Large-Scale Forcing of the Amundsen Sea Low and Its Influence on Sea Ice and West Antarctic Temperature

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ABSTRACT

Using empirical orthogonal function (EOF) analysis and atmospheric reanalyses, the principal patterns of seasonal West Antarctic surface air temperature (SAT) and their connection to sea ice and the Amundsen Sea low (ASL) are examined. During austral summer, the leading EOF (EOF1) explains 35% of West Antarctic SAT variability and consists of a widespread SAT anomaly over the continent linked to persistent sea ice concentration anomalies over the Ross and Amundsen Seas from the previous spring. Outside of summer, EOF1 (explaining ~40%–50% of the variability) consists of an east–west dipole over the continent with SAT anomalies over the Antarctic Peninsula opposite those over western West Antarctica. The dipole is tied to variability in the southern annular mode (SAM) and in-phase El Niño–Southern Oscillation (ENSO)/SAM combinations that influence the depth of the ASL over the central Amundsen Sea (near 105°W). The second EOF (EOF2) during autumn, winter, and spring (explaining ~15%–20% of the variability) consists of a dipole shifted approximately 30° west of EOF1 with a widespread SAT anomaly over the continent. During winter and spring, EOF2 is closely tied to variability in ENSO and a tropically forced wave train that influences the ASL in the western Amundsen/eastern Ross Seas (near 135°W) with an opposite-sign circulation anomaly over the Weddell Sea; the ENSO-related circulation brings anomalous thermal advection deep onto the continent. The authors conclude that the ENSO-only circulation pattern is associated with SAT variability across interior West Antarctica, especially during winter and spring, whereas the SAM circulation pattern is associated with an SAT dipole over the continent.

1. Introduction

Many recent studies have identified significant surface climate change over West Antarctica and the Antarctic Peninsula since the 1950s, including warming of the northeast Antarctic Peninsula during austral summer (Turner et al. 2005; Orr et al. 2008); warming of the western Antarctic Peninsula during austral autumn, winter, and spring (King 1994; Vaughan et al. 2001, 2003; Turner et al. 2005; Ding and Steig 2013; Clem and Fogt 2015); and warming of West Antarctica during winter and spring (Steig et al. 2009; Ding et al. 2011; Schneider et al. 2012; Bromwich et al. 2013; Nicolas and Bromwich 2014). Apart from the warming on the northeast peninsula, the recent Antarctic Peninsula/West Antarctica climate trends lie within their respective ranges of internal variability and are likely tied to natural decadal variability in atmospheric circulation rather than anthropogenic forcing (Jones et al. 2016a; Turner et al. 2016).

The western peninsula and West Antarctic warming are both linked to regional circulation changes associated with teleconnections stemming from the tropical Pacific and Atlantic and related reductions in sea ice concentration in the Amundsen and Bellingshausen Seas. Autumn warming of the western peninsula has been linked to a deepening of the Amundsen Sea low (ASL; Raphael et al. 2016; Turner et al. 2013a; Fogt et al. 2012a) and associated reductions in sea ice concentration along the western peninsula coast that persist through the following winter and spring (Meredith and King 2005; Stammerjohn et al. 2008; Turner et al. 2013b; Ding and Steig 2013). Furthermore, teleconnections from the tropical Atlantic are also suggested to deepen the ASL during winter (Li et al. 2014), further reducing sea ice concentrations along the western peninsula and amplifying the winter warming seen there. During spring, a strengthened anticyclone over the South Atlantic, associated with increased La Niña conditions and/or increased sea surface temperatures (SSTs) over the western tropical Pacific after 1979, is also likely to have contributed to the western peninsula warming and reduced sea ice concentrations in the Amundsen and Bellingshausen Seas during spring (Schneider et al. 2012; Clem and Fogt 2015; Clem and Renwick 2015).
Despite being geographically close, the mechanisms suggested to have caused warming of interior West Antarctica during winter and spring are different from those that have warmed the peninsula. A modeling study by Ding et al. (2011) concluded that winter warming of West Antarctica is caused by an anticyclonic circulation over the Amundsen Sea forced by increasing SSTs in the central tropical Pacific. The anticyclone brings warm air advection onto the continent via western West Antarctica; however, this circulation pattern would be associated with cooling over the peninsula during winter, which is not seen in observations and is inconsistent with the winter deepening of the ASL suggested by Li et al. (2014). In spring, an observed deepening of the ASL over the Ross Sea tied to the Pacific decadal oscillation shift to its negative phase after 1979 brings increased warm air advection to western West Antarctica and the Ross Ice Shelf, which has been linked to the spring warming seen there (Clem and Fogt 2015). This circulation pattern is consistent with western peninsula warming in spring, but it is also associated with cold air advection over central portions of the continent (Clem and Renwick 2015), contrary to the significant warming observed there during spring (Bromwich et al. 2013; Nicolas and Bromwich 2014). Schneider et al. (2012) suggests that spring warming of West Antarctica is more related to the reduced sea ice concentrations in the Bellingshausen and Amundsen Seas seen in this season.

