Advancing Hydrometeorological-Hydroclimatic-Ecohydrological Process Understanding and Predictions

Summary and Findings from a Community Workshop at the Colorado School of Mines, September 3-5th, 2014

Paul A. Dirmeyer[1], David J. Gochis[2], Terri S. Hogue[3], Ana Barros[4], Katja Friedrich[5], Mimi Hughes[5], Noah P. Molotch[5], Christopher J. Duffy[6], and Witold F. Krajewski[7]

[1]George Mason University

[2]National Center for Atmospheric Research

[3]Colorado School of Mines

[4]Duke University

[5]University of Colorado

[6]Pennsylvania State University

[7]University of Iowa

Abstract

An NSF-sponsored community workshop was held in September of 2014 to facilitate progress on the integration of hydrometeorological-hydroclimatic-ecohydrological (HHE) process understanding and improving predictive capabilities, sustainability, and resilience to environmental change. Specifically, processes that bridge traditional disciplines and observational techniques are emerging as the next frontier of hydrologic and meteorologic sciences. The aim of the workshop was to identify high priority interdisciplinary elements that should be addressed. The meeting was organized around three general themes: scientific, modeling and observational challenges and encouraging a framework for collaboration. Using this framework, high-level, cross-discipline research gaps were identified that spanned the atmospheric and hydrological sciences with the explicit goal of breaking down disciplinary barriers. This manuscript provides a detailed articulation of each of the core workshop challenges. Each 'challenge' section has an overarching component and a set of high-level sub-components. Our recommendations are not meant to be fully comprehensive or exclusive, but instead are meant to provide a foundation and organizational framework for addressing HHE challenges and opportunities for the community.

Introduction

There is a pressing need to accelerate progress in understanding how terrestrial hydrologic, ecohydrologic, and hydrometeorological systems respond to weather and climate forcings and, in turn, how weather and climate are influenced by land surface processes. A host of past research and high-level reports have identified multiple ways in which the terrestrial and atmospheric systems are coupled (Duffy et al., 2006; IPCC, 2013; NRC, 2012a, 2012b; Ralph et al., 2012; Smith et al., 2013). More recently, recognition of the complexities of these interactions and their interdependencies has grown significantly as the scientific research and operational prediction communities have moved towards the development of integrated surface-atmosphere prediction systems. These new systems are seeking to represent coupled hydrological, ecological, biogeochemical, and atmospheric processes from bedrock through the lower atmosphere in advanced computational frameworks (e.g., Duffy et al., 2004; Maxwell et al., 2007; Anyah et al., 2008). This new generation of prediction architectures is being developed to conduct fundamental process research into the broader 'Earth system' and, perhaps more importantly, to improve predictive capacity and societal resilience to weather and climate phenomena and their reflection in terrestrial processes. Despite this progress, the research and operational communities are currently limited in their abilities make the necessary advances in these areas due to knowledge gaps in processes occurring across the interface of terrestrial hydrology and atmospheric science.

To address these issues, a community workshop was held during 3-5 September, 2014 in Golden, Colorado for the purpose of motivating and accelerating progress on the integration of hydrometeorological-hydroclimatic-ecohydrological (HHE) process understanding for improving predictive capabilities, sustainability, and resilience to environmental change. Results from the workshop provide a framework for identifying and addressing current challenges in HHE understanding and predictions. These challenges are broadly organized as:

1) Scientific Challenges
2) Observational Challenges

3) Modeling Challenges

There are obvious and significant overlaps in this grouping and a more complete articulation of the challenges is formulated below. The main goal of the workshop was to outline high-level, cross-discipline (i.e. not 'within-discipline' specific) research needs common to atmospheric and hydrological sciences and to define a framework for productive collaborative research between those two areas. Another explicit goal of the workshop was to redefine current disciplinary barriers such that the "boundary conditions" of individual disciplines evolve towards a more holistic process understanding and predictive skill. We recognize that there is significant need to improve understanding of system dynamics, inter-dependencies and causes, and impacts of change. More directly, this implies advancing a more mechanistic and explicit process-based understanding of the coupling between the atmosphere and the terrestrial environment. Finally, we advocate for the education of scientists and students in both research areas to express a common technical language, to work effectively within cross-disciplinary teams and to design and develop observational and modeling systems for scientific discovery in critical application areas. These future leaders will, in turn, begin a process of unifying the hydrologic and atmospheric science communities and support new capabilities and directions for research.

