The Relative Influence of Tropical Sea Surface Temperatures and Radiative Forcing on the Amundsen Sea Low

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ABSTRACT

Recent studies suggest that warming trends across West Antarctica and the Antarctic Peninsula and sea ice loss in the adjacent Amundsen and Bellingshausen Seas are linked to changes in the regional atmospheric circulation, represented by the Amundsen Sea low (ASL). Importantly, changes in the ASL have similarly been tied to forcing from the tropics. Here, several model simulations from the Community Atmosphere Model, version 4, are investigated in order to understand the relative roles of tropical sea surface temperature variability and radiative forcing on the variations in trends in the ASL. In comparing across the simulations, it is observed that the addition of time-varying extratropical SSTs and sea ice conditions in general have a much smaller impact on the ASL than tropical SSTs or radiative forcing. Tropical forcing alone explains much of the climatological variability and extreme intensities of the ASL (both strong and weak relative central pressures). The role of radiative forcing is best observed in the ASL trends, with this simulation leading to a marked deepening of the ASL and pressures across the Southern Hemisphere that is consistent with atmospheric reanalysis in austral summer. In austral winter, the simulation with radiative forcing produces stronger trends than observed in reanalysis data, perhaps reflecting the need to couple to an ocean–ice model in order to more realistically simulate the ASL changes. Together, the results suggest that models need to include both the effects from tropical SST variations and radiative forcing when understanding historic and future variations in the ASL.

1. Introduction

Recent studies note marked regional changes in both Antarctic sea ice extent/concentration and near-surface temperatures across the Antarctic continent. In terms of sea ice, the Ross Sea sector has been displaying increases in sea ice extent (Lefebvre et al. 2004; Comiso and Nishio 2008), while the neighboring Amundsen–Bellingshausen (AB) Seas sector has experienced increasing sea ice extent as well as concentration (Yuan and Martinson 2000; Zwally et al. 2002; Stammerjohn et al. 2008) over the last several decades. Several temperature reconstructions note a widespread warming across West Antarctica and the Antarctic Peninsula since the International Geophysical Year, most marked in austral winter and spring (Steig et al. 2009; O’Donnell et al. 2011; Bromwich et al. 2012; Nicolas and Bromwich 2014). In contrast, statistically insignificant temperature trends have been observed across the majority of East Antarctica.

The regional disparity evidenced in these changes in the near-surface temperature and sea ice conditions is hypothesized to be partly an effect of surface wind changes associated with the Amundsen Sea low (ASL; Stammerjohn et al. 2008; Holland and Kwok 2012). The ASL has become a focal point in recent Antarctic climate studies (Fogt et al. 2012; Hosking et al. 2013; Turner et al. 2013; Clem and Fogt 2013; Fogt and Zbacnik 2014; Raphael et al. 2015) and is believed to exist predominantly because of the Antarctic topography, specifically the nonsymmetric orientation of the continent, such as the high plateau of East Antarctica (which reaches an elevation of over 3000 m) and the western Antarctic Peninsula (Baines and Fraedrich 1989; Lachlan-Cope et al. 2001). The ASL has a seasonal
movement due to the location of the Rossby long waves in the Southern Hemisphere (Turner et al. 2013), being farther east toward the Antarctic Peninsula in austral summer and farther west toward the Ross Sea in austral winter (Fogt et al. 2012; Hosking et al. 2013).

In addition to assessing seasonal variability of the ASL, Hosking et al. (2013) concluded that the longitudinal location had the most profound influence on the climate across West Antarctica and the Antarctic Peninsula. Not surprisingly, the east–west location in particular alters the location of meridional wind anomalies, which influence the patterns of sea ice extent/concentration, warm and cold air advection, and precipitation (through changing the location of the moisture flux from the Southern Ocean). Similarly, the spatial breadth of the ASL—how large the low pressure anomaly is in the Amundsen and Bellingshausen Seas—is an important factor in determining how variations in the ASL will impact the Antarctic Peninsula climate during austral spring (Clem and Fogt 2013).

