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	2025
Project Title:	Simulations of different types of breezes and their interactions.
Computer Project Account:	spesyagu
Principal Investigator(s):	Carlos Yagüe Anguis
Affiliation:	University Complutense of Madrid
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project: 01/01/2025	
Expected end date: 31/12/2027	

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)			400000	1553103
Data storage capacity	(Gbytes)			10000	10000

Summary of project objectives (10 lines max)

This project aims to improve the simulation and understanding of thermally-driven mesoscale flows—such as mountain, valley, coastal, and urban breezes— and their interactions with other atmospheric processes. We use high-resolution numerical modelling with the Weather Research and Forecasting (WRF) model combined with high-quality observational data from complex terrains in the Iberian Peninsula and the French Pyrenees. The project focuses on how land-atmosphere interactions affect key meteorological variables. It addresses model biases and improves the representation of surface turbulence and energy exchanges. Special attention is given to urban effects, thermal comfort, air quality, and the development of operational forecasting tools for thermally-driven flows.

Summary of problems encountered (10 lines max)

Achieving accurate model configurations that properly represent land-atmosphere interactions in complex terrain and surface heterogeneity requires extensive testing. Selecting optimal land surface models (LSMs), and planetary boundary layer (PBL) parameterizations is time-consuming and highly case dependent. Due to this, it has utilized more resources than we originally expected, and we have requested more resources which have been approved and the SBUs have been added to our account. Other challenges include handling large observational datasets for model validation, especially in coastal, mountainous, and urban areas with high microscale variability.

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

We plan to continue optimizing WRF model configurations through operational forecasting simulations, additional sensitivity experiments, and validation with observational datasets. As part of this work, the project also aims to advance the development of operational simulations to improve the automation and validation of the model. In parallel, sensitivity experiments will focus on representative case studies involving thermally-driven mesoscale flows, including events related to the urban heat island, thermal comfort, and air quality, particularly in coastal and mountainous regions. Additionally, WRF with turbulence-resolving capability based on a large-eddy simulation (LES) approach (WRF-LES) will be implemented in selected domains to more accurately represent turbulence and microscale flows.

List of publications/reports from the project with complete references

- Carbone, J., Sanchez, B., Román-Cascón, C., Martilli, A., Santiago, J. L., Ortiz-Corral, P., Cicuéndez, V., Inclán, R. M., Royé, D., Maqueda, G., Viana, S., Sastre, M., and Yagüe, C.: Exploring Madrid's Local Climate: The Impact of Urban Development and Thermally-Driven Flows, 12th International Conference on Urban Climate, Rotterdam, The Netherlands, 7–11 Jul 2025, ICUC12-383, https://doi.org/10.5194/icuc12-383, 2025.
- Yagüe, C., Maqueda, G., Román-Cascón, C., Serrano, E., Carbone, J., Ortiz-Corral, P., Cicuéndez, V., Viana, S., Arrillaga, J. A., Inclán, R. M., and Sastre, M.: How have the temperature and urban heat island evolved in Madrid and its surroundings in the last decades?, 12th International Conference on Urban Climate, Rotterdam, The Netherlands, 7–11 Jul 2025, ICUC12-503, https://doi.org/10.5194/icuc12-503, 2025.
- Sastre, M., Román-Cascón, C., Ortiz-Corral, P., Carbone, J., Cicuéndez, V., Sánchez, B., Martilli, A., Artíñano, B., Gómez-Moreno, F. J., Díaz-Ramiro, E., Alonso-Blanco, E., Narros, A., Borge, R., and Yagüe, C.: Impact of turbulence and meteorological conditions on air quality in Madrid (Spain) analysed through field measurement campaigns, 12th International Conference on Urban Climate, Rotterdam, The Netherlands, 7–11 Jul 2025, ICUC12-519, https://doi.org/10.5194/icuc12-519, 2025.
- Carbone, J., Luján-Amoraga, E., Ortiz-Corral, P., Sanchez, B., Martilli, A., Sastre, M., Yagüe, C., Alvarez, O., and Román-Cascón, C.: Thermal comfort and the role of coastal breezes

