

Spatial Distribution of Freshwater Resources on the Hawaiian Islands

USING GIS 3-D ANALYST TOOLS TO COMPARE ELEVATION AND
RAINFALL PATTERNS

Introduction

Hawaii is a chain of volcanic islands isolated in the center of the Pacific Ocean, the largest saltwater basin on Earth. Natural freshwater resources are therefore limited to what falls and flows on each island. Although rainfall, streamflow and ground water are generally abundant in Hawaii, most urban development is in the dry side of the islands [1]. The challenge is to match freshwater resources spatially with demand.

This analysis aims to understand the natural factors that influence the distribution of freshwater that originates on the Hawaiian Islands. In particular, this analysis explores the shape of each island and its effects on rainfall patterns, aiming to quantify the relationship between elevation and rainfall which is the true source of freshwater for these remote islands.

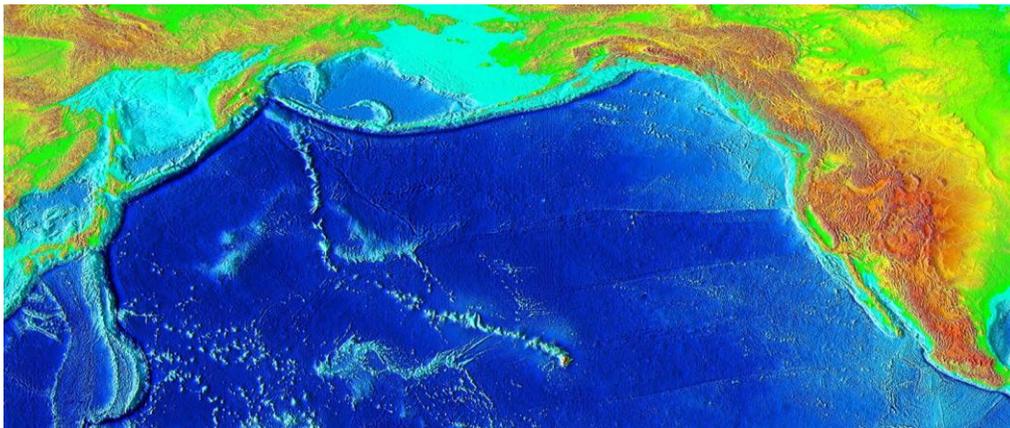
Background

The amount and distribution of rainfall on each island is highly influenced by the shape and height of its volcanic peaks, which in turn is influenced by the island's age and formation.

Formation

The Hawaiian Islands were formed by millions of years of hot spot volcanism over a shifting tectonic plate. Each island was once an active volcano or series of volcanoes that built upwards from the seafloor in a sequence of stacking lava flows. The hot spot of magma that penetrated the ocean's crust remained stationary as the Pacific plate traveled north (creating the Emperor Seamount chain) and then northwest (creating the Hawaiian Islands). This means today, as you travel northwest from the Big Island, the islands are successively older and smaller, eroding away to seamounts.

Figure 1: Elevation Map of the Pacific Ocean



1 The Hawaiian-Emperor seamount chain lies in the center of the Pacific Ocean

The ages of each of the islands are a huge factor in the observed topography and stream networks on each island. Younger islands, such as the Big Island, have had more recent volcanism. In fact, Kilauea is an active volcano that has been continuously erupting since 1983 and has added over 570 acres of new land to Hawaii [1]. Therefore, the higher peaks are located on the islands in the southeast. Generally speaking, the higher the peak, the greater its disruption of local climate patterns.

Older islands, such as Oahu and Kauai, are continuously battered by wind and waves and have slowly been breaking down over the past 2-6 million years. The northwestern part of the Hawaiian Island chain has seen more rainfall than the younger islands. Here, mass wasting events along with millions of years of rain have carved large valleys and defined stream channels. The seven Hawaiian Islands are very different landmasses.

