Professor Chris Turney
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27 November 2015

Dear Michiel,

Resubmission of tc-2015-105: ‘Tropical and Mid-Latitude Forcing of Continental Antarctic Temperatures’

We thank the reviewers for their excellent and insightful comments. Since our original responses we have undertaken further analysis which we detail below.

We have made all of the changes requested, including extensive analyses on the mechanisms behind our observed atmospheric teleconnections. We particularly focused on the spatial and temporal changes and the role of the tropical Pacific in recent years. We feel the work is considerably stronger (and clearer) as a result and makes a significant contribution. We hope you enjoy the revised manuscript.

We look forward to hearing from you.

With best wishes,

Chris

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Response to Reviewers Comments (tc-2015-105)

Reviewer 1: R. Fogt.

- I think the paper could be strengthened significantly by adding a few lines and refer- ences to the joint role of ENSO and SAM on Antarctic climate, as outlined by L'Heuruex and Thompson (2006); Stammerjohn et al. (2008); Ding et al. (2012); and some of my work (Fogt and Bromwich 2006; Fogt et al. 2011). From your GPH composites in Figs. 7E and J, there is both a SAM structure as well as a PSA structure in the Pacific (also seen in Figs. 6E and J). I think a discussion of both of these modes and their interaction is needed on the discussion of potential tropical / ENSO variability on lines 4-25 on page 7.

We agree. We have added further details on SAM and PSA to the Introduction to help the subsequent discussion. Crucially, SAM is known to exhibit spatial and temporal asymmetry with a wave three pattern in the middle latitudes (Fogt et al., 2012) which is particularly pronounced in the Pacific (Steig et al., 2009), and has been linked to the tropics (e.g. Fan, 2007; Ding et al., 2012). Another postulated mode of variability is the Pacific–South American (PSA) pattern, a wave train of anomalies extending from New Zealand, off the coast of Marie Byrd Land (West Antarctica), and into the Weddell Sea/south Atlantic Ocean (Mo and Higgins, 1998) as a consequence of tropical forcing (Karoly, 1989). The relationship between low-latitude change and the mid to high-latitudes of the Southern Hemisphere remains contentious, however, with different observed seasonal teleconnections, such as central Pacific temperature changes in the austral winter (Ding et al., 2012), a linear relationship between ENSO and SAM in the austral summer (L'Heuruex and Thompson, 2006) and phasing of the different modes deciding the magnitude of the response (Stammerjohn et al., 2008). Importantly, the most positive phase of the SAM manifests itself at the surface most strongly during summer and autumn months (Thompson et al., 2011), while the PSA signal is primarily summer focused (Karoly, 1989). Here we observe wave three-like anomaly pressure patterns across the Southern Hemisphere all year round. With the further analysis suggested by the reviewer, we find the tropical Pacific plays a modulating role on the pressure anomalies (particularly during the spring and summer months) but is not the driver of all variability (see below).

2. The discussion on increased ENSO variance and therefore a lowering of pressures in the SWP is misleading. Increased ENSO variance doesn't necessarily mean more El Ninos, and over the last 30 years, the SOI and Pacific SSTs have actually been trending towards a more La Nina-like state (consistent with the shift in the PDO). There are quite a few papers on this, but some of my work at least addresses this shift in austral spring (Clem and Fogt 2015, JGR). Notably, these trends towards increased La Nina events probably aren't significant anymore given the strong El Nino currently developing, but the way this is written makes it seem like the circulation in general is trending towards more El Ninos, and this isn't the case currently, at least not consistently.

The reviewer is correct. While ENSO variance is skewed towards El Niño events (e.g. An, 2004, *Geophysical Research Letters*) the increase in variance is not reporting a shift to more

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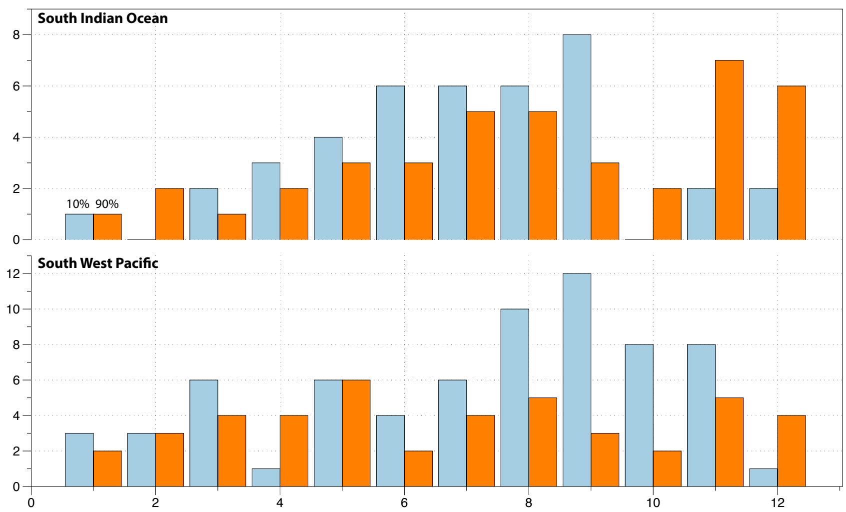
El Niños *per se*. We had not seen the paper by Clem and Fogt (2015) when we submitted the manuscript but this would add significantly to the discussion of the interaction of the different modes. Furthermore, there are several recent papers that demonstrate a trend towards a cooler tropical east Pacific and stronger Walker Cell circulation (e.g. Karnauskas et al., J of Climate, 2009; L'Heureux et al., 2013, Nature Climate Change; England et al., 2014, Nature Climat Change). We have undertaken further analysis of the pressure changes using the latest update of the 20th Century Reanalysis (20CRc). For the satellite era (post-1979) we find the pressure anomalies (10th and 90th percentiles) in the South Indian Ocean (SIO) and South West Pacific (SWP) are observed throughout the year but with a tendency towards September-February (see below).



Thus, our data suggests whilst there is a tropical Pacific role in the east tropical Pacific (particularly with positive pressure anomalies - akin to a more La Niña-like state), this seems to have only a modulating effect.

There is an inverse relationship between SWP pressure and tropical SSTs (detrended and deseasonalised), with the upper panel below showing the regression across the Pacific and Atlantic SSTs (July-June): lower pressures in the SWP equate to warmer conditions in the central and east Pacific.

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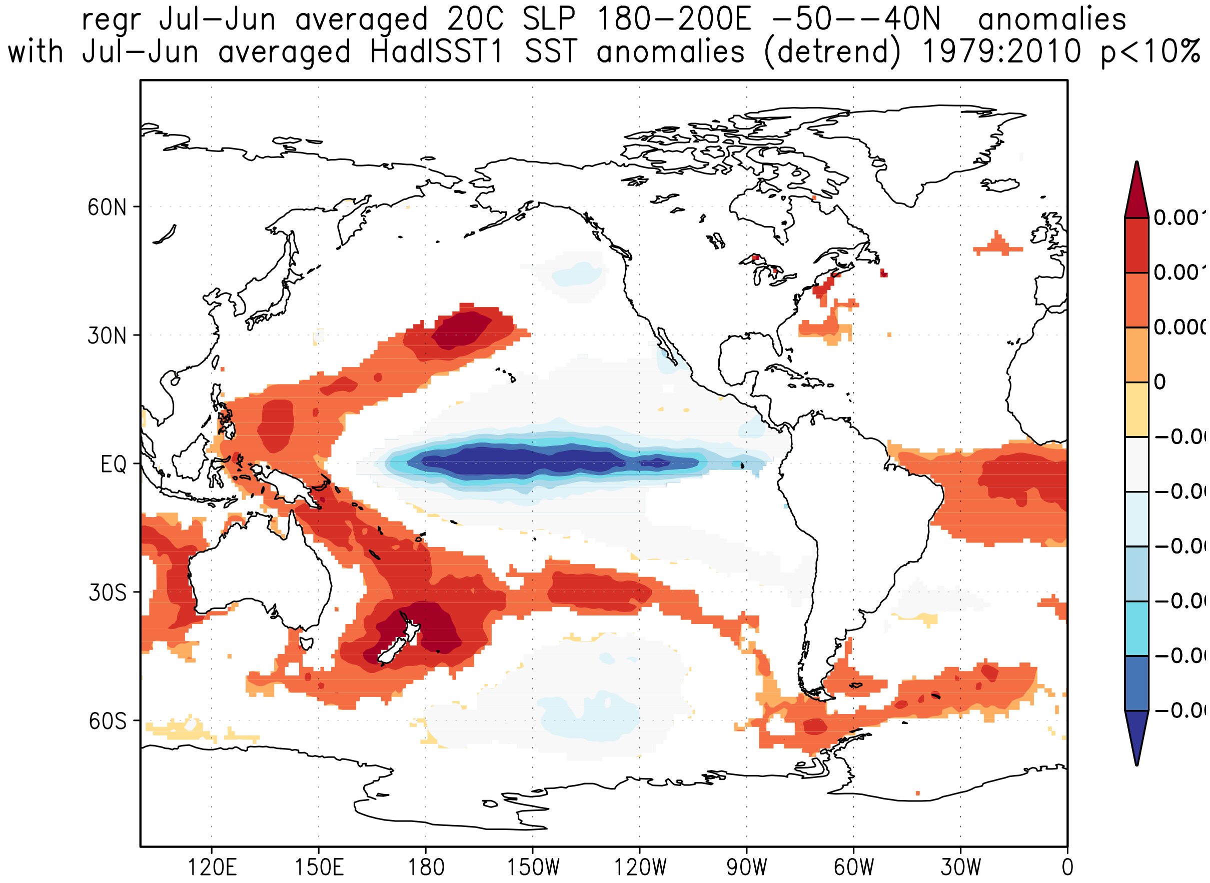