Several mechanisms give rise to long-term changes in the ASL. Both Turner et al. (2009) and Fogt and Zbacnik (2014) found that ozone depletion has led to a deepening of the ASL in austral autumn, although the latter study only observed this in coupled climate model simulations, and the response was weaker than that in austral summer. Other studies linked ASL-related trends in the regional atmospheric circulation to changes in the tropics (Ding et al. 2011; Ding and Steig 2013). In Ding et al. (2011), warming of the central tropical Pacific in austral winter generated a Rossby wave train that led to higher geopotential heights in the Amundsen Sea, which increased northerly flow onto West Antarctica and was therefore associated with the warming there. Ding and Steig (2013) noticed that the decrease of sea ice in the eastern Amundsen and Bellingshausen Seas was driven by the deepening of the ASL in austral autumn and that these changes were linked to the tropical Pacific sea surface temperature (SST) variability. In austral spring, the other season when the ASL also has variability. In autumn and that these changes were linked to the tropical sea surface temperature variability. In particular, they noted opposing impacts in the Amundsen–Bellingshausen Seas sector arising between SST-only variations (where the atmospheric chemical composition was fixed at 1990 levels) and atmosphere-only variations (where global SSTs and sea ice were set to climatological repeating cycles). Deser and Phillips (2009) also observed atmospheric circulation differences in the South Pacific when comparing simulations with tropical-only (20°N–20°S) and global SST variations. Other work by Turner et al. (2009) demonstrated that geopotential height changes in the region of the ASL were simulated with notable skill in the HadAM3 model, an Atmospheric Model Intercomparison Project (AMIP) simulation run by the Met Office Hadley Centre.

In this study, we similarly investigate AMIP simulations rather than coupled simulations since we are particularly interested in understanding the relative influence of tropical SST and radiative forcing on the ASL and, more broadly, the Southern Hemisphere atmospheric circulation. These experiments do not fully allow a two-way interaction between the atmosphere and underlying ocean or ice surface, although this coupling appears to have only a small influence in the high southern latitudes based on previous modeling studies (Sigmond et al. 2010; Fogt and Zbacnik 2014).

For this study, three simulations from the Community Atmospheric Model, version 4 (CAM4), are investigated. CAM4 served as the successor to CAM3 and contained numerous improvements to the model physics, the most

2. Data and methods

a. AMIP simulation data

Deser and Phillips (2009) published an overview of atmospheric circulation trends during 1950–2000 using the Community Atmospheric Model, version 3 (CAM3). In particular, they noted opposing impacts in the Amundsen–Bellingshausen Seas sector arising between SST-only variations (where the atmospheric chemical composition was fixed at 1990 levels) and atmosphere-only variations (where global SSTs and sea ice were set to climatological repeating cycles). Deser and Phillips (2009) also observed atmospheric circulation differences in the South Pacific when comparing simulations with tropical-only (20°N–20°S) and global SST variations. Other work by Turner et al. (2009) demonstrated that geopotential height changes in the region of the ASL were simulated with notable skill in the HadAM3 model, an Atmospheric Model Intercomparison Project (AMIP) simulation run by the Met Office Hadley Centre.

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notable being the parameterization of deep convection, thus improving erroneous behavior in tropical weather (e.g., ENSO patterns) present in previous versions of the CAM (Neale et al. 2013). The model has a 0.9° latitude × 1.25° longitude horizontal resolution, with a finite-volume dynamical core and 26 vertical levels. Wilson et al. (2014) demonstrate that CAM4 has realistic tropical teleconnections, particularly during various flavors of ENSO warm events.

Three sensitivity simulations (as in Neale et al. 2013) are used in this study to investigate the role of tropical SST and radiative forcing on the ASL. These simulations are further outlined in Table 1. The first simulation is the Global Ocean Global Atmosphere (GOGA) experiment, where SSTs and sea ice conditions are prescribed globally and radiative forcing is fixed in time. The second simulation is the Tropical Ocean Global Atmosphere (TOGA) run, which prescribes SSTs only in the tropical ocean (28°S–28°N) and utilizes the climatological seasonal cycle of SSTs and sea ice poleward of 35°, with linear interpolation between 28° and 35°. No IPCC radiative forcing. The third simulation investigated is the IPCC experiment, where SSTs and sea ice poleward of 35° are linearly weighted to the climatological cycle, but as in the GOGA experiment, radiative forcing is fixed in time. To evaluate the role of radiative forcing, the Intergovernmental Panel on Climate Change (IPCC) simulation is investigated. In addition to prescribing SSTs and sea ice conditions globally, the IPCC experiment also includes radiative forcing following the IPCC (2007) requirements. Only monthly mean data are explored in this study; however, each experiment contains at least five ensemble simulations, initialized at various times of a control simulation from the coupled version of CAM4, the Community Climate System Model (Gent et al. 2011). To best investigate the forced signal, ensemble means are used for each simulation (averaging over the 5–6 ensemble members per simulation). Further simulation details are outlined in Neale et al. (2013). Although the Community Atmospheric Model, version 5, has been developed as the successor to the CAM4 model, specific simulations like those investigated here are not yet available, and there has not yet been an extensive published evaluation of this model performance.

