Tropical Cyclone Occurrences in the Vicinity of Hawaii: Are the Differences between El Niño and Non–El Niño Years Significant?*

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(Manuscript received 2 January 1997, in final form 7 April 1997)

ABSTRACT

Tropical cyclones in the vicinity of Hawaii are rare. However, when they occurred, they caused enormous property damage. The authors have examined historical records (1949–95) of cyclones and classified them into El Niño and non–El Niño batches. A bootstrap resampling method is used to simulate sampling distributions of the annual mean number of tropical cyclones for the above two batches individually. The statistical characteristics for the non–El Niño batch are very different from the El Niño batch.

A two-sample permutation procedure is then applied to conduct statistical tests. Results from the hypothesis testing indicate that the difference in the annual mean number of cyclones between El Niño and non–El Niño batches is statistically significant at the 5% level. Therefore, one may say with statistical confidence that the mean number of cyclones in the vicinity of Hawaii during an El Niño year is higher than that during a non–El Niño year. Likewise, the difference in variances between El Niño and non–El Niño batches is also significant. Cyclone tracks passing Hawaii during the El Niño batch appear to be different from those of the non–El Niño composite. A change in large-scale dynamic and thermodynamic environments is believed to be conducive to the increased cyclone incidence in the vicinity of Hawaii during an El Niño year.

1. Introduction

Tropical cyclones in the central North Pacific were generally not thought to be a threat to Hawaii because of the relatively low sea surface temperatures north of 20°N and the large vertical wind shear in this region (Elsberry 1987). This view, however, was changed by Iniki, which ravaged Kauai and a part of Oahu, Hawaii, on 11 September 1992 (Fig. 1), following the wake of the 1991–92 El Niño event. El Niño is manifested as an anomalous warming of surface water along the equatorial central/eastern Pacific. Iniki was a category 4 tropical cyclone on the Saffir–Simpson scale with gust winds up to 64 m s^{-1} recorded (Fletcher et al. 1994). Along with the destructive winds were storm surges and huge waves that crashed over coastal highways and beachfront properties. Estimates of damages were about $2.5 billion for Iniki, the costliest hurricane in Hawaiian history. Even four years after Iniki, Kauai's economy is still in slow recovery.

Before Iniki, homeowner's insurance covered losses from windstorm, hurricane, fire, and other disasters. After Iniki, the state legislature created the Hawaii Hurricane Relief Fund (HHRF), and homeowners have to buy two insurance policies, one from HHRF for hurricane risk and another from the traditional homeowners policy providers. As a result, the premium rates for the homeowner's insurance in Hawaii soared.

Just 10 yr prior to Iniki, Kauai suffered major property damage approaching $250 million from another hurricane named Iwa on 23 November 1982. This weak hurricane occurred when the unprecedentedly strong 1982–83 El Niño event had nearly reached its maximum intensity. In fact, during July 1982, there were two other tropical cyclones that were less intense than Iwa but were nevertheless close and strong enough to cause major concerns to Hawaii.

Chan (1985) noted that the frequency of tropical cyclone formation in the eastern part of the northwest Pacific (150°E to the date line) is above normal during El Niño years. Lander (1993), however, failed to find an overall relationship between tropical cyclone numbers in the western North Pacific and El Niño. Based on general circulation model (GCM) simulations forced with observed monthly sea surface temperatures in the tropical Pacific Ocean, Wu and Lau (1992) found that tropical storms associated with El Niño events are formed more often in the central North Pacific. More observational studies are needed to confirm or refute the GCM's results.

* SOEST Contribution Number 4515.

