

Inversion Variability in the Hawaiian Trade Wind Regime

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ABSTRACT

Using 1979–2003 radiosonde data at Hilo and Lihue, Hawaii, the trade wind inversion (TWI) is found to occur approximately 82% of the time at each station, with average base heights of 2225 m (781.9 hPa) for Hilo and 2076 m (798.8 hPa) for Lihue. A diurnal pattern in base height of nighttime high and afternoon low is consistently found during summer at Hilo. Inversion base height has a September maximum and a secondary maximum in April. Frequency of inversion occurrence was found to be higher during winters and lower during summers of El Niño years than non-El Niño years. Significant upward trends were found for inversion frequency at Hilo for March–May (MAM), June–August (JJA), and September–November (SON) seasons, and at Lihue for all seasons and for annual values.

1. Introduction

The inversion in the trade wind regime of the Tropics and subtropics is the result of the interaction between large-scale subsiding air from the upper troposphere and convection-driven rising air from lower levels (e.g., Malkus 1956; Augstein et al. 1973; Riehl 1979; Albrecht 1984). Albrecht presented a simple model of the thermodynamic structure of the planetary boundary layer (PBL) in the trade wind zone in which inversion height was shown to be influenced by “sea surface temperature, divergence, variations in the temperature and moisture above the inversion, surface wind speeds, and radiative cooling variations.” Betts and Ridgway (1988, 1989) describe how PBL depth (inversion height) is coupled with radiative flux divergence (radiative cooling) within the PBL, but explain that this relationship is influenced by complex feedbacks among SST, surface air thermodynamic properties, radiative cooling, and subsidence. Trenberth and Stepaniak (2003) argue that transport of heat from the subtropics to higher latitudes by transient baroclinic eddies, rather than radiative

cooling, maintains the energy balance of the subsiding air and provides a fundamental driver of the Hadley circulation.

The relatively thin trade wind inversion¹ (TWI) layer caps the convective processes beneath it, limiting cloud vertical development (Leopold 1949; Mendonca and Iwaoka 1969; Riehl 1979, p. 202; Garrett 1980, Fig. 7), resulting in large areas of stratus, stratocumulus, and cumulus clouds with relatively uniform, flat tops over both the Atlantic and Pacific trade wind belts. The occurrence and base height of the inversion are therefore critical determinants of weather and climate in the affected regions. The TWI tops the marine PBL, and understanding its dynamics is very important for modeling the overall climate system (e.g., Ma et al. 1996; Philander et al. 1996; von Engel et al. 2005).

The first to present an inversion base height map for the Atlantic Ocean, von Ficker [1936; as described by Neiburger et al. (1961) and Riehl (1979)] showed that

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¹ The inversion can occur with or without prevailing trade winds. When the subtropical high lies over Hawaii, or the high moves to east or west of Hawaii, the northeasterly trade winds disappear, but an inversion may occur. In this paper, we make no distinction among inversions associated with different wind directions. Any inversion produced by the thermodynamic mechanism described above is referred to as the trade wind inversion.

in the subtropics the inversion base slopes upward from about 300 m near the coast of Africa to about 1500 m at a distance of 1500 km from the coast, then remains fairly constant westward. It also slopes southward from 500 m near 15°N to about 2000 m near 5°N. Neiburger et al. (1961) reported a similar pattern in the eastern North Pacific off the California coast.

Variations in inversion height are an important component of weather variability in the region. A number of studies have shown that the TWI base height fluctuates diurnally (e.g., Neiburger et al. 1961; Brill and Albrecht 1982). Blake (1928) first discovered the diurnal variation, finding that the inversion base is, on average, 85 m lower in the afternoon than in the morning (Neiburger et al. 1961). Neiburger et al. found that the inversion was also highly variable on time scales up to two weeks. Gutnick (1958) examined seasonal variations using three years of TWI data at six stations in the Caribbean. During the months of January, April, July, and October he found little variation. Tran (1995) analyzed two years of Hilo sounding data, showing some significant variability annually. Until now, a lack of long-term TWI data has limited research. As Schubert et al. (1995) noted, improved understanding of the TWI requires better analysis of its variability over the long term, which may be of particular importance for further improving PBL parameterization in current climate and weather models. Long-term TWI data will provide an important means of validating inversion characteristics derived from remote sensing, general circulation model (GCM) output, and reanalysis (e.g., Moeng and Stevens 2000; Wood and Bretherton 2004; von Engeln et al. 2005).

The TWI strongly influences the rainfall pattern of the trade wind region (Giambelluca and Nullet 1991; Tran 1995; Ramage and Schroeder 1999; Chen and Feng 2001), and the trade winds and the inversion heavily impact the weather of Hawaii (Schroeder 1993). Because the TWI is controlled by the large-scale atmospheric circulation and influenced by sea surface temperature (SST), fluctuations in the tropical atmosphere and SST on scales from diurnal to multiyear, including the El Niño–Southern Oscillation (ENSO) cycle, may have an influence on the inversion. In addition, trends in atmospheric and oceanic variables associated with global warming may cause shifts in inversion characteristics.

Information on the variability of the inversion would help to improve our understanding of the regional climate (Neiburger et al. 1961) and possibly enhance predictive capabilities. This study examines the long-term variability of the TWI based on the data at the only two Hawaiian radiosonde stations, Hilo and Līhu'e, be-

tween 1979 and 2003. We identify some dominant characteristics of the inversion, look for fluctuations at various time scales and for possible long-term trends, and discuss the possible reasons for observed variations. Then we examine the sensitivity of our results to the choice of inversion identification criteria. Finally we suggest ways to improve existing research in order to have a better understanding of the tropical atmospheric system.

2. Methods

Overall, this study includes four main components: inversion identification, descriptive statistical analysis, spectral analysis, and error analysis. The inversion identification procedure uses atmospheric sounding data as input and produces a dataset of inversion occurrence and characteristics. In the descriptive statistical analysis, basic statistical parameters and distribution functions, annual cycle and diurnal range, and inversion occurrence frequency maps are produced from the derived inversion dataset. Comparisons between different samples, for example, diurnal or seasonal contrasts, are tested for significance. The null hypothesis for differences in means, using the Student's t test, is that the compared entities are the same. All samples were determined to be approximately normally distributed, as required by the assumptions of the Student's t test. Spectral analysis, conducted through the wavelet approach, is used to identify the inversion variability pattern over a range of time scales. Trend analysis is used to identify tendencies in inversion frequency and height over a 25-yr period. Last, the inversion identification procedure is evaluated to determine the uncertainty arising from the use of different defining criteria. For simplicity, in this paper we denote significance level as $p < \alpha$ ($\alpha = 0.01$ – 0.15), meaning that the result is significant at the α level. A difference in frequency of occurrence between two samples is judged to be significant when the frequency of one sample is not within the $1 - \alpha$ confidence interval of the other sample under a binomial distribution (Wilks 1995).

a. Data

Hawaii has two sounding stations: Līhu'e (21.97°N, 159.33°W) on Kaua'i Island, and Hilo (19.72°N, 155.05°W) on Hawai'i Island, about 510 km apart (Fig. 1). Twice-daily (0000 and 1200 UTC) atmospheric sounding data for Līhu'e and Hilo, from 1973 to the present, are available on a Web site maintained by the University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>). Between 1975 and 1978, there were 21 and 20 months of missing data for Līhu'e and

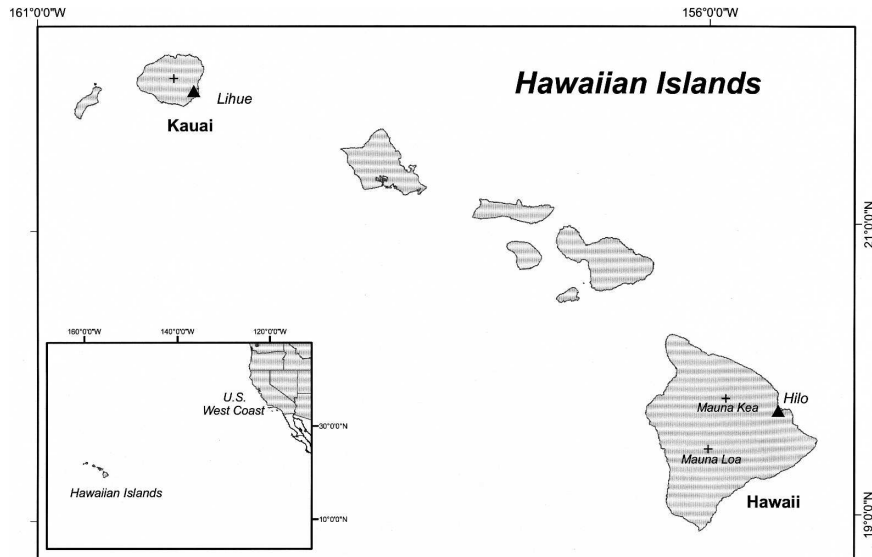


FIG. 1. The location of the Hilo and Lihue sounding stations in Hawai'i.

