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Decadal variability of the Pacific subtropical cells and their influence on the southeast Indian Ocean

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[1] Historical sea level records reveal that a strengthening of the Pacific subtropical cells (STCs) since the early-1990's has reversed a multi-decadal weakening tendency. Stronger STCs correspond to a stronger Leeuwin Current in the southeast Indian Ocean (SEIO) and a stronger Indonesian Throughflow, due to dynamic connections of the Pacific and SEIO through equatorial and coastal waveguides. Multi-decadal trends of the STCs and their influence on the SEIO have confounded the detection of human induced global change signals in the short instrumental records of the two circulation systems. **Citation:** Feng, M., M. J. McPhaden, and T. Lee (2010), Decadal variability of the Pacific subtropical cells and their influence on the southeast Indian Ocean, *Geophys. Res. Lett.*, *37*, L09606, doi:10.1029/2010GL042796.

1. Introduction

[2] Human induced secular trends of the climate system are embedded with interannual, decadal, and multi-decadal coupled ocean-atmosphere variability. While there has been advanced understanding of interannual variability, especially those related to El Niño Southern Oscillation (ENSO) and some good understanding of climate change scenarios, decadal variability and predictability remain a frontier of climate research [*Meehl et al.*, 2009]. Better understanding the dynamics of decadal and multi-decadal variability is crucial to the attribution of observed secular trends in the climate system.

[3] In the southeast Indian Ocean (SEIO), interannual variability of the Indonesian Throughflow (ITF) is to a large extent influenced by zonal wind anomalies in the tropical Pacific related to ENSO, due to the existence of equatorial and coastal waveguides via the Indonesian Archipelago [*Meyers*, 1996; *Wijffels and Meyers*, 2004]. Through coastal waveguides, ENSO has also been found to induce significant interannual variability of the Leeuwin Current (LC) off the west coast of Australia [*Feng et al.*, 2003, 2005] and the poleward transport of the LC is found to be a key factor influencing sea surface temperature (SST) and fisheries recruitments off the coast [*Feng et al.*, 2008; *Caputi et al.*, 2001].

[4] On multi-decadal time scales, *McPhaden and Zhang* [2002] found that the shallow meridional overturning circulation connecting the tropical and subtropical Pacific, the subtropical cells (STCs), experienced a multi-decadal slowdown prior to the 1990's, associated with a weakening trend of easterly trade winds in the equatorial Pacific. Shallow thermocline depth anomalies associated with the STCs trend appear to have transmitted into the SEIO, inducing weakening trends of the LC and the ITF [*Feng et al.*, 2004; *Wainwright et al.*, 2008]. Conversely, during the satellite altimeter era (1993–2008), there has been a multi-decadal trend towards rising (declining) sea surface height (SSH) in the western (eastern) tropical Pacific (Figure 1a), implying a strengthening trend of the STCs.

[5] Decadal variability of the STCs tends to have larger magnitude than their multi-decadal trend [*Zhang and McPhaden*, 2006]. Satellite observations of SSH and wind stress for the period of 1993–2006 reveal a near-coherent decadal variability in the tropical Indo-Pacific Ocean, and the decadal SSH variability in the SEIO is attributed to remote wind forcing in the tropical Pacific [*Lee and McPhaden*, 2008].

[6] To date, the impacts of the decadal variability of the STC on the LC and the ITF have not been thoroughly examined, nor have the multi-decadal strengthening trend of the STCs during recent decades and its influence on the SEIO been documented. In this study, altimeter data and historical sea level records from tidal gauges in the Pacific and at Fremantle, Western Australia, are analysed to address these issues.

2. Data and Methods

[7] Monthly sea levels from Fremantle, Pohnpei, and Christmas are used in this study (Figure 1a). Fremantle (32°03′S, 115°44′E) is a major port in the SEIO and sea level has been recorded since 1897. Both Christmas (1°59′N, 157°28′W) and Pohnpei (6°59′N, 158°15′E) tidal gauge stations in the tropical Pacific have sea level records since 1974. Other Pacific tidal gauge stations that have longer histories tend to have missing data (e.g., Malakal and Yap) or have visual drifts (e.g., Guam).

