RAIN GAUGE ANALYSIS

OF PRECIPITATION ON OAHU

A THESIS SUBMITTED TO
THE GLOBAL ENVIRONMENTAL SCIENCE
UNDERGRADUATE DIVISION IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

GLOBAL ENVIRONMENTAL SCIENCE

MAY 2018

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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ABSTRACT

Abstract:

Historical rain gauge data were analyzed to identify average annual rainfall cycles across the island of Oahu for different time periods. There are diverse microclimates in Hawaiʻi that are regulated by topography of the island and location relevant to the trade winds and to the two mountain ranges, the Koʻolau and Waiʻanae. Data sets were acquired from active rain gauges maintained by USGS. The time periods that time series plots were produced for are the two successive decades 1998-2007, 2008-2017, as well as 2003-2017 and the most recent year, 2017. From data recorded in the last two decades it is unmistakable that location and elevation have an affect on the climate. Characteristics of the climate including the number of days it rains per month, as well as the monthly and seasonal average rainfall patterns. Comparison of rain gauges that were grouped into clusters based on geographic location show there is a distinct polarity in average precipitation from the windward to leeward parts of the island.

PREFACE

Significance:

The use of rain gauges is one important component for modeling microclimates, which is a useful source of information for land use planners and water resource managers. Historically rain gauge observation stations were abundant in agriculture zones for sugarcane and pineapple plantations. As the plantations closed down, the majority of rauges were discontinued. The Hawaiʻi rainfall network that was used by Giambelluca et al. had the largest coverage gaps in the remote mountainous areas, which are important for understanding groundwater recharge and streamflow. Resolution of the current rainfall atlas can always be refined further by increasing the number of rain gauge stations. The state currently has 67,000 acres of land on Oahu designated to agriculture. Improving climate models can help the Department of Agriculture plan harvest seasons, crop rotations, and resource management to maximize productivity. An agricultural hub that coordinates organic small scale (5-15 acre) farmers, commercial aggregation facilities, and value added producers calls for research and data based planning. Improving climate models is also beneficial for the 212,000 acres of conservation land where the forestry affects the amount of water attributing to runoff, erosion, recharge, or evapotranspiration.

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CHAPTER 1
INTRODUCTION

1.1 General Climatology

1.1.1 Cloud formation

Clouds are composed of millions of suspended tiny water droplets that depend primarily on two major components, moisture and temperature. Consider an air parcel or cube, inside the 6 imaginary walls of the cube there is air. The air has water vapor (water in a gaseous state) in it. Two things are necessary for a cloud (liquid water droplets) to form from this water vapor, a high relative humidity (>100%) and a particle or cloud condensation nuclei (CCN) for the water to condense onto.

1.1.2 Atmospheric pressure

As a parcel of air raises in elevation, the pressure forcing on the walls of the cube of air decreases. As the parcel of air gets farther from the sea level, and higher into the atmosphere, there is less mass of air weighing down from above. Therefore pressure decreases exponentially with height. The relationship between pressure and temperature is linear, therefore the temperature of the parcel of air decreases as it rises in elevation too. The dry adiabatic lapse rate (-9.8 K/km) is the rate of temperature decrease for a dry (non saturated) air parcel.

The water vapor content, or humidity, is based on the percentage of the air that consists of water vapor within a cube or parcel. If the temperature of the air drops below the dew point temperature, water vapor will condense to liquid droplets. The altitude and rate at which cloud liquid water will form varies based on seasonal conditions, location and based on the geographical conditions like topography, slope, vegetation and other factors.

Air is considered saturated when the water vapor content is equal to the air's capacity for water vapor or when the temperature equals the dew point temperature. As air cools, the capacity to hold water vapor decreases, so air with high amounts of water vapor content (more humid) will become saturated and form clouds. The altitude at which temperatures are cool enough for liquid water droplets (clouds) to form is the Lifting Condensation Level (LCL). According to Meteorology Researchers at the University of Hawai'i, the LCL varies from 800 m to 1 km on the windward coast of Oahu, the cloud base height is 850 meters on average (Zhang 2012). The LCL altitude varies based on the air being lifted. If air is cooler, and therefore has a lower relative humidity, the LCL will be at a greater altitude. If the air is warmer with a higher relative humidity, the air does not need to be lifted as far to reach saturation. Air traveling over the ocean naturally has high water vapor content from evaporation and latent heating from the sea surface water.

1.2. Climate in Hawai'i

The air being carried across the Pacific Ocean surface is high in water vapor from seaspray and evaporation of sea surface water. When air reaches the Hawaiian Islands and each island takes the air up a unique windward slope, topographic features lift the humid air to higher elevations where it can condense and form liquid cloud droplets.

If the Hawaiian islands did not rise above the sea surface, the average rainfall over the ocean where Oahu is located would likely be about 25" since this is the average rainfall over the ocean nearby. The mountains lift the air and produce 60" of rainfall a year on average (*Giambelluca et al. 2013*). Water demand for the 988,650 people on Oahu (as of 2017) is about 10% of the annual rainfall. Due to percolation through highly porous volcanic rock, runoff caused by urbanization of watersheds, and the transpiration from highly vegetative uplands, rainfall in the uplands is important for recharging the aquifer. Oahu is the most developed Hawaiian island, and the diversion of streams and development of land has affected watershed ecosystems.

1.2.1 Spatial Rainfall Variability

Oahu is comprised of two parallel mountain ranges, which lie almost perfectly perpendicular to the north-east (NE) trade winds. The mountains on Oahu are relatively smaller compared to the rest of the Hawaiian Islands, and it's 4,000 ft summits are in the middle of the LCL. The Koʻolau range stretches parallel with the eastern shore and comes up against the tradewinds before anything else. The Waiʻanae range stretches along the western shore and is called the leeward side. The leeward side receives some onshore winds from the north, but the majority of the leeward side includes the central plain which is blocked from the trade winds by the Koʻolau range. Saddling between the two ranges is the Wahiawa plateau where the elevation reaches 952 feet. From Ewa Plain to Haleiwa, conditions are ideal for farming, with sufficient sunlight, rainfall, and fertile soil.

1.2.2 Koʻolau Mountain Range

The Koʻolau range is unique due to its geologic origin. The cliffs on the windward side were once the inner wall of a volcano caldera, before the eastern rim of the caldera subsided into the ocean. The ridges have steep gradients and the deep and narrow valleys are where the water vapor starts to condense to form clouds. The crest of the range stretches parallel to the north eastern shore, dividing the windward coast from the leeside. The climate and topography of the two sides are very different. On the leeward side the gradient of the ridges are gradual, and the air descending down from the windward side has lost much of its moisture at high altitudes. The peaks range from 600 m to 1000 m, with the majority of the ridgeline in the lower range of the average LCL, 800-1000m (Zhang 2012).

1.2.3 Waiʻanae Mountain Range

The Waiʻanae range has less exposure to the coast than the Koʻolau range. The central plain is shielded from the tradewinds by the Koʻolau Range. Ocean air comes from the north, hitting the North Shore where the mountains produce the most rainfall annually (*Giambelluca et al. 2013*). Air carried over from the Koʻolau range has less water-vapor content after descending from high altitudes. Therefore the Waiʻanae range doesn't get nearly as much annual rainfall as the Koʻolau range. The highest summit on Oahu, Mt. Kaʻala (1,200 m) is in the Waiʻanae range, yet the gradient of the topography does not favor as much cloud formation as the sharp Koʻolau range does. The driest part of Oahu, 20 in. annual rainfall (*Giambelluca et al. 2013*), is on the Leeward side of the Waiʻanae Range, in the southern region. There are few ridges on the leeward side and the gradient is actually steeper than the windward side. This could be the eastern rim of a caldera that formed before the Koʻolau range was formed. The leeward coast, including towns Waiʻanae and Nanakuli are the most isolated parts of the island and most of the land between mauka and makai is close to sea level. The windward valleys of the Waiʻanae range are dominantly used for agriculture, and the highlands are all conservation land.

