Atmospheric regional climate models (RCMs): A multiple purpose tool?

Report of the "Joint WGNE/WGCM ad hoc Panel on Regional Climate Modelling", 12 July 2001modified 11 February 2002 following WGNE’s comments and 27 February 2002 following WGCMs comments:

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Executive summary

Dynamical atmospheric regional climate models (RCM) have matured over the past decade and allow for meaningful utilisation in a broad spectrum of applications. At horizontal scales of 300km and larger simulations are consistent with the nesting (driving) data. At fine spatial and temporal scales, the RCM-simulated patterns of important surface variables, such as precipitation and winds, have demonstrable skill. The grid spacing in RCMs is currently limited by available computing resources to about 50km, which limits the amount of detail available at the finest scales. This implies that for many applications further downscaling will be required. Future increases in computer power and applications of multiple nesting techniques will allow increase resolutions to grid spacing of order of 1km; this horizontal resolution will require the use of fully non-hydrostatic models and scale-dependent parameterisations.

It is recognised that RCMs have deficiencies that need to be ameliorated. The sensitivity of RCM-simulated results to computational domain size, to jump in resolution between nesting data and RCM, to errors or deficiencies of nesting data, and to nesting technique, needs further investigation. Research is required in many areas related to the various applications of RCM. The added value provided by regional modelling should be assessed relative to simpler statistical post-processing of coarse-grid data. An assessment of the performance of an RCM requires climate data on much finer spatial and temporal scales than is traditionally used for validating global models. In some regions such data are available but not necessarily easily accessible, and appropriate gridded analyses have not been carried out. Where such data are not available, methods of validation other than comparison with standard climatological variables need to be developed or applied. The performance of different RCMs needs to be compared both in the simulation of current climate and in their use as dynamical downscaling tool to provide high-resolution climate-change information. This is required both to guide future developments in regional climate modelling and to contribute to the assessment of uncertainty in regional climate simulation and projections.

It is stressed that the final quality of the results from a nested RCM demands realism of the large scales simulated by the driving General Circulation Model (GCM). GCMs remain the ultimate and most sophisticated tool for climate simulations. Hence the reduction of errors, systematic or otherwise, in GCM remains a priority for climate modellers.

Historical background

Two years of discussions of the WGCM and WGNE groups at their respective sessions in 1998 and 1999, led to the establishment by the JSC at its twenty-first session in March 2000, of a "joint WGNE/WGCM ad hoc panel on regional climate modelling". Here is an excerpt of their report (part of the text is omitted for brevity, as indicated by "…"):

> Establishment of a joint WGNE/WGCM ad hoc panel on regional climate modelling.
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> The JSC noted with interest the WGCM and WGNE reviews of regional climate modelling, and the various points and issues discussed. The JSC itself additionally raised the question of the predictability/reproducibility of the smaller scales simulated in regional climate models. The JSC therefore endorsed the establishment of a joint WGNE/WGCM ad hoc panel on regional climate modelling, including the members nominated by WGNE and WGCM, namely:
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> R. Laprise (Convener), University of Québec at Montréal, Canada
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> R. Jones, United Kingdom Meteorological Office
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> H. von Storch, GKSS Research Centre, Geesthacht, Germany
>
> W. Wergen, Deutscher Wetterdienst
>
> It was also agreed that Dr. B. Kirtman, Center for Ocean-Land Studies (COLA), USA, should be invited to represent the interest of the CLIVAR Working Group on Seasonal-to-Interannual Prediction in the application of regional models in seasonal prediction.
>
> The JSC agreed that the panel should undertake the basic task of summarizing the current state of the art in the field of regional climate modelling and reviewing the outstanding questions, particularly those raised by WGNE. … The panel should also consider, as suggested by WGNE, whether any co-ordinated or focussed experimentation … could be useful in further investigating basic issues of regional climate modelling such as choice of domain, scale dependency of parameterizations etc. It would be useful to discuss whether it would be worthwhile to organize an international workshop … with the objective of reviewing and increasing the awareness of the community to the questions to be borne in mind when using regional climate models, and to look forward to progress that can be expected in this area in the coming years. The JSC asked the chairs of WGNE and WGCM to be fully involved in the discussions of the panel and to keep abreast of the views formulated. …

As an example of the on-going concerns about RCM, a part of the WGNE report following their fourteenth session held in Dorval (Québec, Canada) on 2-6 November 1998 is attached in Appendix, along with the comments by the RCM panel.

A preliminary version of this report was presented at the 17th session of the JSC/CAS held October 29 to November 2 2001 in Offenbach, Germany and the 5th (?) session of the WGCM held on 4-7th February 2002 in Bracknell. WGNE's and WGCMs comments were integrated in this revised version.