during heatwaves in the southwestern Iberian Peninsula: insights from observations and WRF modeling., 12th International Conference on Urban Climate, Rotterdam, The Netherlands, 7–11 Jul 2025, ICUC12-377 https://doi.org/10.5194/icuc12-377 , 2025.
- Luján-Amoraga, E., Román-Cascón, C., Bolado-Penagos, M., Ortiz-Corral, P., Jimenez-Rincón, J. A., Izquierdo, A., Bruno, M., and Yagüe, C.: Dynamics of sea breezes: Analysis of recent events in Southwest Spain, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-9247, https://doi.org/10.5194/egusphere-egu25-9247, 2025.
- Román-Cascón, C., Ortiz-Corral, P., Luján-Amoraga, E., Jiménez-Rincón, A., Bolado-Penagos, M., Bruno, M., Izquierdo, A., Sun, J., and Yagüe, C.: Horizontal and vertical analysis of sea breezes in the Gulf of Cádiz (SW Spain) from surface stations and radiosounding data, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-15917, https://doi.org/10.5194/egusphere-egu25-15917, 2025.
- Ortiz-Corral, P., Román-Cascón, C., Jiménez-Rincon, J. A., Lohou, F., Lothon, M., Sastre, M., Sun, J., and Yagüe, C.: Statistical Analysis of Nocturnal Downvalley Flows Over the Annual Cycle: Insights from a Pyrenean Valley (France), EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-16689, https://doi.org/10.5194/egusphere-egu25-16689, 2025.
- Vasquez Rojas, J., Carbone, J., Izquierdo González, A., Benavente González, J., Gómez Enri, J., Fernández -Montblanc, T., Martins, F., Cabos Narvaez, W., Yagüe, C., Román-Cascón, C., Álvarez, O., Fonteles, C., Marques, B., and Campuzano, F.: OceanUCA: Technological innovation for the management and communication of coastal data in Andalusia through numerical modelling and open source technology., EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-18601, https://doi.org/10.5194/egusphere-egu25-18601, 2025.
- Carbone, J., Vasquez-Rojas, J., Izquierdo, A., Benavente, J., Gómez-Enri, J., Fernández-Montblanc, T., Martins, F., Cabos Narvaez, W. D., González, C. J., Yagüe, C., Román-Cascón, C., and Alvarez, O.: OceanUCA: Enhancing Coastal Observation and Forecasting in Andalucía (Spain) through Data Visualisation and Communication, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-8703, https://doi.org/10.5194/egusphere-egu25-8703, 2025.
- Sánchez-Lorente, A., Martilli, A., Sánchez, B., and Yagüe, C.: Mesoscale modeling of the urban boundary layer in a coastal city. The case of Valencia., EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-4133, https://doi.org/10.5194/egusphere-egu25-4133 , 2025.

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.

Coastal Breezes and Thermal Comfort During Heatwaves in Southwestern Spain.

During the first year of the project, we consolidated and quality-checked several observational datasets from the Gulf of Cádiz in southwestern Spain (Figure 1). Preliminary WRF model simulations tested different domain nesting strategies, vertical resolutions, LSMs, and PBL schemes. These experiments confirmed that the model is sensitive to soil moisture initialization and to the choice of physical parameterizations.

Figure 1: Study area and weather stations in the Gulf of Cádiz, southwestern Spain. The blue line shows an approximate boundary separating the southern area, mainly influenced by easterly winds, from the northern area, where sea breezes usually develop. This boundary can change depending on the atmospheric conditions of each event.

One of the main goals during this phase was to study how coastal breezes affect thermal comfort during extreme heat events. In recent years, heatwaves have become more frequent and intense, with the number of such events in Spain almost doubling (Núñez Mora, 2021). In coastal regions, sea-land breezes—caused by temperature differences between land and sea—can play an important role in reducing high temperatures. This is particularly relevant in the southwest of the Iberian Peninsula, where urban development is dense and nearly 60% of Spain's population lives near the coast (de Andrés et al., 2017). In these areas, thermal exposure varies greatly due to small-scale differences in temperature, humidity, wind, and radiation, shaped by both natural features and urban structures.

To investigate the effect of coastal breezes on thermal comfort, we combined observational data from weather stations with high-resolution WRF simulations that included the WRF-Comfort urban module (Martilli et al., 2024). This setup allowed us to analyse how breezes influence thermal conditions during heatwaves and to explore the interaction between mesoscale weather processes and urban environments. Our findings show the value of combining mesoscale models and urban data to better understand and manage the effects of climate extremes in cities.

