Climate of West Antarctica and Influence of Marine Air Intrusions*

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ABSTRACT

High-resolution numerical weather forecasts from the Antarctic Mesoscale Prediction System (AMPS) archive are used to investigate the climate of West Antarctica (WA) during 2006–07. A comparison with observations from West Antarctic automatic weather stations confirms the skill of the model at simulating near-surface variables. AMPS cloud cover is also compared with estimates of monthly cloud fractions over Antarctica derived from spaceborne lidar measurements, revealing close agreement between both datasets. Comparison with 20-yr averages from the Interim ECMWF Re-Analysis (ERA-Interim) dataset demonstrates that the 2006–07 time period as a whole is reflective of the West Antarctic climate from the last two decades. On the 2006–07 annual means computed from AMPS forecasts, the most salient feature is a tongue-shaped pattern of higher cloudiness, accumulation, and 2-m potential temperature stretching over central WA. This feature is caused by repeated intrusions of marine air inland linked to the sustained cyclonic activity in the Ross and western Amundsen Seas. It is further enhanced by the ice sheet’s topography and by the mid–low-tropospheric wind flow on either side of the central ice divide. Low pressures centered over the Ross Sea (as opposed to the Bellingshausen Sea) are found to be most effective in conveying heat and moisture into WA. This study offers a perspective on how recent and projected changes in cyclonic activity in the South Pacific sector of the Southern Ocean may affect the climate and surface mass balance of WA.

1. Introduction

Antarctica is the coldest and driest continent on Earth. While high elevations, the prolonged absence of sun, and the high albedo of the ice surface account for low temperatures, and reduced precipitation through the very low moisture-holding capacity of the air, these features also result from limited ocean influence over most of the ice sheet. Indeed, its steep coastal topography is an effective barrier for the depressions that develop and move over the Southern Ocean and thereby inhibits the intrusion of mild, moist marine air into the ice sheet’s interior. Ocean influence is generally confined to the immediate coastal regions, which receive the bulk of Antarctic precipitation through orographic lifting of air masses.

It follows that a marked contrast exists between the atmosphere of the continental interior and that of the surrounding ocean. The penetration of ocean air generally greatly alters the physical properties of the continental polar troposphere, leaving a characteristic mild and moist signature that can be easily traced. Such marine air intrusions have been reported for several decades (Alvarez and Lieske 1960; Sinclair 1981; Pook and Cowled 1999; Naithani et al. 2002; Massom et al. 2004) as they are generally accompanied by frontal cloud cover far inland, high precipitation amounts, and dramatic rises in surface temperature. The enhanced cyclonic activity over the Southern Ocean in the nonsummer months generates repeated maritime intrusions. The associated warm advections prevent monthly mean temperatures in the Antarctic interior from reaching a sharp minimum during the extended winter season, thus contributing to what has been described as the “coreless” winter (Van Loon 1967), one characteristic feature of the Antarctic climate.

While marine air masses potentially reach over most of the Antarctic ice sheet, the climate of West Antarctica (WA) is much more ocean-dominated than that of East Antarctica. Indeed, the effects of lower terrain elevation and enhanced exposure to offshore depressions combine for higher temperatures and greater annual precipitation amounts (e.g., Bromwich 1984; King and...
The lower average elevation of WA conceals a complex topography, which profoundly differs from the essentially zonal symmetry and dome-shaped profile of East Antarctica (Fig. 1; Fahnestock and Bamber 2001). The topographic divides—radiating from central WA, respectively, to the southern Antarctic Peninsula, to the Transantarctic Mountains, and to western Marie Byrd Land (MBL)—commonly serve to distinguish between a Weddell Sea sector, a Ross Sea sector, and a Bellingshausen–Amundsen (BA) Sea sector.

Poleward-moving air associated with synoptic weather systems that penetrate inland can effectively convey heat and moisture over the ice sheet’s interior. Early studies based on radiosonde observations performed during the 1957–58 International Geophysical Year suggested that the West Antarctic sector was a major source of moisture for Antarctica (Rubin and Giovinetto 1962; Lettau 1969). More recently, the use of operational analyses, reanalysis datasets, and regional climate models has considerably improved our knowledge of the moisture and heat budget of the Antarctic (Bromwich et al. 1995; Giovinetto et al. 1997; Genthon and Krinner 1998; Tiétäväinen and Vihma 2008; van de Berg et al. 2008). In particular, these studies confirmed that the 160°–70°W sector (between the Ross Sea and the Antarctic Peninsula) is the main source region for moisture and energy south of latitude 70°S. Furthermore, the portion of the Southern Ocean adjacent to WA is known to exhibit intense synoptic and mesoscale cyclonic activity (Jones and Simmonds 1993; Simmonds et al. 2003; Carrasco et al. 2003), which is manifested through the permanent surface pressure trough off WA (King and
Three main reasons argue for an investigation of the ocean influence on the West Antarctic Ice Sheet (WAIS). First, intrusions of offshore air masses directly contribute to the ice sheet’s surface mass balance through precipitation. This is a critical aspect since studies converge toward a negative mass balance of the WAIS, mainly due to alterations in the atmospheric circulation pattern induce changes in the heat and moisture inflow over WA. Changes in storm tracks may also affect the WAIS energy budget due to changes in cloud cover (Pavolonis and Key 2003), with impacts on air temperature and precipitation. Finally, knowledge of the spatial and temporal variabilities is crucial for accurately interpreting ice cores drilled in WA, especially as part of the ongoing United States WAIS Divide deep ice coring project (information online at http://www.waisdivide.unh.edu/).

