Coupling Terrestrial and Atmospheric Water Dynamics to Improve Prediction in a Changing Environment

BY STEVE W. LYON, FRANCINA DOMINGUEZ, DAVID J. GOCHIS, NATHANIEL A. BRUNSELL, CHRISTOPHER L. CASTRO, FOTINI K. CHOW, YING FAN, DANIEL FUKA, YANG HONG, PAUL A. KUCERA, STEPHEN W. NESBITT, NADINE SALZMANN, JUERG SCHMIDLI, PETER K. SNYDER, ADRIAAN J. TEULING, TRACY E. TWINE, SAMUEL LEVIS, JESSICA D. LUNDQUIST, GUIDO D. SALVUCCI, ANDREA M. SEALY, AND M. TODD WALTER

Humans have profoundly influenced their environment. It has been estimated that nearly one-third of the global land cover has been modified, while approximately 40% of the photosynthesis has been appropriated. As the interface between the subsurface and the atmosphere is altered, it is imperative that we understand the influence this alteration has in terms of changing regional and global climates. Land-surface heterogeneity is sometimes a principal modulator of local and regional climates and, as such, there are potential aggregation and teleconnection effects ranging in scales from soil pores to the general atmospheric circulation when the land surface is altered across a range of scales. The human fingerprint on land-surface processes is critical and must also be accounted for in the discourse on land–atmosphere coupling as it pertains to climate and global change as well as local processes such as evapotranspiration and streamflow. It is at this pivotal interface where hydrologists, atmospheric scientists, and ecologists must understand how their disciplines interact and influence each other.

Fluxes across the land surface directly influence predictions of ecological processes, atmospheric dynamics, and terrestrial hydrology. However, many simplifications are made in numerical models when considering terrestrial hydrology from the viewpoint of the atmosphere and vice versa. While this may be a necessity in the current generation of operational models used for forecasting, it can create obstacles to the advancement of process understanding. These simplifications can limit the numerical prediction capabilities with respect to how water partitions itself throughout all phases of the water cycle. The feedbacks between terrestrial and atmospheric water dynamics are not well understood or represented by the current generation of operational land-surface and atmospheric models. This can lead to erroneous spatial patterns and anomalous temporal persistence in land–atmosphere exchanges and atmospheric water cycle predictions. Cross-disciplinary efforts are needed not only to identify but also to quantify feedbacks between terrestrial and atmospheric water at appropriate spatiotemporal scales. This is especially true as today's young scientists set their sights on improving process understanding and prediction skill from both research and operational models used to describe such linked systems.

AFFILIATIONS: LYON—Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden; DOMINGUEZ—Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona; GOCHIS, KUCERA, SALZMANN, SCHMIDLI, LEVIS, AND SEALY—National Center for Atmospheric Research, Boulder, Colorado; BRUNSELL—Department of Geography—Atmospheric Sciences Program, University of Kansas, Lawrence, Kansas; CASTRO—Department of Atmospheric Sciences, University of Arizona, Tucson, Arizona; CHOW—Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, California; FAN—Department of Geological Sciences, Rutgers University, Piscataway, New Jersey; FUKA AND WALTER—Department of Biological and Environmental Engineering, Cornell University, Ithaca, New York; HONG—School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma; NESBITT—Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois; SNYDER AND TWINE—Department of Soil, Water, and Climate, University of Minnesota, St. Paul, Minnesota; TEULING—Institute for Atmospheric and Climate Science, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland; LUNDQUIST—Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington; SALVUCCI—Department of Earth Sciences, Boston University, Boston, Massachusetts
CORRESPONDING AUTHOR: Steve W. Lyon, Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden
E-mail: steve.lyon@natgeo.su.se

DOI: 10.1175/2008BAMS2547.1

In recognition of these challenges, a junior faculty and early career scientist forum was recently held at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, with the intent of identifying and characterizing feedback interactions and their attendant spatial and temporal scales—important for coupling terrestrial and atmospheric water dynamics. The primary focus of this forum is on improved process understanding, rather than operational products, as the possibility of incorporating more realistic physics into operational models is computationally prohibitive. We approached the subject of improved predictability through better process understanding by focusing on the following three framework questions described and discussed below.