We also observe an opposing relationship between the southwest Pacific pressures and the West Antarctic (Marie Byrd Land) but see no response in Atlantic MSLP (low or mid-latitudes) (lower panel) - suggesting we are not observing a PSA pattern.

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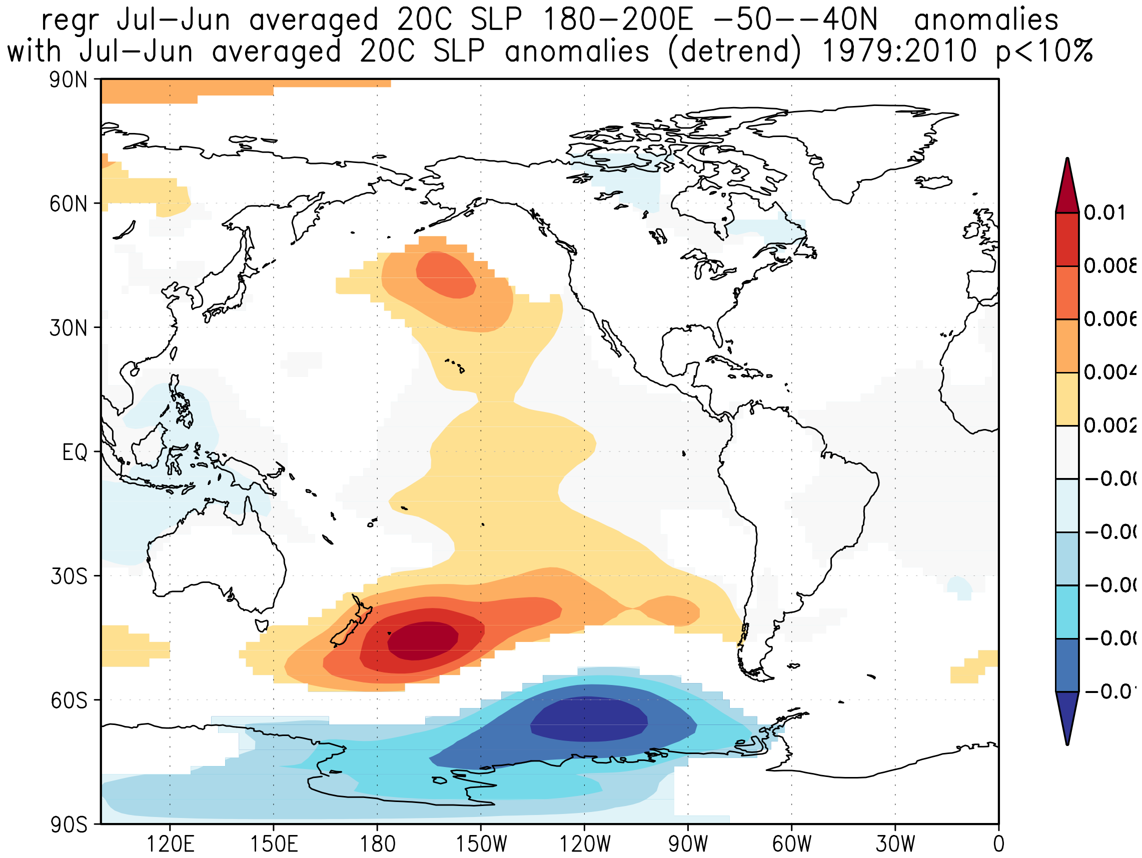

The long-term trend (post 1970) is towards lower pressure in the SWP and warmer temperatures over the Antarctic but importantly both appear to have levelled off in recent years (Figure 3 in the Discussion paper). Reflecting on the reviewers comments and our new analysis we propose that the shift to a stronger Walker Cell circulation (and stronger trade winds) may be offsetting the downward trend in the SWP and warming aloft Antarctica.

Minor comments:
Page 1, line 19: suggest changing 'has' to 'have' since I believe the subject is 'latitudes'.
Done.

2. Lines 27-28: I think this sentence about tropical and midlatitude pressure anomalies playing a larger role than hitherto believed is a bit strong, and should be worded more cautiously, more like 'this work adds to a growing body of literature confirming the important roles of tropical and midlatitude atmospheric circulation variability on Antarctic temperatures' or equivalent.
An excellent suggestion. We have changed the text accordingly.

3. Page 2, Line 28: The Ding et al. (2011) reference here talks only about the role of tropical Pacific SSTs, so using the words 'global SST' is not accurate.
Absolutely. The text has been changed.

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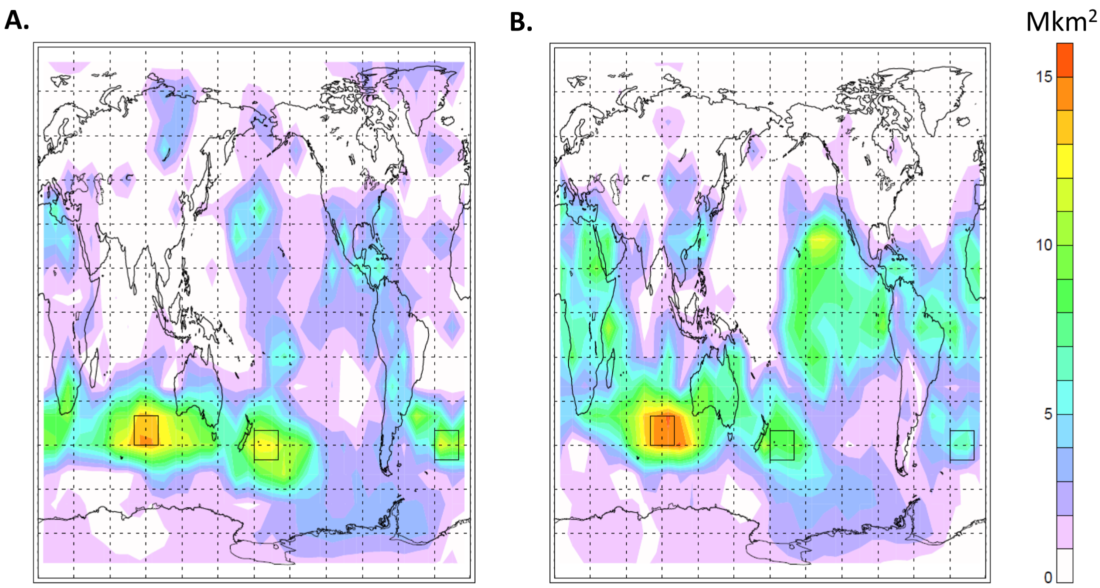
4. Figure 4 (and supplementary figures): I wonder why the region for the SWP was chosen as it was, as there are stronger / larger areas a bit farther north and west towards NZ? I hardly can imagine this changing the results much, but it just seems odd that the region chosen was not in the center of the darkest shading in Fig. 4.
We apologise for the mistake. The reviewer is absolutely correct. We have redone the figure and corrected all key figures/analyses (including those above). The revised figure showing the regression between deseasonalised and detrended SWP with MSLP and SST is given below.



