Changes in precipitation extremes in the Hawaiian Islands under a warming climate

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Abstract

Five climate change indices related to extreme precipitation events in the Hawaiian Islands are investigated using daily observational records from the 1950s to 2007. These indices are suggested by WMO/CLIVAR program. The annual probability density functions of precipitation indices for two epochs (i.e., 1950-1979, and 1980-2007) are compared. Since the 1980s, there has been a change in the types of precipitation intensity, resulting in more frequent light precipitation, and less frequent moderate and heavy precipitation intensity. The frequency and magnitude of precipitation extremes demonstrate a shift toward the left of the distribution over time, suggesting shorter annual number of days with intense precipitation, and smaller consecutive 5-day precipitation amounts and smaller fraction of annual precipitation due to events exceeding the 1961-1990 95^{th} percentile in the recent epoch relative to the first epoch.

A nonparametric trend analysis is then performed for four time periods, with different starting years (e.g., the 1950s, the 1960s) but the same ending year (2007). Long-term downward trends are evident for four precipitation-related indices, and long-term upward trends are observed for the drought related index. To investigate whether the trends are stable throughout the time, the derivatives of trends for each of the 30-year running series are calculated (e.g. 1950-1979, 1951-1980, to 1978-2007) for four precipitation-related indices at each station. For Kauai and Oahu, positive derivatives prevail for all indices in the presence of long-term negative trends, suggestive of a phase change in precipitation extremes and such extremes showing an upswing recently. For the Island of Hawaii, there is also an indication of phase reversal over last 60 years with negative derivatives occurring in the presence of the background positive trends.
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Key words: climate change indices related to precipitation extremes, Hawaii, time-dependent trends

1. Introduction

It is well known that the planet Earth is undergoing an unprecedented warming process since the Industrial Revolution. According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007), the rate of the global average surface temperature increases by 0.074°C±0.018°C per decade over the past 100 years (1906-2005). Since 1981, the rate of warming is faster with a value of approximately 0.177°C±0.052°C per decade. Consistent with the global warming trend, Hawaii temperature experienced an upward trend as well.

Under this warming background, it is expected that extreme events in temperature and precipitation such as heat waves and heavy rainfall are changing over time. The occurrence of extreme events is usually a concern for the society because of their potential damage to humans, property, public infrastructure, agriculture, and others. To better monitor and understand the variations of extreme events, the Climate Variability and Predictability (CLIVAR) program, an international research entity under the World Meteorological Organization/World Climate Research Program has developed a suite of climate change indices. These indices are also widely accepted tools to estimate simulation results from climate models, as exemplified by the AR4 of IPCC. In this study, for the first time, five of the core climate change indices suggested by CLIVAR are applied to Hawaii daily precipitation data to investigate the possible changes of extremes.

2. Climate change indices

Five of the twenty seven indices defined by the joint CLIVAR have been included in this research. This set of indices covers not only different aspects of precipitation, such as intensity, frequency and magnitude, but also dryness conditions. The definitions of the indices used her are given in Table 1.

In Table 1, the simple daily intensity index (SDII) estimates the average wet day precipitation intensity. For simplicity, it is also called as precipitation intensity. The R25, a threshold index, provides frequency of significant precipitation, and R5d is the absolute maximum consecutive 5-day precipitation value. Similar to R5d, another index related to the magnitude of intense rainfall is the percentile-based R95p. These four indices are related to the wetness conditions. The fifth index, CDD, defines duration of excessive dryness.

Table 1. Definition of the five indices for precipitation extremes.