### b. Atmospheric reanalysis data

As the ASL resides primarily off the coast of West Antarctica where in situ observations are sparse, this study also implements atmospheric reanalysis data. Several fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) are examined to validate CAM4. ERA-Interim data were chosen over other contemporary global reanalyses because of its superior performance within the southern high latitudes (Bracegirdle and Marshall 2012). Monthly mean ERA-Interim data are employed from a horizontal (latitude–longitude) resolution of 1.5° × 1.5° spanning the years 1979–2012. Appropriately, only the IPCC runs are directly compared to the reanalysis data for the CAM4 simulations, as the IPCC is the only CAM4 simulation with globally evolving SSTs and the full range of atmospheric forcing agents (such as greenhouse gases and ozone depletion) and is thus most comparable to the reanalysis data.

### c. Methods

We make use of composite and regression techniques to compare the changes in the atmospheric circulation among the sensitivity runs in order to assess the relative roles of tropical SST and radiative forcing on the ASL. We note statistically significant differences using a Student’s t test, assuming independence among the years since the majority of our analysis focuses on seasonal means. When comparing among the simulations, we identify the relative roles of forcing mechanisms following the Venn diagram Fig. 1. For significant differences existing between only the TOGA and GOGA simulations, the response is due to the inclusion of extratropical SSTs and sea ice evolution; regions with no statistically significant difference between these two CAM4 simulations highlight the fact that the forcing is predominantly tropical (or that the time evolution of
tropical SSTs is enough to resolve the pattern or trend under investigation). When comparing the GOGA and IPCC simulations, it can similarly be concluded that significant differences are likely a result of the inclusion of radiative forcing. Should all the simulations show significant differences at the same time/region, forcing cannot be attributed, nor can it be precisely attributed when comparing between only the TOGA and IPCC simulations. Investigating the GOGA simulation in such cases can help in this comparison to better understand the role of extratropical forcing. If all three simulations show no statistically significant difference, it is surmised that tropical SST variability alone is a sufficient forcing mechanism.

3. Model evaluation

Simulation accuracy of ENSO and ASL variability

Since previous work has shown the ASL to be influenced by tropical ENSO teleconnections (Karoly 1989; Renwick 1998; Turner 2004; Turner et al. 2013), we first assess the model simulation of ENSO events. Although the SSTs in CAM4 are prescribed, thereby ensuring the correct timing and amplitude of the oceanic ENSO events, the tropical atmospheric response is not similarly prescribed. Naturally, the atmospheric response will be sensitive to the underlying SSTs, but the exact magnitude of the atmospheric variations is a function of many factors, including the convective parameterization scheme in the model. The near-surface atmospheric response to the tropical SST variability is evaluated here using a monthly model-based Southern Oscillation index (SOI) calculated from the model grid points closest to Tahiti (17.43°S, 150°W) and Darwin (12.72°S, 131.23°E). Correlations of the model SOI with the observed SOI are \( r \approx 0.71 \); \( r \approx 0.72 \) for the GOGA and TOGA simulations during 1951–2011, respectively; and \( r = 0.76 \) for the IPCC simulation during 1979–2010. While not perfect, the correlations are statistically significant \((p < 0.01\) even after accounting for the high autocorrelation present in the monthly SOI).