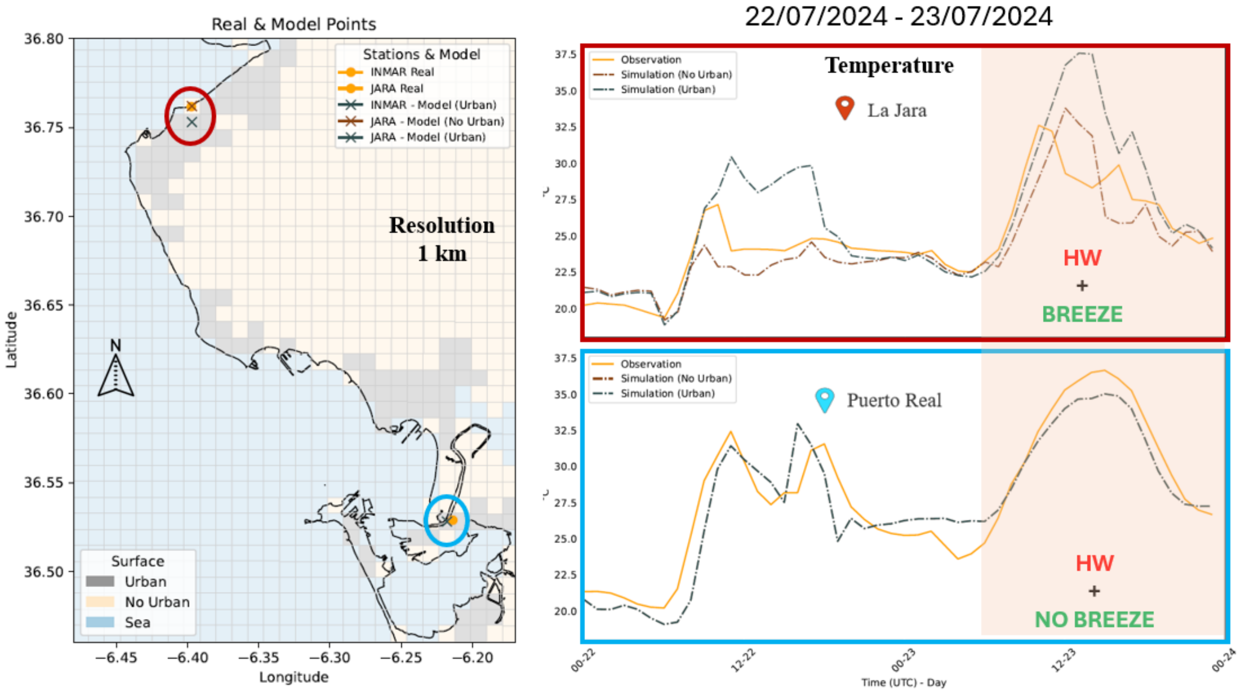


Figure 2: WRF simulation domain with 1 km resolution, showing the location of two weather stations. The plot displays temperature data for two days in July 2024.

To explore these interactions further, we studied two consecutive days in July 2024, one of which occurred during a heatwave. Using WRF simulations with 1-km resolution, we examined how temperatures evolved near several weather stations. In areas where the sea breeze developed, such as near the La Jara station, temperatures dropped significantly in the afternoon instead of following the usual bell-shaped pattern, showing a clear cooling effect (Figure 2). This drop was even more noticeable at urban points, where baseline temperatures were higher due to urban heat, making them more sensitive to the breeze. In contrast, at stations further south like Puerto Real, where easterly winds dominated, no breeze developed and temperatures remained high, demonstrating strong spatial variation in the breeze's influence.

We also evaluated thermal comfort using the Universal Thermal Climate Index (UTCI) at urban locations, as shown in Figure 3. On the day before the heatwave, UTCI values decreased in the afternoon when the breeze arrived, indicating better thermal comfort. However, on the heatwave day, the WRF model showed a delayed arrival of the breeze, leading to higher UTCI values and poorer comfort, even though observed data suggested milder conditions. This mismatch highlights the importance of accurately modelling breeze dynamics in high-resolution simulations.

