Tropical Pacific Climate Trends Since 1960*

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(Manuscript received 14 April 1988, in final form 18 January 1989)

ABSTRACT

Merchant ship observations appear to indicate an increase in the strength of the surface winds in the tropical Pacific and elsewhere in recent decades. Here we report an investigation of trends in tropical Pacific sea surface temperature and sea level, which has repeatedly been shown to be closely related to the winds. The results suggest that sea levels since 1960 have been rising oceanwide at about 3.5 cm/decade, while simultaneously tilting about 2 cm/decade higher in the east and lower in the west, and that surface temperatures have been rising about 0.6°C/decade. These results are not consistent with the apparent wind change; rather, they support the contention that the apparent wind changes are an artifact introduced by changes in measurement technique, and suggest that tropical Pacific winds may have actually decreased in strength.

1. Introduction

Recently, Whysall et al. (1987) discussed a number of long term trends in surface wind strength, among them an apparent strengthening of the trade wind system in the tropical Pacific since the 1950s. The same general trend is apparent in Fig. 1, which is based on the wind analysis carried out at Florida State University (Goldenberg and O'Brien 1981). This figure shows the anomaly in the westerly pseudostress (surface wind speed multiplied by westerly component) in the eastern equatorial Pacific. The negative sign of the trend, -2.81×10^{-2} m^2 s^{-2} month^{-1}, represents a strengthening of the prevailing easterlies. The trend is statistically significant at the 99.9% level. The COADS dataset shows the same trend (O'Brien private communication), and Reverdin and DuPenhoat (1986) noted a similar trend from 1964 to 1984 in the trades over the tropical Atlantic.

While Whysall et al. suggested that the trends in the surface winds might be indicative of a real climate change, Ramage (1987) cautioned that such variations might be an artifact of the measurement technique. All of the wind datasets referred to above are based on merchant ship reports, and it is possible that the trend observed in the last few decades is a consequence of the gradual replacement of Beaufort estimates by shipboard anemometers. A direct investigation leading to a resolution of this question is reported in a companion paper (Cardone et al. 1988). Here we take an indirect approach by considering trends in sea level.

If the trade winds have indeed strengthened over the past 2 or 3 decades, there should be concomitant changes in the tropical Pacific ocean. One would expect the enhanced easterly stresses to drive stronger equatorial upwelling in the eastern Pacific, resulting in colder sea surface temperatures (SSTs). At the same time, if the stronger easterlies were part of a stronger Walker circulation then one would expect to find an enhanced temperature contrast between the eastern and western Pacific. Again, the implication is colder eastern equatorial SST.

Figure 2, based on the analyses of the Climate Analysis Center, NOAA, shows that this is not the case. In fact, SST has warmed since 1970. The monthly sea surface temperature anomalies shown in Fig. 2 were regressed against time for the period January 1970 through April 1987. The temperature trend estimate based on these data is 5.10×10^{-3} °C/month, or a 1.09°C warming during the 16 year period analyzed. The coefficient of correlation, r, is 0.348; the complement of r^2, 0.879, represents the fraction of temperature anomaly variance associated with processes not related to a linear trend, such as ENSO. A student t-test confirms the significance of r at above the 99.9% level.

Now it must be admitted that the relationships between surface wind and SST are not inevitable. They *are* cornerstones of the Bjerknes (1969) hypothesis for El Niño and the Southern Oscillation, and in that context there is considerable observational and theoretical

* Lamont Doherty Geological Observatory Contribution number 4468.

