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### ► To cite this version:

Cyril Palerme, Chantal Claud, Ambroise Dufour, Christophe Genthon, Norman B. Wood, et al..  
Evaluation of Antarctic snowfall in global meteorological reanalyses. Atmospheric Research, 2017,  
190, pp.104-112. 10.1016/j.atmosres.2017.02.015 . insu-03727059

**HAL Id: insu-03727059**

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Submitted on 27 Jul 2022

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## Atmospheric Research

journal homepage: [www.elsevier.com/locate/atmosres](http://www.elsevier.com/locate/atmosres)

## Evaluation of Antarctic snowfall in global meteorological reanalyses

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## ARTICLE INFO

## Article history:

Received 13 September 2016

Received in revised form 16 December 2016

Accepted 24 February 2017

Available online 27 February 2017

## Keywords:

Precipitation

Antarctica

Meteorological analyses

CloudSat

## ABSTRACT

Recent precipitation observations provided by CloudSat are used to evaluate the ability of various meteorological analyses and reanalyses to reproduce Antarctic snowfall. The performance of the ECMWF Interim Re-Analysis (ERA Interim), the Climate Forecast System Reanalysis (CFSR), the Japanese 55-year Reanalysis (JRA55), the Modern Era Retrospective-Analysis for Research and Application (MERRA), and the Modern Era Retrospective-Analysis for Research and Application 2 (MERRA-2), as well as ECMWF operational analyses are compared over the 2007–2010 period. The mean snowfall rate over Antarctica north of 82 °S simulated by the reanalyses between 2007 and 2010 ranges from 165 to 225 mm per year, while CloudSat observations indicate a value of 172 mm per year. ERA Interim produces the closest match to the observed snowfall rate, but all the reanalyses reproduce well the seasonal and interannual variability of Antarctic snowfall reported in CloudSat observations.

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## 1. Introduction

The surface mass balance (the sum of precipitation, sublimation/evaporation, meltwater runoff, and blowing snow) of the Antarctic ice sheet is expected to increase during the 21st century (Frieler et al., 2015; Gregory and Huybrechts, 2006), which should moderate the future contribution of the ice sheet to sea level rise. However, no significant trend in surface mass balance is visible for the last decades from reanalysis data and observations for the entire Antarctic ice sheet (Frezzotti et al., 2013; Monaghan et al., 2006).

In Antarctica, where in-situ observations are sparse, meteorological reanalyses represent a valuable source of information to study the climate of the last decades, and have been used in several studies to characterize snow accumulation (Bromwich et al., 2011; Marshall, 2009; Monaghan et al., 2006). Bromwich et al. (2011) have evaluated Antarctic snow accumulation (defined as precipitation minus evaporation/sublimation) in several meteorological reanalyses using the map of surface mass balance computed by Arthern et al. (2006) from in-situ measurements and extrapolated with remote sensing observations. They concluded that ERA Interim likely offers the most

realistic representation of snow accumulation changes in Antarctica during the period 1989–2009 among various reanalysis datasets. Nevertheless, some processes such as meltwater runoff and blowing snow are not taken into account in the assessments of snow accumulation in the reanalyses, and can induce bias when comparing the reanalyses with surface mass balance observations.

The ability of meteorological analyses to reproduce Antarctic precipitation, the main term of surface mass balance, remains poorly known due to a lack of in-situ observations (there is no precipitation gauge network in Antarctica). Remote sensing observations of precipitation have recently become available in Antarctica (up to 82 °S) with the data provided by the CloudSat satellite (Liu, 2008; Stephens et al., 2008), and Palerme et al. (2014) have generated the first model-independent and multi-year climatology of Antarctic precipitation (up to 82 °S) using two new CloudSat products. In a recent study, Behrangi et al. (2016) have evaluated high latitude precipitation reproduced by various reanalysis datasets, and they suggest that ERA Interim is the closest reanalysis compared to CloudSat observations for Antarctic precipitation.

In this study, we have used the new satellite climatology produced by Palerme et al. (2014) to evaluate Antarctic snowfall in various meteorological reanalysis datasets: the European Centre for Medium-range Weather Forecasts (ECMWF) Interim reanalysis (ERA Interim), the National Centers for Environmental Prediction (NCEP)

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Climate Forecast System Reanalysis (CFSR), the Japan Meteorological Agency (JMA) 55-year Reanalysis (JRA55), the National Aeronautics and Space Administration (NASA) Modern Era Retrospective Analysis for Research and Applications (MERRA), and Modern Era Retrospective Analysis for Research and Applications 2 (MERRA-2). Although the ECMWF operational analyses are less interesting for climate studies due to the constant improvements in spatial resolution, as well as in the model physics and the data assimilation scheme, they have also been compared to the CloudSat observations because ECMWF operational analyses are produced using the latest physics and a better spatial resolution than ECMWF reanalyses. This study focuses on the Antarctic continent with a higher level of details on the spatial pattern and the seasonal cycle of precipitation compared to the survey of Behrangi et al. (2016). Moreover, the interannual variability of the snowfall rate and the atmospheric moisture budget are also analyzed here, and several datasets examined in this study have not been evaluated by Behrangi et al. (2016) (CFSR, JRA55, MERRA-2, and ECMWF operational analyses).

The datasets and the methods used in this study are presented in Section 2. In Section 3, Antarctic snowfall simulated by the meteorological reanalyses is examined and compared to CloudSat observations. The spatial pattern of the snowfall rate, the seasonality, and the interannual variations between 2007 and 2010 of the snowfall rate are evaluated in this section. Moreover, the atmospheric moisture budget is also analyzed in Section 3. The discussion and conclusions about the reliability of the reanalyses used in this study are provided in Section 4.

## 2. Data and methods

The CloudSat 2C-SNOW-PROFILE product (Wood et al., 2016), that provides instantaneous assessments of snowfall since August 2006, has been processed on a  $1^\circ$  (latitude)  $\times$   $2^\circ$  (longitude) grid to generate a map of the snowfall rate in Antarctica as described by Palerme et al. (2014). The period 2007–2010 is used in this study to consider all the full years available in the CloudSat observations (CloudSat lost its nighttime observing capability in April 2011 due to battery problems). It has been shown that the spatiotemporal sampling of CloudSat is sufficient to map the snowfall rate during the period August 2006 to April 2011 over a  $1^\circ \times 2^\circ$  grid (Palerme et al., 2014). It is assumed in this study that the spatiotemporal sampling of CloudSat is also sufficient to map the snowfall rate during the 2007–2010 period due to the small difference in the number of samples per grid cell between both periods. It should be noted that Behrangi et al. (2016) used a different spatial resolution ( $2.5^\circ \times 2.5^\circ$  grid) and a different spatial coverage (north of  $80^\circ$  S in Behrangi et al. (2016) compared to north of  $82^\circ$  S here), which can explain the slightly larger mean snowfall rate from CloudSat observations reported by Behrangi et al. (2016) during the period 2007–2010 (178 mm per year compared to 172 mm per year here). In the 2C-SNOW-PROFILE algorithm, the phase of precipitation is determined using the near-surface air temperature estimated by ECMWF operational analyses, and the snowfall rate is estimated if the melted fraction of precipitation assessed is below 10% (Wood et al., 2016).