5. Page 6, Line 11: Change 'Figure 7' to 'Figure 8'
Done.

6. Page 6, Lines 27-28: suggest deleting the 'did not lead but' on line 27 since this is repeated on line 28.
Done.

7. Page 7, lines 7-9: "Conversely, with increasing ENSO variance, the southwest Pacific pressure anomaly apparently weakens (Figure 4)." This is not at all clear from Fig. 4, since there's no linkage on that figure from ENSO variance. You can infer this however from comparing the red and blue curves on Fig. 3, and I would agree that after 1940 as ENSO variance increases, the SWP pressure anomaly decreases. This however is not clear in earlier times, perhaps due to the uncertainty of the 20CR (but this may be constrained here somewhat due to records in New Zealand and Chatham Island starting before 1900). During 1870-1920 there is a clear increase in ENSO variance, but the SWP anomaly doesn't

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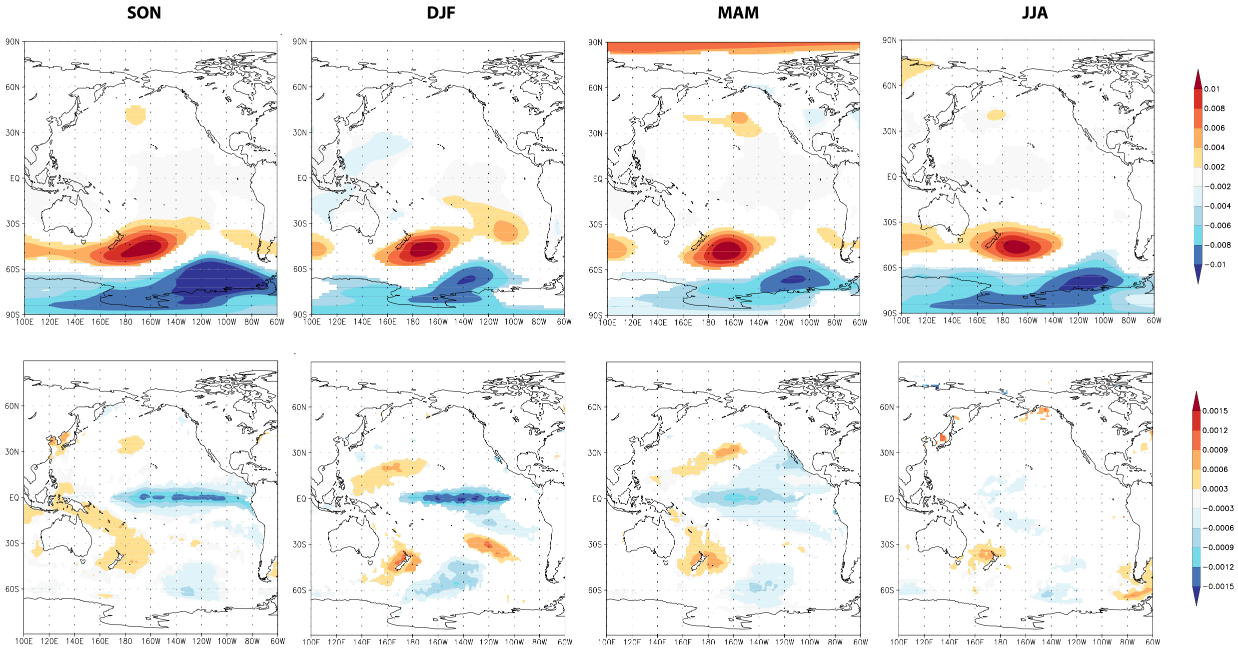
decrease at this time. I think some comment on this needs to be made, and in general the statement on these lines needs to be better justified.

Thanks to the reviewers comments we now consider the tropical Pacific to play a modulating role (possibly though interaction with other modes of variability as raised by the reviewer) and as a result we would not anticipate a direct linear response. We have modified the text appropriately. Furthermore, we have investigated the New Zealand National Climate Database (CliFlo) for the Chatham Islands but unfortunately surface pressure data is only available from 1991, too short to further explore long-term trends. However, is is important to note that the 20th Century Reanalysis product is based on the observational data so any comparisons would not be truly independent. That said, other available datasets in New Zealand would have contributed to the reanalysis trends reported here.

8. Figure 10 needs to be made much bigger and clearer.
We agree completely. We have revised the figure to focus on the Pacific-basin only and pasted below a revised copy of the figure (based on the new SWP region defined above). Upper panels show seasonal relationship with MSLP and lower panels the relationship (with no time lag) with SSTs. Crucially, the opposing relationship between the SWP and MSLP over West Antarctica appears to be year round, suggesting a robust relationship, regardless of changes in the tropical Pacific.



We have also reanalysed the meridional mean mass streamfunction with the new SWP region (bottom panels; upper panel: SIO) and confirm a stronger Ferrel Cell, consistent with increasing poleward heat flux, providing a mechanism for warming over Antarctica.

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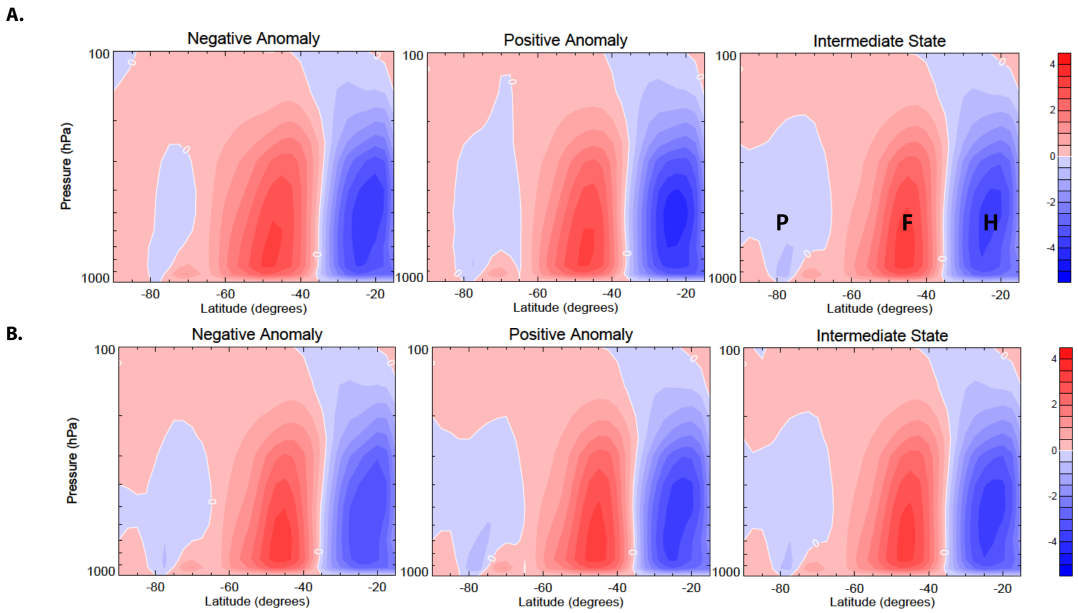

Reviewer 2: Anonymous

1. I think the main omission by the authors is some calculations to clarify the capability of delta D in representing the local temperature and circulation variabilities. Most people reading this article will probably be more familiar with the SH climate, and are less likely to be experts in the ice core products (myself included) and so it is important that readers are pointed to some source of information about what delta D can tell us. I would be particularly worried about the seasonality of annual resolved delta D in representing the hemispheric circulation change in the SH high latitudes. These worries may be unfounded, but without a source of information about the limitation, I'm left wondering how good these isotope data are representing local climate variability.

