# REQUEST FOR A SPECIAL PROJECT 2025–2027

**MEMBER STATE:** SPAIN

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**Project Title:** Dynamical and risk assessment analysis under future climate conditions of tropical cyclones impacting the eastern North Atlantic

To make changes to an existing project please submit an amended version of the original form.)

| | | |
|---|---|---|
| If this is a continuation of an existing project, please state the computer project account assigned previously. | **SP**ESMART | |
| Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.) | 2025 | |
| Would you accept support for 1 year only, if necessary? | YES ☒ | NO ☐ |

| **Computer resources required for project year:** | | **2025** | **2026** | **2027** |
|---|---|---|---|---|
| High Performance Computing Facility | [SBU] | 12000000 | 12000000 | 12000000 |
| Accumulated data storage (total archive volume)[2] | [GB] | 25000 | 25000 | 25000 |

| **EWC resources required for project year:** | | **2025** | **2026** | **2027** |
|---|---|---|---|---|
| Number of vCPUs | [#] | | | |
| Total memory | [GB] | | | |

[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.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

| | | | | |
|---|---|---|---|---|
| Storage | [GB] | | | |
| Number of vGPUs[3] | [#] | | | |

*Continue overleaf.*

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# 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 10,000,000 SBU should be more detailed (3-5 pages).*

African easterly waves (AEWs) are westward propagating tropical synoptic-scale disturbances that develop over northern Africa (mainly during boreal summer) and present their largest wave-amplitude at the mid (~700 hPa) atmospheric levels [Landsea, 1993]. About 60% of Tropical Cyclones (TCs) and 85% of major hurricanes in the North Atlantic (NATL) develop from AEWs [Russell et al., 2017]. Thus, they can be considered as the primary precursor (seed) for Atlantic TCs [Bercos-Hickey et al., 2023]. AEWs are often associated with organized convective precipitation events that produce devastating impacts on vulnerable societies of West Africa [Tomalka et al., 2021]. The large-scale atmospheric environment under which AEWs develop is a crucial factor in their occurrence. In general, a stronger than usual West African Monsoon (WAM) is associated with more frequent and intense AEWs, which tend to propagate more to the north (and vice-versa) [Núñez-Ocasio et al., 2020; 2021]. They typically promote convection downstream of the trough and subsidence upstream, the former being strongly modulated by the atmospheric moisture supply, upper-level dynamical forcing, topography, etc. [Russell et al., 2020]. Although most AEWs propagate westward south of the Azores high embedded within the trade winds, occasionally, they can move anomalously north and develop into TCs. A remarkable case was observed in September 2019, when an AEW departed the African west coast with an abnormal northward trajectory, subsequently developing into Hurricane Lorenzo [NHC, 2019]. Although the system moved through unfavourable atmospheric conditions, Lorenzo hit the Azores Islands and transitioned into an extratropical cyclone (EC). In October 2022, another AEW propagated anomalously north and evolved into Tropical Storm Hermine [NHC, 2022], producing heavy rainfall and strong economic impacts in the Canary Islands. Both systems developed and propagated towards the Macaronesia and western European coasts, an area historically devoid of TCs [Knapp et al., 2010]. Therefore, these regions appear to have become a new domain for AEWs undergoing TC formation [Haarsma et al., 2013; 2021; Lima et al., 2021].

Additional atmospheric events that can hit the eastern NATL (eNATL) as TCs with severe consequences are extratropical systems undergoing tropical transitions (TTs). A TT is a tropical cyclone development process relatively recently described [Davis and Bosart, 2003]. It consists of a baroclinic disturbance (EC) that transforms into a TC (e.g., symmetric vortex, warm core, etc.). These systems have shown an anomalous behavior during the last decades. Notable cases of TCs in eNATL like Delta (2005), Alex (2016), Ophelia (2017) or Leslie (2018) all developed through TT. These systems threatened the European coastlines and left important human and socioeconomic losses, due to their associated heavy precipitation and hurricane-like strong wind gusts [Calvo-Sancho et al., 2022]. The most recent example was hurricane Danielle (2022), one of the northernmost hurricane geneses ever observed, which posed a great challenge in predicting its formation and subsequent intensification [NHC, 2023].