Given the lack of surface observations spanning the entire ice sheet, the uncertainty on this new climatology cannot be easily assessed, but Boening et al. (2012) have shown that the snowfall rate observed with CloudSat agrees well with independent estimates of ice mass changes from GRACE over Dronning Maud Land (East Antarctica). However, there are also substantial uncertainties in the retrievals of ice mass changes from GRACE, such as issues relative to glacial isostatic adjustment (Paulson et al., 2007). Ground-based radars have recently been set up in Antarctica in order to evaluate CloudSat snowfall retrievals, and the analysis of the results is currently in progress. Recent studies have evaluated the snowfall

retrievals from the 2C-SNOW-PROFILE product using ground-based radar networks as reference over the United States (Cao et al., 2014; Chen et al., 2016) and Sweden (Norin et al., 2015). These comparisons have suggested that the 2C-SNOW-PROFILE algorithm performs well for light precipitation, but tends to underestimate snowfall rates for moderate and heavy snowfall (Cao et al., 2014; Chen et al., 2016; Norin et al., 2015). This should not be an important issue in Antarctica due to the low snowfall rates observed on the ice sheet (Palerme et al., 2014). Furthermore, it has also been shown that the phase discrimination of the 2C-SNOW-PROFILE algorithm is in good agreement with ground-based radar observations (Chen et al., 2016).

The analyses and reanalyses, by combining numerical weather forecasts with historical meteorological observations, provide valuable information for investigating the climate of the last decades. It is important to note that these observations do not include precipitation. During the reanalysis period, the forecast models and data assimilation schemes are frozen, but the observations assimilated may change which can induce spurious shifts in the forecasts.

Table 1 shows the main characteristics of the reanalyses used in this study. The spatial resolution of the reanalyses ranges from T255 ( $\approx 80$  km) in ERA Interim (Dee et al., 2011) to T382 ( $\approx 38$  km) in CFSR (Saha et al., 2010). CFSR differs from other reanalyses by using a coupled atmosphere-ocean-sea ice-land model for its forecasts (Saha et al., 2010). The reanalyses employ different physics parameterizations and data assimilation schemes. JRA 55 (Kobayashi et al., 2015) and ERA Interim (Dee et al., 2011) implement four-dimensional variational data assimilation (4D-Var) to account for the temporal evolution of the observations within the assimilation window, while the other reanalyses use three-dimensional variational data assimilation (3D-Var).

Two reanalysis datasets produced by the National Aeronautics and Space Administration (NASA) are examined in this study: MERRA and MERRA-2. They use a 3D-Var assimilation system with the Incremental Analysis Update (IAU) which allows a smooth transition from the model state toward the observed state (Rienecker et al., 2011). In particular, this has improved the problem of spin-up of precipitation. MERRA-2 has been produced more recently and has numerous improvements concerning the model and the data assimilation (Bosilovich et al., 2015). In particular, the atmospheric water budget is now balanced on yearly time scales by construction (Takacs et al., 2016). Moreover, MERRA-2 assimilates recent observations that were not available when MERRA entered production (Bosilovich et al., 2015).

The operational analyses produced by ECMWF had a spatial resolution from T799 ( $\approx 25$  km) to T1279 ( $\approx 16$  km) between 2007 and 2010 ([www.ecmwf.int](http://www.ecmwf.int)). They have been produced using a 4D-Var assimilation system and a more developed physics than ERA Interim reanalyses. The better spatial resolution of ECMWF operational analyses compared to the reanalyses is expected to have an influence on precipitation forecasts in Antarctica due to the strong precipitation gradients between coastal and inland regions (Bromwich, 1988). These two regions (Fig. 1, lower right corner) can be separated by the median altitude of the ice sheet (2250 m), and have been examined separately in this study. Over peripheral areas, where most of the precipitation falls (Bromwich, 1988; Palerme et al., 2014), precipitation is mainly influenced by synoptic-scale depressions (Bromwich, 1988). The high interior plateau is characterized by very weak precipitation rates due to very low temperatures and a larger distance from the ocean. Furthermore, a potentially important fraction of the precipitation falls under clear-sky conditions over this region (Bromwich, 1988; Fujita and Abe, 2006).

In order to compare the reanalyses to the CloudSat observations, all the datasets have been interpolated on a  $1^\circ$  (latitude)  $\times$   $2^\circ$  (longitude) grid. Moreover, because CloudSat observations do not cover the area between  $82^\circ$  S and the pole, the precipitation and the snowfall rates from the reanalyses were averaged over the Antarctic

**Table 1**  
 Characteristics of the reanalyses used in this study. For the ECMWF operational analyses, the characteristics of the version of the model during the period 2007–2010 are given in this table.

Name	Reference	Horizontal resolution	Vertical levels	Assimilation system
CFSR	Saha et al. (2010)	T382 ( $\approx 38$ km)	64	3DVAR
ERA Interim	Dee et al. (2011)	T255 ( $\approx 80$ km)	60	4DVAR
JRA55	Kobayashi et al. (2015)	T319 ( $\approx 55$ km)	60	4DVAR
MERRA	Rienecker et al. (2011)	$0.5^\circ \times 0.67^\circ$ ( $\approx 55$ km)	72	3DVAR
MERRA-2	Bosilovich et al. (2015)	$0.5^\circ \times 0.625^\circ$ ( $\approx 55$ km)	72	3DVAR
ECMWF operational analyses		From T799 to T1279 (from 25 to 16 km)	91	4DVAR

continent up to  $82^\circ\text{S}$  in this study. Furthermore, when the land/sea mask was applied, the precipitation rate was weighted according to the land fraction in the grid cell for grid boxes containing both land and ocean.

