

The Water Cycle across Scales

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The transport and transformations of water substance in the global water cycle are of fundamental and primary importance for understanding the ecosystems, the land surface hydrology that supports them, and the management of water resources for humans. The water cycle is also critical for predicting weather, and the long-term climate balance of the planet. Despite the importance of water and a tremendous body of work researching its processes, critical questions regarding the global water cycle remain. These questions range from fundamental details of the spectroscopy of water, to the forecasting of precipitation, to closing the budget of the hydrological cycle on many scales.

Discussion of these and other topics relevant to contemporary water-cycle research led us to outline some themes, questions, and proposed opportunities. Many of these, and broader, issues have been brought to the forefront of scientific discourse through a number of strategic documents that have recently been published (see “For Further Reading” below). To minimize duplication with earlier efforts, we focus on integrating themes and strategic opportunities identified at the workshop.

TRANSPORT AND TRANSFORMATIONS: ATMOSPHERIC CONVECTION AS PROTOTYPE ISSUE. Addressing the transport and transformation of water and water vapor across the Earth surface and through the atmosphere is the principal focus of water-cycle research. However, the pervasiveness of water throughout nearly all atmospheric processes demands an inherent multidisciplinary and multiscale approach to addressing critical water-cycle research questions. Because of the amount and degree of detail across a range of space and time scales required for comprehensively addressing these questions, collaborations that cut across traditional subdisciplines must be forged. Many participants saw atmospheric convection as a prototype issue for discussing water-cycle interactions across a wide range of scales. The issues raised in studying the convective problem serve as an example of multiscale challenges in water-cycle research.

Approaches to understanding convection often depend on the scale at which a particular problem is being addressed. Convection is a problem requiring understanding micrometeorology and local severe weather, as well as global energy budgets and long-term climate change. Correspondingly, decades of research have yielded numerous analytical and numerical techniques to quantitatively represent convective processes, many applicable only at a particular horizontal and vertical scale.

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One common assumption, and limitation, of these approaches has been to maintain a clear scale separation between processes represented explicitly within numerical modeling frameworks and those represented implicitly in convective parameterizations. However, water-cycle processes and their associated feedbacks cut across many orders of magnitude of length scales. Hence, implicit assumptions about length scales can often yield significant hindrances in solving such problems.

The convective-scale problem (and similar scale-related problems) has been recognized by the broader research community. Progress is being made toward developing enhanced observational capabilities, which can measure convective processes on scales traditionally out of reach. In particular, advances in multipolarization and multifrequency radar, acoustical sounding systems, eye-safe lidar systems, remote sensing platforms such as EOS (NASA Earth Observing System), TRMM (Tropical Rainfall Measuring Mission), and the Global Positioning System, and cloud microphysical measurement devices have each contributed important linkages in the chain of convective processes. These advancements have motivated a new generation of field campaigns, such as the Bow Echo and Mesoscale Vortex Experiment (BAMEX), International H₂O Project (IHOP), and the North American Monsoon Experiment (NAME), which are aimed at studying the multiscale process of warm season atmospheric convection. These field experiments leverage significantly upon operational data-acquisition platforms to characterize the slowly varying synoptic state, and upon several airborne or portable, state-of-the-art research instruments that are locally deployed for intensive observation periods. The result of these efforts has and will continue to be the generation of copious amounts of data on the thermodynamic and microphysical structure of the atmosphere across a wide range of scales.

One paramount challenge will be to synthesize all of the new information into physically consistent conceptual models of convection across a range of scales and then to incorporate these new concepts into numerical weather and climate models. In the development of these new models, significant questions regarding the sufficiency of the traditional scale-separation approach versus an integrated multiscale approach will need to be addressed. Some of the questions brought up in the ECSA forum were:

- What essential prognostic variables must be accounted for and represented explicitly (vs. implicitly)?

- Which processes (and corresponding variables) possess the highest degrees of nonlinear responses?
- What atmospheric precursor variables are critical for accurate initialization of the convective environment?
- What “secondary” processes, such as cloud radiative forcing, are critical for closing the convective cloud energy balance?
- What are the roles of different microphysical constituents in water/ice drop formation and convective development?
- What is the role of the land/ocean surface in initiating and sustaining convection? Correspondingly, what scales of land/ocean surface heterogeneity favor or inhibit convective development?
- How and at what scales does convection begin to organize into a self-sustaining or “quasi steady-state” system?
- What kinds or combinations of models and model parameterizations best represent the natural multiscale cascade of energy and water through a convective event?
- How can NWP models assimilate multiscale observations of variables, such as radar reflectivity, that often only relate to model variables?

