Supplement for:
Review article: using machine learning for snow remote sensing: trends and future directions for global snow measurements

Catherine Breen[1,2], Kehan Yang[1,2], Justin Pflug[1,3], Sujay Kumar[1], Nicoleta Cristea[4], Ibrahim Alabi[5], Carrie Vuyovich[1]

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[2]Science Systems Applications, Inc., Greenbelt, MD, USA
[3]University of Maryland, ESSIC, College Park, MD, USA
[4]University of Washington, Civil and Environmental Engineering, Seattle, WA, USA
[5]Department of Geosciences, Boise State University, Boise, ID

Correspondence to: Catherine M. Breen (catherine.m.breen@nasa.gov)

Table S1. Type, description, example use case, and citations of uses for various machine learning models used in snow remote sensing (not exhaustive, see Table S2 for all papers used in this literature review). These models were identified from a comprehensive literature search from Web of Science.

Model Type	Description	Example Use Case for Snow	Citations of Use Cases
Random Forest	Multiple decision trees each trained on random subset of data; final trees each cast a "vote" for prediction (classification) or averaged (regression)	Fusing multi-sensor data to estimate SWE or snow depth	Bair et al. 2018; Pflug et al. 2024
Extremely Randomized Trees (ERT)	Similar to Random Forest, but builds trees using the entire dataset and chooses node-splitting thresholds at random	Estimating snow depth	Tanniru & Ramsankaran 2023
Support Vector Machine (SVM)	Identifies the "hyperplane" or decision boundary that separates data points of different classes by maximizing the margin between the closest points of each class	Classifying wet vs. dry snow using SAR; extracting snow cover in complex mountainous areas	Kumar et al. 2022; He et al. 2015
Extreme Gradient Boosting (XGBoost)	An ensemble learning method based on decision trees that builds trees sequentially, correcting errors from previous trees. Multiple weak trees are used for one strong prediction. Typically used for tabular data.	Downscaling coarse passive microwave snow depth	Malygin et al. 2024; Boeykens et al. 2025
k-Nearest Neighbors	Supervised method that makes predictions by finding a predefined number (k) of training samples closest in distance to a new query point. a simple, used for both regression and classification tasks.	Classifying wet vs. dry; snow depth estimation	Gallet et al. 2024; Chen et al. 2025
Unsupervised Clustering (k-means, PCA)	An algorithm that groups data points by clusters using a mathematical mean to identify proximal points, a form of unsupervised learning.	Identifying global snow seasonality regimes	Johnston et al. 2024; Bair et al. 2021
Artificial Neural Network (ANN)	A method that receives input and passes that input through a network of "nodes" that learn information about the input data by storing it in matrices. A simple form of a convolutional neural network.	Deriving SWE or snow depth from passive microwave; fusing multi-source data; estimating forest snow depth	Tedesco et al. 2004; Snauffer et al. 2018; Zaerpour et al. 2020.
Convolutional Neural Network (CNN)	A deep learning architecture that uses a series of matrix operations ("convolutions") to extract spatial features from gridded data (i.e., images)	Segmentation for snow/ no snow; snow retrievals for high-res mapping	Cannistra et al. 2021; Xing et al. 2022
Long short-term memory network (LSTM)	A neural network structured to learn and remember dependencies in time-series data	Filling gaps in time series (e.g., snow cover beneath clouds)	Hou et al. 2022; Elyoussfi et al. 2025; Pflug et al. 2025
U-Nets	A specialized form of a CNN model that is specifically used for categorizing pixels in the image.	Pixel-level cloud vs. snow discrimination, mapping high-resolution snow-covered areas	Wang et al. 2022; John et al. 2022
Transformers	Deep learning architectures that use self-attention mechanisms to weigh the significance of different parts of sequential or spatial inputs	Modeling temporal history (SWE changes over time) for deep snowpack estimation	Kumawat et al. 2025; Yu et al. 2025

Table S2. Input data across papers reviewed, categorized by the snow property analyzed.

