SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Simulations of Meteorological Hazards Affecting Aviation Safety in the Iberian Peninsula
Computer Project Account:	spesvale
Start Year - End Year :	2022- 2024
Principal Investigator(s)	Francisco Valero
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Other Researchers (Name/Affiliation):	Javier Díaz-Fernández (UCM), Pedro Bolgiani (UCM), Carlos Calvo (UVa), Lara Quitián-Hernández (UVa), Mariano Sastre (UCM), María Luisa Martín (UVa), Daniel Santos (DMI), José Ignacio Farrán (UVa), Juan Jesús González-Alemán (AEMET), Eloy Piernagorda (UCM) UCM: Universidad Complutense de Madrid. Spain UVa: Universidad de Valladolid. Spain DMI: Danish Meteorological Institute. Denmark AEMET: Agencia Estatal de Metorología. Spain

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

Meteorology is essential in aviation since it has a significant impact on flight planning and safety. High-resolution numerical simulations are suggested for accurately characterising aviation-related meteorological events. SPESVALE simulates mountain waves and severe convective weather phenomena (such as supercells, thunderstorms, and downbursts) on the Iberian Peninsula using the WRF-ARW and HARMONIE-AROME models. The atmospheric factors involved in the formation of mountain waves and severe convective weather events are examined, with a special focus on the assessment of atmospheric turbulence. To this purpose, about 300 mountain wave episodes between 2000 and 2020 have been selected, and they will be simulated using the two models. Furthermore, environments and samples from 262 supercells between 2011 and 2020 in Spain were analysed too.

Summary of problems encountered

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

Díaz-Fernández et al. (2020, 2021, 2022) simulated the mountain waves formation, developing several decision trees that allows us to forecast warning for mountain waves, wave clouds, icing and turbulence with at least 24 h in advance. Additionally, in Calvo-Sancho et al. (2022) differences between hail and non-hail occurrences in supercell convective environments in Spain are analyzed using the ERA5 reanalysis. In 2023 and 2024, we noticed some issues with the HARMONIE-AROME model related to domain size, increased temporal and horizontal resolutions, the establishment of nested domains... which produced running many times for testing such a model, and the usage of more SBUs than originally expected. No other problems of more technical nature have presented.

Experience with the Special Project framework

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

The experience with administrative aspects has been positive. No problems I have had in updating the progress reports and I think the application procedure has been relatively easy.

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.)

Several results on mountain lee waves and severe convective weather phenomena were obtained during these two years, thanks to the SPESVALE special project.

A characterization of turbulence associated to mountain lee waves in the vicinity of the Adolfo Suarez-Madrid Barajas International Airport was carried out using WRF-ARW and HARMONIE-AROME models. The vertical wind speed and the eddy dissipation rate (EDR; shown in the previous report) have been successfully evaluated to know the turbulence intensity associated to these events. Also, the results show the ability of the models to detect clear air turbulence when lenticular clouds are not present. Moreover, based on probability density functions of the maximum EDR, the highest values of EDR were obtained when lenticular cloud bands associated to mountain lee waves are diagnosed in the leeward of the mountain range. Differences in results from WRF-ARW and HARMONIE-AROME are discussed in Díaz-Fernández et al. (2022).

Related to mountain lee waves, some resources have been used to study the potential impact of global climate change on the precursor environments to mountain lee wave cloud episodes over central Iberia. We examine the suitability of several Global Climate Models (GCMs) from CMIP6 in predicting these environments using the ERA5 reanalysis as a benchmark for performance. The dataset was divided into two periods: historical data (2001–2014) and projections for the SSP5–8.5 future climate scenario (2015–2100).

From all the CMIP6 GCMs, the models considered for the current analysis have six-hourly data for both the HIST and S5-8.5 future climate scenario. Also, only GCMs with 700 hPa data available to analyse the favourable atmospheric lee wave conditions (wind speed and direction, specific humidity and temperature) are retrieved. Additionally, the 700 hPa geopotential height is used to study the synoptic configuration in mountain lee wave events. Considering these restrictions, the EC-Earth3 (Döscher et al., 2022), MPI-ESM1-2-HR (Mauritsen et al., 2019) and MRI-ESM2-0 (Yukimoto et al., 2019) GCMs are selected, which are shortly out-lined below. These databases are downloaded through the Earth System Grid Federation data portal (https://esgf-node.llnl.gov/).