In this paper, we explore the West Antarctic climate through archived numerical weather forecasts from the Antarctic Mesoscale Prediction System (AMPS; Powers et al. 2003). This data source offers an unprecedented spatial resolution (20 km) on a continental scale, especially with the ability to capture the terrain complexity of WA. Although primarily designed for the operational needs of the United States Antarctic Program (USAP), the AMPS database has also proven to be a very valuable resource for Antarctic meteorological and climate studies (Monaghan et al. 2005; Parish and Bromwich 2007; Steinhoff et al. 2008; Schlosser et al. 2008). The AMPS project has provided high-resolution weather forecasts over the Antarctic continent since late 2000. Nevertheless, the forecasting nature of the AMPS model does not allow consistent climatological studies over the full-length archive because of upgrades to the model configuration. Therefore, we investigate a 2-yr time period (2006–07) to document how the ocean influence can be traced in the atmosphere of WA.

This paper is organized as follows: in section 2, the data used in this study are described; in section 3, a brief evaluation of AMPS is performed; the results from our analysis of the AMPS archive from 2006 to 2007 are presented in section 4; and a summary and discussion are given in section 5.

2. Data

For the time period investigated here, AMPS employed the Polar MM5, a version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model with physics optimized for high latitudes by the Polar Meteorology Group of the Byrd Polar Research Center (Bromwich et al. 2001; Cassano et al. 2001; Bromwich et al. 2005). A detailed description of the polar modifications is given in these references and will not be repeated here. The configuration of Polar MM5 used to generate AMPS forecasts consisted of six grids with horizontal resolution ranging from 60 km for the outermost domain down to 2.2 km over the McMurdo Sound area, in the western Ross Sea. Our study relies on AMPS forecasts for the 20-km domain 2. The AMPS model underwent a major upgrade in September 2005, with an enhancement in horizontal resolution (from 30 to 20 km for domain 2), an increase in the number of vertical levels (29 to 31), and a raising of the model top (50 to 10 hPa). The model configuration remained unchanged between September 2005 and June 2008. This was the primary motivation for choosing 2006–07 as the period of study since it ensured consistency among AMPS forecasts at the highest resolution available. Note that, since July 2008, AMPS forecasts have been generated with the polar version of the Advanced Weather and Research Forecasting model (Polar WRF; Hines and Bromwich 2008; Bromwich et al. 2009).

AMPS forecasts are run twice daily, with initializations at 0000 and 1200 UTC, and extending up to 72 h for the domain considered here. The time series used in our study were constructed from the 12th and 18th hours of each forecast, yielding 6-hourly time series. Discarding the first 12-h forecasts allows for the model spinup, which is especially important for the hydrologic cycle.

The newly released European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis dataset, ERA-Interim (Simmons et al. 2007; Uppala et al. 2008), is also utilized to characterize the 2-yr AMPS archive with respect to the climatology for a longer time period. The ERA-Interim data used in the present study span 20 yr, from 1989 to 2008. Note that this reanalysis experiment has brought substantial improvements to existing reanalysis datasets, especially with the implementation of a four-dimensional variational data assimilation (4DVAR) scheme, enhanced horizontal resolution, and an increased number of vertical levels. ERA-Interim products were obtained from the ECMWF Data Server at a nominal resolution of 1.5°.

3. Evaluation of AMPS over WA

Bromwich et al. (2005) performed a comprehensive evaluation of AMPS forecasts from September 2001 through August 2003. They found that the AMPS model
predicts surface pressure and temperature with great
detail, yielding high correlations and small biases overall.
Yet, the model shows less skill in predicting surface wind,
especially over areas with complex topography such as
coastal locations. Fogt and Bromwich (2008) evaluated
the atmospheric moisture and cloud cover in AMPS.
The authors found an overestimation of moisture in the
mid- and upper troposphere whereas clouds were un-
derestimated in the lower atmosphere over ice surfaces.
Nevertheless, the simulation of total cloud cover was
found to be fairly realistic. Schlosser et al. (2008) used
the AMPS forecast archive from 2001 to 2006 to study
the precipitation regime over the Dronning Maud Land
(DML). They compared the 6-yr-mean annual precipi-
tation with a net accumulation map of DML derived from
climatological observations (Rothschky et al. 2007). They
found a relatively good level of agreement regarding the
spatial distribution. Yet, owing to the disparity of the time
sampling and the variables compared (simulated pre-
cipitation versus observed net accumulation), this appre-
ciation remained essentially qualitative.

To date, the skill of the AMPS forecasts after, as
compared to before, the September 2005 upgrade has not
been addressed. Nonetheless, a comprehensive evalu-
ation of AMPS forecasts run with the upgraded model lies
beyond the scope of this study. A review of the model’s
forecasting performance is first presented for near-
surface variables over WA. Since clouds are a prominent
signature of moist marine air in the Antarctic atmosphere,
AMPS cloud cover is also compared with a recent cloud
signature of moist marine air in the Antarctic atmosphere,
surface variables over WA. Since clouds are a prominent
forecasting performance is first presented for near-
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simulation of AMPS forecasts run with the upgraded model lies
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forecasting performance is first presented for near-

a. Near-surface variables

Near-surface observations from West Antarctic auto-
matic weather stations (AWSs) were obtained from the
online archive of the University of Wisconsin’s Space
Science and Engineering Center (UW-SSEC; http://amrc.
ssec.wisc.edu/stations.html). We used AWS 10-min re-
cords of 2-m temperature (T2m), surface pressure, and
3-m wind speed. As a quality control procedure, we dis-
carded data outside a ±3-standard deviation window
within 24-h intervals in the temperature and pressure
time series (±4 standard deviations were used for the
wind speed). Six-hourly time series were constructed to
compare with AMPS 6-hourly forecasts. The four AWSs
considered are Mount Siple, Byrd, Harry, and Theresa,
whose respective locations stretch from the coast to the
central and far interior of WA (Fig. 1 and Table 1). It is
noteworthy that the Mount Siple AWS has not been
visited since it was deployed in 1992 so that data from this
record must be considered cautiously (M. Lazzara, UW-
SSEC, 2009, personal communication).

