11.8 A CLIMATOLOGICAL STUDY OF THE KEETHCH/BYRAM DROUGHT INDEX IN THE HAWAIIAN ISLANDS

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1. INTRODUCTION

The Hawaiian Islands have unique and varied microclimates. The localized nature of these microclimates means that they will be affected differently by the larger-scale climatic influences of the region. Included in the principal large-scale climate controls are the position of the islands on the earth's surface, the trade winds, wintertime mid-latitude storms, subtropical storms, and infrequent tropical disturbances (Schroeder, 1993). The island's microclimates are primarily due to the topographical influences of large and small mountains upon the prevailing trade winds. Because of the variety of climates found on the islands, long-term prediction of fire potential is a challenging task for Hawaiian fire managers.

Deficiencies in rainfall can lead to a variety of problems for the Hawaiian Islands (Giambelluca and Sanderson, 1990). One of the problems associated with deficient rainfall is that of wildfires. Although major wildfires in Hawaii are not as large as they are in the western United States, they still pose a significant threat (Chu et al., 2002). It is therefore desirable to create or identify a fire index that may help predict long-term and short-term wild-land fire activity.

Although the Keetch/Byram Drought Index (KBDI) has been used for over thirty years, there has not been an extensive study of its relationship to drought/climate patterns. This paper analyzes the KBDI and its application to fire activity in the Hawaiian Islands. Section two describes the KBDI at length. Sections three and four discuss the methods and data, respectively. Section 5 describes the annual and the long-term cycles of KBDI. The atmospheric circulation patterns for composites of extreme KBDI values are also discussed. Section six summarizes the results.

2. THE KEETCH/BYRAM DROUGHT INDEX

The KBDI, which conceptually describes the soil moisture deficit, is used to assess wildfire potential as part of the U.S. National Fire Danger Rating System (Heim, 2002). In the southeast U.S., the KBDI is used as a stand-alone index for assessing fire danger (Johnson and Forthum, 2001). The KBDI values range from 0 to 800, with 800 indicating extreme drought and 0 indicating saturated soil. The initialization of the KBDI usually involves setting it to 0 after a period of substantial precipitation (Fujioka, 1991). The KBDI, Q, depends on daily rainfall amounts (inches), daily maximum temperature (degrees Fahrenheit), and the mean annual rainfall (inches). The drying factor is increased with higher daily temperatures. The drought index is defined as, "a number representing the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff or upper soil layers" (Keetch and Byram, 1968). The equation for computing the incremental rate of change dQ, is

$$dQ = [800-Q][0.968\exp(0.0486T) - 8.30]dt * 0.001 / [1+ 10.88\exp(-0.0441R)]$$

where T is the daily maximum temperature, R is the mean annual rainfall, Q is the current KBDI, and dt is a time increment set equal to one day.

Note that the temperature factor has no effect unless the day's maximum temperature is above 50 ^{0}F (10^{0}C). If the net accumulated precipitation exceeds 0.20 inch, the excess reduces Q linearly.

The physical theory for the KBDI is based on a number of assumptions. The first assumption is that soil moisture is at field capacity with a water depth equivalent of 8 inches. The second assumption is that the rate of moisture loss in an area depends on the vegetation cover in that area, and vegetation density (and therefore its transpiration capacity) is a function of mean annual rainfall. Hence, daily transpiration is approximated by an inverse exponential function of the mean annual rainfall. Finally, the evaporation rate of soil moisture with time is assumed to be an exponential function of the daily maximum temperature (Keetch and Byram, 1968).

3. ANALYSIS METHODS

Harmonic analysis is used to determine the annual (first Fourier harmonic) and semi-annual (second Fourier harmonic) cycles of climatological monthly mean KBDI. The analysis includes the calculation of the amplitude, phase angle, and portion of variance at each harmonic (e.g., Lee et al., 1998). Spectral analysis is used to help identify periodic tendencies in the KBDI at different stations. Because stations show a pronounced annual cycle, this cycle is removed by subtracting the long-term monthly mean KBDI value from the individual monthly mean KBDI. The Parzen lag window is used to smooth the sample spectrum (Chu and Katz, 1989). Statistical significance of spectral estimates are tested against a Markov red-noise process at the 90 percent and 95 percent confidence limits, respectively, because atmosphere time series generally

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contain persistence. A second check of the local significance is applied using a randomly generated red-noise series with the same lag one auto-correlation as the data being tested. This simulation is repeated in 10,000 trials and the local significance at each frequency band is tested. A band-pass filter (Murakami, 1979) is also employed to compare two time series.

