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Atmospheric corrections for improved satellite passive microwave snow cover retrievals over the Tibet Plateau

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ABSTRACT

Since 1978, satellite passive microwave data have been used to derive hemispheric-scale snow cover maps. The seasonal and inter-annual variability of the microwave snow maps compares reasonably well with simultaneous maps of snow cover derived from satellite-based, visible-wavelength sensors. In general, the microwave-derived maps tend to underestimate snow extent during fall and early winter, due to a weak signal from shallow and intermittent snow cover. During the early snow season the microwave may underestimate by as much as 20%, decreasing to a few percent during mid-winter and spring. The Tibet Plateau is the only large geographic region where microwave retrievals tend to consistently overestimate snow-covered area compared to the visible data. This has been noted in limited case studies comparing visible and microwave snow data. The persistence of the microwave overestimate is also demonstrated in multi-year climatologies. Current microwave algorithms used to derive snow cover are based on ground or aircraft measurements that are later fine-tuned to match satellite retrievals. In this way, the algorithms have implicitly accounted for the presence of an atmosphere, because the surface or scene brightness values applied in the algorithms have actually passed through the atmosphere along their path to reach the satellite sensor. These methods are reasonably accurate when applied as a global algorithm to most snow-covered regions. However, a thinner atmosphere between the surface and satellite is likely the source of the consistent snow extent overestimate on the Tibet Plateau, where elevations range from 3200 to 5000 m. Wang and Manning (2003) have suggested that adjustments to ground or aircraft microwave measurements are needed to compare with satellite-based measurements. Based on their work, we propose a methodology to adjust satellite-based microwave brightness temperatures as a function of the observed surface elevation, thereby reducing the microwave snow cover overestimate on the Tibet Plateau. We include comparisons to snow maps derived from selected visible-wavelength products. We estimate that the adjusted microwave algorithm reduces the Tibet Plateau area of disagreement with the visible products by approximately 17% (468,000 km^2) over the snow season.

1. Introduction

When snow covers the ground, the microwave energy emitted by the underlying soil is scattered by the snow grains, resulting in a decrease in brightness temperature. The passive microwave signature for dry snow is characterized by a negative spectral gradient, decreasing emissivity with increasing microwave frequency, between 19 and 37 GHz (Mätzler, 1994). Passive microwave snow algorithms are based primarily on the increased magnitude of spectral gradient in response to increasing snow thickness.

Numerous satellite microwave snow cover algorithms have been developed, with approaches ranging from the theoretical to the purely empirical, that indicate the presence of snow (Grody & Basist, 1996; Hiltbrunner, 1996) and compute either depth or snow water equivalent (Hallikainen & Jolma, 1986; Chang et al., 1987; Goodison, 1989; Nagler, 1991; Tait, 1998; Kelly & Chang, 2003; Goïta et al., 2003; Kelly et al., 2003; Markus et al., 2006; Cordisco et al., 2006; Derksen, 2008). The NSIDC algorithm used for this study is a modified version of that described in Chang et al. (1987).

The seasonal and inter-annual variability of hemispheric-scale snow extent derived from microwave data versus snow charts derived from visible-wavelength sensors compares reasonably well (Armstrong & Brodzik, 2001). The microwave data tend to underestimate snow extent during fall and early winter due to the weak signal from shallow and intermittent snow cover. At this time of year, the microwave may underestimate by as much as 20%, but this decreases to just a few percent during mid-winter and spring (Armstrong & Brodzik, 2001). The accuracy of the passive microwave algorithms increases with increasing snow depth as long as the snow is dry.

The Tibet Plateau is the only large geographic region in the Northern Hemisphere where the microwave retrievals tend to consistently overestimate snow-covered area compared to the visible data. This

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was noted in limited case studies at the time of the initial comparisons of visible and microwave data (Spies, 1992; Basist et al., 1996). The microwave overestimate is also persistent over time, as demonstrated by the multi-year climatologies provided by Armstrong and Brodzik (2001) and in Fig. 1.

Spies (1992) and Chang et al. (1992) proposed a correction to the microwave overestimate by applying empirical adjustments to force the microwave data to best match the visible data. These adjustments were, however, applied without a full explanation of the physical cause of the initial false signal.

Our initial speculations as to the cause of the microwave overestimate included the following: 1) prevailing soil type generated a microwave scattering signal, which caused microwave algorithms to falsely indicate the presence of snow; 2) the spectral signature of frozen soil mimicked that of snow cover to the extent that a false snow signal resulted; 3) widespread presence of frozen lakes. We ruled out 1) by noting that the false signal disappears during summer. We eliminated 2) by noting that the entire Plateau experiences frozen soil throughout the winter months, while the false signal or overestimate of snow cover appears only in limited regions. We eliminated 3) by comparing regions with large errors to the presence of small lakes, and finding no significant correlation.

There is a fourth possible explanation for the apparent overestimate that involves the influence of the atmosphere on the satellite retrievals.

