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Using land surface microwave emissivities to isolate the signature of snow on different surface types

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ABSTRACT

The objective of this paper is to better isolate the snow signature in microwave signals to be able to explore the ability of satellite microwave measurements to determine snowpack properties. The surface microwave effective emissivities used in this study are derived from SSM/I passive microwave observations by removing the contributions of the cloud and atmosphere and then separating out the surface temperature variations using ancillary atmospheric, cloud and surface data. The sensitivity of the effective emissivity to the presence/absence of snow is evaluated for the Northern Hemisphere. The effect of the presence of snow, the variation of land types, and temperature on the emissivities have been examined by observing the temporal and spatial variability of these measurements between 19 and 85 GHz over the Northern Hemisphere. The time-anomaly of differences between effective emissivity at 19 V and 85 V enabled the constant effects of land surface vegetation properties to be removed to isolate the snow signature. The resulting 12-year snow signal combined with skin temperature data can detect the existence of snow cover over the Northern Hemisphere on daily basis. The results of this method compared with the operational NOAA weekly snow cover maps agree at 90% of locations and times. Most of the disagreements could be explained by rapid evolution of snow emissivities associated with freeze–melt–refreeze cycles and precipitation (snowfall), and some of them by the space–time resolution differences of the microwave and operational snow cover determinations. These results compared with the NISE, NOAA IMS, CMC, and MODIS, and snow products agree within 78% to 92%.

1. Introduction

Seasonal snow typically covers 30% of the total land area of the Northern hemisphere. Snow cover is a significant climate indicator and an important factor controlling the amount of solar radiation absorbed by earth. Snowmelt resulting from a warming trend would increase the absorption of solar radiation, a positive feedback. Moreover, snow plays a different role than liquid water in the processes affecting surface evaporation (latent heat), soil moisture supply to vegetation and runoff. Snow acts as a temporary reservoir of water that is crucial to water supply in many regions (Robinson, Dewey, & Heim, 1993). Because of the complex interaction of snow with the landscape and varying atmospheric conditions, monitoring the spatial and temporal variability of snow properties at relatively high space–time resolution provides valuable information on surface hydrology and radiation.

The use of satellite remote sensing for mapping snow cover and measuring snow characteristics has a long history reaching back to the 1960s. Dietz, Kuenzer, Gessner, and Dech (2012) reviewed all the available methods of measuring snow using satellite data and looked at each method's advantages and disadvantages. For example, passive microwave radiances from satellites overcome the main limitations of visible measurements by being able to sense the surface at night and through non-precipitating clouds, improving time resolution to near daily. Although spatial resolution is poorer and the sensitivity to small amounts of snow is less than for visible radiation measurements, the microwave signal is also sensitive to other snow properties such as density, depth, and crystal-size distribution. However, this sensitivity is confounded by sensitivity to the variations of other land surface properties such as temperature, surface wetness, melting–refreezing cycles, and embedded or covering vegetation.

The main objective of this paper is to better isolate the snow signature in microwave signals to explore the ability of satellite microwave measurements to determine other properties of snowpack besides cover extent. The microwave signal acquired from the satellite is the combination of the land surface and atmospheric contributions. The microwave emission of the land surface itself is the product of its physical temperature and the surface emissivity (this product is the brightness temperature). The surface emissivity represents the intrinsic physical characteristics of the land surface and is sensitive to variations

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of vegetation density, soil moisture, surface composition, and standing water at the surface as well as snow properties. Thus, to isolate the changes in satellite microwave measurements associated with snow, we need to account for all the other contributions to the signal to develop generally valid, global measurement of snow properties such as snow depth, snow grain size, and snow water equivalent.

There are number of studies using passive microwave satellite observation over snow to estimate snow properties (Chang, Foster, & Hall, 1987; Foster et al., 1996; Grody & Basist, 1996; Hall et al., 1991; Kelly & Chang, 2003; Kunzi, Patil, & Rott, 1982), but most of these studies analyze microwave brightness temperatures alone. Brightness temperature variation is strongly affected by the variation of the surface physical temperature as well as changes in other land surface properties. Although using differences of brightness temperatures at different frequencies substantially reduces the surface temperature dependencies, global applications of such results have been questioned because of the complex signature of snow on varying landscapes as well as the relatively low spatial resolution of passive microwave measurements. Many liquid water clouds produce changes in microwave brightness temperatures similar in magnitude to that of water vapor [Lin & Rossow, 1994].

In this study we use land surface emissivities retrieved from the passive microwave brightness temperature (Aires, Prigent, Rossow, & Rothstein, 2001, see Section 2 data), by removing the contributions of cloud and atmosphere and separating surface temperature. The remaining variability in the emissivities is due to changes of the land surface characteristics (soil moisture, vegetation density, surface wetness) as well as the snow properties. To investigate removal of the other non-snow surface effects from the signal, we examined the space–time variability of land emissivities for different vegetation categories with and without the presence of snow. The effect of land is removed from the signal (approximately) by subtracting the mean snow-free emissivity of each location from its emissivity with snow present. The operational NOAA snow cover charts, providing weekly snow cover from satellite visible image analysis, are used for snow/snow free separation in this part of the analysis. When all the contributions to the signal except snow have been removed, the remaining variability of the snow signal is examined over time for each location. Infrared skin temperatures (Prigent, Aires, & Rossow, 2003a,b) and the reference snow cover (see Section 2) data are used to find an emissivity-dependent threshold that distinguishes between snow/snow free land from the microwave emissivities.