As another means of validating the near-surface tropical response, we compared the average SOI during El Niño and La Niña events separately for each ensemble member; the timing of the model ENSO events is defined following the U.S. Climate Prediction Center’s (CPC) oceanic Niño index. Table 2 lists the minimum and maximum number of El Niño and La Niña events that had a statistically different mean SOI value compared to the observations. Notably, CAM4 does much better in representing the magnitude of the tropical Pacific Southern Oscillation pattern during El Niño events compared to La Niña events, although at worst less than half of the events show statistically significant differences. Investigation of the mean SOI by season shows the differences are most marked during
the height of ENSO activity. This is especially true during January–March, when the 3-month overlapping SOI in the models during La Niña events is almost always statistically different than observed ($p < 0.05$; not shown). It is therefore suggested that the model will produce weaker La Niña teleconnections than observed since the tropical atmospheric response is also weaker. Whether this deficiency is due to the nudging choices of the subtropical SSTs in the experimental design or to tropical convection patterns or other model biases is not investigated further here, although Wilson et al. (2014) note that during ENSO warm events, CAM4 produces reliable teleconnections across the Southern Hemisphere. Further, since this bias persists across all simulations, it does not severely limit our ability to assess the relative roles of tropical and radiative forcing on the ASL, as its effects are at least partially removed when comparing across simulations.

Since our primary focus for understanding the atmospheric circulation changes is in the vicinity of the ASL, it is prudent to also ensure the model captures its correct seasonal variability as a last means of model evaluation. We use a slightly modified version of the methodology of Fogt et al. (2012) and define the ASL within the region $60^\circ$–$75^\circ$S, $60^\circ$W–$180^\circ$; the ASL center never moves north of $60^\circ$S in reanalysis data (Fogt et al. 2012; Turner et al. 2013). For the ASL magnitude, we investigate both the absolute minimum pressure in the aforementioned region as well as the relative central pressure following Hosking et al. (2013); the relative central pressure definition defines the ASL intensity as the minimum pressure after removing the area mean pressure (within the same region as the absolute pressure minimum). Removing the area mean helps to focus on regional circulation features, as the influence of the southern annular mode (SAM) is minimal in this intensity index (Hosking et al. 2013). The longitude and latitude (the location of the pressure minimum composing the ASL) is insensitive to the way the ASL magnitude is defined (Hosking et al. 2013). We investigated the climatological seasonal cycle of these ASL metrics in each ensemble member over the full range of available data and present this as moving boxplots in Fig. 2 (showing the range, upper and lower quartiles, and median across all ensemble members), based on the absolute ASL definition as in Fogt et al. (2012); also shown is the ASL seasonal cycle from ERA-Interim in Figs. 2j–l.

Figure 3 compares the seasonal cycle of the ASL magnitude for the absolute and relative central pressure definitions.

The leftmost column of Fig. 2 displays the climatological cycle of ASL absolute magnitude, ranging from a maximum in December–February (DJF; a secondary maximum exists in June–August (JJA) as well) and two relative minima in March–May (MAM) and September–November (SON). This seasonal cycle in the pressure minima reflects the semiannual oscillation and is consistent with ERA-Interim (Fig. 2). As discussed in Hosking et al. (2013), the two minima during the equinoxes is a function of how the ASL is defined; only one minimum in austral winter is seen when using the relative central pressure to define the ASL (Fig. 3). The overall agreement among the simulations, as well as with Fogt et al. (2012), is also observed for the ASL seasonal cycle of its location, as measured in terms of latitude and longitude (center and right columns of Fig. 2, respectively). Interestingly, there is a much wider range of variability in the latitude of the ASL in the CAM4 simulations than in the reanalysis, which may reflect some model biases, such as issues in the boundary layer at the sea ice–ocean–atmosphere interface. Despite the greater range, the overall interquartile range (IQR) resembles the seasonal cycle present in the reanalysis, and only the extreme events in terms of location appear to be different in the model simulation. For longitude, the IQR is noticeably smaller during winter in the models compared to ERA-Interim. Last, the relative central pressure definition of ASL magnitude similarly agrees with reanalysis (Fig. 3), although there is a slightly greater change between summer and winter in the model simulations, even within the IQR. Nonetheless, the differences in Figs. 2 and 3 are small compared to the weaker performance of ASL seasonal variability seen in coupled climate models (Hosking et al. 2013) or chemistry climate models (Fogt and Zbacnik 2014).

