

SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year 2026

Project Title: PHYSICAL MECHANISM AT A BASIN SCALE IN COMPLEX TERRAIN REGIONS: PERSISTENT FOG AND SEA-BREEZE FRONT PROPAGATION

Computer Project Account: spesturb

Principal Investigator(s): Maria Antonia Jiménez Cortés

Affiliation: Universitat de les Illes Balears (Spain)

Name of ECMWF scientist(s) collaborating to the project
(if applicable) Alex Serra Nieto

Start date of the project: 1st January 2024

Expected end date: 31st December 2026

Computer resources allocated/used for the current year and the previous one (if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	5,000,000	5,000,000	5,000,000	2,000,000
Data storage capacity	(Gbytes)	500	500	500	500

Summary of project objectives (10 lines max)

Two complex terrain regions are taken in this project following the results of the previous one. For the eastern Ebro subbasin, a combined study of in-situ observations and simulations will be carried out to better understand the physical mechanisms that take place during fog events (which are very frequent and can persist for several days), colder pooling within the basin and the propagation of the sea breeze front (local wind known as *Marinada*). The runs will be based on observations started after the LIAISE campaign and still made at the site. For the island of Mallorca, simulations will be carried out to further understand the interactions between the sea/land breezes with the locally-generated winds of smaller scale and with the winds of larger scale (interactions between the sea/land breezes generated in the three main basins). The studied cases will be based on observations during the AGROWIND experimental field campaign (2021-24), organized by the members of the special project.

Summary of problems encountered (10 lines max)

None.

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

In line with the objectives of the special project, simulations over the island of Mallorca began in 2025 and are currently under analysis. These simulations consist of a sea breeze period in July 2022 lasting five days, under the influence of a high-pressure system, allowing this regime to develop. However, the characteristics of the sea breeze differ each day, especially during the initiation, mature and decay phases. Further analysis is underway to investigate the physical mechanisms that take place in the convergence zone in the centre of the island. Regarding the eastern Ebro subbasin, we have just started simulating a long-lasting fog event observed in the in December 2021. This case is selected based on data analysis from participants in the experimental field campaign.

List of publications/reports from the project with complete references

A. Serra, M.A. Jiménez, A. Maimó-Far (2026) A sea breeze convergence zone in a complex terrain island (In preparation)

A. Serra, M.A. Jiménez, A. Maimó-Far (2026) A sea breeze convergence zone in a complex terrain island, European Meteorological Society meeting (Utrecht), EMS 2026-409 (oral presentation)

A. Serra, A. Maimó-Far, M.A. Jiménez (2026) Statistical Analysis of sea breeze over complex terrain with the Meso-NH model and CERRA Reanalysis, XIV Congreso Internacional de la Asociación Española de Climatología (AEC), FIS-050 (poster)

A. Grau, M. A. Jiménez, A. Serra (2026) The organization of the flow at lower levels in a complex terrain island under sea breeze conditions (In preparation)

M.A. Jiménez, J. Cuxart, A.A. Boone, P. Le Moigne, T. Lunel, J. Mercader, J.R. Miró, M. Best, J.K. Brooke (2025) Land-surface interactions with the atmosphere over the Iberain Semi-arid Environment (LIAISE): First mesoscale modelling intercomparison. <https://doi.org/10.1002/qj.4949>

M. A. Jiménez, A. Grau, L. Cuadros-Vidal, D. Martínez-Villagrasa, J. Cuxart (2025) Characterisation of clear stable nights in summer and lasting fog in winter in the eastern Ebro basin, 10th International Conference on Meteorology and Climatology of the Mediterranean (Toulouse)

M.A. Jiménez, A. Grau, L. Marí, Ll. Cuadros, A. Serra, A. Maimó-Far (2024) Study of the physical mechanisms during sea breeze events in the Mallorca island through observations and simulations, European Meteorological Society meeting (Barcelona), EMS2024-838 (oral presentation)

