Evaluation of MRMS Snowfall Products over the Western United States

YIXIN WEN,[a,b] PIERRE KIRSTETTER,[c,d] J. J. GOURLEY,[d] YANG HONG,[c] ALI BEHRANGI,[b] AND ZACHARY FLAMIG[a,e]

[a] *Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, Oklahoma*
[b] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California*
[c] *School of Civil Engineering and Environmental Sciences, University of Oklahoma, Norman, Oklahoma*
[d] *NOAA/National Severe Storms Laboratory, Norman, Oklahoma*
[e] *School of Meteorology, University of Oklahoma, Norman, Oklahoma*

(Manuscript received 18 November 2016, in final form 21 February 2017)

ABSTRACT

Snow is important to water resources and is of critical importance to society. Ground-weather-radar-based snowfall observations have been highly desirable for large-scale weather monitoring and water resources applications. This study conducts an evaluation of the Multi-Radar Multi-Sensor (MRMS) quantitative estimates of snow rate using the Snowpack Telemetry (SNOTEL) daily snow water equivalent (SWE) datasets. A detectability evaluation shows that MRMS is limited in detecting very light snow (daily snow accumulation <5 mm) because of the quality control module in MRMS filtering out weak signals (<5 dB*Z*). For daily snow accumulation greater than 10 mm, MRMS has good detectability. The quantitative comparisons reveal a bias of −77.37% between MRMS and SNOTEL. A majority of the underestimation bias occurs in relatively warm conditions with surface temperatures ranging from −10° to 0°C. A constant reflectivity–SWE intensity relationship does not capture the snow mass flux increase associated with denser snow particles at these relatively warm temperatures. There is no clear dependence of the bias on radar beam height. The findings in this study indicate that further improvement in radar snowfall products might occur by deriving appropriate reflectivity–SWE relationships considering the degree of riming and snowflake size.

1. Introduction

Accurate estimation of snow is needed for many applications (e.g., water resources management, hydrology, and recreation), but it has remained a challenging task (Skofronick-Jackson et al. 2015; Behrangi et al. 2014). Routine observations of snowfall have been, so far, mostly restricted to ground-based stations with sparse spatial distribution and inconsistent duration of data record (Walsh 1996; Liu and Seo 2013). Snowfall observations by remote sensing systems have become highly desirable for large-scale weather monitoring and global climate studies (Skofronick-Jackson et al. 2015).

The Multi-Radar Multi-Sensor (MRMS) system utilizes data measured by the Weather Surveillance Radar-1988 Doppler (WSR-88D) Next Generation Weather Radar (NEXRAD) along with automated gauge networks and numerical model outputs to provide real-time and high-resolution (1 km, 2 min) precipitation products including snow (Zhang et al. 2011, 2016). Currently, MRMS quantitative precipitation estimation (QPE) is an independent reference for Global Precipitation Measurement (GPM) mission liquid rainfall products (e.g., Kirstetter et al. 2012, 2015b; Munchak and Skofronick-Jackson 2013). Extending the value of MRMS precipitation products to the snow research community has become desirable. Kirstetter et al. (2015a) performed quantitative evaluations of the MRMS reflectivity–snow water equivalent (SWE) relationship and noted significant underestimation relative to the Hydrometeorological Automated Data System (HADS) gauges. They suggested further investigations on the influence of parameters such as snow density and temperature.

A measuring network called Snowpack Telemetry (SNOTEL) was installed in the western United States to measure snow. SNOTEL was designed to provide cost-effective data from high snow accumulation regions throughout western United States. SWE data are generally available from the early 1980s. Beginning in the early 1980s, the stations started to measure precipitation.

Corresponding author: Pierre Kirstetter, pierre.kirstetter@noaa.gov

DOI: 10.1175/JHM-D-16-0266.1

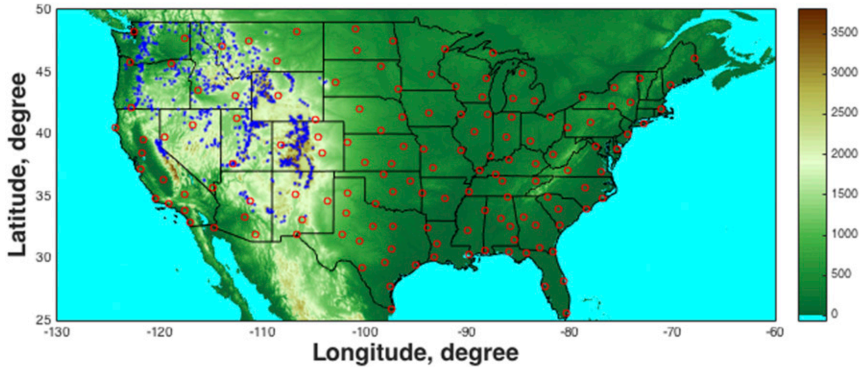

FIG. 1. The locations of WSR-88D radar sites (white circles) and SNOTEL stations (red dots) with terrain elevation (m) as background.