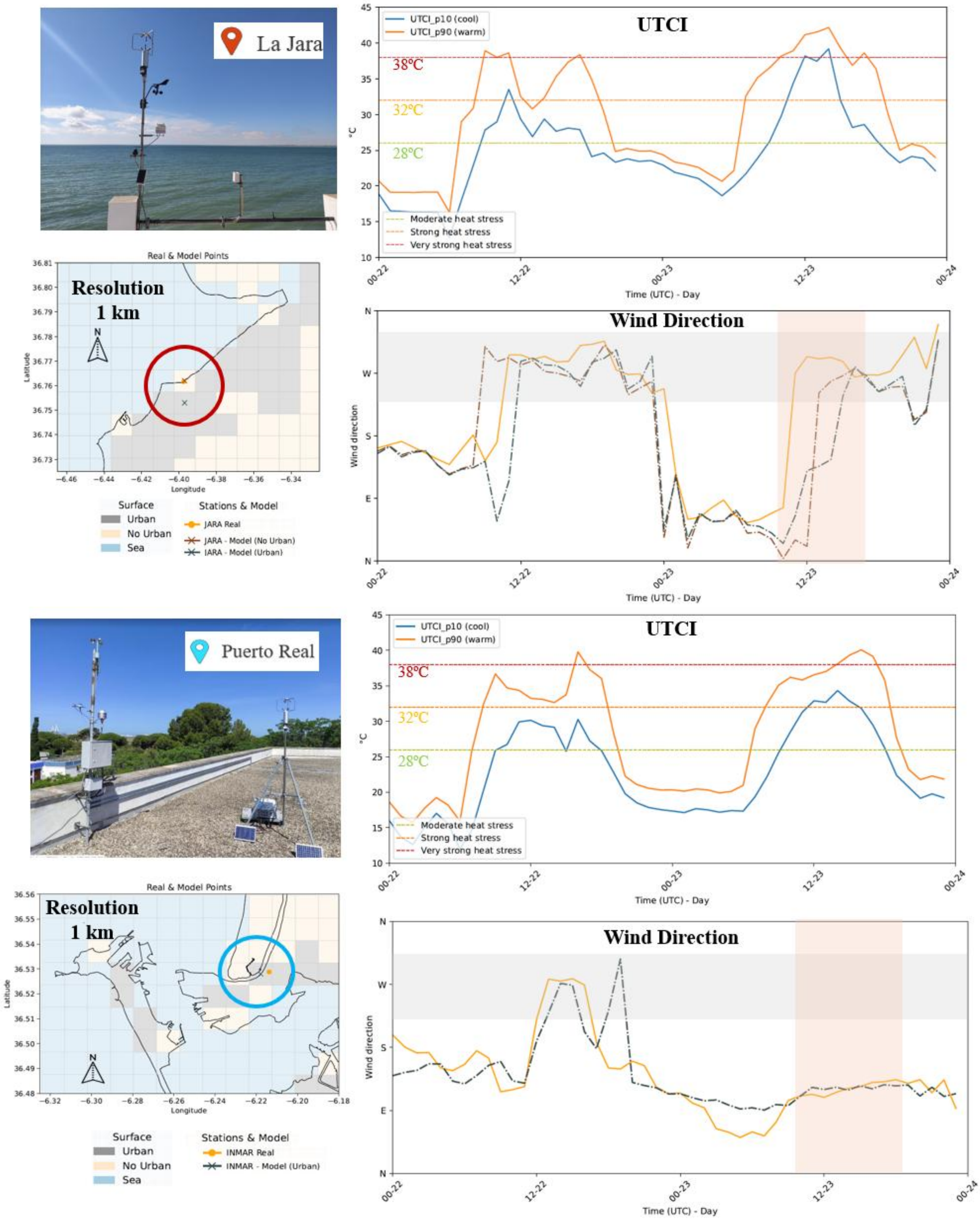


Figure 3: Thermal comfort index (UTCI) and wind direction analysis at the urban points closest to the weather stations.

In summary, coastal breezes can provide valuable cooling during extreme heat events, especially in urban areas. However, their localized nature and the difficulty of capturing them accurately in models present challenges. These results underline the need to improve the representation of local breezes in weather models to better assess climate impacts and support effective heat adaptation strategies in urban regions.

Looking ahead, part of our future work will focus on validating the vertical structure of coastal breezes. Our research group regularly conducts radiosonde campaigns during breeze events to capture vertical profiles of temperature, wind, and humidity. These observational datasets will be essential for comparing and validating the model's ability to simulate breeze development. So far, WRF performs reasonably well in capturing the vertical structure of temperature and wind direction, both before and during the breeze as shown in Figure 4. However, the model tends to underestimate wind speed and specific humidity, particularly in the hours leading up to the breeze onset. Improving this aspect will be key to enhancing model accuracy and understanding the physical processes involved in breeze formation.