Introduction

Global general circulation models (GCMs), due to their complexity, are computationally expensive and their cost increases roughly as the fourth power of the linear horizontal resolution. Also, the length of climate simulations required to investigate past, present and future climates ranges from decades to centuries. As a result, GCMs cannot access spatial scales that are required for climate impact and adaptation studies. This current situation is expected to continue as many scales of interest (resolving features such as mountain valleys, coastal seas) will not be resolvable by GCMs for decades. Thus, for the foreseeable future, methods to add fine scale detail to GCM simulations will be required. Two main classes of techniques are available to produce climate-change projections on finer scales: physically based dynamical models of similar complexity to GCMs, and statistical models based on observed relationships between fine-scale climate and large-scale forcing factors. This report concentrates on the major development in the former class: one-way nested regional climate models (RCMs). It is important to note that statistical downscaling of RCM-simulated climate will still be required for many applications of future climate scenarios obtained from RCMs.

The principle behind the nested-RCM technique is that, given a large-scale atmospheric circulation, a limited-area model with a suitably high-resolution grid resolving physiographic details (topography, land-sea distribution, land use) and less strongly parameterised description of physical processes (such as convection), can generate realistic high-resolution information coherent with the driving large scales. Hence the main aim of RCMs is to add valuable higher resolution details to, but keep the large-scale features of, GCM integrations, most usually, to date, in the context of climate change. Realistic details are expected both spatially and temporally. The former derives directly from the higher spatial resolution, e.g. the impact of more realistic orography on the mean circulation providing realistic patterns of mean precipitation. The latter can be derived from shorter timesteps but more usually is an indirect consequence of higher spatial resolution. For example, distributions of extreme daily precipitation are more realistic as the gridbox-mean amounts simulated by the model are closer in scale to real events as are the gridbox-mean motions forming the precipitation.

Regional atmospheric models have been developed since the 1970s, and are now used in a wide range of different applications in meteorology, ranging from short-term weather forecasting, seasonal prediction, climate reconstruction, climate-change projections, air quality and process studies. The versatility of the regional atmospheric modelling approach constitutes both a strength and a potential pitfall, as the boundary between deterministic predictability and climatological applications is easily crossed, resulting in some confusion in the numerical experimentation community. Here is a partial list of some applications of regional models:

1. Operational numerical weather prediction and analysis, driving a regional model with global model prediction (White et al. 1999);
2. Detailed modelling of atmospheric processes, for example: polar lows (e.g. Gachon et al. 2001), effect of growing ocean waves on cyclogenesis (e.g. Doyle 1995);
3. In observational campaigns aimed at the understanding of atmospheric processes, regional models are used to interpret the limited empirical evidence (e.g. Lynch et al. 1997);
4. Reconstruction and scenarios of pathways of air-borne substances (von Storch et al. 2000b);
5. Reconstruction of regional-scale paleoclimatology, driving RCMs with GCM paleoclimatic simulations (e.g. Hostetler et al. 1994 and 2000);
6. Reconstruction of recent-past states on the regional scale, driving RCMs with historical atmospheric objective analyses (e.g. Machenhauer et al. 1996, Christensen et al. 1997 and 1998, Noguer et al. 1998);
7. Dynamical downscaling of climate-change projections, driving RCMs with GCM climate-change simulations (e.g. McGregor and Walsh 1994, Giorgi et al. 1998, Jones et al. 1997, Machenhauer et al. 1998, Laprise et al. 1998, Durman et al. 2001);
8. Dynamical downscaling of seasonal to interannual prediction, driving RCMs with global model predictions (e.g. Cocke and LaRow 2000), as in the Seasonal Prediction Model Intercomparison Project (SMIP);
9. Assessing implications of regional climate change due to changing regional physiographic factors (mainly land use, but also sea-ice conditions) (e.g. Pielke et al. 1999).

In the above list, only regional models used in applications 5 to 9, which are run typically over decades of years, truly classify as *Regional Climate Models* (RCMs) and will be addressed in this report; regional models used for deterministic prediction (e.g. application 1) or process studies (applications 2 to 4) will not be addressed here. In this report, we will concentrate on the use of "nested" RCMs; alternative methods for regional climate simulations, such as variable-resolution global models, time-slices of high-resolution global models and empirical-statistical downscaling techniques will not be addressed in this report.

In the initial use of RCMs most simulations were for relatively short periods (Dickinson et al. 1989). More recently, the integration of a decade or more has become routine (e.g. Giorgi et al. 1992 and 1998, Jones et al. 1995 and 1997, Christensen et al. 1997, von Storch et al. 2000b). In most cases, stand-alone atmospheric models are used, though in some cases coupled models describing regional seas, sea-ice, vegetation, hydrology, transport or chemistry are added (e.g. Bergström et al. 2001). In the different applications, different information is processed, namely initial states, lateral and surface boundary conditions, large-scale circulation, local information, and more detailed specification of dynamical processes and of physiographic details. Most RCMs used for dynamical downscaling have been based on the hydrostatic approximation [1] and are grid-point models with grid sizes of 20km or more, though more usually in the range 50-60km.