### 3. Results

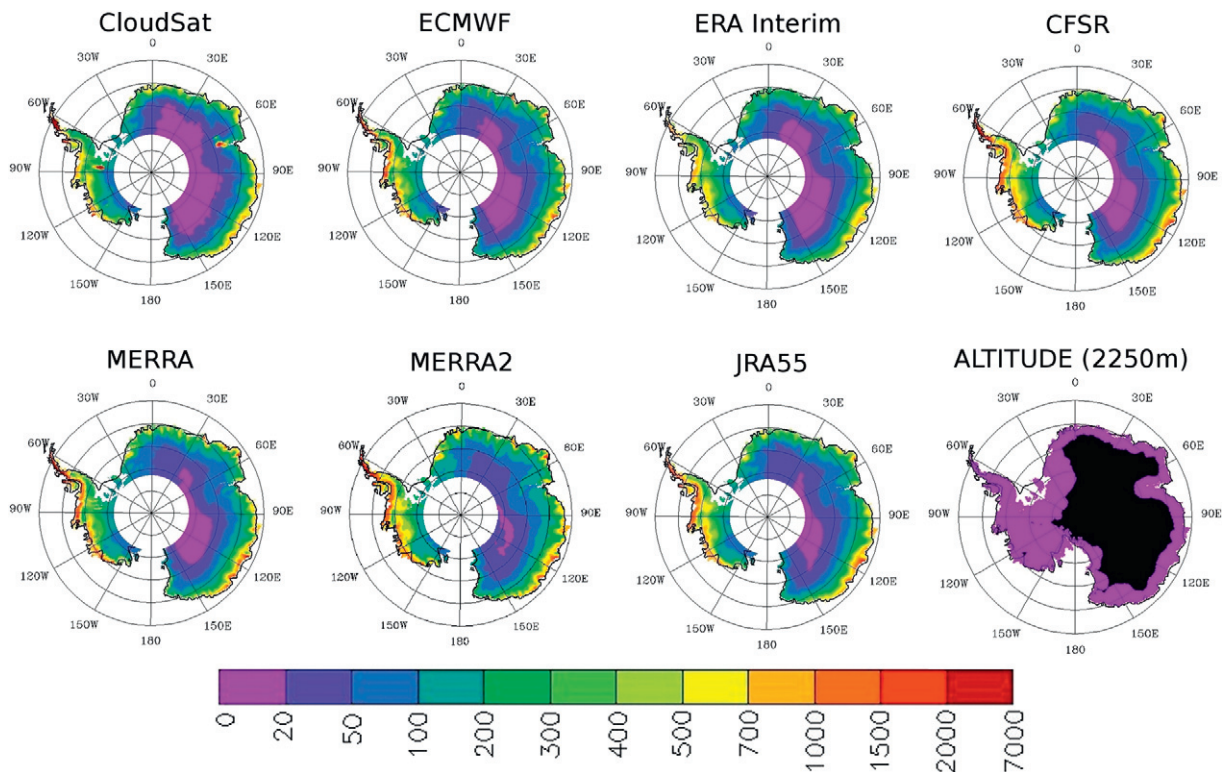
#### 3.1. Mean snowfall rate

The mean snowfall rates simulated by the meteorological reanalyses and the ECMWF operational analyses are compared to CloudSat observations in Figs. 1 and 2. Over the Antarctic continent (north of  $82^\circ\text{S}$ ), all the reanalysis datasets, except ERA Interim, produce a snowfall rate higher than the rate obtained from CloudSat observations (172 mm per year). ERA Interim produces the closest snowfall rate (165 mm per year) to the CloudSat observations, and ECMWF operational analyses simulate a snowfall rate (185 mm per year) slightly larger than the rate observed with CloudSat. The highest snowfall rate is simulated by MERRA-2 (225 mm per year).

It should be noted that CloudSat observations are affected by ground clutter, which obscures the snowfall events occurring in the first 1200 m above ground level in the 2C-SNOW-PROFILE algorithm (Wood et al., 2016). This may explain why CloudSat observations

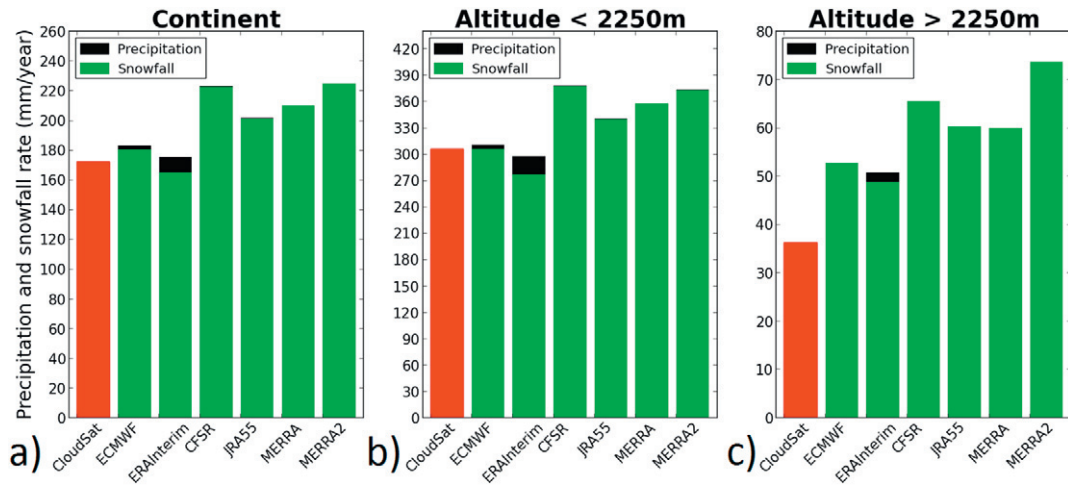
indicate a snowfall rate lower than the other datasets in the interior of the ice sheet, where a potentially significant fraction of the precipitation falls under clear sky conditions (Bromwich, 1988; Fujita and Abe, 2006), and could be formed in the first kilometer above ground level.

The total precipitation rate (rain + snowfall) produced by the reanalyses and the ECMWF operational analyses is also shown in Fig. 2. The intensities of rain and mixed phase precipitation are not available in CloudSat products (2C-SNOW-PROFILE product provides a snowfall rate only when the melted fraction of precipitation is below 10%), which prevents direct comparisons of the fraction of liquid precipitation in the reanalyses with CloudSat observations. The difference between the precipitation and the snowfall rates, indicating the fraction of liquid precipitation, is negligible over the Antarctic continent (up to  $82^\circ\text{S}$ ) in CFSR, JRA55, MERRA, and MERRA-2. However, the fraction of liquid precipitation is about 1% in ECMWF operational analyses, and 5% in ERA Interim. Liquid precipitation is particularly important in ERA Interim over peripheral areas, where it contributes to about 6% of the total precipitation. However, these results must be taken with caution because the definition of the snowfall variable differs between the datasets. For example, in ERA Interim, when mixed precipitation occurs, the melted fraction of precipitation is taken into account in the rain variable, while the



**Fig. 1.** Mean snowfall rate during the period 2007–2010 (mm water equivalent per year). The regions with surface elevation higher than 2250m (black) and lower than 2250m (purple) are shown on the last map (lower right corner).





**Fig. 2.** Mean precipitation (black) and snowfall (green) rates during the period 2007–2010 (mm water equivalent per year). For CloudSat, the red bars show the mean snowfall rate. a) Antarctic continent (north of 82°S). b) Peripheral regions of the ice sheet with surface elevation lower than 2250 m (north of 82°S). c) High Antarctic plateau with surface elevation higher than 2250 m (north of 82°S).