1.2.4 Tradewinds

Tradewinds are dominantly from the north east, due to a semi-permanent high pressure system located in the North Pacific. In the summer, tradewinds account for 90%

of rainfall. Contrastly, in the winter when the Aleutian Low system becomes more dominant in the North Pacific, the tradewinds only account for 50% of rainfall. When tradewinds are strong, they dominate the wind direction (NE) across the island, and most of the clouds are produced via orographic lifting. When tradewinds are weaker, local wind directions are influenced by local sea and land breezes, convergence of the two can result in air being lifted to form clouds.

1.2.4.1 Tradewind Inversion Layer (TWIL)

An inversion layer is where the atmospheric temperature either remains the same or increases with increasing elevation. In Hawaiʻi subsidence from Hadley Cell Circulation drives the inversion layer at around 7,000 ft (Longman et al. 2015). Because of the stability in the TWIL, the tradewind inversion caps the cloud top height resulting in the high moisture content below the TWIL and dry conditions above. When the inversion is disturbed by cold fronts, kona storms, and tropical storms, air has already mixed out the TWIL, so deep convection and thunderstorms are possible. In the winter, disturbances of the TWIL are more common and convection is able to reach higher and produce widespread cloud cover. This results in greater rainfall events, including increased rainfall on the leeward sides of mountain ranges.

1.2.5 Leeward/Windward/Central

Oahu can be segmented into three general sections: Windward coast, Central Valley, and Leeward coast. The windward coast faces the north east, and is commonly known for being the cloudiest and rainiest part of the island (Barnes et al. 2016; Giambelluca et al. 2013). The central valley gets a fair amount of rain in the northern portion, while the southern half of the central valley is at a lower elevation and has more leeward characteristics. The leeward coast, facing the west, is the driest part of the island (Giambelluca et al. 2013).

1.2.6 Hawaiian Seasons

1.2.6.1 *Kau*

In *Olelo Hawai'i*, the summer months (Apr-Sep) are referred to as *Kau*, the dry season, when plants are fruitful. In the summer tradewinds are more consistent, and orographic rain generally remains on the windward coast and near the peaks of the mountains. Widespread rainfall is rare, and leeward regions have long dry periods, receiving a monthly avg. of <1 in. per month in the summer.

1.2.6.2 *Ho`olio*

Native Hawaiians refer to the winter months (Oct-Mar) as *Ho`olio*, the wet season. The weather is cooler and the tradewinds are more interrupted by cold front storms and other mid-latitude disturbances from the northwest. These storms generally spread rain over the entire island without regard to windward and leeward orientation.

1.2.7 Diurnal patterns

Daily rainfall patterns include two peaks, after sunrise, and before sunset, the times of the day when the temperature of the land is rapidly changing. The temperature gradient between air above land and air above the ocean creates a pressure difference which forces breezes (from high to low pressure) off shore in the early morning and onshore in the afternoon. This generates thermally forced orographic rain at the tops of mountains on both windward and leeward sides (Hatley 2010). Convection is caused by lighter air over land being warmed and being lifted to higher altitudes where clouds and precipitation can form.

1.3 Land Zones on Oahu

1.3.1 Agriculture

This research was conducted with the motivation to increase the use of climate research as a tool when planning the use of agriculture land. Oahu has a total land area of 383,000 acres, of which 212,000 acres is conservation land (55%), 104,000 acres is urban area (27%), and 67,000 acres is agriculture land (18%) (HDOA 2015) Most of the land designated to state conservation is located at higher elevations of both mountain ranges above 1,000 ft. Urban area on Oahu is largely concentrated along the South shore, but extends moderately into the central valley, leeward and windward coasts. The agriculture zone is primarily in the central valley, and on windward slopes of the Wai‘anae mountain range, with a few scattered parcels on the windward and leeward coasts.

CHAPTER 2
METHODS

2.1 Data Sets

2.1.1 Rain Gauge Locations

Data sets from 6 active rain gauges were selected for this study. The rain gauge data used is available online by USGS Water Data for the nation. Rain gauges were manually grouped into clusters based on their location.

Cluster one, the leeward cluster, consists of only one rain gauge that was available on the leeward coast. It is in the Waiʻanae Moku, at an elevation of 938 ft. (Table 1)

Cluster two, the central valley cluster, consists of two rain gauges on the north shore, near the end of the Koʻolau range. It is on the border of the windward and the leeward sides, arguably closer to the central valley. The two rain gauges are 440 ft apart in elevation, at 720 ft and 1,160 ft. (Table 1).

Cluster three, the windward cluster, consists of three rain gauges on the windward coast, two at low elevations near sea level *(makai)*, 95 ft and 240 ft, and the third is at the top of the mountain up the nearest ridge, 2,480 ft. elevation.

The rain gauges in each cluster were averaged to determine the rainfall and number of zero rain days to represent a region of Oahu.

Cluster	Station	Location (Moku)	Elevation (ft)	Est. (yr)
1	Makaha	Waianae	938	1993
2	Pupukea	Waialua	720	2003
2	Kamananui	Waialua	1,160	1990
3	Kahana	Ko'olauloa	95	1994
3	Punalu'u	Ko'olauloa	240	2003
3	Poamoho	Ko'olauloa	2,480	1967

Table 1: Individual rain gauges were grouped into clusters based on their relative location. Only two rain gauges were not active for the entire first decade (1998-2007).

2.1.2 Data FrequencyProcessing

The datasets provided daily rainfall. Gaps in the data were not significant enough to impact the monthly averages over a number of years. Our quality check included discarding any months with more than half the data missing. The daily data for each month were summed to produce the total monthly rainfall for each month of each year. Then the monthly average for all the years included in the time period was calculated.

2.1.3 Time periods

There were four time periods chosen for this study, including the most recent year 2017, 2003-2017, 1998-2007, and 2008-2017. The earliest year that all rain gauges were simultaneously active was 2003. (Table 1) Therefore the time period 2003-2017 gives the fairest overall comparison of average rainfall for all the rain gauges. Two successive decades 1998-2007 and 2008-2017 were analyzed to compare any changes in rainfall. Note that some rain gauges were not active for parts of the first decade, and therefore were not included in that time period.

2.2 Data Analysis

2.2.1 Matlab Time Series Analysis

To analyze USGS data sets, the time periods requested between 1998 and 2017 were copied from the website into excel spreadsheets. The format was changed to two vectors, date and rainfall (in.), and saved as a .csv file. The two vectors of data were then uploaded to Matlab R2017b. The uploaded files were saved according to the first three letters of the raingauge name.

A series of time series plots were produced for the average monthly rainfall for the four time periods: 2003-2017 (Figure 1) and 2017 (Figure 2), and for the two decades, each cluster was plotted separately (Figures 3-8). The rain gauge data were graphed in three colors red, blue, and green to correspond with cluster, one (leeward), two (central valley), and three (windward) respectively. For clusters with more than one rain gauge active, the individual graphs had the same color but different line styles.

2.2.3 Zero Rain Days

Similar to the series of time series plots produced for the average monthly rainfall, the number of zero rain days per month were plotted for the same four time periods: 2003-2017 (Figure 9) and 2017 (Figure 10), and for the two decades, 1998-2007 (Figure 11) and 2008-2017 (Figure 12) for both the clusters and individual rain gauges. The same two vectors were uploaded to Matlab and were analyzed to find the number of days that there was a record of zero inches of rainfall. The average number of dry days for a certain month, or harvest season for the case of a farmer, is helpful information for planning, managing irrigation resources. For a cluster with two or more rain gauges active, the number of zero rain days was averaged.

2.2.4 Comparison based on location, grouping, etc.

The reason for the clusters was to compare different parts of the island by using multiple points to represent a region. A grid of rain gauges would be more ideal for monitoring microclimates in an area of interest such as agriculture or conservation ecosystems.

Cluster one represents the Waiʻanae Moku on the Leeward coast, cluster two straddles the border of the Wailua and Koʻolau Moku on the North Shore, and cluster three represents the Koʻolau Moku on the windward coast. Within clusters two and three there are two or more rain gauges, allowing the comparison of precipitation along different gradients. The plots of individual rain gauges within the same cluster were analyzed to compare how rainfall patterns varied based on elevation within a region.

CHAPTER 3
RESULTS

The results from analyzing the data from six active rain gauges on Oahu has shown a distinct contrast in annual rainfall patterns, based on three factors: geographic location, elevation, as well as differences between decades.