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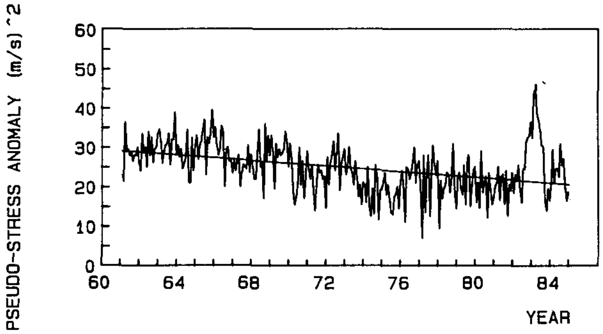

FIG. 1. Monthly anomaly of mean westerly component of the surface wind pseudostress from the FSU analysis, averaged from 5°N to 5°S, and 90°W to 180°W, together with the corresponding regression line.

evidence in their favor. Nonetheless, SST is determined by a complex budget involving many terms, and it may be argued that the expected wind influence was overwhelmed by, for example, an opposing change in the surface heat flux. Similarly, the trades participate in the Hadley circulation, and do not respond solely to equatorial SST.

Sea level is an oceanic variable with a much simpler relationship to wind driving. Support for this statement may be drawn from the many successful simulations of tropical sea level variations achieved by rather simple linear wind-driven models (e.g., Busalacchi and O'Brien 1980, 1981; Cane 1984; Busalacchi and Cane 1985; DuPenhoat and Treguier 1985). In particular, one would expect the sea level slope across the width of the equatorial Pacific to respond to changes in the strength of the trades and little else. (Changes in the mean sea level for the tropics could be more complicated, possibly occurring in response to large scale wind changes in distant parts of the Pacific; cf. Cane and Sarachik 1981).

Inoue and O'Brien (1987) compared western and central equatorial Pacific sea level observations with predictions of the linear numerical model of Busalacchi and O'Brien (1980, 1981) forced by observed ship winds for the period 1974–75 to 1981. In both model and data, they discerned a trend of decreasing sea level in central regions, which was attributed to a weakening of near-equatorial easterly trades in the central Pacific. Trends in the easterly trades south of the equator, however, reversed during the second half of the 8-year period; consistently, so did observed sea level trends at two stations south of the equator.

2. Simulated tropical pacific sea level variations 1960–1984

In the present paper we use a linear wind-driven model to simulate the sea level variations in the tropical Pacific from 1960–1984. The model is the one used in the studies of Cane (1984) and Busalacchi and Cane (1985); it is described in those papers. The principal difference from the Inoue and O'Brien model is that here sea level is calculated from two vertical modes rather than one (cf. Busalacchi and Cane 1985). There are also differences in numerical algorithms and basin geometry. None of the results reported here are sensitive to these differences: any model capable of simulating sea level variations would lead to the same conclusions.

The model was run for 6 years—several times the equilibration period—using the climatological annual mean FSU winds as the external forcing. The results show a sea surface slope down toward the east, the expected effect of the easterly trades.

The model was run again, driven by the time-varying winds from 1960 to 1984. Figure 3 shows the simulated sea level variations at locations corresponding to the 12 tide gauge stations discussed below. The resulting sea level variations are dominated by the ENSO cycles. A weaker but discernible feature of both the simulated and observed (Fig. 4) sea levels is the trend towards higher (or lower) sea level.

The trends of simulated sea level were evaluated by linear regression at each individual location, using time as the independent variable. They are listed in Table 1 as b_i^s. There is a tendency for negative trends (falling sea level) in the east, and positive in the west, a possible effect of the strengthening of the FSU trade winds during the past two decades. The spatial pattern of the simulated sea level trends are nearly proportional to the steady state pattern. In view of the linearity of the model, this result is consistent with the proportional strengthening of FSU winds since 1960. Comparison of the trends of simulated sea levels with those of observed sea levels is the main object of the data analysis discussed next.

3. Sea level data

a. Preliminary data processing

Monthly mean sea levels based on tide gauge data were obtained from the Hawaii Sea Level Data Center.

