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Monitoring of Alpine snow using satellite radiometers and artificial neural networks

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ABSTRACT

The Alps represent an extremely complex environment in which snow properties suffer dramatic spatial variations that cannot easily be followed by space-borne microwave radiometers, due to their coarse spatial resolution: some studies demonstrated that the algorithms developed for global scale monitoring of the snow depth (SD) are unable to retrieve this parameter with a satisfactory accuracy on mountainous areas.

An improved method for monitoring the Snow Depth (SD) on Alpine areas is presented here. Equivalent Brightness Temperature Tb_{eq} at an enhanced spatial resolution, corrected for the effects of orography and forest coverage, were computed from the AMSR-E measurements by using ancillary information on land use, surface temperature, and a digital elevation model (DEM). These equivalent Tb_{eq} values were used instead of the original AMSR-E measurements as inputs of an algorithm that estimates SD on a global scale basing on and Artificial Neural Network (ANN) techniques from AMSR-E brightness temperatures at X-, Ku- and Ka-bands, V-polarization. The improvement in the retrieval accuracy using these Tb_{eq} equivalent values was evaluated using data collected during the winters between 2002 and 2011 on a test area located in the eastern part of the Italian Alps.

1. Introduction

Many studies carried out worldwide in recent years have pointed out that the multi-frequency microwave radiometers from satellites can be successfully used for global and regional retrieval of geophysical parameters of the Earth's surface and of their temporal changes. In particular, these studies, which usually integrate satellite and ground-based datasets collected in field experiments (e.g. Chang, Foster, & Hall, 1987, Chang, Foster, & Hall, 1990; Hallikainen & Jolma, 1992; Goodison & Walker, 1995; Rott & Nagler, 1995; Jin, 1997; Hall, Foster, Salomonson, Klein, & Chien, 2001; Pulliainen & Hallikainen, 2001; Kelly, Chang, Tsang, & Foster, 2003; Tedesco, Pulliainen, Takala, Hallikainen, & Pampaloni, 2004, Pulliainen, 2006, Takala et al., 2011), have revealed a high sensitivity of microwave emission to physical snow cover parameters, that is of great interest for the study of climate dynamics, as well as for water resource management. Indeed, although microwave radiometers from space have a coarse ground resolution, they are able to follow the daily variations of the snow cover parameters, namely Snow Depth (SD) and Snow Water Equivalent (SWE), on a global scale, providing extremely useful information for all the activities related to climatological, hydrological and agricultural applications, as demonstrated by the efforts of the national space agencies toward the development of global SD and SWE products at low resolution, derived from microwave radiometers.

One of the most important sensors for snow cover monitoring has been the Advanced Microwave Scanning Radiometer (AMSR-E) developed by the Japanese Aerospace Exploration Agency (JAXA) (formerly NASDA) for the NASA Earth Observing System AQUA satellite. This instrument provided us with a 10-year collection of data at a global scale before it stopped working, and is now being replaced by the recently launched AMSR-2 instrument on the JAXA Global Climate Observing Mission Water (GCOM-W) satellite, which is equipped with the same frequency channels and has similar performance. Therefore, it can be expected that the operational algorithms developed for AMSR-E can also apply to this new sensor.

Several algorithms for the retrieval of SD and SWE from multi-frequency radiometric systems evidenced that Ku- and Ka-bands, (18.0 and 37.0 GHz for SMMR, 19.35 and 37.0 GHz for SSM/I and 18.7 and 36.5 GHz for AMSR-E) are the key channels for snow monitoring (e.g. Kelly et al., 2003; Pulliainen, 2006; Pulliainen & Hallikainen, 2001; Tedesco et al., 2004). Indeed, as demonstrated in several works, the Frequency Index (FI), defined as the difference between the brightness temperature (Tb) at Ku- and Ka-bands, can be efficiently related to SWE or SD (e.g. Chang et al., 1987; Chang et al., 1990; Hallikainen & Jolma, 1992). In other studies (Jin, 1997; Rott & Nagler, 1995) the 85 GHz channel was added for monitoring shallow snow from the Special Sensor Microwave Imager (SSM/I) data, while a vertically

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polarized Tb gradient ratio algorithm was developed in Canada (Goodison & Walker, 1995) and a SWE regression algorithm based on spectral and polarization differences was proposed in (Hall et al., 2001).

A dynamic approach for retrieving global SD was presented in (Kelly et al., 2003). The algorithm was still based on FI, and the dimensional coefficient (cm/K) was adjusted by using a Dense Medium Radiative Transfer Model (Tsang, Chen, Chang, Guo, & Ding, 2000) to predict how the grain size and snow density might vary and affect the emission from a snowpack. As compared with static approaches, this dynamic algorithm was able to estimate SD with greater root-mean-squared error, but lower mean error. The potential of Artificial Neural Networks (ANNs) in retrieving snow parameters was evaluated in Tedesco et al. (2004), Tsang, Chen, Oh, Marks, and Chang (1992), and Santi et al. (2012), while several approaches for improving the accuracy in SWE retrieval by assimilating satellite radiometric data and ground-based observations can be found in literature (e.g. Pulliainen, 2006 and Takala et al., 2011). A detailed comparison of the existing global SWE products generated from microwave satellite radiometers can be found in Hancock, Baxter, Evans, and Huntley (2013).