AMPS data were bilinearly interpolated to the reported
AWS locations. The temperature and wind speed from
the AMPS model lowest sigma level (~13 m) were in-
terpolated down to 2 and 3 m, respectively, based on the
Monin–Obukhov similarity theory (Stull 1988; Box and
Steffen 2001), with the diabatic terms neglected in the
temperature calculation. Based on King and Turner (1997,
and references cited therein), we used a constant rough-
ness length (z0) of 10^-4 m. The temperature was further
adjusted to the reported station elevation using a dry-
adibatic lapse rate of 0.01°C m^-1. AMPS surface pres-
sure was adjusted to the actual station elevation based on
the hypsometric equation.

The biases (model – observation), root-mean-square
errors (RMSEs), and correlation coefficients are re-
tported in Table 2, which also includes the results from
Bromwich et al. (2005) for comparison. The RMSE is
normalized by the standard deviation of the observa-
tions to allow comparison between sites with different
variations. As a result of persistent outages in the
second half of 2007 among the AWS array, only data
from January 2006 through May 2007 were used in our
evaluation. Note that in Bromwich et al. (2005) the time
series were constructed from the 12th to the 36th hour
of each 0000 UTC initialized forecast from the AMPS
30-km domain. In their evaluation of the model per-
formance as a function of the forecast hour (0–72 h),
Bromwich et al. (2005) found a gradual degradation of
the biases and correlation coefficients with the forecast
moving forward. From this consideration alone, the time
series used in the present study and derived from the 12-
and 18-h model forecasts are expected to yield improved
statistics. However, the actual results also take into ac-
count the effects of the changes in the model configu-
rations, the inherent difference between the time periods,
possible degradations of the AWS sensors over time, etc.

Similar to Bromwich et al. (2005), negative T2m biases
are found at the inland sites whereas Mount Siple,
the only coastal AWS, exhibits a positive bias. A cold
bias in the Antarctic interior was also reported by Guo


| Table 1: Coordinates and altitudes of the four AWSs used for AMPS forecast evaluation. “Height Obs” is the AWS elevation reported by the UW-SSEC. “Height Model” is the AWS elevation interpolated on the AMPS model terrain. Latitudes and longitudes are given in decimal degrees. |
|---|---|---|---|---|
| AWS | Lat (°S) | Lon (°W) | Height Obs (m) | Height Model (m) |
| Byrd | 80.007 | 119.004 | 1530 | 1523 |
| Harry | 83.003 | 121.393 | 945 | 930 |
| Mount Siple | 73.198 | 127.052 | 230 | 124 |
| Theresa | 84.599 | 115.811 | 1463 | 1577 |
et al. (2003), who evaluated a 1-yr simulation of the Polar MM5 in the Antarctic. The authors attributed this bias to excessively low downward longwave radiation under clear-sky conditions. Despite its elevation at 124 m MSL in the model, the location of Mount Siple AWS turns out to be tagged as an ocean–sea ice grid point. In this case, the positive bias mainly results from higher-than-observed winter temperatures. Biases in surface pressure are strongly dependent upon the accuracy of the reported station elevations. Inspection of the time series indicates that the larger bias, larger RMSE, and lower correlation at Mount Siple largely result from abnormally high pressure values recorded by the AWS during December 2006–January 2007, suggesting a possible malfunction of the pressure sensor. The 3-m wind speed is found to be overestimated in AMPS, especially at Theresa, whose bias is very comparable to what Bromwich et al. (2005) reported. In this latter study, Theresa already stood out among other inland stations, which exhibited much lower wind speed biases. A possible explanation, suggested by Parish and Bromwich (1986), is that the Theresa AWS is located in the vicinity of the Ohio Range, a mountain plateau in the southeastern branch of the Transantarctic Mountains. It is assumed that this topographic feature may act to divert the katabatic flow blowing down from the East Antarctic Plateau away from the Theresa AWS. The smoother AMPS terrain may not allow for this sheltering effect, resulting in higher simulated wind speeds. Overall, we note improved correlation coefficients, which exceed 0.9 for T2m and surface pressure. Correlation coefficients are somewhat lower for the wind speed.

b. Cloud cover

Visible and infrared (IR) satellite sensors allow for estimates of cloud cover on a global scale (Rossow and Garder 1993). However, compared to lower latitudes, much greater uncertainty exists over Antarctica as cloud-top and ice sheet surface have comparable temperatures and albedos and, therefore, show weak contrasts in satellite imagery (King and Turner 1997; Rossow and Schiffer 1999). Moreover, thin cirrus cloud layers, typical of the Antarctic upper troposphere, are difficult to detect. Improved detection of polar clouds has been achieved more recently through satellite lidar measurements, in particular, those acquired by the Geoscience Laser Altimeter System (GLAS) aboard the polar-orbiting Ice, Cloud and land Elevation Satellite (ICESat) spacecraft (Spinhirne et al. 2005b; Wylie et al. 2007). This technique, which allows for height retrieval of single- or multiple-layer clouds, shows greater sensitivity to polar clouds when compared to IR sounders (Wylie et al. 2007). The lidar, however, provides coverage limited to along the orbit track. Spinhirne et al. (2005a) used all available orbit tracks from October 2003 to produce a synthetic cloud frequency map over all Antarctica for this month at 1° resolution in latitude and longitude [Fig. 2a; see also Fig. 2 in Spinhirne et al. (2005a)]. Here, the “cloud frequency” (CFreq) is computed as the ratio of the number of times when clouds were detected within each 1° grid box over the total number of observations in October 2003. Therefore, CFreq must be distinguished from the mean cloud fraction (CF), which results from averaging over time, for a given area, the actual fraction of the sky obscured by clouds (see Fig. 2c discussed below). The inclination of the satellite orbit did not allow coverage south of ~87°S. The total CF is not a standard output data source from AMPS Polar MM5. It is approximated as the integrated cloud optical depth, using the longwave absorption properties of the cloud liquid water (CLW) and the cloud ice water (CIW) between the surface and the top of the atmosphere (Fogt and Bromwich 2008). Using AMPS
6-hourly CF time series, a “GLAS similar” CFreq product was computed, defined for each 20-km model grid cell as the number of forecasts with above-zero CF among all AMPS forecasts for October 2003. It is noteworthy that AMPS forecasts from October 2003 were run on a version of Polar MM5 prior to the September 2005 upgrade, especially with lower horizontal resolution (30 km for domain 2). Here, the use of an older model version is only motivated by the comparison with the results from Spinhirne et al. (2005a).

