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THE AMUNDSEN SEA LOW

Variability, Change, and Impact on Antarctic Climate

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The Amundsen Sea low (ASL) has deepened in recent decades, influencing the West Antarctic climate.

The predictability of polar climate on interannual to multidecadal time scales has been identified as one of the Cryosphere Grand Challenges (CGCs) by the World Climate Research Programme (WCRP). Improving polar climate predictability in the Southern Hemisphere (SH) requires a better understanding of the interactions between the subtropical and polar jets, the nonzonal circulation, and the surface climate. Here, we address one aspect of this CGC: the role of nonzonal circulation in driving Antarctic climate variability. In particular, we discuss the Amundsen Sea low (ASL), which represents a key component of the nonzonal climatological circulation with significant influence in the Pacific sector of the high southern latitudes and links to the tropical Pacific. The ASL strongly influences West Antarctic climate, including parameters such as sea ice extent, temperature, and precipitation, by controlling variability in the meridional wind field (Hosking et al. 2013). Recently, the ASL has deepened, perhaps with stratospheric ozone depletion playing a part (Turner et al. 2009). This trend is also concurrent with rapid ice loss from some West Antarctic glaciers, which is being driven by ocean circulation changes (e.g., Pritchard et al. 2009) that in turn are strongly controlled by the surface wind field (Thoma et al. 2008).

As a result of the lack of long-term surface-based in situ observations in the Amundsen, Bellingshausen, and Ross Seas, it is only with the recent advent of reliable reanalysis data that the impact of the ASL on the Antarctic climate is beginning to be better understood. However, given the marked trends in West Antarctic climate (e.g., Bromwich et al. 2013), there is a need to evaluate our understanding of this feature, to identify where gaps in our knowledge exist, and to suggest how these gaps might be filled. In this paper we summarize the current understanding of the ASL, focusing on the following: its variability and change using observations from the last three decades, its impact on the climate of West Antarctica,

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the influence of tropical teleconnections on ASL variability, its behavior over the past millennium as derived from Antarctic ice core records, and projected ASL changes using Coupled Model Intercomparison Project Phase 5 (CMIP5) data.

OBSERVED VARIABILITY OF THE AMUNDSEN SEA LOW. The ASL is the climatological area of low pressure located in the South Pacific sector of the Southern Ocean (SO), which comprises the Ross Sea, the Amundsen Sea, and the Bellingshausen Sea, over the latitude band 60°–70°S. The reanalysis datasets show that climatologically it is the deepest of three mean sea level pressure (MSLP) centers observed around Antarctica (Fig. 1a). Baines and Fraedrich (1989) conducted rotating tank experiments to investigate the mean atmospheric circulation at high southern latitudes and suggested that the ASL results from the interaction of the mean westerly flow with the high orography of Victoria Land. Their experiment was purely barotropic, but modeling studies, such as that of Walsh et al. (2000), showed the importance of baroclinicity, which is in itself dependent on the orography. However, more research is needed to fully understand this particular structure of the MSLP field around the continent.

In simple terms, the ASL is present because of the large number of depressions in the South Pacific sector of the SO that have either moved south from midlatitudes or developed in the highly baroclinic zone of the circumpolar trough around Antarctica (Fig. 1b). Fogt et al. (2012) identified more than 550 individual depressions per year in this sector based on reanalysis fields. At monthly and seasonal time scales the ASL is clearly apparent in most mean MSLP fields (see Fig. 1a), although occasionally two low pressure centers are present in the former. Figure 1 shows that it is not easy to relate the storm density and depths of the depressions to the climatological ASL, since the climatological location of the ASL does not occur at a clear maximum of storm activity.

There is a well-defined annual cycle in the average zonal location of the ASL, with the low being found immediately west of the Antarctic Peninsula in austral summer (December–February) and moving westward to the Ross Sea by winter (June–August) (Fogt et al. 2012; Turner et al. 2013b). There is also an annual cycle in the meridional location of the ASL, as the low is farther north in summer and at its most southerly location in late winter. In contrast, the absolute depth of the ASL has a semiannual form, with the lowest pressures in the equinoctial seasons, since this is the dominant cycle observed in the MSLP fields in the Antarctic coastal zone (Turner et al. 2013b).

Changes in the ASL can also be related to global and hemispheric modes of climate variability. The

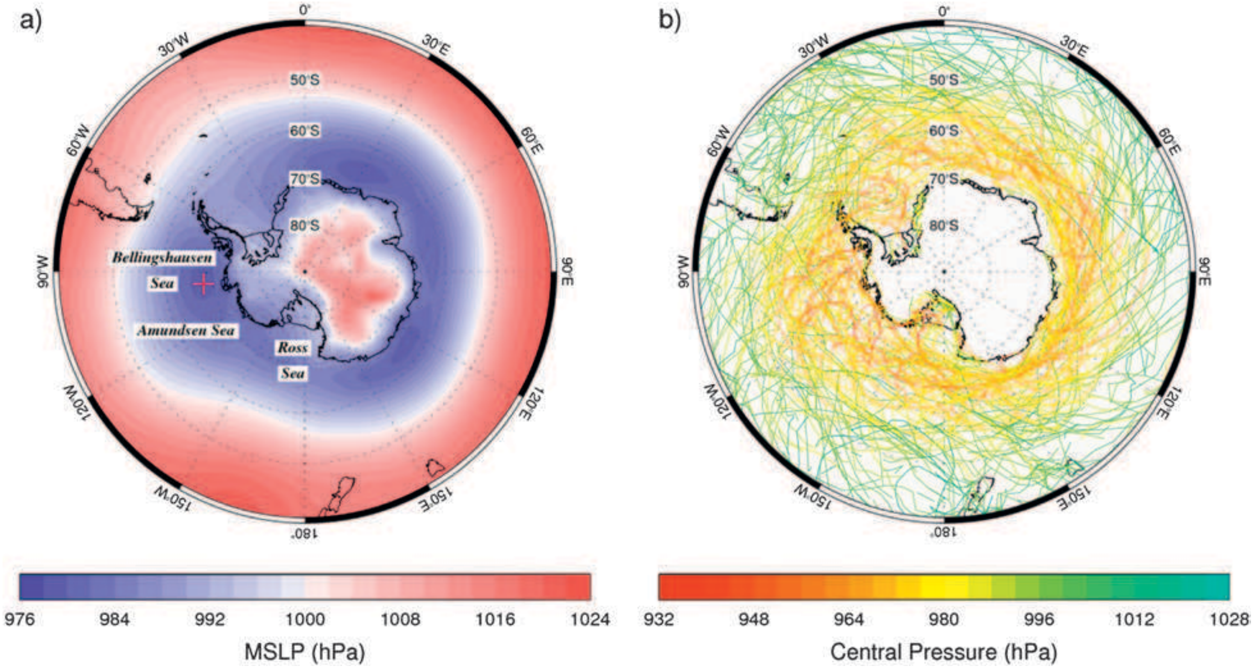

Fig. 1. (a) The mean MSLP for austral fall (Mar–May) 1995 from the ERA-Interim. The red cross marks the center of the ASL in this season. (b) The tracks of all depressions for the same period based on the University of Melbourne cyclone tracking procedure. The colors indicate the central MSLP values of the individual depressions.