4. DATA

Daily precipitation and temperature data from 27 stations were obtained from the Western Regional Climate Center in Reno, Nevada. Most stations had 35 years of reliable data. A few stations contain shorter records because of insufficient data. After the daily values of the KBDI were calculated, we also computed the monthly average.

Surface pressures, surface winds, 200 hPa winds, and 500 hPa geopotential heights were obtained from the NCEP/NCAR Reanalysis data product. The variables were analyzed on a 2.5 by 2.5 degree grid from 0 to 60^0 N and from 165^0 E to 120^0 W

5. RESULTS

a. Harmonic analysis of a drought index

Having tested the relevance of the KBDI to fire data (Dolling et al., 2003), it is important to find the climatological time of year at which the KBDI reaches its peak value. This will correspond to the time of the expected highest fire danger. The islands of Hawaii have varied topography which affect the local rainfall cycles. The localized nature of the climate in the islands should also affect the KBDI.

Because the annual cycle in KBDI is very similar for the northernmost islands, they will be discussed as a group. These islands include Kauai, Oahu, Molokai, Lanai, and Maui (Fig. 1). The island of Hawaii with its large mountains will be discussed separately

The annual cycle of KBDI on the islands of Kauai, Oahu, Molokai, Lanai, and Maui although similar, show distinct patterns. Stations can be separated into either leeward or windward stations with regards to the prevailing northeast trade winds. Leeward stations (e.g., Kekaha on Kauai, Waikiki on Oahu, Lahaina on Maui) have a strong annual cycle as seen by their high portion of variance accounted for by the first harmonic. These stations have portions of variance above 90%. They also tend to have large amplitudes and standard deviations, which is similar to the annual cycle of rainfall (not shown). Wet, cooler winters and dry, warmer summers are normal for these sites. Another interesting feature is in the phase of the leeward stations (Fig. 1 and 2). Figure 2, a harmonic dial, depicts the phase and amplitude of the annual cycle for all 27 stations. There tends to be a gradual shift in phase to later in the year as one travels from northwest to southeast (i.e., from Kauai to Maui). This shift in phase corresponds to a change in the peak dry period for each station. The peak phase of these stations concentrates in a short time window from September to early October. Not surprisingly, this time of maximum in KBDI is coincident with the phase of maximum sea surface temperatures in the vicinity of the Hawaiian Islands (Horel, 1982).

Windward stations (e.g., Kaneohe Mauka on Oahu, Hana Airport on Maui) have lower portions of variance accounted for by the first harmonic and smaller amplitudes and standard deviations. Many windward stations show three peaks in rainfall, with two maxima in cool season (November and March) and a third maxima in summer. This helps account for the absence of either strong annual or semi-annual cycles in the KBDI. The wintertime decline in rainfall (i.e., Jan/Feb) is due to less frequent trade winds. In addition, the upper level atmospheric trough which is located west of the islands usually shifts to east of the islands in February, positioning the island chain in an area of increased subsidence (Giambelluca and Sanderson, 1993). Along with a summertime relative maximum in rainfall, due to more persistent trade winds, windward stations tend to display shifts in phase to earlier in the year (Fig. 1 and Fig. 2). Overall, the annual cycle in the KBDI lags the annual cycle in rainfall (not shown) by about one to three months

The largest Hawaiian Island, and the most interesting, is the island of Hawaii (Big Island). Two main peaks, Mauna Loa (13,677 ft.) and Mauna Kea (13,796 ft.), dominate the landscape. As displayed in Fig. 1, Hilo airport, Kulani Camp, and Hawaii Volcanoes National Park are located on the windward side of the island (i.e., on the eastern slope of Mauna Kea). Much of the rainfall in this area results from thermally driven mountain-valley winds interacting with trade winds and reinforced by land-sea breezes (Chen and Nash, 1994). There are three maxima in rainfall found at these stations, one during the summer, one during late fall, and one in early to mid-spring. This accounts for the unusually low portion of variance accounted for by the first harmonic (e.g., Hilo = 2.4%, Kulani Camp = 14.4%).