DEVELOPING COLLABORATIVE RESEARCH.

Addressing these and the myriad other questions surrounding the convective problem will require the collaborative efforts of many research groups, each capable of contributing expertise in the treatment of the critical processes identified. We will need collaborations among observationalists, who understand emergent measurement technology; diagnosticians, who can elucidate critical processes; and modelers, who can transfer emerging concepts into simulation and prediction tools. Community-based analysis and modeling systems will need to be developed and maintained to aid researchers in the efficient analysis and visualization of scientific research. Similar collaborative strategies can and are being implemented within the scientific community to address additional multiscale processes in land surface hydrology, the coupled ocean–atmosphere climate system, tropospheric–stratospheric exchange processes, and atmospheric (e.g., weather and climate) observational networks.

Significant opportunities for collaborative research are being developed through involvement in cross-disciplinary research teams. For example, NOAA is promoting cross-disciplinary research in their Climate

Process Teams and NCAR through the NCAR strategic initiatives, such as “The Water Cycle across Scales” and “Biogeosciences.” Participation in such a team can offer a valuable, broadening experience for early-career scientists by helping them to think more holistically about their research and stimulating them to address solution alternatives more comprehensively. The interaction among different groups can also help to develop new scientific questions aimed at addressing uncertainties in the linkages between different physical processes (e.g., cloud microphysics and convection) out to different Earth system linkages (e.g., the climate system and the ecosystem). Such collaborations are expected to erode traditional barriers to performing comprehensive research. These barriers have, on occasion, resulted in the application of inappropriate assumptions that pervade model parameterizations and therefore limit model performance and predictability.

FOSTERING OPERATIONAL-RESEARCH LINKAGES. While most of the participants at the ECSA forum were academic researchers, several also possessed close affiliations or collaborations with operational institutions, in particular the NWS. Nonetheless, it was felt that there generally is insufficient dialogue between the operational and research communities, and that opportunities exist for conducting and integrating “societally relevant” research when collaborative partnerships are established. Operational linkages are needed along many facets of research, including weather and climate observational network deployment and evaluation, model development and evaluation, forecast assessment, improved diagnostic techniques, and improved visualization and communication tools. Operational research issues are considered challenging, and many operations personnel are interested in conducting research within the scope of their routine activities. However, they often lack the time and resources to spin up research efforts independently. Hence, the development of collaborations with operational groups can be mutually beneficial.

THE ROLE OF OBSERVATIONS IN WATER-CYCLE RESEARCH. Despite progress in conceptual understanding, diagnostic techniques, and numerical simulation capabilities, understanding and prediction of water-cycle system components is critically dependent on the availability of high-quality, high-resolution observations. Large gaps and inconsistencies in the global observing network stand

STRATEGIC OPPORTUNITIES FOR JUNIOR SCIENTISTS IN WATER-CYCLE RESEARCH

- Become involved in interdisciplinary research teams addressing multiscale, interdisciplinary science questions
- Foster improved operational–research linkages
- Develop improved metrics for the evaluation of theories and simulation tools

as a major obstacle to performing comprehensive climate assessments. Although recently emerging instrumentation such as sensors aboard the NASA *Aqua* satellite will help improve our observing capacity, deficiencies in the historical record will continue to complicate efforts to document variability in global and regional climate systems on interannual to interdecadal time scales. The lack of widely distributed, real-time, mesoscale observational networks (such as the Oklahoma mesonet) both within the United States and abroad impedes the analysis and prediction of key mesoscale processes. The lack of information on mesoscale variations in water vapor complicates forecasting convective activity and warm-season precipitation (e.g., warm-season events where typical length scales for convective precipitation systems are on the order of 1–100 km). There are also critical gaps in the observation of surface–atmosphere exchanges as well as in the sampling of the upper troposphere and lower stratosphere. Taken together, these deficiencies inhibit a more complete characterization of the state of the water cycle at any one time and complicate the task of detecting short- and long-term change.

