INTRODUCTION

The Terrestrial Water Cycle: Modeling and Data Assimilation across Catchment Scales

STEVEN A. MARGULIS

Department of Civil and Environmental Engineering, University of California, Los Angeles, Los Angeles, California

ERIC F. WOOD*

Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey

PETER A. TROCH*,+

Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, Netherlands

Hydrologic science is currently undergoing a revolution in which the field is being transformed by the multitude of available new data streams. Historically, hydrologic models that have been developed to answer basic questions about rainfall–runoff relationships, surface water and groundwater storage and fluxes, land–atmosphere interactions, and so forth, have been optimized for previously data-limited conditions. However, with the advent of remote sensing technologies and increased computational resources, the environment for water cycle researchers has fundamentally changed to one where there is now a flood of spatially distributed and time-dependent data. This transition from a "data poor" to a "data rich" environment has allowed for an increase in the scope and scale of research questions and practical problems that can be addressed, but also requires that we fundamentally change our approaches to solving these problems. Largely due to a lack of historical data, the mean states and fluxes in the terrestrial water cycle remain poorly characterized. Development of diagnostic and predictive frameworks for characterizing the mean states and their natural variability is a crucial first step in understanding how they may be altered under anthropogenic climate change.

The buildup of greenhouse gases during the past century is postulated to be responsible for global warming through increased radiative forcing of the earth system. Changes in the energy balance of earth are likely to affect other climatic factors besides temperature, including the components of the terrestrial water cycle. For example, atmospheric moisture amounts (and thus precipitable water) in the Northern Hemisphere are generally observed to have increased since 1973 (Ross and Elliott 2001). An increase of a few percent in atmospheric moisture is expected to lead to stronger rainfall rates (Trenberth et al. 2003). In terms of evaporation, even though a very robust finding in all climate models with global warming is for an increase in potential evapotranspiration (IPCC 2001), recent studies (e.g., Peterson et al. 1995; Brutsaert and Parlange 1998; Ohmura and Wild 2002; Roderick and Farquhar 2002) indicate there is still a debate about whether land evaporation will increase or decrease under a warming climate. In any case, a reduction in or an augmentation of the global terrestrial evaporation, combined with the increasing trend in global precipitation, will have to be balanced by changes in runoff and soil moisture, and this will effectively spin down or accelerate the hydrological cycle (Ramanathan et al. 2001). Milly et al. (2002) investigated the changes in risk of large floods using both streamflow observations and numerical simulations of anthropogenic climate change. They found that the frequency of large floods increased substantially during the twentieth century, and that this trend would continue into the twenty-first century. However, the frequency of floods with shorter return periods did not increase significantly.

Therefore, evidence would seem to indicate that a potential consequence of global warming is the acceleration of the hydrological cycle. The ability to detect

* Organizers of the International Workshop on Terrestrial Water Cycle.

+ Current affiliation: Department of Hydrology and Water Resources, The University of Arizona, Tucson, Arizona.

potential changes is vital to policy-making decisions related to adaptation or mitigation strategies. According to national research programs, like the National Aeronautics and Space Administration (NASA) Energy and Water Cycle Study (NEWS), and international research programs, like the World Climate Research Program (WCRP) Global Energy and Water Experiment (GEWEX), the most important manifestations of changes in the earth's climate will likely be alterations in the global energy and water cycle. The key scientific question facing these programs, and underlying much of the Intergovernmental Panel on Climate Change (IPCC) assessment reports, is determining the extent that expected climate changes (e.g., warming) entail changes in the rate and mean states of the earth's energy and water cycles. These concerns and questions also are well reflected in NASA's science research questions, which include "How is the global system changing?" and "How does the earth system respond to natural and human-induced changes?"

In fact, analyses of water and energy cycle variables estimated through observations (in situ and/or remote sensing) will not provide water cycle closure due to sampling and retrieval errors. While estimates of water cycle variables obtained through land surface modeling are consistent, that is, water cycle closure is maintained through construct, these estimates are prone to errors due to poor process representation or errors in model inputs and forcing. This suggests that no single information source can provide the data required to address the research questions related to variability of earth's climate system, detection of climate trends, acceleration of the hydrologic cycle, and climate response to disturbance.

Thus there is a strong need for data assimilation systems for the terrestrial hydrologic cycle that can correctly merge different sources of data (in situ, satellite, and model). Such a merging requires knowledge of the uncertainty in all three components of the prediction system: the retrieved remotely sensed variables, the ground-based observation system, and the predictive hydrologic model. Specifically, progress must be made on new water cycle modeling and data strategies related to providing a better understanding of water cycle variability; on the potential of using advanced data assimilation methods to improve parameterization and predictability from water cycle models at all scales, from catchments to continents; and on applying the enhanced information from merged information to address fundamental issues like "intensification of the hydrologic cycle," "detection of climate change," or "impacts of human activities on the water cycle."

