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• Original Paper •

Evaluation of the Antarctic Mesoscale Prediction System Based on Snow Accumulation Observations over the Ross Ice Shelf

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ABSTRACT

Recent snow height measurements (2008–15) from nine automatic weather stations (AWSs) on the Ross Ice Shelf are used to examine the synoptic and seasonal variability in snow accumulation, and also to evaluate the performance of the Antarctic Mesoscale Prediction System (AMPS) for precipitation. The number of snow accumulation events varies from one station to another between 2008 and 2015, thus demonstrating geographic dependence. The interannual variability in snow accumulation is too high to determine its seasonality based on the current AWS observations with limited time coverage. Comparison between the AMPS and AWS snow height measurements show that approximately 28% of the AWS events are reproduced by AMPS. Furthermore, there are significant correlations between AMPS and AWS coincident event sizes at five stations ($p < 0.05$). This finding suggests that AMPS has a certain ability to represent actual precipitation events.

Key words: snow accumulation measurements, precipitation evaluation, Ross Ice Shelf

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1. Introduction

Owing to its huge volume, the Antarctic Ice Sheet can potentially cause a global sea level rise of approximately 58.3 m, if it melts completely (IPCC, 2013). Thus, Antarctic climate change and ice mass variability have been major concerns in many recent studies (e.g., Rignot et al., 2011; Zwally and Giovinetto, 2011; Shepherd et al., 2012). Satellite radar altimetry, interferometry and gravimetry have greatly improved the estimation of Antarctic mass balance, especially ice loss to the ocean. However, there are still controversies regarding whether the ice sheet is gaining mass, is in equilibrium, or is losing mass. Rignot et al. (2011) and Shepherd et al. (2012) reported an acceleration of Antarctic mass loss since 1992 by means of the Gravity Recovery and Climate Experiment and InSAR radar altimetry satellites. In contrast, Zwally et al. (2015) showed that the mass gains of the Antarctic ice sheet exceeded the losses for the time spans 1992–2001 and 2003–08. To address this discrepancy, an accurate quantification of the temporal and spatial variability of the surface mass balance (SMB), which generally leads to mass gain, is required, because the interannual variability in Antarctic mass balance is mainly dependent on the SMB (Wouters et al., 2013). Despite many efforts undertaken to document the SMB, *in-situ* observations remain sparse and discontinuous, which hinders the evaluation of whether any significant variability in snow accumulation has occurred. As a result, Antarctic precipitation/SMB variations are usually directly or indirectly determined using reanalysis products, such as the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) (e.g., Monaghan et al., 2006a) and the ECMWF interim reanalysis (ERA-Interim) (Thomas and Bracegirdle, 2015); and regional climate models, such as the Fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model optimized for polar environments (Polar MM5) (Bromwich et al., 2001; Monaghan et al., 2006b), two versions of the Regional Atmospheric Climate Model (Ettema et al., 2009), the Antarctic Mesoscale Prediction System (AMPS) (Powers et al., 2003), the Modèle Atmosphérique Régional (Gallée et al., 2013), and Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Palerme et al., 2016). Due to the assimilation of changes in observation systems, the utilization of hydrological variables from reanalysis data, such as precipitation and evaporation, requires great caution (Trenberth et al., 2010; Bromwich et al., 2011a; Bosilovich et al., 2011). At present, regional climate models also only provide verifiable results. Therefore, it is crucial to investigate the performance of such models be-

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fore they are used for climate or meteorological diagnoses.

Based primarily on glaciological observations, many attempts have been made to assess the performance of atmospheric reanalysis products and regional climate models for precipitation at annual or longer timescales for different areas in Antarctica (e.g., Agosta et al., 2012; Sinisalo et al., 2013; Medley et al., 2013; Wang et al., 2015), and even for the whole ice sheet (Bromwich et al., 2011b; Wang et al., 2015). However, such evaluations have not assessed the ability of these models to capture the observed precipitation on much shorter timescales. Recently, a short (1–2 year) record from automatic weather stations (AWSs) was used to examine the representation of intra-annual variability in precipitation on the Antarctic Peninsula by ERA-40 and ERA-Interim (Thomas and Bracegirdle, 2009, 2015). Meanwhile, extreme precipitation events can be determined using acoustic depth gauge (ADG) measurements and compared with AMPS (Schlosser et al., 2010). Cohen and Dean (2013) compared ADG observations and reanalysis data, including ERA-Interim and NECP2, at synoptic time scales. To the best of our knowledge, however, few attempts have been made to assess the performance of regional climate models for Antarctic synoptic and intra-annual precipitation (e.g. Schlosser et al., 2010; Welker et al., 2014).

Many attempts have been made with respect to Antarctic precipitation and snow accumulation measurements, including ground-based determination and remote sensing. Ground-based determination involves stake measurements at single sites, ultrasonic sounders, snow pits and ice cores, and ground-penetrating radar (Eisen et al., 2008). Stake measurement is a traditional and simple glaciological method for SMB determination, and is widely used in Antarctica (Kameda et al., 2008). It is accurate for a single site, but constrained by long-term observations and high logistical costs in the extreme polar environment. Snow pits and ice cores are first used to identify reliable dating markers, and then to determine the snow accumulation combined with snow density. Snow pits and ice cores provide the only available data for long-term snow accumulation, but these data are not available at synoptic time scales. Limited by their 2–3 cm operational accuracy, ultrasonic sounders are generally less effective at detecting individual snowfall events on the dry East Antarctic Plateau. However, due to their automatic real-time monitoring, ultrasonic sounders have the advantage of producing data that can be used for examining synoptic and intra-annual variability, as well as seasonal cycles, of snow accumulation. Precipitation, which contributes greatly to SMB, was measured by Schlosser et al. (2016) using a wooden platform at a height of 1 m above the snow surface to avoid the influence of low drifting snow (Schlosser et al., 2016). However, precipitation measurements are unable to quantify errors, and the measurements have some interruptions. Cloudsat, i.e., the first spaceborne radar to provide large-scale Antarctic precipitation observations, has been used to estimate the spatial patterns of snow accumulation simulated by ERA-Interim and CMIP5 models (Boening et al., 2012; Palerme et al., 2014, 2016). However, its coarse spatial and temporal resolution limit its application to specific areas and the synoptic time scale, and data missing during the night since April 2011 is also a problem. Although ground-based remote-sensing instruments have been used to detect cloud and precipitation properties (Gorodetskaya et al., 2015), AWS measurements are still necessary to quantify SMB components. Despite the advantages of satellite products, they are not suitable for the determination of precipitation events on the synoptic time scale.

ADG measurements at the AWSs over the Ross Ice Shelf record snow height changes at a very high temporal resolution (10 min sampling). This provides an important record of snow accumulation, which can be used to determine its variability and evaluate the simulation accuracy by regional climate models on synoptic and seasonal time scales.