More recently, it has been shown that the warming on the Antarctic Peninsula stopped after the late 1990s with significant cooling observed over 1999–2014 (Turner et al. 2016; Oliva et al. 2017). However, other studies in the past five years have identified a continuation of the warming through the 2000s, primarily on the western peninsula (Ding and Steig 2013; Clem and Fogt 2015). Turner et al. (2016) found peninsula-wide cooling to be strongest during summer and to be related to an increase in cold, easterly winds and sea ice compaction along the eastern peninsula. But this summertime circulation differs markedly from the enhanced anticyclonic circulation over the South Atlantic observed in spring over 1979–2012 tied to the western peninsula warming (Clem and Fogt 2015).

Clearly, the mechanisms explaining the regional warming and cooling trends over the West Antarctic region are complex and not fully understood. The goal of this study is to provide a comprehensive seasonal summary of the leading spatial patterns of West Antarctic surface air temperature (SAT) and the role of large-scale climate forcing of the ASL associated with the two leading modes of Southern Hemisphere atmospheric circulation: the southern annular mode (SAM) and El Niño–Southern Oscillation (ENSO).

Our approach builds on previous work and aims to place recent Antarctic SAT change in a longer and seasonal context. Another goal of this study, which has not been previously explored, is to examine the influence of sea ice concentration anomalies and their connection to the ASL and the seasonal SAT patterns. Previous studies have linked patterns of Antarctic-wide surface temperature to the large-scale circulation (e.g., Schneider and Steig 2002; Schneider et al. 2004), but those studies examined temperature over the full continent (rather than focusing on West Antarctica only) with a relatively short (less than 20 years) temperature record. Marshall and Thompson (2016) recently examined how the leading patterns of Southern Hemisphere circulation affect Antarctic SAT, but their study focused on the patterns of circulation rather than patterns of SAT. Here, the focus is on the leading patterns of SAT, and on the West Antarctic region only using 37 years of modern reanalysis SAT data, nearly doubling the period of analysis of previous studies. Using reanalyses provides spatially continuous SAT over the continent and adjacent Southern Ocean, allowing for improved understanding of how West Antarctic SAT patterns are related to sea ice, which has previously been shown to strongly influence West Antarctic SAT (e.g., Meredith and King 2005; Turner et al. 2013b; Schneider et al. 2012).

The paper is laid out as follows: section 2 provides an overview of the data and methods used, results are given in section 3, and a discussion and conclusions are offered in section 4.

2. Data and methods

Monthly-mean atmospheric fields are from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; Dee et al. 2011) employed at 1.5° × 1.5° resolution for the period 1979–2015. As ERA-Interim is considered superior over the high southern latitudes (Bromwich et al. 2011; Bracegirdle and Marshall 2012), particularly in the Amundsen Sea region (Bracegirdle 2013; Jones et al. 2016b), only results from ERA-Interim are shown. Other contemporary reanalysis datasets were examined and the results were consistent with those presented here using ERA-Interim.

The central pressure and location of the ASL is investigated following Fogt et al. (2012a) using the ERA-Interim monthly-mean minimum sea level pressure value in the region 55°–75°S, 180°–60°W. Sea ice concentration is examined using monthly-mean data from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature dataset (Rayner et al. 2003; http://www.metoffice.gov.uk/hadobs/hadisst/) at 1° × 1° latitude–longitude.
resolution. Tropical SSTs are examined using the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST version 4 dataset (ERSSTv4; Huang et al. 2015; Liu et al. 2015) at 2° × 2° latitude–longitude resolution (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v4.html).

Monthly ENSO activity is monitored using the Southern Oscillation index (SOI) and tropical Pacific SST anomalies averaged over 5°N–5°S in the Niño-4 (160°E–150°W), Niño-3.4 (170°–120°W), and Niño-3 (150°–90°W) regions, accessed from the Climate Prediction Center (CPC; www.cpc.ncep.noaa.gov/data/indices). The SAM is monitored using the CPC’s monthly Antarctic Oscillation index, which is calculated by projecting monthly 700-hPa geopotential height anomalies onto the leading empirical orthogonal function of monthly 700-hPa geopotential heights poleward of 20°S. Similar results are obtained using the observation-based index of Marshall (2003), but given our focus on West Antarctica and the gap in pressure observations over the South Pacific/West Antarctic sector used to compute the Marshall (2003) index, the CPC’s reanalysis-based index is preferred.

The leading two patterns of West Antarctic SAT are investigated using the first and second empirical orthogonal function (EOF; Wilks 2011) of seasonal-mean temperature anomalies from the 1981–2010 climatological mean; the anomaly field was weighted by the square root of the cosine of latitude prior to calculating the EOFs. The focus of this study is on the first two EOFs because both are unique and distinguishable from their neighboring EOFs following North et al. (1982); the third EOF is not distinguishable from the fourth EOF in all seasons.

Seasons are defined as 3-month averages with respect to the Southern Hemisphere: summer is December–February (DJF), autumn is March–May (MAM), winter is June–August (JJA), and spring is September–November (SON). Summer refers to the December year (i.e., data span March 1979–February 2016).

Relationships with ENSO, SAM, and the atmospheric circulation/sea ice are investigated using linear regression and correlation analysis. The principal component time series are first standardized and therefore regression coefficients are with respect to changes of one standard deviation. We investigate nonlinear aspects of identified relationships through anomaly composites and composite differences. Statistical significance of regressions, correlations, and composites is calculated using a two-tailed Student’s t test.