Hilo, respectively. Therefore we use the period 1979 to 2003 for the long-term variability study, while retaining the data in the earlier period to obtain the inversion characteristics.

b. Identifying the TWI

The criteria for identifying the inversion are modified slightly from the method of Tran (1995), which is based on earlier work by Grindinger (1992). The criteria are as follows:

- (i) Inversion height is restricted to the 950–600-hPa range. Johnson et al. (1996) point out that another inversion often appears at the 273-K level, above 600 hPa, and its physical mechanism, melting of cloud droplets, is different from that of trade wind inversion. To exclude all such inversions, we impose an upper height limit of 600 hPa and a lower temperature limit of 273 K. We add an additional control at 950 hPa to eliminate surface radiative inversions.
- (ii) Within the 950–600-hPa range and for temperatures above 273 K, the trade wind inversion is identified as a layer with a positive vertical temperature gradient, accompanied by a relative humidity decrease with height.
- (iii) The Grindinger (1992) method is adopted to eliminate spurious superadiabatic layers, accounting for 21% and 20% of the soundings at Hilo and Lihue, respectively, appearing in the soundings just below the inversion base. Grindinger (1992) reasoned that these superadiabatic layers resulted from measurement error caused by wetting of the tem-

perature sensor within a cloud. When the wet sensor ascends into a dry layer, the moisture rapidly evaporates, cooling the sensor below the ambient air temperature. The spuriously low temperature readings increase the calculated lapse rate to values greater than the adiabatic lapse rate, thus becoming physically unrealistic. To correct for this, the higher of the two points defining any apparent superadiabatic layer is ignored in the analysis.

- (iv) For multiple inversion layers accounting for 33% and 35% of the soundings at Hilo and Lihue, respectively, the layer with the greatest relative humidity drop is selected as the inversion layer. Note that the top of the PBL is usually identified in reanalysis data as the level, within the layer where $T > 273$ K, with maximum humidity drop (e.g., von Engel et al. 2005).
- (v) The corresponding inversion top is identified as the level where temperature begins to decrease with height.

The above definition is consistent with the TWI diagrams used by Riehl (1979, Fig. 5.4) and Betts and Ridgway (1989, Fig. 2). After identifying the inversions, random checking is performed to test the appropriateness of the inversion identification. Systematic analysis of the sounding data yields the following variables: inversion base and top locations in height (m) and pressure (hPa) units, the magnitude and thickness of the inversion, that is, the temperature difference (K) and height interval (m, hPa) between the inversion base and top, and the relative humidity decrease (%) within the inversion layer.

Histogram and box plot analyses of above-inversion attributes (not shown) were used to set criteria for identifying data outliers. As a result, inversions stronger than 8 K or thicker than 1000 m are excluded. In the rare cases when humidity increases are found within an inversion layer, they are usually associated with a sharp humidity drop just below the inversion. These instances are considered anomalous and are assigned a humidity decrease of zero.

c. Inversion characteristics

To examine the diurnal effect, we compare inversion characteristics for the times of the twice-daily soundings, 0000 (1400 local time, “daytime”) and 1200 UTC (0200 local time, “nighttime”). The annual cycle is calculated by averaging individual monthly values over 25 years. Monthly and annual means are calculated only from days with inversions during both daytime and nighttime soundings.

To further characterize inversion occurrence, we separate values into discrete classes and use frequency analysis. Inversion base heights between 1000 and 4200 m are grouped into 400-m intervals, plus groups for less than 1000 and greater than 4200 m. Similarly, inversion strength is grouped into 1-K intervals up to 7 K, plus a single group for values greater than 7 K. Intervals of 100 m are used to group inversion thickness values up to 600 m, with an additional group for values greater than 600 m. Using this method, frequency plots for each inversion property are constructed. Inversion properties are also fitted with both the Gamma and normal distributions.

d. El Niño and the inversion

To investigate whether ENSO warm events have any influence on the inversion, composite monthly anomalies of the inversion base height during El Niño events are calculated. El Niño events are identified according to the criteria of Trenberth (1997); that is, a minimum of 6 months during which the 5-month running mean of SST anomalies in the Niño-3.4 region (5°N–5°S, 120°–170°W) exceeded 0.4 K. The SST anomalies are calculated relative to a 1950–79 base period. El Niño frequency anomalies are also calculated for each month, as the inversion frequency during El Niño events minus the mean frequency during non-El Niño years for the corresponding month.

e. Trend and wavelet analysis

Linear regression is used to examine long-term trends in the mean inversion base height and occur-

rence frequency for each season and annual time series. Slopes obtained from the regression analysis were evaluated for significance, with attention to the effects of autocorrelation, using the procedure of Santer et al. (2000).

Wavelet analysis is used to examine the spectral properties of the monthly TWI base height at various time scales. A wavelet is a wavelike form function with zero local average. It can successfully handle the time and frequency information for varying scales, when the variation is less regular or when transient processes may influence variability. Atmospheric processes in the tropical Pacific are influenced by both highly periodic variations, especially the diurnal and annual radiation cycles, and less regular oscillations, such as the Madden-Julian oscillation (MJO), the quasi-biennial oscillation (QBO), and ENSO. To carry out wavelet analysis, we apply a Matlab-based algorithm developed by Torrence and Compo (1998, hereafter referred to as TC), which uses the Morlet wavelet:

$$\psi_0(\eta) = \pi^{-1/4} \exp(i\omega_0\eta) \exp(-\eta^2/2),$$

where $\psi_0(\eta)$ is the wavelet function, η is the nondimensional time parameter, and ω_0 is the nondimensional frequency. In the TC method, the wavelet power spectrum has been normalized by the white-noise variance. Because of the autoregressive nature of atmospheric time series, we compare this normalized spectrum against the red-noise spectrum.

f. Testing TWI criteria

Including *isothermal* layers: Our criteria for identifying the inversion select only layers where temperature increases with height. We do not include cases where the temperature remains constant in a vertical interval (isothermal layer). Physically, an isothermal layer is stable and acts similarly to an inversion. Therefore, we test how the inversion results change if isothermal layers are included.

Alternative *superadiabatic* correction: The correction method of Grindinger (1992) eliminates layers with a superadiabatic lapse rate. This treatment may generate errors because it is possible that temperature within the apparent superadiabatic layer may actually continue to drop (rather than increase as we assume) but at a rate less than the adiabatic lapse rate. We test the original assumption by instead assuming that the temperature in the layer decreases at the normal lapse rate (6.5 K km⁻¹).

Alternative for *multi-inversion* cases: The accuracy of the temperature and humidity measurements are 0.5 K and 5% with a corresponding resolution of 0.1 K and

TABLE 1. The inversion characteristics at Hilo and Lihue, Hawai'i.

	Base height m (hPa)		Thickness m (hPa)		Strength (K)		Humidity drop (%)	
	Hilo	Lihue	Hilo	Lihue	Hilo	Lihue	Hilo	Lihue
Mean	2255 (782)	2076 (799)	281 (26)	282 (27)	2.4	2.3	46.8	50.4
Std dev	497 (45.9)	475 (44.6)	128 (11.7)	129 (12.0)	1.4	1.5	18.9	17.2
CI*	± 14.3 (± 1.4)	± 12.5 (± 0.8)	± 4.0 (± 0.4)	± 3.5 (± 0.3)	± 0.04	± 0.04	± 0.6	± 0.5

* CI: 95% confidence interval of the mean.