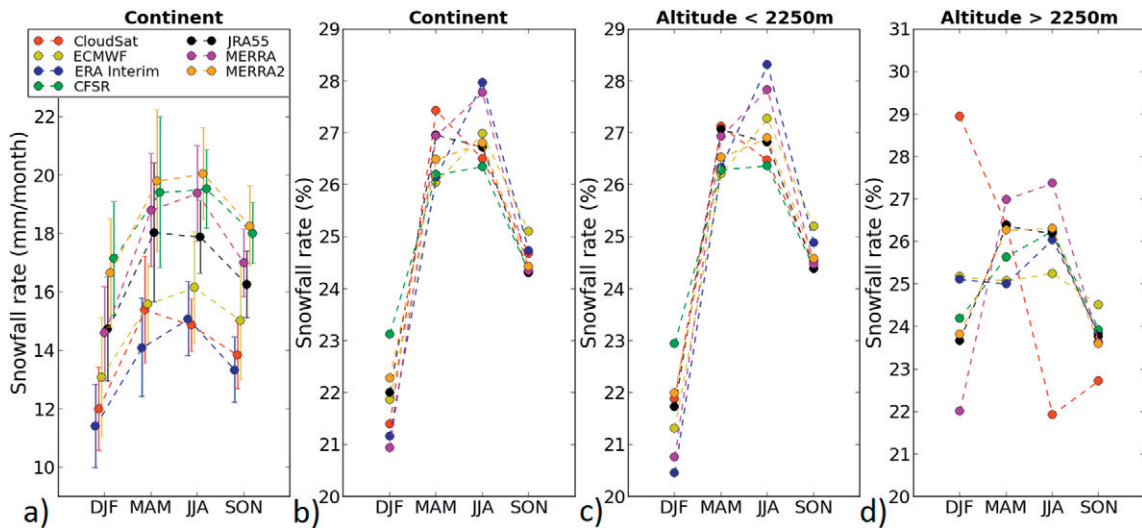
solid fraction is considered as snowfall. Therefore, most of the difference between the precipitation and the snowfall rates could be due to mixed precipitation in ERA Interim. In CFSR, snow product is categorical: it excludes events with even the slightest melt fraction and hence underestimates the snowfall compared to the other reanalyses. The variable we used for CFSR instead is precipitation minus rain.

3.2. Seasonal and interannual variability

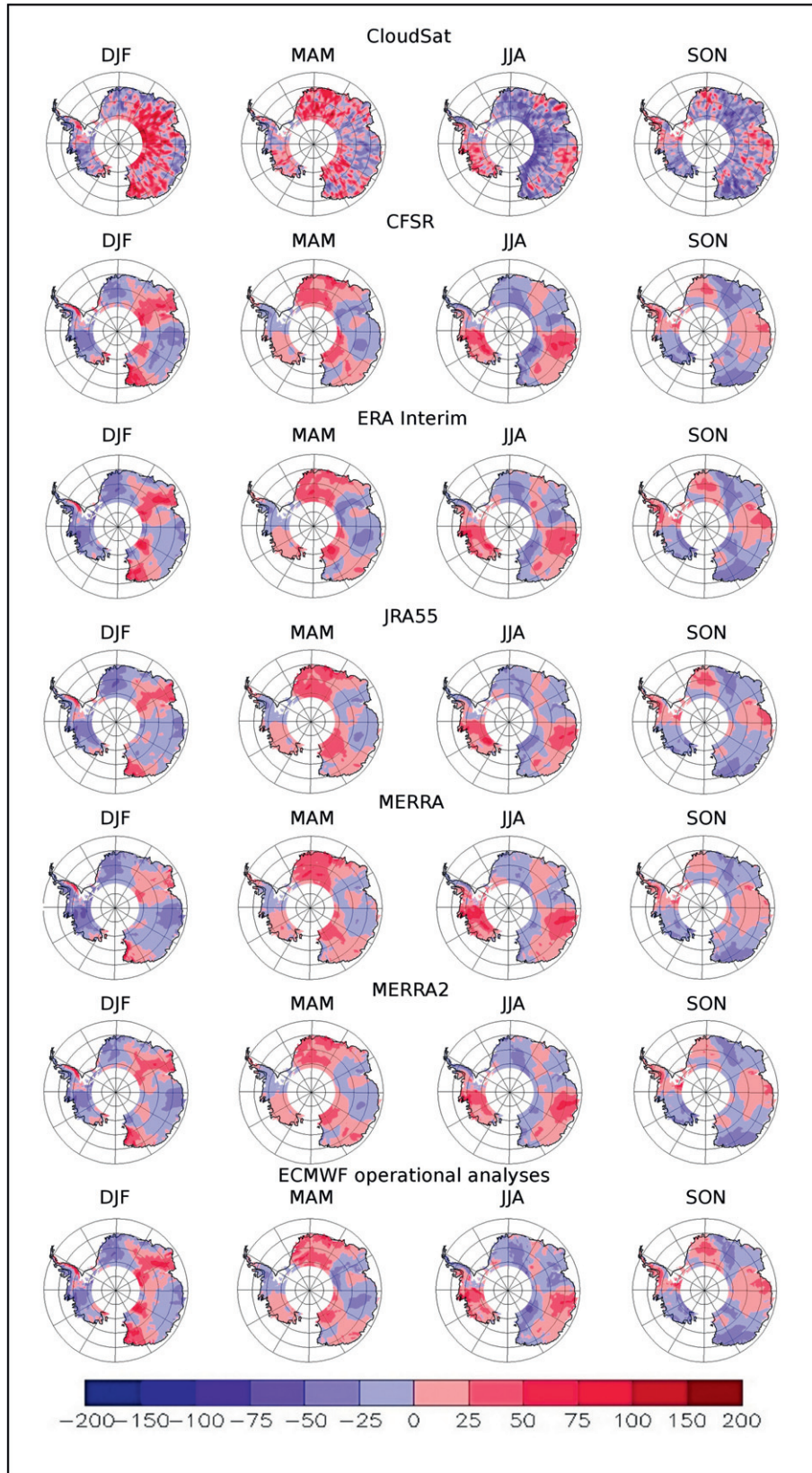
Fig. 3 shows the seasonal variability of the snowfall rates simulated by the reanalyses, ECMWF operational analyses, and observed with CloudSat. Overall, the different datasets produce similar seasonal cycles in snowfall rate over the Antarctic continent (up to 82 °S), with higher snowfall rates in March-April-May (MAM) and June-July-August (JJA), and the minimum snowfall rate in December-January-February (DJF). In CloudSat observations and JRA55, the

season with the highest snowfall rate is MAM, followed by JJA, whereas all the other datasets produce the maximum snowfall rate in JJA, followed by MAM. Nevertheless, the differences between the two seasons with the highest snowfall rates are small in all the datasets, and the standard deviation of the snowfall rate during the seasons MAM and JJA is higher than the difference of the mean snowfall rate between these two seasons in all the datasets. Overall, there is a good agreement between the different datasets for the spatial pattern of the seasonal cycle in snowfall rate (Fig. 4). However, the different datasets differ in their seasonal cycle on the Antarctic plateau. The seasonal cycle from CloudSat observations is completely different from the seasonal cycle reproduced by the reanalyses in the interior of the ice sheet, with a particularly high snowfall rate in DJF, and a particularly low snowfall rate in JJA compared to the reanalyses.