### 4. Results

#### a. ASL trends

To understand the specific changes to the ASL, we first investigate the linear trends in ASL longitude and magnitude (pressure) for two periods: 1957–2012 and
Fig. 2. Monthly running box plots showing the median (middle black line), interquartile range (light green shading), and overall range (dark green shading) for (left) ASL absolute magnitude, (center) ASL latitude, and (right) ASL longitude for the various (a)–(i) CAM4 simulations and (j)–(l) ERA-Interim, as in Fogt et al. (2012).
1979–2010. Longitude is examined here instead of latitude because the climate of West Antarctica and the Antarctic Peninsula has been shown to be most sensitive to the longitude of the ASL (Hosking et al. 2013). Magnitude is also specifically investigated as other recent studies have shown significant trends in the ASL magnitude in spring and autumn (Fogt et al. 2012; Turner et al. 2013; Clem and Fogt 2013, 2015). The two time periods are examined in order to see how the ASL has changed in time, and the latter period can also be compared to the ERA-Interim. Figure 4 displays the trends for the ASL longitude, while Fig. 5 displays the ASL magnitude trends (for both the absolute and relative central pressure definitions). In all cases, the trends in Figs. 4 and 5 are based on the ASL metrics from the seasonal ensemble-mean pressure (or seasonal mean pressure in ERA-Interim).

In many of the model experiments, the trends are positive for longitude, reflecting an eastward trend with time (Fig. 4). This is true for both time periods, despite the fact that the reanalysis only shows a pronounced eastward trend in MAM. The majority of the trends are not statistically significant, although the model confidence intervals are notably smaller in winter because of the smaller spread in the longitude position in the models (reflected in right column of Fig. 2). Because there are no significant differences among the simulations in Fig. 4, it is likely that tropical forcing alone is sufficient to capture the slight eastward progression of the ASL.

For ASL magnitude, a more consistent story is observed, namely, that nearly all of the simulations produce negative trends in the absolute magnitude of the ASL (i.e., a deepening/intensifying ASL) over both time periods, consistent with the trends in ERA-Interim (although the latter has a statistically insignificant positive trend in austral winter; Fig. 5c). During DJF, only the IPCC scenario produces a significant negative trend in the absolute ASL magnitude, in agreement with several studies pointing to the marked decreases in pressure over Antarctica in austral summer and a positive trend in the SAM index as a result of stratospheric ozone depletion (Thompson and Solomon 2002; Arblaster and Meehl 2006; Perlwitz et al. 2008; Fogt and Zbacnik [8546 JOURNAL OF CLIMATE VOLUME 28 Unauthenticated | Downloaded 07/29/22 10:31 PM UTC]
However, the IPCC simulation produces a significant negative trend in the ASL during austral winter, opposite of that in ERA-Interim and much stronger than in both TOGA and GOGA. This discrepancy will be discussed in more detail in section 4c, when spatial pressure trends over the Southern Hemisphere are examined.

The subtraction of the area mean in calculating the relative ASL magnitude removes the influence of the SAM (Hosking et al. 2013) and the semiannual oscillation (Fig. 3). This definition can be thought of as reflecting the strength of the local pressure gradient, with more negative (relative) ASL magnitudes representing larger negative differences from the area mean and hence a tightened pressure gradient within the region. As such, it is not surprising to see positive trends in the relative ASL magnitude (Figs. 5b,d), which indicates that although the ASL is intensifying (Figs. 5a,c), so are all the pressures in the region (and not in one smaller part of the region). In general, there are very few differences between the model simulations in the ASL relative magnitude trends. In SON, there are notable differences between the CAM4 simulations and ERA-Interim, suggesting that not only are pressures decreasing broadly in the Amundsen Sea area but that also the pressure gradient is intensifying as well in this region. The negative ASL magnitude trend in SON reflects the regional deepening of pressure within the Ross Sea, discussed in more detail in other studies (Fogt et al. 2012; Clem and Fogt 2013, 2015). The CAM4 simulations do not produce as strong of a SON intensification of the ASL by this metric as in reanalyses, especially the IPCC experiment (Fig. 5c). This contrast will also be discussed in more detail later.

b. Composite analysis

Since the trends in the ASL indices are at a specific point, we next examine spatial composites based on the ASL magnitude, which enhance the understanding of the relationship between the regional ASL and the atmospheric circulation anomalies across the Southern Hemisphere. To best highlight the role that tropical SSTs or radiative forcing play on the ASL variability, we present the composites as differences among the simulations. This was conducted by first compositing the five strongest (i.e., lowest central pressure) and five weakest (i.e., highest central pressure) years of the ASL, based on its relative central pressure definition (in order to fully remove influence from the SAM), for each seasonal ensemble mean. Next, these composites were subtracted from one another for the various pairs of model simulations to highlight the differences in the ensemble means. Figure 6 displays the composite difference among the simulations for the five strongest ASL years, while Fig. 7 shows the composite difference for the five weakest ASL years. The rows of Figs. 6 and 7 identify the seasons, while the columns are arranged for the specific difference to indicate the forcing agent, as given by the column headers (i.e., left column is IPCC minus TOGA; center column is GOGA minus TOGA; and right column is IPCC minus GOGA). Shading (from lightest to darkest) in both figures shows composite differences that are statistically different from zero at $p < 0.10$, $p < 0.05$, and $p < 0.01$. Recall that Fig. 1 highlights how differences in Figs. 6 and 7 are interpreted; regions where there are no significant differences either indicate that tropical forcing alone is enough to resolve the feature at hand or that the spread is much larger than the differences investigated and nothing can be said about the forcing mechanism.

