ONLINE RAINFALL ATLAS OF HAWAI'I

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Interaction among trade winds, terrain, land thermal effects, and the trade-wind inversion give the Hawaiian Islands one of the most varied rainfall patterns on Earth. Distinct, persistent patterns of uplift lead to dramatic rainfall gradients and, together with elevation-related temperature differences, produce nearly the full range of climate types. This microcosm of global environmental diversity provides a unique natural laboratory for world-class research on topics such as terrestrial ecosystem carbon dynamics, soil geochemistry, and the mechanics of species invasion. Knowledge of mean rainfall patterns in Hawai'i is critically important in support of these research endeavors as well as for managing and protecting groundwater and surface water resources, controlling and eradicating invasive species, protecting and restoring native ecosystems, and planning for the effects of global climate change.

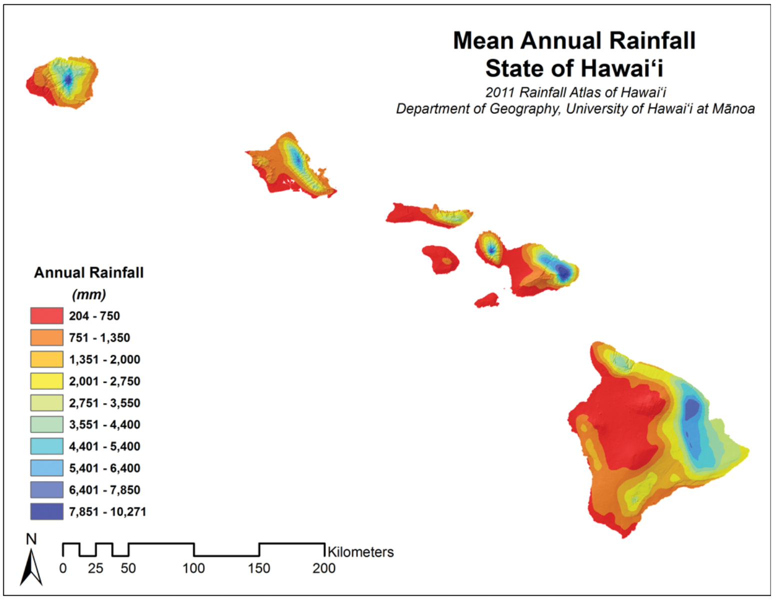

FIG. 1. Color choropleth map of Hawai'i mean annual rainfall.

The Rainfall Atlas of Hawai'i is a set of digital maps of the spatial patterns of 1978–2007 mean monthly and annual rainfall for the major Hawaiian Islands (Fig. 1). For every map of mean rainfall, a corresponding map of uncertainty is also provided. Access to the rainfall maps, data, and related information is available via the Rainfall Atlas of Hawai'i website (http://rainfall.geography.hawaii.edu). Maps can be downloaded as images (color ramp or isohyets), GIS grid (raster) files or shapefiles (isohyets), or Google Earth files. Tabular data include the station monthly data, 30-year means and uncertainties, and station information. The website also has an interactive map (Fig. 2) allowing users to see the patterns of mean monthly and annual rainfall and corresponding uncertainty, zoom in on areas of particular interest, navigate to specific locations with the help of a choice of different base maps, and click on any location to get the mean annual rainfall (Fig. 3) and a graph and table of mean monthly rainfall. The locations of stations can also be shown on the interactive map. Clicking on a station gives both station and mapped estimates of monthly rainfall along with station metadata.

