THESIS

PRECIPITTION AND TEMPERATURE CHANGES AND THEIR EFFECT ON GROUNDWATER ALONG THE KONA COAST OF HAWAIʻI

Submitted by

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ABSTRACT

PRECIPITATION AND TEMPERATURE CHANGES AND THEIR EFFECT ON GROUNDWATER ALONG THE KONA COAST OF HAWAIʻI

Water resources are an important part of the Hawaiian cultural tradition, and a shift to a warmer, dryer climate may initiate physical and biological changes that would inhibit the practice of Native Hawaiian cultural traditions by altering the coastal ecosystem resources such as those found within Kaloko-Honokōhau National Historical Park. The high degree of spatial heterogeneity and numerous microclimates on the Island of Hawaiʻi motivated an in-depth analysis of changes in precipitation and temperature occurring during the time since the park was established in 1978 up to the year 2010 at stations located within the regional recharge area for the Kona aquifer system. The potential long-term implications of changes in climate to groundwater recharge were also modeled using stochastic techniques.

A statistical analysis was conducted on annual, winter, and summer precipitation and minimum and maximum temperature climate records using the Mann-Kendall test to detect the presence of a monotonic increasing or decreasing trend at significance levels of alpha = 0.1, 0.05, 0.01, and 0.001. The similarities and differences between station records were further evaluated by a double mass analysis of the same precipitation datasets. The changes identified during trend analysis were used to create synthetic realizations of temperature and rainfall patterns 50 years into the future using stochastic modeling techniques. The future realizations were analyzed to evaluate changes in net precipitation and the potential effect on groundwater recharge.

Within the Kona aquifer recharge area there is evidence of diverse changes in rainfall that have taken place over recent decades. 13 out of 15 stations evaluated for changes in rainfall have decreasing trends during the 1978 to 2010 time period and over their entire observation record. Decreases in annual rainfall range from 30mm to 250mm per decade with the majority of declines occurring in the summer season. Almost half of the stations had significant changes in rainfall during the summer season, but none of the changes in winter rainfall were significant. The trends displayed in both rainfall and temperature when modeled 50 years into the future indicate declines in net precipitation ranging from 6 to 48% compared to the modeled stationary 50 year mean. All of the modeled scenarios indicated a decline in the number of days with rainfall for all of the locations with the decline resulting in four locations having a season with no rainfall at all. Large declines in modeled net precipitation such as these would affect the overall amount of recharge to the regional aquifer. In an island ecosystem, the constant pressure of saltwater intrusion and the input of freshwater recharge creates a delicate balance of fresh and saline water underground. Any change in net precipitation that affects recharge could disrupt that delicate balance allowing increased saltwater intrusion along the coastline and within the Park.

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CHAPTER 1 – INTRODUCTION

1.1 Background

Freshwater resources on islands experience conditions that are both similar and different from continental resources. Freshwater resources held in groundwater aquifers are limited by the size of the island's land mass. Fresh groundwater exists as a "lens" under the island's land mass with saltwater both surrounding and underlying the freshwater lens (Sanderson 1993; Keener *et al.* 2012). A transition zone of mixohaline, or brackish, water exists between the fresh and salt water bodies. Mixohaline waters are commonly found in coastal wetlands, estuaries, anchialine pools, and groundwater near island coastlines (DeVerse 2006). These waters provide a unique habitat for biota endemic to island ecosystems, such as those found on the Island of Hawaiʻi.

The hydrologic cycle of the Island of Hawaiʻi, like many places in the world, is vulnerable to the impacts of a changing climate. The latest Pacific Regional Climate Assessment report indicates that Hawaiʻi is experiencing decreased precipitation, diminished streamflow volumes, and warming temperatures (Keener *et al.* 2012).

The Island of Hawaiʻi (Hawaiʻi) has a diverse range of climate conditions with seven different climate subregions present on the island (NOAA 1985). The subregions are windward lowlands, leeward lowlands, interior lowlands, Kona coast of Hawaiʻi, rainy mountain slopes on the windward side, lower mountain slopes on the leeward side, and high mountains. The windward side of Mauna Loa and Mauna Kea experience the wettest climate typical of tropical climate and the leeward side of the island along the Kona coast is a semi-arid climate. The habitats of the

Kona coast developed within this particular climate regime and alterations to the climate could lead to shifts in ecosystems (Keener *et al.* 2012).

1.2 Kaloko-Honokōhau National Historical Park

Kaloko-Honokōhau National Historical Park (Kaloko) was established in 1978 "*for the preservation, interpretation, and perpetuation of traditional native Hawaiian activities and culture…*"[16 U.S.C. §396d(a)]. Cultural resources including archaeological sites with petroglyphs, habitation structures, shrines, temples, trails, and an hōlua (stone slide) have been documented within the park (NPS 2005). Water resources such as those within Kaloko are equally important in preserving ancient Native Hawaiian culture. Water played an integral role in the cultural activities of Native Hawaiians (Keener *et al.* 2012). Early settlements clustered around these resources because they provided water for agriculture, aquaculture, bathing, and food harvesting. For example, the anchialine pools were used for bathing, washing, ceremonial purposes, and drinking (NPS 2005).

Kaloko-Honokōhau National Historical Park is a relatively undeveloped microcosm of habitats found along the Kona coastline. Kaloko has 4.69km^2 with abundant water resources (DeVerse 2006) including ponds, wetlands, anchialine pools, and flora and fauna which depend on freshwater discharge from the groundwater aquifer. Island habitats have limited biological diversity due to their geographic isolation and that isolation contributes to the frequent occurrence of endemic organisms (Shea *et al*. 2001). Kaloko has numerous examples of island endemism. It is home to endangered and threatened species including waterbirds, sea turtles, seals, shrimp, plants, damselflies, and migrating whales.

Anchialine pools are depressions in the land surface which are filled with both fresh and salt water that discharges into the depressions from underground. Anchialine pools are unique and rare habitats statewide and threatened by coastal development (DeVerse 2006). Kaloko is one of only three sites with anchialine pools (DeVerse 2006) in the state, with over 100 anchialine pools located within its boundaries (NPS 2005). Anchialine pool habitats are typically species rich with a high degree of endemism (DeVerse 2006). The mixohaline waters of anchialine pools in Kaloko are home to endemic species of shrimp, candidate endangered *Metabetaeus lohena*, species of concern *Halocaridina rubra*, and candidate endangered *Palaemonella burnsi*. Other pool inhabitants include: candidate threatened anchialine pool snails (*Neritilia hawaiiensis*), and candidate endangered orange black Hawaiian damselflies (*Megalagrion xanthomelas*).

The ancient fishponds of Aimakapa and Kaloko are examples of water resources used for Hawaiian aquaculture practices. Both provided Hawaiians living along the coast with a consistent supply of food (NPS 2005). The Kaloko Fishpond is located at the coastal edge with a kuapā (fishpond wall) protecting it from the open ocean. The Aiopio fishtrap was used to bring fish into the pond from the ocean for later harvest. Aimakapa and its associated wetland are located inland and is the fresher water pond. Aimakapa has been recognized by the U.S. Fish and Wildlife Service for the habitat it provides to the endangered Hawaiian coot (*Fulica americana alai*) and Hawaiian stilt (*Himantopus mexicanus knudseni*) waterbirds.

Kaloko is bordered to the south by Honokohau Harbor and related fuel and maintenance facilities. Development along the eastern border is light industrial in nature with a county wastewater treatment plant, county landfill, rock quarry, and gasoline station. To the north, Kaloko is bordered by a resort development with multi-family housing and a golf course (DeVerse 2006). Threats or pressures from invasive species, neighboring developments, non-point source pollution, groundwater withdrawals, and climate change all endanger the quality and quantity of available freshwater (DeVerse 2006).

1.3 Climate of Hawai'i

The Island of Hawai'i is the southeastern end of the Hawaiian island chain of volcanic mountains. Geologically it is the youngest in the island chain and also has the greatest difference in elevation ranging from sea level to 4205 meters atop the highest mountain, Mauna Kea. The ocean surrounding the island exerts strong climatic controls over most of the island but the mountains of Mauna Kea and Mauna Loa are large enough to modify the marine climate effect, producing a great diversity of climatic conditions (NOAA 1985).

Trade winds bring moisture laden air to the eastern side of the island resulting in frequent orographic rainfall as the moist air rises up the slopes of Mauna Loa and Mauna Kea Volcanoes (Sanderson 1993). The high elevation of the volcanoes causes most of the trade winds to diverge north and south around the island with only a small fraction of the trade winds traveling over the saddle between Mauna Kea and Mauna Loa. The western side of the island has much less precipitation than the eastern side due to less beneficial moisture remaining available from trade winds.

Trade winds blowing from the northeast are most prominent in the May through September months. Trade winds provide natural ventilation across the island and warm tropical temperatures to the coastal lowland areas. A few locations on the Hawaiian Islands have more localized land to sea air exchanges due to differences in the solar heating of land and air (Sanderson 1993), and locations along the coast near Kona and Kaloko are one such example. The Kona coast has a diurnal movement of wind from land to sea and back. The air gently moves from land to sea during the night until shortly after sunrise. Air moves more briskly from sea to land during the daytime especially in the afternoon and early evening (Sanderson 1993; NOAA 1985).

Two seasons are recognized and generally divide the year between winter from October through April, and summer from May through September (Sanderson 1993). During the summer, light showers are very common with only occasional heavy downpours. Major storms typically occur during the winter time months of October through March as frontal systems originating south of Japan pass over the islands as they move westward. The island is rarely cloudless with dense cloud layers occurring at the higher mountain elevations and windward slopes.

The topography of Hawaiʻi causes highly diverse climate conditions, and the massive volcanic mountains on the island modify the climate resulting in contrasting conditions on the windward and leeward sides of the island (Sanderson 1993). The area around Kaloko (Figure 1.1) might ordinarily be considered to be in the leeward lowland climatic sub-region but the Kona area has a unique climatic sub-region of its own called "*the Kona coast of Hawaiʻi*" (NOAA 1985). It is the only region where summer rainfall often exceeds winter rainfall with a marked land and sea wind regime. There are frequent late afternoon or early evening rain showers and conditions are warmer and clearly drier than the windward side of the island. Western Hawaiʻi has an average annual precipitation ranging from 200 to 750mm per year compared to the range of 4400 to over 10,000mm per year received on the windward eastern side of the island (Giambelluca *et al*. 2013).

1.4 Climate Change Studies

Characteristics of Hawaiʻi rainfall conditions have been quantified over the years in various reports or state rainfall atlases without evaluating the records for trends. Each succeeding Rainfall Atlas used more recent rainfall records than the previous report and the mean and median calculated for each time frame changed indicating possible changes in climate conditions. The three most recent compilations of station rainfall records calculated mean and median over the time periods of 1916 to 1975 (Meisner 1976), 1916 to 1983 (Giambelluca *et al*. 1986), and 1978 to 2007 (Giambelluca *et al*. 2013). Station means calculated for each time period have been decreasing as more recent years have been evaluated (Meisner 1976; Giambelluca *et al*. 1986; Giambelluca *et al*. 2013).

Concern about the effect of a change in climate has prompted several studies over recent decades to evaluate both current and historical conditions. Most of the studies conducted in recent decades which analyzed changes in climate focused on either precipitation or temperature. Precipitation studies used representative stations for regional areas of either the Island of Hawaiʻi or the entire state (Meisner 1976; Chu and Chen 2005; Diaz *et al*. 2005). Some of these studies attempted to choose station locations that represented important aspect characteristics (orientation to trade winds) and elevation ranges (Meisner 1976). Unfortunately, stations included in the earliest studies often were no longer operating and not available for inclusion in later studies.

Studies focused on pre-1980 time periods found periods of increased (1930's) and decreased (1920's and 1940's) annual rainfall across the state (Meisner 1976) leading to the conclusion that rainfall patterns followed cycles, but no definitive length of cycle was agreed upon and no cause was found. Annual rainfall showed a downward trend on the windward side of the Island of Hawaiʻi and the southeast side showed an upward trend during the years of 1900 to 1977 (Doty 1982). Meisner used representative stations across the state to calculate an index of rainfall from 1916 to 1976 (Meisner 1978). Woodcock used Meisner's rainfall index to evaluate the correlation between water levels in a perched lake atop Mauna Kea and the downward trending rainfall amounts from 1965 to 1979 (Woodcock 1980). Giambelluca used the same method to extend the Hawaiian Rainfall Atlas to 1986.

Downward trends have predominated studies examining precipitation records covering the last 40 years. The period of 1985 to 2000 had a 15% decline from the long term mean when examining trends in a rainfall index developed from stations located across the state of Hawaiʻi (Diaz *et al*. 2005). Stations on the western side of the Island of Hawaiʻi that were chosen for this study were located along the coastline and represented only one-third of the Island's stations used in the study. Rainfall displayed a similar statewide decline from the mid-1970s to 2001 and was correlated to changes in the Pacific Decadal Oscillation (Chu and Chen 2005). These declines were strongly correlated with changes in sea surface temperatures and large-scale climate patterns in the Pacific which may be causing increased subsidence of trade winds across Hawaiʻi. Kruk (2008) analyzed records from the early 1900's to 2007 and found a statistically significant downward trend in annual precipitation in stations located below 1000 meters. Stations in the higher elevations also displayed a downward trend but were not significant.

The warming trend in temperature has not been extensively studied across the state of Hawaiʻi. Giambelluca examined trends in temperature during the two time periods of 1919 to 2006 and 1975 to 2006, and both time periods displayed increased average temperatures with the more recent time period warming more quickly (Giambelluca *et al*. 2008). Also, high elevation stations are warming faster than low elevation stations; which is similar to studies of global temperatures (IPCC 2007). A second study which examined temperature records across the state from 1958 to 2009 found similar warming in annual average temperatures particularly in higher elevations locations (Diaz *et al*. 2011).

1.5 Objectives

Water resources within Kaloko are an important part of the Hawaiian cultural tradition. A shift to a warmer, dryer climate may initiate physical and biological changes by altering coastal ecosystem resources that would inhibit the practice of Native Hawaiian cultural traditions which the Park was established to preserve. The western side of the island (Kona coast) does not have the typical wet tropical climate that one might expect for a Pacific island. The Köppen climate classification for the area near Kaloko is a hot semi-desert class (Oki *et al.* 1999). The park lies within the rain shadow of Hualalai volcano, and the park receives only 458mm annual precipitation on average compared to 3610mm per year (Giambelluca *et al.* 2013) received at Hilo on the windward side of the island.

Surface water along the Kona coastline is limited or nonexistent (Oki 2004) and influenced by the climate regime of the surrounding ocean environment. As recharge to groundwater decreases due to declines in rainfall and water levels within the freshwater lens lower, the size of the freshwater lens retracts and salt water flows into the spaces previously occupied by fresh water (Oki *et al.* 1999). Such salt water intrusion is a hazard for freshwater resources located along the shoreline edge of an island.

The precarious condition of island hydrological systems makes them especially vulnerable to protracted dry conditions or to long term changes in climate (Shea *et al.* 2001). Decreases in precipitation are a concern because if they are severe enough, decreases can result in drought conditions. Drought in this context is defined as "*a period with drier-than-normal conditions that results in water-related problems*" (Moreland 1993). Concerns about the effects of declining precipitation and drought conditions in recent years (Paula Cutillo, personal communication, 2010) have prompted questions asking whether or not climate conditions were already changing on the island.

Previous studies evaluating changes in climate have focused on larger spatial scales such as the chain of Hawaiian Islands or the entire Island of Hawaiʻi using a sampling of stations to represent regional conditions. The Hawaiian Islands are known for their extensive array of microclimates with conditions changing over relatively short distances due to high elevation gradients and topographical differences (Sanderson 1993). Pielke *et al*. (2002) demonstrated that a seemingly homogenous area can experience varying climate conditions and trends. Hawaiʻi's high degree of spatial heterogeneity and numerous microclimates motivated this in-depth analysis of changes occurring at the local level. The study will evaluate changes in the observed climate record of stations located within the regional recharge area for the Kona area aquifer system and the potential implications of a change in climate to the groundwater dependent resources of Kaloko-Honokōhau National Historical Park.

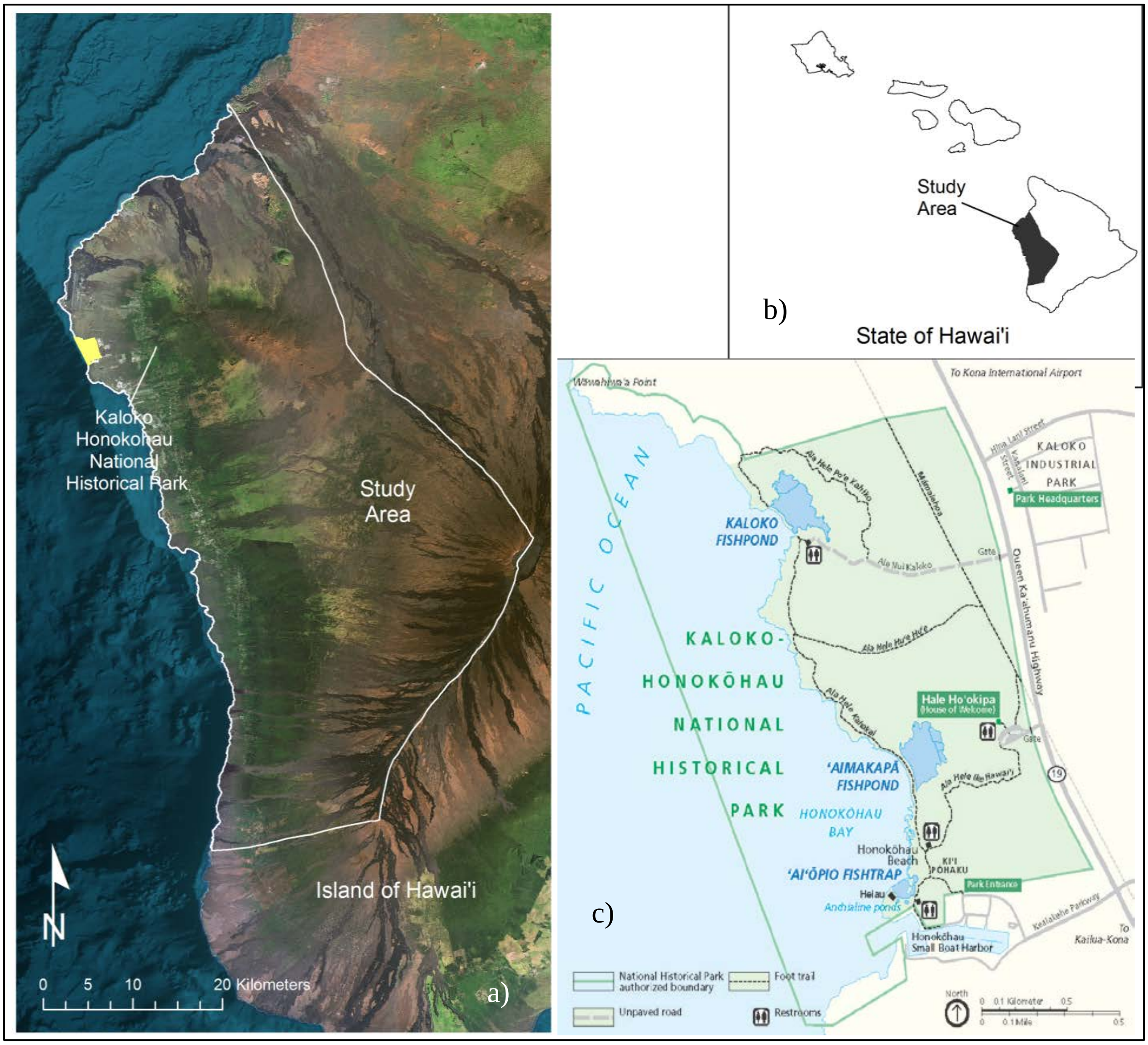

Figure 1.1 a) Location of the Kona recharge area and Kaloko-Honokōhau National Historical Park. Basemap is Landsat 7 mosaic imagery with bathymetric fill from the Hawaiʻi Mapping Research Group. b) Location of the study area within the state. c) National Park Service map of the park and nearby areas.

CHAPTER 2 – STUDY AREA

The Hawaiian Islands lie between the north latitudes of 19 and 22° and 154 to 160° west longitude. The Island of Hawaiʻi, also called the Big Island, is the easternmost of the volcanic island chain. It has two giant volcanoes, Mauna Kea and Mauna Loa which create impressive topological high points rising to over 4,000 meters in elevation (Sanderson 1993). Mauna Kea is to the north of Mauna Loa with another older volcano, Hualalai along its western flank. Two other volcanoes, Kilauea and Halemaumau, are located to the south and east of Mauna Loa. Kaloko lies along the western shoreline of the Big Island approximately three miles north of the city of Kailua-Kona.

The volcanic origins of Hawaiʻi have a profound impact on the transport of precipitation from the land surface to underlying aquifers (Oki *et al.* 1999). The volcanic geology is highly permeable where lava flows exist and relatively impermeable in dike zones. Dikes are near-vertical sheets of cooled magma intruded within the rift zones of lava flows.

The Kona recharge area chosen for this study is based on groundwater modeling done by Oki *et al.* (1999) that is in the vicinity of Kaloko-Honokōhau National Historical Park (Figure 1.1). The area extends from the northwest rift zone of Hualalai Volcano, east to the south-southeast rift zone of Hualalai Volcano, and south to the southwest rift zone of Mauna Loa Volcano. Groundwater within the aquifer system generally flows from the mountainous inland area to the coast where it discharges into the ocean.

The area around Kaloko is primarily highly permeable lava flows and precipitation infiltrates readily resulting in a sparse stream network that is ephemeral in nature (Oki *et al.* 1999; Oki 2004). Surface water features within the park exist where the land surface intersects the water table along the coast (Figure 2.1). Surface water and groundwater discharges within Kaloko are part of the brackish mixing zone found just below the water table along the coast while the freshwater lens common to islands begins further inland (Oki *et al.* 1999).

