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On the development of physically-based regional climate modelling

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There are huge scientific and technical challenges in research directed towards understanding climate and climate change. No clear picture of how the weather and climate system works emerged prior to the 20th century because of the lack of connection between atmospheric variables. In fact, there was still some doubt about deriving a theory about how to interpret daily weather patterns, general circulation of the atmosphere, and the global climate. Atmospheric physics reached a landmark in the early 20th century when empirical climatology, theoretical meteorology and forecasting were about to converge into a conceptualisation of this "vast machine" (Edwards, 2010). The problem of understanding the causes of weather, climate and climate change is not one to be solved quickly or easily, but contributing to its solution is particularly worthwhile. In fact, the status of the climate results from the complex interactions between the atmosphere with the physical and biological systems which bound it - the lakes and oceans, ice sheets, land and vegetation through a spectrum of temporal and spatial scales. These elements all determine the state and the evolution of the Earth's weather and climate, owing to a particular influence of the general circulation of the atmosphere which redistributes energy, along with the ocean currents, from the Tropics to the Poles. This highly-coupled system presents a genuine challenge for modellers, and this has led to a body of literature which details the range and hierarchy of numerical climate models (e.g. Trenberth, 1996, Schlesinger, 1988).

Back in 1904, Vilhelm Bjerknes recognised that a physically-based weather forecast is a fundamental initial-value problem in the mathematical sense; this was later classified as predictability of the first kind according to Lorenz (1975). The foundation of what became a framework of studying the geophysical fluid motions in order to predict the state of the atmosphere was shaping up. The derivation of the equations of motion began in the 17th century with Newton's Laws of Motion, which were later applied for fluid flow purposes by Euler and Bernoulli in the 18th century. The modern conservation of momentum formulation consists of a form of the Navier–Stokes equations, an extension of Euler's (but for viscous flow), that describe hydrodynamical flow. A continuity equation, also accredited to Euler, represents the conservation of mass. Hadley in 1735, and Ferrel, around 1850, showed that the deflection of rising warm air is due to the Coriolis effect, a force that began to be used in connection with meteorology in the early 20th century. The first law of thermodynamics, a version of the law of conservation of energy, was codified near the end of the 19th century by a number of scientists, but the first full statements of the law came earlier from Clausius and Rankine. This led to the thermal energy equation relating the overall temperature of the system to heat sources and sinks. The gas state variables were related in 1834 when, Clapeyron combined Boyle's Law and Charles' law into the first statement of the ideal Gas Law. The basic ingredients employed to approximate atmospheric flow were then gathered to progress from concepts to operational computer forecasting, thus aiming at representing weather by numbers (Harper, 2008). The partitioning of the atmospheric fluid into a dry and water vapour mixture, according to the Dalton's law, was later included in numerical models; this premise led to a genuine improvement when the water cycle and its associated energy exchange was introduced as an extra equation, describing the transport of water vapour handling the effects of changes of water phases for calculating precipitation. All of the above form the basic equations used today for weather forecasting and climate prediction. The conservation equations are partial differential equations. For a unit mass, with a frame of reference attached to the Earth and the origin at its centre, these equations may be written as follows (e.g. Washington and Parkinson, 1986, Henderson-Sellers and McGuffie, 1987, Jacobson, 1998, Coiffier, 2011):

$$\frac{d\boldsymbol{V}}{dt} = -2\boldsymbol{\Omega}\times\boldsymbol{V} - \frac{1}{\rho}\nabla p - \nabla\Phi + \boldsymbol{F} \quad \text{momentum equation (1)}$$

$$\frac{dT}{dt} = \frac{1}{c_p}\left(\frac{dp}{dt} + Q\right) \quad \text{thermodynamic equation (2)}$$

