

An Examination of the Link between Decadal Changes in Precipitation, Winds, and Sea Surface Heights in the Tropical Indo-Pacific during the Period 1993-2010

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Abstract

Climate change has contributed to global sea level rise. However, *in situ* measurements and satellite observations indicate that this increase is not uniform over the tropical Indo-Pacific basin. Furthermore, satellite altimetry data documented large-scale decadal variations in sea level over much of the tropical Indo-Pacific basin, such that sea level trends underwent a decadal change around 1999/2000. Large-scale reversals in sea level trends are associated with fluctuations in the Indo-Pacific branch of the Walker cell. This research examined the nature of decadal sea level change over the tropical Indo-Pacific basin and how these changes relate to low frequency variations in the strength of the Walker circulation. Understanding the causes of decadal sea level variability will aid in adaptation. The relationship between the decadal changes of sea surface heights and zonal wind stress was investigated for 1993-1999 and for 2000-2010 in three regions showing distinct decadal phase reversals near 1999/2000. Changes in the large-

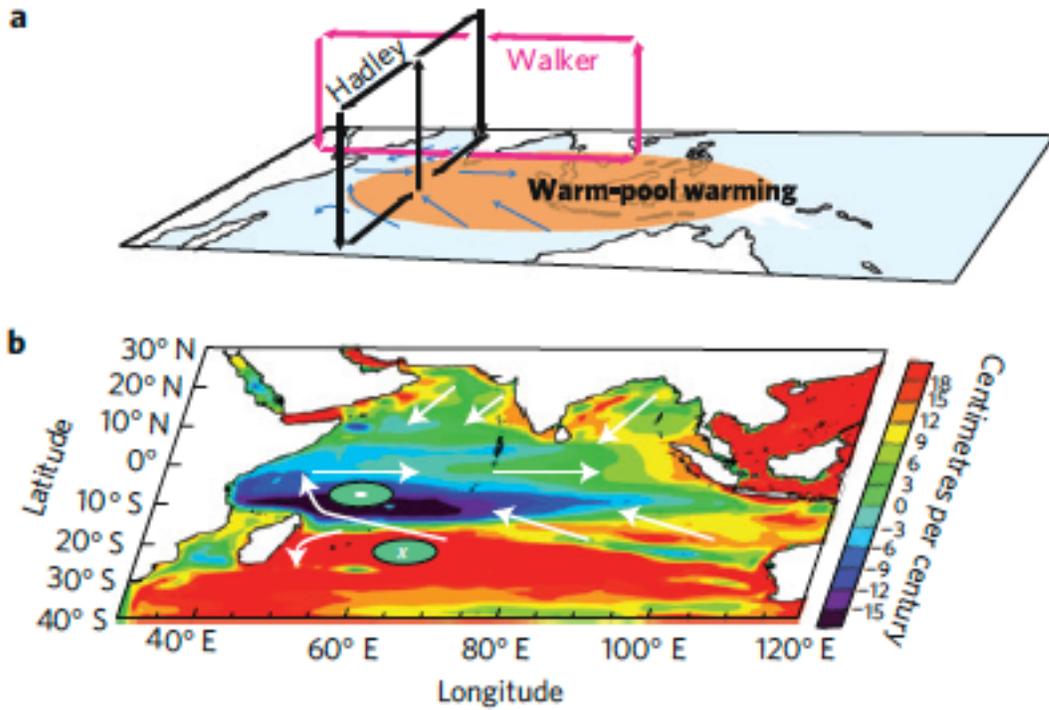
scale circulation associated with the Walker circulation were inferred from decadal changes in the precipitation over the Indo-Pacific warm pool and changes in the zonal winds in both the tropical Pacific and Indian Oceans. To isolate the decadal variability in the three variables, five year centralized running means were used. The results showed a decadal change in the strength of the Walker circulation and a strong correlation to winds and sea levels in the tropical Indian and western Pacific. Variability in the western Pacific and Indian Ocean appeared to be strongly influenced by ENSO.