From the late 1980s, minimum and maximum daily air temperature are also measured. SNOTEL SWE records along with other station measurements have been used in many studies. For example, SNOTEL daily minimum temperature observations are directly ingested by Parameter-Elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 2008) and Daymet (Thornton et al. 1997), two widely used gridded climate products. SNOTEL SWE records have been used to examine seasonal aspects of western United States precipitation (Mock 1996). In this study, we use the daily SNOTEL records of SWE as an in situ snowfall reference to evaluate radar snowfall products.

The objective of this paper is to validate MRMS snowfall daily products over the western United States using daily measurements from the SNOTEL network. Note that the context of complex terrain and sparse radar network is not favorable to the sampling of precipitation and specifically snow. Hence, while this analysis provides a first large-scale assessment of ground-weather-radar-derived snowfall products in mountainous terrain, caution is required in generalizing the results to other contexts such as the relatively dense radar coverage in the Great Plains of the United States.

2. SNOTEL measurements and MRMS dataset

a. SNOTEL measurements

The authors utilized snowfall observations from 788 SNOTEL stations located in the western mountainous region of the United States (Fig. 1) from December 2014 to February 2015. SWE is measured by a snow pillow filled with an antifreeze solution. As the snow accumulates, the weight of the snowpack forces the solution into a manometer column inside the instrument shelter. The height change of the manometer is monitored by a pressure transducer and is converted to SWE in inches. The sensitivity of SNOTEL SWE is 0.1 in. (2.54 mm). Like the snow pillows, SNOTEL gauges also work on the same manometer/pressure transducer principle. The precipitation gauges measure all phases of precipitation, while snow pillows only measure solid precipitation. The snow pillow and precipitation gauges provide hourly SWE and precipitation data, which are much less reliable in relation to daily accumulations because of the wind effects and sensor issues. Radar data were matched to daily SNOTEL measurements to provide a robust and reliable reference for radar evaluation. A quality control procedure based on the one described by Serreze et al. (1999) was conducted.

b. MRMS snowfall products

MRMS is a research system integrating radar, rain gauge, satellite, and numerical weather prediction data and generates automated, seamless national 3D radar mosaic and multisensor QPEs (Zhang et al. 2016). MRMS also provides the seamless hybrid scan reflectivity height (SHSRH) product, which is the height of the lowest nonmissing single radar hybrid scan reflectivity at each MRMS grid cell. The MRMS system uses two criteria to identify snowfall. First, to avoid echoes caused by Bragg scattering (Knight and Miller 1993; Kollias et al. 2007), radar reflectivity must exceed 5 dBZ. Second, the surface temperature and wet bulb temperature from hourly model analyses must be lower than 2° and 0°C, respectively. For each grid cell identified as falling snow, the empirical relation $Z = 75S^2$ (Zhang et al. 2016) is applied to convert radar reflectivity Z to snowfall rate S. MRMS SWEs are not corrected by gauge measurements since most of the HADS gauges are tipping-bucket type and automated gauges have difficulties in measuring frozen precipitation accurately (Rasmussen et al. 2012; Martinaitis et al. 2015). It must be noted that the MRMS algorithms continue to evolve, especially now that dual-polarization radar variables are available and incorporated. While the evaluation is focused on a prior version of the MRMS algorithm before the NEXRAD upgrade to dual polarization, there are a number of users (i.e., satellite validation community, hydrologic modelers, regional climate modelers) who are interested in the error characteristics of SWE for the study period. Moreover, outcomes from the results are envisioned to guide the ever-evolving SWE algorithms that are being developed within the remote sensing community and beyond.

