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Hydrology and Earth System Sciences Discussions

Improving the accuracy of the AFWA-NASA (ANSA) blended snow-cover product over the Lower Great Lakes region

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Abstract

The Air Force Weather Agency (AFWA) – NASA blended snow-cover product, called ANSA, utilizes Earth Observing System standard snow products from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) to map daily snow cover and snow-water equivalent (SWE) globally. We have compared ANSA-derived SWE with SWE values calculated from snow depths reported at ∼1500 National Climatic Data Center (NCDC) co-op stations in the Lower Great Lakes Basin. Compared to station data, the ANSA significantly underestimates SWE in densely-forested areas. We use two methods to remove some of the bias observed in forested areas to reduce the root-mean-square error (RMSE) between the ANSA- and station-derived SWE. First, we calculated a 5-yr mean ANSA-derived SWE for the winters of 2005–2006 through 2009–2010, and developed a 5-yr mean bias-corrected SWE map for each month. For most of the months studied during the 5-yr period, the 5-yr bias correction improved the agreement between the ANSA-derived and station-derived SWE. However, anomalous months such as when there was very little snow on the ground compared to the 5-yr mean, or months in which the snow was much greater than the 5-yr mean, showed poorer results (as expected). We also used a 7-day running mean (7DRM) bias correction method using days just prior to the day in question to correct the ANSA data. This method was more effective in reducing the RMSE between the ANSA- and co-op-derived SWE values, and in capturing the effects of anomalous snow conditions.

1 Introduction

Significant reductions in the extent of spring snow cover in the Northern Hemisphere have been measured during the satellite era (Brown, 2000; Brown et al., 2010) and over the past 90 yr, including about 50 yr of the pre-satellite era (Brown and Robinson, 2011). Accelerated warming is most likely responsible for the observed accelerated decrease

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in Northern Hemisphere spring snow cover in recent years (Brown and Robinson, 2011). It is important to monitor snow depth and snow-water equivalent (SWE) as well as snow extent.

Consistent and reliable snow maps are needed by the climate-modeling community to improve the predictive capabilities of the models, and to validate their performance. Several global snow maps are in widespread use (e.g., Robinson et al., 1993; Ramsay, 1998; Hall et al., 2002; Kelly et al., 2004; Frei et al., 2012). Most satellite-derived global snow maps have relied on utilization of data from one primary satellite, though the NOAA National Ice Center utilizes multiple satellite datasets as well as station data to construct daily maps (Helfrich et al., 2007).

The Great Lakes Basin is a challenging study area for mapping snow using satellite data for several reasons. Persistent cloud cover is a serious issue when observing snow using sensors operating in the visible-near-infrared (VNIR) wavelengths. And passive-microwave algorithms have limitations when mapping the shallow often ephemeral snow in this region as well as the wet snow – daytime temperatures are typically above 0 °C in the lower Great Lakes area. Moreover, the large footprint size of passive-microwave sensors means that small scale lake-effect snow events may be missed.

A blended snow-cover product has been developed jointly by the US Air Force Weather Agency (AFWA) and the Hydrospheric and Biospheric Sciences Laboratory at NASA/Goddard Space Flight Center. A detailed description of the product, derived from the AFWA–NASA Snow Algorithm (ANSA) may be found in Foster et al. (2011). The objective of the present work is to characterize the accuracy of the SWE derived from the ANSA snow maps in a region within the Lower Great Lakes Basin for the winters of 2005–2006 through 2009–2010 using meteorological-station data. We also describe methods to improve the accuracy of the ANSA-derived SWE by reducing the bias in the ANSA measurements.

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2 Study area

The Great Lakes system (Fig. 1) is the largest surface freshwater system on the planet. It drains an area of approximately 1 600 000 km^2 and stretches from northern Minnesota/western Ontario to the Gulf of St. Lawrence. Snow cover is prevalent during winter, and snowfall averages more than 80 cm in southern locations and more than 250 cm at a few locations in the lee of Lake Superior and Lake Ontario and at the highest elevations. Basin relief is rather low – on the order of hundreds of meters. Vegetation consists of transitional mixed forests, northern hardwoods, and Great Lakes spruce and pine forest.