Fairly good agreement is found between AMPS and GLAS-derived products for October 2003. The systematically lower values in Fig. 2c compared to Figs. 2a and 2b result from the weighting of cloud occurrence by the actual cloud fraction when computing the mean cloud cover. Zones of quasi-permanent cloud cover (red) are found over the ocean. Over the continent, the East Antarctic Polar Plateau exhibits the lowest cloud cover, especially over eastern Wilkes Land. The Antarctic Peninsula and a large portion of WA (the BA sector) show extensive cloudiness. A rightward-curved pattern of higher CFreq is seen stretching across central WA up to the southern tip of the Ross Ice Shelf both in AMPS and in the GLAS-derived product. The presence of this band of higher cloud amount will be further discussed in section 4, as it shows up again in our 2006–07 climatology.

Cloud measurements have been similarly derived from the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the National Aeronautics and Space Administration’s (NASA) Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, launched in May 2006. Figure 3 compares CFreq from October 2007 with CFreq from October 2006 (October 2007 – October 2006). The change in CFreq derived from CALIOP (Fig. 3a) is presented along with AMPS data (Fig. 3b). A reduction in CFreq is clearly visible over western WA (Ellsworth Land) in both figures. This brings further confirmation of the ability of AMPS Polar MM5 to correctly simulate the cloud cover. Figure 3 also provides an indication of a large interannual variability of the cloud cover over WA.

4. Results

a. 2006–07 meteorological context

Our study covers 2 yr of the AMPS archive. The significance of our results is conditioned upon the representativeness of the climate of WA during this time interval with respect to its long-term climatology. The ability of this short period to capture the long-term climate is admittedly limited, especially in this region of the globe. Indeed, the portion of the Southern Ocean adjacent to WA has been described as a major center of atmospheric variability in the extratropical Southern Hemisphere (Connolley 1997; Thompson and Wallace 2000; Guo et al. 2004; Van den Broeke and Van Lipzig 2004; Simmonds and King 2004; Fogt and Bromwich 2006; Yuan and Li 2008) and was consequently designated as the “West Antarctic pole of variability” by Connolley (1997). As shown by Yuan and Li (2008), three of the four dominant modes of variability, with time scales ranging from annual to decadal, share a nonnegligible amount of variance in this area. Nonetheless, as will be demonstrated thereafter, a number of indicators suggest that the 2006–07 period overall is
reflective of the average climate of WA from the past two decades.

Table 3 shows annual means calculated from ERA-Interim for the different time periods of interest and for a few atmospheric variables intended to summarize some essential climatic features: net precipitation ($P - E$), mean annual total precipitable water (PWAT), $T_{2m}$, and variables averaged (area weighted) over the Pacific sector of the Southern Ocean (shown in Fig. 1, MSLP). The error interval represents one standard deviation of the 1989–2008 mean annual time series.

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<tr>
<td>Pacific sector</td>
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<tr>
<td>MSLP (hPa)</td>
<td>982.1</td>
<td>983.5</td>
<td>982.8</td>
<td>982.8 ± 2.3</td>
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<tr>
<td>Grounded WAIS*</td>
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<tr>
<td>$P - E$ (mm yr$^{-1}$)</td>
<td>297.6</td>
<td>329.2</td>
<td>313.4</td>
<td>312.0 ± 28.6</td>
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<tr>
<td>PWAT (mm)</td>
<td>2.29</td>
<td>2.32</td>
<td>2.30</td>
<td>2.25 ± 0.10</td>
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<tr>
<td>$T_{2m}$ (K)</td>
<td>-23.4</td>
<td>-23.3</td>
<td>-23.3</td>
<td>-23.8 ± 0.6</td>
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* Area: $2.54 \times 10^6$ km$^2$.

(Pacific sector in Fig. 1). The main conclusion drawn from Table 3 is that, for all variables, the 2006–07 mean falls within the range of one standard deviation from the 20-yr average and, thus, does not depart significantly from the typical meteorological conditions in WA. A similar analysis was carried out using the Japanese 25-yr Reanalysis (JRA-25; Onogi et al. 2007) and produced the same results (not shown).

The moisture and heat transport to WA is also intimately linked to the annual march of the cyclonic activity over the adjacent Southern Ocean. Figure 4 provides a synthetic view of the MSLP monthly climatology during 1989–2008 over the Pacific sector of the Southern Ocean from ERA-Interim. It shows the monthly mean MSLP averaged over this ocean sector as well as the difference in MSLP between the Bellingshausen Sea (BS) and the Ross Sea (RS; BS minus RS). The individual ocean sectors are displayed in Fig. 1.

