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	2023
Project Title:	SIMULATIONS OF TROPICAL TRANSITIONS IN THE EASTERN NORTH-ATLANTIC OCEAN: PAST, PRESENT AND FUTURE PROJECTIONS
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)	……………………………………………………………… ………………………………………………………………
Start date of the project:	01/01/2022
Expected end date:	31/12/2024

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)			2000000	7917382
Data storage capacity	(Gbytes)			25000	25000

Summary of project objectives (10 lines max)

In the last years, tropical transitions (TT) have occurred very close to Iberia and surrounding areas. High-resolution simulations of TTs using improved models are needed to analyse the atmospheric dynamics of these systems. In this sense, in SPESMART several observed TTs (the strongest TTs > 90 percentile in wind speed) are simulated using the WRF and HARMONIE-AROME models. Moreover, simulations of these events using projections in areas nearby the Iberian Peninsula will provide knowledge about these atmospheric systems and their behaviour with respect to the Anthropogenic Climate Change (ACC). To do this, EC-Earth projections will be used. Thus, different climate scenarios will be analysed to study, simulate, and examine possible changes in frequency, tracking and intensity of several TTs.

Summary of problems encountered (10 lines max)

The request document specified three phases with the scientific plan:

The Phase 1 (Selection of TTs in ENA: study of the genesis and atmospheric dynamic) is fully developed. In Calvo-Sancho et al. (2022) a climatology (1979-2019) of TTs in which 30 TT events were identified over the central and eastern North Atlantic basin have revealed differences between TTs formed in the two Atlantic basins. The Phase 2 (Assessment of the skill of the models in simulating the behavior of TTs) is developed. Several TTs have been simulated using both HARMONIE and WRF models. The SPESMART team is analyzing intensity, track and model skillful of the simulated TTs. The Phase 3 (Analysis of TTs in simulations of an advanced climate model) is not completed. The BSC recently have supported us EC-Earth simulations to nest HARMONIE and WRF. Additional simulations are needed to run.

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

As soon as the tracking method is adapted to the simulations facilitated by the BSC, the Phase 3 of the project will continue. A modified tracking method, using the cyclone-space method (CPS) of Hart (2003) of Phase 1, will be applied to select probable cases of TTs of the EC-Earth.

Once the TTs are identified in the present climate of the climate model (EC-Earth CTRL) and HARMONIE and WRF are nested, the models will be evaluated considering the obtained TTs in EC-Earth CTRL. The next steep consists of the analysis of TTs in future ACC projections generated by the BSC. Relationship ACC - TTs will be assessed in this stage.

List of publications/reports from the project with complete references

<u>Journal Publications</u>:

J. Díaz-Fernández, P. Bolgiani, D. Santos-Muñoz, L. Quitián-Hernández, M. Sastre, F. Valero, J. I. Farrán, J.J. González-Alemán and M.L. Martín. Comparison of the WRF and HARMONIE models ability for mountain wave warnings. Atmospheric Research, 265, 1-14. 105890. doi.org/10.1016/j.atmosres.2021.105890. 2022.

Bolgiani, P., Calvo-Sancho, C., Díaz-Fernández, J., Quitián-Hernández, L., Sastre, M., Santos-Muñoz, D., Farrán, J.I., González-Alemán, J.J., Valero, F., Martín, M.L. Wind Kinetic Energy Climatology and Effective Resolution for the ERA5 Reanalysis. Cimate Dynamics. https://doi.org/10.1007/s00382-022-06154-y. 2022.

Díaz-Fernández, J., Bolgiani, P., Sastre, M., Santos-Muñoz, D., Valero, F., Farrán, J.I. & Martín, M.L. Ability of the WRF and HARMONIE-AROME models to detect turbulence related to mountain waves over central Iberia. Atmospheric Research. 274, 1-8; https://doi.org/10.1016/j.atmosres.2022.106183. 2022.

Calvo-Sancho, C., González-Aleman, J.J., Bolgiani, P., Santos-Muñoz, D., Farrán, J.I., Martín, M.L. An Environmental Synoptic Analysis of Tropical Transitions in the Central and Eastern North

Atlantic. Atmospheric Research. 278, 10635, 1-16. https://doi.org/10.1016/j.atmosres.2022.1063532022. 2022.

