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:	*Integrated Physical Numerical Modelling for Assessing Urban Climate Projections over Southwestern European and Brazilian cities*
Computer Project Account:	spptsoar
Principal Investigator(s):	Pedro MM Soares
Affiliation:	Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa
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)	100 M SBU	388,609 SBU	55 M SBU	39,238,721 SBU
Data storage capacity	(Gbytes)	120 000 GB	0 GB	120 000 GB	18 260 GB

Summary of project objectives (10 lines max)

This project aims to advance urban climate projections for Southwestern European cities and the Brazilian megacities São Paulo and Rio de Janeiro. It addresses the misrepresentation of urban processes in climate models by performing high-resolution (3 km) WRF simulations using advanced urban parameterizations (e.g. BEP-BEM) and detailed land cover datasets. The simulations contribute to the CORDEX Flagship Pilot Study on Urban Environments and Regional Climate Change (URB-RCC). The work covers present, historical, and future periods under different emission scenarios, providing key information on urban climate variables, land-atmosphere interactions, and extremes. The ultimate goal is to support effective climate adaptation and mitigation strategies. The project also seeks to evaluate model sensitivity to urban morphological characteristics, such as building heights and urban fractions. Results will help quantify the urban climate change signal and its implications for public health and infrastructure. Collaboration across modelling teams ensures harmonised protocols and inter-comparability of results.

Summary of problems encountered (10 lines max)

During this reporting period, we faced several challenges that delayed the consumption of SBU resources and the start of production simulations. Some bugs were identified in the modelling framework, notably within the setup of the BEP-BEM urban scheme and Noah-MP land surface model, and extraction of variables, which required debugging and code corrections. Resolving these issues involved close collaboration with FPS-URB-RCC teams and multiple model testing phases. Considerable effort was also dedicated to the harmonisation of simulation protocols for Paris and São Paulo, ensuring consistency across modelling groups. The complexity of agreeing on domain settings, land cover datasets, and urban parameter tables added to the delay, especially for São Paulo.

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

We will proceed with STAGE-1 simulations at 3 km resolution following CORDEX FPS-URB-RCC protocols, focusing on Paris (core city) and São Paulo (our selected satellite city). The historical (2005–2014) and future (2046–2055, 2091–2100) runs will be driven by MPI-ESM1-2-HR under SSP2-4.5 and SSP3-7.0. All simulations will use WRF v4.5.1.7 with BEP-BEM urban canopy scheme, a common namelist.input, and harmonised URBPARM_LCZ.TBL parameters. Pre-processed boundary conditions will optimise transfer and runtime. Domains and vertical resolution match STAGE-1 specs, with sensitivity runs exploring building heights, urban fractions, and A/C effects. Outputs will include 2D urban diagnostics and selected 3D variables, contributing to coordinated FPS-URB-RCC ensembles and intercomparisons.

List of publications/reports from the project with complete references

Hoffmann P, Halenka T, Langendijk GS, Aldama-Campino A, Bastin S, Belda M, Brousse O, Bushenkova A, Campanale A, Carril AF, Casanueva A, Chun KP, Constantinidou K, Machado Crespo N, de Leeuw J, Demuzere M, Diez-Sierra J, Ezber Y, Fenner D, Fernandez J, Fita L, Freisen P, Johannsen F, Katragkou E, Le Roy B, Lemonsu A, Lipson MJ, Ludwig P, Mercogliano P, Michau Y, Milovac J, Muñoz LE, Pavlidis V, Pietikäinen J-P, Rechid D, Ribeiro I, Risanto CB, Schulz J-P, Simon-Moral A, Soares PMM, Thatcher M, Toker E, Top S, Villalba-Pradas A, Wang F, Yuan J, Zazulie N (2026). Opportunities and challenges in representing the interactions between urban areas and regional climate change in CORDEX – lessons learnt from FPS URB-RCC. PLOS Climate, submitted (manuscript nº PCLM-D-26-00177).

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.