absolute depth of the ASL is significantly lower during the La Niña phase of the El Niño–Southern Oscillation (ENSO) compared to El Niño. This is consistent with the impact of the Rossby wave train emanating from the central Pacific Ocean during El Niño events, which leads to increased blocking across the South Pacific and the establishment of the Antarctic dipole in sea ice and surface air temperature (Yuan and Martinson 2001). The difference in absolute depth between the two phases of ENSO is greatest in winter. However, there is no statistically significant difference in the zonal location of the ASL between the two phases of ENSO (Turner et al. 2013b).

In addition, the absolute depth of the ASL is strongly influenced by the phase of the southern annular mode (SAM), which is the primary mode of atmospheric variability at high southern latitudes (e.g., Marshall 2003). Variations in the phase of the SAM result in an exchange of mass between the Antarctic and midlatitudes. In the positive (negative) phase, MSLP anomalies are negative (positive) at high (mid) latitudes, resulting in a stronger (weaker) polar jet. In a given season, there is a statistically significant correlation between the longitude of the ASL and the zonal wind speed over the SO to the north of the ASL (40°–50°S): stronger westerlies are associated with the ASL being farther east. Attempts have therefore been made to determine the absolute ASL strength or relative central pressure by subtracting the background area-averaged MSLP (area averaged over the region 60°–75°S, 170°–290°E) in order to remove the SAM influence, as described in Hosking et al. (2013). The annual cycle of the ASL relative depth shows a minimum (maximum) during winter (summer).

Turner et al. (2013b) examined monthly trends in the absolute depth and location of the ASL, based on European Centre for Medium-Range Weather Forecasts (ECMWF) gridded data. They showed that both are highly variable over the 1979–2008 period. For example, there were three months when the absolute depth changed significantly: a decrease in January of 1.7 hPa decade^{-1}, primarily in response to the SAM becoming more positive; an increase in March of 1.4 hPa decade^{-1}, due to higher pressures in the circumpolar trough; and a second decrease of 2.1 hPa decade^{-1} in September, dominated by a remarkably deep ASL in 2008, which had a mean monthly central pressure of only 958 hPa. At a seasonal time scale the ASL has deepened most in austral spring (September–November) and fall (March–May), reflecting an increase in the regional amplitude of the semiannual oscillation since the late 1970s.

IMPACTS OF THE AMUNDSEN SEA LOW ON ANTARCTIC CLIMATE.

Studies examining the impact of the ASL on Antarctic climate have focused on temperature and precipitation across West Antarctica and the Antarctic Peninsula, as well as sea ice concentration in the Ross, Amundsen, and Bellingshausen Seas. Statistically significant relationships with various climate parameters may be noted outside these regions but many of these are likely due to the relationship between the ASL and patterns of large-scale variability such as SAM and ENSO.

Hosking et al. (2013) demonstrated that the main impacts of the ASL on regional Antarctic climate are directly tied to its variations in location and strength. In particular, the longitudinal location of the ASL has the most consistent and persistent influence, often leading to anomalies of opposite sign in temperature, sea ice, and precipitation in the coastal and shelf region from the Antarctic Peninsula to the Ross Sea. Figure 2 shows the impacts on meridional wind (top row) and surface temperature (bottom row) for conditions when the ASL is centered (plus signs in Fig. 2) farther west (toward the Ross Sea) compared to years when it is located farther east (toward the Bellingshausen Sea). Notably, the temperature differences are consistent with changes in the meridional wind, with more northerly flow anomalies (negative meridional wind values) nearly collocated with warmer conditions, and vice versa. These general relationships imply that many of the impacts of the ASL are related to changes in the atmospheric circulation, especially the geostrophic flow.

Hosking et al. (2013) also linked changes in sea ice concentration to the ASL variability. Broadly, increases in sea ice concentration align with regions of below-average temperatures in Figs. 2e–h, while sea ice concentration decreases are observed with regions of above-average temperatures. The changes are most marked at the sea ice's edge and are statistically significant, especially during austral winter [cf. Figs. 6m–p in Hosking et al. (2013)]. These relationships again show the strong dependency of wind-driven climate variability associated in particular with the ASL location. Indeed, a study by Holland and Kwok (2012) demonstrated that sea ice trends surrounding Antarctica are largely consistent with near-surface wind changes associated with a deepening of the ASL. In their study, they observed northerly winds increasing near the Antarctic Peninsula, with southerly winds intensifying off the Ross Ice Shelf. Through these wind-driven changes, the deepening of the ASL thus partially explains the increase in sea ice extent (equatorward ice motion) in the Ross Sea