1) What are the simplifications commonly made when coupling hydrological and atmospheric models? Many physical processes acting at the land-surface–atmosphere interface (e.g., the influence of terrain on soil moisture distribution, geologic controls on near-surface groundwater) are not robustly represented in current operational weather and climate models. However, recent research has shown the importance of incorporating processes such as water-table dynamics in climate modeling. By incorporating a realistic water-table depth, these studies produce more realistic land-surface fluxes for a regional climate model. Often, both the hydrological models and regional climate models lack an accurate representation of the vegetation dynamics—particularly how vegetation evolves in response to seasonal forcing and other disturbances. This issue is important because vegetation draws water from different soil depths at different time scales and responds dynamically to changes in moisture. Vegetation, thus, serves as perhaps the most interactive interface between the atmosphere and the subsurface.

With respect to the representation of the atmosphere in hydrological models, we find that traditional approaches to surface hydrology have often followed a linear pathway, where atmospheric variables such as precipitation, temperature, and winds serve as "forcing" that drive land-surface models and generate a host of hydrologic variables. Rarely has there been significant two-way interaction between traditional hydrological models and the overlying atmosphere. In addition, rainfall is often represented as spatially constant (i.e., "lumped") input using data collected at a few point locations by rain gauges or, at larger scales, radar or satellite rainfall estimates. Evapotranspiration is often viewed as a terminal sink of water from the system, meaning that once evapotranspiration occurs, this water leaves the modeling system and is not allowed to recycle. Boundary layer structure or circulations that modulate canopy venting and, thus, surface-flux behavior are also typically underrepresented in hydrological models.

The recurring theme for the simplifications made when coupling hydrological and atmospheric models appears to be that the complex, three-dimensional processes of one discipline are parameterized into a simple, one-dimensional process for incorporation into the other discipline. This is primarily due to limited cross-discipline process understanding, fundamental scale mismatches and, at times, unidirectional (as distinct from full two-way coupling) communication and has, unfortunately, led to the current situation where process understanding and operational model development at the hydrological and atmospheric interface lags that of "native" disciplines.

2) At what spatial and temporal scales, under such simplifications, can we expect to capture feedback between the land surface and atmosphere? An important task in land–atmosphere research is identification of feedback processes that potentially affect predictability of weather and climate processes. For example, complexities in terrain slope and aspect control, in part, the spatial distribution of incoming solar radiation that, in turn, impacts the distribution of surface heating. These effects can be locally important in complex terrain or seasonally snow-covered regions resulting in differential patterns of snow cover and soil moisture. Spatially varying land-use/land-cover distributions and soil type may also translate into variations in the radiative environment through alterations of surface albedo, surface temperatures, and surface latent and sensible heat fluxes. Under certain atmospheric regimes, this differential partitioning of surface energy fluxes may impart upscale effects, thereby altering mesoscale circulations and convective precipitation patterns. At shorter time scales, heterogeneous patterns in precipitation drive spatial variability in soil moisture, which potentially impacts hydrologic responses from future storm events. The degree to which such variability imparts upscale feedbacks on regional drought and flooding events is currently not well understood. Alternatively, due to the linkage between groundwater and root-zone soil moisture, groundwater can, at times, impart a

larger and predictable spatial structure and long-term memory in land-surface fluxes in regions with shallow groundwater tables. Regionally, fluxes from shallow groundwater sources may be a significant source of moisture to the atmosphere. The task of understanding and correctly predicting these feedbacks presents significant challenges to the research community.