Efforts to map the spatial patterns of rainfall in Hawai'i began as early as the 1920s (see the "History" tab on the Rainfall Atlas of Hawai'i website). As the

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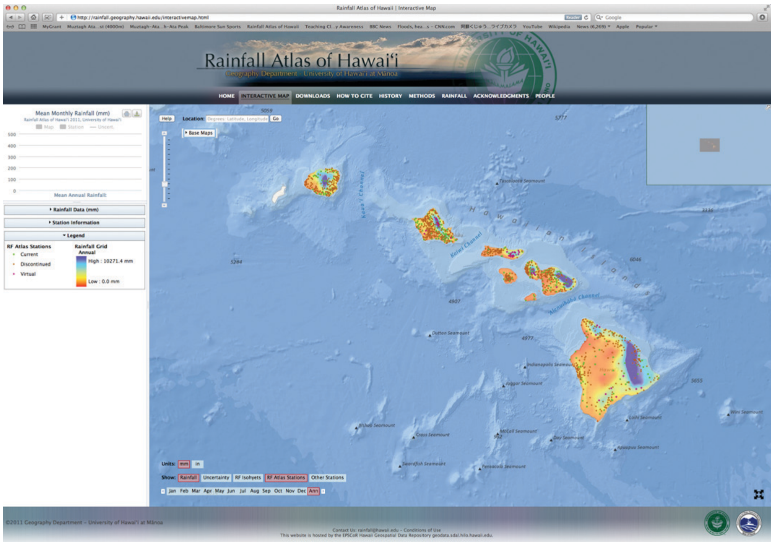

Fig. 2. Interactive map page of the Rainfall Atlas of Hawaiʻi website.

network of rain gauges expanded, understanding of the important rain-producing processes advanced and spatial analysis techniques progressed, with the resulting maps improving over time. The new Rainfall Atlas of Hawaiʻi surpasses previous efforts by using novel techniques to develop serially complete rainfall datasets, employing vegetation-based rainfall estimates in data-sparse areas, incorporating estimates of rainfall patterns derived from weather radar, a meteorological model, and a topographically based rainfall mapping system, and delivering the results via a publically accessible website.

METHODS. The monthly rainfall database compiled for the new Rainfall Atlas of Hawaiʻi includes 1,067 stations, with 517,017 station-months (43,085 station-years) of data over the period 1874–2007. The number of stations operating at any given time increased during the nineteenth and early twentieth centuries, reached a peak of 1,030 stations in 1968, declined in recent decades, and now stands at only 340 stations. To maximize the available information, data gaps were filled using techniques developed by J. K. Eischeid and colleagues for creating serially complete, national daily time series. To test the results of the gap filling, these methods were also used to estimate rainfall at each station for months with actual observations, allowing bias and root mean square error (RMSE) statistics to be calculated for each station-month. On the basis of these error statistics, a total of 69 station-months were removed. Filled data were also tested by examining the tails of the frequency distributions for unusual changes, resulting in the removal of 1,014 station-months. Filling was done for missing months within a record and for periods before and after a station's period of operation. For the purposes of the Rainfall Atlas, with a base period of 1978–2007, and ongoing analysis of temporal rainfall trends, gap filling was done for as many stations as possible for the period 1920–2007. Filling gaps in the time series greatly improves the spatial coverage for a given time period (Fig. 4). Even with more than 1,000 stations, many remote areas lack sufficient coverage. To address this, point rainfall was estimated at "virtual rain gauge" sites in remote areas based on patterns of natural vegetation identified in the work of J. Price et al. While uncertainty is higher for vegetation-based estimates than for real rain gauges, these estimates helped improve map accuracy in several data-sparse areas. Details of gap-filling methods, testing, and virtual rain gauge estimates are given under the Rainfall