Carlos Calvo-Sancho, Javier Díaz-Fernández, Yago Martín, Pedro Bolgiani, Mariano Sastre, Juan Jesús González Alemán, Daniel Santos-Muñoz, José Ignacio Farrán, María Luisa Martín, Supercell Convective Environments in Spain based on ERA5: Hail and Non-Hail Differences. Weather and Climate Dynamics. 3, 1021–1036. https://doi.org/10.5194/wcd-3-1021-20222022. 2022.

C. Calvo-Sancho, L. Quitián-Hernández, P. Bolgiani, J. J. González-Alemán, D. Santos-Muñoz, M. L. Martín. Assessment of HARMONIE-AROME in the simulation of the convective activity associated to a subtropical transition using satellite data. Atmospheric Research, 290, 106794; https://doi.org/10.1016/j.atmosres.2023.106794. 2023.

Calvo-Sancho, C., Quitián-Hernández, L., González-Aleman, J.J., Bolgiani, P., Santos-Muñoz, D., Martín, M.L. 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. 2023.

<u>Meetings</u>:

Díaz-Fernández, J., L. Quitián-Hernández, P. Bolgiani, D. Santos-Muñoz, Á. García-Gago, S. Fernández-González, F. Valero, A. Merino, E. García-Ortega, J.L. Sánchez, M. Sastre, M.L. Martín (2020). Mountain waves analysis in the vicinity of the Madrid-Barajas airport using the WRF model. Advances in Meteorology, Article ID 8871546, 17 pp. https://doi.org/10.1155/2020/8871546.

Calvo-Sancho, C., González-Alemán, J. J., Bolgiani, P., Santos-Muñoz, D., Farrán, J. I., Sastre, M., and Martín, M. L.: A Climatology of Tropical Transitions in the North Atlantic Ocean, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-2395, https://doi.org/10.5194/egusphere-egu22-2395, 2022.

Díaz Fernández, J., Bolgiani, P., Santos Muñoz, D., Sastre, M., Valero, F., Farrán, J. I., González Alemán, J. J., and Martín Pérez, M. L.: Characterization and warnings for mountain waves using HARMONIE-AROME, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-2471, https://doi.org/10.5194/egusphere-egu22-2471, 2022.

Calvo-Sancho, González-Alemán, J.J., Díaz-Fernández, J., Quitián-Hernández, L., Bolgiani, P., Santos-Muñoz, D., Farrán, J.I., Sastre, M., Calvo, J., and Martín, M.L.: Ianos in the HARMONIE-AROME model, I MedCyclones Workshop and Training School, MedCyclones Cost Action, Athens, Greece, 27 June - 2 July 2022.

Díaz-Fernández, J., Calvo-Sancho, C., González-Alemán, J.J., Bolgiani, P., Santos-Muñoz, D., Farrán, J. I., Sastre, M., Quitián-Hernández, L., and Martín, M. L.: WRF vs HARMONIE-AROME: A Comparison in a Supercell Event, Online Mini-European Conference on Severe Storms (mini ECSS), European Severe Storms Laboratory, Online, 27-28 September 2022.

Calvo-Sancho, C., Díaz-Fernández, J., Bolgiani, P., González-Fernández, S., González-Alemán, J.J., Santos-Muñoz, D., Farrán, J. I., Sastre, M., Quitián-Hernández, L., and Martín, M. L.: Microburst and Supercell Analysis - A study of 1 July 2018 Severe Weather Event over Zaragoza's Airport, Online Mini-European Conference on Severe Storms (mini ECSS), European Severe Storms Laboratory, Online, 27-28 September 2022.

J. Díaz-Fernández, M.Y. Luna, P. Bolgiani, D. Santos-Muñoz, M. Sastre, F. Valero, J.I. Farrán, JJ. González-Alemán, L Quitián-Hernández, M.L. Martín (2022). Climatología de ondas de montaña en la sierra de Guadarrama: caracterización con el modelo meteorológico de alta resolución WRF. XII

Congreso Internacional de la Asociación Española de Climatología (AEC): Retos del Cambio Climático: impactos, mitigación y adaptación. Santiago de Compostela (Spain), October 2022.