Kainaliu has a strong annual cycle with 95.7% of the variance accounted for. However, the peak phase has a 180-degree shift relative to most other sites with the driest period on or around March 5. Located to the west of Mauna Loa (Fig. 1), it is likely that the site is shielded from the winter precipitation that comes from the southeast.

b. Spectral analysis of a drought index

One long-term cycle of interest on Kauai is an eighteen to twenty-month cycle at Lihue Airport (Fig. 3a). It is significant at the 90% confidence level (dashed line represents 95% confidence limit and dotted line represents 90% level). This cycle, which is approximately twenty-months, is interesting because it exists on some of the other islands, but not at other Kauai stations. On the island of Oahu, all three stations on the south shore (Honolulu Observatory, Honolulu WSFO Airport, and Waikiki) have cycles in the twenty-month range with Honolulu Airport (Fig. 3b) being marginally significant at the 95% confidence level. All three also have cycles of forty to fifty-months. These cycles are probably attributed to an El Niño signal. However, none of these signals were significant at the 90% confidence level.

The Big Island and Maui are the most interesting. Four of the five stations on Maui have pronounced eighteen to twenty-month cycles. Hana Airport (Fig. 3c) is a good example with the twenty-month cycle being significant at the 95% confidence level. The energy spectrum is also concentrated at the very low frequency end, reflecting trend behavior. There is large variability among different stations on the Big Island. A total of five out of nine stations have pronounced eighteen to twenty-month cycles, all significant at the 90% level. These stations include Hawaii VLNP, Naalehu, Mauna Loa Slopes Observatory, Opihihale and Upolu Point USCG. For Naalehu, the most interesting signal is a forty to fifty-month signal (Fig. 3d), marginally significant at the 90% level.

Another way to view these stations is to separate them into leeward and windward sites. Windward sites show pronounced eighteen to twenty-month and twelve-month cycles. Hana Airport (Fig. 3c) is an example of a typical windward site. Leeward sites have pronounced eighteen to twenty-month and nine-month cycles, but do not show cycles in the twelve month range. Some leeward sites also have cycles in the forty to fifty-month range. Honolulu Airport (Fig. 3b) is an example of a typical leeward site.

c. Band-pass filter of KBDI series

In order to determine whether the KBDI series is related to El Niño, a 36-60 month band-pass filter is applied to Naalehu and Niño 3.4 index series (Fig 4). There appears to be a very strong relationship between the two variables with KBDI lagging the El Niño index during the 1980's and 1990's. Interestingly, there is no lag during the late 1960's and 1970's. The same band-pass was applied to the stations of Honolulu Airport, Honolulu Observatory, Waikiki, and Lahaina (not shown). Each shows a strong relationship between the drought index and the Niño index.

d. Atmospheric circulation patterns during extreme drought index events

An exploration of atmospheric circulation patterns associated with extremely high and low KBDI is warranted. This will hopefully lead to the recognition of circulation patterns which have known origins, therefore leading to a better understanding of the large-scale atmospheric conditions that occur during times of increased fire activity.

In a companion study (Dolling et al., 2003), four reference stations were chosen (Kekaha, Honolulu Airport, Lahaina, and Naalehu). These are the driest stations for each of the four main islands. A composite is made to eliminate any local variability. Kekaha, Kauai does not have a complete record and is not included. The remaining three stations are correlated and Naalehu has a much lower Pearson correlation value with Honolulu Airport and Lahaina than either station has with the other. Previously, it was shown that Naalehu also displayed attributes of windward stations. Therefore it is not included in the subsequent composite analysis. This leaves only Honolulu Airport and Lahaina as reference stations for the composite. The upper (75^{th} percentile) and lower (25^{th} percentile) quartiles of KBDI at these 2 stations are determined. Anomalous surface pressures, surface winds and divergence, 500 hPa geopotential heights, and 200 hPa winds are investigated for each season for both the upper and lower quartiles.

