UNIVERSITY OF HAWAII LIBRARY

A CLIMATOLOGICAL STUDY OF THE KEETCH/BYRAM DROUGHT
INDEX AND FIRE ACTIVITY IN THE HAWAIIAN ISLANDS

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

METEOROLOGY

DECEMBER 2003

By
KLAUS DOLLING

Thesis Committee:

Pao-Shin Chu, Chairperson
Yi-Leng Chen
Kevin Hamilton

ACKNOWLEDGMENTS

I am grateful to my advisor Dr. Pao-Shin Chu for his guidance and encouragement throughout this study. I am also grateful to Dr. David Chen and Dr. Kevin Hamilton for their helpful advice and suggestions. Thank you also to Francis Fujioka of the USDA-Forest Service for his helpful insight and direction.

A special thanks to my parents, Maryann and Ulf Dolling, and also to my brother and his wife, Stephan and Charlotte, for their continued support during this time period. Rebecca Schneider, Eric Lau, Bunmei Taguchi, Luis Bejarano, and Chueh-hsin Chang, thank you for your friendships and the useful meteorological discussions that we have had. Finally, I would like to extend my gratitude to all of the graduate students for making this an enjoyable two years.

Abstract

The Hawaiian Islands experience damaging wildfires on a yearly basis. Periods without substantial rain are part of the natural annual cycle as well as part of natural climate fluctuations. Soil moisture, or lack thereof, influences the amount and flammability of vegetation. Incorporating daily maximum temperatures and daily rainfall amounts, the Keetch and Byram Drought Index (KBDI) estimates the amount of soil moisture by tracking daily maximum temperatures and rainfall.

For the first time, the climatological relationship between the KBDI and fire activity is examined using a number of different techniques. The KBDI is tested separately on four major Hawaiian Islands against total acres burned (TAB). This relationship is explored using various statistical methods and a strong relationship is found between these two variables.

The annual cycle of the KBDI is investigated through the use of harmonic analysis. The times of year at which the KBDI is highest, representing the highest fire danger, are found at each of the 27 stations on the island chain. Spectral analysis is applied to investigate the variability of the KBDI on various time scales. Individual stations are found to have different sensitivities to large-scale climatic fluctuations. An El Niño signal is shown to have a strong relationship with leeward stations through the application of a band-pass filter.

Large-scale atmospheric circulations are also investigated for seasons when KBDI is extremely high and low. Anomalous anticyclonic (cyclonic) circulations and

surface divergence (convergence) are found over the island chain for times when the KBDI is high (low).

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.....	iii
ABSTRACT.....	iv
LIST OF TABLES.....	ix
LIST OF ILLUSTRATIONS.....	xi
CHAPTER 1: INTRODUCTION.....	1
CHAPTER 2: DATA.....	3
CHAPTER 3: METHODS.....	5
3.1 CALCULATION OF THE KEETCH/BYRAM DROUGHT INDEX.....	5
3.2 SPEARMAN RANK CORRELATION.....	6
3.3 WILCOXIN-MANN-WHITNEY RANK-SUM TEST.....	7
3.4 CONDITIONAL PROBABILITIES.....	9
3.5 HARMONIC ANALYSIS.....	10
3.6 SPECTRAL ANALYSIS.....	11
3.7 METHODS OF SIGNIFICANCE TESTING.....	12
3.8 BANDPASS FILTER.....	14

CHAPTER 4:

4.1 RELATIONSHIP BETWEEN FIRE ACTIVITY AND A DROUGHT INDEX.....	16
4.1.1 COMPOSITE AND SPEARMAN RANK CORRELATION.....	16
4.1.2 WILCOXON-MANN-WHITNEY RANK-SUM TEST.....	18
4.1.3 CONDITIONAL PROBABILITIES.....	18
4.2 HARMONIC ANALYSIS OF A DROUGHT INDEX.....	19
4.2.1 KAUAI, OAHU, MOLOKAI, AND MAUI.....	20
4.2.2 HAWAI'I (THE BIG ISLAND).....	21
4.3 SPECTRAL ANALYSIS.....	23
4.4 BAND-PASS FILTER OF KBDI TIME SERIES AND NINO 3.4 INDEX.....	24
4.5 POSSIBLE REASONS FOR THE ANNUAL CYCLE AT WINDWARD STATIONS.....	25
4.6 COMPOSITE OF STANDARD ANOMALIES.....	26

CHAPTER 5: ATMOSPHERIC CIRCULATION PATTERNS DURING EXTREME DROUGHT INDEX EVENTS.....	28
5.1 COMPOSITE OF LEEWARD STATIONS.....	28
5.2 WINTER.....	29

5.3 SPRING.....	30
5.4 SUMMER.....	32
5.5 FALL.....	33
 CHAPTER 6: SUMMARY.....	35
 REFERENCES.....	80

LIST OF TABLES

Table	Page
<p>1. Spearman rank correlation of KBDI (Keetch/Byram Drought Index) with TAB (total acres burned). Time series consist of 20 years of data (1976-1996). Stations for each island's composite are shown. N_{eff} is the reduced degrees of freedom due to the persistence of each time series. Correlation values and the corresponding confidence levels are also shown.....</p>	40
<p>2. Wilcoxon-Mann-Whitney rank-sum test for the four reference stations. Each station contains 20 years of data (1976-1996) with the exception of Kekaha (1981-1996). The two batches consist of months with TAB (total acres burned) values above and below the median KBDI value for each station.....</p>	41
<p>3. Conditional probabilities of TAB values above the median value at four reference stations. Times series consist of 20 years (1976-1996) with the exception of Kekaha (1981-1996). Probabilities are representative of the number of months with TAB values above the median TAB (total acres burned) value for each interval of 100 of KBDI. For Kekaha, Kauai, the interval of 701-800 was never reached, and therefore is not a number (NaN).....</p>	42

4. Harmonic analysis of monthly averaged KBDI data for the first harmonic at 27 stations of the six islands of Hawaii (Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii). Included are elevation of station, length of record, amplitude, phase (January located at 0 degrees and July at 180 degrees), the month and day that correspond to that phase, portion of variance accounted for by the first harmonic, long-term mean monthly KBDI, and the standard deviation of the monthly mean KBDI data.....43
5. List of years used for seasonal composites for upper quartile (75th percentile) and lower quartile (25th percentile) of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui. The time series consists of 35 years of data (1966-2000). For the winter, the year shown is for January and February (December is from the preceding year).....44

LIST OF FIGURES

Figure	Page
1. Map of the Hawaiian Islands and the 27 stations used for this study.....	45
2. Time series of total acres burned (TAB) for the island of Kauai. Time series consists of 20 years of data (1976-1996).....	46
3. Time series of total acres burned (TAB) for the island of Oahu. Time series consists of 20 years of data (1976-1996).....	47
4. Time series of total acres burned (TAB) for the island of Maui. Time series consists of 20 years of data (1976-1996).....	48
5. Time series of total acres burned (TAB) for the island of Hawaii. Time series consists of 20 years of data (1976-1996).....	49
6. Scatter plots of composites of island-wide KBDI and the natural log of total area burned (meters squared). Composites are constructed for each of the four main islands from the stations listed in Table 1. (a) island of Kauai (1976-1996), (b) island of Oahu (1976-1996), (c) island of Maui (1976-1996), (d) island of Hawaii (1976-1996).....	50
7. Scatter plots of KBDI and the natural log of total area burned (meters squared). (a) Kekaha, Kauai (1981-1996), (b) Honolulu Airport, Oahu (1976-1996).....	51

8.	Scatter plots of KBDI and the natural log of total area burned (meters squared). (a) Lahaina, Maui (1976-1996), (b) Naalehu, Hawaii (1976-1996).....	52
9.	Scatter plots of KBDI and the natural log of total area burned (meters squared). (a) Hana, Maui (1976-1996), (b) Hilo, Hawaii (1976- 1996).....	53
10.	Bar graph of total acres burned (TAB) and intervals of KBDI. Bars represent the median value of TAB for each interval of KBDI. (a) Kekaha, Kauai (1981-1996), (b) Honolulu Airport, Oahu (1976-1996).....	54
11.	Bar graph of total acres burned (TAB) and intervals of KBDI. Bars represent the median value of TAB for each interval of KBDI. (a) Lahaina, Maui (1976-1996), (b) Naalehu, Hawaii (1976-1996).....	55
12.	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).....	56
13.	Band-pass filter of KBDI anomalies and anomalous Niño 3.4 index. The Niño 3.4 index is scaled by a factor of 100. Time series consists of 35 years of data (1966-2000). (a) Naalehu, Hawaii, (b) Waikiki, Oahu.....	57