Ll. Cuadros (2024) A numerical study to characterize the winter-time sea-breeze in the Alcúdia basin (Mallorca), Final degree thesis (supervised by M.A. Jiménez), Physics Degree at the University of Balearic Islands

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

During previous speturb projects, mesoscale simulations were carried out over the island of Mallorca to improve our understanding of the organisation of the flow at low levels. Several simulations of some selected sea breeze (SB) events in the Palma, Alcúdia and Campos basins were performed, using the filter proposed by Grau et al. (2021) to select these events. This statistical analysis, based on observations from the AEMET surface network, shows that most of the SB days occur during the warm months of the year (approximately 50%), although the filter also selects 1-2 SB days per year in winter.

The results for the Palma basin show that the SB is stronger in summer than in winter, in line with the horizontal thermal gradient between the sea and land. Advection of cold air from the sea is also more pronounced in summer, as radiative warming stops once the air reaches a certain point in the basin. The propagation of the sea breeze front is clearly visible in summer, but is reduced to a coastal circulation in winter. Sensitivity tests on horizontal resolution also showed that a resolution of around 200 m is required to accurately reproduce the organisation of the flow at low levels in the basin, as well as the interactions between circulations of different scales (e.g. slope winds and sea breezes).

The organisation of the flow at lower levels during the summer SB in the Alcúdia basin (in the northeast of the island) is completely different from that in the Palma basin. The lower parts of the Alcúdia basin are flat and used primarily for agriculture, whereas the lower parts of the Palma basin are smaller and occupied by the airport and the city of Palma. Simulations of a summer SB event in the Alcúdia basin (Marí, 2023) showed that this wind is from northeast, opposite to the general synoptic winds (westerlies at this latitude) and to the SB already generated in the Palma basin. Therefore, interactions between the SB and winds on larger and smaller scales in the Alcúdia basin are important.

1. Organization of the flow under sea breeze conditions in winter in the Alcludia basin

At the beginning of the current special project the attention focusses on the further exploring of the SB in the Alcúdia basin. A winter SB case is taken (based on observations from the AGROWIND experimental field campaign). The simulation starts at 1800 UTC on 24th January 2022 and ends at 0000 UTC on 26th January 2022. The SB event takes place on the 25th January, when the spin-up of the simulation is completed (more details in Cuadros, 2024).

Three nested domains are considered (see Figure 1), but the results are only analysed for the innermost domain, which has a horizontal resolution of 250 m. For the vertical domain, the resolution is 3 m, stretched to better include the physical processes that occur at lower levels. The simulation strategy is similar to that used in the previous special project: the initial conditions are taken from the ECMWF analysis, and the main parameterisations are turbulence, advection and surface.