The study employed three criteria to match MRMS gridded radar SWE to SNOTEL station data. First, only estimates from the closest MRMS grid cells to the surface site were selected. Second, since SNOTEL daily measurements are transmitted at local midnight for the previous day, MRMS hourly data were accumulated to daily in order to match SNOTEL's temporal scale. Third, SNOTEL–MRMS pairs were selected for days at which the daily maximum temperature measured by SNOTEL was less than 0°C to ensure solid precipitation. To validate the simple temperature-based rain–snow separation algorithm, snow pillows and precipitation gauge measurements from the selected days are compared. The agreement between two sensors with a bias ratio of 8.31% [(pillow − gauge)/gauge × 100] and correlation coefficient of 0.90 indicates that only solid precipitation is selected under the specified criteria. The underestimation by precipitation gauges compared to snow pillows may primarily come from the undercatch during windy conditions, which is an oft-noted issue of gauges in snowfall measurements (Wen et al. 2016; Rasmussen et al. 2012). Snow pillows can underestimate the weight of snowpack in case of ice bridges (Gray and Male 1981). Also, snow pillows can underestimate or overestimate the actual SWE because of errors stemming from temperature differences between the instrument and the surrounding soil (Johnson and Schaefer 2002; Johnson 2004). To evaluate MRMS snowfall products, we use the SWE measured by snow pillows.

3. MRMS snowfall detectability evaluation

Two major aspects to address for MRMS snowfall products are 1) the capability to detect falling snow and 2) the accuracy in quantifying snowfall rate. Simple contingency table statistics are applied to answer the first question. The contingency table statistics describing the probability of detection (POD), critical success index (CSI), and false alarm rate (FAR) are used to evaluate MRMS snowfall detectability. These indexes are computed based on the number of hits H, false alarms F, and misses M for data pairs:

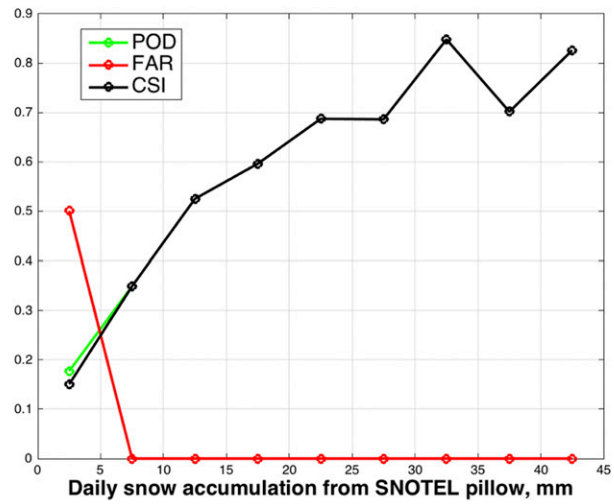

FIG. 2. The POD, FAR, and CSI by MRMS in terms of daily snowfall accumulation.

$$\mathrm{POD} = H/(H + M), \quad (1)$$

$$\mathrm{CSI} = H/(H + F + M), \quad \text{and} \quad (2)$$

$$\mathrm{FAR} = F/(H + F). \quad (3)$$

In total, 17 946 samples are used to test the detectability. Figure 2 shows the POD, FAR, and CSI as a function of daily snow accumulation measured by SNOTEL. The POD and CSI show a trend of improving values with increasing snowfall accumulation. This improvement indicates that MRMS likely misses the light snowfall intensities. For daily snow accumulation less than 5 mm, the CSI is lower than 0.25. The quality control module in MRMS filters out weak signals (<5 dBZ). Thus, instantaneous snowfall rate less than 0.2 mm h^{-1} is classified as no precipitation in MRMS and the detection issue propagates to SWE daily accumulation. Note that for the daily SWE accumulation below 5 mm, the FAR value is higher than 0.5. The high FAR of SNOTEL is due to snow pillow sensitivity. Almost all misses of SNOTEL have MRMS accumulations less than 2.54 mm (0.1 in.), the minimum value that the snow pillows detect (section 2a). To ensure good quality of SNOTEL products, hereafter, SNOTEL daily accumulations less than 2.54 mm have been removed for the quantitative evaluation in the following section. For daily snow accumulation greater than 10 mm, all indices (POD, CSI, and FAR) show good results, indicating good detectability by MRMS.

