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PAGES 337–348

Developing Perturbations for Climate Change Impact Assessments

PAGES 337, 341

Following the 2001 Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [*TAR; IPCC*, 2001], and the paucity of climate change impact assessments from developing nations, there has been a significant growth in activities to redress this shortcoming. However, undertaking impact assessments (in relation to malaria, crop stress, regional water supply, etc.) is contingent on available climate-scale scenarios at time and space scales of relevance to the regional issues of importance. These scales are commonly far finer than even the native resolution of the Global Climate Models (GCMs) (the principal tools for climate change research), let alone the skillful resolution (scales of aggregation at which GCM-observational error is acceptable for a given application) of GCMs.

Consequently, there is a growing demand for regional-scale scenarios, which in turn are reliant on techniques to downscale from GCMs, such as empirical downscaling or nested Regional Climate Models (RCMs). These methods require significant skill, experiential knowledge, and computational infrastructure in order to derive credible regional-scale scenarios. In contrast, it is often the case that impact assessment researchers in developing nations have inadequate resources with limited access to scientists in the broader international scientific community who have the time and expertise to assist. However, where developing effective downscaled scenarios is problematic, it is possible that much useful information can still be obtained for impact assessments by examining the system sensitivity to larger-scale climate perturbations. Consequently, one may argue that the early phase of assessing sensitivity and vulnerability should first be characterized by evaluation of the first-order impacts, rather than immediately addressing the finer, secondary factors that are dependant on scenarios derived through downscaling.

By Bruce Hewitson

The necessity for downscaling then becomes an activity justified on the basis of needs and understanding not addressed through initial sensitivities based on the large-scale perturbations. This assessment of the first-order sensitivity of a regional response develops the essential base understanding for further impact studies, and is as important in developed as well as developing nations.

For climate change issues, there is much uncertainty implicit in the choice of GCM and greenhouse gas forcing scenarios; an uncertainty further compounded by the additional complications introduced by downscaling. This further supports the argument that initial steps in impact studies are better served by regional-scale scenarios that are plausible perturbations of the current climate, and which access the future climate envelope, sidestepping factors such as optimal downscaling solutions. To this end, a methodological approach that produces climate perturbations that relate to the skill resolution of a GCM, and is thus guided by the large-scale response simulated by the GCM, may be a more robust means to address the initial sensitivity questions in impact assessment research.

A particular problem has arisen in this regard with the advent of the ready availability of GCM climate change products on the Internet. The provision of grid cell resolution GCM output invites the use of these at the GCM grid scale. However, the skill resolution of the GCM is typically some spatial and temporal aggregation of the native GCM resolution. "Skill" in this context may be considered the spatial and temporal scales of aggregation where the error between GCM output and observational data does not preclude its use in a given application. For example, comparison of a GCM grid cell value with point station observations is not valid. Even after aggregating station data to estimates of area averages comparable to a grid cell average (a problematic process itself), one still finds significant errors between the GCM and the observations for parameters such as the number of rain days, or for determining frost occurrence, etc. As GCM grid cells are aggregated, however, one finds that the GCM output and the comparable observational data begin to converge. At the final level of aggregation, the global mean GCMs have been shown to track temperature well even over the last century.

Nonetheless, for the unaware, the simplest means of obtaining a regional climate change scenario is to use the values of the GCM grid cell most co-located with the region of interest, possibly interpolating this further to a point location. Apart from the fact that GCM grid cells are area averages and not point values, the GCM grid cell value is typically well below the skill scale of the model, especially with regard to precipitation—the variable most often required. This exacerbates the uncertainty associated with any derived regional-scale climate change scenario, and reduces the value of any impact assessment intended for developing policy and adaptation strategies.

Presented here is a simple approach for regional scenarios appropriate to the user needs described above. Using GCM simulation output of future climate change, at spatial and temporal scales more associated with the GCM skill resolution, one may develop "guided perturbations"—perturbations to baseline observational data that are guided by, or in accordance with, the GCM large-scale anomaly under future climates. This allows the impacts researcher to investigate vulnerability and potential consequences of climate change at the relevant regional scales, using a perturbation of the present climate that is guided by the indicated change from the GCM. Further, this avoids potential errors associated with using raw GCM grid cell output, requires minimal statistical or modeling expertise and infrastructure, and supports the development of an initial understanding of regional sensitivity prior to drawing on more advanced downscaling techniques.

