Comparison of AMSR-E Satellite Passive Microwave and Airborne Gamma Radiation Survey Snow Water Equivalent Estimates, With and Without Filtering AMSR-E for Wet Snow

SAMUEL TUTTLE\textsuperscript{1}, EUNSANG CHO\textsuperscript{1}, CARRIE VUYOVICH\textsuperscript{2}, CARRIE OLHEISER\textsuperscript{3}, AND JENNIFER M. JACOBS\textsuperscript{1}

ABSTRACT:

Remote sensing has the potential to enhance operational river flow forecasting by helping to constrain estimates of snow water equivalent (SWE). Snowmelt contributes significantly to runoff in northern and mountainous areas of North America. In the northern Great Plains, melting snow is a primary driver of spring flooding, so knowledge of the magnitude and spatial distribution of SWE is necessary for accurate flood forecasting. However, ground surveys are relatively sparse in the region and provide only point estimates. Airborne gamma radiation surveys from the NOAA National Water Center (NWC) provide SWE estimates at larger resolution (approximately 5-7 km\textsuperscript{2}), but are available only 1-4 times per winter. Thus, satellite remote sensing can increase the spatiotemporal coverage of SWE observations available for forecasting purposes. The effect of snow grain size changes and wet snow on the satellite SWE estimates remain limitations of the passive microwave method. Awareness of when and how snowpack physical conditions impact retrievals can optimize the useful information provided by passive microwave SWE observations for operational flow forecasting. We compare satellite passive microwave estimates to NWS airborne gamma radiation snow survey SWE estimates in the northern Great Plains, with and without applying screening criteria to remove potential instances of wet snow. The SWE datasets compare favorably in the low relief, low vegetation study area, but the different spatial extents of each measurement complicates the comparison.

Keywords: AMSR-E, snow water equivalent, wet snow, passive microwave, airborne gamma radiation survey, northern Great Plains

\begin{itemize}
\item \textsuperscript{1} Department of Civil and Environmental Engineering, University of New Hampshire, Gregg Hall, 34 Colovos Road, Durham, NH 03824.
\item \textsuperscript{2} U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH.
\item \textsuperscript{3} National Oceanographic and Atmospheric Administration, National Water Center-Chanhassen, 1735 Lake Drive W., Chanhassen, MN 55317.
\end{itemize}
INTRODUCTION

Satellite passive microwave estimates of snow water equivalent (SWE) are a useful tool for monitoring snowpack at large scales. For basin-scale applications, such as snowmelt flood forecasting, satellites can provide SWE estimates with complete spatial coverage at 25 km spatial scale and approximately daily temporal resolution (or better, depending on latitude) (Kelly, 2009). This contrasts with other available SWE estimates, such as in situ ground measurements and airborne gamma radiation surveys. Ground measurements are available at a variety of temporal resolutions (e.g. hourly for snow pillows (Snowpack Telemetry (SNOTEL) network; http://www.wcc.nrcs.usda.gov/snow/) up to weekly from human observers), but only provide “point” estimates on the scale of centimeters. Airborne gamma radiation surveys measure SWE over spatial footprints of 5-7 km² (Carroll, 2001; Jones & Carroll, 1983), but are only available 1-4 times per winter. Because the satellite remote sensing provides indirect estimates of SWE, it is important to compare the satellite estimates to the other SWE sources in order to understand its strengths and weaknesses.

One such vulnerability of passive microwave methods is that the SWE algorithms are designed for dry snow conditions, when volume scattering by snow grains is the dominant physical process affecting the microwave radiation emitted from the earth’s surface (Ulaby & Stiles, 1980; Mätzler, 1987). The degree of attenuation of the microwave signal is related to the depth of the snowpack (Ulaby and Stiles, 1980; Chang et al., 1987). In wet snow conditions, when liquid water is present in the snowpack, absorption and emission become the dominant processes affecting microwave frequencies and it is no longer possible to estimate SWE because the emission originates only from a small portion of the snowpack (Mätzler, 1987; Hallikainen, 1989). In this analysis, we compare SWE estimates from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), with and without filtering out wet snow conditions, to NOAA National Water Center (NWC) airborne gamma radiations snow survey SWE estimates in the northern Great Plains.