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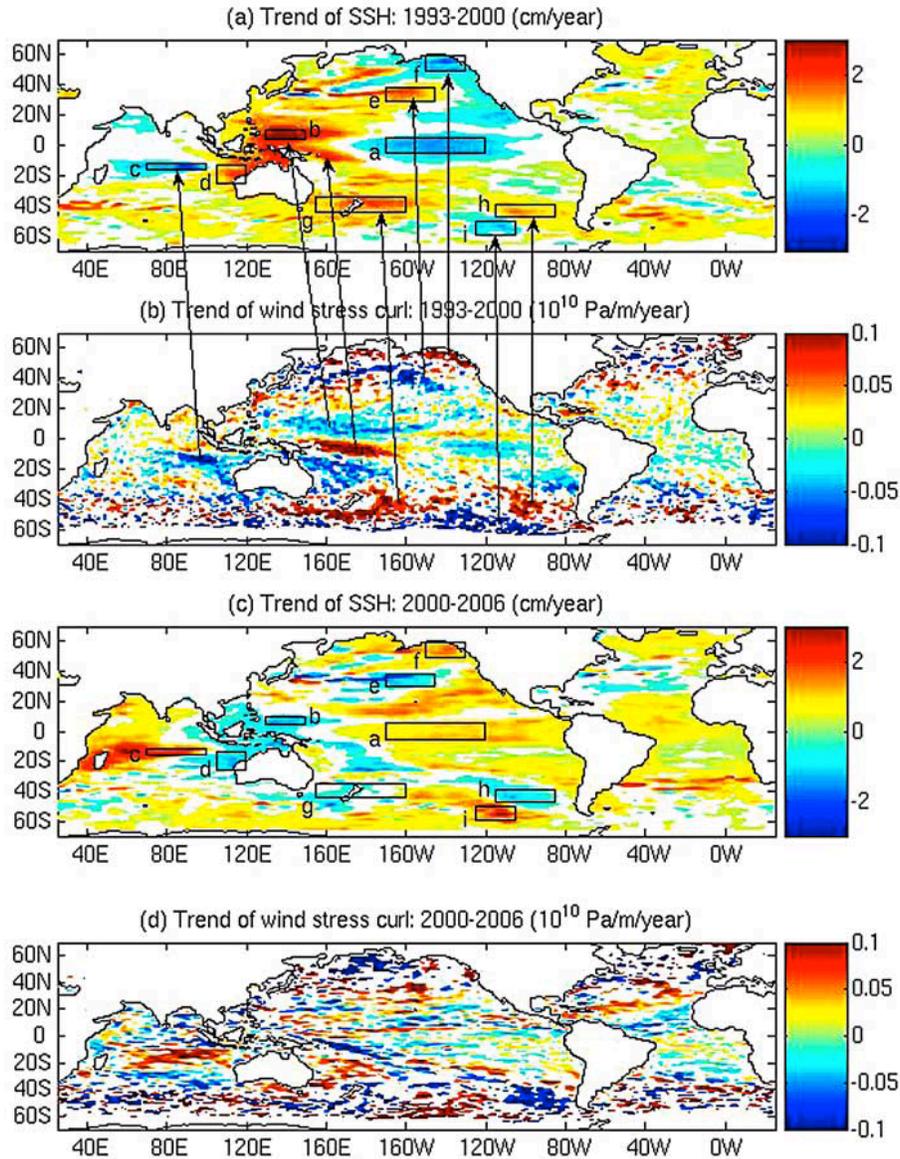
## **1. Background**

As the glaciers around the globe continue to melt, rising sea levels put hundreds of millions of people and trillions of dollars of infrastructure into jeopardy. This is no less true for the millions of people that live in or around the tropical Indo-Pacific basin, where entire island nations are in danger of being submerged. Satellite measurements of sea surface height (SSH) show that the increase isn't uniform across the basin. Available data and Ocean General Circulation Model (OGCM) solutions have found a decreasing trend in the southwest Tropical Indian Ocean since the 1960s and the reverse for the Far East Indian (Fig. 1; Han et al. 2010).

This is primarily due to the changes of the Indo-Pacific section of the Walker circulation, which has climatology characterized by surface westerlies over the tropical Indian Ocean and equatorial easterlies over the Pacific. Where these surface winds interact with the sea surface, the upper ocean water may diverge or converge and thus change sea level and sea surface temperature, through mass redistribution and changes in oceanic upwelling. Climatologically, convergence of the two surface branches of the Indo-Pacific Walker circulation over the Indonesian archipelago region leads to convergence of the sea waters and thus sea level rise. This zone of convergence in the atmospheric circulation is associated with the convection center of the Walker circulation, which is positioned over the warm pool, from where it derives its strength (Han et al. 2010). As the temperature of this pool fluctuates, so could the local sea level pressures and atmospheric stability, which in turn would cause the convection and precipitation of the region to vary. Furthermore, changes in the strength and location of the warm-pool precipitation will likely affect the large scale tropical circulation through the control it places on the surface branches of the flow. Dynamically, tropical sea level variations are forced by the wind stress. As such, changes in the winds will lead to changes in the regional distribution of sea level.



**Fig. 1.a:** Illustration showing how the warming of the warm pool situated in the west pacific and far eastern Indian oceans causes the regional winds associated with the Walker Circulation to strengthen. The wind magnitudes are shown with arrows. Fig. 1b is a color coded representation of the response of SSH in the Indian Ocean reacting to the variations in the Ekman pumping velocity (positive-circle with dot; negative –circle with x). Image taken from Han et al. (2010).