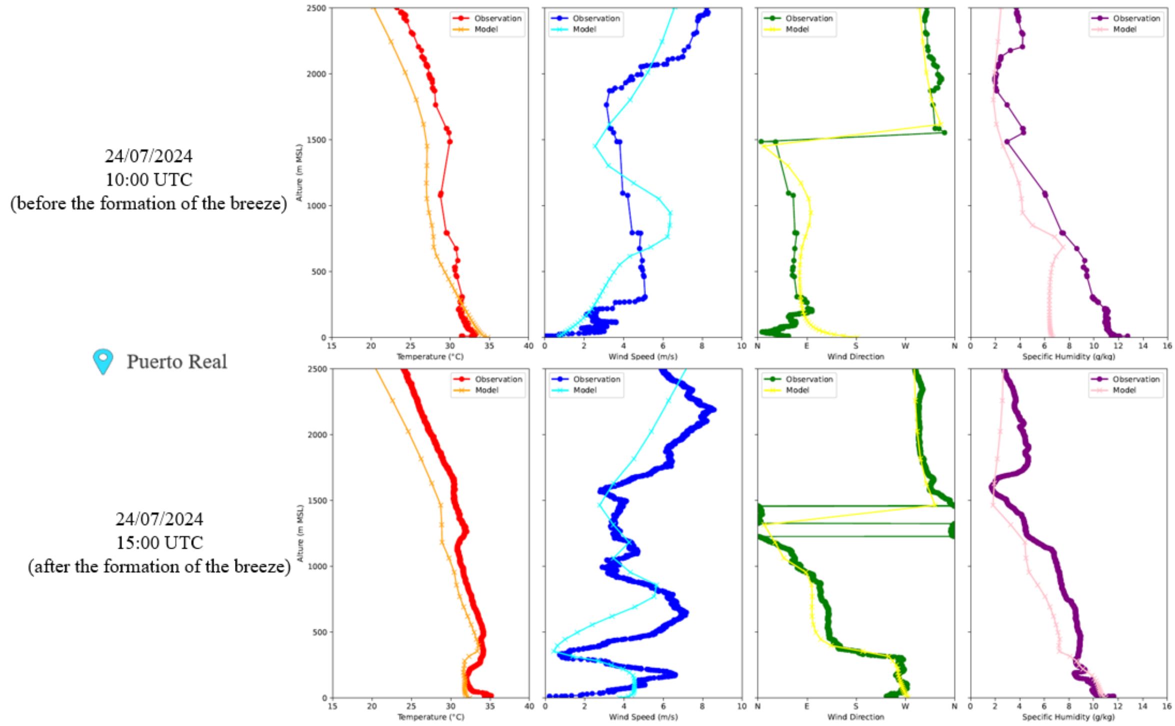
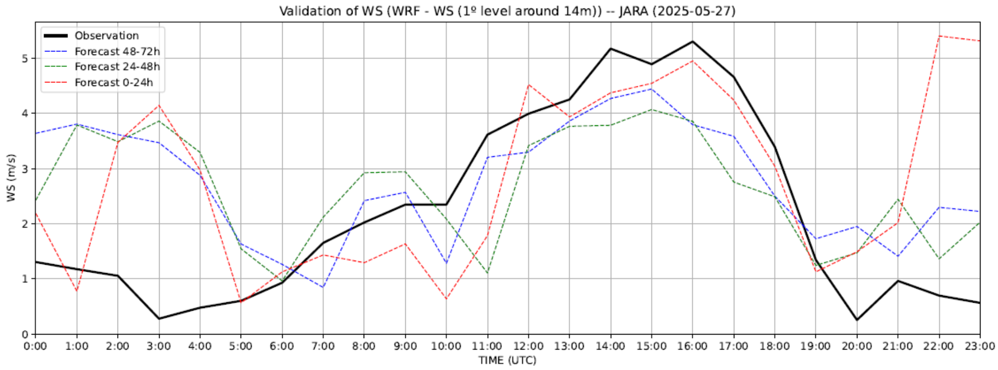
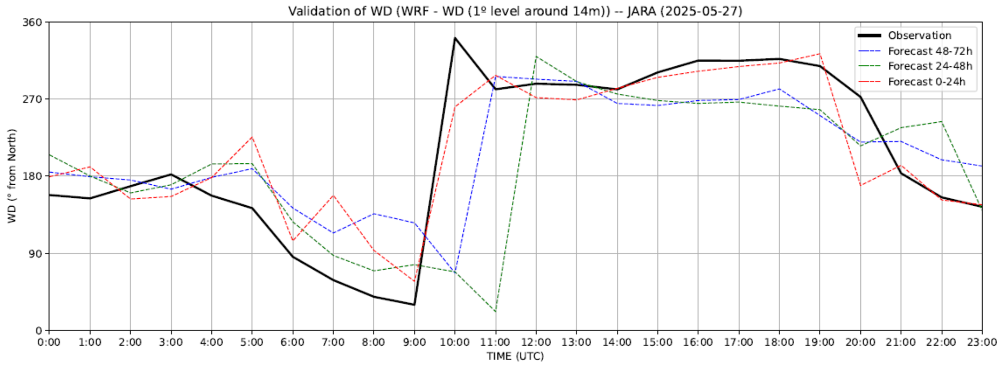


Figure 4: Vertical profiles of temperature, wind speed, wind direction and specific humidity at the Puerto Real university campus.

We are also working on improving the prediction of breeze events, which is especially useful for planning field campaigns. In the Figure 5 shown, you can see the simulated and observed wind direction and speed. The solid black lines represent observations, while the dashed lines show model outputs from 3-day forecasts. Results indicate that even forecasts made one or two days in advance tend to delay the onset of the breeze, consistent with what we observed in previous simulations. This highlights the need for further improvements in short-term forecasting of mesoscale flows.



Forecast	BIAS	MAE	RMSE	IOA
Forecast 48-72h	0.53	1.21	1.48	0.71
Forecast 24-48h	0.41	1.28	1.57	0.66
Forecast 0-24h	0.57	1.27	1.88	0.67



Forecast	BIAS	MAE	RMSE	IOA
Forecast 48-72h	-0.0	48.64	71.69	0.79
Forecast 24-48h	-15.43	55.9	86.83	0.75
Forecast 0-24h	4.73	28.99	42.01	0.94

Figure 5: Wind direction and wind speed from 3-day forecasts compared to observations at the La Jara weather station.

Mountain Breezes in the city of Madrid

Meteorological conditions significantly influence the diurnal evolution of pollutants, particularly through atmospheric dispersion processes. While many studies only link pollutant concentrations to wind speed from conventional anemometers, fewer explore the role of turbulence variables, partly due to the limited availability of suitable instruments in standard air-quality monitoring networks.

