REQUEST FOR A SPECIAL PROJECT 2022–2024

MEMBER STATE:	SPAIN
Principal Investigator[1]**:**	MARÍA LUISA MARTÍN
Affiliation:	ESCUELA DE INGENIERÍA INFORMÁTICA. UNIVERSIDAD DE VALLADOLID
Address:	PLAZA DE LA UNIVERSIDAD 1, 40005 SEGOVIA (SPAIN)
Other researchers:	Daniel Santos (AEMET), Juan Jesús González-Alemán (Aemet), Lara Quitián-Hernández (UCM), Mariano Sastre (UCM), Pedro Bolgiani (UCM), Javier Díaz (UCM), Francisco Valero (UCM), Eloy Piernagorda (UCM), Carlos Calvo (UVA), Jose Ignacio Farrán (UVA) UVA: Universidad de Valladolid. Spain UCM: Universidad Complutense de Madrid. Spain AEMET: Agencia Estatal de Meteorología. Spain
Project Title:	SIMULATIONS OF TROPICAL TRANSITIONS IN THE EASTERN NORTH-ATLANTIC OCEAN: PAST, PRESENT AND FUTURE PROJECTIONS

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ________________	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2022	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2022-2024: (To make changes to an existing project please submit an amended version of the original form.)		**2022**	**2023**	**2024**
High Performance Computing Facility	(SBU)	2000000	2000000	2000000
Accumulated data storage (total archive volume)[2]	(GB)	25000	25000	25000

[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.

Continue overleaf

Principal Investigator: …… MARÍA LUISA MARTÍN …………………

Project Title: SIMULATIONS OF TROPICAL TRANSITIONS IN THE EASTERN NORTH-ATLANTIC OCEAN: PAST, PRESENT AND PROJECTIONS

Extended abstract

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

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.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, and 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 asking for 3,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.

Related to the thermal structure and dynamic, there are different types of cyclones in the troposphere: tropical cyclone (TC), extratropical (EC) and subtropical cyclone (STC), showing the latter, combinations of the two formers in its thermal structure. For decades, the Eastern North-Atlantic Ocean (ENA) has witnessed numerous extreme events. Intense subtropical cyclones (STCs) have been developed in that area, causing important widespread loss and damage. STCs are low pressure systems with both tropical and extratropical characteristics, having hybrid thermal structures. Such structures can mainly be described by cold upper-tropospheric and warm lower-tropospheric thermal anomalies during several days with gale-force winds around 17 ms-1 near the surface, at 925 hPa (Evans and Guishard, 2009). The difference between these systems and conventional ECs is really slight. Contrary to the midlatitude systems, the STCs develop with relatively shallow and weak baroclinicity (González-Alemán et al., 2015). Moreover, the environment in which STCs develop is characterized by little low-level baroclinicity in juxtaposition with diabatic processes (Hart, 2003; Davis, 2010).

Although the ECs have been simulated in numerous studies, few studies have been carried out on numerically simulating a STC development. Quitián-Hernández et al. (2016) examined the STC developed near the Canary Islands on October 2014 from both the large-scale and mesoscale approaches, analyzing the main features in its synoptic evolution and in its environment using three different numerical models (one of them was the Harmonie model).

In the first special project (SPESMART-spmm) of this research team, some subtropical cyclones (including the October 2014 one) were simulated in order to study their transitions from EC to STC and, if happened, to TC (Bentley and Metz, 2016), as in the case of the Ophelia Hurricane. The transition from STC to TC must be deeply analysed due to the important damage that can generate in an inhabited area, in particular, the Canary Islands zone. In order to achieve these objectives, very high-resolution, both spatial and temporal, simulations are needed. The Harmonie Reference system is being maintained on the ECMWF HPC platform. The Reference System includes the code, scripts and needed tools for the deterministic model and those for the Harmonie-based convection-permitting ensemble firecastubg system HarmonEPS. The previous Special Project aims was to obtain very high-resolution simulations of different variables such as wind speed, convective precipitation, temperatures and other derived important variables, very important in the transition phases (EC-STC-TC), implementing the Harmonie model and proving the model performance as well in simulating this kind of atmospheric systems, not done until now. The Harmonie model provides high-resolution variables, very useful to determine both the critical instants in the cyclone transitions and the key atmospheric variables in such instants. Additionally, in the previous special project the WRF model was also implemented. In Quitián-Hernández et al. (2019), innovative HARMONIE-WRF simulation comparisons of several TCs that suffered some transitions (in Quitián-Hernández et al., 2018), are analyzed. With these results, we are able to establish similitudes and differences between the HARMONIE-WRF behaviour in reproducing TCs.

