The general climate around the Hawaiian islands is dry:
- Open ocean rainfall is \(~600 \text{ mm yr}^{-1}\)

The Islands themselves however have diverse rainfall patterns that range from:
- \(204 – 10,271 \text{ mm yr}^{-1}\)
Distinct Spatial Diversity

Mean Annual Rainfall
State of Hawai‘i
2011 Rainfall Atlas of Hawai‘i
Department of Geography, University of Hawai‘i at Mānoa

9,990 mm (33 Ft) of Rain Per Year

10,270 mm (34 Ft) of Rain Per Year

7,600 mm (25 ft) of Rain Per Year

Less than 225 mm (9 in) of Rain per Year

Giambelluca et al. (2013)
Climate Controls the Affect Temporal Variability

Hadley Cell atmospheric circulation

- Trade Winds and Trade Wind Inversion (TWI)

Coupled ocean-atmosphere internal modes of variability

- El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)

Disturbances

- Cold fronts, Kona storms, Tropical Cyclones, etc.
1. Rising in the ITCZ – band of intense thunderstorms
2. Poleward transport in the upper troposphere
3. Descending air between 20˚ and 30˚ latitude – warms
4. Flow toward the equator at the surface – trade winds
Hadley Cell subsidence drives a semi-permanent high pressure cell to the northeast of the islands.

NE Trade Winds occur between 50-90% percent of the time.
Trade Wind Inversion

Temperature

Elevation

- Subsiding air from the Hadley
- Dry air above the TWI
- TWI: Very stable layer that caps cloud development
- Moist air in the marine layer
- Convective mixing

Temperature increase
The Trade Wind Inversion

Air subsiding from the Hadley Cell.

Orographic Lifting

Mean Trade Wind Inversion

Thermal slope wind

Windward

Leeward

Ryan Longman
Trade-Wind Inversion

Trade Wind Inversion Seen in Profiles of Air Temperature and Relative Humidity

Vertical air temperature profile
Hilo, Hawai‘i
2 p.m., 13 July 1994

Vertical relative humidity profile
Hilo, Hawai‘i
2 p.m., 13 July 1994
Trade-Wind Inversion

• Mean altitude ~2200 m (7200 ft)
• Frequency ~80%
• Stable atmospheric layer
• Forms a barrier to rising air
• Because rising air is the predominant means by which clouds form, cloud development is capped at the TWI level
• As a result, relatively thin clouds produce less precipitation when TWI is present
• Atmospheric variation resulting in either more frequent or lower altitude TWI will cause a reduction in rainfall
Hawai‘i lies in a region of high interannual and interdecadal variability
Modes of climate variability

- **El Niño Southern Oscillation**
  - ENSO
  - Positive (El Niño), negative (La Niña) and neutral phase.
  - 3-7 years (inter-annual)
  - Tropical Pacific

- **Pacific Decadal Oscillation**
  - PDO
  - Positive (warm) Negative (cool) Phase
  - 20-30 years (inter-decadal)
  - North Pacific
AR4, IPCC (2007); also see Mantua et al. (1997), Power et al. (1999), and Trenberth and Caron (2000)
ENSO: El Niño – Southern Oscillation
The 2015-16 El Niño

SST Anomalies (°C)

02 DEC 2015
Water vapor image showing large dry air mass affecting Hawaiʻi on Jan. 3, 2016 at 8:32 AM HST. The dry air is associated with El Niño-driven enhanced Hadley cell subsidence.
Precipitation during El Niño

Climate Change and Pacific Islands: Indicators and Impacts - Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA) by Victoria W. Keener, John J. Marra, Melissa L. Finucane, Deanna Spooner, and Margaret H. Smith (eds.)
Pacific Decadal Oscillation

positive phase

negative phase
Disturbances

- Cold Fronts
- Upper Level Lows
- Kona Storms
- Tropical Storms
- Disturbances disrupt Hadley subsidence
- The TWI disappears
- Deep convection can occur
- Widespread, heavy rainfall possible
Hawai‘i Temperature Trends

Changes in Vertical Profiles

Diaz et al., 2011, Global & Planetary Change
New Analysis from Marie McKenzie

- **a) Mean Temperature**
  - Temperature Anomaly (°C)
  - Year

- **b) Minimum Temperature**
  - Temperature Anomaly (°C)
  - Year

- **c) Maximum Temperature**
  - Temperature Anomaly (°C)
  - Year

- **d) DTR Temperature**
  - Temperature Anomaly (°C)
  - Year
How Will Climate Change Affect Water Resources in Hawai‘i
Hawaiian Rainfall and ENSO

Frazier et al. (in preparation)
Trends are not Uniform

Long-Term

Recent

Frazier et al. (in preparation)
Trade Wind Inversion
TWI Trends

Cao et al. (2007)

TWI affected Hawai‘i more of the time starting in early 1990s

Trade-Wind Inversion Occurrence

Frequency of Occurrence (%)


Cao et al. (2007)
Changes in the Trade-Wind Inversion

Longman et al. (2015)
Effects of TWI Change

RAINFALL

Longman et al. (2015)
Effects of TWI Change

CLOUD COVER

Longman et al. (2015)
At High Elevations: 
Dry Days Becoming More Common

Upward Trend in Solar Radiation

Warming, Brightening, and Drying at High Elevations

At high elevations, the 1975-2006 temperature increase was exceptionally high.