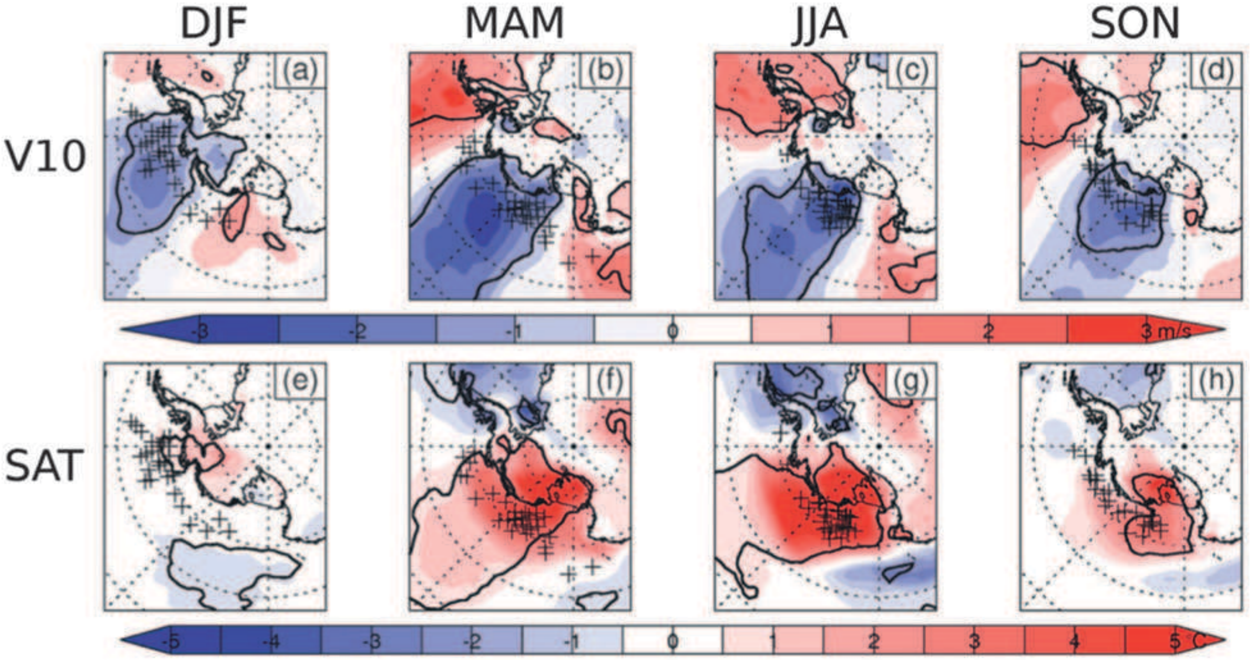

Fig. 2. Composites of the lower minus the upper quartile for the ASL longitude (positive for farther west vs farther east), for (a)–(d) 10-m meridional winds and (e)–(h) surface air temperature for each season (columns), based on ERA-Interim data from 1979 to 2011. Plus signs denote the location of the ASL for each year, and the thick black line indicates statistically significant differences at the $p < 0.05$ level. [Modified from Hosking et al. (2013).]

and decreases in the Amundsen and Bellingshausen Seas (ice compaction toward the coast).

In addition to its location and intensity, the spatial extent of the ASL can be important in determining its impact on Antarctic climate. In particular, Clem and Fogt (2013) demonstrated that the greater breadth of the ASL, stretching from the Ross through the Bellingshausen Seas, leads to uniform impacts on temperature, wind, and pressure across the Antarctic Peninsula in austral spring. In other cases, smaller spatial extents of the ASL tend to only influence the western Antarctic Peninsula, while the northeastern Antarctic Peninsula is more strongly modulated by variations in the SAM.

THE IMPACTS OF TROPICAL VARIABILITY AND TRENDS ON THE AMUNDSEN SEA LOW. The Amundsen–Bellingshausen Sea (ABS) region exhibits some of the largest interannual atmospheric circulation variability in the SH, due in part to orographic forcing and in part to its location in the South Pacific, where atmospheric Rossby waves associated with ENSO variability have a year-round influence (e.g., Schneider et al. 2012b). As previously mentioned, ENSO plays a significant role in determining the depth of the ASL. The most energetic Rossby waves associated with ENSO variability in the SH occur in spring (e.g., Jin and Kirtman 2009), and hence the strongest correlations between ENSO variability and the ASL generally occur in this season too. In its La Niña phase, in spring, ENSO is associated with a deeper ASL and with warm air advection toward the Antarctic Peninsula and West Antarctica. However, from spring to summer the sign of the correlation of the phase of ENSO with respect to air temperature anomalies over Antarctica reverses in many locations.

Given the persistent interannual ENSO signals in the ABS, it is natural to ask how much influence the tropics have had on the ASL and related climate changes in this region. A number of recent studies have suggested that tropical teleconnections have contributed to atmospheric warming in West Antarctica and across the peninsula (e.g., Ding et al. 2011; Schneider et al. 2012a), and to sea ice loss in the Bellingshausen Sea (e.g., Li et al. 2014). However, a different line of research suggests that polar stratospheric ozone depletion has been the major driver of atmospheric circulation trends in the SH over the past few decades (e.g., Polvani et al. 2011). To investigate the relative roles of tropical SSTs and radiative forcing (including ozone depletion) on circulation trends over Antarctica and the Southern Ocean, we conducted a series of experiments with the Community Atmosphere Model, version 4 (CAM4; Neale et al. 2013). Results from two of these experiments are presented in Fig. 3 and are compared with trends in the ECMWF interim reanalysis (ERA-Interim; Dee et al. 2011). In the first experiment, time-varying tropical SSTs were prescribed over 28°N–28°S, with climatological SSTs and sea ice in the extratropics and fixed radiative forcings. In the second experiment, the same SST and sea ice conditions were prescribed, but radiative forcings varied with time. These forcings are consistent with those used in the CMIP5 historical experiment (Taylor et al. 2012). A five-member ensemble was developed and conducted for both experiments, and the results shown are the ensemble mean, using all months of the year.

Both model experiments showed good skill in capturing the reduction of MSLP around Antarctica, and in particular a decrease in ASL central pressure, confirming the mechanism through which tropical SSTs have played a major role in driving circulation trends near West Antarctica, as radiative forcings are not needed to generate the observed trend pattern. The second experiment, with active radiative forcings, produced trends of similar spatial pattern but greater magnitude than the first. In comparison to the SST-only experiment, the radiatively forced experiment exhibited trends closer in magnitude to those observed in midlatitudes for the whole year (Fig. 3) and showed a better match to the trends over high latitudes in austral summer (not shown). Overall, the forcing by tropical SSTs was too weak to explain fully the observed circulation trends around Antarctica, but the deepening of the ASL was well captured in the SST-only experiment. The tropical SST experiment does not address the issue of how much the tropical SSTs themselves have been influenced by anthropogenic radiative forcing, a question that warrants further research. It is likely that the observed circulation trends associated with the ASL are explained by a combination of factors, including tropical SSTs, radiative forcing, as well as unforced, internal variability.