Figure 2: Map of the Hawaiian Islands

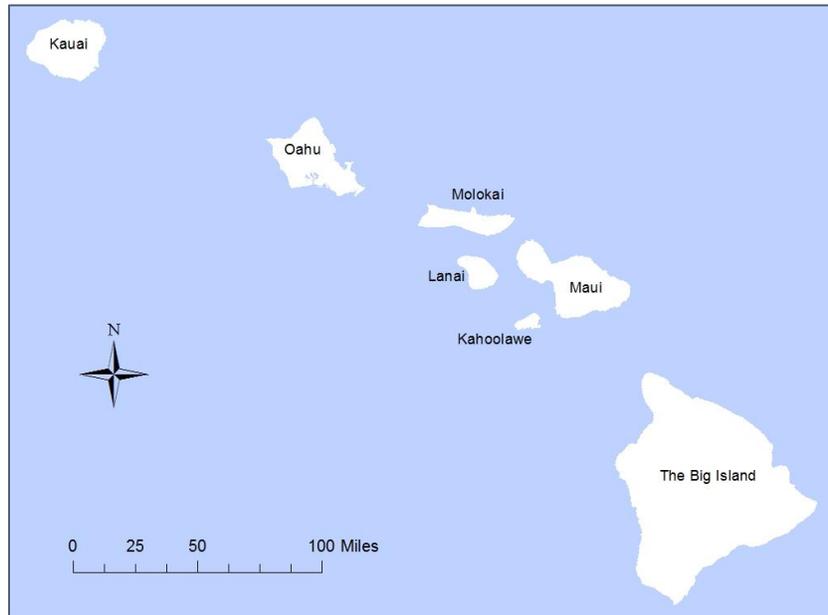


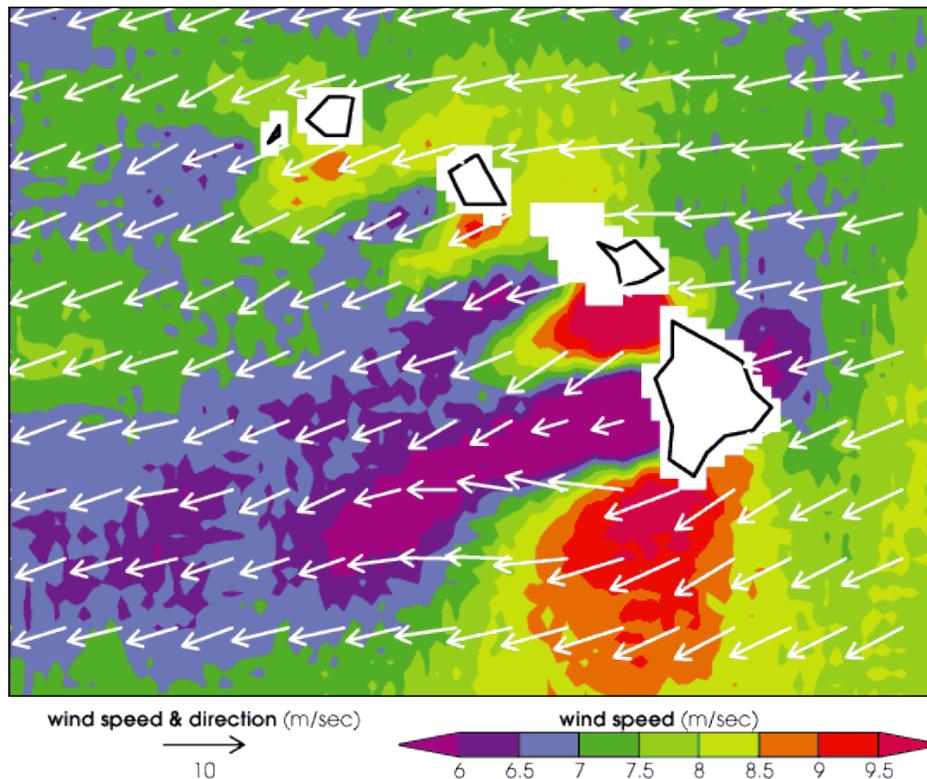
Table 1: Hawaiian Island Data: Age, Peak, Size and Population

Island	Age	Summit -	Altitude	Land Mass	Population
Kauai	1.41 - 5.7 million yrs	Kawaikini	5,243	552 mi ²	58,303
Oahu	0.03 - 3.8 million yrs	Kaala	4,003	597 mi ²	876,156
Molokai	1.3 - 1.8 million yrs	Kamakou	4,961	260 mi ²	7,404
Lanai	0.81 - 1.5 million yrs	Lanaihale	3,366	140 mi ²	3,193
Kahoolawe	1.0 million yrs	Puu Moaulanui	1,483	45 mi ²	Uninhabited
Maui	0.41 - 1.6 million yrs	Haleakala	10,023	727 mi ²	117,644
Hawaii	0 - 0.45 million yrs	Maunakea	13,796	4,028 mi ²	148,677
TOTAL	-	-	-	6,349 mi²	1,293,213

Climate Patterns and Rain Shadows

Because the Hawaiian Islands are so small (only 6,349 square miles of landmass), they are difficult to identify on an ordinary map of the Pacific Ocean. However, a map of wind speed clearly shows the Hawaiian Islands along with the dramatic effect of their volcanic peaks which interrupt the trade winds that blow from northeast to southwest across the Pacific Ocean [2].

Figure 3: Wind Speed and Direction



On almost every island of Hawaii, there is a pronounced dry side and wet side. This is because the wind and the volcanic peaks together produce unique rainfall patterns and a significant rain shadow. The majority of the rain is dropped on the windward side of the peaks on the northeastern flank of each island, but fails to fall far beyond the mountaintop.

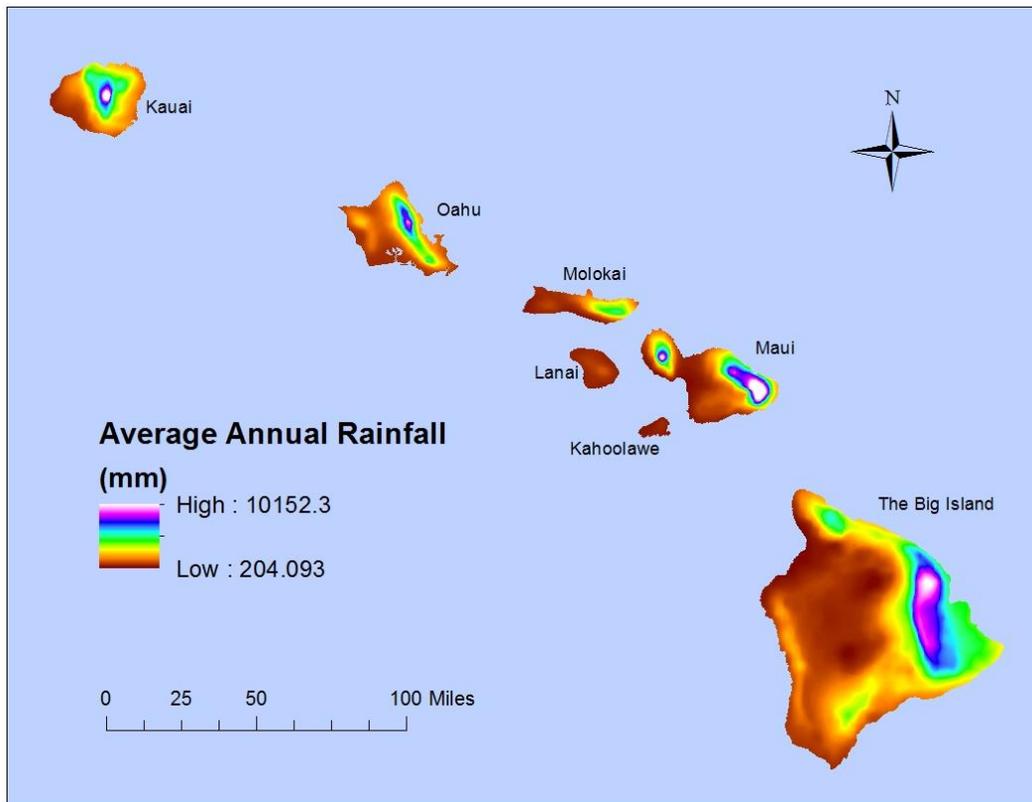
Methodology and Results

This study used ArcGIS to first evaluate the relationship between elevation, wind direction and rainfall, then examine how rainfall distribution (where freshwater originates on the islands) affects stream networks and freshwater storage in aquifers in the State of Hawaii.