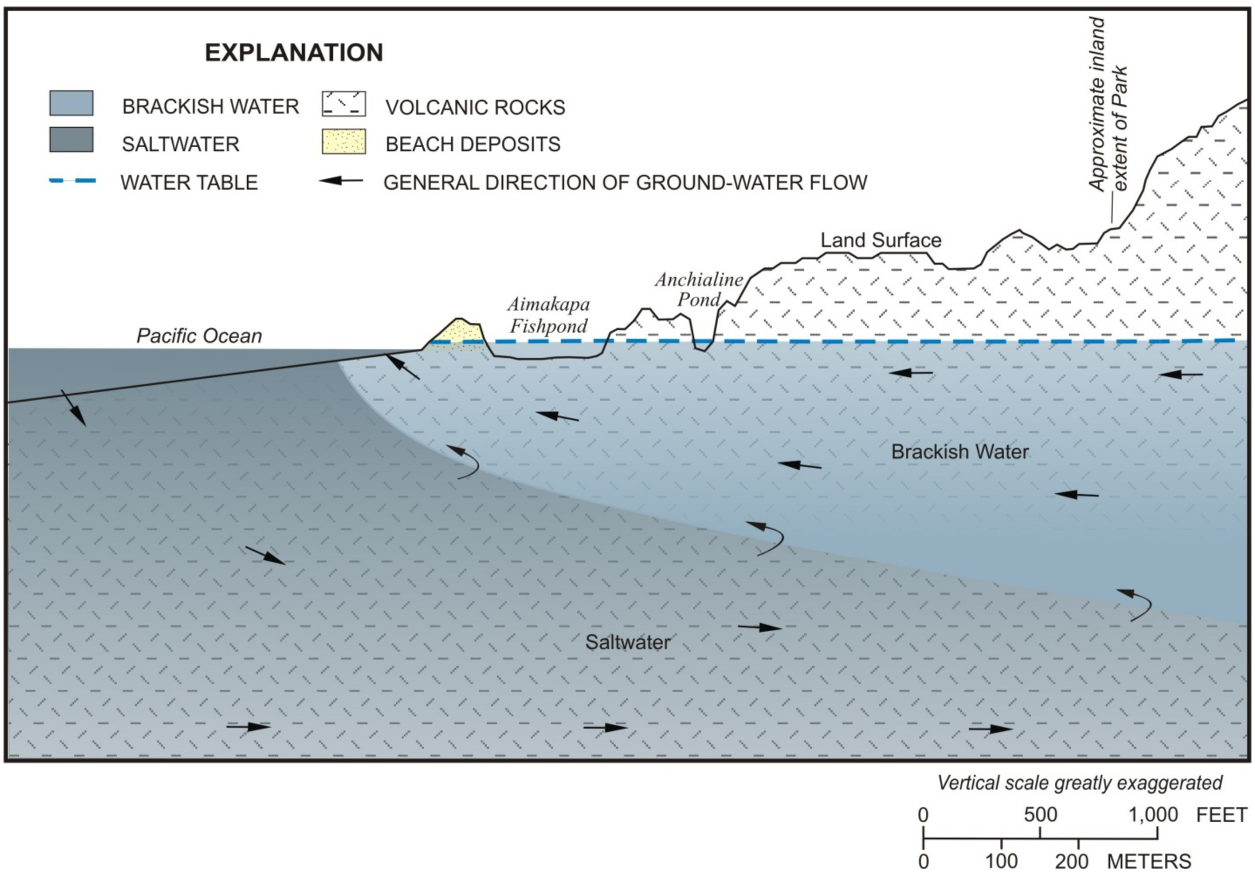

Figure 2.1 Schematic cross section of the ground-water flow system in Kaloko-Honokōhau National Historical Park, Island of Hawaiʻi. (Figure 12 excerpted from Oki *et al.* 1999)

CHAPTER 3 – CLIMATE TRENDS

3.1 Methods

3.1.1 Precipitation Data Preparation

Daily precipitation data sets from meteorological stations located within the Kona recharge area were obtained from the National Climatic Data Center (NCDC 2011). The 44 stations located within the Kona recharge area are listed in Appendix A. The appendix describes station name, code, location, elevation, and period of record for all meteorological stations considered for inclusion in the study. The potential list of stations was decreased to 26 after removing stations with record lengths less than ten years and stations with records unavailable for downloading (Table 3.1).

The selected data sets were checked for missing days and the presence of accumulated precipitation flags before analysis. Precipitation occurring on a given day sometimes is not recorded on that day but included in a subsequent day's total. Two flags are used to indicate accumulated precipitation totals, one to indicate the beginning of a time period where precipitation began to be accumulated (S) and another flag indicating the end of each accumulation period (A) (Reek *et al.* 1992). The practice of accumulating daily precipitation amounts occurred frequently in the data sets used in the study. Such datasets were considered unsuitable for analyzing short time step (daily or monthly) precipitation trends or characteristics so the accumulated precipitation totals were not averaged or spread across the number of days during which the total was accumulated. Instead the aggregated totals were used on the day recorded, and precipitation records were summarized for the winter and summer seasons and on an annual basis.

Flags for missing days were also examined before testing the datasets. The datasets were evaluated to exclude time periods with more than 10% of the days missing during either the annual or seasonal period (Klein Tank and Konnen 2003). Each dataset was also evaluated for the presence of days flagged as missing that were flanked by the flag indicating the beginning and end of an accumulation time period. Days flanked by the accumulated precipitation flags were not considered missing for the purposes of determining a time period's inclusion in the analysis.

Daily precipitation totals were aggregated into seasonal and annual precipitation totals for testing. Two seasons were considered; summer was comprised of May through September and winter was comprised of October through April (Sanderson 1993). The annual data were aggregated on a calendar year basis, and the month of February does include the leap day in each aggregated dataset.

Datasets were compiled for three time periods. The datasets beginning in 1978 were chosen because they correspond to the time from the establishment date of KAHO through 2010. The datasets beginning in 1984 and ending in 2010 were compiled because they correspond to the most recent estimation of recharge for the Kona area (Engott 2011). The last dataset compiled included all the years satisfying the quality checks, and was used to evaluate the consistency of trend over longer periods, when available.

3.1.2 Temperature Data Preparation

Daily maximum and minimum temperature datasets for meteorological stations located within the Kona recharge area were also obtained from the National Climatic Data Center (NCDC 2011). Records from 24 of the 44 stations located within the Kona recharge area indicated possible temperature observations. The potential list of stations was further decreased to eight after removing stations with short record lengths and stations with records unavailable for downloading. Flags for missing days were examined before testing following the same procedure and criteria as described for the precipitation data preparation. The list of potential records for testing was reduced to six after eliminating two stations with large data gaps (stations italicized in Table 3.1). Appendix B describes station name, code, location, elevation, and period of record for all meteorological stations considered for inclusion in the temperature analysis.

Maximum and minimum daily temperatures were averaged over seasonal and annual time periods for testing. The two seasons of summer and winter previously defined for precipitation testing were used again for the temperature testing. The annual data were averaged on a calendar year basis, and the month of February does include the leap day in each averaged data set. Only the Opihihale 2 24.1 station had a record that was long enough for testing over both the 1978 to 2010 and entire observation time periods.

3.1.3 Trend Testing

A statistical analysis was conducted on each dataset using the Mann-Kendall test (Gilbert 1987) to detect the presence of a monotonic increasing or decreasing trend at significance levels of alpha = 0.1, 0.05, 0.01, and 0.001. This procedure does not require that the dataset conform to a particular probability distribution and allows missing values making it valuable for hydrological and meteorological applications. The Mann-Kendall test does assume a constant variance over time which is a condition that may no longer be met given a changing climate (Helsel and Hirsch 2002).

The nonparametric Sen's method (Gilbert 1987) was also used to estimate the slope of the linear trend. The Sen's procedure is not affected by outliers or missing values. The datasets were tested using the MAKESENS Excel application (Salmi *et al*. 2002) for the complete available record, from 1978 to 2010, and from 1984 to 2010. The listing of stations, locations, and the time period where records were available are included in Table 3.1.

3.2 Results

3.2.1 Precipitation Trend Testing

The trend results for stations within the Kona area vary in direction, intensity, and significance both amongst stations and between time periods tested at the same station (Table 3.2). All figures not shown in this chapter are shown in Appendices C, D, and E for annual, summer, and winter respectively. A few groups of stations have record patterns and trends similar to each other, but the groupings are small and the results for all time frames vary even within the groups. Kainaliu 73.2 and Lanihau 68.2 have similar annual records and decreasing rainfall trends when evaluated over the entire period of record. The annual, summer, and winter records indicate more frequent wetter than average years during the earlier decades and more frequent drier than average years during the last 30 years (Figure 3.1). The annual trends (Table 3.2) are among the most significant measured over all three time periods with the period of record trend most significant (α=0.001), the 1978 to 2010 less significant (α=0.01), and the most recent time period of 1984 to 2010 least significant (α=0.1). The summer season trend illustrated decreasing rainfall for Kainaliu (Figure 3.2) and Lanihau (Table 3.2) were significant (α=0.01) during the 1978 to 2010 time period and were also among the largest (116mm and 146mm per decade respectively). The declining summer rainfall trends evaluated over the period of record were more significant (α=0.001) although smaller. Winter trends were smaller than either the summer or annual declines in rainfall during 1978 to 2010 (Table 3.2). Trends at Kainaliu (Figure 3.3) were 55mm per decade and Lanihau (Figure E.10) decreased at 62mm per decade. The winter trends at both stations were not significant during the most recent decades, only over their entire records.

The decreasing trend in annual rainfall measured at Honauanu 27 of 175mm per decade during 1978 to 2010 is similar in intensity to the downward trend of 191mm per decade of Kainaliu. Honaunau (Figure C.15) had a significant (α=0.01) decreasing annual trend when evaluated over the 1978 to 2010 time period, a slightly less intense decreasing trend (121mm per decade) that was not significant over the 1984 to 2010 time period, and a very slight decreasing trend measured over the period of record (3mm per decade) that also was not significant (Table 3.2). Summer season results for 1978 to 2010 of Honauanu (Figure D.15) were again similar in intensity to Kainaliu in the summer. Summer declines in rainfall were 110mm per decade. The decreasing rainfall trend for Honaunau was significant (α=0.05) during 1978 to 2010 but not significant during either the period of record or the 1984 to 2010 time period (Table 3.2). Winter trend results indicate a decrease in rainfall of 51mm per decade during the 1978 to 2010 time period that is not significant (Figure E.15). Less intense declines in rainfall were indicated when evaluating the winter season during 1984 to 2010, and over the period of record winter trends indicated a slight upward trend. None of the winter season trends was significant (Table 3.2).

Holualoa 70 and Honuaula 71 have annual trends similar to each other in their record with declines in rainfall measured over the entire observation record length and the period 1978 to 2010, but increasing trends measured during the latest time period of 1984 to 2010 (Table 3.2). Trends measured over the entire record are statistically significant at the alpha level of 0.001, and neither have statistically significant trends during the more recent 40 years (Table 3.2). Visual examination of the Holualoa record (Figure 3.4) indicates that the increasing trend measured during 1984 to 2010 exists in a dataset with 14 of 16 observations below the long term average annual precipitation. The 1984 to 2010 time period may be evidence of long term drought conditions moderated by a few wet years in the Holualoa station area. Summer trend results indicate a decrease in rainfall over 1978 to 2010 and over the POR and a rebound of rainfall during the 1984 to 2010 time period for both stations (Table 3.2). The 1978 to 2010 decrease in rainfall was 69mm per decade for Holualoa (Figure D.4) and 81mm per decade for Honuaula 71 (Figure D.6). The trend at Honuaula is significant during the 1978 to 2010 time period and over the entire observation record while Holualoa’s trend is significant only when evaluating the entire record. The winter results of Holualoa (Figure 3.5) are consistently downward during all three time periods with similar intensities and are significant only when evaluated over the entire observation record (Table 3.2). The trend results at Honuaula (Figure E.5) are slightly different when comparing the three time periods. The more recent time periods of 1978 to 2010 and 1984 to 2010 have a small decreasing trend of 6mm per decade while the trend over the entire observation record had a decreasing rate of 48mm per decade.

Opihihale 2 24.1, Milolii 2.34, Huehue 92.1, and Napoopoo 28 all had moderate decreasing annual rainfall trends of similar intensity (119mm, 121mm, 113mm, and 119mm per decade respectively) during the 1978 to 2010 time period. Opihihale (Figure C.25) and Huehue (Figure 3.6) were the only ones of the four whose trend was significant (α=0.05 and 0.1 respectively) during that time period (Table 3.2). Opihihale, Huehue, and Napoopoo (Figure C.21) had decreasing trends that were significant although less intense when evaluated over the period of record, and none of the stations had trends that were significant during the 1984 to 2010 time period. The decreasing annual rainfall trends of Milolii (Figure C.19) were not significant when evaluated over any of the three time periods. Opihihale (Figure 3.7), Huehue (Figure 3.8), and Napoopoo (Figure D.21) had moderately decreasing trends during the 1978 to 2010 summer season, but Milolii's (Figure D.19) trend was less intense than the other three. The decreasing trend at Opihihale was 76mm per decade, at Huehue the trend was 68mm per decade, and the trend at Napoopoo was 64mm per decade (Table 3.2). Milolii's decreasing trend was 21mm per decade. Only the trends at Huehue and Opihihale were significant during 1978 to 2010, and Opihihale, Napoopoo, and Huehue all had significantly decreasing trends when evaluated over the entire record. Three of these stations had similar decreasing trends in the winter season during 1978 to 2010, but the trend at Napoopoo (Figure E.21) was increasing instead of decreasing (Table 3.2). Huehue (Figure E.7), Milolii (Figure E.19), and Opihihale (Figure 3.11) had decreasing trends in rainfall of 61mm, 74mm, and 50mm per decade respectively. The trend at Napoopoo was an increasing rate of 37mm per decade. None of the winter season trends during 1978 to 2010 were significant, however, Opihihale and Napoopoo had significant trends when evaluated over their entire period of record.

Honokohau Harbor 68.14 (Figure C.5) has a relatively short record from 1991 to 2010 and one of the few stations with an increasing trend of 69mm per decade in annual rainfall, but the trend was not significant when tested (Table 3.2). Moanuiahea 69.24 is the only other station with an increasing trend (not significant) of 10mm per decade in annual rainfall (Figure C.13), but it is located at a higher elevation and further inland than Honokohau Harbor 68.14. Honokohau Harbor (Figure D.5) and Moanuiahea (Figure D.13) have slight increasing trends of 10mm per decade or less during the summer seasons of 1978 to 2010 (Table 3.2). Winter rainfall trends showed mixed results. Honokohau Harbor (Figure 3.10) had an increasing rate of 59mm per decade while Moanuiahea (Figure E.13) had a decreasing rate of 12mm per decade (Table 3.2). None of the summer or winter trends are significant during any of the time periods evaluated.

Ke-Ahole Point 68.13 (Figure C.9) and Kona Village 93.8 (Figure C.10) like Honokohau Harbor are located along the coastline but have slight decreasing trends in annual precipitation of 26mm and 29mm per decade respectively that are not significant during any time period tested (Table 3.2). Mahaiula 92.7 (Figure C.11) also has a slight decreasing trend of 57mm per decade in annual rainfall that is not significant during any time period, but Mahaiula 92.7 is located in the northern part of the study area and further inland than Honokohau Harbor or Ke-Ahole Point 68.13. All three of these stations have decreasing trends in rainfall of 11mm per decade or smaller in the time period of 1978 to 2010 during the summer seasons (Table 3.2). The trend in Kona Village 93.8's entire record was the only rate of change that was significant. The winter season results were more consistent among the three stations ranging from 16 to 27mm per decade decreases in rainfall during 1978 to 2010, and none were significant during any time period evaluated (Table 3.2).

3.2.2 Temperature Trend Testing

The temperature records at stations within the study area provided fewer opportunities for evaluation. Only six stations had records of sufficient quality, and only the record at Opihihale was long enough to test over the 1978 to 2010 time period. The record at Ke-Ahole Point was almost long enough to include in the 1978 to 2010 testing with a record that extended from 1983 to 2003. The Ke-Ahole Point (Figure F.5) trend in annual minimum temperatures was significant (α=0.05) and cooling at a rate of 3 degrees Celsius per century (Table F.1). The annual minimum temperature record at Ophihale (Figure 3.11) from 1978 to 2010 however, was not significant and cooled at a rate of 1 degree Celsius per century (Table F.1). Summer minimum temperature trends for neither station were significant, and both trends indicated cooling rates slightly less than annual temperatures (Table F.3). Winter minimum temperature trends for Ke-Ahole Point (Figure F.29) but not Opihihale (Figure F.35) were significant (α=0.1) and the rates for both were comparable to the annual minimum temperature trends (Table F.5). It should be noted that the trend at Opihihale when evaluating the trend over the entire record indicates warming annual, summer, and winter minimum temperatures which were not significant.

The annual maximum temperatures at Ke-Ahole Point (Figure F.6) and Opihihale (Figure F.12) during recent time periods were also cooling at rates of 13 and 4 degrees per century respectively

(Table F.2), and trends at both stations were significant (α=0.001). Summer (Table F.4) and winter (Table F.6) trends were equally significant (α=0.001) and comparable to annual trends at Ke-Ahole Point. Summer and winter trends were also equally significant at Opihihale, however, the rates of change varied slightly with summer temperatures cooling at a more intense rate than winter. When evaluated over the entire record of Opihihale, the trends in maximum temperature switched direction again and indicated warming temperatures in the annual, summer, and winter tests. The changes in annual (Table F.2) and winter (Table F.6) maximum temperatures over the entire record were more intense than summer (Table F.4), significant (α=0.05), and had comparable warming rates of 2 degrees per century

Kainaliu displayed a warming trend in average daily minimum temperature that was significant in all three categories; annual, summer and winter during its overall record which extended from 1939 to 1984. Warming rates ranged from two to three degrees per century. Kona AP and Napoopoo were the only other stations with significant trends in minimum temperature when tested over their entire record which ranged from 1921 to 1969. The trends indicated cooling temperatures during these earlier decades.

Kainaliu and Napoopoo were the only stations beside Ke-ahole Point and Opihihale to have significant trends in their maximum temperature records. Kainaliu had significant cooling trends in annual (α=0.01), summer (α=0.05), and winter (α=0.05) categories during the period of 1940 to 1984. Trend test results for Napoopoo indicated warming annual maximum temperatures, a significant cooling trend during summer, and a warming trend in the winter season over its record from 1921 to 1956.

Table 3.1 Meteorological stations chosen for inclusion in the precipitation trend testing. (See Appendix A for a complete listing of precipitation stations evaluated during the study.) Stations included in temperature trend testing are indicated by italics. (See Appendix B for a complete listing of temperature stations evaluated during the study.)

Station Name	Latitude	Longitude	Elevation [meters]	Period of Record Start	Period of Record End
Ahua Umi 75	19.633	-155.783	1592	01/01/1958	11/30/1986
Holualoa Beach 68	19.617	-155.983	3	11/01/1928	02/28/1979
Holualoa 70	19.633	-155.900	982	01/1/1905	08/31/2010
Honaunau 27	19.421	-155.884	287	01/01/1938	12/31/2010
Honuaula 71	19.667	-155.883	1905	10/1/1949	08/31/2010
Honokohau Harbor 68.14	19.683	-156.017	9	01/1/1991	12/31/2010
Hualalai 72	19.698	-155.873	2354	10/1/1949	12/31/2007
Huehue 92.1	19.757	-155.974	598	01/1/1905	07/31/2010
Kaawaloa 29	19.495	-155.919	409	01/01/1942	02/01/1999
Kanahaha 74	19.600	-155.800	1543	10/01/1949	04/30/1963
Ke-Ahole Point 68.13	19.733	-156.067	6	02/1/1981	12/31/2010
Kainaliu 73.2	19.537	-155.929	457	01/1/1939	12/31/2010
Kealakekua 2 28.7	19.500	-155.917	442	01/01/1905	08/31/1977
Kealakekua 26.2	19.495	-155.915	451	01/01/1905	12/31/2010
Kona AP	19.650	-156.017	9	10/01/1949	01/31/1980
Kona Village 93.8	19.833	-155.987	6	05/01/1968	12/31/2010
Lanihau 68.2	19.667	-155.967	466	01/1/1950	12/31/2010
Mahaiula 92.7	19.767	-156.000	293	06/1/1986	12/31/2010
Middle Holualoa 68.1	19.617	-155.967	145	03/01/1958	02/01/1979
Milolii 2,34	19.210	-155.884	357	05/01/1985	12/31/2010
Moanuiahea 69.24	19.742	-155.959	860	07/1/1986	07/31/2010
Napoopoo 28	19.472	-155.909	122	01/01/1905	12/31/2010
Opihihale 2 24.1	19.274	-155.878	415	05/01/1956	12/31/2010
Puu Anahulu 93a	19.817	-155.850	656	01/01/1950	04/30/1963
Puu Lehua 73	19.567	-155.817	1488	10/01/1949	11/30/1986
Puu Waawaa 94.1	19.781	-155.846	768	10/01/1949	12/31/2010

Table 3.2 Results of Mann-Kendall test for trend and the estimated rate of change for the annual, summer and winter datasets. N is the number of years tested.

	Year			Annual		Summer		Winter	
Station Name	Start	End	N	Significance Level	Rate of Change	Significance Level	Rate of Change	Significance Level	Rate of Change
	Entire Period								
Ahua Umi 75	1958	1984	27	N/S	-6.05	N/S	-4.66	N/S	-1.41
Holualoa Beach 68	1929	1978	44	N/S	1.89	N/S	1.14	N/S	1.84
Holualoa 70	1905	2008	63	0.001	-8.66	0.001	-5.78	0.1	-2.61
Honaunau 27	1938	2010	70	N/S	-0.28	N/S	-0.33	N/S	1.12
Honokohau Harbor 68.14	1991	2010	20	N/S	6.92	N/S	0.6	N/S	5.92
Honuaula 71	1950	2008	46	0.001	-12.38	0.001	-6.32	0.05	-4.76
Hualalai 72	1950	2007	40	N/S	-3.07	N/S	-0.02	N/S	-0.95
Huehue 92.1	1905	2009	95	0.01	-3.58	0.001	-2.08	N/S	-0.99
Kaawaloa 29	1942	1998	55	0.001	-10.23	0.01	-4.39	0.01	-6.05
Kainaliu 73.2	1939	2010	72	0.001	-12.33	0.001	-6.23	0.001	-5.7
Kanahaha 74	1950	1962	12	0.1	-24.8	N/S	-0.1	N/S	-14.12
Ke-Ahole Point 68.13	1982	2010	29	N/S	-2.6	N/S	-0.61	N/S	-1.55
Kealakekua 2 28.7	1905	1922	18	N/S	18.21	N/S	6.51	0.05	19.05
Kealakekua 26.2	1957	1973	17	N/S	-20.77	N/S	-4.71	N/S	-9.42
Kona Ap 68.3	1950	1978	29	N/S	-6.13	N/S	-1.38	N/S	-3.35
Kona Village 93.8	1969	2010	42	N/S	-1.69	0.1	-0.64	N/S	-1.09
Lanihau 68.2	1950	2010	61	0.001	-17.73	0.001	-10.6	0.01	-7.39
Mahaiula 92.7	1987	2008	21	N/S	-5.74	N/S	-0.49	N/S	-2.47
Middle Holualoa 68.1	1959	1978	20	N/S	-11.96	N/S	-6.26	N/S	-4.65
Milolii 2.34	1986	2010	24	N/S	-12.08	N/S	-2.14	N/S	-7.41
Moanuiahea 69.24	1987	2009	22	N/S	0.95	N/S	0.99	N/S	-1.22
Napoopoo 28	1937	2010	60	0.001	-5.52	0.05	-1.82	0.05	-2.47
Opihihale 2 24.1	1957	2010	54	0.01	-7.96	0.001	-4.36	0.05	-4.39
Puu Anahulu 93a	1950	1962	13	N/S	7.63	N/S	4.57	N/S	12.72
Puu Lehua 73	1951	1984	34	0.05	-8.96	0.05	-4.34	N/S	-4.84
Puu Waawaa 94.1	1950	1977	28	N/S	-4.65	N/S	-2.1	N/S	0.32

Table 3.2 Continued Results of Mann-Kendall test for trend and the estimated rate of change for the annual, summer and winter datasets. N is the number of years tested.