1%. The humidity criterion is important in the selection of the appropriate inversion from multi-inversion soundings, which account for one-third of all inversion cases. With an accuracy of 5%, the distinction between two candidate inversion layers may often lie within the uncertainty range of the sensor. For example, if the humidity difference is within 5% between layers, the instrument error may dominate the selection. To test this assumption, for cases in which the humidity difference between two layers is within 5%, then the inversion layer with maximum temperature increase, rather than the largest relative humidity decrease, is selected as the inversion layer.

All alternatives: All above alternative methods are combined here.

3. Results and discussion

a. Inversion properties

The inversion is a persistent feature of the Hawaiian climate, appearing in over 82% of soundings (82.4% at Hilo and 82.3% at Lihue). The average inversion properties from 1979 to 2003 are summarized in Table 1. Probability density functions (PDFs) of principal inversion characteristics are shown in Table 2. The average inversion base height is 2255 m (781.9 hPa) at Hilo and 2076 m (798.8 hPa) at Lihue. The Hilo figure is lower than that of the two earlier studies; Grindinger (1992) and Tran (1995) reported mean inversion base heights 2322 and 2405 m, respectively in Hilo. Grindinger's re-

sult was derived from the 2-month Hawaiian Rainband Project (HaRP) dataset taken during July and August 1990, while Tran's result was based on analysis of two years (1993–94) of routine sounding data. The difference may result from using a much longer time series, or from our data screening procedure, in which we eliminated data outliers and 0°C inversions.

In earlier work, the inversion was found to be lower. Mendonca and Iwaoka (1969) reported the average inversion base in Hawai'i to be 1800 m, which corresponds to only the 30th and 18th percentiles in our dataset for Lihue and Hilo, respectively (based on the Gamma distribution in Table 2). Rasmussen et al. (1989), in their dynamic model of Big Island rainfall, assumed an inversion height of 1500 m (850 hPa) for Hilo (5th percentile in our dataset). Schroeder (1993) gave a value of about 2000 m for the inversion base in Hawai'i, comparatively close to our result (32nd and 47th percentiles in our dataset for Hilo and Lihue, respectively).

To our knowledge, no prior studies have shown that the inversion base height is significantly greater ($p < 0.01$) at Hilo than Lihue. Two possible explanations may account for the observed higher inversion at Hilo. First, it is often assumed that the inversion slopes upward toward the intertropical convergence zone (ITCZ) (Riehl 1979; Schubert et al. 1995), and Hilo is more than 2° south of Lihue. Second, numerical studies have indicated that a significant hydraulic jump occurs upstream of Hawai'i Island, near Hilo (Rasmussen et al. 1989). This circulation may lift the inversion layer, although this phenomenon was not explored in the study. The two peaks of 4205 and 4169 m on Hawai'i Island are much higher than that of Kauai Island, 1598 m. The Lihue sounding is at the side of the mountain relative to trade wind flow, while at Hilo the sounding is directly upwind of Mauna Loa. (Fig. 1).

The thickness and strength of the inversion at Hilo (281 m, 2.4 K) and Lihue (282 m, 2.3 K), although statistically different ($p < 0.01$), are very similar in value. The humidity drop for Hilo and Lihue is also similar, but statistically different ($p < 0.01$), 46.8% and 50.4% for each, respectively (Table 1).

TABLE 2. Probability density function parameters of inversion characteristics at Hilo and Lihue, Hawai'i.

Gamma distribution: $f(x) = x^{a-1} \exp(-x/b) / [b^a \Gamma(a)]$	Hilo		Lihue	
	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
Inversion base (m)	20.4	110.8	19.4	106.8
Strength (K)	2.6	1.0	2.3	1.0
Thickness (m)	4.9	56.8	4.9	57.8
Normal distribution: $f(x) = \{1/[\sigma(2\pi)^{1/2}]\} \exp[-(x-\mu)^2/(2\sigma^2)]$	μ σ		μ σ	
Humidity drop (%)	46.8	18.9	50.4	17.2

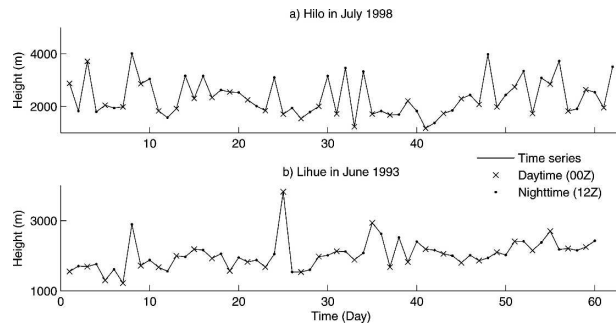


FIG. 2. Sample inversion base height time series in (a) July 1998 at Hilo, Hawai'i, and (b) June 1993 at Lihue, Hawai'i.

Earlier studies showed that the inversion base height is highly variable at time scales of 24 h to several days (e.g., Neiburger et al. 1961; Riehl 1979). Grindinger (1992) found that the Hilo inversion could vary 1000 m within a day. Two sample months of sounding data, July 1998 at Hilo and June 1993 at Lihue, each with complete records and with inversions present during all soundings, are selected to examine the diurnal inversion base height variability (Fig. 2). The graph indicates that the inversion height is highly variable.

The TWI base height at Hilo and Lihue are significantly correlated on a monthly time scale, with a Pearson correlation coefficient (r) of 0.62 ($p < 0.01$, $N = 300$). This suggests that the atmospheric circulation and SST variations that produce month-to-month changes in the inversion are of a large enough spatial scale to affect all the major Hawaiian Islands simultaneously.

b. Diurnal differences

In Hilo, the mean daytime inversion base height is 54 m lower (5.0 hPa higher) than that at night ($p < 0.01$); in Lihue, the daytime inversion is 27 m lower (2.6 hPa higher) than that at night ($p < 0.01$, Table 3). While the average diurnal range in inversion height is almost twice as large at Hilo as that at Lihue, the diurnal range in inversion strength and thickness at the two stations

are very similar (Table 3). Grindinger (1992) found a 300-m difference between maximum (night) and minimum (afternoon) inversion base height for Hilo, based on hourly average observations of inversion base height derived from wind profiler Doppler radar data. Tran (1995) found an average diurnal range of 99 m at Hilo, based on two years of sounding data.

Diurnal variations are more consistent during the warmer months (May–October) at both sites, but especially at Hilo (Fig. 3). During other months, the diurnal patterns are more variable, with the inversion sometimes higher during the day rather than during the night.

It has been known for some time that the inversion height varies diurnally (Neiburger et al. 1961; Riehl 1979). Brill and Albrecht (1982) found a diurnal variation based on 3-h interval observations from the Atlantic Tropical Experiment (ATEX) data: the inversion base reached its maximum height in the morning (0700 local time) and became lower in the afternoon, with an average daily range of 7.2 hPa. The diurnal cycle of radiative cloud-top heating and, to a lesser extent, the observed diurnal fluctuation in horizontal divergence were identified as causes of this observed variation (Brill and Albrecht 1982). A well-defined diurnal divergence pattern was confirmed in an earlier analysis of the Barbados Oceanographic and Meteorological Experiment (BOMEX) data (Nitta and Esbensen 1974). Deser and Smith (1998) associate diurnal and semidiurnal variations in related atmospheric circulation variables with diurnal heating of the sea surface. Ciesielski et al. (2001) found evidence for a “diurnally pulsating Hadley cell” over the Atlantic Stratocumulus Transition Experiment (ASTEX) domain, which they attribute primarily to diurnally varying cloud–radiative processes. Related diurnally varying atmospheric processes over tropical oceans, such as observed fluctuations in stratiform cloud cover (Rozendaal et al. 1995), are also thought to be related to radiative heating of cloud tops near the top of the PBL.

TABLE 3. The average inversion properties and the 95% confidence intervals for 0000 UTC (1400 LT) and 1200 UTC (0200 LT) at Hilo and Lihue, Hawai'i.

