Evaluating the performance and utility of regional climate models: the PRUDENCE project

Jens H. Christensen – PRUDENCE co-ordinator[1],

Timothy R. Carter[2] and Markku Rummukainen[3]

[1]*Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark.*

E-mail: jhc@dmi.dk

[2] *Finnish Environment Institute (SYKE), Box 140, FIN-00251 Helsinki, Finland*

[3]*Rossby Centre, SMHI, SE-60176 Norrköping, Sweden*

Abstract. This special issue of *Climatic Change* contains a series of research articles documenting co-ordinated work carried out within a three-year European Union project 'Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects' (PRUDENCE). The main objective of the PRUDENCE project was to provide high resolution climate change scenarios for Europe at the end of the 21st century by means of dynamical downscaling (regional climate modelling) of global climate simulations. The first part of the issue comprises seven overarching PRUDENCE papers on: (1) the design of the model simulations and analyses of climate model performance, (2 and 3) evaluation and intercomparison of simulated climate changes, (4 and 5) specialised analyses of impacts on water resources and on other sectors including agriculture, ecosystems, energy, and transport, (6) investigation of extreme weather events and (7) implications of the results for policy. A paper summarising the related MICE (Modelling the Impact of Climate Extremes) project is also included. The second part of the issue contains 12 articles that focus in more detail on some of the themes summarised in the overarching papers. The PRUDENCE results

represent the first comprehensive, continental-scale intercomparison and evaluation of high resolution climate models and their applications, bringing together climate modelling, impact research and social sciences expertise on climate change.

In Europe, as elsewhere in the world, there is a growing demand from decision-makers in the public and private sectors, from non-governmental organisations (NGOs), from researchers and from the general public for detailed information on future climate. Only with such information does it become possible to quantify the risks of a changing climate brought about by anthropogenic emissions of greenhouse gases. Quantification is absolutely necessary in order to formulate and implement realistic adaptation and mitigation strategies (e.g Arnell, 1996).

Projections of future climate change from numerical models have existed for three decades, but these remain deficient both in regional detail and in the characterisation of their uncertainty. The assessment of potential regional impacts of climate change has, to date, generally relied on data from global atmosphere-ocean general circulation models (AOGCMs), which do not resolve spatial scales of less than ~300km (Mearns *et al.*, 2001). Such AOGCMs do not provide information on the spatial structure of temperature and precipitation in areas of complex topography and land use distribution (*e.g.* the Alps, the Mediterranean, Scandinavia). Their depiction of regional and local atmospheric circulations (*e.g.* narrow jet cores, mesoscale convective systems, sea-breeze type circulations) and representation of processes at high frequency temporal scales (*e.g.* precipitation frequency and intensity, surface wind variability) are likewise insufficient.

The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) includes several recommendations for intensifying research into high resolution model-based climate projections: *"The need is there to co-ordinate RCM [regional climate model] simulation efforts and to extend studies to more regions so that ensemble simulations with different models and scenarios can be developed to provide useful information for* *impact assessments. This will need to be achieved under the auspices of international or large national programmes. Within this context, an important issue is to provide RCM simulations of increasing length to minimise limitations due to sampling problems"* (Giorgi *et al.,* 2001, p. 616).

In order to address such inadequacies on a European scale, an interdisciplinary project entitled PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) was undertaken during the period November 2001 – October 2004 by a team of 21 European research groups based in 9 countries with funding from the European Commission (contract No. EVK2-CT2001-00132 in the Fifth Framework Programme under Energy, Environment, and Sustainable Development). Its primary objective was to provide high resolution climate change scenarios for Europe at the end of the 21st century using dynamical downscaling methods with climate models.