2. Study area

The Ross Ice Shelf—the largest ice shelf of Antarctica—is located between the West Antarctic Ice Sheet and the Transantarctic Mountains and is adjacent to the Ross Sea (Fig. 1). It is characterized by low pressure, high radiation, and low precipitation in the coastal regions, and by increased inland precipitation because of topographic lift. Changes in the mass balance of the ice shelf play an important role in sea level rise, ocean stratification, and bottom water formation. Satellite-based observation shows a zone of surface lowering,

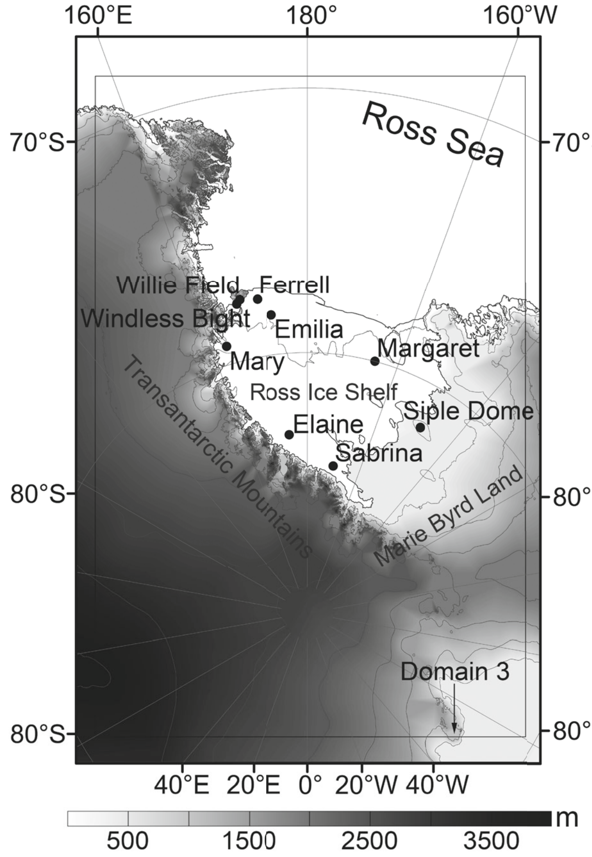

Fig. 1. Ross Ice Shelf and locations of AWSs.

quantified as reaching 0.65 m yr^{-1} during 2003–08 (Pritchard et al., 2012).

3. Data and methods

3.1. *AMPS*

AMPS is an experimental and real-time mesoscale modeling system that was generated by the NCAR and the Byrd Polar Research Center of The Ohio State University. The main goals of this system are to provide synoptic and mesoscale forecasts to serve flight forecasters at McMurdo Station to support Antarctic science and operations and the United States Antarctic Program, improve the model physical parameterizations for Antarctica, and provide qualitative and quantitative system verification (Powers et al., 2012). Starting in 2000, AMPS produced forecasts using Polar MM5 (Bromwich et al., 2001). Since 2005, the polar-optimized version of the Weather Research and Forecasting Model (Polar WRF) has become the base model of AMPS (Skamarock et al., 2009). Polar WRF is estimated to have similar or better performance compared to Polar MM5 (Bromwich et al., 2013). The current AMPS forecasts by means of Polar WRF are conducted twice daily, in either five or six domains, varying over different time periods. The horizontal resolution of the model grid ranges from 20 km or 10 km for the Antarctic Ice Sheet to 3 km or 1.1 km over McMurdo. This study utilizes three-hourly AMPS precipitation data in domain 3 (Fig. 1), with a horizontal resolution of 5 km between November 2008 and December 2012, and 3 km since 2013. The daily precipitation is the sum of the 12–36 h forecast (rather than the 0–24 h forecast), which allows moist process spin-up to occur (Bromwich et al., 2005; Schlosser et al., 2008).

3.2. *AWS data*

Snow height is measured at 10-min intervals by the Campbell Scientific SR50 ADG installed at nine AWSs on the Ross Ice Shelf, as shown in Fig. 1. These measurements cover January 2008 to June 2015, but the record lengths vary from one station to another. Table 1 summarizes the information of each station, including its location, length of record, and elevation. Anomalous values in the sensor can occur due to disturbance from high surface wind (>18 m s^{-1}), blowing snow (Brazenec and Doesken, 2005), extremely low temperatures (<−35°C), and frost on the sensor (Fountain et al., 2010). To keep the sensor at a distance of 1–2 m from the snow surface, the sensor must be artificially reset, which may result in discontinuities in the accumulation data. In addition, the quality of data is affected by ice flowing over the ice shelf where the AWS sites are installed, and data transmission by satellites (Lazzara et al., 2012). More detailed information on the AWSs is available on the University of Wisconsin Antarctic Meteorological Research Center website (http://amrc.ssec.wisc.edu).

3.3. *AWS data quality control*

To better determine the temporal variability in snow accumulation and assess the performance of AMPS, it is necessary to remove the erroneous and anomalous snow accumulation measurements. First, we exclude obviously erroneous values that are considered outside the initial and final accumulations. Then, consecutive measurements with the same values that exhibit obvious observation or transmitting error are removed. We also remove the data outliers as defined by Fountain et al. (2010) and Cohen and Dean (2013), i.e., those outside one standard deviation of each mean daily measurement. Finally, 4.41%–7.93% of the anomalous ADG records at the nine AWSs are omitted (Table 1). The quality-controlled ADG records are averaged to three-hourly data to compare with the AMPS data.

3.4. *Snow accumulation event determination*

Following Fountain et al. (2010) and Cohen and Dean (2013), we determine snow accumulation events for the daily ADG records using the threshold value of 5 mm snow d^{-1}. The threshold value of the daily AMPS precipitation data is 0.5 mm water equivalent (w. e.) d^{-1}, assuming a snow density of 350 kg m^{-3} (Cohen and Dean, 2013). In addition to applying the threshold values (5 mm snow d^{-1} for AWS and 0.5 mm w. e. d^{-1} for AMPS), only snow accumulation or precipitation lasting more than six hours is considered an accumulation/precipitation event (Cohen and Dean, 2013). If the surface snow density is approximately 350 kg m^{-3}, 7 m s^{-1} is considered the threshold of wind speed to cause drifting snow (Lenaerts et al., 2010; 2012). Accumulation events caused by drifting snow lasting more than six hours are particularly rare. Thus, a period of six hours is chosen to minimize the impact of drifting snow on the determination of the

Table 1. AWS locations, lengths of records, elevations and elimination rates.

Station	Location	AWS Data	Data length (yr)	Elevation (m)	Elimination rate (%)
Margaret	80.000°S, 165.000°W	Nov 2008–Jun 2015	6.7	67	4.54
Sabrina	84.247°S, 170.068°W	Feb 2009–Jun 2015	5.7	87.6	4.41
Emilia	78.502°S, 173.121°E	Nov 2011–Jun 2015	3.7	52	4.71
Ferrell	77.833°S, 170.819°E	Feb 2011–Jun 2015	3.2	45	4.91
Windless Bight	77.725°S, 167.687°E	Jan 2008–Jun 2015	5.7	40	6.45
Mary	79.305°S, 162.985°E	Jan 2008–Dec 2011	4.0	58	7.93
Elaine	83.094°S, 174.285°E	Jan 2010–Jun 2015	5.5	58	4.84
Siple Dome	81.656°S, 148.773°W	Jan 2012–Jun 2015	3.3	667.6	7.07
Willie Field	77.867°S, 166.947°E	Feb 2009–Oct 2010	1.8	12	4.46

accumulation events. Additionally, if the precipitation events are within 24 hours of an ADG event, we consider the event to be a coincident event.

4. Results

4.1. *Time series of snow heights from ADG records*

Figure 2 presents a time series of cumulative daily snow height changes from 2008 to 2015 (time coverage varies from one station to another). Three of the nine stations (Windless Bight, Ferrell and Emilia) have data gaps from the sensor reset to remain 1 or 2 m from the snow surface or from data transmission problems. We cannot determine how much the snow height changed in the missing records and thus assume that the snow height has no changes during this period, which does not influence the snow accumulation tendencies. At each station, accumulation outweighs ablation, which leads to positive height changes.