4. Snow daily accumulation comparisons

a. Evaluation statistics

To evaluate how accurately MRMS quantifies the snowfall daily accumulation, the relative bias (RB),

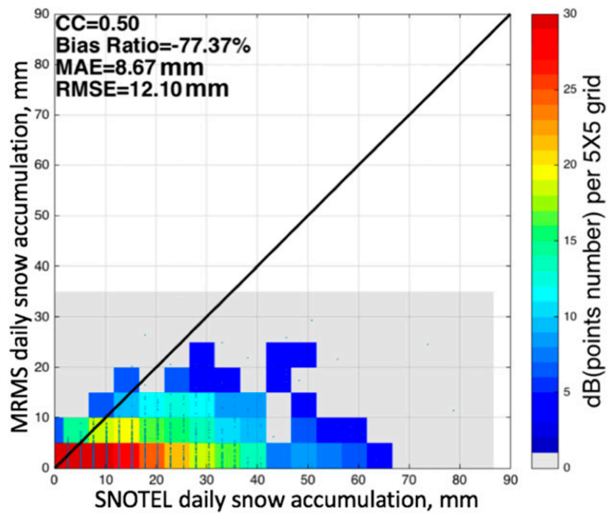

FIG. 3. The color-density scatterplot of SNOTEL and MRMS daily accumulation.

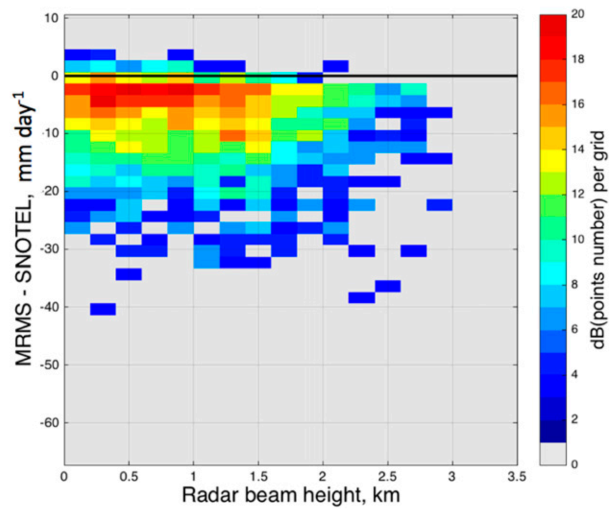

FIG. 4. Difference between MRMS and SNOTEL against radar beam height above ground level.

correlation coefficient (CC), the mean absolute error (MAE) and root-mean-square error (RMSE) are selected for comparison with SNOTEL snow pillow daily measurements:

$$\mathrm{RB} = \frac{\sum R(i) - \sum P(i)}{\sum P(i)} \times 100\%, \tag{4}$$

$$\mathrm{CC} = \frac{\sum [R(i) - \overline{R}] \sum [P(i) - \overline{P}]}{\sqrt{\sum [R(i) - \overline{R}]^2 \sum [P(i) - \overline{P}]^2}}, \tag{5}$$

$$\mathrm{MAE} = \frac{\sum |R(i) - P(i)|}{n}, \quad \text{and} \tag{6}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum [R(i) - P(i)]^2}{n}}. \tag{7}$$

In (5), $\overline{R}$ and $\overline{P}$ represent the arithmetic mean of the MRMS radar and SNOTEL snow pillow measurements, respectively.

The color-density scatterplot in Fig. 3 shows quantitative comparison of MRMS and SNOTEL SWE daily accumulation. Compared to SNOTEL observations, MRMS snowfall daily accumulations show underestimation with an RB of −77.37%. We recall that radar QPE in the western United States is challenging because of insufficient NEXRAD radar coverage and the high spatial variability of precipitation due to orographic enhancements (Maddox et al. 2002). The underestimation of MRMS is mainly due to radar beam volumes increasing in size and height above the terrain at far range, snow mass flux changing with temperature, and uncertainty in the *Z*–SWE relation. These potential factors are elucidated in the following sections.

b. Evaluation with radar beam height

Systematic errors in ground-based radar precipitation estimation are related to the vertical profile of reflectivity (VPR) features combined with the geometric effects of the radar beam. They create the oft-noted radar beam height dependence (Bellon et al. 2005). The VPR always has a negative slope feature in the snow part (Kirstetter et al. 2013), causing underestimation at the surface if the radar beam samples higher parts of the atmosphere. Figure 4 shows the errors between MRMS and SNOTEL as a function of MRMS SHSRH above ground level. The majority of points are located within ±5 mm, indicating that the radar SWE is consistent with SNOTEL measurements. Some points indicate underestimation (MRMS–SNOTEL discrepancies lower than −10 mm); however, no clear trend is revealed. This analysis suggests that radar sampling is not the primary explanatory variable for the significant underestimation of SWE by MRMS.