In DJF, Figs. 6a and 6c both show a significant difference in the vicinity of the ASL in the South Pacific, which points to the fact that the ASL is much weaker in the IPCC simulation during its most intense years when compared to both TOGA and GOGA. Since the majority of the five strongest ASL years during DJF in both TOGA and GOGA occur before the start of the IPCC simulation (i.e., 1979), these differences reflect a locally
intense ASL occurring in the absence of radiative forcing (especially prior to the ozone hole commencing around ~1980). In other words, the natural variability present in the GOGA and TOGA experiments produces extremes in ASL primarily prior to 1980 that are on average more intense than the ASL seen during 1979–2010 in the IPCC simulation (which includes radiative forcing). In contrast, during MAM and SON, the ASL is stronger in the IPCC simulation than in either TOGA or GOGA, implying the addition of radiative forcing is likely aiding to intensify the local pressure gradient, leading to a stronger and more regionalized ASL overall.

The role of extratropical forcing on the relative magnitude of the ASL is identified by examining the center column of Fig. 6, where notable differences are only observed in the transitional seasons of MAM and SON. Here, rather than showing differences only in the Amundsen Sea, these plots suggest an altered/shifted Rossby wave train extending from New Zealand through the South Pacific/ASL region, and into the South Atlantic. Since the composite reflects differences between the strongest relative ASL magnitudes, these plots indicate the addition of extratropical sea ice/SSTs significantly shifts the ASL farther west in these seasons toward the Ross Sea, changing the pressure gradient in the Amundsen Sea and increasing the atmospheric pressure along the Antarctic Peninsula. These two seasons correspond to the annual advance and retreat of sea ice around Antarctica, respectively, and so changes in the boundary layer/surface fluxes at this time are important for modifying the local baroclinicity, which acts to intensify the individual cyclones comprising the ASL. It is therefore not surprising to see the greatest impacts on ASL intensity being dependent upon time-varying conditions of extratropical SSTs and sea ice at these times of the year. In the other seasons, the lack of significant differences near West Antarctica in the center
FIG. 6. MSLP composite difference between the various CAM simulations [indicating forcing agents as identified in the column headings: (left)-(right) IPCC minus TOGA, GOGA minus TOGA, and IPCC minus GOGA] by season (columns) for the 5 years when the ASL relative central pressure displayed the lowest values. Shading, from lightest to darkest, indicates differences that are statistically significantly differently from zero at $p < 0.10$, $p < 0.05$, and $p < 0.01$. 

Radiative or Extratropical SST

Radiative

Strong ASL

Extratropical SST

a)

b)

c)

d)

e)

f)

g)

h)

i)

j)

k)

l)

DJF

MAM

JJA

SON

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Fig. 7. As in Fig. 6, but for the 5 years when the ASL relative central pressures were highest.
column of Fig. 6 indicate that tropical SST variability alone produces equal magnitudes of the ASL during its strongest (relative) years. Altogether, Fig. 6 demonstrates that radiative forcing (IPCC simulation) and extratropical SSTs (GOGA simulation) have their greatest influence on the most intense ASL central pressures during the transition seasons of MAM and SON. During the summer and winter, tropical forcing alone produces ASL central pressures that are as intense or deeper than those in simulations with additional forcing mechanisms.

