Austral Spring Southern Hemisphere Circulation and Temperature Changes and Links to the SPCZ

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ABSTRACT

Significant austral spring trends have previously been observed in West Antarctica and Antarctic Peninsula temperatures and in atmospheric circulation across the southern Pacific and Atlantic. Here, physical mechanisms for the observed trends are investigated through analysis of monthly circulation and temperatures from the ERA-Interim dataset and outgoing longwave radiation (OLR) data. The negative pressure trend over the South Pacific during spring is strongest in September, while the positive pressure trend over the South Atlantic is strongest in October. Pressure trends in November are generally nonsignificant. The authors demonstrate that a significant September trend toward increased convection (reduced OLR) in the poleward portion of the South Pacific convergence zone (SPCZ) is statistically related to Rossby wave–like circulation changes across the southern oceans. The wave response is strongest over the South Pacific in September and propagates eastward to the South Atlantic in October. OLR-related changes are linearly congruent with around half of the observed total changes in circulation during September and October and are consistent with observed trends in South Pacific sea ice concentration and surface temperature over western West Antarctica and the western Antarctic Peninsula. These results suggest SPCZ variability in early spring, especially on the poleward side of the SPCZ, is an important contributor to circulation and surface temperature trends across the South Pacific/Atlantic and West Antarctica.

1. Introduction

Significant trends in Antarctic temperatures since the 1957/58 International Geophysical Year have been noted in several studies (Chapman and Walsh 2007; Steig et al. 2009; O’Donnell et al. 2011; Bromwich et al. 2013; Nicolas and Bromwich 2014). Temperature changes have not been uniform across the continent: trends have been mainly insignificant across East Antarctica, while significant warming trends have been observed across West Antarctica and the Antarctic Peninsula. The warming observed in temperature reconstructions across West Antarctica is supported by warming trends in the recently patched temperature record at Byrd station (Bromwich et al. 2013) located in central West Antarctica and also by nearby observations across the Antarctic Peninsula (Turner et al. 2005), although the peninsula and West Antarctic warming are likely linked to different mechanisms. A strong seasonality to the warming is seen across West Antarctica, being strongest in austral spring [September–November (SON)]. Statistically significant warming is also found in observations across the western Antarctic Peninsula during SON (Turner et al. 2005), and after 1979 SON is found to be the only season with widespread significant warming across both West Antarctica and the Antarctic Peninsula (Schneider et al. 2012; Bromwich et al. 2013; Nicolas and Bromwich 2014; Clem and Fogt 2015).

Consistent with the SON warming are significant changes in regional atmospheric circulation. The Amundsen Sea low (ASL), a semipermanent low pressure center located off the coast of West Antarctica encompassing mainly the Ross and Amundsen Seas (during SON), has been found since 1979 to be deepening over the Ross Sea region (~55°−65°S, 170°−145°W) during SON (Fogt et al. 2012; Schneider et al. 2012; Turner et al. 2013; Clem and Fogt 2015). The deepening of the ASL is likely important to the West Antarctic warming because the ASL impacts regional
temperature, precipitation, and sea ice variability across West Antarctica and in the nearby Ross and Amundsen Seas (Nicolas and Bromwich 2011; Holland and Kwok 2012; Schneider et al. 2012; Hosking et al. 2013). A deepening of the ASL over the Ross Sea is associated with increased warm, moist air advection onto western portions of West Antarctica and with decreased sea ice concentrations in the eastern Ross and Amundsen Seas. This is supported by recent studies that point to the SON warming of West Antarctica being mainly confined to western West Antarctica near the Ross Ice Shelf, in proximity to increased poleward flow associated with the lowering pressure in the Ross Sea (Nicolas and Bromwich 2014; Clem and Fogt 2015).

A positive pressure trend in the southwestern South Atlantic has also been noted during SON (Schneider et al. 2012; Hosking et al. 2013). A deeper ASL in the Ross Sea has also been noted during SON (Schneider et al. 2012; Schneider et al. 2012; Hosking et al. 2013). A deepening of the ASL over the Ross Sea is associated with decreased sea ice concentrations and decreased sea ice variability across the eastern Ross and Amundsen Seas. This is supported by recent studies that point to the SON warming of West Antarctica being mainly confined to western West Antarctica near the Ross Ice Shelf, in proximity to increased poleward flow associated with the lowering pressure in the Ross Sea (Nicolas and Bromwich 2014; Clem and Fogt 2015).