Snow height changes are stepped and episodic and are mainly dependent on precipitation, but there is still a mass of large accumulation events in the measurements. At three stations (Siple Dome, Emilia, Mary), snow height changes fluctuate highly and have obvious negative processes—as in November 2012, November 2013 and March 2015 for Siple Dome; December 2012 and October, November and December 2013 for Emilia; March 2008, December 2009 and July 2011 for Mary—which suggests that wind erosion, densifi-

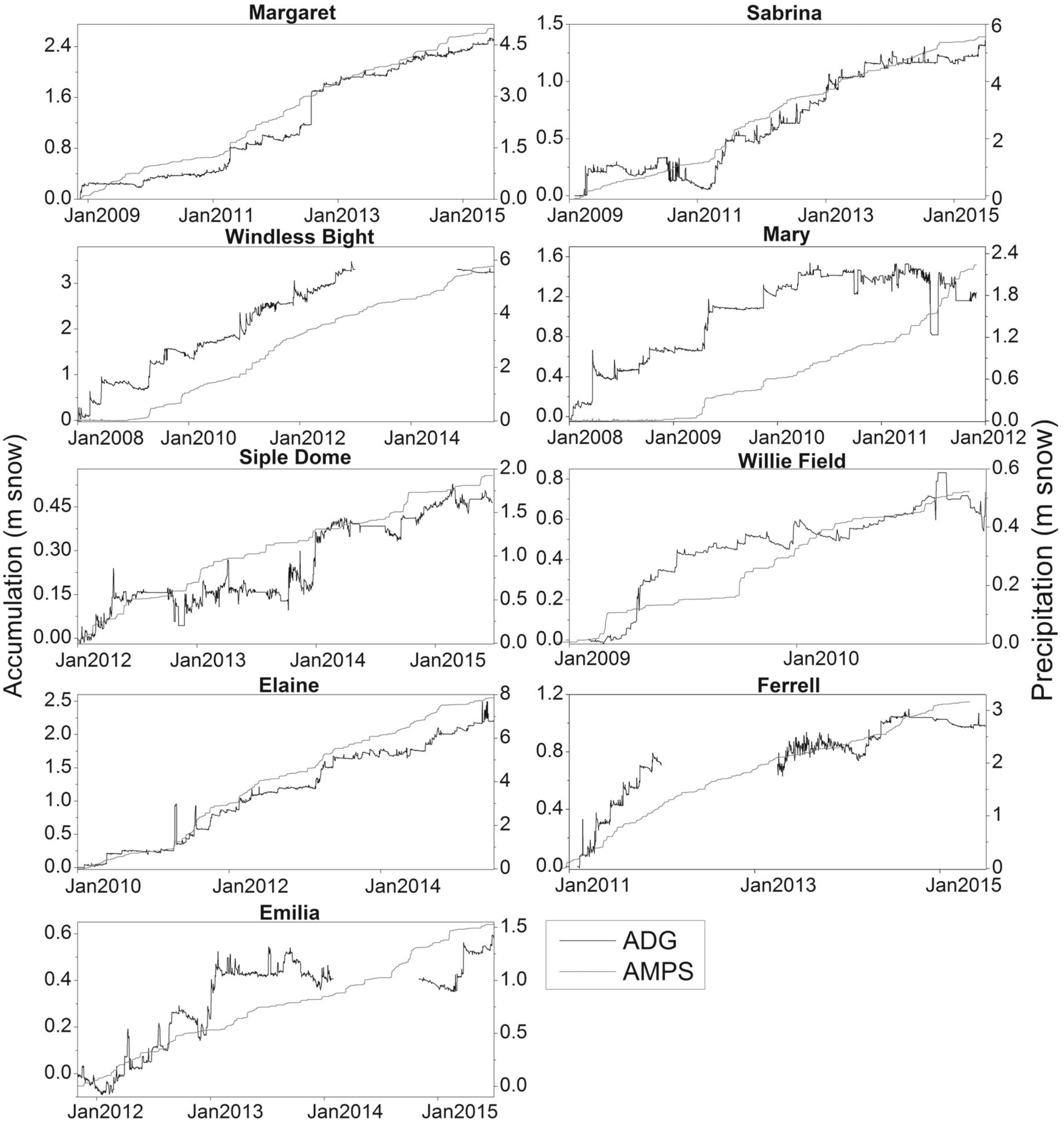

Fig. 2. Daily ADG snow accumulation from AWSs and AMPS precipitation from the start date of AWS observation to 2015. ADG accumulation is shown on the left-hand axes (m snow), and AMPS is on the right-hand axes (m snow).

cation and sublimation have greater influences on snow accumulation changes at these stations. Stations Margaret and Elaine show the smoothest accumulation variation and the least positive processes of surface height compared with other stations during the same periods. At Mary, Margaret and Elaine, low accumulation, i.e., close to zero, lasts several months. The large accumulation events appear in each AWS ADG record, and the snow height changes coincide with relatively high temperatures, wind and specific humidity (Reijmer and van den Brokek, 2003). Although the cumulative monthly snow height changes are smoother than daily snow height, large fluctuations are still distinct (Fig. 3): for instance, in September and December 2012 and April 2015 for Emilia; February 2008 and March and April 2009 for Mary; October 2012 and September 2013 for Siple Dome; February 2009 for Sabrina and Windless Bight; and February 2013 and September 2014 for Elaine. For all AWSs, the monthly snow height changes are consistent with daily snow height changes.

4.2. *Synoptic variability of snow accumulation from ADG records*

Figure 4 shows a close-up of four days in the ADG measurements at a three-hourly resolution, which represents the characteristics of typical snow accumulation events in a running day for the majority of stations. The duration of positive

