# A shift in Pacific sea level trends

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**Abstract**

Pacific sea level trends during the period of high-accuracy satellite altimetry (1993-2009) are examined in the context of longer tide gauge records. The dominant trend patterns include high rates in the western tropical Pacific and minimal to negative rates in the eastern Pacific, particularly along the North American continent. Interannual sea level variations associated with El Niño Southern Oscillation events do not account for these trends. Tide gauge records indicate that the recent high rates in the western tropical Pacific represent a significant increase in trend relative to the period 1950-1990. The trend change in western tropical Pacific sea level rise agrees with ECMWF wind stress products that show an increase in the strength of the trade winds averaged across the Pacific. The recent negative sea level trends at the eastern boundary of the Pacific are linked to changes in trades along the equatorial wave guide, which also have strengthened since the early 1990s but vary on decadal time scales more than the off-equatorial trade winds. It is speculated that the enhancement of the trades winds and the changes in Pacific sea level are associated with a strengthening of the atmospheric vertical overturning circulation.

# 1 Introduction

Since 1993, global mean sea level has risen at a rate of 3.1 $\pm$ 0.4 mm yr$^{-1}$ based on satellite altimeter observations (*Nerem et al.*, 2006). Departures from the global mean are substantial on regional scales (Figure 1), the standard deviation is about 2.8 mm yr$^{-1}$, presumably due in large part to wind-forced ocean-volume redistribution. Notable spatial variations in the Pacific sea level trend include high positive rates ($\sim$10 mm yr$^{-1}$) in the western tropical Pacific (WTP), and zero and negative rates in the eastern tropical Pacific (ETP) and northeast Pacific (NEP). In this study, we consider variations in wind forcing that have accompanied the recent sea level changes in the Pacific, and we examine tide gauge datasets to provide a broader temporal context for the current sea level trend patterns.

Unusually high rates of sea level rise in the WTP typically have been attributed to interannual to decadal variations in sea level, which dominate short-term sea level trend estimates. For example, *Church et al.* (2006) combined tide gauge and altimeter data to produce a reconstruction of sea level variability in the tropical and sub-tropical Indo-Pacific for 1950 to 2001. From 1993-2001, the reconstruction indicated high rates of sea level rise in the western Pacific, similar to Figure 1. The authors concluded that the pattern reflects a shift from weak El Niño conditions early in the record to more La Niña like conditions in 2001. Sea level trends computed from 1950-2001 based on the reconstructed fields do not show unusually high trends in the WTP, with rates close to the global average of $< 2$ mm yr$^{-1}$.

Decadal variations in WTP sea levels were described by *Lee and McPhaden* (2008) for the period 1993-2006. Trade winds in the central equatorial Pacific increased from 1993-2000, leading to high water in the WTP and low levels in the ETP. The pattern reversed as winds diminished from 2000-2005. These observations suggest that the high levels in the WTP during 1993-2000 represent a temporary increase due to decadal wind fluctuations; however, we will show below with subsequent data that the WTP trend has persisted beyond the 2000-2005 reversal, largely due to trends in winds outside the equatorial band.

*Cheng et al.* (2008) examined the high trends in the WTP and surrounding regions in terms of changes in subsurface water properties using the gridded temperature and salinity dataset of Ishii et al. (2006). They found that ocean temperature increases, primarily in the upper 300m, account for much of the rise rate in a sub-region of the WTP from 1993-2005. Although the cause of the increase was not considered, a wind-forced deepening of the thermocline appears likely.

Using a wind-forced, reduced gravity model, *Timmermann et al.* (2010) showed that the high rates of sea level rise in the WTP since 1993 are due to tropical wind forcing. The model also accounts for the longer period of lower sea level rise rates in the region from 1958-2001. They contend that the 1993-2008 sea level trend in the WTP is due in part to the sequence of recent El Niño Southern Oscillation (ENSO) events, particularly the large 1997/98 El Niño that occurred early in the record. *Timmermann et al.* (2010) explored future scenarios of tropical Pacific sea level rise using wind predictions from an ensemble of coupled general circulation models and note the importance of an intensification of the southeast trades in dictating future regional sea level patterns.

*Li and Clarke* (1994) established a linear relationship between Kelvin wave sea level heights and interannual zonal wind stress fluctuations integrated across the equatorial Pacific. Based on this relationship, *Clarke and Lebedev* (1996) considered decadal and longer time scale fluctuations in the equatorial zonal winds using a proxy based on surface pressure differences. Changes on these time scales affect sea level along the eastern boundary of the Pacific basin, such that an increase in trade wind strength leads to a drop in sea level.

In this study we use sea level records from altimetry and tide gauges and ECMWF (European Centre for Medium-Range Weather Forecasts) wind stress (section 2) to show that the pattern of sea level rise in the tropical Pacific is not a manifestation of interannual ENSO events (section 3). Tide gauges indicate that sea level trends in the WTP have increased since the early 1990s compared to the previous 40 years. Sea level trends along the NEP boundary exhibit stronger decadal sea level fluctuations than observed in the WTP (section 4). Enhanced Pacific trade winds since the early 1990s are linked to the high sea level rates in the west and the low rates in the east (section 5). We conclude that the large-scale wind changes and the associated sea level patterns reflect an enhancement of the atmospheric overturning circulation over the Pacific Ocean since the early 1990s (section 6).

# 2 Data

Time series of monthly-averaged sea level from tide gauge stations were provided by the Permanent Service for Mean Sea Level (*Woodworth and Player*, 2003). When possible, these records were extended forward in time using Fast Delivery data from the University of Hawaii Sea Level Center. Inverse barometer adjustments to the sea level time series were not made, as the correction is small at low latitudes and it does not account for the signals of interest.

The ECMWF operational ocean analysis system (ORA-S3, *Balmaseda et al.*, 2008) product was used to describe surface wind stress variability. The time series extend from 1959 through 2009 on a 1° x 1° grid. The sea surface height data were obtained from the multimission, gridded sea surface altimeter product produced by Ssalto/Duacs and distributed by Aviso. The Interpolated Outgoing Longwave Radiation(OLR) data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA from their Web site at http:/www.esrl.noaa.gov/psd/. Optimum Interpolation Sea Surface Temperature (OISST) data were obtained from the NOAA Environmental Modeling Center, Global Climate and Weather Modeling Branch. The NINO3 index was obtained from the NOAA National Weather Service Climate Prediction Center.

Five-year running means are formed from annual-averaged time series. For tide gauge data that include gaps, an annual average is computed if at least eight months of data are available for that year. The five-year running mean is computed if at least four years of data are available.

# 3 1993-2009 sea level trends and ENSO variability

We first consider the extent to which ENSO variability contributes to the 17-year (1993-2009) sea level trends depicted in Figure 1, which are obtained from annual average sea surface height using a standard least squares fit of the form $\hat{\eta} = a_0 + a_1 t$ , where $t$ is time. We repeat the sea level trend calculation using a multiple regression that includes the NINO3 index ($N$ ), and the Hilbert transform of the NINO3 index ($\tilde{N}$ ) as $\hat{\eta} = b_0 + b_1 t + b_2 N + b_3 \tilde{N}$. We treat $N$ as a representation of in-phase ENSO variability across the tropical Pacific, with $\tilde{N}$ included to capture out of phase ENSO variability associated with propagating signals (*Merrifield et al.*, 1999).

