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OPINION

Populated regional climate models (Pop-RCMs): The next frontier in regional climate modeling

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The field of regional climate modeling originated in the late eighties and has steadily grown since then [1]. Several regional climate model systems (RCMs) have been developed and used for a wide range of applications by growing research communities, from regional process studies to paleoclimate simulations and future climate projections. RCM development has mainly proceeded within three primary dimensions: increased model resolution, greater complexity, and production of climate information based on large multi-model ensembles. In the first of these dimensions, today's RCMs have reached "convection-permitting (CP)" resolutions, ~1–3 km, at which cumulus convection can be explicitly represented [2]; in the second, coupled regional Earth System Models have been developed, including multiple interactive components, such as atmosphere, oceans, cryosphere, biosphere and chemosphere [3]; in the third, several large multi-model intercomparison projects have been implemented, culminating in the Coordinated Regional Climate Downscaling Experiment (CORDEX, [4]), an international program aimed at producing ensemble-based climate change projections for regions worldwide. The convergence of these three dimensions provides the grounds for the next frontier in RCM research.

The Earth's climate has entered the so-called "Anthropocene" [5], a period in which human activities substantially affect the climate system, e.g. through the emission of greenhouse gases (GHG) and particulate material or through modifications of the land surface (urbanization, deforestation, agriculture). In turn, human societies are profoundly affected by, and respond to, these human-induced climate modifications [6]. In other words, humans are an essential and two-way interactive component of the climate system, yet most climate models still treat human activities (GHG and aerosol emissions, land use change) as prescribed "external forcings". Integrated Assessment Models [7] that represent the interactions between natural and human systems in a highly simplified modeling framework are currently developed and operated in parallel to climate models. Closing this gap by integrating the explicit description of interactive human population socio-economics and dynamics within the climate modeling framework is the main new frontier in climate system modeling, and RCMs can play a pivotal role in this endeavour.

The inclusion of interactive humans in RCMs is where the model complexity and resolution dimensions converge. In fact, the resolution of today's CP-RCMs allows the detailed description of human environments and activities, such as occurring for example in urban and agricultural settings. One of the advantages of using an RCM framework for modeling human-environment interactions is that specific pilot studies can be designed where such interactions are especially important. As an example of possible pilot case, land use modifications and aerosol emissions can substantially affect the climate of the Sahel region [8, 9], and in turn local agricultural productivity and population dynamics are highly dependent on climate variability in the region [10].

The third main dimension in RCM research is the construction of multi-model ensembles, e.g. for decadal prediction or long-term climate projection, of sufficient size to allow the characterization of relevant sources of uncertainty (e.g., related to different scenarios, driving GCMs, model configuration or internal variability [11]). This is particularly important for supporting robust decision making at regional scales and for the study of phenomena such as climate extremes, that are rare by nature. Today, CORDEX provides an optimal framework to develop coordinated multi-model simulation protocols, and a full integration of CP-RCM applications within the CORDEX program is essential. Running CP-RCM centennial simulations over multiple continental-scale domains is foreseeable over the next years, which will provide climate information at unprecedented detail when international efforts are coordinated. This is where the third dimension in RCM modeling meets the previous two.

Therefore, our long-term vision of primary RCM research directions is the development of coupled "populated RCMs (Pop-RCMs)" and their use at CP or even higher resolutions (e.g. sub-km Large Eddy Simulation, or LES) within coordinated multi-model and multi-domain frameworks (Fig 1). This is clearly a formidable task. On the model development side, a critical challenge is that, while the effects of human activities on the environment (e.g. land use change, pollutant emissions) is already incorporated within most RCM systems, modelling the response of population dynamics to environmental stressors is still an open field of research, which will require the availability of environmental, social, economic, and demographic data of sufficient quality and detail to: i) disentangle the effects of different and possibly concurrent environmental and socioeconomic forcings on population dynamics and responses, such as mitigation and adaptation policies, migration, geopolitical conflict; ii) develop and calibrate distributed population dynamics models; and iii) verify how the coupled models reproduce population-environment interactions. This will likely entail the use of entirely innovative modelling, data gathering and analysis approaches, for example based on mobile system technologies and machine learning. On the computational side, running Pop-RCMs for climate-type simulations will require exascale computing architectures and next generation data management and analysis tools. The technological component of this effort is thus fundamental. Finally, the development of Pop-RCMs will require a strong interdisciplinary effort across the physical, computer, and human science communities, something that has been rather limited so far.