Index	Definition	Unit
SDII	Average precipitation intensity in wet days	mm/day
R25	Annual total number of days with precipitation ≥25.4 mm	days
R5d	Annual maximum consecutive 5-day precipitation amount	mm
R95p	Fraction of annual total precipitation due to events exceeding the 1961-90 95th percentile	%
CDD	Annual maximum number of consecutive dry days	days

3. Temporal and spatial characteristics of climate change indices

The annual probability density functions (PDFs) for all the five indices are shown in Figs. 1a-e. To see the difference in precipitation characteristics over the last six decades, the overall dataset is separated into twonear-30-year epochs, 1950-1979 and 1980-2007. Fig. 1a shows a pronounced drop and shift to the left in the PDF peaks from the early to the recent epoch, implying the frequency of average precipitation intensity has decreased with time. From the empirical data, the average precipitation intensity can be roughly classified into three groups, with light intensity being less than 10 mm/day in wet days, moderate intensity being 10 to 15 mm/day, and high intensity being larger than 15 mm/day. Overall there is a decrease of average moderate and high precipitation intensity and a concomitant increase of light precipitation intensity over time.

For R25 (Fig. 1b), the dominant feature is the shift in the distribution toward the left with time, from a less skewed distribution in the early epoch to that of a strongly skewed one in the second epoch. Specifically, the frequency of annual days with greater than 25.4 mm daily rainfall cluster in the range between 6 to 24 days has decreased from the first to the second epoch. Similarly, the PDFs of R5d (Fig. 1c) display a reduction in the frequency of annual maximum consecutive 5-day precipitation amount in the range between 200 to 400 mm from the early to the recent epoch. This decrease is compensated for by an increase in the peak of the distribution. The changes for R95p in Fig. 1d are less clear than the other three wetness indices; however, on the right side of the PDF, the decrease in the frequency of the fraction of annual total precipitation due to events exceeding the 95th percentile is evident from the first to the recent epoch.

In summary, the shift in PDFs shown in all four wetness indicators is qualitatively consistent with Chu and Chen (2005), in which they noted a descending trend in Hawaii Rainfall Index (HRI) during the last century. The monthly rainfall data from nine stations on each of the three islands, Kauai, Oahu and the Island of Hawaii, were used to construct the HRI. These stations are also arranged at various elevations (i.e., high medium, and low) and different locations in regard to the direction of prevailing trade wind (i.e., windward, leeward, and neutral). HRI approximates the average conditions of monthly or seasonal Hawaii rainfall. Therefore, not only precipitation totals but also extreme precipitation in Hawaii has undergone a long-term downward shift.

As for CDD (Fig. 1e), the location of the peak for two epochs varies slightly and is found to be around 9 to 11 days. There is a marked decrease in the peak distribution with time. This indicates that the frequency of occurrences of the annual maximum number of consecutive dry days near the peak is smaller in the most recent period. Also note a higher percentage of occurrences on the right side of the distribution for the most recent epoch, implying that the annual maximum number of consecutive dry days from 35 to 80 days tends to occur more often in the last three decades.

While the results presented in Fig. 1 reveal qualitatively a shift of PDFs, there is a concern whether the change of the number of stations would influence the corresponding distribution of the PDFs. For this purpose, a two-sample K-S test is applied. For the time period of 1980-2007, two batches of data with different station numbers are sampled. That is, one batch is based on the number of stations identical to the first epoch and the other is just the number of stations available in the recent epoch. For this case, the time period is fixed (i.e. 1980-2007). Our results (not shown) show that, for every data set pairs, the null hypothesis that they were drawn from the same distribution cannot be rejected at the 5 % level. This implies that the change of station numbers, which are associated with the difference in sample sizes, does not influence the underlying distribution of the data set. The two-sample K-S test also can be used to determine whether the PDFs of the two different epochs follow the same distribution. For this test, the data sets compared are two different time periods (1950-1979 verses 1980-2007). Results from the K-S test indicate that for all the five indicators, except

R95p, the null hypothesis can be rejected at the 5 % level, which means there are significant changes in the distributions from one epoch to another.