This is a fair point. We have added further details regarding the application of stable isotopes in the ice core studies and how they relate to climate and broader synoptic conditions, including Jones et al., 2009, *The Holocene*. The important point here is the isotopic values obtained from our new ice core provide a measure of temperature at the inversion layer which can be related to an Antarctic-wide warming trend observed in the radiosonde observations.

2. There is a strong linear trend in the SLP or Z700 in the SH since 1979 in Era-I and NOAA-20th reanalysis data. It is worth testing whether the results in several figures are sensitive to this long term linear trend in the data.

There is a a major trend in the temperature and SLP data series from the 1970s. To satisfy ourselves that the correlation are robust we deseasonalised and detrended the correlations and regressions above.

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3. A caveat ought to be added in the conclusions section that since Fig5 only looks at a simple coherence analysis of two time series there is still a question mark over the statistical significance and physical understanding of the results, and that further studies as new data and modeling become available should help to resolve this issue.

We completely agree and have added the appropriate text.

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Tropical and Mid-Latitude Forcing of Continental Antarctic Temperatures

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Abstract

Future changes in atmospheric circulation and associated modes of variability are a major source of uncertainty in climate projections. Nowhere is this issue more acute than across the mid- to high-latitudes of the Southern Hemisphere (SH) which over the last few decades have experienced extreme and regionally variable trends in precipitation, ocean circulation and temperature, with major implications for Antarctic ice melt and surface mass balance. Unfortunately there is a relative dearth of observational data, limiting our understanding of the driving mechanism(s). Here we report a new 130-year annually-resolved record of δD – a proxy for temperature – from the South Geographic Pole where we find a significant influence from extra-tropical pressure anomalies which act as 'gatekeepers' to the meridional exchange of air masses. Reanalysis of global atmospheric circulation suggests these pressure anomalies play a significant influence on mid- to high-latitude SH climate, modulated by the tropical Pacific Ocean. This work adds to a growing body of literature confirming the important roles of tropical and mid-latitude atmospheric circulation variability on Antarctic temperatures. Our findings suggest that future increasing tropical warmth will strengthen

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meridional circulation, exaggerating current trends, with potentially significant impacts on Antarctic surface mass balance.

1 Introduction

Uncertainty surrounding future changes in atmospheric circulation is exacerbated in the Southern Hemisphere (SH) by the acutely short baseline of observations available only since the onset of continuous monitoring during the mid-Twentieth Century and satellite era (post-1979) (Bracegirdle et al., 2015; Delworth and Zeng, 2014; Hobbs and Raphael, 2010; Marshall, 2003), despite the extreme and often contrasting trends in precipitation, ocean circulation and temperature (Gille, 2014), and Antarctic ice melt (Rye et al., 2014) which it has experienced in recent decades. In the high latitudes of the SH, the limited available data suggest opposing trends over the last few decades; while the Peninsula and West Antarctic provide strong evidence for surface warming (up to 2.5°C since 1950) (Ding et al., 2011), observations and reanalysis data have provided contrasting trends over continental East Antarctica (Jones and Lister, 2014). A potentially confounding factor is the pronounced temperature inversion that exists over much of the high altitude plateau for most of the year (up to 10°C over 30 metres) (Hudson and Brandt, 2005), making the interpretation of surface reanalysis data problematic (Fréville et al., 2014). In marked contrast, radiosonde observations obtained through the upper atmosphere appear to provide a more robust signal, with pronounced warming observed across the mid-troposphere (centred on 650 hPa) during all seasons above the interior of East Antarctica, independent of the trends at the surface but limited to the last five decades (Screen and Simmonds, 2012; Turner et al., 2006).

Previous studies on Antarctic climate have suggested a significant low- and mid-latitude influence (Ding et al., 2011; Jouzel et al., 1983; Screen and Simmonds, 2012; Shaheen et al., 2013). For instance, an early study at the South Pole suggested snow δD closely mirrored the Pacific Decadal Oscillation over the previous century (Ekaykin et al., 2004). More recently, a relationship between surface temperature increases over West Antarctica, sea surface temperature (SST), and atmospheric circulation has been identified (Ding et al., 2011), implying that recent warming may be coupled to the tropical Pacific. Records extending the mid-troposphere temperature record (Screen and Simmonds, 2012; Turner et al., 2006) are

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therefore needed to better understand the driving mechanism(s) of warming over the continent.

Fortunately, clear-sky precipitation (or diamond dust) dominates the total precipitation over much of the continental interior (Casey et al., 2014; Ekaykin et al., 2004; Hou et al., 2007). Unlike coastal areas where different precipitation sources contribute to significant amounts of accumulation, diamond dust is continuously formed in the low atmosphere on the plateau during clear days, where most of the crystals are generated in the relatively moist upper part of the surface inversion (approximately 600-700 hPa) (Ekaykin et al., 2004; Fujita and Abe, 2006; Walden et al., 2003). During these precipitation events, thick plates/short column crystals <150 µm are commonly observed in the South Pole atmosphere (Kikuchi and Hogan, 1978, 1976; Walden et al., 2003), often producing optical effects, such as halos. Crucially, although the quantities of diamond dust can be relatively low on a daily basis (Bromwich, 1988; Massom et al., 2004), estimates suggest that over a year this type of precipitation accounts for 50% to 91% of accumulation on the plateau, including the South Pole (Casey et al., 2014; Ekaykin et al., 2004; Fujita and Abe, 2006; Hou et al., 2007). Importantly, the isotopic content of the ice crystals preserves the temperature during formation (Jones et al., 2009) in the mid-troposphere, providing a measure of conditions at the top of the inversion layer. Diamond dust on the plateau therefore offers an opportunity to investigate long-term forcing of Antarctic temperatures, supplementing radiosonde data in the region.

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2 Methods

In January 2012 a 2-metre snow pit was dug and contiguous snow samples were taken at 5 cm intervals at the South Geographic Pole (Figure 1). The snow pit was extended to 7 metres depth by a snow core (sub-sampled at 2.5 cm) obtained using a 7.5 cm diameter Kovacs corer (hand cored). δD analysis on the samples was undertaken on an IsoPrime mass spectrometer at the Antarctic Climate and Ecosystems Cooperative Research Centre (University of Tasmania). In addition, sodium (Na^+), magnesium (Mg^{2+}), non-sea salt sulfate ($nssSO_4^{2-}$) and methanesulphonic acid (MSA) were also measured; Mg^{2+} and MSA data not shown. To develop a chronology on the core, sodium (peaking mid-winter) (Ferris et al., 2011) and δD (peaking mid-summer; taken here as January) (Jouzel et al., 1983) were used to identify annual layers (Figure 2) using `Linage` in the software programme *Analyseries* (Paillard et al., 1996). The identification of the 1991 Mount Pinatubo and Cerro Hudson eruptions in the 1992-1993 South Geographic Pole core is consistent with previous studies (Cole-Dai and Mosley-Thompson, 1999; Ferris et al., 2011).

The 2012 core overlapped with a previously reported δD sequence for the South Geographic Pole across the year CE 1977 (Jouzel et al., 1983). The chronology for the older part of the sequence was based on visible stratigraphic observations, deuterium maxima, tritium and β peaks (the latter across the 1960s and 1970s) (Jouzel et al., 1983), providing a robust chronology back to 1887 (Figure S1). To investigate multidecadal trends and reduce the impact of any missing years in the new combined South Pole record, we undertook a 30-year smoothing through the sequence.

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3 Results and Discussion

The resulting composite record of temperature-sensitive δD therefore extends the radiosonde record back before 1961 (Screen and Simmonds, 2012; Turner et al., 2006) (Figure 3). Prior to the 1940s we observe high inter-annual variability but with relatively stable long-term (30-year running mean) δD values, implying temperatures did not vary significantly in the mid-troposphere over this period. From the 1940s through to the 1960s, however, we identify a trend to lower temperatures (depleted deuterium content) that was reversed in the late 1960s and apparently sustained through to present day.

