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INTRODUCTION

The road towards RegCM4

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ABSTRACT: The RegCM model system was originally developed in the late 1980s, and it was the first limited area model applied to climate studies. Over the last 25 yr, the system has been improved through successive model versions (RegCM1 to RegCM4), incorporating increasingly comprehensive physics packages and interactively coupled components of the climate system (chemistry/aerosol, ocean, lake, biosphere). The present Climate Special includes studies using RegCM3 and the latest version RegCM4. The papers illustrate that RegCM is a flexible and versatile system which can be used for different regions of the World and for a wide range of applications. Plans for the development of the next non-hydrostatic version RegCM5 are also described.

KEY WORDS: Regional climate model · RCM · Climate change · Model development · Model application · RegCM4

1. The road from RegCM1 to RegCM4 (and beyond)

This *Climate Research* Special presents the development of RegCM4, the latest version of the regional climate modeling system RegCM. The first version of the RegCM system, RegCM1 (Dickinson et al. 1989, Giorgi & Bates 1989), was developed at the National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA, and was the first regional climate model (RCM) documented in the literature. It was based on the Mesoscale Model MM4 (Anthes et al. 1987) with suitable augmentations in the radiative transfer and land surface process parameterizations. While Dickinson et al. (1989) had carried out ensembles of short (3 to 5 d) simulations, Giorgi & Bates (1989) and Giorgi (1990) presented the first month-long, or 'climate mode', simulations driven at the lateral boundaries by reanalysis of observations and General Circulation Model (GCM) data, respectively. These experiments represented a conceptual innovation, since limited area models had never been run for simulation periods longer than 3 to 5 d. Giorgi et al. (1993a, 1994) then represented the first multi-year regional model simulations of present day climate, as well as climate conditions under doubled CO_2 concentration forcing, driven by reanalysis of observations and GCM data, respectively.

The first major upgrade to the RegCM system, which led to the development of the second generation version (RegCM2), was implemented in the early 1990s (Giorgi et al. 1993). RegCM2 was based on the hydrostatic version of the mesoscale modeling system MM5 (Grell et al. 1994), and compared to RegCM1 it included upgrades not only in the model dynamics, but also in all aspects of the model physics packages. An intermediate upgrade (RegCM2.5) was prepared in the late 1990s (Giorgi & Mearns 1999). In addition to several upgrades to the physics components, RegCM2.5 included the first attempts to interactively couple the atmospheric component of RegCM to other Earth system components, such as a lake model (Hostetler et al. 1993, Small et al. 1999) and a simple aerosol module (Qian & Giorgi 1999).

In the early 2000s the maintenance and development of the RegCM system moved to the Physics of Weather and Climate group (now Earth System Physics Section) of the Abdus Salam International Centre for Theoretical Physics (ICTP), and in the

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mid-2000s a third major upgrade of the model was conducted (Pal et al. 2007). Compared to previous versions, RegCM3 was more portable, easy to use, and aimed at simulating tropical climates, reflecting the greater emphasis placed by ICTP on fostering the growth of scientific research in developing countries. A range of applications of RegCM3 was documented in Giorgi et al. (2006).

One of the main developments during the completion of RegCM3 was the inception of the Regional Climate research NETwork (RegCNET; Giorgi et al. 2006, Pal et al. 2007). The RegCNET is the primary means by which the RegCM user community interacts. It includes an email list through which participants can exchange information, ask questions and obtain feedback, receive updates concerning the model etc. Currently, the RegCNET email list includes over 800 participants. Also part of the RegCNET is the organization of regular training and research workshops, either at ICTP (every 2 years) or in different regions. Recent RegCM training workshops have been organized in Amman, Jordan (March 2011), New Delhi, India (December 2010), and Addis Abeba, Ethiopia (September 2010), and 2 more (Beijing, China, and Abidjan, Ivory Coast) are planned in 2012.

RegCM4 represents an update to RegCM3, resulting from the contribution of the RegCNET scientific community. The main upgrades and developments in the model include a complete recoding of the model to increase its flexibility, portability, ease of use and parallelization efficiency and the interactive online coupling with chemistry/aerosol, lake, ocean and biosphere model components (the last of these has yet to be tested); for details see Giorgi et al. (2012, this Special).

Since its inception, the RegCM system was intended to be a community model, now targeting primarily the scientific community in developing countries. The model has been used in more than 60 countries, and the number of publications based on RegCM has increased from a few in the early 1990s to >50 per year. The model has been used for a wide range of applications, from process studies such as land–atmosphere and chemistry/aerosol–climate interactions, to paleoclimate studies, regional climate change projections and, more recently, studies of impacts on health (heat stress), hydrology, and agriculture (see reviews by Giorgi & Mearns 1999, Giorgi et al. 2006, and contributions to this Special). The model grid spacing has spanned the 10 to 100 km range, with simulations ranging from seasonal to centennial periods, over domains covering all land regions of the world (except for the polar regions) with sizes going from subregional (e.g. the Alpine region) to continental (e.g. the African continent). The RegCM model can be driven by lateral boundary conditions from analyses of observations (ERA40, NCEP, ERA-Interim) as well as different GCMs (e.g. the MPI-ECHAM5, NCAR-CCSM, HC-HadCM/HadGEM). A new feature of RegCM4 is that it can be run in full tropical band mode (Coppola et al. 2012, this Special), which opens the door to new applications for the model concerning tropical processes.

