REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Spain

Principal Investigator[1]: Diego Saúl Carrió Carrió

Affiliation: Universitat de les Illes Balears

Address:
Cra. de Valldemossa, km 7.5
07122 – Palma de Mallorca (Illes Balears)

Other researchers:
Romualdo Romero March
Víctor Homar Santaner
Rossella Ferretti
Antonio Ricchi
Dorita Rostkier-Edelstein

Project Title: Design and Implementation of High-Resolution Rapid Refresh Data Assimilation Systems for rapidly evolving tropical-like cyclones in the Mediterranean region.

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SENTINEL**	
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 **X**	NO ☐

Computer resources required for 2025-2027: (To make changes to an existing project please submit an amended version of the original form.)		**2025**	**2026**	**2027**
High Performance Computing Facility	(SBU)	60000000	60000000	60000000
Accumulated data storage (total archive volume)[2]	(GB)	25000	25000	25000

Continue overleaf

---

[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.

Principal Investigator:	Diego Saúl Carrió Carrió
Project Title:	Design and Implementation of High-Resolution Rapid Refresh Data Assimilation Systems for rapidly evolving tropical-like cyclones in the Mediterranean region.

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, disciplinary relevance, 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 1,000,000 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.

Introduction

The Mediterranean basin is recognized as one of the geographical regions most frequently affected by high impact weather events in the world (Petterssen, 1956). This region is naturally predisposed to such events because of its singular orographic features, including a relatively warm sea surrounded by complex terrain. This geographical configuration forces the warm and moist airflow to lift, favoring condensation and triggering convection. Hazardous weather events in this region, such as heavy precipitation (e.g., flash floods, snowstorms), cyclogenesis or windstorms (e.g., squall lines, tornadic thunderstorms), produce huge economic, injury and human losses in populated coastal regions (e.g., Romero et al., 1998b; Llasat and Sempere-Torres, 2001; Llasat et al., 2010; Jansa et al., 2014; Flaounas et al., 2016; Pakalidou and Karacosta, 2018; Amengual et al., 2021). Since 1900, more than 500 billion Euros associated with total property damages and over 1.3 million fatalities related to hydrometeorological disasters has been recorded in the EM-DAT international disaster database. These effects underscore the critical need for accurate and rapid high-resolution weather forecasting systems, aimed at extending the lead time for severe weather warnings, thereby enabling the implementation of effective mitigation strategies to reduce fatalities and economic losses. This clearly reveals the **need for having accurate and fast high-resolution weather forecast systems, with the main objective of increasing the lead time for warnings of severe weather events** and thus, adopting the appropriate set of mitigation strategies to **reduce the number of fatalities and economical losses**.

While the accuracy of weather forecasting has significantly improved in recent years, with better representation of physical processes and dynamics, **accurate prediction of high impact weather events in terms of their location, timing, and intensity remains a major challenge** for the scientific community (Stensrud et al., 2009; Mass et al., 2002; Bryan and Rotunno, 2005; Yano et al., 2018; Torcasio et al., 2021). In this context, a probabilistic approach based on regional convection-permitting ensemble forecast systems has been demonstrated to provide useful and valuable forecast to predict high-impact weather events (Schwartz et al., 2010; Clark et al., 2011; Evans et al., 2014; Schwartz et al., 2019). However, **the best practice in ensemble generation strategies remains unclear**. There are several approaches for producing convection-allowing ensembles. One simple method is to add random noise to a deterministic field (Hohenegger and Schär, 2007; Raynaud and