c. Evaluation with temperature

Changing temperature impacts snow properties at the surface (snowflake size distribution, scattering properties, density, and falling velocity). An evaluation of radar snowfall measurements as a function of temperature is performed to at least partially unravel the discrepancies between estimates by MRMS and SNOTEL. The color-density scatterplots in Fig. 5a show that the agreement between MRMS and SNOTEL deteriorates toward increasing underestimation with temperature increasing and approaching 0°C. The large variability in errors at warmer temperatures (0°C) is also of interest. This temperature-dependent error may be associated

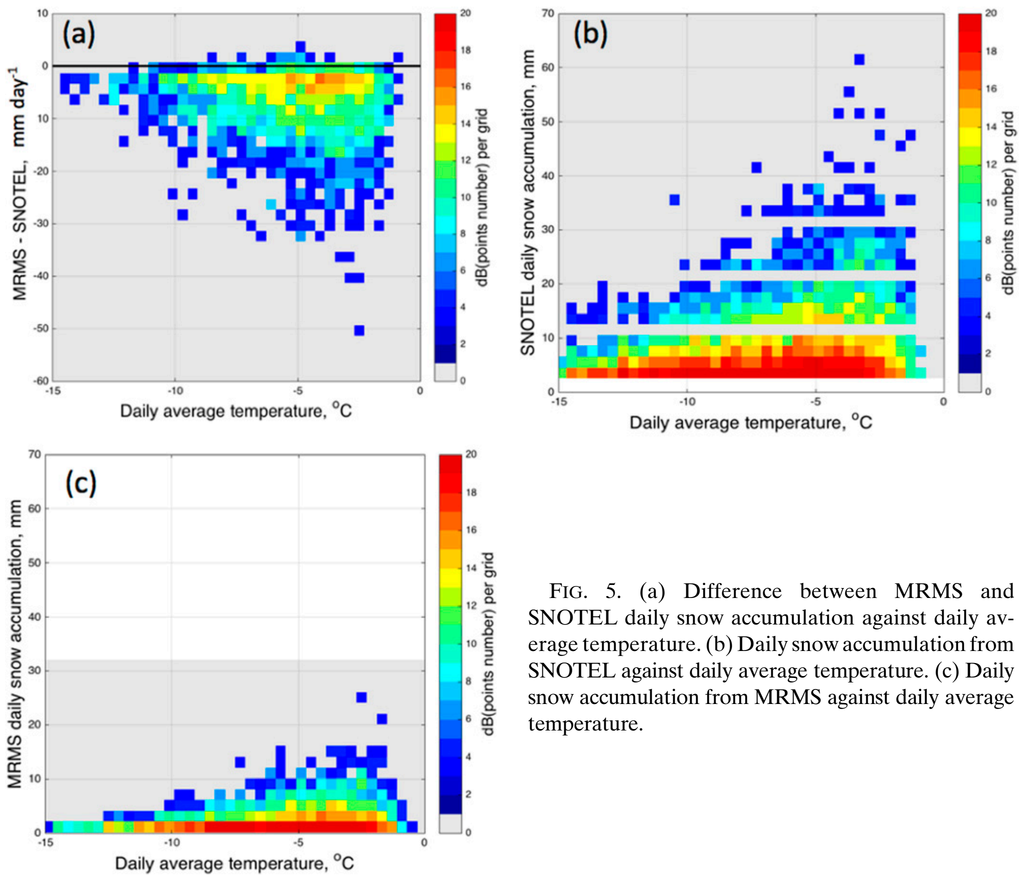

FIG. 5. (a) Difference between MRMS and SNOTEL daily snow accumulation against daily average temperature. (b) Daily snow accumulation from SNOTEL against daily average temperature. (c) Daily snow accumulation from MRMS against daily average temperature.