This white paper provides a detailed articulation of the core workshop challenges in the 'observational' and 'modeling' categories, as the 'scientific challenges' clearly cross-cut the others and emerge in both categories. Each 'challenge' section has an overarching component and a set of high-level sub-components. We don't portend to be fully comprehensive or exclusive in workshop recommendations, but instead intend to lay a sufficient foundation and organizational framework for addressing these issues within the broader community of scientists.

Finally, we provide the following working definitions of terms that are important to achieving our intended outcomes. In the context of this white paper 'environmental change' broadly refers to 'hydrometerological, hydroclimatic and ecohydrological' or HHE change and, more specifically change as a result of population, land-use change, natural hazards (e.g. floods, droughts, earthflows, winds) various disturbances (e.g. wildfire, insect, clear-cutting, mining, macro-infrastructure), or climate change, natural and anthropogenic. Use of the term 'terrestrial hydrology' implies cloud processes, surface precipitation, soil moisture, streamflow, groundwater, snowpack, and evapotranspiration/sublimation or, in other words, the processes which link the atmosphere and the terrestrial via their energy and mass (water) balances.

Current Observational Challenges

Background

Observations of the HHE systems form the frontiers of quantitative understanding of the natural world. Despite their importance, particularly for tracking long-term changes in weather, climate, and hydrology, several major operational observational networks (i.e. streamflow observations) have declined since peak periods in the 1970s-early 1990s. However, a handful of new, integrated observational networks have recently emerged (e.g., AmeriFlux (http://ameriflux.ornl.gov/), Critical Zone Observatories (http://criticalzone.org/national/), the National Ecological Observatory Network (http://www.neoninc.org/), the Atmospheric Radiation Measurement Program (http://www.arm.gov/)). Although promising in many respects, no single network provides adequate consideration of the complex, multi-scale nature of land-atmosphere interactions, but rather provides a partial picture of the atmosphere-terrestrial system. It is also recognized that while many terrestrial-atmospheric interface observational networks are intended to be operational for many years, many purely observational efforts are coordinated for short-term science goals. Scientists at the workshop agreed that campaign-style projects result in fundamental mismatches or discontinuities in temporal scales. Conversely, while many atmospheric observational efforts extend over very broad regions up to tens to hundreds of thousands of km^2 using aircraft and other mobile platforms (e.g., International H2O Experiment, North American Monsoon Experiment (http://www.eol.ucar.edu/field_projects/name), the VAMOS [Variability of the American Monsoon Systems] Ocean-Cloud-Atmosphere-Land Study (http://www.eol.ucar.edu/projects/vocals/rex.html), Green Ocean Amazon (http://campaign.arm.gov/goamazon2014/)), many terrestrial hydrology observing projects are focused on small watersheds or catchments of a few 10s to 100s km^2 or even single hillslopes. As such, the spatial scale does not complement the temporal scale, resulting in a mismatch in research priorities of the atmospheric and hydrologic communities. An overarching observational challenge is to *address the issue that current observational networks are fractured in space and time, in terms of processes observed as well as in data infrastructure (e.g., data formats, data standards, availability, etc.).* This fracturing in observing scale and process inhibits progress to developing an integrated understanding of the causes and impacts of coupled atmospheric-hydrologic processes and impedes advances on broad aspects of environmental change.

There is presently a lack of coupled, retrospective, land-atmosphere observational synthesis activities that are comparable to what is done for atmospheric analyses/re-analyses or classical water resources surveys. This gap in our observing system results in serious deficiencies in water and energy budgets between what atmospheric reanalyses say runoff should be, for instance, and what it is observed. From the terrestrial hydrologic side, detailed analyses of streamflow are used in regional water budget studies while very crude estimation methods for regional evapotranspiration or poorly resolved spatial and temporal distributions of precipitation are implemented. Many such analyses also tend to neglect the often-significant effects of human management, which can also lead to erroneous conclusions about coupled water cycle processes. Each of these shortcomings results in the translation of errors into flux and/or state variables, and which have deleterious impacts on coupled process understanding. By improving the integration of inter-disciplinary observational efforts into coupled land-atmosphere modeling and data assimilation systems there exists significant opportunity to better constrain regional water cycle budget estimates which are, in turn, critical to understanding how various mechanisms of environmental change will impact coupled land-atmosphere exchange processes.