[8] The Pacific STCs are associated with the divergence of warmer Ekman flows out of the tropics forced by easterly trade winds and the convergence of colder pycnocline waters into the tropics. Most of the flows in the pycnocline lie below the Ekman layer, so that to the first order their variability can be inferred from geostrophy [*Lee*, 2004]. In this study we use differences in sea level between Pohnpei and Christmas to infer the strength of the Pacific STCs. It is evident that, on decadal time scales, the sea level difference between the two stations is highly correlated with the east-west contrast of sea level anomalies in the tropical Pacific (Figure 1b) mainly because sea level variability at

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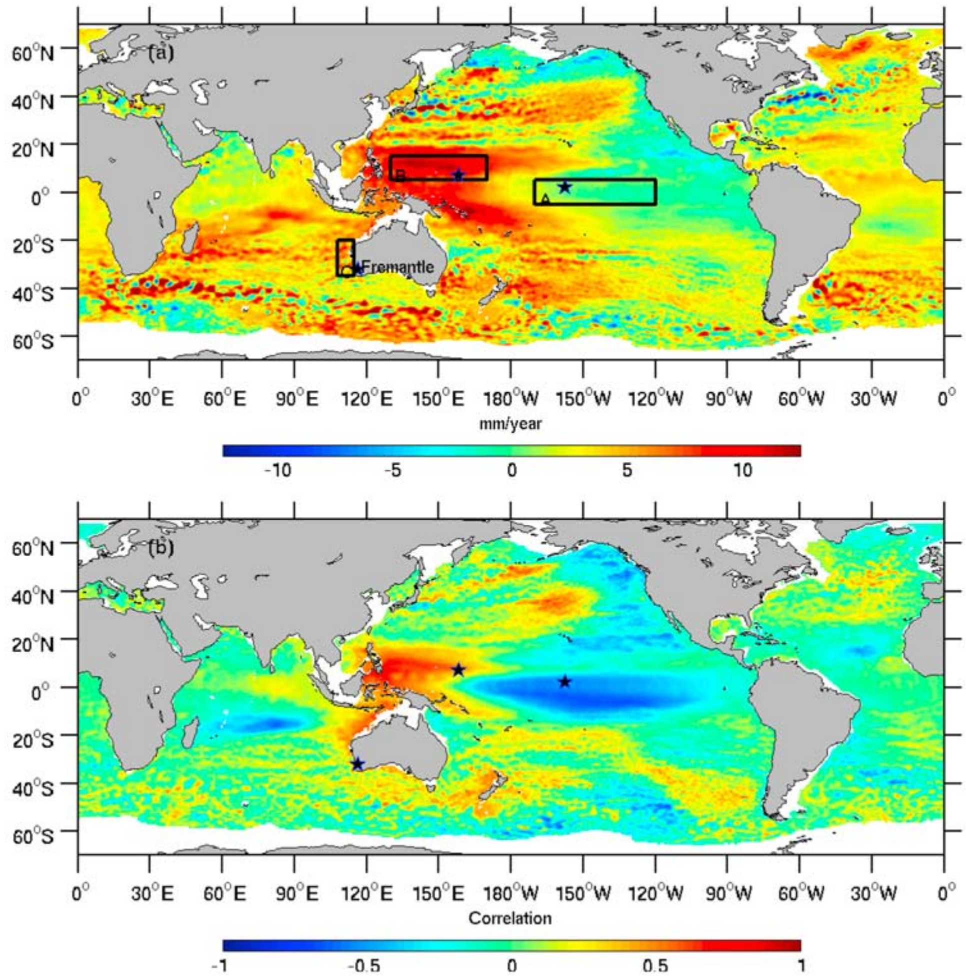

Figure 1. (a) Linear trend of sea level anomalies in the world oceans derived from satellite altimetry data and (b) linear correlation between sea level anomalies from altimetry and sea level differences between Pohnpei and Christmas during 1993–2008. In Figure 1a, boxes A and B are used by *Lee and McPhaden* [2008] to represent sea level anomalies in the tropical Pacific and the stars in boxes A and B denote the locations of the tidal gauge stations of Christmas and Pohnpei. Box C is used for calculation meridional wind stress off the west coast of Australia.

Christmas is connected to that at the east coast through Kelvin wave propagation in the equatorial waveguide and Pohnpei is connected to the west coast through Rossby wave propagation.

[9] Monthly SSH anomalies are derived from AVISO satellite altimeter data [*Ducet et al.*, 2000]. The product has a spatial resolution of approximately 1/3° and covers the period from late 1992 to present. Upper ocean temperature data from a frequently repeated XBT section (IX1) between Fremantle, Australia and Sunda Strait, Indonesia are used to derive geostrophic transports of the ITF in the upper 400 m (referenced to 400m) during 1984–2003, as by *Meyers* [1996].