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\boldsymbol{V} \quad \text{continuity equation (3)}$$

$$\frac{dq}{dt} = M \quad \text{water vapour equation (4)}$$

$$p = \rho R T \quad \text{equation of state (5)}$$

which gives us a set of seven equations with seven unknowns, where $\boldsymbol{V}$ represents the three-dimensional wind velocity, T is the air temperature, p is the pressure, q is the specific humidity, and ρ is the air density, all varying in space and in time. The other quantities are: $\boldsymbol{\Omega}$ is the angular of rotation of the Earth, Φ is the geopotential defined as the product of geometric height above the surface z by the acceleration due to gravity g, (the latter including the Newtonian gravity and the centrifugal acceleration), R and c_p are the specific gas constant and the specific heat at constant pressure, and t is the time. $\boldsymbol{F}$, Q and M represent the sources and sinks of momentum (e.g. frictional forces), heat (e.g. solar and infrared radiation, and latent heat release) and moisture (e.g. evaporation and condensation), respectively, and their expression depends on the scale of the atmospheric motion the model aims to describe, and they represent subgrid-scale processes commonly expressed in terms of resolved quantities. In the prognostic equations (1-4), the derivative of any scalar quantities ψ with respect to time taken following the fluid is expressed as

$$\frac{d\psi}{dt} = \frac{\partial\psi}{\partial t} + \boldsymbol{V}\cdot\nabla\psi \quad (6)$$

where the first term on the right is a local partial derivative at a fixed point in the chosen frame of reference and the second the advection of the same quantity. Advection that induces non-linear effects is a transport mechanism of a quantity by a fluid due to its bulk motion. Simplification and transformation are required in order to resolve for some analytical solutions or the numerical methods used to seek numerical solutions. The discretization of these continuous equations would render them amenable, using appropriate algorithms, to a numerical solution of the continuous behaviour of the circulating atmosphere.

Around 1920, Richardson, who may be considered as the father of today's models for weather and climate, tried to solve a simplified set of equations using numerical methods "by hand and step-by-step". However, his 6-hour "retrospective forecast" proved unrealistic. Computational instability and imbalance in the initial data set were later found to be the cause of this "setback". However, in 1928, Courant, Friedrichs, and Lewy showed that a time step must be less than a certain value in explicit time-marching schemes to warrant stable numerical solutions using the method of finite differences. Then, Richardson realised that *64'000 computers* [human automata] *would be needed to race the weather for the whole globe*, but by the time he published "Weather Prediction by Numerical Process" in 1922, fast computers were unavailable. The development of complex models remained dormant until the development of electronic computers handling self-programmed sequences of instructions. In 1950, Charney, Ragnar Fjörtoft, and von Neumann made the first numerical weather prediction (NWP) using "simplified" equations to represent large-scale eddy motion. This accomplishment then fostered the development of more complex prediction models of even greater spatial resolution, allowing small scales of motion to be resolved. In 1956, Phillips developed a model which could realistically depict monthly and seasonal patterns in the troposphere, which became the first successful climate model. Following Phillips' work, several groups began working out General Circulation Models (GCMs) of the atmosphere of increasing complexities, including the effects of sub-systems such as these induced by oceans. The challenge of numerical models is to run forward in time much faster than the real atmosphere and oceans with available electronic computers. To do this, they must make a large number of simplifying assumptions. Although there have been great advances made in the discipline of climate modelling over the last fifty years, the most sophisticated models remain very much simpler than that of the full climate system (McGuffie and Henderson-Sellers, 2001). The first atmospheric general circulation model applied for long-term integrations, were derived directly from numerical models designed for short-term numerical weather forecasting, which did not have a global coverage at this time. Then, the advance of computing technologies, along with the requirements of weather predictions needing hemispheric or even global computational domains, the longer integration periods became a matter of availability of computer resources. The early climate model grid spacing was very coarse in the horizontal and vertical dimensions. The evolution towards greater resolution and increased complexity has been the rule since. This has been facilitated by the availability of large computing technologies and by new algorithms and numerical methods thus allowing longer numerical time-stepping (Mote and O'Neil, 2000). To this day, climate modelling and weather forecasting groups co-exist, but the needs and focus of the two disciplines differ. For climate modelling, long-term mass, energy and moisture conservation is an important issue. This may thus be considered as a fundamental boundary-value problem in the mathematical sense, classified as predictability of the second kind according to Lorenz (1975). Not all climate models originated from weather forecast models, however. Simpler models based on global energy conservation are collectively called Energy Balance Models, or EBMs (Henderson-Sellers and McGuffie, 1987). They take into account the different forms of energy driving the climate system and look for a steady state solution for the surface temperature. Their main advantage is that they can be extensively used to do sensitivity studies of the role of external forcing on the surface temperature (that of the greenhouse gases, of the Earth's orbital parameters in the very long term, the impacts of volcanic eruptions, etc.), which can thus be investigated at a low computational cost. However, the atmospheric circulation is not explicitly resolved so they cannot be used neither to forecast daily conditions nor the general circulation of the atmosphere.

