

Towards a comprehensive strategy on convection permitting regional climate modelling (CPRCM) in CORDEX

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2026-05-05

DOI: [10.5281/zenodo.20282519](https://doi.org/10.5281/zenodo.20282519)

1. Introduction

Despite the impressive advances in convection permitting regional climate modelling (CPRCM, here understood to encompass grid spacings of ~1-4 km) over the last decade plus, there remain several knowledge gaps surrounding their accuracy, fidelity and fitness-for-purpose (e.g. as the basis for downstream climate services and/or adaptation decision-making or as training datasets for machine learning (ML) algorithms, see section 5d). There is a need for coordinated research and development strategy across CORDEX domains. This includes: (i) developing CPRCM protocols for long climate simulations, including specific configurations that account for relevant regional and local effects; (ii) recommendations for standard evaluation data and practices appropriate for CPRCM simulations; (iii) improved understanding of processes, mechanisms and variability of regional to local climate; (iv) building and maintaining strong connections and collaborations with the global convection-permitting modelling and numerical weather forecasting community. The aim of this TF document is to identify strategic needs, knowledge and/or implementation gaps, links to other CORDEX activities (including other Task Forces) and propose an action plan to develop

and implement a coordinated CPRCM strategy with the CORDEX framework. Further, we aim to deliver such a strategy while maintaining and strengthening the CORDEX commitment to inclusivity, openness, and collaboration.

2. Current landscape of convection permitting regional modelling in CORDEX

CORDEX established Flagship Pilot Studies (FPS) in 2013 to address several emerging scientific challenges that could not be addressed easily within the standard CORDEX framework and protocol. FPS were first and foremost scientifically motivated and were never intended for production of future projections. Moving towards higher resolutions including convection permitting scales was among these challenges. Several FPS focus on CPRCMs as tools to better understand processes driving local to regional scale responses to climate change. Their domains can be seen in **Figure 1**. One will note that they exhibit diverse domains (some large, some small; some wholly within existing CORDEX domains and some that cross CORDEX domain boundaries) and regions with widely varying climates. And we note that not all CPRCM efforts are done under the auspices of CORDEX. An overview of past, present, future CPRCM activity can be found in a living [CPRCM Collection Spreadsheet](#) (additions are welcome). Coordination between these activities is not strong. Rather they learn from each other in an ad-hoc manner by sharing experiences, experiment protocols and occasionally software and analysis tools. While organic and collaborative, this is not an optimal strategy in the long run as it may lead to outcomes that are not comparable through time (e.g., covering different time slices or global warming levels), across CORDEX domains or common meteorological features (e.g., mesoscale convective systems). Stronger linking between CPRCM activities is advised especially in the context of CORDEX's upcoming CMIP7 strategy.

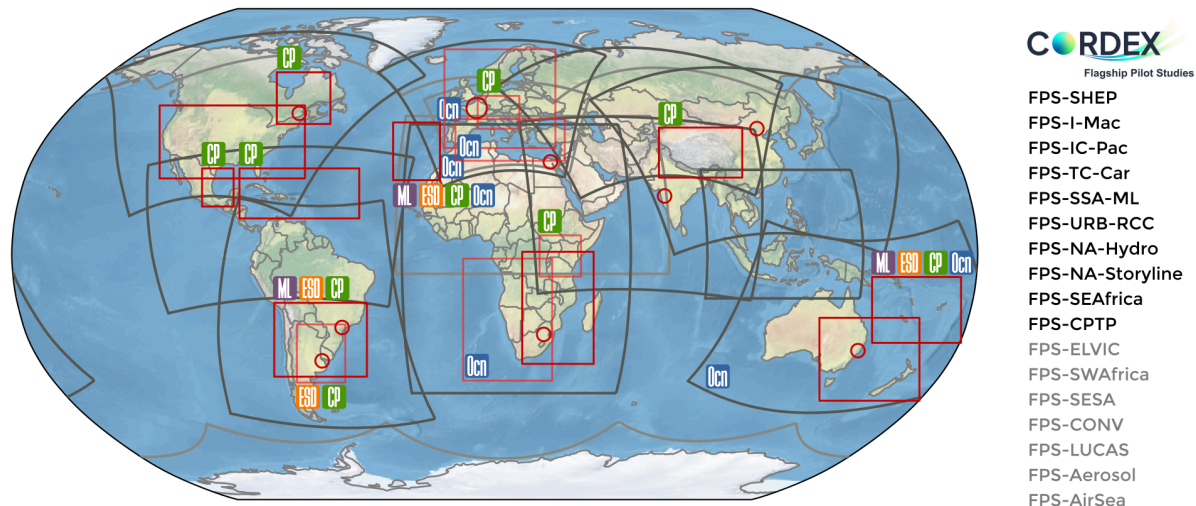


Figure 1. Current (black) and past (grey) Flagship Pilot Studies (list at right) and their domains of interest (map). Domains with a CPRCM focus have a green “CP” indicator above them. Black domain boundaries on the map denote the CORDEX domains.

3. Towards a coordinated strategy

3a. Configuration, domains and experiment design considerations

Model configuration considerations

As RCMs move toward km-scale, several physical parameterisation schemes and surface modules become particularly challenging and warrant focused community attention, including land surface schemes, microphysics, planetary boundary layer (PBL) formulations, agriculture and irrigation, vegetation, urban canopy representation, and lake models (among others).

One of the most pressing issues concerns the treatment of shallow convection. While most CPRCMs disable deep convection parameterisation on the assumption that it is explicitly resolved, the handling of shallow convection varies considerably across modelling groups. The optimal approach is likely a scale-aware convective parameterisation, in which convection that is resolved at the grid scale is represented explicitly, while the parameterisation scheme assumes increasing responsibility as convective motions approach and fall below grid scale. Research in this direction is ongoing; for example, the Met Office is developing the scale-aware CoMorph scheme. Practical experience from other centres supports this direction: NCAR evaluated several

scale-aware convection schemes in both WRF and MPAS, ultimately converging on the scale-aware Tiedtke scheme on the basis of improved model performance. Within the ICON framework, the classical Tiedtke scheme is employed, and DWD retains the shallow convection component of that scheme in kilometre-scale configurations.

