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# A climatological study of the Keetch/Byram drought index and fire activity in the Hawaiian Islands

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**Abstract**

The Hawaiian Islands experience damaging wildfires on a yearly basis. Soil moisture or lack thereof, influences the amount and flammability of vegetation. 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 relationship between the KBDI and fire activity on the Hawaiian Islands is examined using a number of different techniques. The KBDI is calculated daily for a 20-year period and then tested on a monthly time-scale on four major Hawaiian Islands against total area burned (TAB). The use of monthly TAB data for an individual island is a necessity when considering the relatively low frequency of fire activity and the small spatial scale of the islands.

The relationship between the KBDI with TAB is explored with a number of rigorous statistical methods. A strong relationship between the KBDI and fire activity for the islands of Oahu, Maui, and Hawaii is found. At present a network of stations is used to operationally monitor fire danger on a daily basis.


*Keywords:* Fire activity; Keetch/Byram drought index; Total area burned

## 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. It is not uncommon to find dry land areas that receive less than 20 in. rain within a few miles of tropical rainforests that receive well over 140 in. rain. 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, 1993). 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 locally (Chu et al., 2002). It is therefore desirable to identify a fire index that may help predict long- and short-term wild-land fire activity.

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Although the Keetch/Byram drought index (KBDI) has been used for over 30 years in some areas of the United States, there has not been a study of its relationship to fire activity on the Hawaiian Islands. This paper analyzes the variation of the KBDI and its application to fire activity on the island chain. Section 2 describes the KBDI at length. Sections 3 and 4 discuss the data and methods, respectively. Section 5 describes the results of the relationship between KBDI and fire activity.

## 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 revised 1988 U.S. National Fire Danger Rating System (NFDRS) (Heim, 2002). This revised version of the 1988 NFDRS is primarily used in the southeastern U.S. The KBDI in the 1988 NFDRS is used as an intermediate quantity that determines the availability of drought fuel load. 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 wild land 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 zero after a period of substantial precipitation (Fujioka, 1991). In this study, the KBDI was initiated after periods of copious rainfall (a few inches) during the winter months. 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, $\Delta Q$, is

$$\Delta Q = [800 - Q][0.968\exp(0.0486T) - 8.30]\Delta t \times \frac{0.001}{1 + 10.88\exp(-0.0441M)} \quad (1)$$

where $T$ is the daily maximum temperature, $M$ the mean annual rainfall, $Q$ the current KBDI, and $\Delta t$ is a time increment set equal to 1 day. This equation describes the drying rate of the soil.

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 in. (net rainfall), the excess reduces $Q$ linearly. Net rainfall is recorded in inches and is subtracted directly from the KBDI. For example, if the KBDI has a value of 600 and one inch of rain falls that day, the rainfall is multiplied by 100 and subtracted from yesterdays KBDI. Therefore, the new KBDI would be 500. On days with less than 0.20 in. rain, the equation for the drying factor is used. 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 in. 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. Data

Daily precipitation and temperature data from 27 stations as displayed in Fig. 1 were obtained from the Western Regional Climate Center in Reno, Nevada. Most stations had 20 years of reliable data (1976–1996). For each individual station, a monthly average is calculated from the arithmetic mean of the daily KBDI values.

Daily total area burned (TAB) data were obtained from the Hawaii Department of Land and Natural Resources. TAB data was only available for each of the four main Hawaiian Islands (Kauai, Oahu, Maui, and Hawaii) for a 20-year period (1976–1996), thus weather stations on the islands of Molokai and Lanai were not used. Monthly values of total area burned were computed from daily reports for each island (Chu et al., 2002).

## 4. Methods

Three methods are used to explore the relationship between the KBDI and total area burned (TAB). An ordinary Pearson correlation is first used to infer the relevance of monthly KBDI to monthly TAB. TAB