The trends associated with ENSO (Figure 2, middle panel), computed as $a_1 - b_1$, are nearly an order of magnitude smaller than $a_1$ (Figure 1) or $b_1$ (Figure 2, upper panel). In the tropical Pacific, the ENSO trend pattern reflects the prevalence of La Niña events late in the 17-year record as well as the strong El Niño event early in 1997-98. Similar results are obtained using the Multivariate ENSO Index as a proxy for ENSO instead of NINO3. We conclude that the trend pattern in Figure 1 is not an artifact of the timing and amplitude of ENSO events over the 17-year record.

We next examine where trends are significantly different than the global average trend, which we estimate from the Aviso data to be 2.9 mm yr$^{-1}$. We use the $b_1$ trend as it has a smaller confidence interval than $a_1$. For most of the ocean, the global mean falls within the 95% confidence interval of $b_1$ (Figure 2, upper panel). The primary regions of significant trends are the WTP, where the $b_1$ values are significantly above the global average, and the NEP where they are well below the global average (Figure 2, lower panel). We will focus our attention on these regions of significantly high and low trends.

# 4 Sea level trends from tide gauge records

Tide gauge observations indicate that the high positive sea level trends in the WTP during 1993-2009 are associated with a recent shift in regional sea level rise compared to the previous 40 years. Five-year mean time series at Guam and Kwajalein (Figure 3), two of the longest tide gauge records in the WTP, show that the high rate of sea level rise in this region began in the early 1990s (Figure 4). The linear trend for the section of data prior to 1993 is -1.1 $\pm$ 1.2 mm yr$^{-1}$ and 0.7 $\pm$ 0.8 mm yr$^{-1}$ at Guam and Kwajalein, respectively, compared to 9.4 $\pm$ 6.2 mm yr$^{-1}$ and 7.1 $\pm$ 5.0 mm yr$^{-1}$ after 1990.

Tide gauges in the WTP with shorter records than Guam and Kwajalein also are examined. We remove a least squares fit of $N$ and $\tilde{N}$ from the time series prior to forming the five-year mean to help filter contributions from energetic ENSO variability in the tropics. North of the equator, Pohnpei sea level resembles Guam sea level with a rate increase in the 1990s (Figure 5). Malakal, located closer to the equator than Guam, exhibits substantially more decadal time-scale variations than Guam or Kwajalein and the recent trend increase is less apparent given these fluctuations. Majuro is further east from the trend maxima than Kwajalein (Figure 3), and there is little indication of a trend increase at this location.

South of the equator in the WTP the trend increase after 1990 is evident at Kapingamarangi and Nauru (Figure 6). It also appears at Funafuti and Honiara, although a sea level minimum in the late 1980s to mid 1990s also occurs at Honiara. Kanton is located well east of the high trend levels and there is more decadal variability at this location compared to the other sites. Pago Pago and Suva are the southernmost stations in the region. The trend increase is weak at Pago Pago and not clearly linked to a change in the 1990s. A large sea level change occurs in the 1980s at Suva, which presumably places this station in a region of different wind forcing characteristics than the other stations.

In the eastern Pacific, the short record at Santa Cruz does not show an obvious trend change after 1990 (Figure 7). Other tide gauges in the ETP with longer records contain level shifts, due in part to seismic activity, that appear specific to individual stations and not representative of regional sea level changes. We did not consider these stations. Santa Cruz sea level exhibits decadal fluctuations that resemble fluctuations at San Francisco and, to a lesser extent, farther north at Ketchikan. The correspondence amongst these stations suggests the importance of poleward propagating coastal-trapped waves, which have been observed at interannual (*Enfield and Allen*, 1980; *Chelton and Davis*, 1982) as well as decadal time scales (*Clarke and Lebedev*, 1996). Local wind forcing and other wave transformation effects presumably account for modifications of the signal along the coast. The trend change in the early 1990s observed at Guam and Kwajalein is not apparent at San Francisco and Ketchikan, with both stations exhibiting more decadal variability than the WTP stations.

To further emphasize the strong decadal and multi-decadal variations in sea level in the North Pacific, we also include sea level time series from the Hawaiian Islands and Japan (Figure 7). Relative to its long-term trend, sea level at Midway fell from 1940 to 1980, and rose since 1980. Midway falls into the central-Pacific region that has experienced a general rise in sea level since 1993 (Figure 1). In contrast, Honolulu sea level exhibits 10-20 year fluctuations associated with regional wind forcing (*Firing et al.*, 2004). The sea level at Mera includes fluctuations of 20-25 year period in addition to a long-term trend.

## 5 Wind forcing

During 1990-2009, surface wind stress patterns over the Pacific tended to intensify (Figure 8), particularly in comparison to the previous 30 year period. Regions of increasing wind stress trend include the northeast and southeast trade winds over the tropical Pacific, the westerlies at mid-latitudes, and the sub-polar easterlies over the southern ocean.

Near the equator, the increase in easterly winds during 1990-2009 (Figure 8) cause a positive sea level trend anomaly in the west Pacific and a negative anomaly in the east (Figure 3). Off the equator, the strengthening of the north and south trades produce a negative trend in Ekman pumping, $w_e = \nabla \times \vec{\tau}/(\rho f)$, where $\vec{\tau}$ is the surface wind stress, $f$ is the coriolis parameter, and $\rho$ is the density of air (Figure 9). This $w_e$ tendency contributes to increasing water levels over the western part of the basin. The negative $w_e$ trends during 1990-2009 stands out compared to trends over the previous 30 year period. Enhanced trades at the equator also lead to lower sea levels along the eastern boundary of the Pacific via coastal-trapped wave propagation. *Li and Clarke* (1994) relate the zonal trade wind stress at the equator, averaged across the Pacific, to sea level along the eastern boundary of the Pacific as $\eta_E$ = 4.06$\bar{\tau_x}$. For 1993-2009, the trend in $\bar{\tau_x}$ from the ECMWF product is -6.5 x $10^{-4}$ Pa yr$^{-1}$, which corresponds to a trend in $\eta_E$ of -2.6 mm yr$^{-1}$. Adding to this a global mean of 2.9 mm yr$^{-1}$ yields near zero rates along the eastern boundary, which agrees with the computed trends presented in Figure 1.

We next compare five-year means of tropical Pacific wind stress and sea level. The average zonal wind stress across the tropical Pacific (-20° to 20° latitude, and 150° to the eastern boundary) shows a steady increase in the trades from the early 1990s onward (Figure 10). The change in wind stress qualitatively matches the sea level increase observed at Guam and Kwajalein (Figure 3) and other stations in the WTP. In some cases the sea level increase appears to precede the wind increase (e.g., Guam), which may be due to the space-time details of the forcing, which are glossed over in a zonal wind stress average.

Near the equator, the area-averaged zonal wind stress (-1° to 1° latitude, 126° longitude to the eastern boundary), exhibits more decadal variability than the off-equatorial trades (-20° to 20°) (Figure 10). Given that wind stress fluctuations over the equatorial wave guide influence eastern boundary sea levels, the high level of decadal variability of equatorial wind stress agrees with the high level of decadal variability in NEP sea level records (e.g., San Francisco). The correlation between 5-year mean sea level at San Francisco and $\eta_E$ computed from the ECMWF wind product is 0.66, with a regression coefficient of 1.3.

