Investigating the snow water equivalent in Greece

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Abstract Snow parameters of snow coverage, snow depth and snow water equivalent constitute essential variables for hydrological models and the study of climate variability, groundwater recharge and preservation of basic flow of rivers. However, few studies have analyzed both the spatial and temporal trends in snow-covered areas of Greece using ground-based or satellite observations. The aim of this work is to analyze time series of the snow parameters focusing over representative geographical areas of Greece and to examine their seasonal variability, in terms of region and geography. This will provide a unique opportunity to better understand the spatial snow distribution and the seasonality of snow coverage which could be crucial for long term groundwater management, by combining snow data trends from in situ data and satellite statistics. The information is crucial to represent distributions of the snow water equivalent and their seasonal patterns to further improve the water resource management.

1 Introduction

Snow consists a critical parameter in the hydrological balance and is often the form of precipitation with a particularly significant inflow rate. It is a very important source of supply for the enrichment of groundwater and the surface runoff of rivers and torrents, especially during the spring period (Sturm, 2015; Wesemann et al., 2018). Snow is therefore necessary to be taken into account in the hydrological planning and is necessary to accurately calculate the amount of snow height and its accumulation due to the affection morphological conditions, the climatic conditions and the vegetation cover (Pistocchi et al., 2017). At the same time, the snow parameters constitute critical input data in models for calculating the inflow and outflow in a basin (the volume of water stored in the snow is calculated as inflow), thus the accurate calculations from field measurements, with a small error rate is essential. For instance, snow depth (SD) and snow water equivalent (SWE) are key variables in many hydrological models and studies involving groundwater recharge rates, basic flow preservation of rivers and hydropower dam sustainability.

Snow measurements can be performed both with in situ measurements and satellite monitoring. Advantages of the satellite monitoring are the greater spatial and temporal coverage. However, it is necessary to use field measurements from ground stations to calibrate the results (Raleigh et al., 2013). On the other hand, collecting in situ measurements at large scales remains challenging and usually these techniques remain costly and do not provide continuous observations.

To the best of our knowledge, few studies have analyzed both the spatial and temporal trends of the afore mentioned variables in snow-covered areas of Greece using ground-based and satellite observations. Measurements of snow properties carried out both by terrestrial (in situ) and satellite dataset (it is achieved mainly with passive microwave sensors) are taken into account in this study. Aim of this work is to establish time series based on the snow analyses focusing over representative geographical areas of Greece.

2 Data

The dataset processed in the study are described below in Sections 2.1 and 2.2.

2.1 In situ dataset

Coordinated field measurements of snow height have been performed in different geographical regions over Greece, from December 2018 up to now. Two representative areas have been selected in the northern Greece (Kozani and Mount Athos) with different hydrogeological and climatological characteristics. The meteorological stations in Mount Athos (40°12'40.60"N, 24°15'48.36"E) and Kozani (40°24'0.77"N, 22°5'20.04"E) are located at an altitude of 1302m and 889m, respectively (Figure 1). Field measurements of snowfall, snow accumulation and melting rate are daily provided. The snow height measurements are recorded and analysed every hour from the stations. The weather stations in Zoodochos Pigi and Mount Athos are part of the Laboratory of Engineering Geology and Hydrogeology, belonging to the Department of Geology of the Aristotle University of Thessaloniki.

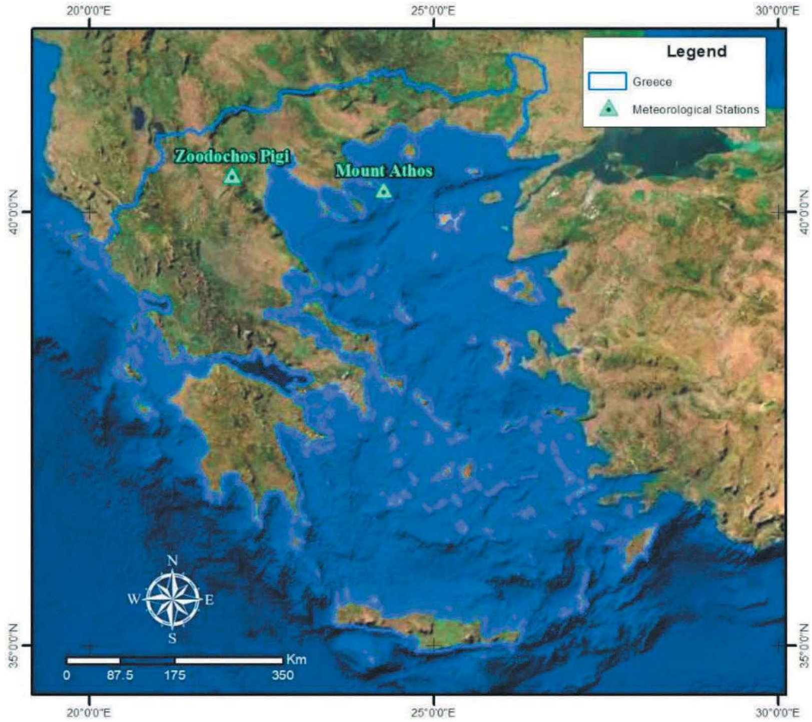

Fig. 1: Meteorological stations in Kozani and Mount Athos regions.