Interannual variations of the snowfall rate between 2007 and 2010 are shown in Fig. 5 and in Fig. 6. Over the Antarctic continent



**Fig. 3.** Seasonal variability of the snowfall rate during the 2007–2010 period. a) Seasonal variability of the snowfall rate (mm per month) on the Antarctic continent (north of 82 °S). The vertical bars represent the standard deviation of the snowfall rate for each season between 2007 and 2010. The different datasets are shifted for more clarity, but the same time periods (December-January-February, March-April-May, June-July-August, and September-October-November) are used for all the datasets. b) Seasonal variability of the snowfall rate (% compared to the mean annual snowfall rate) on the Antarctic continent (north of 82 °S). c) Seasonal variability of the snowfall rate (% compared to the mean annual snowfall rate) on the peripheral regions of the ice sheet with surface elevation lower than 2250 m (north of 82 °S). d) Seasonal variability of the snowfall rate (% compared to the mean annual snowfall rate) in the interior regions of the ice sheet with surface elevation higher than 2250 m (north of 82 °S).



**Fig. 4.** a) Snowfall anomalies (%) for each season during the period 2007–2010 defined as  $100 \times \frac{SF_{season} - SF_{2007-2010}}{SF_{2007-2010}}$  with  $SF_{season}$  the snowfall rate during the season analyzed, and  $SF_{2007-2010}$  the mean snowfall rate during the period 2007–2010.

(up to 82 °S), all the datasets produce the highest snowfall rate in 2009 (Fig. 5). The snowfall rate in 2009 is particularly high on the Antarctic plateau compared to the mean snowfall rate between 2007 and 2010. Fig. 6 shows that the spatial pattern of the inter-annual variations of the snowfall rate produced by the reanalyses and ECMWF operational analyses is also similar to the spatial pattern observed with CloudSat. Particularly strong precipitation events occurred over Dronning Maud Land in 2009, which has been observed with CloudSat (Boening et al., 2012), and simulated by all the reanalyses and ECMWF operational analyses (Fig. 6). It has been suggested that the El Niño Southern Oscillation (ENSO) has played an important role in the formation of these strong snowfall events in 2009 (Boening et al., 2012).

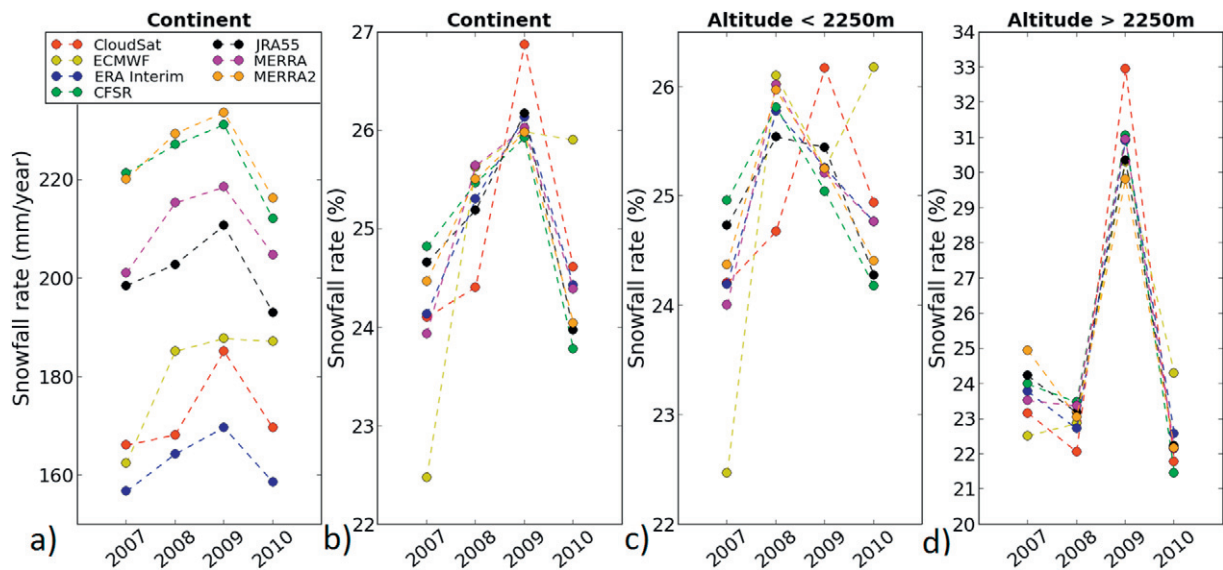
The snowfall rates during the years 2009 and 2010 have been compared in Fig. 6 in order to investigate the role of ENSO in the snowfall observed with CloudSat and simulated by the reanalyses. An El Niño event occurs in most of the year 2009, while a La Niña event occurs in most of the year 2010. The comparison of the two years shows an interesting spatial pattern: the locations of the positive anomalies in 2009 correspond to the locations of the negative anomalies in 2010 and vice versa. Genthon et al. (2003) have suggested that in case of high Southern Oscillation Index (SOI), which corresponds to a La Niña event, low pressure systems in the Amundsen Sea tend to induce moisture advection changes in the Amundsen Sea and West Antarctica. These changes in advection of moisture should be associated with increased precipitation on and east of the Peninsula, and decreased precipitation in the Ross-Amundsen sector (between 180 and 120°W). Conversely, in case of El Niño event, there should be increased precipitation in the Ross-Amundsen sector and decreased precipitation on and east of the Peninsula (Genthon et al., 2003). This is in accordance with the snowfall anomalies in Fig. 6 that are positive on and east of the Peninsula and negative in the Ross-Amundsen sector in 2010, and of opposite sign in 2009. These results suggest that ENSO could have played an important role in the spatial distribution of Antarctic snowfall during the years 2009 and 2010. Furthermore, CloudSat observations and all the reanalyses capture well the snowfall variations associated with the El Niño and La Niña events that occurred in these two years.