Bouttier, 2016). A potential limitation of this method is that randomly produced initial conditions are not flow dependent. Another method is to download preexisting coarser-resolution analyses or short-term forecasts from either an ensemble or collection of deterministic numerical weather prediction models directly onto the limited-area (regional) grid (Jones and Stensrud, 2012; Romine et al., 2014; Schwartz et al., 2015a). However, downscaling from a coarser analysis (typically a global analysis) could result to be not useful to generate an ensemble to predict local small-scale severe weather events due to the lack of effective small-scale information. Alternative methods to generate ensembles accounting for model error are mainly based on the representation of subgrid processes by means of physical parameterizations. The most extended methodologies are the use of multiple parameterization suites across different ensemble members (i.e., multiphysics) or stochastic parameterizations. In this latter case, popular approaches include stochastically perturbed physics tendencies (SPPT; Buizza et al., 1999) and stochastic kinetic energy backscatter (SKEB; Shutts, 2005). Still another approach for generating convection-allowing ensembles is to produce them directly on the regional grid with an ensemble *Data Assimilation* (DA; Kalnay, 2003) system, which provides flow-dependent initial conditions with the forecast model that span all possible resolvable scales (Bouttier et al., 2012, Johnson and Wang, 2016; Keresturi et al., 2019). DA is typically used to enhanced representation of the initial conditions by merging not only the nominal values of the observations and the model, but also their respective error statistics. DA can also improve the forecasting of local high-impact weather phenomena by advecting information from terrestrial areas and also by assimilating remote sensing observations, which, in contrast to *in-situ* observations, provide homogeneously distributed data over maritime areas. This is particularly important in the case of the Mediterranean region, which features scarcity of *in-situ* observations surrounded by complex topography.

Special attention will be paid to improve the predictability of the most intense tropical-like Mediterranean cyclones, a.k.a. medicane (Emmanuel, 2005), which remains a major challenge to current mesoscale numerical weather models. In this case, air-sea interactions can also play a crucial role in the development of medicanes. The sea can play both the role of intensifier, supplying energy to the atmosphere through latent and sensible heat fluxes, or dissipator, moving energy from the sea surface to the depths, and bringing cooler water masses back to the surface. Waves act as modulator of this transfer and contribute to the complex feedback chain. Disentangling and understanding these interactions requires from state-of-the-art numerical models, capable of reconstructing the structure of the atmosphere, ocean and wave fields. To this purpose, a coupled Atmosphere-Ocean-Wave model at kilometer and sub-kilometer scales is also planned to be used to improve the predictability of such extreme cyclones.

Overall, improving small-scale extreme weather forecasts requires from: (a) the use of high-resolution ensemble systems that explicitly resolve (moist) deep convective scale processes, (b) dense observations at high spatial and temporal resolution to be ingested into the system by means of DA techniques and (c) using sophisticated coupled Atmosphere-Ocean-Wave models at high spatial and temporal resolution. The **main objective of this SPECIAL PROJECT** is to investigate the performance goodness from combining convective-scale ensemble generation techniques, data assimilation and coupling Atmosphere-Ocean-Wave models to improve low-predictable severe weather forecasts affecting the Mediterranean basin.

To be able to perform these simulations it is required to use ensemble forecasts using preferably more than 80 ensemble members. In order to produce valuable and informative forecasts regarding deep convection and severe weather events, resolutions as high as 1-3 km must be used. These two requisites combined required massive computational resources that could be supplied by ATOS HPC. The proposed project will be carried out using the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), developed by the Mesoscale and Microscale Meteorology (MMM) Laboratory at the National Centers for Atmospheric Research (NCAR). The suite of programs used to implement the Ensemble Kalman filter is the Data Assimilation Research Testbed (DART, http://www.image.ucar.edu/DAReS/DART/), also from the NCAR group.

Scientific Plan

The primary goal of this special project is to enhance the predictability of severe weather in the Mediterranean region, particularly focusing on convective-scale phenomena that are currently low in predictability. This will be achieved by integrating state-of-the-art ensemble generation strategies with advanced ensemble-based data assimilation (DA) algorithms. The specific objectives are the following:

1. Implementation of Convective-Scale Ensemble Generation Techniques.
2. Assess DA Strategies for Small-Scale Processes.
3. Coupling Ensemble Generation with DA.
4. Implement Regional Atmosphere-Ocean-Wave Coupled Models.

These objectives support the aims of the *MedCyclones* COST-ACTION (CA19109; https://medcyclones.eu/), an international effort that the PI of this project is actively involved with. Additionally, these efforts are also aligned with the goals of the European *Marie-Sklodowska Curie Action* postdoctoral fellowship (*SENTINEL*), currently led by Dr. Carrió.