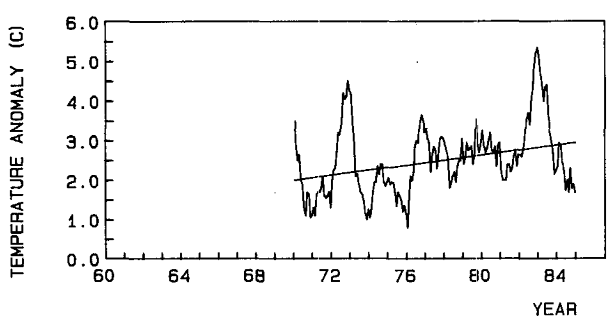

FIG. 2. Average monthly mean sea surface temperature anomalies, based on the CAC/NOAA analysis, in the NINO3 region (5°N to 5°S, 90°W to 150°W), together with the corresponding regression line.

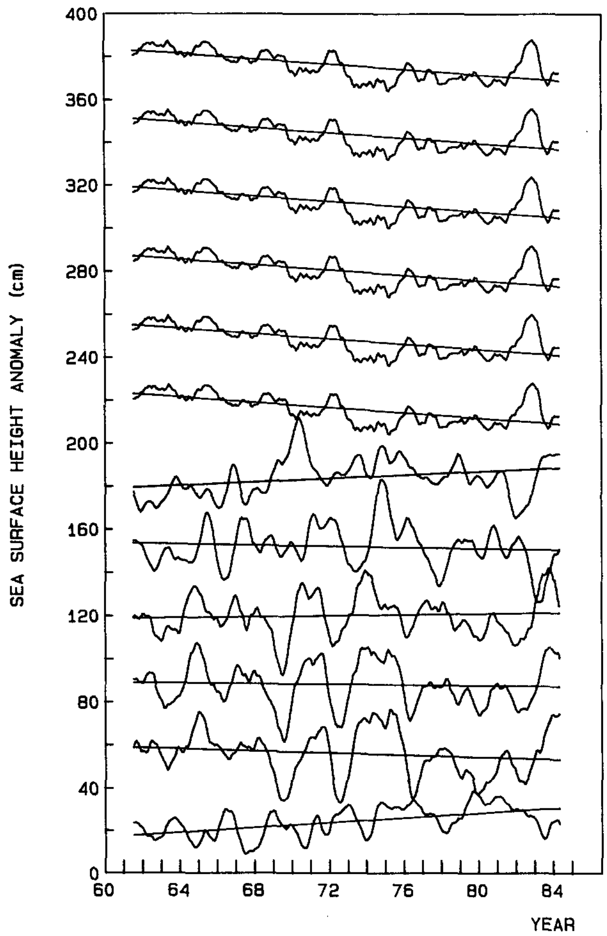

FIG. 3. Simulated sea level time series at 12 gridpoints corresponding to the 12 tide gauge stations discussed. The stations are arranged with eastermost at the top and westernmost at the bottom, in the same order as Table 1. The first six are redundant because in the long-wave low frequency approximation of the model, sea level at the eastern boundary is independent of latitude.

The 12 tropical Pacific locations listed in Table 1, which are the most complete series in the equatorial zone, form the basis of our analysis. The data used began in January 1960, except for the Darwin and Malakal time series which began in January 1966 and April 1973, respectively. The time series ended in December 1984 (Callao and Johnston), December 1983 (Kwajalein, Malakal, Pago Pago, and Truk), November 1983 in Quepos, and December 1982 in Acapulco. Data were available only until October 1980 for Darwin, June 1977 for Balboa, April 1977 for Talara, and September 1975 for San Jose.

