Recent Trends in the Southern Oscillation

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ABSTRACT

The Southern Oscillation Index, the difference between standardized sea-level pressure between Tahiti (18°S, 150°W) and Darwin (12°S, 131°E) (hereafter denoted TN – DN), has tended to be lower during the past few decades than during the earlier part of the record. This shift is mainly a reflection of a pressure rise at Darwin: pressure at Tahiti has not fallen noticeably. The statistical significance of the pressure rise at Darwin and the drop in (TN - DN) that took place in the mid- 1970's is difficult to assess for lack of an a priori hypothesis that the shift should have occurred precisely when it did as opposed to, say, ten years earlier or later. The downward trend in (TN - DN) since the mid-twentieth century is not statistically significant.

The upward trend in (TN + DN) during the second half of the 20th century is quite striking. Fluctuations in (TN + DN) are shown to be significantly correlated with fluctuations in tropical mean sea-level pressure and with indices of the Northern and Southern Hemisphere annular modes. The trend toward the high index polarity of the annular modes accounts for roughly half the observed rise in (TN + DN) since the mid-20th century.

1. Introduction

Among the findings reported in the Summary for Policymakers of the 2001 Third Assessment Report of the Intergovernmental panel on Climate Change is that "Warm episodes of the El Niño-Southern Oscillation (ENSO) phenomenon ... have been more frequent, persistent and intense since the mid-1970's compared to the previous 100-years." A key piece of evidence in support of this finding is Trenberth and Hoar's (1996; hereafter referred to as TH) analysis of an extended record of barometric pressure at Darwin, Australia.

Pressure records for Tahiti (18°S, 150°W) and Darwin (12°S, 131°E) are representative of the opposing poles of the 'Southern Oscillation' (Walker 1924; Walker and Bliss 1932; Troup 1965; Trenberth 1976, 1984; Wright 1985; Trenberth and Shea 1987; Trenberth and Caron 2000). When smoothed as in Trenberth (1984), these time series are negatively correlated with one another at a level of -0.71 for 1935-2002 and their difference (standardized pressure at Tahiti, denoted TN, minus standardized pressure at Darwin, denoted DN, after Trenberth (1984)) is negatively correlated with sea surface temperature in the equatorial Pacific (5°N-5°S, 170-120°W) at a level of -0.92 for 1950-2002 (both series smoothed as in Trenberth (1984)). This so called "Southern Oscillation Index (SOI)" has been used in numerous studies as an indicator of the status of the ENSO phenomenon as viewed from an atmospheric perspective.

Mindful of the high degree of redundancy between the smoothed Darwin and Tahiti pressure records, TH elected to use the longer and more reliable Darwin record as a basis for investigating long term trends in the ENSO cycle. TH reported that Darwin pressure has tended to be above its long term normal since 1977, indicative of a prevalence of the warm (El Niño) phase of the ENSO cycle. This tendency is clearly evident in the updated Darwin pressure time series shown in Fig. 1.

Harrison and Larkin (1997), Rajagopalan et al. (1997, 1999), Wunsch (1999a,b), and Solow and Huppert (2003) have questioned the statistical significance of the prevalence of positive sea-level pressure (SLP) anomalies toward the end of the Darwin record, and Trenberth and Hoar (1997), Allan and D'Arrigo (1999), and Trenberth and Hurrell (1999a,b) have provided additional evidence in support of the TH findings. In this note we will address two issues different from the ones that have been considered in these exchanges: (1) the choice of index that is used to represent ENSO and (2) the choice of metric that is used to test whether the recent behavior of ENSO is significantly different from its prior behavior.

2. Darwin SLP trend versus SOI trend

The trend in the SOI depends upon the trend in barometric pressure, not only at Darwin, but also at Tahiti. It is evident from Fig. 2 and Table 1 that pressure at Tahiti has exhibited little, if any downward trend during the past few decades. Hence, the trend in the standardized SOI (also listed in the Table) is only about half as large as the trend in standardized Darwin pressure.