RAINFALL

A dataset detailing monthly and annual averages of rainfall was downloaded from the online Rainfall Atlas of Hawaii that is maintained by the University of Hawaii at Manoa's Geography Department [3]. This provides the most recent estimates of precipitation in millimeters over each of the islands. I also downloaded general boundaries of Hawaii by island and by county from the State of Hawaii's Office of Planning website for the statewide GIS program (planning.hawaii.gov/gis). Changing the Symbolology of the rainfall data highlighted the windward concentration of rainfall on the northeastern flank of each island.

Figure 4: Average Annual Rainfall (mm) DEM



ELEVATION

The elevation data was downloaded from the University of Hawaii at Manoa's Coastal Geology Group website (soest.hawaii.edu/coasts/data). Each island's 10m DEM was downloaded and combined into a single raster using the **Mosaic to New Raster** tool. Figure 5 below shows the transition from single-island DEMs with varying ranges of elevation to a single mosaic of statewide elevation data.

Figure 5: Island-Specific DEMs (Left) mosaicked into a Statewide DEM (Right)

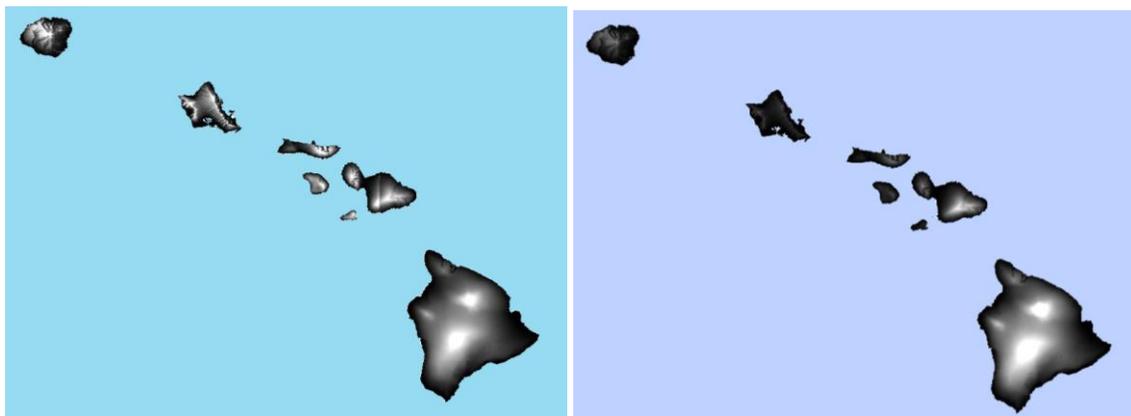
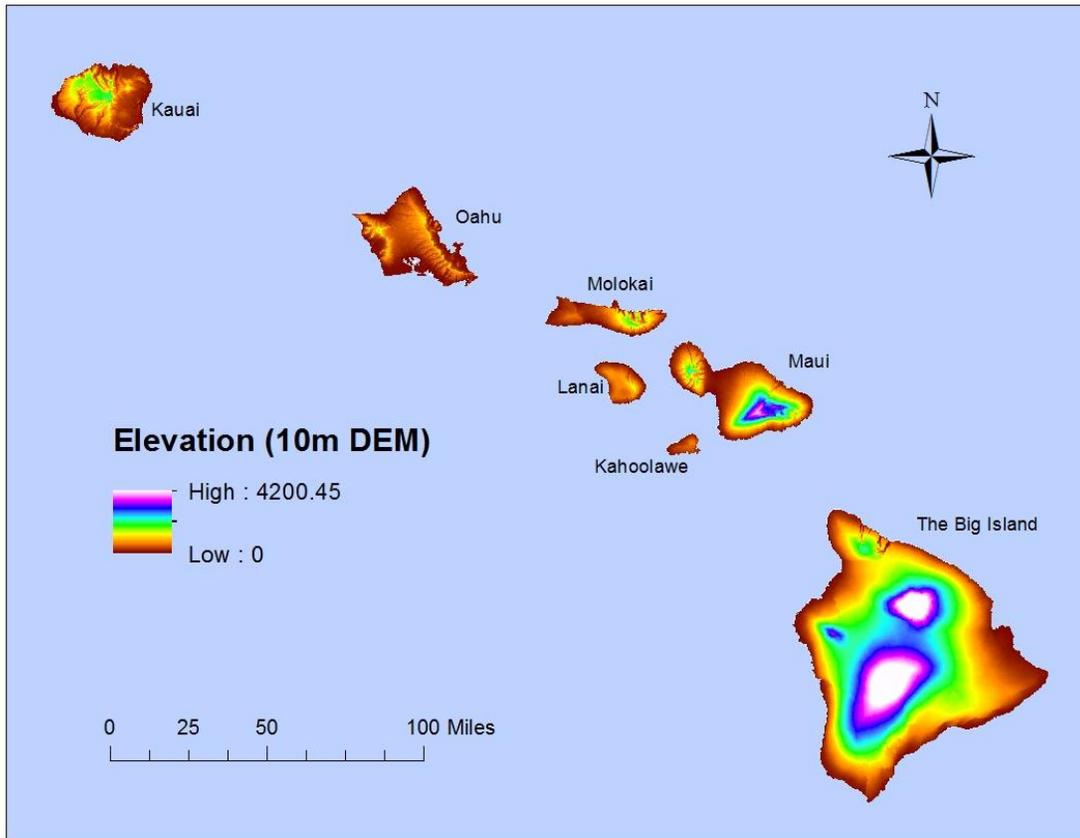
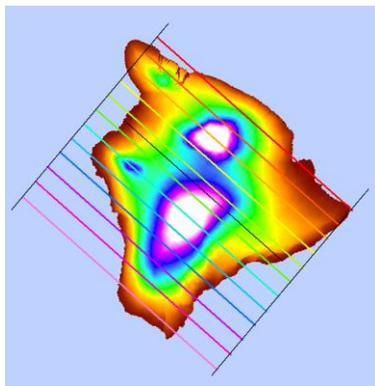


Figure 6: Elevation (10m DEM)



The resulting maps showed the younger islands having much higher peaks, highlighting several of the mountaintops on Hawaii and Maui.