The 1989–2008 MSLP climatology (Fig. 4a) exhibits a marked semiannual cycle with minima in April and October and maxima in June and January. The occurrence of this semiannual oscillation (SAO) is a known climatic feature in the high southern latitudes (van Loon 1967; van den Broeke 1998; Bromwich and Wang 2008), although its amplitude has revealed large interannual and decadal variabilities (Simmonds and Jones 1998). On annual average, persistent low pressure is found off the coast of WA. However, its location generally oscillates between the Ross Sea in the winter and the Bellingshausen Sea in the summer (Bromwich and Wang 2008). While Fig. 4a confirms the existence of this seasonal shift, it also shows slightly more complex variations on the monthly time scale, the low pressure being found over the Ross Sea preferentially from April through July, and September–October, with a negligible MSLP difference in August. The intensity and the prevailing area of marine air inflow onto WA results from the concurrence of these two phenomena.
The years 2006 and 2007 (Figs. 4c and 4d) show significant departures from the climatology in Fig. 4a. The SAO is fairly weak in 2006 whereas it is more apparent in 2007, especially with a remarkable peak in MSLP in July. A sharp longitudinal shift of the low pressure is found between May and June 2006, following an abnormally strong pattern of autumnal cyclonic activity over the Bellingshausen Sea. This longitudinal oscillation is almost completely absent in 2007, which has lower MSLP values over the Ross Sea almost throughout the year. As a result, annual MSLP anomaly maps (not shown) reveal negative (weakly positive) anomalies over the Bellingshausen Sea (Ross Sea) in 2006, and positive (negative) anomalies over the Bellingshausen Sea (Ross Sea) in 2007. Overall, the 2-yr period shows a smaller departure from the 20-yr climatology than each year separately (Fig. 4b). Changes in precipitation over WA are induced by the atmospheric circulation associated with these contrasting MSLP patterns (Figs. 5a and 5b). However, the mean annual precipitation distribution for 2006–07 (Fig. 5c) shows only minimal deviation with respect to the ERA-Interim 1989–2008 climatology over most of WA, which suggests that this time period may be representative of the average precipitation conditions in WA during the last two decades.

b. Annual and seasonal means from AMPS

Figure 6 shows the 2006–07 annual means for four variables computed from the AMPS archive. The mean annual CF is shown in Fig. 6a. Greater CF is found over the BA sector, which is most exposed to moisture-laden ocean air. A major exception to the inland-decreasing distribution is a distinct tongue-shaped feature of higher CF over central WA, stretching from the BA sector up to the Transantarctic Mountains, bounded to the east and west by areas with much lower values. This pattern has already been noticed for October 2003 (Fig. 2). With respect to the topography, this elongation is found on the western (Ross sector) side of the central topographic
ridge, which separates the Weddell and Ross sectors of WA. This band does not follow a strictly meridional direction but shows a southwestward curvature toward the southern Ross Ice Shelf and the Queen Maud Mountain range (Transantarctic Mountains). This curvature likely results both from the persistent cyclonic circulation induced by low pressure systems over the Ross Sea and from the topographic constraint.

Figure 6b shows the mean annual $P - E$, or net accumulation ($P - E$) in mm, (c) 2-m potential temperature in K, and (d) 700-hPa resultant wind (black vectors) in m s$^{-1}$ and 700-hPa specific humidity (color scale) in g kg$^{-1}$. In (a)–(c), the black dashed-line contours show the model topography and the ocean has been intentionally masked. A nonlinear scale is used for the precipitation.

Figure 6c shows the mean annual 2-m potential temperature ($\theta_{2m}$), which removes the adiabatic cooling due to elevation increase. The high-elevated areas in central WA show significantly larger $\theta_{2m}$ than those observed on the flat, low-elevated ice shelves. Higher $\theta_{2m}$ values are found over the BA sector and over the Rockefeller
Plateau. In this latter area, higher $\theta_{2m}$ values are generally found at much lower elevations than in the Weddell sector. The horizontal and vertical components of the 700-hPa wind indicate that adiabatic compression on the leeward side of the MBL likely accounts for the relatively warmer conditions and low cloudiness in this area.

Figure 6d shows, as annual means, the 700-hPa horizontal resultant wind vectors overlaid on the specific humidity ($q$) at the same pressure level. This level, which corresponds approximately to 2600 m MSL, lies above the ice sheet’s surface over most of WA, with the exception of its southernmost part and of isolated peaks and mountain ranges. Over most of the Antarctic ice sheet, katabatic winds flow toward the north, with a leftward component under the action of the Coriolis force (e.g., Parish and Bromwich 2007). MBL is the only Antarctic region where the mean katabatic flow has a strong southward component and therefore has a direction parallel to the 700-hPa flow, suggesting possible mutual enhancement between surface and upper-level flows.

Northeasterly winds prevail at 700 hPa along the coast of WA, in contrast to northwesterly winds farther offshore. The northeasterly component of the wind flow is found to be particularly marked over MBL. The central topographic ridge acts as a major division in the wind pattern, with wind blowing in opposite directions on either side. These distinct flows are related to two cyclonic cells centered, respectively, over the southern Ronne Ice Shelf and northeast of the Ross Ice Shelf. This contrast is manifested in $q$ values, reflecting the moisture transport at 700 hPa. The inflow of moist ocean air on the western side of the central divide and the outflow of dry continental air on its eastern side account for a northeast–southwest bending of the $q$ isopleths. A weak, westerly flow is found across the central topographic divide.