3.1 Monthly Rainfall

3.1.1 General Overview

Starting with the most general observation of the rain gauges, the time period 2003-2017 encompasses all individual rain gauges active simultaneously for the greatest number of years. 15 years of annual rainfall patterns were averaged to compare monthly average rainfall (in.) and the number of zero rain days per month. The first peak in rainfall occurs in March, and is also the max for this time period (Figure 1). The months June, July, and August have the lowest average rainfall for all rain gauges. November is the second peak of the year, lesser than the spring peak, but still apparent.

The cluster with the greatest quantity of total annual rainfall is predictably cluster three, on the windward coast (Figure 1). The driest rain gauge is cluster one, on the leeward coast. The two rain gauges in cluster two, Pupukea and Kamananui, show very similar patterns (peaks and troughs), as well as similar average inches of annual rainfall. In cluster three the annual cycles are very similar for the *makai* rain gauges, Kahana and Punaluu. At Punaluu, the average rainfall is consistently greater than at Kahana. Poamoho rain gauge has a fairly similar patterns as the other two rain gauges in cluster three, but it has nearly double the average rainfall in spring, and from 2-4 more inches in the late summer to winter months. Overall the clusters one and two, and the *makai* rain gauges in cluster three have a from leeward to windward locations respectively. The Poamoho rain gauge is at a high elevation and sets cluster three farther above the rest.

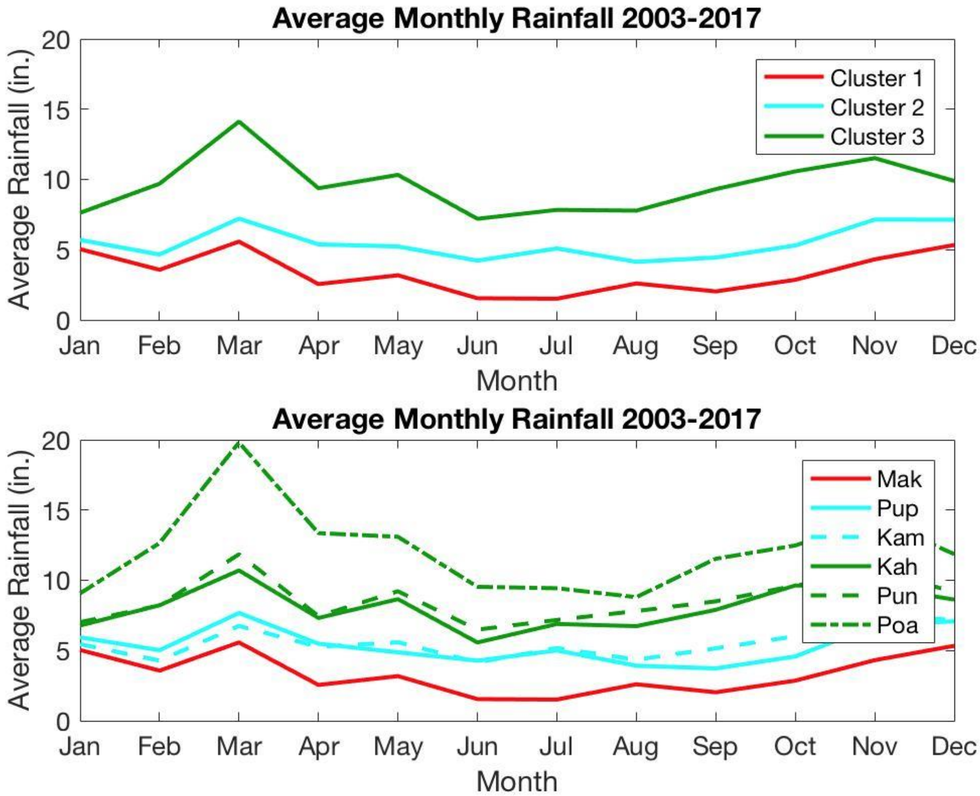

Figure 1: Average monthly rain gauge time series of rainfall (in.) for the time period 2003-2017 shown on top for the average rainfall of the clusters and on bottom for each individual rain gauge.

In the most recent year 2017, the annual rainfall pattern had two peaks in the spring, and a peak in November (Figure 2). Similar to the 2003-2017 time period, November is one of the wettest months on average. The wet season was inconsistent for this time period, also March was no longer the wettest month, but February and April were two high points for for most of the rain gauges. Overall the amount of rainfall from

October to April was the similar, and alternated up and down for the next 4 months. The driest month for almost all the rain gauges was September.

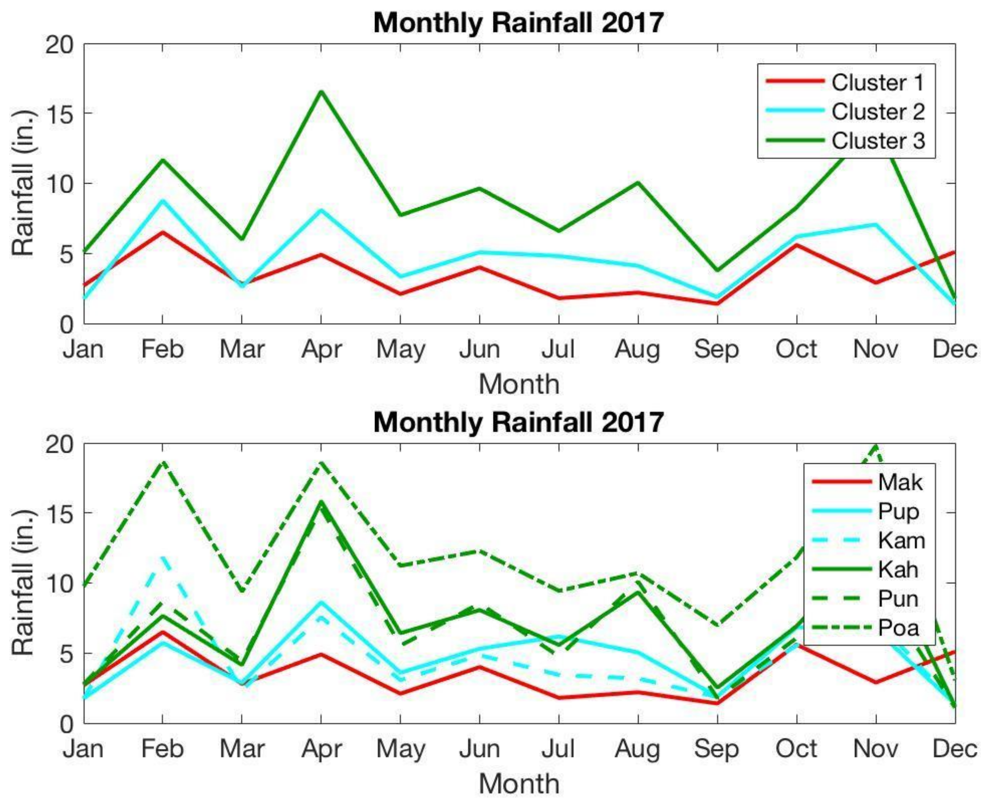

Figure 2: Monthly rain gauge time series of rainfall (in.) for the year 2017 shown on top for the average rainfall of all rain gauges in the clusters and on bottom for each individual rain gauge.

3.1.2 Cluster 1 (leeward)

Cluster one only consists of one rain gauge, so the individual graph is identical to the cluster one graph (Figures 3-4). The first decade, 1998-2007, has a more extreme contrast in rainfall between wet season and dry season. The average rainfall for this time period has a max peak of nearly 7 in., in March. In April it declines steeply to about 2 in. and tapers off until July, when average rainfall reaches minimum, < 1 in..

In the second decade, cluster one's summer months averaged between two to three inches per month, from June to September. In the first decade, the summer appears to have been from April to September, two months longer on average. For both decades there was only one month that average more than 5 in., March for the first decade, and December for the second decade. The winter rainfall pattern appears to have shifted over the years, there used to be a steady increase in rainfall starting in October, and peaking in March. The initial steady increase is similar, but the average rainfall peaks in December at a maximum 6 in. and then fluctuates above and below 4 in. from January to May. For the summer months, the average rainfall for the second decade was at least an inch less per month from April to September (Figure 4).