COMPARING RAINFALL AND ELEVATION PEAKS USING 3-D ANALYST TOOLS



To compare rainfall peaks with underlying elevation, I used **3-D analyst tools**, namely the **Interpolate Line** and **Profile Graph** tools to create profiles of both elevation and rainfall in GIS, then export the data and ultimately graph the profiles in Excel. Each line had to be hand drawn for each layer. This involved a bit of trial and error.

My first attempt was to profile all of the islands with lines stretching across the open space of the ocean. However, the ocean was not part of either the rainfall or elevation raster, so the 3-D analyst tool didn't work. Next I tried to profile only the Big Island by creating lines of equal length and copying

and pasting them at equal intervals in the direction perpendicular to the trade winds (See picture above, to the left). However, the 3-D analyst tool automatically clipped the lines to the boundary of the island (see picture to the right) so they were of unequal lengths. This would complicate profile comparison, as I planned to graph my results on the x-axis as a distance from a similar, perpendicular line.

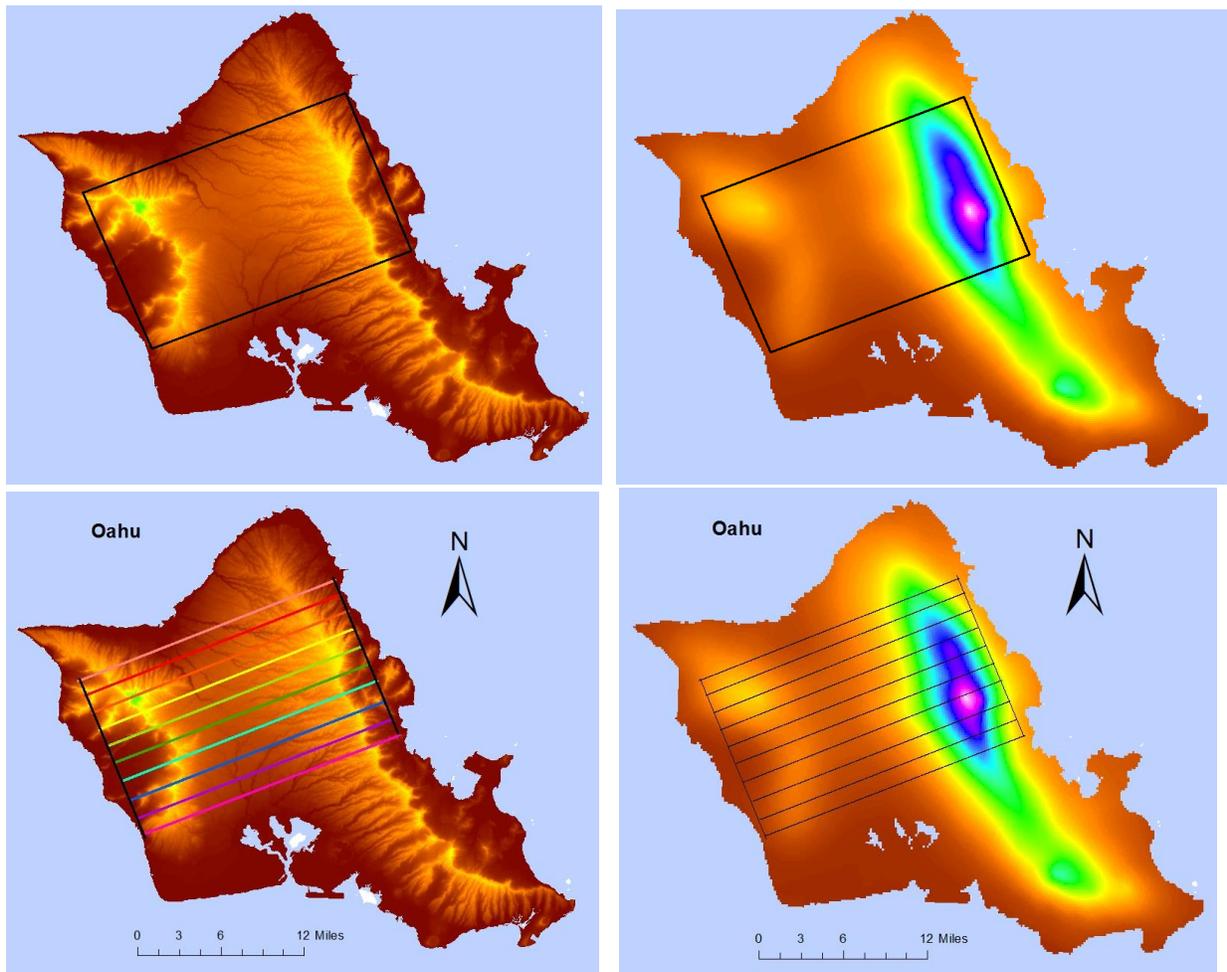


Therefore, I chose two islands of interest to perform more detailed profiles within the boundaries of each island: Oahu and Maui.