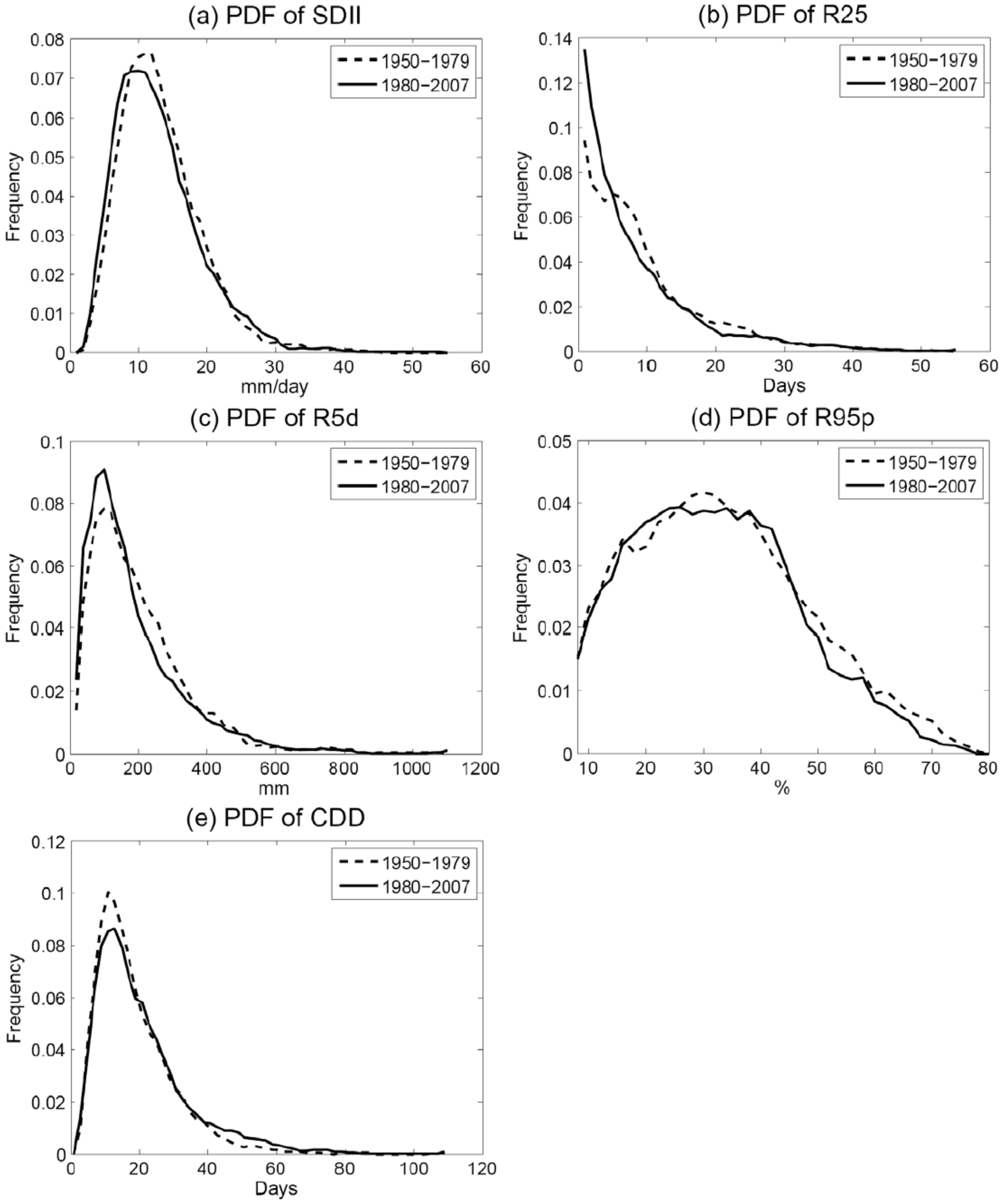

Fig. 1. Annual probability density functions (PDF) for (a) SDII, (b) R25, (c) R5d, (d) R95p and (e) CDD between 1950 and 2007 (winter season) for the two periods: 1950-1979 (dashed line) and 1980-2007 (solid line). The units of SDII, R25, R5d, and CDD are mm/day, days, mm, and days, respectively.