C. Calvo-Sancho, J.J. González-Alemán, M.Y. Luna, P. Bolgiani, D. Santos-Muñoz, L. Quitián-Hernández, M.Sastre, F.Valero, J.I. Farrán, J.Díaz-Fernández, L. López, M.L. Martín. Identificación y Distribución Temporal de Transiciones Tropicales en el Océano Atlántico Norte. XII Congreso Internacional de la Asociación Española de Climatología (AEC): Retos del Cambio Climático: impactos, mitigación y adaptación. Santiago de Compostela (Spain), October 2022.

Díaz-Fernández, J., Calvo-Sancho, C., Quitián-Hernández, L., Bolgiani, P., Santos Muñoz, D., Luna, M.Y., González Alemán, J. J., Sastre, M., Valero, F., Farrán, J. I. & Martín, M. L. (2022). Análisis del evento supercelular del 31 de julio de 2015 en España con el modelo WRF-ARW. 10ª Asamblea Hispano Portuguesa de Geodesia y Geofísica. Toledo (Spain). 2022

Quitián-Hernández, L., J., Calvo-Sancho, C., Díaz-Fernández, Bolgiani, P., Santos Muñoz, D., Luna, M.Y., González Alemán, J. J., Sastre, M., Valero, F., Farrán, J. I. & Martín, M. L. Análisis de un ciclón subtropical en el Océano Atlántico Norte mediante el modelo numérico HARMONIE-AROME. 10ª Asamblea Hispano Portuguesa de Geodesia y Geofísica. Toledo (Spain). 2022

Calvo-Sancho, C., Díaz-Fernández, J., González Alemán, J. J., Martín, Y., Quitián-Hernández, L., Bolgiani, P., Santos Muñoz, D., Farrán, J. I. Sastre, M., & Martín, M. L. Numerical Analysis of a Spanish Supercell Outbreak. European Geosciences Union (EGU) 2023. Vienna (Austria). 2023

Calvo-Sancho, C., González Alemán, J. J., Martín, Y., Calvo, J., Martín, M. L., Martín Pérez, D. & Viana Jiménez, S. (2023). Testing very high-resolution simulations in a high-impact static convective system in Spain using HARMONIE-AROME model. European Conference on Severe Storms (ECSS) 2023. Bucarest (Rumanía). 2023

Calvo-Sancho, C., Díaz-Fernández, J., González Alemán, J. J., Martín, Y., Quitián-Hernández, L., Bolgiani, P., Santos Muñoz, D., Farrán, J. I. Sastre, M., & Martín, M. L. (2023). Supercell synoptic configurations and pre-convective environments in Spain. European Meteorology Society (ECSS) Annual Meeting 2023. Bratislava (Eslovaquia). 2023

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.

During the first project year, a climatology of TTs has been carried out, analysing the synoptic and environmental characteristics of the TTs. The results have shown that there is two different group of TT considering the genesis of the systems: the TTs developed in central Atlantic Ocean and the TTs generated in eastern Atlantic basin. This work has been made using the ERA5 data base.

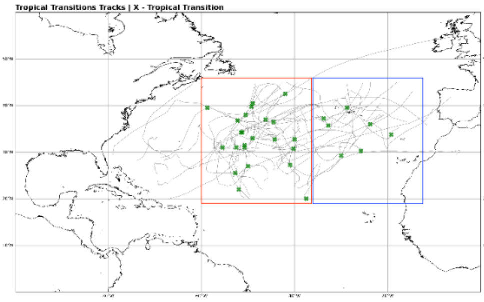

Figure 1: Tracks and transition time (green marks) of several TTs identified (1979 - 2019).

Figure 1 shows tracks of the identified TTs from 1979 to 2019. Simulations of this systems are needed to study during the time before their genesis the possible precursors that can be useful in forecasting and warning this kind of catastrophic events. All this information is shown in the scientific manuscript, currently under review, of Calvo-Sancho et al. (2022).