Oahu

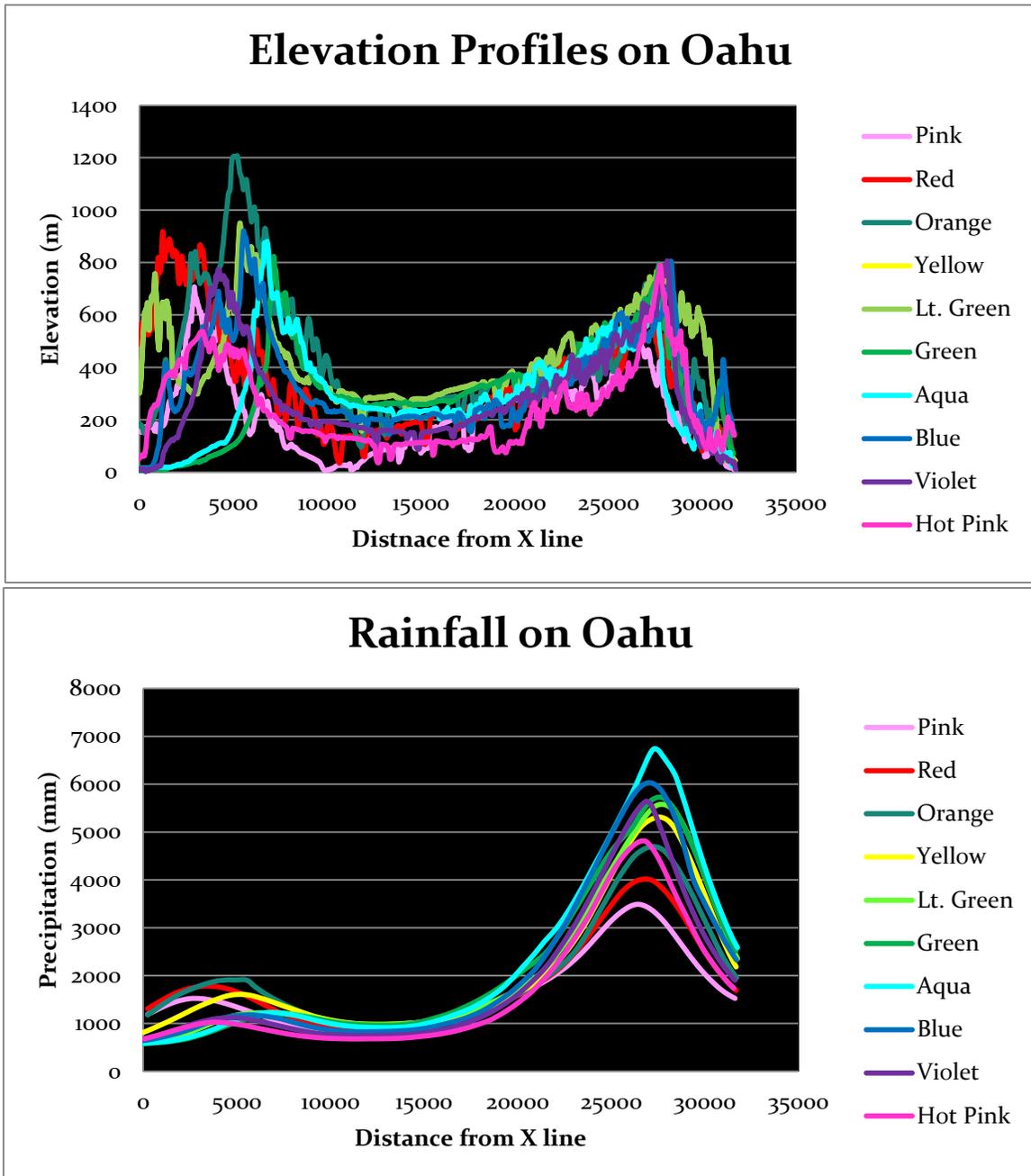
Oahu is the most heavily populated island with 70% of the State's population (976,372 of 1,293,213) and the state's capital, Honolulu, which itself holds 25% of Hawaii's total population. It also has the distinction of having two mountain ranges essentially perpendicular to the direction of the trade winds. Since the interpolation had to be constrained to the coastline and because I wanted lines of equal length and the same starting point, I chose a rectangular area that spans both mountain ranges and the peak concentration area of the annual precipitation.

Figure 7: Oahu Study Area and Profile Lines: Elevation on the Left, Rainfall on the Right



Based off of the previous map of wind direction in Figure 3, I drew ten lines parallel to the trade wind direction at Oahu. Each line was of approximately equal length and spacing (20 miles long, 1.5 miles apart), extending from the southwest, leeward slope of the western range to the northeast windward slope of the eastern ran. Each line was uniquely colored so it would represent the same profile in both rainfall and elevation. The legends in the graph below reflect the N-S rainbow color scheme.

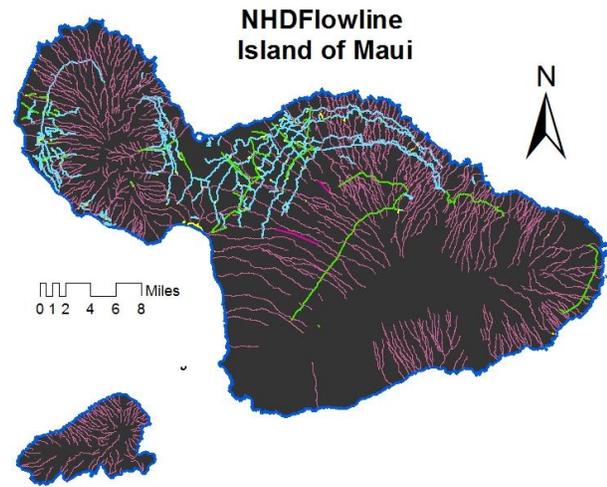
Figure 8: Oahu Results



First, in the elevation graph we see that the western mountain range actually reaches higher peaks than the eastern range that first comes into contact with the trade winds. The western peak is about 1200 m whereas the eastern peak is only 800 m. Next, the rainfall graph reflects what the map originally showed: the peak of rainfall is on the northeastern side of the island. Comparing the two graphs of rainfall and elevation, most of the rain falls directly at the peak of the eastern mountain's ridge, not before. Also, the effect of the winds and the rain shadow is clearly seen here. Even though the western peak is higher than the eastern peak, it sees almost no rain.