	Inversion base		Inversion thickness		Inversion strength (K)	Humidity drop (%)
	(m)	(hPa)	(m)	(hPa)		
Hilo						
0000 UTC	2311 ± 14	776.8 ± 1.3	268 ± 3.9	25.0 ± 0.4	2.2 ± 0.04	40 ± 0.7
1200 UTC	2365 ± 14	771.8 ± 1.3	277 ± 4.1	25.9 ± 0.4	2.4 ± 0.04	40 ± 0.6
Lihue						
0000 UTC	2113 ± 14	795.5 ± 1.3	271 ± 3.9	25.9 ± 0.4	2.1 ± 0.04	45 ± 0.6
1200 UTC	2140 ± 14	792.9 ± 1.3	279 ± 4.0	26.8 ± 0.4	2.4 ± 0.05	47 ± 0.6

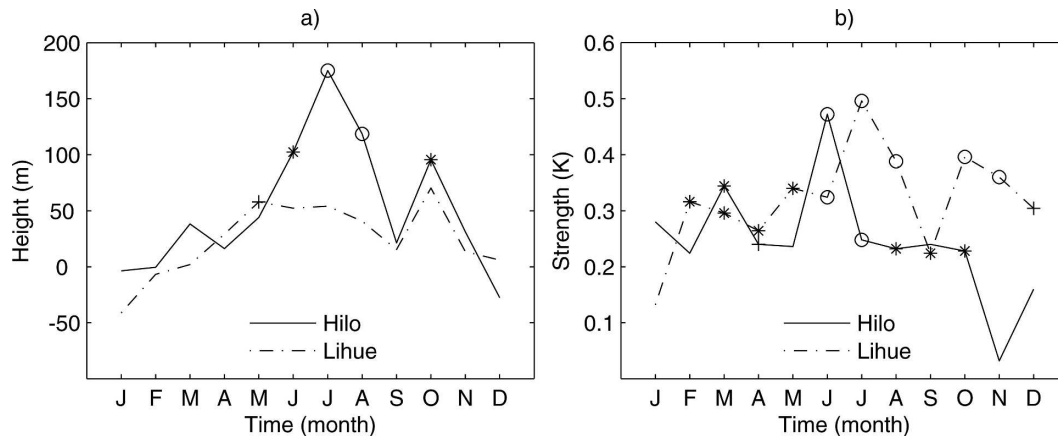


FIG. 3. The annual average monthly mean diurnal difference (0200 minus 1400 LT) for (a) inversion base height and (b) inversion strength at Hilo and Lihue, Hawai'i, during 1979–2003. The symbols $\circ$, $*$, and $+$ denote 0.05, 0.1, and 0.15 significance levels, respectively.

The fact that the diurnal cycle in inversion height at Hilo and Lihue is more pronounced during summer may be related to the cloud-top heating mechanism described above, simply based on the stronger solar heating cycle of summer. Additionally, as Rozendaal et al. (1995) describe for the North Pacific transition zone between stratiform and trade cumulus regions, the amplitude of the diurnal cycle varies with PBL depth. This observation was thought to be related to partial decoupling of the cloud layer from the surface and to the associated weakening of the inversion as the PBL deepens. Perhaps a similar process produces the observed seasonal change in the diurnal signal because, as shown below, the inversion over Lihue and Hilo is highest and weakest in summer.

c. Wavelet analysis

Figures 4 and 5 display wavelet analysis results for the monthly mean inversion base height time series for Hilo and Lihue, respectively. The time series of monthly standard anomalies over 25 years are plotted in Figs. 4a and 5a. Applying the TC method produces the wavelet power spectrum contour analysis at time scales spanning 0.25–16 yr shown in Figs. 4b and 5b. Figures 4c and 5c show the time-averaged wavelet power spectrum in relation to the 95% confidence interval for the corresponding red-noise spectrum (dashed line). Figures 4d and 5d give the spectrum variance time series computed by averaging variance contributions for periods between 0.5 and 2 yr (range selected to encompass all periods with significant wavelet power based on Figs. 4c and 5c).

In Figs. 4b and 5b, the wavelet power is highest at the annual period, as denoted by the two continuous white bands during 1981–88 and 1991–2002 at Hilo, and in a

continuous white band from 1980 to 2002 at Lihue. No other periods show pronounced power peaks. In the global spectrum (Figs. 4c and 5c) only the annual cycle is significant at the 95% confidence level. Figures 4d and 5d show that during most years there are significant contributions of variance within the 0.5–2-yr period (presumably coming mainly from the annual cycle). Albrecht (1984) suggested that the inversion base height is subject to the influence of sea surface temperature, large-scale divergence, surface wind, radiative cooling, and moisture and temperature above the inversion. Each of these variables has an annual cycle and, hence, each may contribute to the observed annual cycle in the inversion base height.

Wavelet power for longer-period oscillations falls out of the 95% confidence limit (Figs. 4c and 5c), failing to detect QBO or ENSO signals. Peaks are seen in the wavelet figure at about 2, 4, and 8 yr for Lihue, but all are below the confidence limit, indicating that the record is still too short to discern oscillations if they exist at these periods (Fig. 5c). Between 1979 and 2003 El Niño has recurred at intervals varying between 16 and 60 months, with an average of 39 months, perhaps making its influence difficult to detect using spectral analysis.

d. Annual cycle

Given the prominence of the 1-yr period in the spectral analysis, we examine the details of the annual cycle in this section. The mean annual cycle of inversion characteristics at Hilo and Lihue are plotted in Fig. 6. At both stations, the inversion base height reaches maxima in April and September and a minimum in January. For both stations, the inversion base height is significantly higher in April than each of the preceding five months

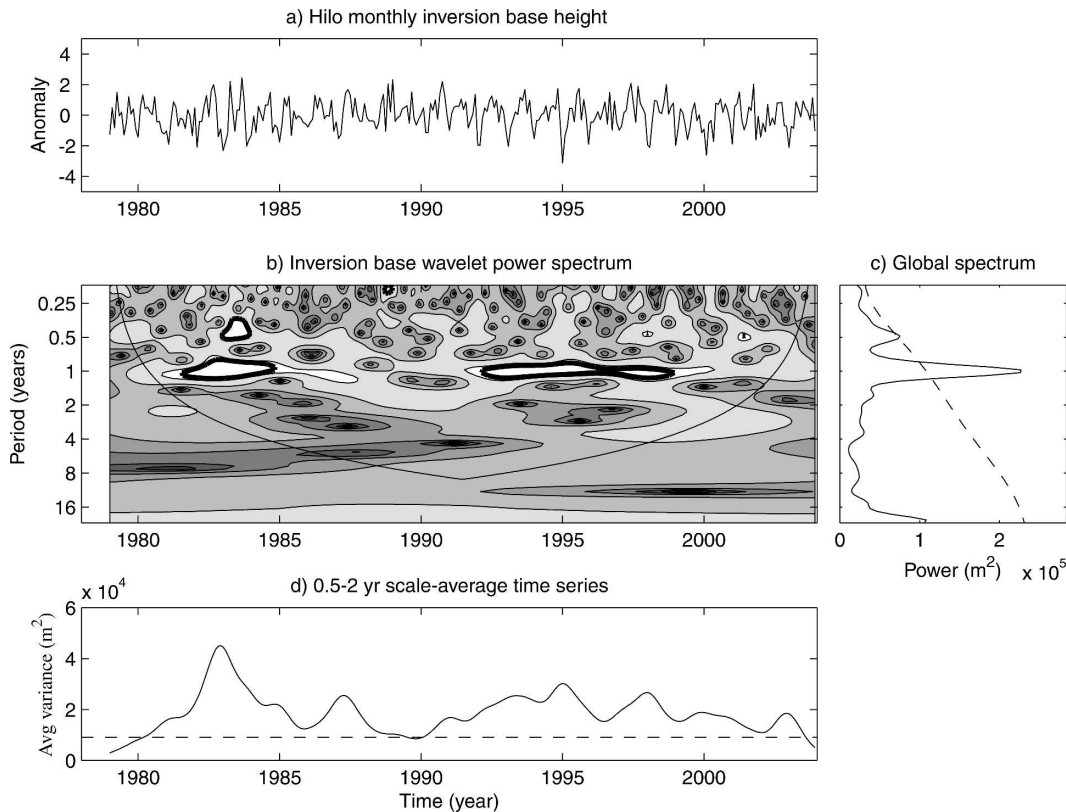


FIG. 4. Wavelet analysis results of the Hilo, Hawai'i, monthly inversion base height time series: (a) monthly inversion base height standard anomalies during Jan 1979–Dec 2003; (b) wavelet power spectrum; the value decreases as the color changes from white to dark; normalized variances of 1, 2, 5, and 10 separate the shaded contours; (c) global wavelet spectrum corresponding to (b) with the dashed line indicating the 95% confidence spectrum from a lag-1 autocorrelation coefficient 0.27; and (d) 0.5–2-yr scale average time series with thin dashed line indicating the 95% confidence level.