14.	Band-pass filter of KBDI anomalies for Hilo, Hawaii and anomalous Niño 3.4 index. The Niño 3.4 index is scaled by a factor of 100. Time series consists of 35 years of data (1966-2000).....	58
15.	(a) Time series of SST anomalies averaged over 170 ⁰ W-120 ⁰ W and 2 ⁰ S-2 ⁰ N. Solid and dashed line indicates unfiltered and 22-month low-pass filtered data, respectively. (b) The real part of the Morlet wavelet spectrum of the time, showing the amplitude as a function of oscillation period and time (Jin et al., 2003). Red box indicates near annual cycle superimposed on cool background state. Green box indicates near annual cycle superimposed on warm background state.....	59
16.	10 to 14 month Band-pass filter of KBDI anomalies. Time series consists of 35 years of data (1966-2000). Yellow dots indicate where on the filtered series February occurs. Red box indicates near annual cycle superimposed on cool background state. Green box indicates near annual cycle superimposed on warm background state. (a) Hana, Maui, (b) Hilo, Hawaii.....	60
17.	Composite of standard anomalies of KBDI from 19 stations located throughout the island chain. Stations used are found in Table 1. Time composite consists of months of El Niño years, Yr(0), and the months following El Niño years, Yr(+1).....	61

19. Winter (Dec/Jan/Feb) composite for anomalous 200 hPa winds.
 (a) Upper quartile of KBDI and (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.....62
20. Winter (Dec/Jan/Feb) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.....63
20. Winter (Dec/Jan/Feb) composite for anomalous surface pressure.
 (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....64
21. Winter (Dec/Jan/Feb) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....65
22. Spring (Mar/Apr/May) composite for anomalous 200 hPa winds.
 (a) Upper quartile of KBDI and (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.....66

23.	Spring (Mar/Apr/May) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.....	67
24.	Spring (Mar/Apr/May) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....	68
25.	Spring (Mar/Apr/May) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....	69
26.	Summer (Jun/Jul/Aug) composite for anomalous 200 hPa winds. (a) Upper quartile of KBDI and (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.....	70
27.	Summer (Jun/Jul/Aug) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.....	71

28.	Summer (Jun/Jul/Aug) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....	72
29.	Summer (Jun/Jul/Aug) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....	73
30.	Fall (Sep/Oct/Nov) composite for anomalous 200 hPa winds. (a) Upper quartile of KBDI and (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.....	74
31.	Fall (Sep/Oct/Nov) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.....	75
32.	Fall (Sep/Oct/Nov) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....	76

33.	Fall (Sep/Oct/Nov) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.....	77
34.	Schematic structure of anomalous equatorial winds for spring and fall. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI.....	78
35.	Harmonic dial showing the phase and amplitude for the first harmonic of the long-term 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.....	79

CHAPTER 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.

When studying the frequency and duration of dry periods, atmospheric oscillations are usually examined. Rasmusson (1987) identified three major atmospheric oscillations: the 30 to 60 day oscillation also known as the Madden and Julian Oscillation (MJO), the quasi-biennial oscillation (QBO), and the El Niño/Southern Oscillation (ENSO). ENSO is of most concern for rainfall variability in the tropical Pacific Islands (Ropelewski and Halpert, 1987). It has been associated with drought in the Hawaiian Islands in the winter and spring following an El Niño event (Chu, 1989, 1995; Cayan and Peterson, 1989). The MJO has been shown to affect the monsoon rains in southeast Asia and India, but is of too short a time period for this study. The QBO cycles approximately every 2.25 years and is associated with shifts in the stratospheric winds and other

variables. The QBO has been correlated only marginally with surface weather features (Rasmusson, 1987).

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 30 years, there has not been an extensive study of its relationship to fire activity and to climate patterns. This paper analyzes the variation of the KBDI and its application to fire activity in the Hawaiian Islands. Sections 2 and 3 discuss the data and methods, respectively. Section 4 describes the relationship between KBDI and fire activity. The annual and the long-term cycles of KBDI are also investigated. Section 5 discusses the atmospheric circulation patterns for composites of extreme KBDI values. Section 6 summarizes the results.

CHAPTER 2

DATA

Daily precipitation and temperature data from 27 stations in the Hawaiian Islands 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. The selection of different stations was based on the consistency of data within the time series. Missing values consisted of less than 5% of the total series, with most stations having only 1% of their values absent. Any missing values of daily rainfall and temperature were replaced by the climatological average value for that particular day. This was kept to a minimum because of the quality of the data set. Daily values of the KBDI were calculated from the daily values of precipitation and temperature. After the daily values of the KBDI were calculated, a monthly average was taken. For most stations, the length of the monthly time series is 420, consisting of 35 years of reliable data.

Total acres burned or TAB data were obtained from the Hawaii Department of Land and Natural Resources. TAB data were available for each of the four main Hawaiian Islands (Kauai, Oahu, Maui, and Hawaii), as shown in Figure1, for a 20 year period (1976-1996). Monthly values of total acres burned were computed from daily reports for each island (Chu et al., 2002). Questions of the quality of this data have arisen. The methods that fire managers use for calculating the TAB are not perfect. Often TAB values are estimated through visual inspection. However, this is the best data

available at the moment and it is hoped that the long-term nature of this study minimizes any inconsistencies in the daily TAB reports.

Monthly sea surface temperatures from the Niño 3.4 region were obtained from the Climate Prediction Centers. The Niño 3.4 region includes the area from 5°S to 5°N and from 170°W to 120°W . The Niño 3.4 region was selected because of its representativeness of El Niño events.

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 70°N and from 130°E to 110°W . Since this data set is from the Pacific basin, it is not expected to be perfect. This occurs because of the scarcity of data over such a large ocean. It is however the best available option at this time. This data set is used to calculate seasonal averages, so it is assumed that any inconsistencies in the time series will be smoothed out.

CHAPTER 3

METHODS

3.1 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 index was developed to function throughout a wide range of climatic and rainfall conditions in forested or wildland areas. 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 KBDI 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 of the index, dQ , is

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

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 °F (10°C). If the net accumulated precipitation exceeds 0.20 inch, the excess reduces Q linearly. Further explanation of the calculations for the index can be found in Keetch and Byram (1968).

The physical theory for the KBDI is based on a number of assumptions (Keetch and Byram, 1968). 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.

3. 2 Spearman Rank Correlation

A Spearman rank correlation is used to infer the relevance of KBDI to total acres burned (TAB). The Spearman rank correlation is chosen because of the nature of the TAB data. Figures 2, 3, 4, and 5 show a graphical representation of the TAB data on each of the four main islands. The data are characterized by a few months with extremely large values of TAB and many months with small or zero TAB. The non-linear nature of the data leads to extremely low ordinary Pearson correlations. To overcome this non-linear problem a Spearman rank correlation is performed. For the rank correlation, the two data series (TAB and KBDI) are ranked separately, and then an ordinary Pearson correlation is applied to the two ranked data batches. The Pearson

correlation can be viewed as the ratio of the sample covariance of the two variables to the product of the two standard deviations and can be written as follows:

$$\frac{[1/(n-1)] \sum_{i=1}^n [(x_i - \text{mean}(x))(y_i - \text{mean}(y))]}{\{[1/(n-1)] \sum_{i=1}^n (x_i - \text{mean}(x))^2\}^{1/2} \{[1/(n-1)] \sum_{i=1}^n (y_i - \text{mean}(y))^2\}^{1/2}}$$

The significance of the rank correlation is calculated by taking into account the persistence of the time series (Quenouille, 1952). This yields the effective number of degrees of freedom for each series,

$$N_{\text{eff}} = N / (1 + 2 * R_x(1) * R_y(1) + 2 * R_x(2) * R_y(2) + \dots)$$

where $R(1)$ and $R(2)$ are the autocorrelations at lag one and lag two, and x and y refer to the two time series, respectively.