According to Calvo-Sancho et al. [2022, 2023], TTs over the central and eastern North Atlantic (cNATL and eNATL) develop under environments characterized by a trough at the 300 hPa geopotential height and the increase of the 1000–500 hPa thickness, i.e., the system evolves into a warm-core, with a strong anticyclone located north, associated with a blocked westerly flow. The transition is accompanied by strong latent heat release which promotes the vertical redistribution of potential vorticity (PV) and a reduction of the 850–300 hPa vertical wind shear. TTs form more frequently over the cNATL compared to the eNATL. This is because the environmental conditions prone to the formation or maintenance of TTs are marginal over eNATL in comparison to cNATL. SSTs in the eNATL are colder due to Ekman transport, and the vertical wind shear is generally higher. Also, during summer, the subsidence associated with the descending branch of the Hadley circulation, through the subtropical ridge and anticyclone, creates stable and dry conditions over eNATL. However, during autumn and winter, these regions change their conditions and can be occasionally affected by TTs. eNATL cyclones typically transition into environments with enhanced surface latent heat fluxes and vertical instability, while cNATL cyclones transition into a more barotropic environment. Moreover, TTs not only can form in-situ over the eNATL, but those forming over the central Atlantic basin can also enter the eNATL driven by the westerly midlatitude flow. Although both cases constitute a great challenge for study due to their damaging effects on society, those systems formed in the eNATL may certainly pose a higher risk over the western European coasts and the Canary Islands.

Since just a few works have studied TTs, numerous scientific questions remain open. A key one is the relationship between Anthropogenic Climate Change (ACC) and TTs. Recent ACC projections indicate potential changes in TCs affecting the NATL basin [Murakami et al., 2020; IPCC 2021]. Under present climate, nearly half of North Atlantic TCs undergo an extratropical transition (ET), evolving into a baroclinic system with potential to affect Europe [Hart et al., 2001]. Several recent studies [Liu et al. 2017; Haarsma et al., 2021] have pointed to a future increase in frequency and intensity of TCs (and their ETs) over the eNATL. Studies based on observational records also indicate such increase [Emanuel et al., 2021]. However, these works lack analyses focusing on detecting contributions derived from both TTs and anomalous AEWs, which are the most likely way by which a TC can affect southwestern Europe. In addition, the assessment of environmental changes for these phenomena due to ACC was disregarded in these works.

The main purpose of the current proposal consists of evaluating the genesis and evolution of anomalous AEWs and TTs that may pose a threat to southwestern Europe, and how ACC could contribute to amplify this risk. With this aim, atmospheric variables related to identified AEW and TT events, as analyzed in Dieng et al. [2017] and Calvo-Sancho et al. [2022, 2023], will be selected to build, at a first stage, climatologies of environments over the NATL under historical and future climate conditions. Once a general overview of such environments is established, the next target will be to show how an altered environment by ACC could affect the meteorological (not climatological) synoptic evolution (e.g., genesis, development, impacts) of these events. 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 eNATL [cf. Haarsma et al., 2021]. The PGW adds a climate change climatological increment, established as the difference between future and present climate, to the initial boundary conditions of a meteorological numerical limited area model (LAM) simulation of a given cyclone evolution. These conditions are obtained for all prognostic variables using the mean change (or a member close to the mean) in an ensemble of climate model simulations (e.g., CMIP6; Eyring et al., 2016). This approach is comprehensively explained in the Methodology Section. The high-resolution WRF (Weather Research and Forecasting Model), HARMONIE-AROME (HIRLAM–ALADIN Research on Mesoscale Operational NWP in Euromed - Applications of Research to Operations at Mesoscale model; hereafter HARMONIE) and MPAS (Model for Prediction Across Scales) 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.

