REQUEST FOR ADDITIONAL RESOURCES IN THE CURRENT YEAR FOR AN EXISTING SPECIAL PROJECT

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MEMBER STATE: Spain

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Project title: Simulations of different types of breezes and their interactions

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Project account: **SPesyagu**

Additional computing resources requested for year		2026
High Performance Computing Facility	[SBU]	7.000.000
Total DHS Data storage capacity	[GB]	0
EWC resources		
Number of vCPUs	[#]	
Total memory	[GB]	
Storage	[GB]	
Number of vGPUs[3]	[#]	

Continue overleaf

[1] The Principal Investigator is the contact person for this Special Project

Technical reasons and scientific justifications: why additional resources are needed

This Special Project focuses on characterizing different types of thermally-driven flows and their interactions in two complementary environments: complex mountain terrain and the urban boundary layer. The following sections first describe the mountain breeze component of the project, which involves studying katabatic and down-valley winds in the Pyrenees, and second describe its urban counterpart, which involves studying thermally-driven flows and their interaction with the Urban Heat Island (UHI) in Madrid, together with the corresponding computational requirements for each.

1. Mountain breezes over complex terrain: the Aure Valley case study.

The research team of this Special Project has as one of its main objectives the improvement of the numerical representation of thermally-driven flows in complex terrain, with a particular focus on stable boundary layers (SBL) and mountain breezes (e.g., katabatic and down-valley winds). Accurately modelling these highly localized phenomena requires bridging the gap between the mesoscale and the microscale, which remains a significant challenge in modern meteorology due to the interactions between steep orography and turbulent fluxes.

To address this, our current methodology involves high-resolution simulations using the Weather Research and Forecasting (WRF) model with Large-Eddy Simulation (LES) approach. We are currently evaluating the model's performance in the Aure Valley (Central Pyrenees) relying on the high-quality observational dataset from the recent MOSAI field campaign (August 2023). This dataset, which includes surface meteorological stations, turbulent flux measurements, and high-frequency nocturnal radiosondes, provides the ideal framework to validate our numerical outputs.

However, capturing the shallow structure of katabatic jets, where the maximum wind speeds often occur within the first 50 to 150 meters above the surface, imposes severe constraints on the model's grid configuration. Consequently, simulating these flows over the steep Pyrenean topography demands a multiscale offline nesting strategy (from a 5 km and 1 km mesoscale down to a 200 m microscale domain) and extremely short temporal steps to maintain numerical stability (avoiding CFL violations over complex slopes).

To optimize the model's capability to resolve these near-surface thermally-driven flows, additional computational resources are required to perform a comprehensive set of sensitivity experiments. Specifically, we have selected 6 Intensive Observational Periods (IOPs) from the MOSAI campaign. For each case study, we conducted 3 distinct vertical structure sensitivity experiments in the WRF-LES configuration to determine the optimal setup:

1. **Increasing the total number of vertical levels** (enhancing the overall vertical resolution of the SBL).
2. **Compressing the first computational levels closer to the surface** (reducing the depth of the bottom layer to better capture the katabatic jet core).
3. **A hybrid approach** combining both a higher number of vertical levels and a near-surface grid refinement.

These highly-resolved vertical setups (often exceeding 80 vertical levels) drastically increase the computational cost of each microscale run. Furthermore, the intermediate processing required for the offline one-way nesting (e.g., using `ndown` to force the LES boundaries with high-frequency mesoscale outputs) involves significant I/O operations and massive data handling.

It is precisely the stringent and demanding nature of these multiscale WRF configurations that explains why we have significantly exceeded our initial computational allocation. While our project was originally granted 400,000 SBUs based on standard mesoscale estimations, successfully capturing the exact microscale physics over steep topography, without compromising numerical stability, proved far more computationally expensive than anticipated. To avoid numerical crashes (CFL violations) and to ensure scientifically robust results, we had to implement extremely short time steps and complex topography smoothing techniques. Consequently, the rigorous execution of these essential sensitivity tests has required 2,843,877 SBUs to date.

The execution of these 18 heavy WRF configurations (6 IOPs x 3 experiments), along with their respective mesoscale parent simulations, requires robust High-Performance Computing (HPC) facilities. This systematic evaluation will allow us to define the most accurate WRF configuration for complex mountainous terrain, opening the door to future operational applications and improved parameterizations for katabatic winds, thermal comfort, and air pollutant dispersion in mountain valleys.

While standard mesoscale case-study simulations usually demand moderate computing facilities, the extremely high horizontal and vertical resolutions of the WRF setups proposed here increase the computational demand significantly (approximately [250.000] SBU per full multiscale case study). Furthermore, additional resources are needed for preliminary testing, spin-up phases, and numerical stability adjustments over the steep topography.

2. The interaction between thermally-driven flows and the UHI in Madrid.

In Carbone et al. (2024), we analyzed the impact of urban growth in Madrid between 1970 and 2020 on near-surface air temperature and turbulent fluxes. Our results showed that the expansion of the urban area progressively intensified the UHI effect. Building on these findings and making use of the high-quality observational network available in the Madrid metropolitan area, we aim to conduct a detailed, high-resolution assessment of the dynamic and thermal impact of thermally driven flows (such as mountain, valley, and urban breezes) on the UHI. For the urban case study, we will perform high-resolution simulations over the Madrid metropolitan area, covering a range of representative case studies with different breeze regimes (mountain/valley breeze dominated and weak forcing conditions). The simulations will use the WRF model coupled with the BEP+BEM+COMFORT (Martilli et al., 2024) urban canopy parameterization to characterize the interaction between these flows and the urban canopy, and their modulation of UHI intensity and structure, urban thermal comfort and pollutant dispersion (Román-Cascón et al., 2023).

To successfully cover the executed work and complete the remaining activities of this comprehensive assessment, we estimate it is necessary to have a total framework of [5.000.000] SBU, distributed as follows:

A. Mountain breezes in complex terrain.

- Mesoscale Parent Simulations (Control runs): [25.000] SBU x 6 IOPs = [150.000] SBU
- WRF-LES Sensitivity Experiments: [250.000] SBU x 18 simulations (6 IOPs x 3 setups) = [4.500.000] SBU
- Topography optimization and numerical stability tests: = [350.000] SBU

B. Thermally-driven flows and interaction with the UHI

- High-resolution WRF-BEP+BEM+COMFORT simulations, mesoscale forcing runs and domain-configuration sensitivity tests: [125.000] SBU x 16 simulations = [2,000,000] SBU

Total = ~[7,000,000] SBU

References:

Carbone, J., Sánchez, B., Román-Cascón, C., Martilli, A., Roye, D., Yagüe, C.: Effects of the urban development on the near-surface air temperature and surface energy balance: The case study of Madrid from 1970 to 2020, Urban Climate, 58, 102198, 2024.

Martilli, A., Nazarian, N., Krayenhoff, E. S., Lachapelle, J., Lu, J., Rivas, E., Rodriguez-Sanchez, A., Sanchez, B., and Santiago, J. L.: WRF-Comfort: simulating microscale variability in outdoor heat stress at the city scale with a mesoscale model, Geosci. Model Dev., 17, 5023–5039, 2024.

Román-Cascón, C., Yagüe, C., Ortiz-Corral, P., Serrano, E., Sánchez, B., Sastre, M., ... & Borge, R.: Wind and turbulence relationship with NO2 in an urban environment: a fine-scale observational analysis. Urban Climate, 51, 101663, 2023.