[10] Monthly wind stress data from the National Center for Environment Prediction (NCEP) [*Kalnay et al.*, 1996] are used to derive the equatorial Pacific zonal wind stress (5°S–5°N, 140°E–90°W box average) and meridional wind stress off the west coast of Australia (36–19°S, 109–116°E box average). Monthly NOAA-Extended Reconstruction of SST (ERSST) is used to derive SST variability in the Niño3.4 region and off the west coast of Australia [*Smith and Reynolds*, 2004]. For most of the monthly time series, a 61-point (5-year) Hanning filter is applied to remove annual and short term (less than 4 years) interannual variations. In this study, decadal scales generally refer to variations longer than 4 years and less than a decade, whereas multi-decadal trend refers to variations longer than a decade. In the supplementary analysis (Figures S1 and S2), it is shown that decadal signals in the sea level indices do not change notably when using a longer cut-off time scale of 8 years.[1]

3. Multi-decadal and Decadal Variability of the STCs Since Mid-1970s

[11] A number of studies have pointed out the multi-decadal weakening trend of the trade winds and the STCs in the tropical Pacific since the "regime shift" in 1976/77 and prior to the 1990's [e.g., *Giese et al.*, 2002], thus the analysis is separated into two multi-decadal periods, prior to and after 1993. Also there appears to be a rapid transition in the sea level indices around 1993.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL042796.

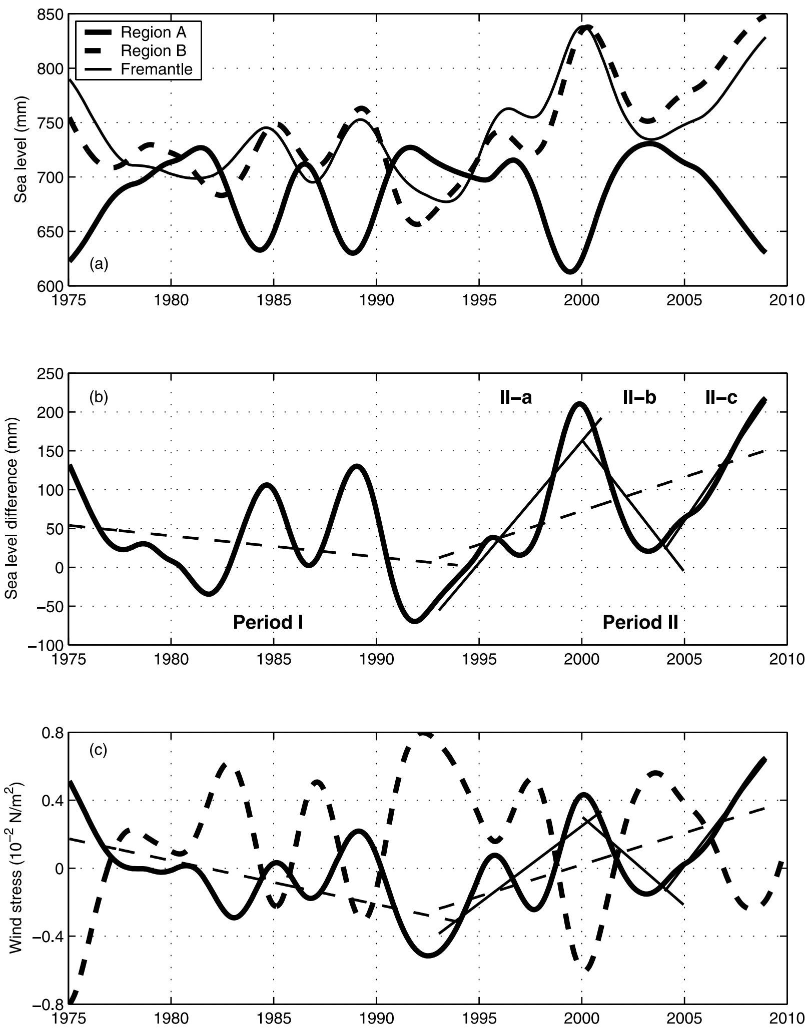

Figure 2. (a) Low-pass filtered time series of sea levels of Christmas, Pohnpei and Fremantle, (b) sea level difference between Pohnpei and Christmas, and (c) westward wind stress and Niño 3.4 SST (dashed curve) anomalies along the equatorial Pacific. Straight lines denote linear trends listed in Table 1.