Seasonal means from December 2006 to November 2007 are shown for CF (Fig. 7) and precipitation (Fig. 8). We note that, as King and Turner (1997) suggest, the standard 3-month definition of seasons may not be as appropriate for Antarctica as for midlatitudes, due to the long winter season and the shortness of the transitional seasons. Note that the seasonal maps are more reflective of the meteorological context from 2007 (Figs. 4d and 5b). The greatest cloudiness and precipitation occur in autumn (March–May, MAM) and winter (June–August, JJA), and the lowest in summer (December–February, DJF). This suggests that moisture transport and precipitation onto WA are primarily controlled by cyclonic activity (more intense in nonsummer months) rather than by the air temperature (the saturation vapor pressure decreases exponentially with temperature). A well-delineated pattern is visible in MAM whereas JJA shows more widespread CF and precipitation.

c. MSLP patterns and marine air inflow onto WA

The intensity and spatial distribution of the cyclonic activity over the Pacific sector of the Southern Ocean play a determinant role in the climate of WA. In this section, we examine how the changing location of the mean center of low pressure off WA affects the inflow of marine air onto the ice sheet, with consequences for CF, precipitation, and surface temperature. The difference in mean MSLP between the Bellingshausen Sea and the Ross Sea (ocean sectors defined as in Fig. 1) was used to sort AMPS 6-hourly forecasts into two categories (termed composites I and II), depending on the sign and magnitude of the difference. Composite I is associated with an MSLP difference being positive above $+5$ hPa (lower pressure in the Ross Sea). Composite II is associated with an MSLP difference being negative, below $-5$ hPa (lower pressure in the Bellingshausen Sea). Figures 9a and 9b show the mean 500-hPa geopotential height ($Z500$) field from AMPS associated with each composite. A Student’s $t$ test is used to determine, for each grid point, whether composites I and II are significantly different from each other. Areas where the statistical significance exceeds the 95% confidence level are shaded gray in Figs. 9a and 9b.

During 2006–07, the two composites accounted for 42% and 34% of occurrences, respectively. Their monthly frequency distributions are shown in Figs. 9c and 9d. Consistent with Fig. 4, composite I is predominantly found in winter–spring whereas composite II occurs primarily in summer–fall. Figure 10 shows the AMPS mean CF, precipitation rate, and T2m anomalies with respect to the 2-yr average conditions.

Composite I shows an amplified $Z500$ wave pattern (Fig. 9a). A deep trough centered over the Ross Sea steers the circumpolar belt of westerlies toward MBL, while the western branch of the cyclonic flow exports continental air northward, along the Transantarctic Mountains and off Victoria Land, in East Antarctica. A second trough centered to the east of the Ronne–Filchner Ice Shelf brings air from the western DML. These differences in air properties on either side of the topographic ridge account for the northeast–southwest bending of the 700-hPa $q$ isopleths (Fig. 10a).

In composite II, the area of greater cloudiness and precipitation is shifted to the east of WA, with minimal cloud cover over the Ross Sea sector and a visible contrast in precipitation across the central topographic ridge. The location of the midtropospheric trough over the Amundsen Sea (Fig. 9b) inhibits the northerly airflow over MBL, steering the westerly belt away from the coast.
of MBL. The position of the trough over the eastern Ross Ice Shelf acts to steer continental air from over the Transantarctic Mountains toward eastern MBL and the Ross Sea sector of WA. Downstream, east of the Amundsen Sea trough, eastern Ellsworth Land receives enhanced precipitation, with the Ellsworth Mountains standing as a major topographic barrier to the atmospheric circulation. The quasi-zonal, easterly flow over the BA sector of WA inhibits the inflow of marine air.

Based solely on the seasonal distribution of composites I and II (Fig. 9), a colder air inflow pattern would be expected to occur over MBL than over Ellsworth Land.
Yet, this conclusion is contradicted by the temperature anomaly patterns seen in Figs. 10g and 10h, suggesting that the effects of the contrasting atmospheric circulation dominate over the seasonal signal. Overall, the magnitude of the cloud and precipitation anomalies is greatest on the coast of western MBL and the limit between the two regimes is found to be almost parallel to the 90°W meridian. For T2m, the area of maximum change is found farther inland, on the Rockefeller Plateau, on the leeward side of the coastal mountain range, extending up to the northeastern coastal edge of the Ross Ice Shelf.
d. Example of marine air inflow onto WA in August 2006

The following case study provides an example of a particularly intense marine air intrusion onto WA in early August 2006. This episode was accompanied by a frontal cloud band clearly discernable in IR satellite imagery. Figure 11 shows the composite IR image for 0900 UTC 5 August 2006, obtained from the UW-SSEC, along with the precipitation rate simulated by AMPS for 0600 UTC 5 August. The cloud band, which is seen extending perpendicularly to the MBL coast, was associated with a low pressure system (Fig. 12) that developed from 1 August over the eastern Ross Sea and remained active as well as quasi-stationary through 5 August, before decaying.

The pressure trough induced, to the west, an equatorward outflow of continental polar air from Victoria Land. Strong temperature gradients formed to the north of the trough, where cold continental air encountered warmer maritime air, and to the east of the trough, due to a pressure ridge in the Bellingshausen Sea (Fig. 12). The latter gradient zone was associated with the frontal cloud band (Fig. 11a), enhanced precipitation (Fig. 11b), and moisture convergence over MBL. This episode produced warm air advection over central WA. Interestingly, the mean T2m recorded by the Byrd AWS from 1 to 3 August reached −16.7°C, only 0.5°C below the mean T2m in December 2006. This case study illustrates how a persistent low pressure area over the Ross Sea, a blocking high over the Bellingshausen Sea, and the northeastward position of Victoria Land create conditions favorable for frontal cloud formation and strong warm and moist air advection over central WA.

5. Summary and discussion

In this study, 20-km horizontal resolution numerical weather forecasts from the AMPS archive were utilized to investigate the climate of WA during 2006–07. An evaluation of this dataset was performed over WA.
FIG. 10. Mean conditions associated with a surface pressure low centered over (left) RS and (right) BS based on the 2006–07 AMPS archive. The variables, shown as anomalies with respect to the 2006–07 mean, are (a),(b) 700-hPa resultant wind vectors in m s$^{-1}$ and 700-hPa specific humidity in g kg$^{-1}$, (c),(d) cloud fraction, (e),(f) precipitation rate initially in mm h$^{-1}$ but expressed here in % with respect to the 2-yr average, and (g),(h) 2-m temperature in K.
Simulated near-surface pressures, temperatures, and wind speeds were compared with observations from the West Antarctic AWS. Overall, the model performance was found to be very similar to a coarser-resolution version of the AMPS model previously evaluated, with small biases and high correlations between modeled and observed variables. AMPS total cloud cover was also compared with estimates of monthly cloud fractions derived from spaceborne lidar measurements. Very good agreement was found between both datasets, both in spatial distribution and in magnitude.