In the realm of modeling—particularly operational, predictive modeling—the appropriate scale of spatiotemporal resolution is often dictated by the intended application. Thus, the scale dependence of the pertinent physical processes and the equations describing them must be carefully considered. This scale specificity complicates and often precludes "fully generalized" approaches to Earth-systems models and may alias observation strategies. There is an obvious trade-off between simple and complex modeling approaches for representing atmospheric dynamics and land-surface hydrological dynamics. Recently developed fully coupled groundwater–land-surface–atmospheric models have been shown to reasonably capture many important water-cycle dynamics at regional scales (i.e., a few hundred square kilometers) over a period of several days. With ever increasing computational power, the temporal duration and spatial resolution of such analysis will be extended. However, when trying to conduct climatological or long-term analyses over a large region, simplifications must be made for the models to be computationally efficient, and these simplifications may significantly affect model predictability. Under such simplifications, it may be impossible to correctly represent time and space variations of soil moisture and surface energy fluxes important in faithfully representing land–atmosphere feedback mechanisms.

Correctly incorporating complex soil moisture–vegetation–atmosphere interactions may be particularly important in some regimes and regions if we are to skillfully model the diurnal cycle of boundary layer fluxes leading to the initiation of convection. In turn, many of these interactions may also have great impact at the seasonal scale. For example, the timing of green-up and senescence of grasslands and agricultural crops in the midwestern United States has a dramatic impact on the magnitude of latent heat flux to the regional atmosphere. Knowledge of the limitations resulting from the use of simplified feedback mechanisms will be essential for the creation of useful and practical models.

3) How can we better represent and understand feedback interactions between the land surface and the atmosphere? In answer to this question, we present a summary of recommendations from the workshop. One such recommendation is the need to define improved feedback metrics for assessing the relative magnitude of soil moisture, vegetation, and snow/ice feedbacks on the atmosphere. Current methods to identify feedbacks include simple correlation and lagged correlation analysis, spectral analyses, or multivariate singular spectrum analysis. While highly useful, we believe these statistics-based techniques are not sufficient to illuminate underlying physical mechanisms responsible for determining the spatial and temporal variability of the magnitude of the feedbacks.

Another recommendation arising from the forum is that observation, modeling, and process-understanding efforts need to be much more iterative. From the modeling perspective, one promising way forward would be to advance community modeling efforts that explicitly account for land–atmosphere interactions at a range of temporal and spatial scales. Such multiscale frameworks should be structured around physically based hierarchal models capable of representing various processes via state-of-the-art components. For the purpose of land–atmosphere interaction research, particular components would include modeling groundwater flow, unsaturated zone subsurface flow, atmospheric flow, vegetation dynamics, and land-surface interface modules that link below- and aboveground hydrologic and biogeochemical regimes. Many of these model components are currently in use in their respective research subfields, but it is their coupling that has the potential to dramatically change our modeling capabilities. Efforts such as the Earth System Modeling Framework (ESMF) or the Weather Research and Forecasting (WRF) mesoscale atmospheric model provide examples of extensible, modular software architectures, but use of such systems in performing fully integrated hydrological–atmosphere studies has not been adequately pursued. Modules of varying complexity need to be developed and provided with guidance and direction as to their use and limitations at different scales.

The inclusion of vegetation dynamics in land-surface models was repeatedly stressed as a key, yet underemphasized area of research. Dynamic vegetation modules are currently used in various climate simulation applications, but have only more recently been applied for regional or mesoscale applications. Improved description of plant phenology

was thought to be crucial for properly capturing surface water-cycle dynamics across a broader range of spatial and temporal scales. In the context of climate change and global warming, changes in growing season length have significant potential to feed back to the climate system at large. As seen in recent experiments in the Niwot Ridge Long Term Ecological Research (LTER) site, lengthening of the growing season significantly alters the seasonal timing of groundwater extraction and canopy fluxes of moisture and carbon. As a consequence, the groundwater is being depleted earlier, with subsequent feedback to the atmosphere and the ecosystem. Such feedback interactions cannot be adequately addressed in future climate without a more integrated coupling and physically robust representation of the land–vegetation–atmosphere hydrologic system.