In the current special project, a continuation of the work started in the project SPESMART will be developed. In this new project, anomalous TCs, that have followed unusual tracks near Western Europe, will be studied. Hurricane Vince (Tapiador et al., 2007; Beven et al., 2008), and Tropical Storm Delta in 2005 (Beven et al., 2008), Hurricane Alex in 2016, Hurricane Ophelia in 2017, or recently Hurricane Leslie in October 2018 have affected different European domains (Figure 1). Their intensification after the extratropical transition (Evans and Hart, 2003) have caused injuries, casualties and huge economical losses along their tracks. Therefore, the analysis of these systems has become one of the most important studies on the domain of the North Eastern Atlantic.

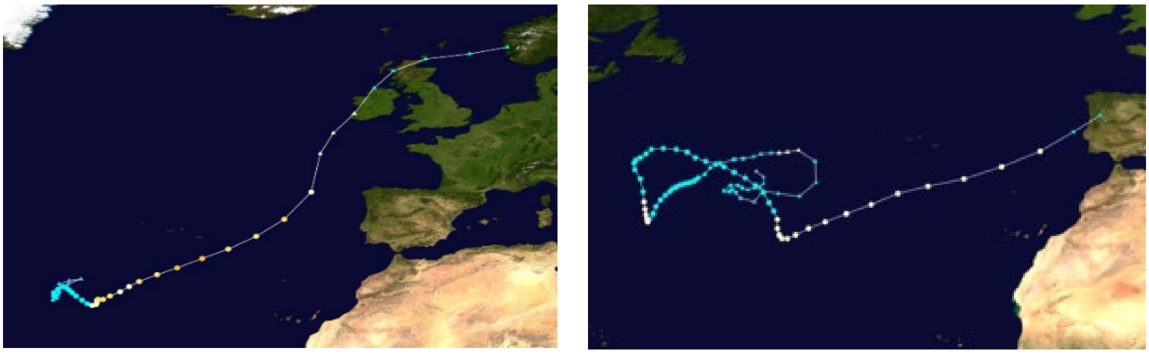

Figure 1: Anomalous tracks of (left) Hurricane Ophelia (2017) and (right) Hurricane Leslie (2018).

The abovementioned storms have shown that they have in common similar formation and transition; In fact, they formed through the so-called Tropical Transition (TT) process, a recently “discovered” form of tropical cyclogenesis. One of the purposes of the present special project will be the study and characterization of these systems, analysing their genesis and, at the same time, trying to understand their essential atmospheric dynamics. The process by which a baroclinic EC is transformed into a fully warm-core TC is known as TT (Davis and Bosart, 2003). TCs formed via TT have the highest likelihood of affecting Europe, because they occur in the subtropics and midlatitudes. TTs form more frequently over the western North Atlantic Ocean, being less common over the Eastern one as the environmental conditions for their formation or maintenance are marginal over the latter. Sea surface temperatures in ENA are lower than over the Western one at the same latitudes, the vertical wind shear is generally high, and during summer, the subsidence associated to the descending branch of the Hadley circulation creates stable and dry conditions. However, during autumn and winter these regions change their conditions and can be occasionally affected by TTs. TTs not only can form in-situ over ENA, but those forming over the Western one can also enter the ENA driven by a westerly large-scale steering flow.

The TT events are associated with a baroclinic contribution near an upper-level potential vorticity (PV) streamers disturbance, where an anticyclonic Rossby wave breaking is instrumental in driving

PV streamers into subtropical and tropical latitudes (Galarneau et al., 2015). Pre-TT disturbances are embedded in mid- and upper-level quasigeostrophic ascent (typical of extratropical cyclogenesis) associated with the PV streamer, with the synoptic-scale anticyclone north of the incipient vortex playing also a role (Galarneau et al., 2015). These events resemble the structure characteristic of extratropical occlusion playing moist convective processes an important role and suggesting that they are reinforced whenever extratropical occlusion occurs over a sufficiently warm ocean surface (Hulme and Martin, 2009).