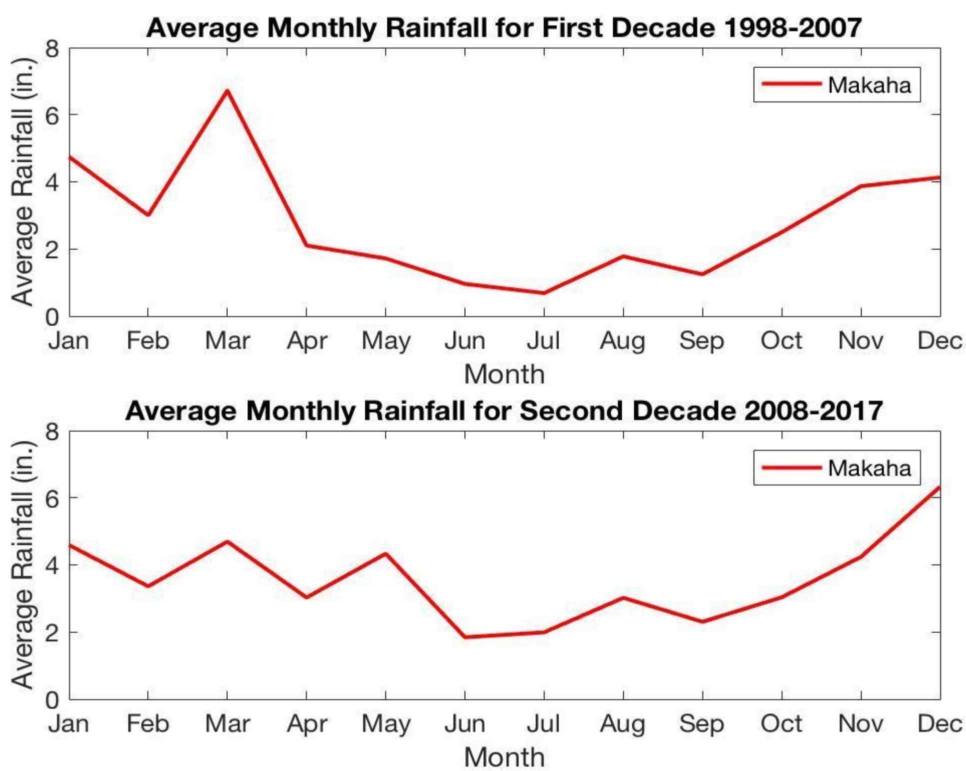

Figure 3: Average monthly rain gauge time series for rainfall (in.) for Makaha rain gauge in cluster one. On top shows the first decade and on bottom shows the second decade.

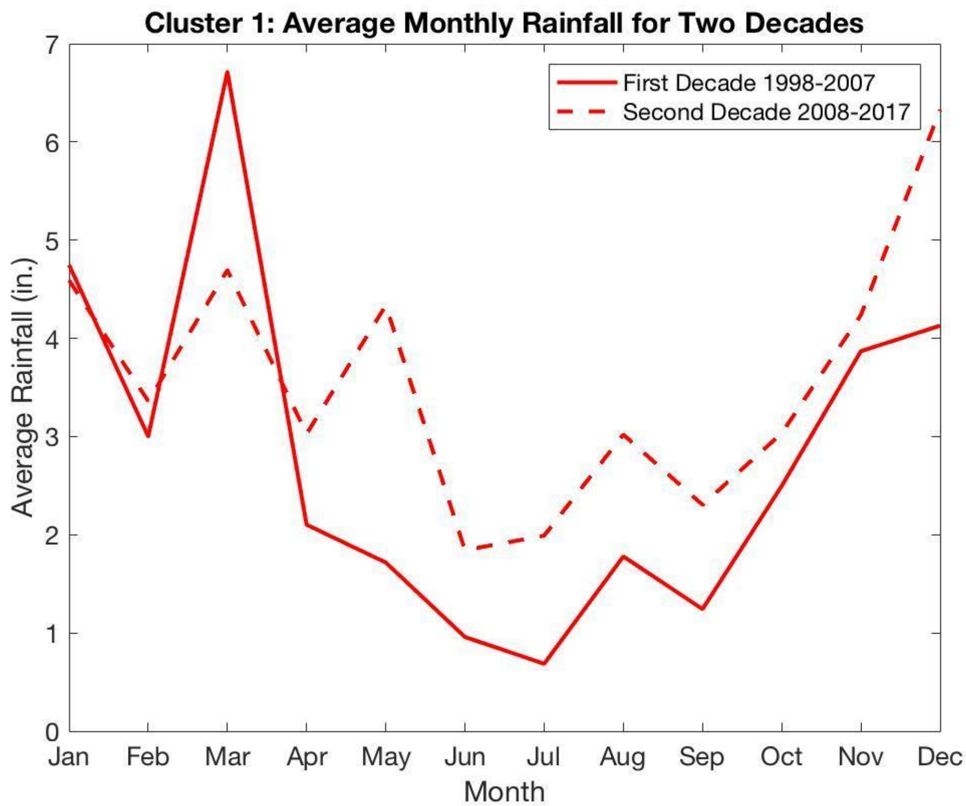

Figure 4: Average monthly rain gauge time series for rainfall (in.) comparing the average rainfall for the rain gauges in cluster one during two successive decades, 1998-2007 and 2008-2017.

3.1.3 Cluster 2 (central)

During the first decade, the Pupukea rain gauge was the only rain gauge active for the entire time period (Figures 5-6). Similar to cluster one, on average, March was the wettest month for cluster two. The contrast between dry and wet seasons is not as extreme as it was for cluster one. The second decade saw a significant increase in average rainfall, overall. In fact the driest month in the second decade, June ~6 in., was within an inch from the second decades wettest month, March ~7 in. Cluster two experienced a similar change in wet season that cluster one experienced. In the first decade the rainfall does not peak until March, and in the second decade rainfall peaks as early as November and tapers off the rest of the winter.

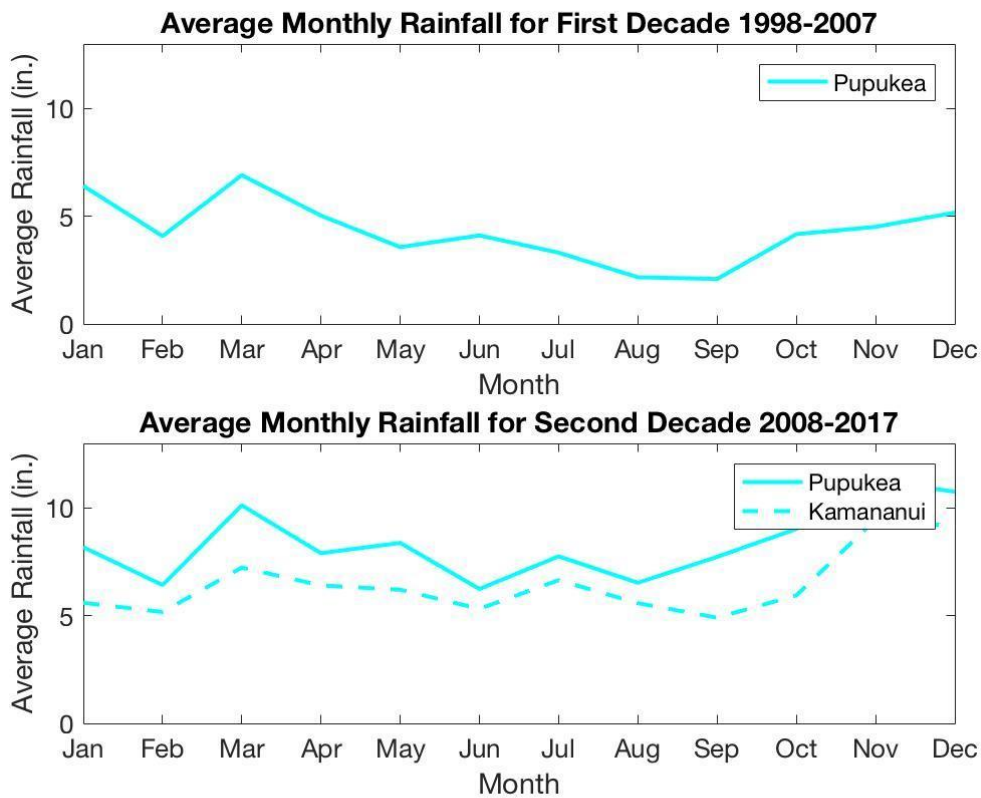

Figure 5: Average monthly rain gauge time series for rainfall (in.) for Pupukea and Kamananui rain gauges in cluster two. The first decade is shown on top, and the second decade on bottom. Kamananui is not shown in top because it was not active for the entire first decade.