The Tahiti record from 1935 onward was examined by Trenberth and Shea (1987) and found to be free of inhomogeneities that might give rise to spurious trends. The availability of this record offers the possibility of considering whether a pattern of variability other than ENSO might have contributed to the pressure trends at Darwin and Tahiti during the past few decades. The sum of the Tahiti and Darwin standardized pressure time series (TN + DN), which is linearly independent of the SOI (Trenberth 1984), is ideally suited for investigating this possibility. (TN + DN) is also a crude 2-station index of variations in tropical-mean SLP. Fig. 3 shows monthly SOI and (TN + DN) time series, together with a time series of marine SLP anomalies averaged over 20°N-20°S for 1950-2002. The monthly (TN + DN) and the tropical marine SLP are correlated at a level of 0.58 (0.40 for smoothed values) for the period of record 1950-2002. As noted by Trenberth (1984), the amplitude of the variations in (TN + DN) are much smaller than those in (TN – DN). They would be of little interest were it not for the fact that they exhibit a substantial upward trend.

The global SLP pattern associated with fluctuations in (TN + DN) is shown in Fig. 4. This figure is constructed by regressing monthly SLP anomalies from the National Centers for Environmental Prediction (NCEP) - National Center for Atmospheric Research (NCAR) reanalysis (Kistler et al. 2001), and a concatenation of COADS and NCEP marine real-time data upon the standardized, unfiltered (TN + DN) time series for the period 1950-2002, all calendar months included. The regression pattern projects strongly on a pattern of variability variously referred to as the “high latitude mode” (Kidson 1988, 1999) and the Southern Hemisphere annular mode (SAM: Hartmann et al. 2000; Compagnucci et al. 2001) and a weaker signature of the Northern Hemisphere annular mode (NAM: Thompson and Wallace 1998) is also apparent. Darwin and Tahiti SLP both tend to be above normal when the annular modes are in their "high index" polarity, with anomalously low pressure over the polar cap regions and strong subpolar westerlies. The close agreement between the maps constructed from different data sets lends credence to this global pattern. Consistent with this result, the global patterns formed by regressing SLP upon the indices of the annular modes are characterized by positive values throughout the tropics (Baldwin 2001). The correlation coefficient between unfiltered time series of (TN + DN) and the NAM, as defined in Thompson and Wallace (2000), is 0.24 for all calendar months in 1950-2002, and the correlation between (TN + DN) and the SAM, derived from Antarctic 500 hPa geopotential heights by Thompson and Solomon (2002), is 0.20 for all calendar months in 1969-98. For reference, the correlations corresponding to a two-tailed p-value of 0.001, accounting for the month-to-month autocorrelation in the (TN + DN), NAM, and SAM time series in the manner suggested by Bretherton et al. (1999), are 0.15 and 0.18, respectively.

Both Northern and Southern Hemisphere annular modes have exhibited pronounced trends toward their high-index polarity, as indicated in Table 2. The trend in the NAM has been documented by Hurrell (1995) and Thompson et al. (2000). The NCEP-NCAR reanalyses shows indications of a trend in the SAM, which is confirmed by Thompson and Solomon's (2002) analysis of station records from 1969 onward. Possible causes of these trends include stratospheric ozone depletion (Thompson and Solomon 2002; Gillett and Thompson 2003), the buildup of greenhouse gases (Shindell et al. 1999), and the trend in tropical sea surface temperatures, particularly over the Indian Ocean sector (Hoerling et al. 2001).

The contribution of the trend in the annular modes to the trend in the (TN + DN) time series can be estimated as the product of the trend in the annular modes (Table 2) and the regression coefficient of (TN + DN) upon the annular mode time series. For standardized indices, the regression coefficients are the same as the correlation coefficients, listed in Table 3. For example, the contribution of the NAM to the (TN + DN) trend is

$$1.43 \text{ std.dev./53 years} \times 0.51 = 0.73 \text{ std.dev. / 53 years}$$

or 44%. Based on a similar analysis for the SAM, it appears that the annular modes account for about half of the positive trend in (TN + DN) from 1950 onward.