As aforementioned, there are significant shifts in the statistical distributions of four of the five indicators. In order to better understand long-term fluctuations in precipitation extremes, a nonparametric trend analysis is applied to records of varying length as trend statistics are sensitive to the time windows chosen. If the statistical significance is not considered, then a large percentage of stations (60-80%) would show downward trends in precipitation-related indices corresponding to various time periods, and upward trends for CDD. While the percentages of stations with significant positive and negative trends corresponding to various time periods for all five indices are given in Fig. 2. In the trend analysis, the last year is fixed to be 2007 but the starting year is not because each station begins its observation differently. Instead of using the same starting year which would limit the number of gages used, we use, say the 1950s, for all gages which show records starting in the 1950s. Hence, the 50s stand for the time period from the 1950s to 2007, and the 60s represent the time period from the 1960s to 2007, etc (Fig. 2).

In a given dataset, one would expect a certain number of stations or grids to pass a significant test at random. To ensure the significance at individual stations is not due to random chance, multiple testing is performed to investigate the field significance (the so-called multiplicity problem). That is, it is also necessary to address the collective significance of a finite set of individual significance tests for the entire field

(Chu and Wang, 1997). Assuming spatial independence, a binomial probability distribution can be used to evaluate the overall significance of the trends.

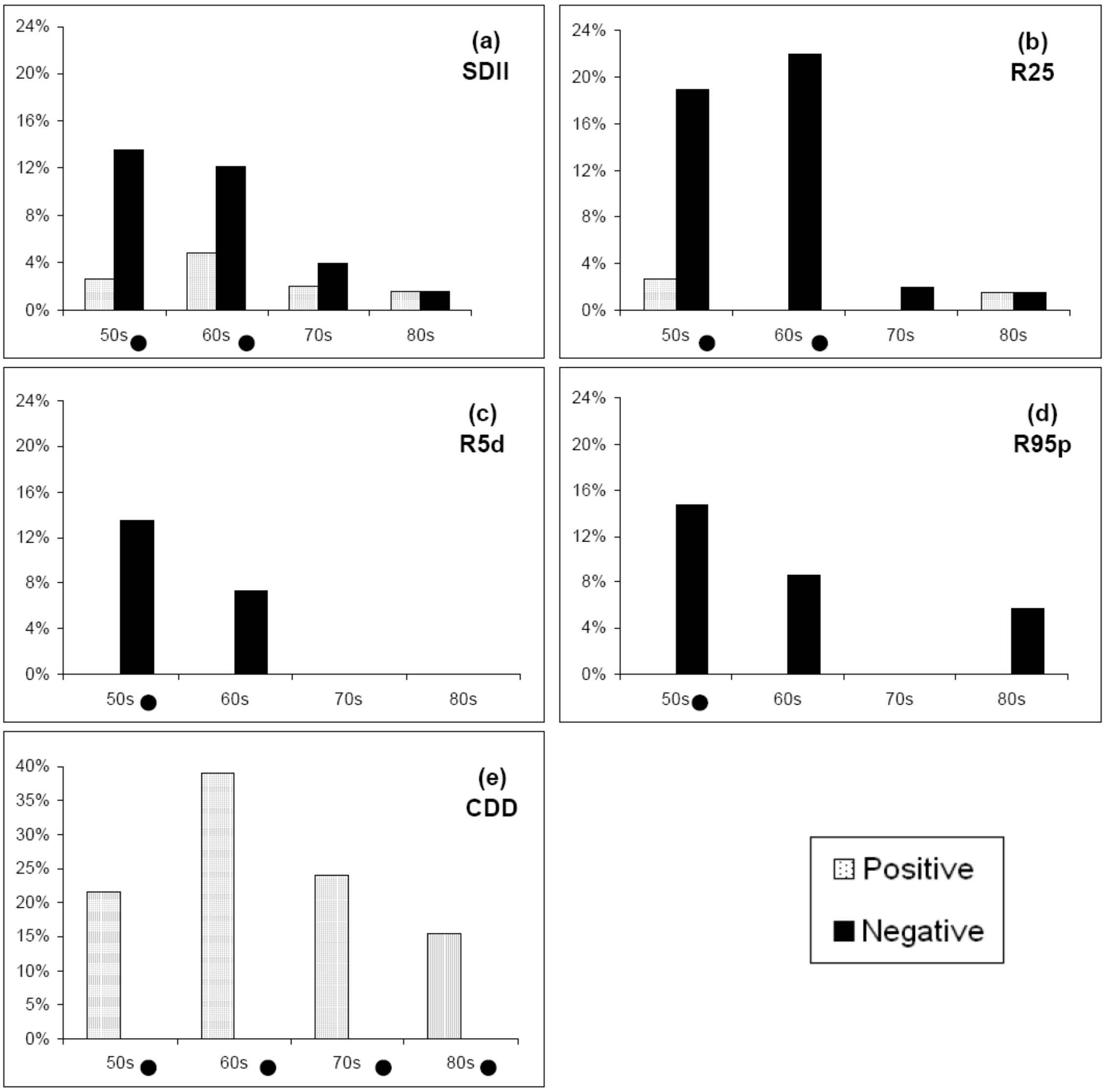

Fig. 2. Percentage of stations with positive or negative trend significant at the 10% level in different time periods for each indices, (a) SDII, (b) R25, (c) R5d, (d) R95p and (e) CDD, winter season. 50s stands for the period from the 1950s to 2007, 60s means from the 1960s to 2007, etc. Solid circle on the right of the time at bottom means field significant at the 5% level.