Although some works have studied TTs, numerous questions are still open. For instance, an improved insight into the relationship between convective processes and the PV streamers throughout the pre-development phase of the disturbance life cycle is needed, which can only be undertaken with higher-resolution simulations. In addition, the role played by warm seclusions (Shapiro and Keyser, 1990) in the development of TTs is not clear yet and how to differentiate between each other (Hulme and Martin, 2009) keeps being a challenge. In this later respect, the Cyclone Phase Space (CPS; Hart, 2003), a widely used tool to identify cyclone structures and transitions, could mislead the identification of a warm seclusion event with a TT event. Another potential field which needs attention is the analysis of the uncertainty, and what can possibly cause it. Its relevance is clearly reflected in the forecast of these events (e.g. Leslie).

It is also worth analysing the effect of the Anthropogenic Climate Change (ACC) is playing any role in development and possible increase of TTs. Recent ACC projections for typical TCs, i.e. those forming via the archetypal tropical cyclogenesis pathway, indicate potential changes in TCs affecting ENA. In present climate, nearly half of North Atlantic TCs experience an ET, evolving into a baroclinic system with potential of affecting Europe (Hart and Evans, 2001). Studies detect a future increase in frequency and intensity of these extratropically-transitioning TCs affecting ENA (Haarsma et al., 2013; Baatsen et al., 2015; Liu et al., 2018). However, these works lack of deep understanding of the processes producing these changes. For instance, no analysis is performed to detect which contribution is derived from TTs (cases like Ophelia and Leslie), which is the most likely way by which a TC could affect Europe. Over the Mediterranean Sea, possible increasing hazard from tropical-like phenomena (Mediterranean tropical-like cyclones) activity has been already linked to ACC (González-Alemán et al., 2019). In addition, these future ACC projection studies have been performed either with uncoupled atmospheric models or with air-sea coupled models with low resolution in the ocean component, and therefore adding uncertainty significantly.

Concerning future projections, the Earth system models are one of the most powerful tools to provide society with information on future climate. In this sense, the EC-Earth atmosphere-ocean coupled climate model is used to address scientific challenges in climate prediction. The EC-Earth is based on the ECMWF's Integrated Forecasting System (IFS) and the NEMO ocean model, and some modifications to the ECMWF's coupled model have been introduced (Doblas-Reyes et al., 2017). EC-Earth generates predictions and projections of global climate and variability, being closely aligned with the ECMWF seasonal forecasting system. One of the purposes of the present proposal will use the EC-Earth model projections to address the relationship between ACC and TTs, deeply analysing the processes causing changes in frequency and intensity of these transitions.

GENERAL OBJECTIVES AND SPECIFIC TASKS

The simulation of TCs, and particularly TTs, entails many difficulties and the results obtained with the numerical models show additional uncertainties. Therefore, new analyses using improved models are required. This fact is particularly needed in areas such as the ENA where in the last years, TTs have occurred (Hurricanes and Tropical Storms as Vince, Delta, Ophelia, Leslie, etc. very close to the Iberian Peninsula and surrounding areas). The importance of the heat fluxes has been addressed in the genesis and development of STCs (Quitián-Hernández et al., 2020), which are related to TTs, and high-resolution simulations are needed to obtain more precise information of these events and their possible TTs. The use of advanced numerical model, such as HARMONIE, should give very high-resolution information about TTs, from a double perspective. Studies of past TTs give us information about the atmospheric dynamics of these systems. Evaluating future simulations of these events in areas nearby the Iberian Peninsula will provide knowledge about these atmospheric systems and their behaviour with respect to the ACC. In this sense, a key collaboration with the Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS, hereafter BSC) is established since the BSC is specialized in high performance computing (HPC) and manages MareNostrum, one of the most powerful supercomputers in Europe. We will use the EC-Earth projections and BSC will provide us the required simulations with different climate scenarios as well as support the project team with expertise and knowledge about climate variability.

To achieve these general objectives, the following specific tasks will be carried out:

- Detecting and selecting TTs in ENA in a reanalysis database of enough high resolution, such as the ERA-5 reanalysis, using the CPS criterion as well other detecting criteria.
- To better characterize the development of TTs over the ENA, and their relationship with PV streamers and midlatitude dynamics from climate perspective.
- Reproducing the selected TTs using both HARMONIE and WRF models. To gain insight into how these models simulate TTs.
- To analyse changes in TTs characteristics under projections, nesting both HARMONIE and WRF in EC-Earth and evaluating the model's behaviour in future TT projections. Relationships between TTs and ACC will give us better understanding about the tropical risk in the Iberian surrounding areas.