The number of cloud-free days, such as this, has increased at high elevations in Hawai‘i over the past 20 years.
Photo: T. Giambelluca

June-November solar radiation is trending upward at all three stations located at high elevations on Haleakalā.
Longman (2011)

The Haleakalā silversword (Argyroxiphium sandwicense, ssp. macrocephalum), an iconic species beloved by visitors to Haleakalā National Park, is in decline, perhaps because of climate changes at high elevations.
Photo: T. Giambelluca

The number of rainless days during the dry season (May-October) has been increasing at this station near the trade-wind inversion level on Haleakalā.

Severe drought and extremely high solar radiation during the summer of 2010 likely contributed to the dieback of the native subalpine shrub pukiawe (Styphelia tameiameiae) at high elevations on Haleakalā.
Photo: T. Giambelluca
Stream Base Flow Also in Decline

Future Projections

At the global scale, projections indicate that wet areas will get wetter and dry areas will get drier.
Future Projections

IPCC AR5
CMIP5 Models
Near Term Projections:
Out to the year 2050
Figure 11.10 | CMIP5 multi-model ensemble mean of projected changes in December, January and February and June, July and August surface air temperature for the period 2016–2035 relative to 1986–2005 under RCP4.5 scenario (left panels). The right panels show an estimate of the model-estimated internal variability (standard deviation of 20-year means). Hatching in left-hand panels indicates areas where projected changes are small compared to the internal variability (i.e., smaller than one standard deviation of estimated internal variability), and stippling indicates regions where the multi-model mean projections deviate significantly from the simulated 1986–2005 period (by at least two standard deviations of internal variability) and where at least 90% of the models agree on the sign of change. The number of models considered in the analysis is listed in the top-right portion of the panels; from each model one ensemble member is used. See Box 12.1 in Chapter 12 for further details and discussion. Technical details are in Annex I.
Temperature Change

Precipitation Change

Seasonal mean percentage precipitation change (RCP4.5: 2016-2035)

Figure 11.12 | CMIP5 multi-model ensemble mean of projected changes (%) in precipitation for 2016–2035 relative to 1986–2005 under RCP4.5 for the four seasons. The number of CMIP5 models used is indicated in the upper right corner. Hatching and stippling as in Figure 11.10.

Precipitation Change

Figure 11.13 | CMIP5 multi-model projections of changes in annual and zonal mean (a) precipitation (%) and (b) precipitation minus evaporation (mm day⁻¹) for the period 2016–2035 relative to 1986–2005 under RCP4.5. The light blue denotes the 5 to 95% range, the dark blue the 17 to 83% range of model spread. The grey indicates the 1σ range of natural variability derived from the pre-industrial control runs (see Annex I for details).

Precipitation Change

Figure 12.22 | Multi-model CMIP5 average percentage change in seasonal mean precipitation relative to the reference period 1986–2005 averaged over the periods 2046–2065, 2081–2100 and 2181–2200 under the RCP8.5 forcing scenario. Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability and where at least 90% of models agree on the sign of change (see Box 12.1).
Future Projections for Hawai‘i

Spatial resolution of global models is too coarse

As a result:

• Topography not represented
• Thermal effects of land on circulation not represented
• Hawai‘i’s extreme spatial variability not represented

NEED DOWNSCALING
Projecting Rainfall Change Using Statistical Downscaling

Large Scale Circulation ↔ Point Rainfall

Hawaii Daily Raingage Sites Used in Study

Līhuʻe Airport
Honolulu Int’l Airport
Kahului Airport
Lānaʻi City
Kailua
Haleakalā Ranger Station
Mauna Loa Slope Obs
Kainaliu
ʻOphihale
Nāʻalehu
Hilo Int’l Airport
Hawaiiʻi Ntl Park HQs
Projecting Heavy Rainfall Frequency

Elison Timm et al., in preparation
Projecting Drought Frequency

6-model ensemble

2046-2065

\[ y = 0.183985x^{0.089846} \]

\[ R^2 = 0.057096 \]