	Snow Cover	**SWE**	**Snow Depth**	**Other**
Optical	Sauter et al., 2010; Dobreva et al., 2011; Hou et al., 2014; Moosavi et al., 2014; Czyzowska-Wisniewski et al., 2015; Kan et al., 2018; De Gregorio et al., 2019; Haq et al., 2019; Nijhawan et al., 2019; Liu et al., 2020; Guo et al., 2020; Hou et al., 2020; Liu et al., 2020; Hu et al., 2022; Yatheendradas et al., 2022; Luo et al., 2022; Hou et al., 2022; Luan et al., 2022; Azizi et al., 2024; Kollert et al., 2024; Esmaeelzadeh et al., 2024; Wang et al., 2024; Mahanthege et al., 2024; Liu et al., 2024; Johnston et al., 2024; Hu et al., 2025; Kesikoglu et al., 2025; Sun et al., 2025; Zhang et al., 2026; Wei et al., 2025	Gao et al., 2023; Yang et al., 2022; Goodarzi et al., 2025; Yang et al., 2025	Wang et al., 2025; Xiong et al., 2022; Elyoussfi et al., 2025	Bloshchinskiy et al., 2020; Kosmala et al., 2018; Zheng et al., 2021; Jin et al., 2022; Yin et al., 2022; Dumont et al., 2024; Johnston et al., 2024; Demil et al., 2025
Passive Microwave	Farmer et al., 2010; Xiao et al., 2021	Gao et al., 2023; Tsang et al., 1992; Chang et al., 1992; Chen et al., 2001; Tedesco et al., 2004; Evora et al., 2008; Tong et al., 2010; Dariane et al., 2014; Zhang et al., 2021; Moradizadeh et al., 2023; Li et al., 2026	Xiao et al., 2018; Zaerpour et al., 2020; Yang et al., 2020; Wang et al., 2020; Yang et al., 2021; Wei et al., 2022; Tanniru et al., 2023; Wei et al., 2023; Liu et al., 2024; Hou et al., 2024; Bai et al., 2025; Tanniru et al., 2025; Yan et al., 2025; Wang et al., 2025; Li et al., 2026; Bai et al., 2026; Wei et al., 2026	Xue et al., 2015; Rostosky et al., 2020; Sun et al., 2024; Gonzalez et al., 2025
Topography	Hou et al., 2014; Czyzowska-Wisniewski et al., 2015; Kan et al., 2018; Nijhawan et al., 2019; Premier et al., 2021; John et al., 2022; Azizi et al., 2024; Kollert et	Zhang et al., 2021; Moradizadeh et al., 2023	Xiao et al., 2018; Yang et al., 2020; Yang et al., 2021; Daudt et al., 2023; Gao et al., 2023; Tanniru et al., 2023; Dunmire et al., 2024; Liu et al., 2024;	Gallet et al., 2024

	al., 2024; Liu et al., 2024; Hu et al., 2025		Esfahani et al., 2025; Yan et al., 2025; Wang et al., 2025; Bai et al., 2026; Li et al., 2026; Wei et al., 2026	
Land Cover	Dobreva et al., 2011; Kuter et al., 2021; Xiao et al., 2021; Azizi et al., 2024; Hu et al., 2025	Zhang et al., 2021; Santi et al., 2022; Moradizadeh et al., 2023	Xiao et al., 2018; Yang et al., 2020; Wei et al., 2022; Gao et al., 2023; Wei et al., 2023; Broxton et al., 2024; Dunmire et al., 2024; Liu et al., 2024; Yu et al., 2024; Esfahani et al., 2025; Wang et al., 2025; Yan et al., 2025	Sun et al., 2024
Reanalysis	Palermo et al., 2023	Santi et al., 2022; Kumawat et al., 2025	Yu et al., 2022; Yu et al., 2024; Yan et al., 2025; Wei et al., 2026	Gonzalez et al., 2025
C-Band SAR	He et al., 2015; Liu et al., 2020; Palermo et al., 2023; Esmaeelzadeh et al., 2024	NA	Yu et al., 2022; Zhu et al., 2022; Daudt et al., 2023; Broxton et al., 2024; Dunmire et al., 2024; Ni et al., 2024; Yu et al., 2024; Ying et al., 2025	Kumar et al., 2022; Gallet et al., 2024
High-Res. Optical	Cannistra et al., 2021; Hu et al., 2022; John et al., 2022	Brodylo et al., 2025	Shaw et al., 2020; Brodylo et al., 2025	NA
Weather Station Data	Esmaeelzadeh et al., 2024	Yang et al., 2022	Wang et al., 2020; Bai et al., 2025; Elyoussfi et al., 2025	Goodarzi et al., 2024
X-Band SAR	NA	Santi et al., 2022	NA	NA
L-Band SAR	NA	Kumawat et al., 2025	NA	NA