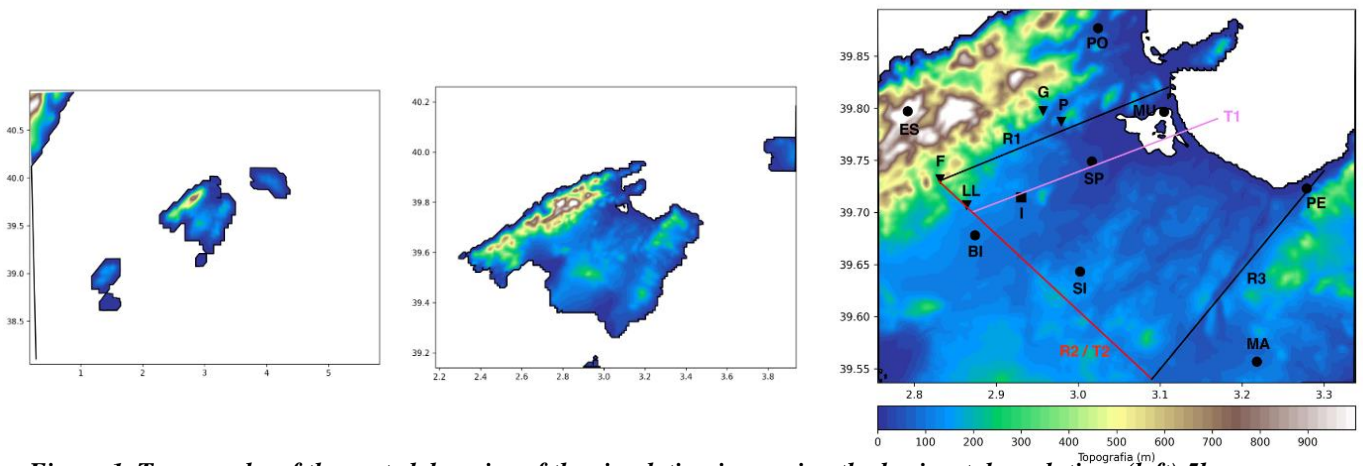


Figure 1. Topography of the nested domains of the simulation increasing the horizontal resolution: (left) 5km x 5km; (middle) 1km x 1km; (right) 250m x 250m. In the latter, the locations of the surface observation network are indicated by a symbol and a label. The dots and squares indicate the AEMET stations, while the triangles represent the observations made during the AGROWIND experimental field campaign by the members of the special project.

The results obtained have been validated using observations from AEMET's surface weather stations and data from the AGROWIND experimental field campaign. The model can reproduce the diurnal cycle of the SB (see, for example, Figure 2, which shows a site close to the coast). While the diurnal cycle of wind is captured well, the model fails to reproduce temperature and humidity during the night. This could be due to the poor spatial resolution needed to reproduce surface heterogeneities, or because the turbulence scheme reaches its limits when winds are weak and nocturnal cooling is strong (i.e. weak and intermittent turbulence). The same run was performed with 3D turbulence, starting at 1200 UTC to represent the night-time cooling of the previous SB day. The results do not change significantly (see the thin line in Figure 2), which suggests that there are difficulties with the model parameterisations in properly reproducing the organisation of the flow at lower levels.

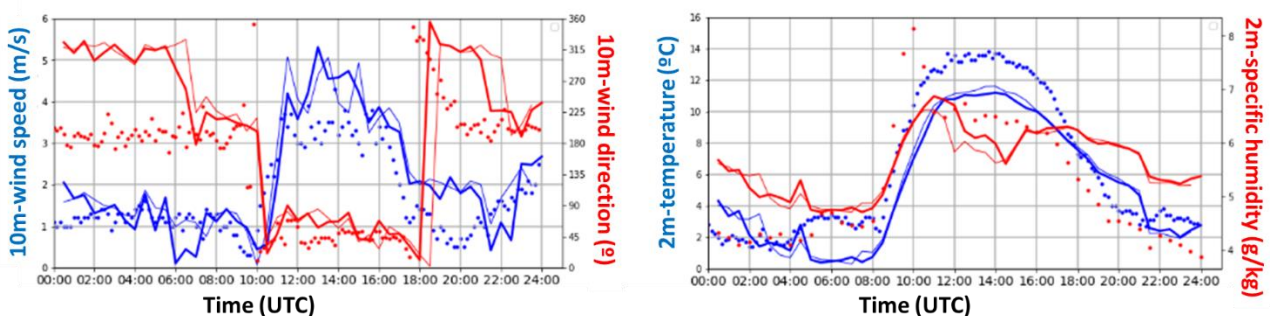


Figure 2. Temporal evolution of 10m wind speed and direction and 2m temperature and humidity for a site near the coast (SP in Figure 1.right) for 25th January 2022. Observations are shown as points and simulations as lines. The thinner line shows the model output using the 3-D turbulence scheme and initiated at 1200 UTC of the previous day.

Inspecting the horizontal cross-sections (Figure 3) at various times reveals that the winds are from the western sector and weak at night (corresponding to the land breeze at 0700 UTC, see Figure 3, left). A maximum wind speed is observed over the sea in the middle of the bay, while the wind is weaker over the land. At 1000 UTC, the land breeze weakens and reverses direction compared to the larger-scale wind over the sea (Figure 3, middle). One hour later, at 1100 UTC, the wind veers and the SB wind direction is present over land, enhanced by the larger-scale wind from the east (Figure 3, right).