**Fig. 2:** Satellite derived trends for SSH (a) and wind stress curl (b) for 1993 to 2000. (C) and (d) are the same as in (a) and (b) but for 2000 to 2006. Values not significantly different from zero at 95% (67%) confidence level for SSH (wind stress curl) are masked out. Image taken from Lee and McPhaden 2008.

In addition to the multi-decadal trend, there is also decadal variability in the SSH, and wind stress. Satellite derived SSH trends taken from Topex/Posidon and Jason-1 altimeters for periods

1993-2000 and 2000-2006 show that the regions of enhanced decadal variability sea level (Fig. 2a and 2c) occur in similar regions as the multi-decadal trends (Fig. 1b). Decadal variability of the tropical Indo-Pacific sea level appears to be related to large scale changes in the tropical atmospheric circulation, note the reversal of wind stress curl for 1993-2000 (Fig. 2b) and 2000-2006 (Fig. 2d). Also, when comparing sea level and wind stress trends for the period 1993-2000 (Fig. 2a and 2b) with trends from the period 2000-2006 (Fig. 2c and 2d), there is a phase change in the trends of the tropical sea level and wind stress around the turn of the century.

It is the goal of this investigation to better understand the nature of the decadal variations in the surface wind and precipitation fields associated with the sea level phase reversal that occurred near 1999/2000 in the Tropical Indo-Pacific basin. The results will aid in identifying the ocean-atmosphere coupled signatures associated with the decadal change. The understanding of the causes of low frequency sea level variability may lead to the formation of better decadal predictions of spatial structure of sea level change. In turn, these results can be used to minimize the social impacts and allow for greater adaptation for the millions of people who live in and around the tropical Indo-Pacific.

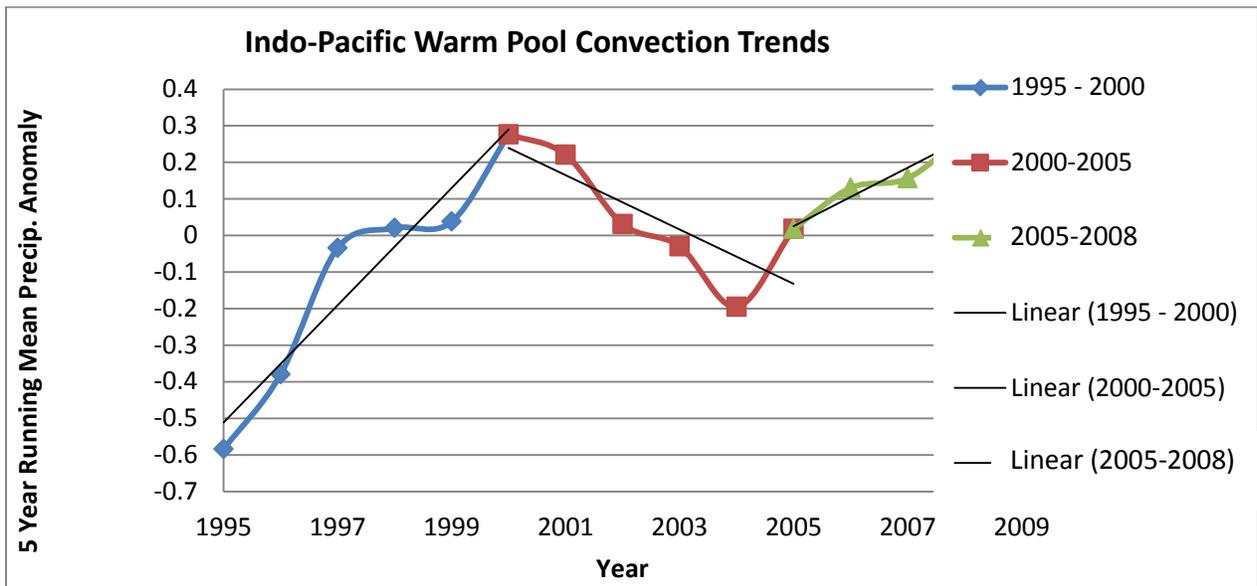
## **2. Methods**

To better understand the decadal change, this paper will analyze the relationship between the anomalous central five year running mean SSH, wind stress and precipitation for the period of 1993-2010, a period when satellite altimeter data, satellite wind and precipitation data are all available. This research will also compare the 1995-2000, 2000-2005, and 2005-2008 trends for these three variables. The SSH will be analyzed over the regions where the sea level variations