The team of this proposal was awarded with a previous research Special Project on this topic (SPESMART). In the previous project (ended in 2024), TTs were identified, selected, and simulated with WRF and HARMONIE. The ACC approach was perfunctorily considered, as just a few TT simulations were performed. Here, the new Special Project stems from the knowledge and experience acquired and represents a step forward as: (i) it will extend the population/classes of cyclones with tropical characteristics under consideration, by including AEWs with anomalous northward tracks; (ii) a larger set of cyclone simulations will be carried out in present climate and also considering the ACC effects in the environments where the TTs and AEWs develop. To do this, more extensive environmental climate data (an ensemble of the CMIP6 models) will be considered; and (iii) it will rely on cutting-edge high-resolution atmospheric numerical models (WRF, MPAS, HARMONIE) and simulation techniques (PGW), in which the research team already has previous experience [Koseki et al., 2021; González-Alemán et al., 2023; Martin et al., 2024]. In this regard, it should be emphasized that the project is designed to break ground in a new and technically complex methodology such as PGW, so that priority will be given to ensuring that the simulations carried out are consistent and realistic, before carrying them out at massive scale.

For all the above reasons, the new Special Project will aim to answer the following questions in a concise way: How will climate change impact the dynamics, evolution, and associated socioeconomic risks of cyclones with tropical characteristics in the vicinity of European territory? Should our societies start preparing for this potential new threat?

## GENERAL OBJECTIVES AND SPECIFIC TASKS

The genesis and evolution of anomalous AEWs and TTs that may pose a threat to southwestern Europe and the contribution of ACC to amplify this risk will be evaluated in this new project.

Thus, denoting objectives as ***OBJ***, as well as specific objectives as **S_OBJ**, of the new project can be summarized as:

***OBJ*-1**: 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.

- **S_OBJ-*1.1***: *To identify and classify TTs and AEWs with anomalous tracks within the eNATL in ERA-5 reanalysis (1940-present).*
- **S_OBJ-*1.2***: *To comprehensively characterize the environmental conditions that promote the development of AEWs and TTs over the eNATL under present climate.*
- **S_OBJ-*1.3***: *To analyze the changes in the above environments under future climate conditions.*

***OBJ*-2**: To apply, for the first time, the novel PWG methodology to simulate, at very high resolution, cyclones with tropical characteristics in the vicinity of Spanish territory.

- **S_OBJ-*2.1***: *To simulate, at very high resolution (500m - 3km), selected AEWs and TTs with HARMONIE, WRF and MPAS mesoscale atmospheric models under present climate conditions.*
- **S_OBJ-*2.2***: *Same as SO-2.1, but under perturbed ACC conditions through PGW, to fulfill GO-3.*

***OBJ*-3**: To evaluate how ACC conditions will affect eNATL AEWs and TTs meteorological behavior.

- **S_OBJ-*3.1***: *To assess the influence of ACC on the dynamics and meteorological evolution of selected events that may pose a threat to Spanish territory.*
- **S_OBJ-*3.1***: *To assess the influence of ACC on the meteorological impacts (wind gusts, precipitation, etc.) of these events.*

## SCIENTIFIC PLAN

Next, a description of the different phases and tasks of the project, as well as the used methodology are indicated:

### <u>PHASE 1</u>: Genesis and characterization of AEWs and TTs: Identification, classification, and selection of case studies

***Task 1.1: Identification/tracking and classification of AEWs and TTs in ERA5.***

Systematic identification of AEW events in the ERA5 database (1940-present) will be carried out through two different tracking algorithms: Belanger et al. [2016] and Dieng et al. [2017]. The use of automated tracking algorithms has proved necessary, since HURDAT2 only includes systems that reach tropical depression intensity. Therefore, to avoid omitting AEWs that do not reach such intensity but whose impacts could be significant, the creation of an AEW database is necessary. Anomalous AEW events in terms of trajectory will be defined by considering the 90th percentiles in longitude and latitude location of their surface center in any time of their life cycle (i.e., closest to Spanish territory). Comparison between both tracking algorithms will reveal the most suitable method (in terms of usability and reliability *vs* HURDAT2) to be considered.