Soil moisture spin-up presents a further challenge at convection-permitting resolution, typically requiring a minimum of one year or longer of spin-up time to reach an equilibrated state — a non-trivial computational investment that must be factored into experiment design.

The specification of static surface fields, particularly topography, demands careful consideration. Realistic, high-resolution topographic data are essential because terrain-driven circulations exert a dominant influence on local climate — not only in mountainous regions and their foothills but also in coastal and island environments characterised by complex land–sea interfaces. Topographic resolution directly affects the simulated diurnal cycle and spatial distribution of orographic precipitation. In the context of global storm resolving/km-scale models, the computational cost of including sufficiently high-resolution topography may be prohibitive; in such cases, alternative strategies should be adopted, such as an optimised sub-grid turbulent-orographic form-drag (TOFD) parameterisation.

Beyond topography, the accuracy of land–atmosphere coupling is central to correctly reproducing PBL structure and local climate. This requires that land-use and land-cover classifications, soil type data, and urban canopy parameters — including building height, population density, and anthropogenic heat fluxes — be specified at CPM-compatible resolution. Critically, these datasets are not static: land use evolves over time as cities expand and agricultural practices change, and model configurations must account for this temporal variability. High-resolution satellite observations offer a practical source for such geospatial data. Where datasets are held by individual countries or municipalities, the establishment of robust data-sharing frameworks would represent a meaningful step toward advancing high-resolution regional climate modelling as a coordinated international enterprise.

Finally, the choice of initialisation strategy — how and when model integrations are started, and from what initial conditions — constitutes an important element of experiment design that requires standardisation and community agreement.

Domain considerations

As with experiment design protocols (see below), setting “required” domain sizes, locations and nesting strategies for CPRCM simulations is challenging. While the specifics of CPRCM domains should remain the purview of the domain communities themselves, the TF does believe that some recommendations can be made that can support stronger coordination and improved scientific outcomes. We list a few of these below:

- Domain size and location: we recommend moving towards larger domains i.e. sub-continental to continental, within existing CORDEX domains and keep sub-division to a minimum; further, consideration should be paid to ML training needs in this context.
 - Nesting strategies can be varied but a common minimum domain should be defined (it is important to discuss trade-offs re: resolution jumps; options with global VR approaches i.e., MPAS, ICON, VR-CAM).
 - It is recommended to discard the rim of the inner domain due to boundary artefacts and the larger the resolution jump the larger the rim region for removal. Related to this it is important that the region of interest is not too close to the lateral boundaries.
 - The need for requisite LBC from CORDEX domain simulations or real-time nested modeling; Coordinated LBCs will improve intercomparability but are more challenging to organize; One option could be a CORDEX data request for CPRCM downscaling coordinated through the SAT.
 - There is a need for coordination in regions with limited number of modelling groups and/or resource limitations
 - Robust evaluation of the driving GCMs including minimum resolution, model top height, vertical levels, in addition to process-based performance metrics.
- Although, not always the case the general consensus is that downscaling the highest resolution GCM available is advised (for both parameterized and CPRCM scale (see e.g., Sobolowski et al., 2025; Moetsim et al., 2026 (in-review)))

Experiment design strategies

There are several approaches to experiment design that FPS groups have taken and others that may be considered. Approaches include: event-based downscaling, long - transient simulations, temporal scenario-based time slices, GWL time slices, pseudo-global warming, etc. Groups have used single model ensemble approaches, multi-model ensemble approaches, as well as single model process-based approaches.

Many considerations go into experiment design such as scientific questions, aims, resources, feasibility, etc. It is a challenge, and perhaps not even desirable, to enforce a one-size-fits-all CPRCM experiment design across all CORDEX domains. However, the TF believes there are opportunities for some coordination on CPRCM experiment design. It is recommended that the experiment protocol be consistent at least in the driving GCMs and scenarios. For example, it could be a strategy that all CPRCM experiments follow the overarching CORDEX scenario recommendations and agree to follow CORDEX-CORE driving GCM selections (to maintain some x-domain consistency). It is most likely not feasible that CORDEX-CORE or individual domain simulations provide CPRCM-ready LBCs for all runs. Therefore the recommendation is that CORDEX-CORE (CMIP6/7) provide the overarching protocol with respect to driving GCMs and scenarios, CPRCM then nest their simulations using the normal domain specifications at an intermediate nest (though other approaches such as variable mesh and stretched grids would also be acceptable). Another option would be to make a dedicated data request in CORDEX for CPRCM simulations. Insofar as it is possible, static fields and input fields should be consistent (Land Use Land Cover Change (LULCC), Soil moisture, topography, aerosols, etc.). Beyond that level of coordination we believe CPRCM experiment protocols will need to be customized to fit specific scientific aims.

3b. Additional Model Complexity

Representation of urban areas and their evolution

Over urban areas, increasing model resolution yields the greatest benefits when paired with improved representation and parameterization of the urban surface. Urban environments significantly influence regional turbulence, thermodynamic properties, and moisture fluxes (Lemonsu et al., 2023; Lemonsu & Masson, 2002; Oke et al., 2017). Enhanced parameterization of urban processes improves the depiction of nighttime urban heat islands (UHI) and feedbacks to larger-scale processes (Daniel et al., 2019; Lemonsu et al., 2023). Dedicated urban schemes outperform simple surface slab representations in capturing these impacts (Bhati & Mohan, 2016; Daniel et al., 2019; Kitagawa et al., 2022), though they require greater computational resources and detailed city-specific data. Multi-layer urban canopy models typically achieve higher accuracy than single-layer models but at higher computational costs, while single-layer models can perform well with appropriate parameter tuning, though their performance is sensitive to the PBL scheme used—necessitating sensitivity analyses. The choice of