Examining the hourly evolution of the horizontal cross-sections for the 10 m-wind (not shown) reveals that this simulated winter sea breeze (SB) is strongly influenced by the larger-scale wind from the eastern sector. This is important at higher levels, but it weakens at lower levels, which allows the SB to form in the lower parts of the Alcúdia basin. Once formed, the SB is reinforced by this larger-scale wind since they have the same wind direction.

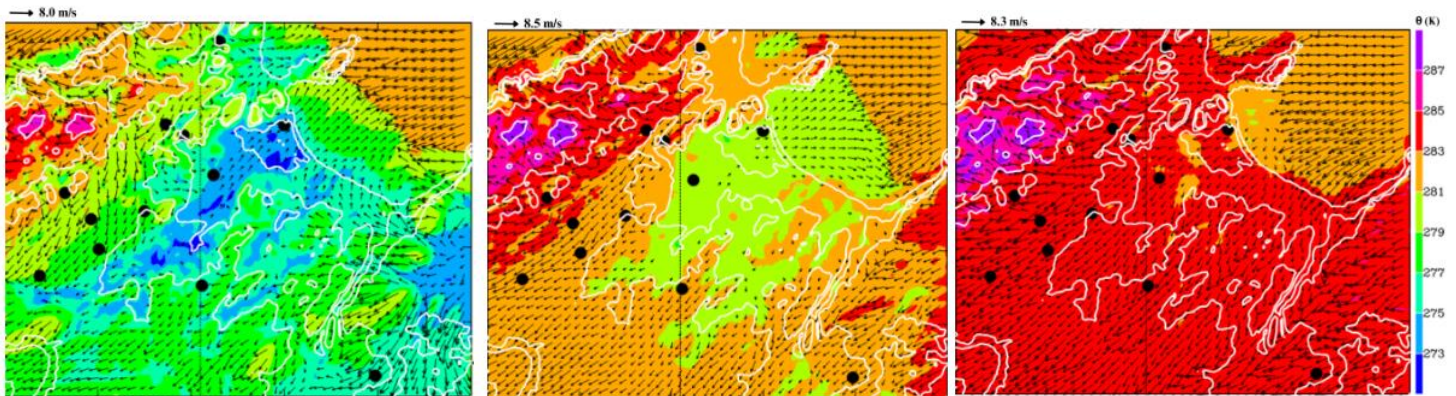


Figure 3. Potential temperature fields at 2m (in colours) together with the 10m wind vectors for the inner domain of the simulation at (left) 0700 UTC, (middle) 1000 UTC and (right) 1100 UTC for the sea breeze event of 25th January 2022.

The results of this winter case were also compared with those of a summer breeze case studied in the previous special project (Figure 4). Results show that the SB is weaker in winter than in the warm months and consequently the temperature and humidity advection are less intense. The results suggest that the horizontal thermal gradient is important for SB occurrence, but other factors, such as the larger scale winds, are crucial for describing the diurnal evolution of the SB.