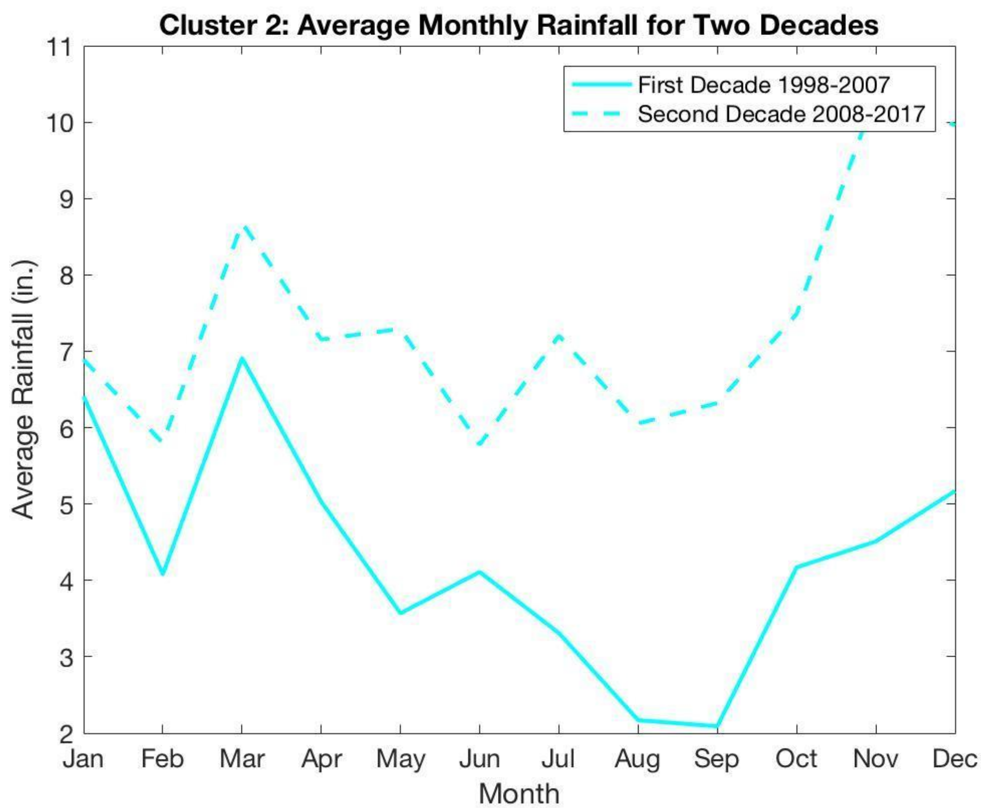

Figure 6: Average monthly rain gauge time series for rainfall (in.) comparing the average rainfall for the rain gauges in cluster two during two successive decades, 1998-2007 and 2008-2017.

3.1.4 Cluster 3 (windward)

The Punaluu rain gauge was not active for the entire duration of the first decade. The Poamoho and Kahana rain gauges show a similar pattern as the first decade of cluster one and two, peaks in March and November (Figure 8). The contrast in wet to dry season is more pronounced in the first decade than in the second decade (Figure 7), which was the case for clusters one and two as well. The dry season occurred between May and August for the first decade. For the second decade the dry season is not as noticeable, with the wet season extending to May. For Kahana the second decade has a nearly constant average of 8 in. per month. The average rainfall for cluster three for the second decade is unmistakably greater than average rainfall for the first decade, throughout the whole year. The summer months especially receive more rainfall in the second decade. The second decade has less variance in rainfall between winter and summer months, ranging from 9-15 inches per month.

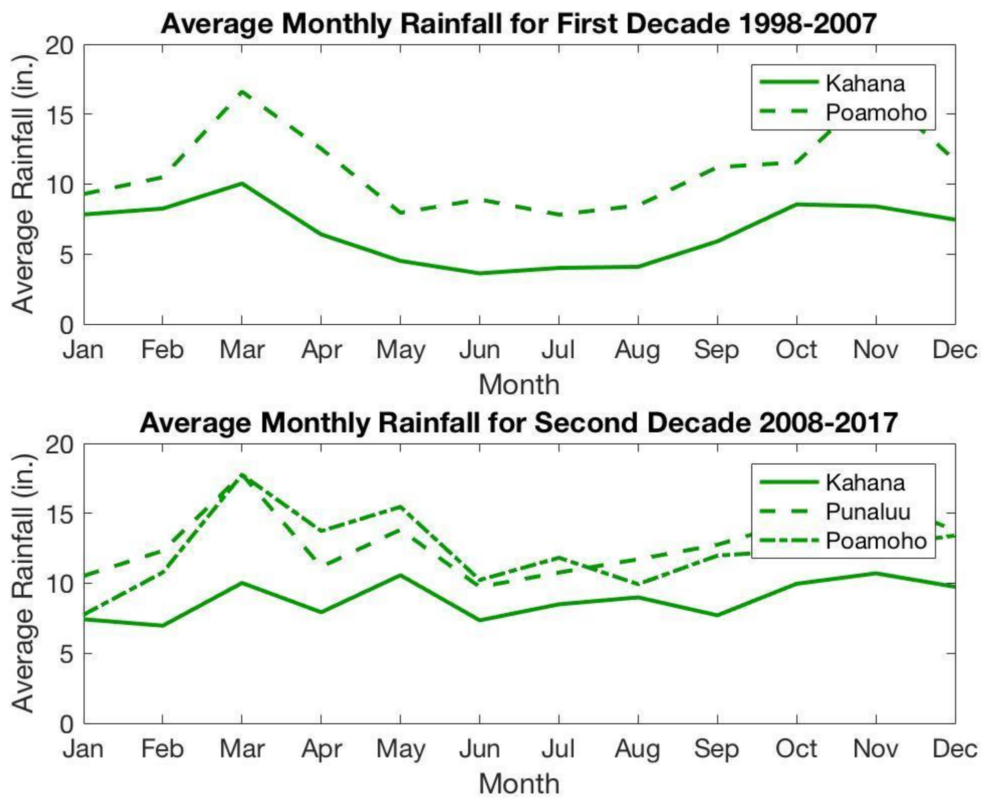

Figure 7: Average monthly rain gauge time series for rainfall (in.) for Kahana, Punalu`u, and Poamoho rain gauges in cluster three. The first decade is shown on top, and the second decade on the bottom. Punalu`u is not shown in top because it was not active for the entire first decade.