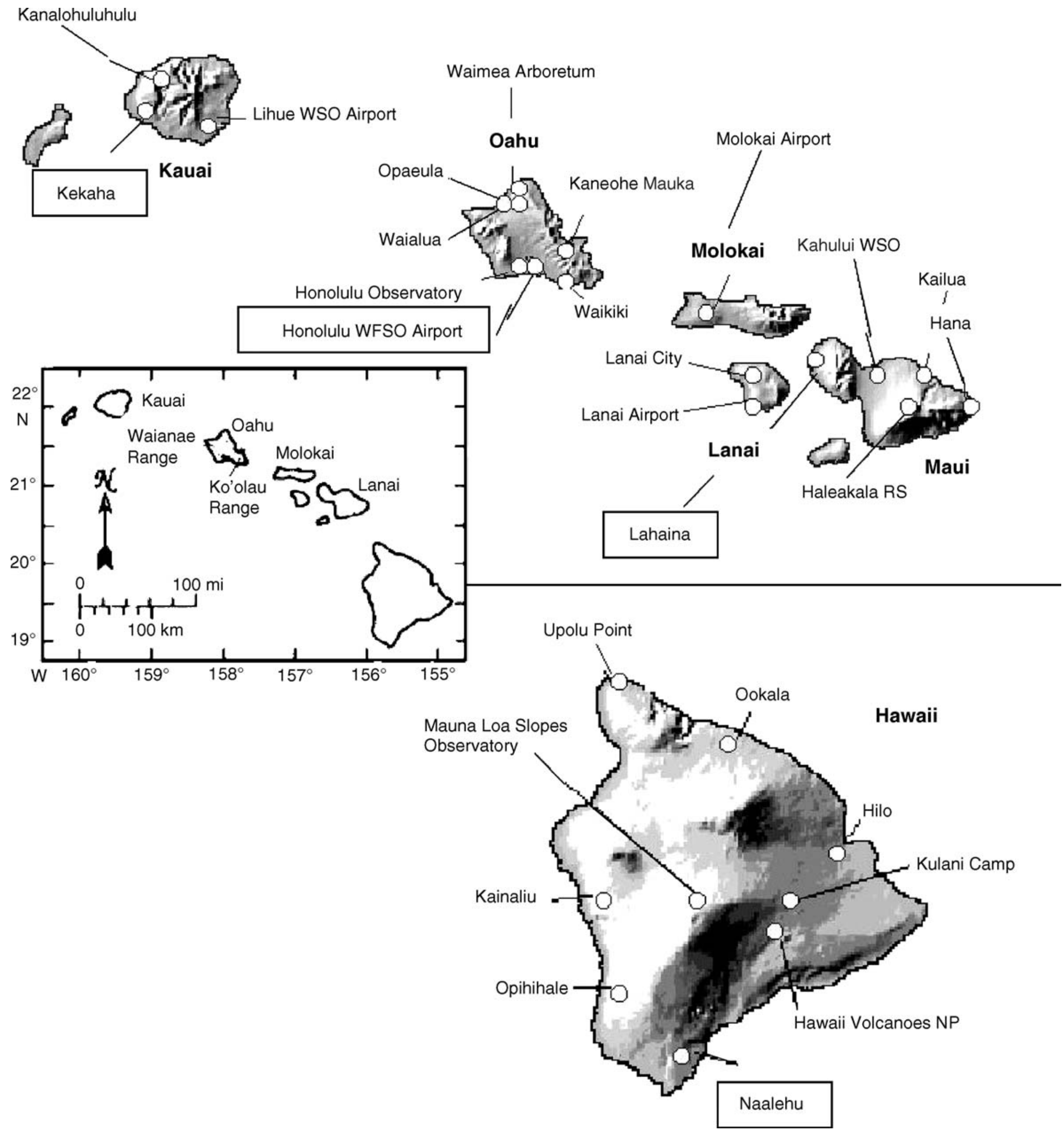


Fig. 1. Map of the Hawaiian Islands and the 27 stations used for this study. Boxes indicate reference stations.

data are characterized by a few months with extremely large values and many months with small or zero TAB. The non-normally distributed nature of the fire data leads to difficult statistical analysis. A log transform is therefore applied to the TAB data before the Pearson correlation is used. The Pearson correlation ($r$) can be viewed as the ratio of the sample covariance of the two variables to the product of the two standard deviations. The significance of the correlations 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,

$$N_{\text{eff}} = N/(1 + 2 \times R_x(1) \times R_y(1) + 2 \times R_x(2) \times R_y(2) + \cdots) \quad (2)$$

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. After temporal degrees of freedom are adjusted, the correlations are evaluated for various confidence levels (Clark and Chu, 2002).

A Wilcoxon–Mann–Whitney test is performed to test for a possible difference in location (overall sense of magnitude) or nonparametric analog of the mean. For this test, the TAB series needs to be ranked. The ranked TAB series is 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 pooled. 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:

$$U_1 = S_1 - n_1/2(n_1 + 1), \qquad U_2 = S_2 - n_2/2(n_2 + 1) \tag{3}$$

where $S_1$ and $S_2$ 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. For a moderately large sample size, the $U$ statistic follows the null distribution and is approximately Gaussian with

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

and

$$\sigma_U = [n_1 n_2 (n_1 + n_2 + 1)/12]^{1/2} \tag{4}$$

The value of $U$ thus corresponds to a standard Gaussian $z$ by using the formula:

$$z = (U - \mu U)/\sigma_U \tag{5}$$

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).

A third method uses conditional probabilities and is 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:

$$\Pr\{E_1|E_2\} \tag{6}$$

This states that we are finding the probability of E1 given that E2 has occurred, where E1 is the event in which a TAB value occurs above the median of the entire TAB series and E2 is a particular interval of KBDI. More formally, the conditional probability can be written:

$$\Pr\{E_1|E_2\} = \frac{\Pr\{E_1 \cap E_2\}}{\Pr\{E_2\}} \tag{7}$$

This equation states that the conditional probability is defined as the intersection of the event of interest ($E_1$) and the conditioning event ($E_2$) provided that the conditioning event is not zero.