are the strongest. These areas are shown by Lee and McPhaden (2008). Specially, we choose 3 regions to examine SSH variability: in the Indian Ocean (12S-17S, 60E-100E) and two regions in the Pacific Ocean: (2N-10N, 130E-150E) and (5S-5N, 160W-120W). The examination of the surface zonal wind stress will be the three main regions where they drive the sea level change. The areas are also shown by Lee and McPhaden (2008) and defined here as: in the Indian Ocean (15S-5S, 80E-110E), in the Western Pacific basin (5S-5N, 160E-160W) and in the central Pacific basin (5S-5N, 140W-100W). Between 1993 and 2000 enhanced easterly trade winds (Fig. 3 of Lee and McPhaden 2008) in the equatorial Pacific increase sea level in the western tropical Pacific and reduce sea level in the central Pacific and Indian basins; enhanced westerlies and their associated wind stress curl in the tropical eastern Indian Ocean increase sea level near Sumatra and reduce sea level in the south tropical Indian Ocean. After 2000, the surface zonal winds relax, causing reversed wind anomalies and allowing for the signs of SSH trends to reverse. Since the strength of the surface winds is associated with the strength of the Walker circulation, this paper will analyze the precipitation in the region of the warm pool defined as (10S-10N, 80E-140E).

### 3. Data and results

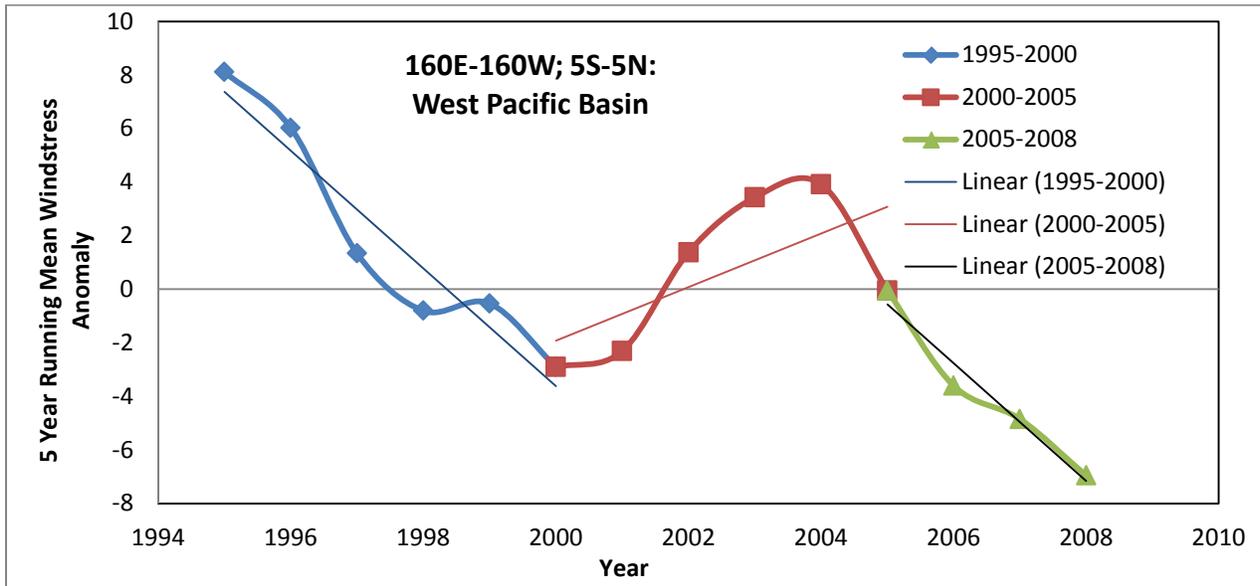
Observations of warm-pool convection manifesting in the form of precipitation show distinct decadal variations in precipitation rates for the examined period. From 1995-2000 the precipitation rate steadily rose. (Fig 3). This period of rise was followed by a reduction period that lasted from 2000-2005. Around 2005 the trend changed again so that the precipitation rates increased from 2005 to 2008 (Fig. 3).