3.3 Wilcoxon-Mann-Whitney Rank-Sum Test

For the Wilcoxon-Mann-Whitney test, the TAB series is ranked. The ranked TAB series is then separated into two data batches according to values above or below the median value of KBDI at each station. These two data batches are then compared. The aim is to test for a possible difference in location (overall sense of magnitude) or the nonparametric analog of the mean. The null hypothesis is that the two batches are from the same distribution of data. The formula to compute the Mann-Whitney U statistic is

given by:

$$U_1 = R_1 - n_1/2 (n_1 + 1)$$

$$U_2 = R_2 - n_2/2 (n_2 + 1)$$

where R_1 and R_2 are the sums of the ranks of batch 1 and batch 2, respectively, and n_1 and n_2 are number of observations in batch 1 and batch 2, respectively. The null hypothesis can be rejected if the difference between R_1 and R_2 is sufficiently unusual against the backdrop of all possible distinct arrangements of these data. The number of distinct arrangements is given by:

$$(n!) / [(n_1!) (n_2!)]$$

The null distribution of all possible arrangements of U_1 for these data closely approximates a Gaussian distribution with

$$\mu_U = (n_1 n_2) / 2$$

approximating the mean and

$$\sigma_U = [(n_1 n_2 (n_1 + n_2 + 1)) / 12]^{1/2}$$

approximating the standard deviation. The value of U_1 thus corresponds to a standard Gaussian z by using the formula:

$$z = (U_1 - \mu_U) / \sigma_U$$

Using a two sided test, the probability of this z value is multiplied by a factor of 2 and checked against our significance level. Further explanation of the nonparametric Wilcoxon-Mann-Whitney rank-sum test can be found in Wilks (1995) and Chu (2002).

3.4 Conditional Probabilities

The conditional probabilities are based on intervals of KBDI and the corresponding monthly values of TAB. The KBDI time series range from 0 to 800 so it is natural to chose an interval of 100. For each interval, we calculate the probability that a value of TAB occurs above the median of the entire TAB series. The conditional probability is given by the formula:

$$\Pr\{E_1 \mid E_2\}$$

This states that we are finding the probability of E_1 given that E_2 has occurred, where E_1 is the probability of a TAB value occurring above the median of the entire TAB series and E_2 is a particular interval of KBDI. More formally, the conditional probability can be written:

$$\Pr\{E_1 | E_2\} = \frac{\Pr\{E_1 \cap E_2\}}{\Pr\{E_2\}}$$

This equation states that the conditional probability is defined as the intersection of the event of interest and the conditioning event provided that the conditioning event is not zero.

3.5 Harmonic Analysis

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). To calculate these values, the long-term mean values of each of the twelve months of the year are found. The coefficients A_1 and B_1 are obtained by the formula:

$$A_k = 2/n \sum_{t=1}^n y_t \cos(2\pi t k / n)$$

$$B_k = 2/n \sum_{t=1}^n y_t \sin(2\pi t k / n)$$

where n is the number of data values in one cycle (12 months), y_t is mean value for each month of the year, k is the value of the harmonic (annual = 1, semi-annual =2) to be found, and t is the time increment. The amplitude may be found by using:

$$C_k = [A_k^2 + B_k^2]^{1/2}$$

The phase angle is found by using:

$$\Theta = \tan^{-1} (B_1 / A_1), \pm 180^\circ \text{ so that } 0^\circ < \Theta < 360^\circ$$

and the portion of variance accounted for by the k^{th} harmonic can be found using:

$$R_k^2 = \frac{((n / 2) (C_k^2))}{(n - 1) S_y^2}$$

where S_y^2 is the sample variance of the data series.

3.6 Spectral Analysis

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 smoothed estimate of the spectral density function is obtained from the following formula:

$$s(f) = 2 [1 + 2 \sum_{k=1}^{m-1} r(k) w(k) \cos (2\pi f k \Delta t)] \Delta t$$

where m is the maximum lag, $r(k)$ is the sample autocorrelation function, $w(k)$ is the lag window, and Δt is the time interval between observations. The Parzen lag window is used to smooth the sample spectrum (Chu and Katz, 1989). $w(k)$ is given by the formula:

$$w(k) = \begin{cases} 1 - 6 (k / m)^2 + 6 (|k| / m)^3, & |k| \leq m / 2 \\ 2 (1 - |k| / m)^3, & m / 2 < |k| \leq m \\ 0, & |k| > m \end{cases}$$

Empirical rules are used in the selection of m . Appropriate values of m can be found by the following criteria based on Chu and Katz (1989):

$$\begin{aligned} m &\approx n / 6, & 100 < n < 200 \\ m &< n / 6, & 200 < n < 1000 \\ m &< n / 10, & 1000 < n < 2000 \end{aligned}$$

where n is the number of observations in the time series. In this study, m is set to 60, because the value of n is 420.

3.7 Methods of Significance Testing

Statistical significance of spectral estimates is tested against a Markov red-noise process at the 90 percent and 95 percent confidence limits, because atmosphere time series generally contain persistence. The red noise spectrum can be expressed as:

$$s^*(f) = \text{mean}(s) [(1 - r_1^2) / (1 + r_1^2 - 2r_1 \cos 2\pi f)]$$

where r_1 is the autocorrelation function at lag one and f is the frequency. The degrees of freedom are given by:

$$v = (2n - (m / 2)) / m$$

where n is the sample size and m is the maximum lag. Our confidence level can be found by using the χ^2 table (0.90 and 0.95) for the specified degrees of freedom and multiplying this number by the red noise spectrum.

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. The test is based on a first-order autoregression (i.e., red-noise) model. The AR(1) model can be written as:

$$x_{t+1} - \mu = \phi (x_t - \mu) + \epsilon_{t+1}$$

where μ is the mean of the time series, ϕ is the autoregressive parameter, and ϵ_{t+1} is a random quantity corresponding to the residual in ordinary regression. Each of the 10,000

trials is analyzed with the spectral method used previously. The 90 and 95 percentile levels are determined from these series.

3.8 Band-pass filter

A band-pass filter (Murakami, 1979) is also employed to compare two time series. The calculation of the band-pass filter consists of two steps. First, the tentative output is calculated using the formula:

$$y_k = a(x_k - x_{k-2}) - b_1 y_{k-1} - b_2 y_{k-2}$$

where x is the corresponding value of the time series and the coefficients a , b_1 , and b_2 are given by the formula:

$$a = \frac{2\Delta\Omega}{4 + 2\Delta\Omega + \Omega_0^2}$$

$$b_1 = \frac{2(\Omega_0^2 - 4)}{4 + 2\Delta\Omega + \Omega_0^2}$$

$$b_2 = \frac{4 - 2\Delta\Omega + \Omega_0^2}{4 + 2\Delta\Omega + \Omega_0^2}$$

and

$$\Delta\Omega = 2 \left| \frac{\sin\omega_1\Delta T}{1 + \cos\omega_1\Delta T} - \frac{\sin\omega_2\Delta T}{1 + \cos\omega_2\Delta T} \right|$$

$$\Omega_0^2 = \frac{4 \sin\omega_1\Delta T \sin\omega_2\Delta T}{(1 + \cos\omega_1\Delta T)(1 + \cos\omega_2\Delta T)}$$

where ω_1 and ω_2 are the frequencies (measured by 2π / period) at which we can get a 0.5 response on both sides of our desired frequency. The output is then reversed in time and processed again to obtain the final output.

CHAPTER 4

4.1 Relationships between fire activity and a drought index

In this section, the KBDI's relationship to fire activity is explored. Once a link is established, we can investigate how the index is affected by short and long-term climatic cycles. The time series of monthly TAB values from 1976 to 1996 are shown in Figures 2, 3, 4, and 5, for each of the four main islands. The TAB series for the four islands are characterized by many months with low TAB values and a few months with extremely large values of TAB.

Fire in the Hawaiian Islands can be a major hazard and is most often caused by human actions. It is therefore important to find an index that can provide some measure of the present fire danger. The KBDI is a candidate measure, but it has not been tested against actual fire data on climate time-scales. Because the present research investigates the long-term climate scale response of the drought index, monthly data will be used. A number of different approaches are taken to explore the relationship between TAB and KBDI.

4.1.1 Spearman Rank Correlation

The first approach involves the use of a Spearman rank correlation between the KBDI and TAB for each of the four main Hawaiian Islands. Table 1 contains a list of the stations used for compositing the KBDI values for each island. Table 1 shows that the strongest relationships are for the islands of Maui and Hawaii. These islands show confidence levels above 99%. The results for Oahu and Kauai display confidence levels

above the 90% level. Therefore, as the KBDI increases in value, the likelihood of more acres burned by fires also increases.

Scatter plots of the KBDI and TAB for each of the four composites are shown in Figure 6. The natural logarithm of TAB is used to display the data in a succinct manner. The results of the Spearman rank correlations are confirmed, as it seems that the islands of Maui and Hawaii have a more robust relationship between the KBDI and TAB than the islands of Kauai and Oahu.