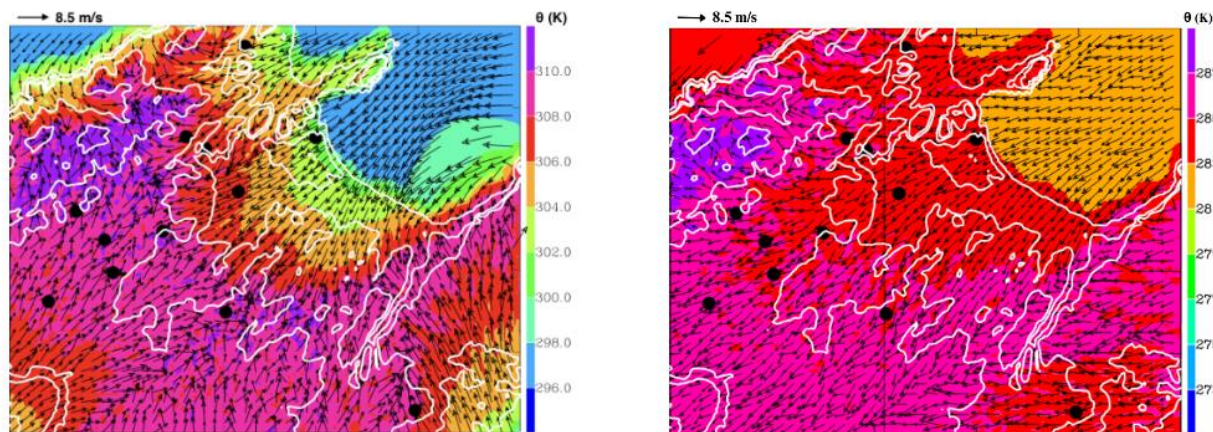


Figure 4. Potential temperature fields at 2m (in colours) together with the 10m wind vectors for the inner domain of the simulation at 1300 UTC for 2 simulated sea breeze events (left) during summer (21st July 2021) and (right) during winter (25th January 2022).

2. Organization of the flow at lower levels during a long-lasting sea breeze event in Alcúdia basin

Attention is now focused on a long-lasting sea breeze event (according to the classification of Grau et al. (2026)) that took place in the Alcúdia basin from 12 to 18 July 2022. The simulation strategy is the same as that described above for the winter case.

A validation of the inner domain model results is shown in Figure 5. The model is able to reproduce the diurnal cycle of the observations from the AWSs placed in the basin.

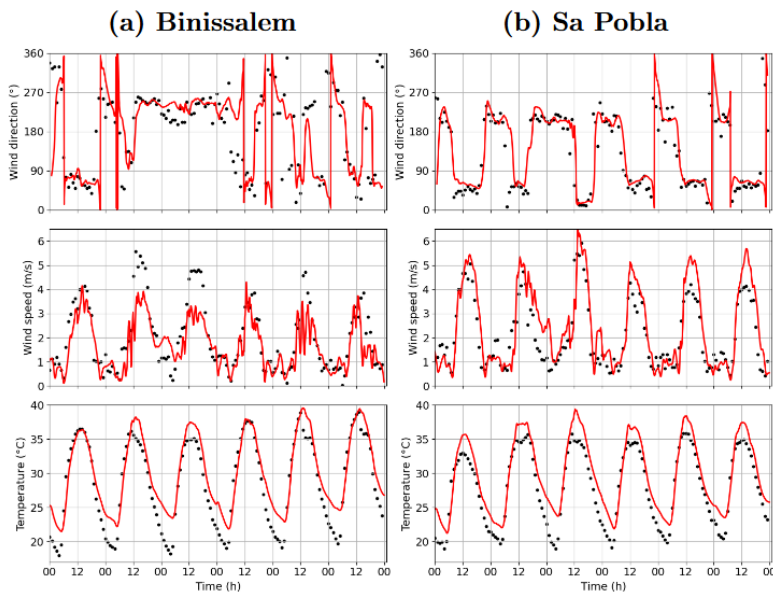


Figure 5. Evolution of AWS (black) and Meso-NH (red) 2 m wind direction, wind speed and temperature for (a) Binissalem and (b) Sa Pobra during the simulated period (labelled as BI and SP in Figure 1).

During the day, the sea breeze in this region comes from the NE. Winds from the SW correspond to the sea breeze generated in the Palma basin (the opposite basin, noticeable in the centre of the island, for example in Binissalem, see Figure 1), while winds from the NW and SE correspond to circulations generated by the mountain slopes of the northern and eastern mountain ranges. At night, however, winds from the SW correspond to the land breeze, while those from the other sectors are related to downslope winds.

Although all the simulated days are classified as sea breezes according to Grau et al. (2026), they have different characteristics. Inspecting the wind patterns and the divergence of the wind at lower levels (Figure 6) the simulated events can be classified into three categories.