The EC-Earth3 (hereafter EC3) is a global climate model that is developed by a consortium of European climate modelling centres with the purpose of simulating the Earth's climate system and its interactions, including the atmosphere, oceans, land surface, and cryosphere. The EC3 model features a 0.703° horizontal resolution and 91 vertical resolution layers (Döscher et al., 2022). The Max Plack Institute for Meteorology in Germany creates the MPI-ESM1-2-HR global climate model (hereafter MPI) using several atmospheric, land surface and ice-ocean submodels. It has 95 vertical levels and a 0.93° horizontal resolution (Mauritsen et al., 2019). Finally, the MRI-ESM2-0 global climate model (hereafter MRI) was created by Japan's Meteorological Research Institute and consists of various sub-models of the major components of the Earth system, such as the atmosphere, oceans, land surface, aerosols, and atmospheric chemistry. The horizontal resolution is 1.125° and it has 80 vertical layers, from the surface to the top of the model at 0.01 hPa, in a hybrid sigma-pressure coordinate system (Yukimoto et al., 2019).

Because the selected GCMs have different horizontal grid resolutions, all models' datasets are regridded to a common 0.703º latitude/longitude grid, which is the EC3 spatial resolution (based on initial results, not shown), to assess the climate change signal on favourable wave conditions. To match the grid resolution of GCMs, ERA5 atmospheric variables are also regridded to a 0.703º latitude/longitude grid. Then, the GCMs datasets are combined into a multi-model ensemble mean (hereinafter ENS).

According to Díaz-Fernández et al. (2022), a synoptic configuration will be conductive to mountain lee wave events in the domain selected for this study. Events with wave cloud precursor environments are defined based on wind direction ($256^\circ - 016^\circ$), wind speed (>5.6 m/s), and relative humidity (>4.7%) thresholds from the ERA5 dataset. For each model, the days complying with the defined wave cloud precursor environments were selected (Table 1). Based on them, an average of 11 events per year are identified for EC-EARTH3$_{S5\text{-}8.5}$ and MPI-ESM1.2-HR$_{S5\text{-}8.5}$, and 9 events for MRI-ESM2.0$_{S5\text{-}8.5}$. However, no statistically significant trends in the occurrence of these events are found in any dataset. The ensemble (ENS) represents the average of these three GCMs.

Table 1. Days with favourable atmospheric lee wave conditions for each model and period.

	HIST	**S5-8.5**
ERA5	116 (8/year)	-
EC3	169 (12/year)	942 (11/year)
MPI	157 (11/year)	927 (11/year)
MRI	112 (8/year)	756 (9/year)
ENS	146 (10/year)	875 (10/year)

Geopotential height composites at 500 and 700 hPa for episodes with wave cloud precursor environments detected in the ERA5 and the GCMs datasets for HIST and S5-8.5 periods are shown in Figure 1. For the S5-8.5 period, the geopotential height composites at 500 and 700 hPa for the wave cloud precursor environments detected in the three datasets show an increase in zonal winds. Expansion of the Azores High towards the Iberian Peninsula and shorter troughs than the ERA5 and HIST period is noted, with these differences being more pronounced for the EC-EARTH3 dataset. Furthermore, the EC-EARTH3HIST synoptic pattern composite is the most like ERA5.