Among the total of 2942 months of data, only 10 were missing, creating gaps of 1, 2, or 3 months at five stations; these were replaced by linear interpolation. A discontinuity which occurred when the San Jose gauge was relocated was corrected by assuming that the offset was equal to the mean difference between the old and new gauges during their 12 months of simultaneous use in 1969. These time series were subjected to 12-month running averaging to eliminate variance caused by annual or higher-frequency variations. The total number of data in the patched, smoothed series was 2818 months. The observed mean sea level during month j at station i is denoted below by x_{ij}.

b. *Statistical properties of tide gauge data*

For purposes of a preliminary comparison between observed and simulated sea level trends, the sea level data x_{ij} were regressed against time (j) for each station (i) individually. The resulting trends, b_i^o, are listed in Table 1. The observed sea level trends are opposite in sign, and typically weaker than, the simulated trends. This inconsistency between simulation and data must be regarded as no more than suggestive because the correlation of the b_i^o with the b_i^s is too weak ($r^2 = .076$) to be statistically significant. The highly tentative suggestion is that the observed sea level trends are opposite in sign, and weaker than, the simulated

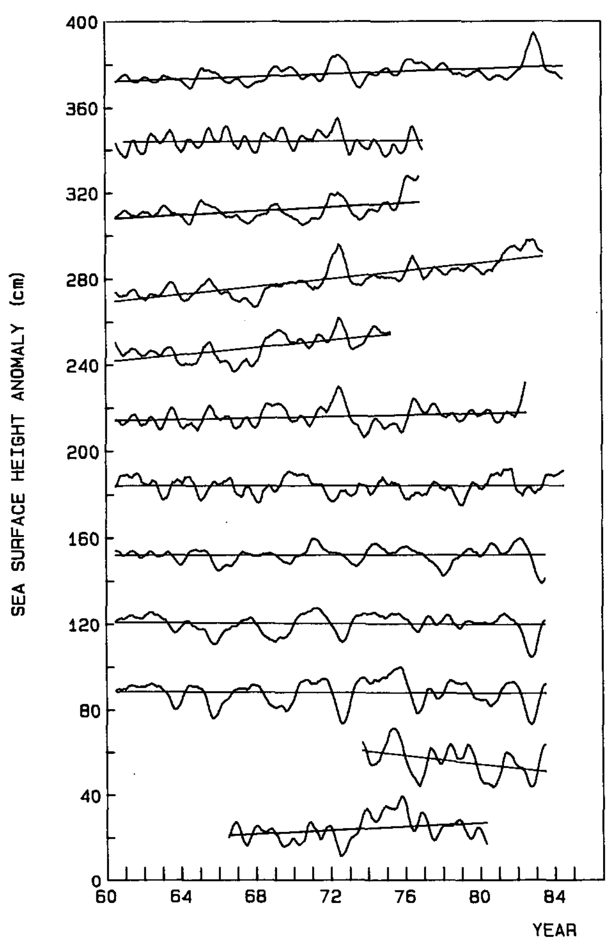

FIG. 4. Tide gauge *observations* time series at 12 tropical Pacific stations. Stations and scales are as in Fig. 3.

TABLE 1. Sea level trends (mm/month) calculated in five different ways: regression of (1) individual stations' SIMULATED sea levels, and of (2) individual stations' OBSERVED sea levels; individual trends based on composite regression of entire data set assuming (3) only TILT (each station's trend is proportional to the trend of simulated sea levels), (4) only RISE (all stations have the same trend), or (5) sum of tilt and rise.

Individual trend				Composite regression trends		
Station	Location	Simulated (b)	Observed (b)	Tilt (Bb)	Rise (C)	Tilt and rise ($C + Bb$)
Callao	12°S, 77°W	−0.508	0.244	0.295	0.171	0.456
Balboa	9°N, 80°W	−0.508	0.041	0.295	0.171	0.456
Talara	5°S, 81°W	−0.508	0.392	0.295	0.171	0.456
Quepos	9°N, 84°W	−0.508	0.766	0.295	0.171	0.456
San Jose	14°N, 91°W	−0.508	0.698	0.295	0.171	0.456
Acapulco	17°N, 100°W	−0.508	0.148	0.295	0.171	0.456
Johnston	17°N, 170°W	0.337	−0.009	−0.196	0.171	−0.026
Pago Pago	14°S, 170°W	−0.116	0.006	0.067	0.171	0.232
Kwajalein	9°N, 168°E	0.103	−0.045	−0.060	0.171	0.107
Truk	7°N, 152°E	−0.060	−0.030	0.035	0.171	0.200
Malakal	7°N, 134°E	−0.027	−0.850	0.120	0.171	0.284
Darwin	12°S, 131°E	0.469	0.371	−0.273	0.171	−0.102

trends. In view of the insignificance of the regression results discussed above, several more powerful but less obvious statistical procedures were used to compare the composite data from all 12 stations, with the composite of all 12 simulated trends.