ECMWF operational analyses differ from the other datasets with a particularly low relative snowfall rate in 2007 and a particularly high relative snowfall rate in 2010. This dataset also exhibits the highest standard deviation (12.2 mm per year) for the snowfall rate between 2007 and 2010. Continual refinements to the ECMWF operational analysis model could induce varying bias when comparing several years of forecasts, which could explain the different interannual variability produced by ECMWF operational analyses compared to the other datasets. The interannual variations of the snowfall rate produced by the reanalyses are similar to the interannual variability observed with CloudSat, with a standard deviation ranging from 5.7 mm per year (ERA Interim) to 8.3 mm per year (MERRA). The standard deviation in CloudSat observations (8.7 mm per year) is similar to the mean standard deviation from the reanalyses and ECMWF operational analyses (8.4 mm per year).

In order to investigate the representativeness of the 2007–2010 period in a longer-term context, ERA Interim has been used to compare the 2007–2010 period to the 1979–2015 period. ERA Interim has been chosen since it is the reanalysis that reproduces the closest snowfall rate to the CloudSat observations over the 2007–2010 period. At the continent scale, the mean snowfall rate from ERA Interim is similar during the 2007–2010 period (165 mm per year) and during the 1979–2015 period (164 mm per year). Furthermore, the standard deviation of the snowfall rate from ERA Interim is also similar during both periods, although it is slightly larger during the 1979–2015 period (7.6 mm per year) than during the 2007–2010 period (5.7 mm per year). Therefore, the 2007–2010 period can be considered as relatively representative of a longer period in terms of interannual variability of the snowfall rate at the scale of the ice sheet.

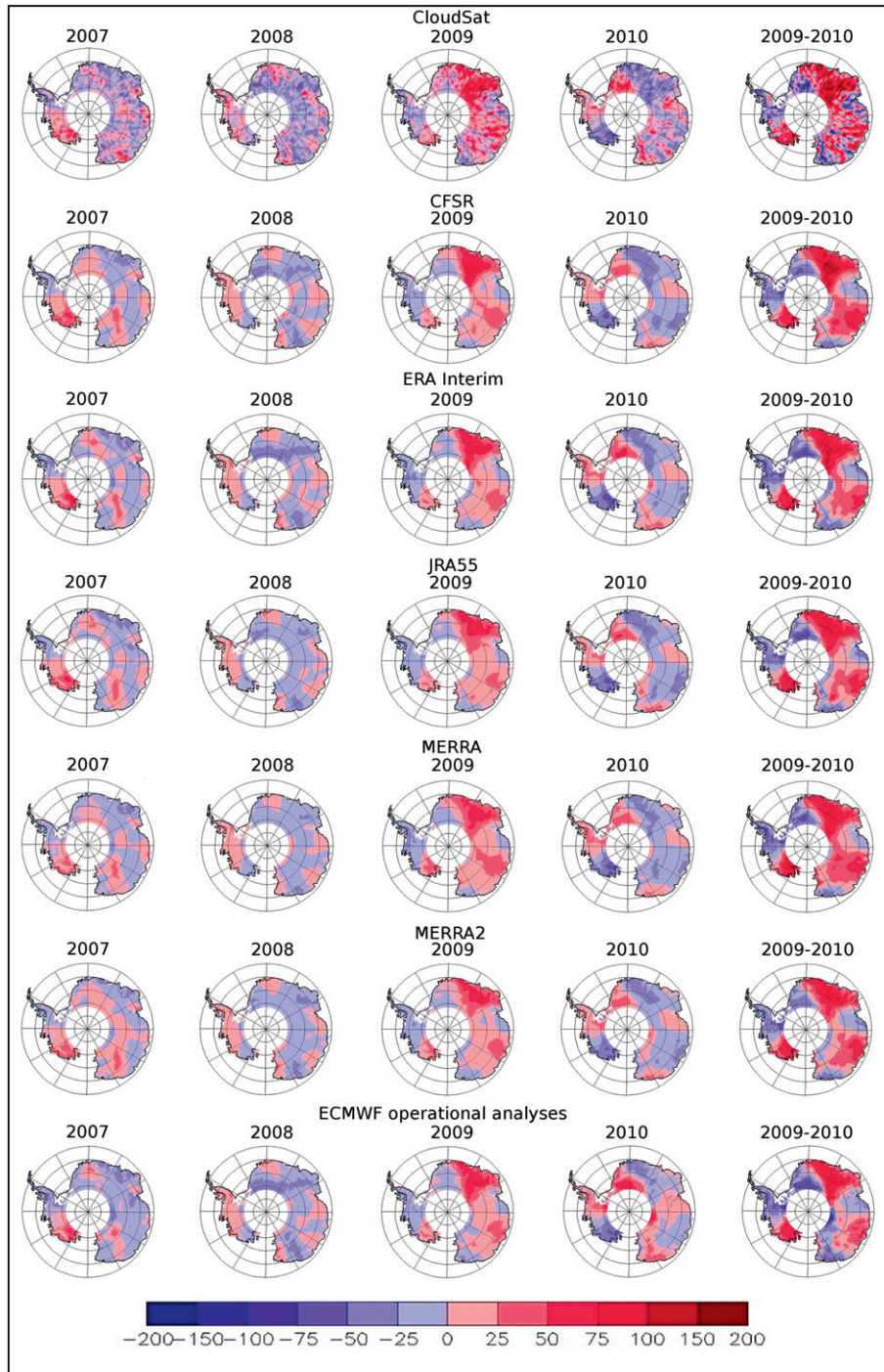
### 3.3. Moisture budget

The atmospheric conservation of moisture implies that the sum of vertically integrated moisture convergence and evaporation is equal to precipitation. However, the moisture budget is usually not closed in meteorological analyses due to the analysis increment associated with uncertainties in the observations and the predictions



**Fig. 5.** Interannual variations of the snowfall rate between 2007 and 2010. a) Interannual variability of the snowfall rate (mm per year) on the Antarctic continent (north of 82 °S). b) Interannual variability of the snowfall rate (% compared to the mean snowfall rate between 2007 and 2010) on the Antarctic continent (north of 82 °S). c) Interannual variability of the snowfall rate (% compared to the mean snowfall rate between 2007 and 2010) on the peripheral regions of the ice sheet with surface elevation lower than 2250 m (north of 82 °). d) Interannual variability of the snowfall rate (% compared to the mean snowfall rate between 2007 and 2010) in the interior regions of the ice sheet with surface elevation higher than 2250 m (north of 82 °S).



