Empirical-Statistical Downscaling in Climate Modeling

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Research into possible impacts of a climate change requires descriptions of local and regional climate. For instance, the local and regional aspect of a climate change is stressed in the U.S. Strategic Plan for the Climate Change Science Program (CCSP) (http://www.climatescience.gov/Library/stratplan2003/default.htm). Global climate models (GCMs) are important tools for studying climate change and making projections for the future. Although GCMs provide realistic representations of large-scale aspects of climate, they generally do not give good descriptions of the local and regional scales. It is nevertheless possible to relate large-scale climatic features to smaller spatial scales.

There are two main approaches for deriving information on local or regional scales from the global climate scenarios generated by GCMs: (1) numerical downscaling (also known as "dynamical downscaling") involving a nested regional climate model (RCM) or (2) empirical-statistical downscaling employing statistical relationships between the large-scale climatic state and local variations derived from historical data records.

The former approach is typically computer intensive (requiring a supercomputer) and involves substantial efforts in adapting RCMs to the region of interest and the specific GCM. The latter method, on the other hand, can be done more inexpensively on a workstation or a personal computer. Empirical-statistical downscaling receives little attention in the CCSP document, but because it is quick and inexpensive, it is an appropriate method for generating long time series and for exploring a range of different GCM results. For instance, empirical-statistical downscaling has successfully been applied to multimodel ensembles consisting of different GCM scenarios from the Intergovernmental Panel on Climate Change (IPCC) in order to explore intermodel similarities and differences. The most severe limitation to empirical-statistical downscaling is the requirement that there be an adequate record of past observations for the local parameter of interest, which limits the downscaling to locations where there are observations.

Software Tools

There are several tools available on the Internet for empirical-statistical downscaling. These include SDSM (Statistical DownScaling Model) (freely available from https://co-public.lboro.ac.uk/cocwd/SDSM/) by Dawson and Wilby, and clim.pact (freely available from CRAN (Comprehensive R Archive Network) Web site: http://cran.r-project.org for the R environment [*Ellner*, 2001]; R is a "GNU version of Splus").

Whereas SDSM is written for the Windows environment, R and clim.pact should be able to run on Linux and MacOS as well as on Windows platforms. The clim.pact package contains a bundle of R-functions for computing empirical orthogonal functions (EOFs), plotting climate data, and performing correlation and composite analysis in addition to empirical-statistical downscaling. The clim.pact package is highly flexible, as it is possible for the user to supplement clim.pact functionalities with a large number of other functions from other contributed packages or functions written especially for a particular problem. It can analyze both daily and monthly data.

A range of predictors (independent variables) can easily be incorporated into the analysis if they are stored in the netCDF (http://www.unidata.ucar.edu/packages/netcdf/) format. These predictors can be gridded temperature from the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/temperature/) or reanalysis by the U.S. National Weather Service's National Centers for Environmental Prediction (NCEP) (http://www.cdc.noaa.gov/). The local variable, the predictand (dependent variable), may, for instance, be taken from NASA Goddard Institute of Space Studies Surface Temperature Analysis (http://www.giss.nasa.gov/data/update/gistemp/).

Transient climate scenarios from GCMs can be downloaded from the IPCC Web site (http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html), and these can be converted to the netCDF format and used in the downscaling analysis. There are numerous ways of carrying out empirical-statistical downscaling in terms of different statistical models, such as linear modeling (regression, canonical correlation analysis, or singular vectors), analog modeling, or neural nets. At present, clim.pact incorporates both regression and analog models.

Choosing the Variable

In addition to the choice of statistical model, there are different options for the predictor. Which variable is most suitable for describing the large-scale climatic conditions that are relevant to the location in question? There may be substantial differences in local values derived from different large-scale variables [*Huth*, 2004]. Useful criteria include (1) large-scale parameters with a strong relationship with the predictand that reflect a well-understood physical connection, (2) predictors that are skillfully predicted by GCMs, and (3) parameters that