We hypothesize that the sea level data x_{ij} are the sum of four independent effects:

1) A constant offset A_i at the ith station.

2) A sea level rise, jC, which is linear with time j and constant throughout the tropical Pacific. Such a trend could result, for example, from long-term changes in the extra-tropical winds, or from rapid glacial melting; it also might be a consequence of an overall change in tropical wind strength (cf. Cane & Sarachik 1981).

3) A sea level "tilt" which increases linearly with time and is proportional to the local, model-predicted sea level trend, b_i^s. Such a trend would result from the linear effect on sea level of proportional stiffening (or slackening) of tropical winds. It can be expressed as jBb_i^s, where B is an unknown constant.

TABLE 2. Composite regression results used in last three trend columns of Table 1. B, "tilt", is the constant of proportionality between the observed trend and the simulated trend. C, "rise", is common to all stations. SSE is the sum of the squares of the differences between each monthly sea level datum and its estimate by regression. F is the ratio with an F-distribution used to find the statistical significance of regression. Asterisks indicate that the value was assumed to be zero a priori.

	Tilt	Rise	Tilt and rise	Neither
B	−0.581	*	−0.477	*
C (mm/month)	*	0.171	0.079	*
SSE (10^6 mm^2)	6.631	6.935	6.563	7.372
F	311.400	175.600	171.700	—

4) Short-term variation, including ENSO and other "noise." The remaining squared variance associated with this hypothesis, compositing all data from all stations, is

$$\mathrm{SSE} = \sum_{ij} [x_{ij} - A_i - j(Bb_i^s + C)]^2.$$

A conventional least-squares approach was used to estimate A_i (offsets) and C (rise), assuming that $B = 0$. A similar approach was used to find A_i and B (tilt), assuming that $C = 0$. A third set of results was the least-squares estimates of A_i (offsets), B (tilt), and C (rise) without assuming the values of any of these. The results are summarized in Tables 1 and 2.

Table 2 shows that SSE is reduced by only 10.1% by removing the tilt, 5.9% by removing the rise, and 11.0% by removing both. The remainder represents the part of sea level variance associated with other phenomena, mainly ENSO. The statistical significance of all three regression results, however, exceeds 99.9%. This was reached by computing the F statistics associated with the three regression results in Table 2. These are far in excess of the 99.9% points in F distributions with (12 787), (12 787), and (2786) degrees of freedom, which are 10.828, 10.828, and 6.908, respectively (Weisberg 1980).

Certainly, the monthly data are not perfectly independent. Even assuming there is only one independent sea level datum per station per 16 months, which would make F values in Table 2 overestimates by a factor of 16, the original F values are so large that they would remain significant at the 99.9% level. (We believe one per 16 months underestimates the degrees of freedom; to go to the extreme, they would have to be reduced by more than a factor of 45 to fall below the 95% level.) Further, F tests show that the differences among all three regressions are also significant at greater than the 99.9% significance level. Even making the conservative assumption of only one independent datum per station per 7 months, these differences remain significant at the 95% level.

We thus conclude that the tropical Pacific sea level has undergone two gradual but statistically significant trends since 1960: a tilt up towards the east, and a general rise. The two effects approximately cancel in the western Pacific, and combine to produce a rise of about 55 mm/decade in the east.