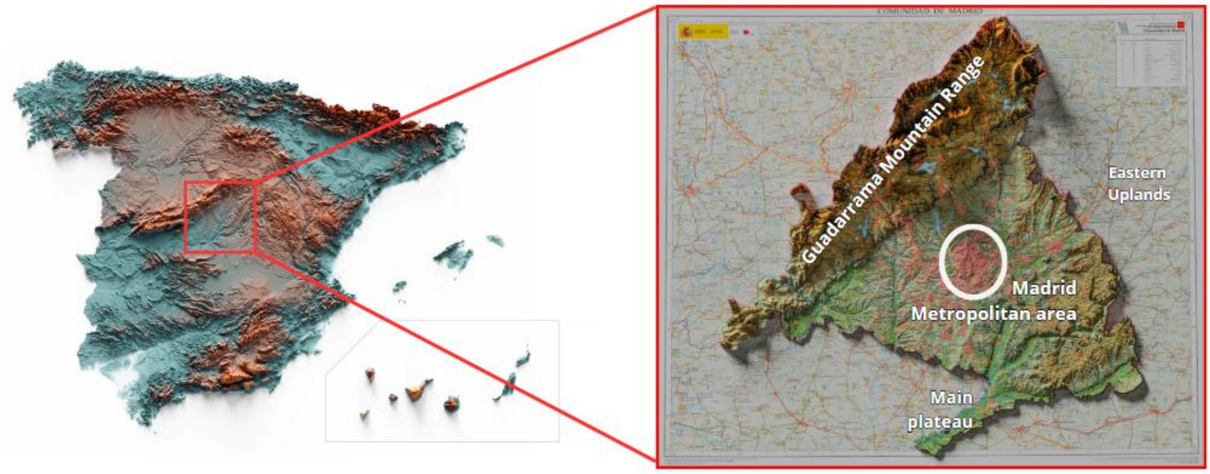


Figure 6: Orography surrounding the city of Madrid.

Apart from that, the city of Madrid is surrounded in the Northern sector by the Guadarrama Mountain range and the Eastern uplands (see Figure 6). Among others, the interaction between the city and this complex orography is far from been understood.

Our main focus is to analyze the relationship between NO_2 concentrations and turbulence variables, comparing it to the more traditional wind speed approach. Observational data from Madrid (winter 2020) were used.

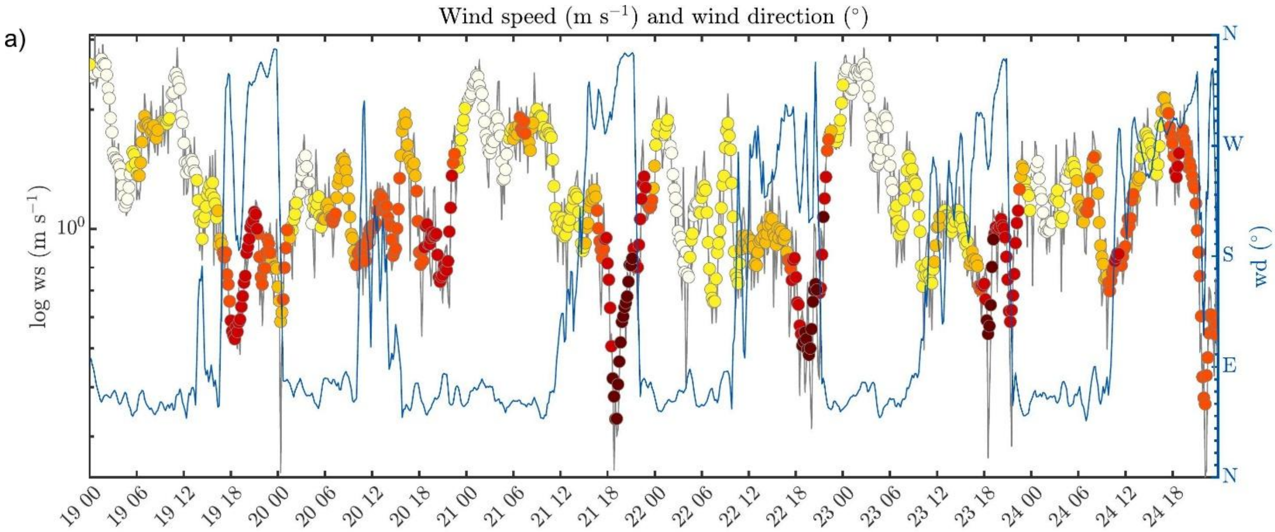


Figure 7: Urban observations during a synoptically-stable period, from 19 to 24 February 2020: a) Wind speed (ms^{-1} with colours of the symbols indicating the NO_2 concentration) and wind direction (° from North, blue line. Wind speed is plotted with logarithmic y-axis, using 10-min data in the grey lines and a 1-h running mean in the coloured symbols signal, for a better visualization.