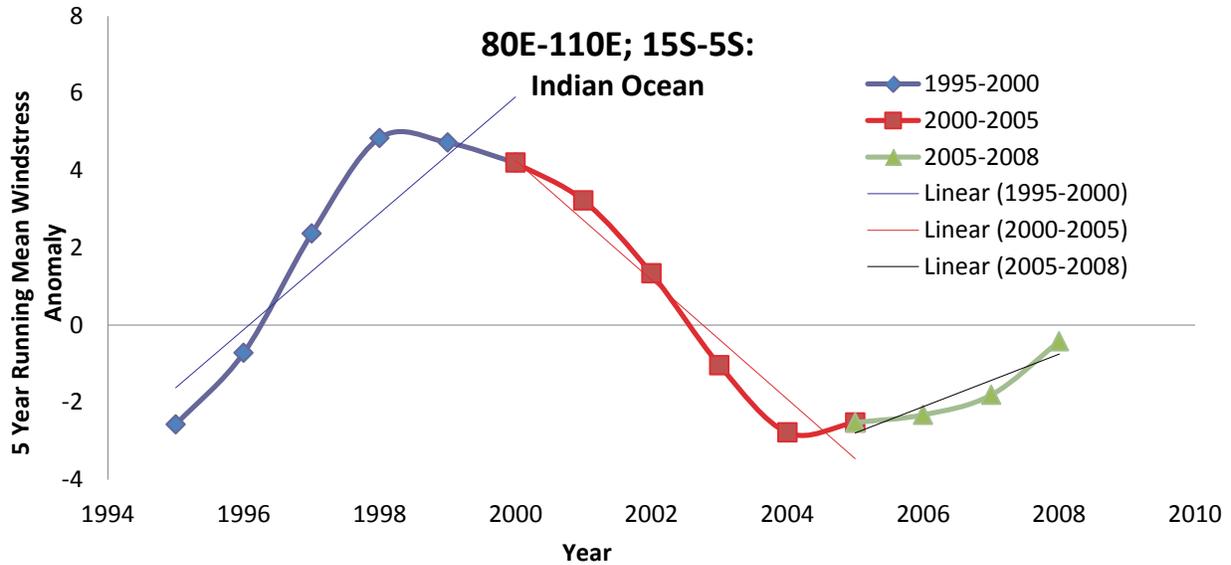
**Fig. 3:** The 5-year running mean precipitation anomaly averaged over the Indo-Pacific warm pool for the 1993-2010 period, together with the linear trends for the 1995-2000, 2000-2005, and 2005-2008 periods.

Observations show variations in precipitation trends for the periods 1995-2000, 2000-2005, and 2005-2008. These changes are associated with changes in the ascending branch of the Walker circulation. By continuity, the tropical zonal winds over the Indian and Pacific Oceans are expected to change simultaneously with the variations in the ascending branch of the Walker Cell.

During the periods 1995-2000 and 2005-2008 the tropical easterlies in the tropical western Pacific is enhanced (fig 4). For the period between these two, 2000-2005 there is a decreasing trend in the trades (fig 4). Conversely the easterly trades in the Indian Ocean shows decadal variation that also occurred in 2000 and 2005, but throughout the 1995-2008 periods the trends remain out of phase. This translates into decreased (enhanced) easterlies for 1995-2000 (2000-2005) and weakened again from 2005-2008 (fig 5).



**Fig. 4:** The 5-year running mean wind stress anomaly averaged over the tropical western Pacific for the 1993-2010 period, together with the linear trends for the 1995-2000, 2000-2005, and 2005-2008 periods.



**Fig. 5:** The 5-year running mean wind stress anomaly averaged over the tropical Indian Ocean for the 1993-2010 period, together with the linear trends for the 1995-2000, 2000-2005, 2005-2008 periods.

With the variations in precipitation rates and in the easterlies of both basins being consistent with each other, it appears that there are decadal variations in the Walker Cell during 2000 and 2005. Since wind is one of the primary drivers in SSH change, it is expected to see SSH to react to the decadal change in the easterlies.

During 1995 to 2000 the easterlies of decreased (enhanced) in the Tropical Indian ocean (tropical western Pacific). Conversely the sea levels fall (rise) in the Tropical Indian Ocean (tropical western Pacific) during this period (fig. 6 fig. 7). As the easterlies' trends reverse for the period 2000-2005 so do the SSH trends. Between 2005 2008, the trades are reduced (enhanced) in the tropical Indian Ocean (tropical western Pacific), causing the SSH in the tropical Indian Ocean to fall and to rise in the tropical western Pacific (fig 6 and fig 7).

