COMMENTARY

Measuring global snow water equivalent from passive microwave remote sensing: opportunities and challenges

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Snow is not only one of the most important components of the cryosphere but also a critical indicator of climate change, with at least 80% of the Eurasian and North American regions covered by snow during winter and ~19% of the global freshwater supply coming from snowmelt.[1] The snow water equivalent (SWE) is the vertical depth of the corresponding liquid water after the snow melts completely and is a key parameter characterizing snow water storage. Accurate estimation of SWE information at global scales is essential for understanding hydrology, ecology, and global climate change.

The importance of the SWE is specifically recognized in the following aspects. First, SWE information is an indispensable initial input parameter for hydrological models (e.g., the coupled routing and excess storage model) and plays an important role in the global radiative energy balance due to the high albedo of snow, which reflects most of the incoming solar radiation.[2] Second, snowmelt is the main replenishment for many rivers and a significant supplement to groundwater, especially in arid and semiarid regions. Monitoring the global SWE distribution is highly important for meeting eco-environmental water demands and for developing water resource management strategies (Figure 1A). Finally, SWE information plays a pivotal role in the validation of regional or global SWE simulated from climate models (e.g., the coupled model intercomparison project phase 6). Accurate monitoring of the SWE at regional and global scales (taking the maximum SWE distribution in 2020 as an example; see Figure 1B) not only helps to reveal the impact of climate change but also provides a scientific basis for formulating strategies to address climate change. However, the current lack of knowledge and inaccurate estimation of the SWE at regional and global scales have led to large uncertainties in hydrological and climate models, which represents a major scientific challenge in the field of global climate change. Therefore, obtaining accurate spatial and temporal distributions of the SWE is a necessary prerequisite for understanding global climate change, surface energy balance, and the regional water cycle.

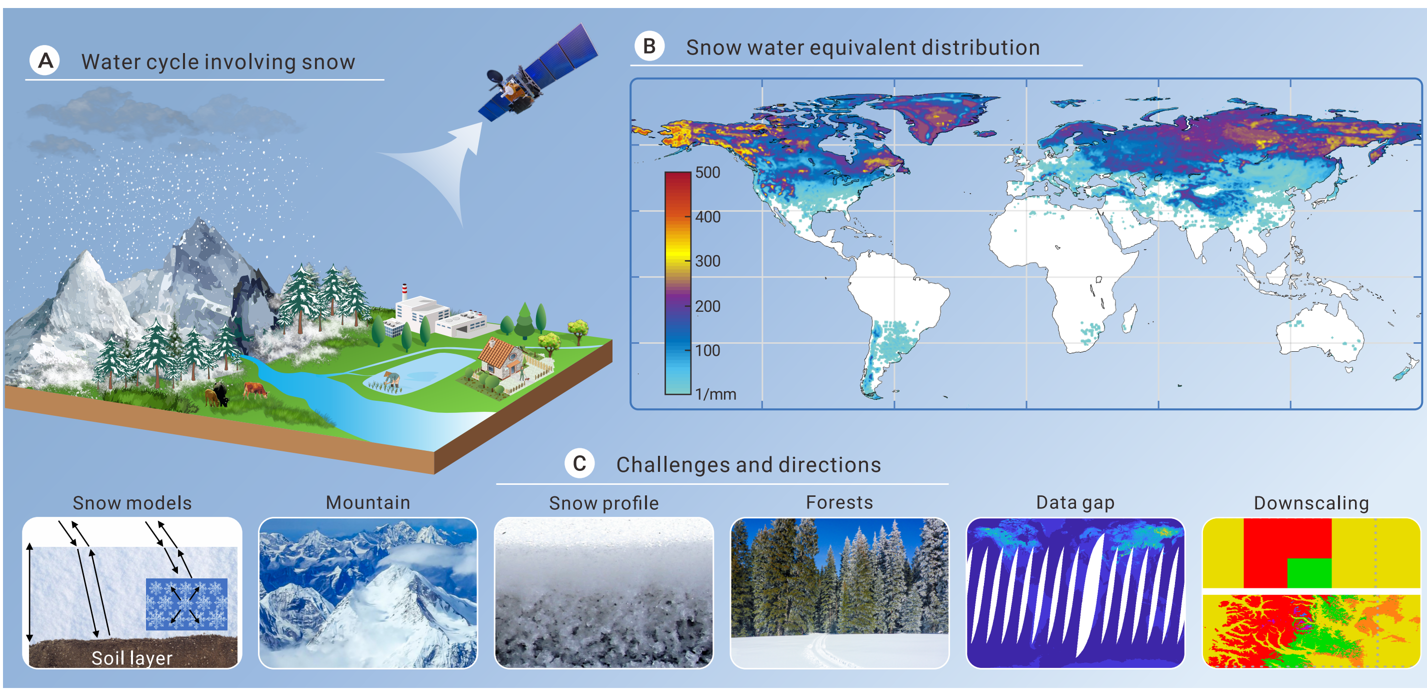

Figure 1. Passive microwave remote sensing of the SWE (A) water cycle involving snow; (B) maximum snow water equivalent distribution in 2020; (C) challenges and directions.