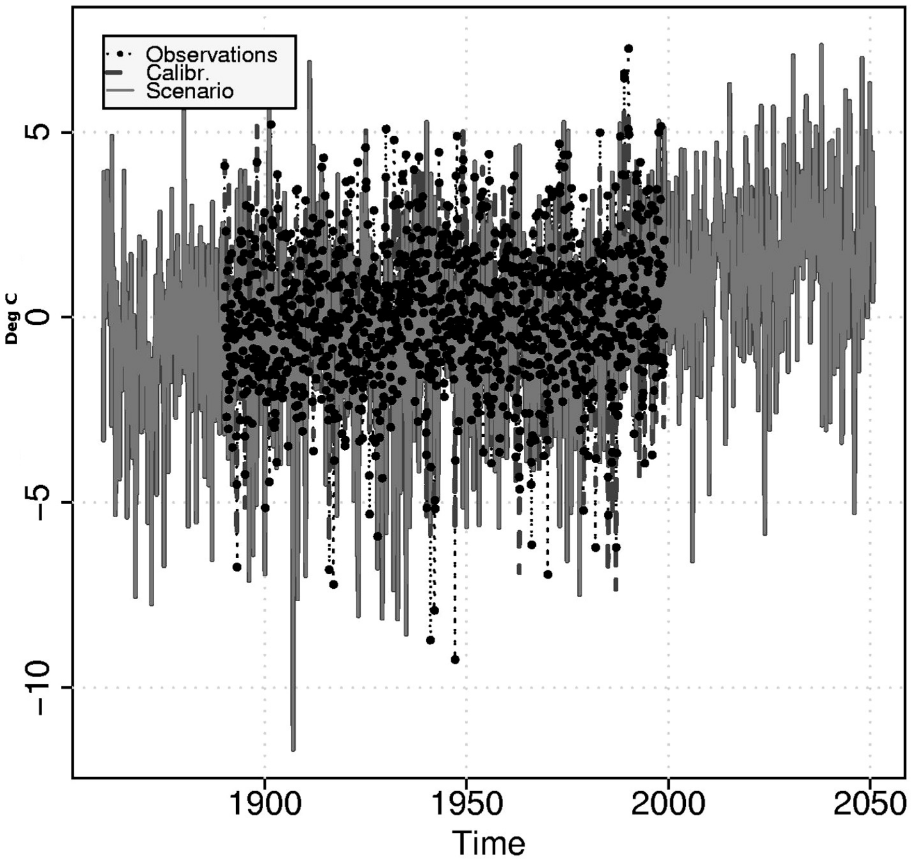

Fig. 1. Example of downscaled monthly 1890–1998 January mean temperature for Oslo-Blindern derived with clim.pact. The example is based on the ECHAM4/OPYC3 model and the IPCC IS92a-based GSDIO integration. (The GSDIO scenario includes the effects of greenhouse gases, tropospheric ozone, and direct plus indirect effects of industrial aerosols). The predictor used for calibration was gridded temperature described by Benestad *[2001].*

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carry the essential signal (e.g., the gradual warming). Some promising candidates are gridded 2-m temperature for local temperatures and gridded large-scale precipitation (e.g., reanalysis) for local precipitation. The sea level pressure, on the other hand, does not give an adequate description of the thermodynamic changes associated with a global warming.

There are a number of choices for relating GCM results to actual observations (gridded values). It is possible to match spatial patterns in the simulations with observed modes that are relevant to a specific local parameter in different ways. The data may first be processed though an EOF analysis and then projected onto the observations [*Heyen et al*, 1996], or the downscaling may be a regression against the respective grid point values where the grid point values in the GCMs are considered as representative of the corresponding values in the gridded observations.

Other approaches use so-called circulation indices [*Wilby et al.*, 1998]. *Benestad* [2001] has suggested using a common EOF framework which is incorporated into clim.pact. Common EOFs are mathematically similar to ordinary EOFs, but differ in the way the data have been preprocessed, e.g., that the data contain a combination of both observations and simulations. It is also possible to apply methods similar to those of *Heyen et al* [1996] or circulation indices in R and clim.pact.

It can easily be shown that an inappropriate choice of predictor domain can give misleading results. Although *Huth* [2002] found that the size of the domain on which predictors are defined is not important for central Europe in terms of explained variance, *Benestad* [2001] demonstrated that a predictor domain covering only northern Europe may produce cooling over western Greenland in a warming world. The empirical-statistical model in this case latches onto the east-west dipole temperature structure associated with the North Atlantic Oscillation (NAO), for which temperatures over Greenland tend to be anticorrelated with those over northern Europe.

The most recent version of clim.pact (v2.1-3) offers an objective criterion for selecting the predictor domain, by examining maps of correlation coefficients between the predictand and the predictor grid point values, and defining the domain according to where the correlation goes to zero.

Because empirical-statistical downscaling usually does not reproduce the variance (often measured in terms of R^2 in the observations), so-called "inflation" has sometimes been used, although this kind of postprocessing is controversial. With a common EOF approach, adjustment of GCM predictors for the calibration period, and predictors that are closely related to the predictand, clim.pact can produce local scenarios with variance close to that of the original series without the need of inflating the values. Figure 1 shows an example of a downscaled time series clim.pact (grey) together with the observed values (black). Both series describe similar variance.