Although these results are satisfactory, further exploration of the connection between KBDI and TAB is warranted. One would expect fire to occur in the driest areas of the island. However, when using the same Spearman correlation for island-wide TAB and the driest station on each island, their correlations are lower than with the composite method (Table 1). An exploration using scatter plots reveals that the driest station on each island shows a clustering of TAB values in the upper values of KBDI (i.e., dry conditions). On the other hand, the lower values of KBDI contain many months with low TAB values or TAB values of zero. Therefore, for the months when the KBDI is high (low) at these dry stations, there are more (fewer) total months with fire activity and larger (smaller) amounts of total acres burned. Figures 7a, 7b, 8a, and 8b show the scatter plots for each of these dry stations (Kekaha on Kauai, Honolulu Airport on Oahu, Lahaina on Maui, and Naalehu on Hawaii). A comparison of these dry stations with wetter stations can be made by viewing the scatter plots of KBDI and TAB for two windward stations in Figures 9a and 9b (Hana on Maui and Hilo on Hawaii). These wetter stations do not display the same clustering of TAB values in the upper values of the KBDI.

4.1.2 Wilcoxon-Mann-Whitney Rank-Sum Test

In addition to using a Spearman correlation, a nonparametric Wilcoxon-Mann-Whitney rank-sum test is used. This test will verify if there is a difference in location between two data samples. The two samples consist of TAB for months when the KBDI is above and below its median value. Four stations are chosen because they have the highest mean KBDI for each island. Some of these stations are located in populated areas where the expected wildland fire danger is small. They are, however, representative of the climate for the driest areas on each island.

To test the null hypothesis that the data batches of TAB come from the same distribution, the Wilcoxon rank-sum test is applied at the 1% level. The results of the test are shown in Table 2. The analysis consists of a 20-year period with the exception of Kekaha which has 15 years of data. In each case, the null hypothesis is rejected. It should also be noted that the p values are extremely low for each test. These results confirm that the KBDI is a good indicator in discriminating groups of high from low TAB for the Hawaiian Islands.

4.1.3 Conditional Probabilities

A third test is performed to determine how TAB is related to intervals of progressively higher KBDI values. Because monthly mean KBDI ranges from 0 (saturated soil) to 800 (completely dry), an interval of 100 is naturally desired. The four reference stations listed in Table 2 are used. The conditional probabilities that the TAB values are above the median value are shown in Table 3. In each case there is a general

upward progression of probabilities. That is, as the KBDI values reach higher intervals, the probability of larger acres burned by fires is proportionally higher. This relationship is not perfect, yet it is not expected to be, since one reference station (i.e., a single point) is being compared to an island-wide TAB. In the case of Kekaha, Kauai, the interval from 701 to 800 was never reached in the time series so it is not shown.

One last way to investigate this relationship is with the use of bar graphs shown in Figures 10a, 10b, 11a and 11b. These graphs display the median value of TAB for each interval of KBDI. The four reference stations representing the stations of highest mean KBDI for each island are used. Kekaha, Kauai looks a bit unusual. The only median TAB value that shows up is in the KBDI interval from 601 to 700. This occurs because of the prevalence of zero values in the monthly TAB time series. The other three stations show a general increase in the median value of TAB with increasing KBDI intervals. For the islands of Maui and Hawaii there seems to be a threshold for the KBDI at which the median value of TAB increases. The threshold occurs around the 400 value of KBDI. Above this value of KBDI there are increased median values of TAB. This is interesting because a KBDI value of 400 is used operationally in states like Texas to alert fire managers to an increased risk of fire.

4.2 Harmonic analysis of a drought index

Having tested the relevance of the KBDI to fire data, 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 affects 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.

4.2.1 Kauai, Oahu, Molokai, and Maui

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 regard 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 (Table 4). 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 (Table 4 and Fig. 1). 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 (Table 4). Many windward stations show three peaks in rainfall, with two maxima in cool season (November and March) and a third maximum in summer. This helps account for the absence of either strong annual or semi-annual cycles in the KBDI. The decline in peak winter 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 (Table 4). Overall, the annual cycle in the KBDI lags the annual cycle in rainfall (not shown) by about one to three months

4.2.2 Hawai'i (The Big Island)

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 Figure 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 summer 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 is what accounts for the unusually low portion of variance accounted for by the first harmonic (Table 4).

Naalehu, located on the south facing slopes of Mauna Loa (Fig. 1), has a strong annual cycle with the portion of variance accounted for at 91.7% (Table 4). It is drier than previous stations with a long-term monthly mean KBDI of 364.2. The peak phase is on August 13. This earlier phase could possibly be caused by an altered winter rainfall maximum due to the orographic effects of increased southerly winds or from the effects of rain that reach Naalehu from windward areas. Southerly winds increase in frequency in the winter months of December, January, and February (Lyons, 1982). Mauna Loa Slopes Observatory, located near the summit of Mauna Loa, has an elevation of 11,150 feet and an extremely low mean KBDI (Table 4). This observatory is located above the vegetation line and therefore is not at risk for fire.

Opihihale, located on the southwest coast of Hawaii, has a moderately strong annual cycle with 44.5% of the variance accounted for (Table 4). The amplitude of the first harmonic is 13.5, which indicates that Opihihale has a KBDI number that does not change much throughout the year. It is likely that Opihihale is mainly affected by localized diurnal circulations and not by the large precipitation events that normally occur at leeward stations during the cool season. Mauna Loa probably shields this station from these cool season rain events.

Kainaliu has a strong annual cycle with 95.7% of the variance accounted for (Table 4). However, the peak phase has a 180-degree shift relative to most other sites with the driest period on or around March 5. Kainaliu also has a higher amplitude (124.8) of the first harmonic than Opihihale. 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. Therefore, it tends to be the driest during that time of year. During the summer months, when the trade winds are more persistent, air flows through the Humu'ula Saddle and interacts with diurnal circulations causing a summer rainfall maximum in the vicinity of this station. This would account for the wetter lower drought numbers that occur at this site during the summer.

4.3 Spectral analysis of a drought index

One long-term cycle of interest on Kauai is an 18 to 20-month fluctuation at Lihue Airport (Fig. 12a). It is significant at the 90% confidence level (dashed line represents 95% confidence limit and dotted line represents 90% level, relative to the red noise spectrum). This cycle 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 20-month range with Honolulu Airport (Fig. 12b) being marginally significant at the 95% confidence level. All three also have cycles of 40 to 50 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 18 to 20-month cycles. Hana Airport (Fig. 12c) is a good example with the 20-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 18 to 20-month cycles, all significant at the 90% level. These stations include Hawaii VNP, Naalehu, Mauna Loa Slopes Observatory, Opihihale and Upolu Point USCG. For Naalehu, the most interesting signal is a 40 to 50-month signal (Fig. 12d), 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 18 to 20-month and 12-month cycles. Hana Airport (Fig. 12c) is an example of a typical windward site. Leeward sites have pronounced 18 to 20-month and 9-month cycles, but do not show cycles in the 12 month range. Some leeward sites also have cycles in the 40 to 50-month range. Honolulu Airport (Fig. 12b) is an example of a typical leeward site.

4.4 Band-pass filter of KBDI series and Niño 3.4 Index

In order to determine whether the KBDI series is related to El Niño, a 36-60 month band-pass filter is applied to Naalehu, Hawaii and Niño 3.4 index series (Fig. 13a). 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. A possible reason is that the onset of the El Niño was different before and after the late 1970's (Wang, 1995). Figure 13b displays another leeward station, Waikiki on Oahu, and a similar relationship is found. The same band-pass filter was applied to other leeward stations (i.e., Honolulu Airport, Honolulu Observatory, and Lahaina); all of which display a strong relationship with the Niño 3.4 index. In contrast to leeward stations the 36 to 60 month band-pass was also applied to windward stations. Figure 14 shows the band-pass for Hilo on Hawaii. There appears to

be no relationship between this station and the Niño 3.4 index. Other windward stations were investigated with this filter; all of these stations lacked a strong relationship with the Niño 3.4 index.

4.5 Possible Reasons for the Annual Cycle at Windward Stations

The spectrum of windward stations displays an unusual result. The spectrum is computed by taking out the annual cycle from the time series. Interestingly, the analysis of the spectrum shows an annual cycle at nearly all windward stations. In a recent paper by Jin et al. (2003), they described a fast mode which is present in the El Niño cycle. This fast mode can be seen from the wavelet transform, Figures 15a and 15b, of the raw time series of sea surface temperatures averaged over the region $170^{\circ}\text{W} - 120^{\circ}\text{W}$ and $2^{\circ}\text{S} - 2^{\circ}\text{N}$. As can be seen from Figure 15b, there is significant variability in the 12 to 18 month period. This variability is in addition to the interannual variability (36 to 48 months). The near annual variability is most significant during the 1970's and the 1990's. These faster fluctuations are characterized by changes in SST, zonal wind stress, zonal current, and sea level in the central Pacific (Jin et al., 2003). The near annual cycle also can be seen as superimposed on either a cold background state during the 1970's or over a warm background state in the 1990's. During the 1970's these near annual events manifest themselves as mini La Niña events. During the 1990's these events manifest themselves as mini El Niño events.