with the snowflakes growth processes and their types (e.g., dendrites vs aggregates), which impacts their size distribution, scattering properties, and the falling velocity. Unlike liquid rain with a constant density, snow presents a large variability in terms of crystal type and degree of riming. It makes it more difficult to estimate the snow rate based on the radar reflectivity factor alone. Previous works on the relationship between snowflake density and temperature indicate a nonlinear increase of snow density with increasing temperature from −15° to 0°C (e.g., LaChapelle 1962; Judson and Doesken 2000). Garrett and Yuter (2014) found a 37% reduction in the mean value of snowflake density with temperature decreasing from −3.5° to −17.3°C. Denser snow particles have higher fall speeds, as shown in wind tunnel studies (e.g., Macklin 1962; Rasmussen and Heymsfield 1985) and used in models of the melting layer (Zawadzki et al. 2005; Kirstetter et al. 2013), and it increases significantly the snow mass flux. This is consistent with results shown in Fig. 5b in which daily snow accumulation measured by SNOTEL snow pillows increase with temperature. However, the temperature-dependent snow mass flux is not captured by a single reflectivity–SWE relationship. While the MRMS shows somewhat higher daily snow accumulation closer to 0°C, it significantly underestimates this dependence (Fig. 5c), resulting in the bias observed in Fig. 5a.

Further improvement in radar snowfall rate retrieval might occur by stratifying the *Z–S* relationships according to the degree of crystal riming and the snowflake size using polarimetric radar signals and/or environmental variables.

d. Evaluation with snow intensity

Figure 6 shows the MRMS–SNOTEL discrepancies as a function of the SNOTEL daily accumulation. An increasing underestimation by MRMS is noticed with increasing snow accumulations. The uncertainties from the *Z–S* relation could be very large and a variety of *Z–S* relations have been derived in previous studies. The one adopted in the MRMS system, $Z = 75S^2$, may be inappropriate to use across the entire CONUS because of the large variability in snowflakes types, size distribution, scattering properties, and falling velocity. This analysis indicates that a new set of *Z–S* relationships is needed to be based on accurate ground snowfall measurements.

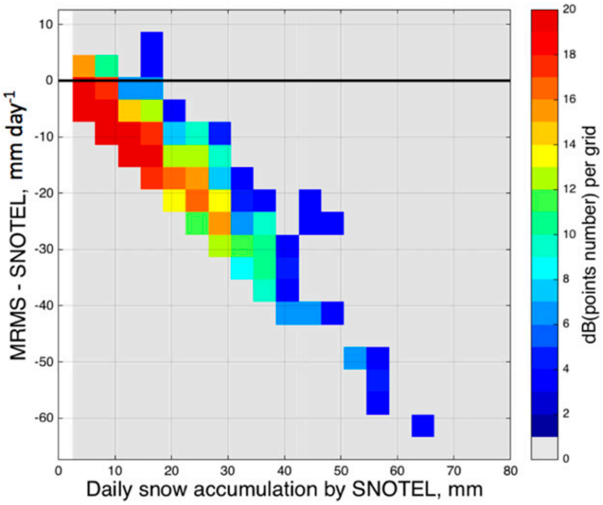

FIG. 6. Snow-intensity-dependent underestimation by MRMS.

This analysis also motivates future studies that incorporate polarimetric variables to estimate SWE.

5. Conclusions and future work

This study provides both a qualitative and quantitative assessment of MRMS snowfall products as compared with SNOTEL SWE measurements in the western United States. Advantages of using SNOTEL data for this assessment are reliable daily SWE measurements. The main findings are summarized as follows:

1) MRMS shows limitations in detecting very light snow, probably due to the quality control module in MRMS filtering out weak signals (<5 dBZ). MRMS has a good detectability for daily snow accumulation greater than 10 mm.
2) Comparisons of MRMS and SNOTEL daily SWE accumulation indicate underestimation by MRMS with an overall bias of −77.37%.
3) By comparing the daily SWE accumulation with respect to radar beam height, temperature, and snow intensity, biases seem to arise primarily from snow mass flux change. Besides the temperature effects, the snowfall-intensity-correlated underestimation indicates that the current Z–S relation needs to be recalibrated or new logic is needed altogether that considers microphysical properties of snowflakes (shape, size, and falling velocity) using polarimetric radar variables.

Recent work undertaken at NSSL to improve the estimation of SWE involves the comparison of S-band polarimetric radar observations and disdrometer measurements to link the microphysical properties of snow hydrometeors with integral polarimetric radar variables. To improve the accuracy of MRMS radar-based snow rates, future work will attempt to

1) stratify the data by degree of riming and by snowflake size from polarimetric radar signals and environmental variables to enable the selection of appropriate radar variables to estimate SWE and
2) develop a probabilistic SWE product accounting for radar sampling and environmental variables, as presented in Kirstetter et al. (2015a).