The specific objectives of PRUDENCE were to:

1. design and execute a large set of 30-year simulations for Europe using high resolution climate models, assuming consistent scenarios of greenhouse gas and aerosol emissions and agreed model boundary conditions;
2. evaluate and intercompare the performance of these climate models in representing 1961-1990 observed climate in Europe;
3. examine and intercompare high resolution climate projections for 2071-2100;
4. characterise the uncertainties in projections attributable to model formulation and natural/ internal climate variability;

5. assess the changing risk of physically and economically important extreme weather events such as flooding, wind storms and heat waves, by providing a more robust multi-model estimation of the likelihood and magnitude of such changes and by studying their potential impacts;
6. investigate the added value (compared to conventional approaches) of applying high resolution climate scenarios for assessing the potential impacts of climate change on, *inter alia*, ecosystems, agriculture, human health and water resources, at a range of spatial and temporal scales in Europe, and assess the additional uncertainties linked to such impact projections;
7. identify socio-economic and policy related issues which could usefully be informed by these new scenarios;
8. disseminate the results of PRUDENCE widely, in particular by means of a project summary aimed at policy makers and non-technical interested parties (see project website[1])

While European collaboration on climate modelling and impacts analyses has been performed for more than a decade based on various EU research and development initiatives, rising to this challenge required a truly international and interdisciplinary effort. In order to provide practically useful measures of the uncertainty in climate projections, the uncertainty space of emission scenarios, model parameterisations, model resolution and natural variability needs to be probed *en masse*. This requires co-ordinated involvement from as many climate-modelling groups as possible.

[1] http://prudence.dmi.dk

PRUDENCE succeeded in designing, executing, analysing, and synthesising European high-resolution climate change simulations involving four high-resolution Atmospheric General Circulation Models (AGCMs) and eight Regional Climate Models (RCMs). The majority of the simulations assumed greenhouse gas and aerosol emissions described by the SRES (Special Report on Emissions Scenarios – Nakicenovic *et al.*, 2000) A2 scenario; the remainder applied B2 emissions. All RCMs were run at horizontal spatial scales of ~50 km though a few were also run at ~20km (and one even at ~10km). The "open doors" policy of the project in encouraging the participation of other research groups from Europe and beyond, added two more European RCMs to this list, funded from non-EC sources. Furthermore, all of the climate model results have now been made freely available to the general research community.[1]

Numerous model-based studies have been conducted in Europe to investigate the potential impacts of climate change on natural and human systems. Many of these have been summarised in the European Commission-sponsored ACACIA report (Parry, 2000) and in successive IPCC reports (Beniston *et al.*, 1998; Kundzewicz *et al.*, 2001). The scenarios used to represent future changes in climate vary widely between impact studies, but only in a few cases are the main sources of scenario uncertainty acknowledged, let alone evaluated (*e.g.* Hulme and Carter, 2000; Mearns *et al.*, 2001). There are differences not only in the model projections of climate but in the methods of applying these in impact assessments (Arnell *et al.*, 2003). Moreover, a general perception persists among impact analysts that estimates of impacts at fine spatial scales (*i.e.* sub-GCM-grid scale) should necessarily be based on information about future climate that has been generated at a comparable spatial resolution. There has been a clamour for access to high-resolution projections, either based on statistical downscaling techniques or generated by RCMs such as those employed in this project.

However, it should also be understood that such procedures introduce uncertainties of their own (Giorgi *et al.*, 2001).

Impact studies in PRUDENCE have compared various methods of scenario development and application. They provide convincing new examples that demonstrate how the application of RCM-based scenarios can confer significant advantages over AOGCM-based scenarios in many impact studies. On the other hand, they also indicate that RCMs do not yet provide a universal panacea, and some of the impact studies highlight potential limitations of relying solely on RCM-based information. Clearly, further joint efforts by climate modellers and impacts analysts are needed for sustained progress on these issues.

The urgent need for improved numerical models and scenarios becomes particularly apparent when considering extreme weather events. The importance of extreme events for the European economy and environment has been demonstrated in dramatic fashion during the last few years with a number of serious events affecting the European continent, including major flooding events in central Europe (May 1999 and August 2002), the southern Alps (October, 2000), and the UK (October/November 2000), severe storms accompanied by avalanches in the Alps (February 1999), storm surges in the North Sea (December 1999) and major wind damage in central Europe (December 1999) and Scandinavia (January 2005); and the unprecedented summer heat wave affecting large areas of western and central Europe in 2003. Each of these events caused fatalities and tremendous capital damage.