3. Results

a. The principal patterns of West Antarctic SAT variability

Figure 2 shows the first and second EOFs of seasonal SAT anomalies across the West Antarctic region. During DJF (Fig. 2a), EOF1 explains 35% of the SAT variability and consists of a widespread anomaly across the interior continent and adjacent Southern Ocean. For seasons outside of DJF (Figs. 2c,e,g), EOF1 explains approximately 40%–50% of the SAT variability and consists of a dipole over the continent with opposite sign anomalies between the Antarctic Peninsula and western West Antarctica/Ross Ice Shelf. The DJF anomalies are maximized over the interior continent, whereas in seasons outside of DJF the anomalies are maximized over the Ross Ice Shelf and offshore in the Ross/western Amundsen Seas.

The EOF2 patterns explain approximately 15%–20% of the SAT variability and they consist of a dipole shifted ~30° westward from EOF1 (Figs. 2b,d,f,h). The EOF2 patterns for MAM, JJA, and SON appear to be in quadrature with EOF1 (i.e., the patterns are shifted half a wavelength from EOF1 to EOF2) such that the maxima in EOF2 lie roughly over the zero regions of EOF1. This suggests a wave response and perhaps a propagating pattern in these seasons, which is not apparent in DJF. A noticeable difference from EOF1 is
FIG. 2. (left) EOF1 and (right) EOF2 of 37-yr (1979–2015) seasonal-mean West Antarctic 2-m temperature anomalies for (a),(b) DJF, (c),(d) MAM, (e),(f) JJA, and (g),(h) SON. Eigenvectors are normalized and indicated by color bar. Also given above each panel is the percentage of variance explained by each EOF. The map domain is 60°–90°S, 169.5°E–49.5°W; longitude interval is 15° starting at 170°E and latitude interval is 10°.
that the SAT anomalies are maximized across the Bellingshausen/eastern Amundsen Seas extending eastward to the Antarctic Peninsula and poleward onto the continent. The EOF2 pattern for DJF is markedly different from the EOF2 pattern seen in other seasons and is more similar to the EOF1 patterns for MAM, JJA, and SON (cf. Fig. 2b and Figs. 2c,e,g) with local maxima in the Weddell Sea and the Ross Ice Shelf.

b. Relationships with large-scale climate forcing and atmospheric circulation

Detrended correlations of EOF1 and EOF2 principal component time series (PC1 and PC2, respectively) with ENSO indices and the SAM index are shown in Table 1. During all seasons, PC1 is significantly correlated with the SAM index, accounting for 30%–50% of PC1 variability in all seasons but DJF. During DJF ENSO and the SAM index are equally correlated with PC1, each accounting for around 10%–15% of the variability in PC1. The same sign and magnitude of the DJF PC1 correlation with ENSO and SAM is consistent with the strong similarities in the ENSO and SAM-related circulation anomalies over the South Pacific during DJF (Karoly 1989; L’Heureux and Thompson 2006). Possible reasons for the relatively weak PC1 correlations with ENSO and SAM compared to other seasons, including the role of lagged sea ice effects, are discussed in the next section.

During MAM, the SAM pattern alone dominates variability in PC1, with nearly 50% of the PC1 variance explained by the SAM index. During JJA and SON, PC1 is significantly correlated with both the SAM index and tropical Pacific SSTs, although the correlations with the SAM are consistently stronger than with the tropics. Therefore the SAM pattern alone dominates PC1 in MAM, while the tropics may play a complimentary (i.e., they reinforce the SAM pattern) but weaker role during JJA and SON. The sign of the correlations implies that positive phases of EOF1 during DJF (i.e., a widespread positive SAT anomaly over the continent) are related to combined El Niño/negative SAM circulations, while outside of DJF positive phases of EOF1 (i.e., strong negative SAT anomalies across western West Antarctica and positive SAT anomalies over the peninsula) are associated with positive SAM and combined La Niña/positive SAM circulation in JJA and SON. It should be noted that during JJA, the negative relationship between central tropical Pacific SSTs and EOF1 is consistent with results presented in Ding et al. (2011).

The PC2 correlations show a much stronger connection to tropical variability, with no significant correlation with the SAM index during any season. Correlations with tropical Pacific SSTs are strongest during JJA and SON ($p < 0.01$), with same-sign but weaker correlations seen in MAM significant only at $p < 0.10$. The sign of the PC2 correlations indicates that negative SST anomalies over the central tropical Pacific/La Niña conditions are associated with positive phases of PC2 (i.e., widespread positive SAT anomalies over the continent during JJA and SON). The SON PC2 correlations are consistent with the findings of Schneider et al. (2012) and Clem and Fogt (2015), which connected recent warming of continental West Antarctica to La Niña–like tropical forcing. However, during JJA the correlations imply that negative SST anomalies over the central tropical Pacific/La Niña conditions are more strongly linked to positive SAT anomalies over the continent compared to the negative phase of PC1 (where warming is confined to extreme western West Antarctica), which suggests that positive central tropical Pacific SST anomalies may not fully explain the continental warming in JJA as previously shown by Ding et al. (2011).