PAST AMUNDSEN SEA LOW VARIABILITY FROM ICE CORES. As the ASL dominates the wind field over the West Antarctica region (Fig. 2), there is the potential for a record of past ASL variability to be retrieved from ice cores. The basic rationale is that a deeper ASL results in stronger meridional flow, which then transports more sea salt aerosol to West Antarctic ice core sites (Kreutz et al. 2000; Kaspari et al. 2005). This hypothesis is complicated by the fact that ice core sea salt concentrations are used by some as indicators of past sea ice extent (Wolff et al. 2003, 2006). The physical basis supporting this latter idea is that sea salt can be concentrated on the sea ice surface via a number of different mechanisms (e.g., frost flowers and brine-soaked blowing snow), eventually forming aerosols that may subsequently be transported inland by favorable winds. This sea-ice-related mechanism for mobilizing sea salt aerosols has been observed at several coastal sites (Wagenbach et al. 1998; Rankin et al. 2002); however, its ability to affect higher-elevation inland locations is less certain (Abram et al. 2013).

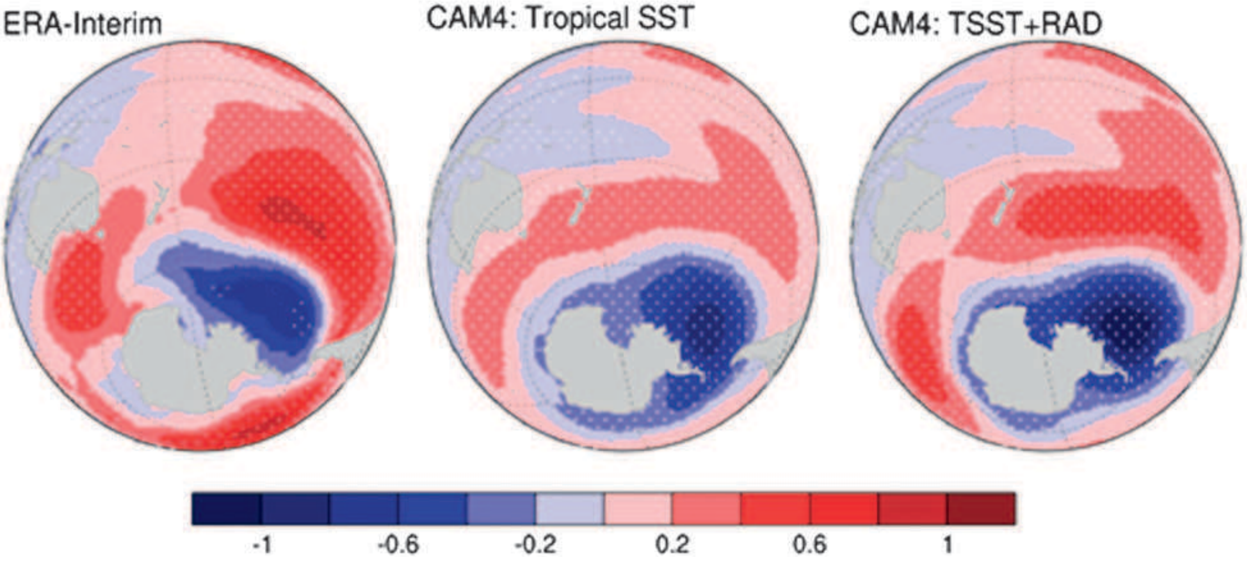

Fig. 3. Monthly MSLP trends (hPa decade^{-1}) for 1979–2011 in the (left) ERA-Interim, (middle) an atmospheric model run with prescribed time-varying tropical SSTs with constant climatological values of other forcings, and (right) an atmospheric model run with prescribed time-varying tropical SSTs and historical values of natural and anthropogenic radiative forcings. White stippling indicates trends significant at $p < 0.05$ based on a two-tailed t test.