Figures 16a and 16b show the 10 to 14 month band-pass filter of two windward stations. These two graphs show some revealing characteristics which might be related to the fast mode of El Niño. There is very strong near annual variability during the 1970's

and the 1990's in both the Hana and the Hilo band-pass filters. The graphs also show yellow dots superimposed on the filtered time series. These dots display the level of anomalous KBDI (of filtered data) for the month of February. Note that during the 1970's, a time of near annual La Niña events, the month of February (representing the winter season KBDI), is found at times of anomalous lowest KBDI. During the 1990's, the February signal is found at the peak of these annual cycles, corresponding to a time of near annual El Niño events. It is curious that the fast modes and the filtered KBDI events seem to coincide. At the very least, the filtered KBDI time series is revealing because of the switch in the annual cycle anomalies during the warm and cool decadal phases of the North Pacific. This reversal of the near annual cycle in KBDI can explain why the 12 month spectral peak is found in the time series.

Another question is why is it only windward stations and not leeward stations that display this near annual cycle? Windward stations tend to receive rainfall throughout the year as opposed to leeward stations, with the exception of the Kona coast on Hawaii, which often receive very little rain during the summer months. Because of this increase in summer rainfall, it is possible that windward station KBDI is more sensitive to fluctuations of SST's on an annual time scale.

4.6 Composite of Standard Anomalies

Past research has found that the Hawaiian Islands experience less rainfall in the winter and spring following an El Niño event. It is expected that the KBDI will react to this decrease in rainfall. To investigate how the KBDI is affected before and after an El Niño event, a composite of 19 stations is constructed. These stations are the same

stations used in the Table 1. To construct the composite the monthly KBDI value at each of these stations were transformed into standardized anomalies. The time composite is made by taking the average anomalies for the months during an El Niño cycle. The year of El Niño is denoted as $yr(0)$ and the year immediately following an El Niño is $yr(+1)$. The definition of an El Niño event is taken from Trenberth (1997).

The analysis in Figure 17 shows that the positive KBDI anomalies persist consecutively from November of $yr(0)$ to December of $yr(+1)$, lasting for 14 months. The largest positive anomalies tend to occur in February, March, and April of $yr(+1)$ when the islands experience extremely low ENSO related rainfall (Chu, 1995). The peak anomalies in March following El Niño events are close to one standard deviation from the mean.

CHAPTER 5

ATMOSPHERIC CIRCULATION PATTERNS DURING EXTREME DROUGHT INDEX EVENTS

5.1 Composite of Leeward Stations

Having established a strong link between the KBDI at leeward stations and TAB for four major islands, 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 giving a better understanding of the large-scale atmospheric conditions that occur during times of increased fire activity.

Earlier, four reference stations were chosen (Kekaha, Honolulu Airport, Lahaina, and Naalehu). These are the driest stations on each of the four main islands. A composite of these stations 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 was also not included in the subsequent composite analysis. This leaves only Honolulu Airport and Lahaina as reference stations for the composite. The upper (75th percentile) and lower (25th percentile) quartiles of the mean KBDI from these two stations are found for each season. The years for each season's upper and lower quartiles are shown in Table 5.

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 (Table. 4). Because of the high persistence of the KBDI time series (lag one auto-correlation of the monthly time series is 0.85), the winter and spring seasons are the focus. Investigation of circulation patterns during these two rainy seasons may provide potential predictability of the KBDI for the following fall when the KBDI reaches its peak at most stations (Table 4). To complete the analysis the summer and fall seasons are also investigated.

5.2 Winter Circulation

The anomalous winter (Dec, Jan, and Feb) upper-air circulation pattern for times when the KBDI reaches its upper quartile is shown in Figure 18a. The years used for the composite are shown in Table 5. It displays an anomalous upper-level anticyclone centered just west northwest of the island chain. The corresponding surface wind and divergence chart (Fig. 19a) displays an anomalous surface anticyclone approximately in the same area as the upper level pattern with high levels of anomalous surface divergence (shaded in brown and red) over the island chain. The anomalous surface pressure and 500 hPa geopotential height patterns shown in Figures 20a and 21a, display higher anomalous surface pressures and positive height anomalies over the Hawaiian Islands and lower anomalous surface pressure and negative height anomalies in the vicinity of the Aleutian low. Interestingly, the anomalous 500 hPa geopotential height pattern looks

similar to the PNA pattern observed in the winters following El Niño events (Horel and Wallace, 1980).

The lower quartile (i.e., 25th percentile) has the opposite patterns, with an anomalous upper and lower level cyclonic circulation centered just west of the island chain, as well as anomalous surface convergence (in blue) over the Hawaiian Islands (Figs. 18b and 19b). Figures 20b and 21b display the anomalous surface pressure and anomalous 500 hPa geopotential height pattern for the lower quartile. As expected, lower anomalous surface pressure and negative 500 hPa geopotential height anomalies are found over the islands of Hawaii and higher anomalous surface pressures and 500 hPa heights are found in the area of the Aleutian low. Again, the anomalous 500 hPa geopotential height pattern for the lower quartile is similar to the PNA pattern but of opposite sign compared to the pattern for the upper quartile of KBDI. For both upper and lower quartiles, the anomalous surface and upper air circulation patterns support the anomalous equivalent barotropic structure throughout the troposphere.

5.3 Spring Circulation

The anomalous 200 hPa winds for the upper quartile of the spring season (Mar, Apr, and May) are displayed in Figure 22a. The years used for the spring composite are shown in Table 5. In the western Pacific, there are anomalous westerly winds near the equator and an anomalous cyclone centered at 17° N and 155° E. To the south and east of the Hawaiian Islands near the equator are anomalous easterly winds. The flow pattern directly south of the islands is from the south. Figure 23a displays the anomalous surface wind and divergence chart for spring for the upper quartile of KBDI. The Hawaiian

Islands are positioned in an area of increased divergence and anomalous anticyclonic winds. The equatorial surface winds east and west of the Hawaiian Islands are of opposite sign to the upper level winds inferring that the island chain is positioned just north of two anomalous Walker type circulations. Directly south of the islands, the surface winds are from the north and again opposite in sign to the anomalous 200 hPa winds. The surface pressures and 500 hPa geopotential height charts (Figs. 24a and 25a) for the upper quartile show a broad region of anomalous high pressure and positive height anomalies over the island chain and most of the southern North Pacific.

The anomalous 200 hPa winds for the lower quartile of spring are shown in Figure 22b. Interestingly, the anomalous equatorial winds for the lower quartile are opposite in sign to the anomalous 200 hPa winds for the upper quartile. To the west of the Hawaiian Islands there are anomalous equatorial easterly winds and to the east of the islands there are anomalous equatorial westerly winds. Directly south of the islands the anomalous 200 hPa winds are northerly. Figure 23b displays the surface wind and divergence for the lower quartile of KBDI. The Hawaiian Islands are positioned in an area of anomalous convergence and cyclonic winds. Again, the anomalous surface equatorial winds are of opposite sign to the anomalous 200 hPa winds, inferring an anomalous Walker type circulation. Also, the anomalous surface southerly winds south of the island chain might be a mechanism for moisture transport from the equatorial regions. For the lower quartile of KBDI, the surface pressures and 500 hPa geopotential heights charts (Figures 24b and 25b) display lower pressures and negative height anomalies over Hawaii. A schematic of the vertical structure of the equatorial winds for the upper and lower quartile of KBDI in spring is shown in Figures 34a and 34b. The

anomalous circulations shown in these schematics are characterized by two anomalous Walker type cells to the south of the Hawaiian Islands and anomalous baroclinic forced equatorial Rossby waves to the west of the island chain.

5.4 Summer Circulation

Although the summer is driest time of year for leeward stations (except on Hawaii's Kona coast), it is still important to investigate the circulation patterns associated with extreme values of the KBDI. The summer (Jun, Jul, and Aug) composite years are displayed in Table 5. Figures 26a and 26b show the anomalous 200 hPa winds for the upper and lower quartile of KBDI. Comparing these figures with the anomalous surface winds in Figures 27a and 27b, the structure of the anomalous equatorial winds are similar to the spring season with minor exceptions. In Figure 26a (upper quartile) the anomalous equatorial 200 hPa westerly winds progress further to the east and the anomalous equatorial easterlies are barely visible. Another exception is that the anomalous Walker type circulation has moved slightly north, probably because of the annual cycle of the ITCZ. The anomalous divergence in Figures 27a and 27b is not impressive as is expected for the summer season at leeward stations.

