Decadal Variations of Tropical Cyclone Activity over the Central North Pacific

Pao-Shin Chu and James D. Clark
Department of Meteorology, School of Ocean and Earth Science and Technology,
University of Hawaii at Manoa, Honolulu, Hawaii

ABSTRACT

Tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific has been found to be on the rise and this increase amounts to about 3.2 cyclones over the last 32 years (1966–97). An examination of time series of tropical storms and hurricanes and hurricane records alone also reveals an increasing trend in both series since 1966.

The upward trend is characterized by decadal-scale variability as manifested by fewer cyclones during the first half of the record (1966–81) and more during the second half of the record (1982–97). The maximum hurricane intensity has also increased in the central North Pacific, as well as the number of intense hurricanes from the first to the second half of the record. Relative to 1966–81, sea surface temperatures in the tropical Pacific and relative vorticity near the surface to the south of Hawaii have increased dramatically during 1982–97. The changes in the frequency and intensity of tropical cyclones in the central North Pacific appear to be modulated by decadal-scale variability of the basic state of SST, which transitioned from a cold to a warm phase in the late 1970s; this warm phase may have resulted in stronger and more frequent El Niño events as seen during the second half of the record, leading to more cyclones in the central North Pacific.

1. Introduction

There is a growing interest in knowing whether there is any long-term variation in tropical cyclone activities. This interest has derived mainly from the concern that global warming due to the increased concentration of greenhouse gases may alter the frequency, intensity, and area of occurrence of tropical cyclones. As the sea surface temperatures (SSTs) become warmer, certain tropical ocean basins may be faced with an increasing number of and/or more intense tropical cyclones; an increase in SST may fuel the overlying atmosphere with additional warmth and moisture, thereby reducing atmospheric stability and increasing the likelihood of deep tropical convection.

Corresponding author address: Prof. Pao-Shin Chu, Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, 2525 Correa Road, Honolulu, HI 96822-2219.
E-mail: chu@soest.hawaii.edu
In final form 26 March 1999.

Lighthill et al. (1994) noted that there is no apparent secular variation in the annual tropical cyclone numbers in the North Atlantic or in the northeast and northwest Pacific basins. Landsea et al. (1996) pointed out that there is actually a downward trend in the frequency of intense hurricanes in the Atlantic over the last five decades. More recently, Bove et al. (1998a) also found no sign of an increase in the landfalling hurricanes in the Gulf of Mexico over the last century. Contrary to the above studies, Chan and Shi (1996) presented a different view regarding the long-term changes of the tropical storms and typhoons in the northwest Pacific. They fitted the cyclone records to a second-order polynomial equation and suggested that cyclone numbers decreased from 1960 to the late 1970s but thereafter increased through 1994. The notable increase during the past 15 years is in stark contrast to trends in the Atlantic Basin.

In comparison to the Atlantic and the western North Pacific basins, little is known about the tropical cyclone activity in the central North Pacific (Fig. 1). Although the central North Pacific has experienced fewer cyclones than the former two basins, a few hurricanes that slammed into the Hawaiian Islands were devastating to the local economies. For instance, Hurricane Iniki in September 1992 caused \$2.5 billion damage and Hurricane Iwa in November 1982 left \$250 million damage (Chu and Wang 1997). For all these reasons, it is desirable to know if there are any long-term changes in the frequency and intensity in tropical cyclones in the central North Pacific.

2. Data and methods

The tropical storm (maximum surface winds between 17 and 32 m s^{-1}) and hurricane (maximum surface winds greater than 32 m s^{-1}) data are obtained from the National Hurricane Center's best-track dataset and are used in Chu and Wang (1997) and Chu and Wang (1998). This dataset contains measurements of latitude, longitude, maximum wind speed, and central pressure at 6-h intervals for all storms and hurricanes from 1949 to 1997 over the central North Pacific. Because satellite observations of tropical cyclone activity and tracks are unavailable in significant quantities prior to 1966 (Frank 1987), the data from 1966 to 1997 are used in the study. The domain chosen (Fig. 1) coincides with the area of responsibility of the Central Pacific Hurricane Center (CPHC), an entity of the National Weather Service in Honolulu, Hawaii. Tropical cyclone counts include both the system that originated within the central North Pacific and those that entered into the study domain from the east.

