RECONCILING ALTERNATIVE APPROACHES TO PROJECTING HYDROLOGIC IMPACTS OF CLIMATE CHANGE*

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Progress in the projection of hydrologic impacts of anthropogenic climate change (ACC) call for reassessing and documenting the state of the art. At this workshop, we placed a particular emphasis on understanding how consistency in the surface energy budget can be maintained, or lost, depending on how general circulation models' internal calculations of hydrologic variables mesh with offline hydrologic models driven by their climatic variables (Lofgren et al. 2011; Sheffield et al. 2012). The science of projecting hydrologic impacts of climate change links the disciplines of meteorology (applied to long-term climate) and hydrology, yet these disciplines typically employ different perspectives on surface hydrological processes, leading to different modeling methods and means of linking models (Gronewold and Fortin 2012). To begin to resolve these inconsistencies, the workshop was structured around the following organizing questions:

1) How do we bridge the gap between climate projection and hydrologic projection?
2) How do we serve the data needs of the hydrologic and meteorological communities in a mutually consistent way?
3) What is the role of empirical and process-based models in a nonstationary regime?
4) How do we educate researchers and the general public about relevant caveats in simulations of hydrologic impacts of climate change?

THE WORKSHOP ON METHODOLOGY FOR PROJECTION OF HYDROLOGIC IMPACTS OF CLIMATE CHANGE

WHAT: Forty-one hydrologists and meteorologists discussed the intersection of these disciplines, especially as applied to issues and impacts of climate change.
WHEN: 27–29 August 2012
WHERE: Muskegon, Michigan

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BRIDGING CLIMATE AND HYDROLOGICAL SCIENCE. Efforts to converge on a consistent answer to the question of how to bridge the gap between projections of climate and hydrology have important implications for human and environmental health, ranging from an understanding of soil moisture dynamics in both agricultural and natural landscapes and groundwater recharge and aquifer levels, to flow and stage variations in streams and water level changes over large lakes and coastal wetlands. Effects on these systems can be further divided into effects on mean conditions and on frequency and magnitude of extreme conditions.

Some of the key difficulties in making this linkage in a satisfactory way were summarized as 1) the handoff problem; 2) the overlap problem; 3) the feedback problem; and 4) the problem of progress. Put briefly, how do we determine what variables to pass between simulations of climate and hydrology and what are the relevant spatial and temporal scales? How do we deal with the fact that climate models and hydrologic models each calculate evapotranspiration (ET), but have often been linked together in ways such that each can arrive at a very different quantitative answer? How do we deal with the fact that atmospheric and surface processes mutually affect each other (i.e., hydrologic responses are not simply caused by climate change, but are themselves a part of climate change), but this two-way interaction can be inconvenient to model and is often ignored? Finally, if you have solved all of these other problems but a new advance alters some aspect of the overall climate–hydrology simulation technique, does the rest of the system need to be reevaluated?

Issues of spatial and temporal scales are important in understanding hydrologic responses to anthropogenic forcing. Changes in land use and land cover can occur on a variety of scales. This can cause not only direct effects on surface hydrology but also changes in atmospheric boundary layer structure and consequent mesoscale circulations (e.g., Kumar et al. 2013).

As another example of the importance of scale, the proportion of precipitation that occurs in very heavy events has been observed to increase, and this is believed to be linked to ACC (e.g., Pryor et al. 2008). Rainfall events that were at the 99th percentile during the period 1901–60 have increased greatly in frequency throughout the eastern and central parts of the contiguous United States, with a large part of this increase due to tropical storms and extratropical fronts. Despite the importance of extreme events and land-use effects, the spatial resolution of even the finest-scale climate models currently available limits their ability to address these questions.

DIFFERING OUTPUT PRIORITIES AMONG SCIENTIFIC DISCIPLINES. Both the atmospheric and hydrologic modeling communities need to calculate ET at the surface, but have different end goals in mind when they do so. Hydrologists are primarily concerned with how much water is left over, which can ultimately lead to groundwater recharge, streamflow, erosion, flooding, etc. Atmospheric modelers are more interested in ET as it directly supplies water vapor to the atmosphere and, of equal importance, how it constitutes a sink of energy from the surface in the form of latent heat flux and the way in which the latent heat flux can modulate the outward longwave radiation and sensible heat flux. These differing priorities for outputs have led to different methods of calculating ET.

Methods such as the soil–vegetation–atmosphere transfer schemes (SVATs) that are now standard within atmospheric models, as well as the Penman–Monteith method and others, have strong theoretical underpinnings, grounded on the conservation of energy at the surface. However, in more operational settings, radiation measurements are not generally available. This has led to the development of methods that use air temperature as a primary input, and posit a proxy relationship between air temperature and potential evapotranspiration (PET)—that is, the amount of ET that would occur in the absence of soil moisture limitation. A prominent example of this type of formulation, on which many others have been based, is Thornthwaite (1948). However, when this type of algorithm is applied to ACC scenarios based on modeled air temperatures, the overlap problem is engaged, and two models intended to simulate the same system can generate strongly divergent ET and surface energy budgets (Lofgren et al. 2011).

EMPIRICAL AND PROCESS-BASED MODELS. For the reasons enumerated in the previous section, there are serious caveats underlying the use, in climate change scenarios, of hydrologic models based on empirically calibrated air temperature proxy relationships for PET. In scenarios of land-use change, these caveats are perhaps even more important, especially if calibration is done only with respect to location and ignoring land use.

However, the process-based simulation schemes within most climate models also need to be used with caution. Shortcomings in these models stem from imperfections in hydrologic formulations, as well as atmospheric processes, particularly clouds, along with uncertainties in future greenhouse gas concentrations and land use. Processes simulated on climate model grids may not be representative at smaller scales.

Ideally, the atmospheric and hydrologic communities will recognize that the surface–atmosphere interface is of common interest, and increasingly coordinate their efforts at studying, understanding, and modeling processes that occur there. Coordinated understanding, methodologies, and results in a coupled system context will be beneficial to both groups. Increased availability of surface radiation data may promote the use of surface energy budget-based methods, and increase the community's level of comfort with them.

Especially in near-real-time applications, improvement in simulation of variables such as ET and snow water equivalent can be achieved by assimilation of variables such as precipitation, soil moisture, and streamflow from gauges, radar, and satellites.

INFORMATION TRANSFER TO DECISION MAKERS. When passing information on climate change and its impacts to decision makers, it is imperative to include advice on uncertainty. While quantitative uncertainty estimates are not always feasible or even appropriate, even for scientific audiences, information regarding uncertainty can be useful to decision makers when expressed qualitatively or in terms of expert opinion with a subjective element.

Among the known uncertainties are differences among existing climate models based on their exact formulations, feedback involving high-latitude snow and ice sheets, and the range of possible concentrations of greenhouse gases. With greater time horizons come increased chances of "big surprises"—sudden and nonlinear shifts in environmental systems.

Use of oceanic states as an initial-value problem is potentially opening up the frontier for projections on the 1–10-yr time scale (Meehl et al. 2009). This presents new opportunities to meet user needs and presents challenges to the understanding of the interface between the atmosphere and the surface. Some "handles" based on surface conditions that can aid in climate projections at these temporal scales are the memory inherent in soil moisture and storage in water bodies and aquifers, as well as the relatively high predictability of land-use change on scales of a few years.

A succinct description of the current state and future needs in the science linking climate change and hydrologic impacts is contained in one presenter's list of "helpful hints": past performance of models does not guarantee future results, ensure that energy is conserved within models, consider feedbacks, and limit your expectations.

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