SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Numerical modelling of Mediterranean weather extremes: new developments in the framework of the Triangle-based Regional Atmospheric Model (TRAM) and Model for Prediction Across Scales (MPAS)
Computer Project Account:	SPESHOMA
Start Year - End Year :	2022 - 2024
Principal Investigator(s)	Romualdo Romero March
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Other Researchers (Name/Affiliation):	Diego Saúl Carrió Carrió / Universitat de les Illes Balears

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The general objective of this special project is to implement recently developed ensemble generation strategies targeted at the short-range meso- and convective-scale forecasting of severe weather in the Mediterranean region. Special efforts will be devoted to improving the forecasts of flash floods and to designing very high resolution climatologies (in the context of present and future climates) of extreme precipitation at sub-hourly timescales. These aims are part of the goals established in the Spanish national project TRAMPAS (PID2020-113036RB-I00 / AEI / 10.13039/501100011033) project funded by the "Agencia Estatal de Investigación (AEI) from Ministerio de Ciencia e Innovación of Spain", which began on 1st September 2021.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

All issues related to the use of the ECFLOW software in our configuration setup were resolved by the end of the previous project phase. During this third and final period, no new problems were encountered. The system operated reliably, allowing us to focus fully on model development and data assimilation experiments without technical disruptions.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

While we experienced significant delays during the first two years of the project—mainly due to technical challenges—the final year saw a notable acceleration in progress. This was largely due to the integration of the ECFLOW workflow manager, which streamlined the interaction between our numerical weather model (WRF) and the external DART data assimilation system. This enabled us to carry out high-resolution, ensemble-based data assimilation experiments using the Ensemble Kalman Filter, coupled with a convection-permitting WRF setup.

From an administrative standpoint, our overall experience with the Special Project framework has been very positive. The application and reporting procedures are clear, straightforward, and efficient, minimizing time spent on bureaucracy and allowing us to focus more on the scientific aspects of the work. This level of administrative support is definitely a strong point of the framework and contributes significantly to the smooth execution of the project.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

We provided a quantitative assessment of the impact of two widely used DA techniques – 3DVar and EnKF – on the predictability of maritime extreme weather events. We evaluated their potential to improve forecast lead time by assimilating observations during the developing stage, as opposed to the mature stage, which affords limited time for preparedness and response. To evaluate the performance of 3DVar and EnKF, we analyze two high-impact weather events triggered over the sea and later affected densely populated coastal regions. These two extreme weather events are known as (a) the high precipitation event registered during the 13th Intensive Observation Period (IOP13) affecting the western, northern and central parts of Italy, and (b) the intense Tropical-like Mediterranean Cyclone (medicane) known as Qendresa, that affected the islands of Pantelleria, Lampedusa, Malta and Sicily. These weather events posed a serious challenge for the numerical weather prediction community due to their low predictability, resulting from their initialization over the sea, where *in-situ* observations are sparse and initial conditions are poorly estimated. Furthermore, their evolution over complex terrain regions introduced additional forecasting challenges.

For these two extreme weather events, both 3DVar and EnKF DA methods were applied, with the type and number of assimilated observations varying based on the data availability. For Qendresa, we assimilated (a) hourly *in-situ* conventional observations and (b) wind speed and wind direction profiles of the entire atmosphere (RSAMVs) derived from geostationary satellites every 20-min, providing high spatial and temporal resolution observations covering the Central Mediterranean Sea, where Qendresa initiated and evolved. On the other hand, for the IOP13, we assimilated (a) hourly *in-situ* conventional observations and (b) 15-min 3D reflectivity observations from two type-C Doppler Weather Radars.

Because of the different thermodynamic characteristics associated with Qendresa and IOP13, a set of different verification metrics were used for each of these extreme weather events. The *Filtering* method (FSS and RMSE), the ROC/AUC and the Taylor diagram were used to verify the numerical simulations from 3DVar and EnKF associated with IOP13. In the case of Qendresa, we used the Whisker diagrams and the Probability Distribution of Cyclone Center Occurrence verification scores. For the IOP13, both the *Filtering* method and Taylor diagram verification show that EnKF slightly outperforms 3DVar, although the differences were not significant. In addition, it was observed that the assimilation of spatial and temporal high-resolution reflectivity observations significantly improved the forecast for both 3DVar and EnKF, showing the key role of this type of observation. On the other hand, the ROC and AUC scores clearly showed that EnKF outperformed 3DVar. For the Qendresa event, while the ensemble mean of EnKF underestimated the intensity of the medicane compared to 3DVar, some individual EnKF ensemble members produced more accurate results than 3DVar. This behavior suggested how important it was using an ensemble forecast system to predict extreme weather events at high spatial and temporal resolution. Regarding the cyclone's trajectory, the EnKF provided a more realistic representation of the Qendresa's observed path.