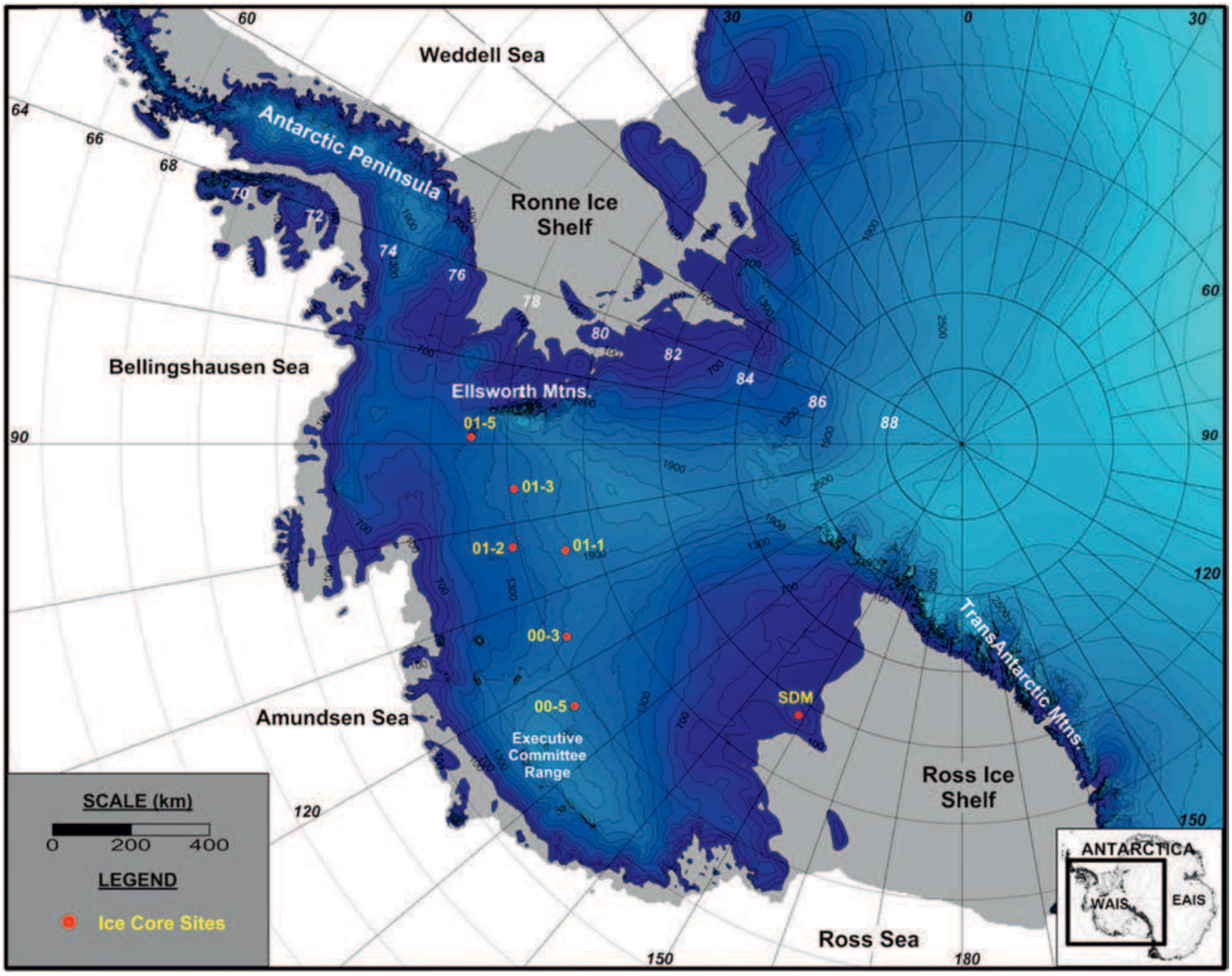

Fig. 4. (a) Locations of the seven West Antarctic ice cores used to provide a regional Na concentration, which was compared with MSLP and ASL parameters.

For West Antarctica, Kreutz et al. (2000) showed that a deeper ASL transports more sea salt aerosol to Siple Dome (81.7°S, 148.8°W) during austral spring. They also showed that no significant correlations exist between Siple Dome sea salt and seasonal mean sea ice extent in the region. Spectral analysis of the subannual portion (AD 1890–1994) of the Siple Dome ice core record suggests ENSO teleconnections (3.3- and 7.1-yr periodicities). Examination of the full record (AD 850–1994) reveals a strong 40–45-yr periodicity over ~AD 850–1700 and an overall deepening of the ASL during the Little Ice Age period (nominally ~AD 1400–1900) accompanied by a distinct shift in periodic structure from 60–80 to 80–140 yr that persists up to the present (Kreutz et al. 2000). Further research by Kaspari et al. (2005) showed that ice core sea salt concentrations increase when sea ice extent increases in some regions of West Antarctica and suggested frost flowers from newly formed sea ice as a potential source. However, Kaspari et al. (2005) ultimately concluded that wind speed and direction are the primary factors controlling sea salt concentrations in West Antarctic ice cores. Intensified atmospheric circulation causes turbulent boundary conditions in winter, resulting in greater production of sea spray aerosols, and/or enhanced transport of frost flower and sea spray aerosols.

To investigate further the association between the ASL and sea salt aerosol transport, we compared mean annual sodium (Na) concentrations in a series of seven West Antarctic ice cores (Fig. 4a) to ASL parameters derived from the analysis of Hosking et al. (2013) and gridded MSLP data from the ERA-Interim atmospheric reanalysis. Individually, each ice core Na record exhibited a negative association with austral spring (September–November) MSLP in the Pacific sector (approximately 67°–75°S and 120°–135°W). To provide a regional signal, we stacked (i.e., normalized and averaged) the seven ice core Na records, resulting in a single time series that spanned 1859–2001.

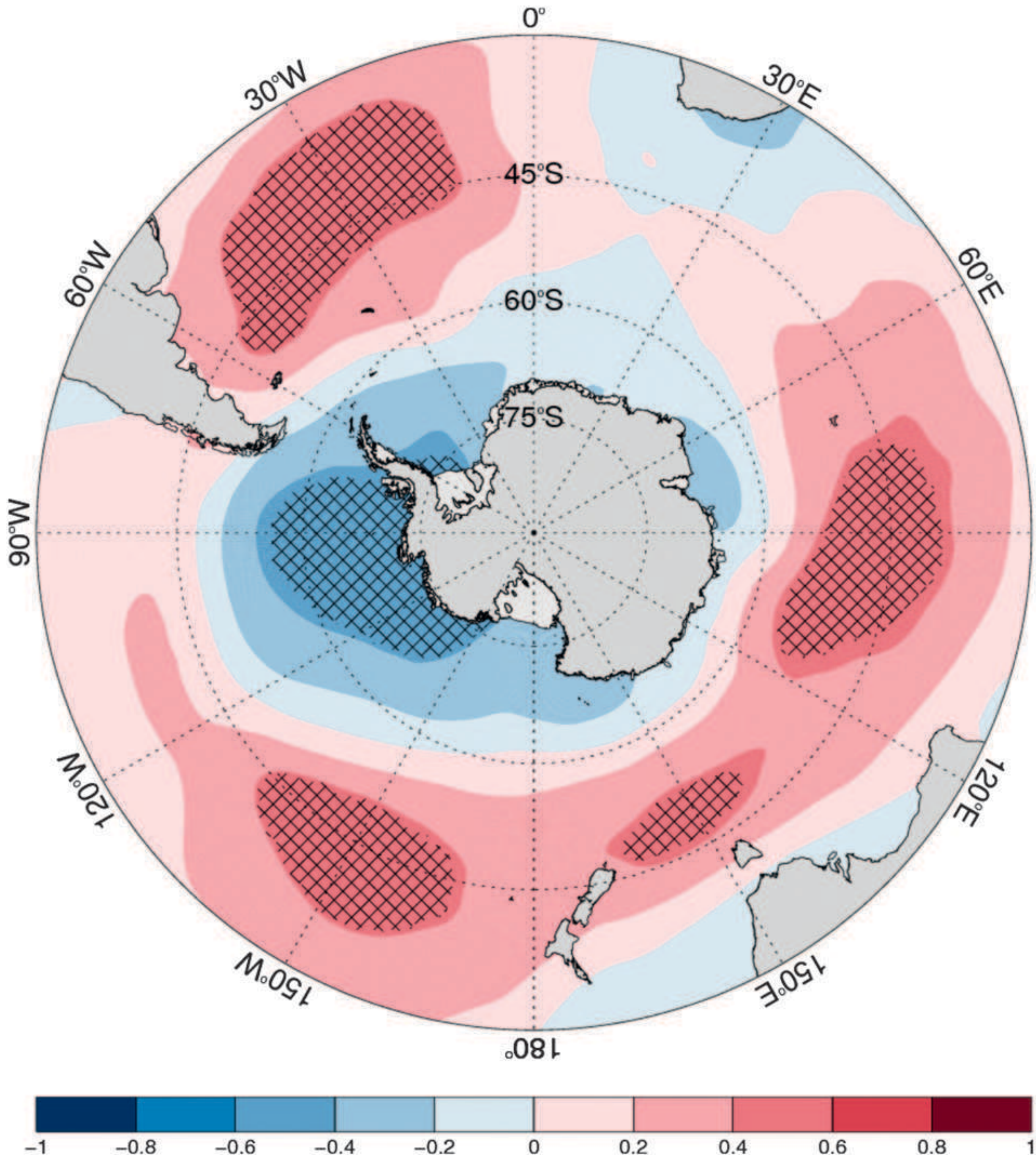

Fig. 4. (b) Correlation between mean annual Na concentrations in the stacked ice core record from West Antarctica and annual MSLP for the 1979–2001 period. Correlations when $p < 0.05$ are highlighted with cross hatching.