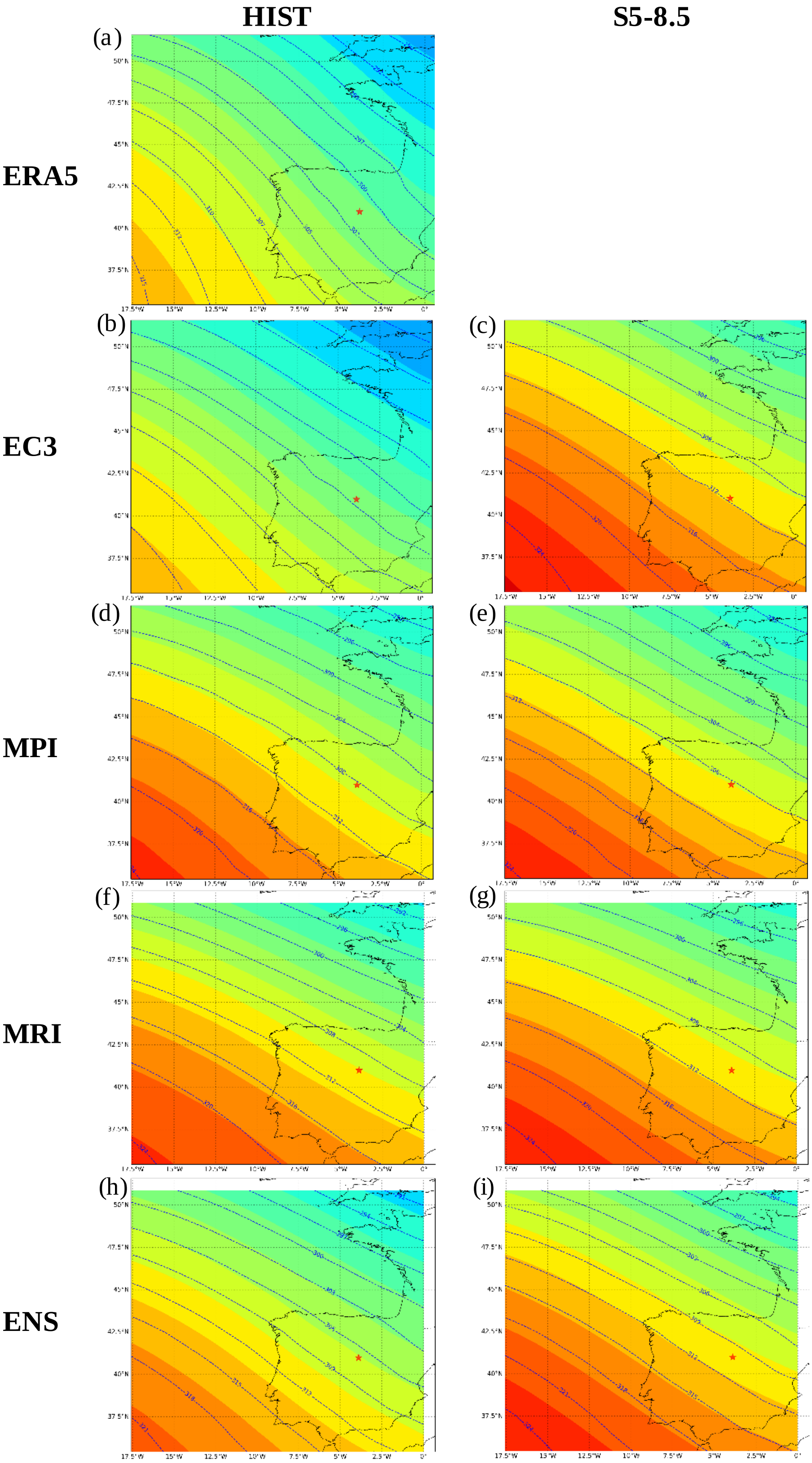


Figure 1. The 500 hPa geopotential height (colored; dam) and 700 hPa geopotential height (blue contours; dam) composites for events with favourable atmospheric wave conditions for a) ERA5, b) EC3$_{HIST}$, c) EC3$_{S5\text{-}8.5}$, d) MPI$_{HIST}$, e) MPI$_{S5\text{-}8.5}$, f) MRI$_{HIST}$, g) MRI$_{S5\text{-}8.5}$, h) ENS$_{HIST}$ and i) ENS$_{S5\text{-}8.5}$. Red star in a) indicates the Guadarrama mountain range and Adolfo Suarez Madrid-Barajas airport surroundings.

For the S5-8.5 period, the geopotential height composites at 500 and 700 hPa for the wave cloud precursor environments detected in the three datasets show an increase in zonal winds. Expansion of the Azores High towards the Iberian Peninsula and shorter troughs than the ERA5 and HIST period are noted, with these differences being more pronounced for the EC-EARTH3 dataset.
Based on the previous distribution patterns and composite results, and assuming that ERA5 is a reliable benchmark for reproducing precursor environments to mountain lee wave clouds, it is reasonably inferred that EC-EARTH3 is the most suitable GCM for assessing future wave cloud precursor environments. This result is based mainly on the fact that EC-EARTH3HIST data closely align with ERA5 data. Furthermore, statistical analysis demonstrates significant differences in EC-EARTH3 data between the HIST and S5-8.5 periods across all variables, in contrast to the ENS data.

Figure 2 depict the 2001–2100 trends in wind components and wind speed derived for the ECEARTH3 and ENS.