The satellite observations and the ancillary datasets used in this study are described in Section 2. In Section 3, the steps to isolate the snow signal are described. Also in this section we emphasize the spatial and temporal variability of the emissivities over snow-covered regions to characterize their fluctuations with vegetation, temperature and precipitation. In Section 4 a global snow cover identification technique is proposed and is compared with the operational NOAA snow cover charts. As a test of sensitivity the specific cases for which our results and the operational snow charts do not agree are examined to see if these disagreements can be explained. Section 5 compares the results of our snow cover detection with the newer daily NOAA IMS snow flag, the Canadian Meteorological Center (CMC) snow depth station data, the MODIS snow cover product, and the Near-Real-Time Ice and Snow Extent (NISE) from microwave. Section 6 examines the variation of snow cover over the whole 12-year record and compares some interesting features with results from other available snow cover products. Section 7 concludes this study.

2. Data

2.1. Land microwave emissivity (EM) & skin temperature (TS)

The SSM/I instruments on board the Defense Meteorological Satellite Program (DMSP) polar orbiters observe the Earth twice daily (typically near dawn and dusk) with observing incident angle close to 53° for flat a surface and a field-of-view decreasing with frequency from 43 km × 69 km at 19 GHz to 13 km × 15 km at 85 GHz (Hollinger, Lo, Poe, Savage, & Pierce, 1987). The SSM/I channels measure brightness temperatures (TB) at 19.3 GHz, 22.2 GHz, 37.0 GHz and 85.5 GHz at vertical and horizontal polarizations except at 22 GHz, which is only in vertical. SSM/I was the first passive microwave satellite that had external calibration by viewing a mirror that reflects cold space and a hot reference target once each scan, every 1.9 s (Gentemann, Wentz, Brewer, Hilburn, & Smith, 2010).

Prigent, Aires, Rossow, and Matthews (2001) and Prigent, Rossow, and Matthews (1997) determined land surface microwave emissivities from the SSM/I brightness temperatures by removing the effects of the atmosphere, clouds, and rain (Aires et al., 2001) using ancillary data from ISCCP (Rossow & Schiffer, 1999) and the NCEP reanalysis (Kalnay et al., 1996). First, the cloud-free SSM/I observations are isolated using collocated visible/infrared satellite observations from ISCCP. The cloud-free atmospheric contribution is then calculated from temperature–humidity profiles from the NCEP reanalysis. Finally, surface skin temperature (TS) is taken from ISCCP (corrected for the original assumption of unit IR emissivity in the ISCCP product using surface-type-dependent IR emissivities) to determine the surface emissivities for the seven SSM/I channels. The calculated emissivities can be related to the intrinsic surface properties independent of atmospheric contributions or the variations of TS. The true emissivity is defined by the normalization of TB by the effective soil temperature corresponding to the contributions of all the surface layers of the ground weighted by their attenuation (Wigneron, Chanzy, de Rosnay, Rudiger, & Calvet, 2008). Hence the emissivities used in this paper are "effective" values because they are derived from the normalization of TB by the skin temperature (TS). The spectral gradient of effective emissivities is an index that approximates the true spectral emissivity difference.

The effective emissivities are determined on an equal area grid equivalent to 0.25° × 0.25° at the equator and are compiled daily from 1992 to 2004 (recently extended through 2008). For illustration, monthly mean effective emissivities (EM) are shown in Fig. 1 for 19 V, 37 V, and 85 V GHz for December 2002. In this paper, we will use EM followed by numbers to indicate frequency and "H" or "V" to indicate polarization, for example, EM19V or EM85H. If no letter is given, it means that the statement applies to both polarizations. EM followed by numbers and letters representing two channels, for example EM19V-37V or EM19H-85H, will represent the difference of effective emissivities at two frequencies. We also consider temporal anomalies of effective emissivity differences as the difference between the instantaneous effective emissivity difference at a location and a time-averaged value at the same location; we represent such quantities by δEM followed by numbers and letters representing the two channels, for example δEM19V-37V or δEM19H–85H.

The skin temperature (TS) is the physical temperature of the Earth's surface (which can be closer to the canopy top for dense vegetation). The infrared surface brightness temperature (IR emissivity assumed to be unity) is determined at 3-hour intervals since 1983 over the globe every 30 km from a combination of polar and geostationary satellite (Rossow & Schiffer, 1999). Two values of TS are reported; one based on the IR clear sky radiances from the 5-day composites and one based on any available clear pixel IR radiances; the former values are a better estimate of TS because the latter values are slightly cloud contaminated by design (Rossow & Garder, 1993). The ISCCP TS values are corrected for non-unit emissivities using a land classification to specify IR emissivities (Zhang, Rossow, Lacis, Oinas, & Mishchenko, 2004). The corrected ISCCP TS values at 3-h intervals are interpolated to match the SSM/I over flight time and mapped to the same 25 km grid. For illustration, the monthly mean skin temperatures for December 2002 are presented in Fig. 1.