This project contributes to the WCRP CORDEX Flagship Pilot Study on Urban Environments and Regional Climate Change (FPS URB-RCC), endorsed in 2021 with the overarching goal of understanding the two-way interactions between urban areas and the regional climate at convection-permitting scales. The FPS brings together a large ensemble of regional climate models (RCMs) coupled with urban parameterization schemes, run under coordinated protocols to ensure intercomparable results and a robust assessment of uncertainties. Our group focused on two cities: Paris, as the FPS designated core city, and São Paulo, as our selected satellite city – with the São Paulo simulation domain also encompassing Rio de Janeiro, enabling the simultaneous study of two major Brazilian megacities within a single nested configuration.

Within the FPS URB-RCC framework, two phases of coordinated experiments have been defined. The first phase (STAGE-0) consisted of short-term test simulations over Paris to evaluate model configurations, urban canopy schemes, and simulation protocol harmonisation across more than 15 participating institutions. The second phase (STAGE-1) extends to 10-year ERA5-driven simulations (2000-2009, with a 1999 spin-up year) at 3 km horizontal resolution using a one-way double-nesting approach. Paris remains the coordinated core city, simulated by most participating groups, while a set of global satellite cities – including São Paulo, Buenos Aires, Johannesburg, Shanghai, Riyadh, and Sydney – is simulated as ensembles to explore urban-regional climate interactions across diverse environmental settings.

Our group actively participated in the FPS URB-RCC STAGE-0 phase for Paris and is contributing for the STAGE-1 satellite city simulations for the São Paulo-Rio de Janeiro domain, using WRF v4.5.1.7. with the Building Effect Parameterization coupled with the Building Energy Model (BEP+BEM) as the urban canopy scheme. BEP+BEM is the most comprehensive urban parameterisation available in WRF: it resolves multi-layer exchanges between the urban canopy and the overlying atmosphere and explicitly represents anthropogenic heat release from air conditioning systems – a particularly relevant process for the hot and humid climate of São Paulo. The WUDAPT-TO-WRF (W2W) protocol was applied to translate Local Climate Zone (LCZ) information into WRF-compatible urban parameter tables (URBPARM_LCZ.TBL), following the standardised procedure adopted across the FPS. Within the FPS, the more complex BEP+BEM configuration coupled with LCZ-based parameters serves as the control (CTRL) setup, executed by most participating institutions, ensuring direct comparability of the São Paulo-Rio de Janeiro runs with the broader coordinated ensemble.

During the STAGE-0 phase, our group contributed with two simulations to the coordinated WRF sub-ensemble over Paris – a control run (CTRL_r5) with the common BEP+BEM and LCZ configuration, and a sensitivity experiment on the planetary boundary layer scheme (PBL1), as part of the multi-institutional effort comprising 30 coordinated simulations across 15 institutions (Fig. 1). This ensemble served as a coordinated testbed to evaluate the capability of the participating RCMs to reproduce key urban climate features over Paris. The analyses, to which our simulations contributed, demonstrated that WRF configurations employing dedicated urban canopy schemes (BEP and BEP+BEM) reproduce the spatio-temporal characteristics of the urban heat island, urban dry island, near-surface wind reduction, and boundary layer height more realistically than simpler bulk approaches, while revealing a considerable spread among ensemble members linked to differences in model configuration and HPC environment. These results are synthesised in a review paper currently under review (Hoffmann et al., 2026, submitted to PLOS Climate). The technical adjustments developed during STAGE-0, in particular the BEP+BEM restart-file and diagnostic fixes, directly informed the production setup adopted for the STAGE-1 São Paulo-Rio de Janeiro runs described below.