urban scheme thus depends on context, region, and resource availability; for instance, Ao et al., 2024 suggest single-layer models suffice for studying urban temperature risks, whereas multi-layer models are preferable for wind engineering or disaster studies. The accuracy of simulations also depends on the quality of the land use/land cover (LULC) dataset used (Bhati & Mohan, 2016). While most regional climate models currently employ static LULC data, the LUH2 dataset—developed for CMIP6—offers integrated past, present, and future land cover information across eight scenarios, though its coarse 0.25° resolution necessitates downscaling for convection-permitting model (CPM) use, a process that can be supported by tools such as the Land Use Translator for the LUCAS dataset (Hoffmann et al., 2022). As convection-permitting climate models (CPCMs) now reach kilometer-scale resolutions (1–4 km), they are increasingly capable of capturing city–climate interactions over decadal to centennial timescales (Langendijk et al., 2024). High-quality, city-specific climate information is critical for urban decision-makers seeking to enhance resilience to climate change impacts (Baklanov et al., 2018). The WCRP CORDEX Flagship Pilot Study “URBan environments and Regional Climate Change (FPS URB-RCC)” addresses these challenges through coordinated RCM ensemble experiments with refined urban representations, focusing on urban–rural contrasts, UHI trends, and city–climate interactions under changing conditions. Intercomparisons between kilometer-scale RCMs and their urban schemes enhance understanding of model behavior, confidence, and uncertainty. To foster climate-resilient cities, CPCMs must represent evolving urban environments using dynamic land cover datasets, advanced urban parameterizations, and—where possible—coupling with chemical transport models to assess air quality effects on urban temperature and moisture under climate change.

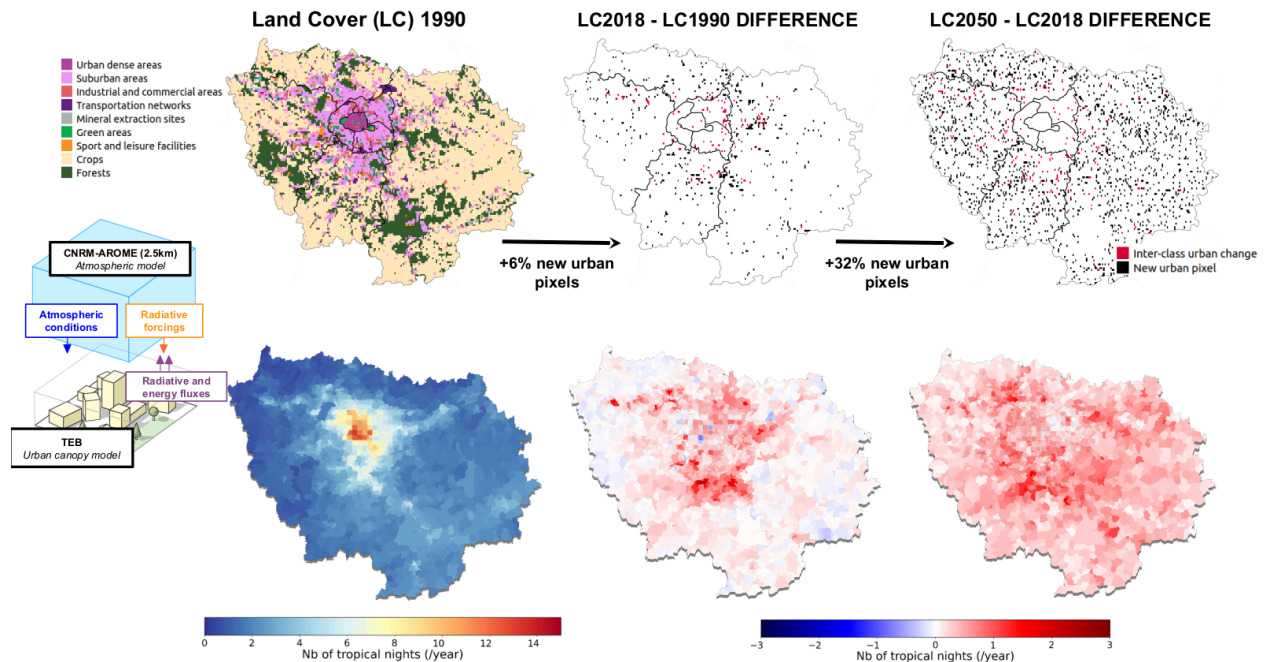


Figure 2. Tropical nights (daily minimum temperature exceeding 20°C) under different urban land cover maps prescribed to the CPRCM CNRM-AROME and aggregated on the French census scale over the Paris region (adapted from Corneille et al. in review). Top row: three different Land Cover (LC) maps (1 km): LC1990 (ECOCLIMAP-I from 1990 satellite data, prescribed by default in CNRM-AROME), difference between LC2018 (actualized with 2018 satellite data) and LC1990, difference between LC2050 (based on a prospective urban sprawl scenario in 2050) and LC2018. Bottom row: the tropical night indicator simulated by the CPRCM CNRM-AROME (2.5 km) coupled with an urban canopy model in present climate (2000-2022) under LC1990 and the differences depending on the land cover map used, showing an increase in the number of tropical nights according to an increase in the number of urban pixels.