Systematic identification of TT events over the eNATL will be primarily done through the filtering of HURDAT tracking data, as in Calvo-Sancho et al. [2022], but for the extended period 1940-present. A complementary but experimental method will also be applied, through which low pressure systems will be tracked [Pinto et al. 2005]. Preliminary tests have shown a good agreement between the tracking outputs and the TT events identified in Calvo-Sancho et al. [2022] in ERA5 (1979-2019) and with HURDAT2. Once a baroclinic low-pressure system propagates towards sub-tropical/tropical areas, the cyclone phase space (CPS) from Hart [2003] will be applied to classify TTs.

The generated TT database (1940-present) will extend that created by Calvo-Sancho et al. [2022] in different NATL areas (1979-2019) along the previous project, where more than 30 TTs were identified. For instance, 2020 was the year with the highest number of TTs (disregarded in previous project) and some of them propagated very close to Canary Islands. Team members have supervised MSc theses where a large number of cyclones with tropical characteristics were identified. From these, more than 15 events were labeled as anomalous AEWs (Figure 1). Therefore, it is expected these above-mentioned methods will find in ERA5/HURDAT2 a robust set of study cases.

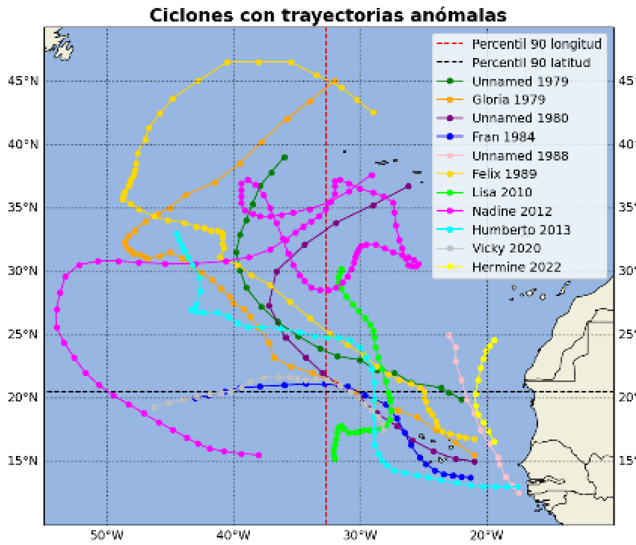


***Figure 1:*** *Cyclones from AEWs (> 90-pctile. latitude and longitude, i.e., the closest to Spanish territory).*

***Task 1.2: Characterization of TT and AEW development over the NATL.***

Considering the previous know-how of this research team, which has shown differences in dynamical TT features with genesis in cNATL and eNATL using the ERA5 reanalysis [Quitián-Hernández et al., 2021; Calvo-Sancho et al., 2022; 2023; Quitián-Hernández et al., 2022], and conclusions from the literature of AEW, the environmental conditions for TTs and AEWs genesis and development will be analyzed. In the current proposal, storm-centered composites of variables such as sea surface temperature, sea level pressure, vertical wind shear, thickness, potential vorticity, relative vorticity, surface latent heat fluxes and instability indices will constitute the starting point to analyze the dynamical and thermodynamical system features [Calvo-Sancho et al., 2022]. The events over eNATL, obtained in Task 1.1, will be considered for this purpose. The analysis of environmental TT/AEW conditions in ERA5/HURDAT2 will establish the baseline reference framework, which will be compared in subsequent project tasks against future climate.