SCIENTIFIC PLAN

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

PHASE 1: Selection of TTs in ENA: study of the genesis and atmospheric dynamic

In this phase, the development of TTs in NATL will be studied. To do this, detecting TTs throughout a period that permit us to establish enough case studies of TTs is firstly need. There is not a reliable dataset of observed TTs in NATL, in part due to the unavailability of reanalysis of enough high-resolution so far. In January 2019, ERA-5 reanalysis in ECMWF was launched. This is a new highest resolution reanalysis available, and they hope to even go until 1950 in autumn 2019. ERA-5, contrary to other reanalysis datasets, has a resolution of 32 km, which is good enough to resolve TTs over the NATL. The found TTs will generate a new TT climatology that will permit us to study and characterize of these systems, analysing their genesis and deepening the underlying atmospheric dynamics from a climatic perspective.

The characterization of TT development over NATL, their relationship with PV streamers and cutoff lows will be carried out in this phase of the project. The ERA-5 database will be mainly used to determine TTs over the NATL. Therefore, we will use existing databases (possibly both ERA-5 and ERA-Interim) for compiling a novel database of observed TTs over NATL. The following workflow will be carried out for identifying TTs in the mentioned databases:

1. To do this, the cyclone-space method (CPS) of Hart (2003) that this research group has previously used (see references) will be applied to select probable cases of TTs.

2. Analysis of several case studies of TTs over NATL will be carried out to better understand the TT dynamics. Thus, relationships between TTs, PV streamers, cutoff lows will be analyzed by using the PV streamers detection (Wernli and Sprenger, 2007), which will be applied to ERA-5.

This process will help us to stablish detection criteria to build a climatology of TTs in ERA-5 which can be used to test global models and obtain ACC projections (next Tasks). With this climatology, we will better characterize the TT dynamics and behavior in the last decades. Some of the TTs have been found in the previous Special Project SPESMART which it gives us preceding information about these kinds of systems.

PHASE 2: Assessment of the skill of the models in simulating the behavior of TTs. Study the atmospheric dynamic of TTs.

Here, the selected TTs of the phase 1 will be simulated by means of both HARMONIE and WRF models. The atmospheric dynamic of some simulated TTs will be analyzed, establishing differences and similitudes with the corresponding observed TTs of the previous phase, and so, proving the skill of both models in reproducing such atmospheric systems.

- Task 2.1: Running past TTs in HARMONIE and WRF.

There are many differences between HARMONIE and WRF. The main differences between HARMONIE and WRF lie on the formulation of the dynamical cores. The HARMONIE model uses a nonhydrostatic dynamical core based on the fully compressible Euler equations (Simmons and Burridge 1981; Laprise 1992), discretized in time and space using a semi-Lagrangian advection scheme on a grid and a semi-implicit two-time-level scheme. The spectral representation of most prognostic variables is based on a double Fourier decomposition. This spectral scheme originates from the global IFS used operationally at ECMWF (ECMWF, 2015). On the other hand, the Advanced Research version of WRF is a three-dimensional, Eulerian nonhydrostatic, fully compressible model widely used among the scientific community for atmospheric research. The equations are expressed in flux form using variables that have conservation properties. The formulation is using a terrain-following mass vertical coordinate. The vertical coordinate and present the flux form equations in Cartesian space, including the effects of moisture in the atmosphere, and the ability of use projections to the sphere.

The physical and dynamical behavior of the selected TTs in phase 1 will be studied through the simulations of both models, HARMONIE and WRF, assessing the skillful of the models in reproducing those observed TTs over the NATL domain. In fact, some of the TTs have been simulated in the previous Special Project SPESMART, giving us preceding information about the features of these atmospheric systems.

- Task 2.2: Analysis of the TTs in ensembles generated from HARMONIE and WRF.

Some TTs simulated in Task 2.1 will be run from a probabilistic point of view. Ensembles via HARMONIE and WRF will be generated. The results will provide similitudes and differences between the two models in their EPS behaviour, helping the operational forecasting of the TTs as well as improving the knowledge about model uncertainty sources of the TT atmospheric dynamics. To do this, the clustering methodology used by González-Alemán et al. (2019) will be used to discern between probable different scenarios of behavior for selected cases.