In this way, hurricanes such as Vince, Ofelia, Delta, Theta, Leslie, selected from Calvo-Sancho et al. (2022) and presenting wind speed values greater than the 90-percentile value, have been simulated with WRF and HARMONIE-AROME. After different test, the configuration of both models is as follows:

- ✓ The WRF numerical model for analysing TTs has been configured with two domains: the outer domain with 7.5 km of grid resolution and the high resolution one with 2.5 km (Figure 2), 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) (Hong and Lim, 2006) parameterization scheme for microphysics, YSU for the planetary boundary layer (PBL), and Dudhia (Dudhia, 1989) and RRTM for short and longwave radiation, respectively. No cumulus parameterization scheme is used in this study, being cloudiness explicitly computed by the model. Finally, the initial/boundary conditions are obtained from the ERA5 Reanalysis of the ECMWF with 0.31° horizontal resolution every 6 hours.

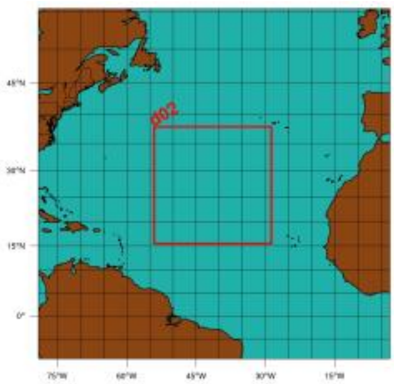

Figure 2: WRF domain configuration to simulate Hurricane Delta.

- ✓ The HARMONIE-AROME configuration (43h2.1 version) was compiled to simulate the different TTs. 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 (Bengtsson et al., 2017), the model also has a main domain with 2.5 km resolution and the same grid dimensions (1000 x 1000) in the west-east and south-north directions (domain in Figure 3) 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 (Bengtsson et al., 2017). 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 (Bengtsson et al., 2017) compared to other models, which may provide an added value to the study of TTs.

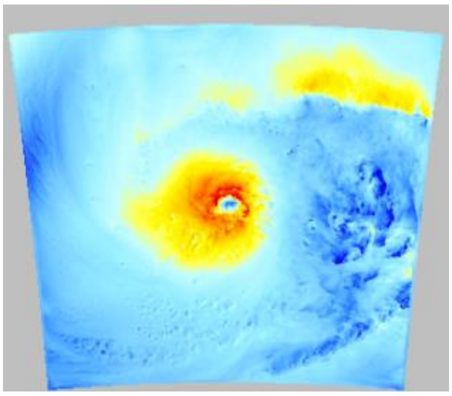

Figure 3: Simulations of wind speed with HARMONIE-AROME for the Hurricane Delta.

On the other hand, tests with other related systems, such as medicanes, have been also carried out using the abovementioned HARMONIE-AROME configuration. In this way, Figure 4 shows the Ianos system simulated using different initial conditions (ERA5 and IFS). The notable differences obtained in the system simulation will be subsequently analyzed.

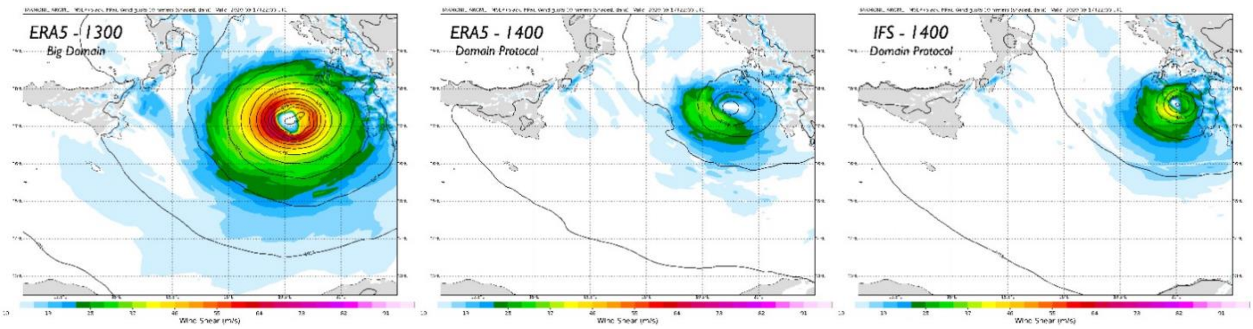

Figure 4: Simulations of wind speed with HARMONIE-AROME for the Medicane Ianos using different initial conditions.