3. Trend versus regime shift

The apparent significance of the prevalence of the low index of the Southern Oscillation in recent decades depends, not only upon the choice of index that is used to represent the Southern

Oscillation, but also on the choice of metric that is used to compare recent decades with prior decades. TH applied a t-test to the difference in mean SLP between the recent epoch beginning in 1977 and the prior part of the record. In the absence of an a priori physical basis for expecting that the response of ENSO to greenhouse warming should manifest itself as a regime shift that takes place late in the 20th century, it could be argued that the trend over an extended time period is a more appropriate metric. Values of the t statistic analogous to those in Table 2, but based on the differences in the mean values of the Darwin and SOI time series between the 1950-76 and 1977-2002 epochs, shown in the top two rows of Table 4, are quite comparable. In contrast, the corresponding t values for the trends, shown in the bottom two rows, differ by a factor of 2. A careful inspection of Fig. 2 reveals why the significance of the recent change in the SOI record is sensitive to the choice of metric, whereas the change in the Darwin record is significant with respect to both metrics. During 1970-76 SLP was anomalously low at Darwin and anomalously high at Tahiti, and over 1977-87 the opposite conditions prevailed. Hence in Table 4, the 1976-77 jump in the SOI is almost as significant as the jump in Darwin SLP. In contrast, the upward trend in Darwin SLP from 1950 onward was not accompanied by a downward trend in Tahiti SLP, so the trend in the SOI is much less significant than the trend in Darwin SLP.

4. Conclusions

The rise in Darwin SLP toward the end of the twentieth century, first noted by Trenberth and Hoar (1996), tests out as statistically significant at the 95% level or above by either of the metrics considered in this study. The unusual strength of the 1982-83 and 1997-98 warm episodes and the occurrence of the prolonged 1991-94 warm episode have contributed to the rise, but ENSO is not its sole cause. We have shown that about half the pressure rise at Darwin is attributable to other factors, which are reflected in the (TN + DN) time series. The trend in the Northern and Southern Hemisphere annular modes toward their high index polarities, with positive SLP anomalies equatorward of 55° latitude, accounts for roughly half of this non-ENSO related component of the pressure rise at Darwin.

The shift toward the warm polarity of ENSO that occurred in the late 1970's is significant at the 95% level, but only on the basis of an *a priori* test. That presumes that the change should take place in a step-wise fashion some time toward, but not too close to the end of the record. More conservative tests based on the trends in the SOI from 1935 onward and from 1950 onward yield p-values well below the 95% significance level.

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Figure Captions

FIG. 1. Standardized monthly Darwin pressure anomalies for 1882-2002. The series is filtered and standardized as for the shaded curve of Fig. 2 of TH (1882-1981 base period). The first and last 5 months are omitted to remove possible endpoint effects.

FIG. 2. Monthly Tahiti and Darwin sea-level pressure time series (hPa) and the SOI (non-dimensional) for 1935-2002. The Tahiti and Darwin traces are obtained by smoothing each series with a 13-month running mean to remove much of the annual cycle, and the resultant Gibbs oscillations (Trenberth 1984) are greatly diminished with a subsequent 9-month running mean. The SOI is defined and filtered as in Trenberth (1984), with the normalization based on the standard deviation of all calendar months combined. The first and last 10 (5) months of Tahiti and Darwin (SOI) series are omitted to remove possible endpoint effects. The lightly shaded vertical bars are intended to highlight the large swings of the ENSO cycle.

FIG. 3. Time series of monthly SOI and (TN + DN) (non-dimensional) for 1935-2002, and marine SLP anomalies (hPa) averaged over 20°N-20°S for 1950-2002, all smoothed as in Trenberth (1984). Anomalies and normalization are with respect to 1950-2002 for all series, and the first and last 5 months of the smoothed series are omitted to remove possible endpoint effects. A plot of smoothed SOI and (TN + DN) for 1935-82 is presented in Trenberth (1984). The marine observations are the Comprehensive Ocean-Atmosphere Data Set (COADS, Woodruff et al. 1998) for 1950-97 and the National Centers for Environmental Prediction (NCEP) marine real-time data (http://www.cdc.noaa.gov/cdc/data.nmc.marine.html) for 1998-2002.

FIG. 4. NCEP-NCAR reanalysis (contours) and COADS/NCEP marine real-time (shading) SLP anomalies regressed onto standardized (TN + DN) (contour and shading intervals of 0.25 hPa per one standard deviation of the index), based on unfiltered monthly data for 1950-2002. The reanalysis data are 2.5° latitude-longitude resolution. The COADS (NCEP marine real-time) data span 1950-97 (1998-2002), and the original anomalies at 2° latitude-longitude resolution have been averaged into 4 by 6° latitude-longitude regions to reduce the noisiness.