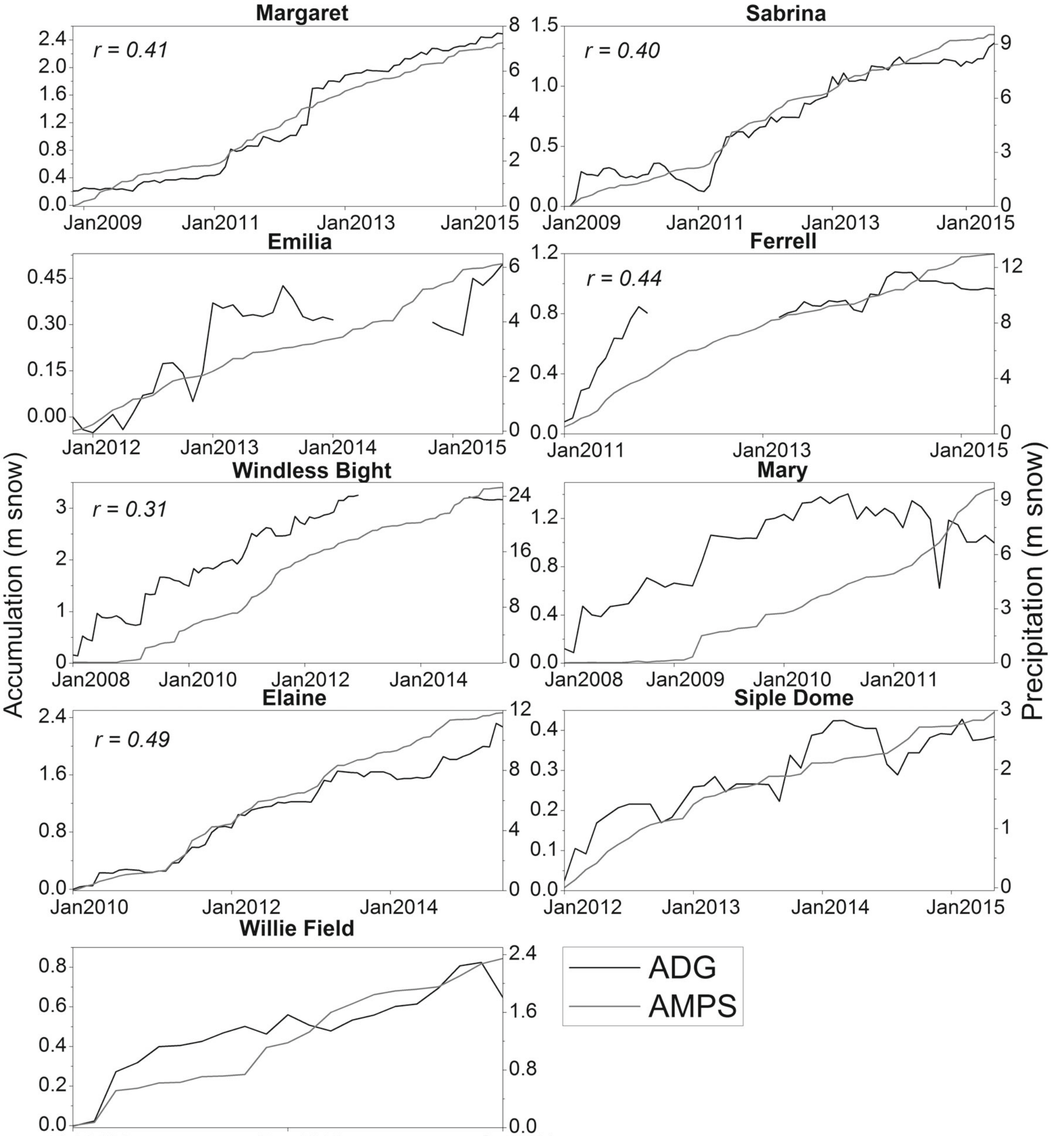

Fig. 3. Monthly accumulation at nine AWSs and corresponding AMPS precipitation from the start date of AWS observation to 2015. ADG accumulation is shown on the left-hand axes (m snow), and AMPS is on the right-hand axes (m snow).

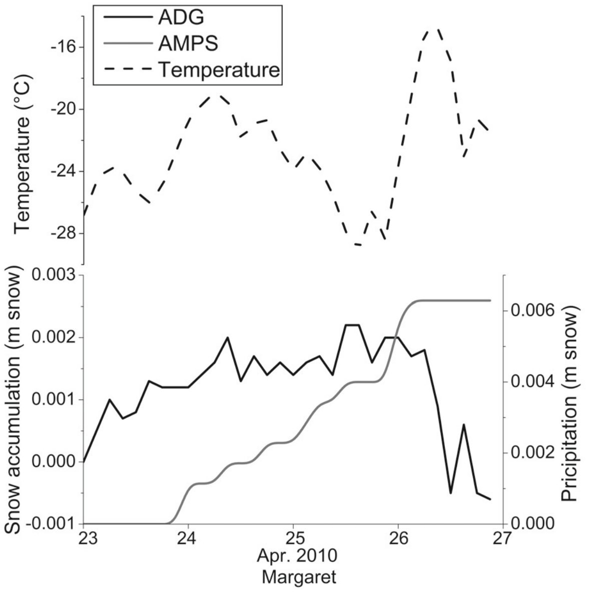

Fig. 4. The different characteristics of coincident events (defined as >5 mm snow d^{-1} and >0.5 mm w. e. d^{-1}) in April 2010. Snow accumulation is on the left *y*-axis, and precipitation is on the right *y*-axis (note the different axis scales).

processes of snow accumulation are different and inconstant. There are many snow height change events over short-term periods that are mainly caused by snowdrift and cannot be defined as snow accumulation events. For example, there is only one accumulation event for each day from the 23rd to 25th. However, on the 25th, there are three instances of positive snow height changes, only one of which lasts more than six hours. The obvious short-term decreases in snow heights (i.e., a few hours) at all stations illustrate the important effects of drifting snow on ADG measurements.

Table 2 shows the number of snow accumulation events at each station. The number of snow accumulation events varies from 72 to 419, with an average value of 257. In general, the stations close to the edge of the ice shelf have more events than inland stations. Despite the limited coverage of ADG records, the Windless Bight station has the largest number of total accumulation events. Over the observational period, the number of annual accumulation events at Sabrina, Mary and Elaine clearly increases, whereas Margaret, Emilia and Windless Bight show a significant decrease of approximately 10%. Possibly caused by large snowfall, there is a more than 70% increase in annual events at Ferrell station since 2012.

4.3. *Seasonal variability of snow accumulation from ADG records*

The seasonality of snow accumulation is important for the SMB estimation and dating of ice core records. To determine the annual cycle of snow accumulation, the monthly averaged snow heights are calculated using ADG data between the AWS start time and 2015 (Fig. 5). As Fig. 5 shows, the large error (standard deviation of the averages) reveals the high interannual variation in snow accumulation. Probably due to the high interannual variability and limited temporal coverage of the data (less than seven years), there is no clear seasonality of snow accumulation at all AWS stations. The relatively high snow accumulation occurs in June for Siple Dome and in the autumn months (April or May) for Sabrina, Willie Field, and Elaine. Margaret and Windless Bight show relatively small amounts of snow accumulation in September and December, respectively.

4.4. *Synoptic and seasonal variability comparison between ADG and AMPS*

The daily accumulated snow height from ADG with the corresponding precipitation from AMPS increase synchronously step by step (Fig. 2). The decline in the ADG records can be clearly observed and results from post-disposition processes such as wind-driven sublimation, erosion, snow ablation or compaction, whereas only positive changes occur in AMPS precipitation due to the exclusion of these processes in AMPS. Despite the negative accumulation process, AMPS precipitation is highly consistent with the overall increasing trend in ADG snow heights. We also compare the monthly ADG recorded snow height and AMPS precipitation (Fig. 3). The overall increasing trend is com-

Table 2. Number of events and coincident events for ADGs and AMPS.

	Number of events (to Dec 2012)				Number of events (to Jun 2015)			
Station name	ADG	AMPS	Coincident	Captured (%)	ADG	AMPS	Coincident	Captured (%)
Margaret	268	192	38	14.2	302	447	76	25.2
Sabrina	170	226	63	37.1	266	355	85	32.0
Emilia	73	86	15	20.5	187	204	35	18.7
Ferrell	72	92	25	34.7	268	277	72	26.0
Windless Bight	401	417	154	38.4	419	446	154	36.8
Mary*	257	287	71	27.6	257	287	71	27.6
Elaine	152	225	52	34.2	292	402	100	34.2
Siple Dome	62	42	14	22.6	252	164	44	17.5
Willie Field*	73	82	17	23.3	73	82	17	23.3

*End date of observations is Dec 2012.