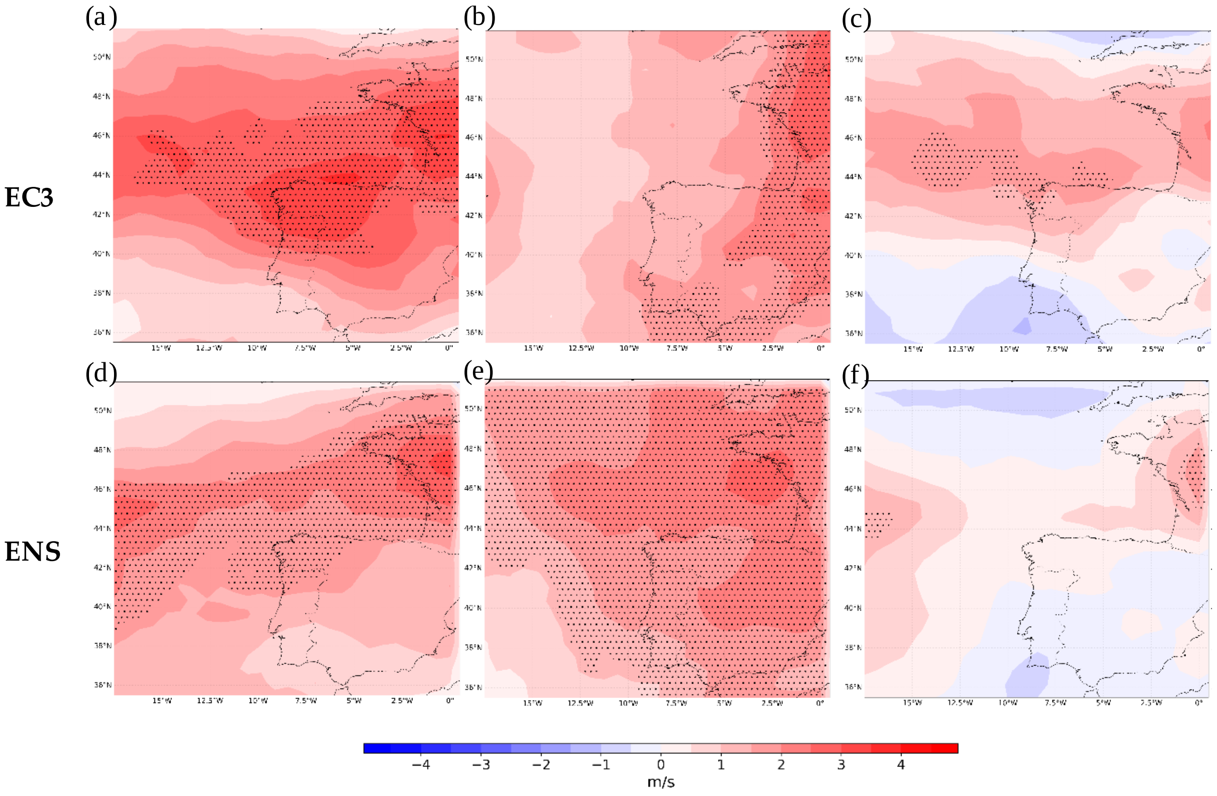


Figure 2. 2001-2100 trend values in events with favorable atmospheric wave conditions for a) zonal wind, b) meridional wind and c) wind speed for EC3; d) zonal wind, e) meridional wind and f) wind speed for ENS. Black dotting denotes statistically significant trends ($p < 0.05$) according to Mann-Kendall trend test.

According to geopotential height composites and other relevant climate studies, zonal wind trends showed a significant increasing tendency (over 4 m/s) windward of the Guadarrama mountain range under the predominant wind direction.

The EC-EARTH3 was the most adequate GCM for forecasting the future behaviour of wave cloud precursor environments because the historical data for the selected atmospheric variables were closer to the reference data (ERA5). Moreover, there were statistically significant differences between EC-EARTH3$_{HIST}$ and EC-EARTH3$_{S5\text{-}8.5}$ in all variables studied, contrary to the other GCMs and the ENS. Therefore, although an increase in zonal winds may result in fewer wave events in the Guadarrama mountains, it was not enough to change the wind pattern (northwesterly winds) associated with the wave cloud precursor environments.

During the last months, on July 1, 2018, many supercells were spotted near the Zaragoza Airport (Spain), and at least one of them generated a downburst that affected the airport, causing significant damage in the surrounding area. This event was simulated using the Weather Research and Forecasting (WRF-ARW) numerical weather prediction model.