Moreover, from the WRF and HARMONIE-AROME simulations, studies related to the spectrum energy of the different TTS have been analysed and compared to a spectrum energy climatology generated by the SPESMART team using the ERA5 data base and published in Bolgiani et al. (2022).

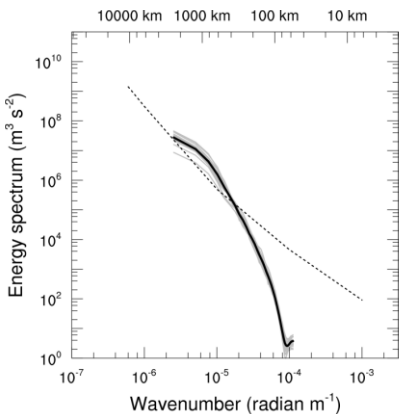

Figure 5: ERA5 wind kinetic energy spectrum at 500 hPa for the domain of storm Delta from 00:00 UTC 22 NOV 2015 to 00:00 UTC 25 NOV 2015. Grey lines are individual spectra, the black line is the average, the dashed line corresponds to the dissipation rate as per Lindborg (1999).

Comparisons and differences between the climatology spectrum energies of the selected TTS (as an example, Figure 5) with those obtained from the high-resolution simulations from the models are being currently analysed.

During the second project year, several TT processes that lead to a hurricane structure [Delta (2005), Ophelia (2017), Leslie (2018), and Theta (2020)] are evaluated using two high-resolution numerical models (WRF and HARMONIE-AROME). Both tracks and intensities of the cyclones (Figures 6, 7) are assessed by comparing the simulated minimum sea level pressure and maximum wind speed to an observational dataset.

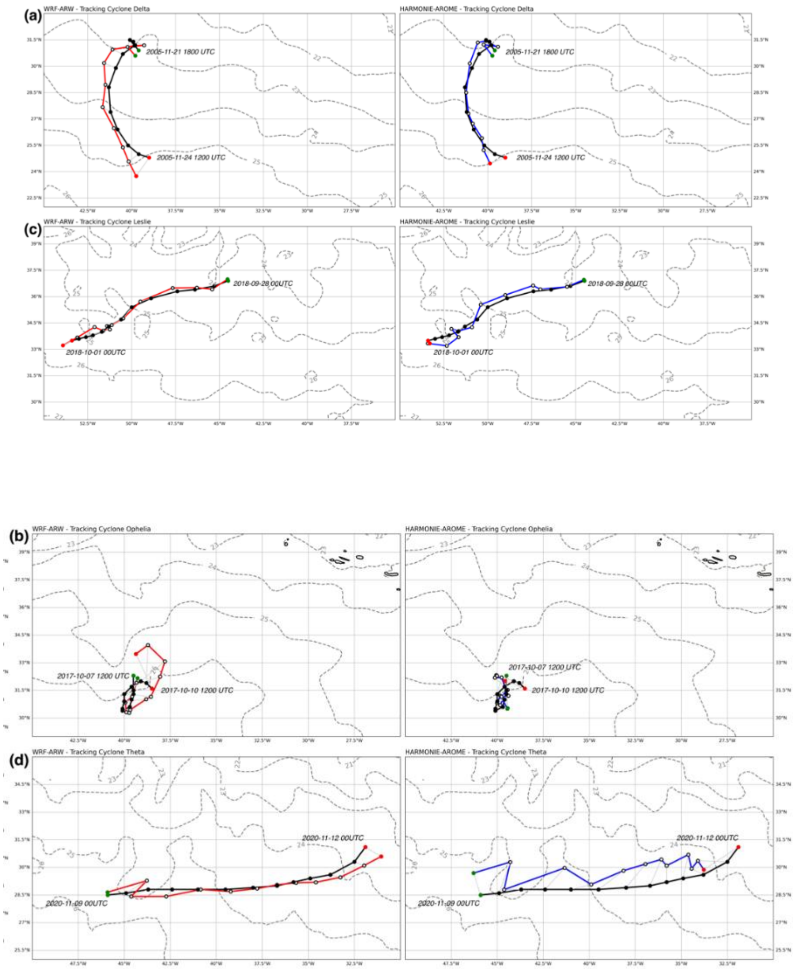

Figure 6: Simulated tracks for WRF (red) and HARMONIE-AROME (blue) models against the HURDAT database (black) for a) Delta, b) Ophelia, c) Leslie and d) Theta. Data is displayed every 6 h. A green circle indicates the beginning of the track, while a red circle marks the end.