From the 1950s to 2007 or from the 1960s to 2007, for all four indices associated with precipitation extremes, including SDII, R25, R5d and R95p (Figs. 2 a-d), downward trends prevail. Take SDII as an example (Fig. 2a). For the time periods from the 1950s to 2007 and from the 1960s to 2007, about 13% of the stations have significant negative trends, while only around 4% show significant positive trends. This feature slightly becomes more pronounced in R25 (Fig. 2b), which is related to the frequency of intense precipitation events. From the 1950s to 2007, approximately 20% of the stations are characterized by significant negative trends. Moreover, significant negative trends are predominant from the 1960s to 2007 as almost 22% of stations (e.g. 9 stations) fall in this category (Fig. 2b). Similarly, for the two indices associated with the magnitude of most intense precipitation events (i.e., R5d and R95p), the percentage of significant negative trend in R5d reaches about 14% (Fig. 2c) and about 15% for R95p from the 1950s to 2007 (Fig. 2d). This suggests that for some stations in Hawaii, extreme precipitation has experienced a significant long-term downward trend. Results from multiple test suggest that all the downward trends from the 1950s to 2007 reach field significance for all four indices, and from the 1960s to 2007 two indices (SDII and R25) achieve field significance.

Another salient feature in Fig. 2 is the decrease of the percentages of significant negative trends from the earlier to the latter epochs. In other words, in the more recent decades stations are inclined to exhibit fewer negative trends or the percentages of positive and negative trends tend to be comparable. This transition appears to occur around the period in the 1970s (Fig. 2a-c). Interestingly, this occurs in the presence of a long-term downward trend in precipitation extremes since the 1950s. Note that the aforementioned positive and negative trends since the 1970s don't reach field significance according to multiple testing. However, as the analysis period shortens, unforced natural variability becomes a greater factor when considering trends; more research need to be done to investigate this feature.

The CDD, which represents drought conditions, shows significant positive trends for all time periods and the trends of all the time periods reach field significance (Fig. 2e). One noteworthy feature is a gradual drop in the percentage of the significant positive trends in the last two time periods. As discussed before, whether this suggests that there are fewer areas with longer annual maximum consecutive dry days since the 1970s needs to be studied in the future.

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