According to other studies related to severe convective weather in Iberia (Calvo-Sancho et al., 2020; Granda-Maestre et al., 2021) or microphysics sensitivity to extreme precipitation events (Tan, 2016; Eltahan and Magooda, 2018), the optimum WRF-ARW physics parametrizations to simulate severe convective weather phenomena include the New Goddard short and longwave schemes (Chou and Suarez, 1999; Chou et al., 2001), the revised MM5 as the surface layer scheme (Jimenez et al. 2012), the 5-Layer as the land surface (Dudhia, 1996), the BouLac as the PBL (Bougeault and Lacarrere, 1989), and the aerosol-aware Thompson as the microphysics scheme (Thompson and Eidhammer, 2014). The cumulus is parametrized in D01 with the Tiedtke scheme (Tiedtke, 1989; Zhang et al., 2011) and explicitly computed by the model in D02 and D03.

Three different WRF-ARW orography experiments were carried out to investigate if the region's complex orography had an important role in supercell and downburst development over the research area. One of the three experiments used the default orography as control; another one used a 90% smoothed orography, and the third experiment was configured with a high-resolution dataset (Figure 3). In Figure 3, the D03 maximum terrain height ranges from 2000 m to 200 m. Therefore, the D03 average elevations are 853 m (HIRES), 852 m (CTRL), and 158 m (NOORO).

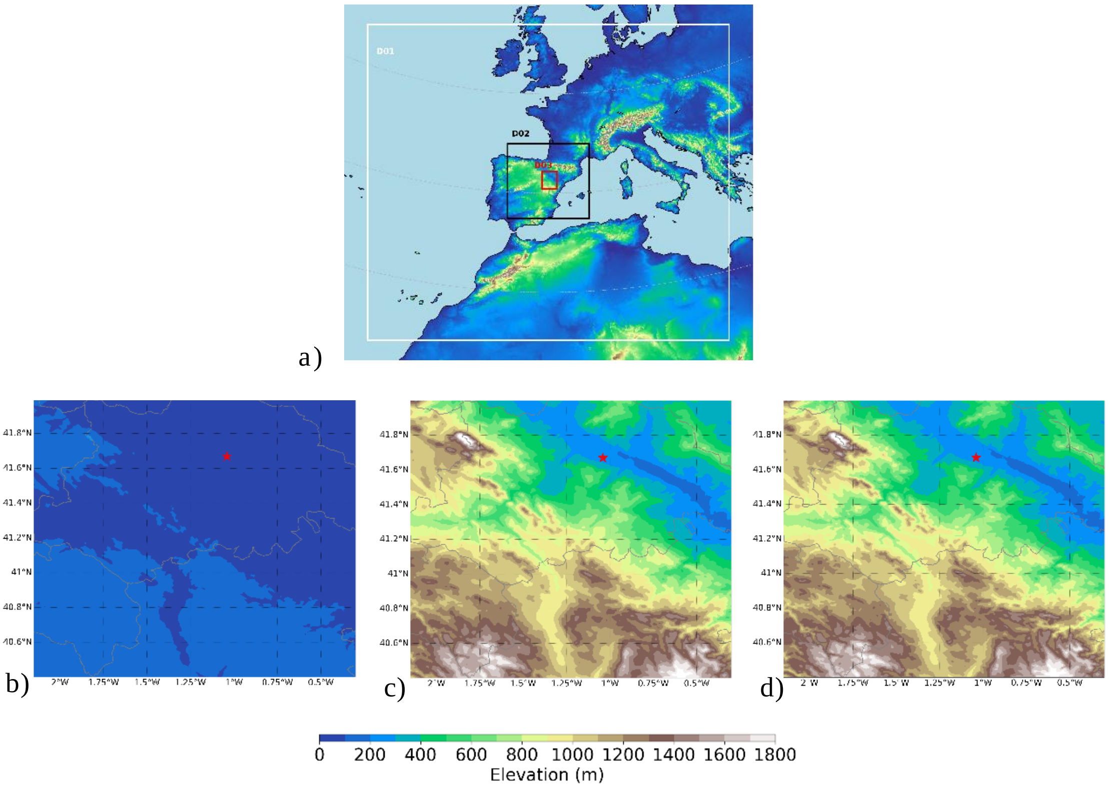
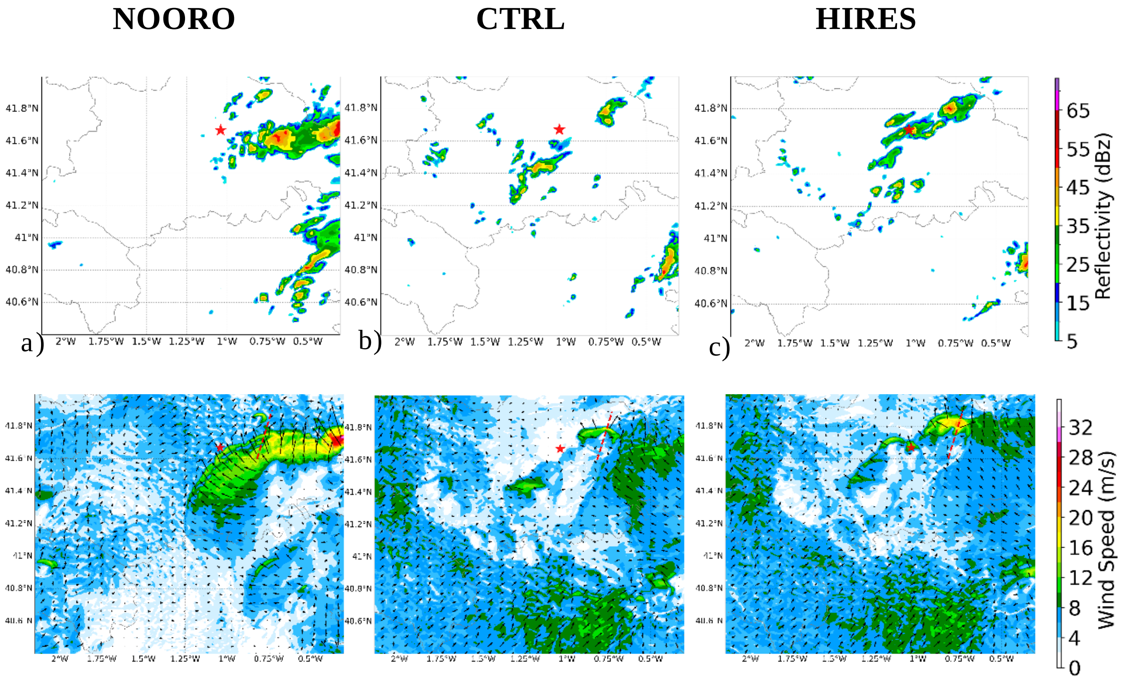