DATA

Level 3 AMSR-E SWE data were obtained from the National Snow and Ice Data Center (NSIDC; https://nsidc.org/data/ae_dysno; Tedesco et al., 2004) from 2002-2011 (nine winters). The SWE estimates are derived from AMSR-E brightness temperature measurements using the Kelly (2009) algorithm. These data only include the descending AMSR-E overpass (1:30am local time) in order to minimize instances of wet snow.

Airborne gamma radiation snow survey SWE estimates were obtained from the NWC (formerly the National Operational Hydrologic Remote Sensing Center (NOHRSC)) website (http://www.nohrsc.noaa.gov/snowsurvey/). The airborne gamma radiation estimates are obtained by flying a plane equipped with a gamma radiation sensor at low altitude (150 m) along a specified flight line (approximately 15-20 km long). The estimated width of the airborne footprint is 330 m (Jones and Carroll, 1983). Each flight line is flown in the late fall over bare ground in order to establish a background gamma radiation estimate, given the amount of soil moisture. The difference in observed gamma radiation between the fall flight and any subsequent winter flights over snowpack is attributed to SWE (Carroll, 2001). There were 2,131 NWC airborne gamma radiation estimates coincident with AMSR-E observations in the study area for this analysis (Figure 1).
METHODS

Spatial Averaging of AMSR-E for Comparison

In order to best compare the two SWE sources, the area-weighted average AMSR-E SWE in the footprint of each airborne gamma radiation survey flight line was calculated.

Screening AMSR-E for Wet Snow

Screening criteria were used in order to identify AMSR-E measurements that were likely affected by wet snow. The Kelly (2009) algorithm is based on the difference in observed brightness temperature at multiple microwave frequencies (i.e. “Chang-type”; Chang et al., 1987). Lower frequencies (20 GHz and lower) are less affected by snow grain scattering than higher frequencies (20 GHz and above), so the difference in observed brightness temperature at two frequencies (e.g. 18.7 and 36.5 GHz for AMSR-E) can be used to estimate the snow depth (Ulaby and Stiles, 1980; Chang et al., 1987). However, liquid water largely eliminates the difference in brightness temperature at different microwave frequencies, leading to erroneous, low SWE estimates (Mätzler, 1987; Walker and Goodison, 1993; Vuyovich and Jacobs, 2011). We analyze two screening scenarios. For the first scenario (hereafter referred to as “unscreened”), we do not exclude any AMSR-E data from the analysis. But, for the second scenario (hereafter, “screened”), we attempt to restrict the analysis to dry, frozen snow conditions by screening the AMSR-E data using air temperature at 2 m height from the North American Land Data Assimilation System (NLDAS-2; Mitchell et al.) and the polarization difference criteria of Walker & Goodison (1993) from the nearby Canadian prairies.

For the “screened” comparison, data are only included if the air temperature in the previous three days never exceeds 0°C (using 3-hour averages), and the average air temperature is below -2°C. These requirements minimize the likelihood of liquid water in the snowpack, because any liquid precipitation or meltwater would likely have frozen under such conditions.

Additionally, any AMSR-E data with a 36.5 GHz polarization difference (vertically polarized brightness temperature minus horizontally polarized brightness temperature) greater than 10 K and SWE less than 5 mm are removed from the analysis. Walker and Goodison (1993) used a SWE
criteria of 0 mm, but the slightly higher limit in this study allows for noise in the SWE data, and is more conservative. For the purposes of this analysis, we assume that the 10 K polarization difference threshold of Walker and Goodison (1993), which was developed in an area that includes the northern portion of our study area, is applicable to the entire region.

These two wet snow criteria restricted the SWE comparison from 2,131 to 1,696 values.

RESULTS AND DISCUSSION

Figure 2. NWC airborne gamma radiation survey SWE estimates versus AMSR-E satellite passive microwave SWE estimates, with points colored by day of water year (DOWY). The left panel shows all data, while the right panel has been screened for possible wet snow conditions. Much of the data removed during screening exhibited low AMSR-E SWE but moderate to high NWC airborne gamma SWE, or was from late winter/early spring.

