Precipitation Extremes in the Hawaiian Islands and Taiwan under a changing climate

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Outline

1. Spatial distribution of extreme precipitation events

2. Trends in climate change indices related to precipitation (Hawaii and Taiwan)

3. Changes in return levels under climate change
Heavy rainfall events are common in Hawaii

- The interaction of synoptic systems (e.g., fronts, kona storms) with local topography often results in heavy rainfall events in Hawaii that cause damage to properties, agriculture, and public facilities (e.g., the Halloween flood of 2004 at the UH-Manoa, the 2006 flood events, the December 2008 flood on Oahu and Kauai, the December 2010 floods).

- Pollutants carried away by stream flows during heavy rainfall events are one of the major threats to near-shores marine ecosystems, especially coastal coral reefs.

Kodama and Barnes, 1997, Wea. & Forecasting

Morrison and Businger, 2001, Wea. & Forecasting

Lyman, Schroeder, and Barnes, 2005, Wea. & Forecasting

Zhang, Chen, Hong, Juang, and Kodama, 2005, Wea. & Forecasting

Tu and Chen, 2011, Wea. & Forecasting

Synoptic analysis of heavy rainfall events
1. Mapping heavy rainfall events

Three different ways of defining heavy rainfall events on the mainland U.S. from climatological perspectives (e.g., Groisman et al., BAMS, 2001).
1. The mean annual number of days on which 24-h accumulation exceeds a given daily rainfall amounts (e.g., 50.8 mm/d for heavy rainfall and 101.6 mm/d for very heavy rainfall)

2. The value associated with a specific daily rainfall percentile (e.g., 90\textsuperscript{th} percentile for heavy rainfall and 99\textsuperscript{th} percentile for very heavy rainfall)

3. The annual maximum daily rainfall associated with a specific return period (e.g., 2-yr for heavy rainfall and 20-yr for very heavy rainfall)
What is the return period?

- The return period, also known as recurrence interval, is interpreted to be the average time between occurrence of events of that magnitude or greater. It is commonly used for engineering design and risk analysis. For example, a 100-yr flood has a 1% chance of being exceeded in any one year.
Estimated return periods of heavy rainfall using annual maximum daily rainfall and a stationary generalized extreme value (GEV) distribution.
• We choose the largest single daily values in each of n years as our database – also known as the block maximum by climate scientists and hydrologists.

• Block maximum vs peaks-over-threshold (POT) approach (to assemble the largest m values regardless of their years of occurrence, i.e., any values larger than a threshold are chosen)
Block maximum approach (annual maximum daily rainfall)

(a) Precipitation frequency at HONOLULU OBSERV, Oahu

(b) Precipitation frequency at NAALEHU 14, Hawaii
Figure 1. Location of the cooperative stations used in this study. The dark circles represent stations and the numbers are the station IDs, with the numbers shown on the maps.

Contour interval: 500 meters
Estimated return periods of heavy rainfall in Hawaii using annual maximum daily rainfall and a stationary generalized extreme value (GEV) distribution. The GEV distribution is fit using the method of L-moments (the expected values of order statistics, see Hosking and Wallis, 1997).

Spatial patterns of heavy rainfall events are mapped for each island. An inverse-distance weighted interpolation scheme is used and the kriging method is chosen for comparison. Caution is exercised in areas where stations are sparse.
The GEV distribution has been used to describe the statistics of extremes in observed hydrometeorological variables and in GCM simulations (e.g., Katz et al., 2002; Kharin and Zwiers, 2005). The GEV model has 3 parameters: the location, scale, and shape parameter.

The commonly used two-parameter extreme value distribution (i.e., Gumbel) is a special case of the GEV when the shape parameter approaches zero.
Leopold, 1949; Garrett, 1980; Chen and Nash, 1994 (diurnal rainfall variation due to an interaction among orographic uplifting, thermal forcing, and island blocking of the trade winds)
Very Heavy Rainfall Events (mm)
20 Year Return Period

25 mm contour intervals

greater than 275mm areas are shaded
Summary for Part 1

- Three different ways of defining extreme rainfall events in Hawaii
- A GEV model is used to estimate return periods for a given rainfall intensity
- Qualitatively similar results are obtained: a concentration of high heavy rainfall events at lower elevations along the windward slopes of the mountains below the trade-wind inversion and a low number of events in the leeward areas (i.e., rain-shadow effects) and atop the high mountains.
2. Trends in climate change indices in Taiwan and Hawaii