Observations from several meteorological campaigns in different urban locations show the influence of atmospheric processes throughout the diurnal cycle on NO_2 levels. The highest concentrations occur in the evening and early night in winter under fair weather, due to the stabilization of the atmospheric boundary layer (ABL). However, especially during days characterized by high stability NO_2 levels are highly sensitive to small changes in afternoon and evening wind speed and turbulence (see Figure 7). These conditions are also characterized by the onset of nocturnal thermally-driven flows, which significantly reduce pollutant concentrations in complex urban terrains like Madrid (Román-Cascón et al., 2023). In Figure 7 we can observe that during the night of 20th-22th of February of 2020, nighttime NE winds reach Madrid after days with predominant stability, leading to a significant drop in pollutant levels (especially NO_2), which tends to accumulate under the preceding stable conditions meteorological (almost no wind during the preceding afternoon-evening) and traffic emissions.

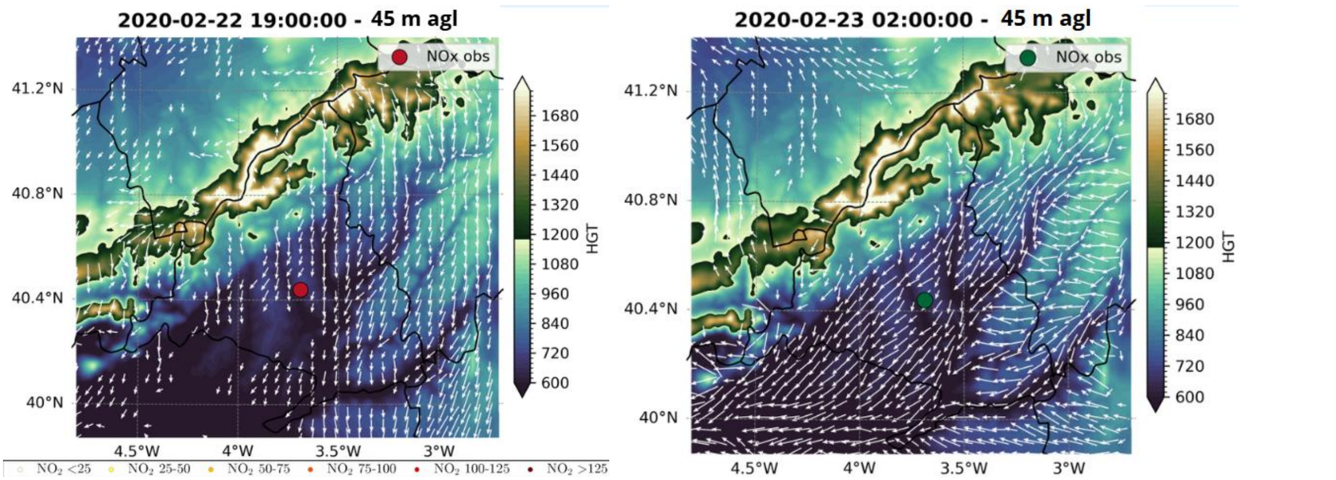


Figure 8: WRF simulation of near-surface wind and observed NO_2 concentrations over the city of Madrid and its surroundings for (a) 19:00 UTC on 22 February 2020 and (b) 02:00 UTC on 23 February 2020. Shaded relief represents terrain height (m a.s.l.), while white vectors depict horizontal wind at 45 m above ground level (AGL). Coloured dots indicate hourly NO_2 measurements at air-quality stations, classified as: < 25 µg m^{-3} (white), 25–50 µg m^{-3} (yellow), 50–75 µg m^{-3} (light orange), 75–100 µg m^{-3} (dark orange), 100–125 µg m^{-3} (red), and > 125 µg m^{-3} (maroon). The pale-green circle marks the reference station used for NO_x observations. Black contours trace major administrative boundaries, and the dashed grey grid denotes latitudes and longitudes at 0.2° intervals.

We performed numerical simulations with **WRF** (including the Building Effect Parameterization, **BEP**) to elucidate the mechanism responsible for the observed nocturnal wind regime. Preliminary results (Figures 8 and 9) reveal pronounced wind-channeling along the lowlands situated between the Guadarrama Mountain Range to the north-west of the city and the eastern uplands to the north-east and east. Near the surface, the Jarama and Henares river valleys enhance this channeling, accelerating the north-easterly flow that ultimately reaches the urban area. The impact on NO_x concentrations becomes evident when the wind field at 19:00 UTC—when the thermally driven circulation is only beginning to develop—is compared with that at 02:00 UTC, by which time the flow is fully established and penetrates the urban boundary layer.
Panels 9b and 9c illustrate daytime (panel b, calm conditions at 20:00 UTC on 21 February) and nighttime (panel c, 02:00 UTC on 22 February) cross-sections along the transect. The nighttime section displays the vertical structure of the thermally driven circulation: a well-defined easterly to north-easterly component confined to roughly the lowest 300 m above ground level, capped by the modelled planetary boundary-layer height.