Tables

Table 1. Trends and associated significance p-values for normalized, annual-mean Darwin, Tahiti, and SOI pressure anomalies for 1935-2002. Yearly values of Darwin and Tahiti are obtained as January through December averages, and they are then normalized by their respective standard deviations (0.67 and 0.51 hPa for Darwin and Tahiti, respectively). These indices are also used to construct an SOI, which is then normalized by the standard deviation of its values (see also Trenberth (1984) and TH). The resultant Darwin, Tahiti, and SOI series have means 0 and standard deviations 1. The trend is estimated with the method of least squares, the trend standard error includes the variance of the trend residual (following Santer et al. 2000), the degrees of freedom are for an effective sample size of order 1 (Jones 1975, Kikkawa and Ishida 1988, Bretherton et al. 1999), and the p-values are for two-tailed tests.

Variable	Trend (std.dev./68 years)	Degrees of Freedom	t-value	p-value
Darwin	0.80	41	1.51	0.14
Tahiti	0.04	46	0.08	
SOI	-0.41	45	-0.78	0.44

Table 2. As in Table 1, but for 1950-2002 and also including (TN + DN), 20°N-20°S average marine SLP anomaly, NAM, and SAM (1969-98 only) indices.

Variable	Trend (std.dev./53 years)	Degrees of Freedom	t-value	p-value
Darwin	1.30	34	2.31	0.03
Tahiti	-0.04	32	-0.07	
SOI	-0.72	34	-1.22	0.23
(TN+DN)	1.67	27	2.79	0.01
20°N-20°S	0.94	33	1.59	0.12
NAM	1.43	31	2.46	0.02
SAM	1.67	30	1.52	0.14

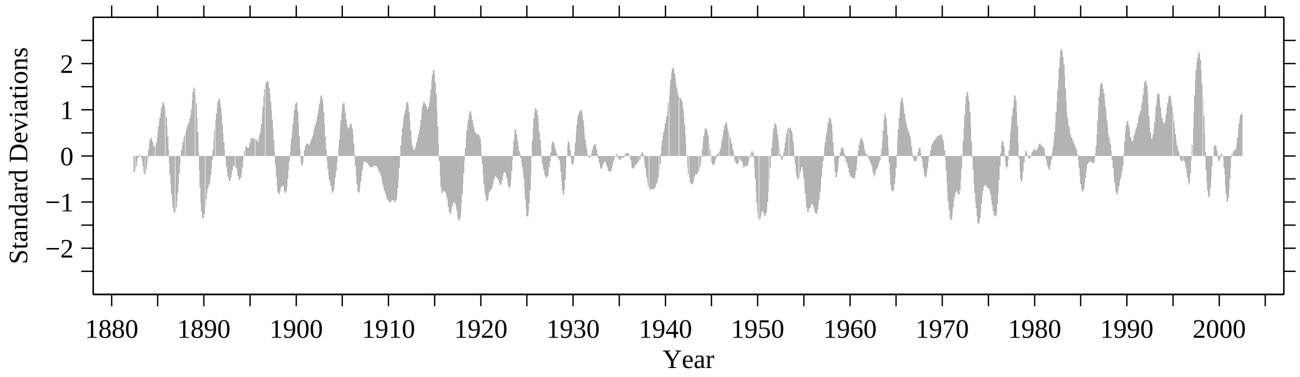
Table 3. Correlation coefficients x 100 between Darwin, Tahiti, SOI, (TN + DN), 20°N-20°S average SLP, NAM, and SAM (1969-98 only) for a) unfiltered monthly- and b) annual-mean pressure indices for 1950-2002.

a) Monthly-means	Tahiti	SOI	TN+DN	20°N-20°S	NAM	SAM
Darwin	-34	-82	58	55	9	12
Tahiti		82	58	12	19	10
SOI			0	-26	6	-2
(TN+DN)				58	24	20
20°N-20°S					21	30
NAM						-2

b) Annual-means	Tahiti	SOI	TN+DN	20°N-20°S	NAM	SAM
Darwin	-72	-93	38	55	18	28
Tahiti		93	38	-29	21	-20
SOI			0	-46	2	-26
(TN+DN)				34	51	12
20°N-20°S					28	28
NAM						4

Table 4. Darwin SLP and SOI t-values, and two-tailed significance p-values for the difference of 1977-2002 and 1950-1976 means, and for the linear trend for 1950-2002. The degrees of freedom estimates are the same for both metrics, are derived as in Table 1, and are 34 for both Darwin and the SOI. Trend statistics are from Table 2.