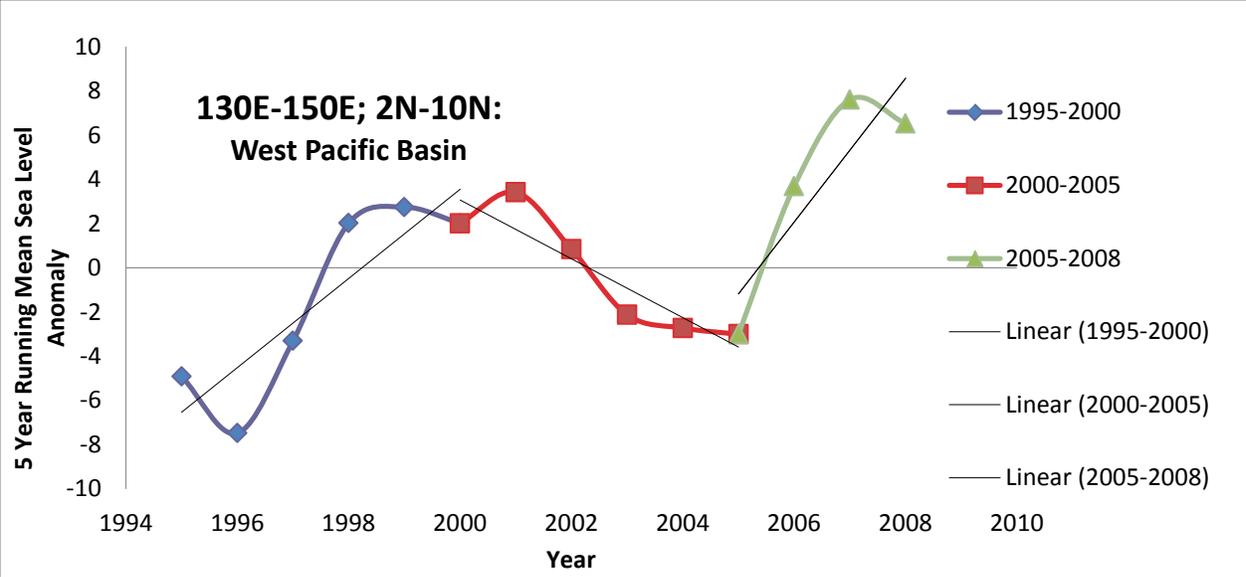
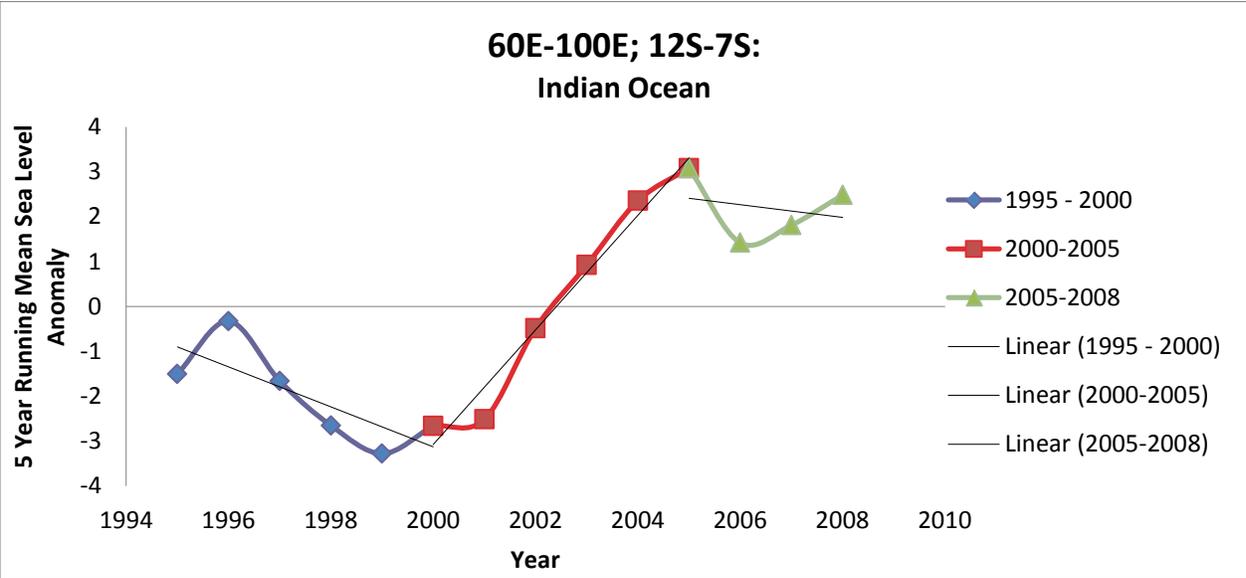


Fig. 6: The 5-year running mean sea level anomaly averaged over the tropical western Pacific for the 1993-2010 period, together with the linear trends for the 1995-2000 2000-2005 and 2005-2008 periods.