2.2 Remote sensing of the snow parameters

Satellite data were also processed to fill the gap in the snow monitoring over Greece. The dataset used in this study is public available at https://search.earthdata.nasa.gov/search. The goal of the Global Land Data Assimilation System (GLDAS) is to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, to generate optimal fields of land surface states and fluxes (Rodell et al., 2004). The high-quality, global land surface fields provided by GLDAS support several current and proposed weather and climate prediction, water resources applications, and water cycle investigations. The products processed in high resolutions (2.5- degrees to 1 km), providing monthly mean values of snow depth and snow water equivalent.

3 Results

In the first research area, the Zoodochos Pigi station in Kozani was used as a ground station to monitor snowfall, snow accumulation and melting rate. Figure 2 shows the changes in the height of the snow compared to the average daily temperature values for the period of operation of the meteorological station in Zoodochos Pigi until December 31, 2019 and the height of the snow compared to the average daily temperature values for the meteorological station in Mount Athos for the same time period. Specifically, during January the first snowfall episodes were recorded in the two meteorological stations. Concerning the Zoodochos Pigi meteorological station, a total of four snowfall episodes were recorded with a cumulative snow height of 40.7 cm. The first episode occurred on 4/1/2019, while the total snow coverage lasted throughout the month. During February, three episodes of snowfall were marked, less intense compared to January, with cumulative snow height of

25.2 cm and mean snow height of 3 cm. The first episode occurred from 7/2/2019 to 11/2/2019 (4.6 cm), the second one lasted from 16/2/2019 to 17/2/2019 (8.5 cm) and the third episode lasted from 24/2/2019 to 27/2/2019 (12.1 cm). The mean snow height recorded for March is 8.9 cm (in an episode lasted from 13/3/2019 to 14/3/2019). During December 2019, three episodes were marked on between 12/12/2019 and 13/12/2019 and between 29/12/2019 and 31/12/2019. No snowfall was recorded during the April-November.

In the Mount Athos research area, during January many intense episodes were recorded with maximum snow height of 137.4 cm and a cumulative snow height of 1981.2 cm. During February, less intense episodes were marked, compared to January, and maximum snow height of 28.7 cm. The mean snow height recorded for March is 8.55 cm, while during December 2019, the mean snow height is equal to 6.82 cm. No snowfall was recorded during the April-November, same as above.

The altitude of Zoodochos Pigi station in Kozani is much higher compared to the altitude of the station on Mount Athos, while there is an inverse relationship between the height of the snow and the altitude. Thus, the two study areas are of particular interest in terms of geographical location and the prevailing climatic conditions.

Figure 3 presents the remote sensing data from satellite missions in monthly averages.