1977-2002 minus 1950-1976	t-value	p-value
Darwin	2.71	0.01
SOI	-2.05	0.05
1950-2002 trend		
Darwin	2.31	0.03
SOI	-1.22	0.23


Standard Deviations
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0
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−2
1880
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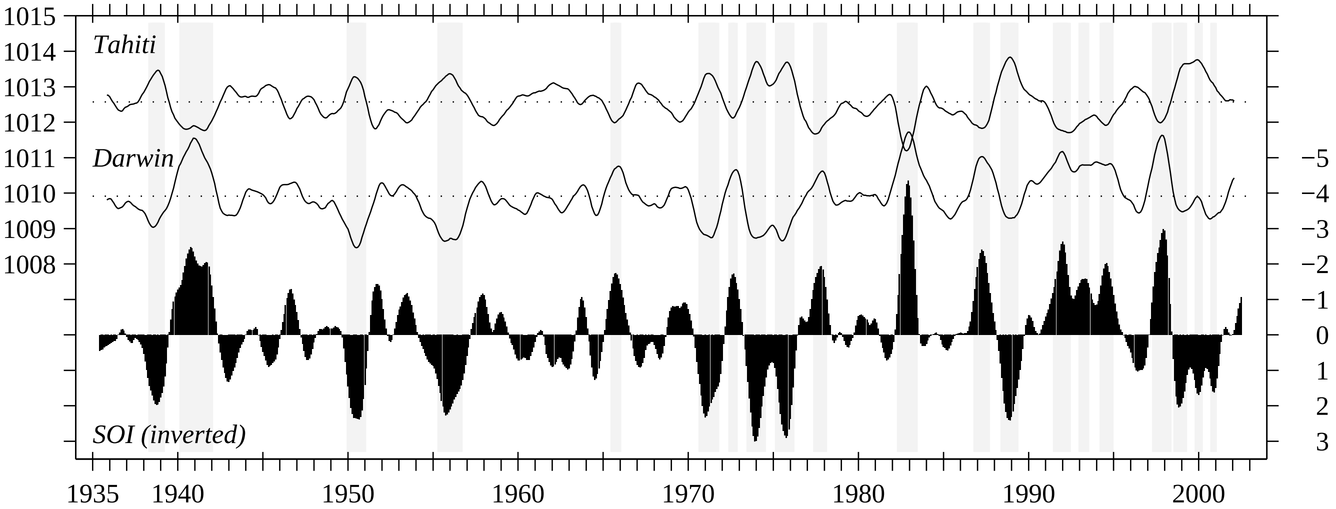
Year

Figure 1


1015
1014
1013
1012
1011
1010
1009
1008
Tahiti
Darwin
SOI (inverted)
−5
−4
−3
−2
−1
0
1
2
3
1935
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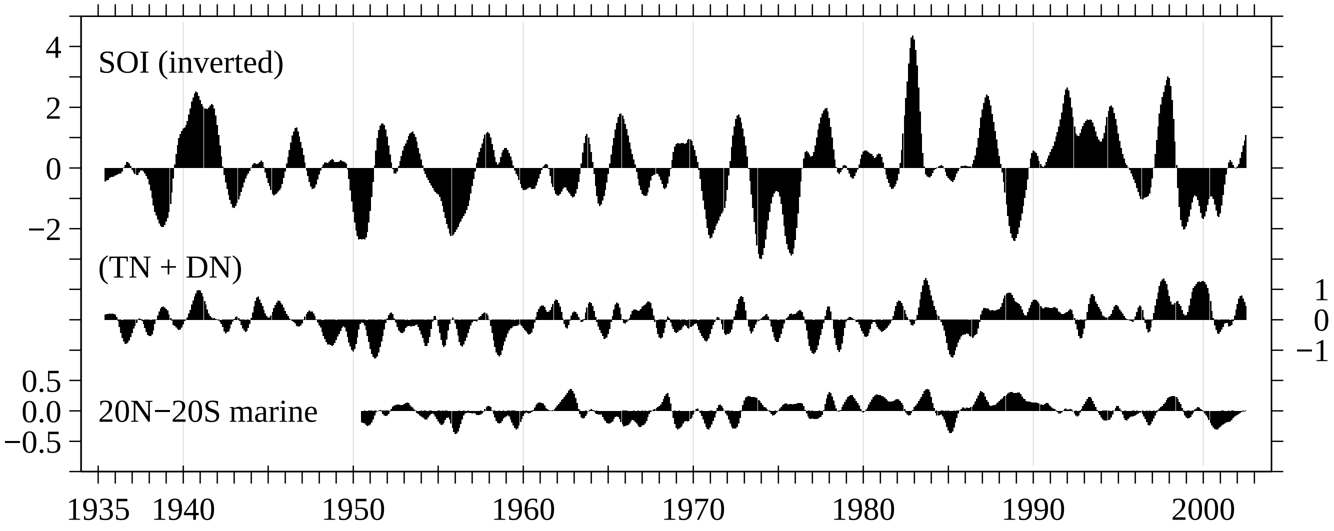
1980
1990
2000

