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ASSOCIATIONS BETWEEN WEST PACIFIC EQUATORIAL ZONAL WINDS AND EAST PACIFIC SST ANOMALIES

by Christopher C. Collimore

P.I.–William M. Gray

Colorado State University

DEPARTMENT OF ATMOSPHERIC SCIENCE

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By
Christopher C. Collimore

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

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ABSTRACT

Temporal relationships between atmospheric circulations in the equatorial West Pacific and sea surface temperature anomalies (SSTAs) in the East Pacific are examined for all phases of the El Nino–Southern Oscillation cycle. Strong correlations between time series of low–level zonal wind anomalies in the equatorial West Pacific and SSTAs over a broad area of the equatorial East Pacific are shown to exist during all phases of the interannual SST cycle, including El Niños, La Niñas and periods of near normal temperatures. Fluctuations of low–level zonal wind anomalies precede changes in SSTAs, suggesting a simple cause and effect relationship. A similar but weaker relationship exists between East Pacific SSTAs and anomalous tropical cyclone activity in the West Pacific, as measured by tropical cyclone days. Weaker correlations with low–level winds and tropical cyclone activity exist for SST anomalies from a smaller area in the extreme eastern Pacific. West Pacific low–level winds and tropical cyclone activity are also compared to the Southern Oscillation.

An interpretation of all these associations is presented. It is suggested that long term fluctuations of low-level zonal winds in the equatorial West Pacific directly modulate SSTs in the equatorial East Pacific through the ocean Kelvin waves they excite while the ocean Rossby waves they excite are negligible in comparison (the wind of the stress associated with the low-level zonal winds may drive anomalous equatorial zonal ocean currents which also directly influence SSTs). Finally, it is speculated that the combined influences of several phenomena not directly associated with El Niño-Southern Oscillation circulations in the Pacific are the primary modulators of the interannual low-level wind fluctuations. In other words, it is suggested that the interannual fluctuations of low-level winds in the equatorial West Pacific are not necessarily part of feedback loops within the Pacific basin alone.

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LIST OF SYMBOLS AND ACRONYMS

El Niño = The large amplitude warm sea surface temperature anomalies that aperiodically appear in the equatorial East Pacific.

ENSO = El Niño–Southern Oscillation. Refers to the oceanic and atmospheric processes associated with large scale equatorial East Pacific sea surface temperature anomalies and the Southern Oscillation, both of which fluctuate together.

La Niña = The large amplitude cold sea surface temperature anomalies that aperiodically appear in the equatorial East Pacific.

LZWA = Low-level zonal wind anomaly.

QBO = Quasi-Biennial Oscillation of stratospheric wind.

SO = Southern Oscillation: The interannual sea level pressure fluctuations which occur over the globe but primarily in the Southern Hemisphere. Periods of anomalously high pressure in some areas are met by periods of anomalously low pressure in other areas. Defined as the anomalous sea-level pressure difference between Tahiti and Darwin.

SSTA = Sea surface temperature anomaly.

TC = Tropical cyclone. A tropical disturbance with maximum sustained winds greater than or equal to 30 knots.

thermocline = the border between the relatively warm water of the ocean's upper-layer and the cold water beneath.

Walker Circulation = The mean zonal tropospheric circulation in the equatorial Pacific Ocean basin; rising motion in the West, westerlies aloft, sinking in the East and easterlies at low levels.

Chapter 1

INTRODUCTION

It has been previously documented that anomalous westerly low-level winds within 10° (North or South) of the equator over the Pacific Ocean are associated with El Niño events (the massive warm anomalies of sea surface temperatures in the normally cold equatorial East Pacific, see Fig. 1.1). Westerly anomalies in areas west of 170 or 180°W seem to precede El Niño onsets. This connection is evident in El Niño composite studies (Rasmusson and Carpenter, 1982) and in time series studies (Luther et al., 1984). Luther et al., analyzed twelve-month running means of zonal wind stress at several low latitude western ocean islands, and consistently found anomalous westerly stress just before the start of El Niños between 1952 and 1978. This finding indicates that East Pacific Sea Surface Temperatures (SSTs) are linked to the long term behavior of wind stress in the western low latitude ocean. Hickey (1975) and Holland (1985) show similar results.

The most widely accepted explanation for this connection involves ocean Kelvin waves. According to most El Niño theories, anomalous westerly changes with time of the surface winds on or within 2° of the equator in the West Pacific create stresses on the ocean surface which excite eastward propagating, downwelling Kelvin waves in the upper ocean layer. Upon arriving in the East Pacific, these Kelvin waves cause the thermocline (the border between the ocean's upper layer of relatively warm water and colder water below) to descend, thus deepening the normally shallow pool of warm water (Fig. 1.2; Busalacchi and O'Brien, 1981; Cane, 1984). The downwelling Kelvin waves transport water eastward from the comparatively deep reservoir of warm water in the West Pacific, a process which also deepens the East Pacific thermocline (Wyrtki, 1975). This abundance of warm water in the East Pacific is reflected in the SSTs, ie., an El Niño. Note that

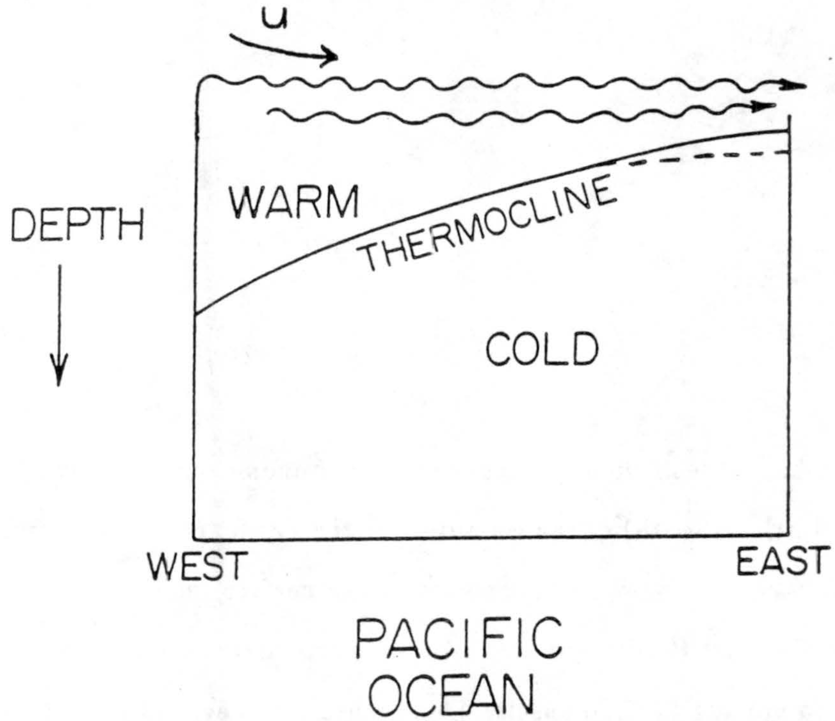

Figure 1.1: El Niño sea surface temperature anomalies (°C) composited from several El Niños near their peak intensity, Rasmusson and Carpenter (1982).

westerly wind change, which does not always require westerly anomalies is considered to initiate El Niño. Many experts feel the eastward transport of warm water takes place in the form of an anomalous surface current induced by the Kelvin waves (Ramage, 1985). In addition, the anomalous westerlies may also drive eastward anomalies of the equatorial zonal ocean currents (not through Kelvin waves but through dynamics associated with the curl of the wind stress on the ocean surface that is usually associated with westerlies) which cause an anomalous import of warm water to the East Pacific (Philander, 1983).

When equatorial surface winds excite downwelling Kelvin waves, they simultaneously excite westward propagating upwelling Rossby waves. It is widely believed these Rossby waves reflect off the western ocean boundary as eastward propagating upwelling Kelvin waves which, upon arriving in the East Pacific weeks or months after the downwelling Kelvin waves, tend to cool SSTs (McCreary, 1984). Upwelling Kelvin waves bring cold lower layer water closer to the surface by raising the thermocline (Busalacchi and O'Brien, 1981). The proximity of cold water to the surface is reflected in SSTs. Furthermore, even though upwelling Kelvin waves propagate eastward, they advect water above the

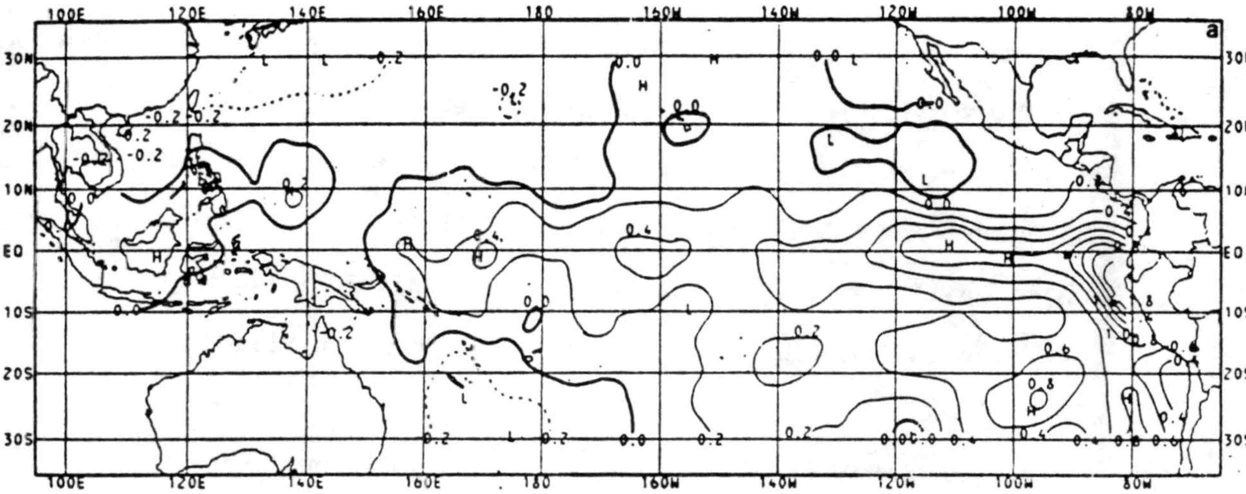

Figure 1.2: A schematic illustrating the direct relationship between surface winds in the equatorial West Pacific and warm sea surface temperature anomalies in the equatorial East Pacific. The winds excite Kelvin waves which alter the depth of the thermocline in the East Pacific. Sea surface temperatures are very dependent on the depth of the thermocline.

thermocline westward, which also tends to raise the thermocline (Dr. Eric Firing, personal communication).

The role of the westerly surface wind anomalies in these theories is to create warming through downwelling Kelvin waves, and later to stop the warming and begin cooling through reflected upwelling Rossby waves. This paper will examine data which suggest that the initiation, intensity and duration of El Niños as well as all other long term SST variations in the equatorial East Pacific are primarily related to the direct influence of Kelvin waves excited by equatorial West Pacific surface winds, with little influence from the indirect effects of the reflected Rossby waves also excited by these winds.

Secondly, the causes of the extended periods of westerly anomalies, and of all interannual fluctuations of equatorial West Pacific surface winds, will be examined. It is widely believed that these fluctuations are part of a positive feedback loop between the winds and East Pacific SSTs. Data will be presented which suggest that the winds behave almost independently of the SSTs; that they are controlled by phenomena not directly related to the SSTs.

Besides the westerly anomalies, another possible precursor to long term changes of East Pacific SSTs may be the amount of TC activity in the tropical West Pacific. Keen (1982) has shown a possible link between cross equatorial cyclone pairs and the onset of El Niño. Ramage (1985) has also connected El Niño onsets with TC activity in the Northwest and Southwest Pacific. A third examination in this paper will show that the precursory relationship of West Pacific to and East Pacific SSTs may go beyond just El Niños and individual events associated with cross equatorial cyclone pairs or TCs at certain locations; it may include all TC activity in the West Pacific tropics and all long term East Pacific SST variations.

The structure of this paper is as follows. Background information on the types of data used are discussed in Chapter 2. In Chapter 3, SST anomalies over a broad area of the equatorial East Pacific are compared to long term variations of the West Pacific low-level zonal wind field near the equator. In Chapter 4, SST data are compared to tropical cyclone (TC) activity in the low latitude West Pacific. Low-level winds and TC activity are also compared to the Southern Oscillation (SO). In Chapter 5, an interpretation of the connections between the low-level wind, TC and SST fluctuations is presented. Finally, speculation on the physical mechanisms driving the observed wind fluctuations is presented in Chapter 6.

Chapter 2

DATA

Data used in these studies include wind measurements at five West Pacific islands and at several other equatorial sites scattered around the globe. Additional data include three sea surface temperature data sets, a pressure based index of the Southern Oscillation and information on the frequency of tropical cyclone days in the West Pacific. Monthly mean values were computed for all these data and used as the basic elements for analysis. All monthly mean data values used in the studies are given in tables contained in Appendix A.

2.1 Low-level Data

Low-level wind data from five equatorial West Pacific islands have been analyzed (see Table 2.1 and Fig. 2.1). Daily rawinsonde reports for each island except Tarawa were obtained from the National Center for Atmospheric Research. Tarawa wind data were obtained from Dr. D. E. Harrison of the NOAA Pacific Marine Environmental Lab (1949-80) and from Mr. A. John Harris, Data Center, New Zealand Meteorological Service (1981-88). Honiara wind data after 1977 were obtained from Monthly Climatic Data for the World. The daily wind observations were decomposed into zonal and meridional components. The zonal components were then converted into simple monthly means. Tarawa data from 1949 to 1980 and Honiara data after 1977 were obtained as monthly means.

The data sets for each island are fairly complete. The number of months without sufficient observations for computing a reliable mean value ranges from 0.1% to 4% of the total possible months, depending on the specific data set. Values for the infrequent

Table 2.1: Low-level wind data from the islands used in this chapter.

Island	Location	Level of Data	Record Length	Number of Values (n)
Koror	07°20'N,134°29'E	850 mb	1952-86	420
Truk	07°28'N,151°51'E	850 mb	1952-86	420
Honiara	09°27'S,159°57'E	700 mb	1959-86	314
Majuro	07°05'N,171°23'E	850 mb	1955-86	384
Tarawa	01°21'N,172°55'E	surface	1949-86	456

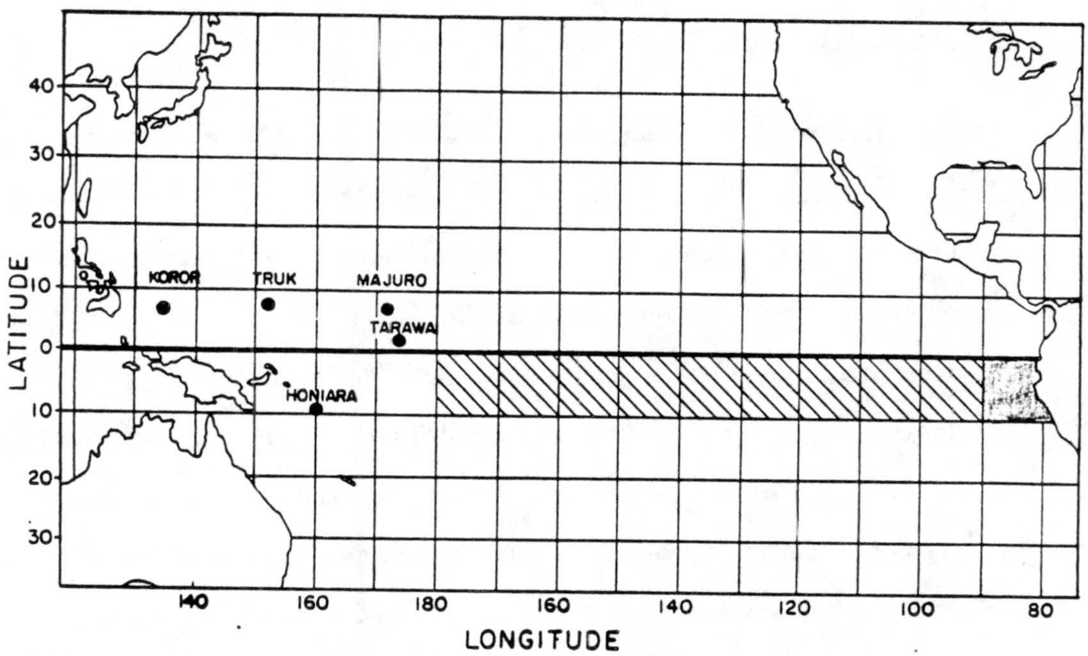

Figure 2.1: Map of the West Pacific islands for which low-level zonal wind data were obtained and the (shaded) area in the East Pacific for which SST anomalies were obtained.

missing months were either obtained from Monthly Climatic Data for the World or linearly interpolated from surrounding months, with consideration given to winds at nearby islands. No data were available at Honiara from July 1977 through April 1979.

The annual cycle was removed from each time series by subtracting the corresponding climatological monthly mean from each individual monthly value. The end result is a time series of monthly mean zonal wind anomalies for each station. (The climatological monthly means were computed using the entire records from each data set.)

The 850 mb pressure level was chosen to represent surface winds over the Pacific Ocean. Previous investigations have shown that 850 mb winds provide good approximations of surface winds in the tropics. The 850 mb level is low enough that winds are similar to those at the surface yet high enough to be only minimally affected by local boundary layer effects. The 850 mb level is also considered a reliable, well measured level in general. Only surface wind measurements were available at Tarawa, but Tarawa is a small island with low terrain and any boundary layer effects should be minimal in long term means. Honiara is on a relatively large island (Guadalcanal) with high terrain that might interfere with the 850 mb flow. The 700 mb level should be above these effects, and therefore winds at this level were analyzed in place of 850 mb winds at Honiara. Luther, et al. (1984) have shown that low-level wind data from island stations are more reliable than those obtained from ship tracks in the West Pacific.

Figure 2.2 shows the time series of the monthly mean low-level zonal wind anomalies for each island. Also shown are six-month running means of the monthly anomalies. Correlation coefficients between the six-month mean anomalies for each pair of islands are listed in Table 2.2. In general, the coefficients are high. Luther and Harrison (1984) showed similar results. The time lags for peak correlation between winds from each pair of NW Pacific islands illustrate the well known eastward propagation of low-level zonal wind anomalies in this area (Gutzler, et al., 1987). For the purposes of this paper, it is important that these zonal wind anomalies approximate anomalies within 2° of the equator. Tarawa (1°N) is within 2° of the equator. The other stations are farther from the equator than 2°, but considering their high correlations with Tarawa, and considering how consistent over a large area the trades and equatorial westerlies are known to be, the data from Koror, Truk, Honiara and Majuro may be considered fairly representative of the zonal surface winds on the equator in the West Pacific. It is reasonable to assume that wind observations from these islands are especially representative of the equatorial zonal winds at their respective longitudes, especially since Majuro and Tarawa, which are nearly at the same longitude, correlate so well.

Table 2.2: Peak correlation coefficients between the six-month running means of 850 mb zonal wind anomalies for each possible pair of islands from the set of Koror, Truk, Honiara (700 mb winds), Majuro and Tarawa (surface winds). The lag, in months, for peak correlation is given in parentheses (negative lag means station on top row lags station in left column). The longitude of each island is listed under the island names.

	Koror 134°E	Truk 152°E	Honiara 160°E	Majuro 171°E	Tarawa 173°E
Koror	*	.80(-1)	.39(-4)	.57(-3)	.50(-3)
Truk	.80(1)	*	.54(-3)	.83(-2)	.68(-2)
Honiara	.39(4)	.54(3)	*	.65(2)	.71(0)
Majuro	.57(3)	.83(2)	.65(-2)	*	.78(-1)
Tarawa	.50(3)	.68(2)	.71(0)	.78(1)	*

Wind data at 850 mb for Singapore (2°N, 104°E), Trivandrum (8°N, 76°E), Nairobi (2°S, 36°E; 700 mb winds), Manaus (3°S, 60°W) and Ascension (8°S, 15°W) were also analyzed. These data were obtained from the same sources listed previously and prepared in the same manner as was used for the West Pacific data.

2.2 SST Data

The SST data, shown in Fig. 2.3, were obtained from Dong (1987). The SST time series is comprised of three-month running mean SST anomalies (SSTAs) for the area shown in Fig. 2.1. The SST data used to make the monthly mean analysis presented briefly in Chapter 3 were obtained from the Comprehensive Ocean Atmosphere Data Set (COADS) at NCAR for the same area in Fig. 2.1, but in montly mean form. Large scale East Pacific SST anomalies between 0° and 10°S are usually similar to those between 0° and 10°N (Rasmusson and Carpenter, 1982), so the values between 0° and 10°S should

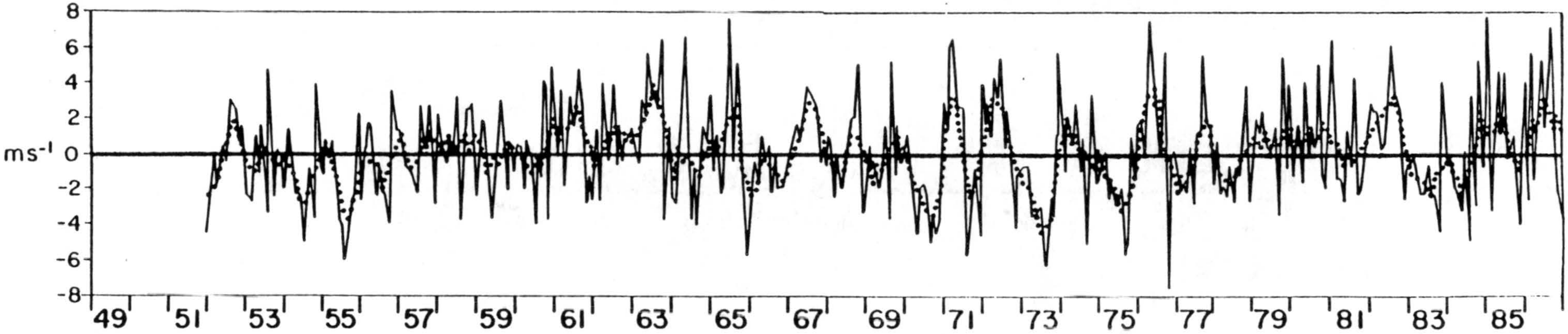

Figure 2.2a: Monthly means (solid lines) and six-month running means (dotted lines) of the 850 mb zonal wind anomalies at *Koror*.

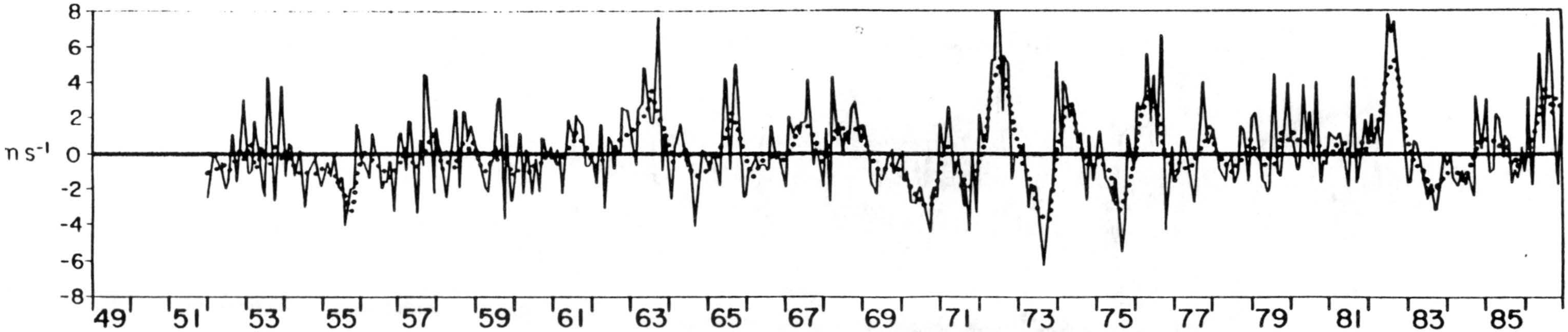

Figure 2.2b: Monthly means (solid lines) and six-month running means (dotted lines) of the 850 mb zonal wind anomalies at *Truk*.

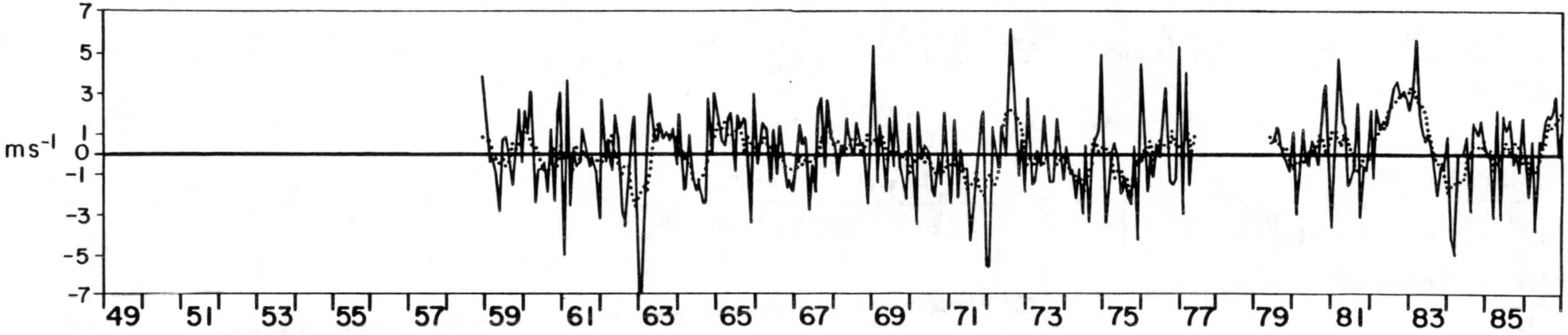

Figure 2.2c: Monthly means (solid lines) and six-month running means (dotted lines) of the 700 mb zonal wind anomalies at *Honiara*.

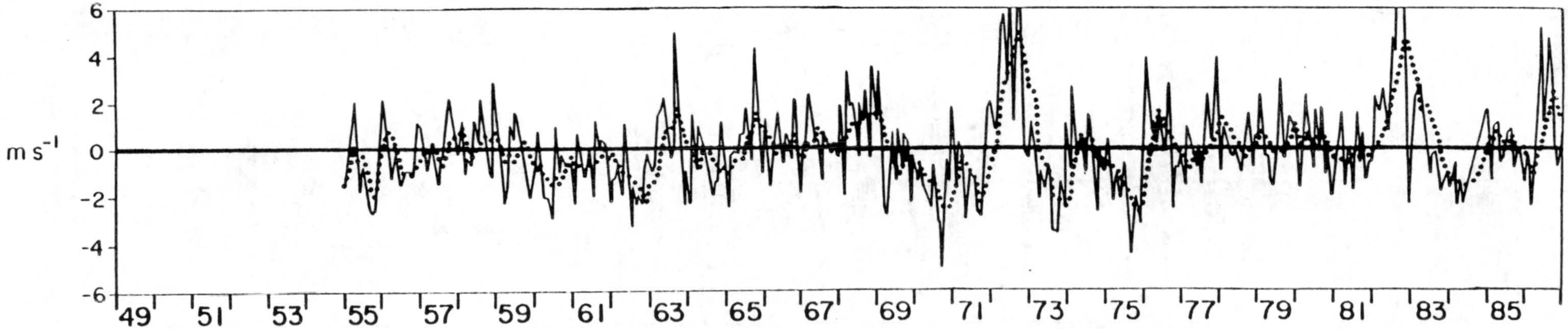

Figure 2.2d: Monthly means (solid lines) and six-month running means (dotted lines) of the 850 mb zonal wind anomalies at *Majuro*.

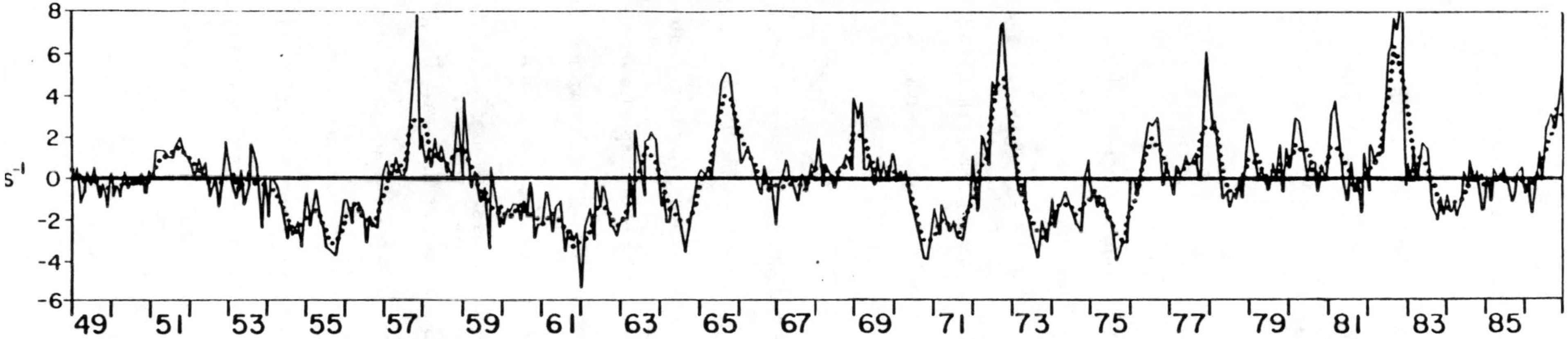

Figure 2.2e: Monthly means (solid lines) and six-month running means (dotted lines) of the surface zonal wind anomalies at *Tarawa.*

be representative of the anomalies between 10°S and 10°N. Both the Dong and COADs SSTA values are similar to those from other sources (Weare, 1986). The 1982-83 El Niño does not show quite as strongly on the COADs data, but most analyses in this paper are with the Dong values. Earlier SSTA data for the Central Pacific may not be as accurate as more recent data due to fewer ship tracks (see Fig. 2.4). Therefore, the more recent SSTA data are considered more reliable and should be given more consideration when comparing them to other variables.

2.3 Southern Oscillation Data

Southern Oscillation (SO) data were obtained from N. Nicholls of the Bureau of Meteorological Research Center (BMRC), Australia. The SO is defined as the anomalous Tahiti minus Darwin sea level pressure. As Philander (1985) noted, the most likely cause of the SO is changes in East Pacific SSTs. Figure 2.3 shows that the SSTAs and the SO index are almost exactly out of phase; they correlate at -.75 with a zero lag.

2.4 Tropical Cyclone Data

Information on West Pacific tropical cyclones (TCs) was obtained from two separate data sets; one for each hemisphere. All Northwest Pacific TC data were obtained from the best track reports compiled at the Joint Typhoon Warning Center at Guam. Best track reports contain information on TC location and atmospheric variables within TCs as determined by reconnaissance flights and synoptic satellite observations, and cover all TCs from 1945 on. Reports are made four times a day during the life of a TC and usually start well before the tropical storm stage (30 knots). This study uses information from 1949 on. The information on Southwest Pacific TCs (defined as those east of 145°E) was acquired from the Naval Environmental Prediction Research Facility in Monterey, CA. Tropical cyclone location and atmospheric variables are estimated from ship and rawinsonde reports in the vicinity of the TCs four times a day. Since the early 1970s, satellites have been used in combination with ship and rawinsonde reports to estimate TC parameters. Thus, the SW Pacific data were taken using methods with significant temporal inconsistencies

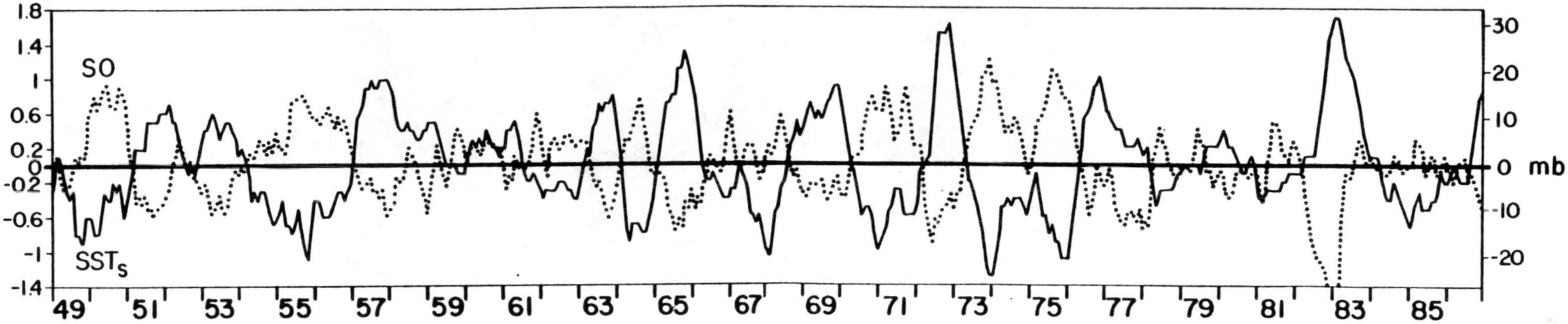

Figure 2.3: Three-month running mean SST anomalies for the East Pacific between 0° and 10°S, 90°W and 180° (solid line) versus three-month running means of the Southern Oscillation as defined by the anomalous sea-level pressure difference between Tahiti and Darwin (dotted line).