		Annual		Summer		Winter	
Station Name	N	Significance Level	Rate of Change	Significance Level	Rate of Change	Significance Level	Rate of Change
1978 to 2010							
Holualoa 70	20	N/S	-6.97	N/S	-6.86	N/S	-1.75
Honokohau Harbor 68.14	20	N/S	6.92	0.05	-11.04	N/S	-5.08
Honuaula 71	18	N/S	-5.24	N/S	0.6	N/S	5.92
Hualalai 72	12	N/S	-6.99	0.1	-8.14	N/S	-0.55
Honaunau 27	32	0.01	-17.48	N/S	-3.62	N/S	5.91
Huehue 92.1	30	0.1	-11.3	0.05	-6.81	N/S	-6.06
Kainaliu 73.2	33	0.01	-19.06	0.01	-11.64	N/S	-5.52
Ke-Ahole Point 68.13	29	N/S	-2.6	N/S	-0.61	N/S	-1.55
Kona Village 93.8	33	N/S	-2.92	N/S	-1.12	N/S	-1.97
Lanihau 68.2	33	0.01	-24.91	0.01	-14.56	N/S	-6.23
Mahaiula 92.7	21	N/S	-5.74	N/S	-0.49	N/S	-2.66
Moanuiahea 69.24	22	N/S	0.95	N/S	-2.14	N/S	-7.41
Milolii 2.34	24	N/S	-12.08	N/S	0.99	N/S	-1.22
Napoopoo 28	22	N/S	-11.88	N/S	-6.36	N/S	3.69
Opihihale 2 24.1	33	0.05	-11.85	0.05	-7.57	N/S	-5.02

Table 3.2 Continued Results of Mann-Kendall test for trend and the estimated rate of change for the annual, summer and winter datasets. N is the number of years tested.

Station Name	N	Annual Significance Level	Annual Rate of Change	Summer Significance Level	Summer Rate of Change	Winter Significance Level	Winter Rate of Change
1984 to 2010							
Holualoa 70	16	N/S	13.22	N/S	-0.8	N/S	-2.42
Honokohau Harbor 68.14	20	N/S	6.92	N/S	-6.18	N/S	-1.91
Honuaula 71	15	N/S	16.32	N/S	0.6	N/S	5.92
Honaunau 27	26	N/S	-12.07	N/S	-3.3	N/S	-0.55
Milolii 2.34	24	N/S	-12.08	N/S	-2.28	N/S	4.22
Hualalai 72	10	N/S	-17.82	N/S	-4.35	N/S	-3.86
Huehue 92.1	25	N/S	-10.05	N/S	-4.39	N/S	-5.34
Kainaliu 73.2	27	0.1	-12.04	N/S	-0.19	N/S	-2.36
Ke-Ahole Point 68.13	27	N/S	-2.94	N/S	-1.18	N/S	-1.51
Kona Village 93.8	27	N/S	-2.13	N/S	-6.93	N/S	-3.47
Lanihau 68.2	27	0.1	-15.04	N/S	-0.49	N/S	-2.66
Mahaiula 92.7	21	N/S	-5.74	N/S	-2.14	N/S	-7.41
Moanuiahea 69.24	22	N/S	0.95	N/S	0.99	N/S	-1.22
Napoopoo 28	20	N/S	-14.84	N/S	-10.08	N/S	3.56
Opihihale 2 24.1	27	N/S	-6.86	N/S	-3.43	N/S	-4.49

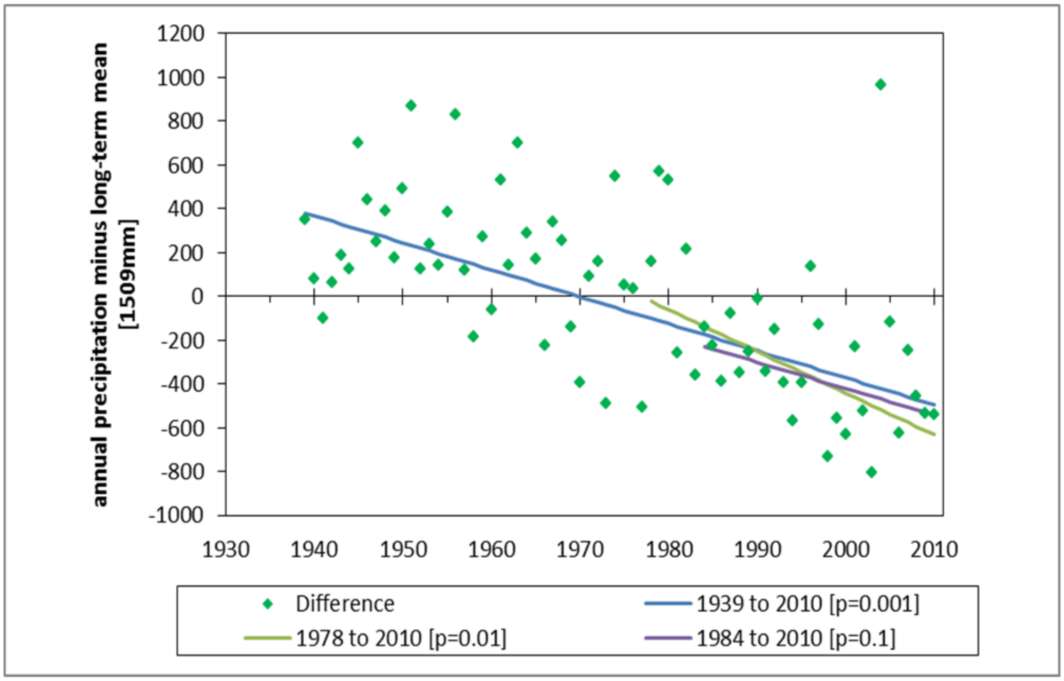

Figure 3.1 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1509mm) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1939 to 2010.

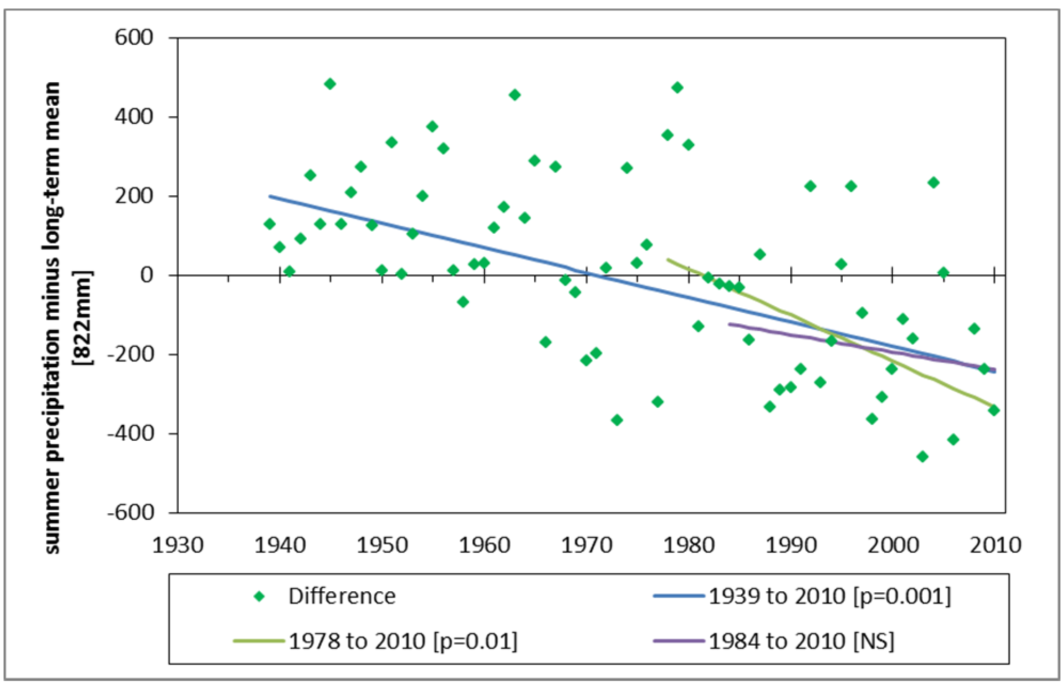

Figure 3.2 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (822mm) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1939 to 2010.

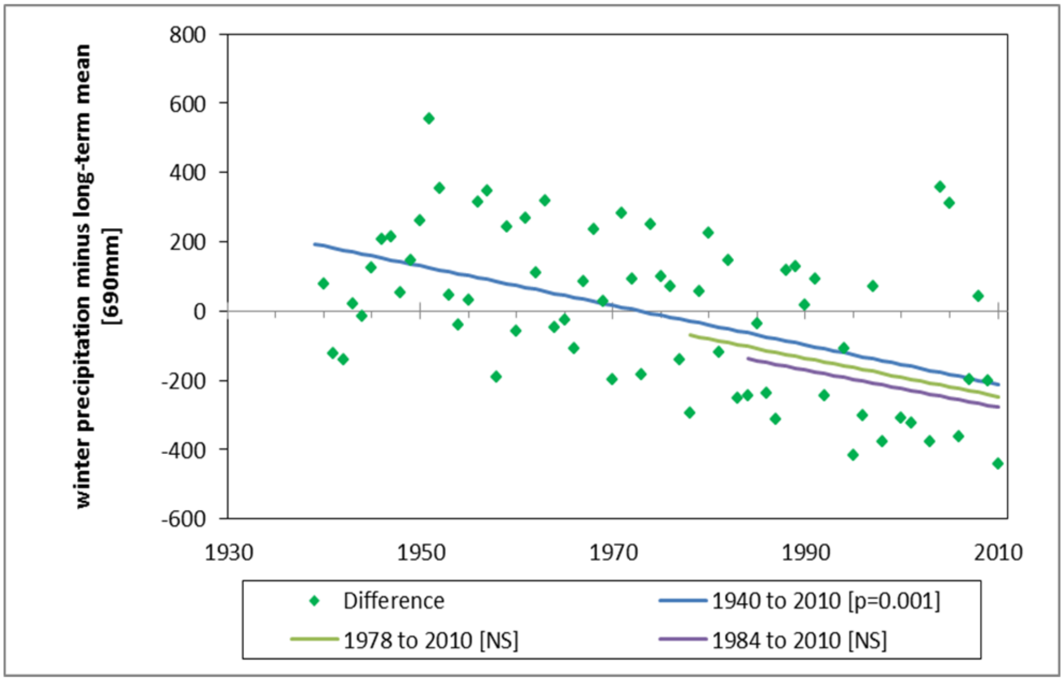

Figure 3.3 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (690mm) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1940 to 2010.

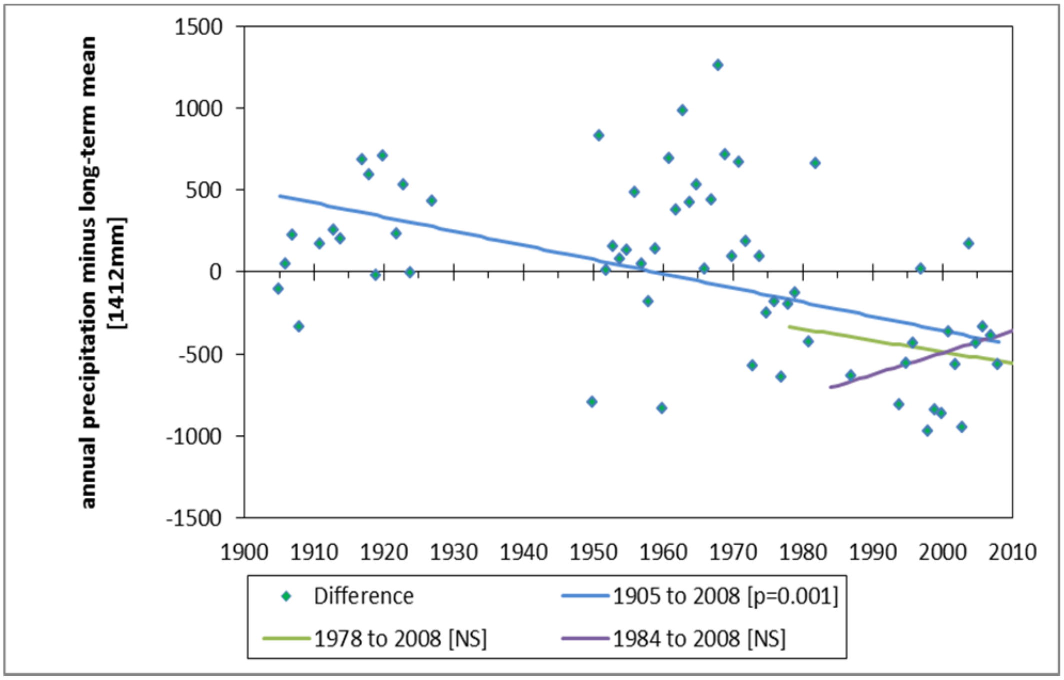

Figure 3.4 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1412mm) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1905 to 2008.

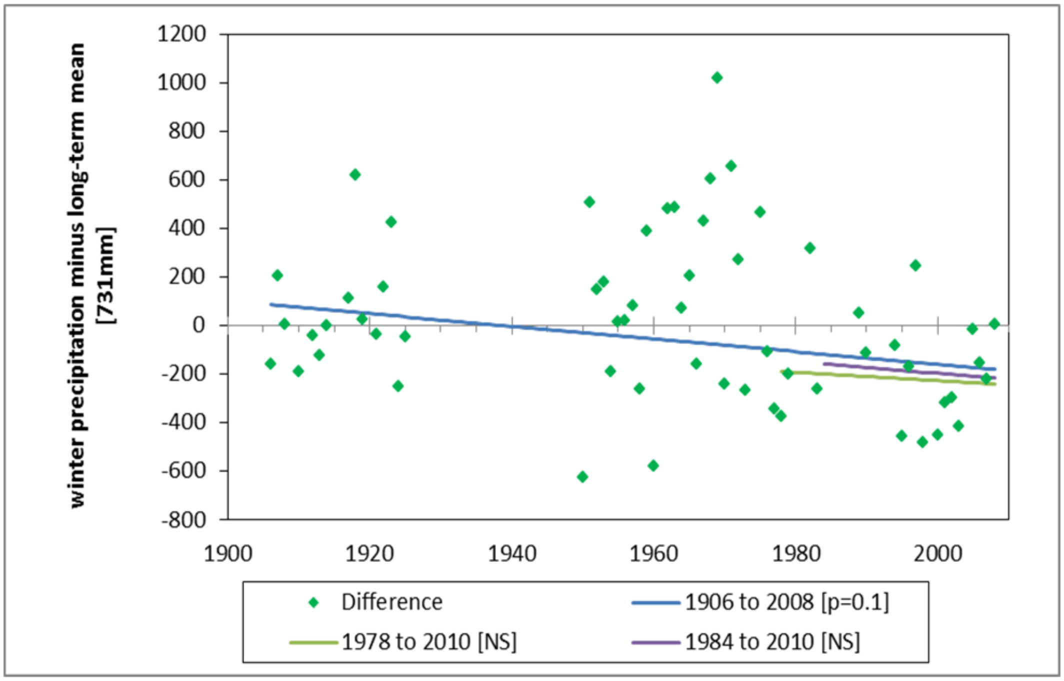

Figure 3.5 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (731mm) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1906 to 2008.

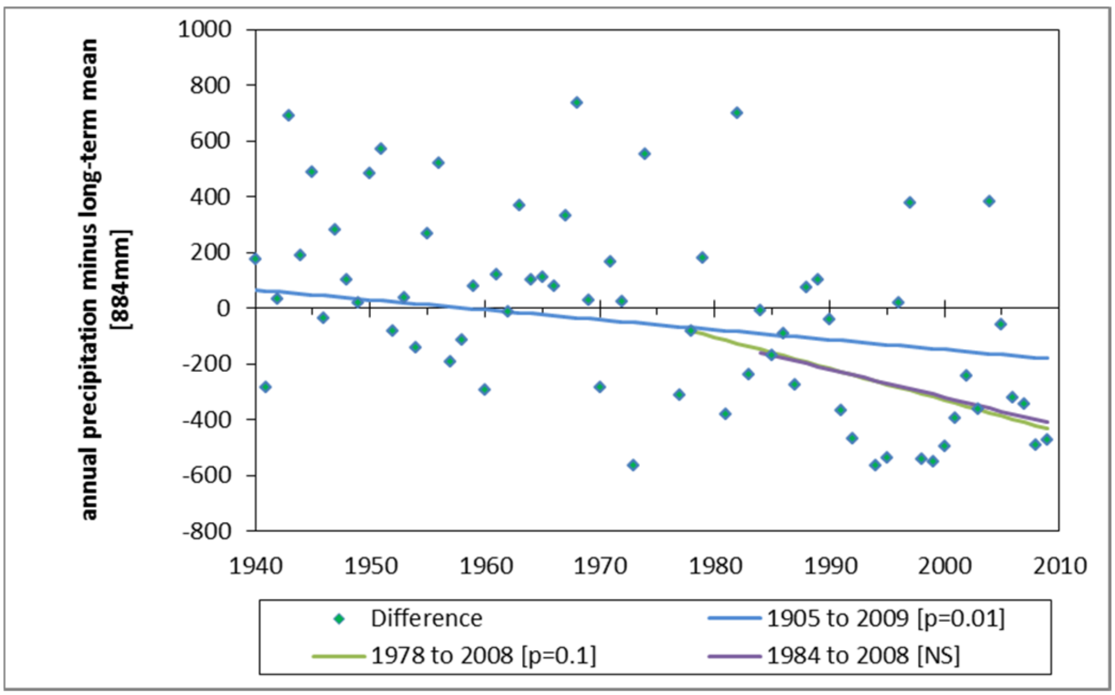

Figure 3.6 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (884mm) for the station, Huehue 92.1. The zero line represents the mean calculated over the period of record, 1905 to 2009.

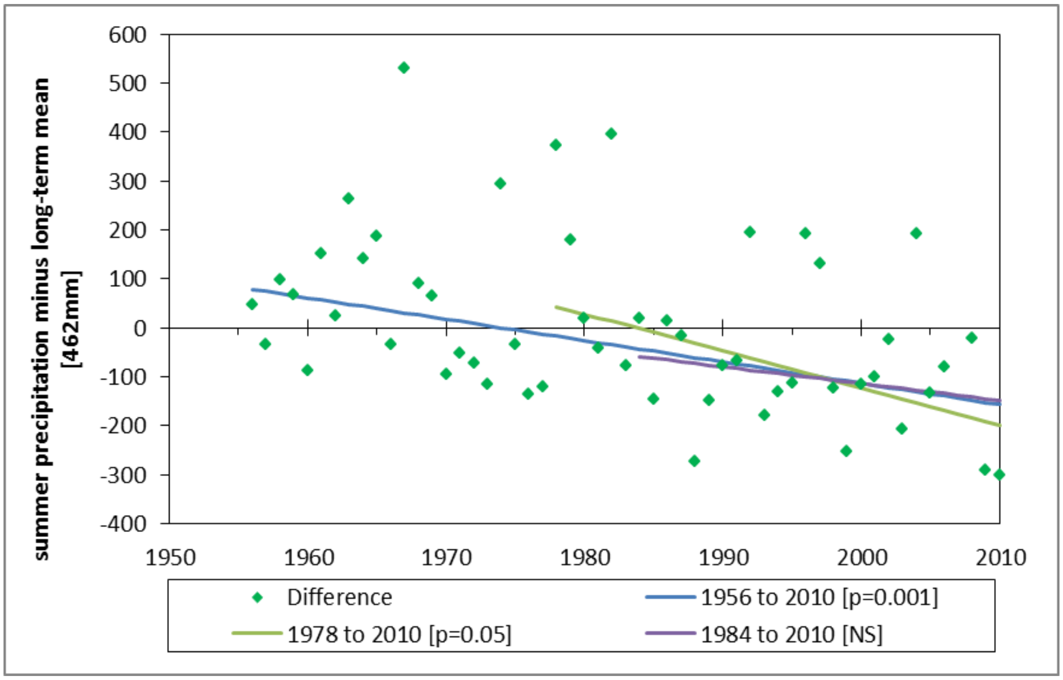

Figure 3.7 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (462mm) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1956 to 2010.

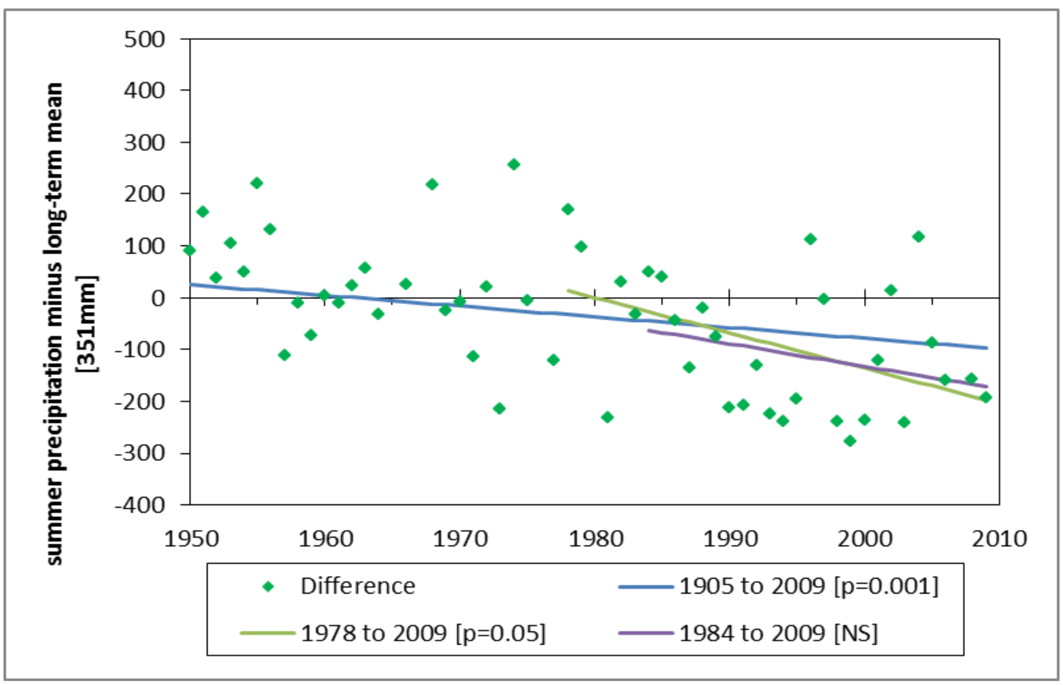

Figure 3.8 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (351mm) for the station, Huehue 92.1. The zero line represents the mean calculated over the period of record, 1905 to 2009.

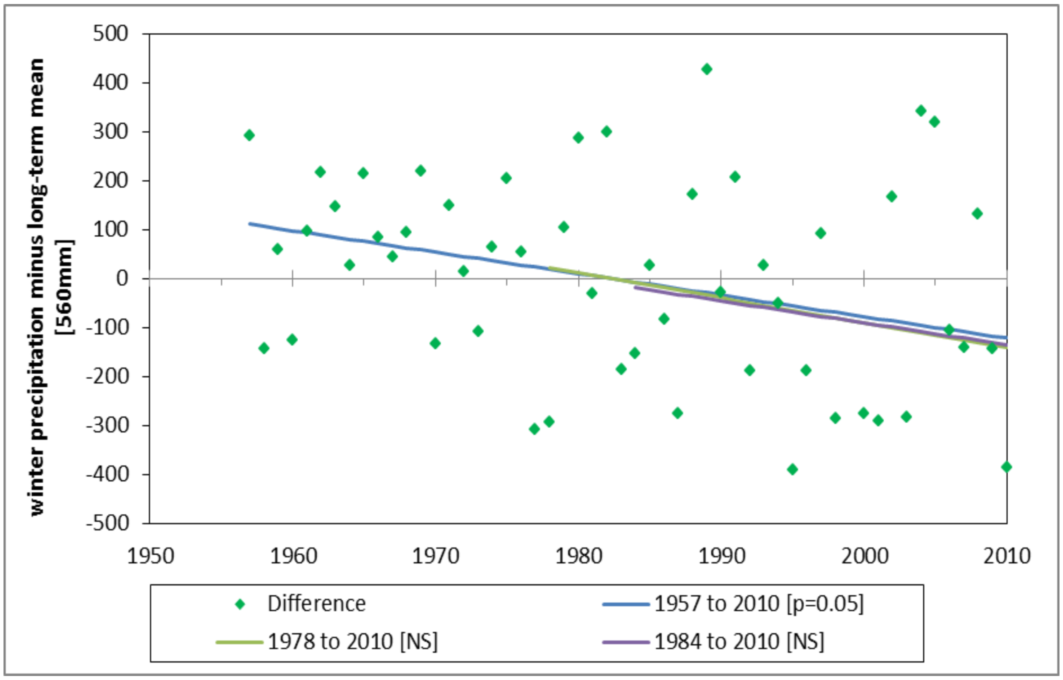

Figure 3.9 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (560mm) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1957 to 2010.