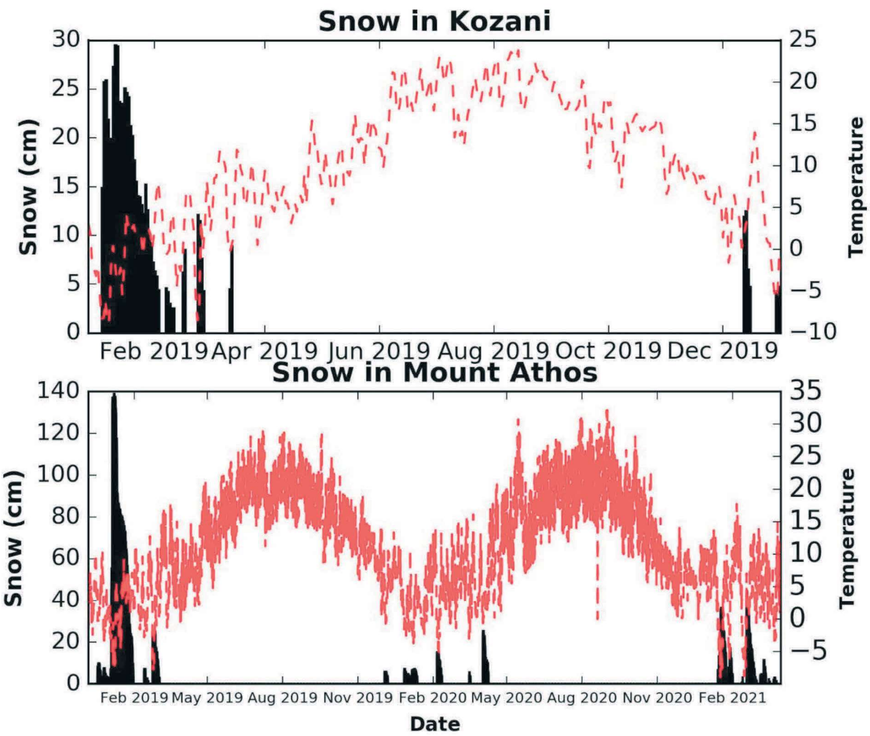

Fig. 2: Changes in the snow height compared to the average daily temperature values for the meteorological stations in Zoodochos Pigi (above) and Mount Athos (below) between January 31, and December 31, 2019.

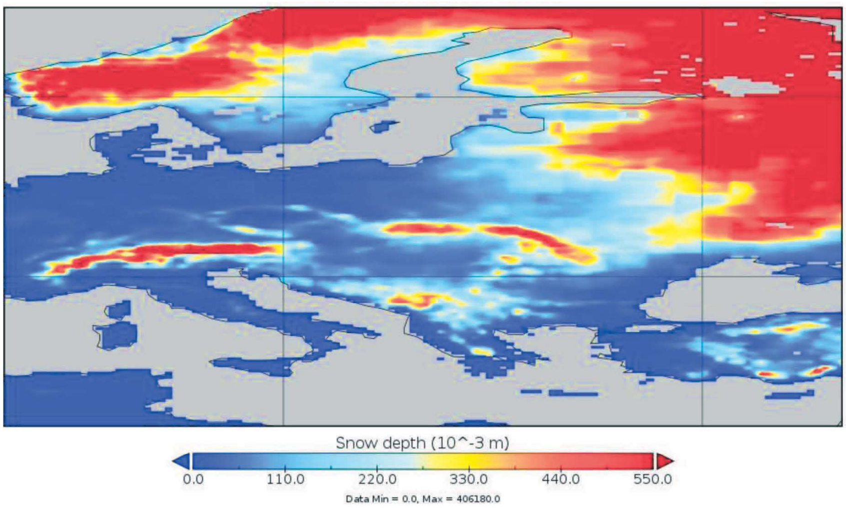

Fig. 3: Mean monthly snow depth for the period 1/1/2019 – 1/2/2019 (GLDAS dataset), https://search.earthdata.nasa.gov/search. Mean montly snow depth values for the two study areas are reported in the text.

From the satellite data the corresponding monthly mean snow depth for January is 65 cm, while for the February is 2.8 cm calculated for each station. The mean value is calculated from the days, where snowfall was reported. The monthly mean value for March for the Zoodochos Pigi station in Kozani is
0.2 cm. The corresponding value for December is 1.4 cm, while no snowfall was recorded during the April-November period. The satellite dataset follows the in situ dataset, with an overestimation during January.
The snowfall density (ρ) is another quantity of interest in many hydrological models and studies involving groundwater recharge rates. It will be included in snow melting modeling process to determine the groundwater recharge for each selected region. The snowfall density can be calculated from the following relation:

$$\rho = SWE / SD \qquad (1)$$

where SWE is in kg/m^2, SD in m and ρ in kg/m^3.
The parameters of snow water equivalent and snow depth, as they recorded from the satellite dataset during the period from 1/2/2019 to 1/3/2019 (averaged monthly value), were as follows:
i) SWE = 0.9221878 kg/m^2 and
ii) Snow depth = 0.00274375 m
From equation 1, the averaged value of snow density was calculated for this period equal to 336.1 kg/m^3.

Typically, the density of snow is derived following the bibliography as $\rho = 0.1\rho_w$ (the average density of snow is 1000 kg/m^3), and usually ranges from 100 to 500 kg/m^3 (Meløysund et al., 2007). However, the snow density is generally larger (due to the subsidence under the influence of gravity and other mechanisms), depending on the residence time of snow and the snow depth.

4 Conclusions

This study is part of an ongoing work aiming to provide a comprehensive study of snow parameters modeling within Greece. Once satellite data will be evaluated against the ground based meteorological observations, a gridded high-resolution dataset including daily snow cover, albedo and snow water equivalent will be constructed for each study area. Seasonal variability and spatial distribution of the above-mentioned snow parameters will also be conducted. Generally, we conclude that the snow cover extent reaches its maximum in January-February, and minimum in December, with more intense snow episodes observed on Mount Athos, compared to the Kozani station.
The present study will evaluate and strengthen our understanding about the importance of estimation of the spatial snow distribution which could be crucial for long term groundwater management, by combining meteorological (snow data trends), hydrological and satellite statistics. This information is crucial to represent distributions of the snow water equivalent, to examine the level of repetition from year-to-year and to improve water resource management.

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