However, some studies demonstrated that the algorithms developed for global scale monitoring generally failed the retrieval of SD on mountainous areas, as in the case of the NASA SWE product (Tedesco & Narvekar, 2010). Also the recent GlobSnow project (Luojus et al., 2010, Pulliainen, 2006) was unable to estimate SWE on Alpine environments. In fact, mountains are an extremely complex environment in which snow properties suffer dramatic spatial variations that cannot be easily reproduced by space-borne microwave radiometers, due to their coarse spatial resolution (Dongyue et al., 2012; Pulvirenti, Pierdicca, & Marzano, 2011).

An improved method for monitoring SD from AMSR-E data on mountainous areas is presented in this paper, by introducing an equivalent brightness temperature Tb_{eq} at improved spatial resolution, which includes a correction for the effects of orography and forest coverage, obtained from ancillary information on land use, surface temperature, and a digital elevation model (DEM) of the area.

These Tb_{eq} values were used instead of the original AMSR-E measurements as inputs to the “Hydroalgo” algorithm for estimating SD (Santi et al., 2012), obtaining an appreciable improvement of the retrieval accuracy. This algorithm, developed for snow monitoring on a global scale, is based on the classical FI at Ku- and Ka-bands to detect the presence of snow, and makes use of additional X-band data for estimating SD by means of Artificial Neural Network (ANN) techniques.

The procedure for computing Tb_{eq} has been assessed on a test area located in the eastern part of the Italian Alps, that includes the Dolomites. AMSR-E measurements, collected on this area during the winters from 2002 to 2011, were used along with the corresponding direct measurements of the snow properties (Brogioni et al., 2009; Macelloni et al., 2005) for this purpose.

2. The Alpine test area

The problem of adapting the “Hydroalgo” algorithm for monitoring SD on mountainous environments was dealt with the selection of a test area (Fig. 1) of about 100 × 100 km^2, (lat 46 ÷ 47 N, lon 11.4 ÷ 12.4 E) that included the Dolomites mountains and where historical data regarding SD and air temperature, obtained from a network of meteorological stations (Table 1), were made available by the CVA — Centro Valanghe Arabba, Italy.

The area roughly corresponded to the mountainous part of the Veneto Region and was characterized by a very complex orography. Elevation varied between few hundred meters a.s.l in the valleys up to above 3000 m on the Dolomites peaks. Low vegetation was mainly composed by grasslands, and coniferous forests covered the area for about 50% of the surface. Nine meteorological stations displaced in order to cover the test area were considered as ground truth (Table 1 and Fig. 1). These stations were located at an elevation ranging between 1600 and 2500 m, generally close to the ski slopes, and provided hourly measurements of snow depth and air temperature. Seven other stations located in the surrounding mountains were also considered. The analysis of the data acquired by these stations pointed out that the snow in

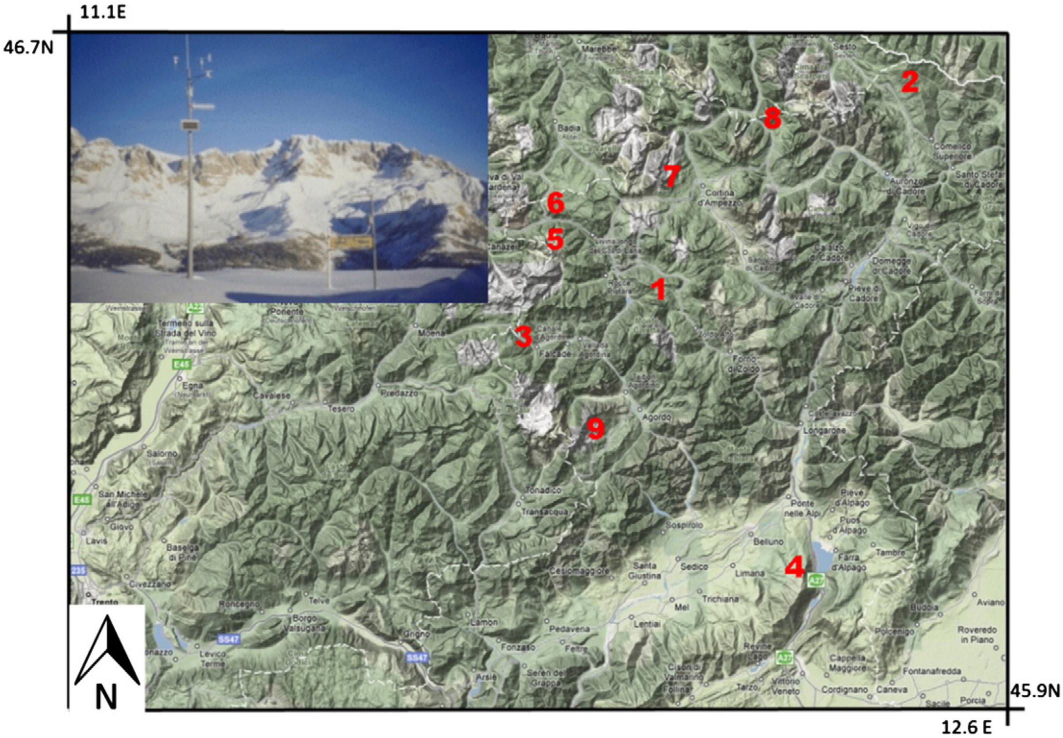

Fig. 1. The test area in the Eastern Italian Alps with the location of the nine meteorological stations.