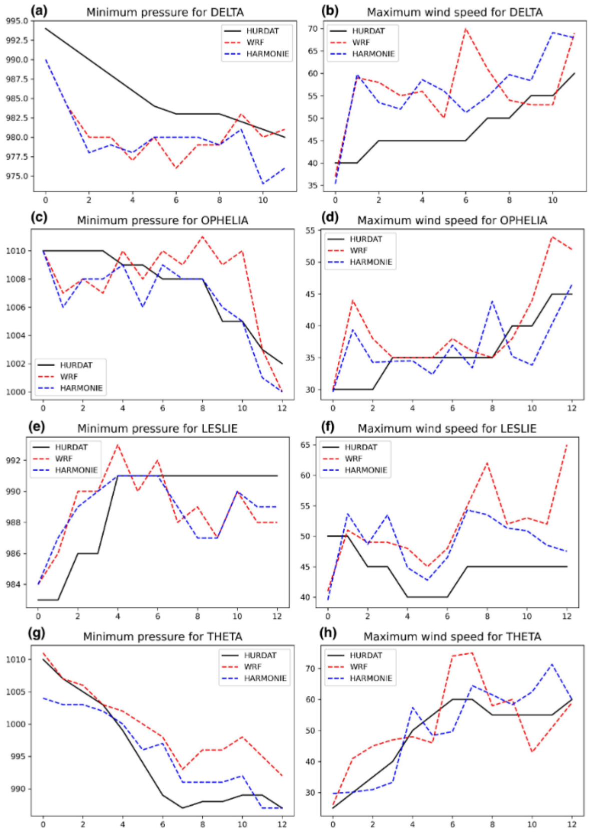

Figure 7: Simulated minimum SLP (left) and maximum SPD (right) by WRF (red) and HARMONIE-AROME (blue) for a), b) Delta, c), d) Ophelia, e), f) Leslie and g), h) Theta.

Moreover, a spatial verification is performed by comparing the MSG-SEVIRI brightness temperature (BT) and accumulated precipitation (IMERG) to the corresponding simulations accomplished by both models. Analyzing the track results, the WRF model, on average, outstands HARMONIE-AROME. However, it is the HARMONIE-AROME model that performs better than WRF when reproducing the intensity of these cyclones. Concerning the BT spatial validation, HARMONIE-AROME slightly outperformed WRF when reproducing the cyclone's structure but failed when simulating the BT amplitude. Besides, both models achieved a nearly perfect cyclone location (Calvo-Sancho et al., 2023). The SAL (Structure, Amplitude, Location) feature-based measurement is another verification method based on a direct attribution of forecasted objects to the observed ones (Wernli et al., 2008) and used to evaluate the level of quality of a particular field, taking into consideration its 'structure' (e.g. dispersed convective cells, frontal rain bands; Früh et al., 2007).

The systems are analysed considering two periods: pre-TT and post-TT times. Concerning BT, SAL results are relatively similar for both analysed periods (Figure 8). While smaller structures ($S < 0$) are generally obtained in comparison to the observation, the amplitude component is slightly underestimated ($A < 0$) for both models and periods (Figures 8a and 8b). The A and S medians have been computed for the WRF and HARMONIE-AROME models (red and blue dashed lines, respectively, depicted in Figure 8). Regarding median results of S during the pre-TT period (Figure 8a), while both models show a negative structure median value, the HARMONIE-AROME model performs slightly better. Similar results are observed for both models when analysing the amplitude median outcomes, with the WRF model outperforming the HARMONIE-AROME model. In terms of the location component, it is remarkable that both models have nearly perfect simulations (L-component median ~ 0.07) during the pre-TT and post-TT periods, with the HARMONIE-AROME model (L-component median ~ 0.07) slightly better than WRF (L-component median ~ 0.08) during the latter period. During the pure TT period (Figure 8b), the WRF model again yields slightly better median amplitude results. The structure median results are slightly worse than during the pre-TT period, but the behavior remains constant, i.e., both models simulate smaller structures (negative S values), and HARMONIE-AROME (blue dashed line) performs slightly better.