Figure 3. a) WRF-ARW domain configuration. Elevation maps of the study area (m) for the b) NOORO, c) CTRL and d) HIRES experiments. Star indicates the Zaragoza Airport.

Figure 4 depicts the reflectivity pattern, the wind direction and speed, and the vertical cross section in the downburst location for each of the three experiments. It is worth noting that the CTRL (15:15 UTC) and HIRES (15:30 UTC) simulated downbursts are located about 30 km northeast of Zaragoza Airport (Figures 3b-c), while the wind flow follows a southwest-northeast track. The WRF-ARW model successfully replicates the storm splitting process, with the CTRL performance better than the remainder experiments, indicating two different cells and a weakening cyclonic cell, in line with observations. The greatest reflectivity simulated in the downburst zone show values of 45–55 dBz for the three experiments, significantly lower than observed (60 dBz). CTRL and HIRES experiments simulated a 40-50 dBz core falling and reaching the surface, resulting in wind surface divergence. However, the downdraft in the NOORO doesn't reach the surface, most probably because of the output timing. Simulated atmospheric soundings from the three experiments in the downburst location show an inverted V pattern in the lower troposphere, suitable to downbursts and high-reflectivity microbursts.

The HIRES experiment simulates a characteristic toroidal-shaped outflow associated to the downburst. On the other hand, the smoothing of orography has been shown to lower wind resistance, allowing for faster acceleration and higher wind speeds due to the absence of wind-channelling over valleys and mountains, which typically occurs in locations with natural, unaltered terrain. The smoothed terrain produces a more continuous flow of wind that can contribute to the formation of many supercells and a gust front. In contrast, areas with a more realistic orography (CTRL and HIRES) generate storms channelled over valleys and mountains, resulting in fewer supercells and, at least in one case, a downburst. The influence of orography on downburst generation on July 1, 2018, can be related to the instability in the research region, enough to allow the development of deep convection. The HIRES experiment is the only one in which the downdraft (-11 m/s) makes the reflectivity core (50 dBz) to reach the surface developing wind divergences.