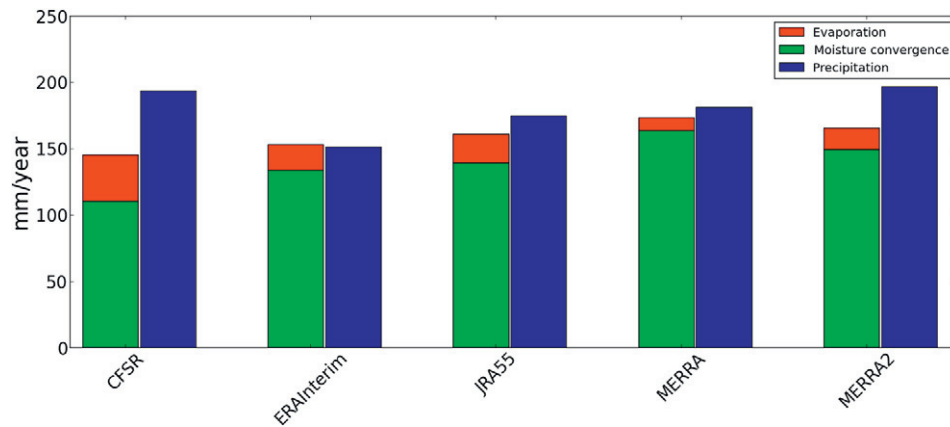


**Fig. 6.** Snowfall anomalies for each year from 2007 to 2010, defined as  $100 \times \frac{SF_{year} - SF_{2007-2010}}{SF_{2007-2010}}$  with  $SF_{year}$  the snowfall rate during the year analyzed, and  $SF_{2007-2010}$  the mean snowfall rate during the period 2007–2010. The last map on the right shows the difference between the years 2009 and 2010.

(Trenberth et al., 2011). In Fig. 7, the precipitation rate produced by the reanalyses has been compared to the sum of vertically integrated moisture convergence and evaporation. ERA Interim is the dataset with the smallest difference between precipitation and the sum of moisture convergence and evaporation (2 mm per year). Furthermore, it is also the only reanalysis with precipitation lower than the sum of moisture convergence and evaporation. The difference between precipitation and the sum of moisture convergence and evaporation is relatively low in MERRA and JRA55 (7 and 14 mm per year respectively), but is higher in MERRA-2 and CFSR (31 and 48 mm per year respectively).

The data assimilation system used in the reanalyses could play an important role in the conservation of moisture. Implementing a 4D-Var assimilation system should reduce the problem of spin-up of precipitation compared to a 3D-Var assimilation system. Among the reanalyses, only ERA Interim and JRA55 use a 4D-Var assimilation system, and the difference between precipitation and the sum of moisture convergence and evaporation is small in these datasets. CFSR and MERRA-2, which use a 3D-Var assimilation, are the two datasets with the largest difference between precipitation and the sum of moisture convergence and evaporation. However, the difference between precipitation and the sum of moisture





**Fig. 7.** Mean precipitation rate (blue), mean evaporation rate (red), and vertically integrated moisture convergence (green) during the period 2007–2010 (mm water equivalent per year) on the Antarctic continent (up to the pole).

convergence and evaporation is small in MERRA which uses a 3D-Var assimilation system.

#### 4. Discussion and conclusions

In this study, Antarctic snowfall produced by various global meteorological reanalyses have been compared to CloudSat snowfall observations. ERA Interim and ECMWF operational analyses reproduce the CloudSat observations of the mean snowfall rate most closely in the peripheral and the interior regions of the ice sheet. ERA Interim also produces consistent seasonal and interannual variability, while the interannual variability simulated by ECMWF operational analyses differs from the other datasets. Moreover, the moisture budget from ERA Interim is almost closed (precipitation is almost equal to the sum of moisture convergence and evaporation), and nearer to the equilibrium than in all the other datasets. Therefore, ERA Interim can be considered as the most reliable meteorological reanalyses for Antarctic precipitation, confirming the conclusions from Bromwich et al. (2011) and Behrangi et al. (2016). However, ERA Interim produces a large fraction of liquid precipitation (5% on the Antarctic continent up to 82 °S), while the fraction of liquid precipitation is much smaller in ECMWF operational analyses (1%), and in all the other meteorological reanalyses.

It has been suggested that ERA Interim has a dry bias over the interior plateau (Bromwich et al., 2011). ERA Interim produces a higher snowfall rate than the observed snowfall rate with CloudSat over the interior plateau, but it is possible that the snowfall rate from CloudSat observations is spuriously low in the interior of the Antarctic ice sheet due to shallow precipitation that is obscured by ground clutter. Furthermore, in some cases, the size of the hydrometeors over the Antarctic plateau may be too small to be detected as precipitating particles in the CloudSat 2C-SNOW-PROFILE algorithm, which would lead to an underestimation of the snowfall rate. Therefore, the current comparisons do not necessarily contradict the study of Bromwich et al. (2011).

Overall, there is fair agreement between the reanalyses, ECMWF operational analyses, and CloudSat observations for the seasonal variability of Antarctic snowfall with higher snowfall rates in MAM and JJA, and the minimum snowfall rate in DJF. Nevertheless, the seasonal variability over the Antarctic plateau observed with CloudSat differs from the seasonal variability simulated by the reanalyses. The interannual variability of the snowfall rate between 2007 and 2010 simulated by the different reanalyses and observed with CloudSat are similar. However, ECMWF operational analyses produce larger interannual variations than the other datasets, which could be due to biases induced by the constant evolution of the model.

The data assimilation system used in the different reanalyses could play an important role on the problem of spin-up of precipitation. The two datasets which implement a 4D-Var assimilation system (ERA Interim and JRA55) produce a moisture budget almost closed, while MERRA-2 and CFSR, which use a 3D-Var assimilation system, simulate much larger precipitation than the sum of evaporation and moisture convergence. Nevertheless, MERRA, which implement a 3D-Var assimilation system, produces a moisture budget almost closed.

This study is based on the comparison between the reanalyses and the climatology of Antarctic snowfall produced from CloudSat observations presented by Palerme et al. (2014). This climatology has not been compared to in-situ observations due to a lack of in-situ measurements of precipitation in Antarctica. Therefore, in-situ precipitation observations are strongly needed in Antarctica to evaluate remote sensing retrievals, and for a more robust evaluation of climate models and meteorological reanalyses. Despite the lack of ground validation, the climatology of Antarctic precipitation presented by Palerme et al. (2014) has a high potential for model evaluation (Palerme et al., 2016) and other applications, and is made available to the general community on the following website: <http://apres3.osug.fr>.

#### Acknowledgments

This research was funded by the French National Research Agency (ANR), through the APRES3 project (ANR-15-CE01-0003) with additional support from the LEFE programme DEPHY2 (Institut National des Sciences de l'Univers). We are thankful to the Centre National d'Études Spatiales (CNES) and the project Expecting Earth-Care, Learning from A-Train (EECLAT). Parts of this research conducted by T. L'Ecuyer and N. B. Wood were performed at the University of Wisconsin-Madison for the Jet Propulsion Laboratory, California Institute of Technology, and sponsored by NASA CloudSat Research Grant G-3969-1.