Methods

The approach to developing GCM-guided perturbations is conceptually simple, and readily undertaken with basic computational infrastructure and skills. Primarily, one seeks to draw useful information from the GCM while accommodating the systematic bias of different GCMs. The "useful information" here refers to the first-order (spatial large-scale) response of the GCM to greenhouse gas forcing. This has the immediate benefit of avoiding the problems associated with the validity of

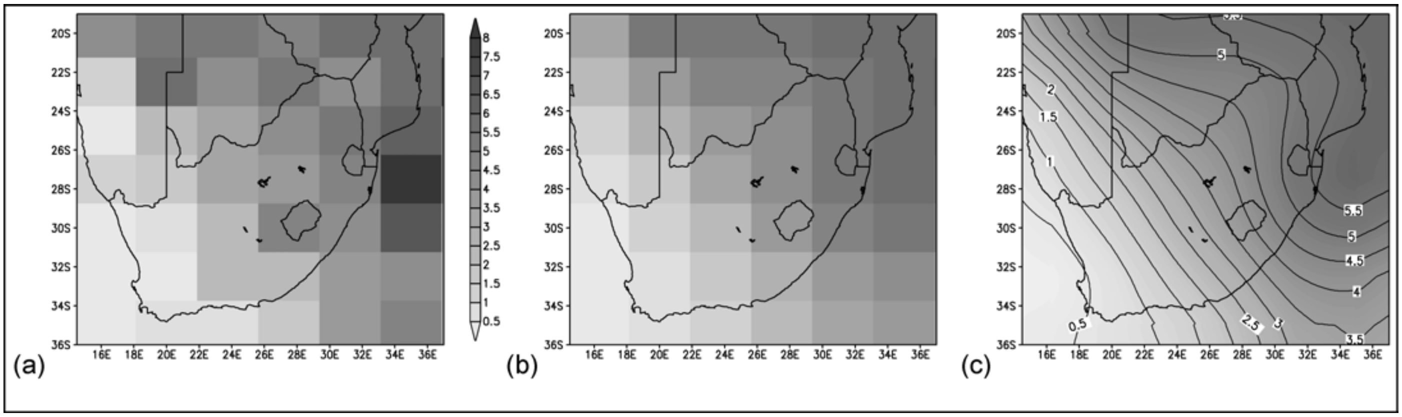

Fig. 1. HadCM3 30-year precipitation climatology (mm/day) for the control climate (a), and smoothed with a spatial moving average (b). Panel (c) shows the bi-cubic spline surface fitted to the smoothed data of panel (b).

single-grid cell values. In essence, this approaches the regional climate change question from the view that there is a spatial large-scale change signal that is closer to the skill resolution of the GCM than individual grid cells, and which provides a first-order anomaly for an impact assessment sensitivity study. It is explicitly recognized that there will be additional local-scale variance of the climate change signal, but this remains the subject for subsequent and more refined impact assessment research.

Inherent in using the GCM climate change output is that significant uncertainty arises from differences in GCMs. This is due in part to differing model physics parameterization of sub-grid scale processes. These differences are reflected in various systematic biases and climate sensitivities to greenhouse gas forcing. The inter-model differences are important, and reveal a measure of the uncertainty envelope of projected future climate change. However, the systematic bias and spatial errors in GCMs obscure the climate change signal. The simple methodology outlined here addresses these issues in a manner appropriate to the objectives outlined earlier for early phases of impact assessments. Only a brief outline of the procedural steps is presented, as the method is simple. Full details are available in the support documentation for the Africa guided perturbation products on the Internet (available late-2003, see http:// www.csag.uct.ac.za/AIACC).

The summary procedure, however, is as follows:

1. Derive a large-scale spatial response surface from the GCM using a simple spatial filter. In this example, a spatial 3 x 3 grid cell moving average is used on the control and future GCM simulation output. Figure 1a shows the unmodified GCM 30-year current climate climatology (1970–1999) from the HadCM3 GCM over southern Africa for the December-February (DJF) season. The same field smoothed with a 3 x 3 spatial smoother (panel b), and the large-scale response surface using a bi-cubic spline is applied to the data in panel (c).

2. Express the climate change anomaly as the difference between the large-scale response (spline) surfaces of the present and future climate simulations, thereby removing systematic bias which affects both the seasonal and spatial magnitudes of the anomaly and facilitating comparison between models. For precipitation this may then further be expressed as a percentage change (anomaly divided by the GCM control climatology), which is a typical treatment of precipitation anomalies in climate change studies (conversely, temperature is more typically treated in terms of absolute anomaly). In this discussion we focus on precipitation, which is commonly the variable of greatest concern. Figure 2 shows the climate change percentage anomaly for DJF for two GCMs, the HadCM3 and the ECHAM4-OPYC GCMs, using the bi-cubic, spline-fitted surface.

3. Perturb the observational climatology by the fractional change indicated by the GCM spline-fitted surface of the large-scale percentage anomaly. This may be applied to observational data at any spatial scale—from station observations to gridded products. Temporal scales should be limited to some time average greater than daily (where GCMs have low skill in reflecting observed climate variability).