On the 2006–07 annual means computed from AMPS forecasts, the most salient feature is a rightward-curved, elongated pattern of higher cloudiness, accumulation, and $\theta_{2m}$ stretching over central WA. The presence of this tongue reveals the frequent intrusions of marine air, mostly on the BA and Ross Sea sectors of WA, induced by depressions centered over the Ross and Amundsen Seas. The ice sheet’s topography, which causes the descent of air onto the Ross and Ronne–Filchner Ice Shelves, also acts to reduce cloudiness and precipitation on either side of the central ice divide. A southerly flow of dry and cold continental air on the eastern side of the divide, as opposed to a moister and milder inflow on its western side, contributes to enhance the contours of the tongue-shaped pattern. In addition, we demonstrate that low pressure areas centered over the Ross Sea are most effective in conveying heat and moisture onto WA, whereas pressure troughs located over the Bellingshausen Sea tend to inhibit the inflow of maritime air onto most of the ice sheet. Using ERA-Interim reanalysis, we found that, during the 2006–07 interval, WA experienced meteorological conditions that were very similar to the 1989–2008 average, suggesting that our results are reflective of long-term climatic features of WA.

The representativeness of the climate of WA in 2006–07 with respect to the 20-yr climatology justifies comparison of the simulated P-E with two recent climatological Antarctic accumulation datasets. Van den Broeke et al. (2006) used a 55-km horizontal resolution regional climate model calibrated with glaciological observations to simulate the Antarctic surface mass balance for 1980–2004. Arthern et al. (2006) utilized satellite passive microwave measurements to interpolate accumulation observations, achieving a coarser resolution of 100 km.

**FIG. 11.** (a) Composite satellite IR image for 0900 UTC 5 Aug 2006 from the UW-SSEC archive. (b) AMPS forecast precipitation rate in mm h$^{-1}$ for 0600 UTC 5 Aug 2006. The thin black contours show the model topography.

**FIG. 12.** The 500-hPa geopotential height in gpm (black contours, 40-gpm intervals) and 500-hPa temperature in °C (grayscale) from ERA-Interim for 0600 UTC 5 Aug 2006.
Table 4. Mean annual total accumulation ($P - E$) for five West Antarctic drainage basins derived from the 2006–07 AMPS archive (this study). The results from Van den Broeke et al. (2006) are shown for comparison (VDB 2006). The error interval was derived by these authors from the calibration procedure. Units are kg m$^{-2}$ yr$^{-1}$ for the accumulation and 10$^3$ km$^2$ for the area of each basin.

<table>
<thead>
<tr>
<th>Description</th>
<th>Basin No.</th>
<th>Area (km$^2$)</th>
<th>Total accumulation$^b$ (P – E)</th>
<th>VDB 2006 Area (km$^2$)</th>
<th>Total accumulation$^c$ (P – E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ross IS sector</td>
<td>11</td>
<td>576</td>
<td>88</td>
<td>584</td>
<td>79 ± 1.6</td>
</tr>
<tr>
<td>Rockefeller Plateau</td>
<td>12</td>
<td>240</td>
<td>49</td>
<td>223</td>
<td>32 ± 0.8</td>
</tr>
<tr>
<td>Coastal MBL</td>
<td>14</td>
<td>135</td>
<td>152</td>
<td>137</td>
<td>125 ± 3.0</td>
</tr>
<tr>
<td>Thwaites Glacier</td>
<td>15</td>
<td>420</td>
<td>260</td>
<td>418</td>
<td>197 ± 4.9</td>
</tr>
<tr>
<td>Coastal Ellsworth</td>
<td>16</td>
<td>82</td>
<td>100</td>
<td>79</td>
<td>70 ± 2.4</td>
</tr>
</tbody>
</table>

$^a$ Basins numbers are based on Van den Broeke et al. (2006).

$^b$ The 2006–07 annual mean.

$^c$ The 1980–2004 annual mean.

In WA, both studies found significantly greater accumulation over MBL than previous accumulation compilations (e.g., Giovinetto and Bentley 1985; Vaughan et al. 1999). Good agreement is found overall between AMPS (Fig. 6b) and Van den Broeke et al. (2006), especially along the high-accumulation coasts of Ellsworth Land and MBL. In our study and in Van den Broeke et al. (2006), accumulation is however substantially higher than in Arthern et al. (2006) over the coastal MBL.

For a quantitative assessment, Table 4 presents the mean annual $P - E$ derived from the 2006–07 AMPS archive for five West Antarctic drainage systems and includes the results from Van den Broeke et al. (2006) for the same five basins. It appears that AMPS values systematically exceed those from Van den Broeke et al. (2006). Our results potentially suggest higher snowfall over WA than has been previously estimated. However, one must bear in mind that this upward adjustment may result from the discrepancy between the periods of study, the enhanced model resolution, the omission of snowdrift sublimation in our calculation of $P - E$ [of the same order of magnitude as $E$; Bintanja (1998)], or a combination of these effects.