Interactive hydrology - groundwater, lateral flow, root zone soil moisture

With a higher spatial resolution of the atmospheric model grids at CPCM resolution, the representation of land surface (such as topography or land cover), and subsurface (soil types, texture, or hydrofacies distributions) properties becomes more detailed and heterogeneous. With this, stronger surface gradients evolve in the models, i.e., river valleys become steeper, the complexity of the river network changes, there is an increase in topographic variance in the catchments. On a landscape level, this leads to strong (soil) moisture gradients between convergence (e.g., valleys) and divergence (e.g., ridges) zones. The related hydrologic processes, such as overland flow, infiltration, exfiltration, subsurface interflow, groundwater flow, need to be explicitly represented, to allow for a realistic vertical and lateral distribution and redistribution of

water at the land surface and in the soil, i.e., the subsurface, including (shallow) groundwater (Polcher et al., 2023). This is complicated by the fact that the very different representation of rainfall in CPRCMs models (i.e. its more realistic intense/intermittent nature) poses real challenges for land-surface schemes that have been developed for coarser resolution models. Too much runoff is a common bias, requiring land-surface scheme developments to alleviate. Subsurface water, soil moisture and groundwater, affects the L-A coupling, e.g., through soil moisture-temperature (Keune et al., 2016) or soil moisture-precipitation feedbacks. Mesoscale dry-to-wet soil gradients enhance convection in many parts of the world (Taylor et al., 2013). In fact, the entire land water balance and the hydrometeorology is affected (Barlage et al., 2021). A physically-based representation of transport processes and feedbacks across scales and sub-systems allows for a closed terrestrial water cycle; long-term drought related groundwater memory effects can be considered (Hartick et al., 2021). The feedbacks in the groundwater-land surface-atmosphere system are scale dependent. Thus the role of flowing water in CPRCMs becomes more important. CPRCM resolution requires 3D hydrodynamics in the subsurface and overland flow calculation at the land surface (Barlage et al., 2021). With the evolution of land surface models, schemes exist to expand the traditionally purely vertical subsurface water flow to lateral subsurface flow processes that account for soil column and groundwater dynamics (Barlage et al., 2021; Devanand et al., 2025; Schlemmer et al., 2018). In integrated hydrological models, where subsurface and surface hydrodynamics are linked, hill slope processes may also be explicitly resolved (Kuffour et al., 2020).

Evolving aerosols with an ambition to interactivity

Aerosols play an important role in the climate system, interacting with radiation and clouds through various complex direct and indirect processes. Indeed, aerosols have strong impacts on regional climates, potentially modifying the radiative budget, surface temperature, past climate trends and air-sea fluxes (Persad et al., 2023). The consideration of aerosols in the latest CORDEX-CMIP6 protocol has thus been emphasised, with as a minimum requirement a static aerosol dataset, but strongly encouraged an up-to-date regional or global aerosol datasets with realistic variability in time (monthly variation and trend) and space. The consistency of aerosol forcing between the CP-RCM and its driving models must also be promoted. There is no doubt that these guidelines for aerosols must also apply to CP-RCMs. Moreover, the interactions between aerosols, radiation, atmospheric thermodynamic profiles, convective activity and clouds are highly complex and high-resolution regional climate models that explicitly resolve deep convection represent very powerful tools for tackling these scientific questions on a climate scale. Next step in the aerosol forcing is therefore to implement in the CP-RCM an interactive and prognostic aerosol scheme (as done for example in the ALADIN (Nabat et al., 2020) or RegCM (Solmon et al., 2006) RCMs) with the explicit representation of the main natural and anthropogenic aerosol types (sulfate, organic matter, black carbon, dust, sea salt, nitrates and

ammonium), their different processes (emission, transport, deposition) and their interactions with radiation and clouds.

Sea ice

In polar regions, sea ice plays an important role in the exchange of momentum, radiative, and moisture fluxes between the atmosphere and the surface below (Vihma, 2014). At the kilometer scales, the performance of regional climate models depend on the representation of critical sea ice features such as the Marginal Ice Zone (MIZ), major leads as well as polynyas, and of sea ice properties such as sea ice fraction, albedo, ice thickness, snow depth. These features and properties are also influenced by the atmosphere, which necessitates the use of sea ice models that can at least represent the thermodynamic processes but preferably include the dynamical processes that underlie the sea ice response to changes in atmospheric conditions (Zhao et al., 2024).

Glaciers and snow processes

Snow plays a crucial role in the climate of the polar regions and high mountainous regions through its albedo and thermal properties. Processes pertaining to snow span the many components of the climate system, for example, microphysical processes in the atmosphere and snow interception by vegetation canopy (Mooney et al., 2022). In these regions, convection permitting scales offer an important advance for the representation of snow processes in the atmosphere, most notably for the physically based approach it uses to separate precipitation into liquid and ice types. This contrasts with the non CP scales, where regional climate models separate precipitation into rain and snow using a temperature-based approach due to their need to parameterise convective processes (Mooney et al., 2020). While this is a major advance for the representation of snow-related processes in the atmosphere, it is recommended that microphysics schemes include more than one ice micrometeor e.g. snow, graupel and hail. At the surface, snow physics is overly simplified and future model developments need to evolve to multi-layer physically based snowpacks (Krinner et al., 2018) and include improved representation of snow albedo (dependency on ageing, grain size, impurities (He et al., 2018), snow-vegetation-atmosphere interactions (Mooney et al., 2022), and the redistribution of snow (Vionnet et al., 2012).

Land-use land-cover change and water use scenarios

Land use and land cover (LULC), including the vegetation type and function are crucial factors of climate change and therefore need to be properly represented in climate models to be able to assimilate and understand atmospheric processes and feedback effects on different scales. Anthropogenic modifications are the most important drivers of change: indeed, deforestation and reforestation and expansion of urban and cropland areas affect biogeophysical (e.g. albedo, roughness, evapotranspiration, runoff) and biogeochemical (e.g. carbon emissions and sinks) surface properties and processes (Davin et al., 2020). In addition to LULC changes, land management practices are being assessed regarding the influence of related land surface modifications on regional climate and also the potential of land management practices regarding climate change adaptation and mitigation efforts. In this perspective, the km-scale representation enabled by CPCMs is recommended to integrate the land use and cover dynamics, to account for the effects of the local anthropogenic modifications and practices on climate change. In this perspective, the LUCAS (Land Use and Climate Across Scales) initiative focuses on coordinated regional climate model experiments for Europe including land use change forcing. It is under the umbrella of the WCRP-CORDEX as a FPS, aiming to identify robust biophysical impacts of land use changes on climate across regional to local spatial scales and at various time scales from extreme events to multi-decadal trends. With the increasing resolution of CPCMs, the role of changing vegetation and practices (as irrigation) in the altered land-atmosphere interaction processes could be locally considered and resolved (Asmus et al., 2023).

