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Editorial

Special Issue on Remote Sensing of Snow and Its Applications

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Abstract: Snow cover is an essential climate variable directly affecting the Earth's energy balance. Snow cover has a number of important physical properties that exert an influence on global and regional energy, water, and carbon cycles. Remote sensing provides a good understanding of snow cover and enable snow cover information to be assimilated into hydrological, land surface, meteorological, and climate models for predicting snowmelt runoff, snow water resources, and to warn about snow-related natural hazards. The main objectives of this Special Issue, "Remote Sensing of Snow and Its Applications" in Geosciences are to present a wide range of topics such as (1) remote sensing techniques and methods for snow, (2) modeling, retrieval algorithms, and in-situ measurements of snow parameters, (3) multi-source and multi-sensor remote sensing of snow, (4) remote sensing and model integrated approaches of snow, and (5) applications where remotely sensed snow information is used for weather forecasting, flooding, avalanche, water management, traffic, health and sport, agriculture and forestry, climate scenarios, etc. It is very important to understand (a) differences and similarities, (b) representativeness and applicability, (c) accuracy and sources of error in measuring of snow both in-situ and remote sensing and assimilating snow into hydrological, land surface, meteorological, and climate models. This Special Issue contains nine articles and covers some of the topics we listed above.

Keywords: remote sensing; snow parameters; spatial and temporal variability of snow; snow hydrology; integration of remote sensing with models (hydrological; land surface; meteorological and climate)

1. Introduction

Snow cover is an essential climate variable directly affecting the Earth's energy balance. Snow cover has a number of important physical properties that exert an influence on global and regional energy, water, and carbon cycles. Surface temperature is highly dependent on the presence or absence of snow cover, and temperature trends have been shown to be related to changes in snow cover [1,2]. Its quantification in a changing climate is thus important for various environmental and economic impact assessments. Identification of snowmelt processes could significantly support water management, flood prediction, and prevention. Remote sensing provides a good understanding of snow cover and enables snow cover information to be assimilated into hydrological, land surface, meteorological, and climate models for predicting snowmelt runoff, snow water resources, to warn about snow-related natural hazards, and for short and long term weather forecasting. This Special Issue invited and encouraged the submission of studies covering all instrumentation/sensors and methodologies/models/algorithms in remote sensing of snow cover parameters (snow extent, snow depth, snow wetness, snow density, snow water equivalent, etc.) and applications where remotely-sensed snow information are used. Our motivation for publishing this Special Issue is to combine all aspects of remote sensing of snow from data retrieval to application. This Special Issue, "Remote Sensing of Snow and Its Applications" [3], contains nine published articles. This guest editorial addresses article contributions in this Special Issue in three categories: (a) New opportunities (Copernicus Sentinels) and emerging remote sensing methods, (b) the use of snow data in modeling, and (c) the characterization of snowpack.

2. Remote Sensing of Snow and Its Applications

2.1. New Opportunities (Copernicus Sentinels) and Emerging Remote Sensing Methods

Copernicus is the European Union (EU)'s Earth Observation (EO) program which offers free and open information services based on satellite Earth Observation and in situ (non-space) data [4]. Since the launch of Sentinel-1A [5] in 2014, the European Union set in motion a process to place a constellation of almost 20 more satellites, carrying a range of technologies such as radar and multi-spectral imaging instruments, in orbit before 2030, and that was to be implemented by the European Space Agency (ESA). These new series of satellites from the Copernicus program are very important for Remote Sensing and its applications. In order to see the status on use of Copernicus Sentinels on snow in general we looked at the published papers in Web of Science during the last five years (2015–2019). We used key words, snow and remote sensing, in searching published papers in Web of Science. A total of 313 published papers were listed by 17:00 (CET), June 7, 2019. A total of 194 out of 313 published papers were found to be related to remote sensing of snow after looking at abstracts and full papers. The papers related to remote sensing of snow using Advanced Very High Resolution Radiometer (AVHRR), Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS), Passive Microwave (PMW) like Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), Sentinel-1 and -2, and emerging technologies are given in Table 1. Of course our objective here is not to give exact statistics but rather to present a general picture. Although there may be errors in the exact numbers of the results, we believe they are good enough to be presented here.