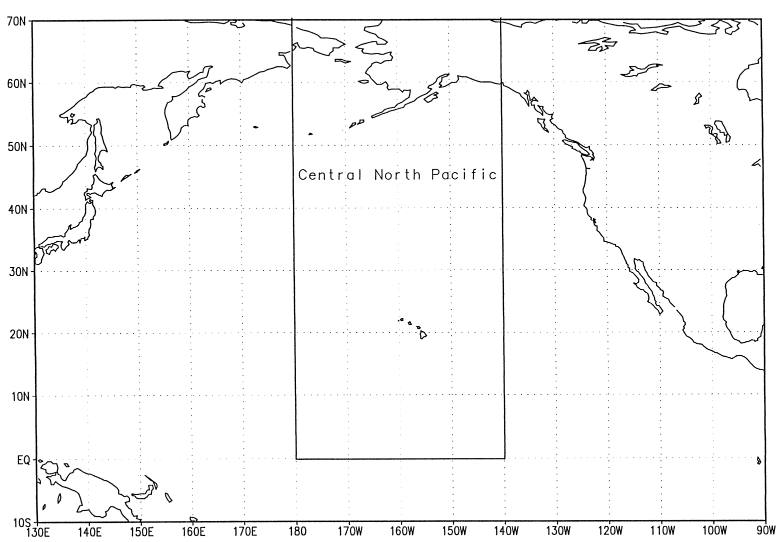

FIG. 1. Orientation map. The central North Pacific is delineated in solid lines.

As described earlier, the best-track dataset includes tropical storms (TSs) and hurricanes (HUs), but not tropical depressions (TDs). For TDs (maximum sustained surface winds less than 17 m s^{-1}), data must be obtained elsewhere. Prior to 1980, TD data can be found in Shaw's (1981) report. From 1980 to 1997, TDs are compiled and published annually by the CPHC as NOAA technical memorandums (NOAA/NWS 1980–97). To be consistent with the CPHC's mission, TDs are also considered in this study.

Surface relative vorticity records, available at 2.5° × 2.5° resolution, are obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996). The SST records are a combination of two datasets. The Global Ocean and Global Atmosphere data (4.5° latitude × 7.5° longitude), derived from the Comprehensive Ocean–Atmosphere Data Set (COADS; Slutz et al. 1985), from 1966 to 1988 are used. For the 1989–97 data, we use the NCEP/Climate Prediction Center blended SST data (Yu et al. 1997). The latter part of the data are derived from a blend of in situ, satellite, and ice data.

3. Results

Figure 2 shows the time series of the annual number of tropical cyclones in the central North Pacific from 1966 to 1997. Tropical cyclones (TCs) here refer to tropical depressions, tropical storms, and hurricanes. A general level of increase is noted in the cyclone records. A linear regression line fitted to the cyclone data reveals an upward trend of 0.1 cyclone per year, a value for which the null hypothesis of the linear slope being zero is rejected at the 95% significance level. This upward trend is equivalent to an increase of about 3.2 cyclones over the last 32 years. The statistical significance of linear trends is assessed in regard to serial correlation in the TC records. Calculations of autocorrelation functions show that TC records are uncorrelated from one year to the next, suggesting that the underlying data are nearly independent.

As also shown in Fig. 2, the TC series appear to have undergone a decadal-scale variability. For the first half of the record (1966–81), the mean number of TCs is about three while the mean number of TCs doubles to six for the second half of the record (1982–97). There is an absence of TCs in 1969, 1975, 1977, and 1979. Interestingly, all the years without TCs are found during the first half of the records. The years marked by relative maxima, that is, above the upper quartile (7 cyclones), in descending order, are 1992 (11 cyclones), 1994 (also 11), 1982 (10), 1997 (9), and 1985 (8). All these years occur in the second half of the record. The year 1994 is not only marked by a record high number of TCs but also by three hurricanes (Emilia, Gilma, and John) whose strength reached category five on the Saffir–Simpson scale (with sustained surface winds of at least 70 m s^{-1}). This is the first time that a category five hurricane has been reported in the central North Pacific since the records began (Garza et al. 1995), let alone three intense hurricanes in a single season.