The anomalous surface pressure and 500 hPa geopotential heights for both quartiles of KBDI for summer are shown in Figures 28a, 28b, 29a, and 29c. Although these figures do not display the distinct pressure and height patterns found in winter and spring, they still show anomalous high (low) surface pressure and positive (negative) 500 hPa height anomalies over the Hawaiian Islands for upper (lower) quartiles of KBDI. Overall there is more of a zonal quality to these anomalies.

5.5 Fall Circulation

Early fall is the time of peak climatological KBDI for leeward stations (Table 4). Wet or dry conditions during this time will influence the exact time at which the peak KBDI occurs for individual years. An extremely dry fall may lead to peak KBDI values later in the season. Therefore, understanding the atmospheric processes that lead to these conditions is important. Table 5 contains the years used for the fall (Sep, Oct, and Nov) composite.

Figure 30a displays the anomalous 200 hPa winds for the upper quartile of KBDI in fall. Similar to the spring, the anomalous equatorial 200 hPa winds are westerly to the west of the Hawaiian Islands and easterly to the east of the islands. Compared to the anomalous surface winds in Figure 31a (upper quartile), we find anomalous equatorial easterlies to the west of the island chain and anomalous westerlies to the east of the islands. Again it appears to be an anomalous baroclinic circulation with two Walker type cells, one near the equator to the west and one cell to the east. The anomalous surface wind and divergence map for the upper quartile (Figure 31a) displays a distinct anticyclone slightly north and west of the islands for the upper quartile, placing them in an area of increased surface divergence and therefore drier conditions. This should lead to higher KBDI numbers. The surface pressures and 500 hPa geopotential heights charts (Figs. 32a and 33a) for the upper quartile show a broad region of anomalously high pressure and positive height anomalies over the island chain.

For the lower quartile of KBDI, Figures 30b and 31b show the anomalous 200 hPa winds and surface wind and divergence. In the equatorial region the pattern is very similar to the 200 hPa wind and surface wind pattern for the upper quartile, but the

pattern is the reverse. A schematic of the equatorial winds is shown in Figures 34a and 34b. Figure 31b shows an anomalous surface cyclone is located slightly north and west of the Hawaiian Islands, placing the islands in an area of increased convergence. We can infer that this leads to wetter conditions and a lower KBDI number. The anomalous surface pressures and height patterns in Figures 32b and 33b also have patterns opposite that of the upper quartile.

CHAPTER 6

SUMMARY

For the first time, the validity of the Keetch/Byram Drought Index (KBDI) as a measure of fire activity on a climate time-scale was tested with a number of different techniques. The relationship between KBDI and total acres burned (TAB), for the four major islands, was investigated using a Spearman rank correlation. A strong positive correlation between the KBDI and TAB was found for the islands of Maui and Hawaii at the 99% confidence level. The confidence values for Oahu and Kauai were slightly lower. Therefore, as the KBDI increased in value, the TAB values also increased.

A further exploration of the data revealed that stations with the highest mean KBDI could be used as reference stations. Although some of these stations are located in populated areas, they do represent the driest areas of each island. A second test involved a nonparametric test (Wilcoxon rank sum test). This test was used to investigate the difference in locations between two TAB data samples based on the median of KBDI. The null hypothesis that the two TAB batches came from the same distribution was rejected at the 1% level in each case. This helped establish that the KBDI is good in discriminating groups of high from low TAB. A third test involved the conditional probabilities of reaching TAB above the median (TAB) for various intervals of KBDI. A strong relationship was found, with a general increase in probabilities of reaching higher TAB values at progressively higher values of KBDI.

The problem of testing KBDI in the Hawaiian Islands was complex considering the many microclimates found on each island. Ideally, the index would be tested in a

large area with a homogeneous climate regime. The results of the test between the KBDI and TAB were surprisingly good considering the varied climates of the Hawaiian Islands.

Harmonic analysis was used to find what times of the year, from a climatological perspective, the KBDI reaches its highest value 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. 35). 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 wintertime 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 to 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 show 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 of the KBDI series revealed some unexpected cycles. Leeward sites had pronounced cycles at 18 to 20 months and at 9 months. Leeward stations also

had spectral peaks in the 40 to 50-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 40 to 50-month cycle. A test with the same bandpass 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 18 to 20 months and at 12 months. Interestingly, the 18 to 20-month cycle was prevalent at most stations while the 40 to 50-month cycle was only evident at leeward stations.

The possible reason for the 12-month cycle at windward stations was also investigated. The time series at windward stations was filtered using a 10 to 14 month band-pass. The filtered KBDI time series is revealing because of the switch in the annual cycle anomalies during the warm and cool decadal phases of the North Pacific. This reversal of the near annual cycle in KBDI may explain why the 12 month spectral peak is found in the time series. Had the anomalies not reversed, the annual cycle would have been subtracted out in the initial handling of the data. It was also shown that the wavelet spectrum of central Pacific sea surface temperatures had distinct annual cycles present during the cool base state of the 1970's and the warm base state of the 1990's. The annual cycle in sea surface temperatures manifest itself as mini La Niña events during the 1970's and mini El Niño's during the 1990's. The corresponding filtered KBDI time series displayed the same pattern implying a possible connection between the two time series.

A composite of standard Gaussian anomalies for the KBDI was constructed to investigate how the KBDI reacts to El Niño events. Past research indicated that the Hawaiian Islands show deficiencies in rainfall in the winter and spring following El Niño

events. Therefore a time composite was constructed during an El Niño cycle. The composite indicates that positive standard KBDI anomalies occur from November of an El Niño year through December of the year following an El Niño with the largest amplitudes in February, March, and April of yr(+1).

Departure patterns of atmospheric circulations over the North Pacific were investigated for composites of extremely high and low KBDI values. The winter, spring, and fall showed an anomalous surface 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. This circulation places the Hawaiian Islands at the right exit region (anticyclonic flank) of the jet stream and in an anomalous deep layer anticyclonic circulation. The pattern for the lower quartile of KBDI showed a weakened jet stream and placed the island chain in deep layer anomalous cyclonic circulation.

The consistency in the anomalous equatorial circulation pattern for the spring and fall seasons was particularly surprising. A schematic of the vertical structure of the spring and fall anomalous equatorial winds for the upper and lower quartiles of KBDI are displayed in Figures 34a and 34b. For both quartiles of KBDI the anomalous equatorial winds had an anomalous vertical baroclinic structure with what appeared to be anomalous Walker circulations. To the west of the island chain there appears to be anomalous equatorial Rossby waves with anomalous baroclinic structure forced by the equatorial winds. The patterns for the upper and lower quartiles are approximately opposite. It is likely that the KBDI is sensitive to equatorial circulation patterns.

Equatorial atmospheric circulations are known to be affected largely by sea surface temperatures and vice versa. Fluctuations in the central Pacific sea surface temperatures and atmospheric circulations might be able to explain much of the variability in the KBDI. Interestingly, the wavelet spectrum shown in Figure 15 displays a high amount of variability in the 12 to 18-month range and the 3 to 5 year range. Leeward stations were shown to have a strong relationship with the 3 to 5 year variability in sea surface temperatures. The 12-month cycle at windward stations was also shown to have possible links with fluctuations in central Pacific sea surface temperatures. The wavelet spectrum displays almost continuous variability in central Pacific seas surface temperatures in the 18-month range. Future investigations into the 18-month cycle in the KBDI might focus on the equatorial central Pacific as a possible source for this cycle.

Acknowledgments

This study has been supported by the USDA Forest Service project 01-CA-11272169-124.

Spearman rank correlation between KBDI and TAB

Island	Stations	N_{eff}	R (Spearman)	Confidence Level
Kauai	Kanalohuluhulu Lihue Airport	65	0.216	90%
Oahu	Waialua Opaehala Kaneohe Mauka Waikiki Honolulu Airport	63	0.235	90%
Maui	Kahulua Airport Kailua Hana Airport Haleakala RS Lahaina	63	0.401	99%
Hawaii	Hilo Airport Kulani Camp Hawaii Volcano NP Naalehu Opihihale Kainaliu	78	0.332	99%

Table 1. Spearman rank correlation of KBDI (Keetch/Byram Drought Index) with TAB (total acres burned). Time series consist of 20 years of data (1976-1996). Stations for each island's composite are shown. N_{eff} is the reduced degrees of freedom due to the persistence of each time series. Correlation values and the corresponding confidence levels are also shown.