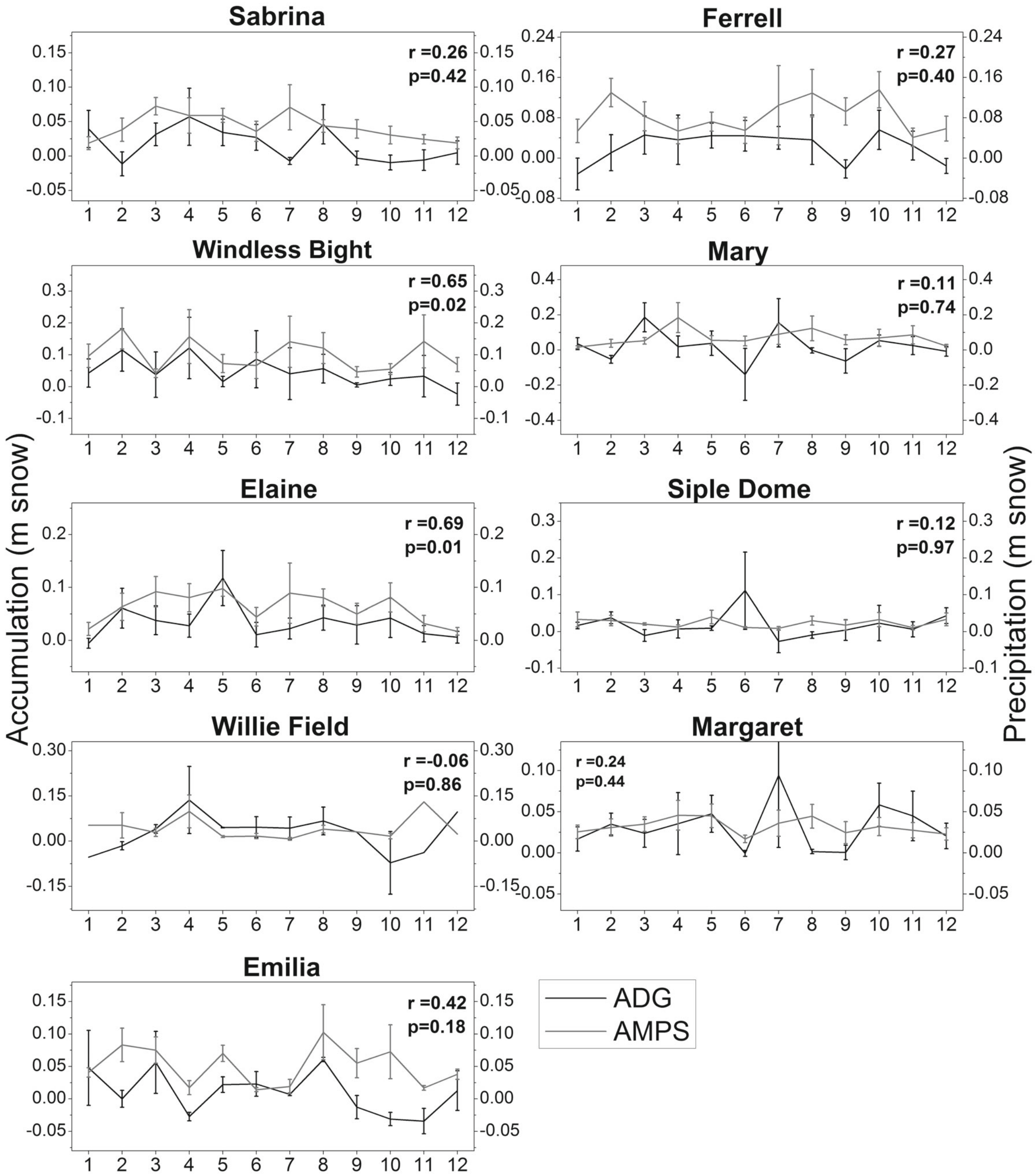

Fig. 5. Seasonal cycle of ADG snow accumulation and AMPS precipitation at each station. The left hand axes show snow accumulation (m snow), and the right hand axes show precipitation (m snow). The error bars represent standard deviation of the means.

mon for all of the AWSs. At five of nine stations (Margaret, Sabrina, Ferrell, Windless Bight, Elaine), the AMPS simulation is significantly correlated with the ADG observations ($p < 0.05$), with correlation coefficients ranging from 0.31 to 0.49. This result suggests AMPS can to some extent represent the intra-annual variability in snow accumulation observed by AWSs. Furthermore, we compare the daily and monthly AMPS precipitation with AWS snow accumulation with no negative values caused by ablation and densification, as Thomas and Bracegirdle (2009) did. The daily accumulation variability shows significant correlations with AMPS for all stations except Siple Dome. The correlation coefficients even reach 0.45 ($p < 0.01$) at Windless Bight, but those of the other stations are less than 0.28. Monthly AWS accumulation is significantly correlated with AMPS precipitation at four stations (Willie Field, Sabrina, Windless Bight and Elaine), with correlation coefficients ranging from 0.45 to 0.81.

To further examine the performance of AMPS for precipitation, we compare the stacked snow height records from all AWSs with precipitation averaged by the AMPS grids containing observations, and AMPS over the entire range of the Ross Ice Shelf, respectively (Fig. 6). The seasonality of the

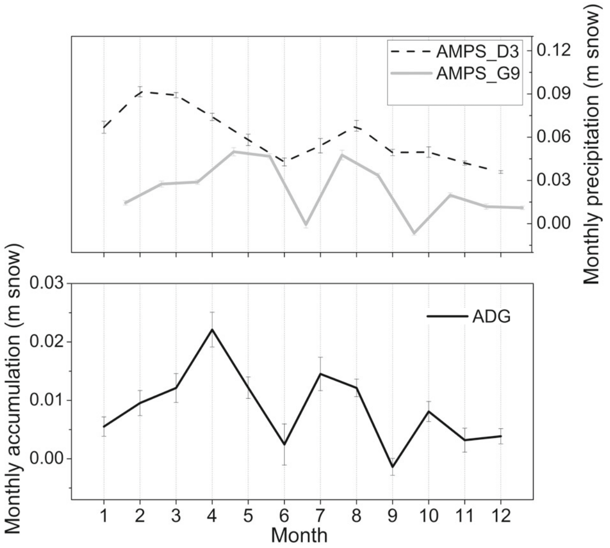

Fig. 6. Seasonal variations of the stacked ADG and AMPS for grid cell containing measurements (AMPS_G9) and the entire range of the Ross Ice Shelf (AMPS_D3). The error bars represent standard deviation of the means.

AMPS grid cells containing measurements agree well with snow height observations, with the minimum in September and the maximum in April (Fig. 6). This shows that precipitation seasonality is reasonably well reproduced by AMPS. For the entire ice shelf, AMPS precipitation reaches a maximum in February, and the minimum occurs in December, which is not in accordance with the stacked ADG record. This can be explained by the limited representation of the current nine AWSs for the whole ice shelf. Clearly, increasing the spatial density of field measurements is very helpful.