With respect to global and regional water cycle processes and water budgets, anthropogenic, or human, water use is an important driver. Anthropogenic water use (AWU) through groundwater pumping and surface water usage for domestic, industrial and agricultural use (mainly for irrigation) is of high socioeconomic relevance and central to water resources management, water safety and security concerns, and part of adaptation and mitigation measures. For example about 30% of global usage relies on groundwater and about 30% of the global annual recharge is extracted (Aeschbach-Hertig & Gleeson, 2012). In concert with the hydrologic process representation in CPCMs AWU by abstraction and irrigation alters the natural water cycle and impacts land -atmosphere coupling, subsurface-land surface-atmosphere feedbacks, e.g., through an increased or decreased surface latent heat flux. This can also impact hydrometeorological extremes, such as heatwaves, droughts, and heavy precipitation events. The effects may be local to regional scale including remote impacts, e.g., through atmospheric moisture transport (Keune et al., 2018). By considering AWU in CPCMs, human and natural systems can be linked through the water budgets, making the simulations more relevant for policy and adaptation planning.

Different AWU implementations into climate models exist (Valmassoi & Keller, 2022). At CP resolution, AWU can be integrated to reflect spatial heterogeneity, e.g., of irrigation, and hence matter more and may help to improve the realism of simulated processes and the reliability of projections for water and climate impacts.

Oceans (see TF on Regional ocean modeling and climate projections)

Ocean coupling is critically important for a number of key phenomena e.g. tropical cyclones, small islands, mesoscale convective systems, and more. There are a number of options for ocean representation - 1D slab ocean or full 3D ocean. For the latter, key issues are ocean boundary conditions and ocean spin-up. At UKMO regional coupled CPM includes tides and waves, with tidal mixing important for ocean stratification and surface temperature. Linking to the CORDEX joint working group on regional ocean modelling and coupling will be critical for development of a comprehensive CPRCM strategy as it might not be necessary for all km-scale domains.

Lakes

Explicitly resolving natural and artificial lakes has a large impact on regional climate in CP simulations. Lakes act as local heat and moisture sources that affect surface atmosphere interactions and result in strong thermal, moisture, and momentum gradients to the surrounding land areas and hence surface boundary conditions. Considering lakes affects the local water and energy cycles, boundary layer evolution, convective processes, e.g., the timing and strength of convection, cloud formation, precipitation spatial patterns as well as timing and intensity; through their thermal inertia they dampen surface temperatures and air temperature diurnal cycles; and lakes generate lake breezes and the lake effect. CP simulations can spatially resolve and delineate lakes, especially in regions with a dense (small) lake coverage or lakes with complex lake–land climatic contrasts; with large lakes also bathymetry can be represented. Rather than prescribing lake surface temperatures, an explicit (two-way coupled) lake representation through simplified bulk schemes or slab models, 1D lake formulations, or 3D hydrodynamic lake models for large lakes, which also allow horizontal dynamics, leads to more realistic energy and moisture fluxes and hence the simulation of local hydroclimate features, e.g., during warm to cold season transition periods with vertical mixing and overturning (Dai et al., 2018; Lucas-Picher et al., 2021; Notaro et al., 2022; Piccolroaz et al., 2024; Van de Walle et al., 2020).

4. Evaluation/validation

Observational limitations

Obtaining high-quality observational data at CPM resolution remains one of the major challenges. Although satellite observations offer global coverage, even surface temperature and precipitation datasets are often limited in their ability to provide the spatial resolution required for the validation of CPM simulations. These datasets provide indirect observations of the climate variables of interest and multiple methods exist to derive them. This leads to multiple estimates of the “observed” variables that can differ from each other. Accounting for this observational uncertainty is a challenge in all climate model evaluation (Evans & Imran, 2024) but may be a particular problem at CPM resolutions. From another perspective, mountainous regions in particular would benefit from more accurate methods for estimating precipitation.

CPM evaluations benefit more from direct comparisons with in-situ station observations than with lower-resolution RCM simulations do, due to reduced scale mismatch between CPMs and point-based measurements. This increases the importance of station observations in the CPM context. For ground-based measurements, maintaining observation infrastructure is often difficult, especially in sparsely populated areas, where both high spatial resolution and continuous temporal coverage are needed. There has also been a noted decline in the number of in situ stations over several regions (e.g. Africa, Russia). A temporal resolution sufficient to capture diurnal variations in meteorological variables is also essential. Alongside this is the expense of the data. Often these ground based stations are funded through requiring a high price for the data use thus making it difficult for researchers to access. New funding strategies would be useful, as well as more novel approaches where data is not available such as using extreme or threshold events as validation.

Weather radar observations become much more relevant and useful at CPM resolutions. This data can provide estimates of atmospheric moisture and precipitation with complete spatial and temporal coverage at resolutions directly comparable to CPMs. These data, however, come with many quality and interpretation issues of their own limiting their immediate use in CPM evaluation. In order to realise the potential of this data significant effort needs to be spent on post-processing and quality assurance of the data. We also note that this data has limited coverage globally and is not available in many parts of the developing world.

To address observational limitations, strong collaboration is needed among researchers working on ground-based observations, satellite-derived products, and CPRCM simulations. Furthermore, with regard to in situ observational data, cross-border data sharing remains a challenge in many regions. Sustained and constructive dialogue will be vital to promoting open and coordinated data exchange. Several initiatives at the WCRP level exist which we can link to such as GPEX, ESMO, etc.