Enhancement of the dynamical core of RegCM is planned for the near future. RegCM4 is still a hydrostatic model, which limits its application for studies requiring very high resolution. We are now developing a new non-hydrostatic dynamical core (Tumolo et al. unpubl.) as the base for the next version of the RegCM system. We are also working to improve the model's cloud microphysics, possibly tied to aerosol microphysics, as another prerequisite for applications with very high resolution. Finally, the long-term goal of the RegCM system is to produce a fully coupled regional Earth System Model, and therefore work is continuing to couple the model with other components of the climate system (ocean, biosphere, hydrology, and eventually the human component as well).

2. Contributions to this Climate Special

The special issue is composed of 2 sets of papers, some utilizing the new version RegCM4 and some deriving from applications with the previous version RegCM3. The model was run for various domains (Europe, Africa, Middle East, Central Asia, East Asia, South America, Central America) and different applications, from model validation to climate change and impact simulations.

Giorgi et al. (2012) describe the main characteristics and developments of RegCM4. This is intended to be the basic reference paper for RegCM4 and includes a description of the model and an analysis of some examples of model performance and sensitivities over different domains specified in the COordinated Regional Downscaling EXperiment (CORDEX; Giorgi et al. 2009).

The following articles are based on the new RegCM4 version. Diro et al. (2012) apply RegCM4 to a series of sensitivity tests aimed at evaluating the model sensitivity to land and ocean surface parameterizations over the Central America CORDEX domain. This is a new region of application for the RegCM system, and the model performs well at seasonal to interannual scales, in particular capturing the mid-summer drought conditions over the region. The main deficiency is in the representation of the diurnal precipitation cycle, with the simulated precipitation peak mostly occurring at mid-day rather than in the early evening, a common problem in climate models.

The model has been applied to 2 new regions by Almazroui (2012; the Middle East) and Ozturk et al. (2012; central Asia). In Almazroui et al. (2012), model experiments are driven by both reanalysis of observations and a GCM, and RegCM4 nesting improves the results from this driving GCM. Similarly, Ozturk et al. (2012) intercompare reanalysis-driven and GCM-driven runs, including a future climate scenario, identifying areas where the regional model improves the quality of the simulation compared to the driving GCM.

A RegCM4 sensitivity experiment is described by Otieno & Anyah (2012), in which land use change in central-eastern Africa transformed natural vegetation cover to crop land. This modifies surface energy and water balance, as well as regional circulation features. A different type of sensitivity study is reported by Solmon et al. (2012) who studied the effect of aerosols on the simulated climate of the Sahel under different model and parameter settings. The ability to include radiatively interactive aerosols of different types (sulfate, OC, BC, desert dust) in long-term regional climate simulations is one of the unique and most useful features of the RegCM system, and this aspect of the model will continue to receive substantial attention in the future.

The last RegCM4-based study in this Special, Coppola et al. (2012) discusses a new configuration implemented in the system: the possibility of running the model over a band covering the entire tropical/subtropical region (from 45° S to 45° N). This configuration, called RegT-Band, provides a stringent test for the physics of the model, since the model itself is less affected by the lateral boundary forcing than in its standard limited area configuration. In some ways, RegT-Band behaves more like a global than a regional model. Despite the fact that the RegCM system was not conceived as a global model, RegT-Band shows very realistic large-scale tropical circulation features, and this configuration will facilitate novel applications.

The set of RegCM3-based articles begins with the study by Dell'Aquila et al. (2012), which analyzes a future climate scenario simulation over the Mediterranean basin with RegCM3 coupled to an ocean model. This is a new feature in the RegCM system; experiments such as that of Dell'Aquila et al. (2012) demonstrate how the use of an interactive ocean can considerably improve model performance. The possibility of using a coupled regional ocean model is now a standard feature in RegCM4.

High resolution simulations with RegCM3 are presented by Önol (2012; 10 km grid spacing double nested domain covering the eastern Mediterranean region), Sen et al. (2012; 20 km grid encompassing Turkey and surrounding regions), Sylla et al. (2012; 25 km grid covering southern Africa) and Gao et al. (2012; 25 km grid covering East Asia). These studies illustrate the high resolution of the model in distinct climate regimes, showing that the model is capable of capturing the fine-scale climatic signal associated with complex topography and coastlines. Gao et al. (2012), in particular, completed a 1950–2100 scenario simulation, showing that the temperature change signal is mostly determined by large-scale conditions, while the precipitation change signal is strongly modulated by fine-scale topographical forcing. Similar conclusions, although with smaller signals, are found in the 35 km grid spacing near term climate scenario experiments over a European domain by Branković et al. (2012). They also focused on the simulation of extremes, showing that a very high resolution is indeed needed to reproduce observed statistics of the most intense precipitation events. Finally, Sen et al. (2012) used the results from their scenario simulations to estimate impacts on drought conditions and crop productivity in Turkey. The use in impact studies is an expanding area of application of RCMs in general and of the RegCM system in particular.

The last 2 RegCM3-based papers of the Special are by da Rocha et al. (2012) and Zanis et al. (2012). The former presents a sensitivity study of RegCM3 to land surface and convection parameters over a South American domain. It shows that adjustments of parameters such as soil water drainage and convective efficiency considerably improve some aspects of the simulated tropical rainfall. Zanis et al. (2012) present a coupled RegCM3 aerosol study over the European region, showing that direct radiative aerosol effects induce small climatic modifications.

In summary, this Climate Special illustrates the versatility of the RegCM modeling system in terms of process and application-oriented studies. The use of the model by the RegCNET research community will provide invaluable information and feedback on the model's capabilities and identify areas in need of improvement; this will provide the basis for further model development, leading to the next generation RegCM model framework.

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