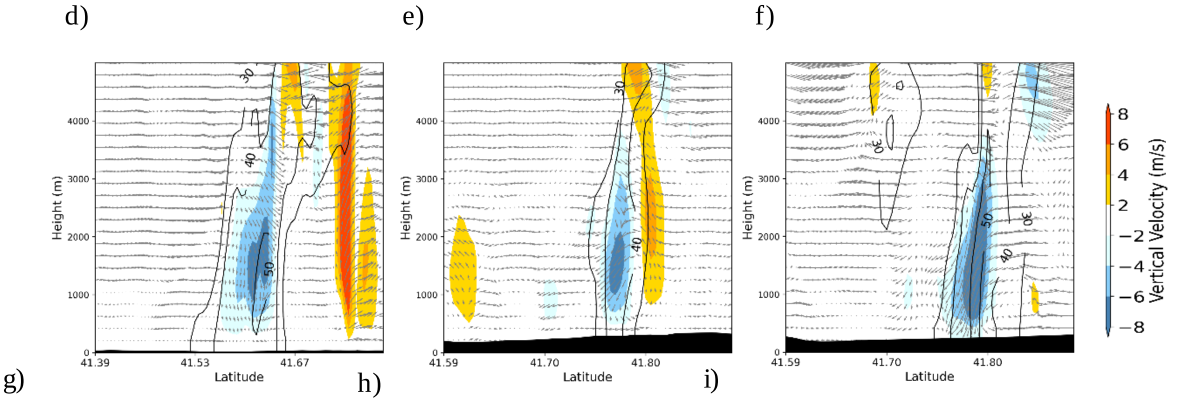


Figure 4. Reflectivity (dBz) distributions for a) NOORO, b) CTRL and c) HIRES; 10-m wind speed (shaded; m/s) and wind direction (arrows) for d) NOORO, e) CTRL and f) HIRES; Vertical cross section (red line in Figures 3d-f) for vertical wind vectors (arrows) and speed (shaded) and reflectivity (contours) for g) NOORO, h) CTRL and i) HIRES, on July 1, 2018.

Finally, a 5-km rectangular grid centred on the downburst location is considered to compute the time series of the atmospheric and convective variables depicted in Figure 5. The NOORO experiment presents a higher 2m temperature (Figure 5a), as expected by the lower elevation. Moreover, the temperature falls by around 8 °C during the downburst event in the HIRES and NOORO experiments, whereas the CTRL has a smaller drop (4 °C). The behaviour of the 2m dewpoint (Figure 5b) is the opposite to that of the 2 m temperature, increasing as the downburst reaches the ground, with the NOORO simulation showing the maximum values while the remaining experiments show values 2-3 °C lower. It is interesting to note that the NOORO simulations presents a second peak for both variables, indicating that the downburst was not produced by an isolated cell. The wind speed evolution (Figure 5c) displays a maximum wind speed for HIRES (36 m/s), which is much lower for the CTRL (23 m/s) and NOORO (20 m/s) experiments at the downburst time.

In the MUCAPE time series (Figure 5d), orography seems to play an essential role, resulting in a moderately unstable environment around the downburst time (between 700 and 1000 J/kg), with the exception of the NOORO experiment which shows severely unstable MUCAPE values (between 1250 and 1500 J/kg). Concerning the CIN results (Figure 5e), the three experiments reproduce an unstable preconvective environment with values near to 0 J/kg prior to the downburst time and a significant drop (down to -100 J/kg) after the event. Figure 5f shows that the three experiments have moderate WS06 values, reaching 24 m/s for CTRL, 22 m/s for NOORO, and 18 m/s for HIRES, just prior to the downburst.

The cold pool strength is defined as the difference between the ambient temperature and the downdraft at the surface and, according to Romanic et al. (2022), it is recognised as the most skilful parameter for downburst identification. As it increases, the likelihood of a downburst improves. The cold pool strength time series (Figure 5g) reveals values around 16 °C for HIRES and NOORO experiments and 14 °C for CTRL. In line with the previous variable, Romanic et al. (2022) developed the DEI index for studying favourable downburst environments. It combines the cold pool strength and WMAXSHEAR (a square root of two times MLCAPE multiplied by 0-6 km wind shear; Taszarek et al., 2020b). Values over 0 suggest a favourable downburst environment with a proportion of the most probable occurrence as the DEI increases. In the current study, preconvective DEI values are positive for all three experiments (Figure 5h), indicating a favourable downburst environment. It is noticeable that the NOORO simulation produces the highest DEI results (exceeding 2), due to the higher CAPE values than the remaining experiments. Finally, precipitable water, as a measure of the total amount of water vapour in an atmospheric column, shows very similar values (around 40 mm) for the three experiments (Figure 5i), despite the differences in the dewpoint (Figure 5b).