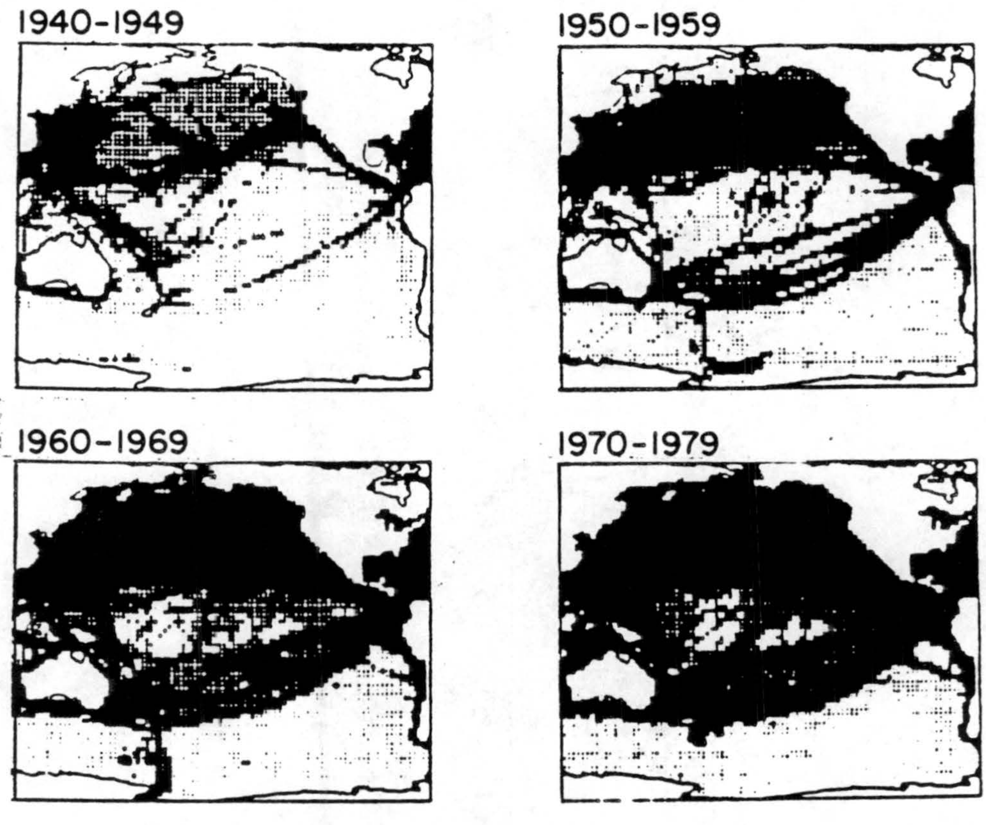

Figure 2.4: Decadal totals of sea-surface temperature observations (70°N-78°S; 110°E-68°W). The three indicated dot sizes show at least 10,100 or 400 observations in a 2° box per decade (i.e., respective averages over 120 months of 0.08, 0.83, or 3.33 observations per month). Reprinted from Woodruff, et al., "A Comprehensive Ocean Atmosphere Data Set", Bulletin of the American Meteorological Society, Vol. 68, No. 10, October 1987.

whereas aircraft reconnaissance was the primary method for estimating TC parameters throughout the study period in the NW Pacific. Because aircraft reconnaissance was the primary method of estimation in the NW Pacific, the NW Pacific data are considered more reliable than those from the SW Pacific.

The climatological mean number of TC days for each month of the year was calculated for the NW and the SW Pacific areas using the entire TC record for each basin and for both basins added together, using both records. Tropical cyclone days were defined by dividing the total number of maximum wind observations for each storm by four. Figure 2.5 is a plot of the number of TC days for each month minus the climatological mean in the West Pacific between 20°N and 20°S, the NW Pacific equatorward of 20°N, and the SW Pacific equatorward of 20°S. A strong seasonality of NW and SW Pacific TC day anomalies exists even though the annual cycle has been removed. This is due to a strong seasonality of TC frequency. The SW Pacific has no TCs during the southern winter. Although NW Pacific TCs are observed year round, they most often form during the Northern Hemisphere late summer and early fall. The TC day anomalies for the entire tropical West Pacific, however, show much less seasonality because the SW Pacific tends to be relatively active when the NW Pacific is relatively inactive, and vice versa.

2.5 Final Data Notes

In order to enhance long term trends, many of the time series in this paper were smoothed by use of simple three, six and twelve-month running means. The value for each six-month (twelve-month) mean was assigned to the fourth (seventh) month of each sequence of six (twelve) months that were averaged (see Figs. 3.4 and 4.2).

Monthly mean values for all of the data sets used in this paper are listed in Appendix A.

All correlations presented in this paper are significant at the 5 percent and 1 percent levels.

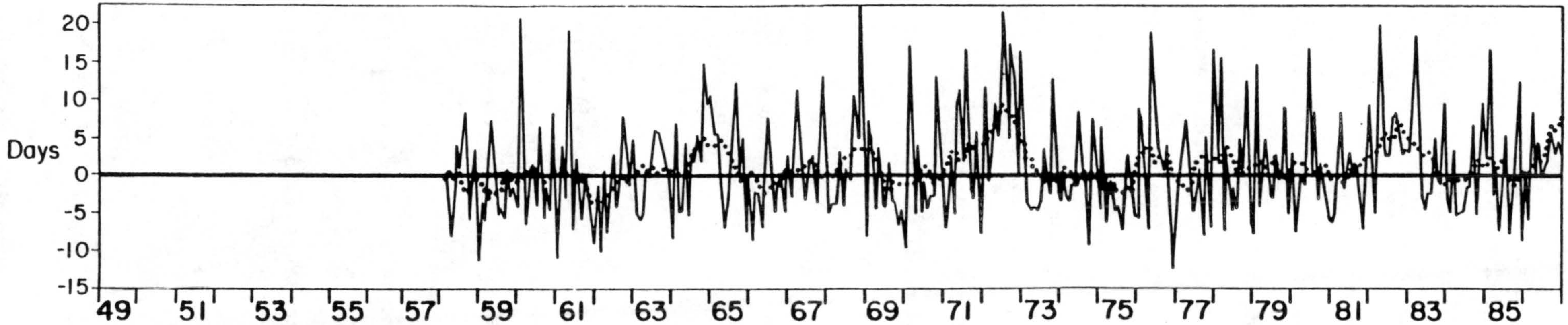

Figure 2.5a: Monthly tropical cyclone day anomalies in the West Pacific, between 20°N and 20°S (solid line), and twelve-month running means of the above (dotted line).

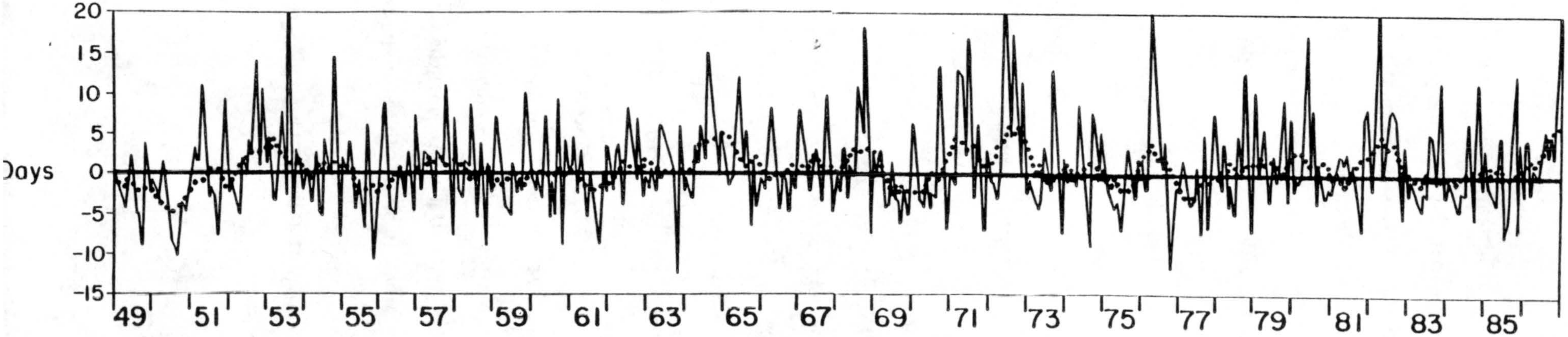

Figure 2.5b: Monthly tropical cyclone day anomalies in the NW Pacific, equatorward of 20°N (solid line), and twelve-month running means of the above (dotted line).

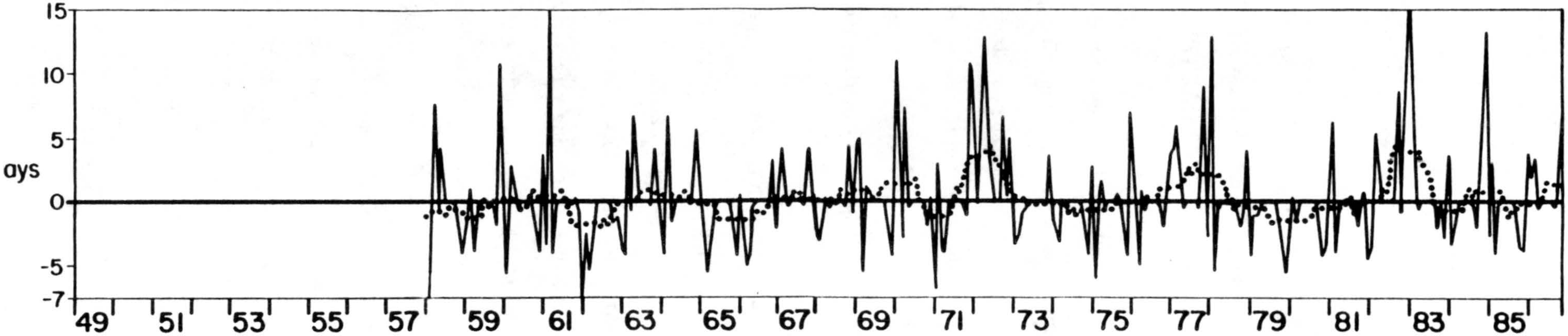

Figure 2.5c: Monthly tropical cyclone day anomalies in the SW Pacific, equatorward of 20°S (solid line), and twelve-month running means of the above (dotted line).

Chapter 3

THE RELATIONSHIP BETWEEN LONG TERM FLUCTUATIONS OF EQUATORIAL WEST PACIFIC LOW-LEVEL ZONAL WIND ANOMALIES AND EQUATORIAL EAST PACIFIC SST ANOMALIES

Figure 3.1 shows six-month running means of low-level zonal wind anomalies (LZWAs) from each of the West Pacific islands versus six-month running means of the Sea Surface Temperature Anomalies (SSTAs) from the area of the equatorial East Pacific delineated in Fig. 2.1. Figure 3.2 is a schematic showing the temporal relationship of the months used to calculate the LZWA and SSTA six-month running means. The SSTA time series corresponds well with the LZWA time series for each island, especially Majuro and Tarawa which are farther east. The relationship starts to weaken at the far western island of Koror (134.5°E), but there are strong correlations with LZWAs over the 20° longitude band from roughly 150°E to 170°E. Easterly anomalies seem to have the same relationship with La Niñas (the massive cold SST anomalies in the East Pacific) that westerly anomalies have with El Niños. When the change with time of LZWAs is westerly, SSTAs become warmer a few months later; when LZWAs become increasingly easterly, SSTAs become colder shortly afterward. The relationship even holds during periods of near average conditions. For instance, between mid-1977 and early 1981, and again during 1984 and 1985, the change with time of LZWAs was near zero and SSTAs were close to normal. Moreover, the shapes of each of the LZWA curves, especially those for Majuro and Tarawa, match the shape of the SSTA curve: the duration and intensity of the SSTAs follow the duration and intensity of the LZWAs. The close correspondence exists regardless of the time of year. Occasionally the association between SSTAs and LZWAs at one or more islands degrades somewhat, as with Truk in 1974. But the winds from one island are not perfect representations of the winds all across the equatorial West Pacific. When all the islands are considered as a group, a strong LZWA–SSTA connection occurs in nearly all years. For example, the LZWA-SSTA correlation was weak in 1974 at Truk, but fairly strong at Majuro.

Peak correlation coefficients between the six-month running means of East Pacific SSTAs and LZWAs at each island are listed in Table 3.1. Coefficients using only more recent data are listed because a lack of SST measurements may have lowered the correlations in the earlier years (see section 2.2, Fig. 2.4). The coefficients are high. Tarawa LZWAs, closest to the equator, correlate the best since 1961 with a coefficient of .73. In general, the farther east the islands, the higher the correlations with SSTAs. Coefficients are maximum for all islands when SSTAs lag LZWAs as can be surmised in Fig. 3.1. SSTAs generally lag each island's LZWAs regardless of the time of year. As shown in Fig. 3.1, lag associations break down with Majuro in 1965, with Truk in 1964 and with Koror in 1961, 1967 and 1985. Every year, however, LZWAs from most of the islands precede SSTA changes by the intervals with which they have their peak correlations with SSTAs.

Table 3.1: Correlation coefficients (r) between six-month running means of 850 mb zonal wind anomalies at Koror, Truk, Honiara (700 mb winds), Majuro and Tarawa (surface winds) versus six-month running means of SST anomalies in the area 0-10°S, 180°-90°W. The number of months SST anomalies lag winds for peak correlation is in parentheses. The data run through 1986.

Island	Year Record Starts	r	r since 1961	r since 1971
Koror (134°E)	1952	.44 (5)	.43 (5)	.54 (6)
Truk (152°E)	1952	.55 (4)	.59 (4)	.72 (5)
Honiara (160°E)	1959	.58 (2)	.59 (2)	.67 (3)
Majuro (171°E)	1955	.65 (4)	.71 (4)	.86 (4)
Tarawa (173°E)	1949	.74 (2)	.74 (2)	.82 (3)

It is important to note that the differences between peak correlation coefficients and coefficients at slightly longer or shorter lags are generally not significant. For example, LZWAs from Honiara, for all available years, correlate with SSTAs at .58 when SSTAs are lagged after them by two and three months. The coefficient at two months is higher only

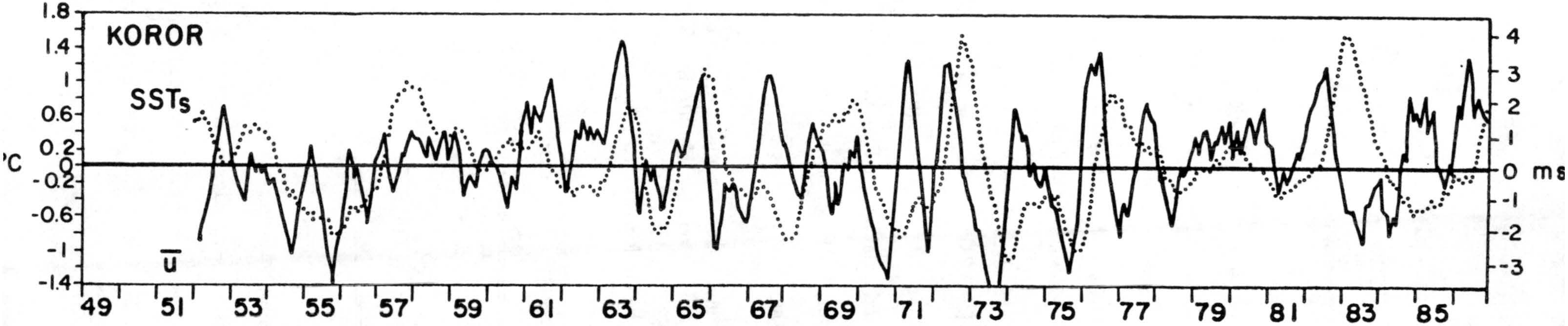

Figure 3.1a: Six-month running means of the 850 mb zonal wind anomalies at *Koror* (7°N, 134°E) (solid line) versus six-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

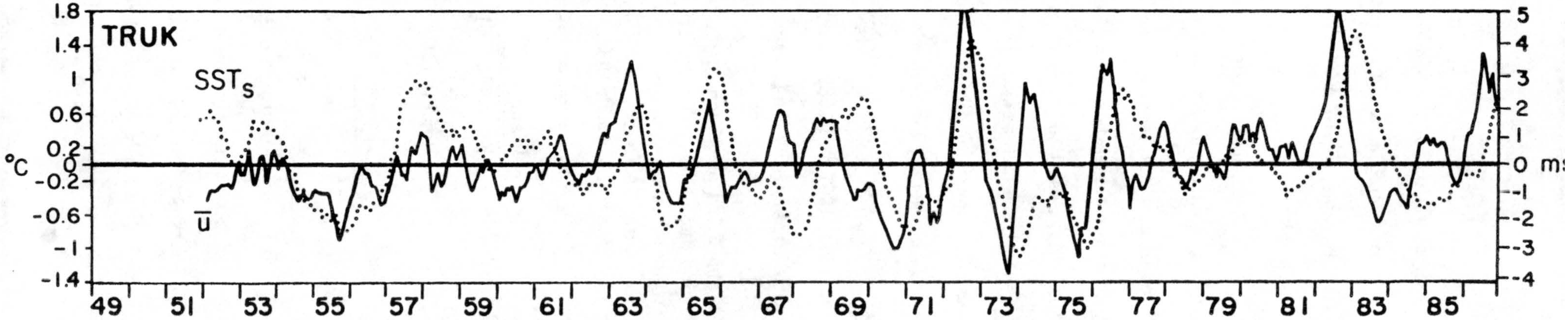

Figure 3.1b: Six-month running means of the 850 mb zonal wind anomalies at *Truk* (7°N, 152°E) (solid line) versus six-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

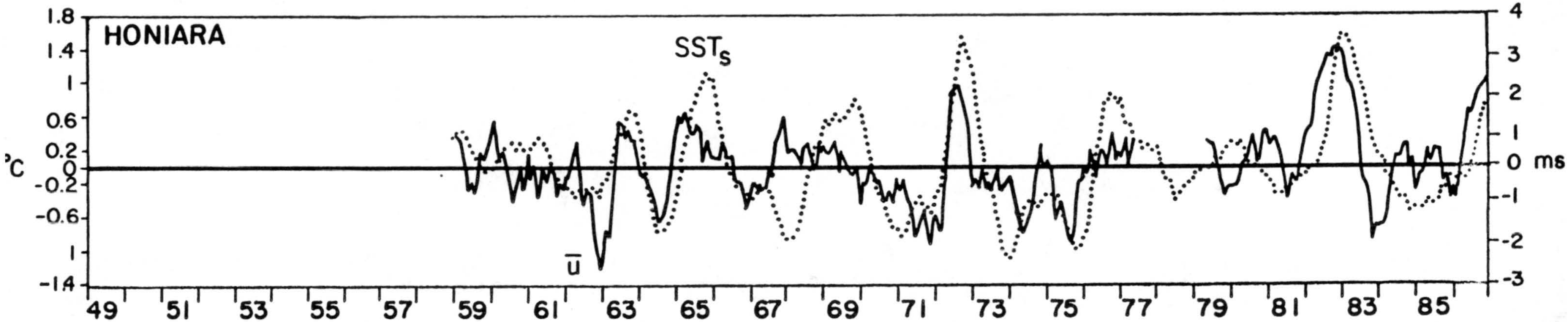

Figure 3.1c: Six-month running means of the 700 mb zonal wind anomalies at *Honiara* (9.5°S, 160°E) (solid line) versus six-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

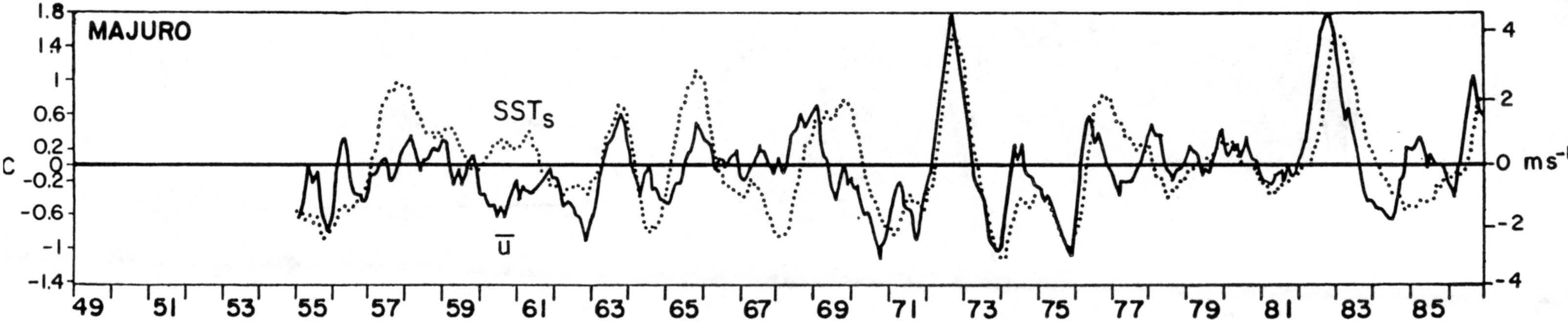

Figure 3.1d: Six-month running means of the 850 mb zonal wind anomalies at *Majuro* (7°N, 171°E) (solid line) versus six-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

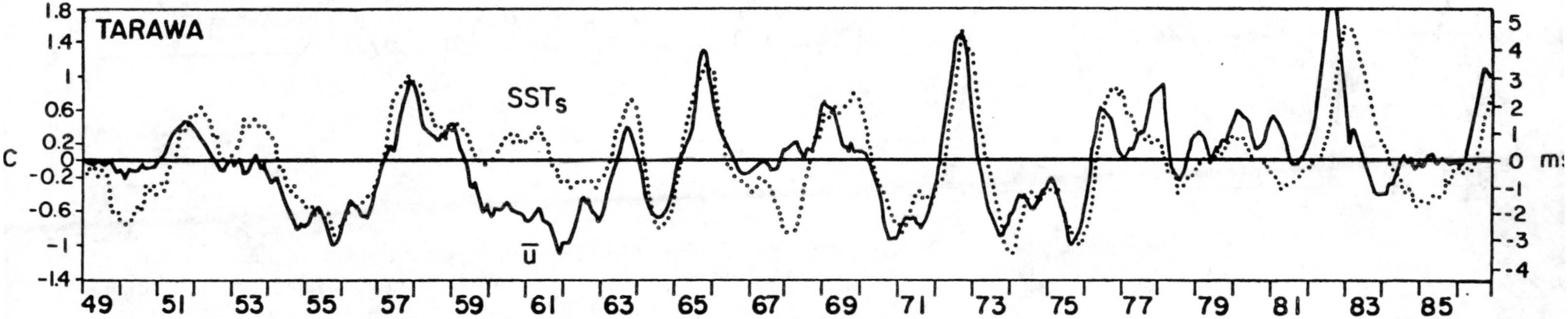

Figure 3.1e: Six-month running means of the surface zonal wind anomalies at *Tarawa* (2°N, 173°E) (solid line) versus six-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

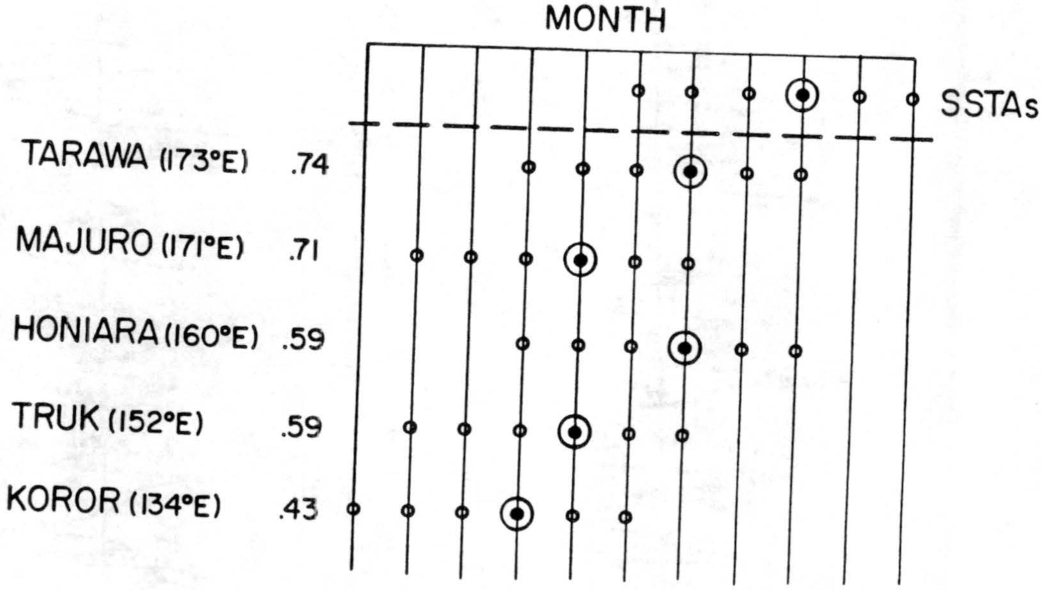

Figure 3.2: Schematic illustrating the temporal relationship between the months used to calculate the peak correlation coefficients between six-month running means of West Pacific island low-level zonal wind anomalies and six-month running means of East Pacific SST anomalies from $0° - 10°S$, $180° - 90°W$. The values of the running means are assigned to the darkened months and the lag shown between zonal wind and SST anomalies corresponds to the peak correlation between the two variables since 1961. The coefficient of peak correlation is listed next to each island.

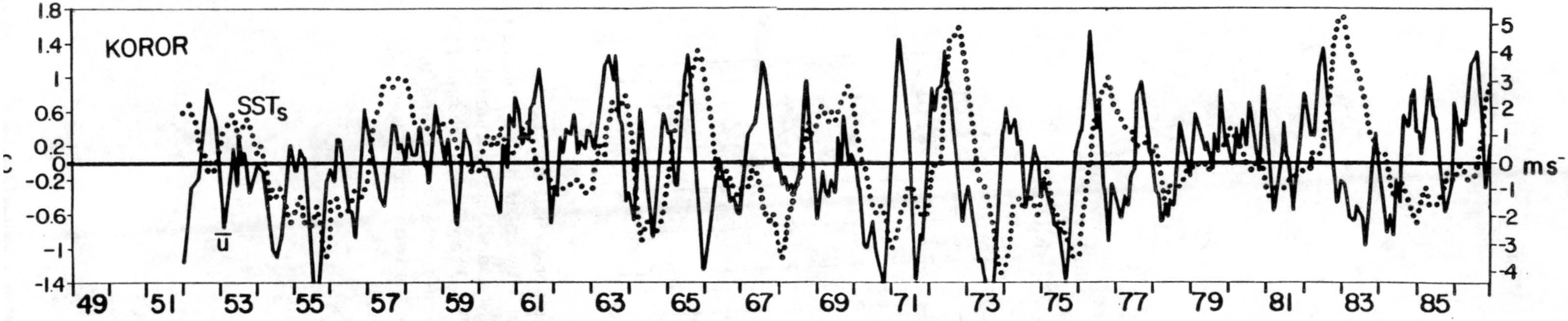

Figure 3.3a: Three-month running means of the 850 mb zonal wind anomalies at *Koror* (7°N, 134°E) (solid line) versus three-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

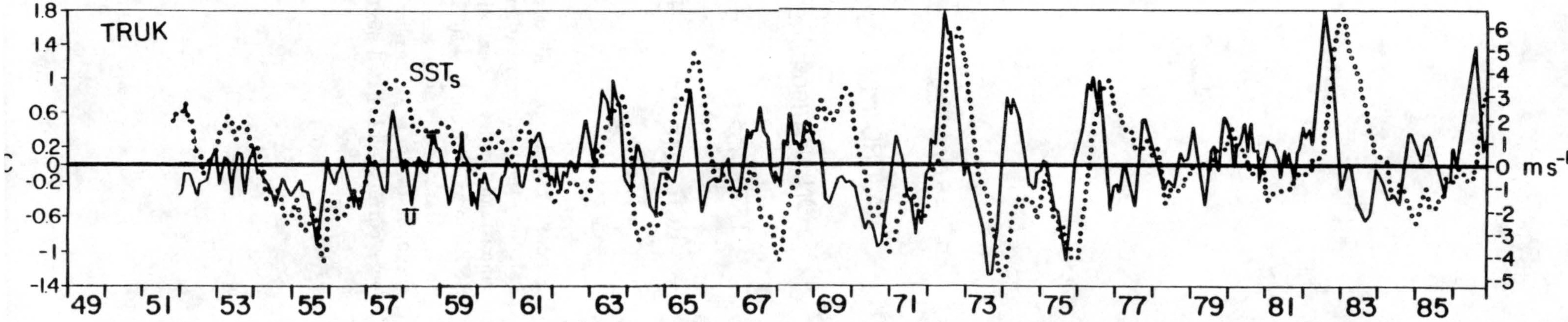

Figure 3.3b: Three-month running means of the 850 mb zonal wind anomalies at *Truk* (7°N, 152°E) (solid line) versus three-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

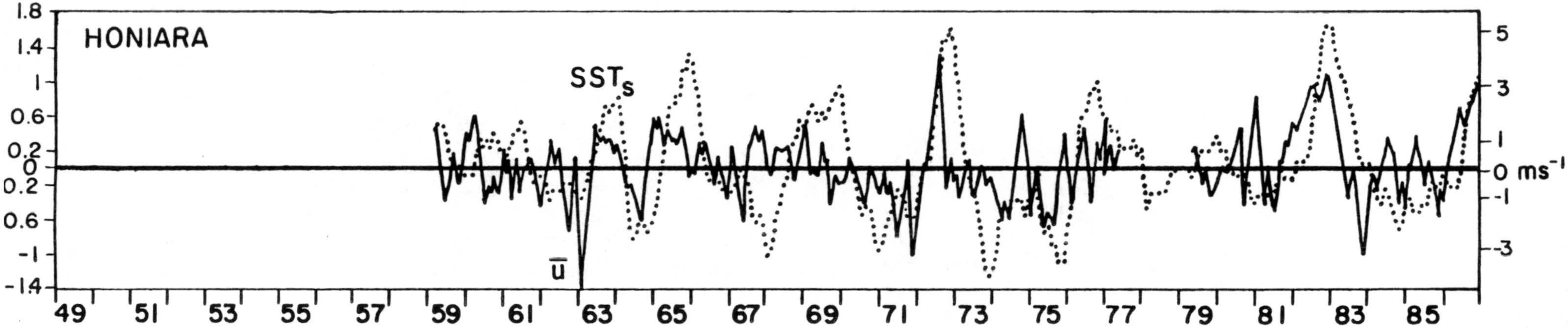

Figure 3.3c: Three-month running means of the 700 mb zonal wind anomalies at *Honiara* (9.5°S, 160°E) (solid line) versus three-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

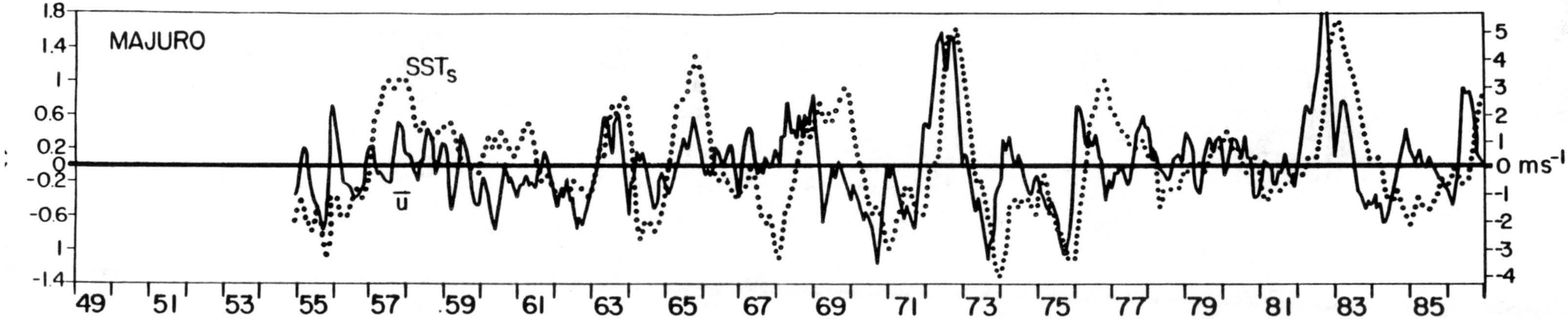

Figure 3.3d: Three-month running means of the 850 mb zonal wind anomalies at *Majuro* (7°N, 171°E) (solid line) versus three-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

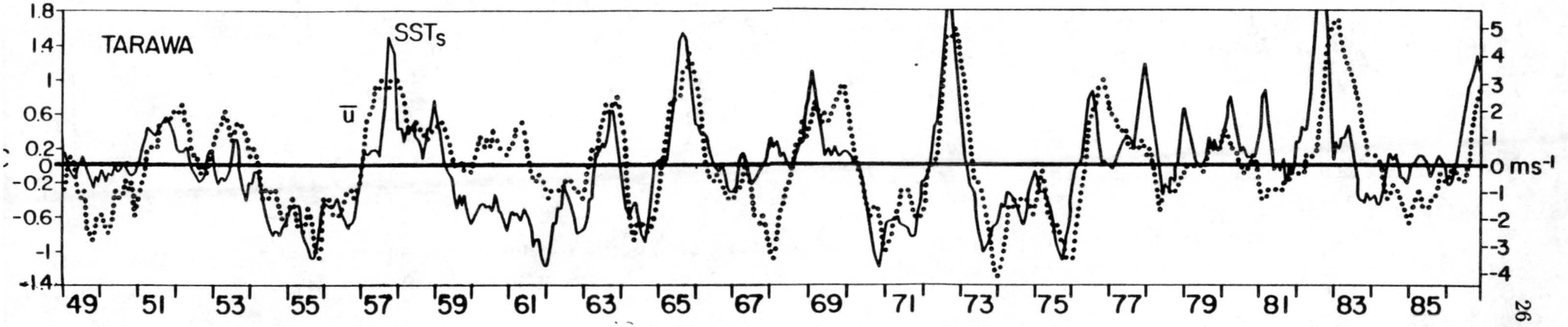

Figure 3.3e: Three-month running means of the surface zonal wind anomalies at *Tarawa* (2°N, 173°E) (solid line) versus three-month running means of the SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

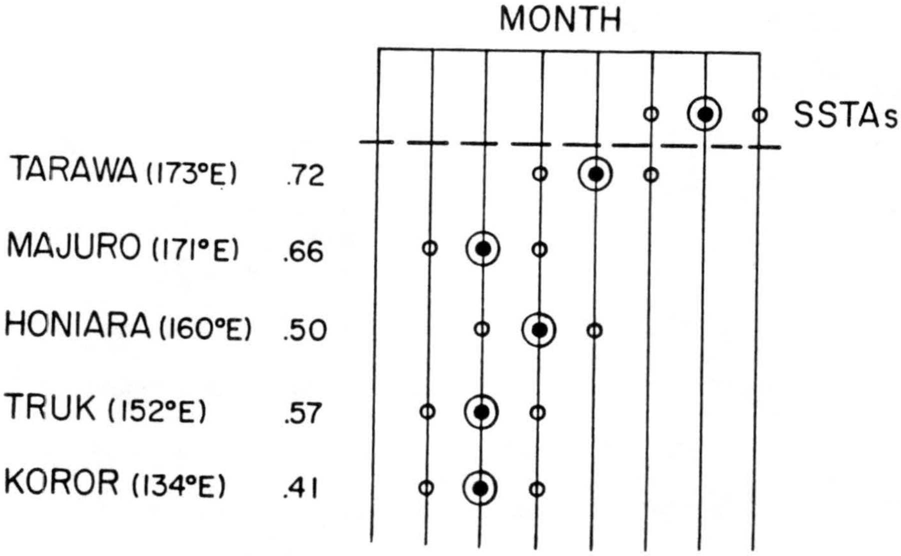

Figure 3.4: Schematic illustrating the temporal relationship between the months used to calculate the peak correlation coefficients between three-month running means of West Pacific island low-level zonal wind anomalies and three-month running means of East Pacific SST anomalies from 0° – 10°S, 180° – 90°W. The values of the running means are assigned to the darkened months and the lag shown between zonal wind and SST anomalies corresponds to the peak correlation between the two variables since 1961. The coefficient of peak correlation is listed next to each island.

when carried out to the thousandths digit. Insignificant differences between correlations at slightly different lags may explain why Tarawa and Majuro have peak correlations with SSTAs which occur two months apart, even though they are at nearly the same longitude. However, difference in latitude between the two stations may be related to the difference in lags for peak correlation. The important point is that the peak correlations for all the islands occur at approximately three months lag, which is consistent with Kelvin wave theory, which was discussed in Chapter 1. In this regard, inspection of all the correlations in Table 3.1 reveals that LZWAs from the more western islands show a slight tendency to precede SSTAs by longer intervals than those from the more eastern islands, especially when the NW Pacific islands are considered.