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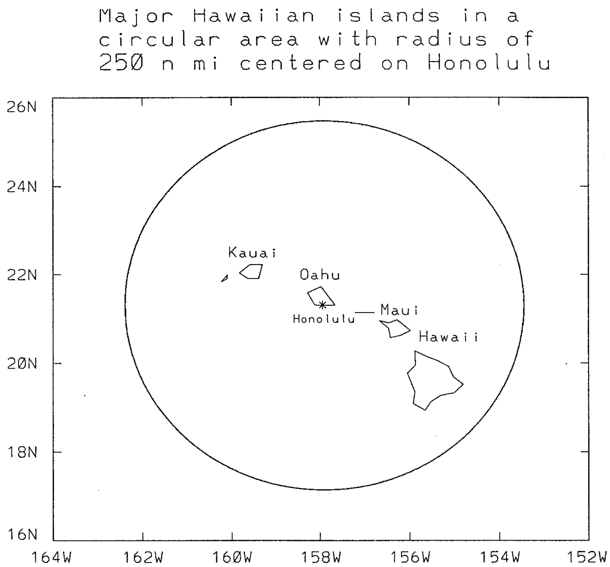

FIG. 1. Map of the major Hawaiian islands and the scan radius of 250 n mi from Honolulu.

Given the large economic loss and the associated social repercussions in Hawaii that resulted from tropical cyclones, it is necessary to know whether there is any difference in the observed tropical cyclone numbers in the vicinity of Hawaii during the El Niño and non–El Niño years. Such a study may also be used to validate the GCM's results. If there is a difference, the next question is whether this difference is statistically significant. This information is vital to the local National Weather Service, state agencies, civil defense, insurance and power utility companies, and many other organizations and residents who are faced with increasing hurricane insurance premium rates.

In this study, we will use a nonparametric bootstrap technique to simulate the frequency distributions of cyclone occurrences during El Niño and non–El Niño years. A two-sample permutation test is used to assess whether there is any difference in the number of tropical cyclones during El Niño and non–El Niño years. Cyclone tracks during El Niño and non–El Niño composites will be presented and discussed.

2. Data and tropical cyclone statistics

The tropical cyclone data are supplied by the National Hurricane Center in Miami, Florida. This dataset contains measurements of latitude, longitude, maximum wind speed, and central pressure at 6-h intervals for all 652 tropical cyclones from 1949 to 1995 over the northeast and north-central Pacific. During the last 47 yr, 26 cyclones occurred within 250 n mi of Honolulu, Oahu.

The second dataset, which comes from the NOAA's National Centers for Environmental Prediction (NCEP), is the monthly mean sea surface temperature (SST) series of Niño 3 region. Niño 3 covers the equatorial Pacific between 5°N–5°S and 150°W–90°W, an area critical to monitoring the development of the El Niño phenomenon by the NCEP. Inasmuch as El Niño refers to anomalous surface warmings over the tropical Pacific, an El Niño event, according to the Japan Meteorological Agency (JMA), is defined when the 5-month running mean of SST anomalies is greater than 0.5°C for at least six consecutive months in the region between 4°N–4°S and 150°W–90°W. We basically adopt the JMA definition but add one more criterion to the Niño 3 region. That is, during the aforementioned period SST anomalies are greater than 1°C at least for 1 month. Thus, our definition for El Niño applies for only pronounced events.

As shown in Fig. 2, an El Niño event may be as short as 9 months (1951–52) or as long as 17 months (1982–83). On average, an event starts in June and ends in the following May or June. The average length of an event is about 12.7 months, or slightly over 1 yr. For the sake of simplicity, a year in this study extends from June to May. As an example, the 1982 event refers to the period from June 1982 to May 1983. Note that this definition is different from the normal calendar year, which runs from January to December.

Initially, we have classified the historical records of cyclones into El Niño, anti-El Niño, and neutral batches. The definition for anti-El Niño is just the opposite of El Niño, and events not falling into these two batches are called neutral. However, splitting the data into three groups is found not to be fruitful because the sample size for the anti-El Niño is extremely small (only two events). Therefore, only El Niño and non–El Niño groups are used.

Table 1 lists the years pertinent to the El Niño and non–El Niño groups, as well as names and dates of tropical cyclones ''passing'' Hawaii for each group. Because of the strict definition for El Niño used in this study, the relatively weak warming period during 1992–94 is not regarded as an El Niño event. Note that tropical cyclones tended to occur more frequently when El Niño occurred, such as during 1957, 1972, and 1982. Watterson et al. (1995) also found an increased cyclogenesis in the central North Pacific during the 1982–83 El Niño event. For the non–El Niño group (36 yr), most years are characterized by none or one cyclone, except 1983 and 1992.