The climate modelling community is moving towards the development of high resolution global and regional "Digital twins" of the Earth System, and modelling beyond the natural system is one of the pillars of such activity [13]. The development of Pop-RCMs can pave the way for the necessary inclusion of interactive humans not only in regional, but also in global models. This requires another element that has lacked to date, i.e., a strong collaboration across the global and regional climate modeling communities. There is much that these communities can learn from each other. On the one hand, GCMs are the drivers of RCMs and they thus need to have a good performance at synoptic to mesoscales to provide high-quality boundary condition fields. On the other hand, RCMs can always be one resolution step head of CGMs. For example, when GCMs will reach CP resolutions as a standard, RCMs may move to sub-km LES ones, and this can feed back into the GCM development. In addition, other downscaling techniques, e.g. variable resolution GCMs [14] and empirical statistical downscaling (ESD,

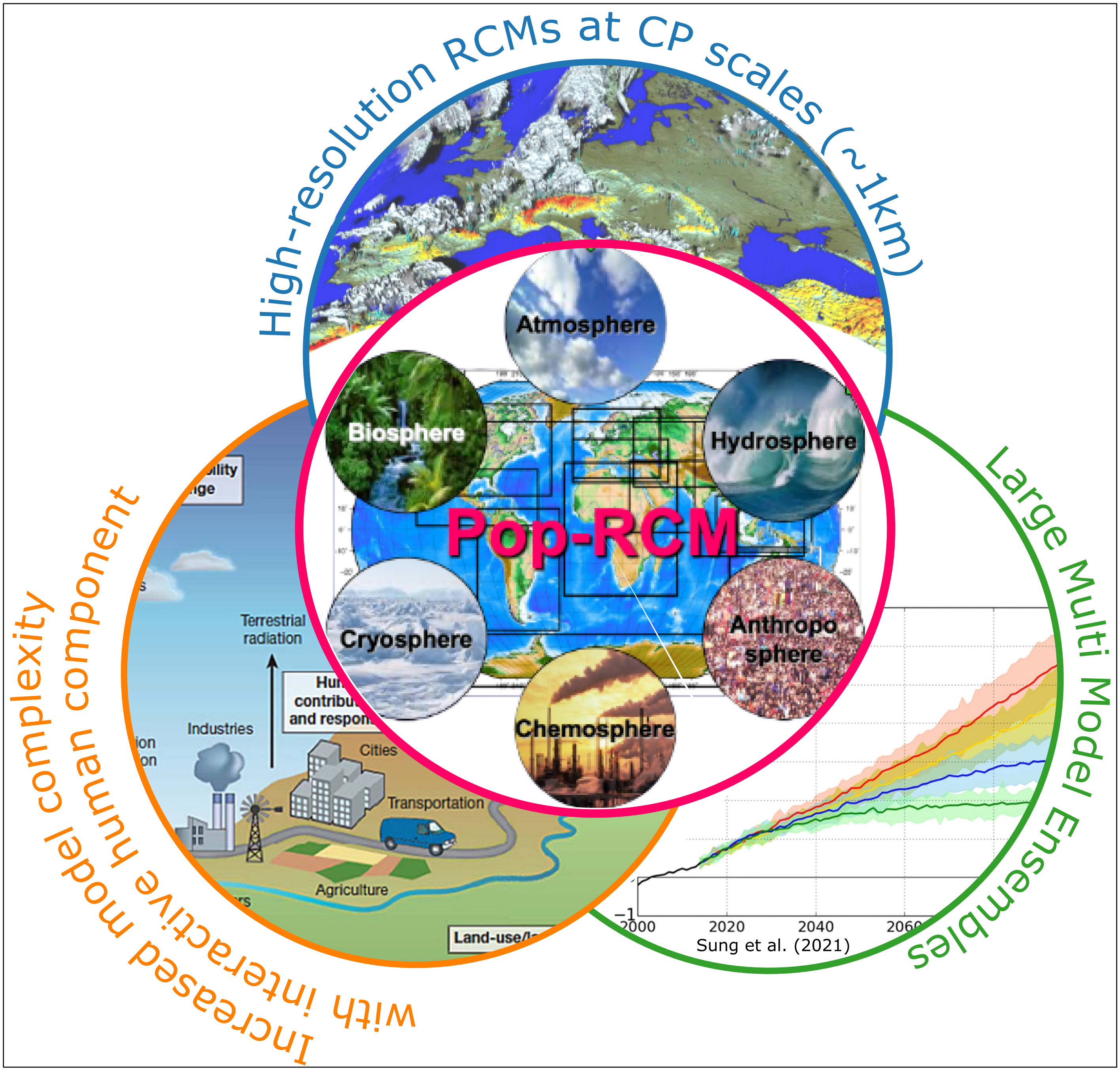

Fig 1. The convergence of the three main dimensions of RCM model development provides the grounds for the frontier Pop-RCM research (see text). The top image (blue circle) was provided by Forschungszentrum Julich (Klaus Goergen, Herwig Zilken, Jens Henrik, Gobbert, Sonja Habbinga, https://www.youtube.com/watch?v=Jz1Hbr-syMQ); the bottom left image (orange circle) is courtesy of GFDL/NOAA, and is available at https://www.gfdl.noaa.gov/climate-and-ecosystems-comprehensive-earth-system-models/; the bottom right image (green circle) is from [12] and is available at https://link.springer.com/article/10.1007/s13143-021-00225-6/figures/3.

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Hewitson et al. 2014 [15]) can provide complementary and synergistic approaches to improve information on regional climates. Therefore, a strong cross-scale, cross-discipline research strategy is paramount for a holistic and integrated understanding of the behavior of the Earth System from the global to the regional and local scale.

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