At leeward stations the time of peak KBDI is in early fall (Fig. 2). Due to the high persistence of the time series (lag one auto-correlation is 0.85), the focus will be on the wettest season, winter. Investigation of circulation patterns during this rainy season may provide potential predictability of the KBDI for the following fall. For the upper quartile of KBDI, the anomalous winter upper air circulation pattern displays an anomalous upper-level anticyclone centered just west northwest of the island chain. The corresponding surface wind and divergence chart (Fig. 5a) displays an anomalous surface anticyclone in the same area with high levels of anomalous divergence located directly over the island chain. The lower quartile has the opposite pattern, with an anomalous upper (not shown) and lower level cyclonic circulation centered just west of the island chain, as well as anomalous surface convergence over the Hawaiian Islands (Figs. 5b). For both upper and lower quartiles, the anomalous surface pressure and 500 hPa geopotential heights support the anomalous equivalent barotropic structure throughout the troposphere.

6. SUMMARY

Harmonic analysis was used to find what times of the year have the highest KBDI at each station in the Hawaiian Islands. This information was important because it should correspond to times in which the fire danger is highest for respective stations. To summarize the results of the analysis, a harmonic dial includes the phase and amplitude of the annual cycle for all 27 stations (Fig. 2). There is a gradual clockwise turning of the harmonic dials when viewing from northwest to southeast. This represents a shift in the KBDI maxima from early September to early October and is due to progressively later winter time precipitation maxima. Exceptions to the gradual phase shift were present. These occur at windward stations that receive higher precipitation during the more consistent summertime trade winds and have a double maximum in the cool season (late fall and early spring). These stations (e.g., Hana on Maui and Kaneohe Mauka on Oahu) tend to show a shift in phase to earlier in the year. They also have a smaller amplitude of the annual cycle because they do not tend to dry out as much during the warmer summer months as compared with the drier leeward stations. One other important exception is on the leeward side of the island of Hawaii. Two stations, Kainaliu and Opihihale, have peak KBDI numbers in late winter and mid-spring. These results showed distinct similarities to the annual cycle of rainfall. The major difference was that the KBDI lags the annual cycle of rainfall by about one to three months.

Spectral analysis revealed some unexpected cycles. Leeward sites had pronounced cycles at eighteen to twenty-months and nine-months. Leeward stations also had spectral peaks in the forty to fifty-month range. A band-pass filter was used to support the link between

El Niño and these leeward stations. Windward stations showed no evidence of the forty to fifty-month cycle. A test with the same band-pass filter confirmed that windward stations did not display the same strong link with El Niño as leeward stations. Windward stations did however show pronounced cycles at eighteen to twenty-months and twelve-months. Interestingly, the eighteen to twenty-month cycle was prevalent at most stations while the forty to fifty month cycle was only evident at leeward stations.

Departure patterns of atmospheric circulations over the North Pacific were investigated for composites of extremely high and low KBDI values during winter. The anomalous surface winds exhibited anomalous anticyclonic (cyclonic) circulations and anomalous divergence (convergence) over the islands for the upper (lower) quartile of KBDI. Interestingly, the winter composite of the 200 hPa winds for the upper quartile of KBDI seems to have similarities to the expected circulation during the winter following an El Niño event.