The Great Lakes Basin is subject to lake-effect snowfall, particularly elevated areas in the lee of the Great Lakes. Lake-effect snowfall is produced when cold winds move across long expanses of relatively-warmer lake water; the warmer water provides energy and a source of water vapor. Snow deposited on the leeward shores can accumulate to significant depths in relatively short periods – 0.5 m or more in 24 h. Though the heaviest accumulations typically occur within 80 km of the lakes, on occasion lake-effect snow may fall 320 km downstream. For example, the highlands of West Virginia receive most non-storm snowfall from lake-effect snows from Lake Erie.

3 Air Force – NASA Snow Algorithm (ANSA) snow product

An example of the ANSA snow product is provided in Fig. 2. The product utilizes the Moderate-Resolution Imaging Spectroradiometer (MODIS) standard snow-cover maps (Hall and Riggs, 2007) and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), a passive-microwave instrument, standard snow-water equivalent (SWE) maps (Kelly et al., 2004; Kelly, 2009; Tedesco, 2011) to map daily snow cover and SWE globally. These products have been described in great detail elsewhere therefore only a brief description will be provided here.

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MODIS standard snow maps provide high-quality, daily and global snow-cover maps at a spatial resolution of up to 500 m (Hall et al., 2002; Riggs et al., 2006). A 500-m resolution MODIS snow-cover map is shown in Fig. 1b, however, in the ANSA product, we use 5-km resolution snow products as the default for mapping snow cover. AMSR-E data can map snow through clouds and darkness and provide estimates of SWE at a spatial resolution of ~25 km. AMSR-E-derived snow cover is used when clouds preclude MODIS from providing a snow map.

SWE derived from the ANSA product comes only from the AMSR-E. The MODIS VNIR bands cannot directly measure snow depth, nor can they image through cloud cover which is persistent in the Lower Great Lakes region during the wintertime.

Previous work (Fig. 3) has shown that use of the ANSA product enables improved mapping of snow-cover extent in the Lower Great Lakes region relative to using either MODIS or AMSR-E maps alone (Hall et al., 2009). Use of the ANSA snow products was also found to improve the mapping of snow-cover extent for the 2007–2008 winter in a mountainous area in the eastern part of Turkey where the elevation ranges between 850 and 3000 m (Akyurek et al., 2010). 91 % agreement was obtained between the ANSA snow maps and in-situ observations for February 2008. This is the first time that the ANSA snow cover product was evaluated in a mountainous area. Daily snow data collected at 36 meteorological stations were used for validation.

4 Methodology

We use National Climatic Data Center (NCDC) co-op station data (Fig. 4) for the five winters from 2005–2006 through 2009–2010 in the Lower Great Lakes region, to compare with ANSA-derived SWE (Fig. 4). Co-op snow depth data were interpolated to develop a daily map (see a sample of an interpolated map for 1 December 2007, in Fig. 5) and then converted to SWE using two different density conversion factors: 0.2 and 0.3 (representing snow densities of 0.2 and 0.3 g cm^{-3}, respectively). Since the exact snow density was unknown (snow density is not routinely made at co-op stations),

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initially, we converted snow depth to SWE using the above snow densities, which are reasonable for the conditions and time of year. (In reality the snow density changes over time as the snow metamorphoses.)

Daily difference maps were then constructed to evaluate the accuracy of ANSA-derived SWE as compared with SWE derived from interpolated station data. These difference maps (ANSA SWE minus station-derived SWE) can be considered a measure of deviation (or error) of the ANSA SWE from the "truth", the co-op station data. The RMSE quantifies an over- or under-estimate of the actual SWE. RMSE was calculated for each pixel for each day's snow map. RMSE was averaged to get a daily value for the entire region of interest (or domain).

We then developed two methods to bias correct the ANSA daily SWE maps. The attributes of each method are described below.

First, a monthly error was determined by calculating the mean difference of ANSA SWE minus station-derived SWE for each cell for each day of each month (November, December, January, February and March of each year). This calculation was repeated for each of the five winters, 2005–2006 through 2009–2010, resulting in a 5-yr bias map for each month. To remove the 5-yr bias from each daily ANSA map, the mean-monthly difference was subtracted from the ANSA SWE in each cell; this produced bias-corrected SWE maps for each day of each month studied.