3. Bootstrap resampling method

Although the historical cyclone data are used, the sample size is limited, that is, only 11 cyclones during 10 El Niño yr and 15 in the other 36 yr. In order to make inferences about the frequency distribution of a parameter of interest (i.e., the annual mean number of cyclones during the El Niño and non–El Niño batches), we use the nonparametric, resampling procedure called the bootstrap technique (Efron and Tibshirani 1993). Recently, O'Brien et al. (1996) used a bootstrap tech-

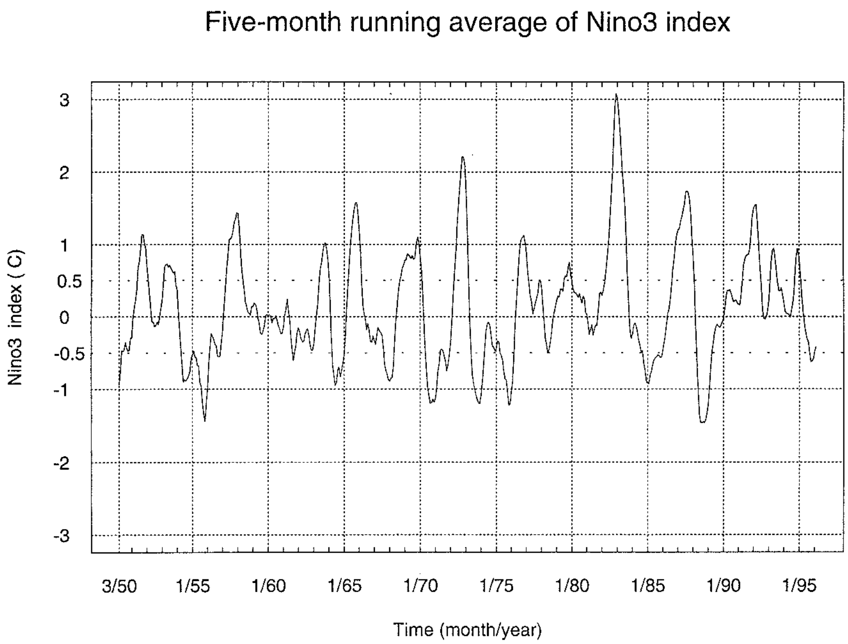

Fig. 2. Time series of sea surface temperature anomalies (°C) in Niño 3 region (5°N–5°S, 150°W–90°W) from 1950 to 1995.

nique to distinguish the relative frequency distribution of Atlantic hurricanes striking the United States during El Niño and non–El Niño years. Details of bootstrap methods applied to climate problems can be found in Zwiers (1990), Downton and Katz (1993), and Wilks (1995), among others.

The bootstrap is a data-based, computer-intensive simulation technique for statistical inference and it operates by generating artificial data batches from the existing sample *with replacement.* Because of this, repetitions of the same observations and absence of others may occur simultaneously in a particular bootstrap batch. The central assumption is that the population can be well represented by the available sample. Each bootstrap sample is drawn from a uniform [0, 1] random-number generator, while keeping the sample size of the artificial data batch the same as the observed sample. The parameter of interest is then computed from the simulated batch. Repeating the above procedure for a large number of trials creates an empirical distribution for a parameter estimator. The expected values of the mean and variance of the bootstrap batches are conservative relative to the observed samples.

In this study, 5000 bootstrap replications of size $n_{\text{Nino}} = 10$ and $n_{\text{non-Nino}} = 36$ are generated from the cyclone data corresponding to the El Niño and non–El Niño batches, respectively. The $(1 - \alpha) \times 100\%$ confidence intervals for bootstrap estimates are obtained using the percentile method. That is, the two end points of the $n_B = 5000$ bootstrap distribution are taken at the $(\alpha/2)$ 100th and $(1 - \alpha/2)$ 100th percentiles. In this study, α is the common 5% level of significance.