During the early days of weather forecasting, the computational domains were restricted to an area of interest. These Limited Area Models (LAMs) were developed to enable short range predictions to be made over a large domain. Their major drawback is that flow field values have to be specified at the area boundary for each time step. Later on, to overcome this problem, these field values were interpolated from those obtained from a global larger-scale model. This technique has led to "nested models" that are the basis of operational prediction systems in most meteorological services. Following the pioneering work in the U.S. in the 1980s (e.g. Giorgi et al., 1989), the approach, consisting of driving a high resolution LAM lateral boundaries with low-resolution GCM flow fields, entered the scene (Laprise, 2008). In practice, one order of magnitude in resolution can be gained with this approach, so the small-scale structures of atmospheric circulation can be reproduced. One advantage of such a LAM is that it can also be driven by atmospheric reanalyses (data derived from global observations using data assimilation schemes and models), rather than by GCM outputs; this feature is very convenient for development and validation purposes. When LAMs are applied to long time scales, they are referred to as Regional Climate Models (RCMs). They are now exploited in a number of research centres around the world and used in a wide range of climate applications, from palaeoclimate to anthropogenic climate change studies (IPCC, 2007). The development and application of such numerical tools has been motivated by the needs of assessing what the impact of global climate will be in different regions. This downscaling approach is very versatile since RCMs are locatable in any part of the world. Moreover, simulating climate and climate change at the regional and national levels is of paramount importance for policymaking. Any regional climate modelling approach affords focusing over an area of the globe with a regional grid-point spacing of a few tens of kms in the horizontal, for operational use on climate timescales. Furthermore, even when the increase of computing power will permit the operational use of GCMs at a resolution of a few tens of km,