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To explore the potential role of SH circulation on temperatures over the South Geographic Pole and the wider Antarctic continent (equatorwards of 65˚S), we investigated monthly average reanalysis data from ERA-Interim (Dee et al., 2011) and the Twentieth Century Reanalysis version 2c (20CRc) (Compo et al., 2011) (see Supplementary Material). For ERA-Interim, we find that on average the largest areas of significant positive temperature anomalies over the Antarctic are associated with negative surface pressure anomalies (Figure 4A) extending up to 700 hPa (Figure S2) in specific regions, most notably over the southeastern Indian Ocean, southwestern Pacific (and to a lesser extent in the southwestern Atlantic) of the SH, and also in the eastern tropical Pacific (similar responses are also

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observed where comparisons are made equatorward of 55˚S and 75˚S; data not shown). In contrast, large areas of significant negative Antarctic temperature anomalies are associated with months of positive pressure anomalies in similar regions but have a stronger association with the southern Indian Ocean and the central-eastern equatorial Pacific (Figure 4B); indeed the southwestern Pacific and southwestern Atlantic centres are relatively weak in this phase. There is a less pronounced connection between the Antarctic and lower latitudes in the other two anomaly combinations (temperature and pressure anomalies either both positive or both negative; Figure S3). Patterns consistent with those shown in Figures 4, S2 and S3 were also obtained using 20CRc (not shown).

The distribution of the key southern mid-latitude centres in Figure 4 may be related to one of several climate modes known to operate across the region. For instance, the pressure anomaly field of the Southern Annular Mode (SAM), the leading mode of climate variability of the mid-latitudes of the Southern Hemisphere, is defined as the pressure difference between around 40˚S and the Antarctic continent (65˚S) (Marshall, 2003). Crucially, SAM is known to exhibit spatial and temporal asymmetry with a wave three pattern in the middle latitudes (Fogt et al., 2012) which is particularly pronounced in the Pacific (Steig et al., 2009b), and has been linked to the tropics (Ding et al., 2012; Fan, 2007; Lim et al., 2013). Another possible mode of variability is the Pacific–South American (PSA) pattern, a wave train of anomalies extending from New Zealand, off the coast of Marie Byrd Land (West Antarctica), and into the Weddell Sea/south Atlantic Ocean (Mo and Higgins, 1998) as a result of tropical forcing (Karoly, 1989). Importantly, the most positive phase of the SAM manifests itself at the surface most strongly during summer and autumn months (Thompson et al., 2011) with marked asymmetry focused on the southwest Pacific during winter-spring (Fogt et al., 2012), while the PSA signal is primarily summer focused (Karoly, 1989). To investigate their possible role, long-term trends in sea level pressure were extracted from 20CRc (Compo et al., 2011). Analysis of the distribution of extremes in the 10th and 90th percentiles in the southern Indian Ocean and southwest Pacific deseasonalised MSLP (1979 to present day) indicate the distribution of anomalies is across the year and not skewed to a particular month or season (Figure 5) suggesting SAM or PSA does not account for the observed anomalies.

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Alternatively, the low pressure anomalies associated here with warming over the South Geographic Pole and wider Antarctica may be linked to the zonal wave-3 pattern (ZW3) (Raphael, 2004) which plays a significant role in meridional flow across 45-55˚S on interannual to decadal timescales (Steig et al., 2009a). ZW3 has been associated with changing sea ice concentration in the Southern Ocean (Raphael, 2007), the delivery of rainfall to southwest Australia (van Ommen and Morgan, 2010) and recent warming over West Antarctica (Steig et al., 2009a). Estimates obtained across the period of satellite observations (post-1979) suggest ZW3 explains some 8% of SH circulation but hemispherically-averaged reconstructions only extend back to the 1960s (Raphael, 2004), hampering our understanding of its significance on multi-decadal timescales. Long-term changes in ZW3 and its influence on the SH remain highly uncertain, with limited observational data in a marine-dominated realm. Recent work has suggested ZW3 provides a mechanism for the meridional exchange of air masses, implying a strengthening since the 1970s (Schneider et al., 2004; van Ommen and Morgan, 2010), a trend coupled models struggle to reproduce (Holland and Raphael, 2006; Landrum et al., 2012; Steig et al., 2009a).

We observe fields at 700 hPa composited for 10th percentile (negative) surface pressure anomalies in the southeastern Indian Ocean (panels A.-E. of Figures 6 and S4) and southwestern Pacific Ocean (panels A.-E. of Figures 7 and S5) are associated with contrasting meridional airflow direction across the SH mid-latitudes (including enhanced northerly airflow extending over southwest Australia, consistent with regional precipitation decline over the past few decades) (Delworth and Zeng, 2014) and an increase in geopotential height (GPH) over the Antarctic continent. Both the ERA (Figures 6 and 7) and 20CRc (Figures S4 and S5) generate similar patterns, providing confidence that large scale processes are being appropriately captured. By examining the meridional mass streamfunction (Figure 8), we find that in comparison with the situation in the intermediate state, the negative anomaly state shows a weakening (reduced volume) of the Polar cell and a strengthening (increased volume) of the Ferrel cell (particularly on the poleward side of the cell), consistent with increased poleward heat transport. In marked contrast, the opposite pattern is observed with positive pressure anomalies in the mid-latitudes, with a stronger Polar cell (particularly with the SIO region) and weaker Ferrel cell (also seen in the SWP), suggesting a greater dynamical barrier to poleward heat transport.

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To explore whether this relationship has changed over annual to decadal timescales (during the pre-satellite era) we undertook wavelet coherence analysis between annually-resolved Pacific and Indian Ocean pressure anomalies as extracted from the 20CRc with our newly obtained South Geographic Pole δD record (Figure 9). Focusing on the second half of the twentieth century (considered to have more reliable reconstructive ability over the mid latitudes of the SH) (Compo et al., 2011), we observe a significant shift in the dominance of the different pressure anomalies. During the 1940s through to the early 1960s, low-pressure anomalies centered on the south Indian Ocean share common periodicities across 4-8 years, paralleling the 30-year trend (Figure 3); in the southwest Pacific, the common periodicity is less strongly expressed over the same time period. During the late 1980s, a similar multiyear coherence appears to have re-established between the southwest Pacific and South Pole across 4-16 years (albeit the most recent period falling within the cone of influence), with limited evidence for a teleconnection between the south Indian Ocean and Antarctica (Figure 9). Further work is now required to extend the observational record of the mid-latitudes beyond the mid-1940s.

Intriguingly, the periodicities (Figure 9) and spatial plots of pressure anomalies versus Antarctic temperature (Figure 4) suggest the tropical Pacific may play a role. Teleconnection(s) have been observed between SH low- and mid to high-latitudes (Bromwich et al., 2000; Ding et al., 2011; Turner, 2004; Vance et al., 2012) but different seasonal teleconnections have been reported, including central Pacific temperature changes in the austral winter (Ding et al., 2011), linear forcing between the El Niño-Southern Oscillation (ENSO) and SAM in the austral summer (Fan, 2007; L'Heureux and Thompson, 2006) and changing teleconnections depending on the relative phasing of different modes (Clem and Fogt, 2015; Stammerjohn et al., 2008).

Here we find no significant relationship between the southwest Pacific pressure anomaly and annual average GPH in the tropical west Pacific (Figure 7), while absolute differences in the tropics are relatively small (Figure 8). These, however, may be masked by seasonal changes. To investigate this more fully, we undertook seasonal correlations between changes in

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southwest Pacific pressure, mean sea level pressure and sea surface temperatures across the period 1979-2013 (Figure 10). We observe a significant inverse relationship with the tropical west Pacific between September and May but no significant correlation during the Austral winter (June to August). Specifically, we find low pressure over the southwest Pacific is associated with the centres of low pressure in the south Indian Ocean and the southwest Atlantic Ocean, high temperatures in the Amundsen Sea and the central and east tropical Pacific, and relatively high pressure over the tropical west Pacific (Figure 10). Whilst the opposing relationship between the southwest Pacific pressures and the West Antarctic (Marie Byrd Land) is observed, this does not extend into the mid-latitudes of the south Atlantic, supporting the conclusion we are not observing a PSA pattern (Mo and Higgins, 1998). Instead, the seasonal and geographical nature of this relationship is consistent with a tropical central and east Pacific modulation of Antarctic temperatures, delivered via the southwest Pacific.