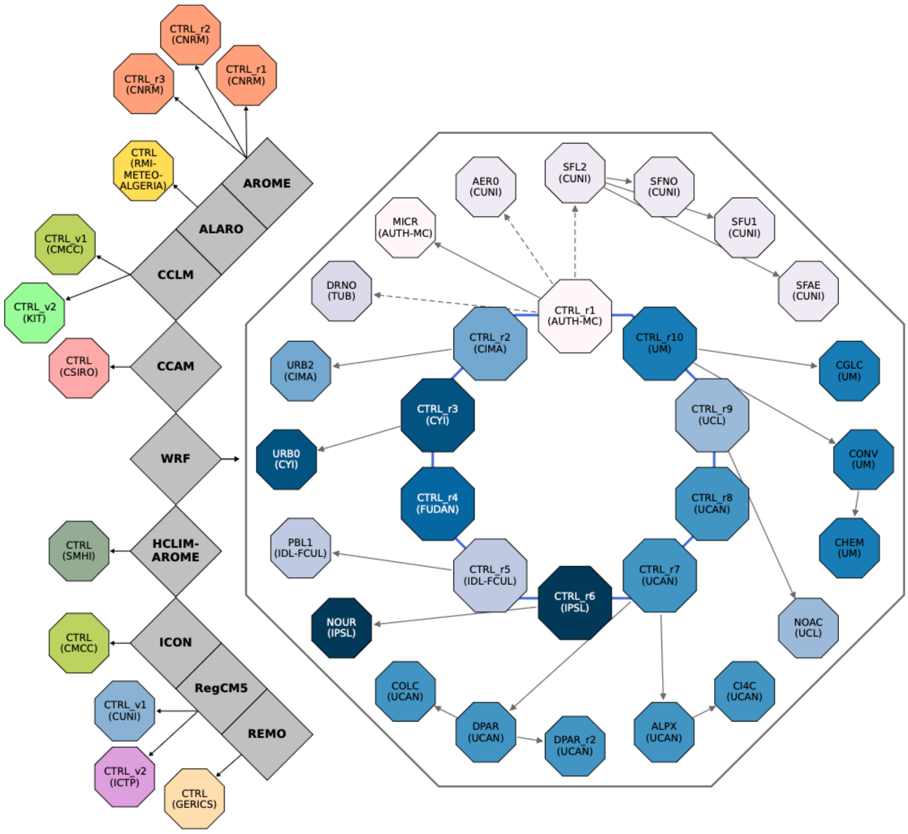


Figure 1 – *Ensemble of STAGE-0 experiment. RCMs are shown as grey diamonds, contributing institutions in different colors and shades, and each octagon represents a particular simulation. The WRF sensitivity sub-ensemble is shown as the large octagon, with experiments in blue shades. Multiple WRF CTRL runs in the centre are connected by a blue line, and arrows link each CTRL run to its corresponding sensitivity runs. Experiments connected with dashed lines indicate cases with no direct CTRL experiment run by the same institution. The extensions in the experiment names indicate different realizations (extension r) and the CTRL settings (extension v) conducted on different HPC systems. Adapted from Hoffmann et al. (2026, submitted to PLOS Climate, PCLM-D-26-00177).*

The simulation domain for the São Paulo-Rio de Janeiro satellite city consists of two one-way nested WRF domains (Fig. 2). The outer domain (D01) covers eastern South America at approximately 12 km horizontal resolution, spanning from aproximately, 66.89°W to 27.09°W and from aproximately 39.52°S to 6.57°S, providing the mesoscale context necessary to capture large-scale circulation features, regional land-sea contrasts, and moisture transport from the Amazon basin and the South Atlantic, all of which strongly modulate the climate of the São Paulo-Rio de Janeiro megacities. The inner domain (D02), at 3 km horizontal resolution, extends from 50.71°W to 41.08°W and from 26.80°S to 18.58°S, centred on the São Paulo metropolitan area and extending eastward to encompass Rio de Janeiro, covering the full urban corridor between the two megacities. This convection-permitting resolution is essential for resolving the complex orographic and coastal influences that characterise the region, in particular the Serra do Mar escarpment - a steep coastal mountain range that separates the São Paulo plateau (~750 m a.s.l.) from the Atlantic coast - and the sea-breeze circulation that strongly modulates urban temperatures in Rio de Janeiro.