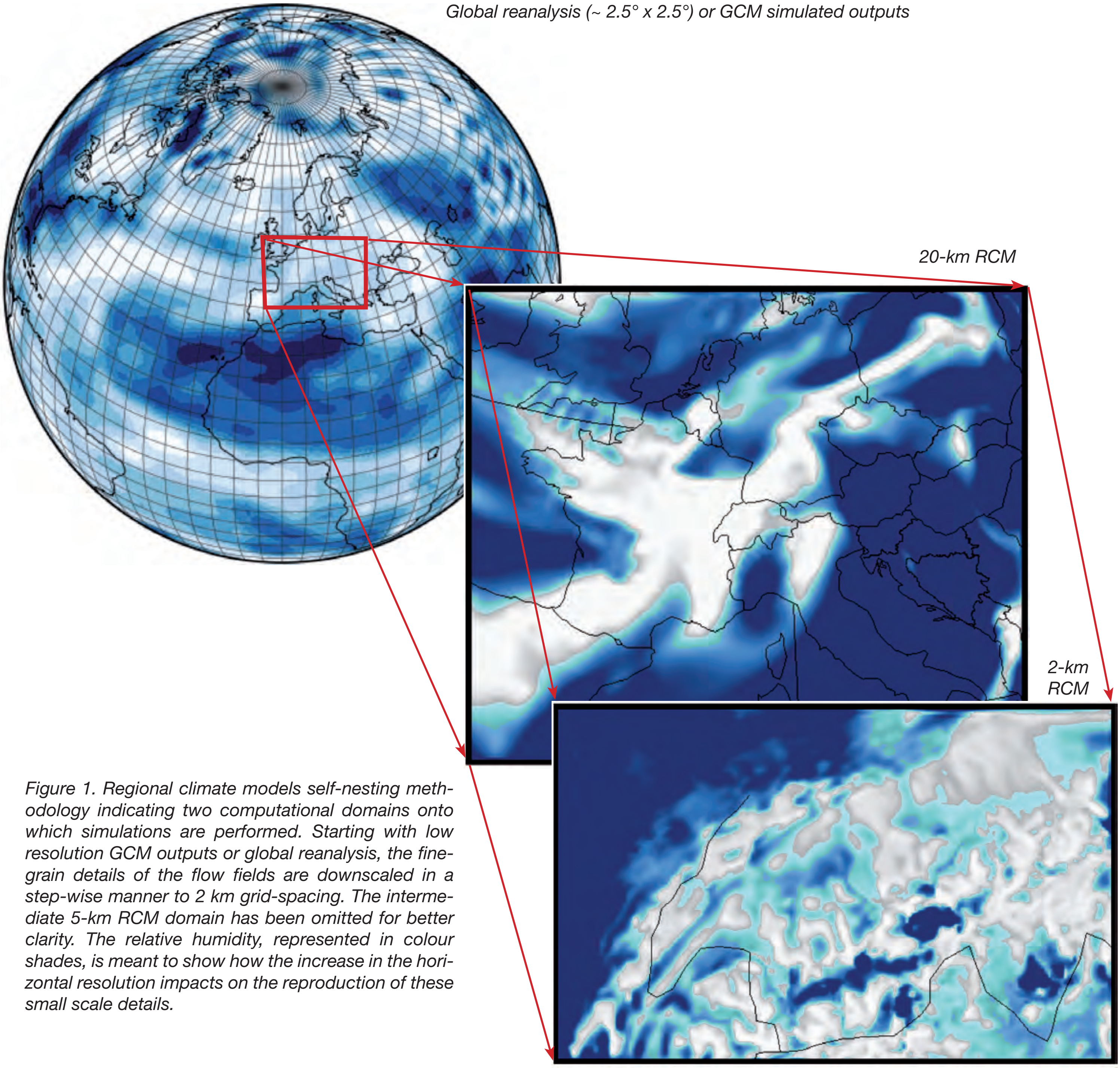

Figure 1. Regional climate models self-nesting methodology indicating two computational domains onto which simulations are performed. Starting with low resolution GCM outputs or global reanalysis, the fine-grain details of the flow fields are downscaled in a step-wise manner to 2 km grid-spacing. The intermediate 5-km RCM domain has been omitted for better clarity. The relative humidity, represented in colour shades, is meant to show how the increase in the horizontal resolution impacts on the reproduction of these small scale details.

the RCM approach could still be useful, allowing reaching resolution of a few kms for a similar computational load. In principle, specific physical parameterizations for the sources and sinks of momentum, heat and moisture, respectively ***F***, *Q* and *M* as depicted in Eqs (1) - (2), and (4) are scale dependent. In the historical development of RCMs, these parameterisations often benefited from packages coming from either NWPs or from GCMs. Improvements to existing schemes and also new developments were nevertheless deemed necessary. This enables RCMs to be applied to a large range of atmospheric flows. This downscaling technique can be further extended to finer detail with the cascade self-nesting capability as shown in Fig 1 (Goyette et al., 2001). The enhancement of horizontal resolution, also prompted for on the specification of surface boundary conditions as a sizeable portion of the performance of RCMs relies on the surface forcing not captured by GCMs. Their success depends on their ability to respond to these forcing factors in a realistic manner in space and time. An important surface forcing not captured by GCMs (Fig 2.) which has received much attention lately is the regional influence of inland water bodies (Goyette et al., 2000). Also, much attention is being paid to the capability of RCMs to reproduce extreme events. Wind gusts are fundamental characteristics of the variability of wind climate; physically-based parameterization to simulate gusts has been developed to better capture the effects of extremes associated with these features (Goyette et al., 2003).