Table 2 presents the events (>5 mm d^{-1} for AWS and >0.5 mm d^{-1} for AMPS), coincident events and percentage of coincident events captured by the ADG and AMPS datasets. All stations except Siple Dome produce more precipitation events than accumulation events. A greater amount of events at Margaret, Sabrina and Elaine occurs in AMPS than in the ADG observations, whereas at other stations the number of events is similar. The coincident event capture rates are higher than 30% at three stations (Sabrina, Windless Bight, and Elaine) but are less than 20% at Emilia and Siple Dome. One possible reason is that snow accumulation is a more complicated process than precipitation and that the resulting coincident events have different durations (Fig. 4). Controlled by large post-disposition processes, such as wind-driven disposition/erosion and sublimation, snow compaction, meltwater, and surface sublimation, snow accumulation records are continuously changing. However, there is no precipitation at many moments or even for many days, and thus many zero values occur in AMPS. The difference can be further demonstrated by accumulation/precipitation events and coincident events in the ADG and AMPS records within four days for station Margaret (Fig. 4). A snow accumulation event occurs on the 23rd, but no precipitation event occurs. The opposite occurs on the 26th. Coincident events occur on the 24th and 25th, and the duration of the AMPS precipitation event (20 hours) is longer than the ADG accumulation event (only 6 hours). To further determine the relationship at the synoptic time scale between AMPS precipitation and ADG observations, we diagnose the correlation of coincident event size in the two databases (AMPS and ADG records) (Fig. 7). Three stations (Ferrell, Siple Dome and Sabrina) exhibit no robust relationships with AMPS; however, there are significant correlations at the other six stations ($p < 0.01$), with r values ranging from 0.27 to 0.52.

Our comparison between in-situ observations and AMPS may be influenced by the difference between the observation scale and model grid resolution (particularly with respect to topography). To minimize this impact, we only use stations at which the weather is not strongly influenced by local features, such as topography. The terrain in the AMPS grids containing in-situ measurement is very flat (Fig. 1), thus suggesting the low impact of topography on precipitation in the AMPS grid scale. In addition, Frezzotti et al. (2004) reported that snow precipitation is fairly homogeneous at a spatial scale of hundreds of km^2 over Antarctica. Of course, even over flat topography, small scale features in atmospheric circulation, particularly in precipitation, have some impact on snow accumulation.

The complex influences of wind on ADG snow accumulation makes the comparison of coincident events between ADG and reanalysis difficult. Figure 8 shows a comparison of the AMPS precipitation events determined by only daily precipitation exceeding 0.05 mm w.e., with the corresponding daily wind speed and ADG snow accumulation from AWSs at Margaret, Sabrina, Elaine and Mary from 2008 to 2013. The number of AMPS precipitation events at Margaret, Sabrina, Elaine and Mary is 213, 250, 278, and 252, respectively. It can be clearly observed from Fig. 8 that parts of AMPS precipitation events occur, whereas negative ADG accumulation and high wind speed (>7 m s^{-1}) occur. Such events account for 19% of the total number of precipitation events at Elaine, 14% at Mary, and 10% at Margaret and Sabrina. This finding suggests that the impact of wind is possibly so strong that precipitation is not accumulated at the AWSs. Thus, such cases should be removed when comparing AMPS precipitation events with ADG accumulation events. In our comparison, we use the threshold of 5 mm d^{-1} for ADG accumulation events to remove the impact of wind-driven ablation. However, wind-driven accumulation also affects our comparison. We further compare accumulation events using the method from Fountain et al. (2010) and Cohen and Dean (2013), as described above, with the corresponding wind speed from the AWSs at the four stations (Margaret, Sabrina, Elaine and Mary). Approximately 10% of accumulation events lasting more than six hours occur with high wind speeds (>7 m s^{-1}). Therefore, despite the complex effects of wind-driven process on snow accumulation, the methodology of Fountain et al. (2010) and Cohen and Dean (2013) for the identification of accumulation events within the ADG records can be used to compare with AMPS precipitation events.

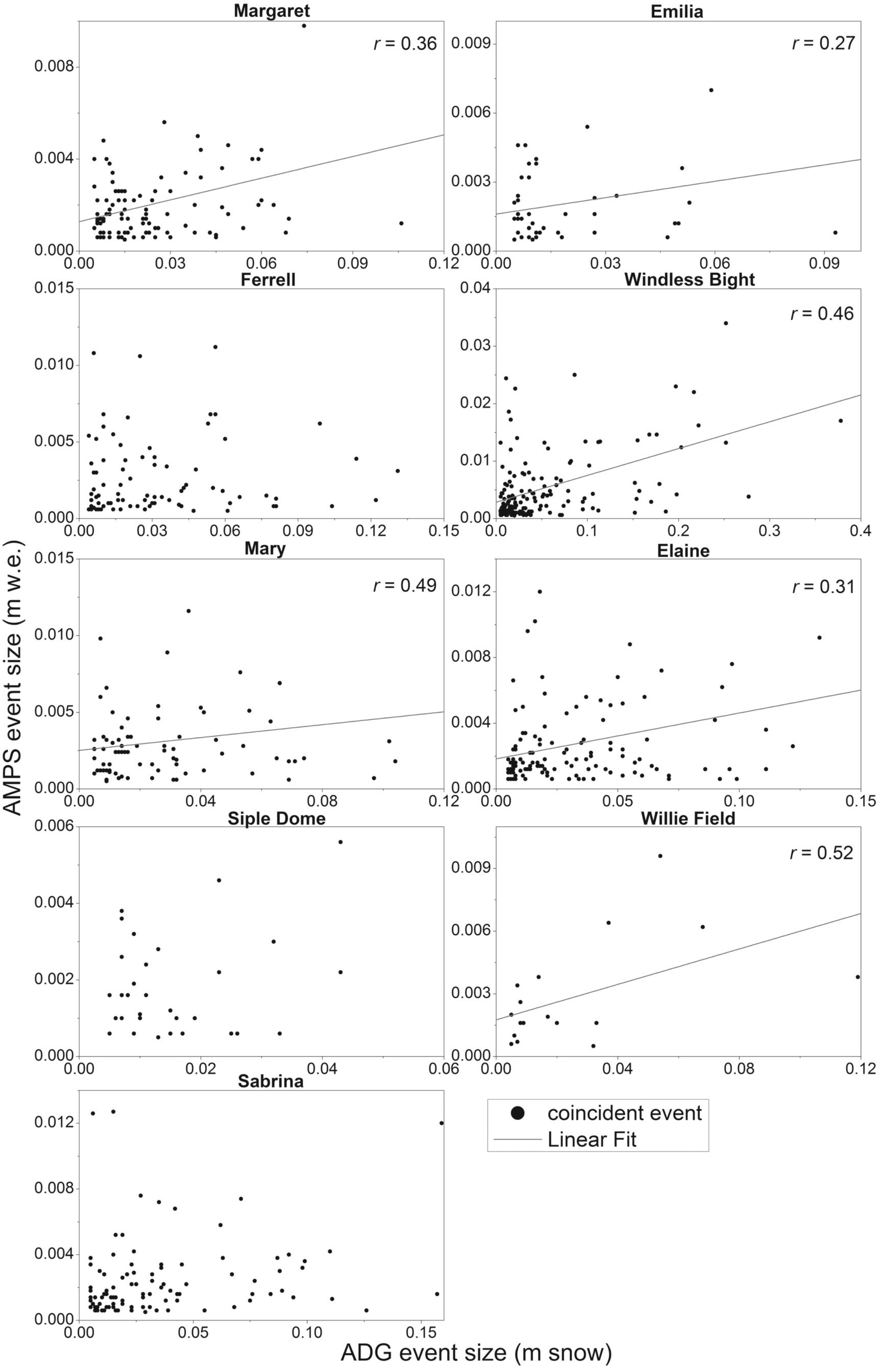

Fig. 7. Different event sizes of all coincident events. ADG event sizes are measured as m snow; AMPS event sizes are in units of m w. e.. Regression lines and *r* values are shown for correlations at the 99% significance level.