($p < 0.15$). The September maximum is significantly different from all months ($p < 0.05$ – 0.15) except August for Hilo and July, August, and October for Līhu'e. The large-scale circulation and thermodynamic properties of the inversion may explain the April and September peaks. In April and September, an upper-troposphere trough frequently sits over Hawai'i. The trough triggers associated low-level disturbances and enhances low-level convection, deepening the PBL. The trough moves west of Hawai'i beginning in May and becomes a stationary climatological feature there during the summer. In September, the trough moves back and weakens (Sadler 1975; Schroeder 1993).

The January inversion height at both sites is significantly lower than that of all other months ($p < 0.05$), except in February for both sites and March for Līhu'e only. This may be explained partly by the relatively low sea surface temperature, providing the least favorable conditions for low-level convection. During periods when Hawai'i is under the influence of the subtropical anticyclone, its more southerly January position favors

a lower inversion. Midlatitude cyclones frequently disturb the inversion during January, except during El Niño years when an enhanced Hadley cell circulation strengthens subsidence (Oort and Yienger 1996), lowering the inversion. As a result of these various influences, January inversion height also exhibits the highest year-to-year variability.

An annual cycle can be identified through wavelet analysis for inversion strength, but not for inversion thickness and humidity drop (not shown). At both sites, inversions are strong during winter and weak during August, September, and October ($p < 0.05$ – 0.15 , Fig. 6b). This apparent association between greater inversion height and lower inversion strength is consistent with Neiburger et al.'s (1961) finding on the spatial correlation between deeper PBL and weaker inversion.

e. Frequency of inversion occurrence

The overall frequency of inversion occurrence by base height is shown for Hilo and Līhu'e in Figs. 7a–b.

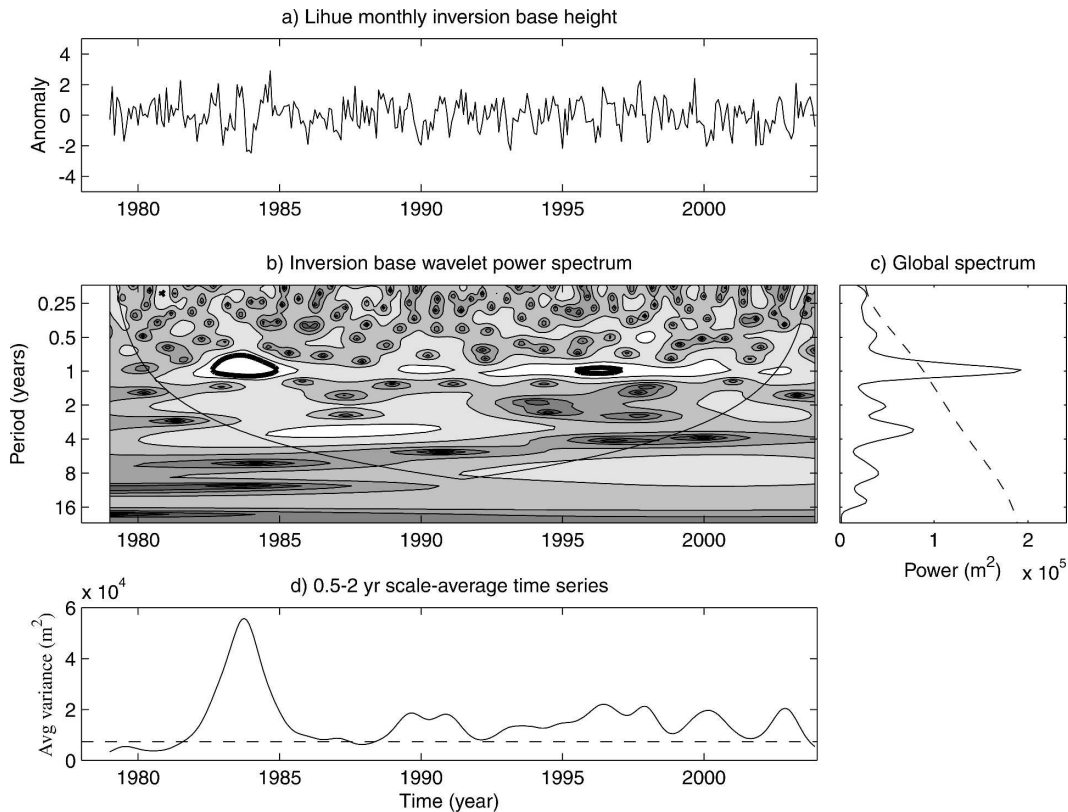


FIG. 5. As in Fig. 4 but for Lihue, Hawai'i. Monthly inversion base height time series lag-1 autocorrelation coefficient is 0.26.

The histograms show that the base heights of almost all inversions lie between 1000 and 4000 m. Changes in inversion base height during the year at Hilo and Lihue are depicted in Figs. 7c–d. At Hilo inversions between 1800 and 2300 m have the highest frequencies (over 20%) for all months except September. At Lihue the

highest frequency, over 20%, is found at a somewhat lower height range between 1600 and 2100 m. At both sites, inversions below 1500 m are more frequently observed during December–February (DJF; hereafter, 3-month periods are denoted by the first letter of each respective month) than during other months. Higher

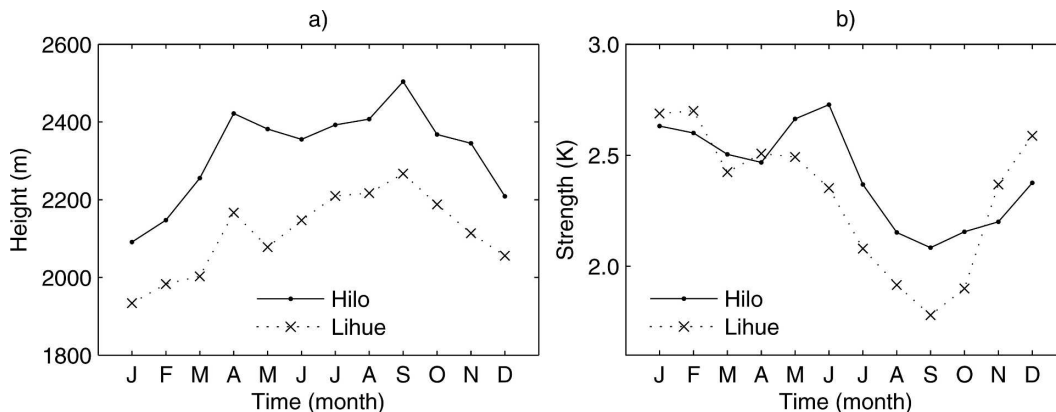


FIG. 6. Annual cycles of the (a) inversion base height and (b) inversion strength at Hilo and Lihue, Hawai'i, based on data from 1979–2003.