3.1. Multi-Decadal Trends

[12] Between the mid-1970's and 1993 (which we designate as Period I), there is a rising trend of sea level at Christmas and a declining trend of sea level at Pohnpei (Figure 2a and Table 1). The sea level difference between the western and eastern Pacific has a trend of −2.7 mm/year during 1975–1993 (Figure 2b). This trend implies a waning equatorward geostrophic transport in the lower branch of the STCs, consistent with the multi-decadal weakening trend of the STCs.

[13] Between 1993 and 2008 (designated as Period II), the multi-decadal trends in sea levels reverse: there is an overall rise in sea level of 7.7 mm/year at Pohnpei and a decline at Christmas of −1.0 mm/year (Figure 2a and Table 1), implying a strengthening trend of the STCs. The linear trends of tidal gauge sea levels in these two regions during 1993–2008 are consistent with the sea level trends derived from satellite altimetry data (in the two tropical boxes in Figure 1a), in which the western Pacific is a hot spot of sea level rise in the world oceans during this period.

Table 1. Linear Trends of Sea Level and Wind Stress[a]

	Period I (1975–1993)	Period II (1993–2008)	Period II-a (1993–2000)	Period II-b (2000–2004)	Period II-c (2004–2008)
Pohnpei (B) (mm/year)	−1.5 (0.3)	7.7 (0.3)	19.3 (0.7)	−17.2 (1.8)	18.7 (0.3)
Christmas (A) (mm/year)	1.2 (0.3)	−1.0 (0.4)	−12.0 (0.9)	16.8 (2.1)	−20.1 (0.5)
B-A (mm/year)	−2.7 (0.2)	8.7 (0.3)	31.3 (0.6)	−34.0 (1.4)	38.8 (0.3)
Fremantle (mm/year)	−1.9 (0.3)	4.3 (0.5)	21.2 (0.6)	−21.8 (1.8)	19.0 (0.6)
Westward wind stress along equatorial Pacific (10^{-4} N m^{-2}/year)	−2.6 (0.2)	3.7 (0.3)	9.1 (0.5)	−10.5 (1.3)	15.6 (2.9)
Northward wind stress off the west coast of Australia (10^{-4} N m^{-2}/year)	2.9 (0.2)	−3.1 (0.3)	−7.1 (0.6)	−2.0 (0.6)	1.6 (0.6)

[a]The numbers in the parentheses are standard errors of the linear trends calculated from a bootstrap method.

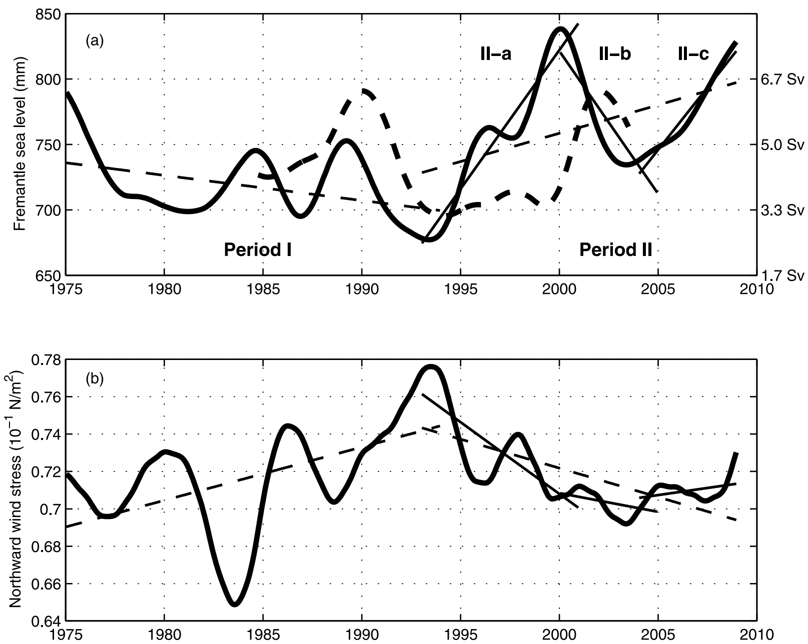

Figure 3. Low-pass filtered (a) Fremantle sea level and upper ocean geostrophic transport of the ITF (dashed line) and (b) northward wind stress off the west coast of Australia. Straight lines denote linear trends listed in Table 1.