Although the six-month running means of LZWAs and SSTAs correlate very well, they are of little use in a predictive sense because the months comprising each parameter overlap at peak correlation (see Fig. 3.2). Therefore, three-month running means of the LZWAs and SSTAs were compared to reduce the overlap. Figure 3.3 shows the three-month mean time series of the LZWAs and SSTAs, and Table 3.2 lists the peak correlation coefficients between these two parameters. Figure 3.4 illustrates the temporal relationship between the months used to calculate the LZWA and SSTA three-month means. The same sort of relationship exists as with the six-month running means. The SSTAs correlate best with the LZWAs when lagged after them by two to four months, and the highest correlations are with the LZWAs from the most eastern islands. The correlations are nearly as high as those for the six-month means, and should prove to be more useful in a predictive sense (compare Figs. 3.2 and 3.4), as will be discussed in Chapter 5. For that matter, the monthly values of LZWAs and SSTAs correlate fairly well, especially if the LZWAs from Tarawa are considered (see Table 3.3).

3.1 Low–level Zonal Wind Anomalies Versus the Southern Oscillation

A strong relationship also exists between equatorial West Pacific LZWAs and the Southern Oscillation (SO). This is to be expected since the Southern Oscillation is dependent on East Pacific SSTs (Philander, 1985a; Rasmusson, 1984). Figure 3.5 shows

Table 3.2: Correlation coefficients (r) between three-month running means of 850 mb zonal wind anomalies at Koror, Truk, Honiara (700 mb winds), Majuro and Tarawa (surface winds) versus three-month running means of SST anomalies in the area 0-10°S, 180°-90°W. The number of months SST anomalies lag winds for peak correlation is in parentheses. The data run through 1986.

Island	Year Record Starts	r	r since 1961	r since 1971
Koror (134°E)	1952	.41 (4)	.41 (4)	.49 (5)
Truk (152°E)	1952	.52 (4)	.57 (4)	.68 (4)
Honiara (160°E)	1959	.50 (3)	.50 (3)	.60 (3)
Majuro (171°E)	1955	.60 (3)	.66 (4)	.80 (4)
Tarawa (173°E)	1949	.71 (2)	.72 (2)	.78 (3)

Table 3.3: Correlation coefficients (r) between monthly means of the 850 mb zonal wind anomalies at Koror, Truk, Honiara (700 mb winds), Majuro and Tarawa (surface winds) versus monthly means of the SST anomalies from the area 0-10°S, 180°-90°W. The number of months SST anomalies lag winds for peak correlation is in parentheses. The wind data run through 1986. The SST data record is for 1951-86.

Island	Year Record Starts	r	r since 1961	r since 1971
Koror (134°E)	1952	.34 (3)	.34 (3)	.42 (4)
Truk (152°E)	1952	.47 (3)	.51 (3)	.56 (4)
Honiara (160°E)	1959	.29 (3)	.30 (3)	.35 (2)
Majuro (171°E)	1955	.52 (3)	.57 (3)	.65 (3)
Tarawa (173°E)	1949	.71 (2)	.72 (2)	.75 (2)

six-month running means of the LZWAs from Truk and the SO index. The curves fluctuate together in much the same way as do the curves for Truk's LZWAs and the East Pacific SSTAs (Fig. 3.3b). Table 3.4 lists the correlation coefficients between the SO index and the LZWAs from each West Pacific island. Note how similar the values are to those in Table 3.1, and that the SO generally lags after the winds at peak correlation. The SO values are most similar to coefficients for SSTA data from 1961 and afterward. Again, the lower values for earlier SSTA data are likely due to the lack of SSTA observations during the earlier years. In short, the SO appears intimately tied to equatorial West Pacific LZWAs with the physical link between the two most likely being the East Pacific SSTAs.

Table 3.4: Correlation coefficients (r) between six-month running means means of the 850 mb zonal wind anomalies at Koror, Truk, Honiara (700 mb winds), Majuro and Tarawa (surface winds) versus six-month running means of the Southern Oscillation Index as defined by the anomalous sea level pressure difference between Tahiti and Darwin. The number of months the SO index lags winds for peak correlation is in parentheses. The data run through 1986.

Island	Year Record Starts	r
Koror (134°E)	1952	-.49 (4)
Truk (152°E)	1952	-.60 (3)
Honiara (160°E)	1959	-.72 (0)
Majuro (171°E)	1955	-.70 (3)
Tarawa (173°E)	1949	-.80 (1)

The LZWAs at Honiara correlate best with the SO at zero lag. Honiara is at a latitude where the SO has a fairly strong influence, and the SO may modulate the winds at Honiara to some degree. But this is unlikely considering the lead-lag relationship between Honiara's LZWAs and East Pacific SSTs and the lead-lag relationship between the SO and LZWAs at the other islands. Alternatively, the fact that the peak correlation does not occur when the SO lags Honiara's LZWAs, as with the other islands, may be related to the fact that 700 mb (rather than 850 mb) LZWAs from Honiara were analyzed, that Honiara is farther from the equator than any of the other islands, or that Honiara is farther south than any of the other islands. However, it is not unlikely that Honiara's LZWAs are, in reality,

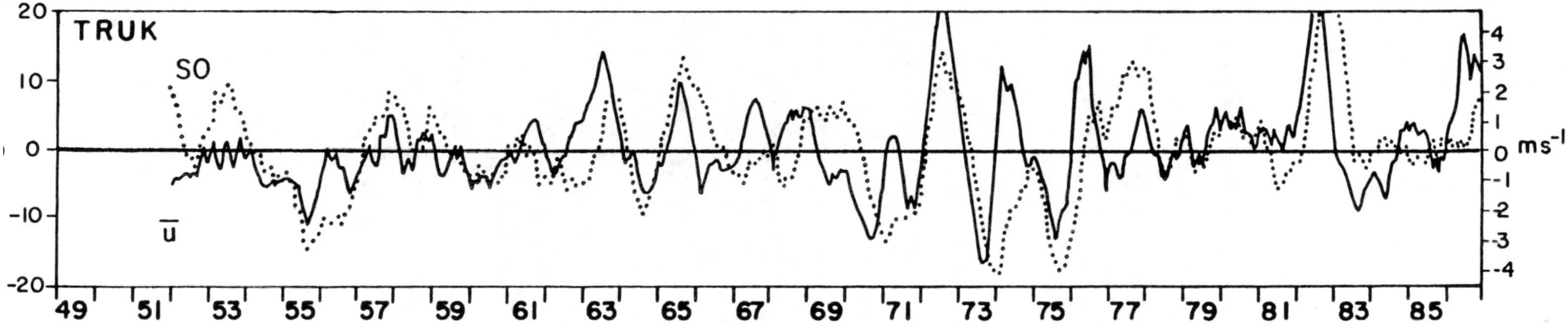

Figure 3.5: Six-month running means of the 850 mb zonal wind anomalies at Truk, 7.5°N, 152°E, (solid line) versus six-month running means of the Southern Oscillation Index, defined as the anomalous difference between the sea level pressures at Darwin and Tahiti (dotted line). The sign of the SO index has been reversed so that the time variations of the two time series are more easily compared.

precursory to the SO. The correlation between the two is .70 when the SO index lags Honiara's LZWAs by 1 month. The difference between this correlation and the one of .72 at zero lag is not significant.

3.2 Summary

Strong correlations have been presented between long term (one month or longer) fluctuations of surface zonal winds, or surface zonal winds approximated by 850 or 700 mb zonal winds; from islands over a 35° longitude band (roughly 135°-170°E) in the equatorial West Pacific and long term fluctuations of equatorial East Pacific SSTs. The relationship is clearly seen when monthly, three-month or six-month running means of both parameters are compared. For most islands, it is best seen when the longer term (season to season and longer)variations are considered; the six-month means correlate highest. The LZWAs from Tarawa correlate exceptionally well and almost equally well regardless of whether six-month, three-month or montly means are considered. The close correspondence between LZWAs and SSTAs is not restricted to El Niños but is present during all phases of the SST cycle and all times of year, with SSTA variations lagging variations of the LZWAs by one to four months. Westerly (easterly) wind changes are followed by warming (cooling) of the SSTs. Periods of near zero wind change are followed by periods of near normal SSTs. In general, the farther east the islands are, the higher the correlations LZWAs have with SSTAs and the shorter the lags for peak correlation. The LZWAs correlate with the SO index much as they do with SSTAs but with opposite sign. The physical link between the LZWAs and the SO is probably through the SSTAs.

It is important to note that each island's long term LZWAs are significant; the range of the six-month mean anomalies is on the order of $8ms^{-1}$ at each island while the standard deviations are on the order of 1.4 ms^{-1}. Equally important is the fact that the SSTA data are for the entire equatorial (0-10°S) East Pacific east of the dateline (to within 10° of the South American coast; see Fig. 2.1). Therefore, and since the anomalies between 0-10°S are usually similar to those between 0-10°N, the SSTAs shown can be thought to represent the "total"amount of anomalous warming or cooling associated with El Niños or La Niñas, not just the warming or cooling near the South American coast.

Chapter 4

THE RELATIONSHIP BETWEEN TROPICAL CYCLONE ACTIVITY IN THE WEST PACIFIC AND EQUATORIAL EAST PACIFIC SST ANOMALIES

4.1 Tropical Cyclone Activity Between 20°N and 20°S

Figure 4.1a shows twelve-month running means of the monthly TC day anomalies in the West Pacific between 20°N and 20°S versus twelve-month running means of East Pacific SSTAs. Figure 4.2 illustrates the temporal relationship of the months used to calculate the twelve-month running means of TC days and SSTs. Twelve-month means, as opposed to six or three month means, are used in this chapter in order to smooth out the extreme annual cycles that occur in the NW and SW Pacific TC day anomalies (see section 2.4 about why the annual cycle shows in the data even though they are anomalies). The relationship between TC day anomalies and SSTAs appears similar to the relationship between LZWAs and SSTAs, although SSTAs lag TC day anomalies by a longer interval for peak correlation. Long term fluctuations in TC activity tend to be followed by similar trends in SSTAs a few months later. Increasing (decreasing) numbers of TC days are followed by warming (cooling) of the SSTs. Periods of minimal change with time in TC activity are followed by near normal SSTs. The peak correlation coefficient between these two curves (since 1961) is .59 when SSTAs lag TC day anomalies by seven months (Table 4.1). This coefficient is comparable to those between SSTAs and most of the island LZWAs from Chapter 3.

4.2 Northwest Pacific TC Activity

Figure 4.1b shows twelve-month running means of TC day anomalies in the NW Pacific, equatorward of 20° N, versus twelve-month running means of East Pacific SSTAs.

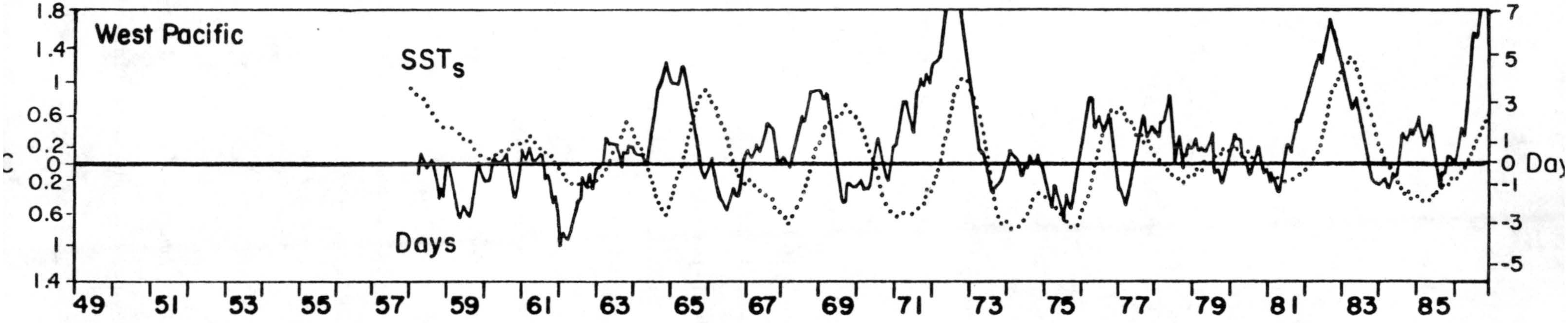

Figure 4.1a: Twelve-month running means of monthly tropical cyclone day anomalies in the West Pacific, between 20°N and 20°S (solid line) versus twelve-month running means of SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line). Southwest Pacific tropical cyclones are defined as those occurring east of 145°E.

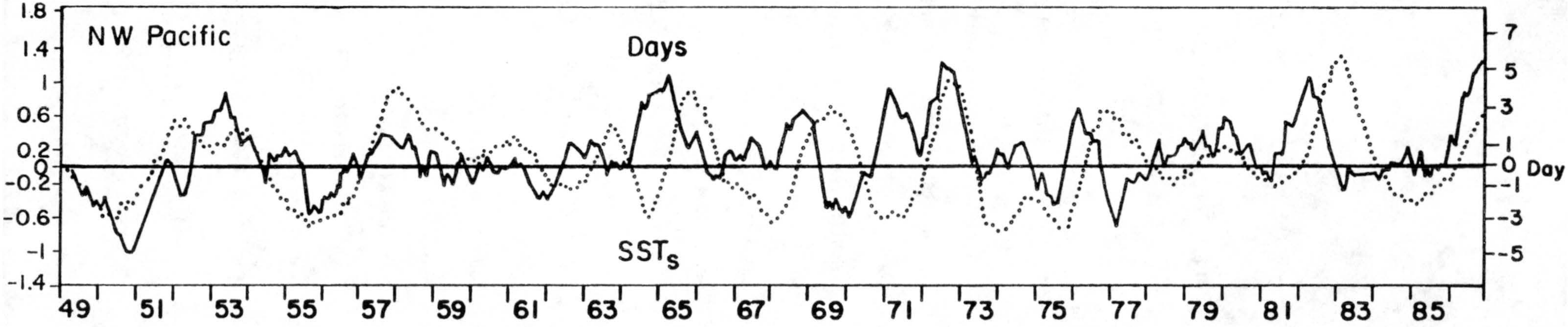

Figure 4.1b: Twelve-month running means of monthly tropical cyclone day anomalies in the NW Pacific, equatorward of 20°N (solid line) versus twelve-month running means of SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

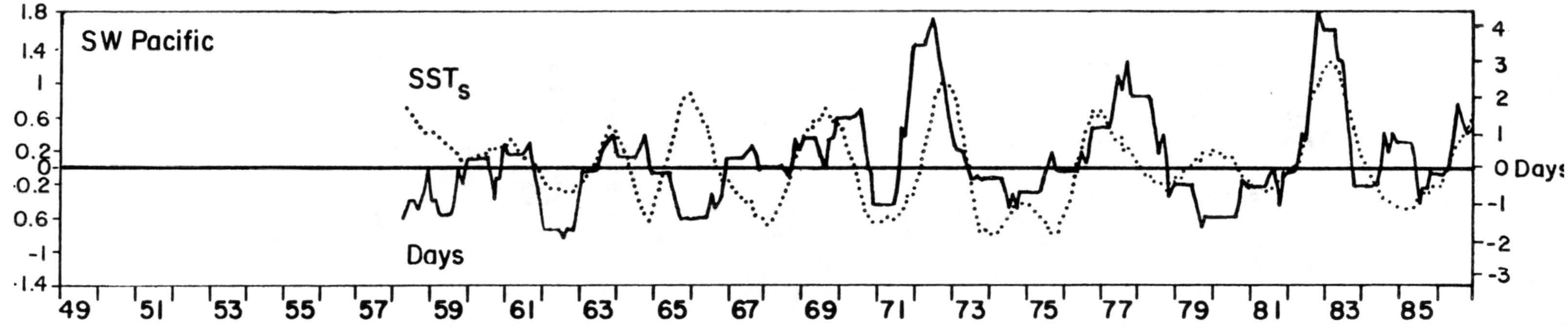

Figure 4.1c: Twelve-month running means of monthly tropical cyclone day anomalies in the SW Pacific, east of 145°E and equatorward of 20°S (solid line) versus twelve-month running means of SST anomalies in the East Pacific between 0° and 10°S, 180° and 90°W (dotted line).

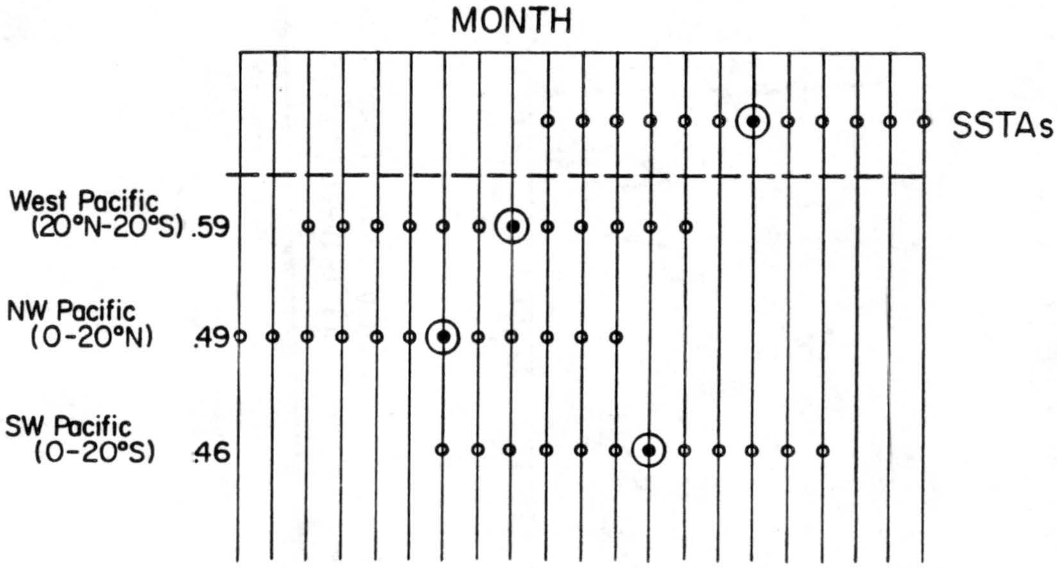

Figure 4.2: A schematic illustrating the temporal relationship of the months used to calculate the peak correlation coefficients between twelve-month running means of monthly tropical cyclone day anomalies in the West Pacific and twelve-month running means of East Pacific SST anomalies from 0-10°S, 180°-90°W. The values of the running means are assigned to the darkened months. The lag shown between TC day and SST anomalies correspond to the peak correlation using data since 1961. The coefficient of peak correlation is listed next to each TC basin.

Table 4.1: Correlation coefficients (r) between twelve-month running means of monthly TC day anomalies in the West Pacific versus twelve-month running means of SST anomalies in the area 0-10°S, 180°-90°W. The number of months by which SST anomalies lag TC day anomalies at peak correlation is in parentheses. The data run through 1986 and Southwest Pacific data are for east of 145°E.

TC Basin	Year Record Starts	r	r since 1961	r since 1971
West Pacific (0-20°N plus 0-20°S)	1958	.55 (7)	.59 (7)	.71 (5)
Northwest Pacific (0-20°N)	1949	.42 (7)	.49 (9)	.43 (6)
Southwest Pacific (0-20°S)	1958	.44 (3)	.46 (3)	.64 (3)

The two curves correspond fairly well with SSTAs generally lagging TC day anomalies. The maximum correlation coefficient between these two parameters is .41, obtained when SSTAs lag TC day anomalies by 6 months (Table 4.1). This lag conflicts with Chan's (1985) suggestion that NW Pacific TC activity fluctuations occur in response to East Pacific SSTs.

4.3 Southwest Pacific TC Activity

Southwest Pacific TC day anomalies correlate with SSTAs at a value of .42 when they precede SSTAs by only two months (Table 4.1). This lag is not consistent as can be observed in Fig. 4.1c. Nicholls (1984) has shown a fairly strong correlation between Australia region TC activity and East Pacific SSTs wherein SST variations precede variations in TC activity, with the physical link most likely being through the Southern Oscillation. In Fig. 4.1c, SW Pacific TC activity lags after SSTAs between 1976 and 1978, but in general, SSTA changes either lag or occur concurrently with TC activity changes. The findings of this study and those of Nicholls are not necessarily in conflict, for his study included TC activity west of Australia while this study considers only TCs east of 145°E.

4.4 Tropical Cyclone Activity vs. the Southern Oscillation

Considering the high correlation between East Pacific SSTAs and the SO, one would expect West Pacific TC day anomalies to correlate with the SO much as they do with the SSTAs, but with opposite sign. Figure 4.3 and Table 4.2 show that this is the case.

4.5 Summary

Interannual trends in West Pacific tropical cyclone activity, as measured by TC days between 20°N and 20°S, correlate well (.59 since 1961) with interannual trends in East Pacific SSTAs. Increasing (decreasing) numbers of TC days are followed by warming (cooling) SSTs. Periods of near zero change in TC activity are followed by near normal SSTs. When TC activity is considered in just the NW or SW Pacific basins, correlations with SSTAs are not as high, although associations can still be seen. Correlations are greatest when SSTAs are lagged after TC day anomalies. The peak correlation for TC

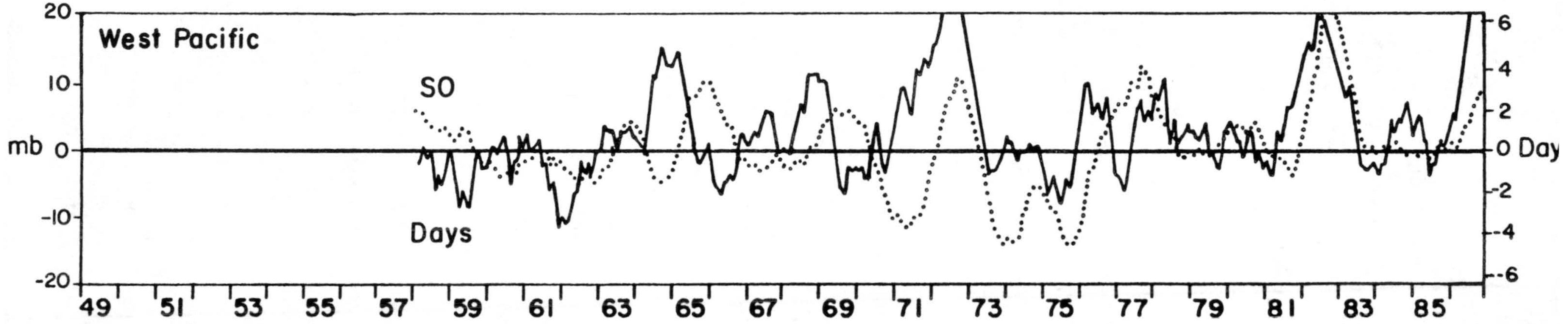

Figure 4.3a: Twelve-month running means of monthly tropical cyclone day anomalies in the West Pacific, between 20°N and 20°S (solid line), versus twelve-month running means of the negative of the Southern Oscillation (SO) Index, defined as the anomalous difference between the monthly mean sea level pressures at Darwin and Tahiti (dotted line). Southwest Pacific tropical cyclones are defined as those east of 145°E. The sign of the SO index has been reversed so that the time variations of the two time series are more easily compared.

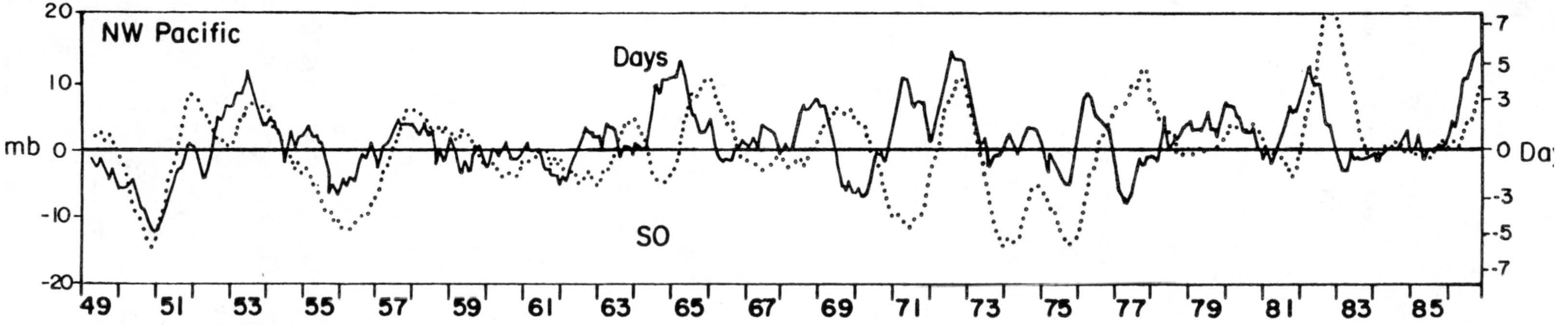

Figure 4.3b: Twelve-month running means of monthly tropical cyclone day anomalies in the NW Pacific, equatorward of 20°N (solid line), versus twelve-month running means of the negative of the Southern Oscillation (SO) Index, defined as the anomalous difference between the monthly mean sea level pressures at Darwin and Tahiti (dotted line). The sign of the SO index has been reversed so that the time variations of the two time series are more easily compared.

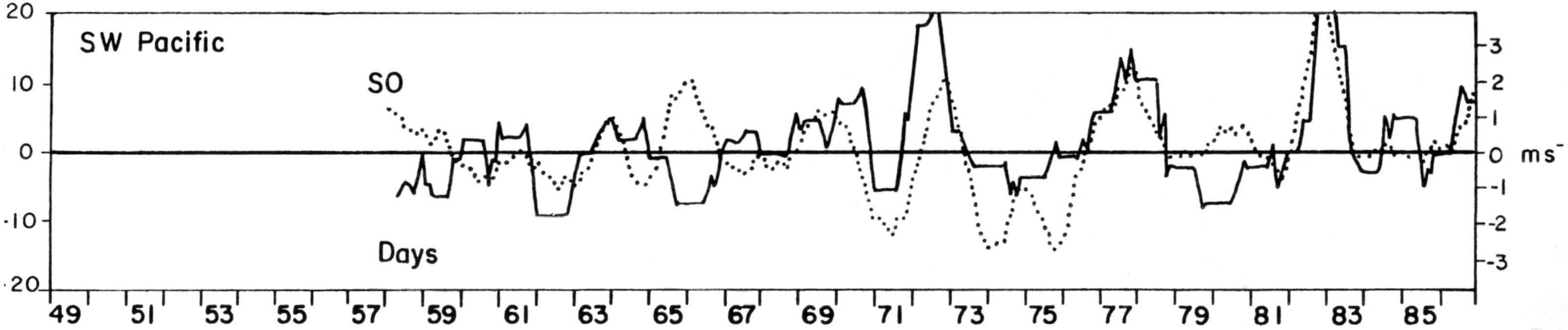

Figure 4.3c: Twelve-month running means of monthly tropical cyclone day anomalies in the SW Pacific, equatorward of 20°S and east of 145°E (solid line), versus twelve-month running means of the negative of the Southern Oscillation (SO) Index, defined as the anomalous difference between the monthly mean sea level pressures at Darwin and Tahiti (dotted line). The sign of the SO index has been reversed so that the time variations of the two time series are more easily compared.

Table 4.2: Correlation coefficients (r) between twelve-month running means of the monthly TC day anomalies in the West Pacific versus twleve-month running means of the Southern Oscillation as defined by the anomalous sea level pressure difference between Tahiti and Darwin. The number of months the SO lags TC activity for peak correlation is in parentheses. The data run through 1986 and Southwest Pacific data are restricted to storms east of 145°E.

TC Basin	Year Record Starts	r
Entire West Pacific		
(0–20°N plus 0–20°S)	1958	-.48 (5)
Northwest Pacific		
(0–20°N)	1949	-.42 (6)
Southwest Pacific		
(0–20°S)	1958	-.49 (0)

day anomalies between 20°N and 20°S occurs at about seven months lag, suggesting a long range predictive signal may exist with these TC day anomalies. In addition, when the Southern Oscillation index is lagged after West Pacific TC activity, similar associations are evident.

Chapter 5

INTERPRETATION OF RESULTS

5.1 Interpretation of Correlations Between West Pacific Low–level Zonal Wind Anomalies and East Pacific SST Anomalies

The curves in Figs. 3.1 and 3.3 show that the East Pacific SST anomalies seem to follow whatever the trends are in West Pacific low-level zonal wind anomalies, especially the wind anomalies from Tarawa and Majuro. Westerly wind anomalies appear to not only trigger El Niños, but also to control the intensity and duration of El Niño events. In general, the longer and stronger the westerly wind anomalies, the longer and stronger the subsequent positive SSTAs. This close correspondence also applies for La Niña events and for intermediate periods as well. In short, there seems to be almost a one to one correspondence between long term variations of equatorial West Pacific low-level zonal wind anomalies and East Pacific SST anomalies.

What is the physical link between these wind and SST anomalies? As discussed in Chapter 1, when surface winds near the equator become more westerly, they excite eastward propagating downwelling Kelvin waves in the upper layer of the ocean which tend to warm SSTs in the East Pacific. It is less well known that easterly changes of the surface winds excite eastward propagating upwelling Kelvin waves. As also mentioned in Chapter 1, the effect of upwelling Kelvin waves on East Pacific SSTs is the opposite of that for downwelling Kelvin waves—the former tend to cool SSTs. During periods spanning several months when low-level winds are becoming more westerly, the periods of westerly change on the scale of days or weeks are many and/or strong compared to the daily or weekly periods of easterly change, and the net change is westerly. The reverse is true during easterly periods of change. During long-term periods of near zero net wind change, short term westerly and easterly wind bursts tend to cancel each other out.

Hence, mostly downwelling Kelvins are excited during periods when low-level equatorial winds are becoming westerly over the long term, mostly upwelling Kelvin waves are excited during periods that are becoming easterly over the long term, and roughly an equal flux of downwelling and upwelling Kelvin waves are excited during periods of near zero net zonal wind change over the long term. The effect of short term (days or weeks) accumulations of Kelvin waves may not be noticeable on SSTs averaged over a large area, but the sustained (several months) fluctuations of Kelvin wave excitation in the West Pacific should be reflected in the SSTs, all other factors being equal.

Considering this information on Kelvin waves and currents, the author's interpretation of the data in Chapter 3 is as follows. Long term (several months) fluctuations of East Pacific SST anomalies occur in approximate proportion to the state of the zonal surface winds in the equatorial West Pacific. The winds directly influence the SSTs through Kelvin waves. Surface winds that become increasingly westerly for extended periods cause the growth of El Niños and decay of La Niñas through the excitation of primarily downwelling Kelvin waves. Similarly, easterly change of the winds over extended periods cause the growth of La Niñas and decay of El Niños through the excitation of primarily upwelling Kelvin waves. Periods of minimal net zonal wind change lead to near normal broadscale SSTs through approximately equal excitation of downwelling and upwelling Kelvin waves which tend to cancel one another in terms of their effect on SSTs. As mentioned in Chapter 1, variations of the surface winds may also affect SSTs by varying the curl of the surface wind stress, thereby modulating the strength of the zonal equatorial ocean surface currents which help modulate the amount of upper layer water imported to and exported from the East Pacific. The unique feature of this interpretation is that surface winds directly influence SSTs through the downwelling and upwelling Kelvin waves they excite, and possibly through the anomalous currents they drive, while the influence of the Rossby waves they excite is assumed to be negligible in comparison.

Several important features are either part of or implied by this physical argument. First, the assumption that the effects of Rossby waves are comparatively negligible is important. As alluded to in Chapter 1, several prior studies have proposed that when equatorial surface winds excite downwelling or upwelling Kelvin waves, upwelling or downwelling

Rossby waves, respectively, are simultaneously excited. These Rossby waves propagate slowly westward and relfect off the western ocean boundary as eastward travelling upwelling or downwelling Kelvin waves which eventually modify East Pacific SSTs several months after the original group of Kelvin waves (McCreary, 1984; Busalacchi and O'Brien, 1981). The curves in Figs. 3.1 and 3.3, however, do not support the notion that the West Pacific winds have a negative or delayed relationship with SSTs. For example, if reflected Rossby waves were important, then the easterly change of LZWAs in late 1982/early 1983 should have produced downwelling Rossby waves which should have lead to warming sometime in 1983 or 1984. No warming occurred. No significant warming occurred until 1986 and this was preceded by westerly change. The LZWAs consistently appear to modulate SSTAs in a positive, direct manner. The initiation of the decay of the 1972 El Niño, for instance was most likely not caused by reflected downwelling Rossby waves, but simply because the LZWAs became more easterly.