PRINCIPLES OF PASSIVE MICROWAVE REMOTE SENSING OF THE SWE

Snow is a porous continuous medium consisting of air gaps and ice particle structures. The snowpack is the layer of snow that covers the surface of land and sea ice after the snowflakes have fallen on the ground, and it gradually evolves over time depending on the local microtopography and climate during the snow season. Passive microwave remote sensing has the advantages of large-scale observations, high temporal resolution, and near all-weather coverage. Microwave radiation signals have the ability to penetrate snowpack, making it possible to use passive microwave remote sensing to monitor the SWE. The microwave radiation obtained from the satellite radiometer contains the upward radiation from the soil and the snowpack as well as the forest radiation in forest regions after atmospheric radiation attenuation. The microwave radiation properties of snowpack change with snow depth, snow grain size, snow density, snow temperature, and subsurface medium.[3] The brightness temperature acquired by passive microwave satellites decreases with increasing snow depth since it produces a stronger extinction effect when penetrating thicker snow. Such patterns of changes in the scattering and absorption characteristics of microwave signals can be used to detect SWE information; therefore, passive microwave remote sensing is regarded as the most effective method for monitoring the SWE at global scales.[4]

OPPORTUNITIES AND CHALLENGES IN ESTIMATING THE SWE FROM PASSIVE MICROWAVE REMOTE SENSING

Satellite observations provide long time series data, which not only allows for tracing past SWE information but also enables real-time monitoring of current SWE conditions and supports modeling future trends. However, there are also some challenges in estimating the SWE from passive microwave remote sensing (Figure 1C). The large uncertainties in the quantitative estimation of the SWE at global scales are mainly due to the lack of precise characterization of the snow metamorphism process and forest radiation attenuation and coupling.[5]

(1) Snow models (e.g., snow emission models and snow evolution models) rely heavily on field observations, leading to large uncertainties in out-of-sample regions. In addition, the models do not fully consider the influence of mountainous terrain.

(2) The microstructural information (snow grain size and density) inside the snowpack changes significantly during the snow season (reflected in significant differences in snow profiles), which can strongly affect the microwave emission signal from the snowpack. Remotely sensed SWE estimates often exhibit significant seasonal biases owing to the lack of high-accuracy snowpack microstructure information.

(3) The shading effect of forests can significantly affect the upward radiation of snowpack, and how to distinguish the upward radiation of forests and the attenuation effect of forest canopies on the upward radiation of snow under forests has become a key issue in the development of forest transmissivity models.

(4) There are gaps in remotely sensed SWE datasets due to satellite orbit coverage and the limitations of SWE retrieval algorithms. Filling gaps in satellite SWE datasets without sacrificing temporal resolution is a major challenge.

(5) The coarse resolution of passive microwave remote sensing greatly limits the regional applications of SWE datasets. Therefore, spatial downscaling has gradually become a key way to improve the spatial resolution of passive microwave SWE datasets.

FUTURE DIRECTIONS IN PASSIVE MICROWAVE REMOTE SENSING OF THE SWE

Future directions emphasize the significance of snow models, auxiliary information (e.g., complex terrain features), and new technologies for obtaining spatiotemporally continuous SWE information at global scales (Figure 1C):

(1) Develop high-accuracy snow models that consider multiple elements, including soil, snowpack, forest, and atmosphere. Future research needs to be devoted to improving the accuracy and applicability of the models by incorporating more field observations during the whole snow season, especially in data-scarce regions, to capture SWE changes more accurately over various regions with different terrains and climates. Terrain models should be integrated into snow models to improve their simulation ability in complex mountainous areas.

(2) Develop high-accuracy snow evolution models to simulate the spatiotemporal distributions of snow microstructural information at global scales to characterize its seasonal changes due to snow metamorphism. Some important physical processes inside the snowpack, such as inverted density gradients caused by water vapor fluxes, should be integrated into the models to improve their simulation ability, especially under very cold conditions.

(3) Investigate the relationship between brightness temperature and forest parameters (e.g., forest transmissivity, forest fraction percentage, and single scattering albedo) based on ground experiments under different forest conditions. It is necessary to conduct extensive observations of different forest species and growth conditions to establish a robust forest transmissivity model to accurately characterize the impact of forests.

(4) Establish and improve SWE gap-filling algorithms to provide a global seamless daily SWE dataset. Future research should combine the spatial and temporal characteristics of regional SWE and topographic information and apply new technological tools, such as deep learning methods, to develop high-accuracy gap-filling algorithms to meet current needs regarding the application of the SWE at regional and global scales.

(5) Propose high-accuracy downscaling algorithms for the SWE to meet the high-resolution requirements at regional or global scales for hydrological and ecological applications. Highly intensive snow observation networks should be built in typical snow regions to investigate the relationships between the SWE and downscaling factors in subpixels. Then, data from multiple sources and machine/deep learning methods (e.g., light gradient boosting machines) can be adopted to construct downscaling models.

The promotion of these future directions is expected to provide new ideas and methods for accurate estimation of the SWE, which will provide more reliable datasets for water resource management, meteorological forecasting, and other applications. At the same time, it will further enhance the status of the SWE in global climate change research and promote scientific progress in related fields.

SUMMARY AND OUTLOOK

As an advanced observation method, satellite-based passive microwave remote sensing can accurately characterize the spatial and temporal distributions of the SWE at regional and global scales. This study briefly introduces the principles of passive microwave remote sensing of the SWE and summarizes the main challenges and future directions in estimating the SWE from passive microwave satellite observations. New technologies and big data platforms should be combined to accurately estimate the spatial and temporal distributions of the SWE to better meet the current needs for utilizing the SWE in hydrological and ecological contexts and in studies on global climate change.

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DECLARATION OF INTERESTS

The authors declare no competing interests.