## 5. Results

### 5.1. Characteristics of fire activity on the Hawaiian Islands

In this section, the nature of fire activity on the Hawaiian Islands is explored. Figs. 2 and 3 display histograms of TAB on monthly time scales for each of the four major islands. These graphs separate TAB values into different bins depending on the size of the fires. All of the islands show a large positive skewness. It can easily be seen that there are numerous fires of smaller size with a few fires on each island that are very large.

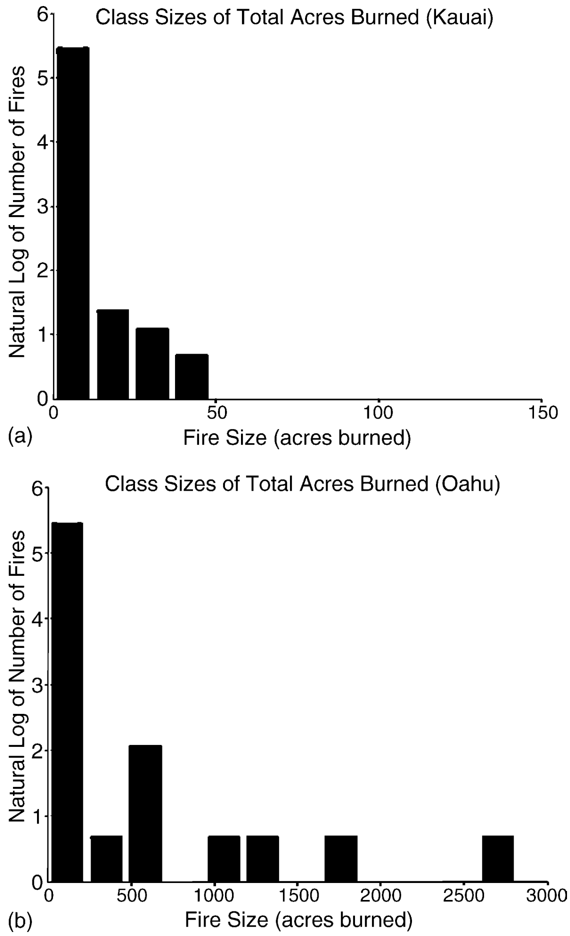


Fig. 2. Bar graph of the number of fires and the total acres burned by class size: (a) Island of Kauai (1976–1996) and (b) Island of Oahu (1976–1996).

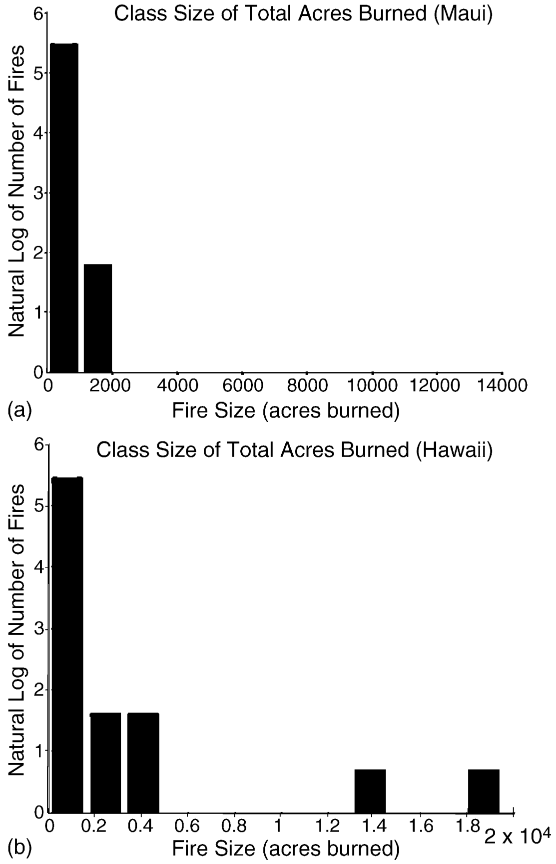


Fig. 3. Bar graph of the number of fires and the total acres burned by class size: (a) Island of Maui (1976–1996) and (b) Island of Hawaii (1976–1996).