Second, a 7-day running mean (7DRM) using days immediately before the day of interest was calculated and the average difference map of those seven days was used as a bias to correct the ANSA SWE data on the following day. For example, the 7-day period, 1–7 January, is used to calculate the 7DRM to bias correct the ANSA SWE on the 8 January snow map, then a correction would be calculated for 2–8 January, from which a new bias is used to correct the 9 January map, and so on. The daily RMSE, the difference between the ANSA data corrected with the 7DRM method, and the corresponding station data, is computed each day.

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5 Results and discussion

The difference between the SWE derived from the interpolated co-op data compared to the ANSA-derived SWE for each cell without any bias correction is shown in Fig. 6a and b. The blue colors indicate where the ANSA map underestimates SWE as compared to station data, and the pink colors indicate that ANSA overestimates SWE. The areas of best agreement are shown in neutral colors.

In January and February of 2008, ANSA underestimates SWE in densely-forested areas such as in the Upper Peninsula of Michigan and in the Adirondacks in New York State by up to ~75 mm (see red circles in Fig. 6a). Even when using its forest-fraction adjustments (Foster et al., 2005), passive-microwave algorithms still underestimate SWE in dense forests.

5.1 Conversion of snow density to SWE

What snow density should be used to convert the co-op snow depths to SWE? Ideally the snow density should vary as described in Foster et al. (2005). However, lacking specific information on snow-cover metamorphism in this study area, we decided to use a fixed snow density to compute the snow depth from the AMSR-E SWE measurements. In both the January and February 2008 difference maps (Fig. 6a and b), there is overall better agreement when a snow density of 0.3 g cm^{-3} was used to convert the snow depths to SWE versus using 0.2 g cm^{-3} (Fig. 6c and d). Note the substantial differences when different snow densities are used to convert snow depth to SWE. This demonstrates the need to improve density estimates, especially in areas where snow conditions change rapidly, and to incorporate dynamic features into SWE algorithm so that the density changes with time.

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5.2 Improvement of ANSA SWE calculation using bias correction

There are both systematic (bias) and random errors associated with the passive-microwave measurements. In order for the remotely sensed SWE observations to be useful for climate modelers, for instance, it is necessary to have both an unbiased SWE estimate and a quantitative, rather than qualitative, estimate of the uncertainty (random errors). This is a critical requirement for successful assimilation of snow observations into land surface models.

First, we experimented with the 5-yr bias information to produce "5-yr bias-corrected" SWE maps as shown in Fig. 7a. Only areas that are currently snow covered are displayed on the maps, and non-snow-covered terrain is shown in green. Using the 5-yr bias correction, the RMSE improves on most days in most months. However when anomalous snow conditions occur, the 5-yr bias correction can substantially increase the RMSE.

In general, there is considerable improvement in the accuracy of the ANSA SWE measurement as compared to station data, when we remove the 5-yr average bias. This can be seen by comparing Fig. 7a and b, and by noting that the RMS errors are lower when the 5-yr bias is removed as seen in Fig. 8. This bias-correction technique works quite well when snow conditions on a given day are reasonably close to "average." However when snow conditions are anomalous, as seen in Fig. 9, use of the 5-yr bias correction can result in higher RMSE values (see green line).

Between 6 and 8 February 2006 we see a change in the RMSE values (Fig. 9) because the original ANSA data (with no bias correction) matches the interpolated snow depth map better than does the 5-yr bias-corrected data. For most of February 2006, snow conditions differed considerably from the 5-yr average and therefore the 5-yr bias correction did not offer improvement in this case. For example, in Indianapolis, Indiana, which is representative of the Lower Great Lakes region, the temperatures were warmer than normal in February and the snowfall was much lower than average. Only three days recorded 2.5 cm of snow on the ground (4–6 February 2006), and there was

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no day that recorded more than 5 cm of snow. In addition, there was no snow on the ground (other than a trace) after 6 February.

In all cases that we studied during the five winters, the 7DRM bias-correction technique worked better than using either no bias correction for the ANSA SWE data, or using the 5-yr average bias-correction technique. The 7DRM approach captures the snow conditions just before the day in question. Future work calls for trying additional ways to bias-correct the ANSA data using data just prior to the day in question, but allowing a few days' delay to acquire the data to perform the bias correction.