It is anticipated that future climate change will affect the frequency and magnitude of such extreme events through an intensified hydrological cycle (Stocker *et al.*, 2001). This has been a focal topic in the PRUDENCE model simulations. Some major limitations to model-based studies of these phenomena in the past have been the lack of appropriate spatial resolution (and a consequent smearing out of the character of sub-grid-scale events), the lack of sufficiently long integrations (which drastically reduces the statistical significance of projections), and the lack of co-ordination between different modelling groups (which led to unresolved differences between different studies). These three issues have all been thoroughly addressed in PRUDENCE, using state-of-the-art climate models at a variety of (high) resolutions, a co-ordinated project layout that also addresses critical aspects of uncertainty, and the application of impact models and impact assessment methodologies to provide a link to the needs of society and the economy. Furthermore, model-based results generated in PRUDENCE have already provided scientific background information in the aftermath of some of the above-mentioned extreme weather events (*e.g.* Christensen and Christensen, 2003; Schär *et al.*, 2004).

This special issue of Climatic Change summarises the scientific outcome of the PRUDENCE project. The papers encompass the final results from the six integrated work packages (WP) of the project, comprising the design of the model simulations and analyses of RCM behaviour (WP1), evaluation and intercomparison of simulated climate changes (WP2), specialised analyses of impacts on water resources (WP3) and on other sectors including agriculture, ecosystems, energy, and transport (WP4), investigation of extreme weather events (WP5) and implications of the results for policy (WP6). In addition, PRUDENCE joined with two other related EC-funded projects to form the PRUDENCE-STARDEX-MICE cluster. STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions; Contract EVK2-CT2001-0115), coordinated by Clare Goodess at the University of East Anglia, was concerned with improving statistical downscaling methods for constructing scenarios of changes in the frequency and intensity of extreme events, while MICE

(Modelling the Impact of Climate Extremes; Contract EVK2-CT2001-0018), coordinated by Jean Palutikof, also at the University of East Anglia, made use of information from both dynamically and statistically downscaled methods to explore the potential impacts of extreme events in Europe..

MICE largely utilised results from climate models and the main findings of the project are summarised in this issue by Hanson et al.[2] In contrast, the STARDEX project undertook a systematic and rigorous intercomparison of 22 statistical downscaling (SD) methods, focusing on 10 indices of extreme temperature and precipitation. Since SD is the most common alternative to dynamic downscaling for developing regional climate scenarios, it is instructive to report the main findings of that study here as a complement to the MICE and PRUDENCE results.

A case-study approach was taken in STARDEX[3], encompassing six European regions and Europe as a whole (the latter utilising a new data set of almost 500 daily station time series for the period 1958-2000). Before the different SD methods were applied to output from global climate models, their performance was assessed using reanalysis data. The use of common data sets, calibration/validation periods and test statistics provided a rigorous experimental framework for answering such well-defined questions as: is there any systematic difference in performance of the methods between different seasons, indices and regions, or between direct methods in which the seasonal indices of extremes are downscaled and indirect methods in which daily time series are generated and the seasonal indices then calculated from these?

[2] For more information, see: http://www.cru.uea.ac.uk/projects/mice/
[3] We are grateful to Clare Goodess for providing details of evaluation studies undertaken in the STARDEX project. More information, including scenario results, can be found at: http://www.cru.uea.ac.uk/projects/stardex/

The extent to which these questions can be addressed is limited by the variation in skill from method-to-method, index-to-index, season-to-season and station-to-station, with the latter dominating. This variability means that it is not possible to identify a consistently superior method in the majority of cases. Hence a major recommendation is to use a range of the better statistical downscaling methods for the construction of scenarios of extremes, just as it is recommended good practice to use a range of global and regional climate models in order to reflect a wider range of the uncertainties.

Overall, PRUDENCE represents the first comprehensive, continental-scale intercomparison and evaluation of high resolution climate models and their applications. The results obtained and new insights gained are testimony to the vigorous and multifaceted nature of climate change research in Europe. In demonstrating the feasibility of such a combined "end-to-end" research effort, and in spite of inevitable resource constraints that precluded a full geographical or sectoral coverage of all elements covered in the project, PRUDENCE can justifiably claim to have set a new standard for interdisciplinary climate change research in Europe[4].