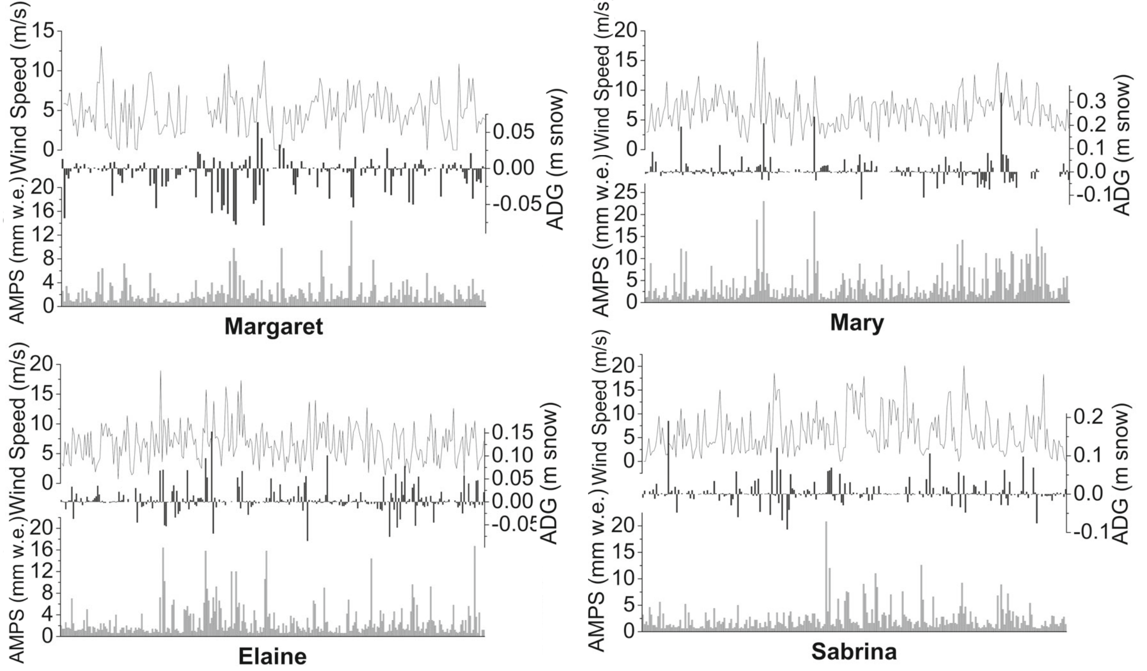

Fig. 8. Comparison of AMPS precipitation events determined by the daily precipitation greater than 0.05 m w. e. with the corresponding ADG snow accumulation and wind speed from the four AWSs of Margaret, Sabrina, Mary and Elaine, with varying time periods (Margaret: November 2008 to December 2013; Sabrina: February 2009 to December 2013; Mary: January 2008 to December 2011; Elaine: January 2010 to December 2013).

5. Conclusions

ADGs installed at nine AWSs over the Ross Ice Shelf provide ground-based snow accumulation measurements with high temporal resolution, which are very useful for examining synoptic and intra-annual variability in snow accumulation between 2008 and 2015. The number of snow accumulation events varies between 72 (Willie Field station) and 419 (Windless Bight station), thus showing geographic dependence. The temporal variability in snow height changes in the ADG records is strongly affected by many processes, such as precipitation, snowdrift, ablation, sublimation and compaction. Therefore, we cannot determine the relative contribution of each of these factors to snow depth change. In addition, no conclusion can be drawn with regard to the seasonal cycle of snow accumulation over the ice shelf based on limited AWS observations, probably due to the high interannual noise and surface sublimation.

Despite the complication of snow height changes, ADG records provide some insight into AMPS precipitation on synoptic and intra-annual time scales. Comparison of events in the two datasets based on an event determination method generated by Fountain et al. (2010) shows approximately 28% of ADG events are captured by AMPS. Furthermore, at more than half of the AWSs, there are significant correlations in the coincident event sizes determined by ADG and AMPS, which suggests that AMPS effectively captures the precipitation events. Additionally, the significant correlations among the monthly ADG records at five stations with AMPS precipitation reveal the fairly reasonable representation of precipitation by AMPS.

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REFERENCES

Agosta, C., V. Favier V, C. Genthon, H. Gallée, G. Krinner, J. T. M. Lenaerts, and M. R. van den Broeke, 2012: A 40-year accumulation dataset for Adelie Land, Antarctica and its application for model validation. *Climate Dyn.*, **38**(1–2), 75–86.

Boening, C., M. Lebsock, F. Landerer, and G. Stephens, 2012: Snowfall-driven mass change on the East Antarctic ice sheet. *Geophys. Res. Lett.*, **39**, L21501.

Bosilovich, M. G., F. R. Robertson, and J. Y. Chen, 2011: Global energy and water budgets in MERRA. *J. Climate*, **24**(22), 5721–5739.

Brazenec, W. A., and N. J. Doesken, 2005: An evaluation of two ultrasonic snow depth sensors for potential use at automated surface weather observing sites. *Proc. 13th Symp. on Meteorological Observations and Instrumentation*, American Meteorological Society.

Bromwich, D. H., J. J. Cassano, T. Kleinet, G. Heinemann, K. M. Hines, K. Steffen, and J. E. Box, 2001: Mesoscale modeling of katabatic winds over Greenland with the Polar MM5. *Mon. Wea. Rev.*, **129**(9), 2290–2309.

Bromwich, D. H., A. J. Monaghan, K. W. Manning, and J. G. Powers, 2005: Real-time forecasting for the Antarctic: An evaluation of the Antarctic Mesoscale Prediction System (AMPS). *Mon. Wea. Rev.*, **133**, 579–603.

Bromwich, D. H., D. F. Steinhoff, I. Simmonds, K. Keay, and R. L. Fogt, 2011a: Climatological aspects of cyclogenesis near Adélie Land, Antarctica. *Tellus A*, **63**(5), 921–938, http://dx.doi.org/10.1111/j.1600-0870.2011.00537.x.

Bromwich, D. H., J. P. Nicolas, and A. J. Monaghan, 2011b: An assessment of precipitation changes over Antarctica and the Southern Ocean since 1989 in contemporary global reanalyses. *J. Climate*, **24**(16), 4189–4209.

Bromwich, D. H., F. O. Otieno, K. M. Hines, K. W. Manning, and E. Shilo, 2013: Comprehensive evaluation of polar weather research and forecasting model performance in the Antarctic. *J. Geophys. Res. Atmos.*, **118**(2), 274–292.

Cohen, L., and S. Dean, 2013: Snow on the Ross Ice Shelf: Comparison of reanalyses and observations from automatic weather stations. *The Cryosphere*, **7**(5), 1399–1410.

Eisen, O., and Coauthors, 2008: Ground-based measurements of spatial and temporal variability of snow accumulation in east Antarctica. *Rev. Geophys.*, **46**(2), RG2001-1–RG2001-39.

Ettema, J., M. R. van den Broeke, E. van Meijgaard, W. Jan van de Berg, J. L. Bamber, J. E. Box, and R. C. Bales, 2009: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling. *Geophys. Res. Lett.*, **36**(12), L12501.

Fountain, A. G., T. H. Nylen, A. Monaghan, H. J. Basagic, and D. Bromwich, 2010: Snow in the McMurdo Dry Valleys, Antarctica. *International Journal of Climatology*, **30**(5), 633–642.