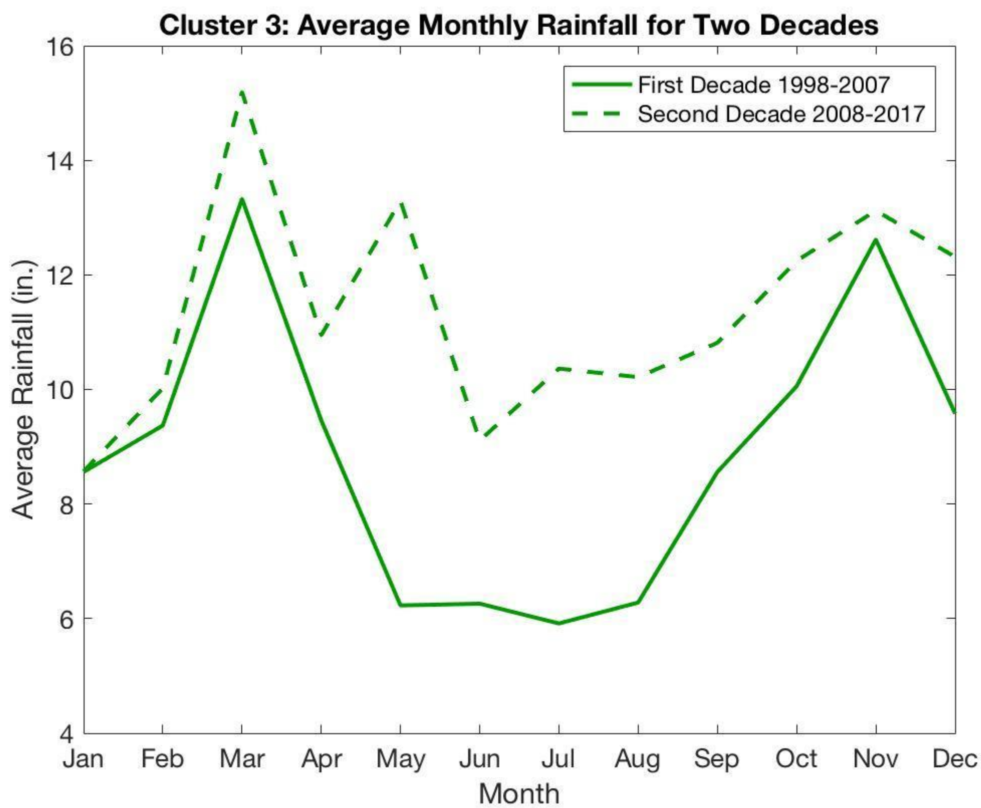

Figure 8: Average monthly rain gauge time series for rainfall (in.) comparing the average rainfall for the rain gauges in cluster three during two successive decades, 1998-2007 and 2008-2017

3.2 Monthly Zero Rain Days

3.2.1 Clusters compared

For the number of days per month that it did not rain, from 2003-2017 Poamoho (highest elevation) rain gauge has the least dry days of the six rain gauges, and Makaha (leeward) rain gauge has the most number of days with zero rainfall (Figure 9). Cluster two and cluster three are close in the number of zero rain days, but on average cluster two consistently has one to three more dry days per month. For clusters two and three the average number of zero rain days is almost the same all year, averaging 10 dry days per month. Cluster one averages ~19 days per month with zero rainfall.

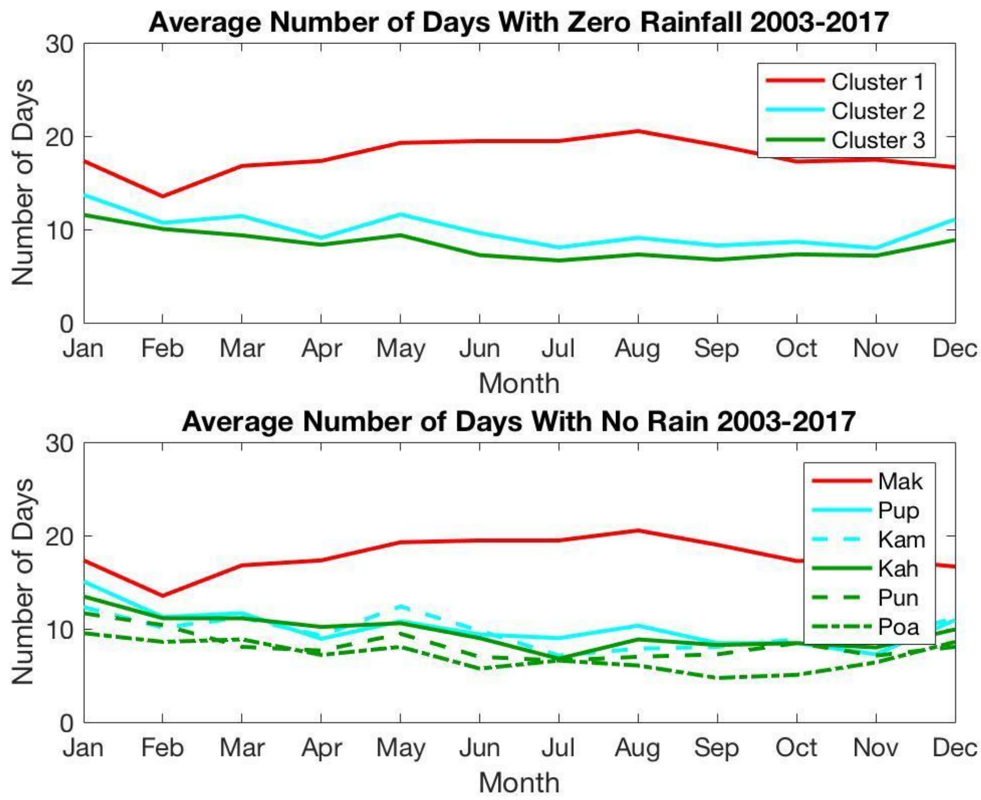

Figure 9: Monthly rain gauge time series for the number of days that there was zero inches of rainfall recorded per month, during the time period 2003-2017. The average number of zero rain days for all the rain gauges in each cluster is shown on top, and the average number of zero rain days for each individual rain gauge is on bottom.

In 2017, the number of zero rain days at the leeward rain gauge was always greatest. The months January to March were drier than usual for all rain gauges (Figure 10). Cluster two averaged 20 days with zero rain, and was closer to cluster one than cluster three in average zero rain days per month. But in the summer, cluster one had ~16 more dry days per month than the other two clusters. The summer of 2017 was very wet for the windward rain gauges. The rest of the year cluster two averaged 10 dry days per month. 2017 was not an average year, compared to the time period 2003-2017.

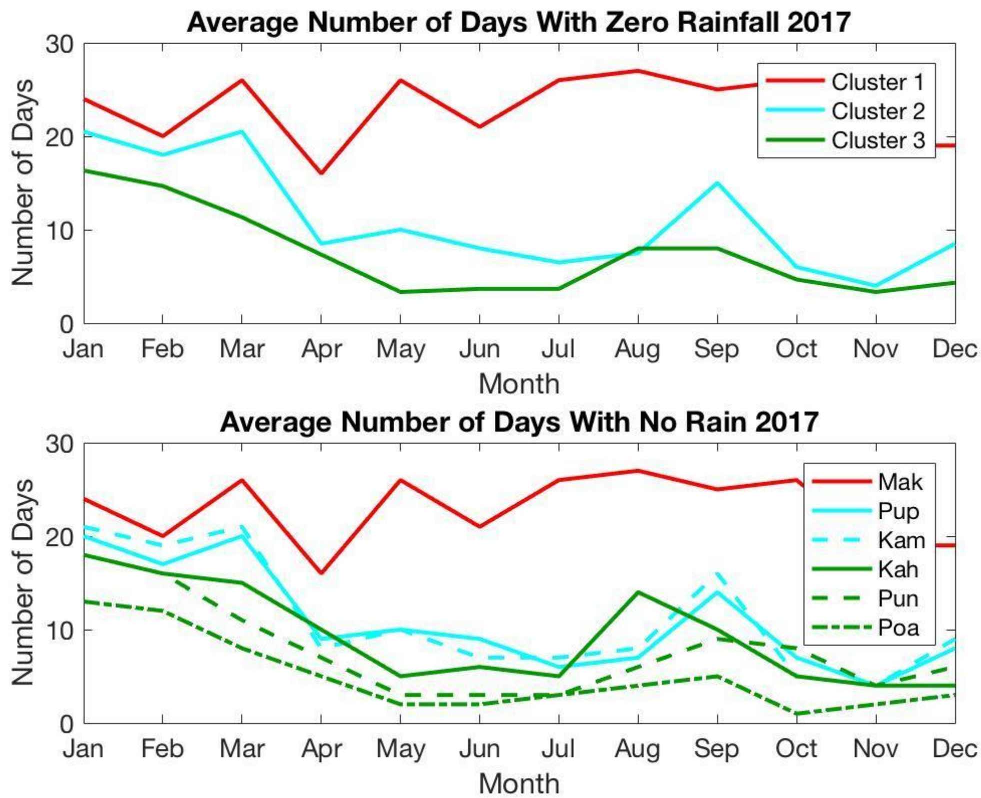

Figure 10: Monthly rain gauge time series for the number of days that there was zero inches of rainfall recorded per month, in the year 2017. The average number of zero rain days for all the rain gauges in each cluster is shown on top, and the average number of zero rain days for each individual rain gauge is on bottom.