Regressions of 500-hPa geopotential heights and 2-m temperature onto the standardized PCs are shown in Figs. 3 and 4, respectively. The DJF circulation associated with PC1 resembles a SAM pattern with positive height anomalies over Antarctica and a zonally oriented band of negative height anomalies across the mid-latitudes (Fig. 3a). Given that PC1 is equally correlated with the SAM index and with ENSO-related SST anomalies in DJF and that ENSO and SAM are strongly correlated in DJF (L’Heureux and Thompson 2006; Fogt et al. 2011), this pattern may represent a combination of ENSO and SAM influences.

Outside of DJF, the PC1 circulation anomalies more strongly resemble a SAM/zonal wave three pattern with same-sign height and SAT anomalies over the Antarctic continent (Figs. 3c,e,f and 4c,e,f, respectively). The most
FIG. 3. Seasonal regression of 500-hPa geopotential heights onto standardized (left) PC1 and (right) PC2, 1979–2015, for (a),(b) DJF, (c),(d) MAM, (e),(f) JJA, and (g),(h) SON. Contour interval is 10 m. Statistical significance of regressions at $p < 0.10$, $p < 0.05$, and $p < 0.01$ are shaded and indicated by color bar. Map domain is 20°–90°S; longitude interval is 15° and latitude interval is 10°.
FIG. 4. As in Fig. 3, but for 2-m temperature. Contour interval is 0.5°C. Map domain is 60°–90°S; longitude interval is 15° and latitude interval is 10°.
prominent circulation feature related to PC1 is over the high-latitude South Pacific near the ASL. During MAM, JJA, and SON, one positive standard deviation of PC1 is associated with a 40–60-m negative height anomaly/deepened ASL over the central Amundsen Sea (between 90° and 120°W), a ~1°C positive SAT anomaly over the Antarctic Peninsula and Weddell Sea, and a 2°–4°C negative SAT anomaly over western West Antarctica and the Ross Ice Shelf.

Consistent with the correlations, the PC1 circulation outside of DJF resembles a SAM-only pattern during MAM, and a combined SAM/tropically forced wave train during JJA and SON like that described by Ding et al. (2012). Therefore, the SAT dipole over the continent is likely tied to the ASL response to SAM forcing during MAM, and to simultaneous in-phase ENSO/SAM forcing during JJA and SON (e.g., Fogt et al. 2011). Moreover, spatial correlations between 500-hPa regression maps using PC1 and the SAM index are highly correlated ($r > 0.8$) in all seasons.

Regression of PC2 for DJF and MAM do not show any robust ENSO or SAM-related circulation characteristics, consistent with the weaker PC2 correlations with climate indices (Table 1). However, in MAM there is a weak zonal wave-3 pattern noted along ~50°S similar to the pattern described by Raphael (2004) (Fig. 3d), and the detrended correlation over 1979–2015 of MAM PC2 and the Raphael (2004) wave-3 index is 0.40, significant at $p < 0.05$.

During JJA and SON, PC2 regression maps depict a wave train emanating from the east coast of Australia that strongly resembles the first Pacific–South American mode of Mo and Paegle (2001), which is consistent with the strong PC2 correlations with ENSO in these seasons. The ASL again appears to be the dominant circulation feature during JJA and SON, with positive phases of PC2 associated with a deepening (by ~20–40 m per positive standard deviation of PC2) and a westward shift of the ASL by approximately 30° (compared to PC1); the deepened ASL is centered near 150°W rather than 120°W for PC1. Following the westward shift of the ASL, the positive SAT anomalies over the peninsula (~1°–2°C) are expanded westward and poleward over both the peninsula and the interior continent, and the negative SAT anomalies over the Ross Ice Shelf are shifted offshore.

The results in Figs. 3 and 4 are similar to those discussed by Simpkins et al. (2012) using modes of Antarctic-wide sea ice concentration, implying both are likely driven by similar circulation patterns. The major differences from the sea ice concentration modes are that PC1 of West Antarctic SAT is more strongly related to a SAM-only pattern during MAM, and PC2 exhibits a stronger relationship with ENSO during JJA, which has not been previously discussed.

c. The influence of ENSO and SAM on sea ice and thermal advection

Regressions of sea ice concentration and 10-m winds onto PC1 and PC2 are shown in Fig. 5. The DJF PC1 is significantly related to offshore sea ice concentration anomalies in the Ross and western Amundsen Seas and meridional winds across the continent and Ross Ice Shelf (Fig. 5a). Positive phases of PC1 during DJF are associated with a weakening of the surface westerlies between 60° and 70°S and negative sea ice concentration anomalies of ~5% over the Ross and western Amundsen Sea, and also with anomalous northerlies over the continent.

Figure 6 shows lag–one season regressions (i.e., the previous season’s sea ice concentrations regressed onto concurrent PC1 and PC2), and lag–one season detrended correlations with ENSO and SAM indices are given in Table 2. Previous SON sea ice concentration anomalies in the Ross and Amundsen Seas are also strongly related to the DJF PC1 (Fig. 6a), and the lagged correlations with SON ENSO and SAM indices are stronger than the concurrent DJF correlations (cf. Tables 1 and 2). This implies that the DJF EOF1 pattern is more related to spring ENSO and SAM conditions as well as spring sea ice concentration anomalies in the Ross and Amundsen Seas. Preceding sea ice concentration anomalies may amplify into the summer season as insolation maximizes and the ice-albedo feedback strengthens, and these offshore SAT anomalies could then be advected onto the continent by the concurrent DJF ENSO and SAM circulation anomalies (i.e., Figs. 3a and 5a).