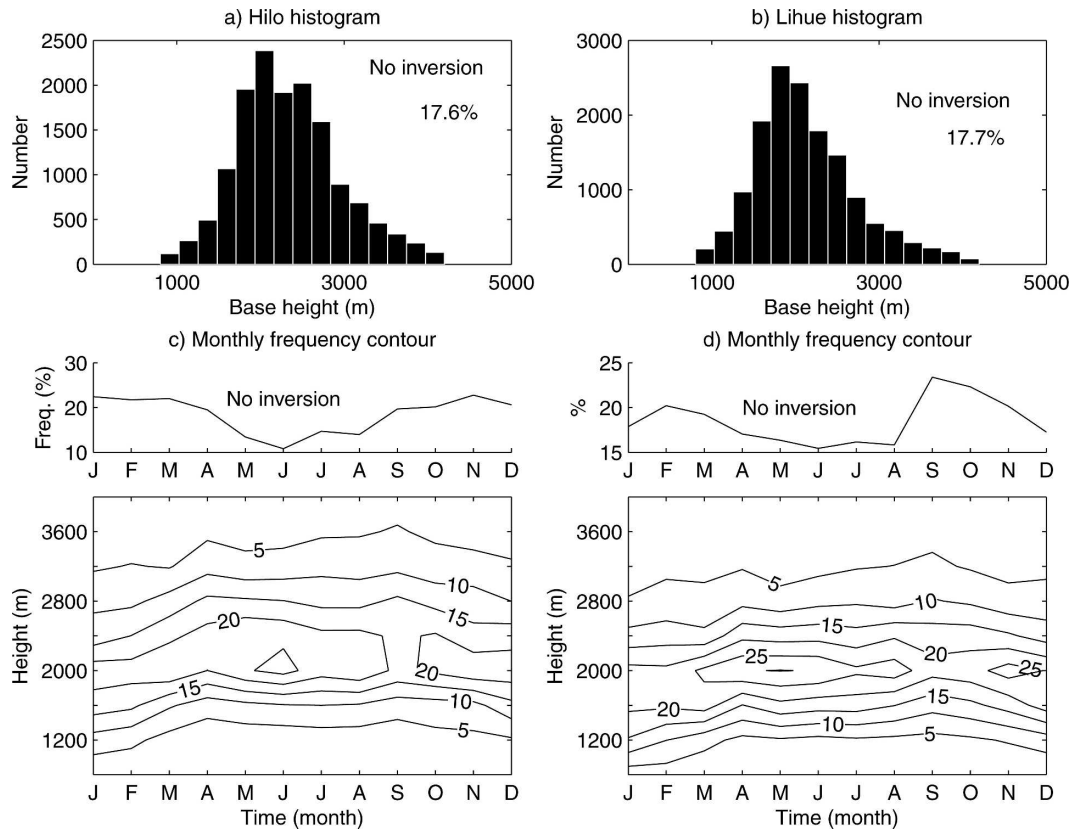


FIG. 7. Inversion base height histogram at (a) Hilo and (b) Lihue, Hawai'i, and monthly frequency contour plot at (c) Hilo and (d) Lihue, in which upper panels of (c) and (d) give the monthly frequency of the no-inversion days, and lower panels give the inversion base height frequency contours for days with inversions. Data are from sounding records during 1979–2003.

inversions more frequently appear in both April and September, in agreement with the mean annual cycle shown earlier (Fig. 6).

Occurrence frequency plots are also given for inversion strength and thickness (Fig. 8). Generally, both strength and thickness plots are similar for Hilo and Lihue. Three main features can be identified. First, the maximum frequency of occurrence for inversion strength and thickness, above 20%, occurs between 0 and 1 K and 100 and 200 m for both Hilo and Lihue (Fig. 8). Second, in each case the frequency of occurrence increases toward the bottom of the plot, which denotes the noninversion cases. From our earlier discussion, noninversion cases account for nearly 18% of the observed periods. Third, a significant portion of inversions, over 40% in total, have both strength greater than 1 K and thickness greater than 200 m. Betts and Ridgway (1989) used 20 hPa as the inversion thickness, which is very close to 200 m, according to the hypsometric equation, assuming a mean virtual temperature of 300 K for the lower troposphere. Regarding temporal characteristics, during June to December

0–1-K inversions are more common than during other months. Inversion strength above 6 K and inversion thickness above 500 m are very infrequent. These results differ somewhat from the inversion strength estimate of Riehl (1979) of about 1 K near Hawai'i.

f. Effects of El Niño

At Hilo, the inversion base height is lower during El Niño for January and February ($p < 0.15$) and higher for June ($p < 0.05$; Fig. 9). No significant effects of El Niño on inversion height are seen at Lihue. For both Hilo and Lihue, the frequency of inversion occurrence is higher during El Niño than non-El Niño years for December through April (except December at Hilo) at the 0.05 significance level and lower from May to September at significance levels between 0.05 and 0.1 (Fig. 10). It is puzzling that the occurrence frequencies of the two sites diverge in October. These results are generally consistent with the existing knowledge on the positive correlation between El Niño and winter drought in Hawai'i (Horel and Wallace 1981; Chu 1989). This relationship suggests that enhanced convection in the

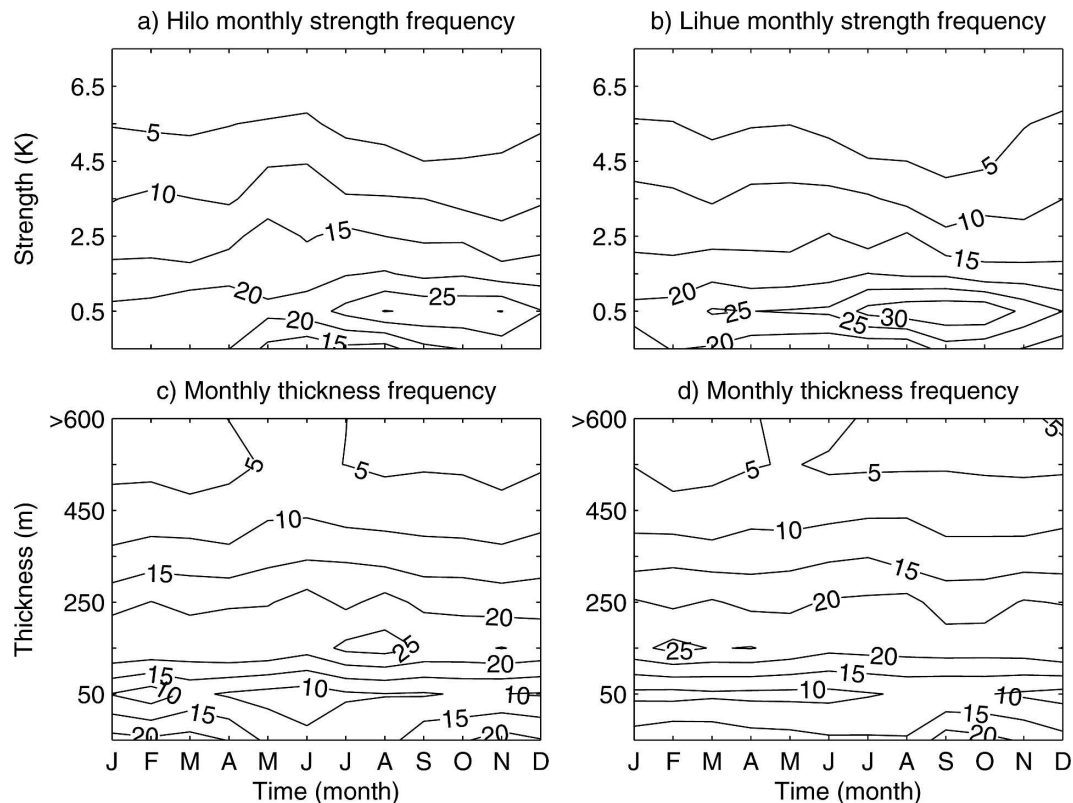


FIG. 8. The occurrence frequency of inversion strength at (a) Hilo and (b) Lihue, Hawai'i, and of inversion thickness at (c) Hilo and (d) Lihue. The bottom line in each plot denotes noninversion cases.

equatorial central Pacific during El Niño results in stronger and more persistent subsidence in the subtropics (Oort and Yienger 1996), producing lower inversions during January and February (at Hilo) and more frequent inversions during most winter months at both sites. The possible cause of significantly lower inversion frequency during summers of El Niño years is not obvious.