Below is a summary of specific observational challenges that were identified during the workshop. These challenges were synthesized on the final day from participant comments after several oral presentations and small group breakout sessions. Following the articulation of specific challenges we provide a set of recommendations of research strategies and specific activities that should be supported in order to meet the observational challenges identified.

Observational challenges

During breakout sessions, many issues related to making both within-discipline and across-discipline measurements were discussed. The following summarizes the most prominent challenges that emerged:

1. Measuring the full temporal and spatial distributions of important HHE variables, such as energy-water-biogeochemical fluxes, terrestrial routing and storage processes, cloud processes, boundary layer exchanges, and atmospheric transport.
2. Designing and developing coordinated terrestrial-atmospheric observations at scales sufficient to characterize land-atmosphere coupling (e.g., from tower sites of ~1km to 'synoptic' scales ~1000 km), especially in regions with acute disturbance of the environment due to fire, pests, acute anthropogenic land cover and land use change (e.g., dense urban areas, deforestation), and dynamic land margins such as wetlands and recharge zones where surface-groundwater coupling is extremely important (cf. NRC 2008).
3. Improving measurement methods for closing water and energy budgets across spatial and temporal scales through better data-model fusion and assimilation, and reconciling current differences where closure criteria for certain variables in the atmospheric sciences does not match the closure criteria in the terrestrial sciences.
4. Improving process-diversity in measurement efforts being developed as part of multi-disciplinary long-term observatories for studies of eco-hydro-climatic change (e.g., Critical Zone Observatories have comprehensive surface and subsurface measurements but lack a meaningful atmospheric component. Similarly, many atmospheric observing efforts aimed at measuring surface fluxes do not address basic partitioning of precipitation into runoff, evapotranspiration and storage components).
5. Accelerate community capacity to conduct more 'dynamic', (e.g. fast-response) observational projects and sampling strategies to adequately observe extreme events and landscape disturbances on atmospheric and hydrologic behavior.

Observational recommendations

1. Fundamental improvements in measurement methods and technologies are urgently needed in order to **improve closure of coupled land-atmosphere water and energy budgets across scales**. While new measurement platforms continue to emerge that improve our ability to bridge scales (e.g., unmanned aerial vehicles, automated chemical and isotopic observations) significant uncertainties exist in how to design, collect, and integrate measurements from multiple observational platforms. Improvements in observations of process-diversity are needed to help characterize the wide spectrum of land-atmosphere states and fluxes. There are still critical needs in measurement technology to achieve the spatial and temporal resolutions and accuracy required for science grade observations, especially at microscales and over highly heterogeneous environments and for fast evolving processes. Related, existing, long-term measurement sites need to be enhanced to improve the observational constraint of diagnosed energy and water budgets.
2. **Existing and new observational campaigns need to be more strategically coordinated** to address uncertainties in energy and water budget closure and in fundamental land-atmosphere interaction behavior. The traditional paradigm of siting instrumentation and sampling in homogenous terrain needs to be enhanced in order to understand the land-atmosphere exchange processes occurring across a diversity of landscapes. Similarly, existing shortcomings in making land-atmosphere exchange measurements in regions of complex terrain, as well as lingering problems over simple terrain, need to be addressed. There is also a significant need to accelerate the community capacity to pursue more

dynamic observational products and sampling strategies for observing extreme events or significant landscape disturbances. Co-location of coordinated, disciplinary field experiments in the atmospheric and hydrologic sciences is needed to address pervasive observational shortcomings of individual disciplinary experiments. While basic coordination of field experiment activities between the atmospheric and hydrologic sciences is encouraged, work is also need to reconcile different observational campaign approaches with respect to temporal and spatial scales.

3. A **requestable, deployable hydrological observational facility** similar to NSF's Lower Atmosphere Observing Facilities is needed to help support large multi-disciplinary research campaigns that are seeking to quantify multi-scale land-atmosphere exchange processes. Such a facility does not presently exist, which places a significant additional burden on researchers to support the acquisition of expensive but powerful hydrological research facilities 'hecto'-scale (O~100 count) node surface hydrological instrument networks, airborne flux platforms and airborne multi-spectral sensors, and in-situ laser spectroscopy. Such facilities are currently cost prohibitive within a traditional research grant or for individual investigators but could be purchased and maintained as a community observational facility in the same way measurement facilities are currently done for the atmosphere. In addition, policies and straightforward funding mechanisms to leverage existing national facilities such as those of EPA, USGS, NOAA, DoE, DoD (ARL and NRL), and NASA observational platforms, and open access to individual or small PI teams, should be developed.