# 6 Summary and Discussion

Since the early 1990s, a steady strengthening of the trade winds over broad sections of the central and eastern tropical Pacific has caused enhanced positive sea level trends in the WTP, and weak to negative trends in the ETP. Along the eastern boundary of the NEP, sea level has fallen since the early 1990s, likely due to enhanced trade winds at the equator and the poleward propagation of negative sea level anomalies. Zonal winds at the equator exhibit larger decadal fluctuations than trade winds off the equator. This may account in part for the large decadal fluctuations observed along the eastern boundary of the NEP. We have not considered the eastern boundary of the South Pacific, although based on the work of *Clarke and Lebedev* (1999) and others we expect a similar connection to the equatorial wind field.

Based on the distinctive increase in WTP water levels, it appears that the intensifying tropical circulation in the Pacific at these time scales is a singular occurrence since the mid-20th century. The pattern may be part of a multi-decadal to centennial fluctuation in the tropical

Pacific atmosphere and ocean state; however, this is difficult to assess as tide gauge and other in situ measurements in the tropics generally do not date back in time prior to the 1940s.

These wind and sea level patterns in the Pacific are opposite to recent observational and modeling studies that suggest a weakening tropical circulation in the Pacific in response to global warming and an enhanced El Niño-like state (*Vecchi et al.*, 2006; *Zhang and Song*, 2006; *Vecchi and Soden*, 2007; *Yu and Zwiers*, 2010). Some of the discrepancy can be attributed to the time period of analysis. Several of these studies base their trends over longer time periods (e.g., 1860 to 2000, *Vecchi et al.*, 2006; 1948 to 2004, *Zhang and Song*, 2006) than the post-1990 period of interest in this study. In general, however, coupled general circulation models (CGCMs) tend to describe a weakening tropical circulation in response to an imposed warming signal (see for example *Collins et al.*, 2010 for a summary), which suggests that the signal described here is a natural variation unrelated to anomalous warming, or that the CGCMs are somehow not capturing the response to recent warming trends.

There are other indicators of an intensifying trade wind pattern since 1990 besides sea level. Recent satellite observations show an increase in outgoing longwave radiation (OLR) in the tropics of 5 W $m^{-2}$ for the period 1985-2000, with most of the increase after 1990 (*Chen et al.*, 2002). The OLR trend for 1993-2009, computed using the NOAA Interpolated OLR data (*Liebmann and Smith*, 1996), shows decreasing OLR in the convergence zones of the Indo-Pacific region, indicative of an intensifying tropical circulation (Figure 11). *Wielicki et al.* (2002) conclude that the OLR variations, as well as short-wave radiative flux variations, are due to changes in tropical cloudiness, which are not simulated accurately in climate models. *Hoerling et al.* (2010) find that increased rainfall rates in the WTP and decreased rates in the ETP and NEP during 1977-2006 are a result of SST trend patterns over that period. SST trends for 1993-2009, computed using NOAA OI-SST data, indicate shifts toward a warm state in the West Pacific and a cold state in the East (Figure 12). In short, ocean and atmospheric variables point to a strengthening tropical circulation since the early 1990s.

The changing patterns in the Pacific appear to indicate a strengthening component of the atmospheric vertical overturning circulation, perhaps driven by an increase in latent heat release in the tropical convergence zones (Figure 11). The extension of the pattern of enhanced trade winds well into the subtropics suggests that the changes are associated with the Hadley circulation cell. Attempts to assess trends in the Hadley circulation have been based primarily on reanalysis datasets, and the results have been somewhat inclusive. For example, *Mitas and Clement* (2005) obtain significantly different estimates of Hadley cell strength based on different reanalysis products. They also found that radiosonde data in the Pacific showed no obvious trend in the Hadley circulation; however, that dataset ended in 1990 prior to the shift discussed here.

The notion of a Hadley spin-up is perhaps overly simplistic as the specific shift of interest is the intensification of the off-equatorial trades. The recent increase in the trades at the equator is not unusual given the high level of decadal variability in this zone (e.g., *Lee and McPhaden*, 2008). The shift in trades off the equator, however, is uncommon over the past 60 years, and further studies are required to determine the nature of this pattern.

## Acknowledgments

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annual sea level at the eastern and western boundaries and the zonally averaged equatorial wind, *J. Phys. Oceanogr.*, **24**, 681-690.

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# List of Figures

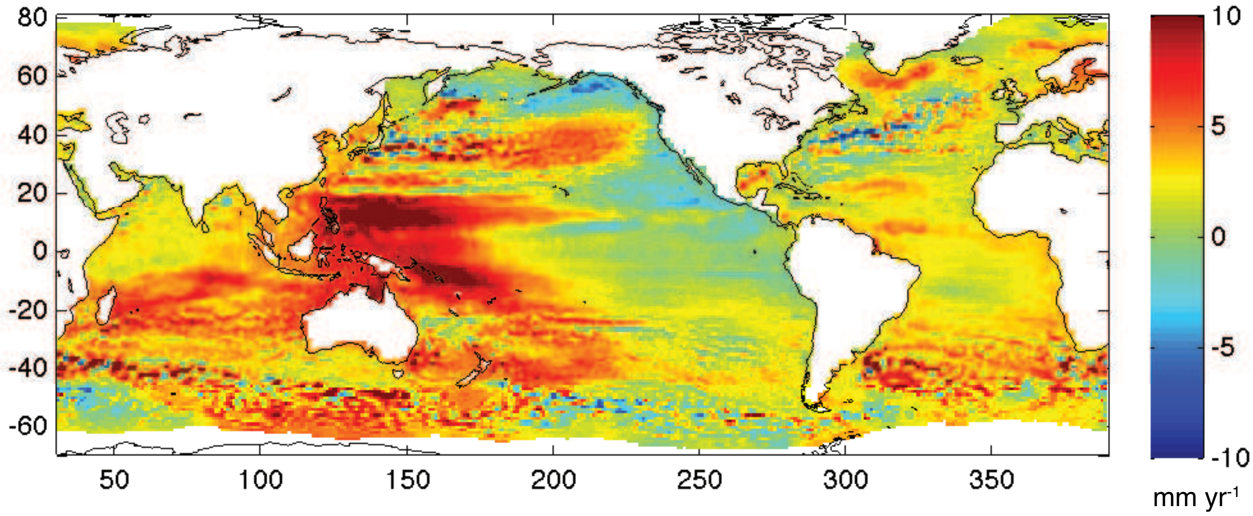


Figure 1: The linear trend in satellite altimetry sea surface height (SSH) for the period 1993-2009, based on the Aviso multi-mission altimeter data product .