g. Inversion trends

One of the chief questions regarding the possible impacts of global warming on local climate in Hawai'i is

whether the TWI will be affected. If the height or frequency of the inversion changes due to warming, significant hydrological and ecological changes can be expected (Loope and Giambelluca 1998). This leads us to test for trends that may be evident during the 25-yr study period, a time during which significant warming has occurred globally and regionally. Based on annual averages, a weakly significant downward trend in base height is detected at Lihue ($p < 0.15$), while no trend is seen at Hilo (Table 4). A stronger downward trend in base height of 7.6 m yr^{-1} , significant at $p < 0.05$, is found for Lihue during the DJF season (Table 4). For

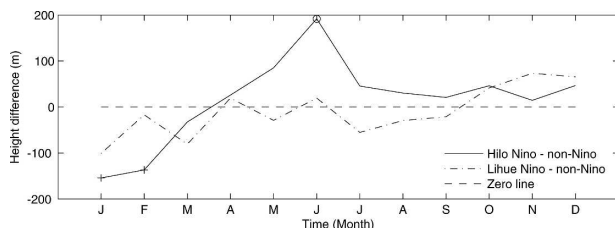


FIG. 9. Inversion base height difference between the composite El Niño monthly average and the 25-yr average at Hilo and Lihue, Hawai'i. The symbols $\circ$ and $+$ denote 0.05 and 0.15 significance levels, respectively, for the differences between the El Niño and non-Niño years.

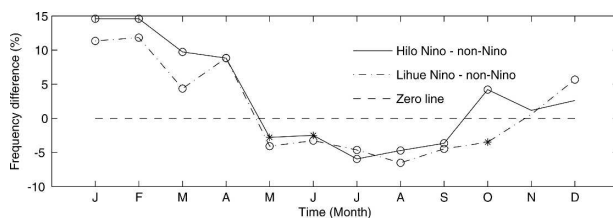


FIG. 10. Inversion frequency difference between the composite El Niño monthly average and the non-El Niño average at Hilo and Lihue, Hawai'i. The symbols $\circ$ and $*$ denote 0.05 and 0.1 significance levels, respectively.

TABLE 4. The linear regression statistics, adjusted for autocorrelation, for inversion base height at Hilo and Līhu'e, Hawai'i.

		Slope (m yr ⁻¹)	95% CI*	90% CI	85% CI
Hilo	Yearly	0.017	±4.383	±3.585	±3.094
	DJF	-2.374	±12.988	±10.494	±8.995
	MAM	-3.560	±3.911	±3.258	±2.840
	JJA	1.736	±4.522	±3.770	±3.287
	SON	4.033	±5.003	±4.159	±3.621
Līhu'e	Yearly	-2.122	±2.570	±2.132	±1.854
	DJF	-7.629	±6.774	±5.606	±4.868
	MAM	-2.567	±5.056	±4.208	±3.666
	JJA	-0.850	±4.942	±4.106	±3.573
	SON	2.334	±4.540	±3.781	±3.295

* CI: Confidence interval.

other seasons at Līhu'e, no significant trends were found. At Hilo, a downward trend was found for the MAM season ($p < 0.10$), and an upward trend was found for SON ($p < 0.15$). In general, the results for inversion height trends are weak and inconsistent (i.e., both downward and upward trends were found). Possible causes of this pattern are not obvious. In contrast, strong, consistent trends were found in inversion frequency (Table 5). Significant upward trends were found in inversion frequency for Līhu'e for the annual series and for all seasons ($p < 0.05$). Significant upward trends in frequency were also found for Hilo for MAM ($p < 0.05$), JJA ($p < 0.05$), and SON ($p < 0.15$).

We have no direct evidence that the observed trends in inversion base height or frequency are associated with climate warming. It is not known whether the Hadley circulation over the North Pacific will strengthen under a global warming scenario. An invigorated Hadley cell, which could explain a trend toward lower inversion base height, is contradicted by the results of Dai et al. (2001), showing that warming will weaken the Hadley cell circulation.

Our results on inversion frequency, suggesting that disruptions of Hadley cell subsidence over Hawai'i are becoming less frequent, may be consistent with the recent (Fyfe 2003; McCabe et al. 2001) and possible future (Yin 2005) warming-related poleward shifts in storm tracks. In Hawai'i (and possibly other locations near the poleward margins of the trade wind belts) disruptions of the TWI are mainly associated with upper-level troughs and accompanying surface low pressure systems (Schroeder 1977a,b). Occurrence of these disturbances near Hawai'i would likely decrease in frequency, at least for the winter months, were storm tracks to shift northward. However, it should be noted that the findings of McCabe et al. (2001) on storm

TABLE 5. As in Table 4 but for inversion occurrence frequency.

		Slope (% yr ⁻¹)	95% CI	90% CI	85% CI
Hilo	Yearly	0.534	±0.823	±0.660	±0.563
	DJF	0.683	±0.971	±0.799	±0.692
	MAM	0.690	±0.663	±0.548	±0.475
	JJA	0.432	±0.351	±0.290	±0.251
	SON	0.616	±0.800	±0.646	±0.553
Līhu'e	Yearly	0.939	±0.745	±0.591	±0.501
	DJF	1.100	±0.686	±0.567	±0.492
	MAM	0.758	±0.694	±0.563	±0.484
	JJA	0.968	±0.833	±0.674	±0.579
	SON	1.190	±0.430	±0.353	±0.305

tracks are not very robust, with a significance level at 0.1. Furthermore, the link between the inversion frequency trend and shifts in storm tracks may not be consistent with the possible association between El Niño and equatorward and eastward shifts in North Pacific storm (Straus and Shukla 1997; Compo et al. 2001).

4. Sensitivity analysis

Using each of the alternative inversion identification criteria discussed in the methods section, we recalculated the time series of inversion characteristic and retested each result presented above to determine the sensitivity of the results to the definition. The outcome of that procedure is summarized below:

Inversion properties: Alternative defining criteria produce significantly different ($p < 0.05$) basic inversion statistics, except for the *isothermal* alternative (Table 6). The frequencies of inversion occurrence recalculated using the four alternative criteria were 88.2%, 80.1%, 82.4%, and 86.4%, compared with the original estimate of 82.4% for Hilo. Similarly for Līhu'e, recalculated inversion frequencies were 89.6%, 79.8%, 82.3%, and 87.7%, compared with the original estimate of 82.3%. All inversion frequency estimates for both sites are significantly different from the original estimates ($p < 0.05$) except for the *multi-inversion* alternative (not significant for either site).

Diurnal differences: Despite the shifts in inversion properties, the diurnal differences for all characteristics previously tested (see Table 3) remain statistically significant at $p < 0.05$ for each of the alternative criteria.

Wavelet analysis: Repeating wavelet analysis for each alternative criterion, the annual cycles of inversion

TABLE 6. Mean inversion properties derived from different inversion selection criteria.

	Base height (m)		Thickness (m)		Strength (K)		Humidity drop (%)	
	Hilo	Līhu'e	Hilo	Līhu'e	Hilo	Līhu'e	Hilo	Līhu'e
Original								
Mean CI*	2255 ± 14.5	2076 ± 12.5	281 ± 4.0	282 ± 3.5	2.4 ± 0.04	2.3 ± 0.04	46.8 ± 0.55	50.4 ± 0.45
Isothermal								
Mean CI	2239 ± 14.5	2056 ± 13.0	294 ± 4.0	296 ± 3.5	2.5 ± 0.04	2.4 ± 0.04	49.4 ± 0.55	52.9 ± 0.45
Superadiabatic								
Mean CI	2286 ± 15.5	2130 ± 14.0	265 ± 4.0	267 ± 3.5	2.2 ± 0.04	2.1 ± 0.04	41.1 ± 0.60	45.1 ± 0.50
Multi-inversion								
Mean CI	2142 ± 14.0	1974 ± 12.5	271 ± 4.0	271 ± 3.5	2.4 ± 0.04	2.2 ± 0.05	44.3 ± 0.55	47.5 ± 0.50
All								
Mean CI	2119 ± 16.5	1966 ± 14.5	268 ± 4.5	269 ± 4.0	2.3 ± 0.05	2.1 ± 0.05	40.3 ± 0.70	44.3 ± 0.65

* CI: the 95% confidence interval.

base height and strength remain prominent in all cases.