It is felt the consideration of Rossby wave effects as comparatively unimportant is dynamically justified because: the Pacific Ocean has a poorly delineated western boundary which most probably interferes with the reflection of Rossby waves; impinging Rossby waves also reflect off the western boundary as gravity waves and eastward propagating short Rossby waves (McCreary, 1985; Philander, 1985b) and therefore only a portion of the energy associated with the original Rossby waves goes to the creation of Kelvin waves; the energy associated with reflected Rossby waves must travel a longer distance (from the area of excitation, to the western boundary and back) and pass more islands (some of them twice) before reaching the East Pacific than the energy associated with Kelvin waves excited in the same area of the open ocean, and therefore is subjected to more general dampening, albeit minor. Whether or not Kelvin waves reflect well off the better defined eastern boundary as westward propagating, Rossby waves is irrelevant to this interpretation because these Rossby waves would have the same effect on East Pacific SSTs as the Kelvin waves which spawned them (ie., downwelling (upwelling) Kelvin waves reflect as downwelling (upwelling) Rossby waves; Inone, et al., 1986).

A second salient feature of this physical argument is that West Pacific LZWAs are compared to SSTAs over a broad area of the East Pacific: 0-10°S, 180-90°W. LZWAs were also compared to SSTAs for a small area in the extreme East Pacific, east of 92°W (see Fig. 5.1 for an example), and although these SSTAs lagged the LZWAs, the correlations were not as high as those obtained using the "total SST anomalies", meaning the anomalies over a large area. The total SST anomaly appears to be the best indicator of the influence of surface winds in the equatorial West Pacific. Where the SST anomalies start and in what direction they spread are irrelevant to the hypotheses presented so far.

Finally, it should be remembered that low-level zonal wind and SST *anomalies* are related. When the annual cycle is not subtracted from each of these data sets, there does not appear to be such a strong connection. The influence of processes local to the East Pacific on raw SSTs appears to dominate over the remote influence of equatorial West Pacific surface winds, at least in a climatological sense (compare curve A with curve B in Fig. 5.2). The Peru current, local upwelling, solar insolation, evaporation and longwave radiation emission all affect SSTS (see Toole, 1984, for a discussion of local East Pacific SST modulators). These and other local East Pacific processes certainly go through year to year changes that cause SST anomalies, but if these changes are relatively small, then fluctuations in Kelvin wave activity and surface current intensity could very well be the prime modulators of interannual SST fluctuations.

For most of the islands mentioned in Chapter 3, LZWAs show higher correlations with SSTAs for six-month running means of both parameters as compared to simple monthly means. It could be argued that the effects on SSTs of reflected Rossby waves are more noticeable on a monthly basis, and may be what makes the monthly correlations lower. But the monthly variance of the SSTAs is very small compared to the longer term fluctuations. The lower monthly correlations are due mainly to the relatively high monthly variance associated with the LZWAs (note how much smoother the SSTA curves are compared to the LZWA curves in Fig. 3.3). The topic is moot anyway because six-month and monthly mean LZWAs at Tarawa correlate almost equally well with SSTAs (.74 and .72, respectively, since 1961). Wind values from individual islands are more likely to deviate from what the winds are like over broad longitudinal spans on a monthly basis than on a six month basis. This is likely why the six-month means correlate higher

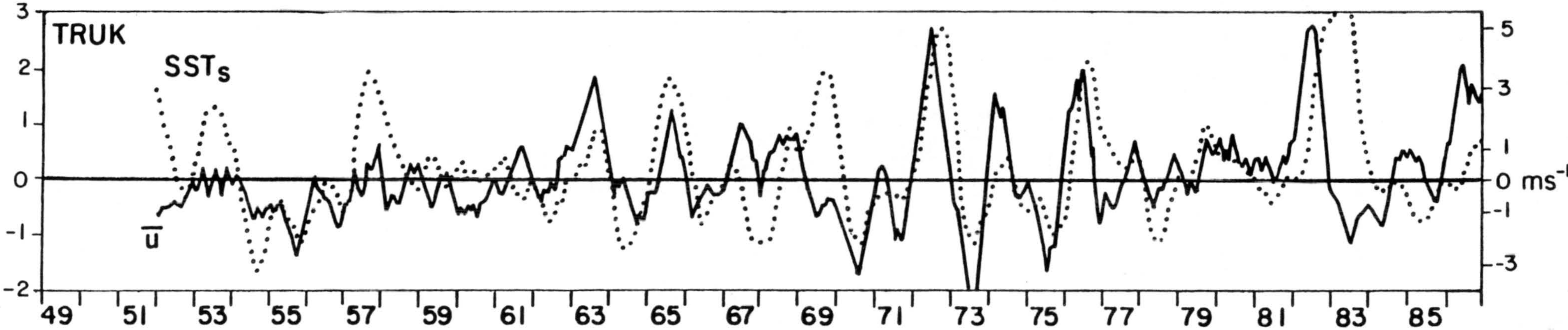

Figure 5.1: Six-month running means of the 850 mb zonal wind anomalies at Truk (7.5°N, 152°E) (solid line) versus six-month running means of the SST anomalies for a 2° by 2° box centered on 2.8°S, 91°W (dotted line). The pre-1980 SST data are taken from the COADS data set at NCAR. After 1979, SST anomalies are taken from the area 0°-10°S, 90°W to the South American coast. The later data are taken from the Climate Diagnositcs Bulletin.

than the monthly means for most islands, because East Pacific SSTs are hypothesized to respond to Kelvin waves excited by winds all along the equator in the West Pacific. Tarawa LZWAs do not have as much monthly variance as the other LZWAs and being so close to the equator perhaps are more representative of LZWA all along the equator in the West Pacific. The high correlation SSTAs have with Tarawa LZWAs on a monthly basis is especially supportive of the concept that the delayed effects on SSTAs of reflected Rossby waves are negligible compared to the direct influences of Kelvin waves. This is the first study to analyze Tarawa winds after 1980.

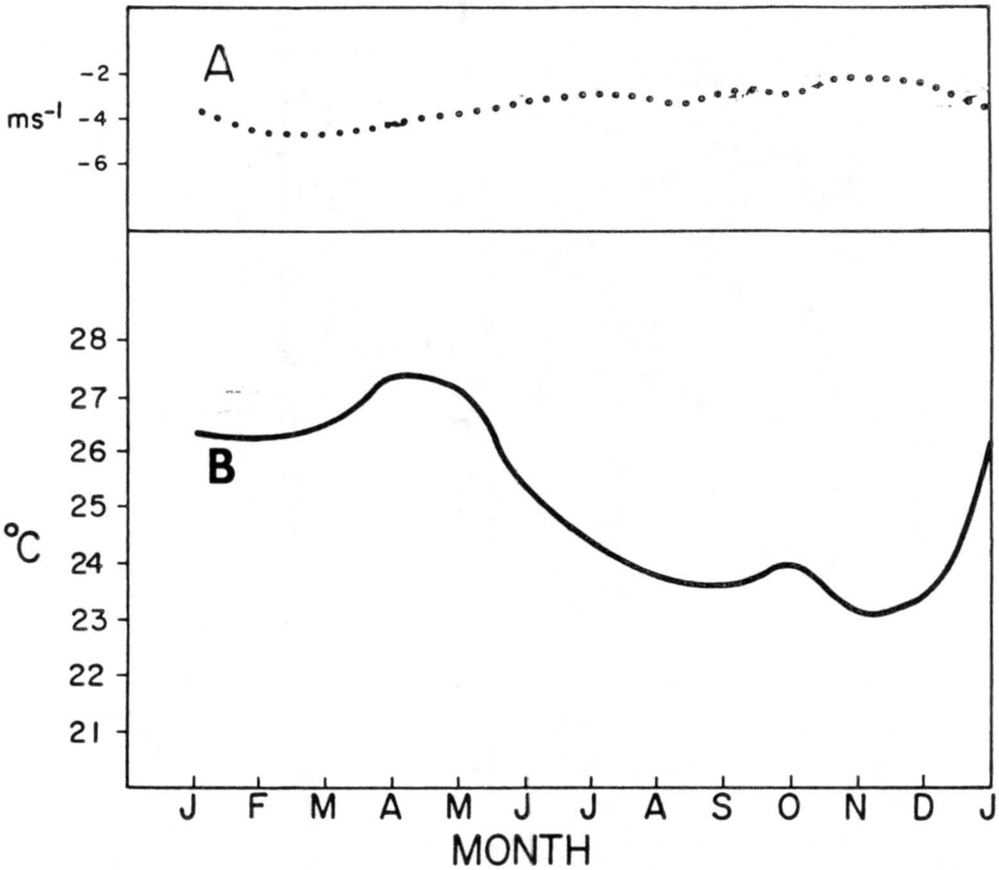

Figure 5.2: Comparative amplitudes of the mean annual cycles of (a) surface zonal winds at Tarawa (1.5°N, 173°E), and (b) SSTs in the area 5°N-5°S, 150°W-90°W. Negative zonal wind values are from the east. The relative scale between °C and ms^{-1} is the same as that used in the other figures of this paper comparing West Pacific island winds and East Pacific SSTs.

The concept of Kelvin waves constantly influencing SSTs in the East Pacific is supported by the fact that the SSTA fluctuations in Figs. 3.1 and 3.3 closely follow LZWA fluctuations regardless of the time of year. The store of relatively warm water in the West Pacific is large enough year round to allow for the generation of eastern Pacific SST warm anomalies at any time of the year, which is important for the formation of El Niños. The east-west SST gradient does, however, change during the course of the year (Table 6.1) mainly due to changes in the depth of the thermocline (Fig. 6.9). Harrison and Schopf (1984) have shown that the annual changes in the SST and thermocline depth gradients may cause the Kelvin wave effect to be weaker during some parts of the year compared to others. They proposed this would cause the Kelvin wave influence on open ocean SSTs to appear to be delayed during some parts of the year. This would explain why the El Niños of 1982-83 and 1986-87 lag LZWAs by a longer interval than other El Niños, because they both started at a different time of year than the others.

The time lags between the SSTAs and LZWAs at each NW Pacific island support the idea that primarily Kelvin waves modulate SSTs in the East (Tables 3.1, 3.2 and 3.3). Kelvin waves travel at 1-2 ms^{-1} and would therefore typically take one to three months to travel from western to eastern Pacific. The time lags between the LZWAs and the SSTAs are in this approximate time range on a fairly consistent basis (Figs. 3.1 and 3.3). Inspection of all the correlations in Tables 3.1, 3.2 and 3.3 reveals that LZWAs from the western most NW Pacific islands show a tendency to have peak correlations with SSTAs at longer lags than those from the more easterly located islands. The longer lags support the Kelvin wave concept because Kelvin waves excited farther west have a longer traverse to the East Pacific. The lags at peak correlation for LZWAs from the SW Pacific [Honiara] are not consistent with this east-west trend. Several characteristics of the Honiara LZWAs may be responsible for this, see section 3.1. In general, there are also lower correlations between the SSTAs and LZWAs from the more western islands, consistent with the fact that Kelvin waves generated in the extreme west are exposed to more general dampening by turbulence and mean currents (if only slightly more) because of the longer transverse.

The LZWAs analyzed in this study are all for locations west of the dateline. Low-level zonal winds in the equatorial central/east Pacific should be similarly correlated with SSTAs.

5.2 Interpretation of the Correlation Between TC Activity and SSTAs

Although supportive of the physical arguments of this chapter, the link between tropical West Pacific TC activity and East Pacific SSTAs is ambiguous. If the correlation between TC day anomalies in the entire West Pacific, 20°N to 20°S, and SSTAs (Fig. 4.1 and Table 4.2) indicates a direct physical linkage, the link would probably be through the effect TCs have on LZWAs. A TC can affect winds at large radii from storm center (Weatherford and Gray, 1988). The quadrant of a low latitude TC nearest the equator can cause anomalous westerly surface winds on or near the equator. In the context of the views presented so far, this would mean the equatorial quadrants of TCs produce LZWA fluctuations on the equator which excite Kelvin waves leading to SST variations in the East Pacific. Tropical cyclone activity is year-round when activity between 20°N and 20°S is considered, and hence the influence on equatorial winds would be year-round. The lag interval for peak correlation between TC activity and SSTAs is not, however, consistent with the time it takes for Kelvin waves to traverse the Pacific. Alternatively, the interannual variations of TC activity may be a result of equatorial LZWA variations. Westerly (easterly) low-level winds near the equator create comparatively high (low) environmental vorticity in the lower troposphere which is favorable (unfavorable) for TC genesis. Therefore, TC day anomalies and SSTAs may show a high correlation because both are well correlated with LZWAs (see Fig. 5.3. Perhaps both explanations apply. Low-level winds may create favorable or unfavorable conditions for relatively active or inactive periods of TC activity which may then enhance or alter the low-level winds in return. This is one example of how TC activity could work in conjunction with LZWAs to influence SSTAs. Entirely different physical processes could link TC activity with SST anomalies.

5.3 Final Notes

The implications for using LZWAs from islands in the West Pacific to forecast El Niños, La Niñas and normal SST periods are obvious. Tarawa island appears to be of special forecast importance. A simple predictive scheme (Eq. 5.1) can be devised by

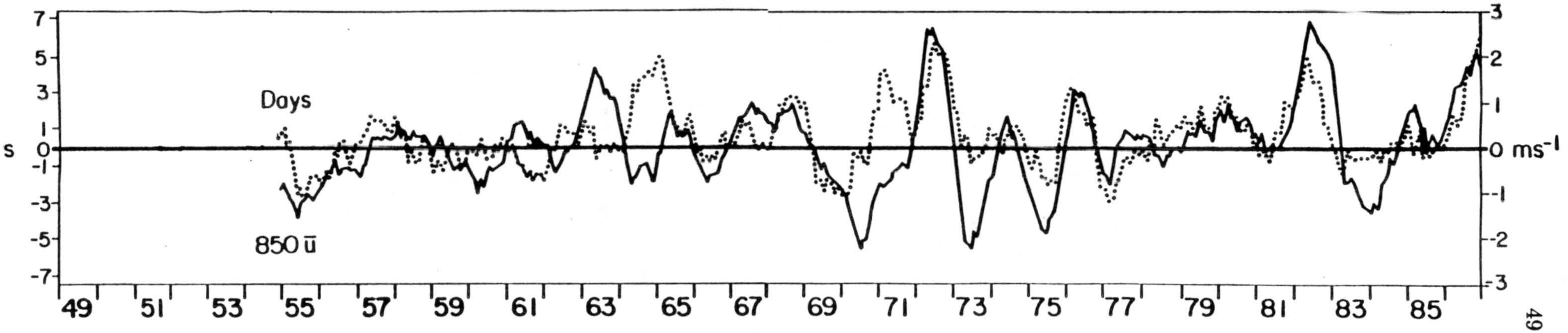

Figure 5.3: Twelve-month running means of the sum of the 850 mb zonal wind anomalies at Koror (7°N, 134.5°E), Truk (7.5°N, 152°E) and Majuro (7°N, 171°E) (solid line) versus twelve-month running means of the monthly TC day anomalies in the NW Pacific, 0-20°N (dotted line). The correlation coefficient between these two curves is 0.56 at zero lag.

comparing the Tarawa LZWA and the SSTA time series (see Figs. 3.1d, 3.3d and Table 3.3).

$$(.32^{\circ}Csm^{-1})A_{zu} = A_{SST} \tag{5.1}$$

In Eq. 5.1, A_{zu} is the most recent monthly mean surface zonal wind anomaly, and A_{SST} is the monthly mean SST anomaly between 0-10°S, 180-90°W two months later. Predictions of similar quality could be made using three-month means from the other islands. The predictions might be less accurate but could be made further in advance, especially if monthly mean SSTAs are predicted (individual monthly SSTA means over the broad area from 0-10°S, 180-90°W do not deviate very much from the three-month means). It may be more appropriate to use the change of zonal wind anomalies to predict the change of SST anomalies.

A true connection between LZWAs and SSTAs does not require that the ideas expressed here involving Kelvin and Rossby waves be correct. The high LZWA-SSTA correlations are strong evidence of a link, regardless of what the physical mechanisms may be.

The remaining question to be addressed is: if interannual East Pacific SSTA fluctuations occur in response to interannual West Pacific low-level zonal wind fluctuations, what causes the West Pacific low-level zonal winds to fluctuate as they do? Some conjecture as to the nature of these causes is given in the next section.

Chapter 6

DISCUSSION

6.1 Speculation on the Causes of Interannual Low–Level Wind Fluctuations in the Equatorial West Pacific

Several theories exist concerning the cause of the interannual fluctuations of equatorial West Pacific low–level zonal winds. Many revolve around explanations for the existence of El Niños. Several authors have suggested that El Niños occur as a result of positive feedback loops between equatorial West Pacific surface winds and equatorial East Pacific SSTs. In a plausible scenario, a period of westerly surface wind anomalies, of random or unknown origin, in the Central and West Pacific initiates anomalously warm SSTs in the East Pacific through Kelvin waves and anomalous eastward moving currents. The warm SSTs reduce the east-west SST gradient, which in turn weakens the thermally direct zonal Walker Circulation. The weaker Walker Circulation then induces even more westerly low-level wind anomalies, not just in the West Pacific but all along the equator in the Pacific, which induce even warmer SSTs, and so on (see Philander, 1983; Rasmusson, 1984; Julian and Chervin, 1978).

Several authors have suggested that SSTs feedback on West Pacific winds through mechanisms other than the Walker Circulation. It has been proposed that warm SSTs draw the Asian monsoon convergence zone eastward, weakening the easterly trades in the Central/West Pacific or even bringing westerlies to the area (Philander, 1985a). Others feel that warm SSTs reduce the surface pressure in the East Pacific, lowering the SO index and thereby raising the surface pressure in the western Pacific which feeds back on the westerly anomalies. Of the many other explanations for El Niño, most also characterize the long period features of West Pacific low-level wind anomalies, such as those in Fig. 3.3, as responses to East Pacific SSTs, usually through unstable feedback loops.

These scenarios, however, do not agree with the data in Fig. 3.1 and Table 3.1. If the east-west feedbacks are positive, why do the westerly low-level wind anomalies consistently weaken and start to become easterly prior to the weakening of El Niño, and why do LZWAs and SSTAs not fluctuate in unison instead of at lag? Long period LZWA variations precede similar SSTA (and SO) variations as if they were controlled by factors not connected to them. Gutzler et al.(1987) has suggested that West Pacific wind fluctuations which occur during El Niños are modulated by forces not connected to El Niño. The same apparent independence of LZWAs from SSTAs also exists during La Niñas and periods of near normal SSTs. In short, it appears there are forces not directly linked to Pacific ENSO (El Niño-SO) circulations which help to modulate the interannual fluctuations of equatorial West Pacific low–level winds.

The annual cycle in the Pacific basin has been suggested as being a modulator of interannual low-level wind fluctuations. For example, it has been proposed that the westerly low-level winds weaken and become more easterly prior to the weakening of El Niños because the Asian monsoon convergence zone makes its annual fall shift to the Southern Hemisphere, bringing easterly trades to the equatorial West Pacific and cutting off the westerly anomalies (Philander, 1985a). The data in Fig. 3.1, however, have the annual cycle of low-level winds removed and the westerlies still weaken before El Niños start to decay. Furthermore, the demise of the 1982-83 and 1986-87 El Niños cannot be explained by the annual cycle because both peaked during the northern winter. Hence, the annual cycle does not appear to be one of the factors influencing interannual low-level wind fluctuations in the equatorial West Pacific, at least not in an obvious way.

The factors controlling the low-level winds may not be specific to the Pacific Ocean basin. An aspect common to most ENSO theories is that the physical mechanisms used to account for the behavior of the low-level winds are all contained within the Pacific Ocean basin. The Pacific Ocean basin, though of great size, is not an isolated box—it has atmospheric interactions with all surrounding areas. Thus, it is reasonable to assume that the West Pacific winds are not impervious to influences from outside of the Pacific Ocean basin. In order to identify all the sources of the interannual low-level zonal wind variations in the equatorial West Pacific, one most likely must look to phenomena around the globe, not just those within the Pacific Ocean basin.

Presented below are speculative discussions of several of the many phenomena which are not directly part of Pacific ENSO circulations but may still influence the low-level wind fluctuations. Many of the suggested phenomena are global in nature. The QBO, tropical cyclones, teleconnections and "other phenomena" are discussed.

6.1.1 The QBO

Recent research suggests the stratospheric quasi-biennial oscillation (QBO) may be a global scale phenomenon which modulates the low-level winds in the equatorial West Pacific. Figure 6.1 shows a time series of the sum of the zonal wind anomalies at 70, 50, 30 and 10 mb from Truk (7.5°N) along with a time series of the sum of the 850 mb zonal wind anomalies from four widely spaced equatorial stations: Tarawa (173°E), Singapore (104°E), Nairobi (36°E, 700 mb) and Ascension (15°W; Manaus, 60°W, was used after 1969). Twelve-month running means have been applied to both time series. Because the QBO exists mainly between 70 and 10 mb and is very homogeneous around the entire circumference of the equator, and because there is an equal amount of mass between each of the four levels chosen, the 70 to 10 mb curve is a very good approximation to a time series of the total amount of zonal angular momentum in the tropical stratosphere. Because the 850 mb stations in Fig. 6.1 are spaced roughly equidistant along the equator and because 850 mb winds have been shown to be a good approximation to winds throughout the lower half of the tropical troposphere, the 850 mb curve can be considered a rough time series representation of the zonal angular momentum in the lower tropical troposphere.

The stratospheric curve in Fig. 6.1 is dominated by the QBO. The 850 mb curve appears to have fluctuations on the QBO time scale which are out of phase with those of the stratospheric curve in most years, especially before 1978. The 850 mb curve has fluctuations on other time scales, but maxima (minima) in the stratospheric angular momentum usually correspond to at least relative minima (maxima) in the lower tropospheric angular momentum. An implication of this apparent association is that in order to satisfy conservation of momentum, the extremes in the stratospheric QBO are balanced by opposite extremes in a QBO of the zonally averaged lower tropospheric tropical zonal winds. The rotation of the earth is also known to speed up and slow down with the phase of the QBO (Roland Madden, personal communication). Other physics, however, could be involved and a much more thorough analysis with a more representative measure of lower tropospheric angular momentum needs to be accomplished. For now, the point is that there is evidence that suggests the stratospheric QBO affects equatorial low-level zonal winds. Yasunari (1987) has shown similar results in the Pacific. If the QBO were responsible for just some of the variance of West Pacific LZWAs, it would explain their apparent independence from the SSTs and SO.

6.1.2 Tropical Cyclones

As mentioned in section 5.2, the relationship of low-level zonal winds to long term fluctuations of TC activity in the tropical West Pacific is ambiguous. Tropical cyclone activity most likely cannot account for all of the year to year wind fluctuations in the equatorial West Pacific, but the TC activity could account for some of the interannual variance.

6.1.3 Teleconnections

Many investigators have shown that the effects of large equatorial East Pacific SST anomalies are global. van Loon et al. (1981), for example, showed ENSO events are correlated with weather in the Arctic Circle (see Fig. 6.2). It is very possible that East Pacific SSTs may act on tropical low-level winds, including those in the West Pacific, through these teleconnections in higher latitudes. The global scale physical mechanisms linking the SSTs to West Pacific winds will not be dealt with here. Rather, the idea is to emphasize that the SSTs affect the global circulation and therefore may indirectly act on equatorial West Pacific low-level winds through a complex global (not just Pacific) feedback loop. Global feedbacks could explain the cessation of strong westerly low level wind anomalies in the West Pacific prior to the decay of an El Niño, among other aspects of these winds.

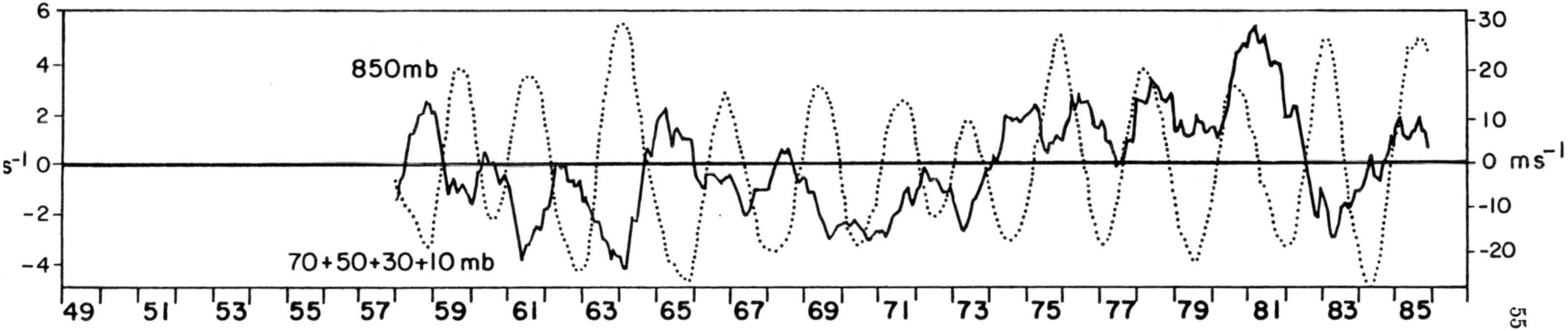

Figure 6.1: Twelve-month running means of the sum of the 70, 50, 30 and 10 mb zonal wind anomalies from Truk (7.5°N, 152°E) (dotted line) versus twelve-month running means of the sum of the 850 mb zonal wind anomalies from Tarawa (1.5°N, 173°E), Singapore (2°N, 104°E), Nairobi (700 mb, 2°S, 36°E), and Manaus (3°S, 60°W; Ascension, 8°S, 15°W, was used before 1969) (solid line). The scale on the left side of the figure corresponds to the 850 mb curve.

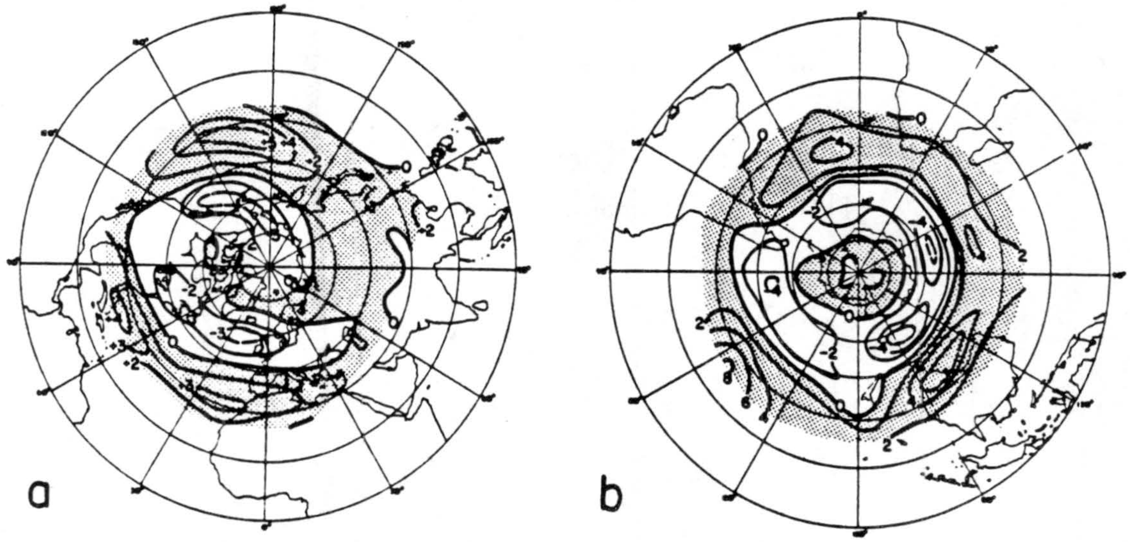

Figure 6.2: The difference between extremes of the Southern Oscillation (which usually coincide with extremes of East Pacific SSTs) in the zonal geostrophic wind (ms^{-1}) at 700 mb in the Northern Hemisphere in Dec-Feb (a), and at 500 mb in the Southern Hemisphere (b), (van Loon, 1981).

6.1.4 Other Phenomena

Research by the author indicates that a planetary scale wave with an interannual period and of unknown origin may exist and propagate around the equator with a period approximating the El Niño/La Niña time scale. The existence of such a wave is supported by Table 2.2 which shows that the LZWAs at the extreme western equatorial NW Pacific islands precede those at islands farther east, as if the anomalies propagate eastward. Gutzler (1987) and Holland (1985) noted a propagation of zonal wind anomalies in the Indonesian/West Pacific area during El Niño events, and Yasunari (1987) has documented an eastward progression of zonal winds across the Pacific on a QBO time scale. Much more research needs to be done on this topic. If, however, an equatorial wave that oscillates on an interannual time scale does exist, it could be another factor influencing the low-level zonal winds in the West Pacific.

Barnett (1985) has noted an eastward progression of near global sea-level pressure anomalies that may play a role in modulating the winds. He proposed that the progression is not due to a wave, but is part of an elaborate feedback system involving Pacific SSTs and Asian snow cover.

Finally, West Pacific SSTs are not necessarily affected by East Pacific SSTs and may be another factor influencing the behavior of West Pacific low-level winds. van Loon et al. (1985) proposed that SST variations east of Australia lead to changes in the amount of convection associated with the South Pacific Convergence Zone. They suggested that different amounts of convection from year to year would lead to sea level pressure fluctuations in the tropical West Pacific. Changes in sea level pressure would lead to fluctuations of the low-level winds. SST fluctuations along the equator itself in the western Pacific, minor as they may be, could also help to modulate interannual low-level wind fluctuations through air-sea interactions.

6.2 Combined Influences

Figure 6.3 is a schematic illustrating some of the factors possibly modulating West Pacific low-level zonal winds that were discussed in this study. Although none of the factors acting alone could account for the observed long term wind fluctuations, perhaps the combined influence of several of them, or others, could. Figure 6.4 is a schematic illustrating this point. One factor, such as the QBO, may cause the winds to tend to fluctuate in a manner similar to that depicted by Fig. 6.4a. Other factors might cause fluctuations on the time scale depicted by Fig. 6.4b. The combined effects of these factors might then produce long term wind fluctuations such as those in Fig. 6.4c, which is a linear superposition of the effects depicted in 6.4a and 6.4b. When Pacific and global feedbacks are added, the low-level zonal wind anomaly time series might finally look like Fig. 6.4d (which is a time series of Tarawa's six-month running mean LZWAs from 1967 to 1977).

Therefore, incorporating the reasoning of Chapter 5, possible scenarios for El Niños and La Niñas are as follows: phenomena not associated with ENSO or annual circulations in the Pacific (and not necessarily those listed in this chapter) combine to create surface wind anomalies in the equatorial West Pacific which, on average, over several months,

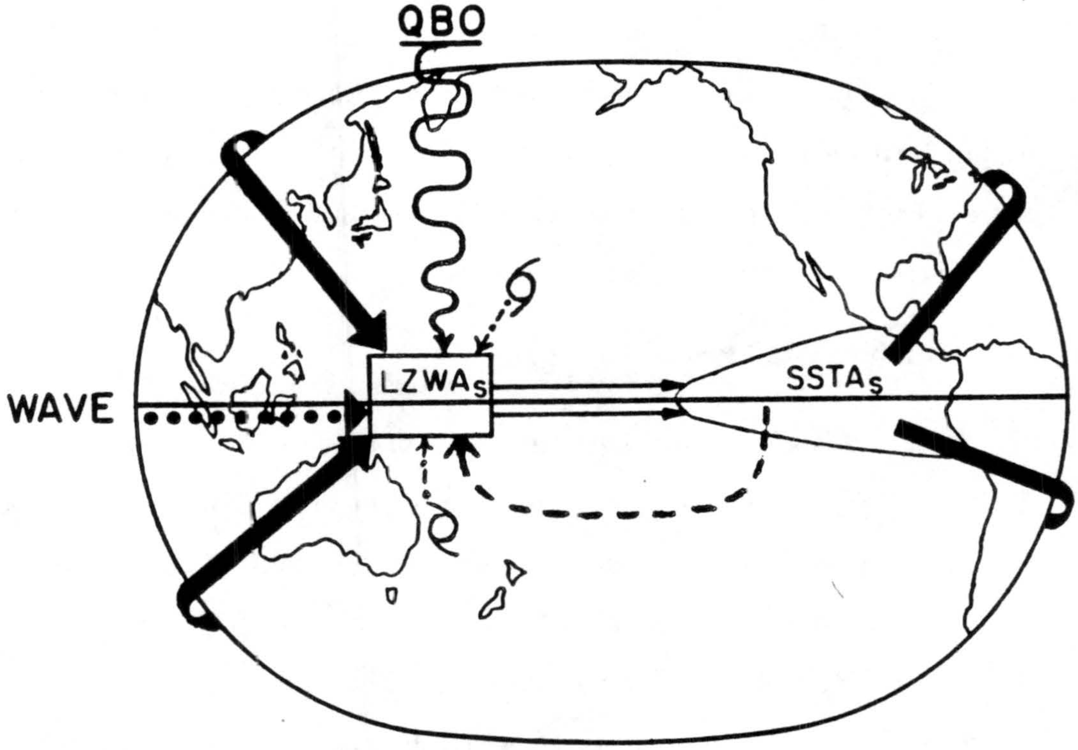

Figure 6.3: A schematic illustrating some of the many possible forces that could influence the low-level zonal winds (LZWAs) in the equatorial West Pacific on an interannual time scale. The wavy arrow represents the possible influence of the QBO. The dotted/dashed arrows represent the effects of low latitude tropical cyclones. The dotted arrow represents the influence of a planetary wave with an interannual time scale, the existence of which has yet to be proven. The dashed arrow represents feedback loops between SSTs and low-level zonal winds through Pacific circulations. The heavy arrows represent global feedbacks.