The DJF PC2 is also significantly correlated with previous SON sea ice concentrations, but farther east over the eastern Amundsen and Bellingshausen Seas (Fig. 6b); however, PC2 shows no significant correlation with ENSO or SAM in the concurrent DJF or the previous SON. Therefore, sea ice plays an important role for both SAT patterns during DJF, but PC2 is not influenced by processes linearly related to ENSO and SAM.

Outside of DJF (Figs. 5c,e,g), PC1 is significantly related to a sea ice concentration dipole between the northeast Bellingshausen/Weddell Seas and the eastern Ross/western Amundsen Seas with opposing meridional wind anomalies over the peninsula and the Ross/Amundsen Seas. The sea ice pattern is similar to that seen for PC1 of Antarctic-wide sea ice concentration in Simpkins et al. (2012), which was also linked to the SAM. The surface wind anomalies over the continent are primarily zonal, which would reduce the potential for
meridional temperature advection across interior West Antarctica when operating in the EOF1/dipole pattern. Both JJA and SON PC1 are significantly correlated with previous season’s ENSO indices (Table 2), but lagged regressions with sea ice are weak and mostly insignificant (Figs. 6c,e,g). Given that there are no lagged correlations with the SAM index in JJA and SON, which dominates the PC1 patterns in these seasons, the lagged

![Fig. 5](image)

Fig. 5. As in Figs. 3 and 4, but for sea ice concentration and 10-m wind. Only vectors with at least one component statistically significant at $p < 0.10$ are shown. Contour interval is 5%, and winds are indicated by reference vector in m s$^{-1}$. Map domain is as in Fig. 2.
correlations with ENSO are likely more related to the persistence of tropical Pacific SST anomalies (especially from JJA through DJF following the ENSO cycle) than to a lagged sea ice effect. Only in DJF are the lagged correlations with climate indices stronger than the lag-0 correlations. The PC2 patterns in MAM, JJA, and SON are associated with a sea ice concentration dipole located farther...
preferred over tropical Pacific SST anomalies to ensure the top five minus lowest five SOI years. The SOI is of the top five minus lowest five SAM index years and with SAM and ENSO. Composite differences are shown thermal advection patterns, respectively, associated with PC1 and PC2 with the previous season SOI, SST anomalies in the Niño-4, -3.4, and -3 regions, and SAM index. Statistical significance of correlations is denoted as in Table 1.

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<th>MAM</th>
<th>JJA</th>
<th>SON</th>
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TABLE 2. Seasonal-lagged detrended correlations, 1979–2015, of PC1 and PC2 with the previous season SOI, SST anomalies in the Niño-4, -3.4, and -3 regions, and SAM index. Statistical significance of correlations is denoted as in Table 1.

west than the PC1 pattern (Figs. 5d,f,h). The strongest sea ice relationships are over the Bellinghausen and Amundsen Seas (rather than the Weddell Sea for PC1), and significant surface meridional wind anomalies extend across the Bellinghausen Sea onto the continent. This pattern would favor sea ice-modified SAT anomalies over the Bellinghausen and Amundsen Seas to be advected meridionally onto the continent, whereas during EOF1 patterns surface meridional wind anomalies are confined to the peninsula and extreme western West Antarctica/Ross Ice Shelf.

The SON PC2 pattern is also significantly correlated with previous JJA ENSO indices (Table 2) and with sea ice concentrations over the Bellinghausen and southern Amundsen Seas (Fig. 6h). Because both the PC2 pattern for SON and the PC1 pattern for DJF consist of a widespread SAT anomaly over the continent and both are significantly correlated with previous season’s sea ice anomalies, we infer that the strongest lagged effects of sea ice anomalies on continental SATs are during SON and DJF. However, each season is tied to different regions of sea ice anomalies: DJF is tied to SON sea ice anomalies over the Ross and Amundsen Seas, and SON is tied to JJA sea concentrations over the Bellinghausen Sea. The close connection of SON continental SATs with sea ice is consistent with Schneider et al. (2012), but an important lagged relationship with JJA sea ice concentrations is noted here, particularly in the southern Amundsen Sea, which is not seen in the lag-0 SON regressions (cf. Figs. 6h and 5h).

Figures 7 and 8 investigate the regional sea ice and thermal advection patterns, respectively, associated with SAM and ENSO. Composite differences are shown of the top five minus lowest five SAM index years and the top five minus lowest five SOI years. The SOI is preferred over tropical Pacific SST anomalies to ensure that both the tropical atmosphere and SSTs are responding to the ENSO event, and also because the location of SST anomalies varies for each ENSO event.

The DJF SAM-related sea ice concentration anomalies (Fig. 7a) are very similar to those for ENSO (Fig. 7b), with positive SAM/La Niña events associated with 10%–20% more sea ice over the Ross and western Amundsen Seas and 10%–20% less sea ice in the Bellinghausen Sea. However, the SAM-related circulation is associated with stronger zonal wind anomalies between 60° and 70°S and stronger meridional wind anomalies over the continent. Differences in 500-hPa meridional temperature advection show that the DJF positive SAM pattern also consists of stronger northerly winds/warm air advection over the Amundsen Sea embayment extending onto the continent to approximately 75°S (Fig. 8a), while the DJF ENSO pattern does not show any significant impact on West Antarctic winds or thermal advection (Fig. 8b). As discussed previously, much of these DJF relationships are likely due to a preconditioning of the sea ice fields during the time of maximum extent and retreat in SON, given that lag-1 SAM/ENSO correlations are stronger than lag-0 correlations.