Models that improve the evolution of snowpack parameters, including grain size information, and use of dynamic algorithms that better account for changes in snow density, should be the focus of future work. A dynamic method of calculating snow density in a passive-microwave SWE algorithm would likely result in improved SWE estimates from microwave sensors.

6 Conclusions

We have examined the ability of the ANSA blended-snow product to measure SWE in the Lower Great Lakes region of the US. The ANSA product underestimates SWE in dense forests. This is a known limitation of passive-microwave SWE algorithms. Thus we employed bias-correction methods to reduce the errors when measuring SWE from ANSA. First, we calculated the 5-yr mean-monthly bias (difference between co-op-derived SWE and AMSR-E SWE) from the daily maps from each month (November through March) of each winter from 2005–2006 to 2009–2010. Those values, on a cell-by-cell basis, were subtracted from the ANSA SWE values for each day of each corresponding month. Results show an improvement in agreement between the co-op station-derived and ANSA SWE after the monthly bias was removed.

Estimation of snow density is needed to convert the co-op station snow depths to SWE values, so that ANSA SWE can be compared with "ground truth." For our study area, use of a conversion factor of 0.3 (corresponding to a snow density = 0.3 g cm^{-3})

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provides overall better agreement between ANSA and co-op SWE for both January and February 2008, than when we used a snow density of 0.2 g cm^{-3}.

For most of the months during the five-year period, the 5-yr bias correction improved the agreement between the ANSA-derived and station-derived SWE. However, anomalous months such as when there was very little snow on the ground compared to the 5-yr mean, or months in which the amount of snow was much greater than the 5-yr mean, showed poorer results. We also used the 7DRM bias-correction method using the 7 days just prior to the day in question. As before, we then corrected the ANSA data. This method was more effective in reducing the RMSE between the ANSA- and co-op-derived SWE values, and in capturing the effects of anomalous snow conditions.

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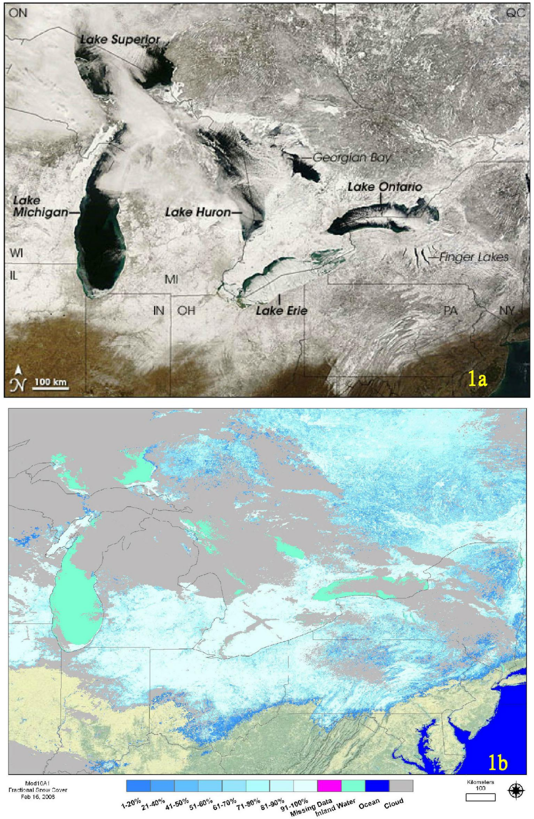

Fig. 1. (a) Terra MODIS image acquired on 16 February 2008 showing snow cover in the vicinity of the Great Lakes in the northern United States and southern Canada. There is ice cover on Lake Erie but the other Great Lakes are mainly cloud covered. Image courtesy of the Earth Observatory Image of the Day http://earthobservatory.nasa.gov/IOTD/view.php?id=8485. **(b)** MODIS snow-cover fraction (SCF) map of the same area shown in **(a)**.