An application of RCM that has received relatively little attention is the use of high-resolution RCM as test-bed for developing, improving and tuning physical parameterisation of GCM at higher resolution, without the computational cost of integrating high-resolution GCM covering the entire Earth's atmosphere. Region-specific components of model physics, such as land-surface processes, are much more easily developed at regional scale than at global scale where not all the relevant geophysical fields are available.

Nesting techniques

The most widely used nesting technique is the lateral boundary forcing suggested by Davies (1976). It consists of imposing the atmospheric RCM fields at the outer limit of the limited computational domain with nesting data. A sponge zone is also defined as a ribbon just inside the limits of the domain in which RCM fields are gradually relaxed towards the nesting data. Damping may optionally be enhanced in the sponge zone. In general this technique has been successful to satisfy the above formulated requirement that, given large-scale atmospheric data at the lateral boundary, a RCM with suitable high-resolution grid and sophisticated physics including detailed surface forcing, can generate high-resolution information coherent with the nesting large scales.

The nesting technique can be either one-way or two-way interactive. In the former large-scale information is passed to the regional model, but no feedback is allowed of the high-resolution model simulation upon the low-resolution nesting model. With two-way nesting, the regional domain feeds back on the large scales, thus reducing potential mismatch between the regional model and the nesting model; obviously this technique is not possible when atmospheric analyses are used to nest a regional

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[1] The Canadian RCM (Caya and Laprise 1999) is non-hydrostatic but it has not yet been applied with sufficiently fine grid for climate application to take advantage of its non-hydrostatic dynamics. Non-hydrostatic models have also been used in the framework of statistical-dynamical downscaling (Frey-Buness et al. 1995)

model. For reasons of computational efficiency, all RCMs to date have employed one-way interaction nesting. Clearly, if the stated aim of an RCM “to enhance spatial details but not modify the large scales” is realised, then the need for two-way interaction is removed.

An alternative technique known as the "spectral nesting" or "large-scale nudging" has known a renewal of interest recently (e.g. Tatsumi 1986, Waldron et al. 1996, von Storch et al. 2000a, Biner et al. 2000). With this technique the large-scale component of RCM fields are replaced by (or nudged towards) the corresponding large-scale component of nesting fields, within the whole RCM computational domain. Hence the large-scale information of the driving fields is fully used, unlike with the lateral boundary nesting. When nesting with OA, the operation of the large-scale nudging of an RCM may be considered a kind of "sub-optimal data assimilation" system. An analogy may be drawn between lateral diffusion affecting the small scales and nudging of the large scales; the former is the small-scale closure required to avoid spectral blocking due to the finite-resolution of the computational grid, while the latter may be viewed as a large-scale closure required to avoid de-coupling due to the finite-size computational domain and the one-way nature of the nesting technique.

Although earlier RCM studies involved an ensemble of relatively short simulations, reinitialised periodically (e.g. Dickinson et al. 1989), nowadays RCMs are integrated in continuous fashion, for long periods without drift (e.g. Jacob 2000, Jacob and Podzun 2000). This continuous simulation mode alleviates initial spin-up difficulties, particularly for processes that have long time scales, such as land surface that may take a year or more to reach equilibrium.

Climate simulations with RCMs are performed with time-variable forcing provided by low- or modest-resolution GCM simulations. It is important to realise that high quality results from a nested RCM require realism of the large scales simulated by the driving GCM (e.g. Noguer et al. 1998). GCMs remain the ultimate and most sophisticated tools for climate simulations. Hence the reduction of errors, systematic or otherwise, in GCM remains a priority for climate modellers. There is no consensus in the RCM community model as to the desirability of the RCM and GCM sharing the same physical parameterisation when considering the quality of the regional modelling system. When they do, the analysis of the behaviour of the system is clearly simpler as is the nesting technique.

Large-scale (LS) atmospheric objective analyses (OA) represent quasi-observed LS nesting data for driving RCMs. Such RCM simulations are very valuable for assessing the performance of the model and can also be used to partition errors in GCM-driven RCMs between those generated internally and those derived from the GCM. Another use of such simulations is to actually downscale these atmospheric OA to higher resolution, and to produce a multitude of derived fields that may not be analysed nor observed in the analysis system. Such mode of operation is a kind of "sub-optimal data assimilation" system (von Storch et al. 2000a).