The general approach adopted by the developers of the hemispheric-scale microwave snow cover algorithms (Chang et al., 1987; Grody & Basist 1996; Armstrong & Brodzik 2001) was to tune the returned snow extents to match well with visible satellite data. Therefore, although the algorithms might have been initially developed using brightness temperatures measured at ground level or from aircraft, these researchers adjusted the algorithm empirically to provide the most accurate results possible when applied to brightness temperatures measured from satellite. In this way, the algorithms have implicitly accounted for the presence of an atmosphere, because the surface or scene brightness values applied in the algorithms have actually passed through the atmosphere along their path to reach the satellite sensor. Therefore, given that an algorithm is tuned to return favorable results across a relatively standard atmospheric thickness between the ground surface and the satellite, a potential problem arises when the same algorithm is applied to an extremely high elevation target where the atmosphere thickness is greatly reduced, such as the region of the Tibet Plateau.

This problem is essentially the reverse of the more commonly cited need to adjust for the presence of an atmosphere, for example when comparing ground or aircraft measurements with those acquired by satellite (Wang & Manning, 2003). Because the Tibet Plateau is located at such a high altitude (3200–5000 m), a much higher elevation than that of regions where most snow cover is located, an adjustment must be made for the decreased atmospheric thickness that exists between the ground surface and the satellite sensor, as compared to retrievals from lower elevations.

2. Current algorithm description

For purposes of comparison, we use a baseline version of the NSIDC microwave algorithm (NSIDC_1) to derive snow water equivalent using

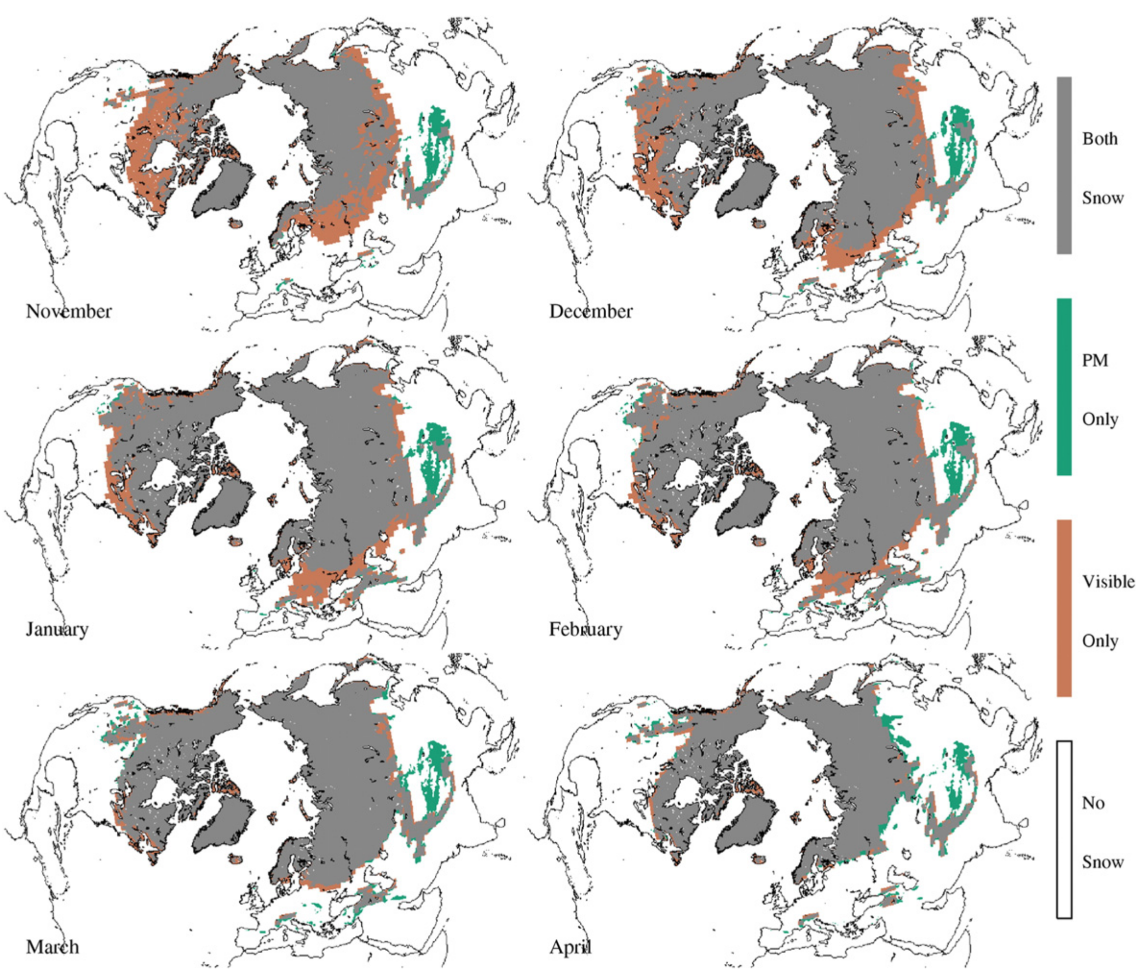

Fig. 1. Northern Hemisphere monthly snow-covered area difference climatologies, 1987–2007, showing better agreement in late winter, and consistent passive microwave "over-measure" on the Tibet Plateau throughout the season. Visible maps are derived from NOAA snow charts. Passive microwave (PM) snow cover is derived from SSM/I (NSIDC version of Chang et al., 1987).