Acknowledgments. Part of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Financial support is also made available from NASA weather program (NNH13ZDA001N-WEATHER). Partial funding was also provided by NOAA/Office of Oceanic and Atmospheric Research under the NOAA–University of Oklahoma Cooperative Agreement NA11OAR4320072, U.S. Department of Commerce. Thank you to the University of Oklahoma (OU) and NOAA/National Severe Storms Laboratory (NOAA/NSSL) and MRMS team for providing the facilities, technical, and data support necessary to complete this work. The MRMS data used in this analysis are prior to MRMS, version 11, and are not representative of the current state of the MRMS science.

REFERENCES

Behrangi, A., Y. Tian, B. H. Lambrigtsen, and G. L. Stephens, 2014: What does *CloudSat* reveal about global land precipitation detection by other spaceborne sensors? *Water Resour. Res.*, **50**, 4893–4905, doi:10.1002/2013WR014566.

Bellon, A., G.-W. Lee, and I. Zawadzki, 2005: Error statistics of VPR corrections in stratiform precipitation. *J. Appl. Meteor.*, **44**, 998–1015, doi:10.1175/JAM2253.1.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, and J. Curtis, 2008: Physiographically sensitive mapping of temperature and precipitation across the conterminous United States. *Int. J. Climatol.*, **28**, 2031–2064, doi:10.1002/joc.1688.

Garrett, T., and S. Yuter, 2014: Observed influence of riming, temperature, and turbulence on the fallspeed of solid precipitation. *Geophys. Res. Lett.*, **41**, 6515–6522, doi:10.1002/2014GL061016.

Gray, D. M., and D. H. Male, 1981: *Handbook of Snow: Principles, Processes, Management and Use.* Pergamon Press, 776 pp.

Johnson, J. B., 2004: A theory of pressure sensor performance in snow. *Hydrol. Processes*, **18**, 53–64, doi:10.1002/hyp.1310.

——, and G. L. Schaefer, 2002: The influence of thermal, hydrologic, and snow deformation mechanisms on snow water equivalent pressure sensor accuracy. *Hydrol. Processes*, **16**, 3529–3542, doi:10.1002/hyp.1236.

Judson, A., and N. Doesken, 2000: Density of freshly fallen snow in the central Rocky Mountains. *Bull. Amer. Meteor. Soc.*, **81**, 1577–1587, doi:10.1175/1520-0477(2000)081<1577:DOFFSI>2.3.CO;2.

Kirstetter, P. E., and Coauthors, 2012: Toward a framework for systematic error modeling of spaceborne radar with NOAA/NSSL ground radar–based National Mosaic QPE. *J. Hydrometeor.*, **13**, 1285–1300, doi:10.1175/JHM-D-11-0139.1.

——, H. Andrieu, B. Boudevillain, and G. Delrieu, 2013: A physically based identification of vertical profiles of reflectivity from volume scan radar data. *J. Appl. Meteor. Climatol.*, **52**, 1645–1663, doi:10.1175/JAMC-D-12-0228.1.

——, J. J. Gourley, Y. Hong, J. Zhang, S. Moazamigoodarzi, C. Langston, and A. Arthur, 2015a: Probabilistic precipitation rate estimates with ground-based radar networks. *Water Resour. Res.*, **51**, 1422–1442, doi:10.1002/2014WR015672.

——, Y. Hong, J. J. Gourley, M. Schwaller, W. Petersen, and Q. Cao, 2015b: Impact of sub-pixel rainfall variability on spaceborne precipitation estimation: Evaluating the TRMM 2A25 product. *Quart. J. Roy. Meteor. Soc.*, **141**, 953–966, doi:10.1002/qj.2416.

Knight, C. A., and L. J. Miller, 1993: First radar echoes from cumulus clouds. *Bull. Amer. Meteor. Soc.*, **74**, 179–188, doi:10.1175/1520-0477(1993)074<0179:FREFCC>2.0.CO;2.

Kollias, P., W. Szyrmer, I. Zawadzki, and P. Joe, 2007b: Considerations for spaceborne 94 GHz radar observations of precipitation. *Geophys. Res. Lett.*, **34**, L21803, doi:10.1029/2007GL031536.