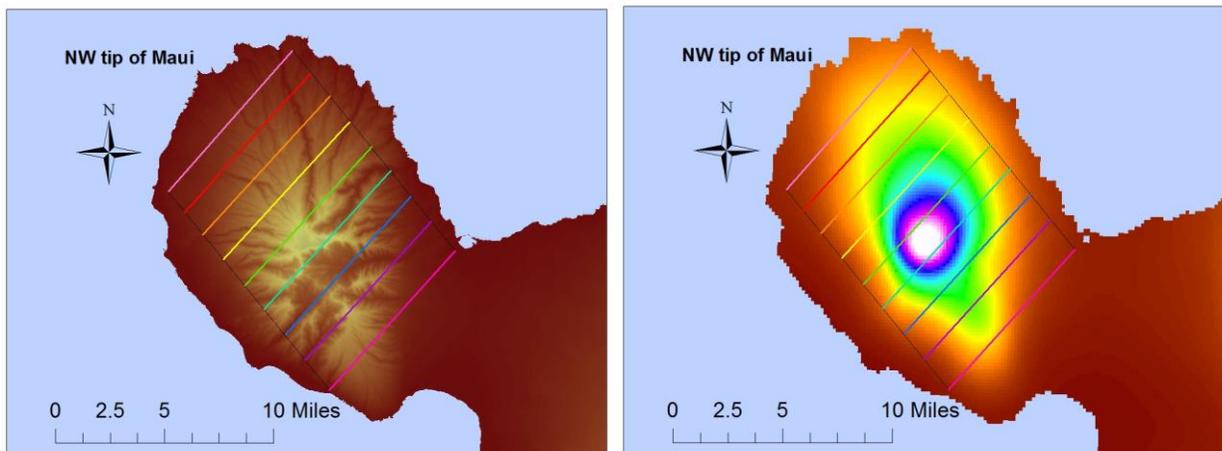
Maui

The next location for rainfall and elevation profiles was the northwestern tip of Maui. The island of Maui is extremely important to the state's economy as it is a hub for tourist activity as well as agriculture. A map of the NHDFlowline data for the island of Maui shows the extent of man-made infrastructure that has altered the distribution of surface water on the island to accommodate the agricultural needs. All streams and rivers are colored pink. All other colored lines are man-made, artificial structures such as pipelines, canals and ditches that divert streamflow. Most of this infrastructure supports the key agricultural lands which lay in the valley between the northwestern and southeastern sections of the island. Also of note is the presence of streams on the windward side and the lack of stream on the leeward side of the island.



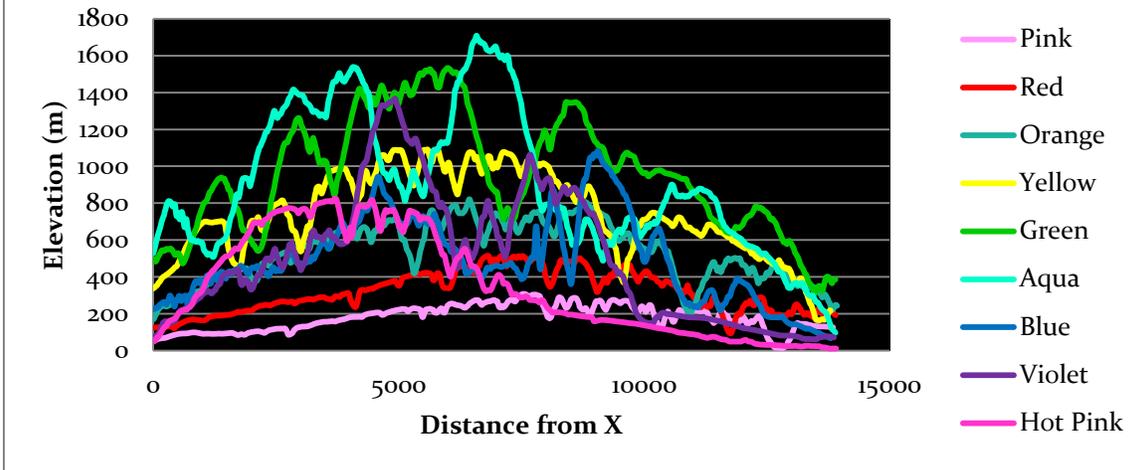
The maps of the study area shown below displays a curious, almost conical distribution of rainfall, seemingly fitted perfectly to the peak and elevation contours. This is in direct contrast to what was observed on Oahu with a defined rainy side and a dry side. Just by looking at the maps we can see the different effects of the shapes of the peaks: a ridge on Oahu creates a large rain shadow on the other side of the peak, but Maui's northwest volcano has rain distributed equally on all flanks.

Figure 9: Study Area on Maui. Elevation on Left, Rainfall on Right

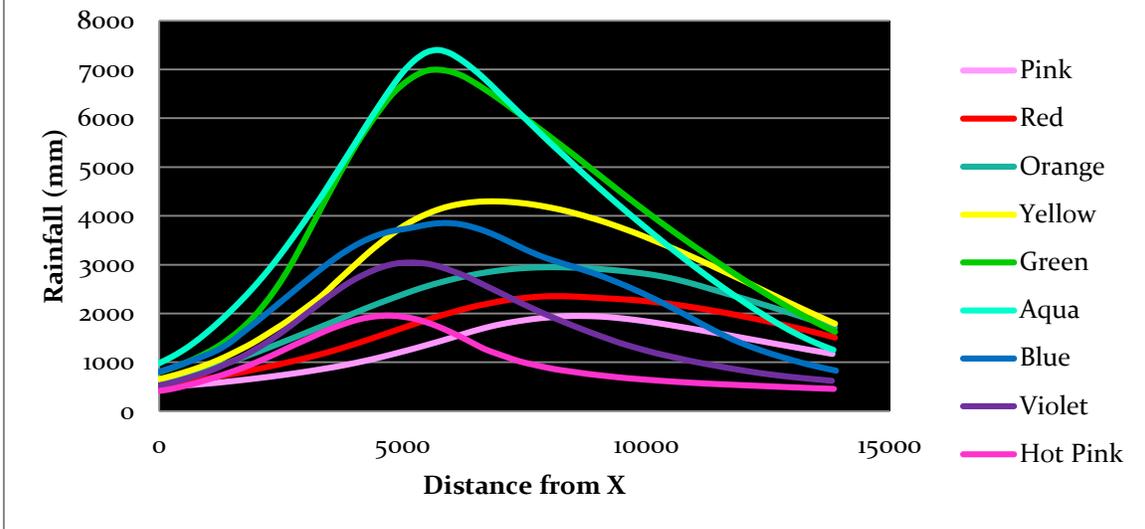


Following the same process for profile interpolation, I traced 9 lines of approximately equal length, colored them in a rainbow pattern from NW-SE, interpolated the 3-D data in GIS and graphed the combined results in Excel.

Elevation Profiles of the NW Tip of Maui



Rainfall Profile on NW Tip of Maui



Here, the peak of rainfall occurs slightly after the peak of elevation in the direction of the trade winds, with more rain falling on the east side of this dormant volcano than the westward, leeward side. Rainfall drops sharply after its peak of about 1700 m. As a note, this peak on Maui is about 500 m higher than the observed peak of the western range on Oahu. However, the maximum rainfall is about the same for both study areas: 6700 mm on Oahu, 7500 mm on Maui.