**<u>PHASE 2</u>: Monthly climatologies of AEW/TT environments over the NATL with CMIP6 in HIST and FUT climate**

***Task 2.1: Calculation of monthly climatologies of relevant variables for AEW/TT genesis and evolution in CMIP6 HIST simulations.***

By considering the most relevant thermodynamic, kinematic, and dynamic parameters (e.g., potential temperature at 2PVU, coupling index, precipitation) that may play role in the formation and evolution in AEWs and TTs in the eNATL (as derived from Task1.2; cf. also Calvo-Sancho et al. 2022; 2023), monthly mean climatologies of these variables will be calculated in CMIP6 HIST simulations for the period 1984-2014 (hereafter baseline monthly climatologies).

***Task 2.2: Calculation of monthly climatologies of relevant variables for AEW/TT genesis and evolution in CMIP6 FUT simulations.***

Same as in Task2.1, but for the period 2025-2055 and 2071-2100 in CMIP6 FUT (SSP4-6.0 and SSP5-8.5).

***Task 2.3: Comparison between CMIP6 HIST and CMIP6 FUT monthly climatologies.***

Monthly climatologies generated in Task2.1 (CMIP6 HIST) and Task2.2 (CMIP6 FUT) will be compared, and their results assessed, depicting possible changes in the atmospheric/oceanic variables that promote AEW/TT formation and intensification in the eNATL.

**<u>PHASE 3</u>: Pseudo-global warming simulations for AEW/TT case studies**

***Task 3.1: High-resolution simulations of selected AEWs/TTs under present climate.***

The most relevant identified AEW/TT events (Delta, Alex, Vince, Leslie, Hermine, Ofelia, Bernard, etc.; as obtained from Phase 1) with respect to their dynamics and evolution (maximum intensity, landfall in Canary/European territory, etc.; Task1.1 and Task1.2 output) will be simulated at very high resolution (500m - 3km) with WRF/HARMONIE/MPAS atmospheric models. To this aim, ERA5 1-hourly data will be used as initial and boundary conditions. The simulations carried out in this task will constitute the baseline to be compared against PGW simulations.

***Task 3.2: Calculation of the PGW increments.***

The response of AEWs/TTs (in terms of meteorological evolution) to future warming will be investigated through the PGW. The PGW approach introduces an increment value associated to ACC into prognostic variables utilized to initialize high-resolution atmospheric models. This increment, $\Delta\overline{\varphi}_{\square}$, is defined as the difference between the ensemble mean future CMIP6 FUT (SSP4-6.0 and

SSP5-8.5) and present climate CMIP6 HIST for prognostic variables (e.g., air temperature, relative humidity, zonal and meridional winds, and SST). As described above, considering monthly climatologies of the occurrence months of the case studies constitutes a fast, efficient, and operative way for obtaining the necessary increments. The obtained increment fields of prognostic variables will be then interpolated (bilinear method) to ERA5 grid and vertical levels using the PGWERA5 package.

***Task 3.3: High-resolution simulations of selected AEWs/TTs under future climate.***

Events selected in Task 3.1 will be simulated with WRF, MPAS and HARMONIE under the PGW methodology for both SSP4-6.0 and SSP5-8.5 (ERA5 prognostic variable fields + $\Delta\bar{\varphi}$ as initial and boundary – perturbed - conditions).

**<u>PHASE 4</u>: Influence of ACC on the meteorological evolution, impacts and potential losses associated with selected AEW/TTs over the eastern North Atlantic.**

***Task 4.1: Effects of ACC on the meteorological evolution of selected AEW/TTs over the eNATL.***

Based on present- and future-climate (SSP4-6.0 and SSP5-8.5) high resolution simulations (*c.* 500m - 3 km; Task3.1 and Task3.3 outputs), an analysis of the differences between cyclones of interest in terms of dynamical (e.g., PV streamers, vertical instability, organized convection, cyclone structure), thermodynamical (e.g., diabatic and latent heat release) and lifecycle (trajectory, deepening rate, maximum intensity, lifetime) cyclone properties will be performed. The focus will be on evaluating significant events in meteorological terms.