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The physical causes of the decreasing pressure in the Ross Sea and the increasing pressure in the South Atlantic during SON are not fully understood, but teleconnections from the tropical Pacific have been implicated in a number of studies. Clem and Fogt (2015) found that post-1979 trends toward increased La Niña–like conditions during SON are associated with (on average) a Rossby wave train that results in both a lowering of pressure in the Ross Sea and an increase in pressure in the southwestern South Atlantic. They found a significant negative trend in the Pacific decadal oscillation (PDO; Mantua et al. 1997) residual index (ENSO variability is linearly removed from the PDO) during SON is linearly congruent with more than 40% of the negative pressure trend in the Ross Sea, and a significant positive trend in the Southern Oscillation index (SOI) is congruent with more than 40% of the positive pressure trend in the South Atlantic. The PDO may be described as the decadal-scale variability of ENSO (i.e., Garreaud and Battisti 1999), defined such that the negative trend in the PDO index and the positive SOI trend are both associated with cooling across the eastern tropical Pacific and an increase in La Niña–like conditions. Although the PDO and the ENSO cycles are strongly related, they reflect variability on different time scales (Folland et al. 2002), which may account for their somewhat different expression in trends in the higher-latitude circulation.

Schneider et al. (2012) found that an increase in sea surface temperatures (SSTs) and precipitation along the South Pacific convergence zone (SPCZ) during SON after 1979 is associated with decreasing pressure in the Ross Sea region. The SPCZ is defined as the region of strong low-level convergence and tropical deep convection that lies in a northwest–southeast-oriented band from the western tropical Pacific to ~30°S, 120°W (Kiladis et al. 1989; Vincent 1994; Widlansky et al. 2011). The SPCZ is known to be modulated by ENSO and the PDO (Folland et al. 2002). Because of the strong and persistent convective activity along the SPCZ, it strongly influences circulation patterns across the southern oceans through the generation of Rossby waves that propagate poleward from this area. Because the SPCZ is modulated by both ENSO and the PDO, the findings of Clem and Fogt (2015) are consistent with Schneider et al. (2012) in that the lowering of pressure in the Ross Sea may be linked to the SPCZ.

According to Clem and Fogt (2015), the positive SOI trend yields a La Niña–like Pacific–South American (PSA; Mo and Higgins 1998) pattern stemming from the western tropical Pacific (leading to increased pressures in the southwestern South Atlantic) while the negative PDO trend is associated with a more meridional Rossby wave train (similar to the ENSO mode of Kidson 1999) originating near the central tropical Pacific. The PSA pattern is associated with increased mean sea level pressure (MSLP) over the South Atlantic while the PDO-related meridional pattern is associated with reduced MSLP over the Ross Sea. Clem and Fogt (2015) also found the negative trend in the PDO index to be consistent with SON warming across western West Antarctica while the positive trend in the SOI was strongly related to SON warming across the western Antarctic Peninsula.

Despite the SON relationships that exist between the PDO index and SOI with regional circulation and Antarctic temperature trends, the exact cause of SON warming in West Antarctica in still unclear. Schneider et al. (2012) suggest that it is related to offshore sea ice anomalies created from the deepening of the ASL. Ding and Steig (2013) found the SON warming across the Antarctic Peninsula to also be caused by a reduction in nearby sea ice. According to Ding and Steig (2013), the decrease in sea ice is associated with a deepening of the ASL in austral autumn (also observed by Turner et al. 2013) and a decrease in the austral autumn sea ice concentrations in the Bellingshausen Sea. The negative sea ice concentration anomaly during autumn persists through winter and spring, leading to warming of the western Antarctic Peninsula during SON.

Neither Schneider et al. (2012) nor Ding and Steig (2013) explicitly showed how the deepening of the ASL in the Ross Sea has warmed continental West Antarctica. Further, despite Clem and Fogt (2015) finding separate forcing mechanisms for the decreasing pressures in the Ross Sea and the increasing pressures in the southwestern
South Atlantic, the relationships were based solely on climate indices (i.e., the PDO index and the SOI, respectively), and a physical relationship was not established.

This study builds upon the work of Clem and Fogt (2015) and Schneider et al. (2012) by investigating on a month-by-month basis the physical changes that have occurred across the tropical Pacific during SON over 1979–2014 and how they are associated with the monthly atmospheric circulation and temperature trends across West Antarctica and the Antarctic Peninsula. The paper is outlined as follows: data and methods employed in this study are discussed in section 2, results are presented in section 3, and summary and conclusions are offered in section 4.

2. Data and methods

a. Data

Daily and monthly atmospheric fields from the ERA-Interim (Dee et al. 2011) at 1.5° latitude–longitude resolution are employed starting in 1979. The SON atmospheric trends across the South Pacific/West Antarctic region since 1979 are similar among contemporary reanalyses (Clem and Fogt 2015), and since a number of studies have shown ERA-Interim best reproduces the high-latitude Southern Hemisphere atmosphere (Bromwich et al. 2011; Bracegirdle and Marshall 2012), only results using ERA-Interim are presented. Results using reanalysis data are briefly validated using the quality-controlled station observation data obtained from the Reference Antarctic Data for Environmental Research archive (Turner et al. 2004), as well as the patched and recently updated Byrd temperature record (Bromwich et al. 2013).