The vertical configuration follows the STAGE-1 protocol, with 54 hybrid coordinate levels and the first model level at approximately 35 m above ground. This near-surface resolution is critical for the BEP+BEM scheme, which distributes urban drag, heat, and moisture fluxes across multiple atmospheric levels within the canopy. Lateral boundary conditions were derived from ERA5 reanalysis. The WRF community fork v4.5.1 was used, incorporating all mandatory bug fixes agreed within the FPS URB-RCC WRF working group: the BEP+BEM restart file size fix (via reduction of nbui_max and urban vertical resolution), the Noah-MP T2/U10 diagnostic correction for LCZ-classified urban points, and the SST interpolation fix in METGRID.TBL.ARW.

Land cover for South America presents a specific challenge within the STAGE-1 framework, as the LANDMATE_PFT dataset – the FPS standard for European domains – is not available outside Europe. For the São Paulo-Rio de Janeiro domain, the MODIS-based land use dataset was used as the background land cover, with urban areas reclassified using LCZ information derived from the WUDAPT global database and processed through the W2W tool. Urban canopy parameters in URBPARM_LCZ.TBL were adapted to the subtropical context of the domain, following guidance from sensitivity analyses conducted within the FPS for analogous South American cities (e.g. Buenos Aires), which identified building height distributions and air conditioning parameters as the most impactful variables on simulated near-surface temperatures.