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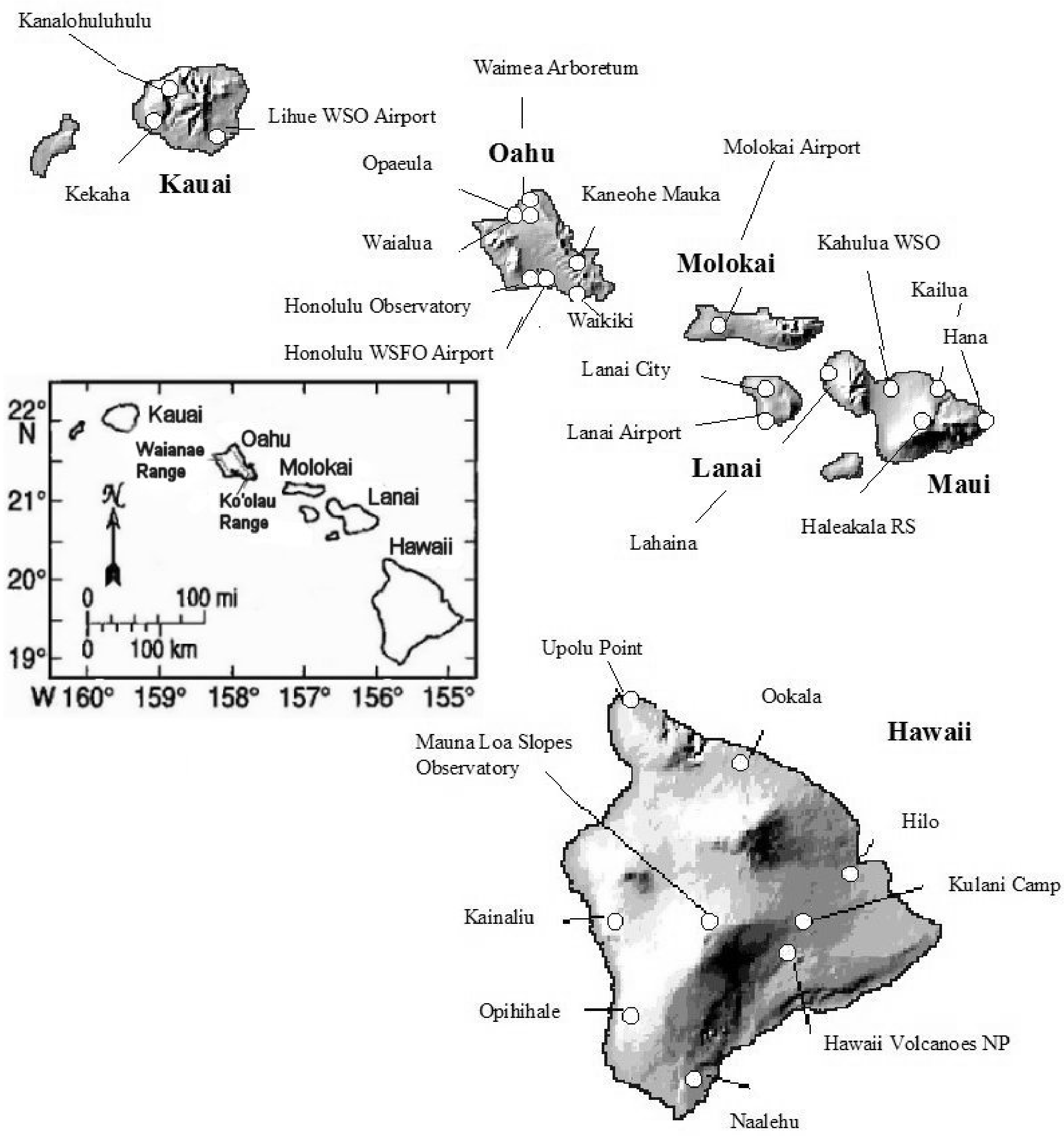

Figure 1. Map of the Hawaiian Islands and the 27 stations used for this study.