Tropical Pacific convective activity is monitored using daily and monthly mean interpolated outgoing longwave radiation (OLR) data employed at 2.5° latitude–longitude resolution provided by the NOAA/OAR/ESRL Physical Sciences Division (PSD), Boulder, Colorado, from their website (http://www.esrl.noaa.gov/psd/; Liebmann and Smith 1996). Trends in sea ice concentration are also briefly assessed. Sea ice concentration data are from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (Rayner et al. 2003) employed at 1° latitude–longitude resolution starting in 1979, accessed freely online (http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html).

b. Methods

Data analysis methods include linear regression, linear congruency, linear (Pearson) correlation, and anomaly composite analysis. All statistical tests and significance levels are based on a Student’s two-tailed $t$ test. For all analyses, the period of study is 1979–2014, and the climatological reference period is defined as 1981–2010. For seasonal analyses, austral summer is defined as the December–February (DJF) average, austral autumn as the March–May (MAM) average, austral winter as the June–August (JJA) average, and austral spring as the SON average. The year corresponds to the first month.

3. Results

a. SON seasonally averaged and monthly trends, 1979–2014

Figure 1 shows the 1979–2014 SON seasonal and monthly linear trends in Southern Hemisphere MSLP and 10-m wind. The SON (Fig. 1a) negative pressure...
trend in the South Pacific is centered at approximately 60°S, 165°W \((p < 0.05)\) and increasing pressure in the southwestern South Atlantic is centered at approximately 50°S, 30°W \((p < 0.01)\). Accompanying the South Pacific/South Atlantic MSLP trends are significant 10-m wind trends (vectors are only displayed if at least one component is significant at the \(p < 0.10\) level). Significant positive pressure trends are observed across the eastern tropical and subtropical Pacific (between \(-5°\) and \(35°S\)) from 160°W to South America. The increasing pressure in the eastern tropical Pacific is associated with significant increases in 10-m easterly winds across the tropical Pacific basin. The MSLP and 10-m wind trends across the tropical Pacific during SON point toward increased La Niña–like conditions after 1979, consistent with the significant positive trend in the SOI noted by Clem and Fogt (2015) during SON over 1979–2012.

The monthly trends (Figs. 1b–d) show the lowering of pressure in the South Pacific is strongest and only statistically significant during September (Fig. 1b; \(p < 0.01\)), and the positive pressure trend in the southwestern South Atlantic is strongest and primarily statistically significant during October (Fig. 1c; \(p < 0.01\)). Across the eastern tropical Pacific, the positive pressure and easterly 10-m wind trends are strongest and most widespread in September. Lower pressures over the South Pacific during September are much stronger and more widespread than the trends observed in the SON average, and the cyclonic response in the 10-m wind field is more marked across the South Pacific and along coastal West Antarctica. The lower pressures have led to significant increases in southerly winds across the Southern Ocean south of New Zealand, and significant increases in northerly winds at \(-110°W\) that extend to coastal West Antarctica and turn easterly (Fig. 1b). During October, the significant negative pressure trend in the South Pacific shifts eastward toward the Antarctic Peninsula (significant at only \(p < 0.05\)), and a positive pressure trend emerges over the South Atlantic significant at \(p < 0.01\). The anticyclonic response in the 10-m wind field is also stronger and more widespread than that observed in the SON average, with a significant northerly wind trend across the northern Antarctic Peninsula and Weddell Sea. In the October pressure trends there appears to be a strong tropical component reminiscent of a PSA pattern (Mo and Paegle 2001). By November (Fig. 1d), the significant pressure trends across the South Pacific and South Atlantic are weakened and primarily not significant at \(p < 0.10\).

Seasonal and monthly SON 2-m temperature and 10-m wind trends are presented in Fig. 2. Significant SON warming is seen across western West Antarctica and the western Antarctic Peninsula (Fig. 2a), as discussed by Clem and Fogt (2015). The warming trend across western West Antarctica is strongest in September (Fig. 2b; more than 2.0°C decade \(^{-1}\)), consistent with the offshore pressure decreases and poleward flow toward the continent during September. The northerly and easterly wind trend to West Antarctica does not align exactly with the inland warming across western West Antarctica and the Ross Ice Shelf; however, it will be shown later that increases in warm advection to portions of interior West Antarctica are occurring. Over the South Pacific between \(-55°\) and \(70°S\), significant cooling is observed during September, consistent with the increased southerly flow on the western side of the negative pressure trend.

The SON warming along the western Antarctic Peninsula is not observed in the reanalysis during September,
but is instead strongest and statistically significant primarily during October. Nearby observations along the western peninsula (Faraday and Rothera) support the reanalysis temperature trends near the peninsula (Table 1). At Faraday, significant warming increases from p < 0.10 in September to p < 0.05 in October, and warming at Rothera is only statistically significant at p < 0.10 during October. Consistent with the October warming on the western peninsula is increased northerly flow to the peninsula arising from the eastward shift in the lowering pressures in the South Pacific and the development of positive pressures in the South Atlantic (Fig. 1c). As with the West Antarctic warming during September, the significant northerly wind trend to the peninsula does not align exactly with the localized areas of strongest warming. However, the absence of significant warming or related wind trends here during September, and the development of the warming trend during October when the significant northerly flow occurs suggests that the circulation and temperature trends are closely related across both West Antarctica and the Antarctic Peninsula.