---

[4] Since the completion of the PRUDENCE project, research in Europe on the regional impacts of climate change has been largely supported in the Sixth Framework Programme under the priority area Global Change and Ecosystems. The ENSEMBLES Integrated Project (No 505539) is aiming to produce a reliable quantitative risk assessment of long term climate change and its impacts. It includes the development of a high resolution RCM ensemble system (up to 25 km) to be applied for Europe and some other regions. Moreover, two additional projects are focusing on climate change impacts on Central/Eastern Europe. The CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment) project (No 0375005) includes applications of RCMs at a resolution of 10 km in hydrology, water quality and management, air quality, agriculture and forestry. The CLAVIER (Climate Change and Variability: Impact on Central and Eastern Europe) project (No 037013) analyses climate change impacts on weather patterns and extremes, human health, natural ecosystems and water resources, and evaluates the economic impacts on agriculture, tourism, energy and public sector industry and services.

References:

Arnell, N.W. 1996:. Global warming, river flows and water resources. John Wiley & Sons Ltd, Chichester, UK.

Arnell, N. W., D. A. Hudson, and R. G. Jones, 2003: Climate change scenarios from a regional climate model: Estimating changes in runoff in southern Africa. J. Geophys. Res., (108), 4519, doi:10.1029/2002jd002782.

Beniston, M., R.S.J. Tol, R. Delécolle, G. Hoermann, A. Iglesias, J. Innes, A.J. McMichael, W.J.M. Martens, I. Nemesova, R. Nicholls, F.L. Toth, 1998: Europe. Chapter 5 in: Watson, R.T. *et al*. (eds.). *The Regional Impacts of Climate Change: An Assessment of Vulnerability*. A Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 149-185.

Christensen, J.H., O.B. Christensen, 2003: Severe summertime flooding in Europe. Nature, 421, 805-806.

Giorgi, F., B. Hewitson, J.H. Christensen, M. Hulme, H. von Storch, P. Whetton, R. Jones, L. Mearns, C. Fu, 2001: Regional Climate Information – Evaluation and Projections. Chapter 10 in: Houghton, J. *et al*. (eds.). *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 583-638.

Hulme, M. and T.R. Carter, 2000: The changing climate of Europe. Chapter 3 in: M. Parry (Ed.). *Assessment of Potential Effects and Adaptations for Climate Change in Europe: The Europe ACACIA Project*. Jackson Environment Partner, University of East Anglia, Norwich, UK, pp. 47-84.

Kundzewicz, Z.W., M.L. Parry, W. Cramer, J. Holten, Z. Kaczmarek, P. Martens, R.J. Nicholls, M. Öquist, M.D.A. Rounsevell, J. Szolgay, 2000: Europe. Chapter 13 in: *Climate Change 2001: Vulnerability, Impacts and Adaptation* [McCarthy, J. *et al*.

(eds.)]. Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 641-692.

Mearns, L.O., M. Hulme, T.R. Carter, R. Leemans, M. Lal, P.H. Whetton, 2001: Climate scenario development. Chapter 13 in: Houghton, J. *et al.* (eds.). Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 739-768.

Nakicenovic, N., J. Alcamo, G. Davis, B. DeVries, J. Fenhann, S. Gaffin, K. Gregory, A. Gruebler, T.Y. Jung, T. Kram, E. Lebre LaRovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. VanRooijen, N. Victor, Z. Dadi, 2000: *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 600 pp.

Parry, M. (Ed.) 2000: The changing climate of Europe. *Assessment of Potential Effects and Adaptations for Climate Change in Europe: The Europe ACACIA Project*. Jackson Environment Partner, University of East Anglia, Norwich, UK.

Schär C, P.L., Vidale, D. Luthi, C. Frei, C. Häberli, M.A. Liniger, C. Appenzeller, 2004: The role of increasing temperature variability in European summer heatwaves. *Nature*, 427, 332-336.

Stocker, T.F., G.K.C. Clarke, H. le Treut, R.S. Lindzen, V.P. Meleshko, R.K. Mugara, T.N. Palmer, R.T. Pierrehumbert, P.J. Sellers, K.E. Trenberth, J. Willebrand, 2001: Physical Climate Processes and Feedbacks. Chapter 7 in: Houghton, J. *et al*. (eds.). *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 417-470.