Table 1 provides a summary of the statistics for the four major Hawaiian Islands. The median values of TAB in each case are fairly low ranging from 0 acres on the island of Kauai to 13 acres on the island of Hawaii. The positive skewness of the data can also be seen by comparing the mean TAB on each island with the median TAB (Table 1). In each case, with the exception of Kauai, the mean TAB is much higher than the median. Also of note are the relatively large standard deviations for the islands of Oahu, Maui, and Hawaii. This implies that the month-to-month variability in fire activity is very large for these islands. Kauai has the

Table 1
Statistics for monthly TAB values. Each of the four main Hawaiian Islands is displayed. Time series is from 1976–1996

| | Kauai | Oahu | Maui | Hawaii |
|---|---|---|---|---|
| Mean | 3.4 | 88.8 | 232.3 | 640.2 |
| Median | 0 | 1.6 | 3.1 | 13.0 |
| Standard deviation | 15.7 | 338.2 | 1076.1 | 2395.5 |
| Inner quartile range | 0.4 | 20.9 | 63.4 | 172.6 |
| Upper outer fence | 1.6 | 83.4 | 253.6 | 691.7 |
| Upper inner fence | 1 | 52.1 | 158.6 | 432.8 |
| Upper quartile | 0.4 | 20.9 | 63.4 | 173.9 |
| Lower quartile | 0 | 0 | 0.2 | 1.3 |
| Lower inner fence | 0 | 0 | 0 | 0 |
| Lower outer fence | 0 | 0 | 0 | 0 |

Table 2
The causes of wildfires and total acres burned for 1 year (1996)

| Wildfire and acres burned by causes | Number | Acres |
|---|---|---|
| Lightning | 2 | 2.2 |
| Campfire | 12 | 6.1 |
| Smoking | 14 | 18.3 |
| Debris burning | 18 | 37.4 |
| Arson | 21 | 106.1 |
| Equipment | 13 | 109.7 |
| Railroads | 0 | 0 |
| Children | 9 | 3.1 |
| Miscellaneous | 41 | 183.8 |
| Total | 130 | 446.7 |

The statistics are for all the Hawaiian Islands.

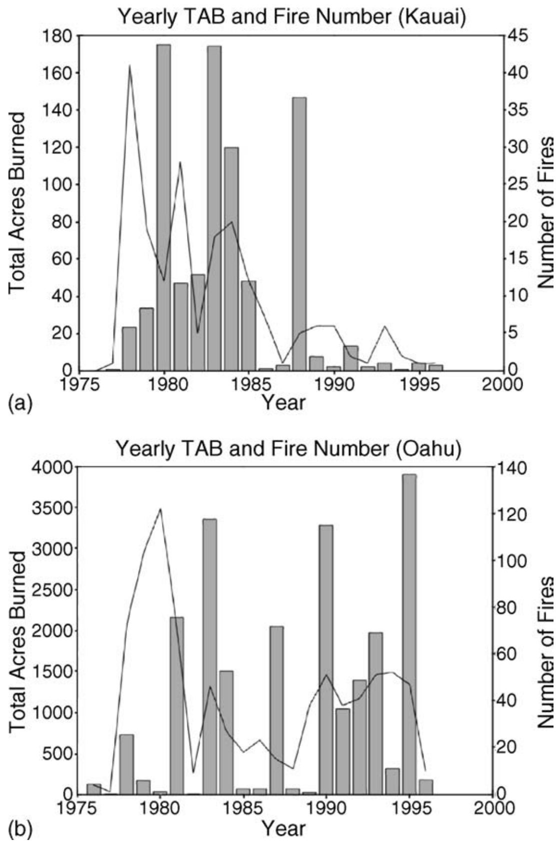


Fig. 4. Yearly time series of total acres burned (bars) and the number of fires (solid line): (a) Island of Kauai (1976–1996) and (b) Island of Oahu (1976–1996).

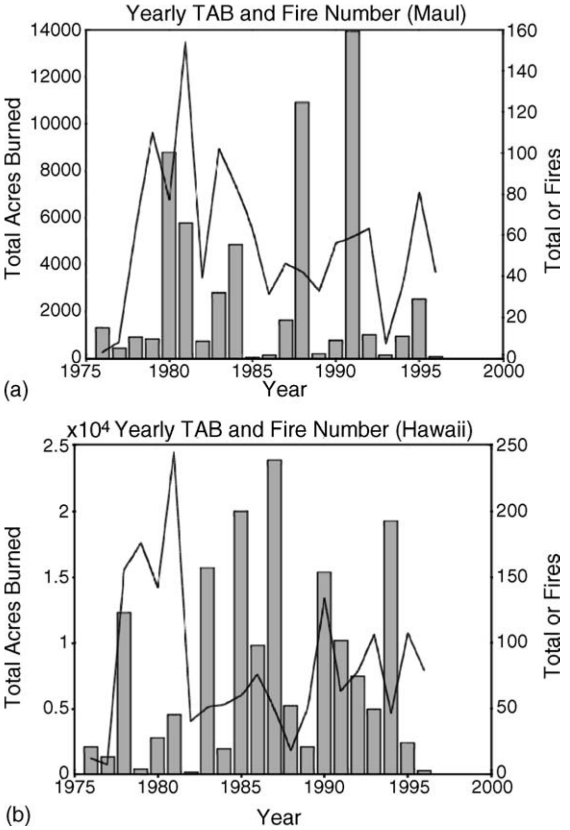


Fig. 5. Yearly time series of total acres burned (bars) and the number of fires (solid line): (a) Island of Maui (1976–1996) and (b) Island of Hawaii (1976–1996).

lowest fire activity and therefore low standard deviations.