Table 1. Number of published papers on remote sensing of snow between 2015–2019 in Web of Science.

AVHRR	Landsat	MODIS	PMV (Mostly AMSR-E)	Sentinel-1	Sentinel-2	Emerging Technologies (UAS-Drone, GNSS, GNSS-R, GPS-IR, Webcam-Camera)
6	21	97	38	9	5	18

The MODIS and PMW were the most used ones in remote sensing snow studies according to our quick analysis. We also see that Copernicus Sentinels and emerging technologies are taking their place in remote sensing snow studies. During a PhD course entitled, "Remote Sensing and It's applications in Cryospheric sciences" given by Dr. Ali Nadir Arslan at the Department of Civil and Environmental Engineering, Politecnico di Milano, PhD students under supervision of Professor Dr Carlo de Michele conducted a user experience study on Copernicus Data Information and Access Systems (DIAS) for Earth Observation (EO) newcomers, where five online platforms allowed users to discover, manipulate, process, and download Copernicus data and information [6]. The purpose of the study was to understand possible ways to lower the data access barriers for this category of users. The following criteria are identified from the study given in Table 2.

Table 2. Criterias for lowering barriers of EO newcomers on data access systems.

User Interface	Database Repository	Database Acquisitions & Services
Simplicity & Clarity	Dataset Services & Descriptions	Advanced Products/Tools/Services
Demonstarte Core Benefits Effectively	Other Dataset than Copernicus	Cloud Services
User Guides & Tutorials	Search Criteria by Region	Ease of Downloading
Help Desk & FAQ	Search Criteria by Products	Example Analysis
User Update	Search Criteria by End-use Application	Customized/Direct Pricing
No Prerequisite Knowledge	Visualization by Timeline	Open Source Software
Mobile Compatibility	Global/Regional Visualization	Monitoring & Dashboard

There has been a tradeoff between the spatial and temporal resolution of remote sensing snow mapping because of the characteristics of available optical and microwave (passive and active) sensors used for snow detection [7]. Medium spatial resolution satellite-derived snow products are good in monitoring snow dynamics, but a better spatial resolution is needed in understanding the spatial variation, especially in rough terrain. Validation of the satellite-derived snow products is also very important and critical. The in situ snow observations may not be representing the field of view of the satellite data. This mismatching problem can be solved by using remote sensing data with high spatial resolution. Piazzi et al. [8] presented the use of Sentinel-2A high resolution satellite data in validating the moderate resolution satellite-derived snow products, namely H10 and H12 supplied by the Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF) project of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). In their study they used the webcam imagery as ground data. Salzano et al. [9] presented the importance of ground based cameras in obtaining a long time series of snow cover. The images taken over a ten-year period were analyzed using an automated snow-not-snow detection algorithm based on Spectral Similarity. Webcam/camera monitoring system is easy to implement and very cheap in comparison to satellites. It provides a valuable data source and can be used as complementary information to different multispectral remotely sensed datasets for validation and calibration processes [9]. The usage of webcam on monitoring snow is growing [10–15] and there are already several tools [16,17] available for processing webcam/camera data.

MODIS snow products provide a good archive since 2000 and, as presented in Table 1, MODIS products have been used in many snow studies. Munkhjargal et al. [18] combined MODIS snow products with Landsat-7 and -8, and Sentinel-2A images to map snow cover and its duration in the mountainous region with 30 m resolution by applying a series of adjustments, including temporal gap-filling and conditional adjustments. In understanding climate related glacier behavior, continuous monitoring of glacier changes is needed. Heilig et al. [19] presented the use of Sentinel-1 data in monitoring the recession of wet snow area extent per season for three different glacier areas of the Rofental, Austria. They showed that surface conditions during the melt season can quasi-continuously be monitored using Sentinel-1 SAR data, which is essential for glacier runoff modeling.