4. Discussion

Within the framework of a linear, wind-driven model—the generally accepted conceptual model—and consistent with the empirical correlations on the ENSO timescale, strengthening easterlies in the tropical Pacific are expected to be contemporaneous with falling sea level and surface cooling in the eastern tropical Pacific. The observations discussed above, however, suggest the opposite: for over two decades beginning in 1960, the easterlies appear to have strengthened, while eastern sea levels rose and temperatures increased. Possible explanations of these contradictory results are:

1) The relationship of wind to sea level suggested by dynamic models, conceptual models, and ENSO empirical studies is invalid. We are reluctant to reject the validity of such broad-based and useful ideas without further corroboration.

2) A different cause of sea level and sea surface temperature changes, such as a teleconnection with strengthening extratropical westerlies, dominated the direct effect of strengthening easterlies. This cannot be firmly rejected, but there is little (if any) evidence or specific theoretical ideas to support it.

3) There were consistent trends in errors in both sea level and sea surface temperature observations. It is unlikely that such errors could be coherent enough to be statistically significant at the levels tested, and that the errors in both types of data would be consistent.

4) A trend in the errors of wind speed observations. As suggested by Ramage (1987), it is possible that the change from Beaufort to anemometer measurements on many reporting ships, which was happening during the period studied here, would account for an apparent increase in wind speeds during a period in which the actual wind speeds were decreasing. We conjecture that this indeed occurred, and that the period from 1960 until 1983 was one of weakening easterlies, rise in eastern sea level, and eastern sea surface warming in the tropical Pacific. It was already noted that an eastern SST increase is expected to coincide with an eastern sea level increase, in response to slackening tradewinds. The mean stratification of the equatorial Pacific, which is used in the model, implies a ratio of surface height anomaly to thermocline depth anomaly of 5.7×10^{-3}. Thus the trend in sea level, 0.46 mm/month, implies a trend in thermocline depth of 8 cm/month. Hence the ratio of the SST trend, 5.1×10^{-3} °C/month, to the thermocline depth trend is 0.06°C/m. If the SST change were due to a rising thermocline, then this value should be the same as the vertical temperature gradient just below the mixed layer. In fact, 0.06°C/m is a reasonable value for the gradient in the thermocline, which is near the surface in the eastern Pacific. This increases our confidence in the consistency of the trends in SST and sea level.

The general rise in sea level, which was a statistically significant factor in addition to the tilt up to the East, might be the result of a redistribution of water towards lower latitudes, or a manifestation of an ocean-wide sea level rise. The best estimate of this rise (see Table 2) is 21 mm/decade (assuming no tilting occurred) or 9.5 mm/decade (if tilting did occur). It follows from the work of Cane and Sarachik (1981) that any proportionate change in wind stress throughout the tropical ocean would affect the divergence of meridional currents, thus causing a change in the zonally averaged equatorial sea level. If the winds were zonally uniform, this average change would be exactly one sixth of the change in east minus west equatorial sea level. In contrast, examining the trends found by the regression in the last column of Table 1, the mean sea level increase (0.286 mm/month) is 5/6 of the mean difference between the six eastern stations and the six central and western stations (0.340 mm/month). The observed increase in mean sea level is probably too large to be accounted for by this effect alone. The increase in mean sea level could also be a teleconnection effect of strengthening extratropical westerlies causing a convergence in the tropics, or a result of increased glacial calving or melting. The time scale of the observed sea level variation may be no longer than the two decades of observations used, or it may be a longer term trend, perhaps related to the onset of a long-term climate trend such as CO_2-induced warming.

Acknowledgments. Our thanks to Vince Cardone and Benno Blumenthal for useful discussions, to Jim O'Brien and Dave Legler for the FSU winds, to Dick Reynolds and CAC for the SST data, and to Klaus Wyrtki and the Hawaii Sea Level Center for the tide guage data. This work was supported by Grants NA84-00031 and NOAADAC081 from the US TOGA Office, NOAA and Grant JPL957647 from JPL.

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