The sea ice and surface wind composite anomalies during MAM, JJA, and SON show the SAM is associated with a sea ice concentration dipole nearly identical to the PC1 sea ice regressions (Figs. 7c,e,g). The sea ice dipole is located farthest east during JJA and SON with maximum anomalies (of opposite sign) centered over the Amundsen Sea and Weddell Sea. Similarly, the thermal advection patterns associated with SAM (Figs. 8c,e,g) show a dipole over the continent that mirrors the EOF1 SAT patterns in these seasons. The advection dipole is strongest over the continent during MAM, whereas in JJA and SON the cold air advection over western West Antarctica shifts offshore to the Ross and Amundsen Seas aligning with increased sea ice concentrations there.

The ENSO-related sea ice concentration and advection anomalies during MAM, JJA, and SON also consist of a dipole but are located slightly west of the SAM pattern, more in line with PC2. Compared to the SAM, ENSO is associated with stronger sea ice concentration anomalies in the southeast Bellinghausen Sea during MAM, and in the Amundsen Sea during JJA and SON. There are also stronger meridional wind anomalies over the continent for ENSO events during JJA and SON compared to the SAM with significant warm air advection anomalies extending across the Bellinghausen Sea and poleward onto the continent (cf. Figs. 8e,g and Figs. 8f,h).

The ENSO and SAM-related advection and sea ice concentration anomalies appear closely tied to the position of the ASL, consistent with Hosking et al. (2013).
FIG. 7. Seasonal composite difference of sea ice concentration (contours) and 10-m wind (vectors) for (left) top five highest SAM index years minus top five lowest SAM index years and (right) top five highest SOI years minus top five lowest SOI years over 1979–2015 for (a),(b) DJF, (c),(d) MAM, (e),(f) JJA, and (g),(h) SON. Shading indicates statistical significance of sea ice concentration differences at the $p < 0.10$, $p < 0.05$, and $p < 0.01$ levels as indicated by color bar. Only vectors with at least one component statistically significant at $p < 0.10$ are shown. Contour interval is 10%, and winds are indicated by reference vector in m s$^{-1}$. Map domain is as in Figs. 2, 5, and 6.
As discussed in Clem et al. (2016) and Turner et al. (2013a) and demonstrated by Figs. 7c and 7d, during MAM variability in the SAM dominates ASL magnitude and the ENSO relationship with ASL magnitude is weak in this season. Similarly, the ENSO relationship with PC1 and PC2 is also weak in MAM. During JJA and SON, the ENSO influence on the ASL appears to be much stronger; La Niña events are associated with a

**FIG. 8.** As in Fig. 7, but for 500-hPa meridional temperature advection [$-v(\partial T/\partial y)$; contours] and 500-hPa wind (vectors). Contour interval is 1°C day$^{-1}$, and winds are indicated by reference vector in m s$^{-1}$. Map domain is as in Figs. 2, 5, 6, and 7.
TABLE 3. Seasonal detrended correlations, 1979–2015, of ASL longitude and latitude with the SOI, SST anomalies in the Niño-4, -3.4, and -3 regions, and SAM index. Statistical significance of correlations is as denoted in Tables 1 and 2.

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The deepening of ASL farther west than the SAM during JJA and farther north and west than the SAM in SON (cf. Figs. 7e,g and Figs. 7f,h). The ENSO-related influence on the ASL during JJA and SON (compared to the SAM) in turn produces stronger meridional wind/thermal advection anomalies across the continent. The ENSO and SAM impacts on ASL position will be investigated further in the next section.

As noted previously, the ENSO and SAM impacts on sea ice concentration over the Ross and Amundsen Seas during SON are linked to the DJF EOF1 pattern. From Figs. 7g and 7h, the SAM impact on sea ice concentration during SON is primarily over the Amundsen Sea while the ENSO impact is farther west over the Ross Sea. As previously shown (Fig. 6a), the DJF EOF1 pattern is significantly related to SON sea ice concentrations over both these regions. We infer it is the combined yet different spatial impacts of ENSO and SAM on the SON sea ice over the Ross and Amundsen Seas that leads to the EOF1 SAT pattern in DJF; negative SAM and El Niño–related impacts on the SON sea ice field are related to widespread positive SAT anomalies over the continent in DJF.

d. ENSO and SAM influences on the ASL

Seasonal correlations of ENSO and SAM with ASL latitude and longitude are given in Table 3. Overall, the ENSO correlations with ASL position are weak and mostly insignificant. La Niña conditions during JJA and SON are weakly associated with an eastward shift in the ASL center, and a northward shift of the ASL center during MAM. Positive phases of the SAM are associated with a poleward shift of the ASL during DJF, a poleward and eastward shift during MAM (in addition to a deepened ASL; Turner et al. 2013a; Clem et al. 2016), and a poleward shift during JJA.