PHASE 3: Analysis of TTs in simulations of an advanced climate model

The increasing TTs over the last years (Vince, Ophelia or Leslie Hurricanes near Iberia) needs the attention of the scientific community to better understand these phenomena and their relationship to ACC. In this stage, the evaluation of present TT features will be carried out by using advanced models. In the present Special Project, an output dataset from Earth system model, the EC-Earth, will be used to find TTs in past and present simulations. Here the TT behaviour will be analysed by taking into account the identified characteristics of the TTs found in the previous tasks, assessing the simulation skill of this advanced atmosphere-ocean coupled climate model. The simulations will correspond to those that will be used in the well-known Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). These past and present simulations cover the period from 1960 to 2014 (hereafter EC-Earth CTRL).

- Task 3.1: Analysis of the TT behaviour in the present climate of the climate model (EC-Earth CTRL).

TTs in the present climate of the EC-Earth CTRL will be identified considering the same methodology of the phase 1. The CPS diagrams will be used to find those systems with features associated to a TT. The ability of this advanced model in reproducing the TTs will be evaluated.

- Task 3.3: Evaluation of the behaviour of TTs in EC-Earth CTRL nesting HARMONIE and WRF.

Once HARMONIE and WRF are nested, the models will be evaluated considering the obtained TTs in EC-Earth CTRL. Thus, selected TTs in EC-Earth found in Task 3.1 will be simulated in HARMONIE and WRF and their behaviour in EC-Earth CTRL will be analysed considering the results obtained by simulating past TTs (Task 2.1). In this way, we will be able to address differences not only in the performance of the two models but also in the behaviour of the detected TTs in EC-Earth CTRL against the simulated ones in Task 2.1.

PHASE 4: Analysis of TTs in future ACC projections

Relationship ACC - TTs will be assessed in this stage. In a first step, future TTs will be identified in the EC-Earth model simulations. These simulations consist on the same ones in phase 3 but for future time period. Currently, the simulations (EC-Earth projections) cover from 2014 to 2040 but BSC is still working on extending the period up to 2100. The emissions scenario in these simulations will involve the Representative Concentration Pathways (RCP), RCP4.5, determining the moderate ACC effects on the TTs characteristics. The use of the RCP8.5 will be also taken into account in order to examine the worst scenario in terms of intensity of emission provoking ACC.

- Task 4.1: Analysis of the TT behaviour in EC-Earth projections.

In this task, a set of future TTs will be obtained and studied, using the CPS diagrams and the cyclone tracking methodology, already used in the Task 1.1. In this way, possible similitudes, and differences with the TTs obtained with ERA-5 (Task 1.1) and with EC-Earth CTRL (Task 3.1) will be assessed. The frequency of TTs future occurrences will be examined, addressing the differences between the incidence of past and future TTs.

- Task 4.2: HARMONIE and WRF simulations of future TTs under ACC perspective.

Once the future TTs are selected in the previous task, a subset of them will be simulated with HARMONIE and WRF nested in EC-Earth projections. Differences between the two models will be established as well as comparisons with the results obtained in Task 3.3 in which TT behaviours in EC-Earth CTRL were assessed. Possible changes in the genesis, intensity, frequency and tracks of

TTs in the NATL domain will be evaluated under future climate change conditions, helping us to understand the role of ACC in altering the potential threat of TTs in the Iberian surrounding areas.

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 (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. Iinitial/boundary conditions will be obtained from the ERA5 Reanalysis of the ECMWF with a 0.31° horizontal resolution every 6 hours.

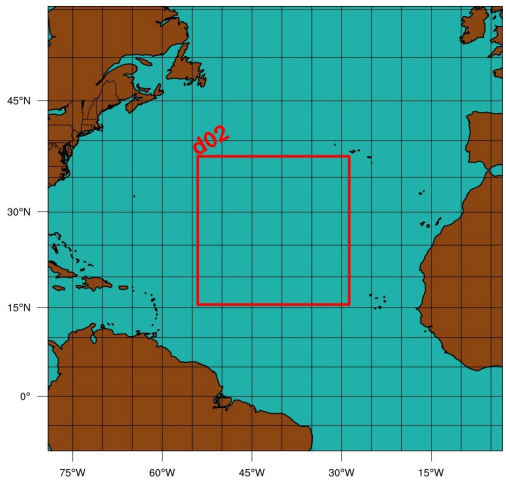

Figure 2: Example of WRF domain configuration to simulate Hurricane Delta.