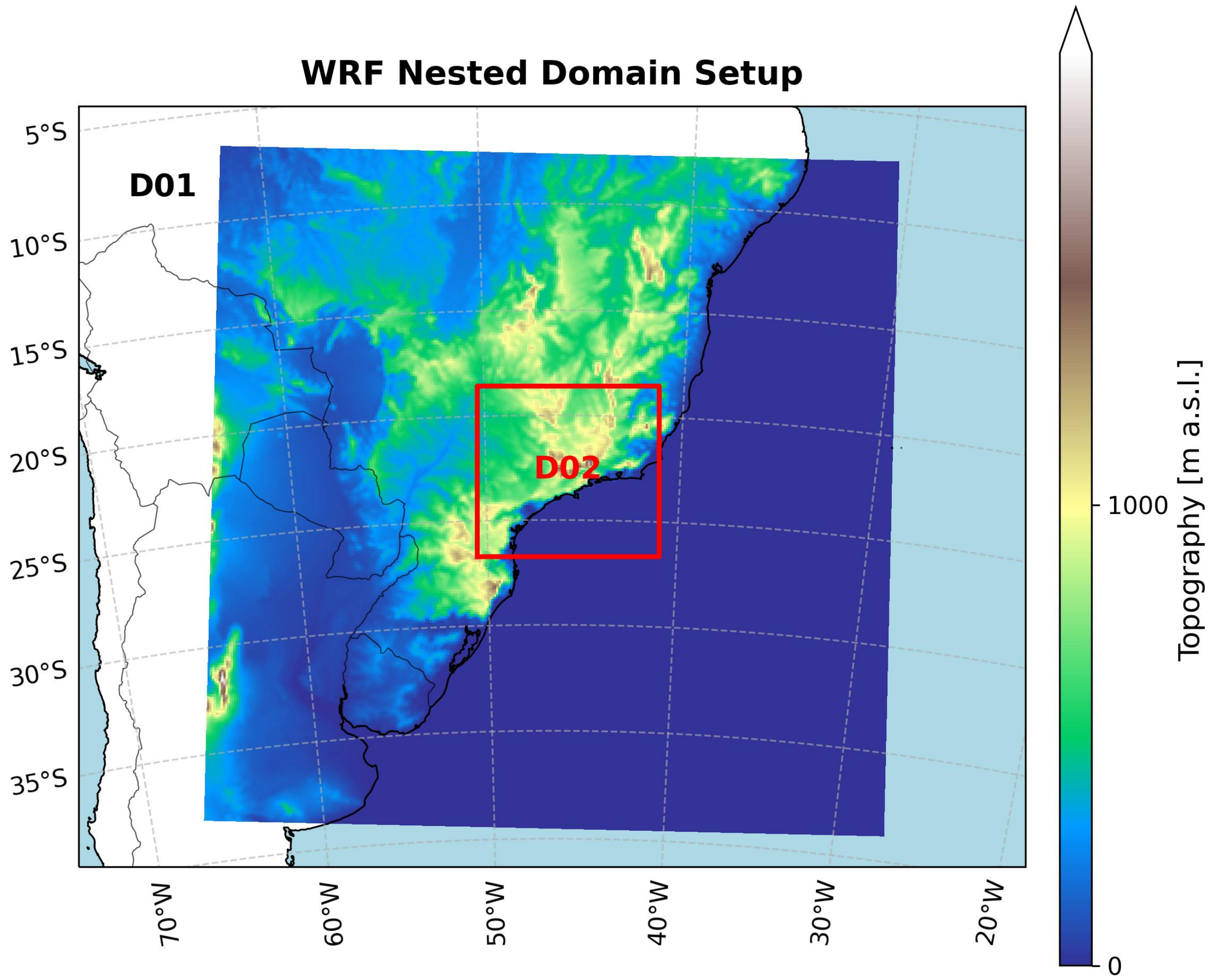


Figure 2 *– WRF nested domain configuration for the São Paulo-Rio de Janeiro city simulations. The outer domain (D01, ~12 km resolution) spans from 66.89°W to 27.09°W and from 39.52°S to 6.57°S, covering eastern South America. The inner domain (D02, ~3 km resolution, red box) extends from 50.71°W to 41.08°W and from 26.80°S to 18.58°S, encompassing the São Paulo–Rio de Janeiro megacies. Topography (m a.s.l.) is shown for D01, illustrating the complex orographic features of the region, including the elevated interior plateau, the Serra do Mar coastal escarpment, and the low-lying Atlantic coastal strip.*

The simulations for the D01 and D02 domains, encompassing eastern South America and the São Paulo and Rio de Janeiro megacities respectively, have been completed, covering the full present-day period 2000-2009 (with 1999 as spin-up year), forced by ERA5 reanalysis. The simulations were performed on the ECMWF HPC facility, consuming approximately 39 million SBU and 18 260 GB of storage during the current reporting year. The two nested domains were run with hourly output, providing the temporal resolution required to resolve the full diurnal cycle of near-surface variables, essential for characterising the urban climate processes such as the urban heat island effect (UHI) and its diurnal evolution. The high temporal and spatial resolution of these simulations is particularly relevant for the study of urban climate, where the most pronounced urban signals, such as the nocturnal amplification of near-surface temperatures and the associated heat stress, emerge from the interplay between the diurnal cycle of incoming radiation, the thermal storage capacity of urban materials, and anthropogenic heat release. The use of the BEP+BEM urban canopy scheme, which explicitly represents the multi-layer exchange of heat, moisture, and momentum between buildings and the atmosphere, together with the energy demand from air conditioning, enables these processes to be captured in a physically consistent manner. This is especially important for São Paulo and Rio de Janeiro, where the combination of a hot and humid subtropical climate, dense urban fabric, and complex coastal orography makes urban climate effects both strong and highly heterogeneous in space and time – characteristics that remain underrepresented in coarser regional climate datasets over South America.

The WRF model produces a comprehensive raw output of 246 variables per history file, spanning the atmospheric dynamic and thermodynamic state, microphysics, radiation, land-surface, and urban-canopy fields. From this raw output, a priority subset is being post-processed into the standard CORDEX-CMIP6 near-surface and surface variables, including 2-metre air temperature (tas), surface temperature (ts), specific and relative humidity (huss, hurs), latent and sensible heat fluxes (hfls, hfss), surface evaporation (evspsbl), surface and sea-level pressure (ps, psl), near-surface wind speed and components (sfcWind, uas, vas), surface roughness length (z0), planetary boundary layer height (zmla), and aerosol optical depth at 550 nm (od550aer). These were complemented by the BEP+BEM urban diagnostic fields, enabling the analysis of urban-canopy processes specific to the two megacities.