2.2. The Use of Snow Data in Modeling

The in situ and satellite snow data contribute to the development of both retrieval algorithms of remote sensing and snowpack models as they are used in validation studies. Recently, data assimilation (DA) has provided an outstanding solution for improving hydrological modeling by synchronously integrating observations from in situ stations or remote sensors. Helmert et al. [20] reviewed approaches used for assimilation of snow measurements, such as remotely sensed and in situ observations into hydrological, land surface, meteorological, and climate models based on a COST HarmoSnow survey exploring the common practices on the use of snow observation data in different modeling environments. As concluded by other authors [21–23], this study highlights the need of assimilation of bias corrected snow data to get consistently improved snow and streamflow predictions. Therefore, it is essential to improve the snow observation data quality before assimilation into hydrological models, otherwise the model performance will deteriorate. Arsenault and Houser [24] presented a new approach to estimating snow depletion curves (SDC) and their application for assimilating snow cover fraction observations using an Ensemble Kalman filter (EnKF) data assimilation approach and a land surface model with a multi-layer snow physics scheme. They presented that the use of observation-based SDC (they derived the new SDC from the MODIS snow cover fraction and SNOTEL snow water equivalent (SWE) observations) showed improvement over the default model-based snow cover fraction (SCF) forecasts and snow state analysis. Appel et al. [25] used the in situ and EO information to assimilate the input and the parameters of the applied hydrological model PROMET (Processes of Mass and Energy Transfer) to calculate SWE, snowmelt onset, and river run-off in catchments as spatial layers. They used newly developed in situ snow monitoring stations based on signals of the Global Navigation Satellite System (GNSS) and Sentinel-1A and -1B EO data in interferometric wide (IW) swath mode on the snow cover extent and on information whether the snow is dry or wet. The snow monitoring stations based on signals of the GNSS is a state-of-the-art remote sensing techniques which was mentioned in [7]. It is known that for hydrologists, snow mass and volume parameters are more critical, because the water volume stored in the snowpack and subsequent snow melt runoff can be estimated. Most in situ snow measurements are still performed using traditional laborious standardized techniques: Sampling with snow tubes, digging snow pits, and manually measuring the density, temperature, hardness, and other quantities. While these techniques are very robust and straightforward, they are very expensive for larger areas or time spans, prone to human errors and biases, and do not provide all requested quantities or provide only qualitative information of snow parameters. Obtaining continuous snow water equivalent at the field is still missing and challenging. Cosmic ray sensors [26] and snowpack analyzers [27] are two new techniques that can be used in the field. Both of the instruments need more validation studies to be considered as robust in situ SWE measurement techniques.

2.3. Characterization of Snowpack

It is a challenging problem of bridging information from micro-structural scales of the snowpack up to the grid resolution in models. In-situ ground-truth snow observations are necessary for developing and validating remote sensing products. The advances in the modeling of the snow-electromagnetic interaction and in the observational capabilities of the satellite-based sensors have pushed the development of new in situ instrumentation, which are able to provide suitable reference and ground-truth data for the validation of snow satellite products and of earth system models [28]. Monitoring of snow extent and SWE requires solid knowledge of the physical properties of snow, high-quality instrumentation, and refined methods for calibration and interpretation of snow observations. Leppanen et al. [29] presented an empirical linear relationship, on taiga snow, between specific surface area (SSA) and reflectance observations of recently developed hand-held QualitySpec Trek (QST) instrument. The microstructure of snow is an important parameter for the modeling of microwave emission and optical reflectance, and it is therefore also important for remote sensing applications. The SSA is an important snow parameter for the modeling of microwave emission and optical reflectance, and is therefore also important for remote sensing applications [29]. Sanow et al. [30] presented terrestrial laser scanner- (TLS) (resolution of +/−5 mm) derived surface geometry and vertical wind profile measurements to compare concurrent aerodynamic roughness length estimates for changing snow surface features of shallow snowpack. The roughness of a snow surface is an important control on air-snow heat transfer and changes in the snow surface can have substantial effects on the energy balance at this interface [30].

3. Summary

Monitoring the snow cover and its components at meso-, regional to global scale is important in order to support weather, hydrological, and climate science, as well as in the monitoring of natural hazards, and the decision-making and formulation of environmental policy. This capability will provide knowledge-based information on potential impacts to society, economy, and safety (e.g., hydro-power, water availability, transportation, tourism, flooding, avalanches, etc.). Snow is a complex media which is why all aspects such as characterization, sensing, and modeling are important to understand. Our aim was to combine these three aspects together as we believe this will be useful for all disciplines dealing with some part of snow science. Although this is a very small effort, we hope that this will be useful for the scientific community.

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