#### References

- Athern, R.J., Winebrenner, D.P., Vaughan, D.G., 2006. Antarctic snow accumulation mapped using polarization of 4.3-cm wavelength microwave emission. *J. Geophys. Res. Atmos.* 111, <http://dx.doi.org/10.1029/2004JD005667>.
- Behrangi, A., Christensen, M., Richardson, M., Lebsock, M., Stephens, G., Huffman, G.J., Bolvin, D., Adler, R.F., Gardner, A., Lambriksen, B., et al. 2016. Status of high-latitude precipitation estimates from observations and reanalyses. *J. Geophys. Res. Atmos.* 121, 4468–4486.
- Boening, C., Lebsock, M., Landerer, F., Stephens, G., 2012. Snowfall-driven mass change on the east Antarctic ice sheet. *Geophys. Res. Lett.* 39, <http://dx.doi.org/10.1029/2012GL053316>.

- Bosilovich, M.G., Akella, S., Lawrence, C., Cullather, R., Draper, C., Gelaro, R., Kovach, R., Liu, Q., Molod, A., et al. 2015. Merra-2, initial evaluation of the climate. Technical Report Series on Global Modeling and Data Assimilation. 43.
- Bromwich, D.H., 1988. Snowfall in high southern latitudes. *Rev. Geophys.* 26, 149–168.
- Bromwich, D.H., Nicolas, J.P., Monaghan, A.J., 2011. An assessment of precipitation changes over Antarctica and the southern ocean since 1989 in contemporary global reanalyses. *J. Climate* 24, 4189–4209.
- Cao, Q., Hong, Y., Chen, S., Gourley, J.J., Zhang, J., Kirstetter, P.E., 2014. Snowfall detectability of nasa's cloudsat: the first cross-investigation of its 2c-snow-profile product and national multi-sensor mosaic QPE (nmq) snowfall data. *Prog. Electromagn. Res.* 148, 55–61.
- Chen, S., Hong, Y., Kulie, M., Behrangi, A., Stepanian, P.M., Cao, Q., You, Y., Zhang, J., Hu, J., Zhang, X., 2016. Comparison of snowfall estimates from the NASA CloudSat cloud profiling radar and NOAA/NSSL multi-radar multi-sensor system. *J. Hydrol.* 541, Part B, 862–872.
- Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, I., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., 2011. The ERA-interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* 137, 553–597.
- Frezzotti, M., Scarchilli, C., Becagli, S., Proposito, M., Urbini, S., 2013. A synthesis of the antarctic surface mass balance during the last 800 yr. *Cryosphere* 7, 303–319.
- Frieler, K., Clark, P.U., He, F., Buizert, C., Reese, R., Ligtenberg, S.R., Van Den Broeke, M.R., Winkelmann, R., Levermann, A., 2015. Consistent evidence of increasing Antarctic accumulation with warming. *Nat. Clim. Chang.* 5, 348–352.
- Fujita, K., Abe, O., 2006. Stable isotopes in daily precipitation at Dome Fuji, East Antarctica. *Geophys. Res. Lett.* 33, <http://dx.doi.org/10.1029/2006GL026936>.
- Genthon, C., Krinner, G., Sacchettini, M., 2003. Interannual Antarctic tropospheric circulation and precipitation variability. *Climate Dynam.* 21 (3), 289–307.
- Gregory, J., Huybrechts, P., 2006. Ice-sheet contributions to future sea-level change. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 364, 1709–1732.
- Kobayashi, S., Ota, Y., Harada, Y., Ebata, A., Moriwa, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K., Takahashi, K., 2015. The JRA-55 reanalysis: general specifications and basic characteristics. *J. Meteorol. Soc. Jpn. Ser. II* 93, 5–48.
- Liu, G., 2008. Deriving snow cloud characteristics from cloudsat observations. *J. Geophys. Res. Atmos.* 113, <http://dx.doi.org/10.1029/2007JD009766>.
- Marshall, G.J., 2009. On the annual and semi-annual cycles of precipitation across Antarctica. *Int. J. Climatol.* 29, 2298–2308.
- Monaghan, A.J., Bromwich, D.H., Fogt, R.L., Wang, S.-H., Mayewski, P.A., Dixon, D.A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S.D., Morgan, V.I., Oerter, H., Van Ommen, T.D., Van der Veen, C.J., Wen, J., 2006. Insignificant change in Antarctic snowfall since the international geophysical year. *Science* 313, 827–831.
- Norin, L., Devasthale, A., L'Ecuyer, T.S., Wood, N.B., Smalley, M., 2015. Intercomparison of snowfall estimates derived from the cloudsat cloud profiling radar and the ground-based weather radar network over Sweden. *Atmos. Meas. Tech.* 8 (12), 5009–5021.
- Palerme, C., Genthon, C., Claud, C., Kay, J.E., Wood, N.B., L'Ecuyer, T., 2016. Evaluation of current and projected Antarctic precipitation in CMIP5 models. *Climate Dynam.* 1–15, <http://dx.doi.org/10.1007/s00382-016-3071-1>.
- Palerme, C., Kay, J.E., Genthon, C., L'Ecuyer, T., Wood, N.B., Claud, C., 2014. How much snow falls on the Antarctic ice sheet? *Cryosphere* 8, 1577–1587.
- Paulson, A., Zhong, S., Wahr, J., 2007. Inference of mantle viscosity from grace and relative sea level data. *Geophys. J. Int.* 171, 497–508.
- Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., et al. 2011. Merra: NASA's modern-era retrospective analysis for research and applications. *J. Climate* 24, 3624–3648.
- Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., et al. 2010. The NCEP climate forecast system reanalysis. *Bull. Am. Meteorol. Soc.* 91, 1015–1057.
- Stephens, G.L., Vane, D.G., Tanelli, S., Im, E., Durden, S., Rokey, M., Reinke, D., Partain, P., Mace, G.G., Austin, R., L'Ecuyer, T., Haynes, J., Lebsock, M., Suzuki, K., Waliser, D., Wu, D., Kay, J., Gettelman, A., Wang, Z., Marchand, R., 2008. Cloudsat mission: performance and early science after the first year of operation. *J. Geophys. Res. Atmos.* 113, <http://dx.doi.org/10.1029/2008JD009982>.
- Takacs, L.L., Suarez, M.J., Todling, R., 2016. Maintaining atmospheric mass and water balance in reanalyses. *Q.J.R. Meteorol. Soc.* 142 (697), 1565–1573. <http://dx.doi.org/10.1002/qj.2763>.
- Trenberth, K.E., Fasullo, J.T., Mackaro, J., 2011. Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J. Climate* 24, 4907–4924. <http://dx.doi.org/10.1175/2011JCLI4171.1>.
- Wood, N.B., L'Ecuyer, T.S., Kulie, M.S., 2016. Optimal estimation of snow properties from space-based millimeter-wavelength radar observations. Submitted to *J. Geophys. Res.*