Importantly, the relationship between the tropical Pacific and the pressure anomalies recognised here is only observed during individual months (i.e. in isolation) and is not exhibited during consecutive months associated with extreme ENSO events. Furthermore, we do not observe substantial warming over the South Pole during the period of increased ENSO variance in the early Twentieth Century (Figure 3). Our data therefore suggests there is a tropical east Pacific role (particularly with positive pressure anomalies – akin to stronger Walker Cell circulation), but that this may only have a modulating effect and is not the driver of variability. Intriguingly, recent work has demonstrated a late Twentieth Century trend towards a cooler tropical east Pacific and stronger Walker Cell circulation (England et al., 2014; Karnauskas et al., 2009; L'Heureux et al., 2013) with potentially confounding effects on temperature trends over the Antarctic (Clem and Fogt, 2015). Our data are consistent with such studies. The recent trend towards a stronger Walker Cell circulation (and trade winds) has an opposing relationship to Antarctic temperatures (Figure 4), suggesting any decrease in atmospheric pressure in the southwest Pacific may be partially cancelled out by an atmospheric Rossby wave response generated in the tropical Pacific, as observed across the Peninsula and West Antarctic (Clem and Fogt, 2015). With projected weakening of the trade winds (England et al., 2014), the observed links to Antarctic temperatures suggest the tropics may in fact play an increasingly significant role in driving high-latitude warming (Figures 4

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and 10), with potentially important implications for understanding past climate states (McGlone et al., 2010; Pedro et al., 2011; Visser et al., 2003) and future Antarctic surface mass balance.

4 Conclusions

By extending historical observations over the South Pole and in combination with reanalysis products we find that meridional circulation changes associated with centres of pressure anomalies are part of a broader change observed over recent decades. Of particular note is the marked decrease in rainfall in southwest Australia since the 1970s. Our results demonstrate this trend is part of a hemispheric pattern of alternating northerly and southerly airflow linked to changes in the southwest Pacific and the tropical Pacific. We explore teleconnections via a strengthening of the Ferrel Cell and a weakening Polar Cell, possibly associated with Zonal Wave 3 (ZW3) circulation. Comparison of 30-year running means of isotopic and climate datasets suggest the long-term low pressure anomalies in the southwest Pacific – with largely stable values in the Indian Ocean – are modulated by low-latitude change. Our findings imply that future increasing tropical warmth will strengthen meridional circulation across the mid-latitudes, exaggerating current trends, with potentially significant impacts on Antarctic surface mass balance.

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Figures and captions

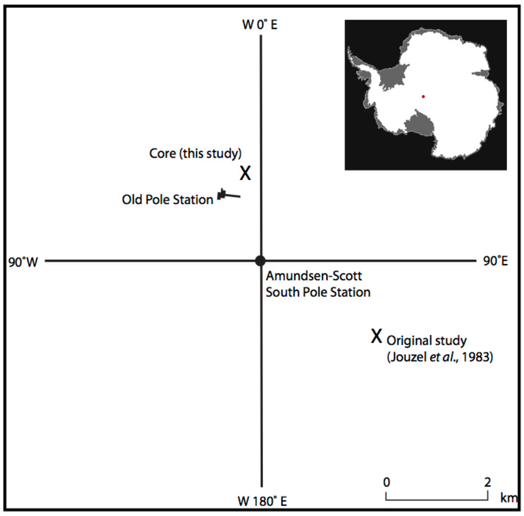

Figure 1: Location of cores investigated at the South Geographic Pole.

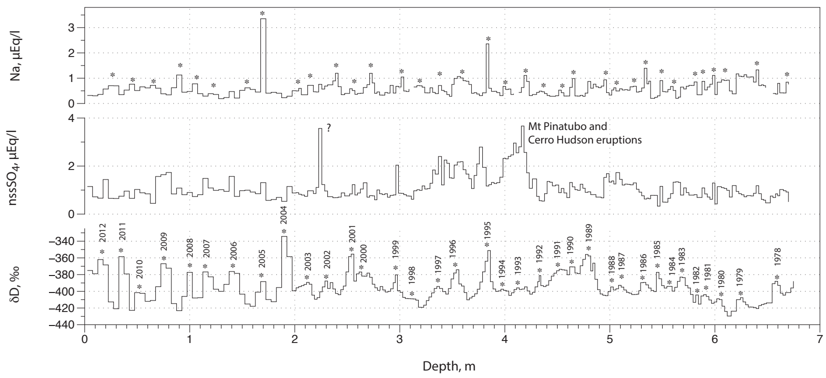

Figure 2: Annual layers identified in the South Geographic Pole core obtained in January 2012. Asterisks denote peaks in sodium (Na^+) and deuterium (δD), marking mid-winter and –summer respectively.

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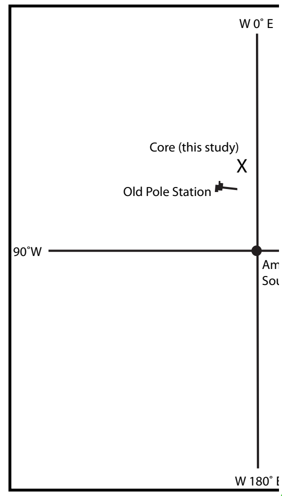

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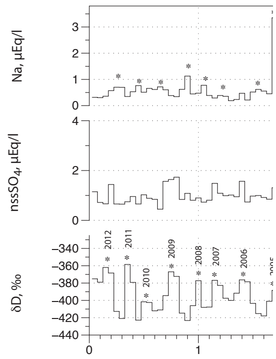

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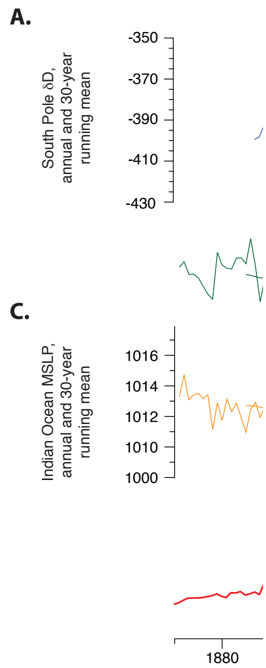

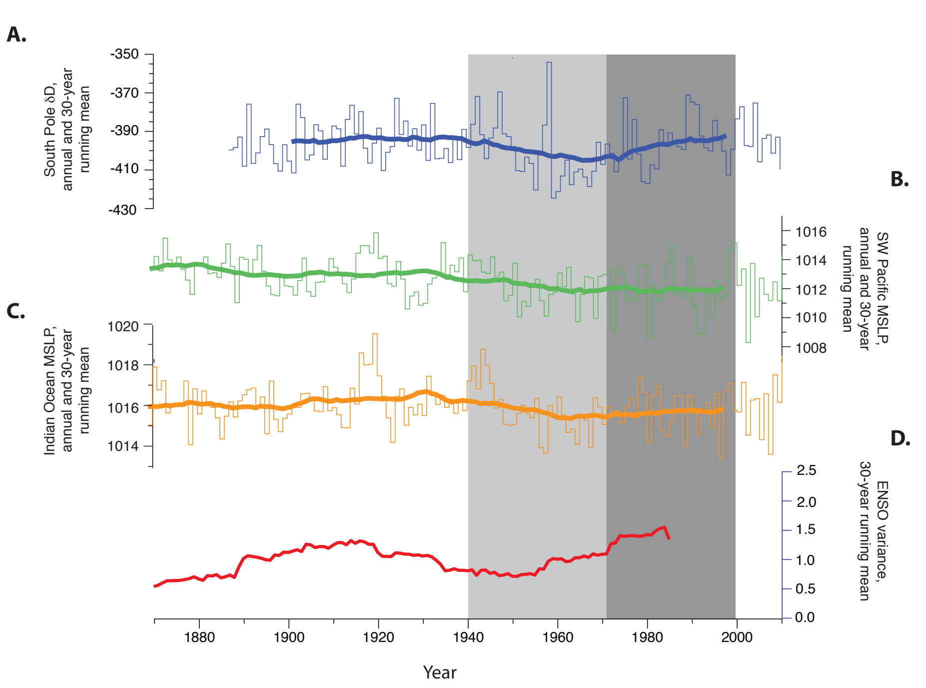

Figure 3. Annual and 30-year running mean of South Pole dD (A.) compared to annual and 30-year running mean sea level pressure (hPa) for the southwestern Pacific (180-160˚W, 55-45˚S) (B.) and southern Indian Ocean (80˚E-100˚E, 35˚S-45˚S) (C.) extracted from 20th Century Reanalysis (Compo et al., 2011), and 30 year variance in El Niño-Southern Oscillation (McGregor et al., 2013) (D.). Light grey column area denotes a period of Indian Ocean MSLP dominance over Antarctic temperatures; the dark grey column denotes the period where sustained decreasing Southwest Pacific MSLP leads to warming over the South Geographic Pole.