Fire in the Hawaiian Islands can be a major hazard and is most often caused by human actions. Fires can threaten crops, wildlife, and personal property. As an example, Table 2 displays the causes and total area burned for all the islands for the last year of this study. Figs. 4 and 5 show the yearly TAB values and the yearly number of fires for each of the four major Hawaiian Islands. From these figures, it can be seen that there is large year-to-year variability in the amounts of TAB and less variability in the number of fires. Interestingly, some years with very large (small) values of TAB have small (large) numbers of fire occurrences. In Fig. 4b (Oahu), the year 1980 displays 120 fire occurrences, yet the total area burned is less than 100 acres.

### 5.2. The KBDI and its relationship to fire activity

With no fire index presently employed by the National Weather Service in Honolulu Hawaii, it is an important step to analyze a commonly used index to investigate its potential for predicting wildfire activity. The KBDI is a candidate measure, but it has not yet been tested against actual fire data.

Table 3
Pearson correlation of monthly KBDI (Keetch/Byram drought index) with the monthly number of fires on each island

| Island | Stations | $N_{eff}$ | $R$ (correlation) | $p$-Value |
|---|---|---|---|---|
| Kauai | Kanalohuluhulu, Lihue Airport | 88 | 0.170 | $1.13 \times 10^{-1}$ |
| Oahu | Waialua, Opaeula, Kaneohe Mauka, Waikiki, Honolulu Airport | 144 | 0.276 | $8.0 \times 10^{-3}$ |
| Maui | Kahului Airport, Kailua, Hana Airport, Haleakala RS, Lahaina | 95 | 0.427 | $1.0 \times 10^{-4}$ |
| Hawaii | Hilo Airport, Kulani Camp, Hawaii Volcano NP, Naalehu | 108 | 0.348 | $2.0 \times 10^{-4}$ |

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 probability values are also shown.

Table 4
Correlation of KBDI (Keetch/Byram drought index) with natural log transform of TAB (total acres burned)

| Island | Stations | $N_{eff}$ | $R$ (correlation) | $p$-Value |
|---|---|---|---|---|
| Kauai | Kanalohuluhulu, Lihue Airport | 120 | 0.167 | $6.8 \times 10^{-2}$ |
| Oahu | Waialua, Opaeula, Kaneohe Mauka, Waikiki, Honolulu Airport | 127 | 0.252 | $4.3 \times 10^{-3}$ |
| Maui | Kahului Airport, Kailua, Hana Airport, Haleakala RS, Lahaina | 125 | 0.399 | $1.0 \times 10^{-4}$ |
| Hawaii | Hilo Airport, Kulani Camp, Hawaii Volcano NP, Naalehu, Opihihale, Kainaliu | 209 | 0.311 | $1.0 \times 10^{-4}$ |
| **Kauai** | **Kekaha** | **122** | **0.215** | $\mathbf{1.7 \times 10^{-2}}$ |
| **Oahu** | **Honolulu AP** | **128** | **0.270** | $\mathbf{2.1 \times 10^{-3}}$ |
| **Maui** | **Lahaina** | **125** | **0.348** | $\mathbf{1.0 \times 10^{-4}}$ |
| **Hawaii** | **Naalehu** | **206** | **0.327** | $\mathbf{1.0 \times 10^{-4}}$ |

Time series consist of 20 years of data (1976–1996) with the exception of Kekaha, Kauai (1981–1996). Stations for each island's composite are shown. The four reference stations are shown in bold type. $N_{eff}$ is the reduced degrees of freedom due to the persistence of each time series. Correlation values and the corresponding probability values are shown.

*5.2.1. Correlations between the KBDI and fire activity*

The first approach involves the use of an ordinary Pearson correlation to investigate the relationship between KBDI and the number of fires on a monthly time scale. Table 3 contains a list of the stations used for the compositing of monthly mean KBDI values for each island. The results for Oahu, Maui, and Hawaii are all statistically significant with extremely low *p*-values. A *p*-value of 0.05 is the standard used for statistical significance. These islands display values well below the 0.05 level. This shows that there is a strong relationship between KBDI and the number of fires on a monthly time scale. Kauai is the only island where the KBDI is not correlated well with the number of fires. The *p*-values for Kauai are above the 0.05 threshold.

The Pearson correlation is also used to display the relationship between the composite KBDI and monthly mean TAB. Because of the non-normally distributed nature of the TAB as shown previously in Figs. 2 and 3, a log transform has been applied to the TAB data. Table 4 shows the results for this analysis. The results for Kauai display *p*-values above the 0.05 threshold. The strongest relationships are for the islands of Oahu, Maui, and Hawaii; these islands show *p*-values below the 0.05 level with Maui and Hawaii having values well below this threshold. Therefore, as the KBDI increases in value, the likelihood of more area burned by fires also increases. This cannot be said for the island of Kauai.