For the case of 12th July, the breeze in the Alcúdia basin is more intense than the one in the Palma basin (in line with a larger horizontal thermal gradient), meaning that the sea breeze front generated in the Alcúdia basin can penetrate further inland and reach the Palma basin by the afternoon. Consequently, the convergence zone (Figure 6a) is located further west.

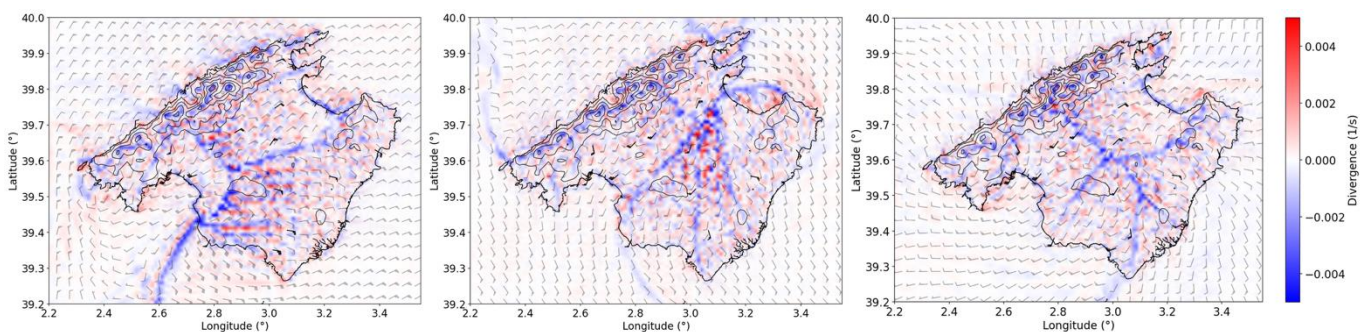


Figure 6. Low level configuration of representative events at 1330 UTC for (LEFT) 12th July; (MIDDLE) 14th July and (RIGHT) 16th July. Barbs show 10 m-wind speed and direction for AWS (black) and the Meso-NH simulation (gray), with half and full barbs, and flags representing 1, 2, and 10 m/s respectively. Modelled wind divergence at 10 m is also shown.

On the 13th and 14th July, a large-scale wind from the south limited the formation of breezes in the Alcúdia basin. The sea breeze fronts from the Palma and Campos basins propagate faster, probably because they were reinforced by large-scale winds from the west. Consequently, the formation of the sea breeze in Alcúdia Bay was delayed, with the sea breeze front propagating inland once the

fronts from Palma and Campos decreased in intensity. Figure 6b shows a clear convergence zone indicating the interaction between the large-scale wind and the locally generated breeze.

For the remaining days (15th, 16th and 17th July), the breeze is generated in all the three basins (Alcúdia, Palma and Campos), creating a convergence zone in the centre of the island (Figure 6c).

To further investigate the physical processes that occur under sea breeze conditions, the temperature and wind budgets obtained from the simulation are analysed. Figure 7 shows the temporal evolution of the vertical profiles of the most important terms in the temperature budgets: tendency, advection and turbulence. After sunrise, convection and turbulence are responsible for transporting heat from the ground to the upper levels. However, once the sea breeze front reaches the site, cold advection stops convection while turbulence strengthens. This occurs close to the coast (SP) and further inland (BI), with the latter being more intense due to increased land heating time.