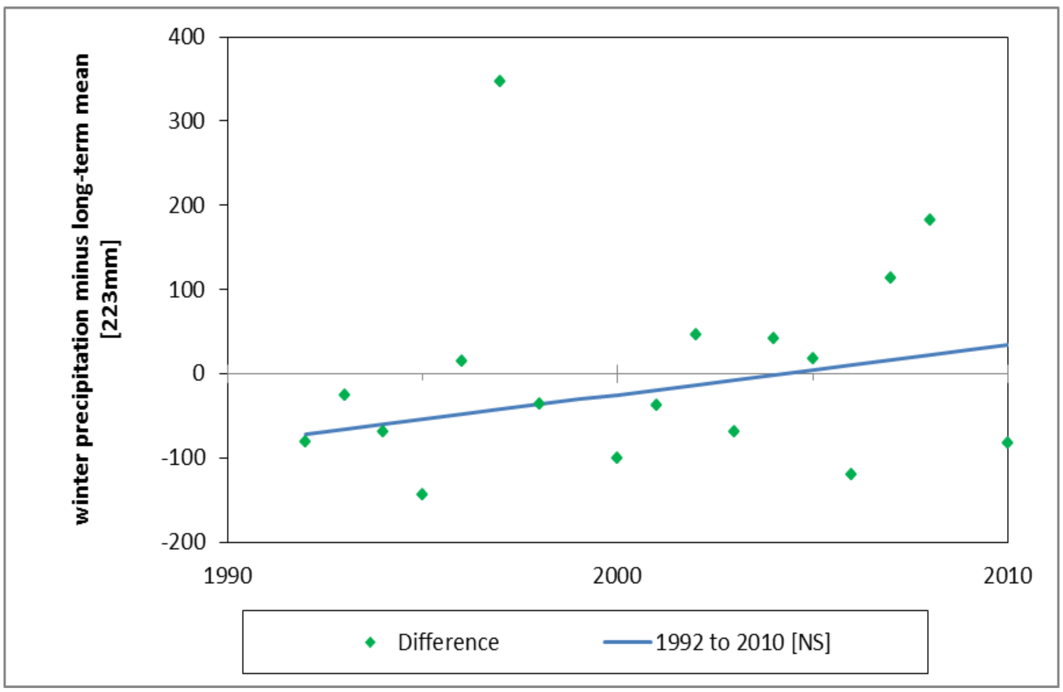

Figure 3.10 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (223mm) for the station, Honokohau Harbor 68.14. The zero line represents the mean calculated over the period of record, 1992 to 2010.

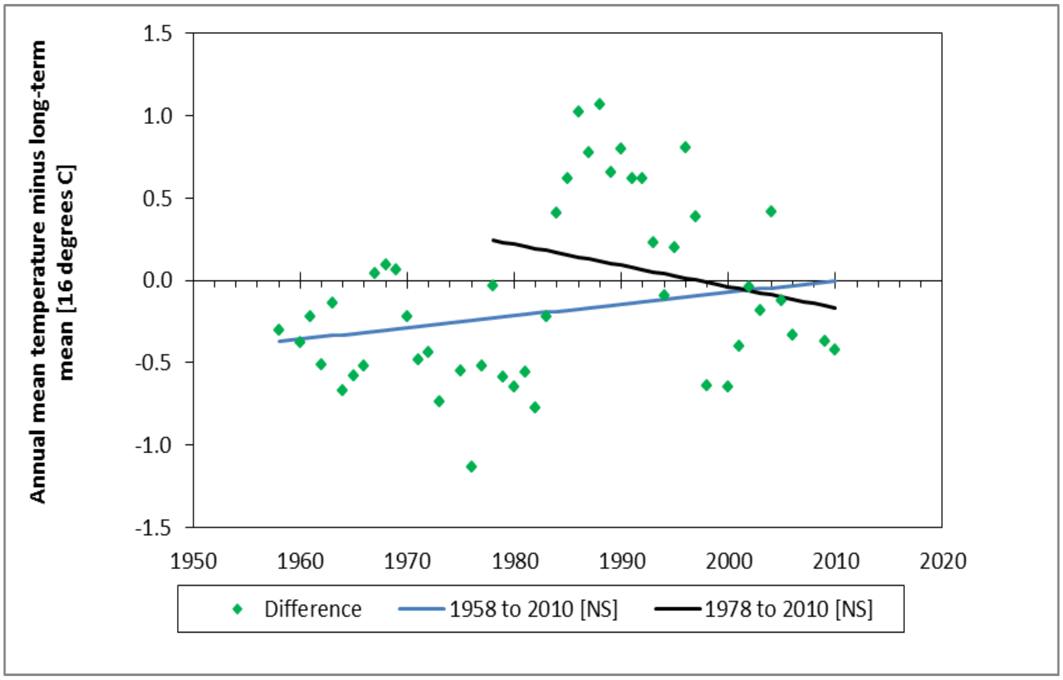

Figure 3.11 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (16 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1958 to 2010.

CHAPTER 4 – DOUBLE MASS ANALYSIS

4.1 Methods

A double mass analysis was conducted following the procedures described by Searcy and Hardison (1960). Double mass analysis techniques have been used by hydrologists to assess the consistency of records at multiple locations (Giambelluca *et al*. 1986), to adjust inconsistent records (Dunne and Leopold 1978), to fill gaps in records, and to extend the length of records for hydrologic data such as rainfall, streamflow, and sediment (Searcy and Hardison 1960).

4.1.1 Precipitation Data Preparation

Precipitation amounts were accumulated for each station for the period of 1978 to 2010. Years missing precipitation totals were filled with a mean calculated using all available years during the same period (1978 to 2010). Each station's accumulated record was compared to a combined accumulated record for all the station's evaluated in the Kona recharge area. The annual, summer, and winter precipitation records were evaluated separately.

4.2 Results

Generally, rainfall at Hawaiian meteorological stations increases with elevation up to the tradewind inversion (TWI) level (Sanderson 1993). Above the TWI level rainfall decreases to amounts more similar to the rainfall totals of stations located at the lowest elevations (Giambelluca *et al*. 2013). If these tendencies hold true then station precipitation totals should have a steeper slope with time at higher elevation stations and the accumulated precipitation lines for each station should be ordered according to increasing elevations up to the TWI level. The mean TWI level is approximately 2000 meters but can vary greatly on a daily basis.

The double mass analysis of annual precipitation (Figure 4.1) demonstrates the aforementioned tendencies for nine of the stations evaluated. Stations along the coastline at the lowest elevations have the lowest accumulated precipitation totals. Hualalai and Honuaula are higher elevation stations that are likely located near or above the TWI since their precipitation totals are more similar to the coastal stations at much lower elevations. Napoopoo on the other hand, is a lower elevation station with higher precipitation totals than might be expected for a station at its relatively low elevation. Napoopoo's accumulated precipitation line also demonstrates breaks in slope that are indicative of possible changes in conditions near the station potentially caused by several relocations of the station during the time period being evaluated. Honaunau is another example of a station that is not integrated alongside stations of similar elevations. Mahaiula has a very similar elevation to Honaunau but much less accumulated precipitation totals (Figure 4.1). Honaunau may be located within the high precipitation band with Lanihau and Kainaliu and thus benefits from additional rainfall although it is not located at the same elevation. The order of station line slopes do not increase as station elevation increases. Within the Kona recharge area there are differences in rainfall likely due to microclimates that order the lines in a manner consistent with the rainfall isohyets developed from Giambelluca *et al*. (2013) rather than the generalized tendencies determined by elevation and rainfall.

The lines of accumulated summer precipitation vary in slope due to differences in precipitation during the summer season every year (Figure 4.2). The lines are fairly smooth with no station displaying a strong or long lasting break in slope. The summer season results also combine into groups that reflect the isohyet bands of the latest Rainfall Atlas (Giambelluca *et al*. 2013). There are a few stations however, that are included with a group of stations that are not in the same isohyet. Honokohau Harbor's summer record is wetter than Ke-Ahole Point and Kona Village records which are located within the same isohyet band as Honokohau Harbor. Mahaiula and Hualalai are within the same isohyet band, but Hualalai has accumulated summer precipitation more similar to the stations within the next higher precipitation isohyet.

Differences in winter rainfall influence the slope of accumulated precipitation lines with steeper slopes displayed by stations with higher yearly winter rainfall (Figure 4.3). The lines are not as smooth as summer results with several stations such as Honuaula and Mahaiula displaying shifts in slope over the 1978 to 2010 time period. These shifts last less than five years and the slope over the entire period is not substantially affected. Both stations were relocated and had equipment upgrades during the 1978 to 2010 time period, and the shifts in slope are likely the result of those changes.

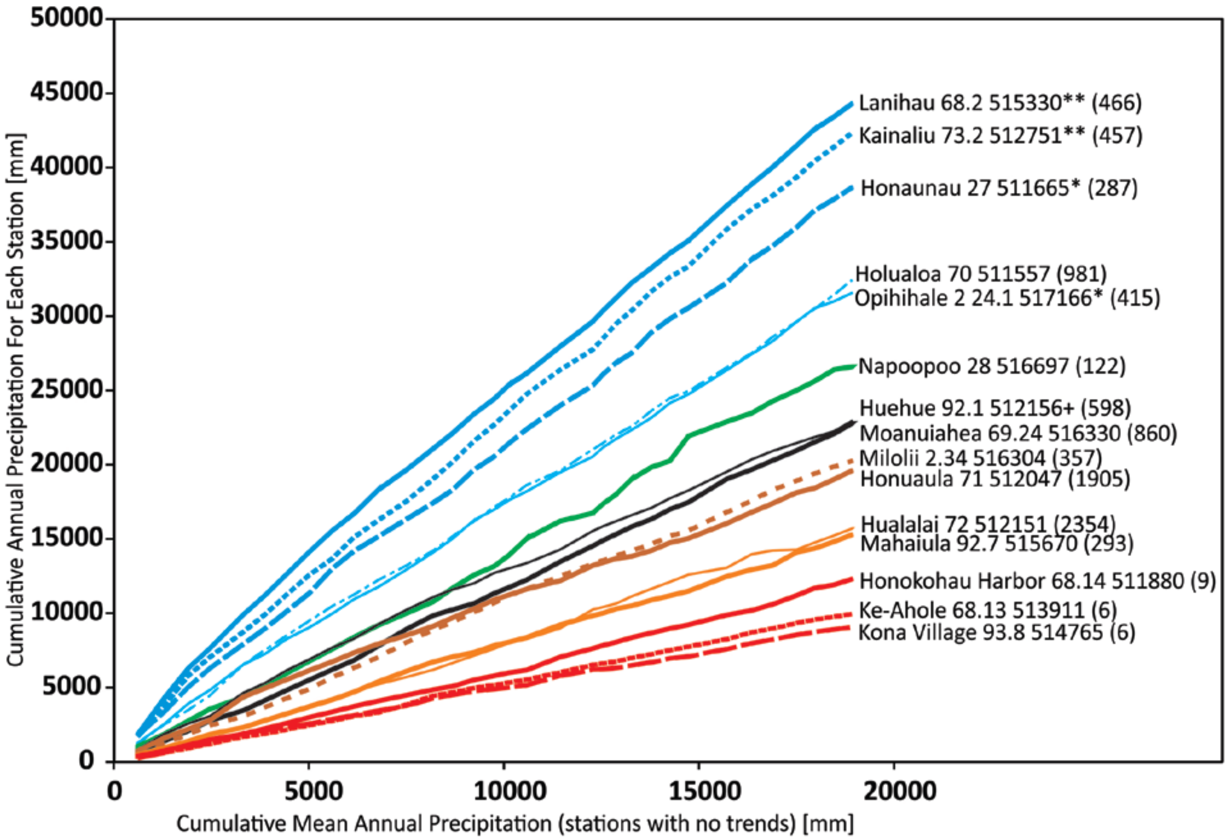

Figure 4.1 Double mass curves for stations located within the Kona recharge area that were evaluated for trends in annual precipitation during 1978 to 2010. The station name, COOP ID, and elevation in meters are listed beside the line representing each station's record. Station's with an additional designation of +, *, and ** are those who had significant results during the trend testing, and the designations correspond to the following alpha levels: +(0.1), *(0.05), and **(0.01).

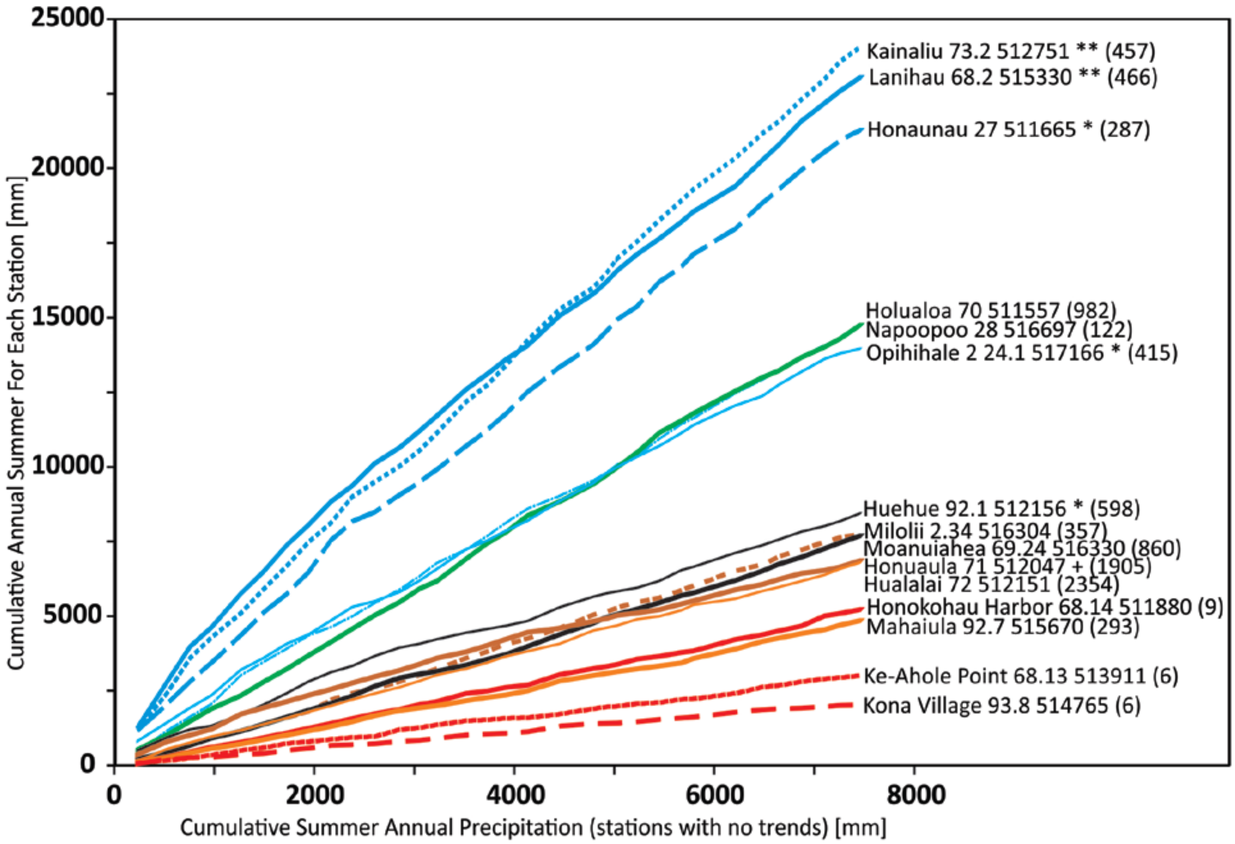

Figure 4.2 Double mass curves for stations located within the Kona recharge area that were evaluated for trends in summer precipitation during 1978 to 2010. The station name, COOP ID, and elevation in meters are listed beside the line representing each station's record. Station's with an additional designation of +, *, and ** are those who had significant results during the trend testing, and the designations correspond to the following alpha levels: +(0.1), *(0.05), and **(0.01).

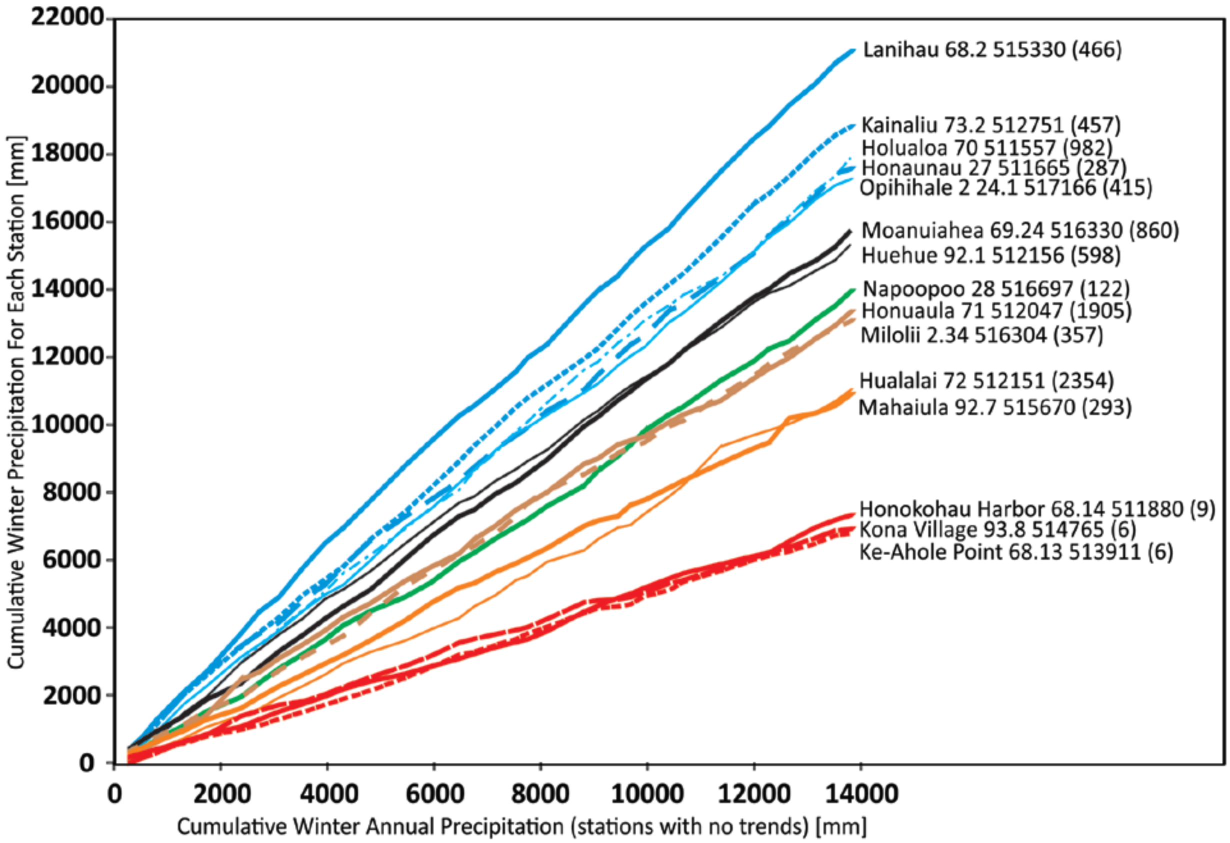

Figure 4.3 Double mass curves for stations located within the Kona recharge area that were evaluated for trends in winter precipitation during 1978 to 2010. The station name, COOP ID, and elevation in meters are listed beside the line representing each station's record. No stations had records with significant trends during testing.

CHAPTER 5 – STOCHASTIC MODELING AND SENSITIVITY ANALYSIS

Uncertainty is a key characteristic of future rainfall and temperature conditions influenced by a changing climate. Climate scientists have used general circulation models to create climate projections modeling future conditions for numerous studies included in the Intergovernmental Panel on Climate Change reports (IPCC 2007). However, general circulation models still lack the spatial resolution needed to model rainfall and temperature conditions at the local scale and are particularly inadequate for modeling conditions on small landmasses such as islands (Keener *et al*. 2012). Stochastic modeling is another tool that has been used by hydrologists and others to model processes, such as climate variables, where uncertainty exists (Loucks and van Beek, 2005).

This analysis will use stochastic modeling techniques to create synthetic realizations of future temperature and rainfall patterns. Rainfall and temperature patterns will be generated using the statistical characteristics of past observations, probability rules, and trend results from earlier analyses (Maidment 1993). The realizations of forecasted temperature and rainfall will then be used to conduct a sensitivity analysis to estimate the impact of rainfall and temperature changes to the hydrologic cycle (Stocker *et al*. 2013), specifically the net precipitation which is defined as the amount of precipitation remaining after losses to evaporation. Net precipitation is a principal driver of recharge to groundwater and influenced by the climate variables of temperature and precipitation (Healy 2010). The sensitivity analysis will be conducted over a fifty year period into the future.

5.1 Methods

The daily precipitation and temperature datasets used for trend testing were also used to inform the stochastic modeling of net precipitation amounts in the future. Both temperature and precipitation datasets were divided into seasonal subsets representing winter and summer so that trends observed in each season could be applied individually. The months within each season are the same used for trend testing, i.e., summer is May through September and winter is October through April (Sanderson 1993).

The sensitivity analysis of a 50 year span of future net precipitation conditions required modeling paired precipitation datasets for each station and paired temperature datasets. The first simulated dataset was constructed with no trend or conditions similar to historical conditions, and the second dataset was constructed with the rate of change identified during the 1978 to 2010 trend testing time period incorporated into the simulation.

5.1.1 Precipitation Data Preparation

Developing the required synthetic precipitation datasets was a three step process. Stations used for modeling represented varying levels of both significant and non-significant trends. Each station's precipitation dataset was screened to identify seasons with complete or nearly complete daily observation records (Table 5.1.). Temporal patterns from daily precipitation records for each season were needed to inform the simulation of precipitation occurrence. The selected records were analyzed to determine the frequency of precipitation occurrence in the historical record. The proportion of days with precipitation (wet days) and days without precipitation (dry days) was used to define the probability of precipitation occurrence as the first step in creating the synthetic precipitation datasets (J. Salas, pers. comm., 2010). A uniform distribution between zero and one was used to generate a random number for every day over the 50 years. If the random number was equal to or less than the percentage identified earlier for days without precipitation then a flag was set for that day indicating a day without precipitation. If the random number was greater than the percentage of days without precipitation then the flag was set to indicate a day with precipitation. The result was two datasets, one for each season with flags for daily precipitation occurrence.