LaChapelle, E. R., 1962: The density distribution of new snow. Project F, Progress Rep. 2, USDA Forest Service, Wasatch National Forest, Alta Avalanche Study Center, Salt Lake City, UT, 13 pp.

Liu, G., and E.-K. Seo, 2013: Detecting snowfall over land by satellite high-frequency microwave observations: The lack of scattering signature and a statistical approach. *J. Geophys. Res. Atmos.*, **118**, 1376–1387, doi:10.1002/jgrd.50172.

Macklin, W. C., 1962: The density and structure of ice formed by accretion. *Quart. J. Roy. Meteor. Soc.*, **88**, 30–50, doi:10.1002/qj.49708837504.

Maddox, R., J. Zhang, J. J. Gourley, and K. Howard, 2002: Weather radar coverage over the contiguous United States. *Wea. Forecasting*, **17**, 927–934, doi:10.1175/1520-0434(2002)017<0927:WRCOTC>2.0.CO;2.

Martinaitis, S. M., S. B. Cocks, Y. Qi, B. T. Kaney, J. Zhang, and K. Howard, 2015: Understanding winter precipitation impacts on automated gauge observations within a real-time system. *J. Hydrometeor.*, **16**, 2345–2363, doi:10.1175/JHM-D-15-0020.1.

Mock, C. J., 1996: Climatic controls and spatial variations of precipitation in the western United States. *J. Climate*, **9**, 1111–1125, doi:10.1175/1520-0442(1996)009<1111:CCASVO>2.0.CO;2.

Munchak, S. J., and G. Skofronick-Jackson, 2013: Evaluation of precipitation detection over various surfaces from passive microwave imagers and sounders. *Atmos. Res.*, **131**, 81–94, doi:10.1016/j.atmosres.2012.10.011.

Rasmussen, R. M., and A. J. Heymsfield, 1985: A generalized form for impact velocities used to determine graupel accretional densities. *J. Atmos. Sci.*, **42**, 2275–2279, doi:10.1175/1520-0469(1985)042<2275:AGFFIV>2.0.CO;2.

——, and Coauthors, 2012: How well are we measuring snow? The NOAA/FAA/NCAR winter precipitation test bed. *Bull. Amer. Meteor. Soc.*, **93**, 811–829, doi:10.1175/BAMS-D-11-00052.1.

Serreze, M. C., M. P. Clark, R. L. Armstrong, D. A. McGinnis, and R. S. Pulwarty, 1999: Characteristics of the western United States snowpack from Snowpack Telemetry (SNOTEL) data. *Water Resour. Res.*, **35**, 2145–2160, doi:10.1029/1999WR900090.

Skofronick-Jackson, G., and Coauthors, 2015: Global Precipitation Measurement Cold Season Precipitation Experiment (GCPEX): For measurement's sake, let it snow. *Bull. Amer. Meteor. Soc.*, **96**, 1719–1741, doi:10.1175/BAMS-D-13-00262.1.

Thornton, P. E., S. W. Running, and M. A. White, 1997: Generating surfaces of daily meteorological variables over large regions of complex terrain. *J. Hydrol.*, **190**, 214–251, doi:10.1016/S0022-1694(96)03128-9.

Walsh, J., 1996: Snowfall and snow depth for Canada 1943–1982. National Snow and Ice Data Center, accessed 23 May 2017, doi:10.7265/N5TD9V75.

Wen, Y., A. Behrangi, B. Lambrigtsen, and P.-E. Kirstetter, 2016: Evaluation and uncertainty estimation of the latest radar and satellite snowfall products using SNOTEL measurements over mountainous regions in western United States. *Remote Sens.*, **8**, 904, doi:10.3390/rs8110904.

Zawadzki, I., W. Szyrmer, C. Bell, and F. Fabry, 2005: Modeling of the melting layer. Part III: The density effect. *J. Atmos. Sci.*, **62**, 3705–3723, doi:10.1175/JAS3563.1.

Zhang, J., and Coauthors, 2011: National Mosaic and Multi-Sensor QPE (NMQ) system: Description, results, and future plans. *Bull. Amer. Meteor. Soc.*, **92**, 1321–1338, doi:10.1175/2011BAMS-D-11-00047.1.

——, and Coauthors, 2016: Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimation: Initial operating capabilities. *Bull. Amer. Meteor. Soc.*, **97**, 621–638, doi:10.1175/BAMS-D-14-00174.1.