4. To maximize the impact of new observations and also to help guide the design of new instrumentation networks **significant increases in coordination between observational and modeling groups** is needed. Significant opportunity exists for improved syntheses of existing and new observational research through structured data assimilation/data fusion studies that can be utilized for applications, for physically-constrained synthesis of observational data sets, and as a tool for probing and improving existing models and providing guidance for development of new ones. Data from observational test-beds need to be assimilated into coupled weather-climate-hydrology models in order provide constraint and error assessment from those models. Similarly, long-term coupled land-atmosphere re-analyses are needed to provide baseline analyses of land atmosphere conditions. Research in this area of coupled observation-data assimilation and re-analysis will force the currently disparate atmospheric and hydrological communities to "own each other's errors and uncertainties" to discourage the passing off of errors as residual terms in other disciplinary model and analysis components. Also, existing and emerging chemistry, isotopic and biological observations offer unique opportunities to evaluate current Earth System models. Collection of such complimentary data needs to advance in order to improve understanding of many key hydrological and thermodynamic pathways and residence times in the coupled land-atmosphere system.

5. **Improved methods to characterize uncertainty** in direct and derived (e.g., retrieval-based) measurements are needed in order to improve confidence in process hypotheses in highly nonlinear exchange processes such as those in the coupled land-atmosphere system. Additionally, modern data assimilation needs proper representation of observational uncertainty in order to develop effective statistical weights or ensemble members.

6. **Advanced education and training is needed** to promote conversion of indirect observations of fundamental processes into meaningful variables of unambiguous scientific content.

Dedicated curriculum and training, with increasing depth on complex technology and observing systems, is needed within higher education. The requirements are intrinsically multidisciplinary (e.g. understand LIDAR engineering and boundary layer meteorology in order to successfully deploy LIDAR systems, and then collect, process, and finally explore the data to investigate turbulence structure). It is important to recognize the challenges this poses to graduate students and early career scientists.

Current modeling challenges

Background

Models of interest here are mathematical conceptualizations and idealizations of the structures, components and processes found in nature. They are increasingly numerical in the form of ever-more complex programs run on computers, and used to simulate aspects of the natural world for purposes of prediction, attribution, and the advancement of understanding. Around a quarter century ago numerical modeling techniques began to profuse deeply through both the atmospheric science and terrestrial hydrological communities. Nearly all college curricula today in these disciplines require coursework in modeling techniques. However, these models have largely evolved piecemeal within their respective disciplines and then are often "coupled" together with the best of intentions but without the cross-disciplinary insight necessary for real progress.

The coupled model systems often fail to capture key characteristics of the Earth system (e.g., Dirmeyer et al. 2006). Some of the relationships, and specifically the scaling behavior we see in nature are absent or poorly represented in coupled land-atmosphere models, while they often exhibit other strong linear and non-linear relationships that are not observed or are unphysical (Nastrom et al. 1986; Over and Gupta 1994; Skamarock 2004; Tuck et al. 2004; Hamilton et al. 2008; Kahn and Teixeira, 2009; Solle et al. 2012; Nogueira et al. 2013 among many others). The problem is that important structures, scales, components and processes that bridge the land and atmosphere, the surface and subsurface, such as topography and hydrogeological heterogeneity are not well represented. The span of water (and related energy and carbon) cycles across the HHE system must be addressed as a first-order characteristic in models. However, a sound method to benchmark and evaluate competing approaches to such integration in coupled hydrometeorological models is still lacking.

Nature varies continuously in space and time, but in models we must discretize in order to represent the structure of nature on computers. Discretization immediately introduces a source of error, as processes below the scale of discretization (the grid boxes and time steps of numerical integration) must be parameterized or are lost. The scales and processes in the atmosphere and the land can be quite different, and historically they have been examined separately. As a result, contrasting conceptual approaches have emerged, and vast differences have developed in data availability and modeling methods between the communities. In addition, as models have become increasingly more complex, mathematical formulation and numerical and computational implementations have not always proceeded in tandem with the introduction of physical parameterizations and feedback among model physics and numerical methods (e.g. Gresho and Lee, 1979).