Table 1. Agreement statistics between the unscreened and screened SWE comparisons

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>$SWE_A$ (mm)</th>
<th>$SWE_G$ (mm)</th>
<th>$s_A$ (mm)</th>
<th>$s_G$ (mm)</th>
<th>MSD (mm)</th>
<th>MAD (mm)</th>
<th>RMSD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unscreened</td>
<td>2,131</td>
<td>68.5</td>
<td>78.0</td>
<td>40.9</td>
<td>31.4</td>
<td>-9.5</td>
<td>34.0</td>
<td>42.7</td>
</tr>
<tr>
<td>Screened</td>
<td>1,696</td>
<td>73.7</td>
<td>78.8</td>
<td>38.7</td>
<td>31.4</td>
<td>-5.0</td>
<td>32.2</td>
<td>40.7</td>
</tr>
</tbody>
</table>

$^1$ n is the number of paired observations in the SWE comparison, $SWE_A$ is mean AMSR-E SWE, $SWE_G$ is mean NWC airborne gamma SWE, $s_A$ is the standard deviation of AMSR-E SWE, $s_G$ is the standard deviation of NWC airborne gamma SWE, MSD is the mean signed difference, MAD is the mean absolute difference, and RMSD is the root mean squared difference.

In the unscreened scenario, the root mean squared difference (RMSD) between AMSR-E and NWC airborne gamma radiation SWE estimates was 42.7 mm, with a mean signed difference (MSD) of -9.5 mm (see Table 1, Figure 2a). The AMSR-E data exhibit a wider range than the NWC airborne gamma radiation data, but a number of points show near-zero AMSR-E values and moderate to high NWC airborne gamma values.

When the data are screened according to the wet snow criteria, the RMSD agreement increases only slightly to 40.7 mm, but the MSD is greatly reduced, to -5.0 mm (see Table 1, Figure 2b). Most of the data excluded by during screening fall below the 1:1 line, indicating that the AMSR-E
estimate was low compared to the gamma estimate. This is consistent with satellite underestimation of SWE due to the presence of liquid water. Many of the data clustered near the x-axis were removed due to the Walker & Goodison (1993) wet snow criteria, as these data exhibited high polarization difference and low AMSR-E SWE (Figure 3). These wet snow criteria were predominantly triggered during March and April (blue colors in Figure 2a), when less data met the air temperature criteria as spring approached.

Figure 3. AMSR-E SWE estimate versus AMSR-E brightness temperature (Tb) difference between the horizontal and vertical polarizations at 36.5 GHz (K). The red points are indicative of wet snow according to the Walker & Goodison (1993) criteria, and were thus removed during screening, while the blue points indicate lack of snow.

While the agreement between the two SWE datasets increased as a result of wet snow screening, it is clear that a large amount of variance still exists. Multiple factors could contribute to this discrepancy. First, the spatial footprints of the two SWE sources are very different (5-7 km$^2$ for the NWC airborne gamma SWE and 625 km$^2$ for AMSR-E). This could result in representativeness errors, because variability in snowpack properties at scales smaller than AMSR-E pixels could lead to differences in the SWE measured by each method. Second, changes in soil water over the course of the winter could lead to differences between the two SWE observations. Gamma radiation techniques detect all water, in any phase, up to 20 cm depth in the ground (Jones and Carroll, 1983), while AMSR-E passive microwave methods are only sensitive to water from the soil surface upwards. Thus, if the soil water or ice content increased after the late fall calibration period, then the airborne gamma method would indicate a higher SWE value than AMSR-E. Finally, the gamma radiation technique is unaffected by snow morphology, but grain size and density change over the course of the winter can affect the microwave signal measured by AMSR-E. Increased grain size and density lead to more attenuation of lower microwave frequencies, and thus lower brightness temperatures, resulting in higher SWE estimates from Chang-type SWE algorithms (Josberger and Mognard, 2002). U.S. Army Corps of Engineers (USACE) St. Paul District weekly in situ snow surveys conducted within the study area of this analysis indicate that, on average, snow density increases throughout the winter. It is possible that the AMSR-E Kelly (2009) algorithm does not completely account for this change.
CONCLUSION

SWE estimates from satellite passive microwave radiometry allow for daily monitoring of water resources at large spatial scales. For instance, satellite SWE estimates could aid in flood prediction in the north central United States and southern Canada by helping to constrain the amount and spatial distribution of SWE in flood forecasting models prior to the spring melt. However, any passive microwave SWE estimates used for this purpose will first need to be filtered for inaccurate estimates, such as those affected by wet snow. Our analysis suggests that screening for wet snow improves the agreement between passive microwave and airborne gamma radiation SWE estimates, considerable disagreement remains due to other differences between the two methods.

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REFERENCES