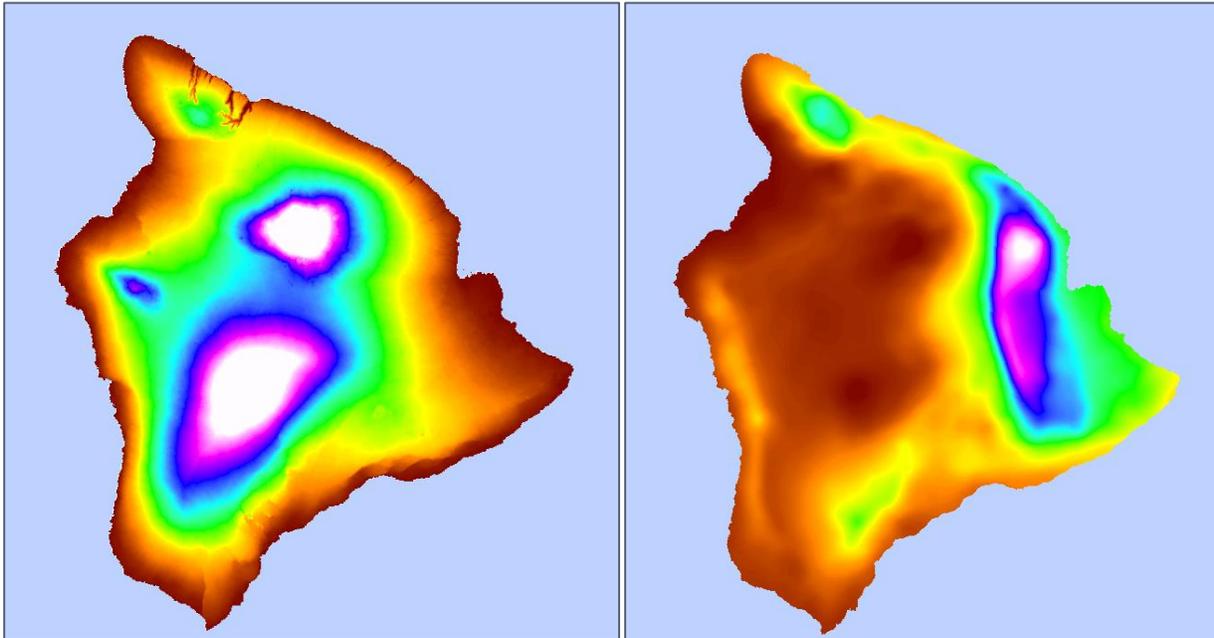
OBSERVATIONS FROM OTHER ISLANDS

Hawaii

There are 5 major volcanoes on the Big Island of Hawaii, yet we only see about 4 peaks in the elevation map shown below on the left. However, these peaks of Mauna Kea and Mauna Loa are substantial. It is rather

interesting, then that we don't see more of a concentration of rain closer to these peaks, as we did on Maui's northwestern tip in our 3-D analysis above. Instead, the rain seems to concentrate on the pocket of lower elevation on the east side of the islands. This is probably due to the orientation of the peaks, lining up perfectly parallel with the direction of the trade winds. Also, Mauna Kea and Mauna Loa cast a large rain shadow over the whole west side of the island, which is to be expected with peaks of that height.

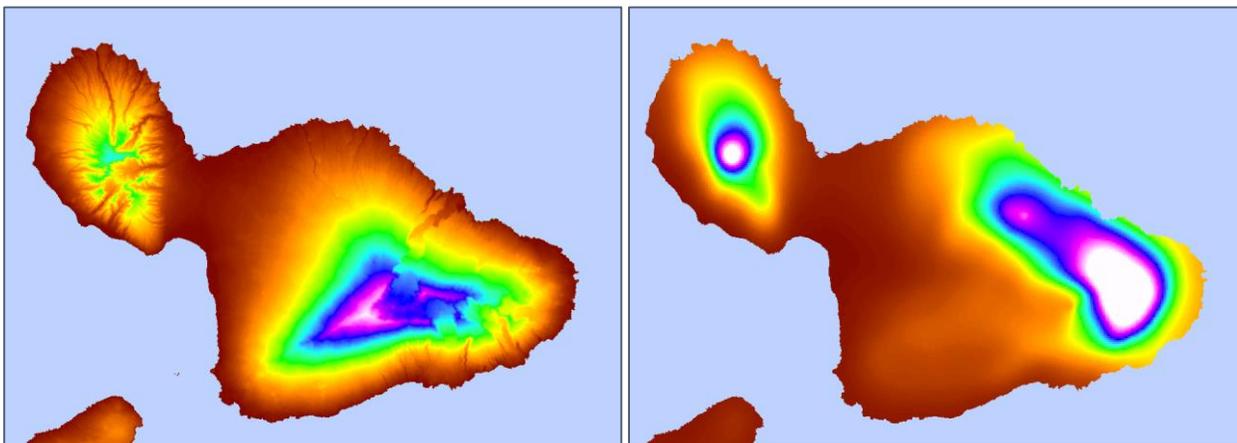
Figure 10: Hawaii Elevation (LEFT) and Average Annual Rainfall (RIGHT)



Maui

To add to the above analysis where we looked at the northwestern tip of Maui, we can see the whole island and the rather textbook-quality of the effect of the trade winds and the peak of Haleakala causing a rain shadow. However, it is noted that the peak of rainfall clearly occurs before the peak of the mountain on the main part of the island. This is separate behavior from the northwestern tip of the same island, which has a much lower peak elevation.