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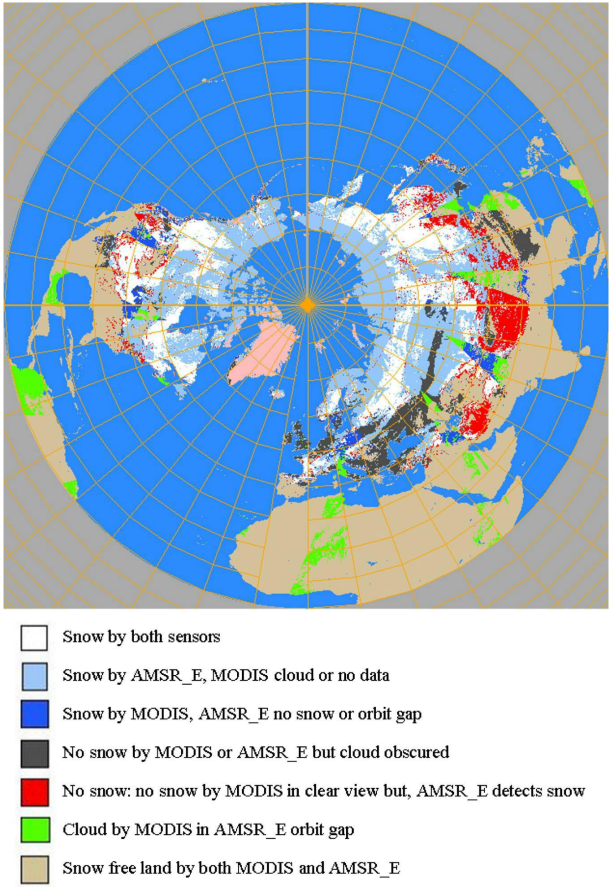

Fig. 2. ANSA blended-snow product for 26 January 2007 in Lambert Azimuthal polar projection (Foster et al., 2011).

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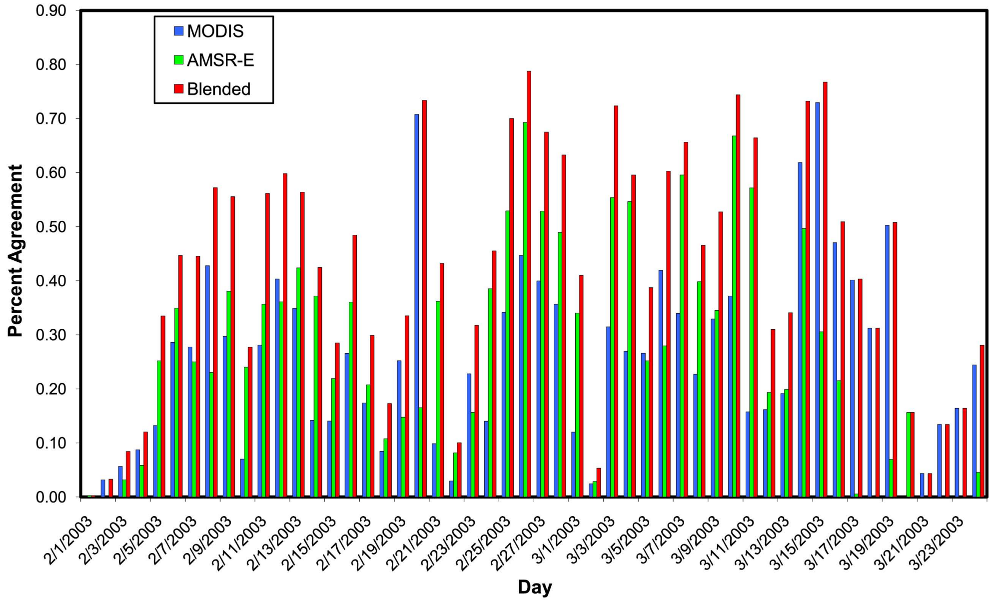

Fig. 3. Relationship of the Percent of Agreement of the ANSA product, and the MODIS and AMSR-E input products, alone, as compared to meteorological station data for the lower Great Lakes region for mapping snow-cover extent in 2003. The AMSR-E contribution (green) becomes more important in late February during periods of cloudiness when MODIS cannot map the snow (after Hall et al., 2009).