Wilcoxon rank-sum test

Station	Median Value KBDI	Null Hypothesis (Alpha = 0.01)	p Value
Kekaha, Kauai	377.72	Rejected	$3.00 * 10^{-6}$
Honolulu AP, Oahu	575.05	Rejected	$9.78 * 10^{-5}$
Lahaina, Maui	513.87	Rejected	$3.24 * 10^{-4}$
Naalehu, Hawaii	364.64	Rejected	$1.20 * 10^{-3}$

Table 2. Wilcoxon-Mann-Whitney rank-sum test for the four reference stations. Each station contains 20 years of data (1976-1996) with the exception of Kekaha (1981-1996). The two batches consist of months with TAB (total acres burned) values above and below the median KBDI value for each station.

Conditional Probability

KBDI Interval	Kekaha, Kauai	Honolulu AP, Oahu	Lahaina, Maui	Naalehu, Hawaii
0 - 100	0.16	0.18	0.31	0.24
101 - 200	0.28	0.29	0.23	0.32
201 - 300	0.16	0.30	0.25	0.41
301 - 400	0.34	0.31	0.36	0.46
401 - 500	0.47	0.43	0.57	0.68
501 - 600	0.41	0.44	0.67	0.66
601 - 700	0.69	0.68	0.53	0.70
701 - 800	NaN	0.60	0.80	0.50

Table 3. Conditional probabilities of TAB values above the median value at four reference stations. Times series consist of 20 years (1976-1996) with the exception of Kekaha (1981-1996). Probabilities are representative of the number of months with TAB values above the median TAB (total acres burned) value for each interval of 100 of KBDI. For Kekaha, Kauai, the interval of 701-800 was never reached, and therefore is not a number (NaN).

Harmonic Analysis of KBDI

Island/Station	Elev. (ft)	Dates	Amplitude	Phase	Mon/Day	Por. of Var.	Mean KBDI	Stand. Dev.
Kaua'i								
Kanalohululu	3600	1966-2000	197.4	250.6	09/11	0.935	197.9	150.7
Lihue WSO Airport	103	1966-2000	153.9	240.9	09/01	0.934	361.0	117.7
Kekaha	9	1981-2000	242.5	242.5	09/02	0.970	367.8	126.8
O'ahu								
Waialua	32	1966-2000	189.5	260.3	09/21	0.982	373.6	141.2
Waimea Arboretum	40	1984-2000	110.2	240.3	09/01	0.727	345.2	95.5
Opaeula	1060	1966-2000	150.3	255.4	09/16	0.911	308.0	116.3
Kaneohe Mauka	190	1966-1998	106.3	241.1	09/01	0.888	298.4	83.4
Waikiki	10	1966-2000	182.9	256.0	09/17	0.961	424.2	137.8
Honolulu WFSO AP	7	1966-2000	180.6	256.0	09/17	0.987	491.2	134.3
Honolulu Observatory	5	1979-2000	166.5	256.0	09/17	0.985	480.5	123.9
Moloka'i								
Molokai Airport	450	1966-2000	197.1	270.0	10/01	0.981	390.5	147.0
Lana'i								
Lanai City	620	1966-2000	107.7	265.6	09/26	0.978	224.1	80.4
Lanai Airport	1300	1975-2000	115.3	265.3	09/26	0.957	368.6	87.1
Maui								
Kahului WSO	48	1966-2000	197.3	273.3	10/05	0.987	441.7	146.7
Kailua	700	1966-2000	16.9	294.1	10/26	0.110	137.6	37.6
Hana Airport	61	1966-2000	75.2	234.7	08/26	0.797	295.3	62.2
Haleakala RS	6960	1966-2000	88.4	252.9	09/13	0.970	129.6	66.3
Lahaina	45	1966-2000	171.5	271.2	10/03	0.977	461.2	128.1
Hawai'i								
Upolu Point USCG	6	1966-1992	135.2	279.0	10/11	0.925	339.3	103.9
Ookala	43	1966-1993	101.8	265.3	09/26	0.712	241.4	89.1
Hilo WSO Airport	27	1966-2000	11.1	286.8	10/19	0.024	263.5	53.0
Kulani Camp	5170	1966-1998	13.7	358.3	12/29	0.144	71.5	26.5
Hawaii Volcanoes NP	3973	1966-2000	28.8	264.0	09/25	0.259	127.3	41.7
Naalehu	800	1966-2000	109.4	222.4	08/13	0.917	364.2	51.0
Opihihale	1360	1966-2000	13.5	131.4	05/13	0.445	271.8	14.9
Kainaliu	1500	1966-2000	124.8	63.2	03/05	0.957	268.2	94.2
Mauna Loa Slopes Obs	11150	1966-2000	12.4	236.2	08/27	0.810	34.4	10.2

Table 4. Harmonic analysis of monthly averaged KBDI data for the first harmonic at 27 stations of the six islands of Hawaii (Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii). Included are elevation of station, length of record, amplitude, phase (January located at 0 degrees and July at 180 degrees), the month and day that correspond to that phase, portion of variance accounted for by the first harmonic, long-term mean monthly KBDI, and the standard deviation of the monthly mean KBDI data.

Composite Years for Atmospheric Circulations

Season	Upper Quartile	Lower Quartile
Winter (Dec, Jan, Feb)	1977 1978 1987 1994 1995 1998 1999 2000	1968 1969 1971 1979 1988 1989 1990 1997
Spring (Mar, Apr, May)	1973 1978 1981 1987 1992 1998 1999 2000	1967 1968 1971 1972 1980 1982 1989 1997
Summer (Jun, Jul, Aug)	1970 1973 1981 1988 1993 1998 1999 2000	1967 1968 1971 1972 1974 1980 1982 1997
Fall (Sep, Oct, Nov)	1973 1976 1977 1981 1983 1995 1998 1999	1967 1968 1978 1982 1985 1989 1991 1996

Table 5. List of years used for seasonal composites for upper quartile (75th percentile) and lower quartile (25th percentile) of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui. The time series consists of 35 years of data (1966-2000). For the winter, the year shown is for January and February (December is from the preceding year).

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

Figure 2. Time series of total acres burned (TAB) for the island of Kauai. Time series consists of 20 years of data (1976-1996).

Figure 3. Time series of total acres burned (TAB) for the island of Oahu. Time series consists of 20 years of data (1976-1996).

Figure 4. Time series of total acres burned (TAB) for the island of Maui. Time series consists of 20 years of data (1976-1996).

Figure 5. Time series of total acres burned (TAB) for the island of Hawaii. Time series consists of 20 years of data (1976-1996).

Figure 6. Scatter plots of composites of island-wide KBDI and the natural log of total area burned (meters squared). Composites are constructed for each of the four main islands from the stations listed in Table 1. (a) island of Kauai (1976-1996), (b) island of Oahu (1976-1996), (c) island of Maui (1976-1996), (d) island of Hawaii (1976-1996).

Figure 7. Scatter plots of KBDI and the natural log of total area burned (meters squared). (a) Kekaha, Kauai (1981-1996), (b) Honolulu Airport, Oahu (1976-1996).

Figure 8. Scatter plots of KBDI and the natural log of total area burned (meters squared). (a) Lahaina, Maui (1976-1996), (b) Naalehu, Hawaii (1976-1996).

Figure 9. Scatter plots of KBDI and the natural log of total area burned (meters squared). (a) Hana, Maui (1976-1996), (b) Hilo, Hawaii (1976-1996).

Figure 10. Bar graph of total acres burned (TAB) and intervals of KBDI. Bars represent the median value of TAB for each interval of KBDI. (a) Kekaha, Kauai (1981-1996), (b) Honolulu Airport, Oahu (1976-1996).

Figure 11. Bar graph of total acres burned (TAB) and intervals of KBDI. Bars represent the median value of TAB for each interval of KBDI. (a) Lahaina, Maui (1976-1996), (b) Naalehu, Hawaii (1976-1996).

Figure 12. 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 13. Band-pass filter of KBDI anomalies and anomalous Niño 3.4 index. The Niño 3.4 index is scaled by a factor of 100. Time series consists of 35 years of data (1966-2000). (a) Naalehu, Hawaii, (b) Waikiki, Oahu.

Figure 14. Band-pass filter of KBDI anomalies for Hilo, Hawaii and anomalous Niño 3.4 index. The Niño 3.4 index is scaled by a factor of 100. Time series consists of 35 years of data (1966-2000).