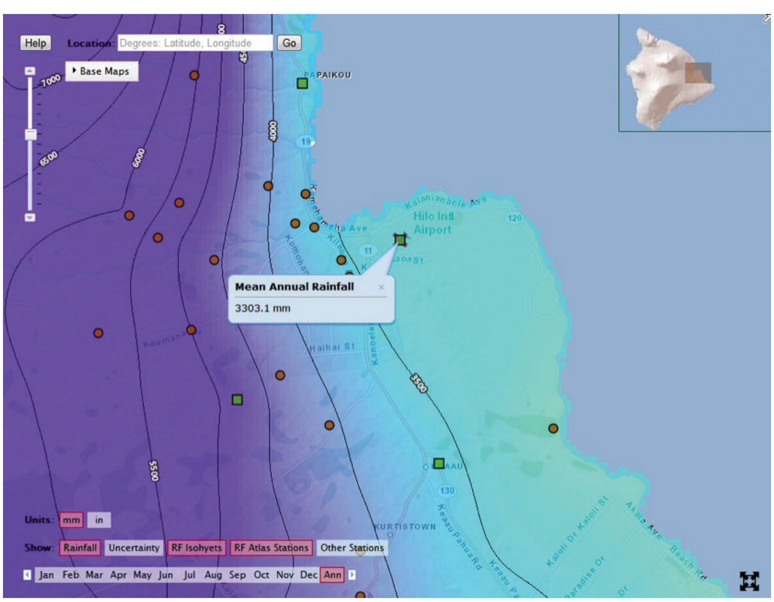

Fig. 3. Pan and zoom features of the interactive map allow users to obtain rainfall information for specific points of interest, such as Hilo International Airport.

Atlas "Methods" tab and in the project report available under the "Downloads" tab of the website.

Point rainfall estimates were used to adjust and evaluate rainfall maps derived from radar rainfall: composite of 2005–08 level-3 data; MM5 rainfall: 2004–09 composited from daily experimental model forecasts using the PSU/NCAR MM5 model; and PRISM rainfall: 1971–2000 mean analysis developed by C. Daly and colleagues' Parameter-elevation Regressions on Independent Slopes Model (PRISM) project. Bayesian data fusion was used to merge this information to generate gridded rainfall maps. In the framework of Bayesian data fusion, each type of data provides evidence for estimating the true rainfall at a given spatial location, with a certain error associated with it. Details of rainfall estimates derived from radar, MM5, PRISM, and the Bayesian data fusion technique are given in the project report available under the "Downloads" tab.

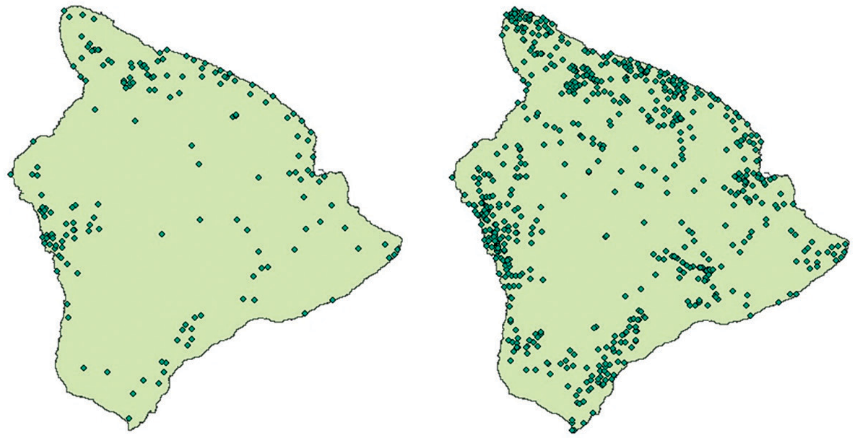

Fig. 4. (left) Locations of rain gauge stations on the Island of Hawai'i with data for 1980 and (right) locations of all of the stations that ever recorded data on the Island of Hawai'i.

Estimates of the uncertainty in station means and mapped means are also provided. Uncertainty in mapped rainfall resulted from the combined uncertainty of the point rainfall means, the interpolation from points to a grid using ordinary kriging, and the uncertainty in each of the predictor datasets (radar, MM5, and PRISM). In general, interpolation uncertainty is low near stations and increases as the distance to the nearest station increases. For complete method details, please refer to the final project report, including its appendix, available under the "Downloads" tab on the Rainfall Atlas website.