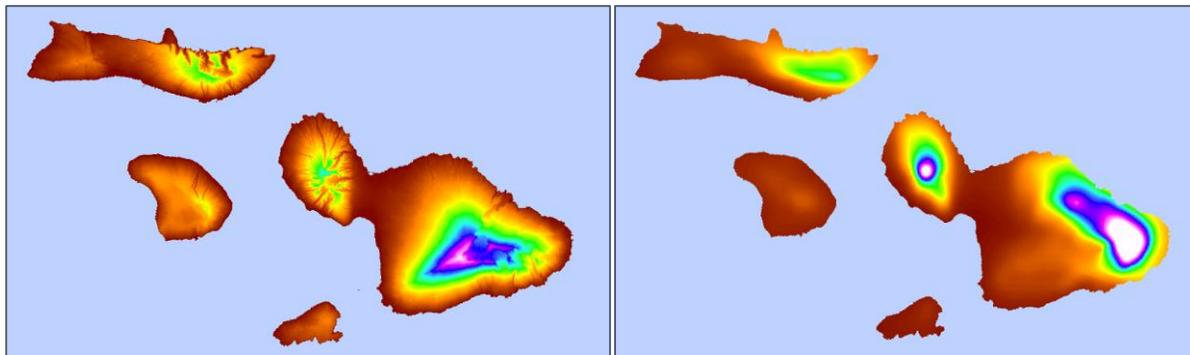
Figure 11: Maui Elevation (LEFT) and Average Annual Rainfall (RIGHT)



Molokai, Lanai and Kahoolawe

Molokai, the island in the top left corner of both maps below, has a rainfall pattern that perfectly matches its elevation pattern. The smaller two islands, Lanai (just next to the northwestern tip of Maui) and Kahoolawe (bottom of the map) seem to be included in the rain shadow of Maui; Lanai less so than Kahoolawe. This makes sense when we consider the direction of the trade winds, coming from the northeast to the southwest, and the difference in peak elevation on the two different sections of Maui.

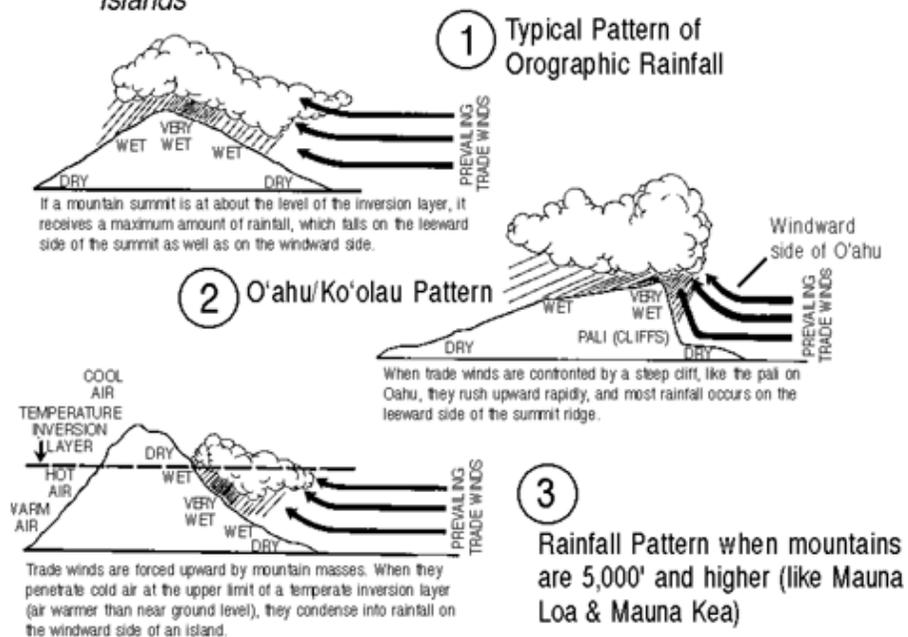
Figure 12: Elevation (Left) and Rainfall (Right) for Molokai, Lanai, Kahoolawe and Maui



Discussion

The figure below helps explain some of what we observed in our analyses. The first pattern was observed on Maui's northwestern tip where rain fell on both the leeward and windward side of the summit. The explanation here is that the summit is at the level of the inversion layer. The figure also perfectly describes the behavior of Oahu's rainfall and the fact that the peak of rainfall on Hawaii was well before the peak of its summits Mauna Kea and Mauna Loa.

Figure 19C: Different Patterns of Orographic Rainfall on Hawaiian Islands



Conclusion

Overall, the results of this analysis indicate that the spatial distribution of freshwater has great variability from island to island. The presence of the trade winds and the effect of wind direction on rainfall patterns is clearly evident in each of the analyses, comparative maps and supporting surficial imagery. If there was a less time-consuming way to perform these profiles, I would have liked to do twice as many on each island and in 5 different orientations: parallel with the wind, perpendicular to the wind, and at differing angles. For this study, a general wind direction was assumed, but there might be small variations in wind direction from island to island that could potentially have a significant effect on rainfall behavior. Further studies on the profiles and cross-sections of elevation and rainfall is encouraged, especially to show the effects of seasonal variations in wind speed and rainfall.

References

- [1] USGS. USGS Fact Sheet 012-99: Hawaii. May 1999. <http://pubs.usgs.gov/fs/FS-012-99/>
- [2] Xie, S.-P., W.T. Liu, Q. Liu, and M. Nonaka. 2001. Far-reaching effects of the Hawaiian Islands on the Pacific Ocean-Atmosphere System. *Science*. 292(5524):2057-2060.
- [3] Giambelluca, T.W., Q. Chen, A.G. Frazier, J.P. Price, Y.-L. Chen, P.-S. Chu, J.K. Eischeid, and D.M. Delaporte, 2013: Online Rainfall Atlas of Hawai'i. *Bull. Amer. Meteor. Soc.* 94, 313-316, doi: 10.1175/BAMS-D-11-00228.1.

Tables and Figures *(not made by Colleen Dawes)*

- Figure 1: Elevation Map of the Pacific
 - Wikipedia: http://en.wikipedia.org/wiki/Hawaii_hotspot
- Table 1: Hawaiian Island Data: Age, Peak, Size and Population
 - University of Hawaii at Manoa, www.soest.hawaii.edu/GG/ASK/volcanoes.html
 - Hawaii Visitors & Convention Bureau, www.hvcb.org
- Figure 3: Wind Speed and Direction
 - [2], <http://earthobservatory.nasa.gov/>
- Figure 19C: Different Patterns of Orographic Rainfall on Hawaii
 - http://emedia.leeward.hawaii.edu/millen/bot130/learning_objectives/1019/19.html