

Reply to comment by Keith J. Beven and Hannah L. Cloke on “Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth’s terrestrial water”

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1. Introduction

[1] The authors of *Wood et al.* [2011, hereafter W2011] would like to thank *Beven and Cloke* [2012, hereafter BC2012] for furthering the discussion about the pathway toward a global-scale hyper-resolution water-energy-biogeochemistry land surface modeling capability: its need, feasibility and development. Their comment brings focus to the discussion and shows that the proposed challenge to our community is one element in a long history of hydrology

model developments with the goal to improving hydrologic predictions and understanding.

[2] What is laid out in W2011 is, first and foremost, a grand challenge because (1) there is a grand need, (2) there are great new opportunities, and (3) if the hydrologic community does not do it someone else will do it, albeit poorly. The reader is directed to W2011 for a discussion of the growing need for continental-scale land surface models that consider improved, scale-appropriate parameterizations of the water, energy and biogeochemical cycles at resolutions on the order of 10^2 to 10^3 m grid resolutions. Some examples are presented, which were not meant to be comprehensive in their scope of detail, that include surface-subsurface interactions, land-atmospheric interactions and coupling, water quality that includes nonpoint pollution, and human impacts that include water management, land cover change and the effects of climate change.

[3] The commentary by BC2012 focuses on just one challenge or building block described in W2011: the issue of parameterization of subgrid heterogeneity and the resulting uncertainty—what they refer to as “epistemic uncertainty.” BC2012 interprets the Grand Challenge in W2011 as “simply moving to finer resolutions.” This is not what W2011 says or proposes. There are many new building blocks available for the research into hyper-resolution modeling: (1) new data sources and measurement techniques for precipitation, topography, vegetation cover, soils, but also soil moisture, evapotranspiration, water storages (rivers, lakes, groundwater storages, soil moisture); (2) new physics—new sets of governing equations, including new approaches to developing closure relations; (3) new approaches to handling known and unknown uncertainties in model structure, variables and numerics, including characterizing subgrid heterogeneity (including new ways to capture their effects) based on new insights into ecohydrology and hypopedology and approaches that utilize the coevolution of climate, soils, vegetation and topography; (4) new approaches that can better include nonlinear feedbacks between various subsystems, and local, regional and global cycles and teleconnections; (5) new regionalization efforts aimed at learning from comparative analysis across climatic, geologic and human-impact

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gradients, and (6) new data assimilation techniques which can contribute to improvements in models and observations, including uncertainty quantification.

[4] This requires coordinated and long-term commitments by all—individual researchers, research groups, agencies—and the proposed challenges transcend approaches the hydrologic community has followed, based on individual places (aquifers, hillslopes, catchments), where the focus is on validating localized models by means of calibration with local data. The paradigm must shift to deal with these new challenges. This is what we have stated in the opinion paper.

[5] The issues of epistemic uncertainty raised by BC2012 are well described in the literature. We agree with BC2012 that they apply at virtually all modeling scales, but research in addressing these are well pursued under “scale issues” in the Project for Ungauged Basins (PUB) and in various other contexts over the last 25–30 years (e.g., *Wood et al.* [1988] where, with the senior author of the comment, the concept of Representative Elementary Area was proposed to represent epistemic uncertainty at scales below 1 km²). Many of BC2012’s concerns are areas of active research where important advances have been reported. For example, there are major advances in the direction of developing sound closure relations to account for *known* heterogeneities, as shown in several journal special issues (e.g., *Hydrol. Earth Sys. Sci.:HESS, Zehe and Sivapalan* [2007]; *JGR-EP, Fofoula-Georgiou and Stark* [2010]), as well as specific papers [e.g., *Schulz et al.*, 2006; *Harman et al.*, 2010]. Likewise, there is considerable effort at developing novel approaches for addressing the effects of unknown or unresolved heterogeneities through recourse to catchment or ecosystem “function,” which shows promise [*McDonnell et al.*, 2007; *Schymanski et al.*, 2009]. There is a large, loosely coordinated effort guided by PUB that focuses on catchment classification (see special issue of HESS: *Castellarin et al.* [2011]) that contains research results on more top-down (data-based) approaches, providing insights into the functioning of catchments and landscapes that can also benefit these otherwise bottom-up initiatives. All of these advances, and others, need time, resources support and encouragement that can be provided by community activities such as the one suggested in W2011. This progress is well underway, so there is little need or rationale to call these, today, grand challenges. We agree that more needs to be done and the results of these efforts require synthesis and coordination to bring together their potential.

[6] The proposed grand challenge in W2011 on hyper-resolution modeling is an inherently positive/optimistic and forward-looking proposal to unify, engage and energize the community to work toward a common goal, which will accommodate many of the needs, challenges and opportunities we have outlined above, as well as the challenges that BC2012 have articulated. Many of the concepts laid out in our proposed grand challenge have been recognized as needs by the commentary authors: the need for improved distributed models [*Beven*, 2001]; need for access to significant computational resources [*Beven*, 2007], which W2011 says should be at the “petabyte computing” scale; need for new and improved observations and data, including data assimilation, which addresses both constraining models by data (articulated in *Beven* [2007, 2008]); and the need for assessing the information content of data (*Beven* 2008). An

important element in the challenge is the development of a global-scale hyper-resolution land modeling capability, within a nested, multiscale system that can incorporate different (and competing) processes that will be important in different landscapes or regions (e.g., urban areas, wetlands, croplands, etc). This is consistent with the “models of everywhere” concept laid forth in *Beven* [2007] and its need is recognized in BC2012.

[7] Many forecasting institutions will be moving to hyper-resolution within the next few years, whether for weather forecasting or in climate projection models. Atmospheric models that include land surface models are already running at these resolutions at regional scales. The development of “Earth System Climate Models” that include many processes discussed in W2011 is well underway at most climate modeling centers, and at resolutions near hyper-resolution. To ignore the challenge to develop “a global-scale hyper-resolution land modeling capability” by hydrologists, is to accept the role of noninvolvement and marginalization as atmospheric scientists implement their land surface models at hyper-resolution into their climate and weather models. We as hydrologists and hydrochemists need to engage with the climate science community to define what is needed to develop robust hyper-resolution Earth System Models that include appropriate hyper-resolution land-surface (and groundwater) parameterizations. In particular, as a community, hydrologists and hydrochemists need a better appreciation and understanding of climate and weather model capabilities to reproduce the “hydrologically interesting weather” that drives hydrological, chemical and ecological processes that are of interest to our community—for example, we need to know about the frequency and intensity of moisture conveyors, cyclones and convection, so that this climate simulation uncertainty can be included in flood frequency projections and the societal impacts from future changes in flood frequency. Some modeling centers (e.g., National Center for Atmospheric Research) are starting this dialogue.

[8] The real challenge is not building hyper-resolution land models, or developing subgrid parameterizations, or better understanding of the impact of uncertainties on predictions. The real challenge is building community so hydrologic sciences can move forward. W2011 provided a vision and call for community action for one particular effort, not an implementation plan. Can the vision be strengthened and clarified? Absolutely. BC2012 states that the community needs to prioritize research to achieve the Grand Challenge goals of W2011 and their stated challenges of addressing scale-appropriate and physioclimatic parameterizations, and model predictions that account for uncertainty. We think this is a wonderful idea and fully support their proposed workshop “to bring the community together to discuss setting priorities in addressing the challenges.” We believe it will help move the challenges forward and we ask the BC2012 authors to organize such a workshop in the very near future.

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