The relationships between the stacked mean annual Na time series and seasonal ASL parameters are shown in Table 1. They indicate that the annual Na signal is dominated by austral spring, the only season to exhibit a statistically significant relationship with ASL central pressure. No significant relationships occurred between the Na concentrations and either ASL longitude or latitude. However, it is worth noting the reversal in the sign of the relationship in the former in summer (Table 1), likely reflecting the fact that the ASL is generally located farther east of the ice core sites in this season.

Similarly, plots of correlation between the stacked Na time series and seasonal MSLP revealed that the strongest negative associations occurred during spring, with significance values of $p < 0.05$ throughout

Table 1. Correlation coefficients between the stacked mean annual Na time series, and the following indices of the ASL over the period from 1979 to 2001: central pressure (cenP), longitude (lon), and latitude (lat). All datasets were detrended prior to analysis.

	DJF	MAM	JJA	SON
Na/cenP	−0.32	−0.30	−0.19	−0.65*
Na/lon	−0.31	0.13	0.05	0.14
Na/lat	−0.17	0.04	−0.06	−0.03

* Significant at $p < 0.01$.

the Ross, Amundsen, and Bellingshausen Seas in this season. This strong negative relationship dominates the correlation plot of annual Na concentration and annual MSLP (Fig. 4b), further demonstrating that regional Na concentrations contained in the West Antarctic ice core record do provide an indication of past ASL variability. While these results are promising, further work needs to be done to obtain a more detailed picture of past ASL variability and its relationship with regional aerosol transport.

FUTURE AMUNDSEN SEA LOW VARIABILITY.

Future changes to the ASL are difficult to predict because of the high regional variability and uncertainties regarding its response to greenhouse gases and stratospheric ozone (e.g., Turner et al. 2009). To assess future changes in the strength of the ASL, we evaluated the multimodel ensembles produced as part of the CMIP5 exercise. The coupled ocean–sea ice model components exhibit large biases over the Southern Ocean leading to large uncertainties regarding future oceanic and sea ice change (e.g., Turner et al. 2013a). However, by comparing CMIP5 coupled models to their atmosphere-only counterparts [Atmospheric Model Intercomparison Project (AMIP) runs], we find that the simulated ASL is insensitive to surface forcing. Therefore, it is likely that any future ASL changes will be driven primarily by the modified atmospheric circulation that results from increasing greenhouse gases and stratospheric ozone recovery. As such, the impact of ocean and sea ice errors (within the coupled CMIP5 runs) on the ASL is assumed to be of secondary importance.

To gain some insight into what the future state of the ASL might be, we focus on the relative central pressure (Hosking et al. 2013). This allows us to disentangle large-scale changes in pressure associated with trends in the SAM from regional variability. Here, we address the following question: Is the ASL relative central pressure sensitive to increasing greenhouse gases?

The 50-yr period (2051–2100) was compared between the representative concentration pathway (RCP) 2.6 and 8.5 future scenario runs for 28 CMIP5 models. This enables us to assess the sensitivity of the ASL to changes in radiative forcing while ensuring that ozone forcing is relatively unchanged. Bracegirdle et al. (2014) concluded that regional future change is insensitive to the horizontal resolution of the model. We therefore assume that intermodel spread arises primarily from the different dynamics and physics schemes used within the models. Histograms of ASL relative central pressure for each model, which include all their model ensemble members, show that the distributions are fairly Gaussian in shape. Therefore, we assess differences in the medians and interquartile range (IQR) between RCP 2.6 and 8.5 to quantify, respectively, the positive–negative shift of the data (corresponding to a shallower–deeper ASL) and any change in interannual variability.

The scatterplots in Fig. 5 illustrate the difference in the medians against the difference in IQR (i.e., RCP 8.5 “minus” RCP 2.6). For example, in fall the Hadley Centre Global Environment Model, version 2—Atmosphere and Ocean (HadGEM2-AO) model shows that the relative central pressure of the ASL is around 1.3 hPa deeper in the “high-emission scenario” RCP 8.5 compared to the “high-mitigation scenario” RCP 2.6. The change in the IQR for this model is small in comparison (~−0.3 hPa).

With the exception of summer, most of the models show a slight negative shift in the median, with differences ranging between −1.0 and 0.5 hPa; that is, the ASL relative central pressure is more negative (deeper) in most models with increasing radiative forcing. However, there is no coincident shift apparent in the IQR. In summer the change in median is distributed fairly evenly around the axis origin. This season also has the smallest range in IQR of ~±0.7 hPa, indicating less year-to-year variability in the meridional wind strength.

The sensitivity of relative central pressure to greenhouse gases differs widely across the models; for example, the Goddard Institute for Space Studies Model E2, coupled with the Hybrid Coordinate Ocean Model (GISS-E2-H) is consistently more positive (shallower ASL) outside of the summer months, and similarly for the Norwegian Earth System Model, version 1 (intermediate resolution; NorESM1-M)