- Long-term winter (Nov-Mar) rainfall variations in Hawaii from 1905 to 2009
- HRI stands for the Hawaii Rainfall Index (9 stations from each of three islands, Kauai, Oahu, and Hawaii) – Bernie Meisner
- The original rainfall data are standardized (Chu and Chen, 2005)
### Definition of the four climate change indices (WMO/CLIVAR)

<table>
<thead>
<tr>
<th>Perspective</th>
<th>Index</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity</strong></td>
<td>SDII</td>
<td>Average precipitation intensity in wet days</td>
<td>mm/day</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>R25 or R50</td>
<td>Annual total number of days with precipitation ≥25.4 (50.8) mm</td>
<td>days</td>
</tr>
<tr>
<td><strong>Magnitude</strong></td>
<td>R5d</td>
<td>Annual maximum consecutive 5-day precipitation amount</td>
<td>mm</td>
</tr>
<tr>
<td><strong>Magnitude</strong></td>
<td>R95p</td>
<td>Fraction of annual total precipitation due to events exceeding the 1961-90 95th percentile</td>
<td>%</td>
</tr>
<tr>
<td><strong>Drought</strong></td>
<td>CDD</td>
<td>Annual maximum number of consecutive dry days</td>
<td>days</td>
</tr>
</tbody>
</table>

The first three indices are related to the wetness conditions; CDD defines the duration of excessive dryness.
The overall data set is split into 2 epochs, Hawaii.

**Table 3.** Percentage of light, moderate, and high PRCP intensity during the two near-30-yr periods, 1950–1979 and 1980–2007, winter season.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>1950–79 (%)</th>
<th>1980–2007 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (&lt;10 mm day⁻¹)</td>
<td>27.08</td>
<td>32.94</td>
</tr>
<tr>
<td>Moderate (10–15 mm day⁻¹)</td>
<td>44.09</td>
<td>39.56</td>
</tr>
<tr>
<td>High (&gt;15 mm day⁻¹)</td>
<td>28.83</td>
<td>27.50</td>
</tr>
</tbody>
</table>
Used a nonparametric Mann-Kendall method with the Sen’s test (MKS) to investigate trends in precipitation extremes (e.g., SDII, R5d, CDD).

In contrast to the common linear regression, the advantages of the MKS approach is that the underlying data need NOT to conform to any probability distribution and missing data are allowed. Also the MKS is robust against outliers and skewed distribution (a robust trend detection method).
Downward trends in SDII and R25 for Kauai and Oahu (Rainfall became less intense since 1950)

Upward trends in SDII for Big Island

Winter (rainy season)

Long-term Spatial Features

Trends from the 1950s to 2007 triangles:

- Downward trends in SDII and R25 for Kauai and Oahu (Rainfall became less intense since 1950)
- Upward trends in SDII for Big Island
For CDD, positive trends prevail. Most islands tend to show longer, consecutive periods of no precipitation days since 1950s.
Figure 3. Spatial distribution of the Sen’s slopes for (a) SDII, (b) R50, (c) R5d, and (d) CDD from 1950 to 2010. Triangles and circles denote the location of stations. Upward (downward) hollow triangles indicate positive (negative) direction of trends and their size corresponds to the magnitude of trends. Light (solid) filled-in triangles indicate trends significant at the 10% (5%) level.
Figure 4. Spatial distribution of the Sen’s slopes for (a) SDII and (b) SDII and (c) R50 from typhoon-induced precipitation, and (d) R50 from monsoon-induced precipitation. The period of analysis is July–October from 1950 to 2010. Triangles and circles denote the location of stations. Upward (downward) hollow triangles indicate positive (negative) direction of trends and their size corresponds to the magnitude of trends. Light (solid) filled-in triangles indicate trends significant at the 10% (5%) level.
Summary for Part 2

- Trends of four climate change indicators are examined over the last 60 years in Hawaii. Results reveal a regional (E-W) pattern. Oahu and Kauai are dominated by long-term downward trends for 3 precipitation related indices, while increasing trends (SDII, R5d) are noted over the Big Island. Long-term upward trends of drought conditions (CDD) are observed on all the major islands.