The regional domain size and location are principal issues, as these are "the" artificial and arbitrary parameters in a RCM. From a naive point of view, one might think of choosing the regional domain size such as to produce a RCM with a pre-set computational cost, for a given resolution. However, more care should be taken in choosing a domain location as demonstrated by previous studies (e.g. Jones et al. 1995) though domain size may not be necessarily as critical (e.g. Bhaskaran et al. 1996). The criteria for choosing a domain are that it should be large enough to permit the development of mesoscale features away from the lateral boundary (the so-called fetch or spin-up condition), but small enough to prevent the large-scale circulation in the regional model departing from driving model circulation (the so-called de-coupling condition). The latter criterion on the maximum useable domain does not exist when using the large-scale nudging technique.

Conceptual Issues

Added Value

In the past, there have been too few efforts to identify the "added value" provided by regional atmospheric and climate modelling. From the very philosophy of regional models, major improvements of the models' skill in describing spatially and temporally varying geophysical fields are to be expected on smaller spatial scales and, because of the usual coupling of spatial and temporal scales, on shorter temporal scales, such as climate extremes. Added value should be seen not only as greater detail in time-mean fields (e.g. Noguer et al. 1998) but also as an increased level of variance of smaller spatial scales and an improved distribution of climate-relevant fields. For spatial/temporal detail to qualify as added value, it must be more realistic then what can be obtained by geostatistical post-processing of the coarse grid information, such as co-kriging of temperature exploiting altitude as an additional variable (e.g. Agnew and Palutikof 1999). The skill at scales finer than that of coupled AOGCMs should also at least match or better that seen in high-resolution AGCMs.

One would not expect large-scale features to be significantly modified by a regional model. In the case of a deviation with large-scale information, the regional model results would be inconsistent with observations, if the driving large-scale conditions are specified from objective atmospheric analyses. If a global model is providing the lateral boundary conditions, the large-scale information may possibly contain errors. These errors may come from a variety of sources, including the lack of resolution to resolve important mesoscale dynamical processes whose ensemble effect may affect the large-scale circulation. It is plausible that a high-resolution RCM may tend to produce a large-scale flow differing from that of the low-resolution global model. It is unclear whether a locally limited increase of resolution can really improve the large-scale flow. However, such differences can produce confusing results when downscaling GCM simulations and possibly invalidate them (e.g. Jones et al. 1997).

Parameterizations

So far, many RCMs with grid increments of as fine as 20km, have been run with physical parameterisation packages either inherited from low-resolution global climate models or originally developed for operational short-range numerical weather prediction models. For example, the regional model REMO (Jacob and Podzun 1997) can be run with the parameterizations from the global ECHAM GCM (Roeckner et al. 1992) or with the physics developed by DWD for operational limited-area forecasting (Schrodin 1999). The former approach has the advantage that the physics package has been globally validated in climate mode, albeit at a coarser spatial resolution. Running the physics package in a higher resolution RCM often requires adjusting a number of parameters, for instance in the large-scale condensation scheme. On the other hand, taking the parameterisations from an operational short-range numerical weather prediction model does not require parameter adjustments because of differences in resolution, but the physics package might have been adjusted to optimise forecasts for a specific region and a particular weather regime, and may need adjustments for its generalisation to other regions and altered climate (Giorgi and Mearns 1999). In consequence, both approaches call for a validation of the parameterisations in a RCM in different climatic regimes before running climate-change experiments. These validations are best done via nesting of RCMs with atmospheric analyses, performing experiments over several regions of the world with different climate regimes.

Non-hydrostatic formulation

The ever increasing computing power of computers will allow the use of nonhydrostatic mesoscale models such as MM5 (Xu et al. 2001), GESIMA (Kapitza and Eppel 1992) and CRCM (Caya and Laprise 1999) for extended simulations. At present, the non-hydrostatic “Lokal-Modell” (Steppeler 1999) of the German Weather Service runs operationally with grid increments of 7 km, and it appears likely that it will serve as the regional atmospheric community model at the German Climate Computer Centre after suitable modifications in the parameterisations. For small grid increments, part of the convection is simulated explicitly and needs no parameterisation.

Divergence of solutions

Some researchers have considered a nested regional atmospheric model as a deterministic device transforming boundary information into definite and well defined states in the interior. Divergence in the interior was considered an irregular behaviour indicating a too large simulation area. This view has limitations as highly nonlinear atmospheric dynamics generate an irregular evolution sensitive to minimal differences, on all spatial scales. Thus, any two simulations made with identical large-scale conditions but minuscule differences in the initial state or the boundary conditions will deviate (de Elía et al. 2002). This will not necessarily lead to large deviations in the solutions (Giorgi and Mearns 1999) when there is a sufficiently strong flow through the domain. Problems can occur though in regions of insufficient “ventilation”, i.e. mean flow through the domain boundaries, such as the case of a circumpolar Arctic domain (Rinke and Dethloff 2000). The spectral nudging technique prevents such divergence of large scales.