There is also a need for future climate projection at local and regional scales. In addition, climate models, either global or regional, are constantly improved so as to include state-of-the-art numerical schemes, physical parameterizations, new scenarios for greenhouse gas forcing, etc. to warrant realistic simulations at an ever-increasing spatial resolution. For example, the European project "PRUDENCE" was

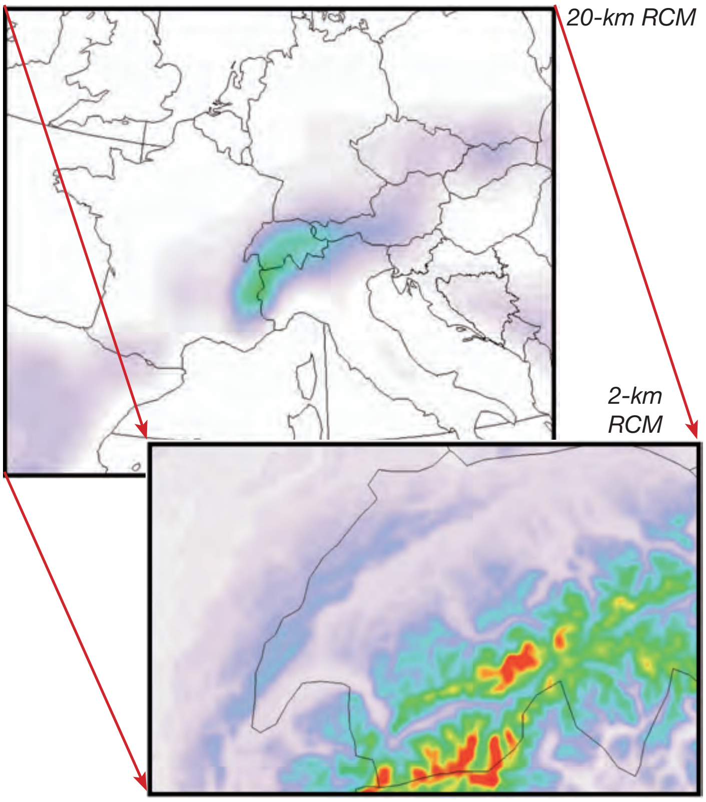

Figure 2. Surface topography prescribed as a lower boundary condition in a 20- and a 2-km RCM. Local weather and climate are significantly influenced by local topographical features such as mountains. Small-scale topographical features are not resolved by GCMs neither by low resolution RCMs (e.g. 20-km RCM) due to the coarse resolution of their computational grids.

aimed at quantifying confidence and uncertainties in predictions of future European climate and its impacts using a suite of high resolution RCMs driven by a coarser resolution GCM (Christensen et al., 2002).

Ultra-high climate simulations, i.e. 30 years or more with an horizontal grid spacing on the order of one kilometre, is not foreseen in the near future due to as yet inadequate computational resources. Some specific case studies using RCMs with 2 and even 1 km grid spacing have been carried out for short term integrations to test the downscaling ability of such an approach (Goyette, 2001). The analysis has shown that the model cannot overcome the massive increase in resolution from coarse resolution GCM or reanalysis data down to these fine scales without introducing intermediate steps (Fig 1). The cascade self-nesting method requires, for long-term simulations, that the ratio between successive grid meshes should range between 3 and 5 to avoid numerical inconsistencies. However, 2.2-km numerical weather predictions do exist and this model is particularly aimed at assisting in short-term local forecasting, showing skill for a 24-h forecast (COSMO [1]). Much research remains to be done, despite all the post World War II achievements. There are still many scientific and technical challenges in weather and climate research, and contributing to these innovations and findings is indeed worthwhile.

1 *www.meteosuisse.admin.ch/web/fr/meteo/previsions_numeriques/cosmo.html*

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