From a glaciological perspective, the high horizontal resolution of the AMPS model allows for realistic simulation of the climate regime at the drilling site of the WAIS Divide deep ice coring project (see location in Fig. 1). Table 5 summarizes the mean annual $P - E$ and $T_{2m}$ at WAIS Divide in 2006 and 2007. The 2006–07 mean annual $P - E$ value (400 mm yr$^{-1}$) is found to be substantially larger than local estimates of long-term accumulation rates derived from ice cores (~200 mm yr$^{-1}$; Banta et al. (2008)). This discrepancy likely results from insufficient model resolution in a high-gradient zone, where the accumulation drops rapidly from 400 to 200 mm yr$^{-1}$, and from ablation processes not accounted for by $P - E$. The 100-mm increase in accumulation between 2006 and 2007 can be linked to the changes in the atmospheric circulation previously described and denotes the marked sensitivity of the local accumulation to the atmospheric variability. The mean annual $T_{2m}$ is found to increase only slightly (+0.5°C) between 2006 and 2007. It has been shown that the stable water isotope signature present in ice cores, used to reconstruct past temperature time series, is affected by the seasonal distribution of precipitation (Schlosser 1999; Van Lipzig et al. 2002; Fujita and Abe 2006) and by the spatial origin of moisture (e.g., Delmote et al. 2000), which also varies seasonally (Sodemann and Stohl 2009). In this respect, the oxygen isotope ratio ($\delta^{18}O$) depends, among other factors, upon the temperature conditions when the condensation and subsequent precipitation occur, and is therefore biased toward warmer-than-normal conditions (Schlosser 1999; Van Lipzig et al. 2002; Fujita and Abe 2006). After Van Lipzig et al. (2002), we present in Table 5 the precipitation-weighted 2-m temperature ($T_{2m}$), where the temperature at each 6-hourly forecast is weighted by the corresponding precipitation rate before calculating the mean. Unlike the increase observed for $T_{2m}$, $T_{2m}$ is found to decrease, which can be attributed to the change in the precipitation seasonality (spring–winter maximum in 2007, more even temporal distribution throughout 2006). Nevertheless, compared to the significant increase in accumulation, the temperature changes are small. It is not clear how the widespread föhn effect observed over MBL influences the temperature and precipitation conditions at WAIS Divide.

Table 5. Net total accumulation ($P - E$), mean $T_{2m}$, and mean precipitation-weighted 2-m temperature ($T_{2m}$) at the WAIS Divide drilling site (79.468°S, 112.086°W) during 2006 and 2007 from the AMPS forecast archive. Neither $T_{2m}$ nor $T_{2m}$ has not been adjusted for the difference between the reported site elevation and the model topography.

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P - E$ (mm w.e.)</td>
<td>361</td>
<td>461</td>
<td>100</td>
</tr>
<tr>
<td>$T_{2m}$ (°C)</td>
<td>-28.0</td>
<td>-27.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$T_{2m}$ (°C)</td>
<td>-22.3</td>
<td>-22.9</td>
<td>-0.6</td>
</tr>
</tbody>
</table>
The present study may yield further insights into recent climate changes in WA. It underlines the importance of the seasonality of changes in offshore cyclonic activity and the spatial distribution of these changes between the Ross and Bellingshausen Seas. For example, we showed that depressions over the Bellingshausen Sea trigger only limited marine air inflow onto WA. Intrusions of offshore air masses are also more consequential in winter when the thermal contrast between continental and marine air is greatest and the temperature inversion at the ice sheet’s surface is marked. These findings must be read within the context of the projected increase in cyclonic activity in the South Pacific sector of the Southern Ocean in the twenty-first century. Krinner et al. (2007) found a deepening of low pressure over the Amundsen Sea between the end of the twentieth century and the beginning of the twenty-first century. Lynch et al. (2006) indicate an amplification of the annual cycle of the MSLP off WA in the first half of the century, with an increase in cyclonicity in the Ross Sea in winter and in the Bellingshausen Sea in summer. Using the AMPS archive, we found that in 2006, when the cyclonicity was lower than average in the Ross Sea, the grounded WAIS (without the Antarctic Peninsula) received 400 mm w.e. precipitation spatially averaged. By contrast, in 2007, when cyclonicity was abnormally strong in the Ross Sea, it received 453 mm w.e. (note that these values substantially exceed ERA-Interim $P - E$ estimates from Table 3). Thus, an intensification or an increased persistence of the pressure trough over the Ross Sea is likely to have positive consequences on the ice sheet’s surface mass balance. We further calculated that the mean annual temperature average over the grounded WAIS increased by 0.5°C, from $-24.6^\circ$ to $-24.1^\circ$C between 2006 and 2007.

While there is little doubt that the climate of WA is influenced by the dominant modes of climate variability over the neighboring Southern Ocean, disentangling these modes and characterizing their interactions with the ice sheet’s environment are particularly challenging tasks. Guo et al. (2004) examined how the El Niño–Southern Oscillation (ENSO) phenomenon modulates the precipitation over western WA, reporting a shift in the correlation between both around 1990. Fogt and Bromwich (2006) demonstrated that the correlation between ENSO and the Southern Annular Mode (SAM) determines the strength of the teleconnection between ENSO and the Antarctic climate. Bromwich et al. (2004) investigated a pronounced El Niño–La Niña cycle in 1996–99 and found that El Niño events were associated with a highly positive pressure anomaly centered over the Bellingshausen Sea, when compared to the subsequent La Niña events. Their results—showing contrasting $T_{2m}$, CF, and $P - E$ between western WA and the western Weddell Sea—are fairly reminiscent of the spatial contrast between eastern and western WA seen in Fig. 10. However, the ENSO signature over the Southern Ocean has proved to vary spatially over time (e.g., the 1987 El Niño versus the 1997–98 El Niño), suggesting that the two ENSO episodes may have had opposite effects on West Antarctic climate. Interestingly, ice cores drilled in WA during the International Transantarctic Scientific Expedition (ITASE) suggest an inverse relationship between the annual accumulation rates in Ellsworth Land and inland of MBL on decadal to centennial time scales (Kaspari et al. 2004, Fig. 5). How the multiple examples of this spatial opposition, such as those presented in our study, relate to the known modes of climate variability certainly deserves further investigation.

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