***Task 4.2: Effects of ACC on meteorological impacts of selected AEW/TTs over the eNATL.***

Additional to the physical AEW/TT characteristics analyzed in Task4.1, the meteorological impacts of present- *vs* future-climate (SSP4-6.0 and SSP5-8.5) simulated case studies will also be assessed. Due to the absence of high-resolution PGW WRF/HARMONIE/MPAS 30-year runs and the limitations that pose comparing different model simulations (e.g., mesoscale vs CMIP6 models; disentangling atmospheric anomalies from systematic errors in event life-cycle simulations would not be straightforward), extreme weather indices based on absolute values (maximum daily and hourly precipitation, maximum wind gust, etc.) instead of statistical thresholds (e.g., return periods, percentiles) will be computed at simulations' grid level. Differences between present-day and future-climate (SSP4-6.0 and SSP5-8.5) simulations will be computed.

**COMPUTER RESOURCES AND TECHNICAL CHARACTERISTICS OF THE CODE**

The WRF numerical model for analysing TTs will be configured with two domains: the outer domain with 7.5 km of grid resolution and the high resolution one with 2.5 km (although higher resolution will be used in experiments, 500 m), using 1000 grid points in the west-east direction, 1000 grid points in the south-north direction and 65 sigma levels unequally spaced, with a greater number of levels in the lower troposphere for a better representation of the convective planetary boundary-layer processes. Adaptative time steps are used. The WRF physics options used in this study are those defined as the default for Hurricane research mode. Among them, it is worth noting the WRF Single-Moment 6-class (WSM6) parameterization scheme for microphysics, YSU for the planetary boundary layer (PBL), and Dudhia and RRTM for short and longwave radiation, respectively. No cumulus parameterization scheme is used in this study, being cloudiness explicitly computed by the model. Iinitial/boundary conditions will be obtained from the ERA5 Reanalysis of the ECMWF with 0.31° horizontal resolution every 6 hours.

In the previous Special Project (SPESMART), the HARMONIE model configuration (v40h1.1.1 version) has been used to study the STCs. With this version we had learning the set up of this model, studying its postprocessing procedures. Once the STCs were simulated with this version of HARMONIE, another model configuration (43h2.1 version) has been compiled to analyse different TTs as a training of using this model. The final set up used to simulate TTs resembles WRF's one as much as possible to maintain the consistency of the study. Defined with the HARMONIE default physics options, the model also has a main domain with 2.5 km resolution (although higher resolution will be used in experiments, 500 m) and the same grid dimensions (1000x1000) in the west-east and south-north directions with 65 hybrid sigma-pressure levels in the vertical. The initial/boundary conditions are the same as those used for WRF. In this case, the model is configured with a temporal resolution of 75 s. Operated at 2.5 km resolution this model has a convection-permitting configuration and uses a non-hydrostatic spectral dynamical core with a semi-Lagrangian and semi-implicit discretization of the equations. In this way, more realistic results are obtained compared to other models, which may provide an added value to the study of TTs.

Finally, in this special project the MPAS will be used. MPAS is a collaborative project for developing atmosphere, ocean, and additional earth-system simulation components for use in climate, regional climate, and weather studies. The MPAS model (version 8.0.1) uses a similar dynamic nucleus and same physical parameterization as the WRF. MPAS is a three-dimensional, global, finite-differences, non-hydrostatic model, used mainly in atmospheric research. MPAS uses a global mesh, which is refined to high-resolution over the area of interest: 60-3km and 15-1km coarse-refined meshes will be used within the project. The horizontal discretization is based on a non-structured Voronoi center type mesh grid-C of the state variables and in the edges the dynamic variables, allowing for both quasi-uniform discretization of the sphere and local refinement. The C-grid discretization is especially well-suited for high-resolution, mesoscale atmosphere and ocean simulations.