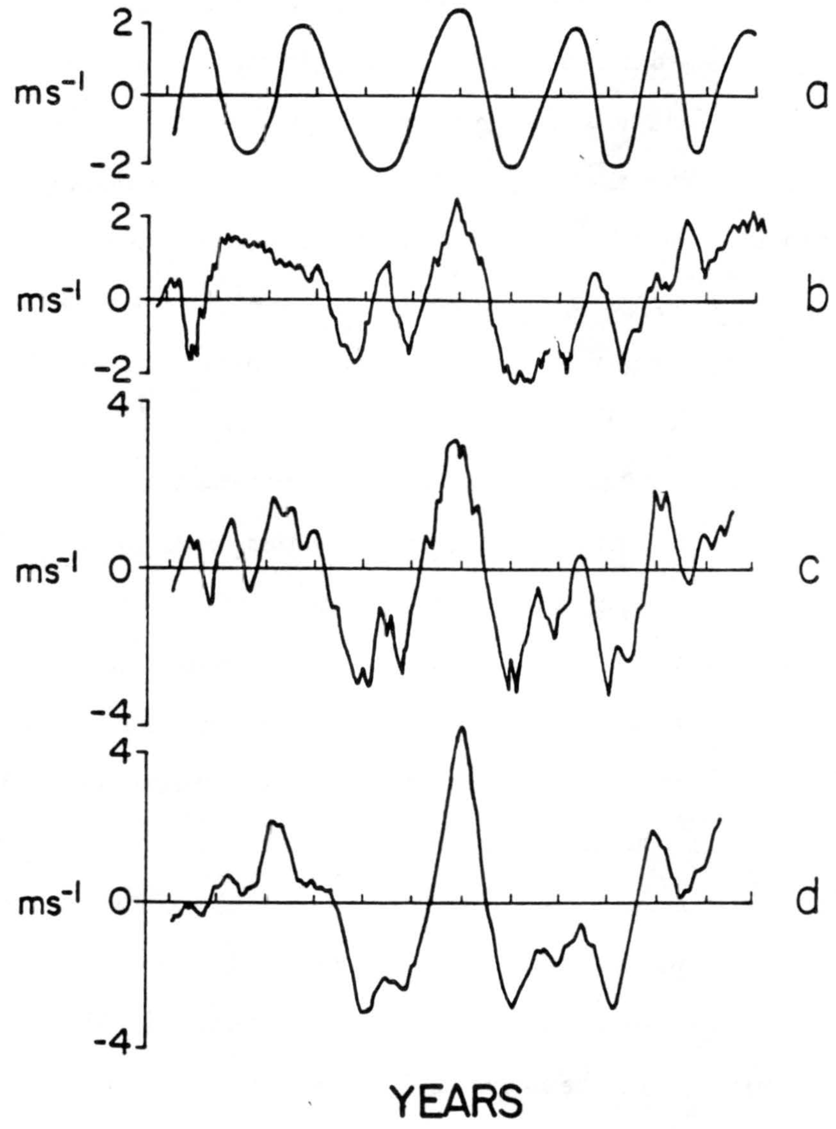

Figure 6.4: A conceptual schematic illustrating the possible combined influences on year to year variations of low-level zonal wind anomalies in the equatorial West Pacific of phenomena which are not directly modulated by long term fluctuations of SSTs in the equatorial East Pacific. The individual contributions of various phenomena (a and b) couple to create distinct variations (c) which are enhanced by global and local feedbacks from East Pacific SSTs (d). (d) are actual six-month running means of Tarawa's zonal surface wind anomalies, 1967 -1977.

become more westerly (easterly). During these periods, anomalously high concentrations of westerly (easterly) wind changes on shorter time scales excite above average numbers of downwelling (upwelling) Kelvin waves which cause warming (cooling) of the SSTs to the east. The combined influence of the phenomena *might* also create variations of the curl of the surface wind stress, driving anomalous zonal ocean currents which may also affect SSTs. The SST anomalies may then feedback and slightly enhance or otherwise alter the surface wind pattern through global and/or Pacific basin circulation changes. A similar scenario applies to periods of near normal surface winds and SSTs.

The concept of combined influences on the West Pacific winds would explain the sparadic nature of El Niños and La Niñas. El Niños and La Niñas comprise a series of events separated by periods of relatively normal conditions, rather than a continuous periodic oscillation such as the QBO. Perhaps the long periods of westerly and easterly low-level wind change that have been suggested to cause El Niños and La Niñas, respectively, occur only when two or more of the phenomena modulating the winds couple in a certain manner, which depending on the phenomena, could happen at sporadic intervals.

Many investigators have noted that interannual fluctuations of equatorial West Pacific upper-level winds tend to be out of phase with those of the low-level winds (Gutzler et al., 1987). The many possible factors influencing the lower levels may also modulate these upper-level winds directly, or indirectly through their effect on low-level winds. For example, changes in the low-level wind field might create changes in low-level convergence, which lead to changes in the amount of Convergence Zone convection, which create changes in the amount of upper-level divergence.

6.3 Influences Around the Globe

If one or more of the phenomena affecting the West Pacific winds are global in nature, then similar long period low-level zonal wind fluctuations should be observed elsewhere around the equator. Figures 6.5-6.8 are time series of low-level zonal wind anomalies (at 850 mb except for Nairobi, for which 700 mb was used) from four equatorial stations around the globe: Singapore (2°N, 104°E), Trivandrum (8°N, 76°E), Nairobi (2°S, 36°E) and Manaus (3°S, 60°W). Simple six-month running means have been applied to these data. Also plotted are the six-month mean SSTAs used throughout this paper. Twelve-month means had to be used at Trivandrum and Nairobi to average out extraordinary semi-annual and annual fluctuations that showed even in the anomalies. The interannual wind fluctuations are indeed on a time scale approximately that of the West Pacific LZWAs (compare the LZWAs in Figs. 6.5-6.8 with those in Fig. 3.1). There seem to be associations with ENSO events. Perhaps some of these associations occur through the global "teleconnections" discussed earlier. It is certainly possible that the other factors influencing these wind anomalies are also global in nature. The similarity between the low-level wind anomalies in the West Pacific and elsewhere around the globe is not proof that global circulations strongly modulate these winds, but it is supportive evidence.

Assuming that some of the phenomena responsible for the long term behavior of West Pacific low-level winds are indeed global in nature, and that East Pacific SST anomalies are proportional to these winds, it could be argued that El Niños and La Niñas should occur in both the Atlantic and Indian Oceans. The global scale phenomena should create long term LZWA fluctuations in the western equatorial Atlantic and Indian Oceans on time scales similar to those in the West Pacific, which should then modulate eastern SSTs by exciting downwelling and upwelling Kelvin waves in varying degrees. Weak warming events similar to El Niños have been observed in the Atlantic, but nothing on the scale of an El Niño or La Niña has been noted in either the Atlantic or Indian Oceans. This can be explained by the depths of the thermoclines in the equatorial eastern Atlantic and Indian Oceans. These thermocline are deep in comparison to the thermocline in the equatorial East Pacific (see Fig. 6.9 and Table 6.1). The warming effects of downwelling and importation of warm water in the East Atlantic and Indian Oceans are reduced because of the relative abundance of warm upper layer water that already typically exists in these regions. Deepening a thermocline that is already deep does not affect SSTs as much as when the thermocline is shallow. Also, the addition of warm water to an ocean area has a diminished effect on SSTs as the water becomes warmer because of surface heat fluxes; Newell, 1986). The cooling effects of upwelling and exportation of upper layer water are

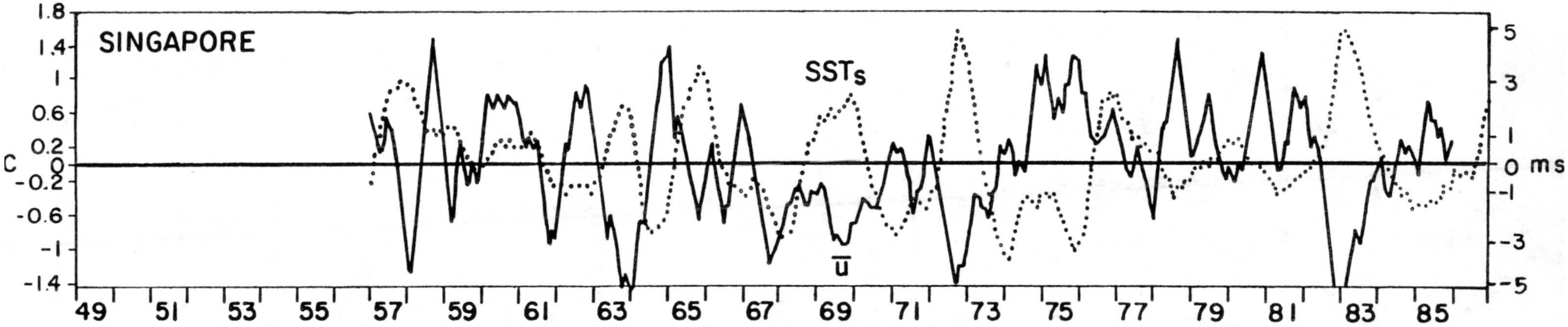

Figure 6.5: Six-month running means of 850 mb zonal wind anomalies at Singapore (2°N, 104°E) (solid line) versus six-month running means of the SST anomalies between 0-10°S, 180°-90°W (dotted line).

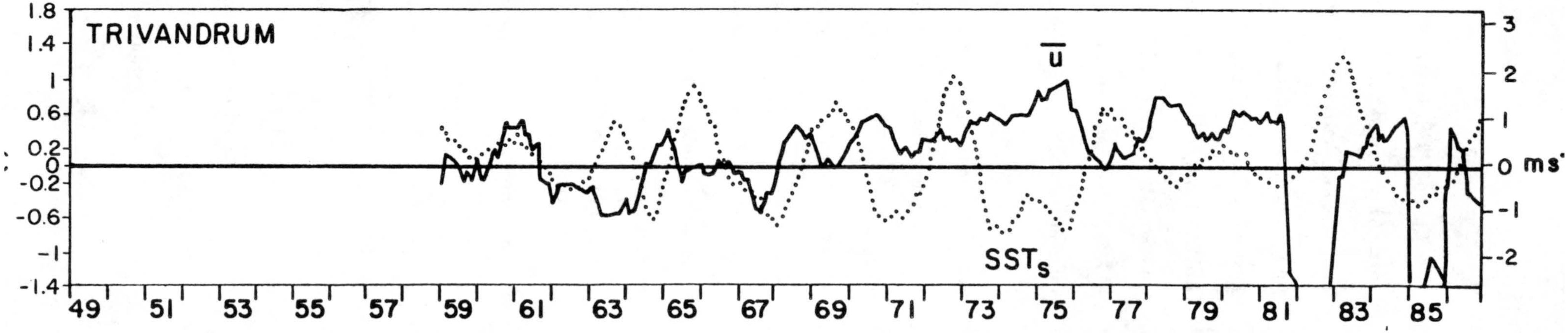

Figure 6.6: Twelve-month running means of 850 mb zonal wind anomalies at Trivandrum (8°N, 76°E) (solid line) versus twelve-month running means of the SST anomalies between 0-10°S, 180°-90°W (dotted line).

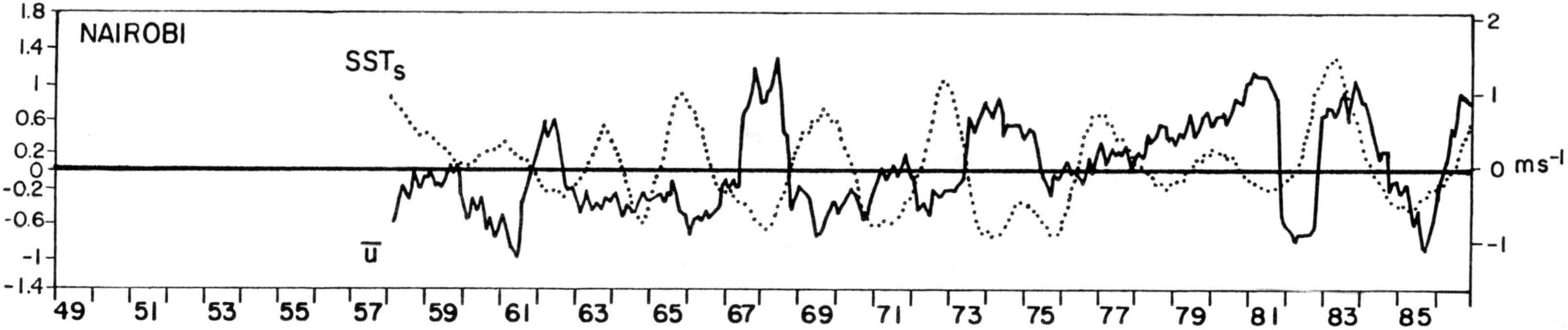

Figure 6.7: Twelve-month running means of 700 mb zonal wind anomalies at Nairobi (2°S, 36°E) (solid line) versus twelve-month running means of the SST anomalies between 0-10°S, 180°-90°W (dotted line).

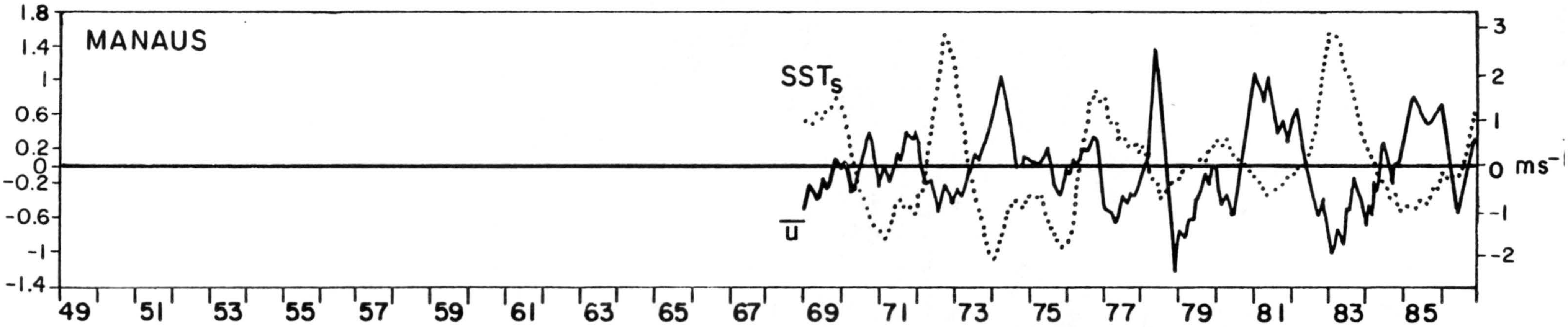

Figure 6.8: Six-month running means of 850 mb zonal wind anomalies at Manaus (3°N, 60°W) (solid line) versus six-month running means of the SST anomalies between 0-10°S, 180°-90°W (dotted line).

diminished in these two areas because the relative abundance of warm upper layer water can absorb the loss of more water before it is reflected in SSTs. In addition, the Atlantic and Indian Oceans have better defined western boundaries than the Pacific which may enable reflected Rossby waves to have a stronger impact on SSTs than they do in the Pacific; an impact that may be detrimental to the development of El Niños and La Niñas. Furthermore, the size and configuration of the Atlantic and Indian Oceans as well as oceanic and atmospheric processes specific to these two oceans may prohibit El Niño or La Niña type SST anomalies from occurring. The fact that the Atlantic does have weak El Niño type anomalies supports the previously stated hypotheses concerning the physical processes leading to SST anomalies in the Pacific.

Table 6.1: The warmest isotherm of sea surface temperature to cross the equator in the western half of the Atlantic, Indian and Pacific Oceans minus the coldest isotherm to cross the equator in the eastern half of each of those oceans for the months shown. Sea surface temperatures are an approximate measure of the depth of the thermocline. In general, the warmer the SSTs are, the deeper the thermocline. From Sadler et al. (1987).

	ΔT(°C)			
	Jan	April	July	October
Atlantic	0	-.5	3.5	2.5
Indian	-1.0	0	-2.5	-1.5
Pacific	5.0	3.0	6.0	7.0

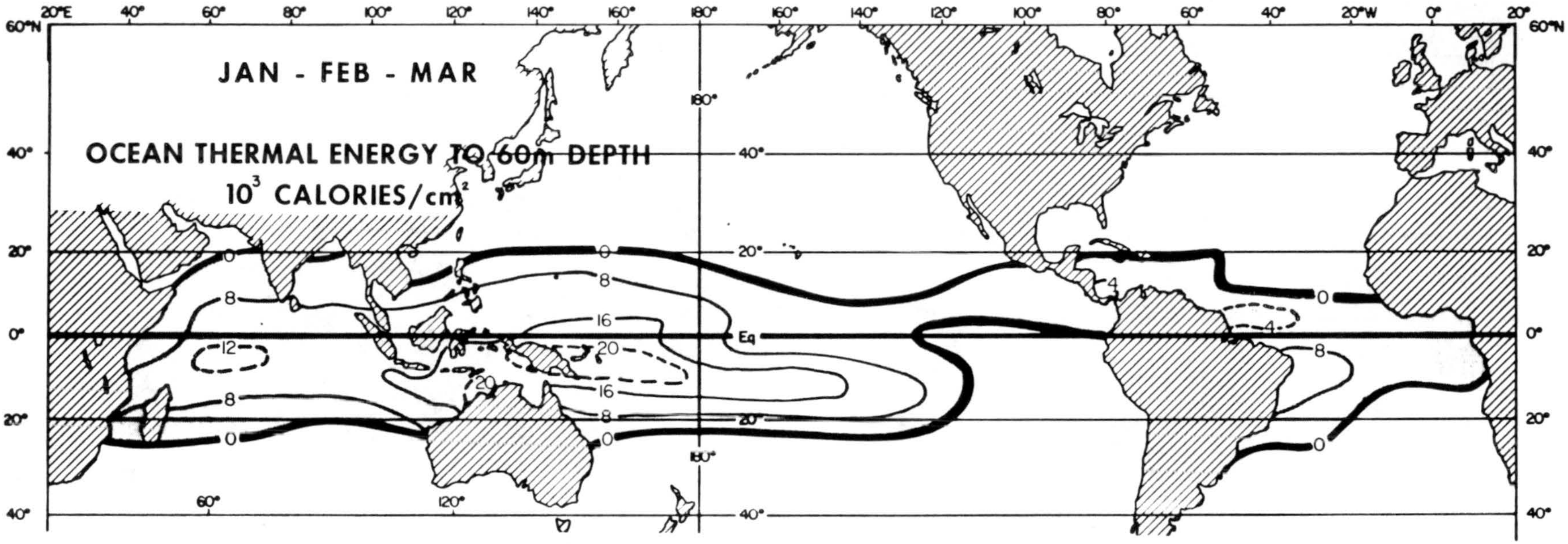

Figure 6.9: a. Seasonal values of ocean thermal energy to 60 m depth. This value is taken as a measure of the thermocline. In general, higher values of ocean thermal energy correspond to a deeper thermocline. From Gray (1975).

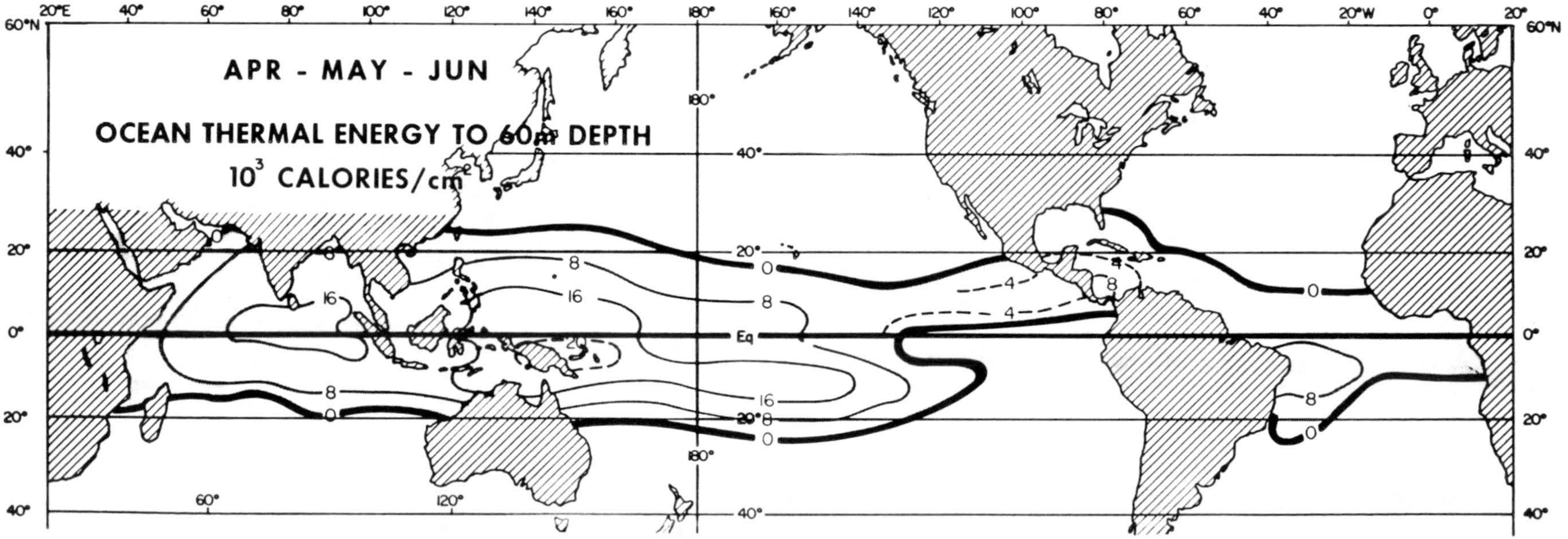

Figure 6.9: b. Continued

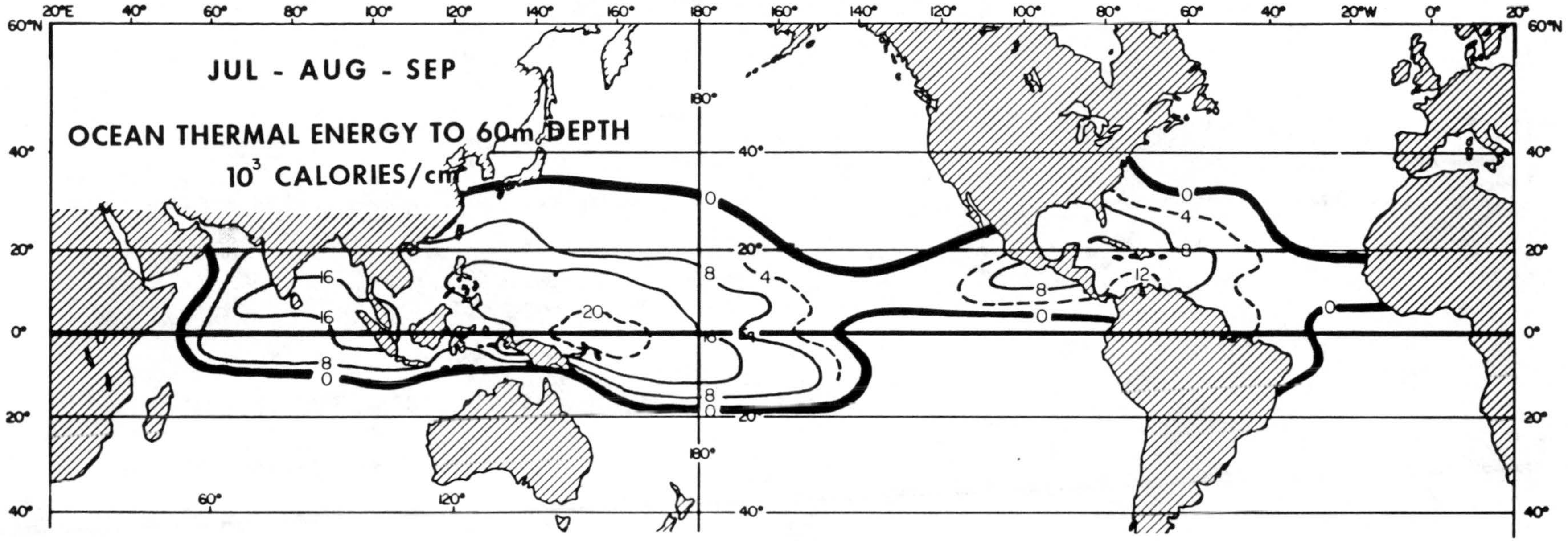

Figure 6.9: c. Continued.

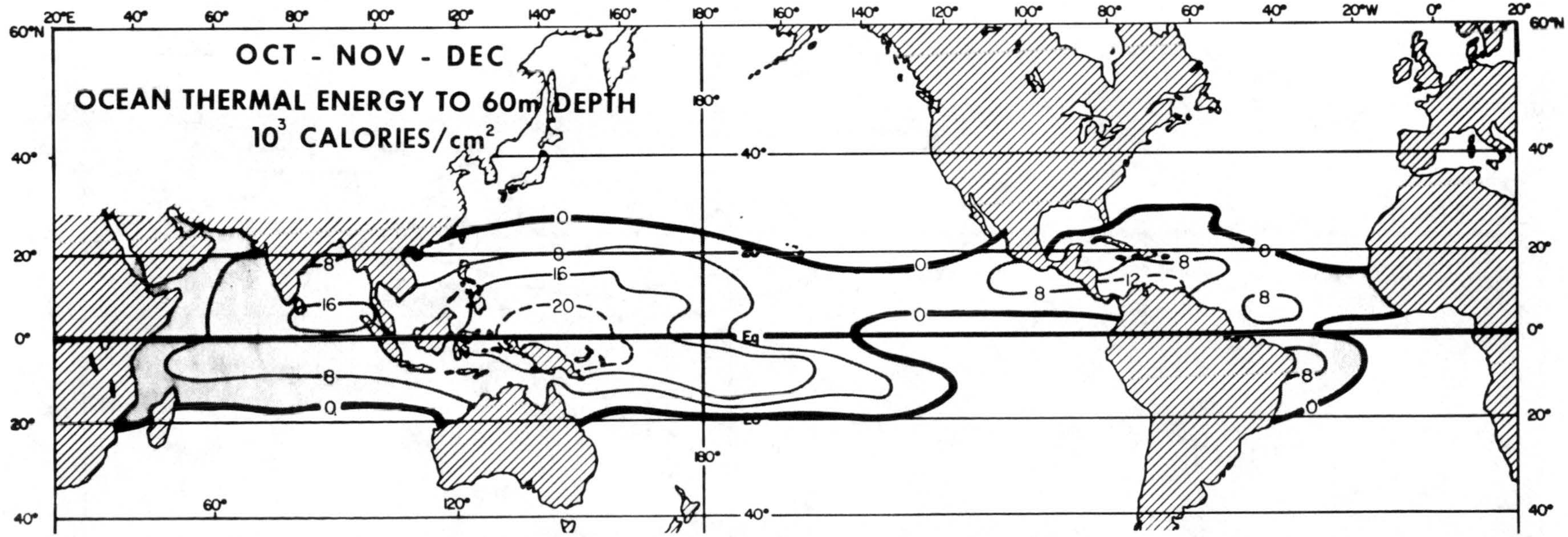

Figure 6.9: d. Continued.

Chapter 7

CONCLUSION

Strong correlations are observed between long term (one month or longer) fluctuations of surface zonal wind anomalies in the equatorial West Pacific and long term fluctuations of equatorial East Pacific SSTs. Winds that become westerly (easterly) over the long term are followed by SSTs that become warmer (colder). Periods of near zero wind change are followed by near normal SSTs. The close correspondence between these low-level zonal wind anomalies (LZWAs) and SST anomalies (SSTAs) is present during all phases of interannual SST cycles (nor just El Niños) and during all times of year, with SSTA variations lagging variations of the LZWAs by one to four months. The relationship is best seen when SSTAs over a broad longitude band are considered and when six-month running means of LZWAs and of SSTAs are compared. However, correlations are also fairly high when three-month means and simple monthly means are compared. The correlations with Tarawa LZWAs are exceptionally high; the monthly means correlate with SSTAs at .72. Tarawa may be a key station for predicting East Pacific SST changes. In general, the further east the islands, the higher the peak correlation with SSTAs. The LZWAs show the same relationship with surface pressure anomalies of the Southern Oscillation, but with opposite sign.

Tropical cyclone (TC) activity in the tropical West Pacific also correlates well with East Pacific SSTAs and the SO. Peak correlations occur when SSTAs and the SO lag long term fluctuations of TC day anomalies by several months. The highest correlations are found when TC day anomalies are considered for the area between 20°N and 20°S as opposed to either the NW or SW Pacific separately.

The strong correlations and consistent lags between SSTAs and LZWAs suggest that modifications of the current interpretations relating these two parameters may be appropriate. It was proposed that long term East Pacific SSTA fluctuations occur almost in direct proportion to long term West Pacific LZWA fluctuations. During periods when LZWAs become more westerly over the long term, short term (days or weeks) westerly changes with time dominate short term easterly changes with time, while the opposite is true during periods of long term easterly change. Changes with time, westerly and easterly changes occur with approximately equal frequency during periods when the long term means show near zero change. It was therefore hypothesized that when the mean long term net wind change is westerly, primarily downwelling ocean Kelvin waves are excited by the winds which lead to warming in the East Pacific, either by lowering the thermocline, or by transporting warm water eastward, or both. During periods of long term easterly wind change, primarily upwelling Kelvin waves are excited which tend to cool SSTs. Similarly, minimal net zonal wind change over the long term leads to near normal SSTs in the East because of nearly equal excitation of downwelling and upwelling Kelvin waves. In addition, anomalies of the curl of the wind stress may drive anomalous zonal ocean currents near the equator which affect SSTs. A unique feature of this interpretation is that the surface winds are suggested to directly modulate SSTs through Kelvin waves (and possibly anomalous currents) and that the effects of the Rossby waves excited by the winds is negligible in comparison. Several reasons were listed to justify the consideration of reflected Rossby wave effects as negligible in comparison.

The strong correlation between SSTAs and interannual fluctuations of TC activity in the West Pacific Northern and Southern Tropics is more puzzling. It is possible that the correlation exists because TC activity variations partially modulate LZWA variations, or because LZWAs influence both SSTAs and TC activity. Regardless of the physical relations, TC activity in the West Pacific appears to be a long range predictive signal for East Pacific SST variations.

The question as to what causes the interannual variability of West Pacific low-level winds was left somewhat open. The apparent independence of LZWAs from SSTAs suggests that the widely accepted idea of a positive feedback loop between low-level winds and East Pacific SSTs is not a complete explanation. Therefore, it was speculated that phenomena not directly linked to ENSO circulations in the Pacific may be primarily responsible for the year to year variations of these winds. A few phenomena, mostly global in scale, were identified as possible modulators of low-level winds, not just in the equatorial West Pacific but around the circumference of the equator. The data presented which support these phenomena as possible modulators is not very complete, and possible modulating phenomena are not limited to those listed in this paper. Much more research needs to be done on this topic. Nevertheless, the idea of primary forcing from external phenomena, not tied to ENSO circulations in the Pacific is still viable. ENSO circulations may then still enhance the effects of these other modulators.

It should be remembered that two distinct concepts have been discussed: first, East Pacific SST anomalies are directly proportional to the long term changes of equatorial West Pacific zonal surface winds with the effects of reflected Rossby waves being negligible in comparison to the influence of Kelvin waves, and secondly, the changes in these winds are determined in large part by circulations which are not necessarily part of Pacific feedback loops between the winds and SSTs and are possibly global in scale. The validity of the former concept does not depend on the validity of the latter.

The next step in this research should be a more complete and detailed examination of the global-scale circulation features which lead to these long period equatorial zonal wind anomaly changes. The relationship of the stratospheric QBO to ENSO needs special study. Another area needing research is that of establishing how warm and deep ocean water is accumulated in the western equatorial Pacific and how strong and over what time period such warm pools are able to be established. Such warm pool buildup is likely related to the intensity of El Niño events.

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Appendix A

BASIC DATA SETS

The 20 tables in this appendix contain all basic monthly data values used in the analyses described in this report. These data include monthly mean values for ten wind measurement sites, two sea surface temperature fields, and a pressure index of the Southern Oscillation. Information on the number of tropical cyclone 6-hourly reports above various wind velocities in the Northwest and Southwest Pacific-Australian region, equatorwards of 20° latitude, is also included.

Tables A1-5 contain monthly average zonal wind speeds of five West Pacific island sites. All wind reports are given in m/s. Data for three sites (Koror, Truk and Majuro) are for the 850 mb level while 700 mb data are given for Honiara (to accommodate local terrain effects) and surface wind reports are given for Tarawa. Monthly average Sea Level Pressure Anomaly (SLPA) data for Tahiti and Darwin are shown in Figs. A-6a and A-6b. Monthly low-level zonal wind data for several additional equatorial sites include 850 mb data for Singapore, Trivandrum, Manaus and Ascension Island, (Tables A7-A9) and for 700 mb data for Nairobi (Table A10). Note that the 1958-68 data for Ascension Island were appended to 1969-86 data for Manaus in Table A9, to provide a complete data series for this portion of the globe. Tables A11-A13 contain SST data for portions of the Eastern Pacific Ocean and Table A14 is a pressure index of the Southern Oscillation. Tables A15 through A20 contain monthly totals of 6-hour tropical cyclone reports for the Northwest and Southwest Pacific regions stratified for three classes of observed maximum wind speeds above 30, 65 and 90 knots, respectively.

Table A-1. Monthly average 850 mb zonal wind speeds in m/s at Koror for 1951-1985.

Table A-2. Monthly average 850 mb zonal wind speeds in m/s at Truk for 1951-1985.

Table A-3. Monthly average 850 mb zonal wind speeds in m/s at Majuro for 1955-1986.

Table A-4. Monthly average 700 mb zonal wind speeds in m/s at Honiara for 1958-1987.

Table A-5. Monthly average surface zonal wind speeds in m/s at Tarawa for 1949-1987.

Table A-6a. Monthly average Sea Level Pressure Anomaly (SLPA) for Tahiti. Values in 10^{-1}mb - supplied by N. Nicholls.

Table A-6b. Monthly average Sea Level Pressure Anomaly (SLPA) for Darwin. Values in 10^{-1}mb - supplied by N. Nicholls.

Table A-7. Monthly average 850 mb zonal wind speeds in m/s at Singapore for 1957-1985.

Table A-8. Monthly average 850 mb zonal wind speeds in m/s at Trivandrum for 1959-1986.

Table A-9. Monthly average 850 mb zonal wind speeds in m/s at Ascension Island for 1957-1968 and at Manaus for 1969-86.

Table A-10. Monthly average 700 mb zonal wind speeds in m/s at Nairobi for 1958-1986.

Table A-11. Three-month running mean sea surface temperature anomalies (°C) for the area shown in Fig. 2.1 (from Dong, 1987).

Table A-12. Monthly mean SST anomalies for the East Pacific area shown in Fig. 2.1, obtained from COADS data set as explained in the text.