Thus the motivating research question is the following: How can in situ and satellite data be combined with land surface model predictions, using data assimilation techniques, to produce improved, coherent merged products that are space–time continuous over the land areas of the globe?

This implies that the following issues be addressed and resolved in order to make fundamental progress on characterizing the terrestrial water cycle and understanding and detecting its change:

1) What are the best data assimilation procedures for combining satellite data with in situ and land surface modeling, given the spatial, temporal, and physical characteristics and scales of the remote sensing, in situ, and modeled variables?
2) How much improvement is provided by the assimilation of satellite data into land surface modeling, over its use alone or with land surface modeling alone, for the estimation of the terrestrial water cycle components?
3) To what extent can remote sensing observations, assimilated into land surface models, be used to improve estimates of the terrestrial water balance at continental and global scales, to help better represent the variability of water cycle components in space and time, and provide more accurate predictions regarding climate change?

To help assess the state of the art by the hydrology and climate community in making progress on these topics, the second international workshop on Catchment-scale Hydrological Modeling and Data Assimilation (CAHMDA-II) titled "The Terrestrial Water Cycle: Modeling and Data Assimilation Across Catchment Scales" was held on 25–27 October 2004 at Princeton University. The workshop's overall goal was to bring together experts in hydrological modeling and data assimilation to discuss modeling and observation strategies to improve understanding of the terrestrial water cycle and its variability across temporal and spatial scales.

The workshop was organized around five themes: (i) the water budget and the acceleration of the hydrological cycle; (ii) scaling in time and space: methodological approaches; (iii) hydrological modeling across scales; (iv) data assimilation: potential areas for advancement; and (v) computational approaches for large-scale hydrologic problems.

The papers in this special issue of the *Journal of Hydrometeorology* represent a selection of material presented at the workshop. In the area of closing the water budget and its variability, Bosilovich and Chern investigate water sources and precipitation recycling in three large basins across the globe; Wojcik et al. propose a new method for describing the uncertainty in surface evaporation estimates; and Hasan et al. model the impact of various hydrologic fluxes on the gravity field (a quantity that can be remotely sensed and is being measured from space at large scales by the GRACE mission). On the topic of space–time scaling and hydrologic modeling across scales, Haddeland et al. investigate the impact of spatial and temporal aggregation on the modeling of water balance; Rigon et al. and Bertoldi et al. describe a distributed hydrologic model that can be applied at basin scales and investigate how geomorphic characteristics impact the water and energy budgets at these scales; and Coudert et al. investigate the time-varying nature of parameter influence on radiometric surface temperature and its impacts on model calibration. In the area of potential advancements in data assimilation, Crow and Van Loon and Wilker et al. examine the important issue of model error in assimilation schemes and in particular on the prediction of surface soil moisture; Durand and Margulis investigate the feasibility of a multifrequency radiometric assimilation approach for estimating large-scale snow water equivalent from remote sensing observations; and Pauwels et al. and Slater and Clark examine the impact that the assimilation of in situ observations (streamflow and snow water equivalent, respectively) has on the improved prediction of hydrologic states and fluxes. Finally, on the topic of approaches for large-scale hydrologic problems, McLaughlin et al. discuss computational issues specific to land surface data assimilation systems and provide insight into promising solution methods; Margulis et al. explore the integration of complex input uncertainty through the use of ensemble precipitation forcing in land surface modeling and data assimilation; Pan and Wood introduce a new method for adding a terrestrial water balance closure constraint to assimilation applications over large domains; and Vrugt et al. introduce an efficient methodology for combined parameter and state estimation for a rainfall–runoff model from discharge observations.

The workshop, as illustrated by the papers presented in this special issue, provided a forum for the discussion of many of the key current issues in the areas of diagnosing the terrestrial water cycle through modeling and data assimilation. While significant progress has been made, most of the work to date has been limited to studies involving development of new models, assessment of hydrologically relevant remote sensing observations, and the initial implementation of data assimilation frameworks for merging some of these measurements and models. Significant work is still needed to assess the uncertainty in our models and especially in the remote sensing observations and products we are using. This, combined with more efficient data assimilation frameworks capable of assimilating multiscale (spatial and temporal) and multitype (multifrequency remote sensing and in situ) observations, should finally allow us to begin to diagnose the natural and anthropogenically induced dynamics of the states and fluxes in the terrestrial water cycle over large scales.

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