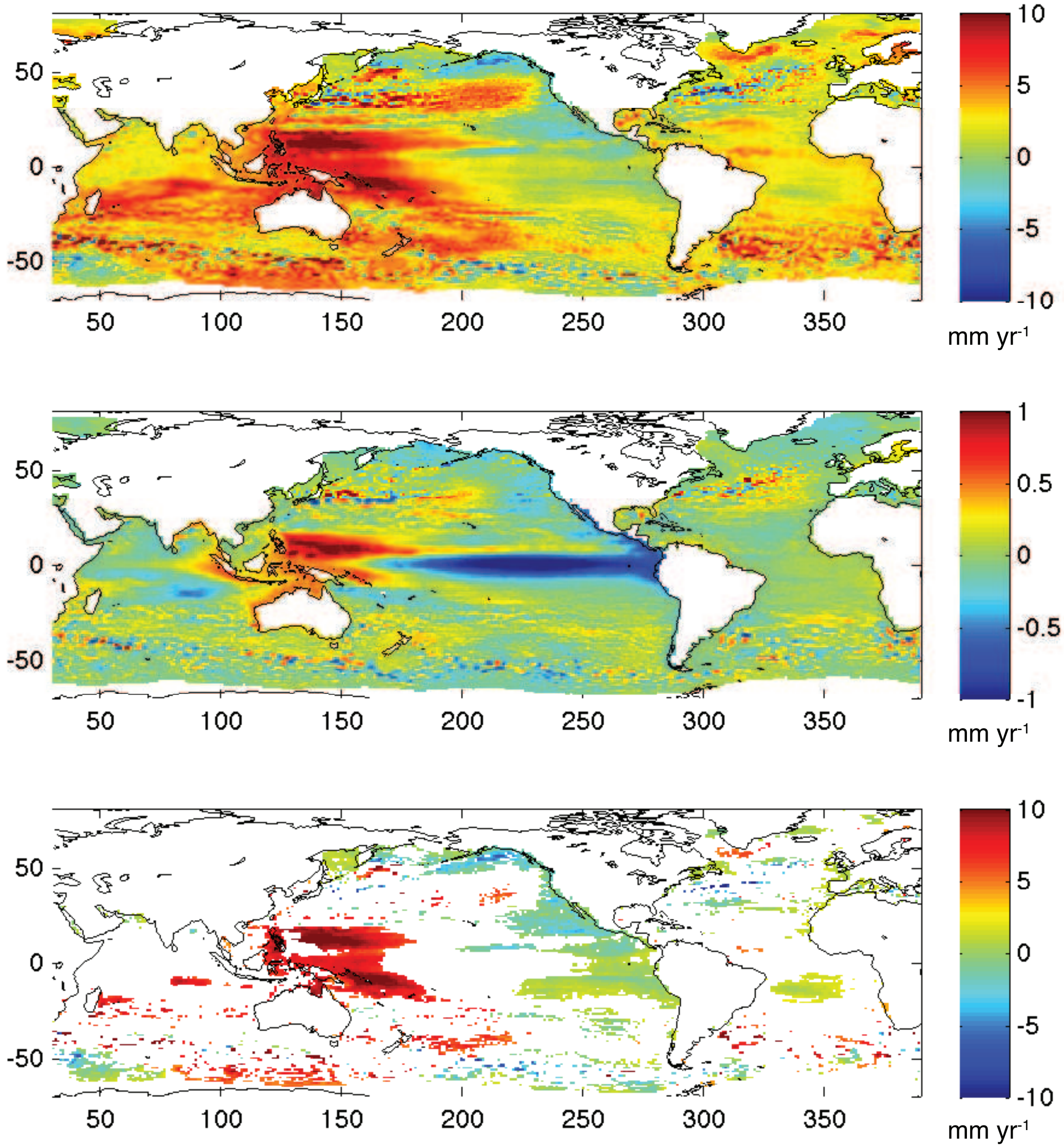


Figure 2: (upper panel) SSH trends obtained in a multiple regression including the NINO3 index ($N$) and its Hilbert transform ($\tilde{N}$). (middle panel) Sea level trends associated with ENSO, taken here as the difference $a_1 - b_1$. (lower panel) SSH trends from the multiple regression that are significantly different (95% confidence) than the global mean sea level trend of 2.9 mm yr$^{-1}$.

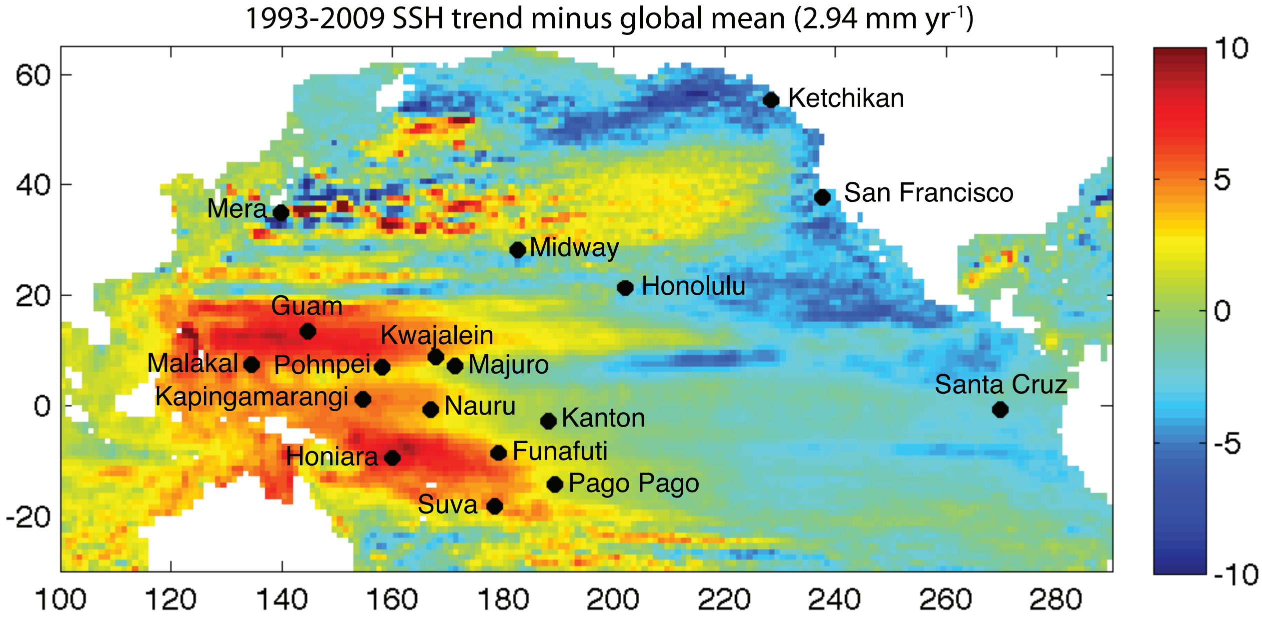


Figure 3: Map of SSH trends, from the multiple regression with $N$ and $\tilde{N}$, with the global mean sea level (2.9 mm yr$^{-1}$) removed. The locations of tide gauge stations that are used in this study are included.