Anthes et al. (1989) have long ago shown that the divergence of solutions obtained by nested regional models is limited to a magnitude lower than natural variability, unlike the case with autonomous global models. This bounded divergence (also called “extended predictability” in the case of deterministic forecasts) is the result of the control exerted by the nesting technique that constrains the large scales in the regional model (at least with modest-size computational domains and under sufficient ventilating flow, as mentioned above). Recent results of Denis et al. (2001) and de Elía et al. (2002) obtained with a perfect-prognosis type study called the "Big-Brother Experiment" has shed some light on the process of divergence of nested-RCM solutions. A scale decomposition of the simulated fields over the limited-area domain shows that, in the absence of de-coupling, the large scales that are provided as nesting information at the lateral boundary of a RCM are almost perfectly reproduced owing to the control exerted by the nesting technique. On the other hand, shorter scales that are absent in the nesting information behave chaotically and diverge as in an autonomous global model. Thus, consideration should be given to running regional climate and forecast models in ensemble mode.

Validation

When RCMs are forced with operational atmospheric objective analyses or re-analyses they should reproduce the observed present-day climate, i.e. its mean behaviour, variability and extremes. Clearly the RCMs should reproduce the statistics of the driving data and the validation can be extended to compare model output with independent surface observations (either at point locations or as gridded fields) and high-resolution satellite data (e.g. wind estimates from ERS over the sea). In situations where the large-scale conditions have strong control over the interior solution, then aspects of individual events may be reproduced (but note the discussion in the previous section). When comparing RCM simulations to high-resolution observed data, care should be taken to use equivalent spatial scales. When high-resolution RCMs are used to post-process (downscale) lower resolution GCM simulations, the RCM output may be compared to the nesting GCM output, to global high-resolution GCM time-slice simulations and to available observed climate archives. Furthermore, it may be tested whether RCMs produce results consistent with empirical downscaling schemes (Busuioc et al. 1999, Murphy 2000, Osborn et al. 1999, Charles et al. 1999). When intended for climate-change projections, the RCM should be validated in several regions with different present-day climate regimes, in order to make sure it can properly handle different climatic regimes.

RCM simulation of seasonal and inter-annual anomalies may be viewed as a subset of simulations of present-day climate, and there is a large demand for fine scale (both in space and time) extended-range, climate forecasts. In research mode, studies may be made by driving RCMs with a large set of historical objective analyses or re-analyses and observed sea surface temperatures (SST) to assess the ability of the dynamical downscaling technique to simulate fine-scale features associated with large-scale seasonal anomalies. This is an analogue to AMIP used for GCMs, with the additional forcing of RCMs through the atmospheric nesting technique. Such a standardised experimental protocol could constitute a co-ordinated Regional Model Intercomparison Project (RMIP). With only 2-year season-long simulations, PIRCS is a highly reduced version of this type of study (Takle et al. 1999, Ji and Vernekar 1997). Positive results with the above RMIP protocol would lend confidence in the dynamical downscaling of individual members of an ensemble of global seasonal prediction.

While it is clear that accurate fine-scale seasonal forecasts would be of societal benefit, it is not clear that the same downscaling techniques applied to weather prediction can be applied to seasonal prediction. Indeed, the scientific community has not yet adequately assessed the limit of regional seasonal climate predictability. Currently, there is no co-ordinated scientific activity to address these problems and this is a scientific gap that needs to be addressed. The RMIP protocol mentioned above would be a possible mechanism for beginning to bridge this gap.

In organising a co-ordinated effort designed to address downscaling of seasonal to interannual climate predictability there are a number of difficulties that require careful consideration. Here we enumerate two issues that come to the forefront because of past experience with large-scale seasonal to interannual forecasts. First, there needs to be a standardisation of the procedures used to verify the downscaled forecasts. This not a trivial task; however, there has been significant progress in the area for large-scale seasonal forecasts which can be used as a model for downscaled forecasts. Second, since the utility of both large-scale and downscaled seasonal forecasts is intimately tied to the applications community, it is strongly recommended that localised projects for specific applications be developed that bring together seasonal forecast providers and users. The close interaction also serves as a useful verification technique. Moreover, this kind of interaction between the user community and the science community will foster realistic expectations in terms of what can and cannot be predicted using regional climate models.

RCM validation may also proceed through some form of virtual-reality experiment. A "perfect-prognosis" approach, nicknamed the Big-Brother Experiment (BBE), has been experimented with by Denis et al. (2001). The BBE consists in running a high-resolution large- (ideally global-) domain climate model to establish a reference climate. This reference simulation is then degraded to the low resolution of operational GCM, either by filtering or smoothing. These low-resolution fields are then used to nest a high-resolution RCM over a smaller domain. The resulting RCM climate is compared with the reference over the same window. Preliminary experiments, so far only for a few months, show promising perspectives. This BBE technique has the advantage of addressing directly errors resulting from limited-domain and nesting techniques, and not general model defects; the former are specific to RCM while the latter are shared with GCM.