Scatter plots of the KBDI and TAB for each of the four island composites are shown in Fig. 6. The natural logarithm of TAB is used in the abscissa to display the data in a succinct manner. The plots for Maui and Hawaii display a clustering of points around a 45° line, indicating a more robust relationship between the KBDI and TAB than on the other two islands.

A further exploration of the connection between KBDI and TAB is warranted. One would expect fire to occur in the driest (leeward) areas of the island not in windward regions, which receive constant rainfall throughout the year. Historical records show that most

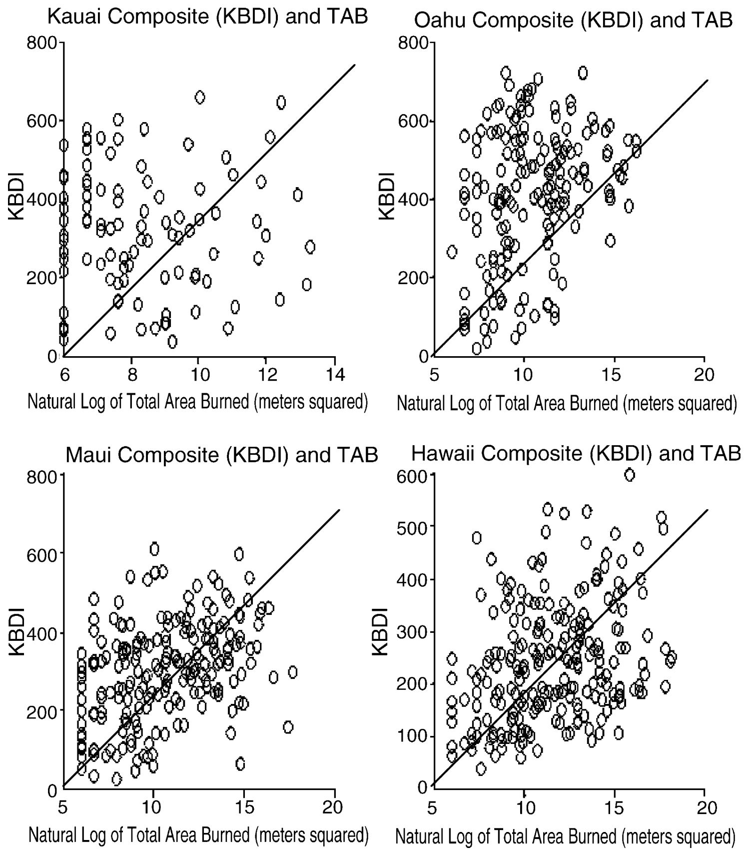


Fig. 6. Scatter plots of composites of island-wide KBDI and the natural log of total area burned ($m^2$). Composites are constructed for each of the four main islands from the stations listed in Table 1: (a) Island of Kauai (1976–1996), (b) Island of Oahu (1976–1996), (c) Island of Maui (1976–1996) and (d) Island of Hawaii (1976–1996).

fires occur in leeward (drier) areas (Chu, 2003). 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 wild-land fire danger is small (located in cities where there is a lack of forests or continuous fuels). They are, however, representative of the climate for the driest areas on each island.

When an ordinary Pearson correlation is applied to the natural log transform of island-wide TAB and the KBDI for driest station on each island, their $p$-values are equivalent or lower than with the composite method (Table 4). Every station displays $p$-values well below the 0.05 level. 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 area burned. Fig. 7a shows the scatter plot for one of these dry stations (Honolulu Airport on Oahu). A comparison of this dry leeward station with a wetter station can be made by viewing the scatter plot of KBDI and TAB for a typical windward station in Fig. 7b (Kaneohe on Oahu). These wetter stations do not display the same clustering of TAB values in the upper values of the KBDI. Because the dry stations represent the most fire prone areas of the island, they will be the focus of the investigation in the following sections.

### 5.2.2. Wilcoxon–Mann–Whitney rank-sum test

In addition to using a Pearson correlation, a nonparametric Wilcoxon–Mann–Whitney rank-sum test is used. This test is said to be the nonparametric version of a simple $t$-test. The 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.

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 5. The analysis consists of a 20-year period with the exception of Kekaha, Kauai, which has 15 years of fire 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.