Table A-13. Monthly mean SST anomaly values (°C) for the 2° by 2° area centered on 2.8°S, 91°W prior to 1980; from COADS. Values are from the *Climate Diagnostics Bulletin*, Nino 1 + 2 for 1980 and thereafter.

Table A-14. Monthly mean Southern Oscillation index of the anomalous pressure difference of Tahiti minus Darwin (in mb x 10).

Table A-15. Monthly number of 6-hour tropical storm reports in the Northwest Pacific with sustained maximum winds equal to or greater than 30 knots ($\sim$ 15 m/s).

Table A-16. Same as for Table A-15, but for number of 6-hourly reports of tropical cyclones of typhoon intensity with maximum sustained winds equal to or greater than 65 knots ($\sim$ 32 m/s).

Table A-17. Same as for Tables A-15, but for number of 6-hourly typhoons with maximum sustained winds equal to or greater than 90 knots ($\sim$ 45 m/s).

Table A-18. Monthly number of 6-hour tropical storm reports in the Southwest Pacific Ocean east of 145°E and equatorwards of 20°S with sustained maximum winds equal to or greater than 30 knots (~ 15 m/s).

Table A-19. Similar to Table A-18, but for number of 6-hourly reports of tropical cyclones of typhoon intensity with maximum sustained

winds equal to or greater than 65 knots (~ 32 m/s).

Table A-20. Similar to Table A-18, but for the number of 6-hourly monthly reports of storms with maximum sustained winds equal to or greater than 90 knots (~ 45 m/s).

Table A-1. Monthly averages 850 mb zonal wind speeds (m/s) at Koror for 1951-1985.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
51	999.99	999.99	999.99	999.99	999.99	999.99	0.10	6.80	0.60	3.10	-4.40	-2.50
52	-10.70	-10.50	-6.50	-6.30	-3.90	-1.20	1.40	5.90	5.80	5.50	-0.20	-3.20
53	-8.50	-10.10	-9.10	-3.50	-3.90	0.20	-1.40	7.90	1.60	0.50	-0.60	-4.80
54	-8.10	-6.30	-6.50	-6.70	-5.40	-3.60	-3.00	-0.20	2.10	-0.60	3.00	-5.40
55	-7.50	-6.80	-6.30	-3.90	-3.30	-4.80	-2.40	-3.00	-1.30	0.40	-2.70	-2.30
56	-8.90	-7.70	-5.80	-2.70	-2.90	-3.80	1.10	0.80	0.70	-0.90	2.80	-3.80
57	-4.80	-7.00	-7.00	-5.30	-4.30	-2.90	-0.40	5.80	2.60	4.60	1.80	-7.80
58	-3.90	-6.80	-6.30	-5.00	-2.30	-1.00	5.10	-0.60	2.80	4.20	1.60	-2.20
59	-8.70	-7.30	-4.70	-3.90	-5.70	-5.10	1.00	4.60	5.80	1.10	-0.10	-4.40
60	-7.30	-6.90	-6.10	-6.50	-2.50	-1.50	-2.10	2.60	1.40	7.00	-4.50	0.10
61	-3.90	-7.60	-2.90	-6.50	-1.90	1.80	3.40	5.60	7.60	6.20	-3.80	-6.20
62	-8.90	-6.10	-9.10	-0.50	-3.60	-1.50	5.80	2.40	4.50	2.60	0.00	-3.80
63	-4.80	-6.90	-7.00	-1.50	-1.00	4.20	5.00	6.30	5.20	9.50	-4.80	-3.20
64	-8.40	-10.50	-8.10	-4.30	3.50	-2.50	-2.20	2.70	-1.20	2.00	0.70	-4.00
65	-3.00	-8.70	-5.50	-6.70	-4.80	2.30	9.50	2.40	7.90	3.00	-2.40	-10.60
66	-10.60	-8.90	-7.20	-6.10	-2.20	-2.10	2.10	0.80	2.60	1.10	-2.80	-6.60
67	-8.30	-7.50	-5.20	-3.00	-2.50	0.70	5.60	6.70	6.20	5.70	-1.40	-4.70
68	-7.00	-6.50	-9.10	-4.30	-3.70	-3.40	1.30	3.60	4.80	5.10	4.30	-8.20
69	-9.40	-7.10	-7.30	-5.00	-5.10	-2.60	3.40	-0.70	7.90	1.80	0.70	-5.40
70	-6.30	-6.50	-8.10	-7.50	-7.70	-3.30	0.10	0.60	-2.30	-0.60	-5.30	-8.50
71	-3.20	-7.00	-1.40	1.90	-1.10	0.40	4.50	-2.90	-1.20	0.10	-1.70	-9.60
72	-2.40	-5.80	-3.70	-3.60	1.10	1.70	7.20	3.30	5.00	3.10	-5.10	-6.20
73	-7.30	-8.40	-7.20	-8.20	-6.60	-5.10	-1.20	-2.80	-3.60	0.40	-4.50	-5.20
74	-0.70	-8.70	-4.70	-2.60	-2.80	1.10	0.90	3.90	-2.50	3.70	2.20	-6.70
75	-7.30	-8.20	-6.30	-7.10	-4.90	-4.00	-0.90	1.00	-2.90	-2.20	-0.10	-6.20
76	-4.90	-5.70	-6.50	0.30	4.30	1.00	3.50	2.60	8.50	-4.70	-2.20	-4.80
77	-7.30	-9.70	-8.40	-6.70	-2.90	-4.20	2.90	4.00	8.30	4.70	0.70	-4.10
78	-8.10	-7.00	-8.70	-6.60	-5.70	-2.10	-0.90	2.50	1.40	4.70	2.90	-7.70
79	-7.10	-5.60	-5.40	-2.20	-2.80	-1.40	2.80	4.60	-0.70	8.30	-1.80	-1.00
80	-7.70	-7.70	-4.90	-6.10	0.60	-1.70	3.30	3.30	7.80	1.90	-2.90	-3.00
81	0.10	-7.40	-8.10	-6.00	-6.10	-0.10	1.00	7.30	0.30	0.90	-2.10	-3.60
82	-3.40	-5.20	-4.10	-4.50	-2.80	1.10	8.00	6.20	6.10	5.50	-3.60	-6.00
83	-7.10	-7.90	999.99	-7.00	-5.50	-3.30	1.10	0.50	0.20	-1.50	3.10	999.99
84	-6.60	-7.90	-8.70	-6.90	-6.60	-1.30	-3.10	6.20	-0.40	8.20	0.60	-5.70
85	1.30	-10.80	-7.30	0.10	-2.30	3.10	1.90	3.10	3.80	-0.20	-5.10	-1.00
MEAN	-6.20	-7.61	-6.46	-4.54	-3.16	-1.32	1.84	2.97	2.73	2.69	-1.08	-4.95

Table A-2. Monthly average 850 mb zonal wind speeds (m/s) at Truk for 1951-1985.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
51	999.99	999.99	999.99	999.99	999.99	999.99	-3.30	5.80	-3.10	-0.90	-4.60	-1.80
52	-10.60	-9.30	-7.00	-6.50	-6.70	-6.00	-4.80	-3.20	0.30	-2.30	-5.60	-4.00
53	-8.20	-9.40	-8.20	-4.60	-5.40	-7.20	-5.30	2.60	-1.10	-3.30	-5.10	-3.20
54	-9.30	-8.30	-6.60	-7.60	-6.80	-5.30	-5.80	-3.10	-1.90	-1.10	-4.40	-8.20
55	-9.70	-9.20	-7.70	-7.70	-5.90	-7.20	-4.20	-5.90	-3.30	-4.10	-6.50	-4.80
56	-8.10	-8.70	-7.80	-7.90	-4.60	-5.40	-2.80	-3.80	-2.40	-2.40	-4.60	-10.30
57	-7.90	-7.00	-7.10	-7.40	-4.00	-6.00	-6.20	-1.10	-1.70	3.80	-0.90	-9.40
58	-6.50	-7.90	-8.20	-8.80	-7.00	-5.60	-0.40	-3.70	-1.80	1.70	-3.70	-5.50
59	-7.70	-8.10	-8.30	-8.00	-8.00	-6.00	-2.80	0.00	2.40	-4.40	-3.10	-9.80
60	-9.80	-9.30	-5.90	-8.60	-5.50	-6.50	-5.10	-2.00	-2.90	0.20	-4.10	-7.10
61	-7.60	-8.80	-7.00	-8.70	-6.40	-3.60	-1.70	-1.20	1.30	1.00	-4.90	-7.60
62	-8.60	-8.50	-8.90	-4.60	-8.90	-4.50	-2.10	-2.70	-0.90	-0.90	-1.70	-4.60
63	-6.90	-7.90	-8.00	-4.00	-2.80	-0.80	-0.90	-0.10	1.20	7.10	-5.20	-6.00
64	-8.90	-10.90	-6.90	-5.50	-4.10	-5.50	-3.60	-2.20	-4.90	-2.60	-5.20	-6.90
65	-8.00	-9.20	-7.20	-6.80	-7.40	-4.60	1.50	-2.80	3.10	4.10	-2.80	-9.50
66	-10.40	-9.40	-8.20	-6.70	-6.60	-6.00	-3.50	-2.80	0.60	-1.10	-4.50	-8.50
67	-10.10	-8.70	-5.20	-5.40	-4.10	-4.30	-0.90	0.20	3.30	-1.40	-4.10	-7.30
68	-9.80	-6.70	-9.90	-2.00	-4.60	-3.80	-2.70	-0.60	-0.20	1.70	-1.40	-6.50
69	-7.00	-6.80	-6.40	-8.00	-8.00	-6.50	-4.30	-2.90	-1.10	-0.80	-5.40	-8.00
70	-7.90	-9.70	-8.40	-9.00	-8.30	-8.30	-4.80	-4.30	-4.30	-5.20	-6.50	-9.30
71	-6.20	-8.40	-6.00	-3.70	-6.90	-6.70	-3.20	-4.70	-2.70	-5.10	-4.20	-10.40
72	-5.80	-7.60	-6.60	-4.80	-0.30	-0.30	7.10	0.40	4.50	4.60	-5.80	-6.90
73	-8.10	-8.00	-6.70	-9.40	-7.40	-7.10	-6.10	-6.20	-7.10	-4.00	-7.20	-8.70
74	-2.70	-8.30	-3.20	-3.90	-3.30	-2.80	-2.30	-0.60	-1.90	-3.40	-3.10	-8.60
75	-8.30	-6.90	-7.20	-7.80	-7.40	-8.20	-4.20	-4.90	-6.30	-4.70	-3.10	-7.20
76	-8.60	-5.40	-4.80	-3.50	-0.20	-3.60	1.60	-1.40	5.90	-4.90	-6.30	-6.60
77	-9.40	-9.40	-7.60	-5.60	-6.00	-6.60	-5.50	-3.30	0.60	3.30	-3.40	-6.40
78	-6.50	-7.40	-7.90	-7.30	-7.20	-5.90	-3.00	-3.50	-1.70	0.90	-3.50	-8.70
79	-6.20	-5.90	-6.30	-7.80	-7.40	-7.70	-3.80	2.90	-2.10	-1.80	-2.50	-3.00
80	-7.40	-7.20	-8.20	-6.50	-1.70	-5.80	-0.60	-2.10	3.20	-2.20	-4.70	-7.70
81	-6.70	-7.20	-6.40	-5.30	999.99	-5.90	-4.70	2.60	-2.50	-1.60	-4.00	-5.10
82	-7.20	-5.90	-6.50	-4.70	-5.50	-2.30	5.30	5.20	6.50	3.20	-2.30	999.99
83	-9.50	-9.50	-6.40	-5.80	-6.40	-6.60	-5.20	-3.90	-2.60	-3.80	-6.10	999.99
84	-8.50	-8.10	-8.30	-8.10	-7.00	-6.50	-4.50	-2.90	-3.10	2.70	-3.40	-7.00
85	-4.90	-9.20	-8.10	-4.00	-3.70	-5.80	-1.80	-1.20	-2.50	-1.70	-5.50	-6.70
MEAN	-7.91	-8.18	-7.15	-6.35	-5.62	-5.44	-2.70	-1.64	-0.83	-0.84	-4.27	-7.01

Table A-3. Monthly average 850 mb zonal wind speeds (m/s) at Majuro for 1955-1986.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
55	999.99	-9.10	-8.10	-5.40	-8.90	-9.20	-6.70	-7.10	-6.50	-6.50	-7.40	-3.50
56	-7.00	-6.00	-8.00	-8.80	-8.60	-7.60	-7.50	-6.50	-4.90	-4.80	-6.50	-8.40
57	-6.70	-7.20	-8.50	-8.40	-7.80	-7.50	-7.60	-5.50	-4.10	-2.90	-3.10	-6.20
58	-8.10	-8.20	-7.00	-8.60	-8.30	-8.10	-4.80	-4.90	-1.70	-3.10	-6.10	-8.80
59	-5.00	-7.80	-9.40	-9.90	-9.60	-6.50	-5.60	-3.50	-3.80	-3.90	-6.80	-9.60
60	-9.20	-9.10	-7.50	-9.50	-10.00	999.99	999.99	999.99	999.99	-4.00	-6.10	-8.40
61	-8.70	-10.50	-7.60	-8.20	-9.00	-8.20	-6.20	-7.20	-2.70	-3.80	-5.00	-7.60
62	-10.30	-9.50	-9.40	-8.20	-9.90	-6.40	-9.40	-6.80	-6.30	-5.80	-7.70	-8.90
63	-8.30	-9.10	-9.00	-6.40	-6.10	-5.30	-5.00	-5.50	-3.90	1.20	-4.90	-10.00
64	-8.80	-10.60	-6.80	-8.40	-6.90	-7.20	-6.30	-6.70	-5.90	-5.30	-6.80	-6.60
65	-8.60	-10.70	-8.60	-7.80	-8.10	-6.90	-5.50	-3.50	-4.50	-2.20	-1.10	-8.80
66	-8.80	-6.90	-9.90	-7.80	-7.30	-6.00	-6.80	-5.00	-3.30	-4.30	-3.30	-9.30
67	-10.10	-8.40	-8.00	-5.30	-6.50	-7.20	-5.80	-6.60	-3.30	-3.90	-5.40	-7.50
68	-8.30	-6.40	-10.30	-4.30	-6.00	-5.60	-6.40	-3.30	-2.80	-1.20	-5.80	-4.10
69	-6.80	-5.00	-10.40	-10.50	-9.60	-6.80	-7.50	-4.40	-5.00	-3.10	-5.20	-10.10
70	-8.30	-9.80	-8.80	-9.30	-9.90	-10.10	-6.80	-8.40	-7.10	-8.80	-5.80	-9.10
71	-6.20	-10.10	-8.20	-7.80	-10.90	-9.60	-7.10	-6.80	-6.60	-6.70	-6.00	-6.10
72	-5.80	-7.30	-7.60	-3.00	-2.10	-4.70	0.00	-3.80	-0.80	6.00	-4.70	-7.80
73	-8.20	-7.00	-8.50	-9.80	-9.00	-9.30	-6.80	-8.70	-7.50	-7.40	-6.80	-10.10
74	-6.80	-9.10	-5.70	-7.80	-7.50	-6.90	-7.10	-3.80	-4.30	-6.60	-5.40	-8.30
75	-9.10	-7.90	-10.60	-9.10	-9.10	-9.70	-6.80	-7.70	-8.50	-6.70	-7.40	-11.00
76	-6.40	-4.20	-7.50	-6.40	-7.60	-6.00	-5.40	-5.30	-1.10	-6.30	-6.20	-8.40
77	-8.20	-9.80	-7.30	-7.80	-8.70	-7.30	-7.60	-5.40	-1.60	-3.50	-4.20	-3.80
78	-8.90	-7.20	-7.90	-7.80	-8.30	-7.60	-6.60	-6.30	-3.60	-2.40	-6.20	-7.10
79	-7.40	-5.90	-8.50	-7.90	-9.30	-9.10	-6.40	-2.20	-4.40	-3.40	-4.00	-6.60
80	-7.40	-9.80	-8.40	-5.30	-7.20	-8.30	-4.50	-5.20	-2.10	-4.90	-5.60	-9.80
81	-9.30	-7.90	-6.70	-9.20	-8.10	-7.80	-7.80	-3.70	-4.40	-3.20	-6.70	-8.40
82	-8.50	-6.00	-6.60	-5.00	-5.80	-6.80	-1.30	-1.00	4.20	2.60	-1.10	-10.00
83	-6.90	999.99	999.99	-4.70	-5.80	-7.10	-7.20	-5.50	-4.10	-5.60	999.99	999.99
84	-9.10	-9.80	-8.80	-10.00	-9.30	-9.80	-7.40	-6.00	-4.10	-3.60	-4.60	-6.10
85	-6.20	-9.70	-7.30	-6.40	-8.40	-7.90	-5.50	-4.30	-4.70	999.99	999.99	999.99
86	-9.40	-8.50	-10.80	-8.50	-2.50	-6.20	-4.00	-0.40	-2.40	-3.20	-6.00	-6.90
MEAN	-7.96	-8.21	-8.31	-7.60	-7.88	-7.51	-6.11	-5.19	-3.93	-3.78	-5.40	-7.91

Table A-4. Monthly average 700 mb zonal wind speeds (m/s) at Honiara for 1958-1987

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
58	999.99	999.99	999.99	999.99	999.99	999.99	999.99	-7.70	-6.00	-3.00	-0.40	0.40
59	5.90	2.80	0.30	-1.80	-4.20	-7.40	-4.40	-4.50	-4.40	-4.60	-0.90	3.10
60	1.60	3.40	1.70	1.50	-5.80	-5.30	-5.90	-5.80	-6.50	-1.80	-3.40	2.60
61	5.20	-3.70	4.40	-4.20	-3.00	-5.20	-5.60	-4.20	-4.20	-3.70	-1.20	-0.10
62	-1.20	4.00	0.50	-0.90	-4.10	-2.60	-4.40	-8.20	-8.20	-4.20	-0.10	2.70
63	-4.40	-5.90	-1.30	-0.40	-0.40	-3.80	-4.60	-3.90	-3.70	-2.20	-0.40	2.10
64	1.50	3.20	-1.10	-3.30	-2.40	-5.60	-7.00	-7.00	-7.10	-5.50	1.70	0.70
65	5.00	3.20	1.40	-1.30	-1.70	-2.50	-6.10	-3.50	-3.40	-1.30	-0.50	-2.60
66	5.00	0.70	1.30	-0.20	-2.10	-6.00	-4.10	-6.50	-3.40	-2.90	-2.80	-0.40
67	0.00	0.10	2.20	-1.20	-2.50	-7.40	-5.80	-7.40	-2.50	-0.30	-1.70	3.50
68	3.00	1.70	-0.50	-1.30	-3.40	-2.80	-5.00	-5.50	-3.10	-2.70	-0.50	-1.60
69	2.20	6.60	-0.80	-0.20	-3.60	-6.40	-3.40	-6.10	-2.30	-3.60	-2.20	-1.50
70	3.50	1.60	-2.90	0.40	-3.50	-4.10	-5.10	-7.00	-6.90	-3.30	-2.60	2.80
71	1.40	-1.20	2.40	-3.90	-3.20	-5.40	-5.90	-9.80	-7.20	-4.30	-0.20	3.00
72	-3.50	-4.40	2.00	-1.70	-4.20	-3.20	-5.30	-0.90	1.50	-1.20	-2.20	1.50
73	0.10	4.00	-0.90	-3.10	-3.60	-5.20	-3.40	-6.10	-6.10	-4.50	0.70	0.90
74	0.60	1.60	-0.20	-2.60	-5.60	-5.30	-8.20	-5.10	-8.10	-2.50	-0.40	2.10
75	6.90	-2.20	-1.50	-1.60	-2.90	-4.90	-7.20	-6.70	-6.90	-5.60	-0.80	-3.40
76	6.50	3.20	-1.30	-1.90	-4.50	-4.10	-5.50	-3.90	-1.40	-4.30	-2.60	-0.30
77	7.30	-1.70	4.70	-3.20	-3.20	-4.00	999.99	999.99	999.99	999.99	999.99	999.99
78	999.99	999.99	999.99	999.99	999.99	999.99	999.99	999.99	999.99	999.99	999.99	999.99
79	999.99	999.99	999.99	999.99	-2.80	-4.00	-3.90	-5.00	-4.70	-3.50	-2.00	2.00
80	-0.90	-0.50	1.90	-2.00	-4.00	-3.90	-4.90	-6.00	-2.70	0.30	-1.20	-2.80
81	2.20	6.00	2.80	-0.30	-5.00	-6.00	-6.00	-2.90	-7.70	-3.70	-1.90	3.00
82	0.80	3.40	2.00	0.00	-2.00	-2.40	-2.00	-1.90	-1.80	0.10	1.80	3.00
83	5.00	7.00	3.00	0.00	-2.70	-3.50	-4.70	-6.00	-6.70	-3.70	-1.60	1.70
84	-1.80	-3.80	0.40	-1.70	-3.30	-3.70	-8.00	-3.90	-3.70	-1.40	-0.70	1.00
85	2.00	-1.90	2.90	-4.80	-1.40	-3.30	-3.50	-5.90	-4.50	-4.00	0.90	0.50
86	0.00	2.00	-3.10	-1.00	-3.00	-3.00	-3.20	-3.60	-1.80	-3.00	0.00	3.50
87	6.00	5.90	-0.10	-2.00	-3.90	999.99	999.99	999.99	999.99	999.99	999.99	999.99
MEAN	2.22	1.30	0.75	-1.58	-3.29	-4.48	-5.12	-5.37	-4.57	-2.98	-0.93	1.01

Table A-5. Monthly average surface zonal wind speeds (m/s) at Tarawa for 1949-1987 as supplied by E. Harrison (1949-80) and the New Zealand Meteorological Service (1980-87).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
49	-2.90	-4.40	-3.80	-5.20	-4.40	-2.90	-2.80	-2.50	-3.00	-3.50	-2.60	-3.90
50	-3.30	-5.20	-4.80	-5.00	-3.40	-3.70	-2.90	-3.20	-3.00	-2.50	-2.80	-3.30
51	-3.40	-4.50	-3.10	-2.80	-2.40	-2.10	-1.70	-2.20	-1.30	-0.70	-0.60	-1.50
52	-2.60	-4.20	-4.20	-3.10	-3.50	-2.60	-3.50	-3.70	-2.80	-4.10	-2.50	-0.80
53	-3.40	-4.80	-5.10	-5.10	-3.30	-4.60	-3.00	-1.50	-1.40	-2.90	-4.60	-2.50
54	-5.50	-4.60	-4.50	-4.60	-4.90	-5.00	-5.50	-5.40	-5.60	-5.10	-4.30	-5.90
55	-4.40	-6.80	-6.20	-4.70	-5.80	-5.30	-6.00	-6.60	-6.40	-6.30	-5.00	-4.50
56	-4.70	-5.60	-6.60	-5.40	-5.00	-4.40	-4.20	-6.20	-4.60	-5.00	-4.60	-4.00
57	-3.40	-3.70	-4.10	-4.10	-2.80	-2.60	-2.80	-2.90	-0.80	0.60	6.50	-1.40
58	-1.50	-3.70	-3.20	-3.60	-1.70	-2.30	-1.00	-2.90	-2.50	-2.70	-1.20	0.60
59	-3.30	-0.60	-4.20	-4.50	-3.50	-3.60	-3.70	-3.70	-6.20	-2.20	-3.70	-5.00
60	-5.70	-6.60	-6.00	-5.70	-5.00	-4.70	-4.60	-4.40	-4.80	-2.90	-5.10	-4.80
61	-5.80	-6.70	-5.20	-6.70	-5.90	-4.70	-3.70	-6.80	-5.70	-5.20	-5.10	-5.40
62	-9.10	-7.40	-6.50	-5.60	-6.70	-3.50	-4.20	-3.60	-4.40	-5.10	-4.50	-5.40
63	-5.80	-6.60	-6.50	-3.80	-5.50	-1.00	-1.60	-4.10	-1.10	-0.80	0.00	-0.60
64	-4.90	-5.30	-6.70	-6.30	-5.00	-4.30	-4.50	-6.00	-6.40	-5.00	-3.10	-2.80
65	-3.40	-4.10	-4.60	-3.80	-3.70	-1.50	0.70	1.20	2.20	2.40	2.20	-0.90
66	-1.00	-3.80	-3.30	-2.60	-2.80	-2.50	-2.90	-4.10	-2.30	-3.30	-2.20	-3.60
67	-5.50	-4.80	-4.50	-3.20	-3.50	-3.40	-3.50	-4.30	-2.70	-2.90	-2.70	-1.90
68	-3.30	-2.50	-4.80	-3.40	-3.20	-3.30	-3.00	-3.20	-2.30	-2.00	-0.90	-2.20
69	0.30	-1.60	-0.70	-3.60	-3.30	-2.30	-3.00	-2.10	-2.60	-2.00	-2.30	-2.30
70	-2.50	-4.50	-4.30	-4.20	-3.40	-4.40	-4.00	-5.60	-5.60	-6.60	-6.20	-6.10
71	-5.00	-6.50	-7.20	-5.40	-5.80	-5.80	-4.80	-5.40	-5.80	-5.60	-4.20	-3.90
72	-2.40	-6.20	-4.70	-2.10	-2.00	-2.70	2.10	1.20	3.70	4.90	0.80	-0.90
73	-2.10	-3.80	-5.10	-5.00	-3.80	-5.20	-5.10	-6.40	-6.60	-4.70	-4.90	-5.60
74	-4.60	-6.80	-5.60	-5.30	-4.40	-4.60	-4.10	-4.90	-5.00	-5.30	-3.50	-1.70
75	-4.40	-5.20	-5.70	-5.00	-4.60	-5.20	-4.60	-5.70	-6.80	-6.10	-5.30	-5.50
76	-3.80	-4.60	-5.10	-3.50	-3.00	-1.20	0.00	-0.60	0.10	-3.00	-2.50	-1.70
77	-3.80	-5.20	-3.80	-3.70	-3.20	-2.20	-1.90	-2.10	-1.50	-2.70	0.10	3.60
78	-1.30	-1.70	-3.00	-3.00	-4.60	-3.90	-3.90	-3.70	-3.80	-2.70	-3.00	-0.90
79	-0.90	-2.70	-4.40	-3.80	-3.50	-3.40	-3.10	-2.40	-2.40	-0.90	-2.80	-1.00
80	-3.10	-3.60	-1.60	-1.20	-1.90	-3.10	-2.30	-2.40	-2.10	-3.30	-1.50	-2.60
81	-2.90	-1.60	-0.60	-2.60	-3.60	-3.10	-3.60	-2.40	-3.40	-2.50	-3.90	-1.40
82	-4.00	-2.90	-3.40	-2.80	-2.50	-1.30	3.10	3.10	4.90	4.50	6.80	-2.80
83	-2.90	-4.40	-2.90	-3.80	-2.60	-1.50	-1.10	-4.00	-4.10	-4.50	-3.00	-4.20
84	-4.30	-6.00	-5.60	-5.80	-4.90	-2.90	-3.00	-2.10	-3.00	-2.30	-2.80	-4.00
85	-3.30	-5.40	-4.00	-3.90	-3.60	-2.70	-2.60	-3.60	-3.80	-2.50	-1.80	-2.10
86	-4.20	-4.40	-6.20	-4.40	-2.40	-3.20	-0.50	-0.40	0.30	-0.10	1.40	3.10
87	-2.70	-1.90	-2.50	-1.10	-0.60	-0.90	3.20	0.80	1.20	-0.30	-1.30	-0.70
MEAN	-3.61	-4.48	-4.47	-4.09	-3.74	-3.27	-2.66	-3.20	-2.86	-2.69	-2.22	-2.58

A-6A -- Monthly Average Sea Level Pressure Anomaly (SLPA) for Tahiti. Values in 10-1 mb
Supplied by N.Nicholls

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1945	11	10	5	-1	2	3	9	12	14	8	-1	11
1946	-7	-3	5	-3	-9	-5	-8	-1	-19	-9	1	-12
1947	0	-13	14	-5	-4	4	16	-1	15	-4	7	3
1948	2	-8	-9	-2	2	-4	-6	-13	-10	7	-6	-8
1949	-7	-7	-5	7	-7	-5	-3	-1	2	0	-8	-7
1950	-7	12	20	1	-2	15	23	11	9	16	-5	15
1951	16	-3	-17	-11	-8	-15	-18	-5	-14	-13	-7	1
1952	-15	-11	8	-1	2	9	7	-6	-2	-3	-11	-13
1953	9	-7	-8	-7	-15	-3	7	-25	-10	0	1	-2
1954	-4	-3	-3	-11	-5	-5	-1	5	3	3	6	16
1955	8	1	-6	-13	-2	3	14	8	14	12	11	20
1956	7	6	9	0	2	3	0	4	-4	21	2	1
1957	11	-8	-3	0	-4	-2	1	-9	-5	7	-8	-3
1958	-15	-9	1	-4	-15	-9	-1	0	-10	-12	-5	-3
1959	-21	-9	8	0	-2	-4	-2	-4	0	5	6	3
1960	2	-2	5	0	-5	-3	2	7	-2	0	9	12
1961	2	10	-22	7	2	0	3	3	3	-11	14	20
1962	22	-2	2	2	6	-2	-8	12	0	6	-1	2
1963	13	20	3	0	-5	-6	1	-9	-3	-7	0	-7
1964	1	1	6	12	-6	2	-2	16	8	10	-7	-4
1965	-10	-6	-2	3	0	0	-10	-8	-10	-1	-11	-5
1966	-15	-8	-16	-4	1	9	-2	5	-2	2	1	-5
1967	16	16	10	7	-5	7	-1	9	17	0	-7	-7
1968	-15	4	-1	-2	3	12	7	-1	-2	0	4	2
1969	-35	-18	6	3	-9	1	-6	-1	-19	-11	2	2
1970	-4	-18	-2	-1	-2	6	-1	-2	3	-3	16	13
1971	-1	11	18	12	5	8	-3	12	15	17	5	-12
1972	1	0	-6	4	-7	-12	-21	-4	-7	1	4	-2
1973	2	-13	-2	-8	1	0	3	6	17	5	17	25
1974	19	11	15	6	13	2	15	3	11	4	-13	-10
1975	-11	13	10	0	1	8	20	17	23	11	14	19
1976	11	14	3	5	12	1	-8	-6	-11	-2	3	-16
1977	-14	8	-14	-14	-11	-12	-17	-11	-5	-5	-11	-13
1978	11	-31	7	-4	3	-7	-9	-6	-2	-9	3	-2
1979	-13	16	-4	-5	6	8	3	-3	0	-1	-5	-3
1980	1	-2	-21	-14	-2	-5	-1	8	-1	-2	-3	-3
1981	-8	-12	-9	-3	5	8	1	4	6	-5	-1	10
1982	20	4	1	3	-2	-10	-15	-18	-11	-15	-25	-23
1983	-31	-35	-28	-15	13	4	2	14	18	5	7	11
1984	9	-2	-8	8	0	-4	3	-3	1	-2	10	-26
1985	4	1	-18	-3	-13	-11	2	9	-4	-9	-7	6
1986	-1	-21	8	-1	-3	-2	1	-20	-6	12	-17	-4
1987	-7	-20	-1	-10	-12	-19	-11	-7	-3	-4	-2	-5
1988	11	-11	-5	2	10	9	14	20	18	8	17	13

A-6B -- Monthly Average Sea Level Pressure Anomaly (SLPA) for Darwin. Values in 10-1 mb
Supplied by N.Nicholls

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1945	2	-2	-18	8	2	-6	4	-6	-1	4	4	0
1946	0	-11	10	9	5	8	8	6	7	11	3	1
1947	12	-3	-6	1	13	2	2	-12	-5	-1	-7	-5
1948	10	-1	0	-5	-3	3	-7	-6	2	-3	-13	5
1949	10	-10	-14	6	0	11	0	6	-2	-9	1	-20
1950	-16	-23	-11	-18	-12	-17	-9	-8	-3	-12	-24	-28
1951	-10	-15	-6	-1	8	-12	3	4	5	7	6	17
1952	4	5	7	8	-8	1	0	-2	1	-8	-12	12
1953	6	7	4	-6	20	1	9	2	12	1	5	9
1954	-14	7	1	-18	-10	-1	-6	-10	-1	0	2	-7
1955	20	-29	-9	-6	-17	-15	-13	-14	-11	-14	-13	4
1956	-15	-19	-7	-12	-20	-11	-18	-13	-6	-10	-2	-16
1957	2	-2	2	0	12	1	-1	5	11	8	9	5
1958	22	5	5	-6	-2	-8	-6	-12	-5	-11	2	11
1959	-2	21	-7	-6	-7	4	5	3	-1	-2	-12	-11
1960	2	1	-5	-10	-11	1	-5	-3	-15	0	-2	0
1961	9	-2	20	-4	0	4	4	4	1	-3	3	-5
1962	-12	8	8	3	-10	-9	-7	5	-9	-10	-8	1
1963	-4	14	-9	-10	-8	9	5	-4	7	17	14	18
1964	10	5	-6	10	-15	-6	-10	-7	-16	-12	-11	4
1965	0	-9	-7	17	1	16	25	9	13	17	15	-6
1966	12	1	10	4	12	9	-1	-2	1	6	0	4
1967	-13	-10	-4	12	-1	1	-2	0	7	1	0	6
1968	-22	-15	6	2	-16	-2	-3	-1	2	3	9	1
1969	-5	-3	7	14	-1	3	5	6	-2	8	2	-3
1970	19	6	-4	5	-5	-6	8	-8	-19	-20	-14	-19
1971	-5	-21	-16	-15	-7	6	-5	-11	-12	-12	-6	-14
1972	-5	-15	-9	11	26	4	8	10	17	19	9	24
1973	10	17	-2	-5	-3	-14	-6	-13	-6	-11	-33	-6
1974	-23	-22	-21	-7	-1	0	-3	-7	-10	-10	-11	-11
1975	2	3	-10	-17	-7	-10	-12	-15	-15	-18	-7	-16
1976	-12	-12	-20	4	9	1	12	13	10	-7	-12	23
1977	-5	-10	5	-3	2	11	6	8	10	16	11	9
1978	19	23	19	6	-18	-13	-17	-9	-4	0	6	2
1979	-3	3	3	2	1	2	-19	5	-3	3	2	13
1980	-4	-3	-4	2	2	1	2	6	7	0	2	1
1981	-12	-4	23	4	-6	-9	-12	-4	-5	4	-5	3
1982	2	4	-1	6	8	15	15	19	23	18	22	21
1983	35	37	25	6	6	9	14	13	1	-2	8	13
1984	8	-13	5	6	0	8	2	-6	-3	6	4	-21
1985	14	-12	-13	-20	-17	2	6	-4	-5	0	-5	4
1986	-16	3	8	-2	5	-14	-2	-8	2	2	4	25
1987	8	8	31	20	15	7	18	15	15	5	0	6
1988	15	1	-8	6	-3	15	-3	-3	-14	-16	-18	-6