Only in recent years have more comprehensive, integrated models of physical processes from bedrock through the atmosphere begun to emerge (e.g. Duffy et al., 2004; Maxwell et al., 2007; Anyah, et al., 2008). These integrated models are often "loosely coupled systems" of disciplinary model components linked through software architectures that often fail to properly transfer information across spatial and temporal scales relevant to the coupled HHE processes being represented. There are also major differences in the mass and energy closure assumptions used in different modeling systems. One important challenge as we look forward is that as the range of spatial scales increases, so does the range of temporal scales in coupled land-atmosphere modeling, reaching deeper into the soil catena and hydrogeological systems and posing challenges in reconciling slow and fast scales that is not unlike that faced in coupled atmosphere-ocean models.

Together, these differences represent a significant barrier to community efforts to make either deterministic or probabilistic predictions of environmental change or its impacts across scales, despite the fact that modeling studies have shown the potential for predictability from the slow manifolds within the coupled HHE system (e.g., Koster et al. 2010, Yuan et al. 2013). Advances in understanding these interactions must overcome these barriers, if we are to make progress regarding the improvement in errors due to coupling, drift and biases among models developed in isolation (e.g. hydrological, ecological, land-surface and atmosphere models).

Against this historical backdrop, an opportunity is emerging. The root causes of poor performance in loosely-coupled model systems of the atmosphere, land surface and subsurface have been largely unaddressable because of a deficiency of co-located observational data of relevant components of the coupled system sampled over significantly long time periods. However, there is promise now that a new generation of observational data are becoming available or are being planned, allowing for proper coupled model testing and evaluation. As mentioned above, networks like AmeriFlux are beginning to be used for multifaceted analysis and model validation, proving the concept of a coupled hydrological, ecological, biogeochemical and atmospheric analysis from bedrock through the lower troposphere. The potential to capitalize on the burgeoning observational data, awareness and willingness to cooperate in the scientific community, computational advancements and growing process understanding can make great strides if resources are available to address the problems listed above. A revolution in co-located HHE observations will lead to a revolution in HHE modeling and forecasting. With this in mind, specific challenges for coupled HHE modeling were articulated during the course of the workshop. From these, recommendations were gathered on the final day of the workshop and were synthesized as well.

Modeling challenges

A number of modeling challenges emerged in the course of invited presentations, plenary discussions, panel sessions and breakout meetings. Salient issues included the following:

1. Improving our understanding of the effects of scaling, scale mismatches and heterogeneity in the coupled land-atmosphere system. This necessitates closure of budgets (water, energy, carbon) at appropriate scales across the system, and effective ways to bridge scales (both up and down) within and between models, including dynamical means to bridge scales and the use of "scale-aware" parameterizations of processes that cannot be represented explicitly in both atmospheric and terrestrial models.
2. Extending the model development and validation process as a matter of course to coupled HHE models. Calibration and metrics for individual classes of models are no guarantee of performance when coupled to other model components.

3. Developing comprehensive data-model fusion and data assimilation systems as well as parameter estimation and adaptive characterization. Methodologies for physically constrained model development, inverse modeling, and automated parameter selection are still needed for short-term forecast systems and applications to support decision-making. These developments feed into the development of models for long-term simulation and projection.
4. Evolving more dynamic, prognostic formulations for important structures and components of the hydrologic cycle that are not purely hydrologic but epi-hydrologic (e.g. ecosystems, soils/geomorphology, topography, permafrost, glaciers, agriculture, episodic disturbance such as fire or pine-beetle) and representing additional biogeochemical constituents that move between the surface and atmosphere (e.g. dust, biological particles, aerosols, reactive chemistry).
5. Expanding and improving the representation and physical basis of currently tunable parameters in models, including making them more concretely related to processes that can be observed directly or through inverse modeling strategies and field-scale experiments taking advantage of existing or new observatory infrastructures.
6. Connecting modelers to burgeoning current and planned observational programs, data sets and their providers, as well as creating channels of communication and collaboration between observational and modeling communities to inform each other of needs, limitations, and the possibilities afforded by better coordination.