The double penalty problem

When performing evaluations at high spatial and temporal resolutions we encounter the “double penalty problem”. Most traditional metrics compare model output to observations at the same time and location. At high resolution this means that a very good model that produces a realistic climate but displaces a precipitation cell by just a kilometre or two (enough to put it in a nearby gridcell) will be penalised twice - once because the rain is not in the observed gridcell, and once because there is now rain in a gridcell without observed rain. Meanwhile a less realistic model that produces no rain is penalised only once - in the gridcell with observed rain. This means that many traditional metrics will (unintentionally) produce results that favour poorer models. At CPM resolutions this problem needs to be considered explicitly. There are several methods that have been developed in the NWP context that could be applied to CPM evaluation. Metrics such as the Fractional Brier Score, Fractional Skill Score or object based methods like SAL (Prein et al., 2023; Wernli et al., 2008; Wolff et al., 2014).

5. Technical realization/Data handling/dissemination

CPCM simulations are computationally very demanding (Schär et al., 2020). CPCM simulations use short timesteps and hence many integrations of their dynamical core to ensure a numerically stable integration without violating the Courant-Friedrichs-Lewy condition. Even with an optimized simulation setup (compilation, configuration, etc.) this leads to either long wall clock runtimes or increased resource needs in terms of the number of supercomputer cluster nodes. Real data CPCM simulations are strong scaling, and eventually go from compute bound to communication bound with an increase in compute nodes. Proven strategies include: less frequent physics parameterization calls, reduced-resolution compute grids, e.g., for radiation, adaptive time-stepping of the dynamical core, single precision instead of double precision. The key is to strike a balance between the required accuracy and efficiency.

CPCM simulations also pose a considerable big data challenge; primarily due to very large data volumes: Due to increasingly large computational domains at fine horizontal (and vertical) grid spacings, combined with short output intervals of typically one hour or less for some variables and applications (e.g., in renewable energy). Adhering to experiment protocols of community ensemble experiments, such as CORDEX, helps to unify data output (formats, metadata, resolution, naming schemes). According to FAIR principles, data reusability in the data life cycle is increased, provenance is ensured. At the same time data volumes might be excessively large for long-term storage and may not be needed by the individual modelling group. Tiered and prioritized variable lists help in separating community accessible data from those stored on tape only. A variable-dependent compression as well as reduced precision helps to reduce data volume. Parallel and /or asynchronous I/O in combination with HPC filesystems reduces file operations wall clock times of simulations, in-situ processing and diagnostics (Yildiz et al., 2024) reduces this further; pre- and post-processing tools also need to be big-data analytics ready.

Cost (in terms of energy consumption, time, cost of ownership) of data storage (tape or spinning disk or a combination thereof, depending on local or federated storage and data access patterns) vs cost of re-running simulations vs reproducibility need to be taken into account. A common usage scenario is still to produce data once, and store as much processed protocol-compliant model output as possible, for a maximum reuse of the simulation results.

Compute capacity for CPCM simulations has increased, e.g., with the advent of the first exascale supercomputers (Sharma, 2024). Despite many challenges in using latest (hybrid, CPU and GPU based on only GPU-based) supercomputers (Bauer et al., 2021), performance portability has increased and many CPCM have been ported to latest supercomputer architectures. With a reduction in energy consumption (FLOPs/Watt) in combination with an increase in computational capacity GPU-based HPC systems also lead to a better efficiency and hence more sustainable CPCM simulations.

Equitability considerations in CPCM

The very large data volumes of CPCM simulations pose a challenge for accessibility and create a significant barrier to usage in regions without appropriate computational facilities. This has been one of the main challenges for wider analysis of the data from

simulations of the Global South, such as the 4km South America Affinity Group (SAAG) (Dominguez et al. 2024). Efforts to increase accessibility include reduced size output of key variables, or direct analysis of the data by providing access to the machines where the data is stored. However, a more long-term solution would be the establishment of regional centralized computational platforms where datasets are stored and made directly accessible for analysis—eliminating the need for local downloads. These hubs could also serve as regional centers for education, outreach, and capacity building, supporting scientists, stakeholders, and decision-makers seeking to work with kilometer-scale climate data in the Global South.

6. Inter- and intra-community engagement

6a. CPM in the context of CORDEX-CMIP6/7

Strong engagement and shared members between the TTCPM and TTPI (CORDEX-CMIP7 Protocol and Infrastructure) Task Teams is necessary in order to 1) future proof CPM in CORDEX and 2) ensure coordinated complementary efforts. At the very least CPM experiments will require either driving data from CORDEX CMIP6/7 or will need to follow CMIP6/7 protocols for their intermediate domains to ensure intercompatibility and maximize scientific impact. See also the [report](#) from the CMIP6/7 Task Force.

6b. Collaboration with broader high-res communities (Digital Earths, DestinE, High-res MIP)

Building strong connections with other kilometer-scale modeling initiatives must be a high priority. In particular, establishing collaborations with the WCRP Digital Earth Lighthouse Activity (DE-LHA) would be highly beneficial, given its goal of linking regional and global km-scale modeling efforts. DE-LHA has initiated several process-oriented intercomparison projects, such as a land–atmosphere coupling project and a tropical convection project, which offer natural connection points for collaboration.

Within the European-funded Destination Earth (DestinE) initiative, two digital twins of the Earth system are being developed—one focused on weather, the other on climate. DestinE’s emphasis on km-scale coupled modeling and its focus on local-scale and extreme processes make it a promising strategic partner.

Engaging with the WCRP GEWEX Regional Hydroclimate Projects (RHPs) would also be valuable, as many of these—such as ANDEX and H2US—have dedicated efforts in km-scale modeling. In addition, the DYAMOND project (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains), a global storm-resolving model intercomparison hosted under GEWEX, presents further opportunities for collaboration in global-to-regional model evaluation, process studies, and joint model development.

6c. Engagement with impact modelling community (e.g., ISIMIP)

The CORDEX CPM community needs stronger engagement with downstream impacts modelling communities, including ISIMIP. In some cases there are already close institutional links – for example, at CORDEX participants that are also responsible to national climate and weather services such as MetOffice (UK), DWD (Germany), MSS (Singapore) – but these links currently do not propagate upstream to the domain and global CORDEX level. CPM experiment protocols that incorporate additional complexity such as active vegetation, urban canopy models and/or hydrological models will naturally bring these communities closer together and the mechanisms for achieving this will be detailed in the official strategy document.