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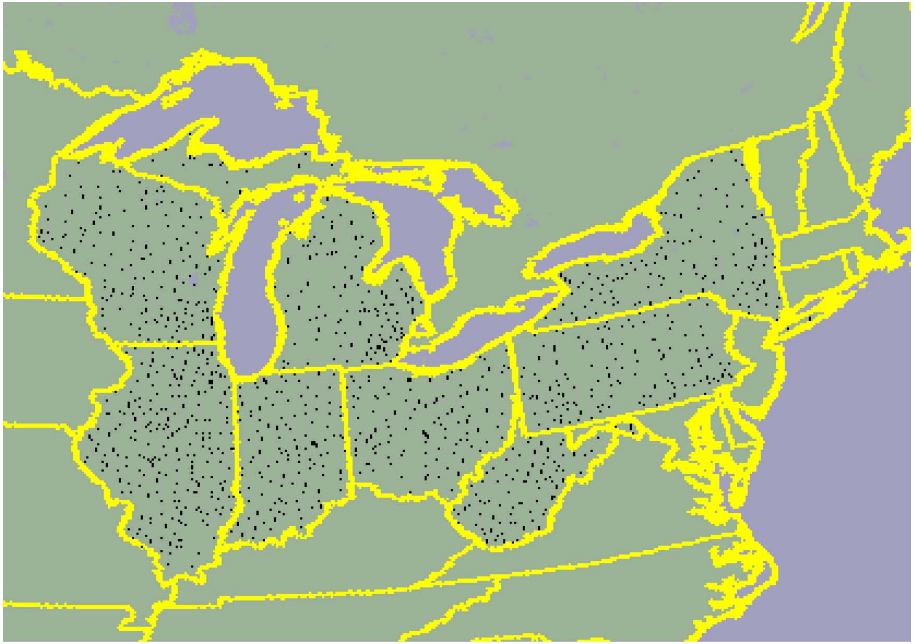

Fig. 4. Dots represent locations of NCDC co-op stations used in this study.

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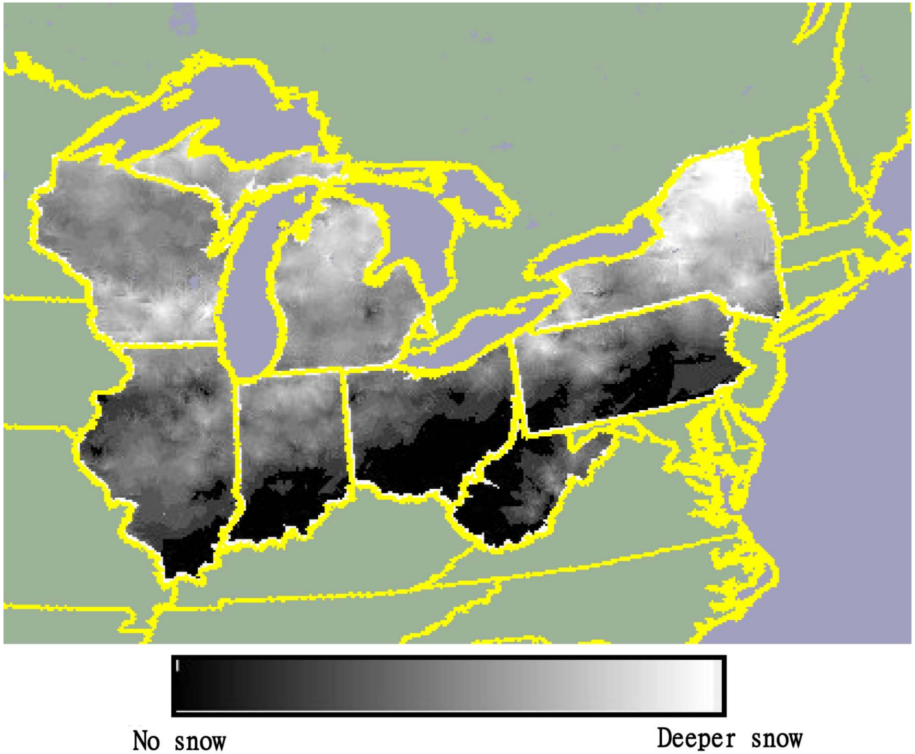

Fig. 5. 1 December 2007 snow depth map interpolated from co-op station measurements. Snow depths are shown in various shades of black and white (lighter grey indicates deeper snow).