Modeling recommendations

1. **A synthesis exercise of existing data, leading to a "hydro-reanalysis"** should be conducted – a coupled atmosphere, land surface, surface water, subsurface analysis incorporating data assimilation in all components. A key aspect of a hydro-reanalysis, different from atmosphere or ocean reanalyses which only strive to estimate the actual state as accurately as possible at each point in time, would be to enforce conservation of energy, water and other modeled constituents through time. Such a reanalysis could be spatially limited at first in a very well observed (and augmentable) region in order to prove the concept and expose the weakest aspects of the models and data sets. It would also be a development platform for statistical estimation techniques related to integrated atmosphere, cloud, precipitation, terrestrial hydrology and vegetation data assimilation, as well as provide a validation data set.
2. **Promotion and support of Hydrologic (or Land-Atmosphere) Process Teams** (HPTs) could accelerate the larger-scale multi-institutional collaborative model development that cannot be tackled at the individual PI or single institution level. Such HPTs would be geared to cross-cut traditional atmospheric and hydrologic science modeling (and possibly also ecology and other related disciplines) to develop parameterizations and models to better simulate and understand coupled HHE processes (e.g., evapotranspiration, lateral moisture transports, land surface feedbacks on local-regional precipitation).
3. **Development of hydrometeorological observing system simulation experiments** (OSSEs – also called data denial experiments) in existing and new model frameworks will help in the planning of observational networks, to estimate sensitivities and the potential impact of uncertainties in the system. This element has the potential to link with both the reanalysis

and HPT elements above, as well as with several of the observational recommendations presented in the previous section.

4. Development of a better path to **convey new process knowledge into evolving multi-scale Earth System Models** is needed. Methodologies for full characterization of models' internal dynamics that results from both numerical and physical formulations as they evolve is needed for error attribution and characterization and to distinguish unambiguously artificial sensitivities from physical sensitivities of the natural systems being modeled.
5. Operational weather, climate and hydrologic forecasting have all suffered from an inherently conservative, overly risk-averse approach to innovation that slows the pace of innovation. An opportunity exists **to reinvent the research-to-operations (R2O) process** along with the development of fully coupled hydrometeorological models. A key facet to such an undertaking will be facilitating operations-to-research (O2R) communications to guide continuing model development, and particularly to 'prove the concepts' through experimental model development.
6. Related to the R2O pathway, the **development of baseline metrics and benchmarking techniques** is needed to guide model development in coupled Earth System Model frameworks, much like what exists and continues to be developed today for many component model categories. This can include the necessary evolution away from unobservable and unconstrainable parameters in models toward a more tractable philosophy of model design, calibration and validation.
7. Direct **inclusion of the human element** in coupled hydrometeorological models should be pursued, including the effects of agricultural practices, water management, urbanization, and current and future policy scenarios.
8. **Training of a new generation of scientists** who bridge traditional boundaries within the Earth system hydrologic cycle will facilitate its integrative treatment into the future.

Conclusions

Natural and manmade systems are under increasing pressure and experiencing growing variability due to a combination of climate and land use change, economic and population growth pressures. There is unprecedented urgency to understand, model and predict acute and chronic disturbances related to hydrometeorological, hydroclimatic and ecohydrological (HHE) processes that underpin agriculture, natural resources, transportation; effectively every aspect of civilization and the environment. However, the disciplinary character of scientific research and the ways that the institutions that support research have evolved to mirror the fractured structure of the natural sciences has become an impediment to the system-based understanding of coupled HHE processes now needed.

This NSF-sponsored workshop was targeted to identify and articulate the linkages that need to be forged to rapidly advance HHE research. These include bridging both disciplinary boundaries such as hydrology, meteorology and ecology, but also between theoreticians, numerical modelers and observationalists in these disciplines. Though presented above as separate lists for observational and modeling challenges, our key recommendations clearly extend across that division as much as they are cross-disciplinary. We contend that integrative progress in HHE observations will automatically enable breakthroughs in modeling, and vice versa. Thus, there is a significant need for advancing the communication, collaboration and coordination between observational and modeling groups that will help inform advances in each community. It should be noted that there are distinct cyber-infrastructure needs that also require addressing, such as differences in computational approaches between the atmospheric science and terrestrial hydrologic communities. Specifically, conflicting standards and concepts in hydrometeorological, hydroclimatic and ecohydrological data and modeling systems need to be resolved in order to address the challenges listed above. A growing challenge that may already be handicapping research and analysis is the growing conflict between the expectations for data stewardship (e.g. NSF data management plans, evolving scientific journal requirements and data served from multiple agencies) and reproducibility of scientific results, storage needs and policies, and computational resources for co-located data analysis.