In November (Fig. 2d), statistically significant trends in 10-m wind and 2-m temperature continue across the South Pacific, but they are less obviously related to changes in regional atmospheric circulation. The November circulation patterns in Fig. 1d show primarily insignificant positive pressure trends in the South Pacific at ~120°W, and insignificant negative pressure trends at ~170°W. Their collective influence on the pressure gradient between ~160° and 120°W results in statistically significant increases in northerly flow to western West Antarctica, which appears strongly related to the November warming there (Fig. 2d). The November circulation changes are important to understanding the overall SON-averaged warming across western West Antarctica, but they are different than the regional circulation pattern that propagates from west to east across the South Pacific to the South Atlantic during September and October.

To better understand the temperature trends in Fig. 2 and the relative role of the regional circulation changes, seasonal and monthly sea ice concentration and thermal advection trends are presented in Figs. 3 and 4, respectively. Figure 3a shows significant SON average decreases in sea ice concentration along coastal West Antarctica from approximately 120°W toward the date line. Farther offshore, between 60° and 70°S and west of 120°W, significant increases in sea ice concentration are

<table>
<thead>
<tr>
<th>Temperature trend</th>
<th>Congruent with Sep OLR SPCZ</th>
<th>Percent congruent (%)</th>
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<tbody>
<tr>
<td>September</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byrd</td>
<td>0.97 ± 1.22</td>
<td>0.60</td>
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<tr>
<td>Faraday</td>
<td>0.79 ± 0.86</td>
<td>0.64</td>
</tr>
<tr>
<td>Rothera</td>
<td>0.66 ± 0.94</td>
<td>0.65</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byrd</td>
<td>0.42 ± 0.81</td>
<td>−0.03</td>
</tr>
<tr>
<td>Faraday</td>
<td>0.73 ± 0.58</td>
<td>0.40</td>
</tr>
<tr>
<td>Rothera</td>
<td>0.59 ± 0.64</td>
<td>0.40</td>
</tr>
</tbody>
</table>
observed for the SON average. As with the temperature trends, the monthly sea ice concentration trends demonstrate that the SON average is closely tied to the changing monthly circulation. In September (Fig. 3b), the region of significant sea ice decreases along coastal West Antarctica aligns with the increase in northerly and easterly 10-m wind to the West Antarctic coast, and the offshore increases align with the increased southerly flow. During October (Fig. 3c), significant sea ice loss is occurring along much of the west coast of the Antarctic Peninsula. The sea ice losses/gains offshore of western West Antarctica persist into October, which may represent memory in the sea ice field from the circulation-driven trends in September (i.e., Ding and Steig 2013; Holland 2014). The continued negative sea ice concentration anomalies along coastal West Antarctica during October may explain why warming continues across western West Antarctica during October (Fig. 2c) despite the circulation trends shifting eastward. During November, localized sea ice decreases continue along the northwestern peninsula near Faraday and Rothera Stations, which again likely reflects the memory in the sea ice field from the trends in October. The significant sea ice increases observed along the outer sea ice edge in October (between ~160° and 135°W; more than 15% decade$^{-1}$) weakens slightly during November as do the negative sea ice concentration trends near coastal West Antarctica. Both trends appear to be affected by the increased northerly flow to this region during November, which would push the outer sea ice edge toward the continent and increase sea ice compaction (increase sea ice concentration) along the coast.