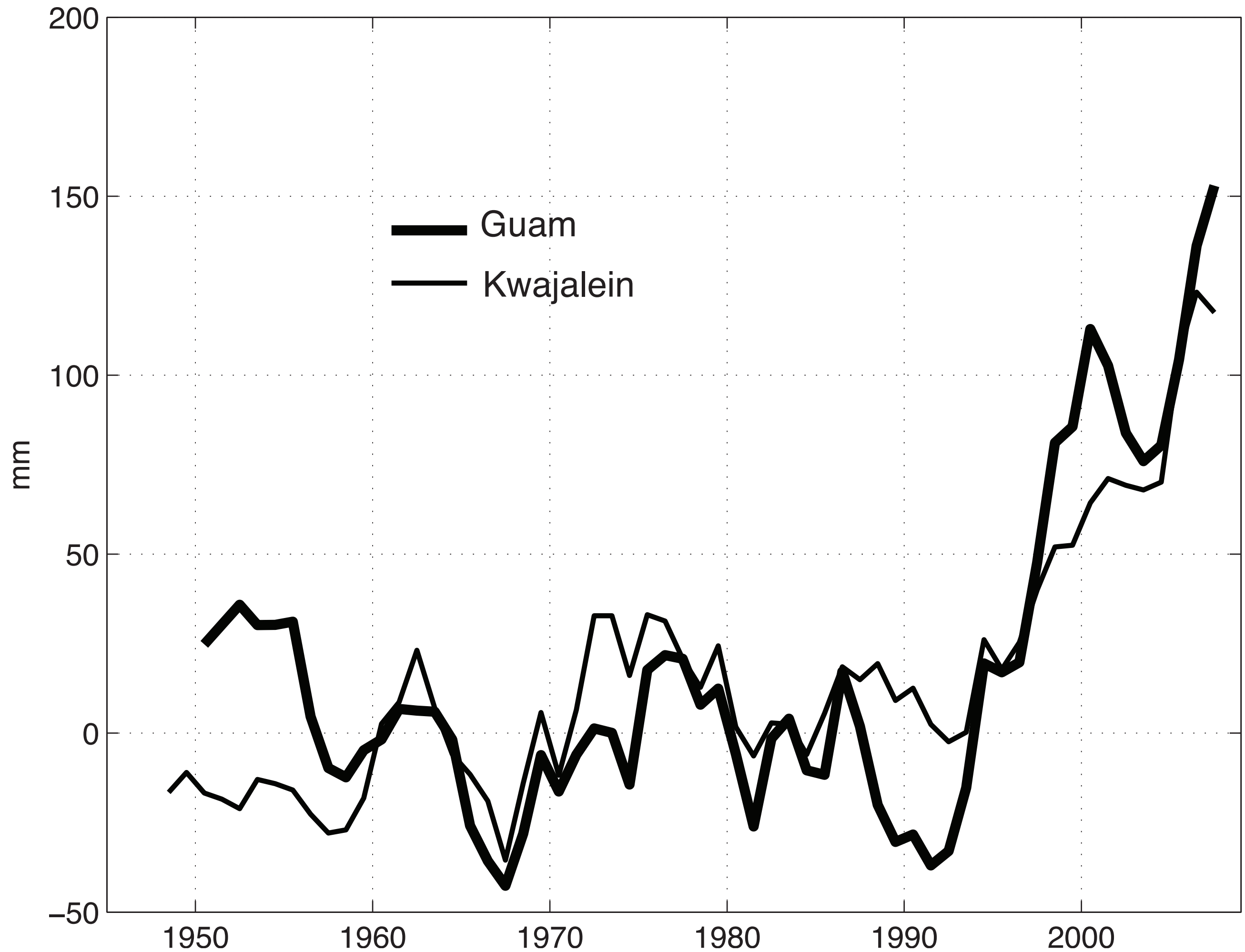


Figure 4: Five-year mean sea level from the Guam and Kwajalein tide gauges. The data are presented relative to arbitrary means.

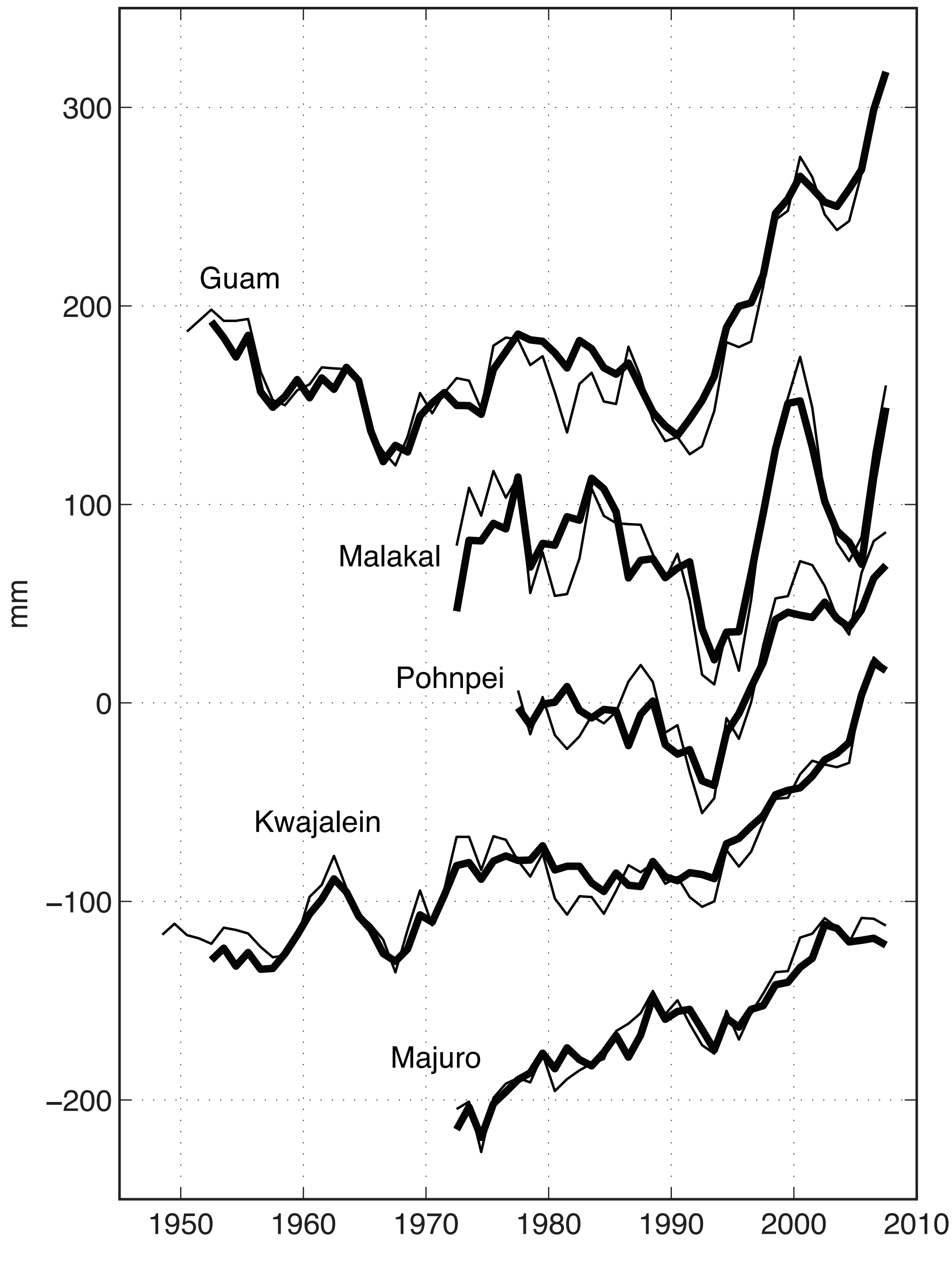


Figure 5: Five-year mean sea level from tide gauges in the WTP north of the equator. The dark line is the running mean after a least squares fit of $N$ and $\tilde{N}$ are removed from the time series.