- For Taiwan, upward trends in precipitation intensity (SDII) and 5-d precipitation amounts (R5d) during the typhoon season prevail from 1950 to 2010. Longer drought duration is noted, in Southern Taiwan in particular. Precipitation intensity induced by both typhoons and monsoon systems has both increased; these two components collectively contribute to strong upward trend in precipitation intensity during the typhoon season.
3. Estimating trends in return levels using a non-stationary GEV model, which tacitly assumes that precipitation extremes are changing with time as the climate changes.
• For a stationary GEV, a cumulative distribution function given by

\[
G(z) = \exp \left\{ - \left[ 1 + \xi \left( \frac{z-\mu}{\sigma} \right) \right]^{-\frac{1}{\xi}} \right\}, \quad 1 + \xi \left( \frac{z-\mu}{\sigma} \right) > 0
\]  

(1)

• where \( \mu, \sigma \) and \( \xi \) are the location, scale, and shape parameter, respectively.

• Estimates of the extreme quantiles, known as the return level \( z_p \), corresponding to the return period \( (\tau) \) where \( p \) is the probability of occurrence

\[
\tau = \frac{1}{p}
\]  

(2)

\[
z_p = \mu - \frac{\sigma}{\xi} \left[ 1 - \left\{ -\log(1 - p) \right\}^{\frac{1}{\xi}} \right], \quad \xi \neq 0
\]  

(3)
For the non-stationary GEV,

\[ \mu_t = \mu_0 + \mu_1(t - t_0), \]  
\[ \log \sigma_t = \sigma_0 + \sigma_1(t - t_0), \quad \xi \text{ is constant.} \]  

The return level \( z_p \) becomes

\[ z_p = \mu_0 + \mu_1(t - t_0) - \frac{\exp[\sigma_0 + \sigma_1(t - t_0)]}{\xi} \left[ 1 - \left\{ -\log(1 - p) \right\}^{-\xi} \right], \quad \xi \neq 0 \]

It is now obvious that the location and scale parameters and the return level \( z_p \) are also a function of time.
Spatial pattern of trends for location parameter $\mu$ for 1-day maximum precipitation according to non-stationary GEV distribution. Triangles denote the locations of the individual stations. Upward (downward) triangles indicate positive (negative) direction of change, and their size corresponds to the magnitude of trends. Black triangles indicate trends significant at the 5% level. Field significance is reached for Oahu.
Spatial pattern of trends for scale parameter $\sigma$ for 1-day maximum precipitation according to non-stationary GEV distribution.
Trends of return levels for 1-day maximum precipitation at (a) MOANALUA 770, Oahu, (b) HAWAII VOL NP HQ 54, Hawaii, according to non-stationary GEV. The solid, dashed, and dash-dot lines represent the 2-yr, 20-yr, and 100-yr return levels, respectively. The circles stand for observational data.

230 mm in 1960 to 102 mm in 2009

300 mm in 1960 to 420 mm in 2009

An event with a 20-yr recurrence interval threshold values in 1960 has occurred once every 4 to 5 years by 2009
Spatial pattern of trends for non-stationary GEV return level for 1-day maximum precipitation at 20-yr return period. Triangles denote the locations of individual stations. Upward (downward) triangles indicate positive (negative) direction of change, and their size corresponds to the magnitude of trends. All the trends are significant at 5% level. Field significance is reached.
Summary for Part 3

- A non-stationary GEV model is recently developed to examine trends in return levels for annual maximum 1-day precipitation amounts since 1960.

- The return-level threshold values are also found to change with time. For example, a rare storm with daily rainfall of 300 mm (20-yr return period) in 1960 has become a less rare event (4 to 5 yr return period) in 2009 on the Big Island.
Impact of this study

- In the engineering design (e.g., urban drainage) and environmental regulations in Hawaii and perhaps in Taiwan, return-period rainfall amounts are assumed to be constant at a given threshold level (e.g., 20-yr return level). Because climate is changing, this assumption of stationary precipitation climatology should be revisited.

- Need to modify existing facilities and safety preparation (e.g., reservoirs, dams, high-impact structures) as heavy rainfall and flooding are common in Hawaii and Taiwan.
References


Review

Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate

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Thank you!

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