The extraction and standardisation of the output variables into the CORDEX-CMIP6 CF-compliant format, following the FPS URB-RCC variable protocol, is currently ongoing, after which the full dataset will be made available for the coordinated ensemble analysis. A preliminary analysis of the completed dataset has focused on the 2-metre air temperature (T2m) field, which provides a direct diagnostic of the near-surface thermal structure. The following diagnostics present the DJF (December-January-February, austral summer) mean T2m fields, computed over the 2000-2009 period, at four representative times of day: 06 UTC (night), 12 UTC (morning), 16 UTC (afternoon peak), and 20 UTC (evening). Together, these four time steps capture the full diurnal evolution of the temperature field across both the outer (D01, ~12 km) and inner (D02, ~3 km) domains.

Figure 3 presents the DJF mean T2m fields for the outer domain (D01, ~12 km resolution), providing the broad regional thermodynamic context of the simulation. At 06 UTC (Fig. 3a), the continental interior retains elevated near-surface temperatures, in contrast to the cooler, ocean-modulated Atlantic coastal strip and the southern portion of the domain. As the day progresses, the continental warming intensifies, reaching its maximum at 16 UTC (Fig. 3c), with mean near-surface temperatures of the order of 30-32 °C over the interior, while the coastal zone remains comparatively mild under the influence of the adjacent ocean. By 20 UTC (Fig. 3d), the evening cooling is markedly heterogeneous, with the interior retaining heat longer than the elevated and coastal regions. Across all time steps, the coastal mountain ranges and the elevated interior plateau are clearly resolved, producing pronounced near-surface temperature gradients at the ~12 km scale.

Figure 4 presents the equivalent DJF mean T2m fields for the inner domain (D02, ~3 km resolution), focused on the São Paulo and Rio de Janeiro megacities. At this convection-permitting resolution, the spatial structure of the near-surface temperature field is substantially more detailed than in D01, resolving the contrasts between the elevated interior, the coastal areas, and the urban regions of the two megacities. The fields display a marked diurnal cycle: during the afternoon (16 UTC, Fig. 4c), near-surface temperatures reach their maximum across the domain, whereas at night and early morning (06 UTC, Fig. 4a) the temperature field is considerably cooler and more spatially heterogeneous. The finer 3 km resolution clearly resolves the imprint of the Serra do Mar escarpment, visible as a sharp thermal transition between the cooler elevated plateau and the warmer low-lying Atlantic coast. Notably, at 06 UTC the urban heat island of São Paulo is discernible as a localised warm anomaly relative to its cooler surroundings (Fig. 4a), confirming the capability of the BEP+BEM configuration to capture the nocturnal urban warming signal at this resolution.