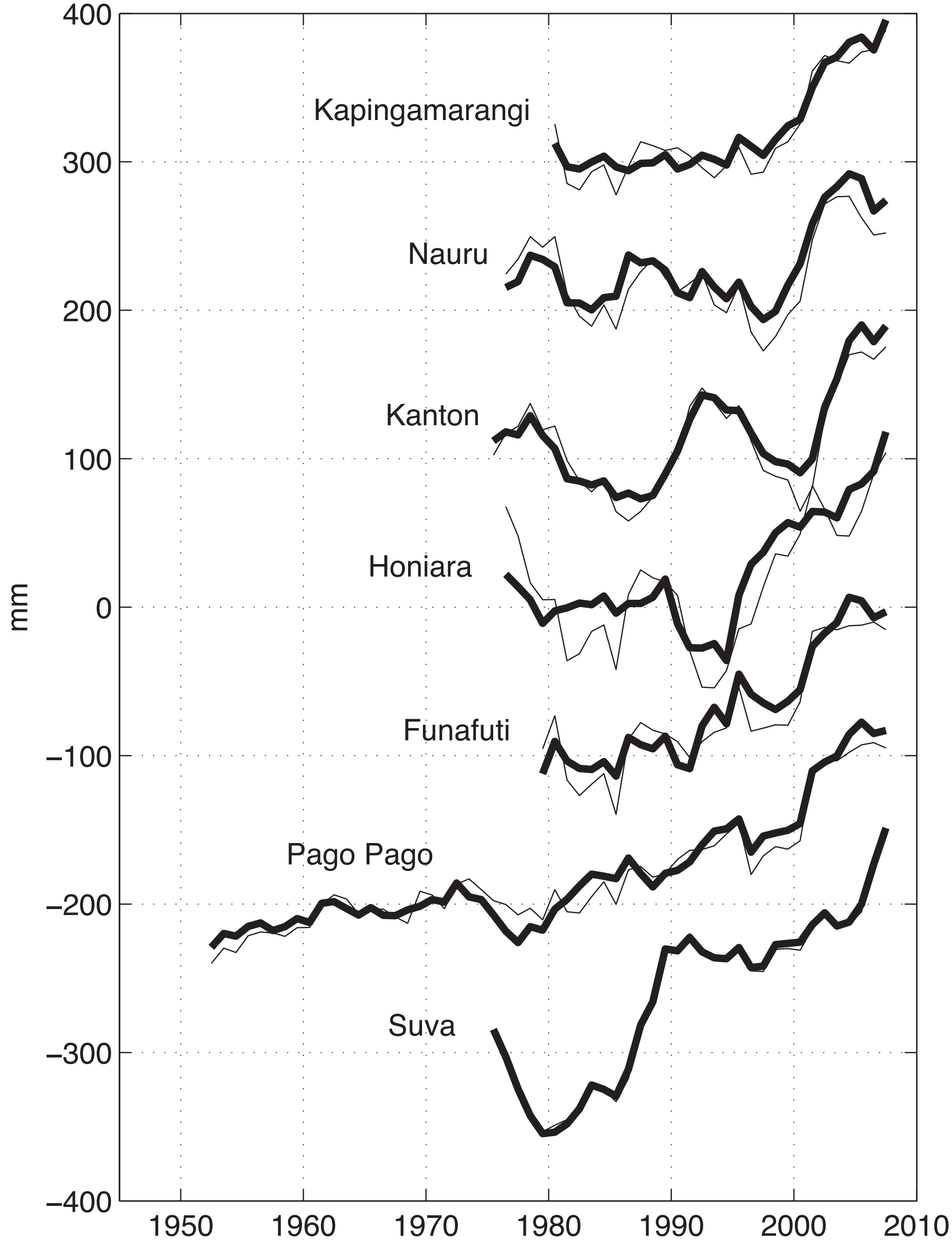


Figure 6: Same as Figure 5 but for stations in the WTP south of the equator.


Figure 7: Same as Figure 5 but for stations in the ETP, Northeast and Northwest Pacific, and mid-Pacific. The least squares fit of $N$and $\tilde{N}$ leads to small changes in the time series at higher latitudes. Because we do not have the NINO3 index prior to the 1940s, we did not correct the high latitude time series.

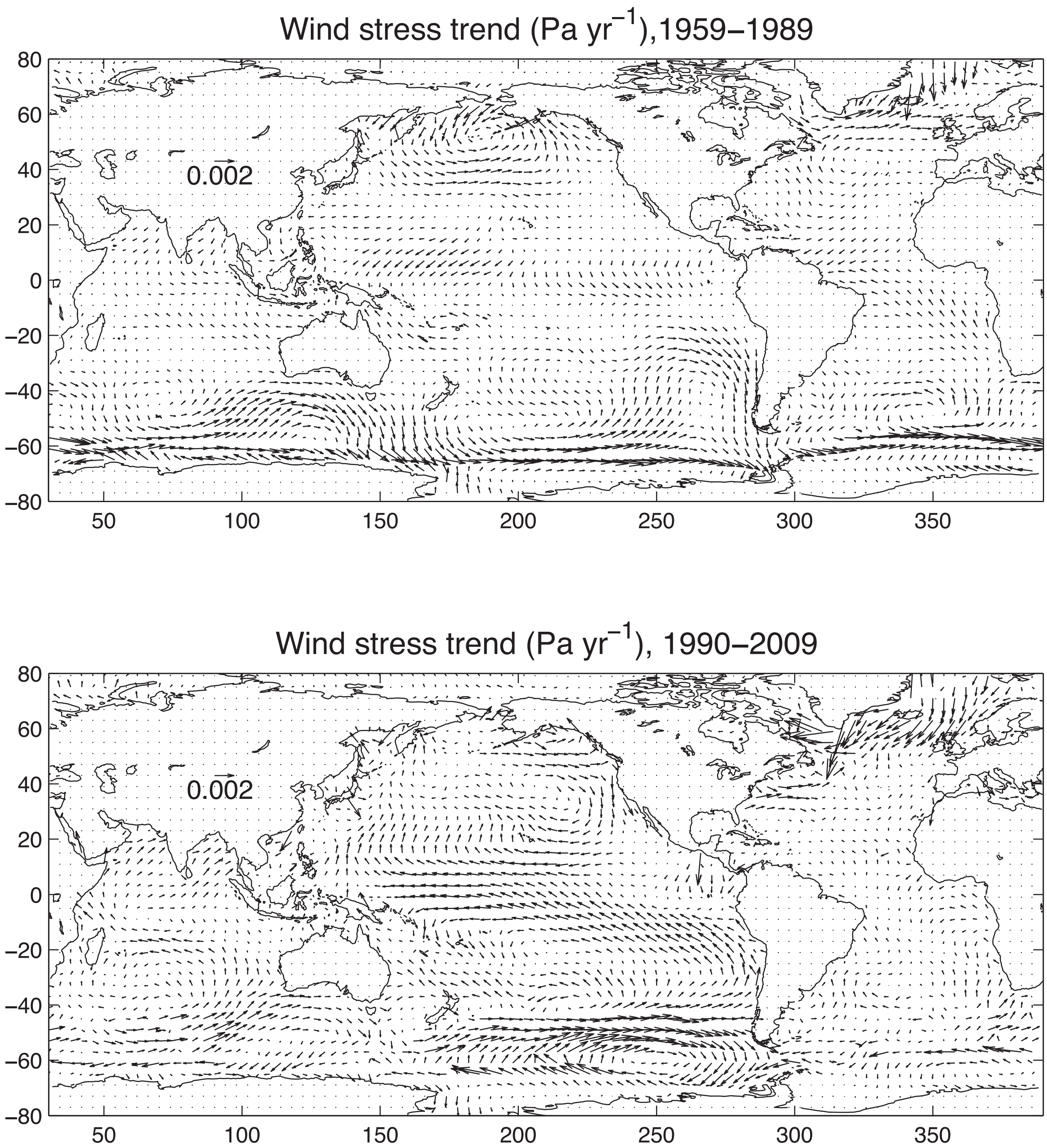


Figure 8: Linear trend in ECMWF wind stress for 1959-1989 (upper panel) and 1990-2009 (lower panel).