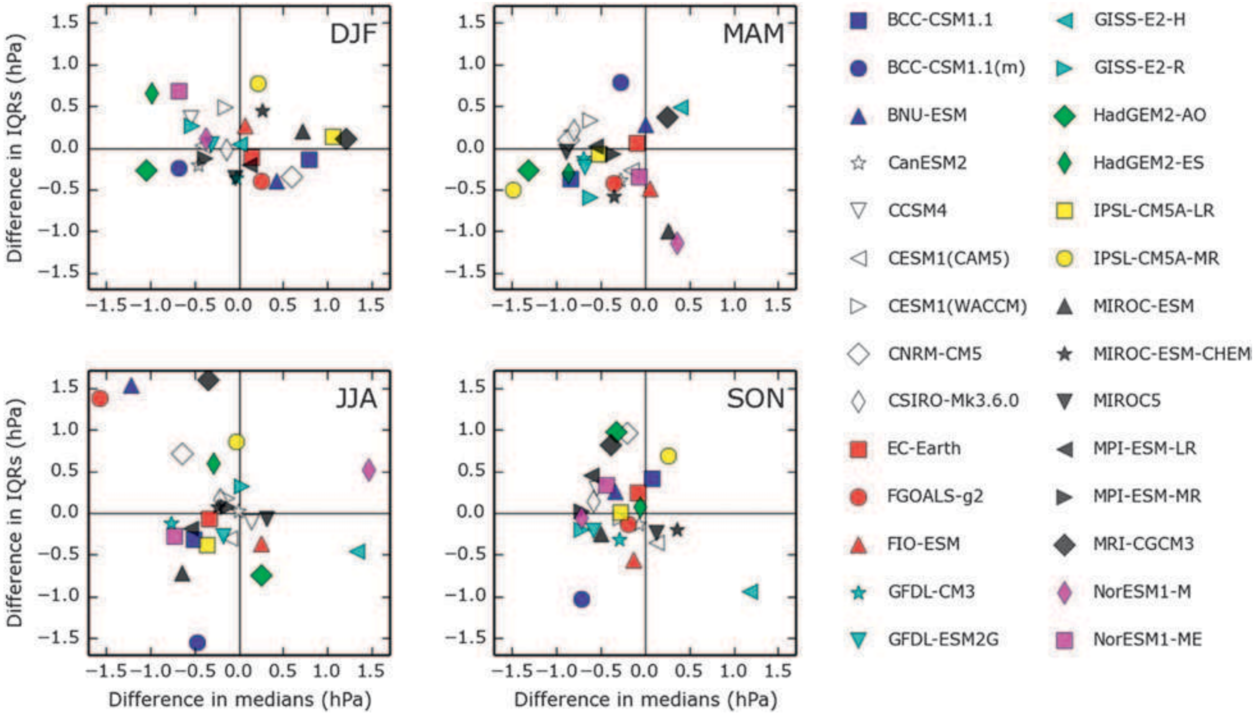

Fig. 5. The sensitivity of simulated relative central pressure for each season in 28 CMIP5 models, to different concentrations of greenhouse gases. Sensitivity is assessed for each model by calculating the difference between the median (*x* axis) and IQR (*y* axis) from histograms of 50-yr periods (2051–2100) from two contrasting future scenarios, RCP 8.5 minus RCP 2.6.

in fall and winter. In contrast, the First Institute of Oceanography (FIO) Earth System Model (ESM; FIO-ESM), EC-Earth Consortium (EC-Earth), and Second Generation Canadian Earth System Model (CanESM2) simulations are relatively insensitive to such changes. The best agreement across the models is seen in fall, suggesting that the regional meridional winds controlled by the ASL will be stronger in the future as greenhouse gases continue to rise. Similarly, Bracegirdle et al. (2008) found that fall has the largest increase in regional surface wind speeds over the twenty-first century when simulated by CMIP3 models following a medium mitigation scenario.

Following the conclusions of Hosking et al. (2013), the reduction in relative central pressure across the models here indicates that northerly winds, temperature, and precipitation near the coast of Ellsworth Land are expected to increase in seasons other than summer as greenhouse gases rise. Given the observed changes in the annual cycle of ASL absolute central pressure (Turner et al. 2013b), it is possible that such a response has already begun.

SUMMARY AND DIRECTIONS FOR FUTURE RESEARCH. The ASL is an important circulation feature that influences West Antarctic climate variability. Observations reveal that the ASL has deepened in recent decades with potential impacts on the regional climate through its influence on the meridional wind field. The majority of climate model projections suggest that the ASL will deepen over the twenty-first century in response to greenhouse gas increases. Given the observed decrease, it is possible that this process has already started. However, atmospheric model simulations of the past few decades indicate that tropical variability has played a major role in the observed deepening of the ASL, suggesting that a longer time period may be needed to clearly detect the signals of anthropogenic forcing in the ASL.

Although its influence on West Antarctic climate is clear, the ASL has been the central subject of relatively few studies; most ASL-related studies have been focused on variability within the SAM (e.g., Fogt et al. 2011) and ENSO (e.g., Lachlan-Cope and Connolley 2006). It is important, however, to understand the intrinsic variability of the ASL and its role in Antarctic climate. Many questions about the ASL remain to be answered. Some of these are fundamental, such as, why does the ASL exist where it does, how do different weather systems contribute to the climatological ASL, and how does the ASL vary at different temporal scales? The influence of the ASL on recent Antarctic sea ice growth as well as its role in regional ocean and shelf seas processes also need to be further examined. Research focused on these questions should provide answers that will ultimately improve our understanding of Southern Hemisphere polar climate and its predictability.

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REFERENCES

Abram, N. J., E. W. Wolff, and M. A. J. Curran, 2013: A review of sea ice proxy information from polar ice cores. *Quat. Sci. Rev.*, **79**, 168–183, doi:10.1016/j.quascirev.2013.01.011.

Baines, P. G., and K. Fraedrich, 1989: Topographic effects on the mean tropospheric flow patterns around Antarctica. *J. Atmos. Sci.*, **46**, 3401–3415, doi:10.1175/1520-0469(1989)046<3401:TEOTMT>2.0.CO;2.

Bracegirdle, T. J., W. M. Connolley, and J. Turner, 2008: Antarctic climate change over the twenty-first century. *J. Geophys. Res.*, **113**, D03103, doi:10.1029/2007JD008933.

——, J. Turner, J. S. Hosking, and T. Phillips, 2014: Sources of uncertainty in projections of twenty-first century westerly wind changes over the Amundsen Sea, West Antarctica, in CMIP5 climate models. *Climate Dyn.*, **43**, 2093–2104, doi:10.1007/s00382-013-2032-1.

Bromwich, D. H., J. P. Nicolas, A. J. Monaghan, M. A. Lazzara, L. M. Keller, G. A. Weidner, and A. B. Wilson, 2013: Central West Antarctica among the most rapidly warming regions on Earth. *Nat. Geosci.*, **6**, 139–145, doi:10.1038/ngeo1671.

Clem, K. R., and R. L. Fogt, 2013: Varying roles of ENSO and SAM on the Antarctic Peninsula climate in austral spring. *J. Geophys. Res. Atmos.*, **118**, 11 481–11 492, doi:10.1002/jgrd.50860.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, doi:10.1002/qj.828.