The specific tasks proposed to accomplish the above objectives are outlined below:

Task 1: Implementation of Convective-Scale Ensemble Generation Techniques

Task 1.1: Downscaling from Global Ensemble Prediction System

This task involves downscaling the global ECMWF Ensemble Prediction System (EPS), based on singular vectors (Buizza and Palmer, 1995), for selected catastrophic weather events and intense medicane cases across the Mediterranean region. WRF model will be used to downscale the entire global EPS-ECMWF, which consists of 50 ensemble members, to a high grid resolution of 2-3 km centered over the different selected cases. Each case will include a spin-up period of 6-12 hours to ensure physically balanced fields, with various tests conducted to optimize model configuration such as nested domain numbers, spin-up duration, and physical parameterizations to obtain the most accurate forecast.

Task 1.2: Adding Random Noise to a Deterministic field

For each case study, the global deterministic initial and boundary conditions from the ECMWF, available at higher resolution compared to the EPS-ECMWF (e.g., 9 km vs 16 km, respectively), will be downscaled to a 2-3 km WRF grid resolution with a 6 hour spin-up period. To obtain our ensemble of initial and boundary conditions, Gaussian random noise will be applied to the prognostic WRF variables of the downscaled deterministic field. Ensemble spread evolution of this ensemble method will be compared with those obtained in Task 1.1 to assess its effectiveness in predicting convective-scale weather events.

Task 1.3: Multiphysics Ensemble based on Physical Parameterization

The multiphysics ensemble will be generated according Stensrud et al., (2000) and Wheatley et al., (2012), where each ensemble member uses different set of parameterizations. The diversity in this type of ensemble will consist in using different (a) short- and long-wave radiation schemes, (b) cumulus parameterizations, (c) planetary boundary layer schemes. However, the same microphysics and land surface scheme will be used along the different ensemble members. The cumulus parameterization is only applied in the WRF domains using grid resolutions larger than 3 km.

Task 1.4: Stochastically Perturbed Physics Tendencies Ensemble

Various popular stochastic techniques will be implemented and tested in WRF. Popular strategies such as SPPT or SKEB will be applied to the downscaled fields of the deterministic IFS ECMWF, to generate our ensemble. With this technique we could also increase the number of ensemble members we will use to improve the forecasts of extreme weather events. In this way, we avoid the limitations of the EPS-ECMWF direct downscaling ensemble generation method (Task 1.1). Ensemble spread evolution will be compared with the ensembles generated on Task 1.1, Task 1.2 and Task 1.3.

Task 1.5: DART-CV3 Climatological Covariance based Ensemble

Initial and boundary conditions for each ensemble member will be produced by perturbing forecasts from IFS-ECMWF with random, correlated, Gaussian noise with zero mean (e.g., Torn et al., (2006)) drawn from the default "CV3" background error covariances provided by the WRF Model's Data Assimilation system (WRFDA; Barker et al., (2012)), which were produced with the "NMC method" (Parrish and Derber, (1992)) based on differences between 48- and 24-h forecasts.

Task 2: Ensemble-based data assimilation

Task 2.1: Assimilation of Conventional Observations

Conventional *in-situ* observations obtained from NOAA's Meteorological Assimilation Data Ingest System (MADIS, https://madis.ncep.noaa.gov/madis_qc.shtml), which has the main advantage of providing high-level quality-controlled data worldwide, will be hourly assimilated. In particular, it will be assimilated pressure, temperature, humidity and horizontal wind speed and direction observations from instruments such as METARs, maritime buoys, rawinsondes and aircrafts.

Task 2.2: Assimilation of Weather Radar Observations

Reflectivity and Doppler radial wind velocities provide essential information of near-coastal dynamic and thermodynamic conditions. However, these observations are typically not quality controlled and present aliasing features together with very noisy data, especially at low levels (i.e., ground cluttering, attenuation of the radar signal, orographic false echoes, etc.). After post-processing and cleaning these data using different algorithms (e.g., *Wradlib*, *BALTRAD* or *Py-ART*), they will be assimilated by means of EnKF using EnKF within the *Data Assimilation Research Testbed* (DART) software (Anderson et al., 2009). DART provides the observation operators required to assimilate different types of observations, including reflectivity and radial velocities from radar. Data from AEMET, *MeteoFrance* and other radar meteorological services will be gathered for each case study.