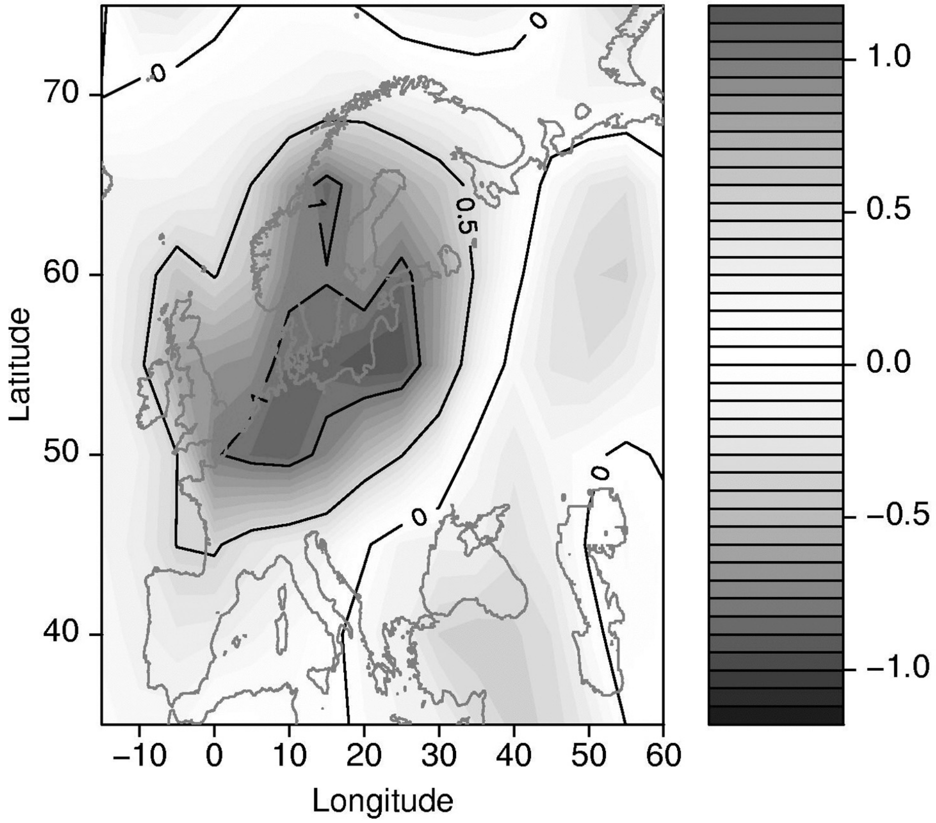

Fig. 2. The large-scale T(2m) pattern associated with January mean temperature anomalies at Oslo-Blindern, Norway, for the downscaling in Figure 1. The units are degrees Celsius and are obtained by taking the regression coefficients to construct a pattern that goes with a 1°C local temperature anomaly.

Perceived Disadvantages

A common objection to empirical-statistical downscaling is that it may be limited by the assumption of stationarity. It is possible to examine the empirical-statistical models for such shortcomings, and *Benestad* [2001] tested a downscaling model by taking one GCM grid point value as the predictand and using one half of the GCM results to calibrate the model. An evaluation against the second half (warmer climate) did not give any indication of significant nonstationarities present in the modeled relationship between the large and small spatial scales. *Murphy* [1999] compared the results from numerical and empirical-statistical downscaling and reported similar levels of skill. *Hanssen-Bauer et al* [2003] examined RCM-based and empirical-statistical downscaling results and found them to be similar. Hence the statistical relationships between the large and local scales in the past appear to hold in a perturbed climate.

In principle, empirical-statistical relationships between large and small spatial scales are not any more prone to nonstationarities than parameterization schemes and bulk formulae used in both GCMs and RCMs (for certain choices of predictor variables, e.g., using large-scale surface temperature to predict local temperature). However, nonstationarity can, in fact, be a greater problem in the GCMs. It is important to keep in mind that some predictor choices may entail nonstationarities, such as using geopotential height to derive local surface temperature.

Another objection to empirical-statistical downscaling is a lack of consistency between locations and different parameters. The use of analog models in downscaling can produce local scenarios that are consistent within a certain region. Furthermore, GCMs and RCMs often have similar shortcomings, as both tend to exhibit systematic biases. The choice of parameterization schemes or the various ways they describe, e.g., sea ice yield different details in climate reconstructions, and the need for flux correction in many GCMs is direct evidence of model inconsistencies (an increasing number of GCMs are run without the need of flux correction).