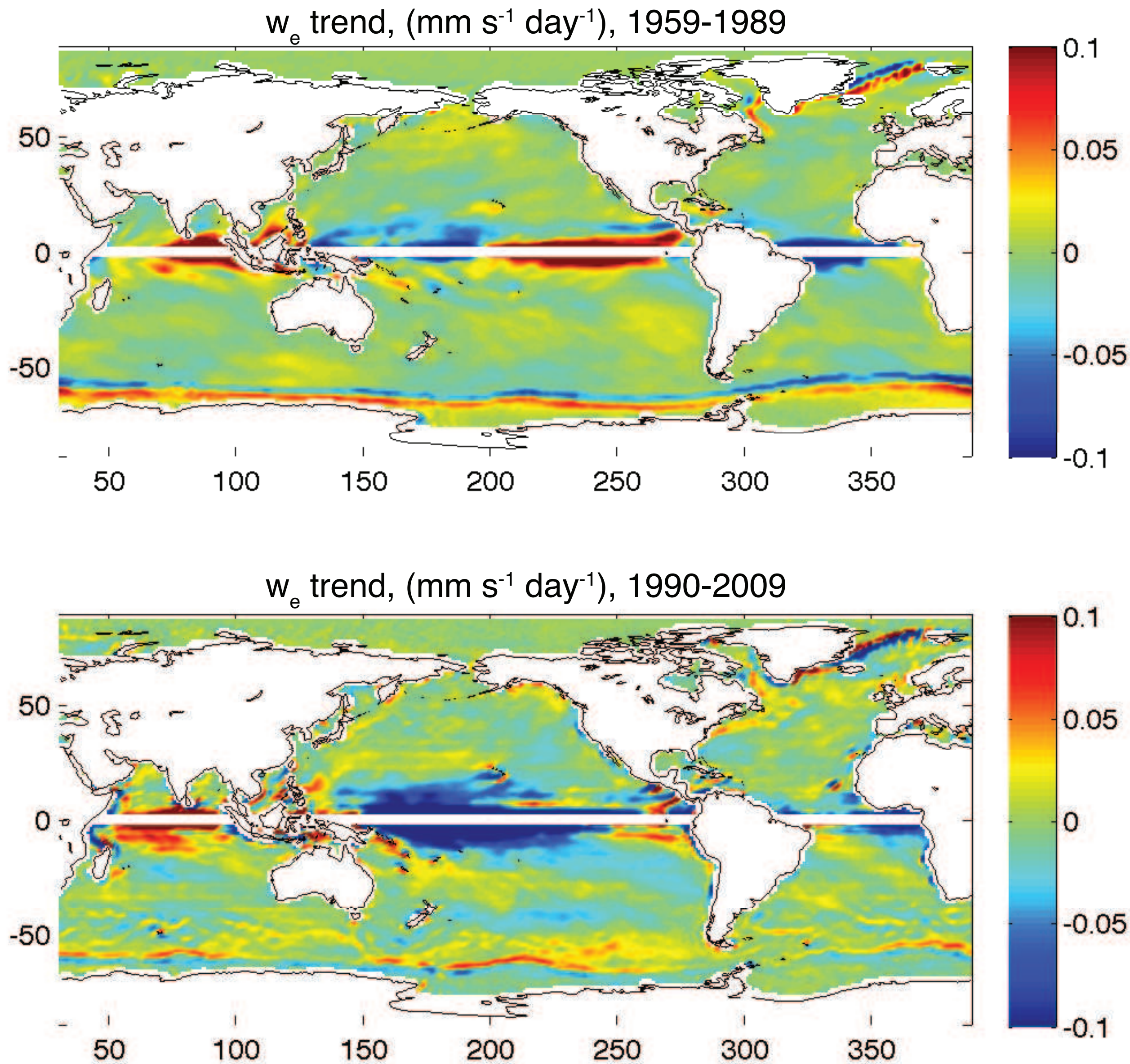


Figure 9: Trends in Ekman pumping for 1959-1989 (upper panel) and 1990-2009 (lower panel).