Recognizing the pervasive problem of insufficient data, and the fact that it is unlikely that many of the deficiencies in the observing network will be filled, we discussed where opportunities may lie in the coming years for improving the characterization of the land–atmosphere system. Clearly, remote sensing from both ground-based and space-borne platforms will provide much-needed timely information on spatial scales relevant to some water-cycle research areas. Improved understanding of what these observations are providing, their associated errors, and their relationship to local “point” measurements need to be gained in order to optimize their integration into water-cycle research. Much work is also needed to provide guidance on where the existing operational system is critically deficient. As an example, the TAO array of monitoring equipment in the tropical Pacific Ocean has provided a wealth of information on El

Niño–Southern Oscillation-related phenomena. Similar studies are needed to quantify the impact of both new and existing observations on diagnostic studies and numerical predictions. Those sites and platforms deemed to yield highly significant impacts on diagnostic and predictive capabilities need to be implemented in the operational observing network. We generally agree that such detailed assessment is critical to obtaining the sustained funding required for a new operational observing system. This work will certainly require improved training of new scientists as well as increased collaboration between observationalists, diagnosticians, and modeling groups beyond what is generally present.

IMPROVED METRICS FOR EVALUATING THEORIES AND MODELS. While many water-cycle research priorities have been compiled in strategic documents and literature reviews, we discussed additional opportunities, such as interdisciplinary collaboration and research–operational linkages, for developing research strategies aimed at addressing the scientific issues detailed in previous works.

Much recent work, mostly modeling, has suffered from a lack of standardized metrics. We generally agreed that many published modeling studies are failing to contribute to improved forecasts or conceptual understanding in a tangible way. For example, model-estimated mean daily rainfall in warm season convective environments offers little informational value on the validity of simulated or predicted atmospheric processes that generate precipitation. The method to best improve this research is to better utilize observations in model validation. Improved metrics should be established that take advantage of emerging instrument platforms. A new generation of metrics should include radar-based climatologies of subdaily rainfall (i.e., the diurnal cycle), lidar-sensed boundary-layer structure, remotely sensed soil wetness, vegetation phenology, and streamflow as a basin-scale integrator of hydrological processes. Moreover, further emphasis should be placed on utilizing ensemble simulations and forecasts. Ensembles improve probabilistic characterization of a simulated or forecasted climate at time scales beyond deterministic numerical weather prediction. Ensemble techniques should also be used in short-term forecasts, especially quantitative precipitation forecasts.

In support of modeling work, we also see a need for increased collaboration between observationalists and modelers in order to improve the disconnect between model parameters and observable quantities.

Many studies have documented marked sensitivities in simulated weather and climate to a small handful of parameter values. Where possible, collaborative research should be directed at developing optimal values for parameters based on observations. There should be improved dialogue between modelers and observationalists in determining which model parameters are realistically quantifiable through observations, and which parameters are relatively impossible to constrain observationally. Collaborations could also strive to replace unobservable parameters with those that do have observable components. Distributed parameter datasets should be developed, where possible, as opposed to obtaining single values.

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FOR FURTHER READING

- CUASHI, 2003: *The CUASHI Draft Science and Implementation Plan*. Consortium of Universities for the Advancement of Hydrologic Sciences, Inc., 56 pp.
- Emanuel, K., and Coauthors, 1995: Report of the first prospectus development team of the U.S. Weather Research Program to NOAA and the NSF. *Bull. Amer. Meteor. Soc.*, **76**, 1194–1208.
- Entekhabi, D., and Coauthors, 1999: An agenda for land surface hydrology research and a call for the Second International Hydrological Decade. *Bull. Amer. Meteor. Soc.*, **80**(10), 2043–2058.
- Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the IPCC. Cambridge University Press, 881 pp.
- National Center for Atmospheric Research, 2001: The water cycle across scales. Technical document. [Available online at www.ncar.ucar.edu/stratplan/water_cycle.html.]
- National Research Council, 2001: *Basic Research Opportunities in the Earth Sciences*. National Academies Press, 168 pp.
- U.S. Global Change Research Program, 2001: *A Plan for a New Science Initiative on the Global Water Cycle*. U.S. Global Change Research Program, 118 pp.