Table S3. Reference data across papers reviewed, categorized by the snow property analyzed.

	Snow Cover	**SWE**	**Snow Depth**	**Other**
Weather Station Data	Kan et al., 2018; Xiao et al., 2021; Hou et al., 2022; Esmaeelzadeh et al., 2024; Hu et al., 2025; Zhang et al., 2026	Chen et al., 2001; Tedesco et al., 2004; Dariane et al., 2014; Zaerpour et al., 2020; Zhang et al., 2021; Moradizadeh et al., 2023; Li et al., 2026	Xiao et al., 2018; Wang et al., 2020; Yang et al., 2020; Yang et al., 2021; Wei et al., 2022; Zhu et al., 2022; Gao et al., 2023; Wei et al., 2023; Dunmire et al., 2024; Hou et al., 2024; Ni et al., 2024; Yu et al., 2024; Bai et al., 2025; Chen et al., 2025; Tanniru et al., 2025; Wang et al., 2025; Bai et al., 2026; Li et al., 2026; Wei et al., 2026	Johnston et al., 2024; Gallet et al., 2024; Sun et al., 2024
Optical	Dobreva et al., 2011; Hou et al., 2014; Moosavi et al., 2014; He et al., 2015; De Gregorio et al., 2019; Guo et al., 2020; Hou et al., 2020; Kuter et al., 2021; Rittger et al., 2021; Xiao et al., 2021; Luan et al., 2022; Yatheendradas et al., 2022; Azizi et al., 2024; Kollert et al., 2024; Liu et al., 2024; Hu et al., 2025; Sun et al., 2025; Zhang et al., 2026	NA	Li et al., 2026	Kosmala et al., 2018; Bloshchinskiy et al., 2020; Jin et al., 2022; Dumont et al., 2024
Reanalysis	NA	Santi et al., 2022; Kumawat et al., 2025	Meloche et al., 2025	Gallet et al., 2024; Sun et al., 2024; Gonzalez et al., 2025
Airborne Lidar & ASO	Liu et al., 2020; Cannistra et al., 2021; John et al., 2022	Yang et al., 2022; Yang et al., 2025	Shaw et al., 2020; Daudt et al., 2023; Broxton et al., 2024; Brodylo et al., 2025; Ying et al., 2025	NA
Field Measurements	Haq et al., 2019; Liu et al., 2020; Luo et al., 2022	NA	Zhu et al., 2022; Yu et al., 2024; Bai et al., 2025	Bloshchinskiy et al., 2020; Rostosky et al., 2020; Kumar et al., 2022
Passive Microwave	NA	NA	Tanniru et al., 2023; Chen et al., 2025; Tanniru et al., 2025	NA
High-Res. Optical	Czyzowska-Wisniewski et al., 2015	NA	NA	NA
Reconstructed SWE	NA	Bair et al. 2018	NA	NA
Synthetic Data	Xue et al., 2015	Chang and Tsang 1992	Tsang et al., 1992	NA