The second step involved determining a rainfall amount for each day identified as a wet day in the first step. The method used during this step assumes that the amount of precipitation to be simulated is normally distributed (Maidment 1993). The raw seasonal precipitation datasets of days with rainfall were exponentially distributed so a log-transformation was used to normalize the dataset. The mean and standard deviation of the transformed dataset was calculated for use in the simulation. The procedure used to calculate each day's rainfall amount is called the inversion method where a random number determines the value of the cumulative distribution function, and then the function is inverted to find the rainfall amount (Maidment 1993). Uniformly distributed random numbers were generated between zero and one, and used to define the probability corresponding to a rainfall amount from the cumulative distribution function developed from the sample of days with rainfall. The log rainfall data was then reverse transformed and integrated with the dry days to create complete seasonal datasets composed of dry and wet days with rainfall in millimeters. These datasets represent 50 years of winter and summer seasons with rainfall patterns similar to statistical conditions calculated over the observation period for each station. Statistical characteristics for both the observed and simulated records were compared to ensure the two sets of data represented the same population. The two seasonal datasets were combined to create an annual dataset for each station. The annual datasets were organized according to water year conventions in order to keep the winter and summer seasons continuous.

The third step required creating a second dataset that incorporated each station's seasonal rate of change identified during trend testing. The summer and winter seasons were simulated separately due to different seasonal trends. Each season's daily rainfall dataset was adjusted by an amount determined by the rate of change and the number of years during which the trend had been active. The adjustment amount was spread over the wet days within each season. The rainfall days were adjusted on a weighted basis considering the rank of the rainfall amount within each season's sample of wet days with higher rainfall days weighted more heavily. The weighting adjustment was used to preserve the ratio of wet to dry days as much as possible. The trend adjustment was limited by each season's modeled rainfall. The full trend adjustment was applied only to season's with rainfall amounts equal to or exceeding the full trend adjustment. The rainfall for the season was set to zero when the full trend adjustment could not be applied. The two seasonal datasets were combined to create an annual dataset for each station with trend adjusted rainfall amounts.

5.1.2 Temperature Data Preparation

Opihihale 2 24.1 was the only station that had a complete enough record to allow for trend testing for the study period from 1978 to 2010 (Chapter 3). Thus the record for temperature at Opihihale 2 24.1 defined the pattern used to create a simulated temperature dataset for modeling (Table 5.1). The yearly minimum and maximum temperature datasets were screened for completeness. The maximum and minimum temperature datasets from the observation record were averaged to calculate a daily mean temperature dataset for each selected year. All the yearly daily mean temperature datasets were combined and the statistical characteristics of the sample record were calculated. A sine equation was fitted to the daily mean temperature record over five years by optimizing the Nash-Sutcliffe coefficient. The equation was parameterized using the statistical characteristics of the selected daily mean temperature dataset. The equation did not include a factor incorporating inter-annual variability and stationarity was assumed for the simulated dataset representing the no trend condition. The resulting equation was used to create a matrix of daily mean temperatures for 365 days by 50 years with no trend over that time period.

The annual rate of change for the daily mean temperature was a negative three degrees Celsius per century. The three degree rate of change was used to create a temperature dataset incorporating trend over the 50 year simulation time period. This cooling was incorporated into the mean annual temperature value used in each year’s temperature equation. A set of annual equations was used to create a daily mean temperature dataset for each future year. The result is a matrix of 365 days by 50 years of synthetic daily mean temperatures, not including leap days.

5.1.3 Sensitivity Analysis of Net Precipitation

Net precipitation was modeled using a combination of the two synthetic temperature datasets and two precipitation datasets for each station analyzed. The four dataset combinations enable an examination of future conditions assuming no change from the past in either precipitation or temperature, a change in precipitation only, a change in temperature only, and a change in both precipitation and temperature over a future period of 50 years (Table 5.2).

Four estimations of net precipitation were made for each station; one for each of the four combinations. Evaporation losses were calculated using a Thornthwaite equation (Dingman 2002) that is influenced by changes in temperature and day length. This equation was chosen to demonstrate the influence of changes in temperature without the confounding influence of changes in other factors affecting evaporation such as wind and cloud cover. Day length could also affect the calculation of evaporation losses, but Hawai‘i’s location results in minimal day length changes over the course of the year (Sanderson 1993), the minimum day length is approximately 11 hours and the maximum day length is approximately 13 hours. The limited change in day length reduces the effect of the day length variable in the calculation of evaporation losses allowing temperature changes to predominate. The calculation of evaporation loss was not a maximum potential evaporation calculation. The daily evaporation losses were limited to the total amount of precipitation received that day. The two simulated temperature datasets described earlier were used in the evaporation losses calculation to estimate the influence of temperature change.

5.2 Results

5.2.1 Precipitation Simulation

All of the trends modeled in the precipitation simulation were declining trends and resulted in decreases in mean annual rainfall up to one-third of the mean annual rainfall amounts observed over the period of record (Table 5.3). Modeling the trend estimated rainfall declines required shifting the relative proportion of dry and wet days by increasing the number of dry days in every case. Several stations had the number of wet days decrease to such an extent that an entire winter or summer season was left without rainfall. Modeling the precipitation declines individually by winter and summer season prevented an entire year from becoming dry during the simulation. That was possible during this simulation because no individual year was modeled with no rainfall during both seasons. However, that does not indicate that it would not be possible for an entire year to be dry only that such a realization was not modeled during the random generation of the simulations. Four stations had a dry season. Milolii was the only station to have a dry winter season modeled starting in year 39 of the simulation, while dry summer seasons were modeled for Kona Village, Huehue, and Opihihale starting in years 28, 39, or 40, respectively.

5.2.2 Net Precipitation Modeling

Scenario one was the benchmark that the other three scenarios were compared against. Scenario two modeled a change in temperature only and resulted in minor changes in annual mean net precipitation, compared to scenario one (Table 5.4). The annual trend in temperature evaluated represents a decrease of 14% over the annual mean temperature from 1978 to 2010, but the impact of temperature decreases to the sensitivity analysis of evaporation losses were small, averaging 1.6%. The impact due to a change in temperatures may be tempered due to a lack of modeled precipitation on some days, as modeled evaporation losses were limited by the amount of precipitation available on each day.

Scenario three evaluated the impact of declines in precipitation only, and yielded net precipitation declines from eight to forty-nine percent of the scenario one results. Milolii, Huehue, and Honaunau had the greatest declines in rainfall even though they did not have the most intense trends. All three stations are located in the 750 to 1000mm rainfall band on the Hawaiʻi Rainfall Atlas (Giambelluca *et al*. 2013). Kainaliu is located in a higher rainfall band (1000 to 1500mm) and has the more intense trend, but declines in its net precipitation over the 50 year period being simulated are not as great a proportion of the net precipitation calculated during the scenario one modeling. Kona Village is located on the coast where it receives an annual mean rainfall of 190mm per year. The scenario three modeling resulted in a decrease of one-third of its net precipitation which is a significant impact for a location that receives so little rainfall annually. Scenario four combined the effects of cooling temperatures and decreasing rainfall. There is no change to the relative order of the station declines in net precipitation from scenario three. The reductions in net precipitation seen in scenario three are, however, slightly less intense in scenario four. The cooling temperatures moderated declines in net precipitation caused by the decreasing annual rainfall amounts. The declines in net precipitation under this scenario ranged from six to forty-eight percent.

Table 5.1 Listing of stations for which datasets were prepared to use in the sensitivity analysis. There are two 50 year datasets for each station listed. One dataset maintains the observed period of record mean and the second dataset assumes a consistent rate of change equal to the trend identified for the period of 1978 to 2010.

Precipitation Datasets	
Holualoa 70	Kona Village 93.8
Honaunau 27	Milolii 2.34
Huehue 92.1	Napoopoo 28
Kainaliu 73.2	Opihihale 2 24.1
Temperature Dataset	
Opihihale 2.24.1	

Table 5.2 The four combinations of datasets used for each temperature and precipitation pairing used in the sensitivity analysis.

Scenario 1	No change in precipitation or temperature
Scenario 2	No change in precipitation and trend in temperature
Scenario 3	Trend in precipitation and no change in temperature
Scenario 4	Trend in precipitation and temperature

Table 5.3 Characteristics of the precipitation datasets with trend applied. The values included in the table below are the highest, mean, and lowest simulated annual precipitation values (in mm) included in the 50 year dataset, and the observed annual mean precipitation calculated over the period of record.

Station Name	**Simulated Annual Rainfall**			**Observed Mean Rainfall**
	Highest	**Mean**	**Lowest**	
Holualoa 70	2174	1225	575	1440
Honaunau 27	1193	784	378	1192
Huehue 92.1	1455	568	162	890
Kainaliu 73.2	2323	1086	127	1523
Kona Village 93.8	426	199	48	275
Milolii 2.34	853	392	82	632
Napoopoo 28	1206	868	520	941
Opihihale 2 24.1	1780	700	195	1022

Table 5.4 Results from the four modeling scenarios. The values included in the table below are the mean net precipitation (in mm) calculated from 50 annual amounts. The percent change was calculated by comparing the mean net precipitation from scenarios two through four against the mean available water from scenario one. An increase and decrease are represented by the up and down arrows, respectively.

Station Name	Scenario One	Scenario Two	Scenario Three	Scenario Four
Holualoa 70	1088	1099 (1.0%↑)	869 (20.1%↓)	880 (19.1%↓)
Honaunau 27	603	624 (3.5%↑)	319 (47.1%↓)	333 (44.8%↓)
Huehue 92.1	603	612 (1.0%↑)	318 (47.3%↓)	324 (46.3%↓)
Kainaliu 73.2	1067	1081 (1.3%↑)	671 (37.1%↓)	682 (36.1%↓)
Kona Village 93.8	190	193 (1.6%↑)	127 (33.2%↓)	129 (32.1%↓)
Milolii 2.34	418	424 (1.4%↑)	213 (49.0%↓)	217 (48.1%↓)
Napoopoo 28	622	631 (1.5%↑)	574 (7.7%↓)	582 (6.4%↓)
Opihihale 2 24.1	689	698 (1.3%↑)	423 (38.6%↓)	429 (37.7%↓)

CHAPTER 6 – DISCUSSION

6.1 Climate Trends

Precipitation trends demonstrate a variety of responses within the region defined by the Kona recharge area. The trends vary by becoming dryer or wetter at different locations within the recharge area, in the amount of change observed per year, and in the significance of observed trends. For the time period from 1978 to 2010, annual trends ranged from an increase in rainfall of 69mm to a decrease of 250mm per decade (Table 3.2), with the largest declines occurring during the summer season. This range of trends demonstrates the influence of topography and climate circulation (Sanderson 1993) at the local level resulting in multiple microclimates within the recharge area.

The stations of Holualoa 70, Honaunau 27, Kainaliu 73.2, Lanihau 68.2, Napoopoo 28, and Opihihale 2 24.1 in the higher rainfall bands that parallel the coastline (Giambelluca *et al.* 1986, Giambelluca *et al*. 2013) have the largest declines in annual rainfall during the 1978 to 2010 period (Figure 6.1) and also over the longer periods of their entire observational record (Table 3.1). This area is a mixing zone of moist winds from both the trade winds coming around the island and winds blowing inland from the ocean (Sanderson 1993). Several of these stations have been used to calculate rainfall indices that have shown a decreasing trend in rainfall (Chu and Chen 2005; Diaz *et al*. 2005). The summer season (Figure 6.2) had larger decreases that were more statistically significant than what was observed over the winter (Figure 6.3). The summer season rainfall is driven mainly by tradewind influences (Sanderson 1993) whereas winter rainfall is augmented by synoptic storms which can result in heavy rainfall events. Changes in the tradewind frequency, direction, or TWI could be influencing the greater changes in summer rainfall (Cao *et al*. 2007, Garza *et al*. 2012). One station, Kainaliu 73.2, had the most consistent statistically significant downward trend in annual, winter, and summer rainfall in all three time periods, with the exception of summer rainfall for the most recent time period (1984 to 2010). The record at Kainaliu 73.2 also demonstrated larger decreases in annual and summer rainfall during the 1978 to 2010 time period compared to either the entire record (1939 to 2010) or the more recent 1984 to 2010 time period. Winter rainfall declines remained consistent throughout all three time periods. These changes in rainfall declines are similar to differences observed by Chu and Chen (2005) who found the mid-1970s to 2001 to be a time with lower rainfall compared to the preceding 28 years, and these multi-decadal shifts were correlated with changes in the Pacific Decadal Oscillation.

Moanuiahea 69.24, Huehue 92.1, and Milolii 2.34 are in a transition zone between the high rainfall band stations and the low rainfall coastal stations (Figure 6.1). Huehue 92.1 and Milolii 2.34 have larger decreases in precipitation over the 1978 to 2010 time period compared to Moanuiahea 69.24. The record at Moanuiahea 69.24 had more consistent annual, summer, and winter rainfall amounts resulting in a small non-significant trend overall. Huehue 92.1 is near Moanuiahea 69.24, but had a much greater significant declining trend in annual rainfall. At Huehue 92.1, the summer (Figure 6.2) and winter season (Figure 6.3) declines in rainfall were very similar to each other, but only the summer trend was significant. Milolii 2.34, located further south, has annual declining trends similar to Huehue 92.1, but the winter declines are greater than the summer. None of the trends at Milolii 2.34 were significant and the higher winter decline is different from the stations in the high rainfall band. Strong summer declines in rainfall are not present in the records of these stations and do not indicate a possible change in the trade wind regime in contrast to the high rainfall band stations.

Results at the low elevation coastal stations of Kona Village 93.8, Ke-Ahole Point 68.13, and Mahaiula 92.7 are smaller overall with little difference between summer and winter trends (Figures 6.1-3). None of these stations had statistically significant changes in rainfall regimes and their similar rainfall decreases between seasons indicate a general decline in rainfall which cannot be attributed to a specific rainfall source or mechanism. The coastal station of Honokohau Harbor 68.14 had a trend indicating an annual rainfall increase (Figure 6.1), mostly influenced by an increase in winter rainfall (Figure 6.3). Winter season rainfall is usually augmented by frontal systems, but the inconsistent results along the coastline do not support a change in frontal activity as the cause of the increase. The length of record at Honokohau Harbor 68.14 is short only covering the years of 1991 to 2010, and the more likely source of increased rainfall. While small, the changes at all coastal stations represent important shifts in rainfall patterns when considered over the long term for an area that receives little annual rainfall.

Two high elevation stations on the slopes of the Hualalai volcano had declining trends in annual rainfall (Figure 6.1) but the variability of rainfall year to year and gaps in the record resulted in very different trends depending on the time period or season tested, in particular the Hualalai 72 and Honuaula 71 stations. This scarcity of reliable information at higher elevations is common in the Hawaiian Islands (Kruk and Levinson 2008). Honuaula 71's trends over the entire period of record were statistically significant for annual, summer, and winter seasons, but significant only in summer during the 1978 to 2010 testing period (Figure 6.2). The summer season has a stronger decrease that is consistent with a potential shift in trade wind level or activity and the resultant rainfall from those winds (Garza *et al*. 2012, Cao *et al*. 2007). At 1905 meters, Honuaula 71 is lower in elevation than Hualalai 72 at 2354 meters, and is located near the approximate mean inversion level of 2,000 meters (Sanderson 1993). Any downward shift in the TWI would result in a decrease in rainfall observed at the Honuaula 71 station.

Two studies have examined trends in precipitation records for the Hawaiian Islands. Both studies calculated a state-wide rainfall index based on a sampling of stations throughout the state. Diaz *et al*. (2005) used seven stations from within the Kona recharge area and found a 15% decline in annual rainfall for 1985 to 2000 compared to the long term mean. Trend testing for the 1978 to 2010 time period indicated a majority of stations with decreases in annual rainfall. For example, Kainaliu 73.2 whose record extended from 1939 to 2010 and Lanihau 68.2 whose record extended from 1950 to 2010 both had 15% decreases compared to their long term mean annual rainfall. Chu and Chen (2005) also calculated a state-wide rainfall index, and for the Kona recharge area only used the Napoopoo 28 station. They compared annual rainfall from 1950 to mid-1970s versus mid-1970s to 2001, and found that rainfall declined in the more recent time period. The decreasing rainfall trends calculated for a majority of the stations within the Kona recharge area including Napoopoo 28 in the time period of 1978 to 2010 are consistent with the declines found by Chu and Chen (2005) in the more recent decades.

Temperature records suitable for trend testing were few within the Kona recharge area. Additional records would have strengthened the results of this study and better demonstrated the differences within the region. Opihihale 2 24.1 was the only station tested over multiple time periods, and displayed contradictory trends when comparing the 1958 to 2010 and 1978 to 2010 periods. The maximum and minimum temperature records had cooler temperatures from 1958 to 1980, warmer temperatures during the 1980 and 1990 decades, and then cooler temperatures again from 2000 to 2010 (Figure 3.11 and F.12). This variability resulted in the trends of direction when considering the two time periods. The choice of time period for testing makes a great deal of importance when evaluating this record. Giambelluca *et al*. (2008) evaluated trends over the 1919 to 2006 and 1975 to 2006 time periods using a statewide temperature index calculated from annual mean temperatures. In both cases, the results indicated warming trends with the more recent decades warming more quickly. The addition of cooler years from 2007 to 2010 appears to have shifted the trend from warming to cooling at Opihihale 2 24.1.

Kainaliu 73.2 was the only station from the Kona recharge area included in the Giambelluca *et al*. (2008) study (Tables F.1-6). This study's results indicated significant warming trends in annual, summer, and winter minimum temperatures. The maximum temperatures for annual, summer, and winter are all cooling and also significant. These trend directions for minimum and maximum temperatures are in agreement with trends identified in Giambelluca *et al*. (2008).

The two low elevation coastal stations had cooling trends in minimum temperatures when considering annual, summer, and winter season averages (Tables F.1 and F.2). Trends at both stations were statistically significant in all three categories except for the summertime Ke-Ahole Point 68.13 results. The cooling trend at Kona AP 68.3 is not unexpected since the record covers an earlier time frame from 1950-1970, but the Ke-Ahole Point 68.13 station's record is the more recent and the cooling trend there is unexpected. These results are in contradiction to global minimum trends (IPCC 2007) and statewide Hawaiian studies (Giambelluca *et al*. 2008, Diaz *et al*. 2011).

6.2 Net Precipitation Modeling

The net precipitation modeling revealed several interesting developments. Precipitation declines over the 50 year simulation period sometimes resulted in a season with no rainfall, but no full year was simulated without rainfall. It was possible that another realization of the 50 year future time period could result in an entire year being simulated as dry if both seasons have lower than average rainfall amounts. The decreasing rainfall trends had significant effects on the simulated rainfall at stations located throughout the Kona recharge area. The mean annual rainfall calculated over the 50 year future with declining trends decreased by approximately one-third compared to the mean annual rainfall simulated with no change in future conditions. The calculations of trends in specific amount decreases per year results in varying amounts of decreases at individual stations, but the decreases are more consistent across the study area once those trends are applied and considered as percentage changes in mean annual rainfall.

Modeled net precipitation amounts increase by small amounts when incorporating a temperature trend both as a sole contributor to change and coupled with changes in rainfall. The modeled changes in rainfall had the greatest influence on net precipitation, directly decreasing mean annual net precipitation by amounts ranging from 19 to 49 percent. The changes in precipitation also had an indirect effect on net precipitation by limiting daily evaporation on days with no low or no rainfall.

Changes in net precipitation will have significant impact on recharge within the local area, and the coastal aquifer will be quickly influenced by changes in net precipitation. Decreases in net precipitation and recharge within the larger Kona regional area will also be influenced by geological differences across the area. Many of the stations located in the higher elevation area and within the higher rainfall band running parallel to the coast have large decreases in modeled net precipitation and will result in greater impact to the higher elevation aquifer. A recent isotopic study (Fackrell and Glenn 2013) has confirmed that the higher elevation aquifer is hydrologically connected to the coastal aquifer, but movement of recharge from the higher elevation aquifer to the coastal aquifer will be determined by the degree of connectivity and the rate of water movement from the higher elevation aquifer to the coastal aquifer (Oki *et al*. 1999.

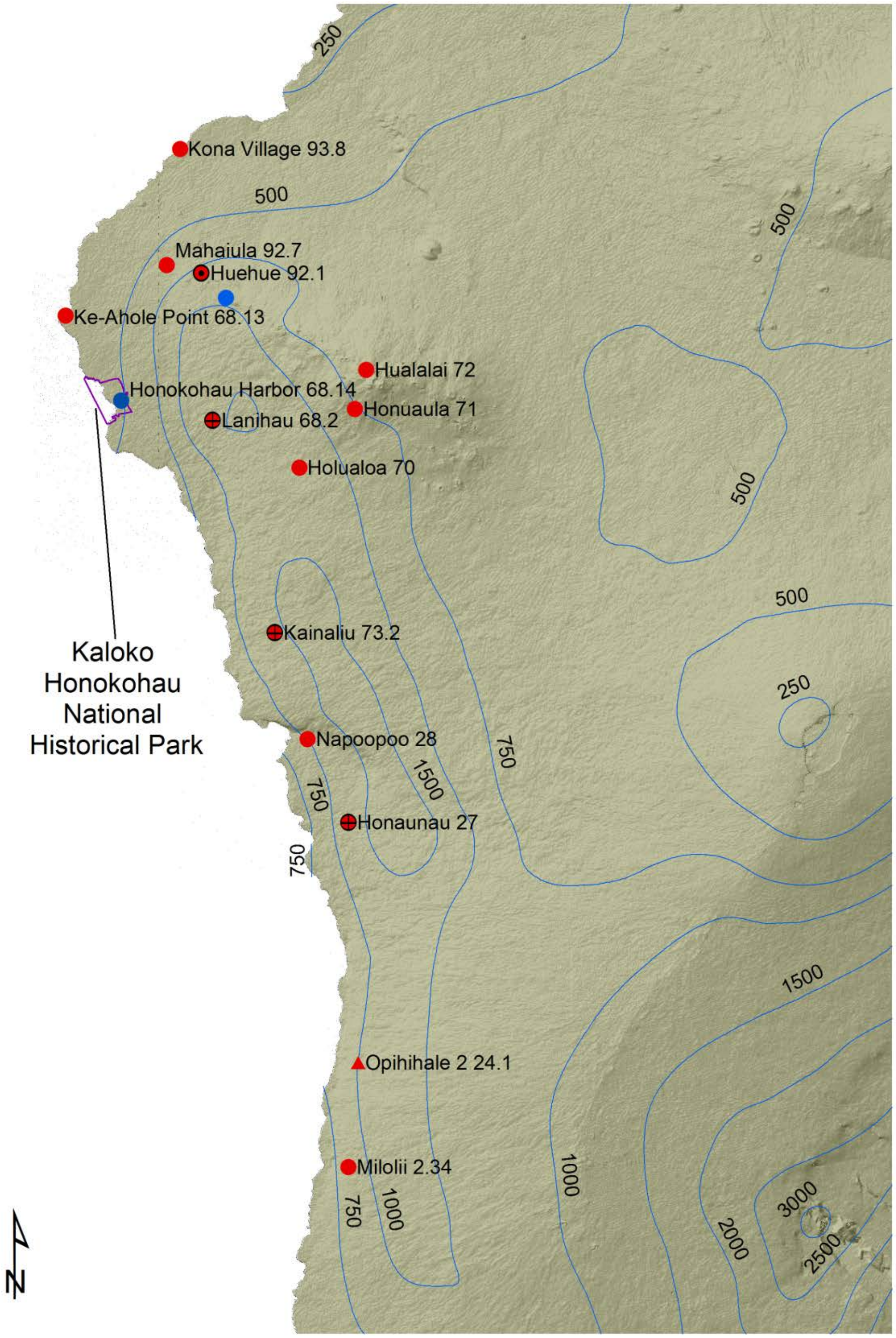

Figure 6.1 Annual trend results for the period of 1978 to 2010 with rainfall isohyets from Giambelluca *et al.* (2013). Stations with trends of increasing rainfall are colored blue, and stations with decreasing trends are colored red. Stations with significant trends have a black dot in a circle (α=0.1), a triangle symbol (α=0.05), or cross-hatching over a circle (α=0.01).