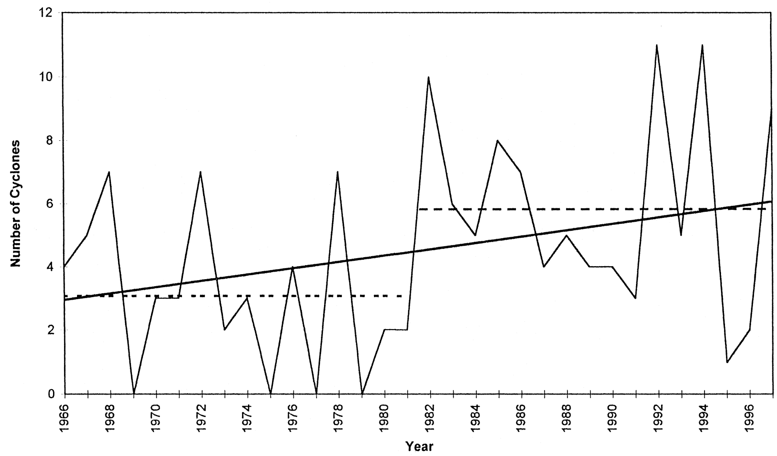

FIG. 2. Time series of tropical cyclones (TD + TS + HU) in the central North Pacific from 1966 to 1997. Heavy solid line denotes a simple regression line fitted to the records. Heavy broken lines denote the means for the periods 1966–81 and 1982–97.

Other notable features in Fig. 2 are the presence of a quasi-biennial oscillation (QBO) phenomenon in the TC series and a tendency for a relative maximum of TC occurrences during some of the El Niño years. For instance, the strong El Niño years in 1982 and 1997 are marked by a relative maximum in cyclone incidences (10 and 9, respectively). The influence of the El Niño and stratospheric QBO winds on hurricane development has been known for sometime (e.g., Gray 1984; Gray et al. 1993; Chan 1995). Chu and Wang (1997) found that the mean number of TCs in the vicinity of Hawaii is higher during an El Niño year than that during a non–El Niño year.

The long-term increase is likewise found in both the tropical storm plus hurricane (TS + HU) and hurricane-only (HU) records from the linear regression analyses in which their slopes are different from zero at the 90% level. Over the last 32 years, the increase in TS + HU is 2, and for HU it is 1.2. Without tropical depressions, a marked shift in the early 1980s is still conspicuous in the tropical storm and hurricane series (Fig. 3). Specifically, the mean number of TS + HU increases by a factor of 2 from the first to the second half of the record (Fig. 3 and Table 1). In terms of hurricanes, only 13 were observed from 1966 to 1981 as compared to 30 from 1982 to 1997. This results in an average of 0.81 during the first half of the record and 1.88 during the second half of the record (Table 1). Because the frequency of TCs is high in 1982 and 1997, which correspond to two extremely strong El Niño years, there is a concern whether the results of the previous analysis would be changed drastically without these two years. In fact, after removing 1982 and 1997, the mean number of TCs during 1983–96 is 5.43, which is still considerably higher than the mean number of cyclones during the first half of the period (Table 1).

As a measure of the intensity of TCs, the maximum sustained wind speed from the strongest hurricane for each year is selected, as in Landsea et al. (1996) for the intensity of Atlantic hurricanes. In

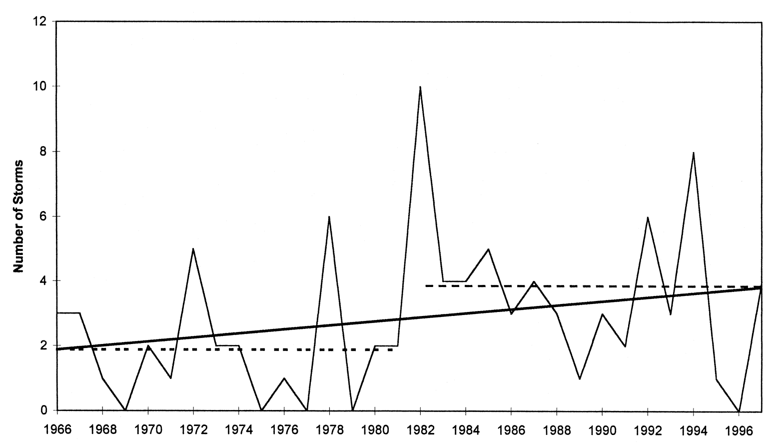

FIG. 3. Same as Fig. 2, except for tropical storms and hurricanes (TS + HU).

TABLE 1. Mean number of the tropical cyclone incidences in the central North Pacific during 1966–81, 1982–97, and 1983–96. The acronym TD refers to tropical depression, TS denotes tropical storm, and HU denotes hurricane. Tropical cyclone (TC) includes tropical depressions, tropical storms, and hurricanes.