Although the EnKF technique had shown in general better performance against the 3DVar for the two extreme weather events analyzed in this study, it was also important to account for the computational resources required by each method. The EnKF required approximately 36 times more model integrations per cycle than 3DVar's single forecast, in addition to the overhead of computing ensemble updates. This makes the 3DVar appealing because it was much faster and cheaper than the EnKF, and it makes this technique particularly suitable for operational purposes at the small weather forecast centers.

An interesting result of this study was that, for highly non-Gaussian extreme events the deterministic 3DVar forecast can occasionally outperform the EnKF ensemble mean in terms of point forecasts (e.g., minimum central pressure), because averaging across ensemble members tends to smooth out the tails of a skewed probability distribution. In contrast, probabilistic metrics like ROC/AUC consistently favor the EnKF, reflecting its superior ability to capture forecast uncertainty. We attributed these contrasting behaviors to the different approaches to background error covariances: 3DVar employs a static covariance, while EnKF uses a flow-dependent covariance estimated from a finite ensemble. Results of these simulations were used to write a scientific research paper at the international *Natural Hazards and Earth System Sciences* (NHESS) Journal (Scopus IF: 7.6).

Further work will investigate the impact of using hybrid DA schemes in comparison to standard 3DVar or EnKF. In this scenario, it is expected that the hybrid error covariance matrix will be more precise than the one derived from the ensemble members or from climatology, which on their own are not able to reproduce key aspects of challenging extreme weather events. High temporal and spatial observations from Doppler Weather radars, such as reflectivity and radial wind velocities, will be assimilated for different case studies to obtain accurate analysis and thus, improve the short-range forecast of catastrophic flash-flood events. In addition, it is important to highlight that satellite-based data assimilation provides a significant opportunity for enhancing convective-scale forecasting, particularly in data-sparse maritime regions such as the Mediterranean, where the formation of extreme weather events like tropical-like cyclones is increasingly impacting densely populated areas. Future studies integrating high-resolution satellite observations, such as cloud top heights, thermodynamic profiles or cloud properties, could further enhance the accuracy of convective-scale predictions, improving early warning capabilities and disaster preparedness.

List of publications/reports from the project with complete references

The ECMWF computer resources of the present project were used to perform the numerical simulations of the following study (**in production**):

Carrió, D. S., Mazzarella, V., and Ferretti, R.: *High-Resolution Data Assimilation for Two Maritime Extreme Weather Events: A comparison between 3DVar and EnKF,* Nat. Hazards Earth Syst. Sci.

According to the *Guidelines on handling Special Projects*, we will add the following acknowledgement to the paper:

"*Acknowledgement is made for the use of ECMWF's computing and archive facilities in this research*."

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The simulations performed under the SPESHOMA Special Project significantly improved the forecasting of two severe weather events affecting densely populated regions. While the assimilation of remote sensing observations yielded substantial improvements in forecast accuracy, the limited number of case studies prevents drawing broad conclusions. The next step is to extend this methodology to a larger set of real-case scenarios to better assess the general applicability and benefits of data assimilation in high-impact weather forecasting. Future work will also investigate the impact of using hybrid Data Assimilation schemes in comparison to standard 3DVar or EnKF. In this scenario, it is expected that the hybrid error covariance matrix will be more precise than the one derived from the ensemble members or from climatology, which on their own are not able to reproduce key aspects of challenging extreme weather events. High temporal and spatial observations from Doppler Weather radars, such as reflectivity and radial wind velocities, will be assimilated for different case studies to obtain accurate analysis and thus, improve the short-range forecast of catastrophic flash-flood events. In addition, it is important to highlight that satellite-based data assimilation provides a significant opportunity for enhancing convective-scale forecasting, particularly in data-sparse maritime regions such as the Mediterranean, where the formation of extreme weather events like tropical-like cyclones is increasingly impacting densely populated areas. Future studies integrating high-resolution satellite observations, such as cloud top heights, thermodynamic profiles or cloud properties, could further enhance the accuracy of convective-scale predictions, improving early warning capabilities and disaster preparedness.

These future activities are already embedded in a newly granted **Special Project,** led by Diego Saúl Carrió Carrió, entitled "*Design and Implementation of high-resolution rapid refresh Data Assimilation systems for rapidly evolving tropical-like cyclones in the Mediterranean region*". This project is currently active and will run until 2027.