Figure 3 shows the probability distribution of the number of cyclones per year for El Niño and non–El Niño batches from n_B bootstrap realizations. The distribution appears to be smooth because of the choice of the width interval. Different distribution characteristics are noted between El Niño and non–El Niño batches. For the non–El Niño case, the distribution is characterized by a high peak and is concentrated around the mean value in a nearly perfect Gaussian shape, whereas for the El Niño case, the distribution is relatively flat.

Table 2 lists some summary statistics of the annual number of tropical cyclones. The mean annual number of cyclones during an El Niño year is 1.1 and its true value lies in the interval between 0.5 and 1.8 with 95% confidence. While the mean of the yearly occurrence of the observed cyclones during the El Niño batch is evidently larger than those during the non–El Niño batches (i.e., 1.1 vs 0.417), the 95% confidence intervals of the mean during the El Niño batch also spread out far more than those during the non–El Niño batch in the simulations. The variance of the annual number of cyclones during an El Niño year is 1.433, with its 95% confidence intervals between 0.278 and 2.044. As expected, there is more variability in the annual number of cyclones during the El Niño batch than those in the non–El Niño batch.

4. Hypothesis testings with two-sample permutation procedures

While the bootstrap method described in section 3 is applied to a one-sample problem, permutation proce-

TABLE 1. List of El Niño and non-El Niño years, and names of tropical cyclones in the vicinity of Hawaii. Dates refer to the entire life period of a tropical cyclone.

El Niño group		
	Tropical cyclones passing through Hawaii	
Year	Name	Date
1951	—	—
1957	Kanoa	15–26 July
	Della	1–12 Sept
	Nina	29 Nov–6 Dec
1963	Irah	12–21 Sept
1965	—	—
1969	—	—
1972	Diana	11–20 Aug
	Fernanda	20 Aug–1 Sept
1976	Gwen	5–18 Aug
1982	Daniel	7–22 July
	Gilma	26 July–2 Aug
	Iwa	19–25 Nov
1987	—	—
1991	Fefa	29 July–8 Aug
Non-El Niño group		
	Tropical cyclones passing through Hawaii	
Year	Name	Date
1949	—	—
1950	Hiki	12–21 Aug
1952	—	—
1953	—	—
1954	—	—
1955	—	—
1956	—	—
1958	Not named	7–9 Aug
1959	Dot	1–8 Aug
1960	—	—
1961	—	—
1962	—	—
1964	—	—
1966	—	—
1967	—	—
1968	—	—
1970	Maggie	20–27 Aug
1971	—	—
1973	—	—
1974	—	—
1975	—	—
1977	—	—
1978	Fico	9–28 July
1979	—	—
1980	Kay	16–30 Sept
1981	Jova	14–21 Sept
1983	Gil	23 July–5 Aug
	Raymond	8–20 Oct
1984	—	—
1985	—	—
1986	—	—
1988	Gilma	28 July–3 Aug
1989	Dalilia	11–20 July
1990	—	—
1992	Orlene	2–14 Sept
	Iniki	5–13 Sept
1993	Eugene	15–25 July
1994	Emilia	16–25 July

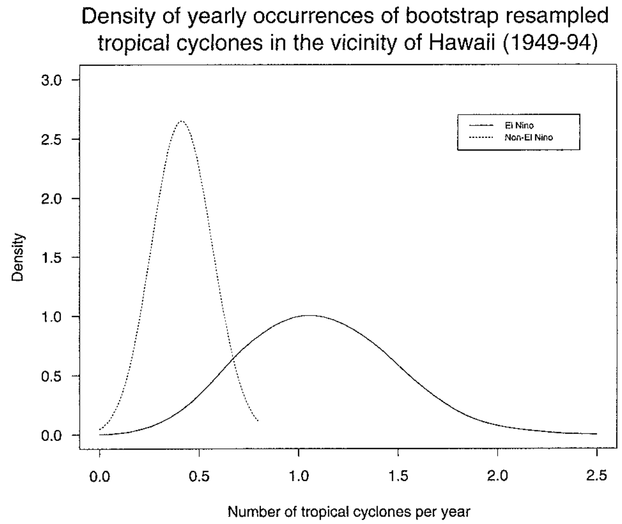

FIG. 3. Density distributions of the annual mean number of tropical cyclones in the vicinity of Hawaii for the El Niño and non-El Niño batches as simulated by bootstrap.