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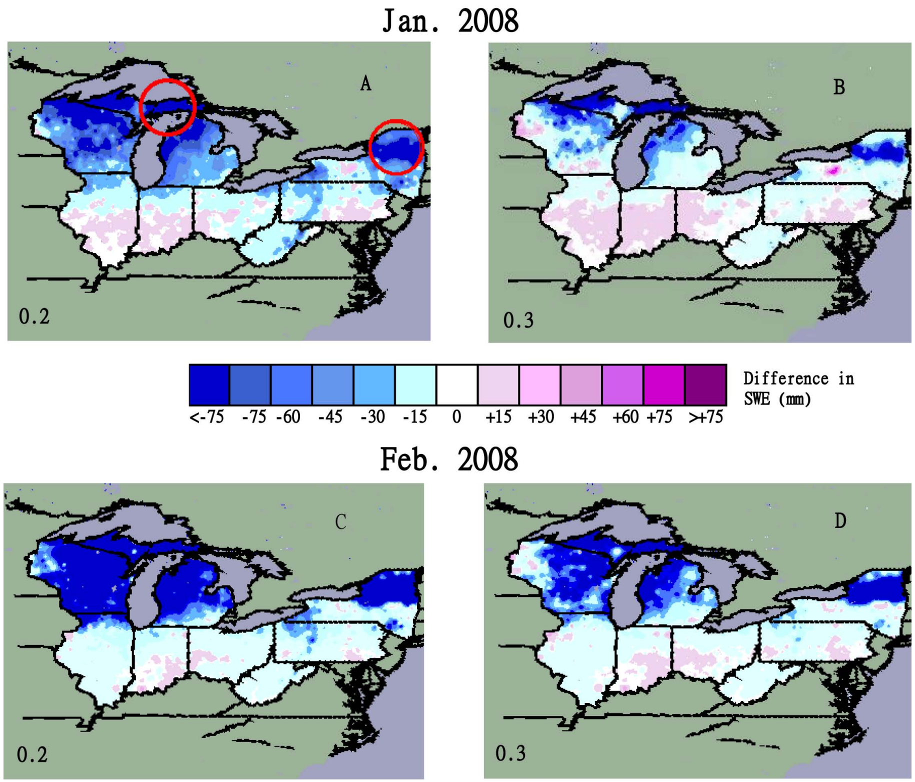

Fig. 6. Mean difference between ANSA and station-derived SWE for January (**A** and **B**) and February 2008 (**C** and **D**) using 0.2 conversion factor (**A** and **C**), and 0.3 conversion factor (**B** and **D**). Conversion factors are used to convert co-op station snow-depths to SWE and are based on snow density. The blue colors indicate where the ANSA map underestimates SWE as compared to station data, and the pink colors indicate that ANSA overestimates SWE.

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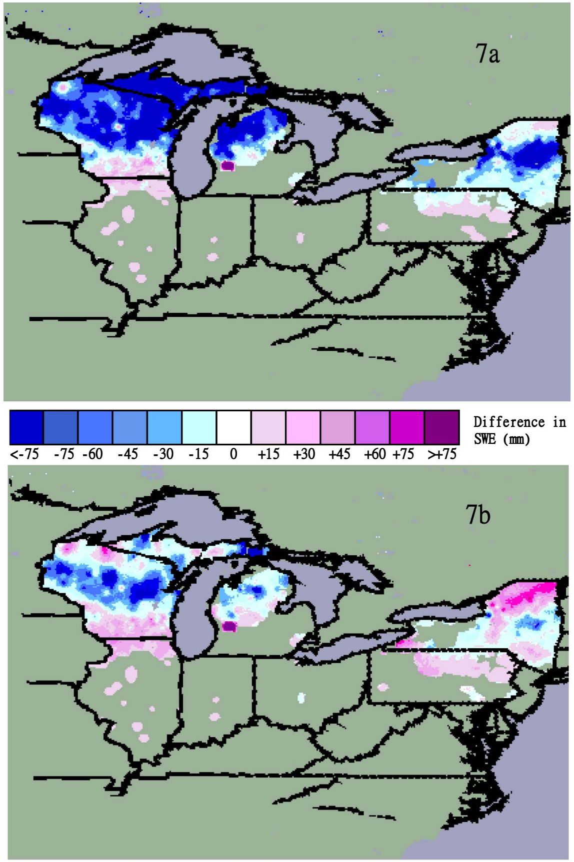

Fig. 7. **(a)** Mean difference between ANSA and station-derived SWE for 2 January 2009. **(b)** Mean difference between ANSA and station-derived SWE for 2 January 2009, but in this image, the 5-yr bias was subtracted from the result in **(a)**, for each cell. In these images, the non-snow-covered land areas are shown in green.