6d. Coordination with AI-ML

Further work is needed to establish the skill of ML downscaling emulators, but if these are shown to be skilful then these may play a key role in augmenting km-scale climate model projections in the provision of local climate change information (Kendon et al., 2025). This then has implications for the optimal design of CPM simulations.

There will be a need for CPM simulations sampling the full range of conditions (including high end scenarios and cold climate states) as ML methods are currently better at interpolation than extrapolation, and for these simulations to be long enough to provide training data on extreme behaviour. Since spatial transferability of ML emulators is difficult, this suggests that there needs to be at least some CPM data available for each region of interest, and that coordination of spatial domains in order to achieve this would be beneficial. It is likely that ML downscaling emulators may be more skilful for predicting behaviour for other time periods and scenarios, providing the training data spans the range of conditions, reducing the need for CPM groups to necessarily downscale the same time periods and scenarios. Critical is the quality of the data for training ML models, so focus should be on running high resolution models with

adequate complexity for capturing the key processes and the community to come together to address existing biases.

A key area of coordination should be around the development of benchmarks i.e. how we assess whether a ML model is good enough. The Task Force on ML is in the process of developing a CORDEXbench. We suggest that many of the metrics and evaluation approaches for establishing the reliability of CPMs should also be used to evaluate ML models (see Table 2), although with the difference being that in the case of ML emulators the CPM simulations for both present and future climate constitute the ‘truth’ i.e. good performance is adequately capturing what a CPM would have predicted (including biases and all).

7. Recommendations

Below we list our key recommendations for the SAT to consider. Overall, It is recommended that, regarding CPRCM experiments, CORDEX moves towards a more comprehensive, coordinated and long-term strategy. We believe this will enable improved intercomparability, complementarity (with standard CORDEX simulations and the coming ML emulators) accessibility and use of outputs for downstream impacts studies and assessments such as IPCC AR7.

The list is organized into two equally important tiers - science strategy and technical developments/protocols. For more details behind each recommendation head to the relevant section(s) of the document. We are transparent with respect to the level of agreement among the contributors. We note where we are unable to come to unanimous agreement, either further discussion. We also note that on some topics (e.g., domain selection) a firm recommendation is not possible out of deference to domain communities.

Tier 1 - Science Strategy

- 1) We strongly recommend increased model complexity anchored in the need to answer outstanding science questions. Insofar as it is possible to prioritize we note that aerosols, LULCC, vegetation, land surface and hydrology have large impact on water and/or energy budgets in nearly all domains; cold climate, high latitude/altitude processes and features depend on the domain (e.g., glaciers) and sea-ice needs proper consideration in polar domains; Representation of

urban features and interactions are critical in many tropical, sub-tropical and mid-latitude domains.

- 2) Ensembles should aim to be balanced (see section 7 in Sobolowski et al., 2025) but not necessarily large; a coordinated approach can leverage ML emulators for exploring uncertainty while relatively few CPRCM projections are used for process understanding. We strongly recommend close collaboration with the ML Task Team as the skill of these approaches will have implications for the optimal design of CPRCM ensemble simulations. For example it may advocate focus of simulations on high-end scenarios to avoid extrapolation errors, and will inform required simulation length and optimal GCM sampling.
- 3) We see severe inequities in capacity and focus (i.e., which regions are chosen) that are challenging to address; We recommend resource sharing where possible (sharing the compute load, joint application to e.g., EuroHPC), democratization (e.g., ML emulators trained for all domains) and a high level initiative (WCRP) to effectuate access to reliable compute and storage for underserved regions. In particular, we recommend a strategy that considers known hot spots of climate change in underserved regions.
- 4) We recommend a concrete link to the global km-scale community. In particular an assessment of the relative strengths and limitations of a regional compared to global CPM modelling approaches is needed. There needs to be a coordinated effort to compare regional CPMs with global results as they emerge to understand what we may be missing through a regional modelling approach.
- 5) A broader CORDEX-wide recommendation is to re-design our frameworks to be future proof – that is, designed from the outset to include new information e.g. CMIP7, CMIP8 etc. as comes available, and does not require a complete new set of projection experiments with each new cycle. For example, one could envision an updatable system, with heavy reliance on ML emulation, that only requires a handful of high resolution (0.11°) and CPRCM simulations.

Tier 2 - Technical developments/protocols

- 1) CPRCM experiment protocols should start from the overarching CORDEX experiment design provided by the SAT (<https://zenodo.org/records/15268192>) and add additional configuration considerations as needed e.g., shallow convection, high resolution static fields, increased vertical resolution (especially in the PBL), complexity, etc.
- 2) We recommend a coordinated approach to the provision and the use of the same geospatial datasets for static fields and initialization; One could consider building

a common set of default fields that modelling teams can select from and curate them in a common repository under e.g., <https://github.com/WCRP-CORDEX>.

- 3) Domains: the recommendation is to move towards larger domains¹ taking into account theoretical considerations such as distance from lateral boundaries to allow for spatial spin-up (Matte et al., 2017); However, we note that domain communities may have good reasons for more limited CPRCM domains.
- 4) Experiment design must necessarily be flexible but if possible we should aspire to an overarching coordination on GCMs (performance, resolution, complexity, etc.), Scenarios and length; Recommendation is close coordination with the TTPI to achieve this.
- 5) We recommend establishing consistent standards of practice for evaluation/validation where known shortcomings are mitigated and consistency is adhered to where relevant and practical; one could imagine a set of universal metrics paired with domain/climatology specific metrics²; This effort should be linked to the ML Benchmarking activity.
- 6) We strongly recommend that CPRCM protocols follow the CORDEX-defined archiving specifications as closely as possible and ensure that model output is FAIR and not stored on e.g., servers inaccessible to the public. We also recommend a coordinated effort to establish consistency in output diagnostics/run-time post-processed diagnostics calculated on the fly e.g. regridded outputs, tracking outputs, which can greatly reduce data storage costs
- 7) There are several advances that can be made in terms of technical realization; Use of GPUs, use of in-situ processing and analysis, federated storage need to be part of CPRCM CORDEX strategy; However, these require significant resource investment; We recommend stronger coordination and sharing of software advances. Best practices approaches can be developed and shared (e.g., <https://github.com/WCRP-CORDEX>).