Trends in 500-hPa meridional temperature advection and 500-hPa wind are presented in Fig. 4. Temperature advection is calculated as the negative of the product of daily ERA-Interim 500-hPa transient meridional wind anomalies and the meridional gradient of daily ERA-Interim 500-hPa temperatures ($-\nabla^\alpha T/\nabla y$). Since much of interior West Antarctica’s elevation rises through the midtropospheric pressure levels, temperature advection patterns at the 500-hPa pressure level are shown to best depict realistic temperature advection across interior West Antarctica. Temperature advection patterns at 850 hPa (not shown) yield similar results over the South Pacific. The SON-average advection trends (Fig. 4a) show that the SON 2-m warming trends across western West Antarctica and the western Antarctic Peninsula (Fig. 2a) are closely tied to increased warm advection. In September (Fig. 4b), when the lowering of pressure occurs in the South Pacific, increased poleward flow brings increases in warm advection to all of coastal West Antarctica from the western peninsula to the Ross Ice Shelf. Statistically significant warm advection (yellow and orange shading) is located just offshore of West Antarctica centered at ~105°W and across the Ross Ice Shelf. Both regions of significant warm advection during September align with significant 500-hPa wind trends, which closely resemble the 10-m wind trends. The increased warm advection across the Ross Ice Shelf also aligns with the significant 2-m warming trends observed there in September (Fig. 2b). Significant cold advection is found west of 150°W between 55° and 70°S, also aligning with the significant 2-m cooling and increases in sea ice concentration (Figs. 2b and 3b, respectively).
During October, the significant warm advection shifts eastward to the peninsula, consistent with the 2-m warming and decreased sea ice concentration along the western peninsula during October. Significant cold advection is found across portions of inland and coastal central West Antarctica during October (between 135° and 95°W) as cold, southerly flow develops on the western side of the lowering pressure in the South Pacific. During November, significant warm advection develops again near the Ross Ice Shelf, likely enhancing the warming observed there (Fig. 2d), cold advection continues across portions of coastal central West Antarctica, and warm advection continues along the western Antarctic Peninsula. Aside from the warm advection along the western peninsula during November (which could be related more to the reduced sea ice/open water from the October circulation trends than from November circulation), all regions of significant temperature advection closely follow the circulation trends as they develop west to east across the South Pacific and the South Atlantic during September and October, and the wave three-like pattern that develops in November. The cold advection across central West Antarctica during October and November explains the absence of significant warming across all of West Antarctica for the SON average and helps explain the regionally distinct nature of the SON warming across West Antarctica and the peninsula.

The monthly trends in Figs. 1b,c suggest that the negative pressure trend in the South Pacific and the positive pressure trend in the South Atlantic may be part of an eastward-propagating circulation pattern stemming from the tropical Pacific. The propagation of the September and October circulation trends from the South Pacific to the South Atlantic appears to take approximately two months, starting first in September with a meridionally oriented pressure dipole across the South Pacific reminiscent of a Rossby wave train, and terminating in the South Atlantic in October with a clear tropical component to the circulation. When the pattern first develops in September, it lowers pressures in the high-latitude South Pacific, which forces increased northeasterly flow and warm advection/sea ice decreases (Figs. 4b and 3b, respectively) along the West Antarctic coast. As the pattern propagates eastward, the pressures decrease west of the peninsula and increase over the South Atlantic, collectively strengthening the northerly flow and warm advection to the peninsula, and reducing sea ice concentrations along the western peninsula (Figs. 4c and 3c, respectively). Significant cooling across portions of the Southern Ocean in September and October also follows the increase in cold, southerly flow on the western side of the negative pressure trends.

Seasonal and monthly trends in tropical Pacific OLR and 10-m wind are presented in Fig. 5. The average location of the SPCZ is drawn as a black line for all panels, and the September OLR region used for area averaging is drawn as a red box in (b). Contour interval is 1.0 W m⁻² decade⁻¹, and zero contours are omitted.

**b. September and October circulation trends and linear relationships with the SPCZ**

Seasonal and monthly trends in tropical Pacific OLR and 10-m wind are presented in Fig. 5. The average location of the SPCZ is drawn as a black line, extending from the western Pacific warm pool to ~30°S, 120°W (i.e., Trenberth 1991; Vincent 1994). Figure 5a shows several statistically significant OLR trends across the tropical Pacific, primarily a reduction in OLR (increase in tropical deep convection) in the western tropical Pacific and along the poleward side of the SPCZ, consistent with increased La Niña–like conditions (Vincent 1994; Folland et al. 2002). The negative OLR trend in the western tropical Pacific and along the
SPCZ aligns with significant increases in 10-m wind convergence for all panels in Fig. 5, which would encourage upward vertical motion and increases in tropical deep convection along the SPCZ.

The most significant reduction in OLR in the SPCZ region occurs in September (Fig. 5b; center at 27.5°S, 180°–165°W; denoted with a red box), suggesting a significant increase and a poleward shift of deep convection along the southeastern SPCZ. In October, the negative OLR trend along the SPCZ is located farther west and equatorward nearer the average position of the SPCZ. November sees significant negative OLR trends farther east along the SPCZ, centered at approximately 20°S, 170°W, also farther equatorward than during September. Since the significant extratropical circulation trends occur in September and October, we hypothesize that they may be linked to the negative OLR trend in September. Not only is the reduction in OLR during September the strongest and of highest statistical significance, but also it is the most anomalous in terms of location as it is farthest poleward from the average SPCZ region.