[14] Multi-decadal variations in sea level difference between the western and eastern Pacific are associated with trends in westward wind stress along the equatorial Pacific of -2.6×10^{-4} N m^{-2} per year during Period I and 3.7×10^{-4} N m^{-2} per year during Period II (Figure 2c and Table 1) These trends indicate an evolving, coupled dynamic balance between wind stress and zonal pressure gradient in the upper ocean. Multi-decadal weakening (strengthening) of the trade winds and the STCs during Period I (II) are also coupled with a warming (cooling) trend of Niño 3.4 SST, if a global sea surface temperature trend over the same period was removed (Figure 2c).

3.2. Decadal Variability

[15] Decadal variability of tidal gauge sea level at Christmas is almost a mirror image of that at Pohnpei, and the correlation between the two time series is −0.73, with Christmas leading Pohnpei by about two seasons (Figure 2a). During period I, decadal sea level variations in the Pacific have amplitudes less than 100 mm, with high (low) sea levels in the western (eastern) Pacific in mid-1970's and mid-1980's and then again in the late 1980's (Figure 2a), indicating periods with strong STCs (Figure 2b).

[16] Decadal variability during Period II is characterized with lower frequency and larger amplitude (greater than 100 mm) sea level variations, compared with Period I (Figure 2a). The sea level at Pohnpei increases steadily between 1993 and 2000, followed by a sharp decrease between 2000 and 2004. However, beginning in 2004, sea level in the west Pacific starts to rise again, reaching the 2000 level in 2008. Decadal sea level variability in the eastern Pacific is opposite to that at Pohnpei.

[17] Decadal trends in sea level difference between Pohnpei and Christmas during 1993–2000 (designated Period II-a) and 2000–2004 (designated Period II-b) are similar to those given by *Lee and McPhaden* [2008] (Table 1). The more recent sea level records from both altimeter (not shown) and tidal gauge data indicate a linear trend in sea level difference of 38.8 mm/year during 2004–2008 (Period II-c), which has resulted in the overall strengthening trend of the STCs during 1993–2008.

[18] Linear correlations show that about 80% of the decadal variance in sea level differences between western and eastern Pacific can be explained by the equatorial zonal winds. This is consistent with the Sverdrup balance on the equator, namely the balance between depth integrated pressure gradient and zonal wind stress [*Yu and McPhaden*, 1999]. There is also a close connection between decadal variability of the zonal wind stress and the Niño 3.4 SST (Figure 2c) through Bjerknes feedback in which stronger

Table 2. Linear Correlations and Regressions Between Fremantle Sea Level (mm) and Other Variables on Decadal Time Scales[a]

	Alongshore Wind Stress	Equatorial Pacific Wind Stress (mm/(10^{-4} N/m^2))	Pohnpei (mm/mm)	Christmas (mm/mm)	Southern Oscillation Index (mm)
Correlation	0.46*	−0.84++	0.84++	−0.78++	0.90++
Regression	-	−1.3 (0.04)	0.77 (0.02)	−0.75 (0.05)	7.6 (0.29)

[a]The units are for the linear regression coefficients. The correlation denoted with * is less than 95% significant and correlations denoted with ++ are significant above 99% level. The numbers in the parentheses are standard errors of the linear regression coefficients.

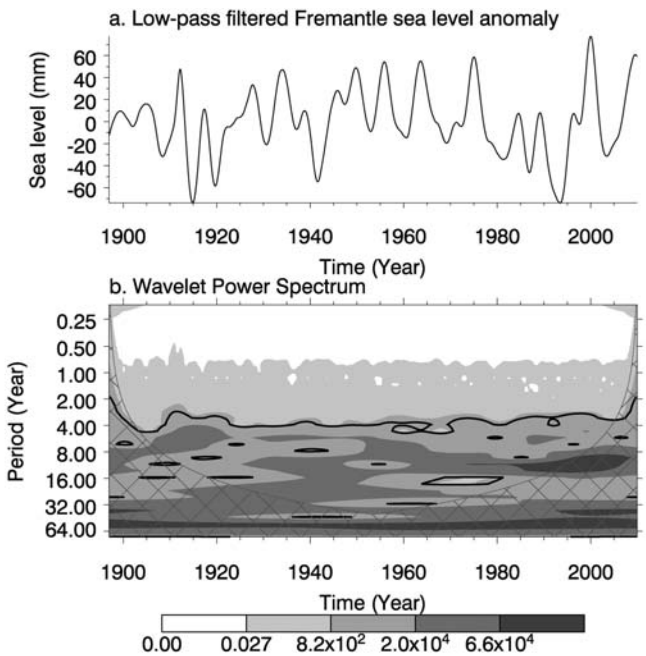

Figure 4. (a) Low-pass filtered Fremantle sea level anomaly, after removing a linear trend of 1.54 mm/year, and (b) the wavelet power spectrum. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 10% significance level, using a white-noise background spectrum.