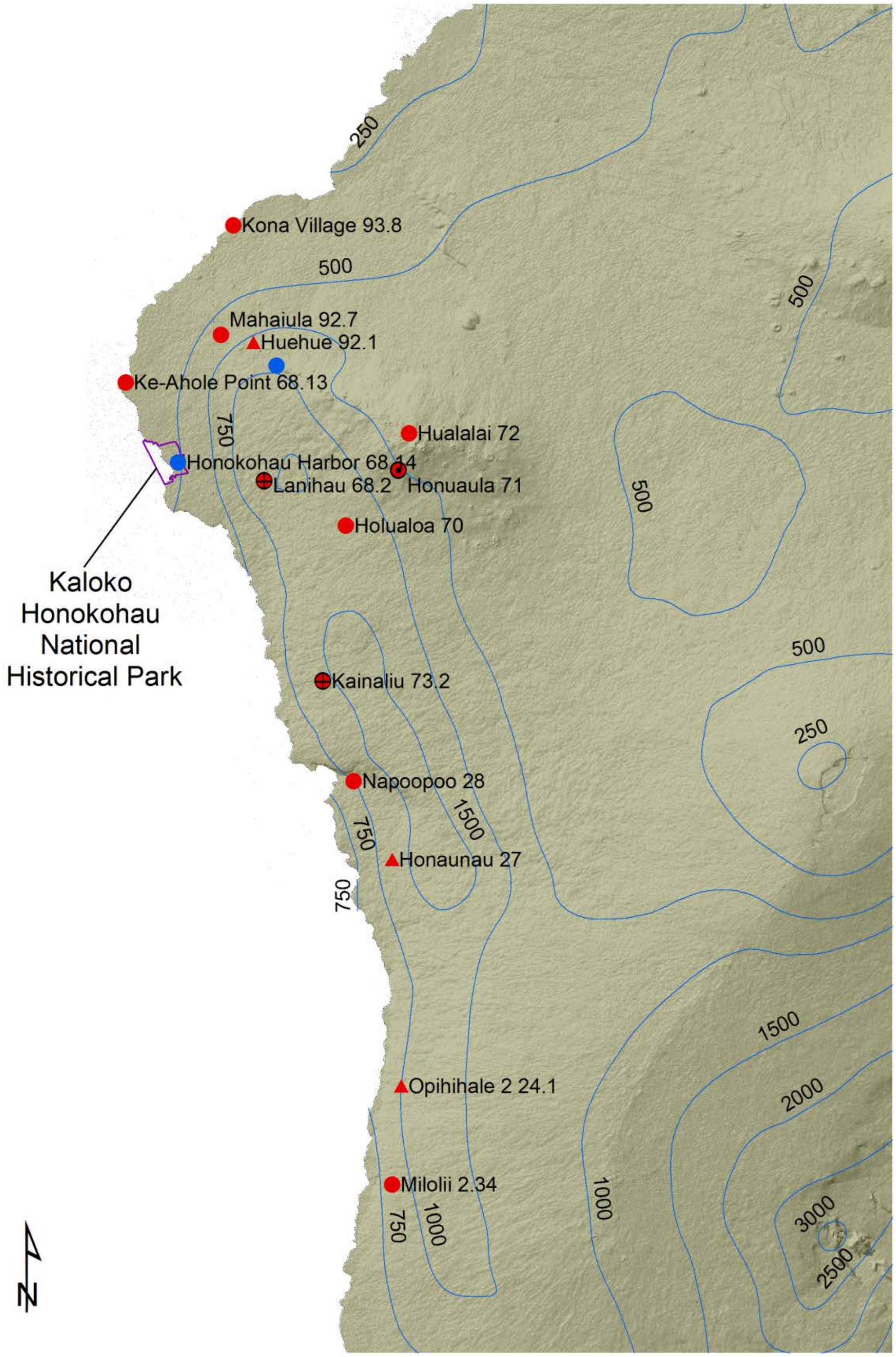

Figure 6.2 Summer trend results for the period of 1978 to 2010 with rainfall isohyets from Giambelluca *et al.* (2013). Stations with trends of increasing rainfall are colored blue, and stations with decreasing trends are colored red. Stations with significant trends have a black dot in a circle (α=0.1), a triangle symbol (α=0.05), or cross-hatching over a circle (α=0.01).

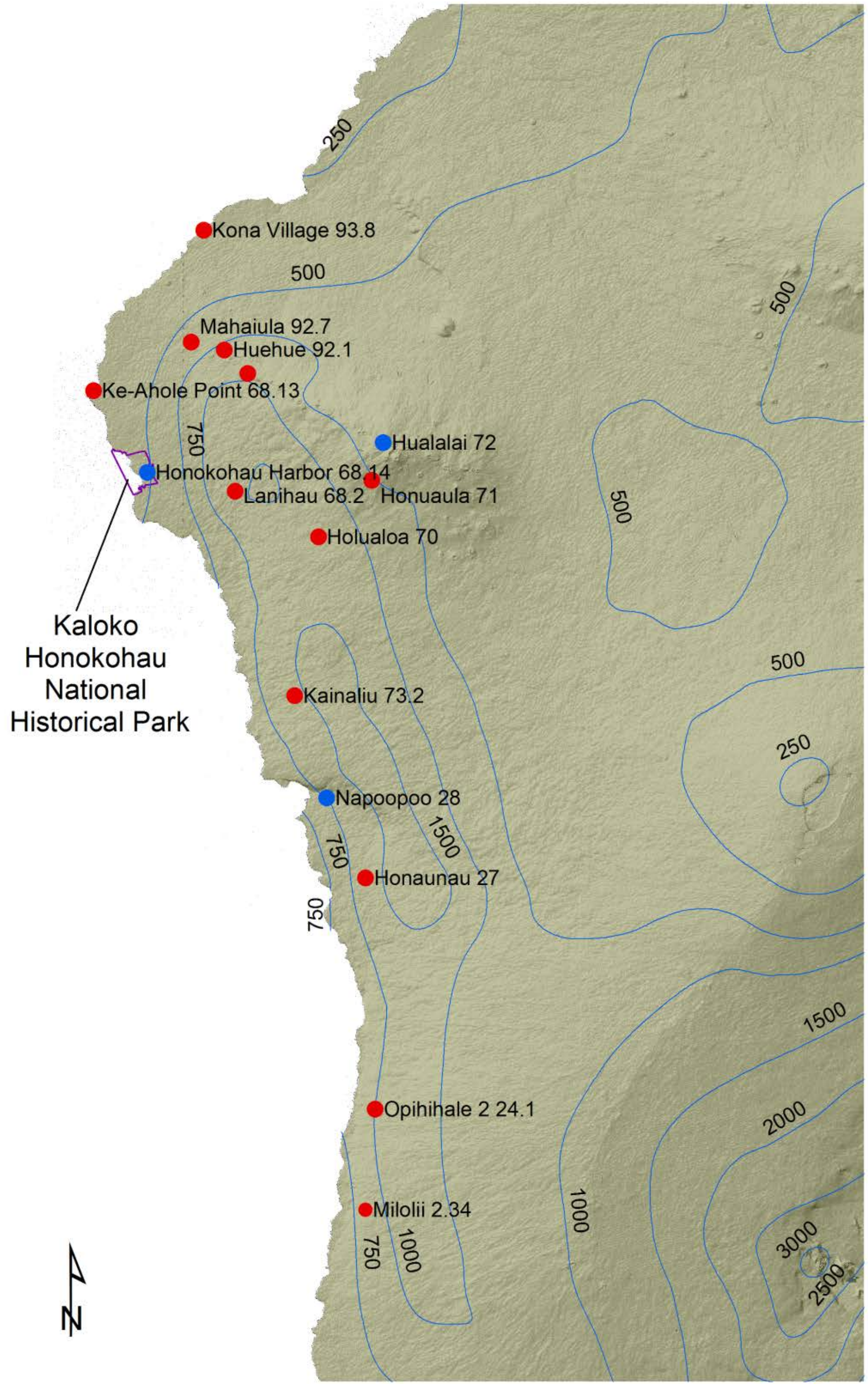

Figure 6.3 Winter trend results for the period of 1978 to 2010 with rainfall isohyets from Giambelluca *et al.* (2013). Stations with trends of increasing rainfall are colored blue, and stations with decreasing trends are colored red. Stations with significant trends have a black dot in a circle (α=0.1), a triangle symbol (α=0.05), or cross-hatching over a circle (α=0.01).

CHAPTER 7 – CONCLUSIONS

The combined factors of steep elevations gradients, trade wind influences, diurnal heating and cooling of the land surface, and a stable high elevation atmospheric layer all interact creating diverse rainfall patterns over even short distances (Giambelluca *et al*. 2011). Local or regional variations in precipitation are important as drivers of recharge and ultimately groundwater resources. Within the Kona recharge area there is evidence of diverse changes in rainfall that have taken place over recent decades. Thirteen out of 15 stations evaluated for changes in annual rainfall have decreasing trends during the 1978 to 2010 time period as well as over their entire observation record. Decreases in annual rainfall range from 30mm to 250mm per decade with the majority of declines occurring in the summer season. Almost half of the stations had significant changes in rainfall during the summer season, but none of the changes in winter rainfall were significant. The two stations with increases in rainfall have small trends that are not sufficient to moderate the amount of rainfall decreases across the regional recharge area.

The two stations of Kainaliu 73.2 and Opihihale 2 24.1 have the longest temperature records and both indicate warming in annual mean minimum temperature trends ranging from less than one to 2 degrees Celsius per century with the majority of change in the winter season. The more recent decades of 1978 to 2010 demonstrate a one degree Celsius cooling trend at Opihihale 2.24.1 which was not significant. Kainaliu's record indicated a significant cooling trend of 2 degrees Celsius per century, and conversely, Opihihale had a significant 2 degree warming trend in annual mean maximum temperature. Both changes were strongest in the winter season. The

1978 to 2010 time period for Opihihale, however, indicated a reversal in the trend direction with a 4 degree Celsius rate of cooling per century in annual mean maximum temperatures.

The trends displayed in both rainfall and temperature when modeled 50 years into the future indicate declines in net precipitation ranging from 6 to 48% compared to the modeled stationary 50 year mean. All of the modeled scenarios indicated a decline in the number of days with rainfall for all of the locations with the decline resulting in four locations having a season with no rainfall at all. Three of those four dry seasons occurred during summer with only one winter season modeled as dry throughout. The change in temperature had only a small effect on modeled net precipitation while the changes in rainfall had the most impact. Large declines in modeled net precipitation such as these would affect overall amount of recharge to the regional aquifer. However, there is a wide range of changes at work within the regional area. Connectivity between the higher elevation portion of the aquifer and the low elevation or coastal portion of the aquifer will determine the degree and timing of impact to the coastal aquifer from changes in net precipitation received in the higher elevation areas. The coastal aquifer will display impacts caused by declines in net precipitation and recharge to the local area first with an intensification of changes in freshwater as decreased amounts of recharge water move from the higher elevation areas to the coast. The presence of a positive trend or increase in rainfall predicted at the Honokohau Harbor location, which is closest to the Park, is encouraging for possible future recharge to the coastal aquifer. Further study in the aquifer’s characteristics and geologic structure over the region would improve the prediction of future effects to recharge resulting from localized changes in rainfall.

Ecosystems inhabiting the coastal areas are dependent on groundwater discharges and sporadic episodes of surface runoff for freshwater. In an island ecosystem, the constant pressure of saltwater intrusion and the input of freshwater recharge create a delicate balance of fresh and saline water underground. The natural resources of Kaloko-Honokōhau National Historical Park have evolved to thrive in an ecosystem with stable temperatures and both fresh and saline water sources. Any change in net precipitation that affects recharge could disrupt that delicate balance allowing increased saltwater intrusion along the coastline and within the Park.

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APPENDIX A: STATIONS EVALUATED FOR PRECIPITATION TREND TESTING

Table A.1: Information for stations located within the Keauhou aquifer recharge area that were evaluated for precipitation testing. (N equals the numbers of years in the period of record.)

Station Name	Station Code	Latitude	Longitude	Elevation [meters]	Network	Period of Record Start	Period of Record End	N
Ahua Umi 75	510040	19.633	-155.783	1592	COOP	01/01/1958	11/30/1986	28
Hapuu 31	511240	19.433	-155.817	1391	COOP	10/01/1949	12/31/1952	3
Holualoa Beach 68	511562	19.617	-155.983	3	COOP	11/01/1928	02/28/1979	51
Holualoa 70	511557	19.633	-155.900	982	COOP	01/01/1905	08/31/2010	105
Honaunau 27	511665	19.421	-155.884	287	COOP	01/01/1938	12/31/2010t	72
Honaunau No.2 27.6	511668	19.466	-155.885	398	COOP	02/24/2003	12/31/2010	7
Honomalino 2.35	511922	19.202	-155.862	610	COOP	02/01/1999	08/01/2002	3
Honuaula 71	512047	19.667	-155.883	1905	COOP	10/01/1949	08/31/2010	61
Honokohau Harbor 68.14	511880	19.683	-156.017	9	COOP	01/01/1991	12/31/2010	19
Holualoa Makai 69.16	511570	19.633	-155.967	317	COOP	07/01/1970	10/31/1976	6
Hualalai 72	512151	19.698	-155.873	2354	COOP	10/01/1949	12/31/2007	58
Huehue 92.1	512156	19.757	-155.974	598	COOP	01/01/1905	07/31/2010	105
Kailua Kona Ke-Ahole Airport	21510	19.736	-156.049	13	ASOS	08/01/1970	12/31/2010	40
Ke-Ahole Point 68.13	513911	19.733	-156.067	6	COOP	02/01/1981	12/31/2010	29
Kaawaloa 29	512327	19.495	-155.919	409	COOP	01/01/1942	02/01/1999	57
Kalaoa 69.22	512887	19.733	-155.983	610	COOP	05/01/1975	02/20/1986	11
Kailua Heights 68.15	512686	19.617	-155.967	152	COOP	10/01/1975	12/01/1983	8
Kailua Kona 68.3	512687	19.650	-156.017	9	COOP	03/01/1956	02/01/1999	43
Kainaliu 73.2	512751	19.537	-155.929	457	COOP	01/01/1939	12/31/2010	71
Kainaliu Upper 73.29	512762	19.531	-155.890	713	COOP	02/24/2003	11/01/2005	2
Kanahaha 74	513095	19.600	-155.800	1543	COOP	10/01/1949	04/30/1963	14
Kealakekua 2 28.7	513980	19.500	-155.917	442	COOP	01/01/1905	08/31/1977	72
Kealakekua 26.2	513977	19.495	-155.915	451	COOP	01/01/1905	12/31/2010	105

Station Name	Station Code	Latitude	Longitude	Elevation [meters]	Network	Period of Record Start	Period of Record End	N
Kealakekua 3 29.11	513985	19.517	-155.917	466	COOP	05/01/1978	10/28/1986	8
Kealakekua 4 74.8	513987	19.514	-155.924	433	COOP	07/01/2002	12/31/2010	8
Kealakekua T.F. 29.12	513990	19.521	-155.919	537	COOP	02/24/2003	12/31/2010	7
Kaohe Makai 24.4	513146	19.317	-155.883	37	COOP	01/01/1984	01/01/1995	11
Kona Ap 68.3	514764	19.650	-156.017	9	COOP	10/01/1949	01/31/1980	31
Kona Village 93.8	514765	19.833	-155.987	6	COOP	05/01/1968	12/31/2010	42
Keauhou 2 73a	514163	19.567	-155.933	589	COOP	10/01/1949	11/30/1956	7
Lanihau 68.2	515330	19.667	-155.967	466	COOP	01/01/1950	12/31/2010	60
Mahaiula 92.7	515670	19.767	-156.000	293	COOP	06/01/1986	12/31/2010	24
Middle Holualoa 68.1	516268	19.617	-155.967	145	COOP	03/01/1958	02/01/1979	21
Milolii 2.34	516304	19.210	-155.884	357	COOP	05/01/1985	12/31/2010	25
Moanuiahea 69.24	516330	19.742	-155.959	860	COOP	07/01/1986	07/31/2010	24
Napoopoo 28	516697	19.472	-155.909	122	COOP	01/01/1905	12/31/2010	105
Ohia Lodge 24	516942	19.267	-155.883	403	COOP	08/01/1948	06/30/1950	2
Opihihale 2 24.1	517166	19.274	-155.878	415	COOP	05/01/1956	12/31/2010	54
Pahoehoe	517541	19.350	-155.883	305	COOP	09/01/1930	12/31/1947	17
Puu Anahulu 93a	518346	19.817	-155.850	656	COOP	01/01/1950	04/30/1963	13
Puu Lehua 73	518460	19.567	-155.817	1488	COOP	10/01/1949	11/30/1986	37
Puu Waawaa 94.1	518555	19.781	-155.846	768	COOP	10/01/1949	12/31/2010	61
Puuhonua-O-Hona 27	518552	19.421	-155.914	5	COOP	11/01/1970	12/31/2010	40
Waiaha Stream 70.16	518960	19.633	-155.950	469	COOP	10/01/1975	07/01/2008	33

APPENDIX B: STATIONS EVALUATED FOR TEMPERATURE TREND TESTING

Table B.1: Information for stations located within the Keauhou aquifer recharge area that were evaluated for temperature testing. (N equals the numbers of years in the period of record.)

Station Name	Station Code	Latitude	Longitude	Elevation [meters]	Network	Period of Record Start	Period of Record End	N
Ahua Umi 75	510040	19.633	-155.783	1592	COOP	01/01/1958	11/30/1986	28
Hapuu 31	511240	19.433	-155.817	1391	COOP	10/01/1949	12/31/1952	3
Holualoa Beach 68	511562	19.617	-155.983	3	COOP	11/01/1928	02/28/1979	51
Holualoa 70	511557	19.633	-155.900	982	COOP	01/01/1905	08/31/1928	23
Honaunau 27	511665	19.421	-155.884	287	COOP	01/01/1938	12/31/2010t	72
Honaunau No.2 27.6	511668	19.466	-155.885	398	COOP	02/24/2003	12/31/2010	7
Honomalino 2.35	511922	19.202	-155.862	610	COOP	02/01/1999	08/01/2002	3
Honuaula 71	512047	19.667	-155.883	1905	COOP	10/01/1949	08/31/2010	61
Honokohau Harbor 68.14	511880	19.683	-156.017	9	COOP	01/01/1991	12/31/2010	19
Holualoa Makai 69.16	511570	19.633	-155.967	317	COOP	07/01/1970	10/31/1976	6
Hualalai 72	512151	19.698	-155.873	2354	COOP	10/01/1949	12/31/2007	58
Huehue 92.1	512156	19.757	-155.974	598	COOP	02/01/1905	05/07/1912	7
Kailua Kona Ke-Ahole Airport	21510	19.736	-156.049	13	ASOS	08/01/1970	12/31/2010	40
Ke-Ahole Point 68.13	513911	19.733	-156.067	6	COOP	02/01/1981	12/31/2010	29
Kaawaloa 29	512327	19.495	-155.919	409	COOP	01/01/1942	02/01/1999	57
Kalaoa 69.22	512887	19.733	-155.983	610	COOP	05/01/1975	02/20/1986	11
Kailua Heights 68.15	512686	19.617	-155.967	152	COOP	10/01/1975	12/01/1983	8
Kailua Kona 68.3	512687	19.650	-156.017	9	COOP	03/01/1956	02/01/1999	43
Kainaliu 73.2	512751	19.537	-155.929	457	COOP	01/01/1939	12/31/2010	71
Kainaliu Upper 73.29	512762	19.531	-155.890	713	COOP	02/24/2003	11/01/2005	2
Kanahaha 74	513095	19.600	-155.800	1543	COOP	10/01/1949	04/30/1963	14
Kealakekua 2 28.7	513980	19.500	-155.917	442	COOP	12/01/1976	08/31/1977	1
Kealakekua 26.2	513977	19.495	-155.915	451	COOP	01/01/1905	12/31/2010	105
Kealakekua 3 29.11	513985	19.517	-155.917	466	COOP	05/01/1978	10/28/1986	8

Station Name	Station Code	Latitude	Longitude	Elevation [meters]	Network	Period of Record Start	Period of Record End	N
Kealakekua 4 74.8	513987	19.514	-155.924	433	COOP	07/01/2002	12/31/2010	8
Kealakekua T.F. 29.12	513990	19.521	-155.919	537	COOP	02/24/2003	12/31/2010	7
Kaohe Makai 24.4	513146	19.317	-155.883	37	COOP	01/01/1984	01/01/1995	11
Kona Ap 68.3	514764	19.650	-156.017	9	COOP	10/01/1949	01/31/1980	30
Kona Village 93.8	514765	19.833	-155.987	6	COOP	02/01/1974	05/01/1981	7
Keauhou 2 73a	514163	19.567	-155.933	589	COOP	10/01/1949	11/30/1956	7
Lanihau 68.2	515330	19.667	-155.967	466	COOP	01/01/1950	12/31/2010	60
Mahaiula 92.7	515670	19.767	-156.000	293	COOP	06/01/1986	12/31/2010	24
Middle Holualoa 68.1	516268	19.617	-155.967	145	COOP	03/01/1958	02/01/1979	21
Milolii 2.34	516304	19.210	-155.884	357	COOP	05/01/1985	12/31/2010	25
Moanuiahea 69.24	516330	19.742	-155.959	860	COOP	07/01/1986	07/31/2010	24
Napoopoo 28	516697	19.472	-155.909	122	COOP	11/01/1918	08/31/1961	43
Ohia Lodge 24	516942	19.267	-155.883	403	COOP	08/01/1948	06/30/1950	2
Opihihale 2 24.1	517166	19.274	-155.878	415	COOP	05/01/1956	12/31/2010	54
Pahoehoe	517541	19.350	-155.883	305	COOP	09/01/1930	12/31/1947	17
Puu Anahulu 93a	518346	19.817	-155.850	656	COOP	01/01/1950	04/30/1963	13
Puu Lehua 73	518460	19.567	-155.817	1488	COOP	10/01/1949	11/30/1986	37
Puu Waawaa 94.1	518555	19.781	-155.846	768	COOP	05/01/1973	07/31/1976	3
Puuhonua-O-Hona 27	518552	19.421	-155.914	5	COOP	11/01/1970	12/31/2010	40
Waiaha Stream 70.16	518960	19.633	-155.950	469	COOP	10/01/1975	07/01/2008	33

APPENDIX C: ANNUAL MANN-KENDALL TREND TEST RESULTS

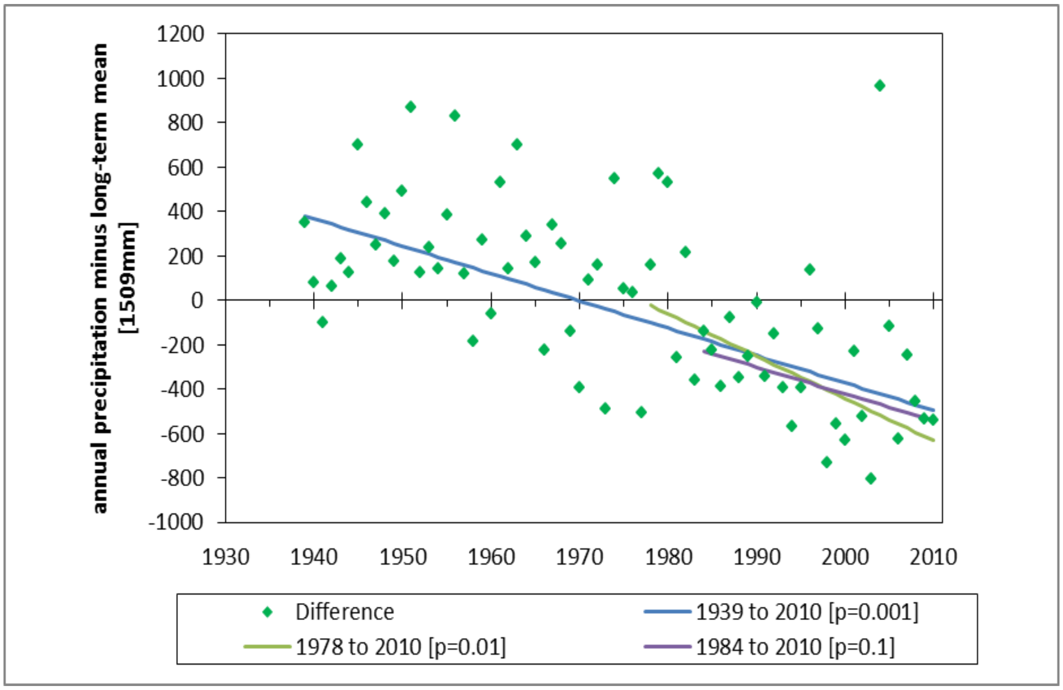

Figure C.1 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1509mm) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1939 to 2010.