In this example, the focus is on the DJF seasonal mean; and subjectively, it is suggested that monthly means are likely to be close to the finest temporal resolution one should use. In the example here, the GCM percentage anomalies are applied to an experimental, high-resolution, 10-km gridded precipitation climatology for South Africa, demonstrating the application of the perturbation on a fine spatial resolution for a developing nation.

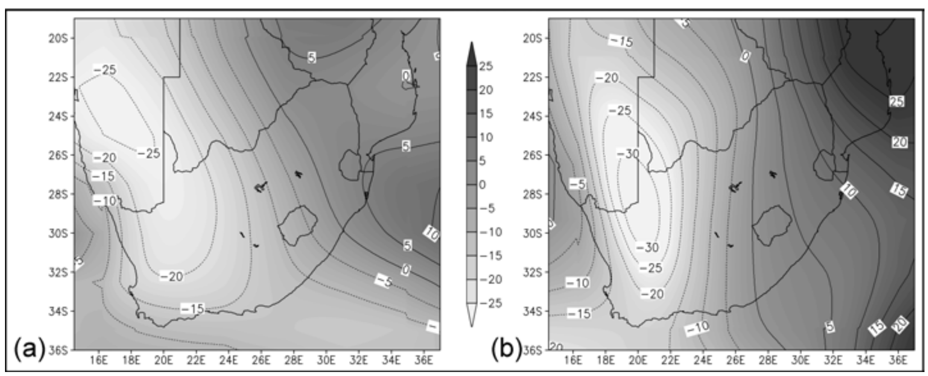

Fig. 2. Precipitation percentage change for DJF from the spline surface fitted to the current and future climate means for (a) HadCM3 and (b) ECHAM4. Dashed lines are negative.

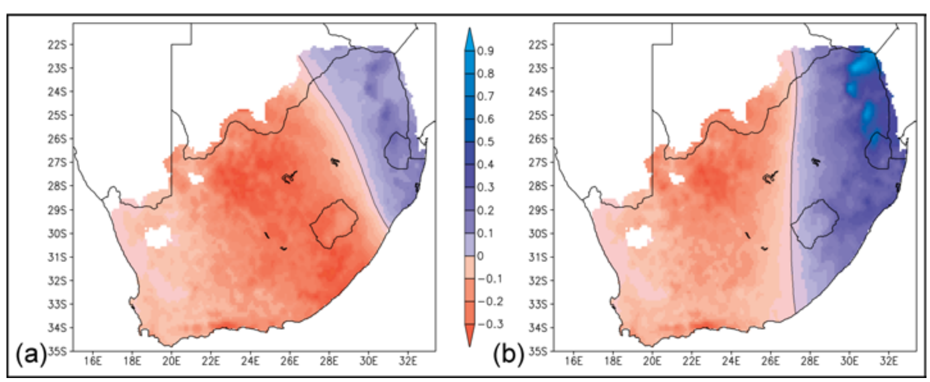

Fig. 3. Precipitation anomaly (mm/day) of the DJF baseline climatology using the GCM percentage change. This represents a guided perturbation of the current observed climate, guided spatial large-scale anomaly from (a) the HadCM3 and (b) the ECHAM4 models.

The final GCM-derived perturbation of the baseline climate (GCM percentage anomaly x baseline observed climate) is shown in the panels in Figure 3.

Assessment and Caveats

By using the GCM percentage change, the derived absolute magnitude of the perturbation is naturally a function of the magnitude of the baseline climatology. Consequently, when comparing Figures 2 and 3, it is apparent that the spatial expression of the derived anomaly has differences even where the spatial component of GCM large-scale anomaly field is the same for different locations. The perturbation thus captures the spatial differences of the existing climate, while maintaining agreement with the large-scale response of the GCM, the scale better associated with the model skill, as opposed to the single-grid cell values. Of note here is that the two models in Figure 3, which have notable differences in their control climatologies (not shown), indicate a degree of convergence in the regional anomaly pattern as derived here. Both models clearly indicate similar west-east patterns of wet-dry anomalies, and the HadCM3-derived anomaly is, to a large extent, very similar to a "dry-shifted" ECHAM4-derived anomaly.

Such agreement does not necessarily indicate that the models are right in their future projection of climate, but does suggest that there is some common response, giving credibility to the plausibility of the anomaly. For impact assessment research, this is exactly what is needed in initial studies; namely, that one has a plausible, credible perturbation on which to develop initial understanding of the regional sensitivities to climate change forcing.

Thus, assuming that regional climate boundaries do not undergo dramatic lateral shifts, the results suggest that this approach provides a future climate perturbation at spatial scales appropriate for initial sensitivity studies in a range of impact assessment activities. Related to this is the important requirement that the GCM does not misplace, or fail to resolve, fundamental physical climate boundaries. For example, if the GCM allows one climate domain (say, maritime) to extend into the adjacent but different climate region (say, continental arid zones), this will result in inappropriate application of the GCM anomaly in that region. This serves to highlight the need to carefully evaluate the GCM fields prior to application.

