing the reliability of the results for further analysis. 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 (Fig. S3). 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 favorable in the eastern region. Indeed, the development pattern of observed NATL TT cases from 1981 to 2010 closely corresponds with regions that exhibit high values in the historical climatology of the TTFI (Fig. S4), indicating that the TTFI serves as a reliable metric for identifying areas favorable for TTs development.

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 modeling 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. Future research

should focus on refining the representation of TTs processes in climate models and exploring potential feedback mechanisms that may influence the frequency and intensity of TTs in a warming climate.

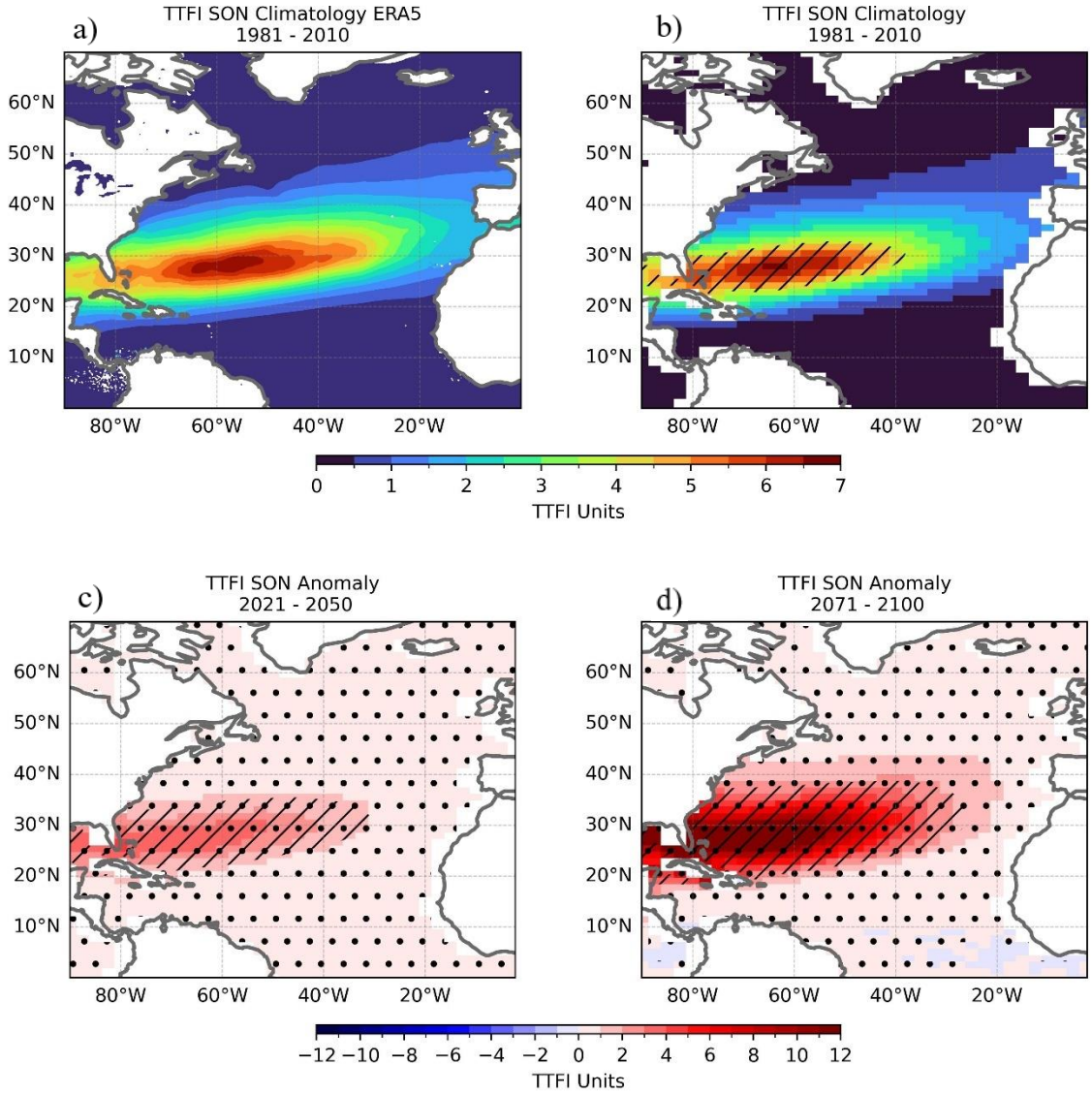


Figure 3. SON historical climatology of the TTFI (TTFI Units) from a) the ERA5 reanalysis dataset, b) the multi-model CMIP6 composite. SON anomaly values with respect to b) for the c) near future period and d) far future period. Black dots indicate statistically significant anomalies based on the Mann–Whitney 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.

References

Calvo-Sancho, C., González-Alemán, J. J., Bolgiani, P., Santos-Muñoz, D., Farrán, J. I., & Martín, M. L. (2022). An environmental synoptic analysis of tropical transitions in the central and Eastern North Atlantic. *Atmospheric Research*, *278*, 106353.

Galarneau, T.J., McTaggart-Cowan, R., Bosart, L.F., Davis, C.A., 2015. Development of North Atlantic tropical disturbances near upper-level potential vorticity streamers. J. Atmos. Sci. 72, 572–597. https://doi.org/10.1175/JAS-D-14-0106.1

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