Table A-7. Monthly average 850 mb zonal wind speeds (m/s) at Singapore for 1957-1985.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
57	0.70	3.90	2.40	1.60	0.80	7.30	10.90	8.20	5.40	-1.00	-1.10	-0.80
58	-5.50	-3.30	0.30	-0.30	7.40	9.00	9.10	9.50	3.80	13.10	12.40	-1.80
59	-5.70	-1.50	-0.80	4.10	2.20	5.90	10.70	4.20	-0.50	-0.30	5.70	6.90
60	0.70	0.20	5.10	4.10	8.30	6.40	5.40	8.70	6.40	4.40	12.00	3.40
61	0.40	0.60	-2.60	2.00	9.20	8.20	3.60	5.70	0.70	-3.10	-2.40	3.10
62	1.60	-1.50	1.50	3.30	6.50	3.50	12.60	6.20	7.60	7.40	3.50	6.20
63	2.90	-7.10	0.30	-0.60	2.30	5.10	-0.20	4.40	2.00	-3.80	-4.00	0.30
64	-2.10	-8.80	-0.30	-2.10	9.50	3.70	0.40	6.20	4.90	11.40	17.70	1.00
65	2.60	1.30	4.60	-0.60	5.80	9.00	7.50	0.40	3.70	-3.10	0.10	5.60
66	0.80	1.10	3.50	-1.10	4.40	1.00	3.40	1.80	2.60	4.60	6.90	9.30
67	4.61	-0.87	1.03	0.64	1.00	2.57	3.82	2.49	-0.01	-0.70	1.53	-2.50
68	-0.87	0.71	-1.53	-1.29	3.94	2.95	4.92	6.89	2.49	0.34	1.54	3.07
69	1.01	0.01	0.35	-0.17	0.64	2.59	2.49	0.00	4.32	-0.34	0.94	0.01
70	-0.28	-2.08	1.37	0.59	1.99	3.71	3.15	2.72	2.36	4.85	3.90	4.50
71	0.71	1.83	1.95	0.15	4.00	4.97	3.19	0.51	0.77	7.00	5.61	2.49
72	1.14	2.13	1.31	-0.56	1.55	-0.01	3.08	1.20	0.69	-2.16	-0.88	0.31
73	-1.37	-0.90	1.18	1.84	0.98	3.71	3.14	2.40	3.39	1.22	5.97	2.47
74	5.60	0.40	-0.80	2.20	3.90	3.30	4.80	8.70	0.80	11.70	10.00	6.50
75	5.00	-1.40	5.80	3.10	5.70	8.20	5.30	8.70	4.70	12.80	6.10	10.60
76	1.90	2.20	1.50	3.40	5.50	3.90	7.00	4.20	7.70	4.00	7.80	4.30
77	4.40	-0.30	-0.60	0.60	0.50	6.50	6.80	6.40	9.60	-2.50	0.90	-0.30
78	0.80	-0.20	0.80	2.20	4.60	11.80	6.60	11.30	9.70	6.60	8.60	-1.30
79	-2.50	-0.10	2.30	5.60	7.60	7.40	8.20	7.10	1.60	4.30	4.60	1.90
80	2.20	-3.60	1.50	0.10	2.30	8.80	5.40	6.40	6.30	6.20	6.10	10.80
81	7.40	2.60	-4.70	0.30	0.70	8.00	8.00	8.20	3.90	3.20	13.60	2.70
82	2.10	1.30	3.50	1.20	1.80	7.60	3.90	3.60	2.20	-2.80	-4.50	-4.40
83	-6.90	-2.20	-1.30	-1.50	2.70	1.60	1.90	4.00	-0.70	1.50	9.90	3.60
84	-1.10	-0.70	-0.90	0.60	1.40	6.10	2.90	8.50	6.20	7.80	-0.50	4.50
85	-3.20	2.00	-0.70	7.00	4.10	13.00	5.70	2.50	2.80	5.20	7.20	3.00
MEAN	0.59	-0.49	0.90	1.26	3.84	5.72	5.30	5.21	3.63	3.37	4.80	2.95

Table A-8. Monthly average 850 mb zonal wind speeds (m/s) at Trivandrum for 1959-1986.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
59	-3.00	-3.52	-5.62	-1.54	2.38	11.66	13.27	9.57	7.92	1.70	-2.44	-3.12
60	-3.71	-5.03	-3.19	-2.82	6.70	11.16	9.24	9.08	11.28	2.74	0.34	-3.99
61	-4.14	4.50	-5.09	-1.76	6.25	10.72	10.21	9.97	7.01	3.07	-3.73	-3.23
62	-2.46	-5.87	-4.97	-2.60	2.44	8.67	14.28	10.67	8.84	3.32	-4.53	-3.28
63	-3.94	-6.29	-4.33	-3.19	0.58	10.79	10.71	10.13	6.25	3.50	-4.85	-3.23
64	-3.71	-4.85	-5.87	-2.60	4.25	7.70	9.81	10.61	10.06	4.10	2.74	-2.72
65	-3.35	-3.94	-2.62	-1.78	3.37	10.98	11.39	8.92	6.57	-0.28	-2.49	0.79
66	-2.54	-3.11	-2.52	-1.31	3.84	7.26	11.70	8.45	6.58	0.24	1.60	-1.29
67	-0.75	-5.14	-3.46	-2.83	3.50	10.14	11.60	6.03	6.07	0.75	-2.57	-3.11
68	-2.68	-3.83	-2.00	-1.20	2.51	11.42	13.92	10.92	9.98	2.43	-1.70	-1.41
69	-2.08	-3.11	-4.37	-2.26	4.92	10.06	12.99	5.74	9.54	1.68	-0.72	-2.40
70	-1.97	-3.32	-3.88	-1.07	6.54	12.99	11.89	11.16	7.73	4.54	-0.24	-2.43
71	-2.19	-2.01	-3.99	-1.88	6.35	10.30	11.63	9.44	6.40	1.81	-0.68	-0.68
72	-3.53	-3.28	-2.23	-1.64	5.30	13.47	11.49	9.03	6.62	5.31	-1.60	-3.23
73	-2.49	-2.88	-3.94	-1.50	5.88	11.42	13.25	12.60	7.65	4.83	-0.28	-2.40
74	-2.78	-3.60	-3.19	0.06	3.69	10.98	12.30	13.14	8.10	6.07	0.41	-2.30
75	-2.68	-3.28	-3.32	-1.03	6.73	15.39	8.84	13.26	7.83	9.15	1.39	-1.93
76	-2.73	-2.68	-3.43	-0.17	5.88	8.10	9.07	11.80	6.13	1.93	0.46	-3.15
77	-1.75	-3.15	-4.45	-0.88	2.86	12.37	14.11	8.84	5.95	0.33	-0.81	-1.49
78	-1.46	-1.20	-2.26	-0.48	5.04	14.02	13.01	12.80	9.15	1.73	-0.98	-2.41
79	-2.18	-1.76	-2.88	-0.94	5.37	10.63	12.99	11.36	7.37	0.39	-0.50	-1.00
80	-2.19	-4.37	-1.73	-0.62	3.78	12.66	13.82	11.80	6.40	5.53	-0.62	-1.50
81	-2.08	-3.83	-3.23	0.11	3.48	12.72	12.02	11.98	9.57	1.97	0.27	-2.30
82	-2.16	-0.31	999.99	-0.78	2.01	11.29	999.99	10.41	8.47	-0.84	-1.93	-2.67
83	-2.29	-3.32	-3.46	-2.78	2.94	10.47	10.41	11.14	9.75	3.47	-0.14	-2.40
84	-3.06	-3.21	-3.94	-1.03	3.55	14.43	11.70	11.49	5.60	4.94	-2.01	-1.27
85	-2.19	-1.76	-3.11	-0.14	5.15	13.40	999.99	10.80	7.20	3.57	-0.17	3.40
86	-0.72	-2.57	-4.41	-1.53	3.54	10.92	8.73	9.38	7.30	0.79	-0.45	-4.70
MEAN	-2.53	-3.10	-3.61	-1.44	4.24	11.29	11.71	10.38	7.76	2.81	-0.94	-2.12

Table A-9. Monthly average 850 mb zonal wind speeds (m/s) at Ascension Island for 1957-1968 and zonal wind anomlies at Manaus for 1969-1986.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
57	999.99	999.99	999.99	999.99	999.99	999.99	999.99	999.99	-6.10	-6.70	-7.70	-4.60
58	-3.40	-4.10	-4.70	-7.20	-5.80	999.90	-5.20	-3.70	-5.60	-7.00	-5.20	-3.70
59	-2.30	-1.10	-2.00	-4.60	-2.10	-4.60	-3.80	-4.10	-6.80	-6.10	-6.80	-4.20
60	-3.70	-3.60	-2.90	-3.50	-3.10	-3.30	-2.40	-4.50	-5.50	-7.70	-5.10	-4.00
61	-2.40	-2.70	-2.50	-3.60	-3.70	-3.20	-3.10	-4.30	-5.10	-6.30	-4.30	-3.70
62	-.80	-1.70	-2.20	-3.90	-3.50	-2.60	-3.60	-5.60	-6.50	-7.20	-5.60	-4.60
63	-.20	-2.30	-3.00	-1.50	-1.40	-2.50	-2.90	-4.70	-5.70	-7.10	-4.40	-2.90
64	-4.50	-2.90	-5.40	-6.00	-2.00	-3.60	-1.10	-5.30	-6.20	-6.10	-7.10	-5.20
65	-3.80	-2.60	-2.50	-3.20	-4.50	-2.60	-5.20	-5.10	-7.60	-7.00	-8.00	-5.60
66	-2.50	-1.80	-4.60	-3.40	-3.40	-4.40	-5.00	-3.40	-6.70	-5.70	-6.90	-4.80
67	-3.00	-2.00	-3.70	-2.90	-3.80	-5.60	-2.90	-6.00	-7.90	-7.70	-4.90	-4.00
68	-2.40	-2.60	-.40	-2.20	-2.00	-3.70	-4.90	-6.70	-6.50	-8.00	-6.30	-2.90
69	-0.70	-2.07	-0.30	1.36	-0.59	-1.18	-2.03	0.31	0.79	-0.60	0.09	1.26
70	-0.21	-0.68	-0.49	0.46	-0.68	-2.03	0.88	1.14	1.83	-1.27	3.23	-0.82
71	-0.45	-1.96	-1.52	1.93	1.24	-1.18	-0.06	0.13	-0.16	0.42	3.99	0.21
72	-0.57	-0.26	0.24	2.38	-1.76	-2.28	-0.68	0.01	-1.08	-0.56	0.48	-0.21
73	-2.12	-1.27	-1.47	1.03	0.74	-1.22	0.16	0.13	-0.21	1.78	-0.53	0.99
74	1.14	1.17	4.20	2.71	2.24	0.16	-0.47	-0.59	-1.11	0.58	1.22	0.06
75	0.48	0.04	-1.64	0.46	1.24	-0.37	1.32	-0.09	-0.22	-0.12	-2.94	-1.41
76	0.39	2.10	1.15	-0.64	-0.72	-2.76	-0.28	4.73	0.80	0.54	-1.04	-0.73
77	-0.43	0.34	-2.52	-1.89	-0.75	-1.24	-1.58	0.18	-0.21	-0.44	-1.77	-0.52
78	-0.19	-0.73	1.39	0.37	-0.74	999.99	0.05	-7.15	-0.14	-1.41	-2.24	-1.65
79	-1.72	-1.07	-1.11	-1.62	-1.65	-0.16	-1.32	1.11	-0.17	-0.46	0.22	-1.95
80	0.89	1.37	-2.60	-2.63	-0.26	-0.72	0.21	-0.99	0.85	2.39	2.30	2.19
81	0.64	2.23	2.56	0.85	1.24	0.71	3.93	-0.22	-0.22	-0.62	0.76	1.79
82	1.48	2.10	1.28	-0.45	0.42	-1.24	-1.07	0.01	-0.22	-1.62	-2.24	-1.77
83	0.71	-2.97	-1.81	-3.62	-1.74	0.93	-1.07	1.21	-1.21	0.51	-1.87	-0.63
84	-2.22	-2.78	0.73	0.16	2.28	-1.86	1.63	0.06	-0.17	-0.49	-1.69	0.79
85	1.33	2.36	1.81	0.79	1.25	1.18	0.25	1.01	1.28	0.39	0.97	1.99
86	1.58	2.07	0.09	-1.65	-1.74	-2.00	-0.48	0.01	-0.21	2.38	0.07	0.79

Table A-10. Monthly Average 700 mb zonal wind speeds (m/s) at Nairobi for 1958-1986.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
58	-11.10	-2.76	-4.57	-6.92	-2.36	0.12	0.33	2.13	0.33	-3.94	-6.33	-6.36
59	-5.59	-4.72	-5.81	-6.65	-0.87	-0.42	1.67	0.12	-0.46	-3.60	-7.08	-4.53
60	-3.21	-6.21	-5.14	-5.89	-7.90	-2.76	1.53	3.98	-1.00	-4.96	-4.45	-7.06
61	-6.47	-4.77	-7.87	-6.53	-3.98	-2.00	-1.57	1.71	-2.67	-5.74	-4.99	-1.43
62	-1.43	-3.53	-5.59	-5.71	-0.72	-0.58	2.00	-0.52	0.00	-4.73	-7.36	-5.59
63	-4.91	-4.95	-6.86	-5.00	-2.98	-1.95	0.97	3.90	-3.00	-5.89	-6.66	-5.34
64	-5.36	-5.19	-5.19	-4.50	-4.00	-0.87	0.99	0.00	-1.00	-5.91	-6.89	-6.20
65	-5.80	-1.55	-4.86	-5.60	-3.71	-0.51	0.92	0.71	-2.98	-3.99	-7.98	-3.21
66	-5.98	-5.85	-5.59	-5.85	-4.96	-2.60	2.99	1.93	-2.94	-4.96	-5.99	-5.03
67	-5.73	-4.97	-4.59	-4.91	-0.49	-0.78	1.73	-0.59	-1.98	-6.00	-5.98	3.28
68	-0.35	-4.95	2.76	-4.83	-4.98	-2.99	1.50	0.50	-0.64	-4.92	-0.80	-5.44
69	-4.91	-4.91	-8.15	-7.52	-3.98	-0.42	2.29	-0.27	-1.53	-5.79	-7.52	-5.36
70	-4.24	-4.59	-6.06	-5.98	-2.99	-0.09	0.34	0.84	-0.57	-3.94	-6.93	-5.65
71	-5.14	-5.78	-8.19	-6.06	-1.88	1.41	1.14	4.92	-0.69	-4.98	-6.34	-4.09
72	-6.89	-5.14	-5.36	-6.34	-4.98	0.58	0.98	0.34	-0.26	-4.92	-6.58	-5.36
73	-2.53	-5.73	-6.13	-5.98	-4.92	0.87	0.90	1.00	0.71	-4.98	-4.33	3.82
74	-5.36	-5.36	-5.19	-4.33	-2.82	-0.17	0.00	1.00	-0.26	-2.60	-0.52	-4.53
75	-3.53	-5.73	-4.95	-4.70	-3.00	-2.30	0.09	2.60	0.00	-4.50	-5.79	-6.13
76	-4.59	-6.89	-5.65	-0.52	-3.99	-0.98	1.72	1.92	-1.93	-4.33	-5.19	-7.66
77	-5.36	-2.50	-6.89	-2.30	-0.17	-0.17	2.72	-1.73	-1.80	-1.99	-6.76	-6.97
78	-4.59	-3.21	-4.24	-5.79	-3.63	0.71	1.93	1.99	-0.71	-3.98	-6.06	-3.21
79	-6.06	-2.29	-3.21	-4.33	-4.00	0.94	0.34	1.93	-0.94	-5.64	-3.86	-4.59
80	-1.29	-5.36	-3.86	-4.33	-0.97	1.29	0.97	-0.09	-1.00	-4.00	-4.53	-3.44
81	-3.21	-3.86	-3.06	-2.82	-1.15	0.52	2.96	1.28	-0.71	-2.50	-4.53	-4.09
82	-3.21	-3.21	-4.59	-2.82	-3.63	999.99	1.14	0.57	-0.71	-3.99	-3.86	-3.53
83	-3.06	-3.21	-4.59	-2.72	-2.90	-1.00	0.91	2.39	-0.82	-3.94	-5.44	-1.03
84	-2.50	-1.71	-7.79	-4.70	3.94	-1.29	0.00	0.91	-1.81	-5.79	-5.79	-5.73
85	-5.73	-0.35	-8.15	-4.00	-2.99	0.34	-0.87	-0.77	-0.94	-4.83	-12.12	-6.93
86	-3.21	-6.89	-7.79	-3.62	-1.04	2.99	3.87	1.00	-0.94	-5.19	-6.34	-3.21
MEAN	-4.14	-4.35	-5.42	-4.87	-2.83	-0.43	1.19	1.16	-1.08	-4.57	-5.76	-4.01

Table A-11. Three-month running mean sea surface temperature anomalies (degrees Celsius) for the area shown in Fig 2.1 (from Dong, 1987).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
49	-0.3	-0.3	0.1	0.1	-0.1	-0.3	-0.4	-0.3	-0.8	-0.8	-0.9	-0.6
50	-0.6	-0.6	-0.8	-0.8	-0.6	-0.3	-0.4	-0.4	-0.2	-0.3	-0.2	-0.6
51	-0.4	-0.3	-0.1	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.6
52	0.6	0.6	0.7	0.5	0.5	0.2	0.1	0.1	-0.1	0.0	-0.1	0.1
53	0.2	0.4	0.4	0.5	0.6	0.5	0.3	0.4	0.5	0.5	0.4	0.3
54	0.1	0.2	0.1	-0.1	-0.4	-0.3	-0.4	-0.3	-0.3	-0.5	-0.6	-0.7
55	-0.6	-0.5	-0.4	-0.7	-0.7	-0.8	-0.7	-0.5	-0.7	-1.0	-1.1	-0.9
56	-0.4	-0.4	-0.4	-0.6	-0.6	-0.6	-0.5	-0.4	-0.3	-0.3	-0.4	-0.3
57	-0.2	0.2	0.5	0.6	0.7	0.9	0.9	1.0	0.9	0.9	1.0	1.0
58	1.0	0.9	0.8	0.5	0.4	0.4	0.5	0.4	0.4	0.3	0.3	0.4
59	0.4	0.5	0.5	0.5	0.3	0.2	0.0	0.0	0.0	0.0	-0.1	-0.1
60	-0.1	0.1	0.2	0.3	0.2	0.3	0.2	0.4	0.3	0.2	0.2	0.1
61	0.2	0.2	0.4	0.4	0.5	0.4	0.1	-0.1	-0.2	-0.2	-0.1	-0.2
62	-0.3	-0.4	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4
63	-0.4	-0.1	0.0	0.2	0.1	0.4	0.5	0.7	0.6	0.7	0.7	0.8
64	0.6	0.3	-0.3	-0.7	-0.9	-0.7	-0.7	-0.7	-0.8	-0.8	-0.7	-0.5
65	-0.3	0.0	0.2	0.5	0.7	0.7	0.8	0.8	1.1	1.1	1.3	1.2
66	1.0	0.8	0.5	0.1	-0.1	-0.2	-0.2	-0.1	-0.2	-0.3	-0.4	-0.4
67	-0.4	-0.3	-0.3	-0.2	0.0	-0.1	-0.3	-0.6	-0.6	-0.7	-0.6	-0.8
68	-1.0	-1.1	-0.9	-0.6	-0.5	-0.3	-0.2	0.0	0.2	0.3	0.5	0.3
69	0.4	0.6	0.7	0.6	0.5	0.6	0.5	0.6	0.7	0.8	0.9	0.9
70	0.7	0.4	0.2	0.0	-0.1	-0.3	-0.5	-0.6	-0.5	-0.5	-0.6	-0.9
71	-1.0	-0.9	-0.8	-0.6	-0.5	-0.3	-0.3	-0.3	-0.4	-0.6	-0.6	-0.6
72	-0.5	-0.1	0.0	0.0	0.1	0.6	1.1	1.5	1.5	1.5	1.6	1.4
73	1.1	0.9	0.5	0.2	-0.2	-0.2	-0.3	-0.4	-0.6	-0.8	-1.1	-1.3
74	-1.3	-1.1	-0.9	-0.5	-0.5	-0.4	-0.5	-0.4	-0.4	-0.4	-0.5	-0.6
75	-0.4	-0.2	-0.1	-0.3	-0.6	-0.6	-0.8	-0.7	-0.9	-0.9	-1.1	-1.1
76	-1.1	-0.7	-0.5	-0.2	0.1	0.5	0.6	0.7	0.9	0.9	1.0	0.8
77	0.6	0.6	0.5	0.4	0.4	0.4	0.2	0.2	0.2	0.2	0.3	0.2
78	0.1	0.2	0.0	-0.2	-0.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1
79	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.1	0.2	0.2	0.2	0.2
80	0.3	0.4	0.3	0.2	0.2	0.1	0.0	-0.1	-0.1	0.0	0.1	0.0
81	-0.2	-0.4	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.1	-0.1
82	-0.1	-0.1	-0.1	0.1	0.1	0.1	0.1	0.4	0.6	1.0	1.4	1.6
83	1.7	1.7	1.5	1.3	1.2	1.1	1.0	0.8	0.7	0.4	0.3	0.1
84	0.1	0.1	0.1	0.0	-0.3	-0.4	-0.4	-0.2	-0.3	-0.4	-0.5	-0.6
85	-0.7	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5	-0.4	-0.4	-0.3	-0.1	-0.2
86	-0.2	-0.1	0.0	-0.1	-0.2	-0.2	-0.2	0.0	0.3	0.6	0.8	0.9

Table A-12. Monthly mean SST anomalies for the East Pacific area shown in Fig. 2.1, obtained from COADS data set as explained in the text.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
51	-0.33	-0.32	-0.28	-0.11	-0.02	0.05	0.26	0.58	0.28	0.31	0.27	-0.14
52	0.57	0.28	0.02	0.39	-0.02	-0.35	-0.14	-0.02	-0.32	0.11	-0.43	-0.24
53	0.17	-0.22	0.02	0.29	0.08	0.45	0.46	0.18	0.48	-0.19	-0.13	-0.24
54	-0.13	-0.02	-0.28	-0.31	-0.42	-0.65	-0.64	-0.32	-0.92	-0.49	-0.43	-0.44
55	-0.23	-0.32	-0.38	-0.51	-0.52	-0.45	-0.34	-0.62	-0.72	-1.29	-1.63	-0.94
56	-0.83	-0.12	-0.68	-0.61	-0.42	-0.75	-0.64	-0.52	-0.52	-0.69	-0.63	-0.14
57	-0.53	0.08	0.22	0.39	0.38	0.45	0.56	1.08	0.58	0.51	0.67	0.86
58	0.97	1.08	0.72	0.59	0.38	0.45	0.26	0.08	-0.02	0.01	0.67	0.06
59	0.47	0.38	0.22	0.49	0.28	0.05	-0.04	-0.12	0.18	0.51	-0.13	-0.24
60	-0.03	-0.12	0.02	0.19	-0.22	-0.15	-0.34	-0.02	0.08	0.01	-0.43	0.06
61	-0.13	0.08	0.12	0.09	-0.02	0.15	-0.24	-0.32	-0.62	-0.59	-0.23	-0.24
62	-0.13	-0.12	-0.08	-0.11	-0.42	-0.05	-0.24	-0.02	-0.42	-0.49	-0.23	-0.64
63	-0.33	-0.22	0.12	0.09	0.18	-0.05	0.56	0.58	0.68	0.41	0.77	0.56
64	0.57	0.28	-0.08	-0.51	-0.52	-0.45	-0.14	-0.72	-0.72	-0.69	-0.63	-0.94
65	-0.53	-0.12	-0.08	-0.31	0.28	0.45	0.46	0.88	0.78	1.01	0.97	1.26
66	0.97	0.58	0.62	0.29	0.08	0.15	0.26	0.18	-0.12	-0.09	-0.03	-0.14
67	-0.33	-0.12	-0.38	-0.01	0.08	0.25	-0.04	0.08	-0.32	-0.29	-0.23	-0.24
68	-0.43	-0.42	-0.38	-0.21	-0.12	0.35	0.46	-0.42	0.28	0.31	0.57	0.66
69	1.07	0.78	0.72	0.59	0.98	0.45	0.26	0.48	0.58	0.51	0.47	0.86
70	0.77	0.48	-0.08	0.39	-0.02	-0.05	-0.64	-1.02	-0.62	-0.49	-0.63	-1.14
71	-1.13	-1.22	-0.78	-0.61	-0.52	-0.55	-0.44	-0.42	-0.62	-0.59	-0.63	-0.54
72	-0.53	-0.12	0.02	0.39	0.98	0.55	0.86	1.08	0.88	1.21	1.27	1.36
73	1.27	0.78	0.42	-0.11	-0.02	-0.55	-0.64	-0.82	-1.12	-1.09	-0.93	-1.14
74	-1.03	-0.82	-0.68	-0.41	-0.52	-0.05	-0.34	-0.02	-0.42	-0.39	-0.63	-0.54
75	-0.43	-0.22	-0.28	-0.21	-0.52	-0.85	-0.64	-0.92	-1.02	-0.89	-1.03	-1.14
76	-1.33	-0.82	-0.08	-0.21	-0.22	0.35	0.06	0.28	0.58	0.71	0.67	0.36
77	0.37	0.28	0.32	-0.11	-0.02	-0.05	0.46	0.18	0.48	0.31	0.37	0.76
78	0.57	0.28	0.22	-0.11	-0.12	-0.35	-0.24	-0.52	-0.02	0.01	0.17	0.36
79	0.07	-0.02	0.42	0.49	0.28	0.25	0.16	0.28	0.68	0.31	0.17	0.26
80	0.27	0.08	0.22	0.09	0.38	0.45	0.06	-0.02	0.08	0.01	0.17	0.16
81	-0.23	-0.22	-0.38	-0.31	-0.22	-0.25	-0.34	-0.32	0.08	-0.09	-0.33	-0.24
82	-0.13	-0.02	0.02	0.29	0.48	0.35	0.26	0.48	0.68	0.81	0.97	0.96
83	0.87	0.48	0.32	-0.01	0.48	0.65	0.36	0.18	-0.02	-0.09	-0.23	-0.34
84	-0.43	-0.32	-0.28	-0.21	-0.42	-0.75	-0.54	-0.42	-0.42	-0.69	-0.63	-0.94
85	-0.93	-0.62	-0.48	-0.41	-0.42	-0.35	-0.34	-0.22	-0.22	0.01	0.07	0.06
86	-0.33	-0.22	-0.08	-0.31	-0.12	0.05	0.16	0.18	0.38	0.71	0.87	0.86
87	0.87	0.68	0.72	0.59	0.68	0.85	0.96	0.98	1.28	1.31	1.07	0.96

Table A-13. Monthly mean SST anomaly values (degrees Celsius) for the 2 degree by 2 degree area centered on 2.8S, 91W prior to 1980; from COADS. Values are from the Climate Diagnostics Bulletin, Nino 1 + 2 for 1980 and thereafter.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
49	-1.5	0.1	0.0	0.6	1.1	-0.5	-1.0	-0.8	-1.1	-1.7	-1.6	-1.0
50	-0.4	-1.0	-0.3	0.1	0.0	0.6	-0.1	0.3	-0.5	0.3	-0.5	-0.5
51	1.0	1.2	0.8	0.9	1.1	2.3	2.3	3.1	2.4	2.0	2.0	1.2
52	1.3	0.7	0.8	0.1	0.6	0.6	-0.4	-1.1	-0.5	-0.2	-0.5	0.6
53	0.7	0.9	1.0	1.4	1.7	1.7	0.7	1.1	1.2	0.9	1.1	0.6
54	-1.0	0.4	0.5	-1.1	-1.4	-1.4	-2.1	-1.9	-1.6	-1.8	-0.8	-0.8
55	0.1	0.1	-1.1	-0.8	-0.4	-0.5	-1.0	-0.8	-1.3	-1.6	-1.5	-0.8
56	-1.0	-0.4	-0.1	-0.4	-0.3	-0.5	0.6	0.3	-0.2	-0.5	-0.8	-1.2
57	-1.0	-0.1	0.4	0.1	1.8	2.5	2.3	1.6	2.2	1.4	1.9	1.4
58	1.0	1.2	0.3	0.6	0.4	0.5	-0.1	0.4	-0.5	0.0	-0.3	-0.1
59	-0.6	0.1	0.6	1.2	1.1	-0.2	-0.5	-0.7	-0.5	0.3	0.4	0.2
60	0.8	-0.4	0.0	0.7	-1.3	-0.1	0.6	0.4	0.6	-0.9	-0.6	0.1
61	0.7	1.0	0.2	0.2	-0.2	0.2	-0.8	-0.9	-0.1	-0.4	-0.3	0.3
62	0.1	0.3	-0.1	-2.0	-0.5	-1.1	-0.9	-0.2	0.2	-0.4	-0.4	-0.7
63	1.2	0.2	0.0	-0.3	0.5	0.1	0.8	1.6	1.4	0.6	0.7	0.3
64	-0.2	-0.6	-1.0	-0.7	-2.3	-2.1	-0.9	-0.8	-0.5	-0.6	-1.1	-0.8
65	0.2	0.3	0.6	1.0	1.9	2.3	1.8	1.9	1.6	1.2	1.6	1.0
66	1.6	0.8	-1.1	0.0	-1.5	-0.8	-0.6	-0.8	-0.7	0.4	-0.1	-0.5
67	-0.2	0.0	0.3	0.6	1.1	-0.2	-0.5	-1.2	-0.8	-1.0	-1.1	-1.5
68	-1.6	-0.9	-1.0	-1.1	-0.7	-1.9	0.2	1.3	1.2	0.6	0.6	1.2
69	0.5	-0.8	0.8	0.6	1.6	2.1	0.9	2.0	2.4	2.3	2.0	1.6
70	1.3	0.0	0.0	-0.2	-0.5	-1.0	-2.3	-1.7	-0.9	-0.2	-1.1	-0.5
71	0.2	-0.6	-0.7	0.3	-0.5	-0.4	0.2	-0.6	-0.5	-0.1	-0.5	-0.8
72	0.5	0.3	0.2	0.8	0.7	2.3	2.4	3.3	2.6	2.5	2.7	2.6
73	2.9	1.5	0.6	-0.6	-0.6	-1.7	-1.6	-0.6	-1.0	-1.0	-1.1	-0.3
74	-0.8	0.0	-0.5	0.2	0.5	0.8	0.1	0.3	0.1	0.4	-0.7	-1.2
75	-0.7	-1.1	-0.2	0.1	0.0	-1.1	-0.5	-0.5	-1.4	-0.7	-1.8	-1.4
76	-0.3	-0.3	-0.4	-0.1	0.9	2.3	2.7	3.0	2.0	1.6	1.2	1.1
77	0.9	0.5	0.3	0.4	0.6	0.6	0.1	0.1	-0.3	0.2	0.4	0.8
78	0.9	0.9	-0.9	-1.4	-1.1	-2.1	-0.1	-0.9	-1.0	-1.6	-0.6	0.5
79	0.7	0.6	-0.6	0.0	-1.0	0.1	0.9	0.6	1.3	1.5	0.9	0.3
80	0.7	-0.1	0.0	0.8	0.9	0.7	0.0	-0.1	0.1	0.0	0.9	0.6
81	-0.5	-0.8	0.5	-0.5	-0.1	-0.1	-0.4	-1.3	-0.3	-0.4	0.5	0.9
82	-0.2	-0.1	-0.5	-0.4	0.6	0.6	0.6	1.5	2.0	2.3	3.3	3.4
83	3.0	2.3	2.7	3.0	4.0	4.2	4.0	3.3	1.3	1.6	1.0	0.7
84	-0.2	-0.1	-0.3	0.2	-0.5	-0.2	0.2	-0.7	0.2	0.0	0.1	-0.2
85	0.0	-0.5	-0.3	-1.0	-1.0	-0.9	-0.6	-0.5	-0.6	-0.7	-0.3	-0.3
86	0.5	0.3	0.3	-0.6	-0.5	-0.6	0.0	0.4	0.6	0.9	0.4	1.0
87	1.3	1.3	1.9	999.9	999.9	999.9	999.9	999.9	999.9	999.9	999.9	999.9

Table A-14. Monthly mean Southern Oscillation index of the anomalous pressure difference of Tahiti minus Darwin (in mb x 10).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
45	4.5	5.7	10.8	-6.7	0.3	6.5	3.3	11.2	8.7	2.9	-3.4	5.4
46	-3.1	3.7	-2.7	-8.9	-10.0	-6.8	-9.5	-4.0	-15.3	-12.3	-1.5	-6.8
47	-5.5	-5.2	9.4	-4.5	-12.2	1.7	8.7	6.9	11.7	-1.6	8.7	3.9
48	-3.6	-3.7	-4.6	2.1	4.0	-4.6	0.8	-4.0	-7.1	6.6	4.2	-6.8
49	-7.9	1.2	4.1	0.6	-4.8	-10.9	-1.6	-4.0	2.3	6.0	-5.9	6.4
50	4.5	17.0	14.6	13.8	7.7	22.6	19.6	11.8	7.0	18.0	11.8	21.7
51	12.7	5.7	-5.5	-7.4	-11.5	-1.8	-12.5	-5.2	-11.2	-12.3	-8.5	-8.3
52	-8.9	-8.1	0.2	-6.7	7.7	5.8	4.5	-2.2	-1.8	3.5	0.4	-12.9
53	1.6	-7.1	-6.0	-0.8	-25.5	-2.5	-1.0	-16.1	-13.0	-0.3	-2.7	-5.8
54	5.0	-5.2	-2.2	5.0	4.0	-2.5	3.3	9.4	2.3	2.2	2.3	11.5
55	-5.5	14.6	1.2	-5.2	11.4	12.8	16.6	13.6	14.6	16.7	15.0	7.9
56	10.8	12.1	7.4	8.7	16.5	10.0	11.1	10.6	1.1	19.9	2.3	8.5
57	4.5	-3.2	-2.7	-0.1	-11.5	-1.8	1.4	-8.2	-9.4	-0.3	-11.0	-4.3
58	-17.5	-7.1	-2.2	1.3	-9.3	-0.4	3.3	7.5	-3.0	-0.3	-4.6	-7.3
59	-8.9	-15.0	7.0	4.3	4.0	-5.3	-4.0	-4.0	0.5	4.7	11.2	6.9
60	0.2	-1.7	4.5	7.2	4.7	-2.5	4.5	6.3	7.6	0.3	6.8	5.9
61	-3.1	5.7	-20.5	7.9	1.8	-2.5	-0.4	-0.3	1.1	-4.7	6.8	12.5
62	16.5	-5.2	-3.1	-0.8	12.1	5.1	-0.4	4.5	5.2	10.4	4.2	0.3
63	8.4	2.7	5.5	7.2	2.5	-10.2	-2.2	-2.8	-5.9	-14.8	-9.1	-12.9
64	-4.1	-2.2	5.5	1.3	6.9	5.8	5.1	14.2	14.0	14.2	2.3	-4.3
65	-4.6	1.2	2.1	-10.4	-0.4	-10.9	-21.0	-10.1	-13.5	-11.0	-16.7	0.3
66	-12.7	-4.7	-12.8	-6.0	-7.8	0.3	-0.4	4.5	-1.8	-2.2	0.4	-4.8
67	14.1	12.6	6.5	-3.2	-2.6	4.5	0.8	5.7	5.8	-0.3	-4.6	-6.8
68	3.6	9.1	-3.6	-3.0	14.3	10.0	6.3	0.3	-2.4	-1.6	-3.4	0.3
69	-14.2	-7.6	-0.7	-8.2	-5.6	-1.1	-6.4	-4.0	-10.0	-11.6	-0.2	2.3
70	-10.8	-12.1	0.7	-4.5	2.5	6.6	-5.2	3.9	12.8	11.0	16.8	16.1
71	2.1	15.5	15.1	19.6	9.2	1.7	1.4	14.2	15.8	18.6	6.8	0.8
72	3.1	7.2	1.2	-5.2	-24.0	-10.9	-17.3	-8.2	-14.1	-11.0	-3.4	-13.4
73	-3.6	-15.0	-0.3	-2.3	3.3	10.0	5.7	11.3	13.4	10.4	31.5	15.6
74	20.3	16.0	17.0	9.4	10.6	1.7	11.1	6.3	12.2	9.2	-1.5	0.3
75	-6.0	4.7	9.4	12.3	6.2	12.8	19.6	19.7	22.2	16.6	13.1	17.6
76	11.2	12.6	10.8	0.6	2.5	0.3	-11.9	-11.3	-12.4	3.5	9.3	-20.0
77	-4.1	8.6	-9.4	-8.2	-9.3	-15.8	-13.7	-11.3	-8.8	-12.9	-14.2	-11.4
78	-3.6	-26.9	-6.0	-7.4	15.8	4.5	5.1	2.1	1.1	-5.3	-2.1	-2.2
79	-4.6	6.2	-3.6	-5.2	4.6	4.5	13.6	-4.6	1.7	-2.2	-4.6	-8.3
80	2.6	0.3	-8.4	-11.8	-2.6	-3.9	-1.6	1.5	-4.7	-0.9	-3.4	-2.2
81	2.1	-4.2	-15.6	-5.2	8.4	12.1	8.1	5.1	6.4	-5.3	2.3	3.4
82	8.8	-0.2	0.7	-2.3	-7.1	-17.2	-17.9	-22.2	-20.0	-20.5	-30.0	-22.6
83	-31.4	-35.7	-25.7	-15.5	5.5	-3.2	-7.0	0.9	9.9	4.7	-0.8	-1.2
84	0.7	5.2	-6.5	1.3	0.3	-8.1	0.8	2.1	2.3	-4.7	3.6	-2.7
85	-4.6	6.2	-2.7	12.3	3.3	-8.8	-2.2	8.2	0.5	-5.3	-1.5	0.8
86	7.4	-12.1	-0.3	0.6	-5.6	8.6	2.0	-7.0	-4.7	6.6	-13.5	-15.0
87	-7.0	-14.0	-16.1	-23.5	-19.6	-17.9	-17.3	-13.1	-10.6	-5.3	-1.5	-5.8
88	-1.7	-6.2	1.2	-3.0	9.9	-4.0	-99.9	-99.9	-99.9	-99.9	-99.9	-99.9

Table A-15. Monthly number of 6-hour tropical storm reports between 0-20 degrees N in the Northwest Pacific with sustained maximum winds equal toor greater than 30 knots (~15 m/s).