Finally, we stress the need for advanced training and education of scientists and students in both hydrologic and atmospheric sciences that share a common technical language and work effectively across historic disciplinary boundaries to advance observational and modeling systems. These future leaders will, in turn, cross-fertilize the two communities and provide new capabilities and directions for research.

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References

Anyah, R.O., C. Weaver, G. Miguez-Macho, Y. Fan, A. Robock, 2008: Incorporating water table dynamics in climate modeling: 3. Simulating groundwater influence on coupled land-atmosphere variability. *J. Geophysical Res.-Atmos.*, 113, D07103.

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, doi: 10.1175/JHM532.1.

Duffy, C., 2004: "Semi-discrete dynamical model for mountain-front recharge and water balance estimation, Rio Grande of southern Colorado and New Mexico." Groundwater recharge in a desert environment: The southwestern United States. *Water and Science Application*, 9 (2004): 255-271.

Duffy, C., et al., 2006: Towards and integrated observing platform for the terrestrial water cycle: From bedrock to boundary layer. Available online: http://www.usgcrp.gov/usgcrp/Library/watercycle/ssg-whitepaper-dec2006.pdf

Gresho. P. M., and lee, R.L., 1979: Don't Suppress the Wiggles- They're telling you something. LLBL, UCRL-82979, 26pp.

Hamilton, K., Y. O. Takahashi, and W. Ohfuchi, 2008: Mesoscale spectrum of atmospheric motions investigated in a very fine resolution global general circulation model. *J. Geophys. Res.*, 113, D18110.

Intergovernmental Panel on Climate Change (IPCC) 2013: The Physical Science Basis. Available online at: http://www.ipcc.ch/report/ar5/wg1/#.Ut2n6bTFK1s

Kahn, B., and Teixeira, J., 2009: A global climatology of temperature and water vapor variance scaling from the Atmospheric Infrared Sounder. *J. Climate*, 22, 5558–5576
Koster, R., S. Mahanama, T. J. Yamada, G. Balsamo, M. Boisserie, P. Dirmeyer, F. Doblas-Reyes, C. T. Gordon, Z. Guo, J.-H. Jeong, D. Lawrence, Z. Li, L. Luo, S. Malyshev, W. Merryfield, S. I. Seneviratne, T. Stanelle, B. van den Hurk, F. Vitart, and E. F. Wood, 2010: The contribution of land surface initialization to subseasonal forecast skill: first results from the GLACE-2 project. *Geophys. Res. Lett*., **37**, L02402, doi: 10.1029/2009GL041677.
Maxwell, R., T. Chow, S. Kollet, 2007: The groundwater–land-surface–atmosphere connection: Soil moisture effects on the atmospheric boundary layer in fully-coupled simulations. *Adv. In Water Resources*, (30)12, 2447-2466.
Nastrom, G. D., Jasperson, W. H. and Gage, K. S., 1986: Horizontal spectra of atmospheric tracers measured during the global atmospheric sampling program. *J. Geophys. Res.*, 91, 13 201–13 209.
National Research Council, 2008: Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks, The National Academies Press, Washington, D.C., 250 pp.
National Research Council. 2012a: Challenges and Opportunities in the Hydrologic Sciences. Washington, DC: The National Academies Press, 200pp.
National Research Council. 2012b: Weather Services for the Nation: Becoming Second to None. Washington, DC: The National Academies Press, 74pp.
Nogueira, M., Barros, A. P., and Miranda, P. M., 2013: Multifractal properties of embedded convective structures in orographic precipitation: toward subgrid-scale predictability. *Nonlinear Processes in Geophysics*, 20 (5), 605-620.
Over, T. M., and Gupta, V. K., 1994: Statistical analysis of mesoscale rainfall: Dependence of a random cascade generator on large-scale forcing, *J. Appl. Meteor.*, 33, 1526–1542.
Ralph, M., et al., 2012: "Understanding the Water Cycle" – Final Report Issued from NOAA's Water Cycle Science Challenge Workshop. Available online at: http://hmt.noaa.gov/news/2012/112812.html
Skamarock, W., 2004: Evaluating mesoscale NWP models using kinetic energy spectra. *Mon. Wea. Rev.*, 132, 3019-3032.
Smith, R.B., 2013 et al.: The lower atmosphere observing facilities workshop: Meeting the challenge of climate system science. Workshop final report. https://www.eol.ucar.edu/node/116
Stolle, J., Lovejoy, S., and Schertzer, D., 2012: The temporal cascade structure and space-time relations for reanalysis and Global Circulation models. *Quart. J of the Royal Meteor. Soc.*, 138 (668), 1895-1913.
Yuan, X., E. F. Wood, J. K. Roundy, and M. Pan, 2013: CFSv2-based seasonal hydroclimatic forecasts over the conterminous United States. *J. Climate*, **26**, 4828–4847, doi: 10.1175/JCLI-D-12-00683.1.