Concerning the statistical differences between the two models for the SAL components' distributions, it is outstanding that, while the A and L-components are statistically different (p-value < 0.05), the S-component shows no significant differences (p-value > 0.05). Besides, in general terms, both models depict a relatively symmetrical and concentrated distribution with few outliers (not shown). The WRF model depicts the range and a median closer to zero when simulating the A-component, implying a somewhat more accurate simulation than the one generated by HARMONIE-AROME; on the other hand, both models reproduce the S-component with similar results (not shown).

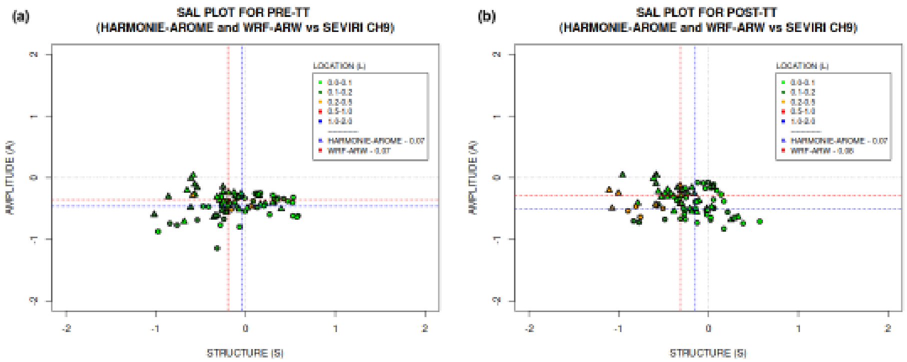

Figure 8: HARMONIE-AROME (triangles) and WRF (circles) model SAL results for the BT field during the a) pre-TT and b) post-TT periods. The medians are displayed in dashed lines for HARMONIE-AROME (blue) and WRF (red).

In terms of accumulated precipitation results, the HARMONIE-AROME model overestimates the larger structures while underestimating the smaller ones, whereas the WRF model underestimates the bigger structures, being poorly located by both models. Although it is difficult to establish which numerical model performs better, the overall results show an outstanding of the HARMONIE-AROME model over the WRF model when simulating TT processes.

In a similar way as done for BT, the accumulated precipitation amplitude and structure medians have also been computed for both models and displayed in Figure 9. During the pre-TT period (Figure 9a), despite both models showing higher median structure values, HARMONIE-AROME performs slightly better than WRF. Moreover, in terms of amplitude, both models display relatively higher median values, with again the HARMONIE-AROME model outperforming the WRF. These results agree with the results obtained in the probability density function (not shown). Finally, concerning the location median outcomes, both models yield similar values (L-component median ~ 0.08).

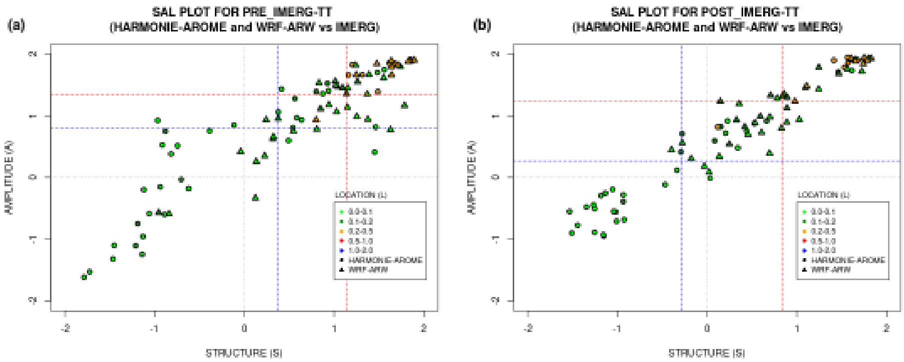

Figure 9: HARMONIE-AROME (triangles) and WRF (circles) model SAL results for the accumulated precipitation field during the a) pre-TT and b) post-TT periods. The medians are displayed in dashed lines for HARMONIE-AROME (blue) and WRF (red).