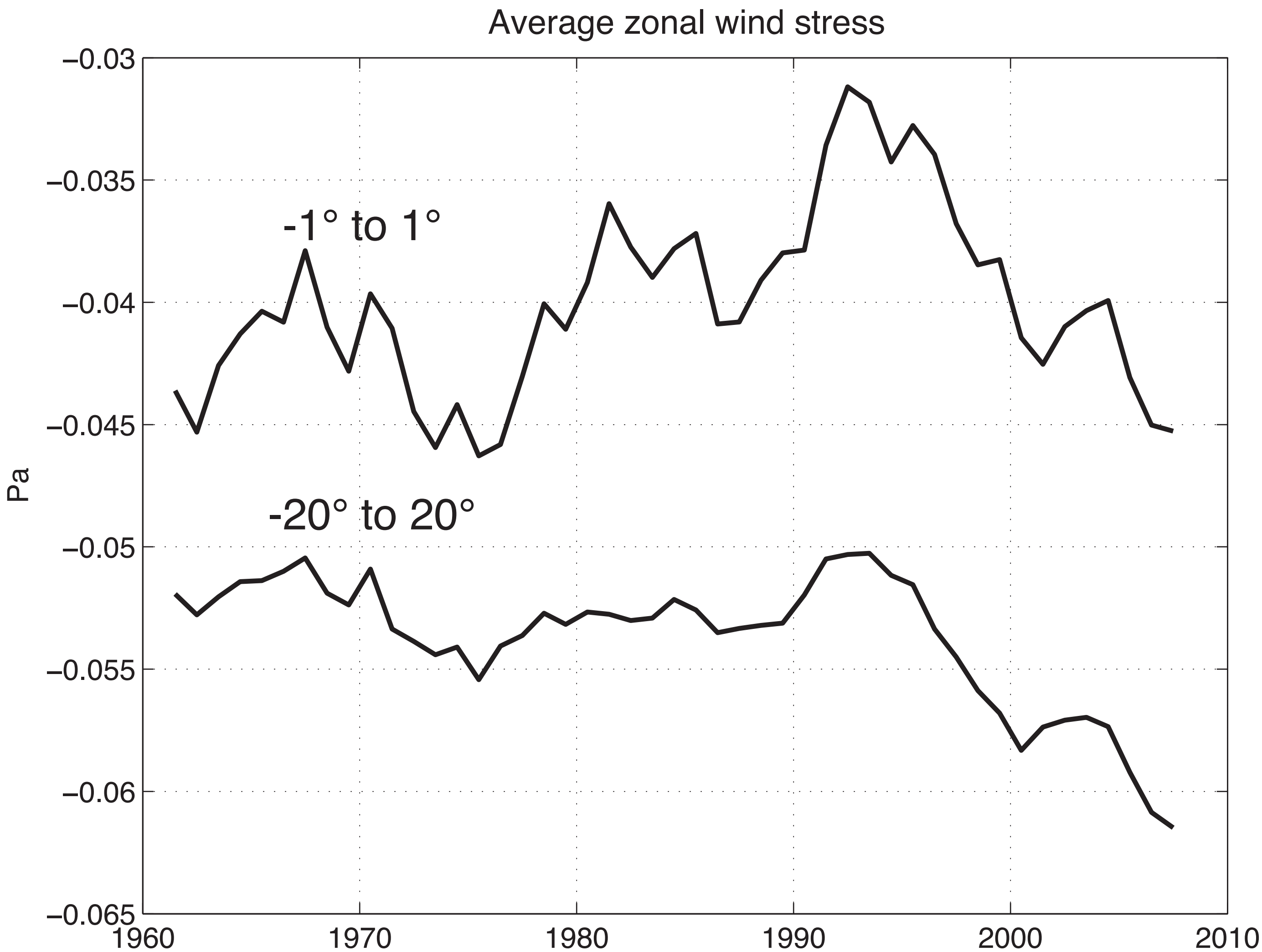


Figure 10: Five-year mean wind stress averaged over the central and eastern tropical Pacific (-20° to 20° latitude, and 150° longitude to the eastern boundary, and over the equatorial Pacific (-1° to 1° latitude, and 128° to eastern boundary).

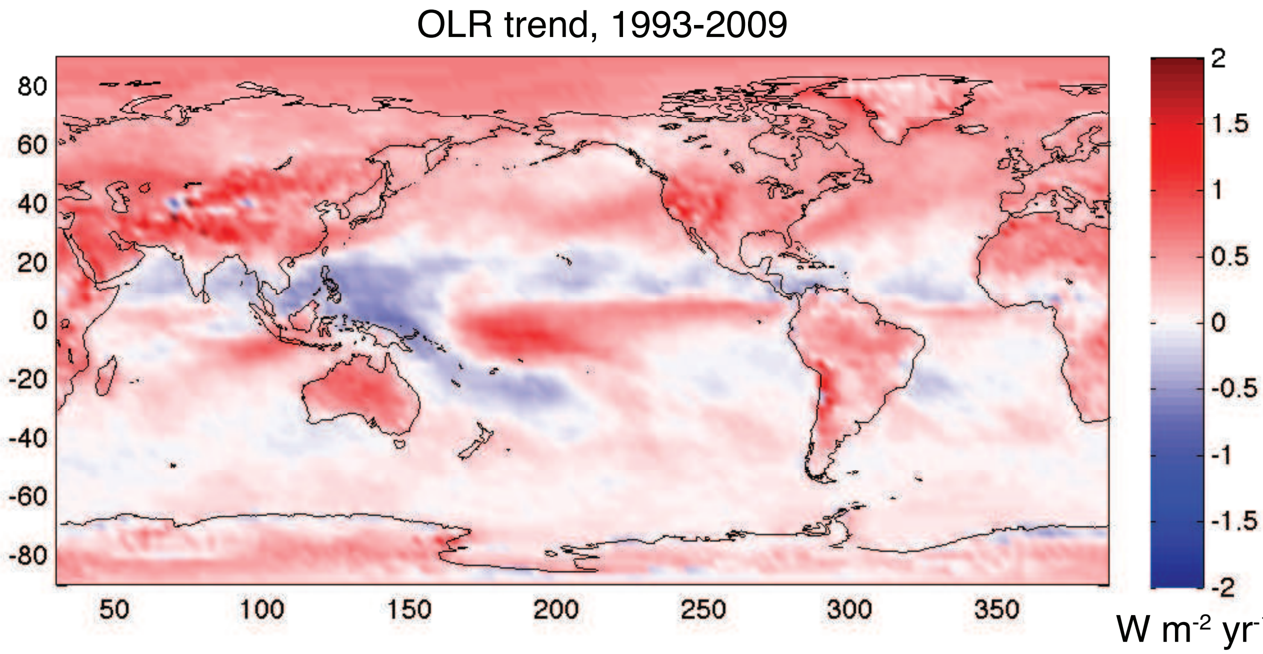


Figure 11: Trends in outgoing long-wave radiation from NOAA Interpolated OLR data for the time period 1993-2009.

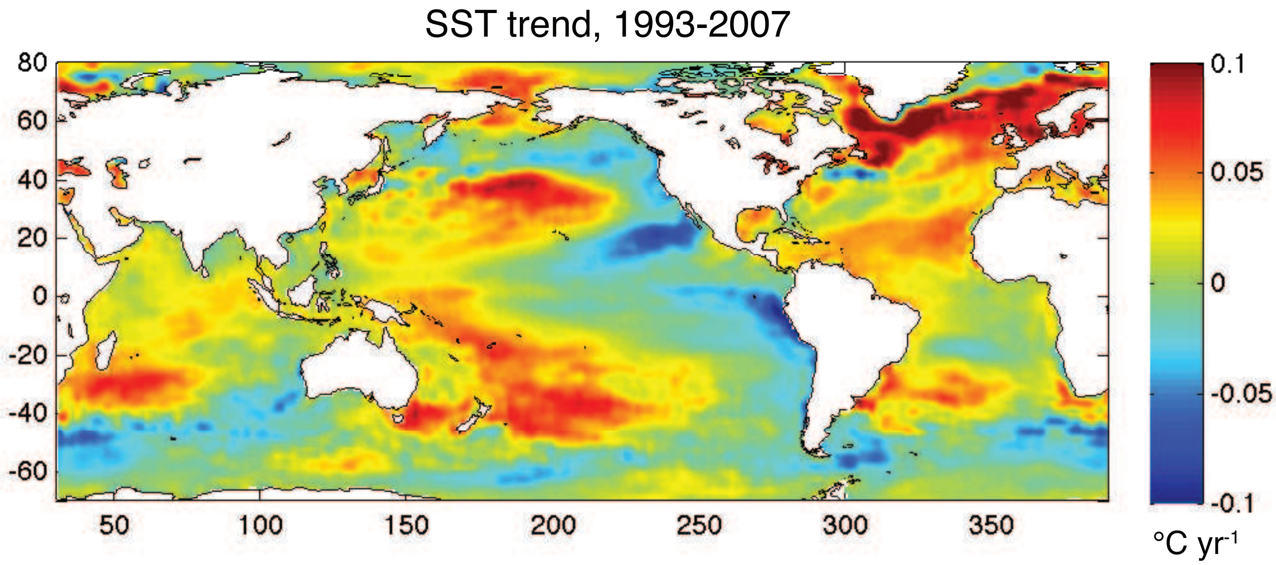


Figure 12: Trends in sea surface temperature (SST) from NOAA OISST data for the time period 1993-2007.