3.2.2 Decades Compared

During the first decade, 1998-2007, Kamananui (cluster two) and Punaluu (cluster three), were not active for the entire time period (Figure 11). The Poamoho rain gauge (cluster three) consistently had the least number of dry days per month during both decades. In the second decade, the average number of dry days was less than the first decade, for all rain gauges.

The leeward rain gauge consistently had an average of 20 days of zero rain per month, from December to April. (Figure 11) The leeward gauge then had its peak from

May to August, followed by a decline from August to November. In the second decade, the average was 20 days again, but with a dip down in December and February (figure 12).

Cluster two had an average 15 days per month of zero rainfall. With dips in April and October/November (Figure 11). During the second decade, the summer months, June to September, the number of dry days was below average (Figure 12).

For the first decade, cluster three was nearly a constant at ~11 in. year round, similar to cluster two's pattern (Figure 11). Cluster three experienced a slight dip in the number of dry days per month in the summer, June to September. For the second decade, the average number of zero rain days for the whole year is less than the average for the first decade (figure 12). The number of dry days is highest in January, ~12 days, and steadily decreases until the minimum number of dry days in July, ~4 days.

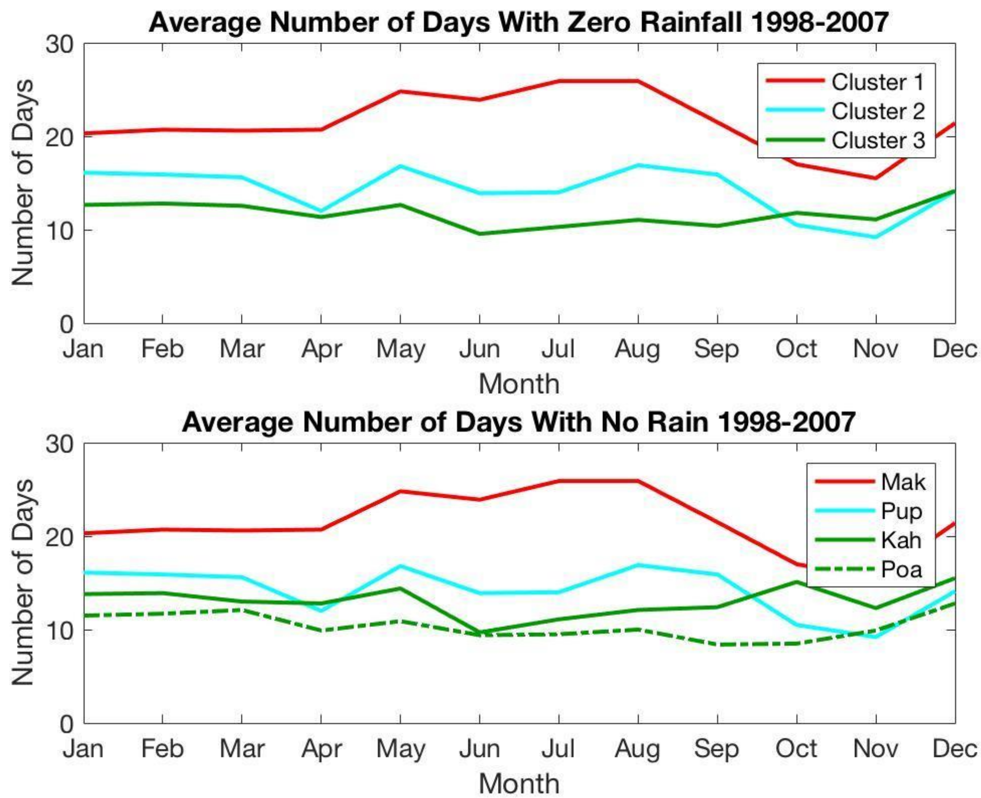

Figure 11: Monthly rain gauge time series for the number of days that there was zero inches of rainfall recorded per month, during the time period 1998-2007. The average number of zero rain days for all the rain gauges in each cluster is shown on top, and the average number of zero rain days for each individual rain gauge is on bottom. Rain gauges Kamananui and Punalu`u are not included in this time series because they were not active for the entire decade.

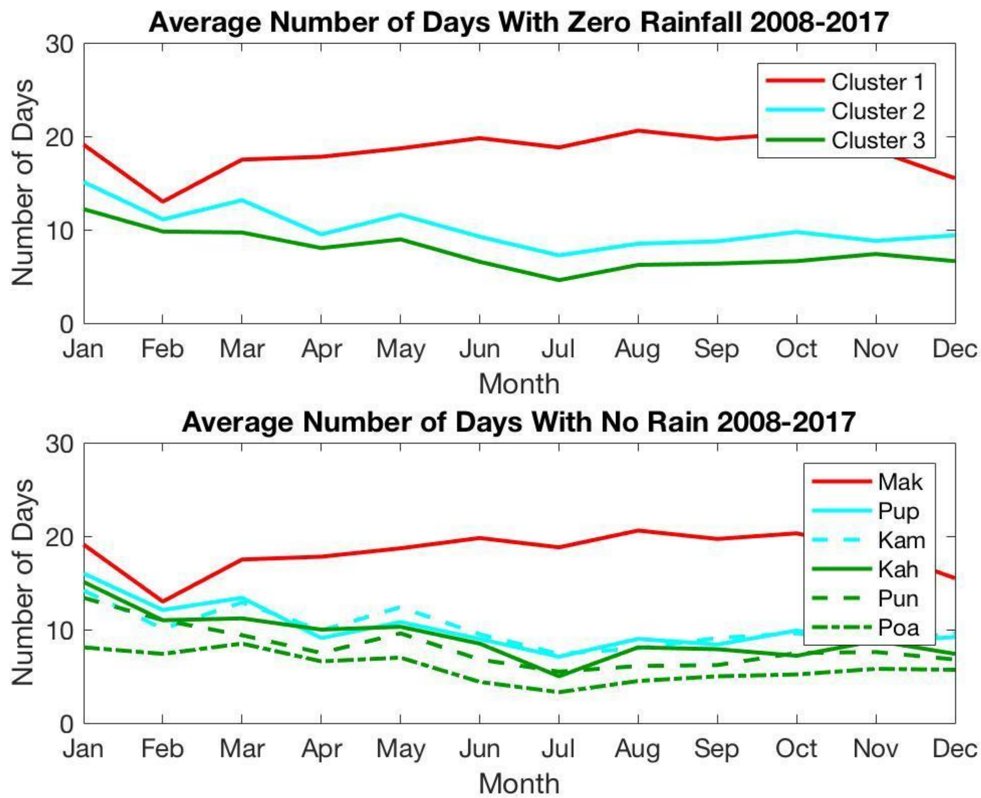

Figure 12: Monthly rain gauge time series for the number of days that there was zero inches of rainfall recorded per month, during the time period 2008-2017. The average number of zero rain days for all the rain gauges in each cluster is shown on top, and the average number of zero rain days for each individual rain gauge is on bottom.

CHAPTER 4
CONCLUSIONS

4.1 Average Rainfall by Cluster

There were three clusters grouped in different parts of the island, leeward coast cluster one, central valley cluster two, and windward coast cluster three. The average annual rainfall cycles for the three clusters were directly related to the location along the spectrum from leeward coast to windward coast, leeward coast being the driest, windward coast being the wettest, and the central valley cluster lying in between, with stronger similarities to the windward coast. Windward clusters two and three are located in the Koʻolau range, and cluster one is in the Waiʻanae range. Cluster three had the greatest rainfall overall, and is situated near the center of the Koʻolau range axis that extends North West/South East, parallel to the coast, and perpendicular to the NE trade winds. Cluster two is located on the north edge of the Koʻolau range and does not receive as much rainfall as cluster three, likely because the terrain gradient is not as steep. The topography around cluster two is not as enclosed as cluster three. The incoming air is more likely to wrap around the edge of the mountains into the central valley, rather than being forced up the windward slope toward the LCL. The average rainfall at cluster three is almost double the average rainfall at cluster one for the time period 2003-2017. The rain gauges in cluster two have very similar rainfall patterns and quantities. Throughout the year, cluster two rain gauges stay about midway between cluster three's lower elevation rain gauges and cluster one's rainfall. Poamoho in cluster three, the greatest elevation, skews the average because it is further inland, and it takes a little bit of time for rain to form, it is more likely to fall at the inland higher elevation site first.