Linear congruency between September OLR averaged over the SPCZ portion trending negative during September (25°–32.5°S, 180°–165°W; denoted as a red box in Fig. 5b) and the September and October Southern Hemisphere MSLP and 2-m temperature trends are presented in Figs. 6 and 7, respectively. Linear congruency is calculated by regressing the area-averaged September OLR onto the September and October reanalysis data at every grid point. The linear regression coefficients are multiplied by the observed trend in September OLR to yield an expected trend in MSLP and 2-m temperature (contours in Figs. 6 and 7). The area-averaged September OLR trend over 1979–2014 is $-2.80 \text{ W m}^{-2} \text{ decade}^{-1}$ significant at $p < 0.01$. Shading in Figs. 6 and 7 represents the percentage of the expected trend that is linearly congruent with the observed trends in Figs. 1b,c and 2b,c, respectively. Percentage shading is plotted only at grid points where the observed trends are significant at $p < 0.10$.

**Figure 6a** shows the reduced September OLR along the SPCZ is associated with a wave train across the South Pacific (contours) reminiscent of a PSA pattern. The OLR-related increase in September MSLP across the subtropical Pacific is congruent with more than 40%–60% of the statistically significant positive MSLP trends between 15° and 35°S from the date line to coastal South America (shading in Fig. 6a; reference Fig. 1b). The OLR-related negative MSLP trend over the South Pacific is congruent with 40%–60% or more of the observed negative MSLP trend, and the positive MSLP trend over the southern Weddell Sea is more than 40% linearly congruent with observed increase in pressure there.

In October (Fig. 6b), the lowering of MSLP in the South Pacific (contours) associated with the September OLR shifts eastward toward the peninsula and is centered at ~95°W, consistent with the trends in Fig. 1c. OLR-related increases in MSLP over the South Atlantic shift northeastward, also consistent with observed
October trends. The lowering of pressure west of the peninsula is congruent with more than 40%–60% of the negative pressure trend and the increases in pressure in the South Atlantic are congruent with 20%–60% of the positive pressure trends there (shading in Fig. 6b; reference Fig. 1c). The linear congruency analysis supports the hypothesis of a tropically forced, eastward-propagating wave train that first influences the South Pacific in September, and the South Atlantic in October.

Following these connections, it is plausible that linear relationships exist between the September SPCZ and the September and October 2-m temperature trends. As in Fig. 6, linear congruency maps are generated for September and October 2-m temperature trends across West Antarctica and the Antarctic Peninsula (Fig. 7). During September, a warming trend of more than 0.6°C decade⁻¹ is expected across western West Antarctica and the Ross Ice Shelf (contours), warming trends of more than 0.4°C decade⁻¹ along most of coastal West Antarctica and the western Antarctic Peninsula, and cooling trends farther offshore across the Southern Ocean between the date line and 120°W. The estimated warming over western West Antarctica is linearly congruent with more than 20%–40% of the statistically significant September warming there, and more than 20%–40% of the statistically significant September cooling found across the South Pacific (shading in Fig. 7a; cf. Fig. 2b).

Turning to October (Fig. 7b), OLR-related warming trends of ~0.4°C decade⁻¹ are estimated along the western Antarctic Peninsula, which is linearly congruent with 40%–60% of the localized statistically significant warming (shading; cf. Fig. 2c). A large portion of the significant cooling over the South Pacific between 120° and 75°W is 20%–40% or more linearly congruent, as is the warming east of the peninsula over the northern Weddell Sea.

The linear congruency results for ERA-Interim temperature trends in Fig. 7 are compared with nearby station observations in Table 1. The Byrd temperature trend is not significant at p < 0.10 in September or October, consistent with ERA-Interim 2-m temperature trends showing the statistically significant warming west of Byrd. However, Byrd exhibits a warming trend during September that is more than twice as strong as in October, consistent with the 500-hPa warm and cold advection across central West Antarctica from September to October, respectively (Fig. 4). The observed warming at Byrd during September is more than 60% linearly congruent with the reduced September OLR in the SPCZ, lending confidence to the results in Fig. 7a. For the western peninsula stations (Faraday and Rothera), more than 80% of the observed warming in September is linearly congruent with the reduced OLR in the SPCZ, and ~50%–70% of the observed warming in October is linearly congruent with the SPCZ. As noted previously, the statistical significance of the warming at Faraday and Rothera increases from September to October, consistent with ERA-Interim 2-m temperature trends/significance.

c. Atmospheric composites and correlations for September SPCZ OLR

We now investigate the relationships between SPCZ OLR in September and the circulation and temperature changes through composites. Composite anomalies of MSLP and 10-m wind during September and October for the six lowest September OLR years in the 25°–32.5°S, 180°–165°W region during 1979–2014 are presented in Fig. 8. Anomalies are calculated by subtracting the September and October 1981–2010 climatological mean, respectively. Shading (from lightest to darkest) indicates MSLP anomalies (hPa) that are statistically different than zero at p < 0.10, p < 0.05, and p < 0.01, respectively, and 10-m wind anomalies (m s⁻¹; indicated by reference vector) are only plotted if at least one of the wind components is anomalous at the p < 0.10 level. Contour interval is 1.0 hPa.
In September (Fig. 8a), positive MSLP anomalies of up to 4 hPa ($p < 0.01$) are seen over the eastern subtropical South Pacific along with increased 10-m easterly flow across the tropical Pacific to the southeastern SPCZ (where the increased convection occurs). A broad negative MSLP anomaly of up to 7 hPa ($p < 0.05$) is observed over the South Pacific, and positive MSLP anomalies are found in the Weddell Sea, both of which are consistent with the September MSLP trends in Fig. 1b. The reduced MSLP in the South Pacific is maximized at ~120°W, but anomalies significant at $p < 0.10$ extend westward to ~170°W, encompassing a large portion of the negative MSLP trend found there during September. The September MSLP anomalies are associated with significant increases in northerly flow across much of coastal and interior West Antarctica.