Figure 15. (a) Time series of SST anomalies averaged over 1700W-1200W and 20S-20N. Solid and dashed line indicates unfiltered and 22-month low-pass filtered data, respectively. (b) The real part of the Morlet wavelet spectrum of the time, showing the amplitude as a function of oscillation period and time (Jin et al., 2003). Red box indicates near annual cycle superimposed on cool background state. Green box indicates near annual cycle superimposed on warm background state.

Figure 16. 10 to 14 month Band-pass filter of KBDI anomalies. Time series consists of 35 years of data (1966-2000). Yellow dots indicate where on the filtered series February occurs. Red box indicates near annual cycle superimposed on cool background state. Green box indicates near annual cycle superimposed on warm background state. (a) Hana, Maui, (b) Hilo, Hawaii.

Figure 17. Composite of standard anomalies of KBDI from 19 stations located throughout the island chain. Stations used are found in Table 1. Time composite consists of months of El Niño years, Yr(0), and the months following El Niño years, Yr(+1).

Figure 18. Winter (Dec/Jan/Feb) composite for anomalous 200 hPa winds. (a) Upper quartile of KBDI and (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.

Figure 19. Winter (Dec/Jan/Feb) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.

Pressure (hPa) Anom, Winter (DJF), Upper Quartile of KBDI

(a)

Pressure (hPa) Anom, Winters (DJF), Lower Quartile of KBDI

(b)

Figure 20 Winter (Dec/Jan/Feb) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Geopotential Height(m) Anom, Winters(DJF), Upper Quartile of KBDI

(a)

Geopotential Height(m) Anom, Winters(DJF), Lower Quartile of KBDI

(b)

Figure 21. Winter (Dec/Jan/Feb) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Figure 22. Spring (Mar/Apr/May) composite for anomalous 200 hPa winds. (a) Upper quartile of KBDI and (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.

Figure 23. Spring (Mar/Apr/May) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.

Pressure (hPa) Anom, Spring (MAM), Upper Quartile of KBDI

(a)

Pressure (hPa) Anom, Spring (MAM), Lower Quartile of KBDI

(b)

Figure 24. Spring (Mar/Apr/May) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Geopotential Height Anom(m), Spring(MAM), Upper Quartile of KBDI

(a)

Geopotential Height(m) Anom, Spring(MAM), Lower Quartile of KBDI

(b)

Figure 25. Spring (Mar/Apr/May) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Anom 200mb Wind (m/s), Summer (JJA), Upper Quartile of KBDI

(a)

Anom 200mb Wind (m/s) Summer (JJA), Lower Quartile of KBDI

(b)

Figure 26. Summer (Jun/Jul/Aug) composite for anomalous 200 hPa winds. (a) Upper quartile of KBDI and (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.

Figure 27. Summer (Jun/Jul/Aug) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.

Pressure (hPa) Anom, Summer (JJA), Upper Quartile of KBDI

(a)

Pressure (hPa) Anom, Summer (JJA), Lower Quartile of KBDI

(b)

Figure 28. Summer (Jun/Jul/Aug) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Geopotential Height Anom(m), Summer(JJA), Upper Quartile of KBDI

(a)

Geopotential Height Anom(m), Summer(JJA), Lower Quartile of KBDI

(b)

Figure 29. Summer (Jun/Jul/Aug) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Figure 30. Fall (Sep/Oct/Nov) composite for anomalous 200 hPa winds. (a) Upper quartile of KBDI and (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.

Figure 31. Fall (Sep/Oct/Nov) composite for anomalous surface winds and divergence. (a) Upper quartile of KBDI and (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.

Pressure (hPa) Anom, Fall (SON), Upper Quartile of KBDI

(a)

Pressure (hPa) Anom, Fall (SON), Lower Quartile of KBDI

(b)

Figure 32. Fall (Sep/Oct/Nov) composite for anomalous surface pressure. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Geopotential Height Anom(m), Fall(SON), Upper Quartile of KBDI

(a)

Geopotential Height Anom(m), Fall(SON), Lower Quartile of KBDI

(b)

Figure 33. Fall (Sep/Oct/Nov) composite for anomalous 500 hPa geopotential height. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI. The reference stations used for the composites are Honolulu Airport on Oahu and Lahaina on Maui.

Anomalous Equatorial Circulation for Spring and Fall of the Upper Quartile of KBDI (a)

Anomalous Equatorial Circulation for Spring and Fall of the Lower Quartile of KBDI (b)

Figure 34. Schematic structure of anomalous equatorial winds for spring and fall. (a) Upper quartile of KBDI and (b) Lower quartile of KBDI.

Figure 35. Harmonic dial showing the phase and amplitude for the first harmonic of the long-term 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.

References

- Cayan, D.R., and D.H. Peterson, 1989: The influence of North Pacific atmospheric circulation on stream flow in the west. Aspects of climatic variability in the Pacific and the Western Americas. Geophysics Monogr., No. 55, Amer Geophysics Union, 375-397.
- Chen, Y.-L. and A. J. Nash, 1994: Diurnal variation of surface airflow and rainfall on the island of Hawaii. *Mon. Wea. Rev.*, **122**, 34-55.
- Chu, P.-S., 1989: Hawaiian drought and the Southern Oscillation. *Int. J. Climatol.* **9**, 619-631.
- Chu, P.-S., 1995: Hawaii rainfall anomalies and El Niño. *J. Climate*, **8**, 1697-1703.
- Chu, P.-S., 2002: Large-scale circulation features associated with decadal variations of tropical cyclone activity over the central North Pacific. *J. Climate*, **15**, 2678-2689.
- Chu, P.-S., and R. W. Katz, 1989: Spectral estimation from time series models with relevance to the Southern Oscillation. *J. Climate*, **2**, 86-90.
- Chu, P.-S., W.-P. Yan, and F. Fujioka, 2002: Fire-climate relationships and long lead seasonal wildfire prediction for Hawaii. *Int. J. Wildland Fire*, **11**, 25-31.
- Fujioka, F. M., 1991: Starting up the Keetch-Byram Drought Index. 11th Conf. on Fire and Forest Meteor. Extended Abstract, 16-19 April, Missoula, Montana, Soc. Amer. Foresters, 74-80.

- Giambelluca, T. W. and M. Sanderson., 1993: The Water Balance and Climate Classification. *Prevailing Trade Winds*, M. Sanderson, Ed., University of Hawaii Press., 56-72.
- Horel, J. D. and Wallace, J. M., 1981: Planetary-scale phenomena associated with the southern oscillation. *Mon. Wea. Rev.*, 109, 813-829.
- Heim, R. R., 2002: A review of twentieth century drought indices used in the United States. *Bull. Amer. Meteor. Soc.*, **83**, 1149-1165.
- Horel, J. D., 1982: On the annual cycle of the tropical Pacific atmosphere and ocean. *Mon. Wea. Rev.*, **110**, 1863-1878.
- Jin, F. -F., Kug, J. -S., An, S. -I., and Kang, I. -S., 2003: A near-annual coupled ocean-atmosphere mode in the equatorial Pacific ocean. *Geophy. Res. Lett.*, **30**, 1-4.
- Johnson, M. B., and G. Forthum, 2001: Spatial mapping of KBDI for the southeast United States. 4th Symp. on Fire and Forest Meteor. Preprints, 13-15 November, Reno, Nevada, Amer. Meteor. Soc., 64-65.
- Keetch, J. J., and G. M. Byram, 1968: A drought index for forest fire control. *USDA Forest Service Research Paper*, SE-38, 1-32.
- Lee, H.-K., P.-S. Chu, C.-H. Sui, and K.-M. Lau, 1998: On the annual cycle of latent heat fluxes over the equatorial Pacific using TAO buoy observations. *J. Meteor. Soc. Japan*, **76**, 909-923.
- Lyons, S. W., 1982: Empirical orthogonal function analysis of Hawaiian Rainfall. *J. Appl. Meteor.*, **21**, 1713-1729.

- Murakami, M., 1979: Large-scale aspects of deep convection activity over the gate area. *Mon. Wea. Rev.*, 107, 994-1013.
- Quenouille, M. H., 1952. *Associated Measurements*. Butterworths, London
- Rasmusson, E.M. 1987. Global prospects for the prediction of drought: A meteorological perspective. *Planning for Drought, Toward a Reduction of Societal Vulnerability*. Westview Press, 31-43.
- Ropelewski, C. F. and M.S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.*, 115, 1606-1626.
- Schroeder, T. A., 1993: Weather and climate in Hawaii. *Prevailing Trade Winds*, M. Sanderson, University of Hawaii Press., 12-37.
- Wang, B., 1995: Interdecadal changes in El Niño onset in the last four decades. *J. Climate.*, 8, 267-285.
- Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences*, Academic Press., 138-145.