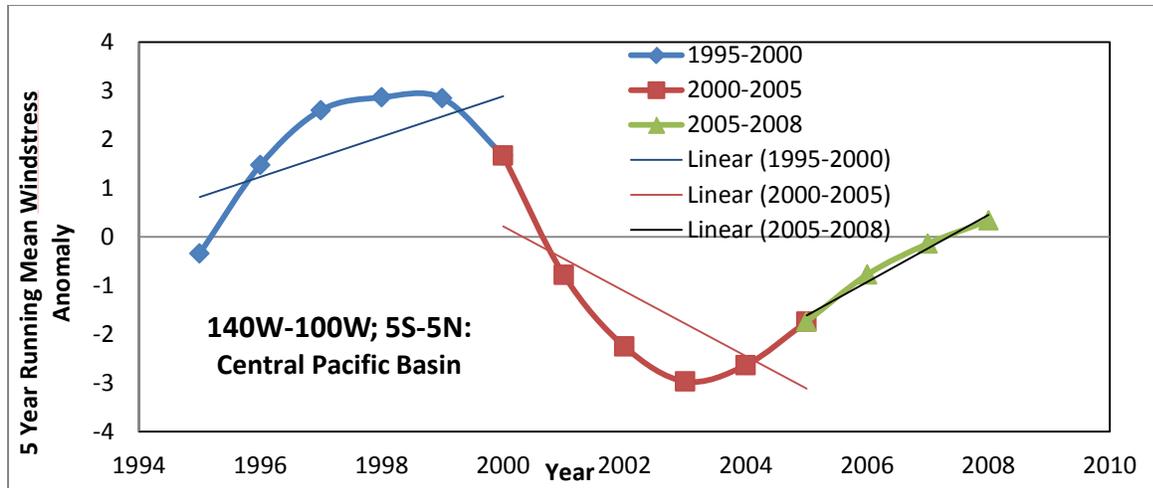
**Fig. 7:** The 5-year running mean sea level anomaly averaged over the tropical Indian Ocean for the 1993-2010 period, together with the linear trends for the 1995-2000, 2000-2005, 2005-2008 periods.

While there are direct correlations between the precipitations, wind stress, and SSH in the Tropical Indian Ocean and in the tropical western Pacific, the correlations between the 3 variables are very poor to negligible in the tropical central Pacific (fig 8).

	5 year running mean
Indian SH vs. Winds	-0.837
Indian winds vs. Precipitation	0.4067
West Pacific SSH vs. Winds	-0.906
West Pacific Winds vs. Precipitation	-0.926
Central Pacific SSH vs. Winds	-0.473
Central Pacific Winds vs. Precipitation	0.075

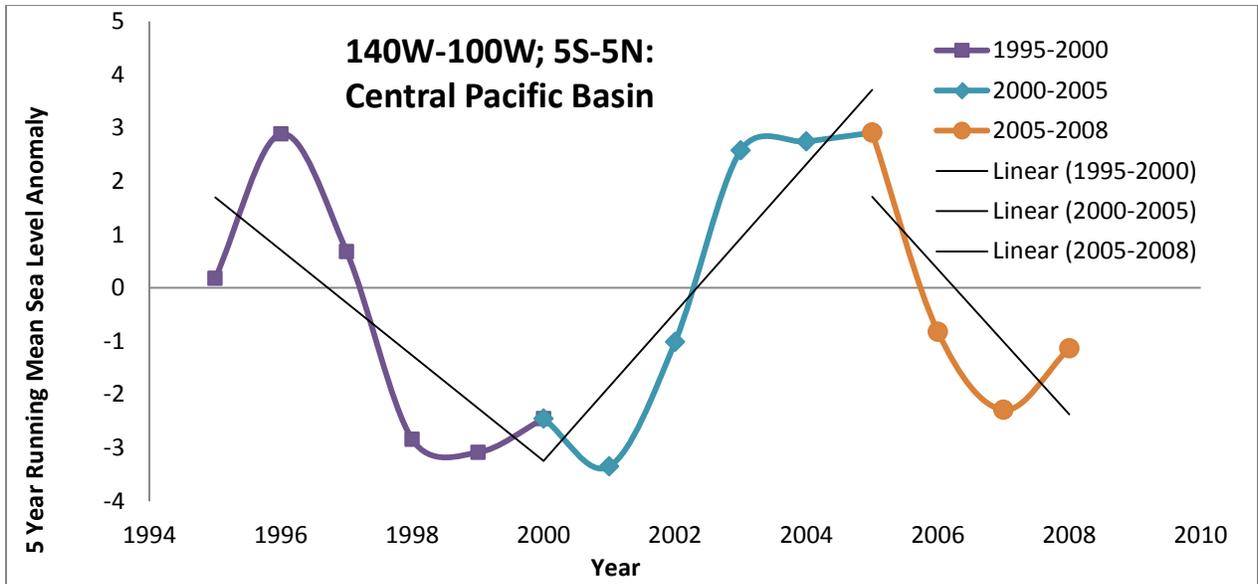
Fig. 8 table of five year running mean correlation between SSH, wind stress and precipitation.