dures, which have a close connection to the bootstrap, are amenable when a comparison of a statistical property between two samples is involved. Mielke et al. (1981) discussed a case of permutation procedure when more than two samples are compared simultaneously. In permutation, each sample is drawn randomly only once *without replacement.* The permutation procedure does not need to make any assumptions of the sampled distribution (i.e., nonparametric), and its versatility relative to classical parametric methods is succinctly discussed by Zwiers (1990). Hypothesis testing based on permutation procedures is conducted via a Monte Carlo simulation method. The Monte Carlo simulation is, in essence, a data-generating technique used to simulate the random process by a computer random number generator (Chu 1995).

Specifically, the permutation procedure operates in the following way. As two different batches are compared, they are combined (e.g., $n_{\mathrm{Nino}} + n_{\mathrm{non\text{-}Nino}}$) to form a large batch. The pooled batch is resampled to form a new pair of batches. The test statistic is recomputed from these new batches and then the above steps are repeated a large number of times. The collection of the test statistic from the simulations is used to produce an empirical estimate of the reference distribution. If the test statistic from the actual observations falls outside the central 95% of the reference distribution, the permutation test rejects the null hypothesis at a 5% level.

In order to test whether the annual mean number of cyclones during El Niño is statistically different from that of non–El Niño, a natural test statistic such as the difference of means between two batches is used. Because the resampling procedure (both bootstrap and permutation tests) used destroys the time ordering of the data, it is necessary that the cyclone

TABLE 2. Mean and variance of the annual number of tropical cyclones in the vicinity of Hawaii and their corresponding 95% confidence intervals based on actual observations and the bootstrap resampling method.

Batch	Mean of the annual number of cyclones from observations	The 95% confidence intervals for the mean of the annual number of cyclones from bootstrap	Variance of the annual number of cyclones from observations	The 95% confidence intervals for the variance of the annual number of cyclones from bootstrap
El Niño	1.1	(0.5, 1.8)	1.433	(0.278, 2.044)
Non-El Niño	0.417	(0.222, 0.611)	0.364	(0.143, 0.542)

data are *not* serially dependent. A check of the original data shows a lack of autocorrelation pattern from year to year, suggesting that the underlying data to be resampled are nearly independent. However, the variance of the yearly occurrence of cyclones between the El Niño and non–El Niño batches is certainly not common (Fig. 3). Assuming that the variances of two distributions are not equal but the ratio of one variance to the other is known, we therefore use a modified procedure to compare the means of two batches (DeGroot 1986). The test procedure is based on the statistic U at a specified level of significance (α) with the following hypotheses:

$$H_0: \quad \mu_i = \mu_j,$$
$$H_1: \quad \mu_i \neq \mu_j, \tag{1}$$

where the subscripts i and j refer to the El Niño and non–El Niño batches being compared. The statistic U is defined as

$$U = \frac{(n_i + n_j - 2)^{1/2}(x_i - x_j)}{[(n_i - 1)\,\mathrm{var}_i + (n_j - 1)\,\mathrm{var}_j/\mathrm{kk}]^{1/2}(1/n_i + \mathrm{kk}/n_j)^{1/2}}, \tag{2}$$

where n is the sample size, x the mean, and var the variance. The factor kk is the population variance ratio, which is replaced by the sample variance ratio.

The means for each batch are calculated from the resampled data, and using (2), we get the $n_b = 2000$ values of the U statistic. Figure 4 shows the histograms of the U statistics between the El Niño and non–El Niño batches. There is an indication that the U statistic is somewhat positively skewed (i.e., skewed toward the higher positive values). As shown in Table 3, the actual U statistic lies outside of the 95% confidence intervals of the bootstrap estimates, and the null hypothesis is rejected. This result suggests that the annual mean number of tropical cyclones during the El Niño and non–El Niño batches are significantly different from each other at the 5% test level.