	1966–81	1982–97	1983–96
TC (TD + TS + HU)	3.06	5.94	5.43
TS + HU	1.88	3.81	3.36
HU	0.81	1.88	1.79

Fig. 4, only years with hurricane occurrences are plotted. There are seven years without hurricanes during the first half of the record but only three years without hurricanes during the second half of the period. The intensity index of hurricanes seems to fluctuate at a lower level during the first half of the period as compared to the second half of the record. On average, the maximum wind speed is 43 m s^{-1} during 1966–81, in contrast to 49 m s^{-1} during 1982–97. In analyzing intensity estimates of the tropical cyclones for the eastern and central North Pacific from the historical records, T. S. Kimberlain (1999, personal communication) recently noted a possible underestimation of wind speed by about 2–4 m s^{-1} before 1988. If this underestimation is added to the mean maximum wind speed observed during 1966–81, the intensity of hurricanes still appears to be a bit stronger in more recent years.

To further illustrate the frequency and intensity changes concurrently, Fig. 5 shows the collection of all individual hurricane tracks during 1966–81 and 1982–97. The tracks of hurricanes whose strength reached category three or above (i.e., intense hurricanes) are darkened. It is clear that more hurricanes traversed into the central north Pacific from the east during 1982–97. In addition, more intense hurricanes were also observed during 1982–97 relative to 1966–81. Furthermore, six hurricanes formed in the western half of the central North Pacific (160°W–180°) during 1982–97 but only two hurricanes originated in the same region during 1966–81. Therefore, not only have more hurricanes formed in the central Pacific basin, but more hurricanes moved into the basin from the east since 1982.

4. Summary and discussion

By analyzing tropical cyclone occurrences in the central North Pacific from 1966 to 1997, an upward trend is found in the records. Among the three series analyzed (TD + TS + HU, TS + HU, HU), this trend is most pronounced in the TC (TD + TS + HU) records. More importantly, the TC series seems to have undergone a dramatic decadal-scale change over the last 32 years, as manifested by a few TCs during 1966–81 and more TCs during 1982–97. Tropical cyclones have become not only more frequent but also more intense.

Now the question is, What are the possible physical processes that are responsible for an upward trend in TCs? One convenient answer would point toward the greenhouse-induced global warming effect, which may give rise to more TCs from the thermodynamic effects alone. But since the global warming is a gradual process, it cannot explain why there is a steplike change in the TC incidences in the early 1980s.

A more plausible explanation for the upward trend in TCs invokes the decadal-scale variability of SST in the Pacific Ocean (e.g., Nitta and Yamada 1989; Trenberth 1990; Graham 1994; Mantua et al. 1997). It is known that the background state of SST has undergone a rapid transition from the cold to the warm phase in the late 1970s and such a warm phase has remained thereafter in the decadal mode. This warm decadal mode may act to enhance the interannual climate variability in such a way that extraordinarily strong El Niño events are

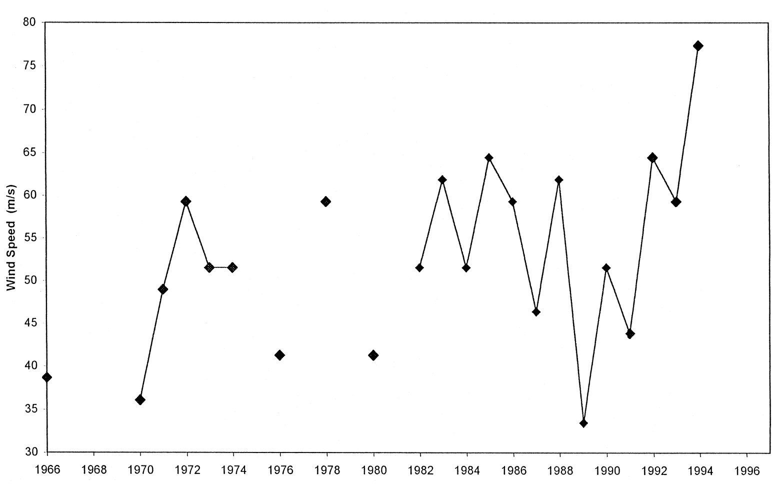

FIG. 4. Time series of the maximum intensity of hurricanes in the central North Pacific.