Figure 2


SOI (inverted)
4
2
0
−2
(TN + DN)
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20N−20S marine
1935
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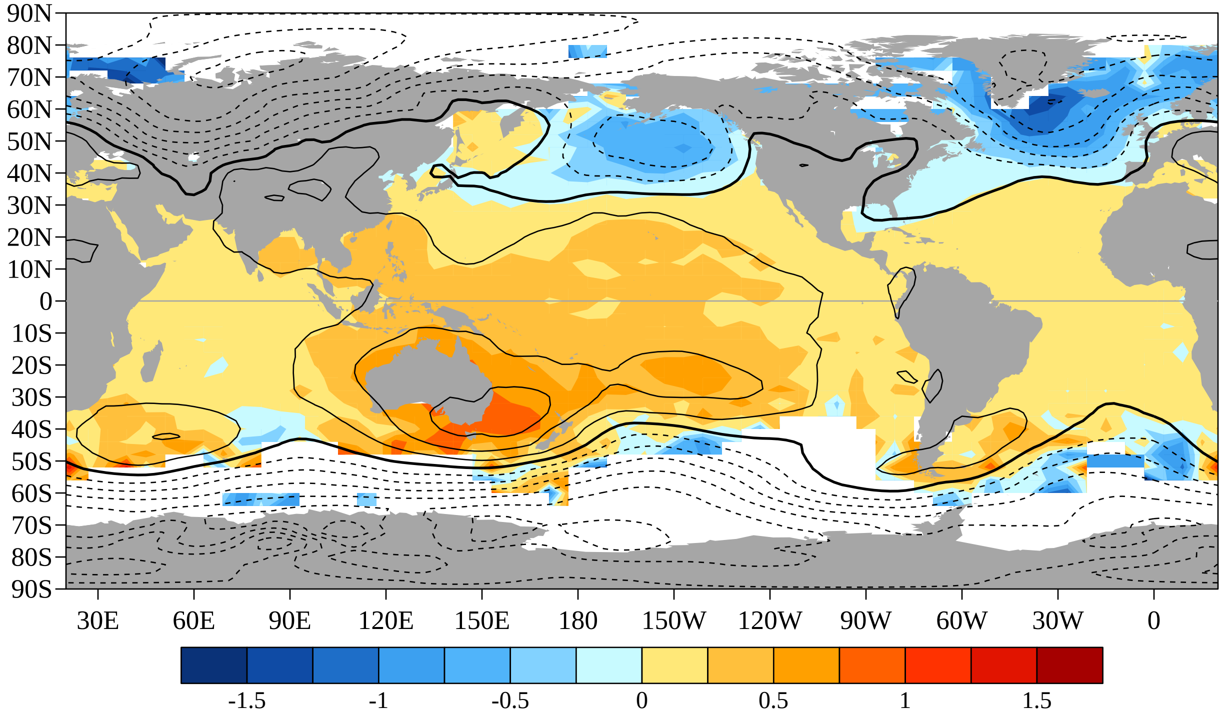
Figure 3


90N
80N
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60N
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70S
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30E
60E
90E
120E
150E
180
150W
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90W
60W
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0
-1.5
-1
-0.5
0
0.5
1
1.5

Figure 4