For each of these atmospheric systems that will be studied in this new project, at least 93000 units approximately have been used using WRF and, around 40000 units have cost using HARMONIE, in the low-resolution case. It is worth to note that some previous experiments to the final simulations, that is, WRF set-ups, and some proofs with different HARMONIE domains will be needed as well as the units needed for MPAS simulations. Therefore, we believe that 12000000 units will originally be required for simulating these tropical systems.

**REFERENCES**


Belanger, J.I., Jelinek, M. T., Curry J. A. (2016) A climatology of easterly waves in the tropical Western Hemisphere. Geosci. Data J., 3, 40-49. https://doi.org/10.1002/gdj3.40

Bercos-Hickey, E., Patricola, C. M., Loring, B., and Collins, W. D. (2023) The relationship between African easterly waves and tropical cyclones in historical and future climates in the HighResMIP-PRIMAVERA simulations. J. Geophys. Res. Atmos. 128, e2022JD037471. https://doi.org/10.1029/2022JD037471

Calvo-Sancho, C., González-Aleman, 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. Atmos. Res. 278, 10635, 1-16. https://doi.org/10.1016/j.atmosres.2022.106353.

Calvo-Sancho, C., Quitián-Hernández, L., González-Alemán, J.J., Bolgiani, P., Santos-Muñoz, D., Martín, M.L. (2023) Assessing the performance of the HARMONIE-AROME and WRF-ARW numerical models in North Atlantic Tropical Transitions. Atmospheric Research, 291, 106801; https://doi.org/10.1016/j.atmosres.2023.106801.

Davis, C. A., Bosart, L. F. (2003) Baroclinically induced tropical cyclogenesis, Mon. Wea. Rev., 131, 2730–2747.

Dieng, A. L., Sall, S. M., Eymard, L., Leduc-Leballeur, M., Lazar, A. (2017) Trains of African Easterly Waves and Their Relationship to Tropical Cyclone Genesis in the Eastern Atlantic. Mon. Wea. Rev., 145, 599–616 DOI: 10.1175/MWR-D-15-0277.1.

Emanuel, K. (2021) Atlantic tropical cyclones downscaled from climate reanalyses show increasing activity over past 150 years. Nat. Commun. 12, 7027. https://doi.org/10.1038/s41467-021-27364-8.

Eyring, V., et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev., 9, 1937–1958. doi:10.5194/gmd-9-1937-2016.

González-Alemán, JJ., et al. (2023) Anthropogenic Warming Had a Crucial Role in Triggering the Historic and Destructive Mediterranean Derecho in Summer 2022. BAMS, 104, 8. https://doi.org/10.1175/BAMS-D-23-0119.1.

Haarsma, R. (2021) European windstorm risk of post-tropical cyclones and the impact of climate change. Geophys. Res. Lett., 48, e2020GL091483. https://doi.org/10.1029/2020GL091483

Hart, R. E., Evans J.L. (2001) A Climatology of the Extratropical Transition of Atlantic Tropical Cyclones. J. Climate, 14, 546–564, DOI:10.1175/1520-0442(2001)014<0546:ACOTET>2.0.CO;2

Hart, R.E. (2003) A Cyclone Phase Space Derived from Thermal Wind and Thermal Asymmetry. Mon. Wea. Rev., 131, 585–616, https://doi.org/10.1175/1520-0493(2003)131<0585:ACPSDF>2.0.CO;2.

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, et al.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., Neumann, C. J. (2010) The International Best Track Archive for Climate Stewardship (IBTrACS). Bull. Amer. Meteor. Soc., 91, 363–376, https://doi.org/10.1175/2009BAMS2755.1.

Koseki, S., Mooney, P. A., Cabos, W., Gaertner, M. Á., de la Vara, A., and González-Alemán, J. J. (2021) Modelling a tropical-like cyclone in the Mediterranean Sea under present and warmer climate. Nat. Hazards Earth Syst. Sci., 21, 53–71. https://doi.org/10.5194/nhess-21-53-2021

Liu, M., Vecchi, G., Smith, J.A., Murakami, H. (2017) The Present-Day Simulation and Twenty-First-Century Projection of the Climatology of Extratropical Transition in the North Atlantic. J. Climate, 30, 2739–2756DOI:10.1175/JCLI-D-16-0352.1.