Interestingly, the story for when the relative magnitude of the ASL is the weakest (reflecting a weakened/reduced pressure gradient in the Amundsen Sea) is quite different. Only in winter does radiative forcing have a notable impact (Figs. 7g,i), producing an ASL that is more intense/not as weak as seen in both the TOGA and GOGA simulations. The notable difference in the IPCC simulation in winter in Fig. 7 is consistent with the marked trends in absolute ASL pressure during winter in the IPCC simulation (Fig. 5c). The negative trend in absolute pressure reflects a decrease in the magnitude of the pressures across the entire ASL region; however this also would imply an increase in the “weak” relative central pressures at the same time since the area mean is decreasing uniformly (reflected to some extent by the nearly significant positive trend in the IPCC winter ASL relative central pressure; Fig. 5d). As the remainder of the plots in Fig. 7 primarily does not display statistically significant differences near West Antarctica, the impact of radiative forcing is negligible in all the other seasons, as is the role of extratropical SST and sea ice variability. Compared to intense ASL years, regional sea ice or SST conditions play a much smaller role than the role of tropical forcing in producing weak ASL years, or the internal variability in the 5-yr composites is much larger and masks any potential forced signal.

c. Mean sea level pressure trends

To better understand the changes in the ASL further, we conclude by examining the mean sea level pressure (MSLP) trends by season during 1979–2010, the period of overlap among the three simulations. The MSLP trends are contoured in Fig. 8, with the shading representing significant differences in the trends among the simulation pairs, as in Figs. 6 and 7, and identified in the column headings of Fig. 8. For reference, the MSLP trends from ERA-Interim during 1979–2010 are displayed in Fig. 9.

A prominent feature is the lack of significant difference in the trends within the vicinity of the ASL between the TOGA and GOGA simulations (center column of Fig. 8). This suggests, in agreement with Figs. 3 and 4, that the addition of globally varying SSTs and sea ice conditions does not significantly alter the trend magnitude in the region of the ASL (and across much of the Southern Hemisphere). Further, Fig. 8 clearly indicates that the addition of radiative forcing produces statistically different/stronger trends in the vicinity of the ASL and across much of the Southern Hemisphere (consistent with Fig. 4). In austral summer, the pattern of the trends projects strongly onto the pattern for the positive phase of the SAM, again highlighting the role of stratospheric ozone depletion on Southern Hemisphere circulation trends in this season (Thompson and Solomon 2002; Arblaster and Meehl 2006; Perlwitz et al. 2008; Fogt and Zbacnik 2014); the IPCC trend during summer also aligns very well with the trend in ERA-Interim (Fig. 9a). Outside of summer, the trend pattern in the IPCC simulation (contours rightmost column in Fig. 8) is more regional, with distinct negative pressure trends only in the South Pacific and not over Antarctica, rather than reflecting a SAM-like pattern (i.e., the trend pattern/contours in Fig. 8c), broadly consistent with ERA-Interim (Fig. 9). However, because the pressure decreases are more uniformly negative across all of the ASL region ($60^\circ$S–$75^\circ$S, $60^\circ$W–$180^\circ$), when the area mean is removed for the calculation of the relative central pressure ASL magnitude, the trends become positive, especially in the IPCC simulation in JJA and SON where the spatial trends are the strongest (Figs. 8g–l and 5d).

Although the trends in the IPCC are significantly different than in GOGA and TOGA simulations in the vicinity of the ASL during summer and winter, reanalysis trends have the largest areas of statistical significance across the high southern latitudes in DJF (Fig. 9a), with also a small region of weakly significant ($p < 0.10$) trends in the eastern Ross Sea in SON (Fig. 9d). Combined, this implies that radiative forcing is acting to deepen the ASL in all seasons, as seen in Fig. 3, but only in DJF are these trends large enough to fall outside the range of the considerable interannual variability and achieve statistical significance based on ERA-Interim. The differences between the magnitude of the trends in ERA-Interim and the IPCC simulation, most pronounced during JJA (Figs. 4b, 8i, and 9c), may reflect feedbacks between the underlying ocean–ice surfaces observed in the real world and captured by observations assimilated into ERA-Interim but not fully captured only with one-way interaction in the IPCC simulation. In this way, the underlying ocean–ice surface, which has a longer memory/response time, may reduce the changes over time and produce weaker trends in ERA-Interim than in IPCC simulation; further tests are needed to understand the stronger model.
Fig. 8. (top)-(bottom) Seasonal MSLP trends (contoured, hPa decade$^{-1}$) during 1979–2010, along with the significant differences among the model simulations shaded (as in Fig. 6, columns).
trends in winter. For the stronger trends in the absolute ASL magnitude in the ERA-Interim compared to the model simulations in SON (Fig. 4), it is evident that the ERA-Interim negative pressure trend stretches over a larger region of the South Pacific (Fig. 8d), while the model trends are much more regional in nature (Figs. 8j–l). Nonetheless, it is perhaps not surprising that the general pattern in all simulations, and the general lack of differences among them in SON, points to the primary role of tropical forcing in the South Pacific and Atlantic pressure trends during SON (Schneider et al. 2012; Clem and Fogt 2015).