This template is available at:
http://www.ecmwf.int/en/computing/access-computing-facilities/forms

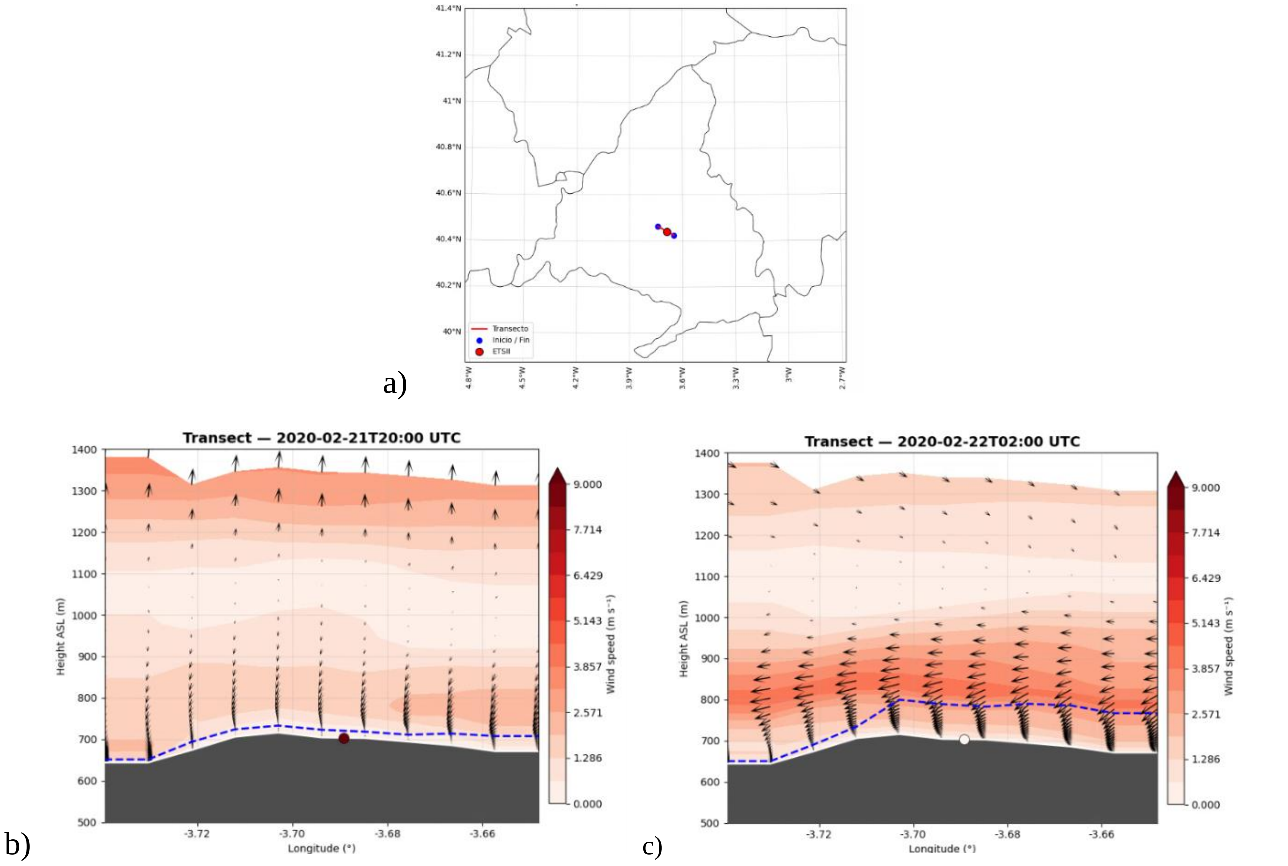


Figure 9: (a) Geographic location of the cross-section analysed in panels (b–c). The red segment traces the transect axis, while the blue dots mark its start/end points and the ETSII air-quality station. (b) WRF vertical transect at 20:00 UTC on 21 February 2020. Shading denotes simulated wind-speed magnitude (m s^{-1}) and black arrows give the horizontal wind vectors. The dashed blue curve is the planetary-boundary-layer height (PBLH) diagnosed by the model; the grey area corresponds to the underlying terrain. The filled circle at the surface shows the observed hourly NO_x concentration at ETSII, coloured according to the same categories used in Fig. 8.
(c) As in (b) but for 02:00 UTC on 22 February 2020.

These findings should be regarded as preliminary. A comprehensive, dedicated investigation including higher-resolution numerical experiments, and a systematic sensitivity analysis is required to fully unravel the complex wind regimes that emerge from the interplay of orography, land-use heterogeneity, urban morphology, and valley circulations in and around the Madrid metropolitan area.

References:

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- Mora, N. J. Á. (2021). Arcimis: Tiempo, clima e intensificación de fenómenos extremos en España. https://repositorio.aemet.es/handle/20.500.11765/13961

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