Martin, M.L., et al. (2024) Major Role of Marine Heatwave and Anthropogenic Climate Change on a Giant Hail Event in Spain. Geophys. Res. Lett. (accepted).

Mooney, P. A., Sobolowski, S., Lee, H. (2020) Designing and evaluating regional climate simulations for high latitude land use land cover change studies. Tellus A: Dyn. Meteorol, Oceanograph., 72(1), 1-17. https://doi.org/10.1080/16000870.2020.1853437.

Murakami, H., et al. (2020) Detected climatic change in global distribution of tropical cyclones. PNAS, 117 (20), 10706-10714. https://doi.org/10.1073/pnas.1922500117.

NHC (2019) Hurricane Lorenzo. Tropical Cyclone report by David A. Zelinski. https://www.nhc.noaa.gov/data/tcr/AL132019_Lorenzo.pdf

NHC (2022) Tropical Storm HERMINE Advisory Archive. https://www.nhc.noaa.gov/archive/2022/HERMINE.shtml?.

NHC (2023) Tropical Cyclone Report Hurricane Danielle. https://www.nhc.noaa.gov/data/tcr/AL052022_Danielle.pdf

Nuñez-Ocasio, K. M. N., Evans, J. L., Young, G. S. (2020) Tracking Mesoscale Convective Systems that are Potential Candidates for Tropical Cyclogenesis. Mon. Wea. Rev.148(2), 655-669. DOI:10.1175/MWR-D-19-0070.1.

Núñez-Ocasio, K. (2021) Tropical cyclogenesis and its relation to interactions between African easterly waves and mesoscale convective systems. The Pennsylvania State University ProQuest Dissertations Publishing, 2021. 28841717.

Pinto, J. G., T. Spangehl, U. Ulbrich, P. Speth (2005) Sensitivities of a cyclone detection and tracking algorithm: individual tracks and climatology. Meteorol. Z., 14, 823–838. DOI:10.1127/0941-2948/2005/0068.

Quitián-Hernández, L., González-Alemán, J. J., Santos-Muñoz, D., Fernández-González, S., Valero, F., Martín, M. L. (2020) Subtropical Cyclone Formation via Warm Seclusion Development: The Importance of Surface Fluxes. J. Geophys. Res. Atmos., 125, e2019JD031526. https://doi.org/10.1029/2019JD031526

Quitián-Hernández, L., et al. (2021) Analysis of the October 2014 subtropical cyclone using the WRF and the HARMONIE-AROME numerical models: Assessment against observations. Atmos. Res. 260, 105697. https://doi.org/10.1016/j.atmosres.2021.105697

Russell, J. O., Aiyyer, A., White, J. D., Hannah, W. (2017) Revisiting the connection between African Easterly Waves and Atlantic tropical cyclogenesis. Geophys. Res. Lett., 44, 587– 595, doi:10.1002/2016GL071236

Russell, J. O. H., Aiyyer, A., White, J. D. (2020). African easterly wave dynamics in convection-permitting simulations: Rotational stratiform instability as a conceptual model. J. Advanc. Model. Earth Syst., 12, e2019MS001706. https://doi.org/10.1029/2019MS001706.

Schär, C., Frei, C., Lüthi, D., & Davies, H. C. (1996) Surrogate climate-change scenarios for regional climate models. Geophys. Res. Lett. 23(6), 669-672. https://doi.org/10.1029/96GL00265.

Tomalka, J., et al. (2021). Climate Risk Profile: Sahel. A joint publication by the Potsdam Institute for Climate Impact Research (PIK) and the United Nations High Commissioner for Refugees (UNHCR) under the Predictive Analytics project in support of the United Nations Integrated Strategy for the Sahel (UNISS).