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEA. TOTAL	YR
45	0	0	0	22	0	18	15	25	69	27	49	0	225	45
46	0	0	20	17	20	29	28	13	59	15	27	0	228	46
47	0	0	3	0	5	14	14	12	20	61	82	29	240	47
48	34	0	0	0	19	8	26	32	57	20	45	50	291	48
49	29	0	0	0	0	12	42	16	27	21	67	30	244	49
50	0	0	0	0	23	0	0	0	7	19	34	12	95	50
51	1	0	20	18	60	16	21	26	38	24	34	74	332	51
52	0	0	0	0	0	26	33	49	59	111	54	72	404	52
53	14	20	0	0	16	48	20	109	29	53	58	34	401	53
54	0	0	11	0	28	0	10	48	47	74	109	1	328	54
55	18	0	10	29	0	1	28	5	59	33	6	21	210	55
56	0	0	40	48	0	0	12	34	46	43	60	10	293	56
57	38	0	0	24	27	26	20	44	57	58	95	0	389	57
58	36	0	0	0	24	19	66	11	37	71	14	32	310	58
59	0	8	36	33	0	0	9	37	36	52	42	70	323	59
60	7	0	0	14	4	44	10	28	26	91	15	46	285	60
61	11	5	27	3	30	16	10	33	38	36	14	30	253	61
62	0	16	0	21	31	0	31	65	58	51	77	17	367	62
63	0	0	0	16	7	41	55	46	53	53	0	51	322	63
64	0	0	0	0	32	24	53	40	106	91	78	29	453	64
65	30	14	3	10	22	43	81	33	66	28	56	11	397	65
66	0	0	0	31	51	15	12	29	46	37	46	21	288	66
67	0	12	39	34	7	12	40	43	31	60	88	10	376	67
68	0	0	0	26	4	20	28	53	89	75	123	0	418	68
69	21	0	11	24	0	0	37	21	31	30	41	7	223	69
70	0	28	0	0	0	13	14	22	35	108	73	0	293	70
71	9	0	2	66	66	24	97	33	34	76	22	0	429	71
72	21	0	2	0	16	56	117	51	116	84	49	74	586	72
73	0	0	0	0	0	2	45	30	38	108	44	0	267	73
74	17	0	7	11	14	50	30	30	9	86	79	28	361	74
75	29	0	0	0	0	0	2	18	57	58	38	23	225	75
76	17	9	0	61	95	34	41	34	61	6	24	21	403	76
77	0	0	13	0	1	4	35	0	66	27	49	63	258	77
78	25	0	0	27	0	8	13	51	46	105	34	0	309	78
79	51	0	17	36	13	3	41	29	48	92	36	58	424	79
80	0	0	5	14	87	15	64	18	50	49	38	21	361	80
81	0	0	17	22	23	26	31	35	38	26	75	62	355	81
82	0	0	101	13	15	26	62	65	73	64	28	44	491	82
83	0	0	0	0	0	7	21	53	46	49	96	19	291	83
84	0	0	0	0	0	9	24	59	25	74	97	23	311	84
85	22	0	0	0	16	37	0	11	57	103	23	46	315	85
86	0	20	0	17	19	18	40	56	56	75	59	133	493	86
TOT	430	132	384	637	775	764	1378	1447	2046	2424	2178	1272		
MEAN	10	3	9	15	18	18	33	34	48	58	52	30		

Table A-16. Same as for Table A-15, but for number of 6-hourly reports of tropical cyclones of typhoon intensity between 0-20 degrees N with maximum sustained winds equal to or greater than 65 knots (~32 m/s).

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEA. TOTAL	YR
45	0	0	0	0	0	0	0	4	13	0	19	0	36	45
46	0	0	18	17	16	16	24	5	44	13	22	0	175	46
47	0	0	0	0	0	6	0	11	5	37	56	17	132	47
48	22	0	0	0	16	0	12	11	17	0	17	23	118	48
49	17	0	0	0	0	6	14	0	4	11	31	9	92	49
50	0	0	0	0	21	0	0	0	7	13	21	4	66	50
51	0	0	15	5	29	3	19	19	22	21	31	62	226	51
52	0	0	0	0	0	7	21	15	15	55	37	35	185	52
53	10	15	0	0	3	29	7	59	10	28	16	13	190	53
54	0	0	0	0	9	0	7	15	20	54	87	0	192	54
55	1	0	0	20	0	1	14	0	32	2	1	18	89	55
56	0	0	30	28	0	0	2	21	32	29	29	8	179	56
57	12	0	0	8	23	17	12	7	48	18	56	0	201	57
58	35	0	0	0	24	12	35	8	29	38	7	10	198	58
59	0	0	0	27	0	0	3	18	16	30	15	57	166	59
60	0	0	0	4	0	14	4	4	0	53	8	37	124	60
61	0	0	22	0	16	5	0	26	29	22	14	20	154	61
62	0	0	0	18	1	0	7	29	13	33	52	0	153	62
63	0	0	0	14	4	20	28	27	20	19	0	32	164	63
64	0	0	0	0	9	13	27	16	49	29	26	23	192	64
65	4	0	0	1	6	25	47	14	27	6	14	0	144	65
66	0	0	0	15	29	9	5	5	11	14	1	8	97	66
67	0	0	6	24	0	5	8	11	23	40	56	0	173	67
68	0	0	0	17	1	16	6	14	55	40	35	0	184	68
69	14	0	0	14	0	0	16	0	14	11	22	0	91	69
70	0	19	0	0	0	6	3	4	26	65	16	0	139	70
71	0	0	0	11	33	18	51	21	9	25	11	0	179	71
72	9	0	0	0	3	18	55	24	29	39	29	31	237	72
73	0	0	0	0	0	0	10	7	8	55	0	0	80	73
74	0	0	0	0	4	9	13	3	0	41	39	1	110	74
75	3	0	0	0	0	0	0	3	6	7	18	0	37	75
76	7	1	0	29	32	10	11	6	7	0	15	0	118	76
77	0	0	0	0	0	0	12	0	14	0	24	23	73	77
78	0	0	0	10	0	0	1	0	12	32	10	0	65	78
79	31	0	7	8	0	0	16	7	4	50	15	11	149	79
80	0	0	0	0	31	0	20	2	9	16	25	0	103	80
81	0	0	7	0	0	2	5	0	23	8	28	31	104	81
82	0	0	19	3	7	1	31	30	23	36	12	9	171	82
83	0	0	0	0	0	0	6	16	26	4	38	0	90	83
84	0	0	0	0	0	0	4	9	15	29	64	13	134	84
85	0	0	0	0	4	15	0	0	13	45	0	19	96	85
86	0	5	0	7	14	3	24	10	26	25	13	67	194	86
TOT	165	40	124	280	335	286	580	481	805	1093	1030	581		
MEAN	4	0	3	7	8	7	14	11	19	26	24	14		

Table A-17. Same as for Table A-15, but for number of 6-hourly reports of tropical cyclones of typhoon intensity reports (0-20 degrees N) with maximum sustained winds equal to or greater than 90 knots (~45 m/s).

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEA. TOTAL	YR
45	0	0	0	0	0	0	0	0	0	0	0	0	0	45
46	0	0	7	2	0	4	17	3	25	8	10	0	76	46
47	0	0	0	0	0	3	0	2	0	17	18	3	43	47
48	7	0	0	0	0	0	3	0	0	0	9	0	19	48
49	0	0	0	0	0	1	6	0	0	2	27	0	36	49
50	0	0	0	0	11	0	0	0	3	7	12	0	33	50
51	0	0	10	0	9	0	15	9	3	16	10	27	99	51
52	0	0	0	0	0	0	9	0	2	44	26	20	101	52
53	9	1	0	0	0	22	7	33	2	18	10	11	113	53
54	0	0	0	0	5	0	0	12	5	3	61	0	86	54
55	0	0	0	2	0	1	7	0	19	0	0	14	43	55
56	0	0	11	16	0	0	0	11	12	21	2	0	73	56
57	11	0	0	2	19	15	4	1	31	8	39	0	130	57
58	31	0	0	0	23	0	15	5	18	22	6	9	129	58
59	0	0	0	12	0	0	0	10	8	27	7	46	110	59
60	0	0	0	0	0	5	0	1	0	7	5	21	39	60
61	0	0	16	0	8	0	0	7	27	8	14	17	97	61
62	0	0	0	13	0	0	0	8	11	23	40	0	95	62
63	0	0	0	12	4	11	14	17	8	8	0	17	91	63
64	0	0	0	0	0	3	18	12	28	3	13	18	95	64
65	0	0	0	0	0	15	16	3	15	4	12	0	65	65
66	0	0	0	0	7	4	0	0	2	0	0	1	14	66
67	0	0	0	14	0	0	0	6	19	16	39	0	94	67
68	0	0	0	10	0	8	1	7	35	25	20	0	106	68
69	0	0	0	7	0	0	11	0	11	3	12	0	44	69
70	0	14	0	0	0	3	3	0	10	40	9	0	79	70
71	0	0	0	2	18	2	26	10	2	7	7	0	74	71
72	4	0	0	0	0	7	45	7	4	20	12	16	115	72
73	0	0	0	0	0	0	0	0	0	24	0	0	24	73
74	0	0	0	0	0	0	3	0	0	5	19	0	27	74
75	0	0	0	0	0	0	0	1	0	3	13	0	17	75
76	0	0	0	14	21	3	9	2	2	0	13	0	64	76
77	0	0	0	0	0	0	0	0	3	0	21	12	36	77
78	0	0	0	0	0	0	0	0	0	25	7	0	32	78
79	14	0	2	0	0	0	4	4	0	33	12	7	76	79
80	0	0	0	0	17	0	9	1	1	6	20	0	54	80
81	0	0	3	0	0	0	0	0	19	2	15	17	56	81
82	0	0	6	0	4	0	21	7	5	14	7	0	64	82
83	0	0	0	0	0	0	3	13	17	0	23	0	56	83
84	0	0	0	0	0	0	0	1	9	12	43	10	75	84
85	0	0	0	0	0	3	0	0	0	21	0	4	28	85
86	0	0	0	1	11	0	17	0	6	6	3	31	75	86
TOT	76	15	55	107	157	110	283	193	362	508	616	301		
MEAN	1	0	1	2	3	2	6	4	8	12	14	7		

Table A-18. Monthly number of 6-hour tropical storm reports in the Southwest Pacific Ocean and Australian region equatorwards of 20S with sustained maximum winds equal to or greater than 30 knots (~15 m/s).

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEA. TOTAL	YR
58	20	13	22	64	0	17	0	0	0	0	0	5	141	58
59	81	21	63	37	0	0	0	0	0	0	0	70	272	59
60	41	7	64	48	0	0	0	0	0	0	0	37	197	60
61	84	71	88	0	0	0	0	0	0	0	9	13	265	61
62	67	97	0	0	0	0	0	0	0	0	1	11	176	62
63	65	50	38	32	28	0	0	0	0	0	25	23	261	63
64	89	42	88	9	0	0	0	0	0	0	56	60	344	64
65	66	65	53	0	0	0	0	0	0	0	0	45	229	65
66	51	54	24	5	0	0	0	0	0	0	21	13	168	66
67	49	27	70	18	0	0	0	0	0	0	25	28	217	67
68	76	65	16	17	0	0	0	0	0	0	25	48	247	68
69	48	72	32	21	6	0	0	0	0	0	0	0	179	69
70	83	105	31	46	21	0	0	0	0	0	12	58	356	70
71	28	77	22	0	0	0	0	0	0	0	3	110	240	71
72	83	64	56	93	24	8	0	0	0	28	10	37	403	72
73	82	26	110	12	0	0	0	0	0	0	59	49	338	73
74	51	41	117	16	0	0	0	0	0	0	1	47	273	74
75	41	22	88	44	0	0	0	0	0	0	24	58	277	75
76	100	75	51	20	0	0	0	0	0	0	0	54	300	76
77	73	57	89	34	8	0	0	0	0	0	45	50	356	77
78	62	109	21	70	0	0	0	0	0	0	0	27	289	78
79	65	59	18	39	0	0	0	0	0	0	0	0	181	79
80	999	999	999	999	0	0	0	0	0	0	0	44	44	80
81	39	62	92	0	0	0	0	0	0	0	0	29	222	81
82	75	33	29	53	14	0	0	0	0	2	43	14	263	82
83	76	121	89	76	0	0	0	0	0	0	11	26	399	83
84	41	86	38	9	0	0	0	0	0	0	0	72	246	84
85	92	97	72	48	0	0	0	0	0	0	21	24	354	85
86	46	67	47	30	0	0	0	0	0	0	0	0	190	86
TOT	1774	1685	1528	841	101	25	0	0	0	30	391	1052		
MEAN	63	60	55	30	3	0	0	0	0	1	13	36		

Table A-19. Same as Table A-18, but for number of 6-hourly reports of tropical cyclones of typhoon intensity with maximum sustained winds equal or greater than 65 knots (~32 m/s).

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEA. TOTAL	YR
58	0	0	5	2	0	0	0	0	0	0	0	0	7	58
59	0	5	0	0	0	0	0	0	0	0	0	1	6	59
60	1	2	11	0	0	0	0	0	0	0	0	34	48	60
61	8	15	4	0	0	0	0	0	0	0	0	6	33	61
62	0	1	0	0	0	0	0	0	0	0	0	0	1	62
63	0	5	1	0	0	0	0	0	0	0	7	0	13	63
64	10	5	10	4	0	0	0	0	0	0	0	1	30	64
65	0	8	7	0	0	0	0	0	0	0	0	0	15	65
66	1	1	6	5	0	0	0	0	0	0	0	0	13	66
67	17	0	0	0	0	0	0	0	0	0	0	1	18	67
68	0	2	0	0	0	0	0	0	0	0	0	0	2	68
69	1	2	0	0	0	0	0	0	0	0	0	0	3	69
70	5	5	7	0	0	0	0	0	0	0	0	6	23	70
71	2	12	2	0	0	0	0	0	0	0	0	35	51	71
72	26	24	21	13	11	4	0	0	0	15	0	8	122	72
73	13	2	28	0	0	0	0	0	0	0	7	7	57	73
74	0	10	23	0	0	0	0	0	0	0	0	8	41	74
75	13	15	31	3	0	0	0	0	0	0	1	22	85	75
76	25	13	0	5	0	0	0	0	0	0	0	10	53	76
77	12	0	14	5	0	0	0	0	0	0	4	0	35	77
78	27	16	6	3	0	0	0	0	0	0	0	0	52	78
79	5	3	1	0	0	0	0	0	0	0	0	0	9	79
80	999	999	999	999	0	0	0	0	0	0	0	44	44	80
81	16	23	59	0	0	0	0	0	0	0	0	26	124	81
82	8	8	11	12	0	0	0	0	0	0	4	0	43	82
83	15	61	50	26	0	0	0	0	0	0	4	0	156	83
84	3	15	9	0	0	0	0	0	0	0	0	11	38	84
85	33	6	26	4	0	0	0	0	0	0	0	8	77	85
86	0	22	11	9	0	0	0	0	0	0	0	0	42	86
TOT	241	281	343	91	11	4	0	0	0	15	27	228		
MEAN	8	10	12	3	0	0	0	0	0	0	0	8		

Table A-20. Same as Table A-18, but for number of 6-hourly reports of tropical cyclones of typhoon intensity with maximum sustained winds equal to or greater than 90 knots (~45 m/s).

YR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SEA. TOTAL	YR
58	0	0	0	0	0	0	0	0	0	0	0	0	0	58
59	0	1	0	0	0	0	0	0	0	0	0	0	1	59
60	1	0	0	0	0	0	0	0	0	0	0	0	1	60
61	4	2	3	0	0	0	0	0	0	0	0	0	9	61
62	0	0	0	0	0	0	0	0	0	0	0	0	0	62
63	0	1	0	0	0	0	0	0	0	0	0	0	1	63
64	2	0	0	0	0	0	0	0	0	0	0	0	2	64
65	0	0	0	0	0	0	0	0	0	0	0	0	0	65
66	0	0	0	0	0	0	0	0	0	0	0	0	0	66
67	0	0	0	0	0	0	0	0	0	0	0	0	0	67
68	0	1	0	0	0	0	0	0	0	0	0	0	1	68
69	0	0	0	0	0	0	0	0	0	0	0	0	0	69
70	0	0	0	0	0	0	0	0	0	0	0	0	0	70
71	0	7	0	0	0	0	0	0	0	0	0	16	23	71
72	15	5	5	10	0	0	0	0	0	0	0	0	35	72
73	0	0	5	0	0	0	0	0	0	0	0	0	5	73
74	0	0	0	0	0	0	0	0	0	0	0	2	2	74
75	0	5	14	0	0	0	0	0	0	0	0	17	36	75
76	4	2	0	0	0	0	0	0	0	0	0	4	10	76
77	0	0	0	0	0	0	0	0	0	0	0	0	0	77
78	0	0	1	3	0	0	0	0	0	0	0	0	4	78
79	0	1	0	0	0	0	0	0	0	0	0	0	1	79
80	999	999	999	999	0	0	0	0	0	0	0	44	44	80
81	7	17	34	0	0	0	0	0	0	0	0	26	84	81
82	0	8	9	4	0	0	0	0	0	0	0	0	21	82
83	0	30	18	9	0	0	0	0	0	0	0	0	57	83
84	0	0	7	0	0	0	0	0	0	0	0	0	7	84
85	14	0	19	0	0	0	0	0	0	0	0	0	33	85
86	0	1	7	0	0	0	0	0	0	0	0	0	8	86
TOT	47	81	122	26	0	0	0	0	0	0	0	109		
MEAN	1	2	4	0	0	0	0	0	0	0	0	3		

PROJECT REPORTS, PUBLICATIONS, and CONFERENCE PROCEEDINGS TO DATE

Summary of W. M. Gray's CSU research project reports, publications and conference proceedings since 1965. A majority of these reports and publications have made use of the rawinsonde compositing techniques here being advocated.

- a) Project Reports
- b) Publications
- c) Conference Proceedings

W. M. GRAY'S FEDERALLY SUPPORTED RESEARCH PROJECT REPORTS SINCE 1967

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
104	The Mutual Variation of Wind, Shear and Baroclinicity in the Cumulus Convective Atmosphere of the Hurricane (69 pp.). W. M. Gray. February 1967. NSF Support.
114	Global View of the Origin of Tropical Disturbances and Storms (105 pp.). W. M. Gray. October 1967. NSF Support.
116	A Statistical Study of the Frictional Wind Veering in the Planetary Boundary Layer (57 pp.). B. Mendenhall. December 1967. NSF and ESSA Support.
124	Investigation of the Importance of Cumulus Convection and ventilation in Early Tropical Storm Development (88 pp.). R. Lopez. June 1968. ESSA Satellite Lab. Support.
Unnumbered	Role of Angular Momentum Transports in Tropical Storm Dissipation over Tropical Oceans (46 pp.). R. F. Wachtmann. December 1968. NSF and ESSA Support.
Unnumbered	Monthly Climatological Wind Fields Associated with Tropical Storm Genesis in the West Indies (34 pp.). J. W. Sartor. December 1968. NSF Support.
140	Characteristics of the Tornado Environment as Deduced from Proximity Soundings (55 pp.). T. G. Wills. June 1969. NOAA and NSF Support.
161	Statistical Analysis of Trade Wind Cloud Clusters in the Western North Pacific (80 pp.). K. Williams. June 1970. ESSA Satellite Lab. Support.
—	A Climatology of Tropical Cyclones and Disturbances of the Western Pacific with a Suggested Theory for Their Genesis/Maintenance (225 pp.). W. M. Gray. NAVWEARSCHFAC Tech. Paper No. 19-70. November 1970. (Available from US Navy, Monterey, CA). US Navy Support.
179	A diagnostic Study of the Planetary Boundary Layer over the Oceans (95 pp.). W. M. Gray. February 1972. Navy and NSF Support.
182	The Structure and Dynamics of the Hurricane's Inner Core Area (105 pp.). D. J. Shea. April 1972. NOAA and NSF Support.
188	Cumulus Convection and Larger-scale Circulations, Part I: A Parametric Model of Cumulus Convection (100 pp.). R. E. Lopez. June 1972. NSF Support.
189	Cumulus Convection and Larger-scale Circulations, Part II: Cumulus and Meso-scale Interactions (63 pp.). R. E. Lopez. June 1972. NSF Support.

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
190	Cumulus Convection and Larger-scale Circulations, Part III: Broadscale and Meso-scale Considerations (80 pp.). W. M. Gray. July 1972. NOAA-NESS Support.
195	Characteristics of Carbon Black Dust as a Tropospheric Heat Source for Weather Modification (55 pp.). W. M. Frank. January 1973. NSF Support.
196	Feasibility of Beneficial Hurricane Modification by Carbon Black Seeding (130 pp.). W. M. Gray. April 1973. NOAA Support.
199	Variability of Planetary Boundary Layer Winds (157 pp.). L. R. Hoxit. May 1973. NSF Support.
200	Hurricane Spawned Tornadoes (57 pp.). D. J. Novlan. May 1973. NOAA and NSF Support.
212	A Study of Tornado Proximity Data and an Observationally Derived Model of Tornado Genesis (101 pp.). R. Maddox. November 1973. NOAA Support.
219	Analysis of Satellite Observed Tropical Cloud Clusters (91 pp.). E. Ruprecht and W. M. Gray. May 1974. NOAA/NESS Support.
224	Precipitation Characteristics in the Northeast Brazil Dry Region (56 pp.). R. P. L. Ramos. May 1974. NSF Support.
225	Weather Modification through Carbon Dust Absorption of Solar Energy (190 pp.). W. M. Gray, W. M. Frank, M. L. Corrin, and C. A. Stokes. July 1974.
234	Tropical Cyclone Genesis (121 pp.). W. M. Gray. March 1975. NSF Support.
—	Tropical Cyclone Genesis in the Western North Pacific (66 pp.). W. M. Gray. March 1975. US Navy Environmental Prediction Research Facility Report. Tech. Paper No. 16-75. (Available from the US Navy, Monterey, CA). Navy Support.
241	Tropical Cyclone Motion and Surrounding Parameter Relationships (105 pp.). J. E. George. December 1975. NOAA Support.
243	Diurnal Variation of Oceanic Deep Cumulus Convection. Paper I: Observational Evidence, Paper II: Physical Hypothesis (106 pp.). R. W. Jacobson, Jr. and W. M. Gray. February 1976. NOAA-NESS Support.
257	Data Summary of NOAA's Hurricanes Inner-Core Radial Leg Flight Penetrations 1957-1967, and 1969 (245 pp.). W. M. Gray and D. J. Shea. October 1976. NSF and NOAA Support.
258	The Structure and Energetics of the Tropical Cyclone (180 pp.). W. M. Frank. October 1976. NOAA-NHEML, NOAA-NESS and NSF Support.

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
259	Typhoon Genesis and Pre-typhoon Cloud Clusters (79 pp.). R. M. Zehr. November 1976. NSF Support.
Unnumbered	Severe Thunderstorm Wind Gusts (81 pp.). G. W. Walters. December 1976. NSF Support.
262	Diurnal Variation of the Tropospheric Energy Budget (141 pp.). G. S. Foltz. November 1976. NSF Support.
274	Comparison of Developing and Non-developing Tropical Disturbances (81 pp.). S. L. Erickson. July 1977. US Army Support.
—	Tropical Cyclone Research by Data Compositing (79 pp.). W. M. Gray and W. M. Frank. July 1977. US Navy Environmental Prediction Research Facility Report. Tech. Paper No. 77-01. (Available from the US Navy, Monterey, CA). Navy Support.
277	Tropical Cyclone Cloud and Intensity Relationships (154 pp.). C. P. Arnold. November 1977. US Army and NHEML Support.
297	Diagnostic Analyses of the GATE A/B-scale Area at Individual Time Periods (102 pp.). W. M. Frank. November 1978. NSF Support.
298	Diurnal Variability in the GATE Region (80 pp.). J. M. Dewart. November 1978. NSF Support.
299	Mass Divergence in Tropical Weather Systems, Paper I: Diurnal Variation; Paper II: Large-scale Controls on Convection (109 pp.). J. L. McBride and W. M. Gray. November 1978. NOAA-NHEML Support.
—	New Results of Tropical Cyclone Research from Observational Analysis (108 pp.). W. M. Gray and W. M. Frank. June 1978. US Navy Environmental Prediction Research Facility Report. Tech. Paper No. 78-01. (Available from the US Navy, Monterey, CA). Navy Support.
305	Convection Induced Temperature Change in GATE (128 pp.). P. G. Grube. February 1979. NSF Support.
308	Observational Analysis of Tropical Cyclone Formation (230 pp.). J. L. McBride. April 1979. NOAA-NHEML, NSF and NEPRF Support.
—	Tropical Cyclone Origin, Movement and Intensity characteristics Based on Data Compositing Techniques (124 pp.). W. M. Gray. August 1979. US Navy Environmental Prediction Research Facility Report. Tech. Paper No. CR-79-06. (Available from the US Navy, Monterey, CA). Navy Support.

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
—	Further Analysis of Tropical Cyclone Characteristics from Rawinsonde Compositing Techniques (129 pp.). W. M. Gray. March 1981. US Navy Environmental Prediction Research Facility Report. Tech. Paper No. CR-81-02. (Available from the US Navy, Monterey, CA). Navy Support.
333	Tropical Cyclone Intensity Change—A Quantitative Forecasting Scheme. K. M. Dropco. May 1981. NOAA Support.
—	Recent Advances in Tropical Cyclone Research from Rawinsonde Composite Analysis (407 pp.). WMO Publication. W. M. Gray. 1981.
340	The Role of the General Circulation in Tropical Cyclone Genesis (230 pp.). G. Love. April 1982. NSF Support.
341	Cumulus Momentum Transports in Tropical Cyclones (78 pp.). C. S. Lee. May 1982. ONR Support.
343	Tropical Cyclone Movement and Surrounding Flow Relationships (68 pp.). J. C. L. Chan and W. M. Gray. May 1982. ONR Support.
346	Environmental Circulations Associated with Tropical Cyclones Experiencing Fast, Slow and Looping Motions (273 pp.). J. Xu and W. M. Gray. May 1982. NOAA and NSF Support.
348	Tropical Cyclone Motion: Environmental Interaction Plus a Beta Effect (47 pp.). G. J. Holland. May 1982. ONR Support.
—	Tropical Cyclone and Related Meteorological Data Sets Available at CSU and Their Utilization (186 pp.). W. M. Gray, E. Buzzell, G. Burton and Other Project Personnel. February 1982. NSF, ONR, NOAA, and NEPRF Support.
352	A Comparison of Large and Small Tropical Cyclones (75 pp.). R. T. Merrill. July 1982. NOAA and NSF Support.
358	On the Physical Processes Responsible for Tropical Cyclone Motion (200 pp.). Johnny C. L. Chan. November 1982. NSF, NOAA/NHRL and NEPRF Support.
363	Tropical Cyclones in the Australian/Southwest Pacific Region (264 pp.). Greg J. Holland. March 1983. NSF, NOAA/NHRL and Australian Government Support.
370	Atlantic Seasonal Hurricane Frequency, Part I: El Nino and 30 mb QBO Influences; Part II: Forecasting Its Variability (105 pp.). W. M. Gray. July 1983. NSF Support.
379	A Statistical Method for One- to Three-Day Tropical Cyclone Track Prediction (201 pp). Clifford R. Matsumoto. December, 1984. NSF/NOAA and NEPRF support.
—	Varying Structure and Intensity Change Characteristics of Four Western North Pacific Tropical Cyclones. (100 pp.). Cecilia A. Askue and W. M. Gray. October 1984. US Navy Environmental Prediction Research Facility Report No. CR 84-08. (Available from the US Navy, Monterey, CA). Navy Support.

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
—	Characteristics of North Indian Ocean Tropical Cyclone Activity. (108 pp.). Cheng-Shang Lee and W. M. Gray. December 1984. US Navy Environmental Prediction Research Facility Report No. CR 84-11. (Available from the US Navy, Monterey, CA). Navy Support.
391	Typhoon Structural Variability. (77 pp.). Candis L. Weatherford. October, 1985. NSF/NOAA Support.
392	Global View of the Upper Level Outflow Patterns Associated with Tropical Cyclone Intensity Change During FGGE. (126 pp.). L. Chen and W. Gray. October, 1985. NASA support.
394	Environmental Influences on Hurricane Intensification. (156 pp.). Robert T. Merrill. December, 1985. NSF/NOAA Support.
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—	Recent Colorado State University Tropical Cyclone Research of Interest to Forecasters. (115 pp.). William M. Gray. June, 1987. US Navy Environmental Prediction Research Facility Contractor Report CR 87-10. Available from US Navy, Monterey, CA. Navy support.
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429	Investigation of Tropical Cyclone Genesis and Development Using Low-level Aircraft Flight Data. (94 pp.) Michael G. Middlebrooke. May, 1988. USAF, NSF support.
436	Environmental and convective influence on tropical cyclone development vs. non–development. (105 pp.) Patrick A. Lunney. December, 1988.
446	The structural evolution of typhoons. (198 pp.). Candis Weatherford. September, 1989. NSF/NOAA and ONR Support
457	Relationships between tropical cyclone deep convection and the radial extent of damaging winds. (109 pp.) Daniel N. Shoemaker. October, 1989.