Likewise, one can also test to see if there is any difference in variances between two distributions based upon the two-sample permutation test. It is desired to test the following hypotheses:

$$H_0: \quad \sigma_i^2 = \sigma_j^2,$$
$$H_1: \quad \sigma_i^2 \neq \sigma_j^2. \tag{3}$$

The test statistic V is defined as

$$V = \mathrm{var}_i/\mathrm{var}_j, \tag{4}$$

where the subscripts i and j have the same meaning as stated in (1).

Table 3 shows that the actual V value lies outside the 95% confidence interval of the reference distribution, suggesting that the variance of the annual number of cyclones is also significantly different between the El Niño and non–El Niño batches.

5. Summary and discussion

From the historical data that span from 1949 to 1995, 11 and 15 tropical cyclones are observed in the vicinity of Hawaii during the El Niño and non–El Niño batches, respectively. Because the sample size from the real data is small, there is a concern whether the frequency of annual cyclone incidences from each batch can be regarded as a ''reliable'' estimate. To overcome this problem, modern statistical techniques such as the nonparametric bootstrap and permutation methods are used to artificially generate large data batches from a collection of real data. In the bootstrap method, artificial samples are drawn with replacement from the real data themselves. The permutation method operates in a way similar to the bootstrap, except that it deals with two different samples simultaneously and each value from the real data is drawn only once.

Results from the bootstrap method show that sampling distributions of the yearly occurrence of tropical cyclones in the vicinity of Hawaii during El Niño is quite different from the non–El Niño condition. The procedures to compare the means and variances are applied to the two-sample data batches generated from the permutation. The difference in the annual mean number

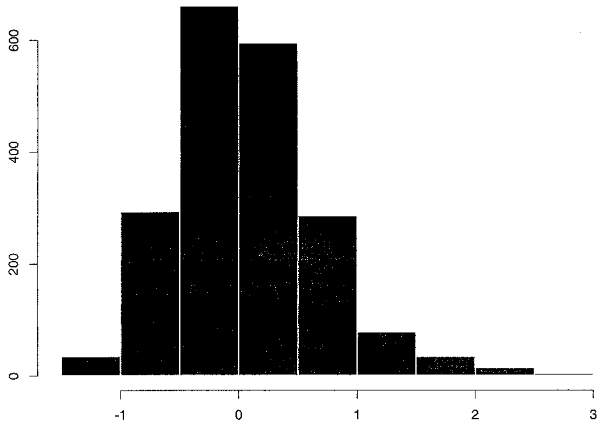

FIG. 4. Histograms of the U statistic from simulations for the El Niño and non-El Niño batches.

of cyclones during El Niño and non–El Niño years from the real sample is unusual relative to that from the simulated sample, suggesting that there are indeed more tropical cyclones during an El Niño year than during a non–El Niño year, and this difference is statistically significant. The current results, which are based on actual observations using statistical resampling techniques and hypothesis testings, thus lend support to the GCM simulations (Wu and Lau 1992). Likewise, the difference in variance in the annual number of cyclones is also significant between El Niño and non–El Niño batches in real data.

Now the natural question arises as to why there is an increased tendency for tropical cyclones in the central North Pacific following the onset of El Niño. The following conjecture is offered. At the height of El Niño events, warm pools of sea water and the attendant monsoon convection and trough shift eastward to the central Pacific. Accompanying this drastic eastward displacement are the low-level westerlies on the equatorward side of the monsoon trough. The presence of westerlies in low latitudes and easterly trade winds in the subtropics creates an environment favorable for the generation of low-level cyclonic shear and cyclonic relative vorticity in the tropical central North Pacific, factors important for the cyclone formation. In addition, the anomalously warm ocean surface water would fuel the overlying atmosphere with more warmth and moisture, decreasing atmospheric stability and increasing the likelihood of atmospheric convection. Taken together, the aforementioned dynamic and thermodynamic factors are helpful in maintaining and/or generating tropical cyclones (e.g., Gray 1968; Ramage 1995) and, therefore, lead to an increasing frequency of cyclone occurrences in the central North Pacific during El Niño years.