RAINFALL PATTERNS. Hawai'i's rainfall pattern is spectacularly diverse (Fig. 1). Annual means range from 204 mm (8 in) near the summit of Mauna Kea to 10,271 mm (404 in) near Big Bog on the windward slope of Haleakalā, Maui. In general, high mean rainfall is found on the windward mountain slopes, and low rainfall prevails in leeward lowlands and on the upper slopes of the highest mountains. This pattern is explained by the main controls on Hawai'i's rainfall: orographic lifting of persistent east-northeast winds give rise to distinct windward-leeward rainfall gradients on each island; thermal effects on slopes and along coasts enhance and alter this pattern (especially for the Kona area of Hawai'i Island); and the stabilizing effect of the trade wind inversion produces extremely dry zones at the summits of Haleakalā (East Maui), and Mauna Kea and Mauna Loa (Hawai'i Island). For a detailed description of the rainfall patterns in Hawai'i, please see the "Rainfall" tab on the Rainfall Atlas of Hawai'i website.

The maps comprising the new Rainfall Atlas of Hawai'i give an up-to-date picture of normal rainfall amounts and patterns. However, rainfall in Hawai'i is known to vary significantly over time. For example, interannual variability in Hawai'i rainfall is strongly associated with ENSO. In particular, El Niño is consistently associated with lower-than-normal rainfall during winter months. The Pacific Decadal Oscillation (PDO) also exerts a strong influence on Hawai'i rainfall. In addition to natural variations in rainfall, we are now aware of long-term trends that might be caused by global warming. Over the past 90–100 years, while the effects of ENSO and PDO caused large ups and downs, the work of P.-S. Chu and H. Chen showed that rainfall in Hawai'i has slowly declined overall. This decline has been especially apparent during recent decades, in part, because it coincides with the low rainfall phase of the PDO.

Rainfall declines at some stations in the Kona coffee-growing region of the Island of Hawai'i since the early 1980s correspond with the current eruptive phase of Kīlauea Volcano, which began in 1983. A plume of aerosol-rich volcanic smog ("vog") streams downwind of Kīlauea and makes its way around the southern flanks of Mauna Loa and up through the South Kona District. The particulates forming the vog can act as cloud condensation nuclei (CCN), helping to produce more cloud droplets. With an overabundance of CCN, areas within the plume may experience greater cloudiness. But condensed water is divided into a greater number of droplets, producing droplets too small to fall as rain.

FURTHER DEVELOPMENTS. The 1920–2007 gap-filled monthly database developed under the Rainfall Atlas project has been used to develop month–year rainfall maps over the whole 88-year period. Using the 30-year (1978–2007) base period as a reference, relative anomalies were calculated for each month at each station. For each month, a relative anomaly pattern was interpolated. The product of the relative anomaly maps and the respective mean monthly map from the Rainfall Atlas gave the individual month-year maps as described in A. Frazier's 2012 master's thesis. Now complete, this 1,056-month series of maps provides unprecedented detail on the historical variations in the amounts and patterns of rainfall in Hawai'i, allowing mean rainfall patterns to be analyzed for any period of interest between 1920 and 2007, and facilitating a wide variety of retrospective analyses on the natural and anthropogenic impacts on island climate.

ACKNOWLEDGMENTS. The new Rainfall Atlas of Hawai'i was developed under an agreement between the State of Hawai'i Commission on Water Resource Management and the U.S. Army Corps of Engineers, Honolulu District, under Section 22 of the Water Resources Development Act of 1974. Contract No. W9128A-04-D-0019, Contract Task Order No. 0038 was awarded to Wil Chee Planning, Inc., which subcontracted the work to the University of Hawai'i at Mānoa, Department of Geography. The Rainfall Atlas of Hawai'i website is hosted by the EPSCoR Hawai'i Geospatial Data Repository developed under NSF Grant No. EPS-0903833.

FOR FURTHER READING

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