4.2 Average Rainfall within each Cluster

4.2.1 Cluster 1

Cluster one had one rain gauge at 938 ft, there are no other USGS rain gauges on the leeward coast to compare to. Notably the Makaha rain gauge is at an elevation in the middle of cluster two's rain gauges.

4.2.2 Cluster 2

Cluster two has two rain gauges, Pupukea at 720ft and Kamanui at 1160 ft. The difference of 440 ft did not result in a major difference in rainfall. In 2017 there was a major rainfall event in late February that hit Kamananui with nearly 7 more inches of rain than Pupukea. For a month that had relatively little rainfall, this one day was the greatest difference all year between the two rain gauges. All graphs show a strong similarity in average rainfall year round for the rain gauges in cluster two.

4.2.3 Cluster 3

Cluster three contains three rain gauges, and the elevations vary from near sea level, Kahana at 95 ft, to the ridge crest, Poamoho at 2,480 ft. The third rain gauge is at the second lowest elevation of the study, 240 ft. There is no rain gauge that collects more rain than the Poamoho rain gauge. The extremely steep gradient of the Ko'olau's windward cliffs and deep valleys likely trap air from getting around the mountains without being lifted above the LCL. The lower elevation rain gauges are affected by the cloud production at the same times, but with lighter rainfall. The rain gauges that are on the valley floor get less rainfall than if they were the same distance from the shore, but on a ridge, where air condenses more frequently. Kahana and Punaluu rain gauges are at a similar elevation, but are separated by one ridge, the ridge that follows to the top where

Poamoho rain gauge is. Punaluu and Kahana valley are very similar in topography, therefore the annual rain pattern is nearly identical. The <200 ft higher elevation at Punaluu rain gauge expectedly receives slightly more rainfall than the Kahana rain gauge. Seasonal cycles in cluster three are consistent with all rain gauges, low rainfall in the summer and higher in the winter. The difference is that Poamoho rain gauge has a greater range of rainfall, varying from 10 inches in the dry months to 20 inches in the wettest month. The average rainfall during the driest month at Poamoho rain gauge is the same amount of rain as the wettest month at the two lower rain gauges. The range of average rainfall for the two lower rain gauges is about 5 inches, half of what poamoho receives. At Poamoho, the heavy rainfall event in late February 2017 lasted two days, producing drastically more rain than at lower elevation that only received one day of greater rainfall.

4.3 Average Zero Rain Days by Cluster

For the zero rain days analysis, the same three clusters were used (leeward, central valley, and windward). The number of zero rain days is largely connected to the mountain range. The rain gauges bound within the Koʻolau range had a nearly identical average number of zero rain days per month. On the other side of the island, on the leeward side of the Waiʻanae range the Makaha rain gauge had a pattern of it's own, averaging a consistent 15 to 20 days without rain per month. That was for the years 2003-2017. In 2017 alone, the average number of dry days per month for Makaha rain gauge was between 20 and 25. In 2017 the rain gauges in clusters two and three showed a high number of days with zero rain in the first 3 months of the year averaging about 20 days without rain per month. Then the summer months delivered more than 20 days a month of rain at cluster two and more than that at cluster three.

The first decade 1998-2007 had a distinct pattern, at the beginning of the year all rain gauges were constant, cluster one with the greatest number of dry days, cluster two with the second most and cluster three with the least. In the summer cluster one increases the number of dry days until september. The two Koʻolau clusters do not vary much, until september when all clusters had at least one rain gauge that decreased in the number of dry days. Then November had the least number dry days of the year. Cluster three varied the least throughout the year staying in a range of +/-1 day for the average number of zero rain days. Cluster one and two had similar increase and decreases, with similar changes in number of days between each month.

For the second decade 2008-2017 the pattern was not quite the same, but there were similarities. The dip that is apparent in November from 1998-2007 looks like it shifted to February for the second decade. Following the dip, the cluster one returns to an average 20 days of zero rain per month for the rest of the year until November and December. As for the Koʻolau rain gauges, on average the year started off with the most days of zero rainfall per month, and slightly decreased the number of days from about 15 to about 10 for all months after April. The second decade contains fewer days with zero rain overall. From 2008-2017, the Waiʻanae cluster did not exceed 20 dry days per month very often, the Koʻolau clusters also averaged high the first month, with at least 10 dry days per month for the entire year. During the second decade, the average number of dry days per month was below ten for the entire second half of the year.

4.4 Average Rainfall for Two Decades

4.4.1 Leeward

The leeward cluster contained only one rain gauge, so the individual and cluster graphs are identical. The annual rainfall cycle for the first decade has more distinct high points, months december November through March have the most rainfall on average. The stretch of months April through september do not get more than 2 inches of rain on average. There is more variability throughout the year, and no consistent high or low points. This could be due to change in frequency and severity of rainfall events. Distribution of rainfall is becoming less consistent, with sporadic surges of heavy rainfall impacts the distribution of rainfall. Decadal weather phenomenon such as ENSO and PDO influence the year to year weather events. The month with the highest average rainfall is December in the second decade, but the following 5 months are between 3 to 5 inches a month. There is not any one of these months that is more likely to have the heaviest rainfall event of the year. If there was one month that had the most heavy rainfall events during it, the peak would be easily identifiable. The average rainfall for August is greater than July and September in both decades. Also, following September the average rainfall per month increases steadily through December.

4.4.2 Central

Cluster two as situated on the border of central valley and the windward coast. Along the most northern slope of the Koʻolau range where moving any further east or west would be considered windward or central valley. It is categorized as central for this study, and has rainfall conditions more similar to the leeward cluster. The annual cycle of rainfall for the Pupukea rain gauge is almost identical from the first decade to the second. The average rainfall per month kept the same seasonal patterns, but overall the amount of rainfall per month was an inch or two more throughout the year, especially in the summer months. An increase in frequency of El Niño summers in the second decade could be the explanation for the increase rainfall observed. The two rain gauges in the second decade average out to a very similar average annual rainfall.

4.4.3 Windward

The change in the annual rainfall cycles for cluster one is very similar to the change observed in cluster three. The first decade contained the Poamoho rain gauge (highest elevation) and Kahana rain gauge (lowest elevation). They both had similar patterns with a peak of average rainfall in the months of March and November. It rains the least during the summer months, May through August, for both rain gauges almost in unison. The second decade has less noticeable peak month in spring, but there is a higher chance for having heavy rainfall in the months March through May. The high average rainfall in November 1997-2007 is less pronounced in the second decade by prior months averaging a similar rainfall year round. The only rain gauge in cluster three that has a noticeable high point is Poamoho, and the month of heaviest rainfall ranges from March to May. The increase in average monthly rainfall per month in the months between March and October is likely due to an increase in storm and ENSO summer events that are more frequent in the second decade.

4.5 Rainfall on Oahu

The island of Oahu has a variety of microclimates that gives it a diverse range of vegetation that grows on the island. The tradewinds can not produce clouds on their own; it is the topography of the Ko‘olau and Wai‘anae mountain ranges that give the air an orographic lift to set in motion the formation of clouds. The annual rainfall pattern largely influenced by the macroclimate and weather systems of the North and South Pacific. Consistent tradewinds in the summer (dry season) sets a stable tradewind inversion layer that moderates cloud formation. In the winter (wet season) low pressure systems from the stormy North Pacific cause lulls in the tradewinds, and widespread heavy rainfall events for the whole island.

Here we have analyzed rainfall patterns at a few land surface locations varying in elevation, and position with regards to the tradewinds (windward, leeward). The lack of USGS rain gauges near agriculture zones left few options for this study, there were still clear differences. The quantity of rainfall and seasonal patterns differed based on location. Adding more site locations for future studies would be beneficial for resolution and accuracy of microclimate mapping. Along with rain gauges, streamflow and reservoir stations would increase our understanding of rainfall on Oahu. Farmers and conservationists alike can make data-based decisions from rainfall records to predict, protect, and maintain life on this secluded island.

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