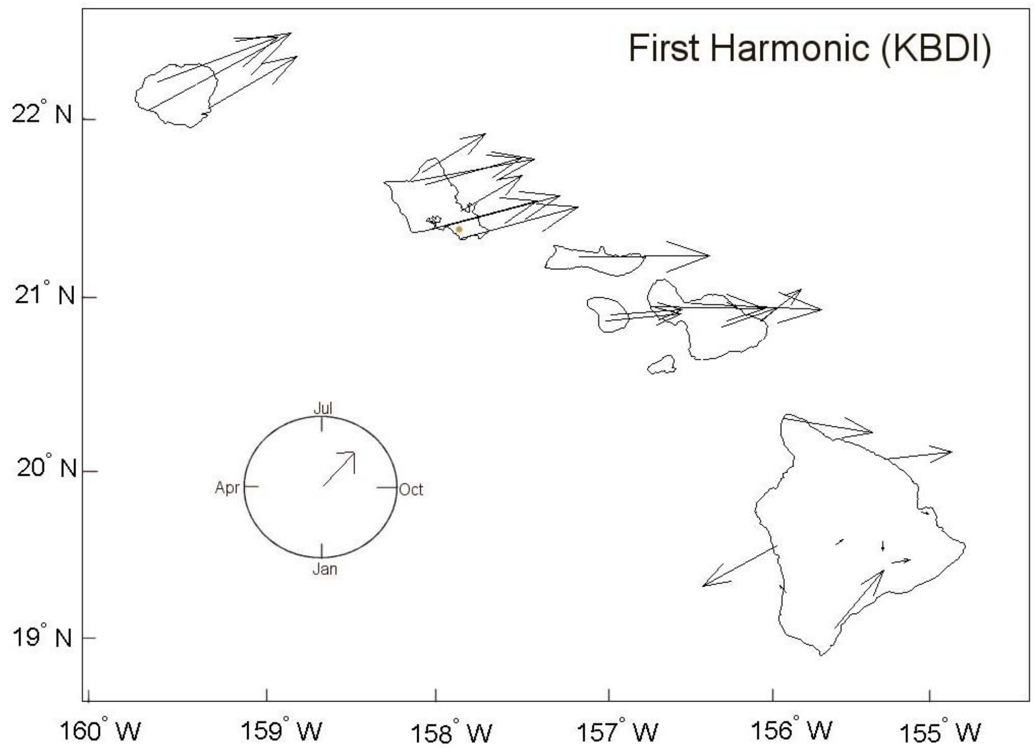

Figure 2. Harmonic dial showing the phase and amplitude for the first harmonic of the monthly mean KBDI data for 27 stations. Length of the dial corresponds to the amplitude. The direction corresponds to the phase. An arrow pointing from the top of the page indicates a maximum KBDI on 1 January; from the right margin a maximum on 1 April, etc.