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 (Bengtsson et al., 2017), the model also has a main domain with 2.5 km resolution and the same grid dimensions (1000x1000) in the west-east and south-north directions (domain in Figure 3, left) 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 shows tracks of additional identified TTs by this research team from 1950 to 2019, that we will need to simulate with both models to study during the time before their genesis, analysing possible precursors that can be useful in forecasting and warning this kind of catastrophic events.

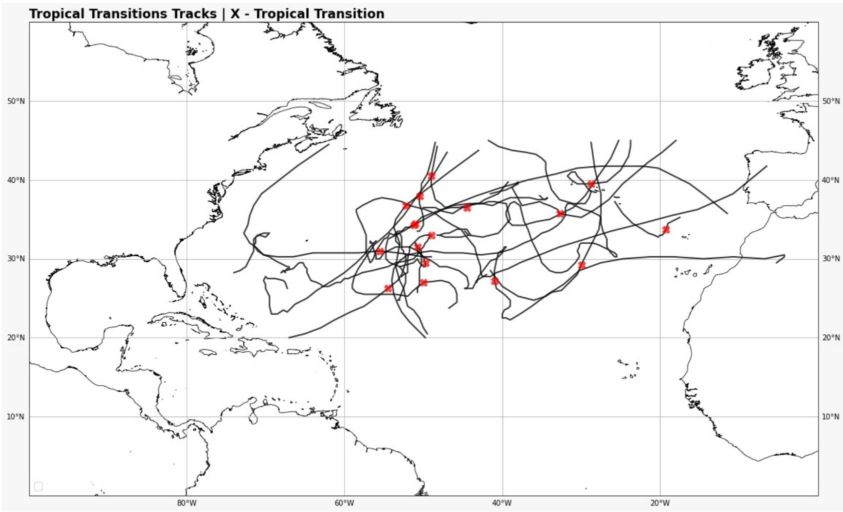

Figure 3: Tracks of several TTs identified (1979 - 2019).

For each of these atmospheric systems, 93000 units approximately have been used using WRF and, around 40000 units have cost using HARMONIE. 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. Therefore, we believe that 2000000 units will originally be required for simulating these TTs.

References:

Baatsen, M., Haarsma, R. J., Van Delden, A. J. and de Vries, H. (2015): Severe autumn storms in future western Europe with a warmer Atlantic Ocean', Clim. Dyn. 45(3–4), 949–964 (DOI: 10.1007/s00382-014-2329-8).

Bengtsson, L., Andrae, Ulf, D. Santos-Muñoz et al. (2017): The HARMONIE-AROME Model Configuration in the ALADIN-HIRLAM NWP System. Mon. Wea. Rev., 145, 1919-1935.

Beven, J. L., and Coauthors (2008): Atlantic hurricane season of 2005. Mon. Wea. Rev., 136, 1109–1173.

Bentley, A. M., and Metz, N. D., 2016: Tropical transition of an unnamed, high-latitude, tropical cyclone over the eastern North Pacific. Mon. Wea. Rev., 144, 713–736, doi:10.1175/ MWR-D-15-0213.1.

Davis CA, 2010. Simulations of Subtropical Cyclones in a Baroclinic Channel Model. J. Atmos. Sci., 67, 2871-2892.

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

Doblas-Reyes, F.J., J.C. Acosta Navarro, M. Acosta, O. Bellprat, R. Bilbao, M. Castrillo, N. Fučkar, V. Guemas, Ll. Lledó, M. Ménégoz, C. Prodhomme, K. Serradell, O. Tintó, L. Batté, D. Volpi, A. Ceglar, R. Haarsma, F. Massonnet (2017) Using EC-Earth for climete prediction research. ECMWF Newsletter, 154, 35-40.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two–dimensional model. J. Atmos. Sci., 46, 3077-3107.

ECMWF, 2015: Operational implementation 12 May 2015. PartIII: Dynamics and numerical procedures. European Centre forMedium-Range Weather Forecasts IFS Doc. Cy41r1, 29 pp.[Available online athttp://www.ecmwf.int/en/elibrary/9210-part-iii-dynamics-and-numerical-procedures.]

Evans JL and Hart RE (2003): Objective Indicators of the Life Cycle Evolution of Extratropical Transition for Atlantic Tropical Cyclones. Mon Weather Rev, 131(5), 909-925.