Technical Issues

Lack of conservation and spurious budgets: Most models (global or otherwise) do not even conserve correctly mass, let alone other quantities. The advent of the semi-Lagrangian transport algorithm just exacerbates this difficulty. RCM have an additional lateral forcing that further complicates proper conservation. It would probably be desirable to diagnose the lack of conservation that is induced by the nesting technique in RCM. A related problem is the lack of consistency between ocean surface fluxes in driving GCM and nested RCM (Jones et al. 1997).

Pre-processing: An issue that has not received enough attention is the question of interpolation and extrapolation of atmospheric fields near topography, from low to high resolution, while conserving fluxes of relevant quantities. Vertical interpolation probably constitutes the aspect requiring most attention.

Nesting interval: The time interval for providing nesting information is a sensitive parameter. Majewski (1997) showed that 6-hourly updating can result in a substantial smoothing of depressions rapidly crossing the boundary of a nested model.

Jump in resolution between nesting fields and RCM: For cloud simulations (with meshes of the order of the kilometre), it has been established for many years (e.g. Clark and Hall 1996) that a jump by a factor of at most 3 or 5 was the largest tolerable for an adequate simulations. For RCM operating with meshes of a few tens of km, somewhat higher jumps (up to about 10) have frequently been employed without apparent difficulty (e.g. Denis et al. 2001). Vertical resolution should be commensurate with horizontal resolution in all models; many RCM increase insufficiently vertical resolution for the increase of horizontal resolution compared to GCM.

Recommendations

- Obviously, all models suffer from various defects. In fact, trivially, numerical models are a reduced image of a considerably more complex reality. In this sense, all models are wrong and can be made more realistic in very many different ways. Therefore the process of improving models should be guided by the needs of the specific applications. The reduction of errors in the driving GCMs should remain a priority for climate modellers, as RCM simulations rely on a proper large-scale flow for their lateral boundary nesting; this include not only systematic errors in the mean and stationary patterns, but also transient variability and reproduction of several documented oscillations of the climate system. Monitoring properties of RCM simulations such as the level of conservation of certain quantities (such atmospheric and water vapour mass) and the spin-up of fine-scale details away from the lateral boundaries should become part of the RCM modelling procedure. Sensitivity of the RCM-simulated equilibrium climate to domain size or nesting strategy should also be better documented. It would be desirable that the subgrid-scale parameterisation package of an RCM should be tested in different climate zones than that on which they were developed and tuned.

- An international RCM Workshop should be organised bringing together, not only RCM modellers, but also global climate modellers, diagnosticians and dynamicists, users of RCM results, research managers and funding agencies, under the theme "The added value of Regional Climate Model simulations" in many applications. Such a Workshop could play a vital role in “educating” consumers of model and model-data in the proper use of these tools in their studies; the increasing ease of obtaining these tools to virtually anyone necessitates this educational aspect. Time-wise, this Workshop could take place around March 2003, after passing the levels of recommendation and approval by JSC, WGNE, WGCM and WGSIP. The panel would recommend holding the Workshop in the Southern Hemisphere, possibly in Buenos Aires, Argentina, where there exists convenient international travel connections and a growing community of scientists who could contribute to the essential local arrangements.

- The assessment of RCM climate simulations continues to be hampered by the lack of high-resolution observed gridded climate data over many regions of the globe. Regional data re-analysis projects using observations from national archives should be encouraged.

- Long, multi-decadal RCM simulations nested within OA and forced by observed SST could be made to assess the RCM skill to reproduce fine-scale features associated with large-scale year-to-year anomalies. This would constitute a RMIP, analogous to AMIP for global models. The recently completed European Commission funded project MERCURE has delivered such simulations for the European region using three RCMs and could act as a model for such an exercise.

- When intended for climate-change projections, the RCM should be validated in different climate regimes in order to establish their general applicability. It would be most useful to carry a co-ordinated international modelling effort to nest a number of RCMs with a number of GCM-simulated data sets over a few regions. This considerable matrix work plan would require a strong international support at high levels, to convince the funding agencies of the usefulness of such intensive and long-term endeavour. The recently funded European PRUDENCE project is much more ambitious and will involve some 3 coupled atmosphere-ocean low-resolution GCM (CGCM), 4 medium-resolution atmospheric GCM (AGCM) and 8 RCM.

Appendix

The report of the 14th session of WGNE is reproduced below in Arial 10 points, and the comments of the RCM panel in Times 12 points.

The fourteenth session of the CAS/JSC Working Group on Numerical Experimentation (WGNE) was kindly hosted by Recherche en Prévision Numérique (RPN), Environnement Canada, Dorval, Québec, Canada, from 2-6 November 1998.