trade winds are coupled with cooler Niño 3.4 SST and *vice versa*. As evidence of this feedback, we find a linear correlation of 0.93 between these two parameters.

4. Multi-decadal and Decadal Variations of Fremantle Sea Level and the ITF

[19] The dominance of the remote forcing on multi-decadal time scale is supported by the fact that the multi-decadal trends of Fremantle sea level during periods I and II are similar in magnitude and phase compared to those at Pohnpei (Table 1 and Figure 2a). In addition, the rising trend of Fremantle sea level during period II is also similar to the satellite SSH trends in the western Pacific and SEIO (Figure 1a). The weak trends of local alongshore winds only play a minor role (Figure 3b).

[20] On decadal time scales, Fremantle sea level follows variability in the Pacific closely (Figure 2a and Table 2). Linear regression shows that Fremantle sea level rises (falls) 1.3 mm for every 10^{-4} Nm^{-2} increase (reduction) of the trade winds in the equatorial Pacific (Table 2). The ratio of Fremantle sea level rise and fall with sea level is 0.77 in the western Pacific and −0.75 in the eastern Pacific. From linear regression analysis, variability in equatorial winds in the Pacific explains about 70% of the decadal variance of Fremantle sea level, while local meridional winds off the coast, in contrast, only explain about 20% (Figure 3 and Table 2). Thus, on decadal time scales, remote signals from Pacific dominate the variability of Fremantle sea level (the LC). The correlation between local winds off the west coast of Australia and Pacific trade winds is also low (0.37) on decadal time scales, as supported by *Lee and McPhaden* [2008].

[21] The shorter record of ITF volume transport shows decadal variability similar to that of Fremantle sea level, though there tends to be a 1–2 year phase lag in their peaks (Figure 3a), which is likely related to climate variability in the Indian Ocean.

5. Fremantle Sea Level Variations Since 1897

[22] Long term changes of the decadal variability of the LC may be inferred from the Fremantle sea level record dated from 1897, after removing a linear trend of 1.54 mm/year [*Feng et al.*, 2004]. The high correlations with the tropical Pacific indices (Table 2) suggest that decadal variability in Fremantle sea level can be used as an index of decadal variability in the Pacific STCs. If so, then the declining trend in the STCs prior to 1993 started in the 1960's (Figure 4a), and there was a slow rising tendency of the STCs before 1960s. The record also captures the Pacific regime shifts in the 1920's and 1940's [e.g., *Minobe*, 2000].

[23] Over the past century, there is a trend of increasing energy in decadal variability of the LC and presumably the STCs, especially after mid-1980's (Figure 4b), as derived from a wavelet analysis [*Torrence and Compo*, 1998].

6. Summary and Discussion

[24] 1. A multi-decadal strengthening trend of the Pacific STCs since early the 1990's, which is coupled with a strengthening trend of the trade winds and a cooling trend of Niño 3.4 SST, reversed the multi-decadal weakening trend of the STCs prior to the early 1990's.

[25] 2. Decadal variations of the STCs are also coupled with variability of trade winds and Niño 3.4 SST, and there seems to be a strengthening in the amplitude of decadal variability towards the end of the 20th century.

[26] 3. Decadal variations of the ITF and the LC are coherent with variations in the STCs due to oceanic teleconnections transmitted along equatorial and coastal waveguides.

[27] The reversal of multi-decadal trend since the early 1990's and the enhancement of decadal variability toward the end of the 20th century may limit our ability to attribute the secular trends in the STCs and the LC derived from instrumental data to human induced global warming. It appears that neither the trends prior to the early 1990's nor those after the early 1990's can be fully attributed to greenhouse gas forcing. Thus, one should use caution when interpreting trends in the STCs and the mean state of the tropical Pacific [e.g., *Vecchi et al.*, 2008].

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