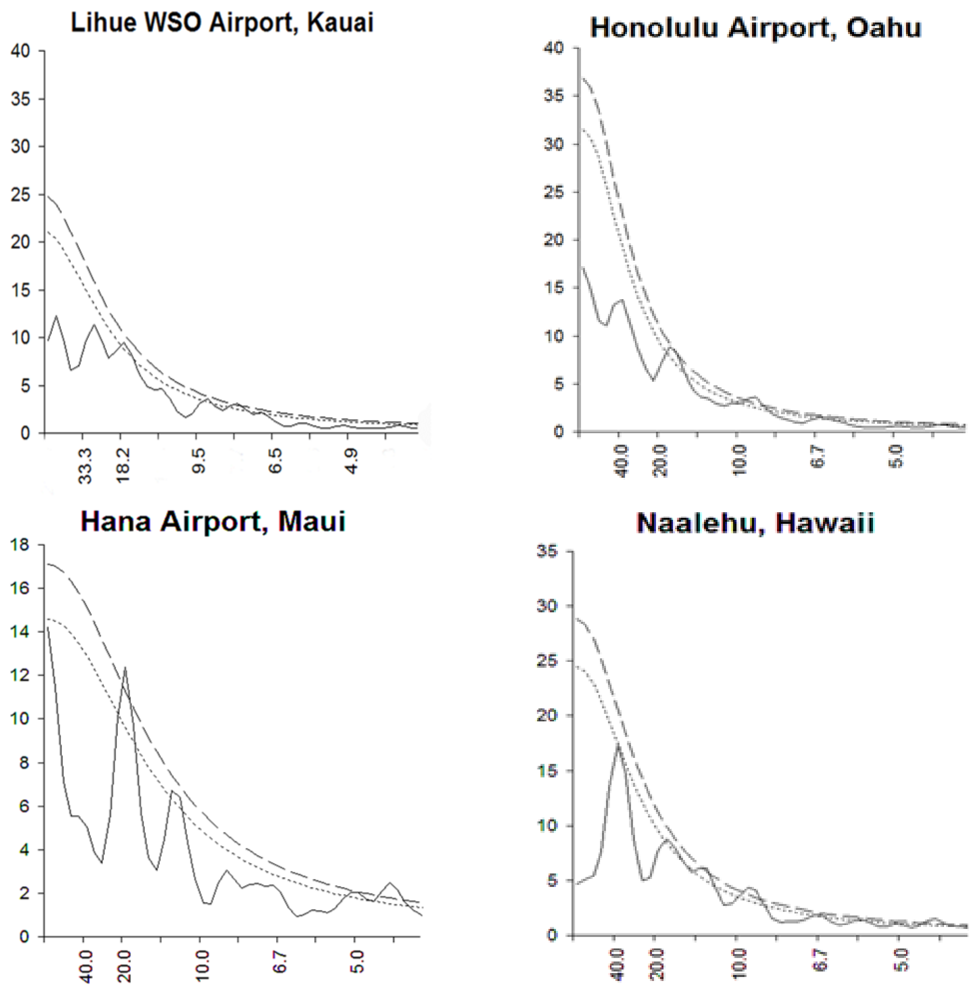

Figure 3. Spectral analysis of monthly mean KBDI data. The annual cycle is removed. The y-axis is a spectral density function and the x-axis is in months. Dashed and dotted lines represent the red-noise test with 95 and 90 percent confidence levels, respectively. (a) Lihue WSO Airport, Kauai (1966-2000), (b) Honolulu Airport, Oahu (1966-2000), (c) Hana Airport, Maui (1966-2000) and (d) Naalehu, Hawaii (1966-2000).

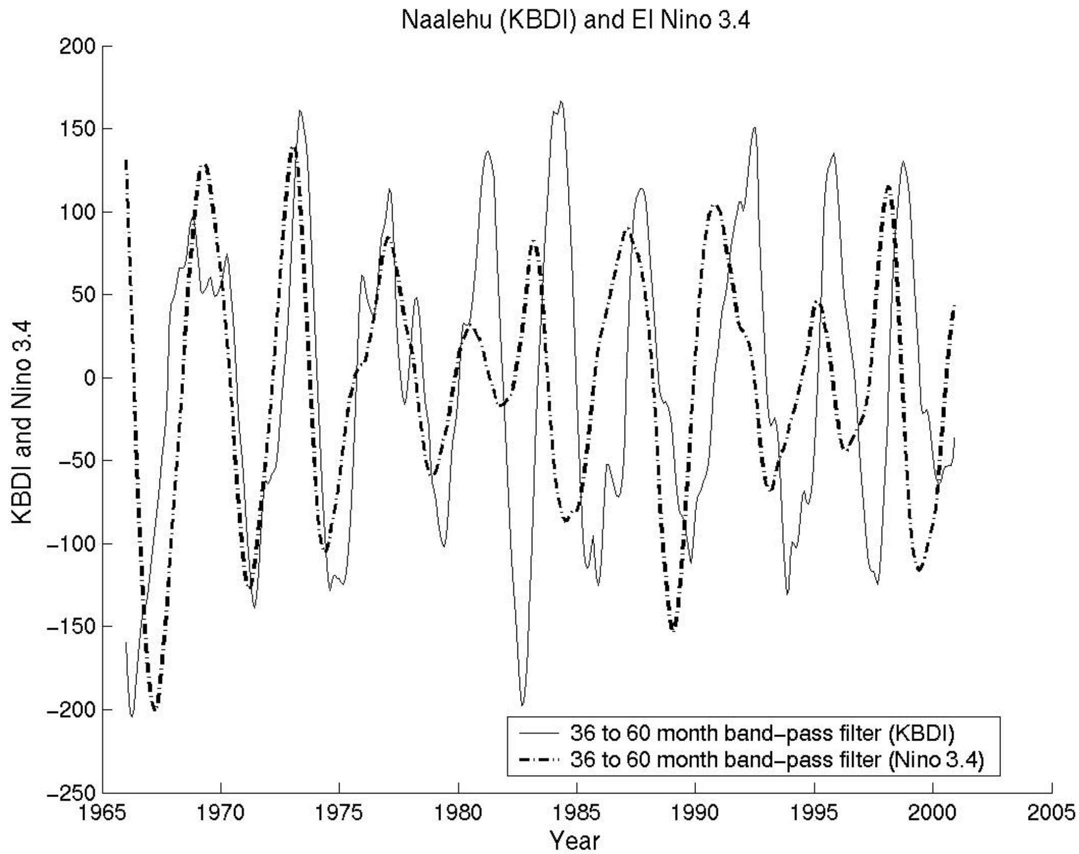

Figure 4. Band-pass filter of KBDI anomalies for Naalehu, Hawaii and anomalous Niño 3.4 index. The Niño 3.4 index is scaled by a factor of one hundred. Time series consists of thirty-five years of data (1966-2000).