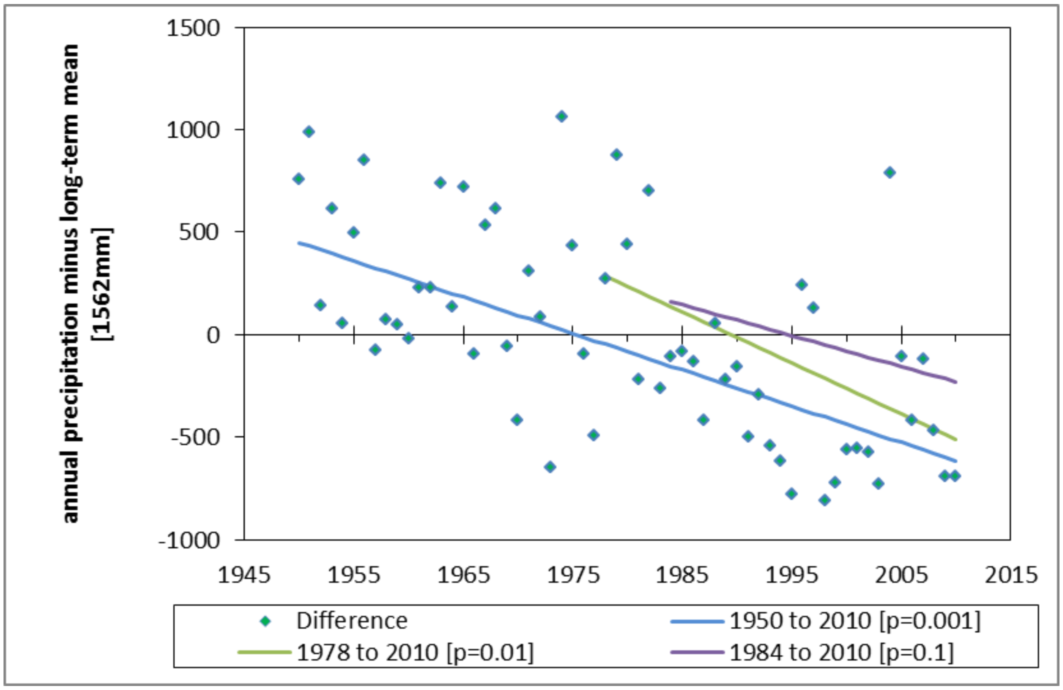

Figure C.2 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1562mm) for the station, Lanihau 68.2. The zero line represents the mean calculated over the period of record, 1950 to 2010.

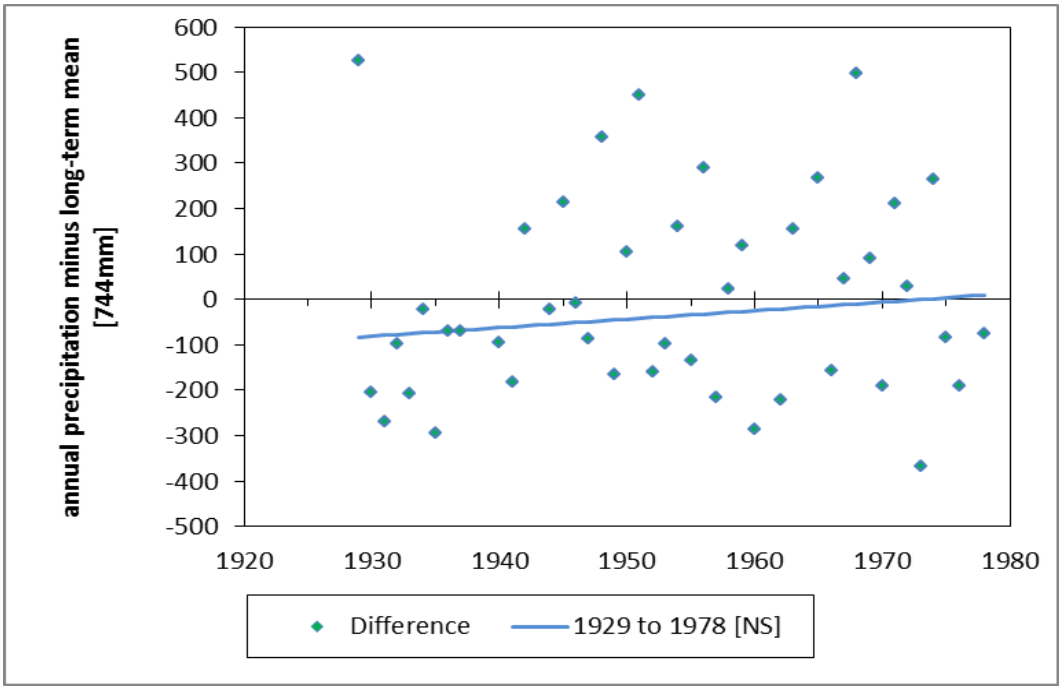

Figure C.3 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (744mm) for the station, Holualoa Beach 68. The zero line represents the mean calculated over the period of record, 1929 to 1978.

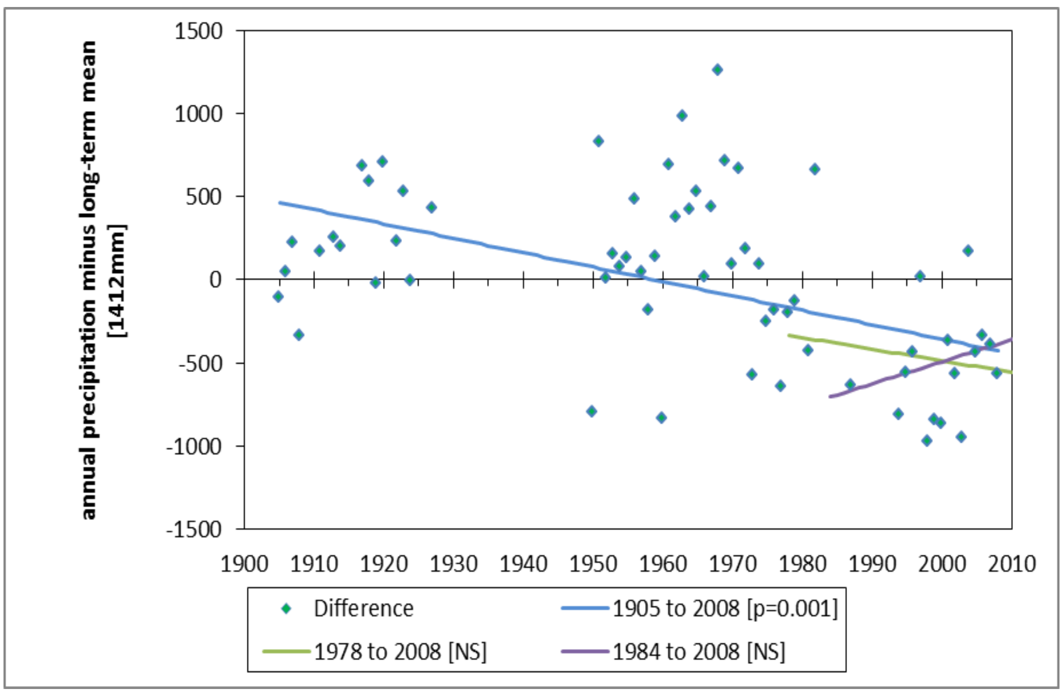

Figure C.4 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1412mm) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1905 to 2008.

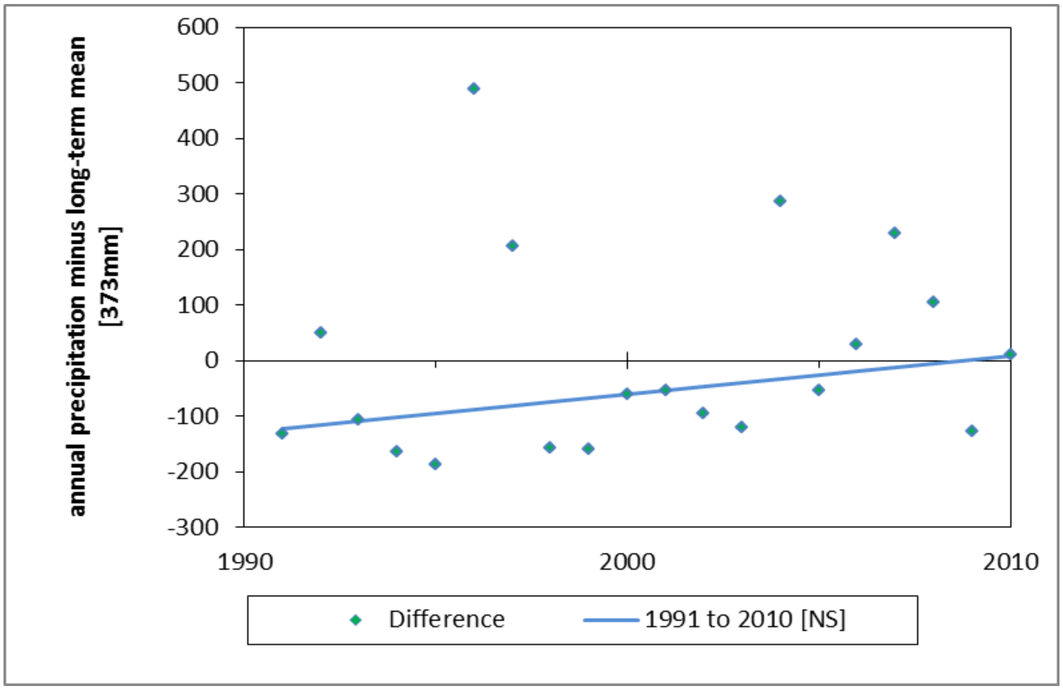

Figure C.5 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (373mm) for the station, Honokohau Harbor 68.14. The zero line represents the mean calculated over the period of record, 1991 to 2010.

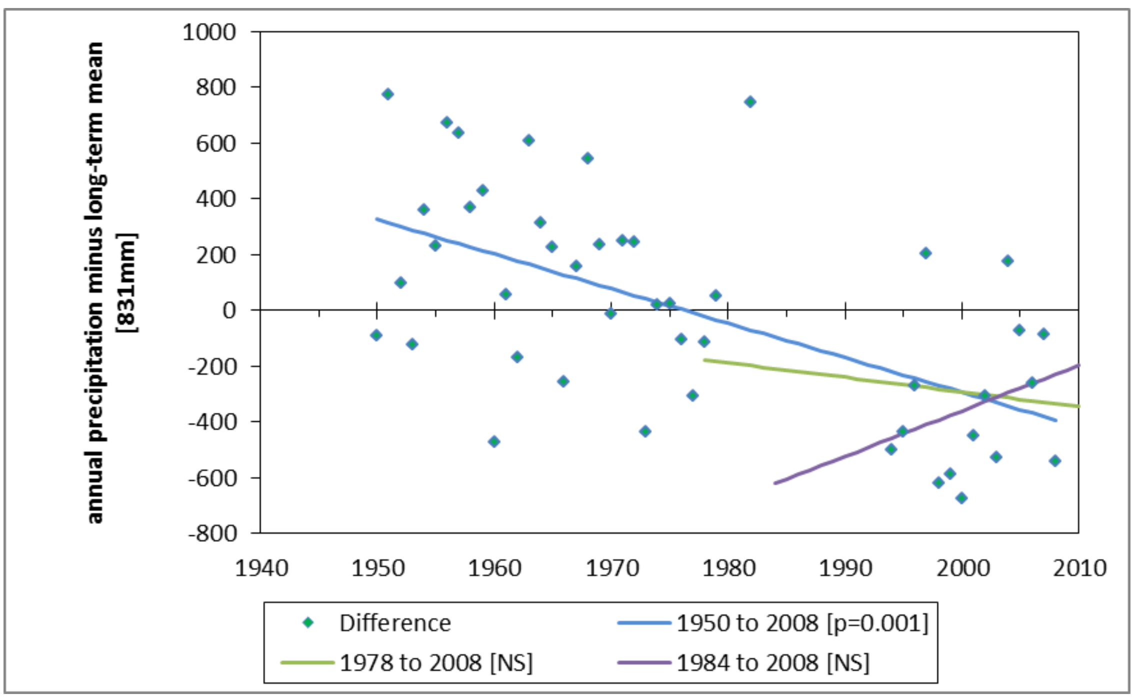

Figure C.6 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (831mm) for the station, Honuaula 71. The zero line represents the mean calculated over the period of record, 1950 to 2008.

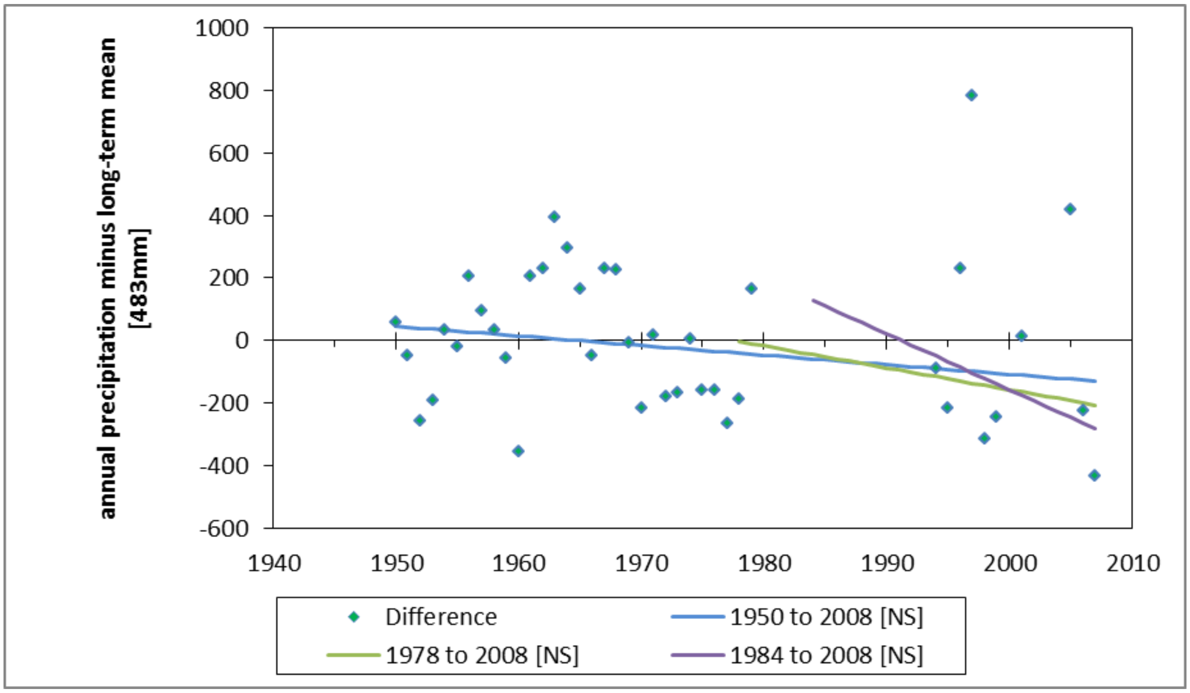

Figure C.7 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (483mm) for the station, Hualalai 72. The zero line represents the mean calculated over the period of record, 1950 to 2008.

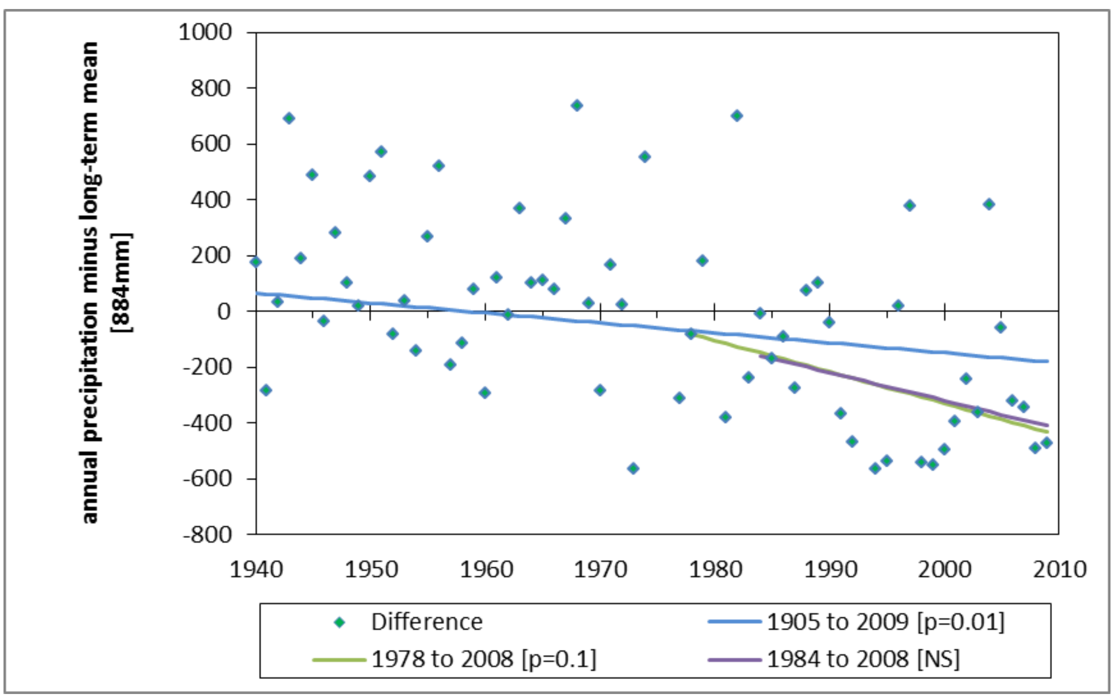

Figure C.8 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (884mm) for the station, Huehue 92.1. The zero line represents the mean calculated over the period of record, 1905 to 2009.

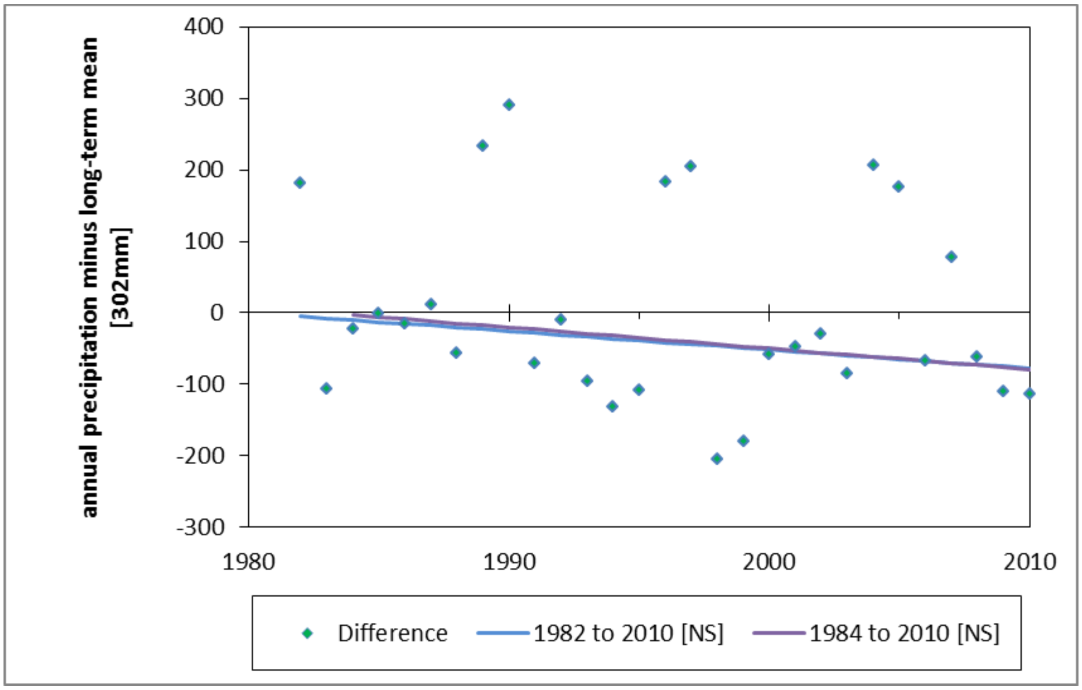

Figure C.9 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (302mm) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1982 to 2010.

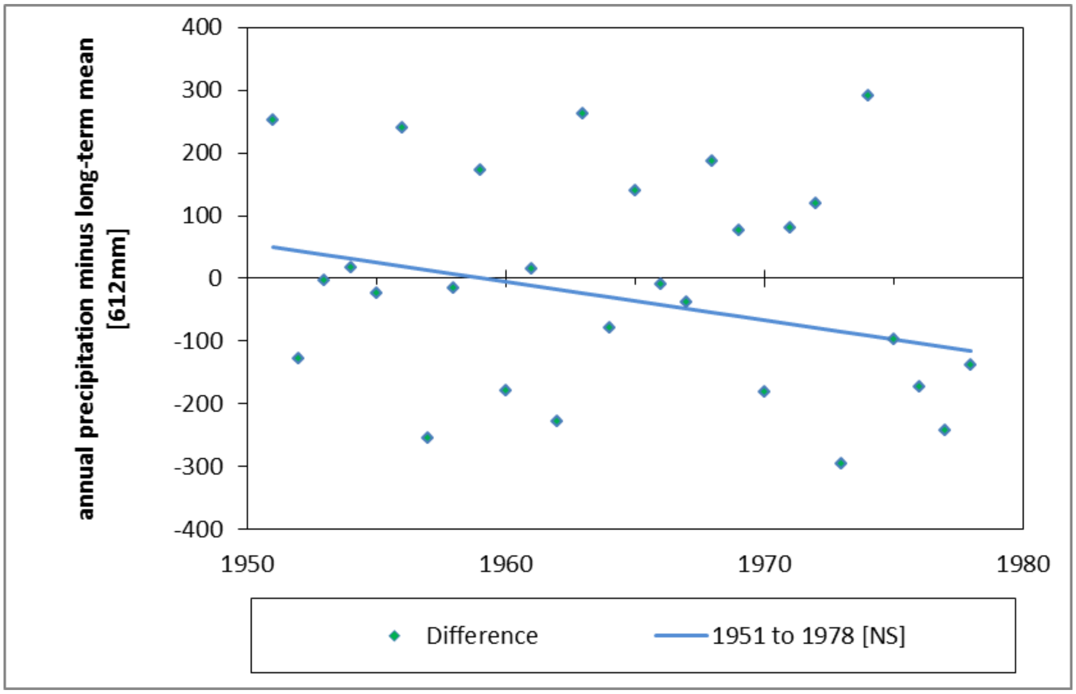

Figure C.10 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (612mm) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1951 to 1978.