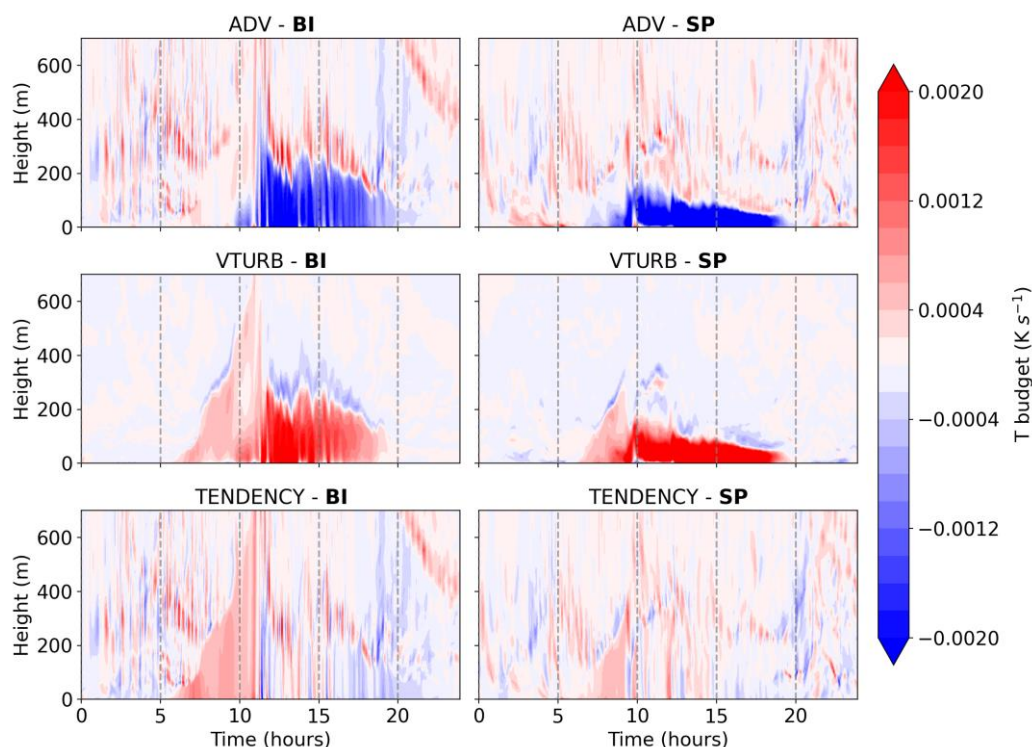


Figure 7. Vertical evolution of some selected terms of the temperature budgets vertical evolution at Binissalem (BI) and Sa Pobra (SP) for 16th July 2022.

A similar analysis is performed for the horizontal wind budget in Figure 8. The results show that the sea breeze front propagates inland thanks to the pressure gradient generated by the horizontal thermal gradient at the coast, while shear and friction generate turbulence that reduces the front's propagation. Sea breeze fronts in the Alcúdia and Palma basins behave similarly, whereas in the convergence zone at the centre of the island, the terms of the horizontal budgets are nearly zero because vertical velocity is more important there. When inspecting the vertical velocity and turbulence budget terms, coastal results were coherent with Cuxart et. al. (2014), while inland convergence proved to be driven by buoyancy and pressure. Thermal, shear and turbulent terms lift air at low levels when the fronts meet, while an inversion is found at nearly 500 m. At that height, the shear term keeps lifting the air and providing turbulence for higher levels, while the thermal and turbulent contributions due to solar heating no longer help convection.

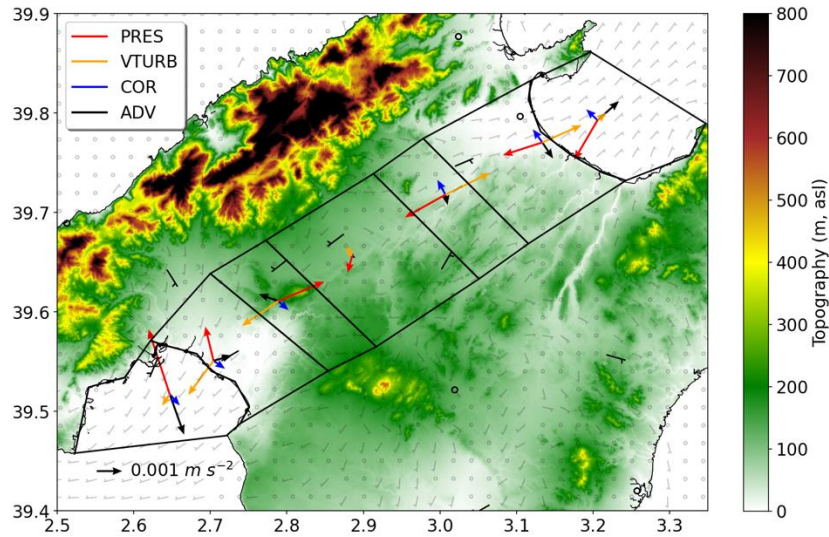


Figure 8. Horizontal moment budget vector components for 16th July at 1330 UTC, averaged vertically between 0 and 300 m for each polygon.