Review of regional climate modelling questions

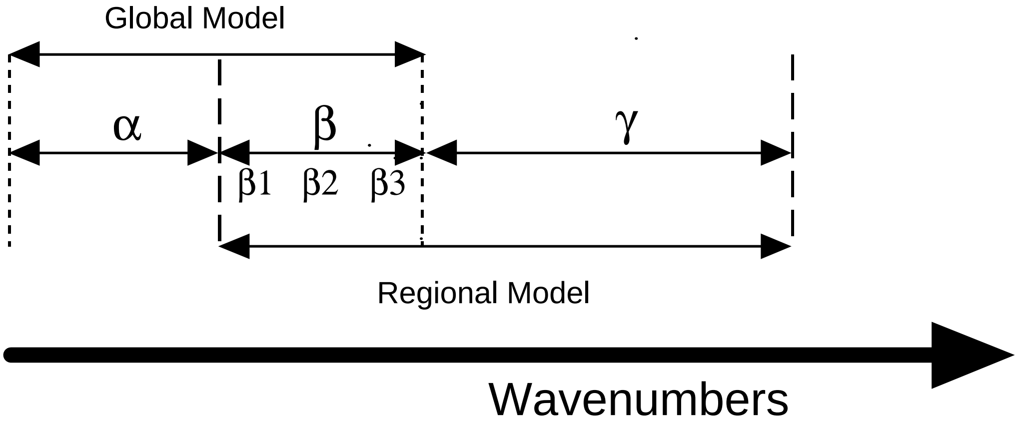
Generally, in respect to regional climate modelling, WGNE stressed that efforts to intercompare or validate models needed to consider carefully the way in which they are to be used – a good model for one purpose might not be satisfactory for another.

In theory, a good model for one application should be good in every region, but not necessarily for other applications. For example a model good for forecasting need not necessarily be good for climate (and conversely), owing to the time scales relevant for a specific application. In practice, choosing and tuning a model for a specific application might result in a 'customisation' issue (Giorgi and Mearns 1999), thus limiting the transferability of the results.

Bearing in mind that the main use of regional climate models is to add higher resolution detail to, but keep the large-scale features of global model integrations particularly in the context of climate change, attention was drawn to several points:

(i) *Regional climate models should realistically represent the mesoscale meteorological phenomena which are important for their contribution to local climate, but which may not be properly represented in a larger-scale general circulation model;*

This is indeed the purpose of RCM. The following figure (adapted from Laprise 2002) is presented to clarify this point and establish a clear meaning to horizontal scales.



Horizontal scale bands resolved by a coarse mesh GCM and a fine-mesh nested limited-area RCM are displayed in wavenumber (inverse length-scale) space. (The wavenumber abscissa is not drawn to scale.) The interval labelled α corresponds to the largest scales that are only resolved by the global GCM (the planetary scales are inaccessible to RCM owing to their finite domain), the interval γ corresponds to the small scales that are only resolved by the fine-mesh RCM, and the interval β the intermediate scales that are resolved by both the GCM and RCM; this common scale band is further subdivided to distinguish those common scales that are closest to the large-scale resolution limit of RCM owing to their finite domain (β1), intermediate scales (β2), and those near the truncation limit of GCM (β3).

Hence γ corresponds to the higher resolution details that are added by RCM upon the larger scale features of GCM. Clearly RCM cannot attempt to modify the α band. The situation for the β band is less clear. Presumably the RCM-simulated β3 band may be better than the corresponding band simulated by the GCM because it is at the limit of GCM resolution. Similarly the GCM-simulated β1 band may be better than the corresponding band simulated by the RCM because this scale is near the upper limit of resolvable scales on a finite domain. But the width of the transition scale band β2 is not well determined and needs to be clarified.

(ii) Regional climate models should, in their domain, reproduce the large-scale behaviour of the general circulation model providing the boundary conditions. This should be checked by scaling up regional model results to the global model scale, and comparing over a large range of conditions (i.e. across the seasonal cycle, different geographical regions, perturbed climates), to ensure that the regionally-simulated response is indeed a down-scaled global model simulation;

Scaling up RCM results to GCM scale is equivalent to demanding that the RCM-simulated β band be identical to the GCM's β-band, which is not always desirable. An example of a "regional" effect that is much larger than the scale of the RCM surface forcing was reported by Giorgi et al. (1994). In their North American simulation the better resolved Rocky Mountains have a moisture shadow effect that extended very far downstream from the actual region of forcing. Another example could be constructed in which an earlier cyclogenesis allowed by the finer resolution of a RCM would lead to a different cyclone life and synoptic situation that in a nesting GCM. In those GCM-nested applications, the RCM is actually trying to correct, within its domain, deficiencies of coarse-mesh GCM. The situation is vastly different when a RCM is nested by Objective Analyses (OA). In such case the α and β bands are presumably well analysed and the RCM should only add information in the γ band. Even then it is possible that the band β3 strongly reflects the forecast by the model serving in the data assimilation system, and may not be a reliable estimate of reality.