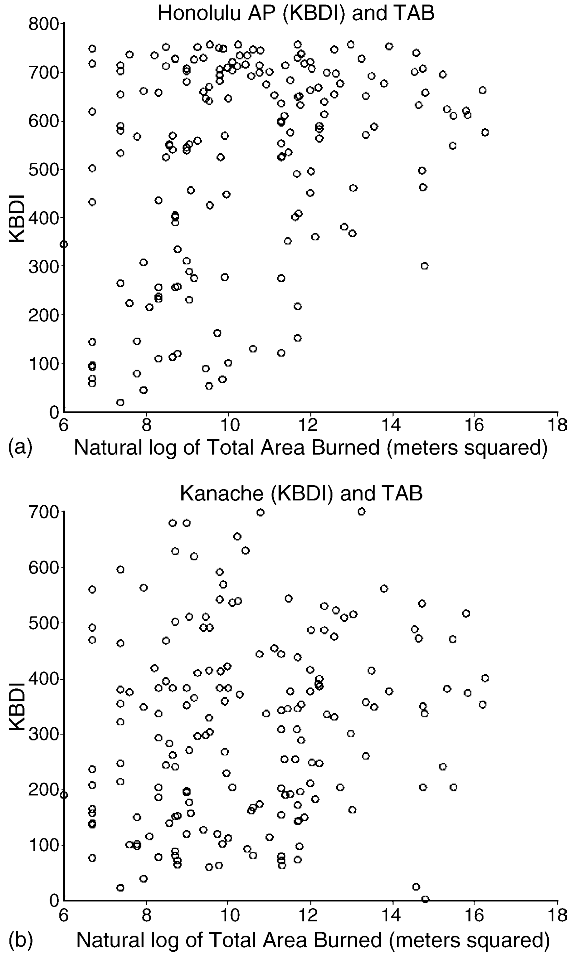


Fig. 7. Scatter plots of KBDI and the natural log of total area burned ($m^2$): (a) Honolulu Airport, Oahu (1976–1996) and (b) Kaneohe, Oahu (1976–1996).

### 5.2.3. 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

Table 5
Wilcoxon–Mann–Whitney rank-sum test for the four reference stations

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

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.

Table 6
Conditional probabilities of TAB values above the median value at four reference stations

| 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 |

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).

0 (saturated soil) to 800 (completely dry), an interval of 100 is naturally desired. The four reference stations listed in Table 4 are used. The conditional probabilities that the TAB values are above the median value are shown in Table 6. In each case, there is a general upward progression of probabilities. That is, as the KBDI values reach higher intervals, the probability of more months with TAB above the median is 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 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.

Another way to investigate the fire and KBDI relationship is shown in Figs. 8 and 9. The bar graphs display the median value of TAB for each interval of KBDI. They also display the relative probability of

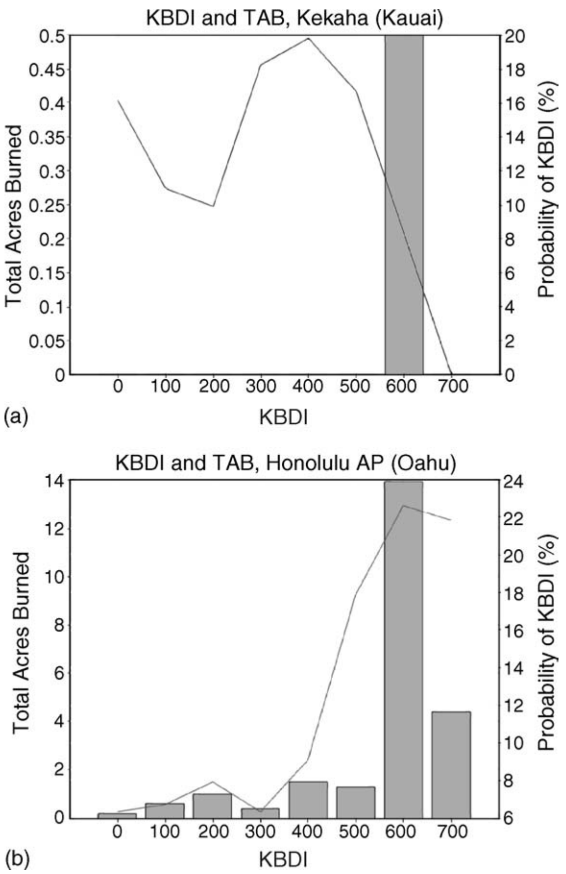


Fig. 8. Bar graph of total acres burned (TAB) and intervals of KBDI. Bars represent the median value of TAB for each interval of KBDI. Also shown is the probability distribution (KBDI) for each interval (solid line): (a) Kekaha, Kauai (1981–1996) and (b) Honolulu Airport, Oahu (1976–1996).