Task 2.3: Assimilation of Satellite Radiances

Extreme weather events in the Mediterranean region regularly initiate offshore far from radar coverage. In these cases, satellite observations, especially radiances, are fundamental to obtain an adequate representation of the atmospheric state. However, observational operators for radiances are currently not available in DART, thus requiring an adaptation of such operator from an additional source. In this context, the *Gridpoint Statistical Interpolation* (GSI) system, which is a variational DA used in a variety of forecast models, including the Hurricane Weather Research and Forecasting model and NASA's Goddard Earth Observing System model, will be used to obtain radiance observational operators. We plan on testing the use of Advanced Microwave Sounding Unit-A and Unit-B, Microwave Humidity Sensor, IASI temperature and humidity profiles, and AMSU-A.

Task 2.4: Evaluation of the performance of various Kalman filters

EnKF is only one type of approach of ensemble DA algorithms based on Kalman filters. The performance of alternative of other schemes, such as the *Local Ensemble Transform Kalman Filter* (Hunt et al., 2007) or the *Adjustment Kalman Filter* (Anderson, 2001) over the Mediterranean area remains unknown. We will compare the performance of these Gaussian and linear data assimilation filters against a recent type of filter known as "*Particle Filters*", which are more general, and they are not limited by the Gaussian and linearity assumptions from Kalman filter. In particular, we will use the *Local Particle Filter* (LPF; Poterjoy, 2016). The LPF will be used for the first time to improve predictability of severe weather events in the complex geographical region of the Mediterranean basin.

Task 3: Coupling Ensemble Generation Techniques and Data Assimilation.

Although severe weather forecasts could be improved using separately the different ensembles generated in the subsections of Task 1 and the DA schemes mentioned in Task 2, combining both techniques are expected to provide much significant improvements. The ensembles generated by the different techniques will be combined with the different DA schemes to find which combination provides better results.

Task 4: Implementation of Regional Atmosphere-Ocean-Wave Coupled Models
Extreme weather events in the Mediterranean, such as medicanes, typically rely on uncoupled atmospheric models that do not consider interactions with the ocean surface. Recent studies have indicated that strong mixing in the oceanic surface layer may significantly influence cyclone intensities.

Task 4.1: Perform Coupled Atmospheric-Ocean Simulations
Compile and run the coupled Atmospheric-Ocean model in ATOS. Run a battery of simulations at high grid resolution for the most intense cyclones in the Mediterranean region (e.g., Ianos, Rolf, Qendresa, among others). Results will be compared against what it is obtained running the uncopled WRF atmospheric model to see the impact of considering ocean feedback. Additionally, sensitivity experiments updating the Sea Surface Temperature (SST) using high-resolution data, such as the ones from *Copernicus Marine Service* (https://marine.copernicus.eu/) or data from NASA (https://weather.ndc.nasa.gov/sport/sst/) will be also assessed.

Task 4.2: Perform Coupled Atmospheric-Ocean-Wave Simulations
Like the previous Task, but now using a more complex coupled model considering the effect of marine waves. A similar analysis will be performed and compared with Task 4.1 to assess the effect of having the wave component in the coupled model.

Task 4.3: Perform DA + Coupled Atmospheric-Ocean-Wave Simulations
This task proposes integrating advanced DA techniques with coupled Ocean-Wave-Atmosphere models at high-resolution to enhance accuracy of tropical-like cyclones forecasting. Using the coupled DA system, assimilate *in-situ* conventional observations together with spatial high-resolution scatterometers surface wind information over the sea, where the medicanes initiated, together with *Atmospheric Motion Vectors* wind information at different pressure levels obtained from satellite.

Justification of Computational Resources

The proposed activities rely on running multiple ensemble convective-scale simulations with horizontal grid spacing ≤ 2.5 km and 60 vertical levels, using Atmospheric-Ocean-Wave coupled and uncoupled models, resulting in a highly computationally demanding setup. Since these experiments are aimed at investigating the potential of the proposed ensemble generation strategies to forecast extreme events, ensemble size must be moderately large in order to make a sufficiently vast sampling of the phase space to capture risk scenarios. Furthermore, the DART filter used for data assimilation is an extremely demanding algorithm that needs the entire statistical description of the atmosphere (i.e., all ensemble members) in memory to perform the ensemble assimilation step. Therefore, this process requires massive use of memory, disk access and CPU.