Ding, Q., E. J. Steig, D. S. Battisti, and M. Kuttel, 2011: Winter warming in West Antarctica caused by central tropical Pacific warming. *Nat. Geosci.*, **4**, 398–403, doi:10.1038/ngeo1129.

Fogt, R. L., D. H. Bromwich, and K. M. Hines, 2011: Understanding the SAM influence on the South Pacific ENSO teleconnection. *Climate Dyn.*, **36**, 1555–1576, doi:10.1007/s00382-010-0905-0.

——, A. J. Wovrosh, R. A. Langen, and I. Simmonds, 2012: The characteristic variability and connection to the underlying synoptic activity of the Amundsen–Bellingshausen Seas low. *J. Geophys. Res.*, **117**, D07111, doi:10.1029/2011JD017337.

Holland, P. R., and R. Kwok, 2012: Wind-driven trends in Antarctic sea-ice drift. *Nat. Geosci.*, **5**, 872–875, doi:10.1038/ngeo1627.

Hosking, J. S., A. Orr, G. J. Marshall, J. Turner, and T. Phillips, 2013: The influence of the Amundsen–Bellingshausen Seas low on the climate of West Antarctica and its representation in coupled climate model simulations. *J. Climate*, **26**, 6633–6648, doi:10.1175/JCLI-D-12-00813.1.

Jin, D., and B. P. Kirtman, 2009: Why the Southern Hemisphere ENSO responses lead ENSO. *J. Geophys. Res.*, **114**, D23101, doi:10.1029/2009JD012657.

Kaspari, S., P. A. Mayewski, D. A. Dixon, S. B. Sneed, and M. J. Handley, 2005: Sources and transport pathways of marine aerosol species into West Antarctica. *Ann. Glaciol.*, **41**, 1–9, doi:10.3189/172756405781813221.

Kreutz, K. J., P. A. Mayewski, I. I. Pittalwala, L. D. Meeker, M. S. Twickler, and S. I. Whitlow, 2000: Sea-level pressure variability in the Amundsen Sea region inferred from a West Antarctic glaciochemical record. *J. Geophys. Res.*, **105**, 4047–4059, doi:10.1029/1999JD901069.

Lachlan-Cope, T. A., and W. M. Connolley, 2006: Teleconnections between the tropical Pacific and the Amundsen-Bellingshausen Sea: Role of the El Niño/Southern Oscillation. *J. Geophys. Res.*, **111**, D23101, doi:10.1029/2005JD006386.

Li, X., D. M. Holland, E. P. Gerber, and C. Yoo, 2014: Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature*, **505**, 538–542, doi:10.1038/nature12945.

Marshall, G. J., 2003: Trends in the southern annular mode from observations and reanalyses. *J. Climate*, **16**, 4134–4143, doi:10.1175/1520-0442(2003)016<4134:TITSAM>2.0.CO;2.

Neale, R. B., J. Richter, S. Park, P. H. Lauritzen, S. J. Vavrus, P. J. Rasch, and M. Zhang, 2013: The mean climate of the Community Atmosphere Model (CAM4) in forced SST and fully coupled experiments. *J. Climate*, **26**, 5150–5168, doi:10.1175/JCLI-D-12-00236.1.

Polvani, L. M., D. W. Waugh, G. J. P. Correa, and S.-W. Son, 2011: Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. *J. Climate*, **24**, 795–812, doi:10.1175/2010JCLI3772.1.

Pritchard, H. D., R. J. Arthern, D. G. Vaughan, and L. A. Edwards, 2009: Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature*, **461**, 971–975, doi:10.1038/nature08471.

Rankin, A. M., E. W. Wolff, and S. Martin, 2002: Frost flowers: Implications for tropospheric chemistry and ice core interpretation. *J. Geophys. Res.*, **107**, 4683, doi:10.1029/2002JD002492.

Schneider, D. P., C. Deser, and Y. Okumura, 2012a: An assessment and interpretation of the observed warming of West Antarctica in the austral spring. *Climate Dyn.*, **38**, 323–347, doi:10.1007/s00382-010-0985-x.

——, Y. Okumura, and C. Deser, 2012b: Observed Antarctic climate variability and tropical linkages. *J. Climate*, **25**, 4048–4066, doi:10.1175/JCLI-D-11-00273.1.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Thoma, M., A. Jenkins, D. Holland, and S. Jacobs, 2008: Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. *Geophys. Res. Lett.*, **35**, L18602, doi:10.1029/2008GL034939.

Turner, J., and Coauthors, 2009: Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase in Antarctic sea ice extent. *Geophys. Res. Lett.*, **36**, L08502, doi:10.1029/2009GL037524.

——, T. J. Bracegirdle, T. Phillips, G. J. Marshall, and J. S. Hosking, 2013a: An initial assessment of Antarctic sea ice extent in the CMIP5 models. *J. Climate*, **26**, 1473–1484, doi:10.1175/JCLI-D-12-00068.1.

——, T. Phillips, S. Hosking, G. J. Marshall, and A. Orr, 2013b: The Amundsen Sea low. *Int. J. Climatol.*, **33**, 1818–1829, doi:10.1002/joc.3558.

Wagenbach, D., F. Ducroz, R. Mulvaney, L. Keck, A. Minikin, M. Legrand, J. S. Hall, and E. W. Wolff, 1998: Sea-salt aerosol in coastal Antarctic regions. *J. Geophys. Res.*, **103**, 10 961–10 974, doi:10.1029/97JD01804.

Walsh, K. J. E., I. Simmonds, and M. Collier, 2000: Sigma-coordinate calculation of topographically forced baroclinicity around Antarctica. *Dyn. Atmos. Oceans*, **33**, 1–29, doi:10.1016/S0377-0265(00)00054-3.

Wolff, E. W., A. M. Rankin, and R. Rothlisberger, 2003: An ice core indicator of Antarctic sea ice production? *Geophys. Res. Lett.*, **30**, 2158, doi:10.1029/2003GL018454.

——, and Coauthors, 2006: Southern Ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles. *Nature*, **440**, 491–496, doi:10.1038/nature04614.

Yuan, X. J., and D. G. Martinson, 2001: The Antarctic dipole and its predictability. *Geophys. Res. Lett.*, **28**, 3609–3612, doi:10.1029/2001GL012969.

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