Frezzotti, M., and Coauthors, 2004: New estimations of precipitation and surface sublimation in East Antarctica from snow accumulation measurements. *Climate Dyn.*, **23**, 803–813.

Gallée, H., A. Trouvilliez, C. Amory, C. Agosta, C. Genthon, X. Fettweis, V. Favier, and F. Naaim-Bouvet, 2013: Simulations of blowing snow over Antarctica. International Snow Science Workshop, Grenoble Chamonix Mont-Blanc, Grenoble, Chamonix, International Snow Science Workshop, 120–125.

Gorodetskaya, I. V., and Coauthors, 2015: Cloud and precipitation properties from ground-based remote-sensing instruments in East Antarctica. *The Cryosphere*, **9**, 285–304.

Kameda, T., H. Motoyama, S. Fujita, and S. Takahashi, 2008: Temporal and spatial variability of surface mass balance at Dome Fuji, East Antarctica, by the stake method from 1995 to 2006. *J. Glaciol.*, **54**(184), 107–116.

Lazzara, M. A., G. A. Weidner, L. M. Keller, J. E. Thom, and J. J. Cassano, 2012: Antarctic Automatic Weather Station Program: 30 years of polar observations. *Bull. Amer. Meteor. Soc.*, **93**(10), 1519–1537.

Lenaerts, J. T. M., M. R. van den Broeke, S. J. Déry, G. König-Langlo, J. Ettema, and P. K. Munneke, 2010: Modelling snowdrift sublimation on an Antarctic ice shelf. *The Cryosphere*, **4**, 179–190.

Lenaerts, J. T. M., M. R. van den Broeke, S. J. Déry, E. van Meijgaard, W. J. van de Berg, S. P. Palm, and J. S. Rodrigo, 2012: Modeling drifting snow in Antarctica with a regional climate model: 1. Methods and model evaluation. *J. Geophys. Res.*, **117**, D05108.

Medley, B., and Coauthors, 2013: Airborne-radar and ice-core observations of annual snow accumulation over Thwaites Glacier, West Antarctica confirm the spatiotemporal variability of global and regional atmospheric models. *Geophys. Res. Lett.*, **40**(14), 3649–3654.

Monaghan, A. J., and Coauthors, 2006a: Insignificant change in Antarctic snowfall since the International Geophysical Year. *Science*, **313**(5788), 827–831.

Monaghan, A. J., D. H. Bromwich, and S. H. Wang, 2006b: Recent trends in Antarctic snow accumulation from Polar MM5 simulations. *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences*, **364**(1844), 1683–1708.

Palerme, C., J. E. Kay, C. Genthon, T. L'Ecuyer, N. B. Wood, and C. Claud, 2014: How much snow falls on the Antarctic ice sheet? *The Cryosphere*, **8**(4), 1577–1587.

Palerme, C., C. Genthon, C. Claud, J. E. Kay, N. B. Wood, T. L'Ecuyer, 2016: Evaluation of current and projected Antarctic precipitation in CMIP5 models. *Climate Dyn.*, 1–15, doi: 10.1007/s00382-016-3071-1.

Powers, J. G., A. J. Monaghan, A. M. Cayette, D. H. Bromwich, Y.-H. Kuo, and K. W. Manning, 2003: Real-time mesoscale modeling over Antarctica: The Antarctic Mesoscale Prediction System. *Bull. Amer. Meteor. Soc.*, **84**(11), 1533–1545.

Powers, J. G., K. W. Manning, D. H. Bromwich, J. J. Cassano, and A. M. Cayette, 2012: A decade of Antarctic science support through AMPS. *Bull. Amer. Meteor. Soc.*, **93**, 1699–1712.

Pritchard, H. D., S. R. M. Ligtenberg, H. A. Fricker, D. G. Vaughan, M. R. van den Broeke, and L. Padman, 2012: Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature*, **484**(7395), 502–505.

Reijmer, C. H., and M. R. van den Brokek, 2003: Temporal and spatial variability of the surface mass balance in Dronning Maud Land, Antarctica, as derived from automatic weather stations. *J. Glaciol.*, **49**(167), 512–520.

Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. T. M. Lenaerts, 2011: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.*, **38**(5), L05503.

Schlosser, E., M. G. Duda, J. G. Powers, and K. W. Manning, 2008: Precipitation regime of Dronning Maud Land, Antarctica, derived from Antarctic Mesoscale Prediction System (AMPS) archive data. *J. Geophys. Res.*, **113**, D24108.

Schlosser, E., J. G. Powers, M. G. Duda, K. W. Manning, C. H. Reijmer, and M. R. van den Broeke, 2010: An extreme precipitation event in Dronning Maud Land, Antarctica: A case study with the Antarctic Mesoscale Prediction System. *Polar Research*, **29**, 330–344.

Schlosser, E., B. Stenni, M. Valt, A. Cagnati, J. G. Powers, K. W. Manning, M. Raphael, and M. G. Duda, 2016: Precipitation and synoptic regime in two extreme years 2009 and 2010 at Dome C, Antarctica – implications for ice core interpretation. *Atmos. Chem. Phys.*, **16**, 4757–4770.

Shepherd, A., and Coauthors, 2012: A reconciled estimate of ice-sheet mass balance. *Science*, **338**(6111), 1183–1189.

Sinisalo, A., and Coauthors, 2013: Surface mass balance on Fimbul ice shelf, East Antarctica: Comparison of field measurements and large-scale studies. *J. Geophys. Res. Atmos.*, **118**(20), 11 625–11 635.

Skamarock, W. C., and Coauthors, 2009: A description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN–475+STR, 113 pp.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Thomas, E. R., and T. J. Bracegirdle, 2009: Improving ice core interpretation using in situ and reanalysis data. *J. Geophys. Res. Atmos.*, **114**(D20), D20116.

Thomas, E. R., and T. J. Bracegirdle, 2015: Precipitation pathways for five new ice core sites in Ellsworth Land, West Antarctica. *Climate Dyn.*, **44**(7–8), 2067–2078.

Trenberth, K. E., J. T. Fasullo, and J. Mackaro, 2010: Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J. Climate*, **24**(18), 4907–4924.

Wang, Y. T., S. G. Hou, W. J. Sun, T. M. Lenaerts Jan, M. R. van den Broeke, and J. M. van Wessem, 2015: Recent surface mass balance from Syowa Station to Dome F, East Antarctica: Comparison of field observations, atmospheric reanalyses, and a regional atmospheric climate model. *Climate Dyn.*, **45**(9–10), 2885–2899.

Welker, C., O. Martius, P. Froidevaux, C. H. Reijmer and H. Fischer, 2014: A climatological analysis of high-precipitation events in Dronning Maud Land, Antarctica, and associated large-scale atmospheric conditions. J. Geophys. Res. Atmos., 119, 11932—11954.

Wouters, B., J. L. Bamber, M. R. van den Broeke, J. T. M. Lenaerts, and I. Sasgen, 2013: Limits in detecting acceleration of ice sheet mass loss due to climate variability. *Nature Geoscience*, **6**(8), 613–616.

Zwally, H. J., and M. B. Giovinetto, 2011: Overview and assessment of Antarctic Ice-Sheet mass balance estimates: 1992–2009. *Surveys in Geophysics*, **32**(4–5), 351–376.

Zwally, H. J., J. Li, J. W. Robbins, J. L. Saba, D. H. Yi, and A. C. Brenner, 2015: Mass gains of the Antarctic ice sheet exceed losses. *J. Glaciol.*, **61**(230), 1019–1036.