The cost of running a WRF at high-resolution is approximately 1 million SBU for each ensemble experiment and a similar cost for the assimilation step on the current ATOS system. The requested 60 million SBUs per year provide enough flexibility to adapt the proposed experiments to the obtained results.

The completion of the above ambitious scientific plan will provide the atmospheric modelling community with new forecast strategies to improve predictability of extreme weather events in complex regions, such as the Mediterranean basin. In addition, the focus on extreme events will provide improvements in the understanding and modelling of these phenomena, which constitute a persistent threat to society. The extremely demanding setting needed to successfully accomplish these tasks requires access to world-class high performance computing facilities, such as the ECMWF infrastructure.

References

Amengual, A., Hermoso, A., Carrió, D. S., & Homar, V. (2021). The Sequence of Heavy Precipitation and Flash Flooding of 12 and 13 September 2019 in Eastern Spain. Part II: A Hydrometeorological Predictability Analysis Based on Convection-Permitting Ensemble Strategies. Journal of Hydrometeorology, 22(8), 2153-2177.

Anderson, J. L. (2001). An ensemble adjustment Kalman filter for data assimilation. *Monthly Weather Review*, *129*(12), 2884–2903. https://doi.org/10.1175/1520-0493(2001)129<2884:AEAKFF>2.0.CO;2

Anderson, J., Hoar, T., Raeder, K., Liu, H., Collins, N., Torn, R., & Avellano, A. (2009). The data assimilation research testbed a community facility. *Bulletin of the American Meteorological Society*, *90*(9), 1283–1296. https://doi.org/10.1175/2009BAMS2618.1

Barker, D., Huang, X. Y., Liu, Z., Auligné, T., Zhang, X., Rugg, S., ... & Zhang, X. (2012). The weather research and forecasting model's community variational/ensemble data assimilation system: WRFDA. Bulletin of the American Meteorological Society, 93(6), 831-843.

Bryan, G. H., & Rotunno, R. (2005, October). Statistical convergence in simulated moist absolutely unstable layers. In Preprints, 11th Conf. on Mesoscale Processes, Albuquerque, NM, Amer. Meteor. Soc. M (Vol. 1).

Buizza, R., Miller, M., & Palmer, T. N. (1999). Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System. *Quarterly Journal of the Royal Meteorological Society*, *125*(560), 2887–2908. https://doi.org/10.1256/smsqj.56005

Clark, A. J., Kain, J. S., Stensrud, D. J., Xue, M., Kong, F., Coniglio, M. C., ... & Du, J. (2011). Probabilistic precipitation forecast skill as a function of ensemble size and spatial scale in a convection-allowing ensemble. Monthly Weather Review, 139(5), 1410-1418.

Emanuel, K. (2005). Genesis and maintenance of" Mediterranean hurricanes". Advances in Geosciences, 2, 217-220.

Evans, J. P., Ji, F., Lee, C., Smith, P., Argüeso, D., & Fita, L. (2014). Design of a regional climate modelling projection ensemble experiment–NARCliM. Geoscientific Model Development, 7(2), 621-629.

Flaounas, E., Lagouvardos, K., Kotroni, V., Claud, C., Delanoë, J., Flamant, C., ... & Wernli, H. (2016). Processes leading to heavy precipitation associated with two Mediterranean cyclones observed during the HyMeX SOP1. Quarterly Journal of the Royal Meteorological Society, 142, 275-286.

Hohenegger, C., & Schar, C. (2007). Atmospheric predictability at synoptic versus cloud-resolving scales. Bulletin of the American Meteorological Society, 88(11), 1783-1794.