There exists a pervasive need for more integrative observational datasets, field campaigns, and long-term monitoring systems that specifically address the bidirectionality of land–atmosphere feedbacks. Long-term monitoring sites that combine surface, subsurface, and atmospheric profile measurements (e.g., deep wells, soil moisture profiles, and wind profiler or rawinsonde observations) must be developed and maintained. Aggregation and dissemination of existing and new datasets is imperative. For example, while many sources of hydrological data exist, such as groundwater data and subsurface hydraulic properties, many are in formats unusable for regional applications. Therefore, there is a need for data consolidation efforts [such as those put forward by the Consortium of University for Advancement of Hydrologic Science (CUAHSI) and the National Integrated Drought Information System (NIDIS)], as well as for improved standards that allow for easy incorporation in widely used land-surface and atmosphere modeling systems. Such synthesis efforts could potentially be viewed as a series of "hydrological" reanalysis products similar to those of the North American Land Data Assimilation System (NLDAS) effort. New observational programs should, whenever possible, be developed in conjunction with existing long-term sites, such as AmeriFlux, NEON, and FLUXNET. Such an effort would begin to provide a more complete suite of data containing not only atmospheric information but also measures of carbon exchange, soil moisture, groundwater, and biogeochemicals.

Finally, one of the key regions identified that will likely emerge at the forefront of research in the years to come is that of ecological transition zones. These regions present significant challenges from the modeling perspective, as most dynamic vegetation models perform better in homogeneous zones, while often failing to capture the dynamic behavior of more heterogeneous and fractured ecological communities. This is particularly important for land–atmosphere interactions where transition zones, at least at regional scales, have been shown to be "hot spots" of land–atmosphere coupling where soil moisture variations may significantly impact precipitation patterns. Lastly, natural and anthropogenic disturbances such as fire, grazing, and urbanization present important challenges and opportunities for improving our understanding of coupling between the land and atmosphere.

ACKNOWLEDGMENTS. The authors would like to thank Roger Pielke, Sr., for his motivating keynote address to our group at the forum. In addition, special thanks go to our invited speakers, Guido Salvucci, M. Todd Walter, and Ying Fan, for helping stimulate and offer expertise to the discussion. NCAR and the University Corporation for Atmospheric Research (UCAR) are thanked for their sponsorship of the forum. NCAR is operated by UCAR under the sponsorship of the National Science Foundation.

FOR FURTHER READING

Bierkens, M. F. P., and B. J. J. M. van den Hurk, 2007: Groundwater convergence as a possible mechanism for multi-year persistence in rainfall. *Geophys. Res. Lett.,* **34,** Lo2402.

CUAHSI, 2007: *Hydrology of a Dynamic Earth: A Decadal Research Plan for Hydrologic Science*. Consortium of Universities for the Advancement of Hydrologic Sciences, Inc., 41 pp.

Dekker, S. C., M. Rietkerk, and M. F. P. Bierkens, 2007: Coupling microscale vegetation–soil water and macroscale vegetation–precipitation feedbacks in semiarid ecosystems. *Global Change Biol.,* **13,** 671–678.

Dirmeyer, P. A., R. D. Koster, and Z. Guo, 2006: Do global models properly represent the feedback between land and atmosphere? *J. Hydrometeor.,* **7,** 1177–1198.

Ek, M. B., and A. A. M. Holtslag, 2004: Influence of soil moisture on boundary layer cloud development. *J. Hydrometeor.,* **5,** 86–99.

Eltahir, E. A., 1998: A soil moisture–rainfall feedback

mechanism: 1. Theory and observations. *Water Resour. Res.,* **34,** 765–776.

Gutowski, W. J., C. J. Vörösmarty, M. Person, Z. Ötles, B. Fekete, and J. York, 2002: A Coupled Land-Atmosphere Simulation Program (CLASP): Calibration and validation. *J. Geophys. Res.,* **107,** 4283.

Koster, R. D., and Coauthors, 2004: Regions of strong coupling between soil moisture and precipitation. *Science,* **305,** 1138–1140.

Pielke, R., 2001: Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Rev. Geophys.,* **39,** 151–177.

Seuffert, G., P. Gross, C. Simmer, and E. F. Wood, 2002: The influence of hydrologic modeling on the predicted local weather: Two-way coupling of a mesoscale weather prediction model and a land surface hydrologic model. *J. Hydrometeor.,* **3,** 505–523.