While the trends show a decrease in easterlies for the periods of 1995-2000 and 2005-2008 and enhanced easterlies from 2000-2005, very little can be inferred from them, because the amplitude of the five year running mean is far greater than the trends (fig. 9). It is suspected that this could be due to decadal variation in ENSO, considering how there are spikes in the averages during the 1997-1998 and 2004-2006 ENSO events. However the N34 shows a low correlation between the winds and ENSO.



**Fig. 9** The 5-year running mean wind stress anomaly averaged over the tropical Central Pacific for the 1993-2010 periods, together with the linear trends for the 1995-2000 2000-2005 and 2005-2008 periods.

Unlike the SSH trends being directly correlated to the wind stress in the tropical Indian Ocean and tropical western Pacific basins, the SSH trends in the tropical central Pacific are not. It should be noted however that there trends are in phase with the SSH in the Tropical Indian Ocean. This equates to decreasing sea levels in 1995-2000 and 2005-2008, and rising sea levels in 2000-2005 (fig 10).



**Fig. 10** the 5-year running mean sea level anomaly averaged over the tropical central Pacific for the 1993-2010 periods, together with the linear trends for the 1995-2000 and 2000-2005 periods.

#### 4. Summary

As discussed in Fig.1, climatologically there are westerlies along the equator in the Indian and easterlies in the Pacific. They make up the two surface branches of the Walker Circulation. The confluence of the two branches over the Indo-Pacific warm pool forms the ascending branch which can be observed through convection. Variations in the strength of the Walker Circulation can be detected by positively correlated anomalies through the three branches. Centralized five year running mean trends of the precipitation (Fig. 3) detects enhanced precipitation from 1995 to 2000 and decreased precipitation from 2000 to 2005. This trend is then reversed for 2005-2008. These trends are in phase with the tropical western Pacific trades (Fig. 4). The trade winds in the Indian Ocean are out of phase with the trends in the western Pacific. Satellites have

detected decreased easterlies (Fig. 5) for 1995-2000 and 2005-2008, and enhanced easterlies for 2000-2005. With all three branches in phase, the data illustrates that there is a decadal change in the Walker circulation near 2000 and 2005.

The effects of the decadal change likewise show up in the SSH trends in the south tropical Indian and the tropical Western Pacific. Responding to the decadal variations of the wind stress in the Western Pacific enhanced easterlies from 1995-2000 and 2005-2008 and weakened easterlies from 2000-2005; sea levels (Fig. 6) in the western tropical Pacific are high for the periods of 1995-2000 and 2005-2008, while low for 2000-2005. In contrast, just like the easterlies over the Indian Ocean are out of phase with the trades in the western Pacific, the SSH trends in the tropical southern Indian basin and in the tropical western Pacific are the same. With the reduction of the easterly trades in the tropical south Indian Ocean from 1995-2000 and 2005-2008, which corresponds to negative wind stress curl (see Fig. 2 above) and positive Ekman pumping velocity, the sea level falls (Fig 7). In contrast, wind stress curl is positive and Ekman pumping velocity is negative from 2000-2005, causing sea level rise (Fig. 7).

Since the precipitation is strongly correlated (fig. 8) to the wind stress in the western Pacific and tropical Indian basins, which are in turn strongly correlated to the SSH in the respected basins, the decadal variations in both seas are linked to the Walker circulation. However, the tropical central Pacific Ocean does not seem to be strongly correlated to the Walker Circulation. There is a low correlation (0.075) between the precipitation the Indo-Pacific warm pool and the wind stress in the central Pacific and a low correlation (-0.473) between the wind stress and the SSH in the same region (fig 8). The easterlies in this basin are weaker (enhanced) and the sea levels are lower (higher) during 1995-2000 (2000-2005) (Fig. 9 and Fig. 10). During the 2005-2008 period the trends reverse so that the winds become weaker and the SSH become lower.

Due to the low correlation that the three variables have between them, and the way that the internal variability dominates the trends, it is suspected that there are other factors at play. The changes in the equatorial winds in the Indian Ocean and those in the tropical Pacific show a large correlation with the NINO3.4 index ( $r^2 \sim 0.6$ ), indicated that nearly 60% of the variance in the winds in these two locations is associated with ENSO. It is unclear from this study, if the apparent variations in ENSO reflect variations in the periodicity of ENSO, or modulations of ENSO. The nature of decadal variability within the tropical ocean-atmosphere system is currently an area that the scientific community is trying grapple with, and is complicated by presence of non-linearity in the system and teleconnections from the tropics. Due to the complexity of this problem and limitations in time, these aspects of this study will not be explored.

## **6. Acknowledgments :**

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