Hunt, B. R., Kostelich, E. J., & Szunyogh, I. (2007). Efficient data assimilation for spatiotemporal chaos: A local ensemble transform Kalman filter. *Physica D: Nonlinear Phenomena*, *230*(1–2), 112–126. https://doi.org/10.1016/j.physd.2006.11.008

Jansa, A., Alpert, P., Arbogast, P., Buzzi, A., Ivancan-Picek, B., Kotroni, V., ... & Speranza, A. (2014). MEDEX: a general overview. Natural Hazards and Earth System Sciences, 14(8), 1965-1984.

Jones, T. A., & Stensrud, D. J. (2012). Assimilating AIRS temperature and mixing ratio profiles using an ensemble Kalman filter approach for convective-scale forecasts. Weather and forecasting, 27(3), 541-564.

Johnson, A., & Wang, X. (2016). A study of multiscale initial condition perturbation methods for convection-permitting ensemble forecasts. Monthly Weather Review, 144(7), 2579-2604

Kalnay, E. (2003). Atmospheric modeling, data assimilation and predictability. Cambridge university press.

Keresturi, E., Wang, Y., Meier, F., Weidle, F., Wittmann, C., & Atencia, A. (2019). Improving initial condition perturbations in a convection-permitting ensemble prediction system. Quarterly Journal of the Royal Meteorological Society, 145(720), 993-1012.

Llasat, M., & Sempere-Torres, D. (2001). Heavy rains and floods in west mediterranean areas: a climatic feature. Geophysical Research Abstr acts, 3.

Llasat, M. C., Llasat-Botija, M., Prat, M. A., Porcu, F., Price, C., Mugnai, A., ... & Nicolaides, K. (2010). High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. Advances in Geosciences, 23, 47-55.

Mansell, E. R., Ziegler, C. L., & Bruning, E. C. (2010). Simulated electrification of a small thunderstorm with two-moment bulk microphysics. *Journal of the Atmospheric Sciences*, *67*(1), 171–194. https://doi.org/10.1175/2009JAS2965.1

Mass, C. F., Ovens, D., Westrick, K., & Colle, B. A. (2002). Does increasing horizontal resolution produce more skillful forecasts?: The Results of Two Years of real-Time Numerical Weather Prediction over the Pacific Northwest. Bulletin of the American Meteorological Society, 83(3), 407-430.

Nakanishi, M., & Niino, H. (2006). An improved Mellor-Yamada Level-3 model: Its numerical stability and application to a regional prediction of advection fog. *Boundary-Layer Meteorology*, *119*(2), 397–407. https://doi.org/10.1007/s10546-005-9030-8

Pakalidou, N., & Karacosta, P. (2018). Study of very long-period extreme precipitation records in Thessaloniki, Greece. Atmospheric Research, 208, 106-115.

Parrish, D. F., & Derber, J. C. (1991). The National Meteorological Center's spectral statistical interpolation analysis system.

Petterssen, S. (1956). Weather analysis and forecasting: motion and motion systems. McGraw-Hill.

Petrucci, O., Aceto, L., Bianchi, C., Bigot, V., Brázdil, R., Pereira, S., … Zêzere, J. L. (2019). Flood fatalities in Europe, 1980-2018: Variability, features, and lessons to learn. *Water (Switzerland)*, *11*(8), 1682. https://doi.org/10.3390/w11081682

Poterjoy, J., Sobash, R. A., & Anderson, J. L. (2017). Convective-scale data assimilation for the weather research and forecasting model using the local particle filter. *Monthly Weather Review*, *145*(5), 1897–1918. https://doi.org/10.1175/MWR-D-16-0298.1

Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., … Duda, M. G. (2017). The weather research and forecasting model: Overview, system efforts, and future directions. *Bulletin of the American Meteorological Society*, *98*(8), 1717–1737. https://doi.org/10.1175/BAMS-D-15-00308.1

Raynaud, L., & Bouttier, F. (2016). Comparison of initial perturbation methods for ensemble prediction at convective scale. Quarterly Journal of the Royal Meteorological Society, 142(695), 854-866.

Romero, R., Guijarro, J. A., Ramis, C., & Alonso, S. (1998). A 30-year (1964–1993) daily rainfall data base for the Spanish Mediterranean regions: First exploratory study. International Journal of Climatology: A Journal of the Royal Meteorological Society, 18(5), 541-560.

