The Need for Improved Understanding and Remote Sensing of Snow Depth and Snow Water Equivalent

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**White Paper Description**: Snow is critically important to human welfare, affecting security, economics and climate. We currently lack effective means for accurately tracking snow, but recent developments in 4 areas, if integrated into a seamless system, could deliver snow depth and snow water equivalent data at local to global scales, benefiting billions of people.

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?

A key challenge in Earth System Science is quantifying the amount of snow that blankets Earth’s surface each winter as well as how that amount is changing spatially and temporally. Snow is critically important to human welfare, affecting business, food security, power generation, recreation, and climate. More than 25% of terrestrial Earth is snow-covered more than four months each year. But that fraction underestimates snow’s overall importance, because so many towns and agricultural areas lie in snow-free lowlands adjacent to mountains and rely on mountain snowmelt for their water supplies. Current estimates suggest 1/6th of the world’s population relies on snow for agricultural, industrial, and consumptive use. Snow blankets a further 13 million km2 of Arctic sea ice and 15 million km2 of Antarctic sea ice, controlling the thermodynamic growth of the ice and to a large extent the fate of the ice and its interactions with the rest of the climate system.

Despite the obvious importance of snow, we currently lack effective means for accurately tracking global, regional, and even local snow resources. We now find ourselves faced with needing to predict future snow conditions and snowmelt runoff without a reliable estimate of current snow resources. Our operational numerical prediction systems are also hampered by limits in our ability to monitor snow. These systems ingest satellite measurements of snow cover that have poorly-constrained errors, degrading weather and hydrological forecasts. Snow is the only component of the water cycle for which there has not been, or is there planned, a satellite mission.

Poor real-time monitoring capabilities exist at a time when we have worrying indications that the ***amount*** and ***timing*** of snow accumulation and melt are changing, in some cases at rapid rates. Changes in either snow amount or timing will have major ramifications: changing amounts will affect snowmelt-dominated water resources, the growth and melt of sea ice, glacier mass balance, and the thermal state of permafrost. Changing timing, particularly that of the spring freshet, will alter how much of the melting snow can be utilized by people, as well as the overall impact of snow on the global climate through changes in the surface energy balance.

Four interacting trends make predicting future snow cover conditions challenging. One is the intensification of the water cycle, which is altering patterns of precipitation, including snowfall. A second is the rising trend in global temperatures, which is pushing seasonal zero-degree isotherms toward higher elevations and latitudes, altering the boundary between liquid and solid precipitation. This trend is altering snow cover build-up and therefore stream runoff: snow storage is actually the largest seasonally-varying storage term in the global water budget. A third trend is the shift in the delivery of snowmelt water, driven by the earlier arrival of above-freezing air temperatures in spring. In many instances, meltwater, formerly stored as snowpack until runoff in the summer dry season, is likely to run-off to the ocean because of insufficient reservoir capacity downstream. Fourth and finally, the changing snow cover itself, and the period it lies on the ground, is altering the overall climate through feedback processes related to albedo, soil temperature, and sea-ice melt. Estimates suggest snow cover alone is responsible for -5 to -2 Watts m-2 of cooling across the globe, an effect that has already declined more than 10% due to reductions in the extent and duration of snow cover.

It is essential that we be able to monitor what is happening to the snow cover. The current state of the science is that we are able, with reasonable skill and resolution, to determine where the snow is, ***but not how much there is***. This problem – the problem of determining the ***snow water equivalent*** (SWE) – was identified as a critical need more than 35 years ago, yet remains a key unanswered challenge today. Solving the problem of accurately and reliably determining how much snow (SWE) there is, and how and why it is changing now and in the future, requires both basic and applied research. Any improvement in our knowledge and understanding of snow and snow-related processes will have a positive and immediate impact on billions of people and economic benefits worth billions of dollars.

1. Why are these challenge/questions timely to address now especially with respect to readiness?

Significant progress has been made in four areas that now make it possible to monitor SWE and snow depth. First, ***airborne lidar*** has become a proven tool for measuring snow depth with high accuracy and resolution at the basin scale. Second, significant progress has been made in understanding the interaction of radar with the snow cover, with preliminary algorithms for converting ***microwave radar*** signals into SWE already developed. Third, there have been major improvements in physically based snow ***modeling***, and fourth, techniques for sophisticated ***data assimilation*** are now available that can be used to ingest remote sensing data into a modeling system. By integrating these four components into a seamless system, local to global snow monitoring would be possible.

Recent efforts show that we can now map snow depth to ±10 cm using ***airborne lidar***. Subtracting snow-free elevation maps from maps with snow-cover produces spatially explicit, high-resolution snow-depth measurements. When combined with observations or model estimates of snow density, spatially distributed SWE (±3 cm) values are achieved. Moreover, the NASA/JPL Airborne Snow Observatory has demonstrated that airborne lidar measurements can be made on operational time scales, enabling new, more precise water management operations that are resilient to changing hydroclimatic conditions. Existing sensors and rapid technological development present a clear pathway to implement lidar on high altitude aircraft and perhaps orbital platforms, expanding full-watershed lidar snow depth mapping to the regional and global scale.