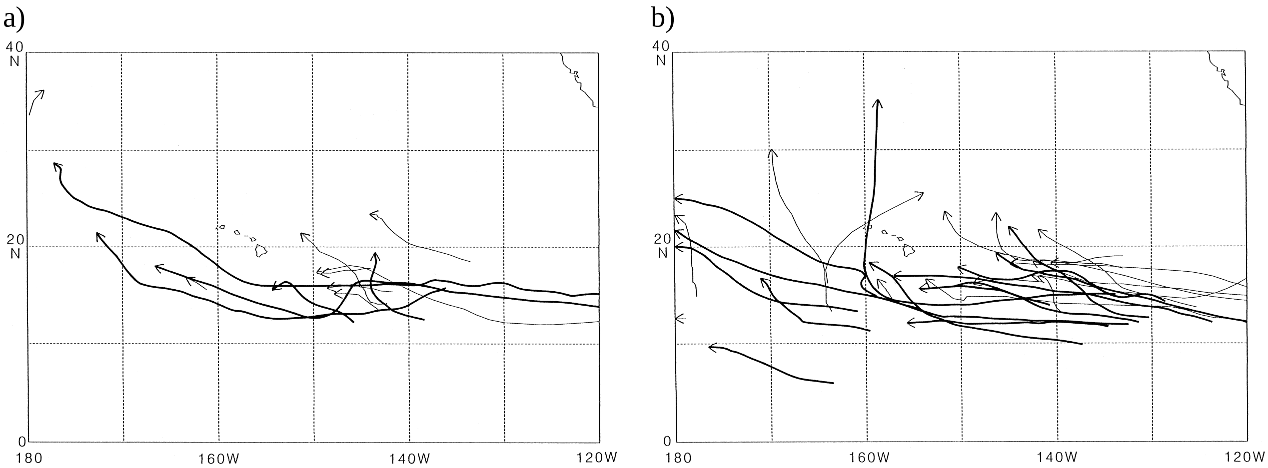

FIG. 5. (a) Hurricane tracks for the periods 1966–81 and (b) 1982–97. Heavy curves denote hurricanes whose strength have reached category three and above (sustained winds of at least 50 m s^{-1}) on the Saffir–Simpson scale.

observed during 1982–83 and 1997–98. Furthermore, the warm decadal mode may result in more El Niño and fewer La Niña events. According to the Japan Meteorological Agency, an El Niño event is defined as a 5-month running mean of SST anomalies greater than 0.5°C for at least six consecutive months in the region between 4°N–4°S and 150°W–90°W. Based on this definition, five El Niño events occurred during 1982–97 and three El Niño events occurred during 1966–81 (Bove et al. 1998b). Conversely, five La Niña events (the opposite of El Niño) are identified during the first half of the cyclone series but only one La Niña event is reported during the second half of the series. This then leads to another question: why the recurring and sometimes very strong or more frequent warm events that prevailed in the tropical Pacific in the 1980s and 1990s would give rise to more TCs in the central North Pacific?

Because tropical cyclones generally develop over the warm ocean where the supply of latent and sensible heat fluxes is abundant, it is instructive to know the changes in SST over the Pacific during the study period. Figure 6 shows the SST difference between 1966–81 and 1982–97 averaged for the period from July to September, a peak season of TC activity in the central North Pacific. The spatial structure of the SST difference is characterized by a juxtaposition of a warm anomaly in the entire tropical Pacific and a cold anomaly in the midlatitudes, a difference pattern reminiscent of Fig. 2 in Nitta and Yamada (1989) for the periods between 1977–86 and 1967–76. In the latitudinal band between 10° and 20°N, to the south of Hawaii where most hurricanes traversed (Fig. 5), SST has warmed by about 1°C. Warmer SSTs allow tropical cyclones to maintain strength and induce low-level wind convergence. Therefore, atmospheric circulation patterns in the tropical central North Pacific are expected to be altered concurrently with changes in the background state of SST over the last 32 years.

