11.7 THE VALIDITY OF THE KEETCH/BYRAM DROUGHT INDEX IN THE HAWAIIAN ISLANDS

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1. INTRODUCTION

The validity of using the Keetch/Byram Drought Index (KBDI) in the Hawaiian Islands is explored using various statistical analysis methods. 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.

Although the KBDI has been used for over thirty years, there has not been an extensive study of its relationship to fire activity and to climate patterns. This paper analyzes the KBDI and its application to fire activity in the Hawaiian Islands. Section two describes the KBDI at length. Sections three and four discuss the methods and data, respectively. Section 5 describes the relationship between KBDI and fire activity. Section six summarizes the results.

2. THE KEETCH/BYRAM DROUGHT INDEX

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

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

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

Note that the temperature factor has no effect unless the day's maximum temperature is above 50 ^{0}F (10^{0}C). If the net accumulated precipitation exceeds 0.20 inch, the excess reduces Q linearly. 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. The first assumption is that soil moisture is at field capacity with a water depth equivalent of 8 inches. The second assumption is that the rate of moisture loss in an area depends on the vegetation cover in that area, and vegetation density (and therefore its transpiration capacity) is a function of mean annual rainfall. Hence, daily transpiration is approximated by an inverse exponential function of the mean annual rainfall. Finally, the evaporation rate of soil moisture with time is assumed to be an exponential function of the daily maximum temperature (Keetch and Byram, 1968).

3. METHODS

A Spearman rank correlation, Wilcoxon-Mann-Whitney rank-sum test, and conditional probabilities are used to infer the relevance of KBDI to total acres burned (TAB). To perform a Spearman 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. For the Wilcoxon 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. These two data batches are then compared. Further explanation of the Wilcoxon-Mann-Whitney rank-sum test can be found in Wilks (1995). The conditional probabilities are based on intervals of KBDI and the corresponding monthly values of TAB. For each interval, we calculate the probability that a value of TAB occurs above the median of the entire TAB series.

4. DATA

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

Total acres burned (TAB) data were obtained from Hawaii's 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 Fig.1, for a twenty-year period (1976-1996). Monthly values of total acres burned were computed from daily reports for each island (Chu et al., 2002).

5. RESULTS

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Fire in the Hawaiian Islands can be a major hazard and are 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.

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 island wide KBDI values. Figure 1 displays a map of the Hawaiian Islands and the station locations. 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,

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

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. 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 larger areas burned by fires also increases.

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 less than with the composite method. 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 TAB values of zero. Therefore, for the months when the KBDI is high (low) at these dry stations, there are more (less) total months with fire activity and larger (smaller) amounts of total acres burned. The lack of a linear relationship between KBDI and TAB at the leeward stations is a probable source for the low Spearman correlations.

In addition to using a Spearman correlation, a 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 twenty-year period with the exception of Kekaha which has fifteen 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.

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 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.

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, averaged from stations, and total acres burned (TAB), for the four major islands, was investigated using a Spearman rank correlation. The strongest relationship between the KBDI and TAB was found for the islands of Maui and Hawaii. The significance 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 Wilcoxon rank sum 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 TAB values above the median 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.