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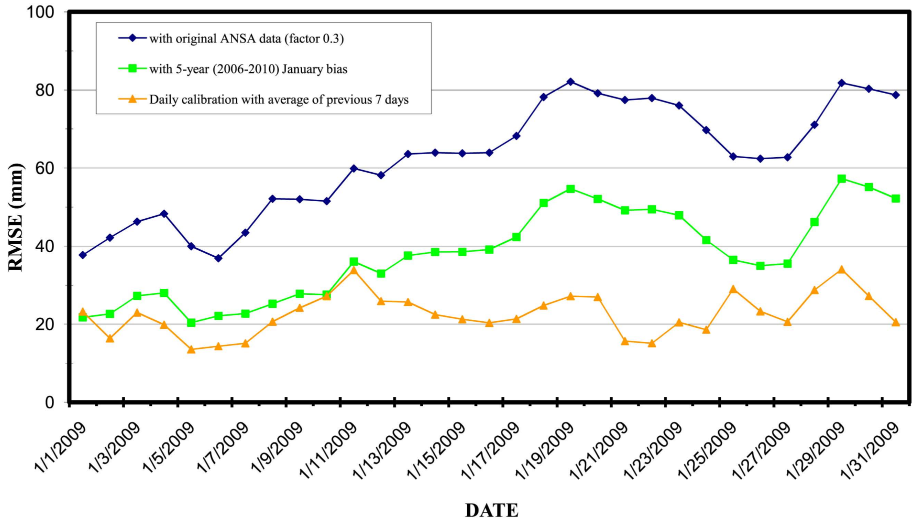

Fig. 8. Plot of the RMSE for January 2009. The top (blue) line corresponds to Fig. 7a (no bias correction), and the green line corresponds to Fig. 7b (5-yr bias correction method). The orange line represents results using the 7-day running mean (7DRM) bias-correction method.

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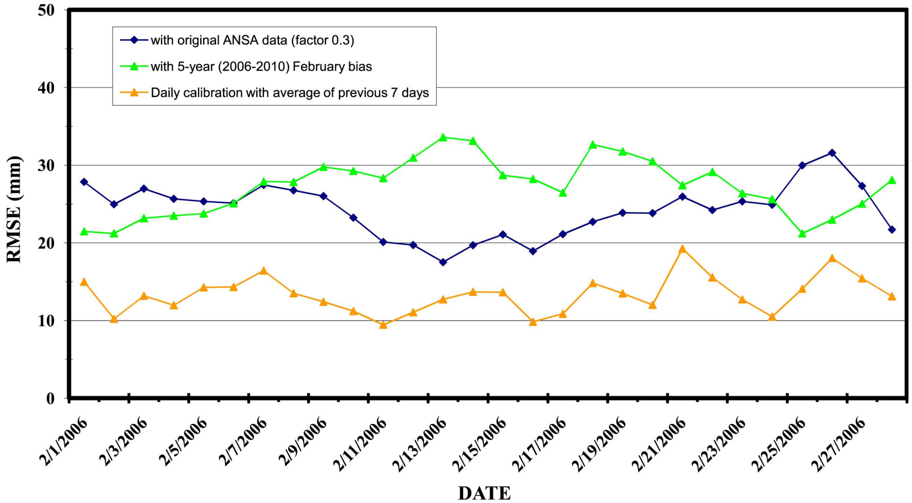

Fig. 9. Plots of the RMSE for the month of February 2006. The blue line represents the case where the original ANSA data were compared with the station-derived SWE (no bias correction), and the green line represents the case where the 5-yr bias correction was used. Note in the middle of the month that the errors are greater when the 5-yr bias correction is used. The orange line represents results using the 7-day running mean (7DRM) bias-correction method.

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