Numerical and empirical-statistical downscaling have different strengths and weaknesses and the most appropriate method will depend on the use. In most cases, it is helpful to use inexpensive and relatively simple empirical-statistical downscaling in addition to using RCMs to downscale GCMs.

Empirical-statistical downscaling can be viewed as part of an analysis that provides valuable diagnostics that can illuminate various aspects of the GCMs and relate these to the real world. Figure 2 shows an example of some diagnostics obtained through empirical-statistical downscaling. In this case, January temperature anomalies in Oslo, Norway, are associated with a large-scale temperature anomaly covering most of southern Scandinavia.

Despite empirical-statistical downscaling only being barely mentioned in the CCSP report, both clim.pact and SDSM are useful tools for climate research where regional to local scales are important. Empirical-statistical downscaling complements nested modeling and provides a valuable independent approach for studying local climates.

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Earth Science and Applications From Space: A Community Assessment and Strategy for the Future

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The Space Studies Board, in consultation with other units of the U.S. National Research Council (NRC), has begun a study to generate prioritized recommendations from the Earth and environmental science and applications community regarding a systems approach to the space-based and complimentary observations that encompasses the research programs of NASA and the related operational programs of the National Oceanic and Atmospheric Administration (NOAA).

The study, which will be carried out over a 2-year period and is organized in a manner similar to other NRC "decadal surveys," will seek to establish individual plans and priorities within the subdisciplines of the Earth sciences, as well as an integrated vision and plan for the Earth sciences as a whole. It will also consider Earth observations requirements for research and for a range of applications with direct links to societal objectives. Richard Anthes and Berrien Moore have been appointed by the NRC as study cochairs.

An open Web site (http://qp.nas.edu/decadalsurvey) has been created to describe the study and to provide an opportunity for community input throughout the study process. In addition, a number of outreach activities are planned, including community forums in conjunction with the AGU 2004 Fall Meeting and the January 2005 meeting of the American Meteorological Society.

The confluence of several factors prompts this study, including:

1. NASA is nearing completion of the deployment of the Earth Observing System (EOS) and is now considering an appropriate strategy for follow-on exploratory and systematic missions.
2. In the coming decade, NASA plans to transition a number of environmental measurements from research-oriented programs to operationally-oriented programs.
3. In the coming decade, NOAA will launch the National Polar-orbiting Operational Environmental Satellite System (NPOESS)—successors to the current generation of civil Polar Operational Environmental Satellite (POES) and military Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites—which will be used to monitor global environmental conditions and collect and disseminate data related to weather, atmosphere, oceans, land, and the near-space environment.
4. The United States is leading the development of a Global Earth Observing System of Systems (GEOSS; see http://usinfo.state.gov/gi/Archive/2004/Aug/18-488169.html).

Earth observation systems are providing valuable data, particularly in the areas of improved weather forecasts, El Niño predictions, earthquake and volcanic eruption precursors, and ecological assessments. However, additional and higher-quality observations are needed to address a wide range of applications, including climate monitoring and modeling, agriculture and forest management, water and energy resource management, watershed and marine ecosystem management, disaster management support, and sustainable development, and to meet the needs of international environmental conventions.

Solutions to these challenges will require advancements in both remote sensing capabilities and in situ observational techniques. Acquisition, quality control, processing, assimilation, summarization, dissemination, and preservation of the vast array of environmental data that will be generated by national and international sources pose a further challenge.

On 23–25 August 2004, the NRC held a workshop in Woods Hole, Massachusetts, to help organize the study (see the study Web site for details and summary). At the workshop, there was general consensus that the study be led by an executive committee and seven panels, each organized along the following societal themes: 1. Earth science applications and societal needs; 2. land-use change, ecosystem dynamics, and biodiversity; 3. weather (including space weather and chemical weather); 4. climate variability and change; 5. water resources and the global hydrologic cycle; 6. human health and security; and 7. solid-Earth dynamics, natural hazards, and resources.

With this structure, disciplines such as oceanography and atmospheric chemistry, although not visible in the title of a given panel, will influence the priorities of several panels, not just one. All panels will interact with the executive committee throughout the study process. The chairs of each of the panels will be members of the executive committee. Additional members of the executive committee will represent the private sector, government, nongovernmental agencies, and the broad scientific and user communities.

The study is intended to be a community assessment; broad and active participation by the Earth science community is essential for the success of this effort, which will affect the scientific research and operational communities, and society at large, for many years.

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