5. Conclusions and discussion

Several AMIP-style model simulations were compared in order to understand the relative roles of tropical sea surface temperatures and radiative forcing on the Amundsen Sea low. Comparing trends and composites for key periods across these simulations allows for an understanding of how the various components create changes in the regional atmospheric circulation off the coast of West Antarctica and how these circulation changes are associated with other changes across the Southern Hemisphere more broadly. Notably the model simulations employed have a realistic depiction of the seasonal ASL variability, especially compared to other types of models, but they do tend to underrepresent the magnitude of the Southern Oscillation in the tropical Pacific during La Niña events.

When examining various indices that measure ASL variability, only significant trends in the ASL magnitude can be readily linked to forcing mechanisms. Here, an intensification of the ASL during austral summer is clearly linked to radiative forcing, continuing to demonstrate the role of stratospheric ozone depletion on the

![1979–2010 ERA-Int MSLP Trends](image)

**FIG. 9.** Seasonal MSLP trends (hPa decade⁻¹) for ERA-Interim, 1979–2010. Shading, from lightest to darkest, indicates trends that are statistically significant at $p < 0.10$, $p < 0.05$, and $p < 0.01$. 

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recent negative pressure trends south of 60°S in summer. Composites during years when the ASL was most intense (deepest) and weakest in the ensemble mean for each simulation were subsequently examined, and it was found during summer and winter that tropical variability alone (as in the TOGA simulation) produced similar amplitudes to the ASL during its strongest years compared to the GOGA simulation, which prescribed sea surface temperatures and sea ice conditions globally. However, during the transition seasons of MAM and SON, time-varying sea ice and SST conditions are important to understand the ASL during its most intense years, likely needed to have the correct amplitude of low-level baroclinicity that intensifies cyclones locally. During these same seasons, the addition of radiative forcing also acts to increase the intensity of the ASL during its most extreme years, the causes of which are not precisely understood from this study. In contrast, tropical variability alone generally creates statistically indistinguishable atmospheric circulation patterns during the years with very weak relative central pressures of the ASL.

When examining extratropical seasonal MSLP trends during 1979–2010, the patterns are also generally statistically indistinguishable among simulations with only time-varying tropical SSTs and time-varying global SSTs/sea ice conditions. However, the addition of radiative forcing leads to more pronounced trends overall, especially a marked decrease in the pressures in the ASL in summer and winter. While the summer changes are in agreement with reanalyses, highlighting the role of radiative forcing in this season, the trends in austral winter in particular are overestimated compared to the reanalyses in the IPCC simulation. This either identifies inaccurate model sensitivities to the forcing mechanisms or more likely that nonlinear processes such as two-way coupling to the ocean are also offsetting the trends due to radiative forcing and making them weaker than in this AMIP experiment. Further work is needed to understand the model and reanalysis differences in winter.

This study increases the understanding regarding the relative roles of tropical sea surface temperature variability and radiative forcing on variations in the ASL. Since changes in the ASL have been hypothesized to be linked to changes in the Antarctic climate (Bromwich et al. 2012; Clem and Fogt 2013, 2015; Holland and Kwok 2012), this study adds to this literature by showing that radiative forcing in general has a more profound impact on ASL variations than extratropical SSTs and sea ice conditions. Although many previous studies have linked changes in the ASL to the tropics (Ding et al. 2011; Schneider et al. 2012), these studies primarily provide statistical linkages without separating out the role of tropical SST variability alone. We expand these studies by demonstrating that in many cases tropical SST variability alone produces similar variations to models that employ globally prescribed SSTs and sea ice conditions, even during extremes in the ASL magnitude. However, the temporal trends are only best reproduced in a model that includes not only tropical SST variability but also radiative forcing. Therefore, it is likely that both processes are leading to changes in the ASL, and additional work should seek to investigate how future changes in both tropical SSTs and radiative forcing over the next century might act to alter the ASL and the Antarctic regional climate.

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