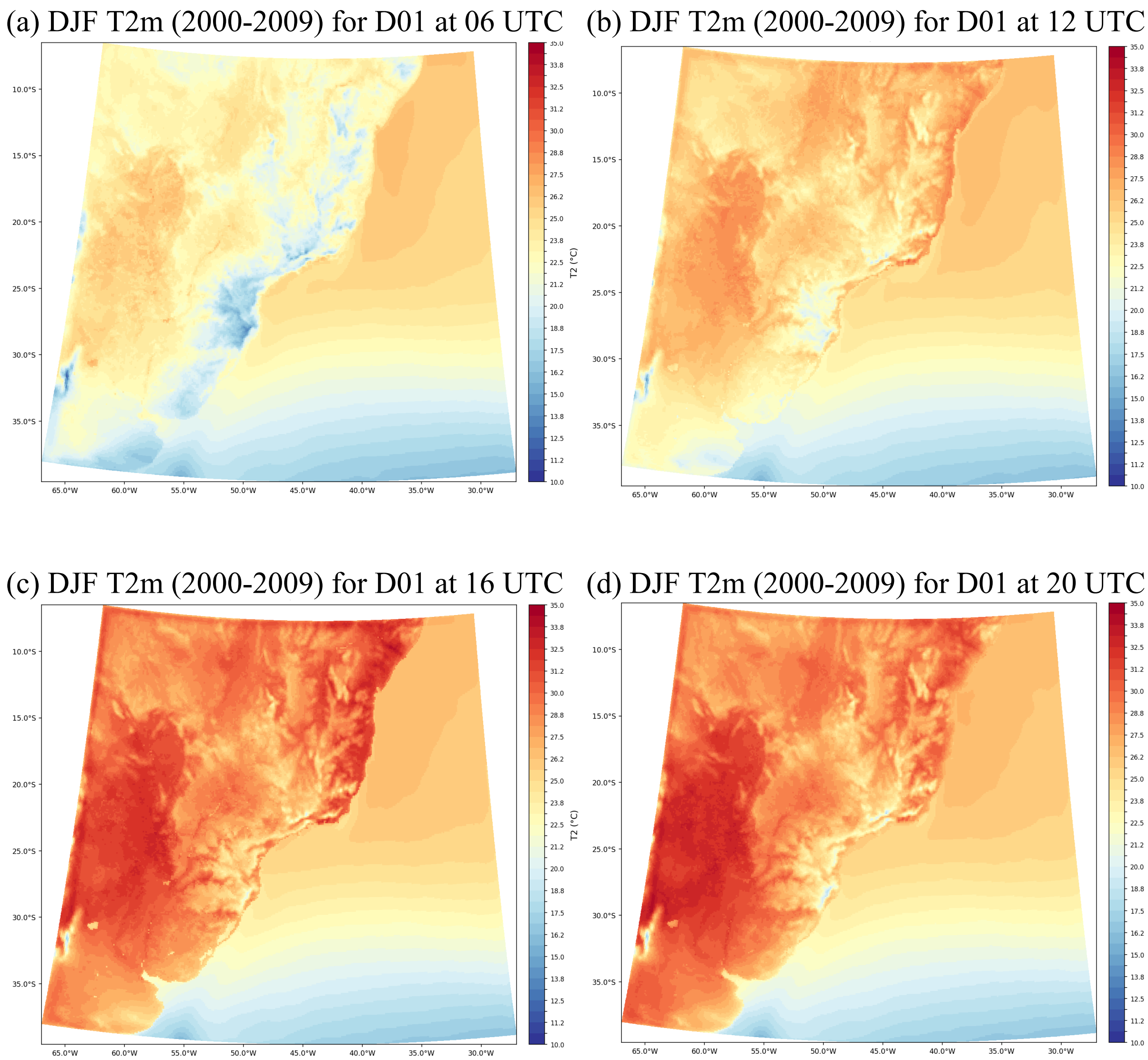
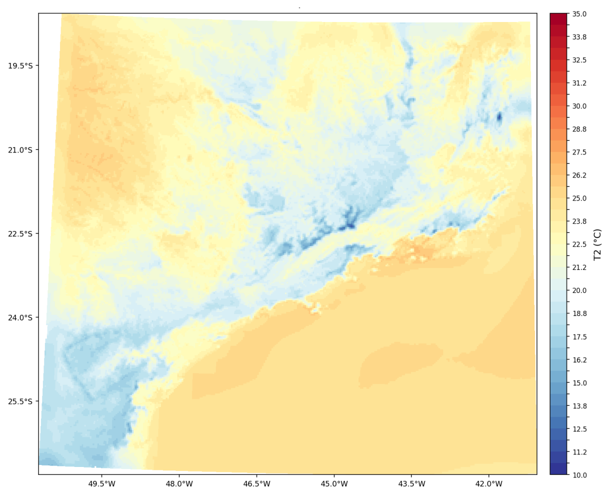
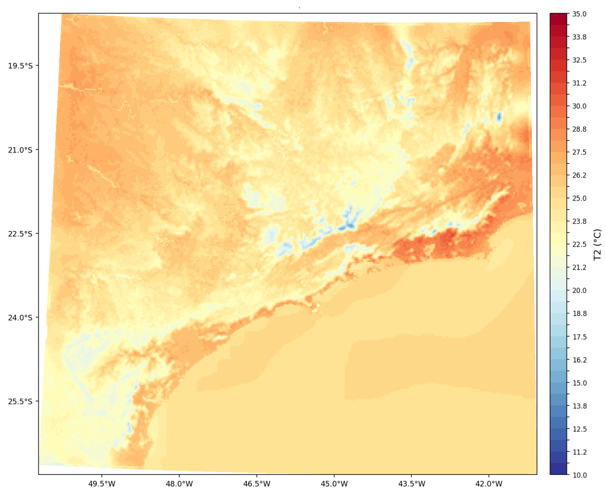