Annual cycle: Mean monthly inversion base height calculated for each of the alternative criteria are shown in Fig. 11. Annual cycles are largely unchanged except for uniform upward or downward shifts.

Effects of El Niño: Repeating the analysis of El Niño effects on inversion base height for the alternative

defining criteria resulted in changes from the original results (from significant to nonsignificant) only at Hilo during January and February for the *multi-inversion* alternative and during June for the *all alternatives* case. Alternative criteria yield results similar to the original definition for the difference in frequency of inversion occurrence during El Niño events except for a change from significant to nonsignificant for at least one alternative defini-

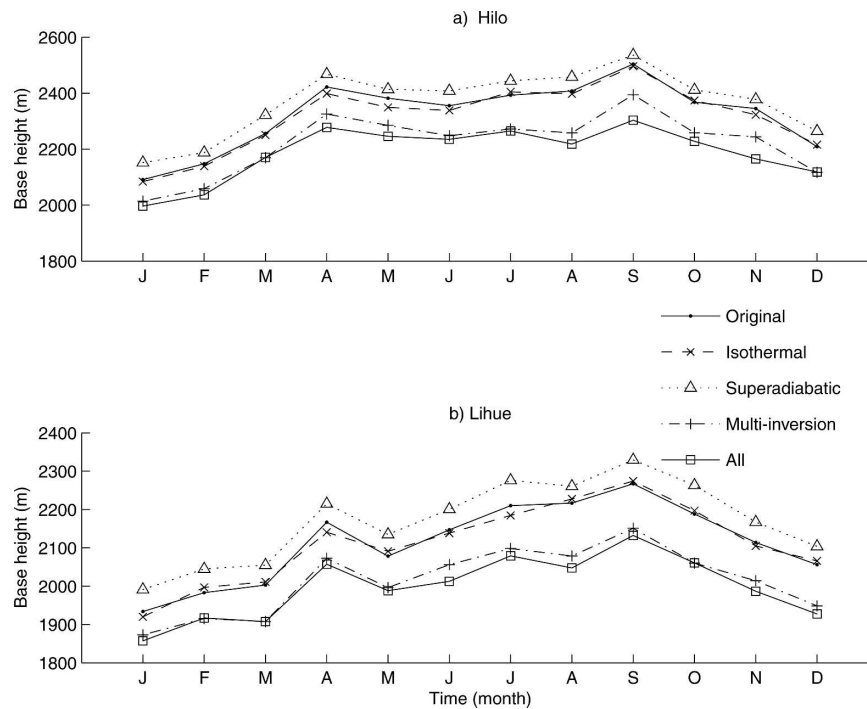


FIG. 11. Annual cycles of the average monthly mean inversion base height under different inversion selection criteria for (a) Hilo and (b) Līhu'e, Hawai'i, in which the legend "Original" denotes the annual cycle in Fig. 6a, and *isothermal*, *superadiabatic*, *multi-inversion*, and *all* refer to alternative TWI criteria (see text).

tion for May, June, August, and September at Hilo and for March, August, and December at Līhu'e.

Inversion trends: Retesting trends in inversion base height, resulted in all previously significant trends (see Table 4) becoming nonsignificant for at least one of the alternative defining criteria. Conversely, for the trends in frequency of inversion occurrence, alternative criteria produced results nearly identical to the original definition (see Table 5).

We note that differences among the altered TWI criteria have magnitudes exceeding those of the detected differences and trends in the original analysis. This may appear to weaken confidence in these findings. However, with the exception of weakly significant trends in base height which were not upheld by these tests, alternative criteria generally produce consistent shifts in monthly TWI characteristics, either upward or downward. Hence, each outcome remained parallel to that of the original definition, resulting in relatively few changes in differences or temporal trends. We identify as robust those differences and trends found to be insensitive to the choice of defining criteria, as described above.

5. Conclusions and suggestions

Based on the analysis presented in this paper, we can make the following conclusions regarding the TWI over Hawai'i:

- Mean inversion characteristics for Hilo and Līhu'e, respectively, are frequency of occurrence: 82.4% and 82.3%; base height: 2255 and 2076 m; thickness: 281 and 282 m; and strength: 2.4 and 2.3 K.
- The finding that the inversion base is higher at Hilo than Līhu'e, not previously reported in the literature, may reflect a general spatial variation across the region or may be the result of local topographic effects.
- Inversion base height at Hilo and Līhu'e are correlated at the monthly time scale, suggesting that the atmospheric circulation and SST variations that produce month-to-month changes in the inversion are of a large enough spatial scale to affect all the major Hawaiian Islands simultaneously.
- On average, daytime inversion base height is 54 m lower at Hilo and 27 m lower at Līhu'e than the nighttime inversion base; these diurnal differences are more consistent during the summer at Hilo, while at other times and at Līhu'e high day – night differences are more variable.
- A strong annual cycle was detected in inversion base height at both sites.
- At both sites, inversion base height maxima occur in April and September and the minimum occurs in January.

- Most inversions are found between 1000 and 4000 m; inversions below 1500 m are more frequent during December through February than during other seasons.
- High inversions are more frequent during both April and September.
- Based on the original inversion definition, inversion base height was found to be significantly lower during El Niño for the months of January, February, and June. However, in the sensitivity analysis, each of these differences was found not significant for at least one alternative definition. No significant effects of El Niño on inversion height are seen at Līhu'e.
- Inversion occurrence frequency is significantly higher at both sites than average during El Niño events for the months of December through April, except for December at Hilo, and significantly lower at both sites for the months of May through September. Sensitivity analysis subsequently called into question the results for May, June, August and September at Hilo, and March, and August for Līhu'e.
- Significant downward trends in annual and December–February inversion base heights were found at Līhu'e but were not sustained by all alternative defining criteria. Similarly for Hilo, a downward trend in MAM inversion base height and an upward trend in SON base height were significant for the original inversion definition, but were not significant for one or more alternative defining criteria.
- Significant upward trends were found for inversion frequency at Hilo for MAM, JJA, and SON seasons and at Līhu'e for all seasons and for annual values. These trends were consistently found regardless of the inversion definition criteria.

Our finding that the inversion is present more than 82% of the time illustrates the importance of the TWI at Hawai'i, especially considering that it acts as a dominant control on local weather and climate (e.g., Schroeder 1993). It is known that the relatively shallow vertical cloud development below the TWI results in less precipitation than would occur in the absence of an inversion. Orographic rainfall on high mountain slopes is strongly influenced by the presence of the inversion (Tran 1995).

While we have no direct evidence that the observed inversion trends are associated with climate warming, increasing inversion frequency may be consistent with a link between a warming-related poleward shift in storm tracks (Fyfe 2003; McCabe et al. 2001; Yin 2005) and a possible declining frequency of disruptions of Hadley cell subsidence over Hawai'i. However, this connection is speculative and may not be consistent with related

findings regarding shifts in storm tracks associated with El Niño (Straus and Shukla 1997; Compo et al. 2001). Alternatively, the apparent trends may represent an incomplete sample of a longer period oscillation, such as the Pacific decadal oscillation (PDO) (Barnett et al. 1999). However, should they prove to be indicative of long-term trends, the observed frequency changes would indicate a shift toward drier conditions for Hawai'i. A more frequent inversion would extend limits on vertical cloud development and rainfall in Hawai'i. Consequently, Hawaiian mountainous tropical ecosystem and water resources would be affected.

The findings presented here can serve as a basis for testing current efforts to improve the PBL parameterization in weather and climate prediction models and provide an impetus for further research on the variability and future changes in inversion characteristics. Our results are based entirely on data derived from soundings at the two Hawai'i sites, both of which may be influenced by local topographic and thermal effects. In future work, we intend to apply the Weather Research and Forecasting (WRF) model to examine spatial and temporal inversion patterns, determine the causes of the observed diurnal and year-to-year variability in the inversion, and test hypotheses regarding the possible influences of climate warming.

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