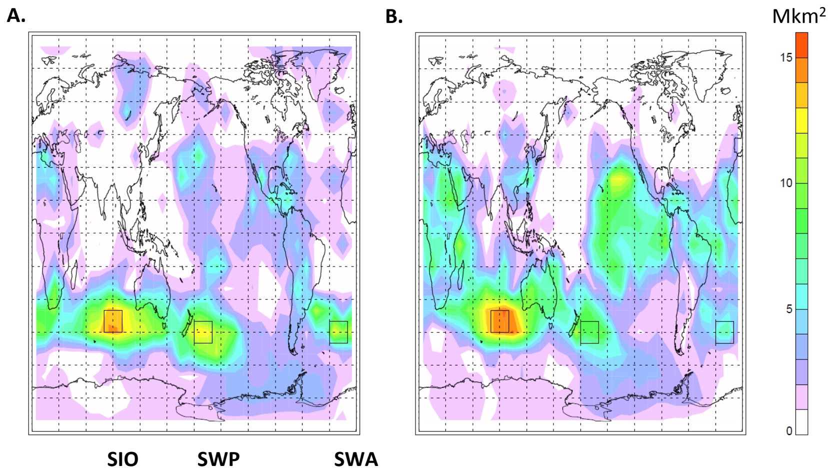

Figure 4. Panel A. The cumulative area of significant positive surface temperature anomalies poleward of 65˚S (in million km^2) produced by compositing months having negative surface pressure anomalies (thresholded at the 10^{th} percentile) in each 10˚ x 10˚ (longitude x latitude) box, obtained from deseasonalised monthly ERA-Interim reanalysis data for 1979-2012 (Dee et al., 2011). The three boxes define the positions referred to in the text as Southern Indian Ocean (SIO), Southwestern Pacific (SWP) and Southwestern Atlantic (SWA). Panel B. shows the opposite relationship i.e. the area of negative temperature anomalies produced by compositing months of positive surface pressure anomalies (thresholded at the 90^{th} percentile). The grid spacing is 15˚ in longitude and latitude. For reference, the area of the Antarctic continent is 14 million km^2 and the area poleward of 65˚S is 25 million km^2.

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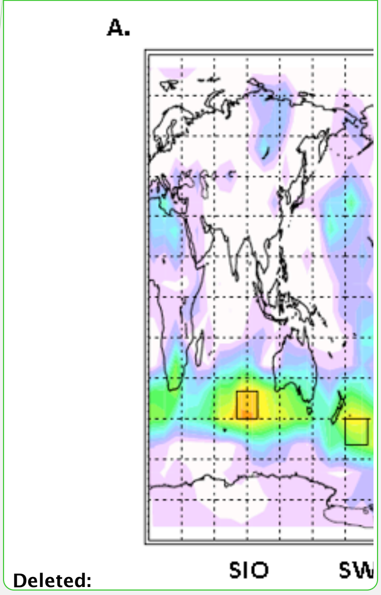

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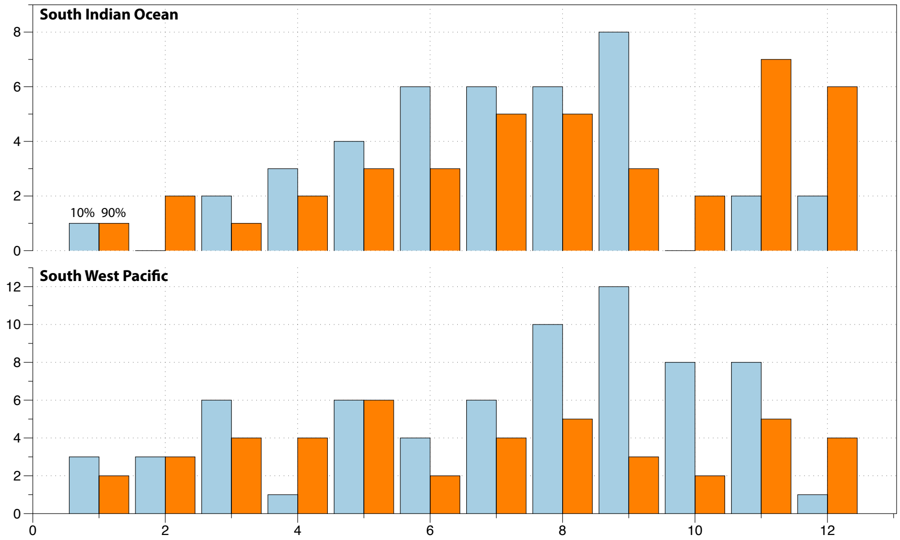

Figure 5: Distribution of 10th and 90th percentile deseasonalised surface pressure plotted for each month from 1979 to 2012 extracted from 20CRc for the south Indian (A) and Southwest Pacific (B.) oceans. Note that anomalies occur throughout the year.

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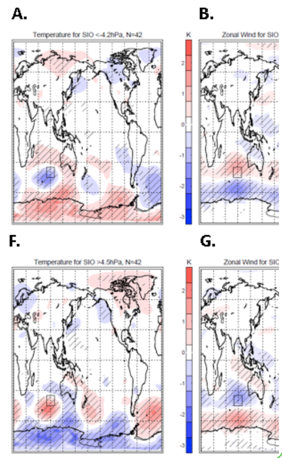

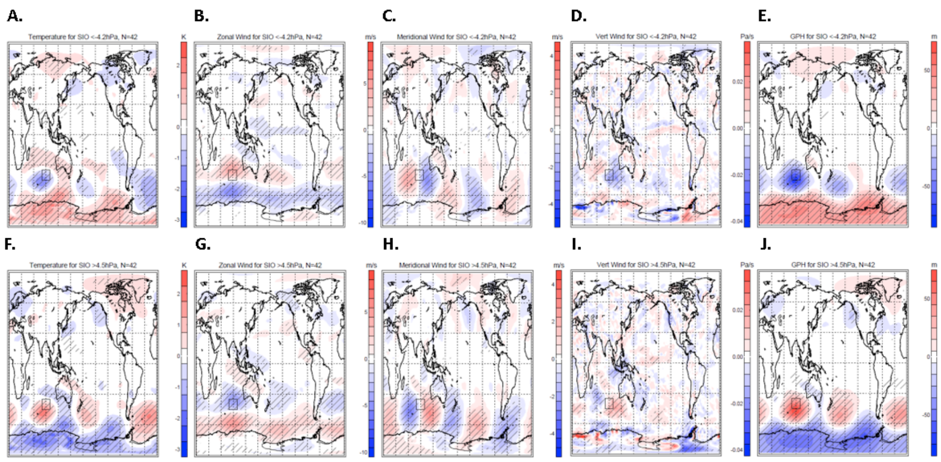

Figure 6: Composites of deseasonalised monthly ERA-Interim fields at 700 hPa for surface pressure 10th percentile (negative) and 90th percentile (positive) anomalies in the southern Indian Ocean (SIO) (80-100˚E, 35-45˚S) for 1979-2012 (Dee et al., 2011). Shown are temperature (A. and F.), zonal wind speed (B. and G.; positive = eastward) and meridional wind speed (C. and H.; positive = northward), vertical pressure wind (D. and I.; positive = downward) and geopotential height (E. and J.). The SIO surface pressure anomaly threshold and the number of months (N) contributing to each composite are shown along the top of each panel. Hatched areas denote areas of statistical significance (95% confidence).