The SAM and ENSO correlations with ASL position, although weak, are consistent with the EOF1 patterns. The PC1 regressions with surface winds during MAM, JJA, and SON (Figs. 5c,e,g) show the ASL being located farther poleward and eastward compared to the PC2 circulation pattern (Figs. 5d,f,h), and the correlations (although weak) generally imply an eastward shift of the ASL associated with positive SAM phases and in-phase La Niña/positive SAM phases. This is likely related to the preference for ENSO events to be in-phase with the SAM in all seasons (Fogt et al. 2011), especially over the Pacific (Ding et al. 2012; Fogt et al. 2012b).

We investigate how the ASL position is tied to the JJA and SON PC2 patterns (and ENSO) in Fig. 9. The SOI and Niño-4 SSTs are used to monitor ENSO; Niño-4 SSTs are used because this region is most strongly correlated with PC2 in JJA and SON. There is marked covariability between PC2 and ENSO during both seasons (Figs. 9a,b) with positive SOI values/negative Niño-4 SST anomalies generally occurring with positive phases of PC2 (see correlations in Table 1). There are seven JJA years (1981, 1984, 1988, 1998, 2000, 2005, 2008, 2010) when positive phases of PC2 (above 0.5 standard deviations) occurred with La Niña events (either the SOI was above 0.5 standard deviations or the Niño-4 SST anomaly was below 0.5 standard deviations). However, the PC2 time series with ASL longitude and latitude (Figs. 9c,d) reveals that there is no consistent signal in ASL position during these events. For instance, during JJA of 1981 the ASL was located northeast of its mean position, whereas during 1988 the ASL was located west of its mean position. The same holds true for SON: during 2000, the ASL was located southwest of its mean position whereas during 2008 the ASL was located northeast of its mean position. This implies that the ASL position is not the only factor driving the PC2 patterns in JJA and SON, and there may be other components of the ENSO-related circulation that favor the PC2 pattern.

Anomaly composites of the seven JJA and SON years (listed above) when La Niña conditions occurred with positive phases of PC2 are shown in Figs. 10 and 11, respectively. During JJA (Fig. 10), there are significant negative SST anomalies over the central tropical Pacific and weak positive SST anomalies over the western tropical Pacific and along the South Pacific convergence zone resembling a La Niña or a developing La Niña. The circulation anomalies show a wave train emanating from the central tropical Pacific with a deepened ASL near 150°–120°W and an anticyclone over the Weddell Sea, similar to that seen in the PC2 regressions with 500-hPa heights (Fig. 3f). No significant SST anomalies are seen...
in other tropical basins and there are no other circulation anomalies resembling a SAM/wave-3 pattern (although there are weak positive height anomalies over Antarctica of ~15 m), indicating that the circulation is related predominantly to tropical Pacific forcing.

The deepened ASL combined with the anticyclone over the Weddell Sea results in significant northerly winds that reduce sea ice concentrations over the Bellingshausen and eastern Amundsen Sea (Fig. 10c) and brings warm air advection deep onto the continent (Fig. 10d). The reduced sea ice concentrations in the Bellingshausen Sea would warm the western peninsula through sensible heat fluxes, and the warmer SAT would advect onto the continent via northerly wind anomalies. This explains both the warming along the peninsula (through reduced sea ice concentration in the Bellingshausen Sea and air–sea heat fluxes) and across interior West Antarctica (through warm air advection), all of which is consistent with the JJA EOF2 pattern.

During SON (Fig. 11), the tropical SST and circulation anomalies are nearly identical to those seen for JJA. The tropical Pacific SST anomalies reflect a La Niña and the circulation anomalies depict a wave train that deepens the ASL between 150° and 120°W with an anticyclone over the Weddell Sea. The circulation produces strong decreases in sea ice concentration over the Bellingshausen and Amundsen Seas and brings strong warm air advection (over 0.6°C day$^{-1}$) onto the continent. Again, this sea ice/advection pattern would warm both the peninsula (through reduced sea ice concentrations over the Bellingshausen Sea) and continental West Antarctica (through warm air advection), consistent with the same-sign SAT anomaly seen across both the peninsula and interior continent for the SON EOF2 pattern.

As seen for JJA, there are no other significant SST anomalies in other tropical basins and there are no circulation anomalies resembling the SAM, implying the...
circulation is predominantly tied to the tropical Pacific. An important feature of the wave train that was less clear in the regression analysis is the strong anticyclone over the Weddell Sea, which is not typically seen for SAM events [e.g., see Fig. 2 in Fogt et al. (2012b)]. Therefore, the ENSO-only pattern (i.e., not occurring with a SAM event) is tied to the PC2 pattern via a combined (westward) deepening of the ASL in conjunction with an anticyclone over the Weddell Sea rather than a linear westward shift of the ASL. We infer that without the opposite-sign circulation anomaly in the Weddell Sea, longitudinal movement of the ASL alone
does not produce widespread continental SAT anomalies as seen for the EOF2 pattern.

4. Summary and conclusions

This study provides a seasonal analysis of the principal patterns of SAT variability across the West Antarctic region and links them to large-scale forcing of the Amundsen Sea low (ASL) and sea ice by ENSO and SAM. Consistent with previous studies, the longitudinal position of the ASL affects the spatial pattern of SAT anomalies across continental West Antarctica and the Antarctic Peninsula, but longitudinal position of the ASL alone does not result in widespread SAT variability over the interior continent.