2081-2100

\[ y = 0.466974x^{0.282411} \]

\[ R^2 = 0.221616 \]
Drought Projection

2081-2100 Projection
SRES A2 Scenario

Mean of 6 Models:
CCCMA
ECHAM
MRICGCM
GFDL0
GFDL1
UKMO

Winter Drought Probabilities
- Blue: Significant Decrease
- Yellow: No Significant Change
- Red: Significant Increase
Statistical downscaling of rainfall changes in Hawaii based on the CMIPS global model projections

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Abstract Seasonal mean rainfall projections for Hawaii are given based on statistical downscaling of the latest Coupled Model Intercomparison Project phase 5 (CMIPS) global model results for two future representative concentration pathways (RCP4.5 and RCP8.5). The spatial information content of our statistical downscaling method is improved over previous efforts through the inclusion of spatially extensive, high-quality monthly rainfall data set and the use of improved large-scale climate predictor information. Predictor variables include moisture transport in the middle atmosphere (700 hPa), vertical temperature gradients, and geopotential height fields of the 1000 and 500 hPa layers. The results allow for the first time to derive a spatially interpolated map with future rainfall change estimates for the main Hawaiian Islands. The statistical downscaling was applied to project wet (November–April) and dry (May–October) season rainfall anomalies for the mid- and late 21st century. Overall, the statistical downscaling gives more reliable results for the wet season than for the dry season. The wet-season results indicate a pronounced dipole structure between windward facing mountain slopes and the leeward side of most of the islands. The climatically wet regions on the windward slopes of the mountain regions are expected to become wetter or remain stable in their seasonal precipitation amounts. On the climatically dry leeward sides of Kauai, Oahu, Maui, and Hawaii Island, future precipitation exhibits the strongest drying trends. The projected future rainfall anomaly pattern is associated with a circulation anomaly that resembles a shift in the position or strength of the subtropical high and the average location of extratropical troughs. These new results suggest that a negative trend dominates the area-averaged changes in the statistical downscaling over the Hawaiian Islands. However, the islands are expected to experience a greater contrast between the wet and dry regions in the future.

1. Introduction

In the last few decades, wet-season (November through April) rainfall for the Hawaiian Islands has exhibited a drying trend in excess of 10% of the mean (Diaz and Giambelluca, 2012). Climate projections for business as usual and moderate emissions mitigation scenarios derived from the Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIPS) suggest a general wet-season drying trend to the end of the 21st century for Hawaii, according to the two most recent Intergovernmental Panel on Climate Change (IPCC) assessment reports (Intergovernmental Panel on Climate Change, 2007, 2013, Annex I Fig. A7A). Higher precipitation is projected over the central and eastern tropical Pacific, but the subtropical regions around the Hawaiian Islands show a negative precipitation change of small amplitude (Power et al., 2012). These projected regional rainfall changes represent mostly open-ocean conditions and as such cannot be used as reliable estimates for changes in the water budget calculations over land.

Mullin and McGarigal (1988) used the station network of rain gauge stations in Hawaii to show that a rainfall enhancement factor of 3.4 is likely to describe the net effects orographic effects on the rainfall budget. This statewide perspective is integrated over spatial rainfall gradients that range between 250 mm and more than 11,000 mm annual total rainfall within horizontal length scales of 10–100 km and vertical scales of the order of 1–4 km. With the advances in satellite remote sensing of precipitation over oceans it has become possible to measure the general effects of small islands on the enhancement (or reduction) of precipitation compared with the open-ocean conditions (Sobel et al., 2011). It was found that the dimensions of islands and their geometry and orographic features lead to different enhancement effects. It is therefore not...
Projected Change in Wet Season Rainfall

CMIP5 ECP8.5 ensemble median scenario for late 2071-2099 average (Elison Timm et al. 2014).
Climate Change Influences on Evapotranspiration

- **Moisture Availability**
- **Potential ET**
  - Solar radiation (cloud cover)
  - Humidity
  - Temperature
  - Wind
Lower Rainfall $\rightarrow$ Greater Solar Radiation

Areas that experience decreasing rainfall will also experience increasing evaporation rates, which will increase water demand and further decrease water supply in those areas.
Summary

• Temperature
  • Slow warming over 20th century
  • Rapid warming in 1970s-1990, especially at high elevations
  • Warming pause late 1990s-2014
  • Strongly influenced by PDO
  • Continued moderate warming projected for 2100

• Rainfall
  • Slow drying over 20th century
  • Mostly very dry since late 1970s
  • Strongly influenced by PDO, ENSO, PNA
  • No clear climate change signal yet
  • Connections with TWI
  • SD Projections: wet season: dry areas drier; wet areas slightly wetter; drought probability higher in dry areas

• Solar
  • Increasing at high elevations due to decreasing clouds
  • Connections with TWI