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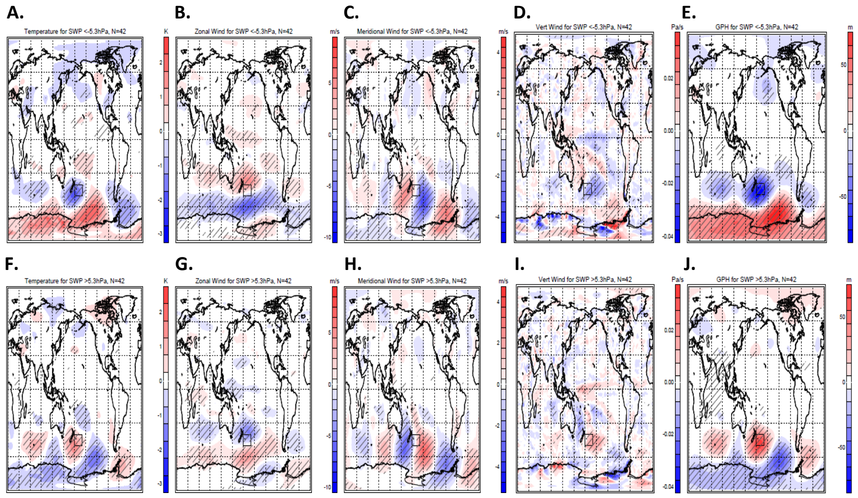

Figure 7: Composites of deseasonalised monthly ERA-Interim reanalysis fields at 700 hPa for surface pressure 10th percentile (negative) and 90th percentile (positive) anomalies in the southwestern Pacific (SWP) Ocean (180-200˚E, 45-55˚S) for 1979-2012 (Dee et al., 2011). Shown are temperature (A. and F.), zonal wind speed (B. and G.; positive = eastward) and meridional wind speed (C. and H.; positive = northward), vertical pressure wind (D. and I.; positive = downward) and geopotential height (E. and J.). The SWP surface pressure anomaly threshold and the number of months (N) contributing to each composite are shown at the top of each panel. Hatched areas denote areas of statistical significance (95% confidence).

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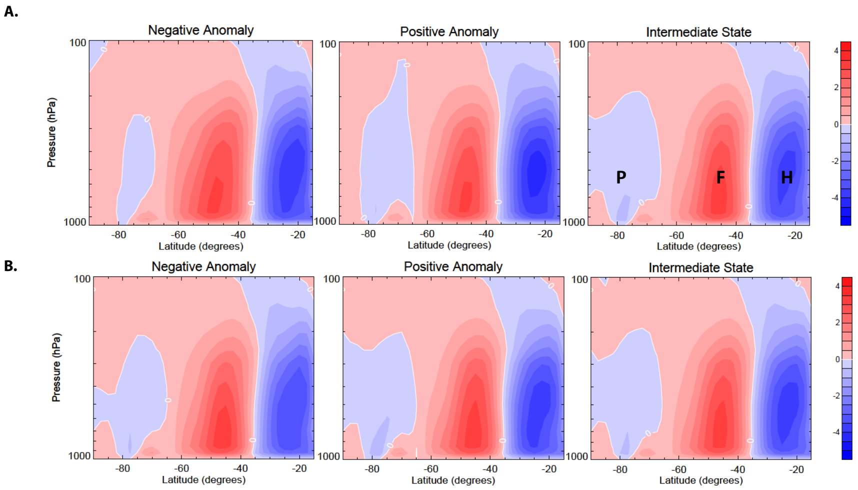

Figure 8: The deseasonalised mean meridional mass streamfunction obtained from daily mean NCEP/NCAR reanalysis (1979-2012) (Kalnay et al., 1996). Shown left to right are composites for negative, positive and intermediate monthly surface pressure anomalies in the SIO region (upper row A.) and SWP region (lower row B.). Positive (negative) values denote clockwise (anticlockwise) rotation in the plane of the figure; the Hadley, Ferrel and Polar cells are marked H, F and P, respectively. The units are 10^{10} kg/s.

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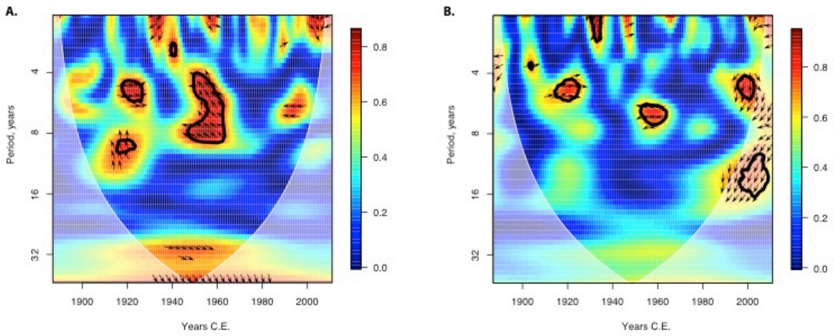

Figure 9: Wavelet coherence plots between annually-resolved South Geographic Pole δD and the SIO (A.) and SWP (B.) surface pressure extracted from the 20CRc (Compo et al., 2011). Major periodicities (95% confidence) are defined by solid black contours; the white dashed lines denote the cone of influence. Arrows indicate relative phase with angle measured anticlockwise from in-phase (pointing to the right) through SIO and SWP pressure leading South Pole δD (temperature) in quadrature (pointing upwards) to anti-phase (pointing left).

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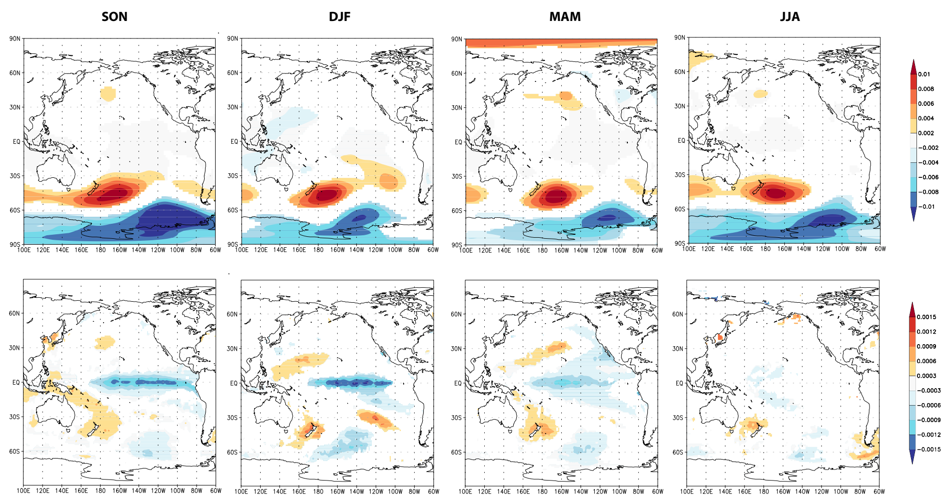

Figure 10: Contoured regressions between detrended and deasonalised Southwest Pacific (SWP) sea level pressure and Pacific-wide 20CRc sea level pressure (Panels A-D) (Compo et al., 2011), and sea surface temperatures (SSTs) (Panels E-I) (Rayner et al., 2003) (1979-2013) during September-November (SON), December-February (DJF), March-May (MAM) and June-August (JJA). Significance $p_{field} < 0.1\%$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers, 2005). Note the significant inverse relationship between SWP, tropical west Pacific sea level pressure and central and east tropical Pacific SSTs during September-November, December-February and March-May (but not June-August), a region and seasons closely associated with tropical Pacific variability (Collins et al., 2010).

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