Outside of DJF, the SAM pattern is associated with a SAT dipole over the continent between the Antarctic Peninsula and western West Antarctica. The SAM pattern influences ASL depth primarily over the central and eastern Amundsen Sea, and in-phase ENSO events (i.e., La Niña with positive SAM, El Niño with negative SAM) reinforce the SAT dipole over the continent. In contrast, the ENSO-only pattern (i.e., when ENSO forcing occurs without the SAM) impacts ASL depth...
farther west near 150°–120°W and is associated with an opposite sign circulation anomaly in the Weddell Sea. The ENSO-only pattern shifts the SAT dipole westward and poleward with SAT anomalies maximized over the interior continent; however, both the westward shift of the ASL and the opposite sign circulation anomaly over the Weddell Sea are needed to bring anomalous meridional wind/thermal advection deep onto the continent.

During DJF, the leading pattern of West Antarctic SAT (EOF1) explains 35% of the SAT variability and consists of a same-sign temperature anomaly over the continent spanning all West Antarctica and the Antarctic Peninsula. The DJF EOF1 pattern is primarily correlated with previous SON ENSO and SAM-related circulation anomalies which influence sea ice concentrations across the eastern Ross and Amundsen Seas. During SON, the SAM pattern impacts sea ice concentrations primarily over the Amundsen Sea, while the ENSO pattern impacts sea ice concentration anomalies farther west over the Ross Sea. It is the combined yet spatially different ENSO/SAM influences on sea ice concentrations across the Ross and Amundsen Seas during SON, which becomes amplified into the following DJF, that lead to the widespread SAT anomaly over the continent in DJF. More work is needed to identify the relative roles of thermal advection and radiation on the summertime temperatures across continental West Antarctica, but lagged sea ice effects appear to have a significant influence on the DJF SAT patterns.

Outside of DJF, the leading West Antarctic SAT patterns explain ~40%–50% of the SAT variability and are characterized by a SAT dipole over the continent between the Antarctic Peninsula and western West Antarctica. The dipole is significantly correlated with the SAM index and SAM-related variability in ASL magnitude over the central and eastern Amundsen Sea (near 120°–90°W) that results in a sea ice concentration dipole between the northeast Bellingshausen/Weddell Sea and the western Amundsen/Ross Sea. Thermal advection patterns associated with the SAM are consistent with the SAT dipole over the continent, with positive phases of SAM associated with warm air advection across the peninsula and cold air advection across western West Antarctica and the Ross Ice Shelf. When ENSO events occur in phase with the SAM, the SAM-related ASL response and the continental SAT dipole is reinforced.

The second leading pattern of West Antarctic SAT (EOF2) during MAM, JJA, and SON explains ~15%–20% of the SAT variability and consists of a dipole shifted approximately 30° west of EOF1 with a widespread same-sign temperature anomaly encompassing both the Antarctic Peninsula and the interior continent. During JJA and SON, EOF2 is significantly correlated with ENSO variability and a wave train emanating from the tropical Pacific that impacts ASL depth near 135°W with an opposite sign circulation anomaly over the Weddell Sea. The ENSO-related circulation pattern is also associated with a sea ice concentration dipole that is shifted westward following the westward shift of the ASL, with stronger sea ice concentration anomalies seen over the western Bellingshausen and Amundsen Seas compared to the SAM/EOF1 pattern where sea ice anomalies are maximized in the Weddell Sea. The combination of a westward shift in the ASL and an opposite-sign circulation anomaly over the Weddell Sea brings strong thermal advection anomalies deep onto the continent, while anomalous sea ice concentrations in the Bellingshausen Sea favor a same-sign SAT anomaly along the western peninsula.

In contrast to Ding et al. (2011), we find negative SST anomalies over the central tropical Pacific/La Niña conditions during JJA to be more associated with widespread warming of both the Antarctic Peninsula and continental West Antarctica, while positive SST anomalies in the central tropical Pacific are associated with localized warming confined to western West Antarctica. Our findings support those of Schneider et al. (2012) and Clem and Fogt (2015) in that a La Niña pattern/deepened ASL/reduced sea ice concentrations in the Amundsen and Bellingshausen Seas are tied to continental warming during spring.

Altogether, this study suggests that widespread continental warming of West Antarctica is predominantly tied to forcing from the tropics, especially during JJA and SON, which is consistent with previous studies (e.g., Schneider and Steig 2008; Marshall and Thompson 2016). In contrast, the SAM pattern is more tied to a SAT dipole over the continent, with relatively weak SAT anomalies across Marie Byrd Land. More work is needed to confirm the relationships identified here. Numerical simulations are needed to separate the ENSO-related circulation from the SAM pattern, with forcing from the central tropical Pacific appearing to be a critical source region for the wave train that influences SAT anomalies over the interior continent. Numerical simulations are especially needed for MAM, as a similar tropically forced circulation pattern linked to continental SAT anomalies appears possible, but given the dominance of the SAM/wave-3 pattern and the preference for in-phase ENSO/SAM events is this season, numerical simulations are needed to separate the ENSO signal from the background circulation.

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REFERENCES