Additionally, these four TT events, simulated with WRF and HARMONIE-AROME, are selected to study the main features of the horizontal kinetic energy (HKE) spectra of this kind of high-energetic atmospheric systems. Though most of the times similar results are obtained with both models, HAR shows a more intense filtering and numerical dissipation, whereas WRF tends to represent over-energized spectra in the synoptic scale and especially at smaller wavelengths (Figure 10). Predictability is dissimilar for the four TTs studied due to the different spectral curve slope obtained for each case, ranging from unlimited to very poor predictability at synoptic scale. Additionally, an increased HKE is presented in the middle-upper troposphere spectra due to vorticity and convection, which are characteristic features of tropical cyclones.

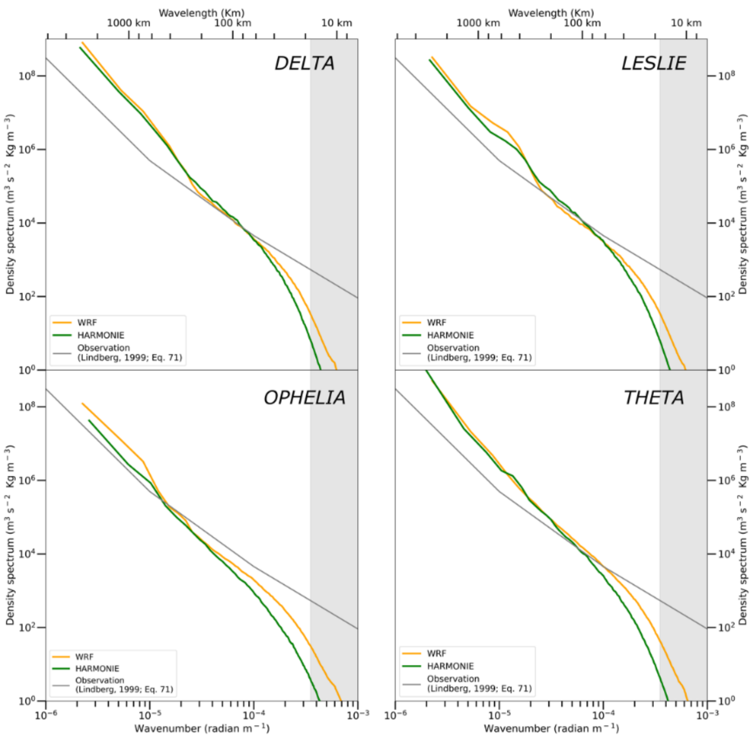

Figure 10: 500 hPa wind HKE spectra for the TTs selected, simulated with WRF and HARMONIE-AROME. The observed energy horizontal wavenumber spectral curve is shown for reference. The shaded area corresponds to the wavelengths below the theoretical effective resolution of the models.

We hope that throughout the remainder of the year, the WRF and Harmonie-Arome models will be used to simulate more TTs and medicanes in the vicinity of the Iberian Peninsula at very high-resolution. As soon as the runs are finished, we will be able to analyse the simulations to study differences and similitudes between key simulated variables (for Harmonie-Arome and WRF) in the genesis, developing and tracking of these systems. The Phase 3 (Analysis of TTs in simulations of an advanced climate model) of this special project will be completed during the next year of the project, tracking and simulating those future TTs. To do this, the EC-Earth simulations will nest HARMONIE-AROME and WRF.

For each atmospheric system, 93000 units approximately have been used using WRF and, around 600000 units have cost using the very-high resolution in HARMONIE. Considering the needed different experiments before the final simulations, that is, WRF set-up, and some proofs with different HARMONIE versions, that they have cost around 800000 units, we have also consumed additional 1900000 units in simulating the TTs. This is the reason why we have exceeded the original request.

It is worth noting that the huge domain and very high resolution used to simulate TTs (500m with the second version of the HARMONIE model) require previous needed tasks which means additional SBUs. We are sorry but finally the system setup has utilized more resources than we originally expected. Currently, the setup has been fixed and therefore in this project step we consider that the new estimation of SBUs we may need is realistic. To sum up, we would need additional SBUs (a request is recently made and positively answer) to continue simulating these TTs at very high-resolution, because these experiments require additional resources that in the original request, we did not expect to need.

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