Finally, although this is not a downscaled product, and does not include local feedbacks and other forcings under future climates, it does represent a regional-scale perturbation in accord with the GCM first-order response to greenhouse gas forcing. Using this approach with a range of GCMs allows one to undertake an assessment of fundamental regional sensitivities to climate change that are not arbitrary, but guided by the envelope of future climate, as characterized by GCMs. The approach is computationally simple and appropriate for a broad range of researcher sectors. The procedure is equally applicable to large areas and for single station time series, and lends itself to data-sparse regions, as commonly found in developing nations. Hence, especially for many developing regions (although not excluding impact assessment work in developed nations), this approach serves to provide a first look at the regional climate change envelope.

Reference

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Geophysical Project in Ethiopia Studies Continental Breakup

PAGES 337, 342–343

As continental rift zones evolve to sea floor spreading, they do so through progressive episodes of lithospheric stretching, heating, and magmatism, yet the actual process of continental breakup is poorly understood. The East African Rift system in northeastern Ethiopia is central to our understanding of this process, as it lies at the transition between continental and oceanic rifting [*Ebinger and Casey*, 2001].

We are exploring the kinematics and dynamics of continental breakup through the Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE), which aims to probe the crust and upper mantle structure between the Main Ethiopian (continental) and Afar (ocean spreading) rifts, a region providing an ideal laboratory to examine the process of breakup as it is occurring. EAGLE is a multidisciplinary study centered around the most advanced seismic project yet undertaken in Africa (Figure 1). Our study follows the Kenya Rift International Seismic Project [e.g., *KRISP Working Group*, 1995], and capitalizes on the IRIS/ PASSCAL broadband seismic array [*Nyblade and Langston*, 2002], providing a telescoping view of the East African Rift within this suspected plume province.

EAGLE fieldwork was undertaken between October 2001 and March 2003. Many results will be presented in a session at the "The East African Rift System: Development, Evolution and Resources" Meeting to be held in Addis Ababa in June 2004. The lead Ethiopian institutions were the Geophysical Observatory, the Department of Geology and Geophysics of Addis Ababa University, the Ethiopian Geological Survey, and the Petroleum Operations Department of the Ethiopian Ministry of Mines. The lead European and U.S. institutions were the universities of Leicester, Royal Holloway London, Leeds, and Edinburgh, together with Stanford, the University of Texas, El Paso, Southwest Missouri State, and Penn State universities. The entire project was coordinated in Ethiopia by the Commission of Science and Technology of the Democratic Republic of Ethiopia.

Models for Continental Breakup

The three-dimensional structure of oceanic rifts is primarily controlled by the supply of magma [e.g., *Phipps-Morgan and Chen*, 1993], whereas that of youthful continental rifts is controlled by the spatial arrangement of large displacement border faults [e.g., *Hayward and Ebinger*, 1996]. Thus, magmatic processes increase in importance as rifting proceeds to sea floor spreading, but there is no consensus as to when or how this transition occurs. The volume of melt produced and its seismic velocity structure provide critical constraints on mantle dynamics as continental breakup proceeds to sea floor spreading, but there remain fundamental questions regarding the three-dimensional distribution of strain and melt as continents rift apart.

Our approach in EAGLE is to examine the nature of crust and upper mantle along a highly extended, magmatically active continental rift prior to the modifying effects of post-rift sedimentation, erosion of the uplifted rift flanks, and thermal decay. In the Ethiopian Rift we can (1) trace the evolution from broadly distributed to focused strain during rift development; and (2) study the active processes of continental breakup associated with a mantle plume (or other upper mantle convective upwelling), while avoiding interactions between subducted slabs and asthenospheric flow; the region has been tectonically stable since 600 Ma.

Ethiopia-Afar Rift Zone

There is general agreement that the broad uplifted Ethiopia-Yemen plateau and Oligocene flood basalt province have been affected by one or more Cenozoic plumes [e.g., *Nyblade and Langston*, 2002]. A synthesis of $^{40}Ar/^{39}Ar$ data shows that flood basalts were erupted across an ~1000-km diameter region at ~31 Ma, presumably coincident with plume head contact with Afro-Arabian lithosphere [e.g., *Hofmann et al.*, 1997]. Previous geophysical studies show crustal thinning northward into the Afar depression. Refraction profiles in Afar, interpreted as near-one-dimensional structures due to the very small number of shots and receivers, suggest thinned 25-km-thick crust underlain by a 10-km-thick layer with anomalously low upper mantle P-wave velocities above apparently normal mantle [*Berkhemer et al.*, 1975].