During October (Fig. 8b), a month after the anomalous convection in the SPCZ, the significant circulation anomalies across the South Pacific are weakened and the northerly flow across West Antarctica becomes southerly. The most striking feature during October is that the significant cyclonic circulation anomalies over the South Pacific shift eastward toward the peninsula and the anticyclonic circulation anomalies over the South Atlantic shift northeastward out of the Weddell Sea, consistent with Fig. 1c. The October MSLP anomalies are associated with increased northerly flow from the peninsula eastward across the Weddell Sea, which is also consistent with the trends.

A final analysis of the relationship between the September SPCZ OLR and extratropical circulation is presented in Fig. 9. Here, correlation maps between the detrended September OLR in the SPCZ region and detrended September–October MSLP fields during 1979–2014 are calculated to remove any influence the trends have on the linear relationships in Figs. 6 and 7. Because the September OLR in the SPCZ region has been trending negative, the correlation coefficients are inverted so the correlations represent the appropriate sign in MSLP anomalies. During September (Fig. 9a), the detrended response across the Southern Hemisphere is characterized by a tropically forced Rossby wave train with significant positive correlations ($p < 0.01$) across the subtropical South Pacific, significant negative correlations throughout much of the high-latitude South Pacific ($p < 0.01$), and weaker but still statistically significant positive correlations over the South Atlantic. In October (Fig. 9b), the significant negative correlations across the high-latitude South Pacific shift east toward the peninsula, and the positive correlations in the South Atlantic shift northeast.

Because all trends are removed, Fig. 9a implies that interannual variability of September OLR in the 25°–32.5°S, 180°–165°W region is associated with significant same-month pressure anomalies over the South Pacific and the South Atlantic reminiscent of a PSA pattern. Compared to typical same-month correlations between ENSO indices (i.e., the SOI and Niño-3.4 SST anomalies) and pressure fields (not shown), the significant correlations in Fig. 9a are more meridionally structured across the South Pacific and extend farther westward and poleward to encompass more of the Ross Sea and western West Antarctica. In October (Fig. 9b), significant linear relationships still exist over the South Pacific and South Atlantic with the preceding month’s OLR variability in the SPCZ, but the negative MSLP anomalies in the South Pacific shift eastward toward the peninsula, and the positive MSLP anomalies in the South Atlantic shift northeastward, consistent with the composite anomalies in Fig. 8.

d. The SPCZ teleconnection to the Southern Hemisphere

Finally, a more general investigation of the seasonality of the SPCZ teleconnection and the influence of the position of tropical deep convection is presented. The seasonality of the teleconnection from the region trending negative in September (25°–32.5°S, 180°–165°W; red box in Fig. 5b) is shown in Fig. 10. Detrended, inverted correlation maps (as in Fig. 9) between ERA-Interim MSLP and contemporaneous OLR in “the September region”
are provided for all four seasons for the 1979–2013/14 period (2013 for DJF and 2014 for all other seasons).

In all seasons, an east–west dipole in pressure anomalies/Southern Oscillation feature is observed across the tropical Pacific indicating that ENSO variability strongly modulates OLR variability in the southeastern SPCZ year-round. Increased convection here would be associated with La Niña–like conditions for all seasons, with positive pressure anomalies in the eastern tropical Pacific and negative pressure anomalies in the western tropical Pacific (Vincent 1994; Folland et al. 2002).

The atmospheric response in the extratropics is markedly different for each season. In DJF (Fig. 10a), a negative pressure anomaly is seen over the Antarctic Peninsula, farther east than typical ENSO-related teleconnections to the South Pacific, and negative pressure anomalies are found over Antarctica resembling southern annular mode (SAM) positive conditions. This pattern is likely due to the more zonally symmetric background circulation across the South Pacific during DJF that would steer the tropical signal farther east to the peninsula, and also the more zonally oriented ENSO response in the Southern Hemisphere found during DJF (Seager et al. 2003; L’Heureux and Thompson 2006). The teleconnection to the South Pacific during MAM (Fig. 10b) is relatively weak and is absent during JJA (Fig. 10c). The high-latitude teleconnection during SON (Fig. 10d) is the most robust of all seasons, with more than 30% of the MSLP variability in the South Pacific accounted for by convection in the southeastern SPCZ. A strong SAM component to the circulation is also evident during SON, suggesting SPCZ variability and SAM variability are closely tied in SON, consistent with the results of Clem and Fogg (2013). Figure 10 demonstrates that SON is the key season for strong South Pacific teleconnections arising from convection along the poleward portion of the SPCZ. Further, compared to DJF and MAM, the SON teleconnection is associated with more regionally distinct MSLP anomalies across the South Pacific and Atlantic.