3. Organization of the flow at lower levels under a long-lasting fog event in the Ebro river basin

A long-lasting fog event in the Ebro river basin was reported during 13-24 December 2021 in the framework of the LIAISE experimental field campaign (Boone et al, 2025). Analysis of these observations is underway and will be complemented by mesoscale simulation results to improve our understanding of flow organisation at lower levels under such conditions. Figure 9 shows the land-surface temperature (LST) field obtained from MODIS, together with an estimation of the horizontal extension of the fog during the studied period, based on Meteosat and MODIS LST data.

The simulations will be performed using the MesoNH model with a setup is similar to the one used in the 1st intercomparison of the mesoscale models performed in the LIAISE community (Jiménez et al., 2025). It consists in a two nested domains: the outer one at 2km resolution covers the whole basin (Figure 9) and the inner one at 400m resolution is centered in the western side of the basin. It is expected that these runs will end by July 2026 and the results will be explained in the final report of this current special project.

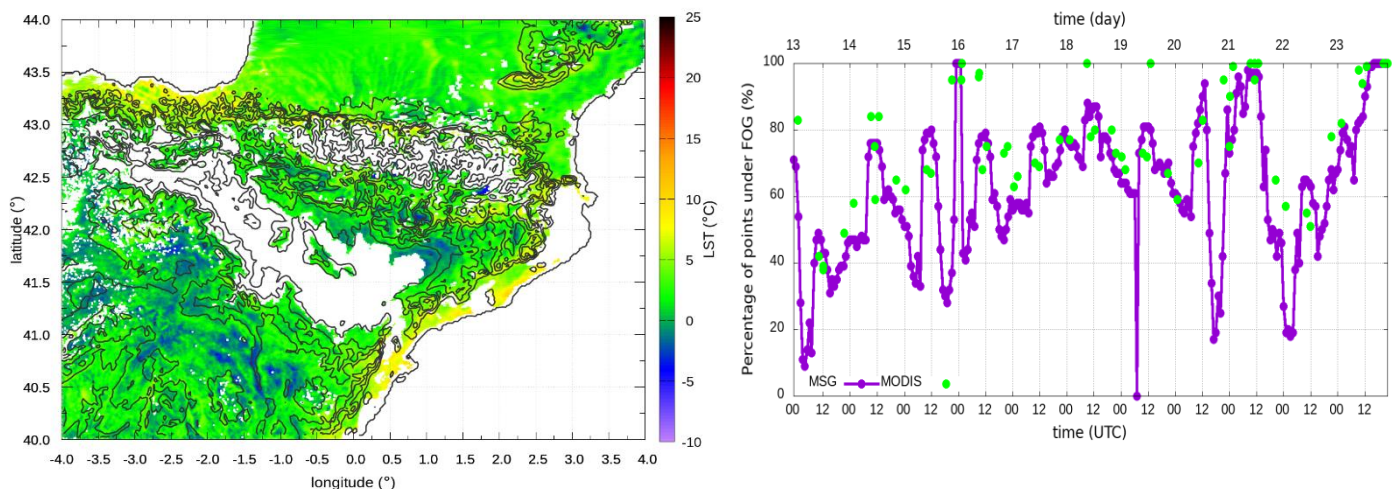


Figure 9. (Left) Land-surface temperature (LST) obtained from MODIS for 13th December 2021 at 2215 UTC. (Right) Temporal evolution of the percentage of the NaN points in the LST field (taken from MSG and MODIS satellites) in the bottom parts of the Ebro river basin during 13-24 December 2021.