(iii) The dependency on resolution of the model's parameterizations needs to be carefully assessed to verify that they do not result in large-scale deviations between the regional model and the forcing model (e.g. the more intense and localized vertical motion in a high resolution model leading to more efficient and intense precipitation, hence lower mean-humidity and greater run-off from the land surface). These aspects are most important when a higher resolution version of essentially the same model is nested. Dependency on timestep should also be checked.

The sensitivity of a model to its spatial and temporal resolution is pervasive in all models and it is an issue that all modellers must confront; this issue is not specific to limited-area models and is not different from other model applications such as GCM. We note that large-scale deviations of RCM simulations from GCM may also be result from the dynamics being computed on a finer grid. The different intensity of the energy and water cycles in the outer and inner model remains a concern.

(iv) The role of boundaries in determining the large-scale flow of a nested regional model should be explored, and hence an appropriate domain for the regional model chosen. The large-scale flow is stronger in winter, so a larger regional domain may be required if the model is used in this season.

The current consensus amongst RCM modellers is that the domain needs to be large enough for small-scale features to have time to develop as weather moves within the regional domain away from the lateral boundary. When traditional lateral boundary nesting is applied, the domain should however not exceed some size in order to keep a proper representation of the α and some β bands scales in the RCM domain. Such upper limit of domain size is not necessary when employing the technique of nudging of large scales (trivially because then the α and some β bands are prescribed or forced).

Above all an important element in the choice of a domain is the weather regime of the region, the scales of the phenomena of interest, the physics of the climate elements to be simulated and finally the resolution and quality of the driving data; the need for accurate GCM-simulated climate for nesting RCM shall never be repeated enough.

(v) The lack of conservation at the boundary should not significantly affect the energy and water cycles in the regional model (e.g. a spurious source or sink in moisture at the boundary of the regional model should not be reflected in a spurious trend in the soil moisture budget).

The need for a good model formulation is not specific to RCM. We would reword the above point in stating that in addition to difficulties common with global models, RCM have additional lateral boundary difficulties: all one-way nested RCM have some spurious behaviour at their rim. RCM-modellers should ensure that these do not significantly impact on the simulations. Practical experience is that this is not a major problem when applied with some care.

In addition, questions remain concerning the computational robustness of the underlying approach. As previously pointed out by WGNE, the most straightforward approach may be the "identical twin" paradigm with a very high resolution (comparable to the regional model) global simulation as a control and a simulation with a regional model identical to that of the global model. The regional model should then be run, firstly, with boundary conditions from the full resolution global simulation and, secondly, with boundary conditions from the global simulations that have been degraded to the type of resolution expected in practice. The first test should expose computational problems such as noise generation by the boundary conditions or suppression of the signal from extra smoothing. In the second, the statistics of the smaller scales of the global simulation should be reproduced if the basic nesting approach is correct. However, there is additionally the issue of how the large-scale flow in the global model is determined by unresolved scales – this cannot be compensated by downscaling using a regional model. One way this could be investigated in the framework of the above tests is to compare the results using a lower resolution version of the global model and nested regional model with those from the matching resolution global and regional model control integrations. All these studies need to be carried out for a range of climatic regimes (e.g. mid-latitude, tropics, summer and winter) and applied similarly to other techniques such as variable-mesh models that are sometimes employed as an alternative to nested regional models.

The recent paper by Denis et al. (2001) reports on some experiments with a "identical twin" approach in what they referred to as the "Big-Brother Experiment". A large-domain RCM simulation (the Big Brother) served as the control run as a cheaper substitute to a global high-resolution GCM. The paper addresses the ability of a smaller domain nested RCM (the Little Brother, nested with a low-resolution version of the Big-Brother simulated data) to reproduce the climate statistics of the Big Brother, namely the time mean stationary and time variability transient components), with spatial scale separation between those larger scales that are provided at the lateral boundary (the α and β bands) and the finer scales that are not (the γ band). It is shown that large scales are well reproduced (not much of a surprise since forced at lateral boundaries by nesting); the fine-scale transients were also well reproduced, as were most of the fine-scale stationary associated with surface forcing. These preliminary conclusions were based on limited experimentation: one region, one resolution and domain size, and only a few months-long simulations; this experiment must be extended to ascertain the robustness of the conclusions to different seasons, weather regimes and domain sizes.

WGNE emphasized that, since the ultimate success of regional models is dependent on the realism of the large-scales simulated by global models, it attached great importance to the continuing investigation of the convergence of both the basic dynamical and complete model solutions with resolution (the former is the objective of the WGNE-sponsored comparison of dynamical cores of atmospheric general circulation models, see section 3.3).

We concur with the statement that the quality of RCM simulations is ultimately dependent on the quality of the nesting GCM simulations.

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