Terrestrial Water Cycle Science: Key Unknowns and Frontiers to Support Research, Applications and Water Management

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Summary

In spite of several decades of focused hydrologic research, critical gaps in our understanding of the stocks and fluxes of the terrestrial water cycle still exist. In particular, knowledge of the volume of the seasonal snowpack, its variations in space and time, and its interactions with climate and society, remain surprisingly poorly constrained. While most other components of the terrestrial water cycle are currently being observed from space (or will be within the next 5 years), a critical missing link is a satellite mission for measuring key components of the snowpack, especially its snow water equivalent, snow color and albedo.

In order to address fundamental questions of human and water security, the Earth science community must ultimately provide a comprehensive water cycle observing system. Such a system must include space-based assets for monitoring storage of snow and ice, and also for surface water, soil moisture and groundwater storage, as well as the fluxes of precipitation, evapotranspiration and runoff/streamflow. These observations should be integrated into an advanced hydrological modeling platform that also includes in situ and aircraft data.

Once assembled, such a framework would enable holistic assessment of freshwater availability from regional to global scales that will significantly advance water cycle research and greatly enhance sustainable water management. At present, lack of understanding of the dynamics of seasonal snow volume variations and their Earth system interactions remains a critical obstacle to progress.

1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

In spite of several decades of effort and investment in hydrologic observing resources and modeling capabilities, critical gaps in our understanding of the stocks and fluxes of the terrestrial water cycle still exist. For example, important difficulties remain in understanding a) the volume of terrestrial freshwater on the planet; b) how it is distributed among snow, ice, surface water, soil moisture and groundwater reservoirs, and c) how these storages and associated fluxes vary in space and time (1). Addressing this challenge is both essential for supporting basic and applied research, and fundamental for enabling sustainable water management, from local scales to the scales of large, trans-boundary aquifers and watersheds.

While important advances have been made in understanding soil moisture (2), surface water (3) and groundwater (4) variations, characterizing variations in seasonal snowpack volume (ie. its snow water equivalent [SWE] and albedo) and its interactions with climate remain perhaps the most significant, large-scale unknowns in hydrologic science (5). The alpine snowpack dominates the hydrologic cycle in most high latitude and high altitude regions of the world, controlling a diversity of processes from biogeochemical to ecologic to climatic, as well as practical concerns such as seasonal flooding and water availability. Lower altitude snow cover is equally important, playing a central role in seasonal albedo and ground insulation changes. However, methods for estimating the volume of water stored in the seasonal snowpack remain primitive; and the lack of routine SWE and changing color and albedo information have limited the progress of hydrologic and climate science in this critical area.

Note that understanding the size of the seasonal snowpack, its dynamics and its Earth system interactions fit squarely into a broader, practical understanding of global water availability. Society, and we as Earth scientists, must strive to answer a set of practical questions that form the foundation of sustainable water resources management. These include:

- How much water do we have – as snow, ice, surface water, soil moisture and groundwater?
- How much do we need – for the humans and the environment, to grow food, for energy production and for economic growth?
- How is the gap between supply and demand changing with time – due to population growth, climate change, advances in technology, changes in human behavior and water management?

Clearly, significant progress towards characterizing the seasonal snow load – namely its water equivalent but also its optical properties as well as its extent – is essential to answer the questions above. Note further that the challenge is an observational one, but also one of maintaining a robust network of ground-based hydrological measurements, airborne campaigns, and of ingesting these observations into data integration platforms. Given that climate and the hydrological cycle are changing, and that world population and associated food and energy requirements are growing, it is essential that an overarching observational-modeling framework that includes major snow properties including SWE and albedo is established to address the issues listed above.

2. Why are these challenge and questions timely to address now especially with

respect to readiness?

Timeliness is relevant to both societal need and to technological readiness. The narrative above underscores the pressing need to address major unknowns in water availability, and therefore in water, food, energy, national and human security. It is simply impossible to advance critical issues in sustainable water management unless the most fundamental issues outlined above are embraced and addressed. Changes in the seasonal snow water volume represent perhaps the largest unknown in total, annual renewable terrestrial water storage.

Technologically, the capabilities now exist or are being developed to a) observe the major stocks and fluxes of the terrestrial water cycle; and b) to integrate them into advanced, data-integrating hydrological models to provide the best-available, holistic assessment of the stocks and fluxes of the terrestrial water cycle. The hydrologic community is fortunate that an array of terrestrial water cycle satellites has been launched (SMAP (2), GRACE (6) or will be launched (SWOT (3), GRACE-FO, ECOSTRESS) in the near future. Importantly, other white paper input to this RFI point out the needs for surface and root zone soil moisture (7), for joint sediment/carbon remote sensing (8), for snow water equivalent and albedo (9) and more.

While all of surface water, soil moisture and groundwater are (or will be) measured by current and future missions, measurement of the SWE of alpine and lowland snowpack remains a critical missing link in a space-based observing system. Likewise, characterization of albedo/snow color, which are now known to strongly influence seasonal melt rates and snowpack life, is essential to understand the timing of spring melting, changing snow season length, spring green-up, etc. When viewing the water cycle as a whole, we make the point in this white paper that a spaceborne snow mission will help close the water storage balance and provide near complete coverage of all major terrestrial water reservoirs. Given the demonstrated success of airborne snow observations (e.g. NASA's Airborne Snow Observatory), science and applications, a snow water equivalent mission is timely -- technologically, scientifically and societally.

3. Why are space-based observations fundamental to addressing these challenges and questions?

A comprehensive picture of the distribution Earth's freshwater over and through the land surface will only result from a combination of in situ observations, space-based measurements, and a data-integrating modeling framework. Unfortunately, in situ observational networks are insufficient for providing observations at space-time frequencies required to address the problems outlined above. Moreover, from a global perspective, international data sharing, including policies of data denial, remain in many cases, immovable obstacles. Satellites offer the global, apolitical perspective that is an important cornerstone of Earth observing (1).

The challenges of in situ snow monitoring are many, in particular in mountainous regions. While the sight of the lone snow observer on cross-country skis is a quaint reminder of how we can best measure snow depth and snow water equivalent at a point, it is impossible to construct a meaningful, mountain range-wide estimate with such an approach. A satellite-based SWE mission represents the only way to capture variations in the world's mountainous regions, and one that is essential for advancing hydrologic science, applications and for modernizing regional water management. Similarly, it will be impossible to map changing snow albedo and color without a dedicated spaceborne platform.

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