Thirty-five years of research in using ***microwave radar*** to measure SWE is now bearing fruit. Radar has always been an attractive instrument for a snow satellite mission because of its relative insensitivity to clouds, wide swath, and moderate to high spatial and temporal resolution. Improved physical scattering models, as well as extensive analysis of quantitative field observations, explain much of radar’s sensitivities to parameters other than SWE (like snow grain size). Despite these difficulties, significant functional relationships between SWE and backscatter remain and can be utilized for SWE retrievals. Two approaches appear viable: 1) using radar returns with ancillary data on snow grain size or depth to constrain the SWE inversions, or 2) estimating SWE change between two passes using radar phase differences at L-band, capitalizing on the linear density-dielectric relationship. An additional advantage of radar is that snow mission concept studies are presently underway at the Canadian Space Agency (CSA) and at NASA’s Jet Propulsion Laboratory (JPL); these efforts leverage the extensive progress made on X- and Ku-band radar retrievals done as part of the ESA CoReH20 project, which completed Phase A at ESA, although was not chosen for an ESA mission.

***Snow modeling*** has evolved from a collection of disconnected models that seldom agreed, to the point where we now have modular systems that can integrate different representations of physical processes. This collection of tools now provides insight into how any given model parameter will impact model output, providing capabilities to improve model fidelity and better characterize uncertainty. At the same time, systems for distributing process-based snow models across space and time have advanced. These models include meteorological downscaling, snowdrift development, the ability to force models with lidar measurements, as well modeling snow microstructure to guide microwave remote sensing. By capitalizing on continually increasing computer power, specifically cloud computing and model sharing facilitated by high-speed internet connections, the snow community is ready to: 1) ingest remote sensing measurements at high resolution, 2) combine these observations using models that are based on physical processes, and 3) provide temporal/spatial snow map products that build on remote sensing results, fill in data gaps, and provide snow information that cannot be monitored in any other way.

Similar progress has been made in developing ***data assimilation*** procedures for snow. Simplified snow assimilation methods have given way to more optimal systems in both research and operational settings. The Ensemble Kalman Filter (EnKF) allows us to apply modern computing capabilities to the problem of merging physically based models with remote sensing and in-situ measurements, including the ability to handle multi-scale observations. One advantage of these data assimilation methods is that they propagate information from one (observed) variable to other model variables or locations. Furthermore, the EnKF, and more advanced particle filter approaches, explicitly enable accounting for the sources of uncertainty in the modeling-assimilation system via generation of probabilistic forcing. Radiance-based assimilation techniques, which allow coupling of microwave emission models to traditional snow mass and energy models, now allow inference of snow properties using microwave measurements and snow models, including snow stratigraphy.

1. Why are space-based observations fundamental to addressing these challenges/questions?

Forty-five million km2 of Earth’s surface[[1]](#footnote-1) is heavily impacted, or even dominated, by snow cover. Many of the snow-covered regions of Earth are sparsely populated. Hence they have a very limited (and insufficient) network of ground stations that measure snow. In other more populated regions (like those in and around the Rocky Mountains and the Himalaya), the snow that people rely on for water is stockpiled high in the mountains in rugged and inaccessible terrain. In most locations, the snow cover is extremely heterogeneous, making spot measurements unrepresentative and of limited value. In short, the only feasible way to monitor and understand such an extensive Earth feature, one that literally can change overnight due to wind, snowfall, or melt, is to monitor it with remote sensing tools. A space-based approach is essential to assess whether global stocks of seasonal snow are increasing, decreasing, or shifting in location, pattern, and timing.

1. Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?
2. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs;

There are currently no planned NASA programs targeting remote sensing retrieval of SWE or snow depth that address the needs identified here. A small field program designed to establish optimal synergy between existing methods of SWE/depth remote sensing (informally called *SnowX*) is in the planning stage, but is not yet funded. NASA currently funds a snow lidar program at JPL; this program demonstrates an important capability, but currently has limited geographic extent. Internationally, a retrospective program will be supported by ESA to examine all of the radar data acquired during CoReH2O Phase A, and informal planning is underway for various active and passive microwave missions related to the upcoming ESA Earth Explorer-9 call for missions. None of these efforts is large enough or comprehensive enough to make the substantial progress needed. What is required is a coordinated series of laboratory and field/aircraft programs designed to identify the best way to use radar and lidar in concert, while designing and implementing a seamless modeling and data assimilation system that can ingest, interpret, and extrapolate/interpolate (in time and space) the remote sensing products.

1. The anticipated scientific and societal benefits;

Development of better snow remote sensing will serve science and society through: a) quantification of the state and change of snow resources regionally and globally on relevant time scales, b) improved snow-related water-resource information for managers, planners, and stakeholders, c) SWE information at the spatial resolution and uncertainty requirements necessary to meet operational environmental monitoring needs, services, and prediction, and d) increased information supporting other snow-interactive aspects of the climate-system.

1. The science communities that would be involved.

The communities directly involved would include the snow community, the cryospheric community in general (glaciers, ice sheets, permafrost, and sea ice), and the hydrologic community. There would also be strong interest within the ecology communities, including forest resources, soil-biologic processes, and snow-wildlife interactions; the global change communities for quantification of global water and energy cycles; and the natural hazards communities addressing snowmelt and rain-on-snow flooding, snow avalanches, and landslides.

*N.B. A fully referenced (77 references) version of this White Paper is available upon request (*[*matthew.sturm@gi.alaska.edu*](mailto:matthew.sturm@gi.alaska.edu)*). Additionally, detailed plans for for the integration of snow remote sensing, modeling, an data assimilation are available at the iSWGR website (http://www.iswgr.org/).*

1. *This total is based on Northern Hemisphere land areas where 40% of the precipitation comes as snow, plus the area of the Arctic and Antarctic sea ice. The total would be higher if Greenland and Antarctica were included, and if areas where snowmelt is important to agriculture and commerce, so the figure is conservative.* [↑](#footnote-ref-1)