Romero, R., Vich, M., & Ramis, C. (2019). A pragmatic approach for the numerical prediction of meteotsunamis in Ciutadella harbour (Balearic Islands). *Ocean Modelling*, *142*, 101441. https://doi.org/10.1016/j.ocemod.2019.101441

Romine, G. S., Schwartz, C. S., Berner, J., Fossell, K. R., Snyder, C., Anderson, J. L., & Weisman, M. L. (2014). Representing forecast error in a convection-permitting ensemble system. Monthly Weather Review, 142(12), 4519-4541.

Shutts, G. (2005). A kinetic energy backscatter algorithm for use in ensemble prediction systems. *Quarterly Journal of the Royal Meteorological Society*, *131*(612), 3079–3102. https://doi.org/10.1256/qj.04.106

Schwartz, C. S., Kain, J. S., Weiss, S. J., Xue, M., Bright, D. R., Kong, F., ... & Wandishin, M. S. (2010). Toward improved convection-allowing ensembles: Model physics sensitivities and optimizing probabilistic guidance with small ensemble membership. Weather and Forecasting, 25(1), 263-280.

Schwartz, C. S., Romine, G. S., Sobash, R. A., Fossell, K. R., & Weisman, M. L. (2019). NCAR's real-time convection-allowing ensemble project. Bulletin of the American Meteorological Society, 100(2), 321-343.

Shutts, G. (2005). A kinetic energy backscatter algorithm for use in ensemble prediction systems. Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography, 131(612), 3079-3102.

Stensrud, D. J., Xue, M., Wicker, L. J., Kelleher, K. E., Foster, M. P., Schaefer, J. T., ... & Tuell, J. P. (2009). Convective-scale warn-on-forecast system: A vision for 2020. Bulletin of the American Meteorological Society, 90(10), 1487-1500.

Skamarock, W., Klemp, J., Dudhia, J. Gill, D.O., Barker, D., Duda, M.G., Huang, X.Y., Wang, W., Powers, J.G., 2008. A Description of the Advanced Research WRF Version 3. NCAR Tech. Note NCAR/TN-475+STR. https://doi.org/10.5065/D6DZ069T.

Skamarock, W. C., Klemp, J. B., Duda, M. G., Fowler, L. D., Park, S. H., & Ringler, T. D. (2012). A multiscale nonhydrostatic atmospheric model using centroidal Voronoi tesselations and C-grid staggering. *Monthly Weather Review*, *140*(9), 3090–3105. https://doi.org/10.1175/MWR-D-11-00215.1

Tanamachi, R. L., Wicker, L. J., Dowell, D. C., Bluestein, H. B., Dawson, D. T., & Xue, M. (2013). EnKF assimilation of high-resolution, mobile doppler radar data of the 4 may 2007 greensburg, kansas, supercell into a numerical cloud model. *Monthly Weather Review*, *141*(2), 625–648. https://doi.org/10.1175/MWR-D-12-00099.1

Torcasio, R. C., Federico, S., Comellas Prat, A., Panegrossi, G., D'Adderio, L. P., & Dietrich, S. (2021). Impact of lightning data assimilation on the short-term precipitation forecast over the Central Mediterranean Sea. Remote Sensing, 13(4), 682.

Torn, R. D., Hakim, G. J., & Snyder, C. (2006). Boundary conditions for limited-area ensemble Kalman filters. Monthly weather review, 134(9), 2490-2502.

Tudurí, E., & Ramis, C. (2002). The Environments of Significant Convective Events in the Western Mediterranean. *Weather and Forecasting*, *12*(2), 294–306. https://doi.org/10.1175/1520-0434(1997)012<0294:teosce>2.0.co;2

Wheatley, D. M., Stensrud, D. J., Dowell, D. C., & Yussouf, N. (2012). Application of a WRF mesoscale data assimilation system to springtime severe weather events 2007–09. Monthly weather review, 140(5), 1539-1557.

Yano, J. I., Ziemiański, M. Z., Cullen, M., Termonia, P., Onvlee, J., Bengtsson, L., ... & Wyszogrodzki, A. A. (2018). Scientific challenges of convective-scale numerical weather prediction. Bulletin of the American Meteorological Society, 99(4), 699-710.