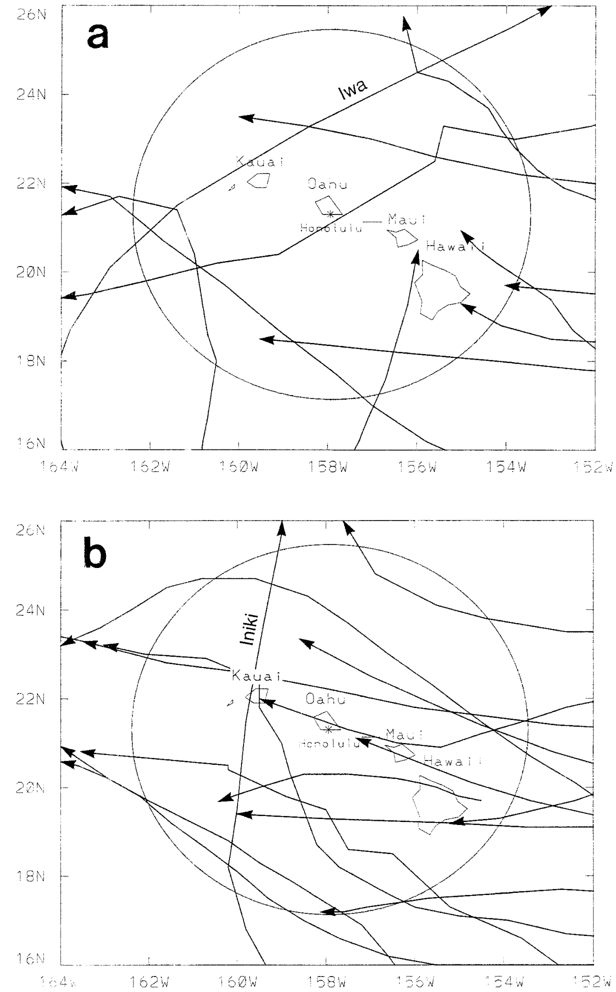

FIG. 5. Tropical cyclone tracks within 250 n mi of Honolulu during (a) El Niño and (b) non-El Niño composites. Hurricanes Iwa and Iniki are labeled in (a) and (b), respectively. Note that some cyclones passed through the scan circle while maintaining strength but others weakened to tropical depressions or less.

As tropical cyclone incidences in a specific region are closely related to the passage of cyclones, it is also interesting to see whether there is any change in cyclone tracks passing Hawaii during El Niño and non–El Niño years. Climatologically, cyclones in the central North Pacific follow an east to west or northwest track within the latitudinal band approximately between 15° and 25°

TABLE 3. U and V statistics of the annual number of tropical cyclones and their corresponding 95% confidence intervals between El Niño and non-El Niño batches based on actual observations and permutation tests.

Batch	U statistic from observations	The 95% confidence intervals for U from simulations	V statistic from observations	The 95% confidence intervals for V from simulations
Niño/non-Niño	1.744	(−0.928, 1.341)	3.935	(0, 2.498)

where easterly trade winds prevail. Figure 5 shows the composite maps comparing cyclone tracks in the vicinity of Hawaii during El Niño and non–El Niño years. During the El Niño composite, a few cyclones have tracks toward the west, but the northward, northwestward, northeastward, or even southwestward tracks are also observed (Fig. 5a). In contrast, cyclone tracks are more or less consistent following an east to west or northwest track during the non–El Niño composite, with the notable exception of Iniki, which has an almost northward course through Kauai (Fig. 5b). Therefore, tropical cyclone tracks generally follow a typical path during the non–El Niño batch. Nevertheless, cyclone tracks become more erratic during the El Niño years, a feature somewhat expected because large-scale dynamic and thermodynamic environments have changed from a normal condition during El Niño.

Acknowledgments. Pao-Shin Chu would like to thank Francis Zwiers and Dan Wilks for their careful reading the paper and making suggestions for improvement. Thanks are also due to Prof. S. Hastenrath and an anonymous reviewer for their insightful comments. This study has been partially funded by the Federal Emergency and Management Agency via Hawaii State Civil Defense. Jianxin Wang was supported by the NWS Pacific fellowship to the Department of Meteorology at the University of Hawaii through NOAA Cooperative Agreement NA 67RJ0154.

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