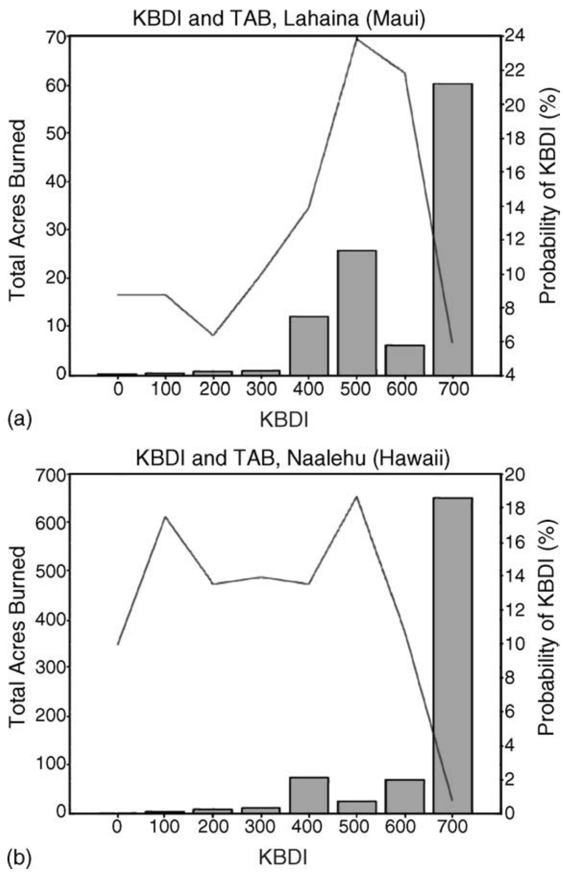


Fig. 9. Bar graph of total acres burned (TAB) and intervals of KBDI. Bars represent the median value of TAB for each interval of KBDI. Also shown is the probability distribution (KBDI) for each interval (solid line): (a) Lahaina, Maui (1976–1996) and (b) Naalehu, Hawaii (1976–1996).

having KBDI values in each interval (solid line). The probability distribution allows us to see the prevalence of certain monthly KBDI values for each interval. 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 highest probabilities are seen between KBDI values of 300 and 600. This helps to exclude the possibility that the high median value in the 600–700 interval is just an artifact of the distribution. 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. The only island, which might be suspect, is Oahu. Its probability distribution shows that there are many months with high KBDI and fewer months with low KBDI values. It is possible that this distribution has an effect on the median values of TAB.

## 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 monthly KBDI, averaged from stations, and total area burned (TAB) for four major islands, was investigated using a Pearson correlation. For the composite method, the confidence value for Kauai was not statistically significant. The strongest relationship between the KBDI and TAB was found for the islands of Oahu, Maui and Hawaii. The Pearson correlation was also used to investigate the relationship between the KBDI and the monthly number of fires on each island. For this test, all the islands were statistically significant.

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. Pearson correlations between TAB and the reference stations revealed statistically significant correlations for all of the islands. A nonparametric Wilcoxon rank-sum test was used to investigate the difference in locations between two TAB sub-samples based on the median of KBDI. The null hypothesis that the two TAB batches came from the same distribution was rejected at the 99% confidence (or $\leq 0.01$) level in each case. This helped to 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 the probability of reaching a TAB value above the median TAB at progressively higher values of KBDI.

The problem of testing KBDI in the Hawaiian Islands was complex considering the many micro-climates found on each island. Ideally, the index would be tested in a large area with a homogeneous climate regime. It is hoped that this research leads to more extensive testing of other fire indices in the Hawaiian Islands and to the possible implementation of a KBDI network that can give fire managers a better assessment of fire risk in an operational setting.

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## References

Chu, P.-S., 2002. Large-scale circulation features associated with decadal variations of tropical cyclone activity over the central North Pacific. J. Clim. 15, 2678–2689.

Chu, P.-S., 2003. Drought Risk and Vulnerability Assessment and GIS Mapping Project. Department of Meteorology, University of Hawaii, pp. 100–148.

Chu, P.-S., Yan, W.-P., Fujioka, F., 2002. Fire-climate relationships and long lead seasonal wildfire prediction for Hawaii. Int. J. Wildland Fire 11, 25–31.

Clark, J.D., Chu, P.-S., 2002. Interannual variation of tropical cyclone activity over the central North Pacific. J. Meteorol. Soc. Japan 80, 403–418.

Fujioka, F.M., 1991. Starting up the Keetch-Byram drought index. In: Proceedings of the 11th Conference on Fire and Forest Meteorology, Missoula, Montana, Soc. Amer. Foresters, Extended Abstract, pp. 74–80.

Giambelluca, T.W., Sanderson, M., 1993. The water balance and climate classification. In: Sanderson, M. (Ed.), Prevailing Trade Winds. University of Hawaii Press, pp. 56–72.

Heim, R.R., 2002. A review of twentieth century drought indices used in the United States. Bull. Am. Meteorol. Soc. 83, 1149–1165.

Johnson, M.B., Forthum, G., 2001. Spatial mapping of KBDI for the southeast United States. In: Proceedings of the 4th Symposium on Fire and Forest Meteorology, 13–15 November, Reno, Nevada, American Meteorological Society, Preprints, pp. 64–65.

Keetch, J.J., Byram, G.M., 1968. A drought index for forest fire control. USDA Forest Service Research Paper No. SE-38, pp. 1–32.

Quenouille, M.H., 1952. Associated Measurements. Butterworths, London.

Schroeder, T.A., 1993. Weather and climate in Hawaii. In: Sanderson, M. (Ed.), Prevailing Trade Winds. University of Hawaii Press, pp. 12–37.

Wilks, D.S., 1995. Statistical Methods in the Atmospheric Sciences. Academic Press, pp. 138–145.