The SON teleconnection associated with various positions of convection along the SPCZ is presented in Fig. 11. Using OLR as a proxy for convection, OLR is area averaged over the northwest SPCZ near the west Pacific warm pool (northwest; 10°–20°S, 155°E–165°W), the middle SPCZ (middle; 15°–25°S, 165°E–170°W), and the southeast SPCZ (southeast; 25°–35°S, 170°E–165°W). Respective OLR regions used for area averaging are drawn as a red box.

During anomalous convection along the northwest/equatorward portion of the SPCZ during SON (Fig. 11a), there is only a local atmospheric response, apparently related to localized ascent or descent associated with the convection, and a South Pacific teleconnection is absent. Additionally, convection on the northwest portion does not appear to be linearly related to ENSO activity with the absence of significant correlations across the tropical Pacific. Farther east and poleward along the SPCZ, the South Pacific response to convection become more marked. When anomalous convection occurs in the middle portion (Fig. 11b), a small region of negative pressure anomalies is observed over the South Pacific (p < 0.05), and the teleconnection is strongest when the convection occurs farthest poleward in the southeast region (p < 0.01; Fig. 11c). Similar to the teleconnection pattern associated with “the
September region” (Fig. 10d), a strong SAM component to the circulation anomalies is also noted.

Figure 11 demonstrates that SPCZ-related circulation anomalies over the South Pacific during SON are strongest when the convection is farthest poleward, while Fig. 10 suggests SPCZ teleconnections to the South Pacific/Atlantic are most marked during SON.

4. Summary and conclusions

In reality, it is unlikely that Rossby wave forcing and propagation operates perfectly on calendar-month time scales, as is implicit in the monthly based analysis shown here. Relationships using daily OLR and height fields were investigated (not shown) and they support the hypotheses presented here. The wave propagation is strongest early in spring and weakens toward the end of spring as the background circulation weakens. The wave response peaked on average around a week after the maximum OLR anomaly in the SPCZ. We also investigated mean 300-hPa zonal wind during September and October (not shown) and found the South Pacific midlatitude jet strengthens from September to October, partly explaining why the wave train propagates eastward across the South Pacific during these two months.

The results of this study show that the SON-average regional circulation trends observed across the South Pacific and South Atlantic are not stationary in time; instead, they are part of a dynamic pattern that develops and dissipates over the two-month period of September–October, propagating eastward across the South Pacific to the South Atlantic. Furthermore, this study finds strong evidence that the primary forcing for these circulation trends is a significant increase in tropical deep convection along the poleward portion of the SPCZ during September, and a resultant Rossby wave train that roughly follows a great circle trajectory across the South Pacific to the South Atlantic from September to October. The increase in convection along the SPCZ during September appears to be a result of increased low-level convergence from significant increases in pressure across the eastern half of the tropical Pacific during September, and the associated increase in easterly winds across the tropical Pacific that converge along the SPCZ. The increased easterly flow (especially toward the poleward portion of the SPCZ) is most marked in September, helping to explain why the increase in convection there is strongest in September.

Consistent with the September and October circulation trends are significant trends in 2-m temperatures, sea ice concentration, and 500-hPa meridional temperature advection across localized regions of the Southern Ocean, West Antarctica, and Antarctic Peninsula. The deepened ASL during September brings increased warm, northeasterly flow to western West Antarctica and the Ross Ice Shelf, consistent with around half of the significant warming found there during September. The circulation trends shift eastward during October, decreasing pressures west of the Antarctic Peninsula and increasing pressures in the South Atlantic. The October circulation allows cold, southerly flow to develop across central West Antarctica (explaining the absence of warming there in the SON-average 2-m temperature trends) and brings warm, northerly flow to the peninsula that is consistent with around half of the October warming of the western peninsula. During November, the statistically significant pressure trends diminish across the southern oceans; however, significant trends in 10-m wind are still noted in the South Pacific, which appears to be important for the November warming found across western West Antarctica.
Additional modeling work is needed to understand how the position of convection along the SPCZ during September influences wave propagation across the Southern Hemisphere during SON. Investigations of katabatic flow across the Ross Ice Shelf region would also be helpful in fully understanding the warming trends across western and central West Antarctica. Last, the influence of the southern annular mode on the SON South Pacific and South Atlantic circulation trends is also of interest in order to better understand how the tropical and high-latitude atmospheric modes collectively influence the SON temperature trends across West Antarctica and the Antarctic Peninsula.

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