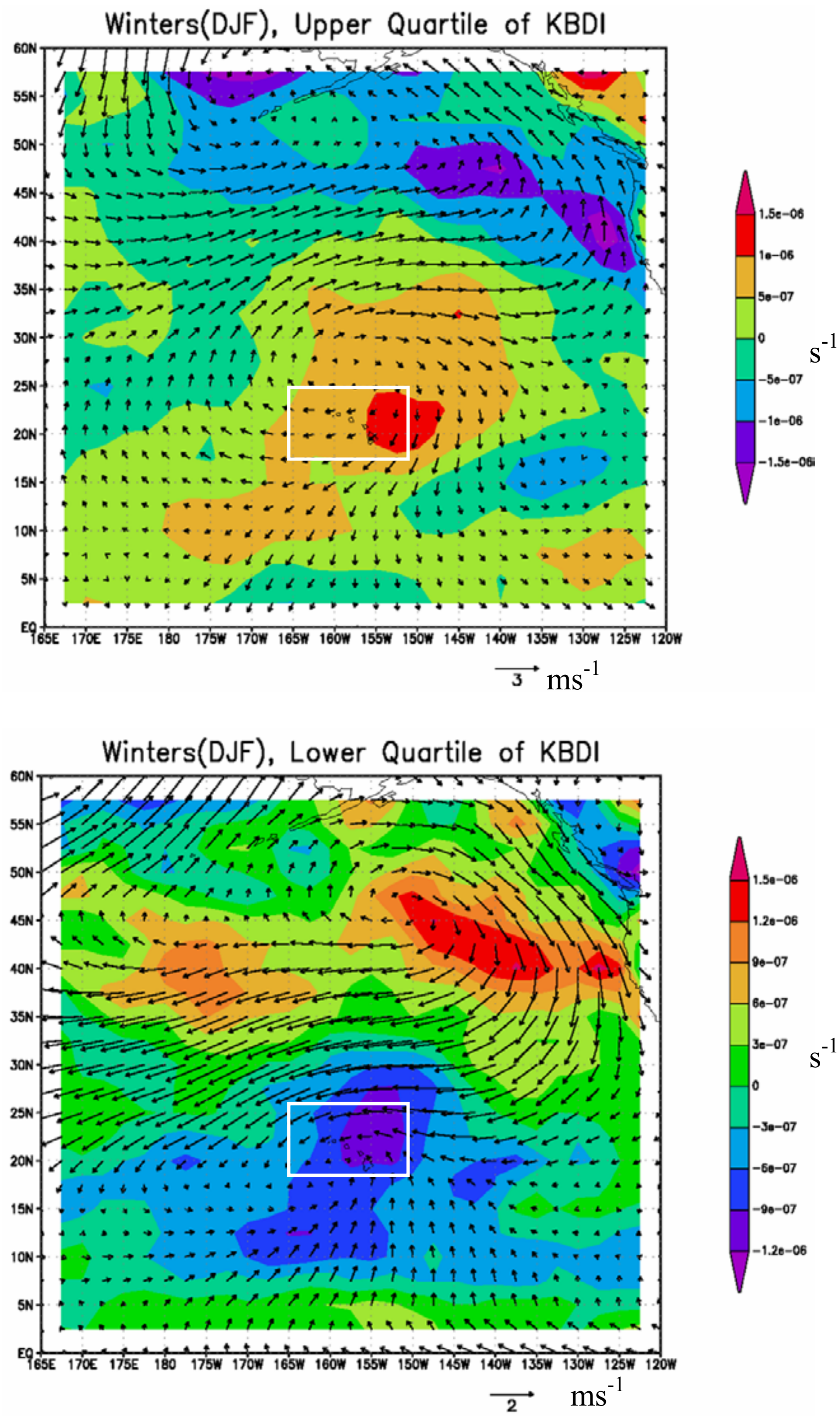

Figure 5. Winter (Dec/Jan/Feb) composite for anomalous surface winds and divergence. (a) upper quartile of KBDI, (b) lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui. Box indicates area of the Hawaiian Islands.