Evans, J.L., Guishard, M.P., 2009. Atlantic subtropical storms. Part I: diagnostic criteria and composite analysis. Am. Meteorol. Soc. 137, 2065–2080. http://dx.doi.org/10.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016): Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958.

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(2), 572–597.

González-Alemán, J.J., Valero, F., Martín-León, F., Evans, J.L. (2015): Classification and synoptic analysis of subtropical cyclones within the northeastern Atlantic Ocean. J. Clim. 28, 3331–3352.

González-Alemán J.J., Pascale , S. Gutierrez-Fernandez J., Murakami H., Gaertner M. A. Gabriel, Vecchi A. (2019): Potential Increase in Hazard From Mediterranean Hurricane Activity With Global Warming. Geophys Res Lett, 46, 1754–1764.

Haarsma R.J., Hazeleger W., Severijns C., Vries H., Sterl A., Bintanja R. Oldenborgh G., BrinkH. (2013): More hurricanes to hit western Europe due to global warming Geophys Res Lett, 40, 1783–1788.

Hart, R.E. (2003): A cyclone phase space derived from thermal wind and thermal asymmetry. Mon. Wea. Rev. 131, 585–616.

Hart, R. E., Evans J.L. (2001): A climatology of the extratropical transition of Atlantic tropical cyclones, J. Clim., 14, 546–564.

Hong, S.–Y., and Lim, J.–O. J., 2006: The WRF single-moment 6–class microphysics scheme (WSM6). J. Korean Meteor. Soc., 42, 129-151.

Hulme, A. L., Martin, J. E. (2009). Synoptic- and frontal-scale influences on tropical transition events in the Atlantic basin. Part I: A six-case survey. Mon. Wea. Rev., 137, 3605–3625.

Laprise, R., 1992: The Euler equations of motion with hydrostaticpressure as an independent variable.Mon. Wea. Rev.,120, 197–207.

Liu M., Vecchi, G. Smith, J.A., Murakami, H. (2018): The present-day simulation and twenty-first-century projection of the climatology of extratropical transition in the North Atlantic. J. Climate, 30, 2739–2756.

Quitián-Hernández, L., M.L.Martín, J.J. González-Alemán, D. Santos-Muñoz, F. Valero (2016): Identification of a Subtropical Cyclone in the proximity of the Canary Islands and its analysis by numerical modeling. Atmos. Res., 178–179, 125–137 .

Quitián-Hernández, L., S. Fernández-González, J.J. González-Alemán, F. Valero, M.L. Martín (2018): Analysis of sensitivity to different parameterization schemes for a subtropical cyclone. Atmos. Res.,204, 21-36.

Quitián-Hernández, L., Daniel Santos-Muñoz, Juan Jesús González Alemán, Javier Diaz-Fernandez, Sergio Fernández-González, Pedro Bolgiani, Mariano Sastre, Francisco Valero, Maria Luisa Martin (2019). Analysis Of Several Subtropical Cyclones By Means Of The High-Resolution HARMONIE-AROME Model. Congress of American Geophysical Union (AGU). General Assembly Conference. San Francisco, USA.

Quitián-Hernández, L., J. J. González-Alemán, D. Santos-Muñoz, S. Fernández-González, F. Valero, M. L. Martín (2020): Subtropical cyclone formation via warm seclusion development: The importance of surface fluxes. J. Geophys. Res.: Atmospheres.

Shapiro, M. A., & Keyser, D. (1990). Fronts, jets streams, and the tropopause. Extratropical Cyclones: The Erik Palmén Memorial Volume, C. W. Newton and E. Holopainen, Eds., American Meteorological Society, 167–191.

Simmons, A., and D. M. Burridge, 1981: An energy and angular-momentum conserving vertical finite-difference scheme andhybrid vertical coordinates.Mon. Wea. Rev.,109, 758–766.

Tapiador FJ, Roca R., Genio A., Dewitte B., Petersen W., Zhang F. (2007): Is precipitation a good metric for model performance? BAM Meteorol Soc, 88(7), 1027-1032.

Wernli H, Sprenger M. (2007). Identifcation and ERA-15 climatology of potential vorticity streamers and cutoffs near the extratropical tropopause. Journal of the Atmospheric Sciences 64: 1569–1586, doi: 10.1175/JAS3912.1.