Figure 3 *– DJF (December–January–February, austral summer) mean 2-metre air temperature (T2m, °C) from the WRF STAGE-1 simulation for the outer domain D01 (~12 km resolution, spanning 66.89°W–27.09°W and 39.52°S–6.57°S), averaged over the period 2000-2009. Panels show four representative times of day: (a) 06 UTC (night/early morning); (b) 12 UTC (late morning); (c) 16 UTC (afternoon peak); and (d) 20 UTC (evening cooling). The maps illustrate the broad regional thermodynamic context of the simulation, with the marked diurnal evolution of near-surface temperature over the continental interior contrasting with the comparatively stable, ocean-moderated coastal and oceanic areas.*

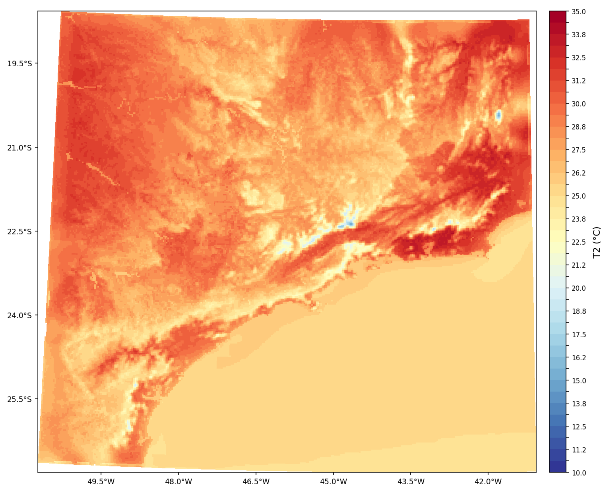
(a) DJF T2m (2000-2009) for D02 at 06 UTC



(b) DJF T2m (2000-2009) for D02 at 12 UTC



(c) DJF T2m (2000-2009) for D02 at 16 UTC



(d) DJF T2m (2000-2009) for D02 at 20 UTC

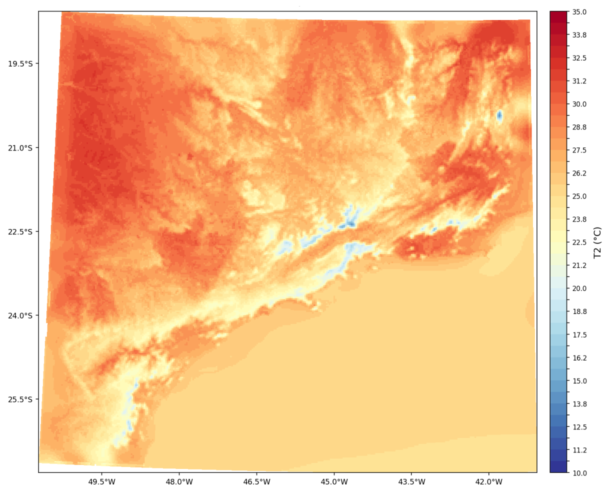


***Figure 4** – DJF (December–January–February, austral summer) mean 2-metre air temperature (T2m, °C) from the WRF STAGE-1 simulation for the inner domain D02 (~3 km resolution, spanning 50.71°W–41.08°W and 26.80°S–18.58°S), averaged over the period 2000-2009. Panels show four representative times of day: (a) 06 UTC (night/early morning); (b) 12 UTC (late morning); (c) 16 UTC (afternoon peak); and (d) 20 UTC (evening cooling). The maps illustrate the broad regional thermodynamic context of the simulation, with the marked diurnal evolution of near-surface temperature over the continental interior contrasting with the comparatively stable, ocean-moderated coastal and oceanic areas.*

The forthcoming months will be devoted to analyze the present-day simulation (2000-2009), inter-compare it with the other team runs, and start the historical and future simulations.