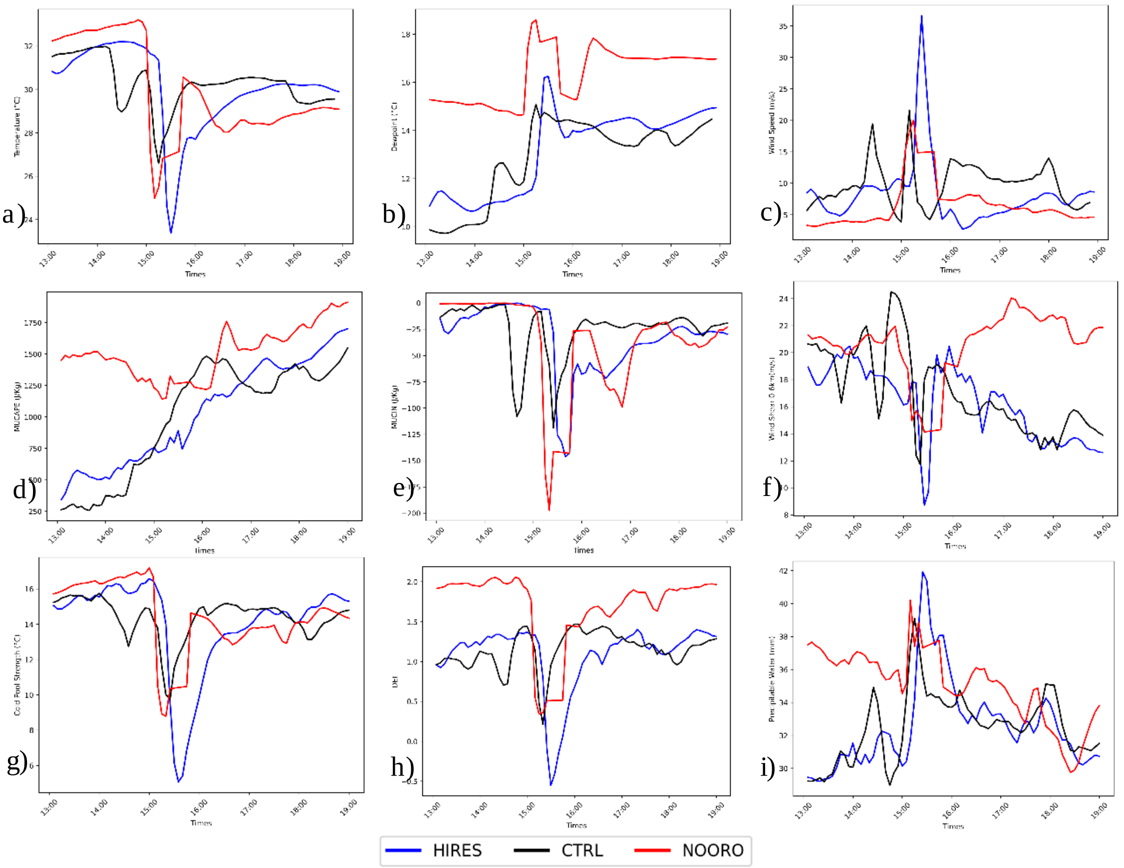


Figure 5. Time series of WRF-ARW (a) 2 m temperature (°C), (b) 2 m dewpoint (°C), (c) wind speed (m/s), (d) MUCAPE (J/kg), (e) MUCIN (J/kg), (f) WS06 (m/s), (g) Cold Pool Strength (°C), (h) DEI and (i) Precipitable water (mm). Every variable is the average from at a 5 km grid to centre at the downburst location for NOORO (red line), CTRL (black line) and HIRES (blue line) experiments.

Several supercell events are now being simulated and analysed using HARMONIE-AROME's different horizontal resolutions. It is worth noting that the very high resolution used to simulate the different severe convective systems require previous needed tasks which means additional SBUs. We apologise, but the system setup has used more resources than we planned. The high-resolution simulations of supercells and downbursts each needed 180,000 SBUs, as these tests required extra resources that were not anticipated in the initial request. Therefore, in this Special Project the final SBU usage has been more than 400000 SBUs.

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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.)

Whitin the research team, our future plans are to apply for a new Special Research Project. This year, the IP of this Special Project (Dr. Francisco Valero) will retire and asked not to be the PI but to continue working as a member of the team. Dr. Mariano Sastre will be the IP of the new project. Dr. Sastre is a member of the research team from the beginning of the team. He will lead the new Special Project without hesitation.

It will deal with the study of severe weather in the Iberian Peninsula. This project will carry out the analysis of severe convective phenomena such as downburst, supercells, giant hail, … and their relationship with the anthropogenic climate change (ACC). To do this, the methodology named pseudo global warming approach will be used to analyze the influence of the ACC in the genesis, development and evolution of these severe convective events.