Attendee List

1	Ying Fan Reinfelder	yingfan@eps.rutgers.edu
2	Ahmed Tawfik	abtawfik@cola.iges.org
3	Alexandr Zak	
4	Alexandra Isern	aisern@nsf.gov
5	Allison Steiner	alsteine@umich.edu
6	Ana Barros	barros@duke.edu
7	Andy Wood	andywood@ucar.edu
8	Anil Kumar	anil.kumar@nasa.gov
9	Chung Lu	CLU@nsf.gov
10	Dave Gochis	gochis@ucar.edu
11	David Lawrence	dlawren@ucar.edu
12	Dev Niyogi	climate@purdue.edu
13	Ethan Gutmann	gutmann@ucar.edu
14	Francina Dominguez	francina@hwr.arizona.edu
15	Gil Bohrer	bohrer.17@osu.edu
16	Hannah Cloke	h.l.cloke@reading.ac.uk
17	Jessica Lundquist	jdlund@uw.edu
18	Jim Smith	jsmith@princeton.edu
19	Kate Smits	ksmits@mines.edu
20	Katja Friedrich	Katja.Friedrich@colorado.edu
21	Kelly Mahoney	kelly.mahoney@noaa.gov
22	Kenneth Davis	kjd10@psu.edu
23	Kristie Franz	kfranz@iastate.edu
24	Martyn Clark	mclark@ucar.edu
25	Michal Benes	benesmic@kmlinux.fjfi.cvut.cz
26	Mimi Hughes	mimi.hughes@noaa.gov
27	Noah Molotch	Noah.P.Molotch@jpl.nasa.gov
28	Ondrej Partl	
29	Paul Brooks	brooks@hwr.arizona.edu
30	Paul Dirmeyer	pdirmeye@gmu.edu

31	Pierre Gentine	pg2328@columbia.edu
32	Radek Fucik	radek.fucik@fjfi.cvut.cz
33	Reed Maxwell	rmaxwell@mines.edu
34	Richard Hooper	RHooper@cuahsi.org
35	Roy Rasmussen	rasmus@ucar.edu
36	Ruby Leung	ruby.leung@pnl.gov
37	Scott Denning	denning@atmos.colostate.edu
38	Sean Swenson	swensosc@ucar.edu
39	Thomas Torgersen	ttorgers@nsf.gov
40	Tilden Meyers	tilden.meyers@noaa.gov
41	Tissa Illangasekare	tissa@mines.edu
42	Xu Liang	xuliang@pitt.edu
43	Xubin Zeng	xubin@atmo.arizona.edu
44	Ignacio Rodriquez-Iturbe	irodrigu@princeton.edu
45	John McCray	jmccray@mines.edu
46	Terri Hogue	thogue@mines.edu
47	David Yates	yates@ucar.edu
48	James Gilbert	jagilber@mymail.mines.edu
49	Lindsay Bearup	lindsaybearup@gmail.com
50	Jen Jefferson	jejeffer@mymail.mines.edu
51	Bryant Reyes	brreyes@mymail.mines.edu
52	Kim Manago	kmanago6@gmail.com
53	Kyle Knipper	kknipper@mymail.mines.edu
54	Jessica Shirey	jshirey@mymail.mines.edu
55	Laura Condone	lcondon@mymail.mines.edu
56	Andrew Christian Trautz	atrautz@mymail.mines.edu
57	Lauren Foster	lfoster@mymail.mines.edu
58	Ali Moradi Gharehtapeh	amoradig@mymail.mines.edu
59	Benjamin Michael Wallen	bwallen@mymail.mines.edu