As the warm pools of water and low-level westerlies and the attendant tropical convection shift from the western Pacific to the central Pacific at the height of El Niño, so does the monsoon trough, which is regarded as the birthplace of tropical cyclones (Ramage 1995). The equatorial westerlies, together with easterly trade winds on the poleward side of the monsoon trough, generate cyclonic shear and vorticity in the central North Pacific. It is this dynamical "spin-up" process that is important for TC formation. To sup-

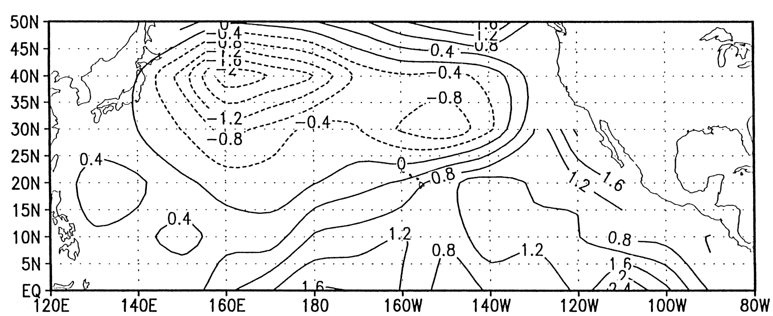

FIG. 6. Sea surface temperature difference (°C) between 1966–81 and 1982–97 in the North Pacific from July to September. Negative values are dashed.

port this argument, Fig. 7 shows the time series of the relative vorticity near the surface in the tropical central North Pacific. Indeed, the mean relative vorticity to the south of Hawaii has increased from about 0.4 $\times 10^{-6}$ s^{-1} during 1966–81 to 0.99 $\times 10^{-6}$ s^{-1} (0.70 $\times 10^{-6}$ s^{-1}) during 1982–97 (1983–96).

Schroeder and Yu (1995) and Kimberlain (1999) noted that tropical cyclones in the eastern North Pacific have a longer track toward the west during El Niño years. Therefore, although the eastern Pacific cyclone frequency did not change appreciably (Lighthill et al. 1994), the cyclone track and its longevity have changed since 1982 when El Niño events became more intense or more frequent. In the central North Pacific, persistent low-level easterly trade winds and upper-tropospheric westerlies in summer and fall produce large vertical wind shear, making this area unfavorable for cyclone formation climatologically. However, corresponding to a shift in enhanced heating over the equatorial central Pacific in association with El Niño, atmospheric circulation patterns have changed, eroding the strength of the climatological vertical wind shear. Consequently, cyclones entering from the east would tend to be longer lived and have a greater chance to enter the central North Pacific. In addition, more cyclones are formed within the central North Pacific as large-scale dynamic and thermodynamic environments have become more favorable (Figs. 6 and 7). Taken together, more TCs have developed and entered the central North Pacific since 1982 when El Niño became stronger or more frequent, coinciding with a warm phase of the decadal-scale mode of SST.

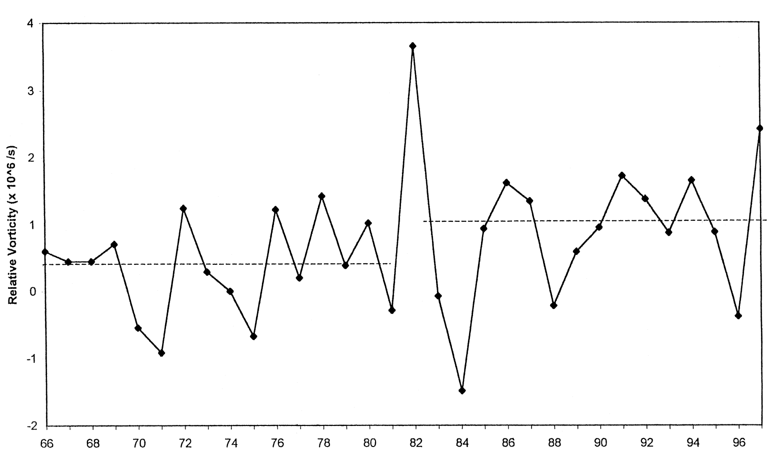

FIG. 7. Area-averaged relative vorticity at 1000 hPa in the tropical central North Pacific (10°–20°N, 140°W–180°) for the months of July through September from 1966 to 1997. Unit is 10^{-6} s^{-1}.

Acknowledgments. This study was partially funded by the Federal Emergency and Management Agency via Hawaii State Civil Defense. J. D. Clark was funded by the NWS Pacific Fellowship to the Department of Meteorology at the University of Hawaii at Manoa through the NOAA Cooperative Agreement. We thank Johnny Chan, Colin Ramage, and an anonymous reviewer for their constructive criticism on this paper. Thanks are also due to Rich Yeh, Jerry Wang, and Weiping Yan for their computer programming assistance. This is SOEST Publication Number 4847.

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