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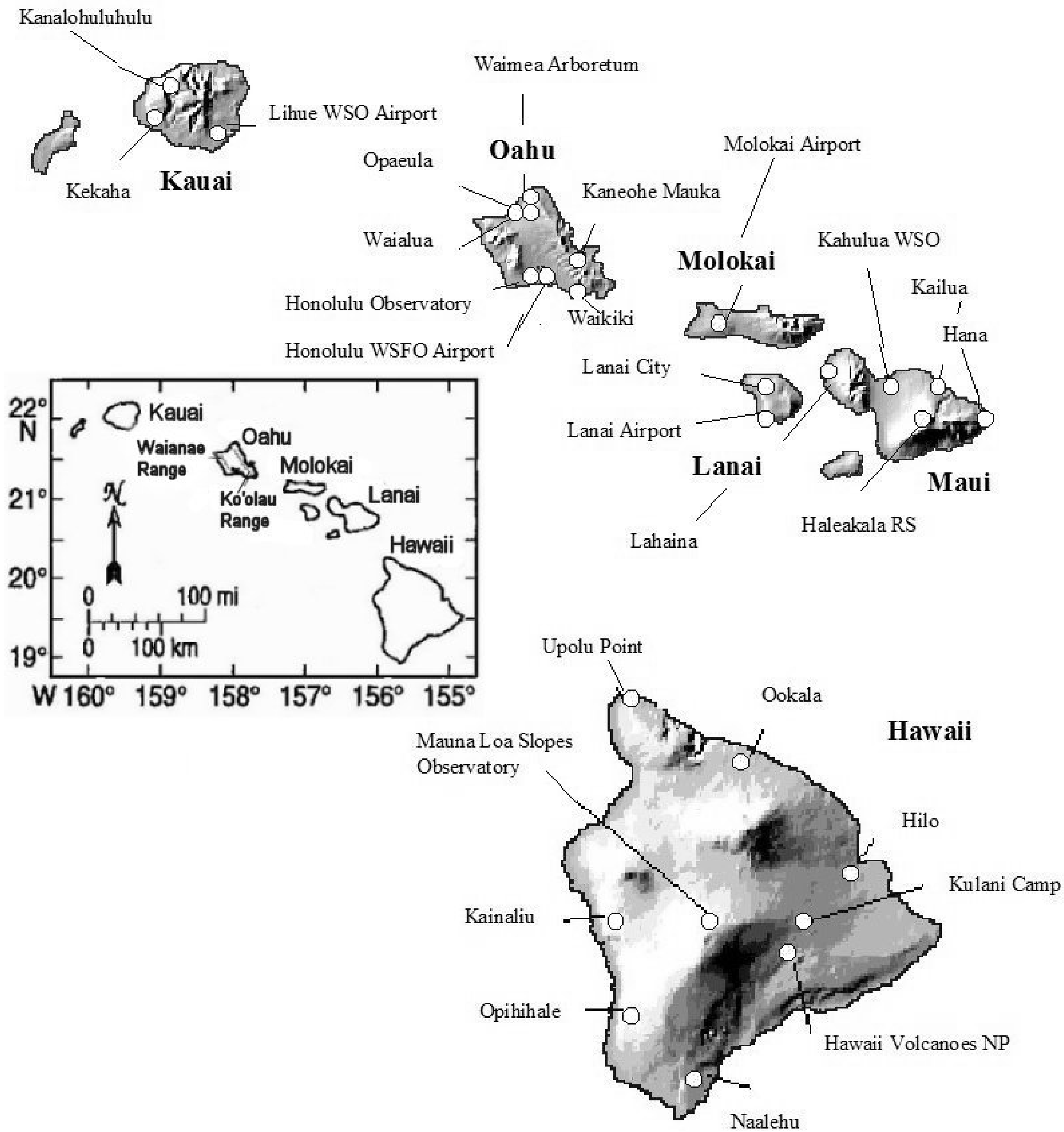

Figure 1. Map of the Hawaiian Islands and the 27 stations used for this study.

Island	Stations	N_{eff}	R (Spearman)	Confidence Level
Kauai	Kanalohuluhulu Lihue Airport	65	0.216	90%
Oahu	Waialua Opaeula 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 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 twenty-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.

Station	Median Value KBDI	Null Hypothesis (Alpha = 0.01)	p Value
Kekaha, Kauai	377.72	Rejected	0.000003
Honolulu AP, Oahu	575.05	Rejected	0.0000978
Lahaina, Maui	513.87	Rejected	0.000325
Naalehu, Hawaii	364.64	Rejected	0.00123

Table 2. Wilcoxon-Mann-Whitney rank-sum test for the four reference stations. Each station contains twenty-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.

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 4 reference stations. Times series consist of twenty-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).