To put these recommendations into practice we recommend the SAT establish a CPRCM Task Team as soon as possible. Their task will be to turn this report into a strategy document and integrate/synchronize/coordinate with those of the ML and CMIP7 Task Teams; The goal is to be ready with a coordinated CPRCM strategy in time for CMIP7 downscaling activities.

¹ We note that there is not consensus on how “large” is large enough. There is consensus that smaller domains e.g., ALP3 are not optimal. However, if the community aspires to full CORDEX domains at convection permitting scale then the intermediate nests will necessarily be much, much larger and there are few modelling groups who can achieve this coverage. This point needs further discussion.

² For example: <https://zenodo.org/records/15348836>

8. Action plan and timeline

Given the above-stated goal the timeline for preparing a coordinated strategy in time for CMIP7 downscaling activities are very tight and must be well-aligned with those of the CMIP7 Task Force (see Figure 3 in their planning document and reproduced below). The first outputs from CMIP7 Assessment Fast Track (AFT) are expected by mid 2026 and the CORDEX-CMIP7-AFT simulations are projected to start shortly thereafter. As such, the CPRCM Task Team will already need to have a preliminary protocol in place that at the least details a coordinated approach to data availability for driving CPRCM simulations.

Tasks:

- Establish CPRCM Task Team & launch (Q3-2026)
- Gather planned CMIP6 CPRCM experiments (coordinate insofar as possible) “fast-track” CMIP6 protocol (Q4-2026 – Q1-2027)
- Integrated activities with ML-TT, CMIP7-TT, CORE-TT (Q4-2026 – Q4-2027)
- Bridge building activities with e.g. km-scale global, impacts, GPEX, etc. (Q1-2027, Q3-2027, Q1-2028)
- CMIP7 CPRCM Experiment Protocol (Q1-Q3, 2027)
- CMIP7 coordinated experiments (Q4-2027 – Q2-2028)

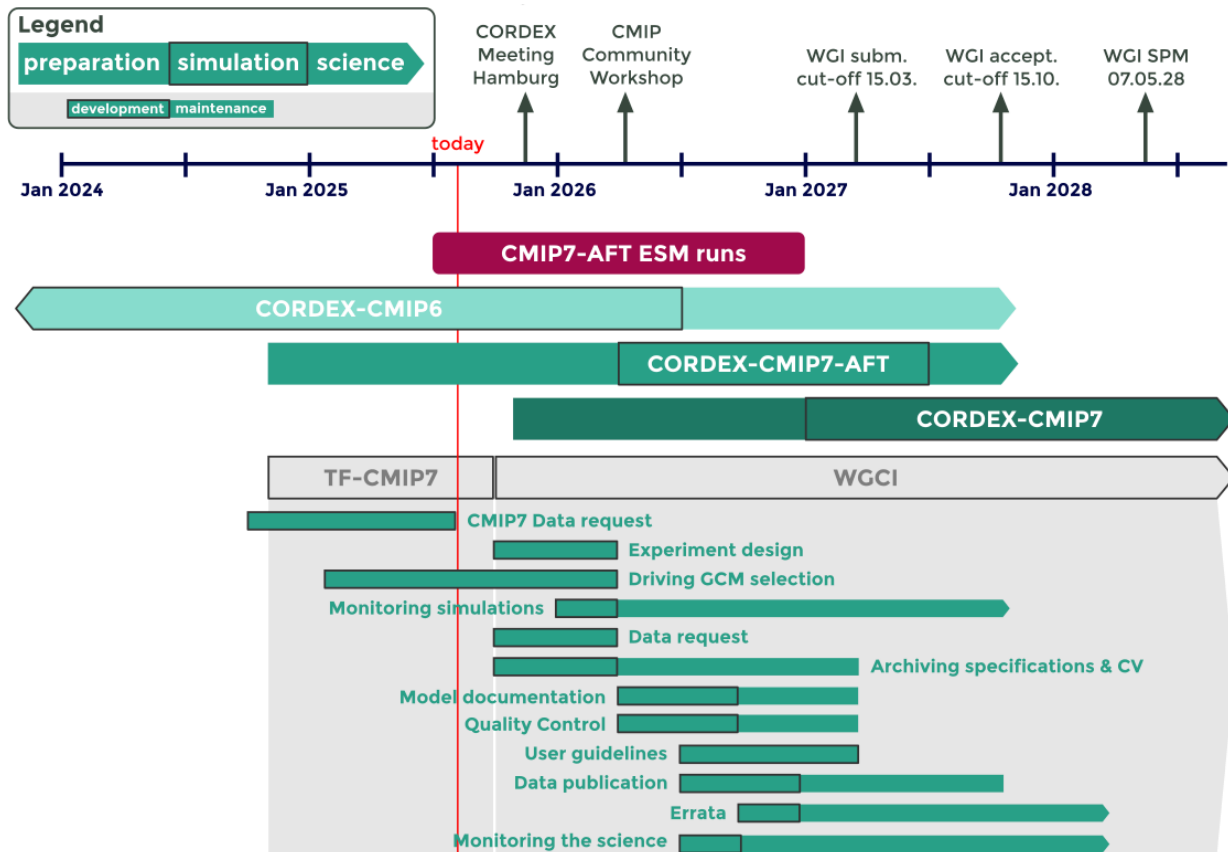


Figure 3. Schematic timeline from CORDEX CMIP7 TF (see [their document](#) for details).

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