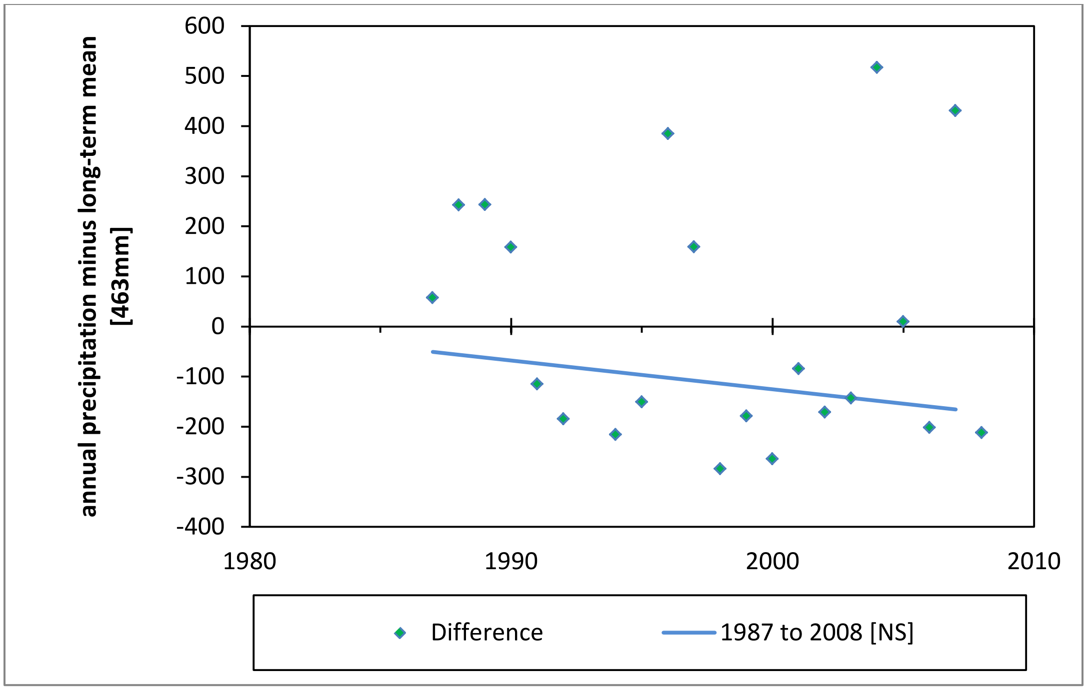

Figure C.11 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (463mm) for the station, Mahaiula 92.7. The zero line represents the mean calculated over the period of record, 1987 to 2008.

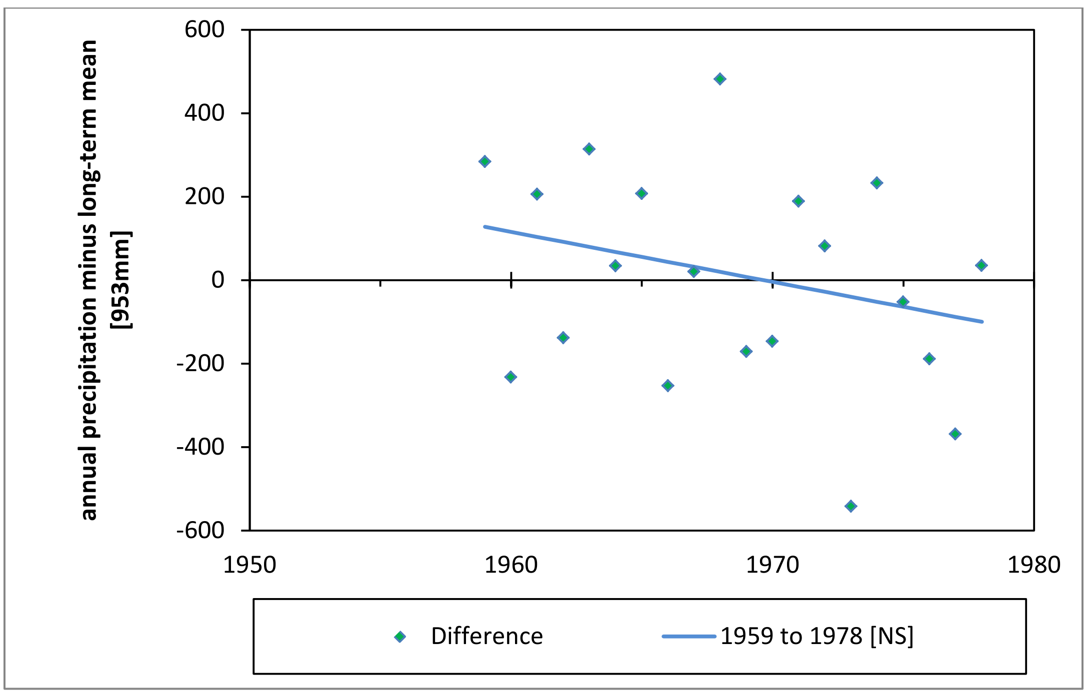

Figure C.12 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (953mm) for the station, Middle Holualoa 68.1. The zero line represents the mean calculated over the period of record, 1959 to 1978.

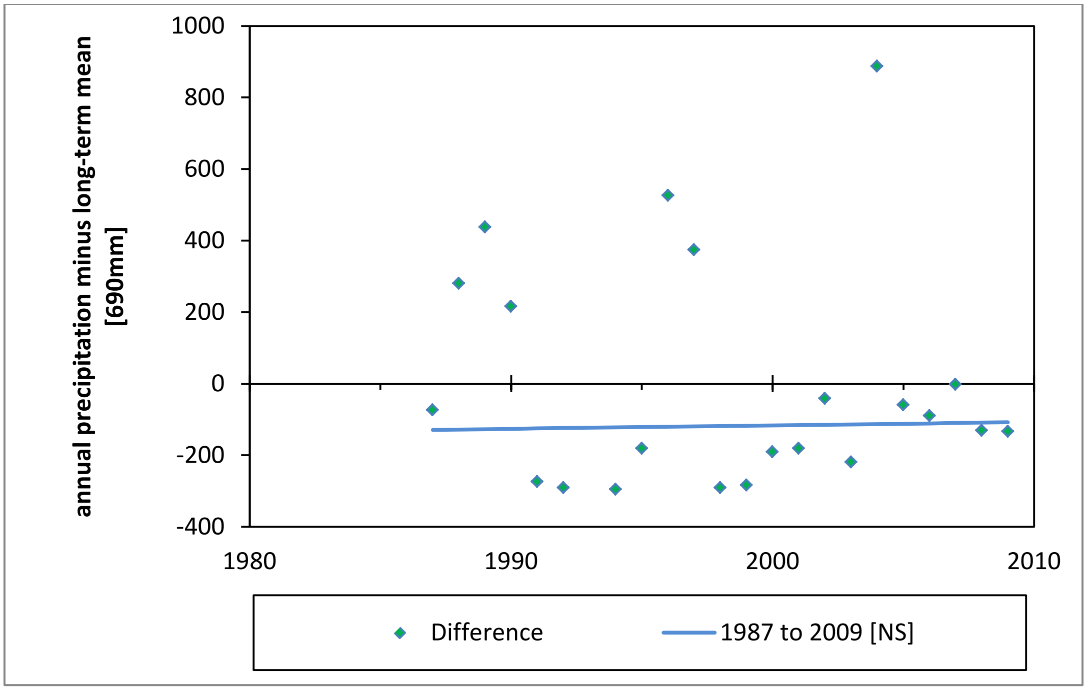

Figure C.13 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (690mm) for the station, Moanuiahea 69.24. The zero line represents the mean calculated over the period of record, 1987 to 2009.

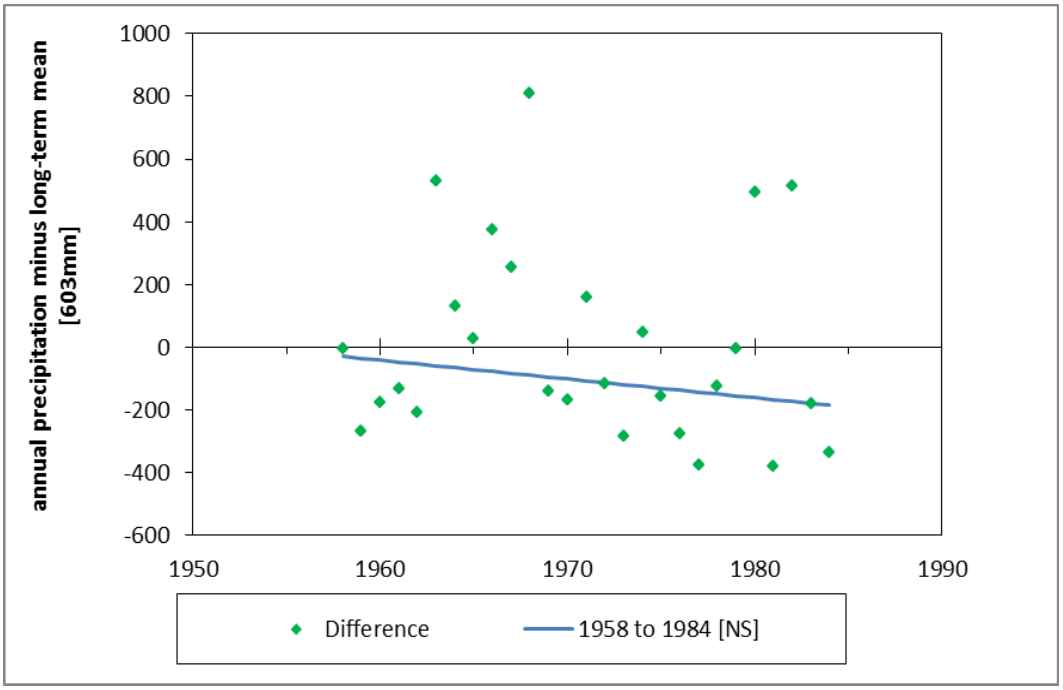

Figure C.14 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (603mm) for the station, Ahua Umi 75. The zero line represents the mean calculated over the period of record, 1958 to 1984.

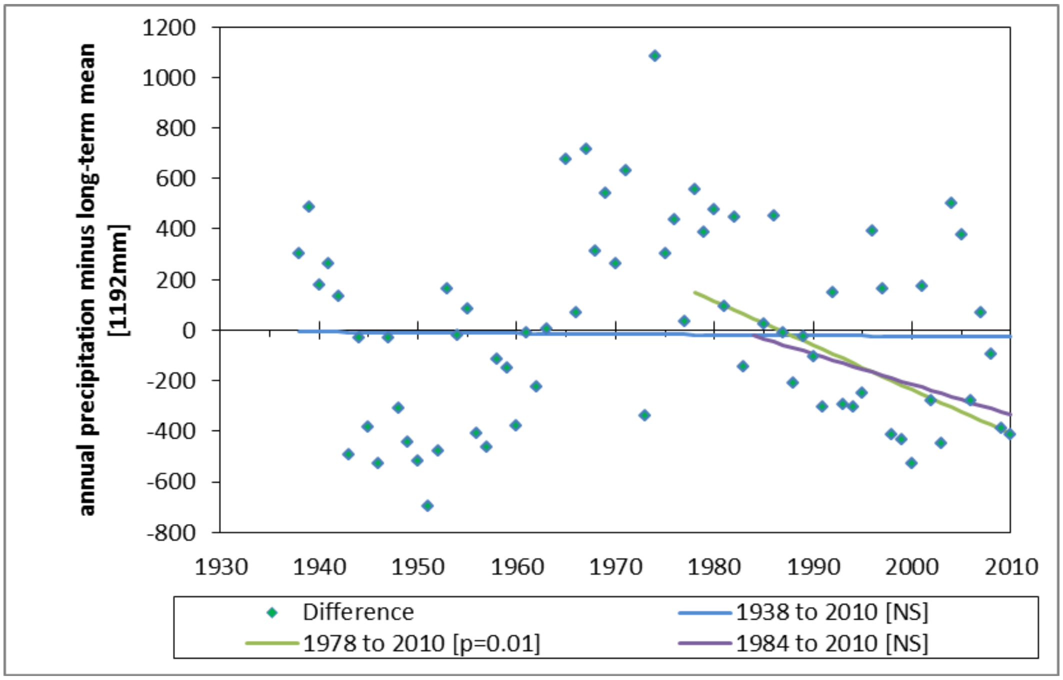

Figure C.15 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1192mm) for the station, Honaunau 27. The zero line represents the mean calculated over the period of record, 1938 to 2010.

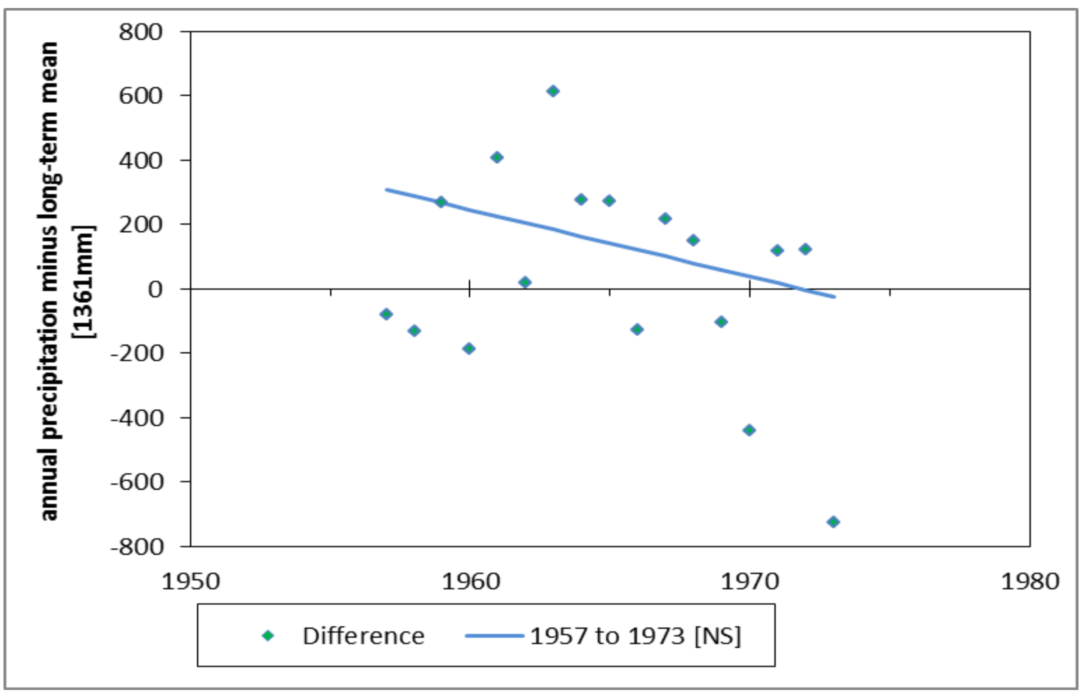

Figure C.16 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1361mm) for the station, Kealakekua 26.2. The zero line represents the mean calculated over the period of record, 1957 to 1973.

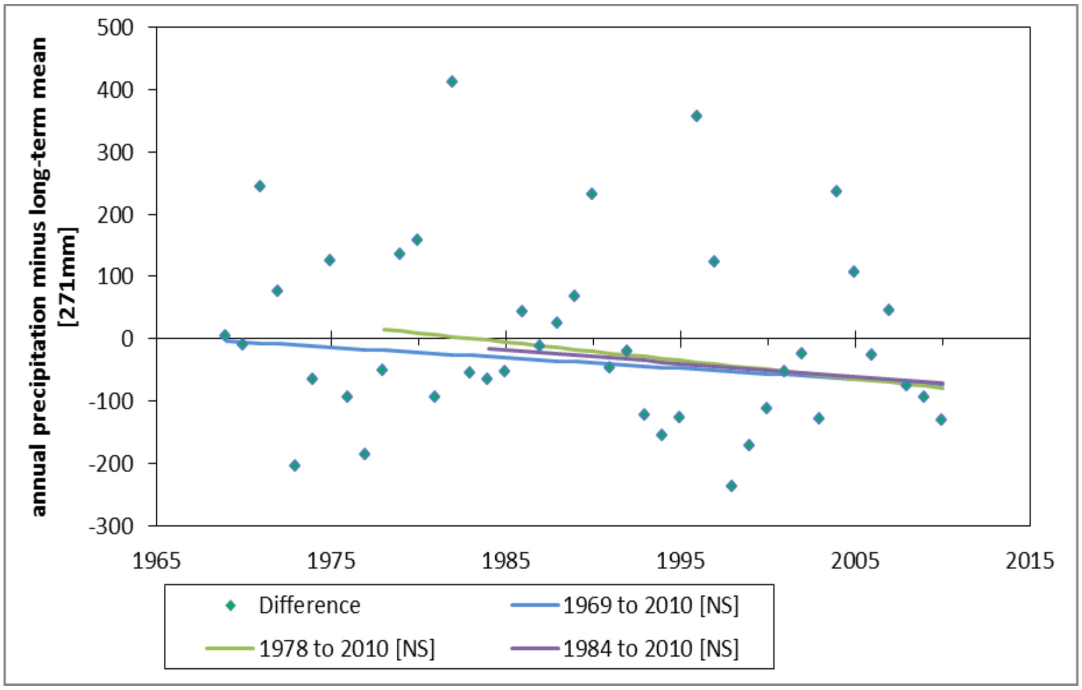

Figure C.17 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (271mm) for the station, Kona Village 93.8. The zero line represents the mean calculated over the period of record, 1969 to 2010.

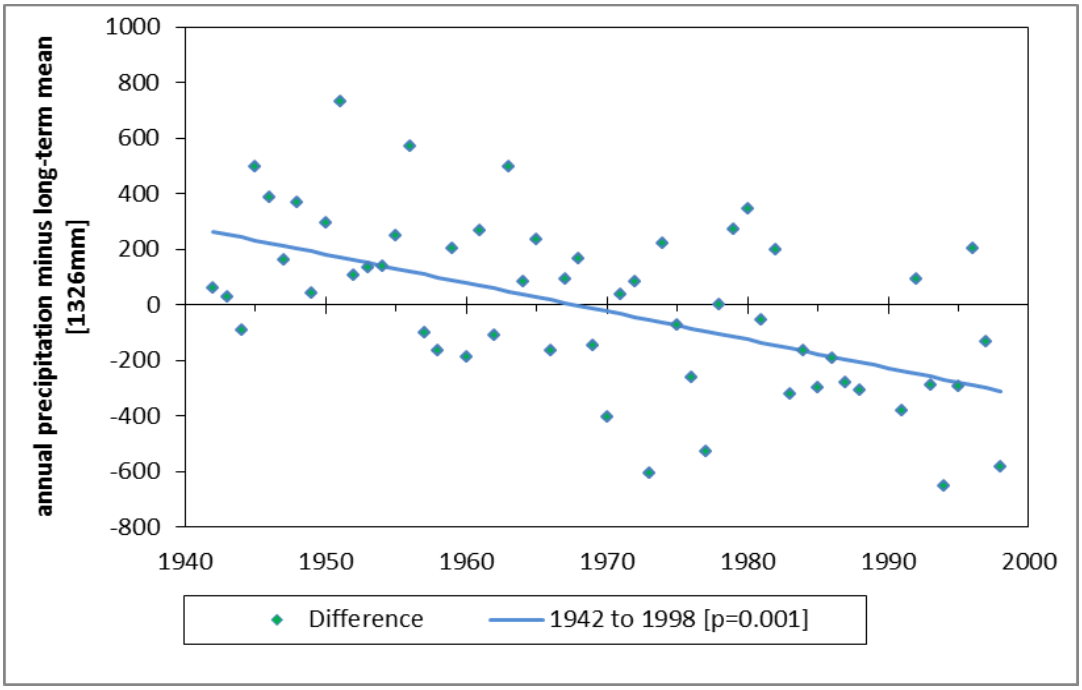

Figure C.18 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1326mm) for the station, Kaawaloa 29. The zero line represents the mean calculated over the period of record, 1942 to 1998.

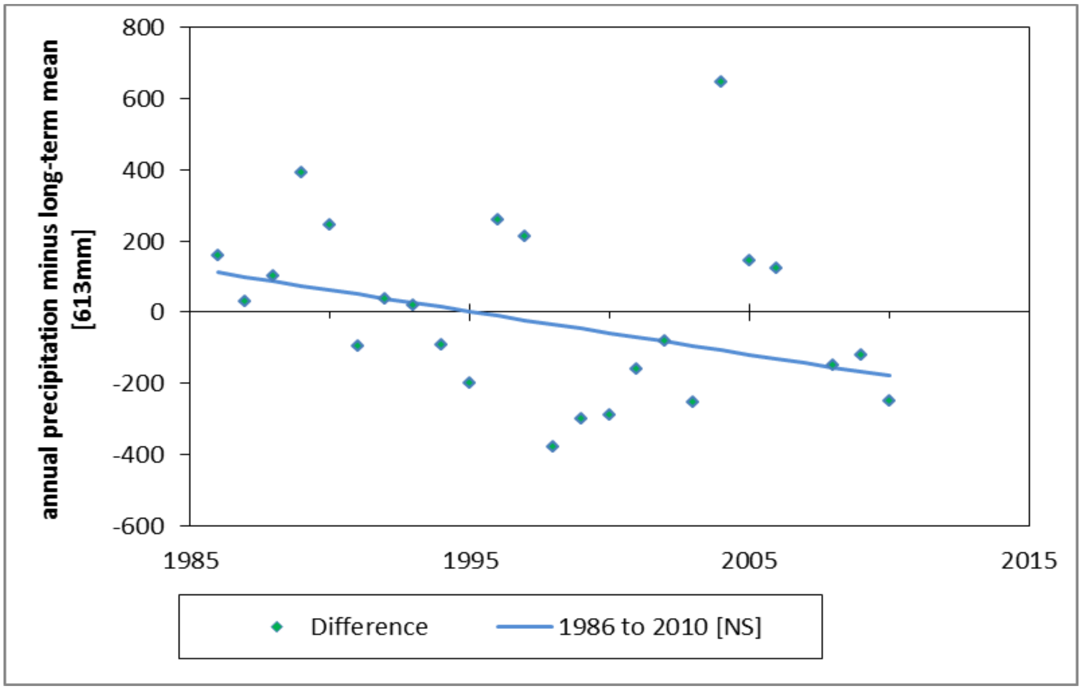

Figure C.19 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (613mm) for the station, Milolii 2.34. The zero line represents the mean calculated over the period of record, 1986 to 2010.

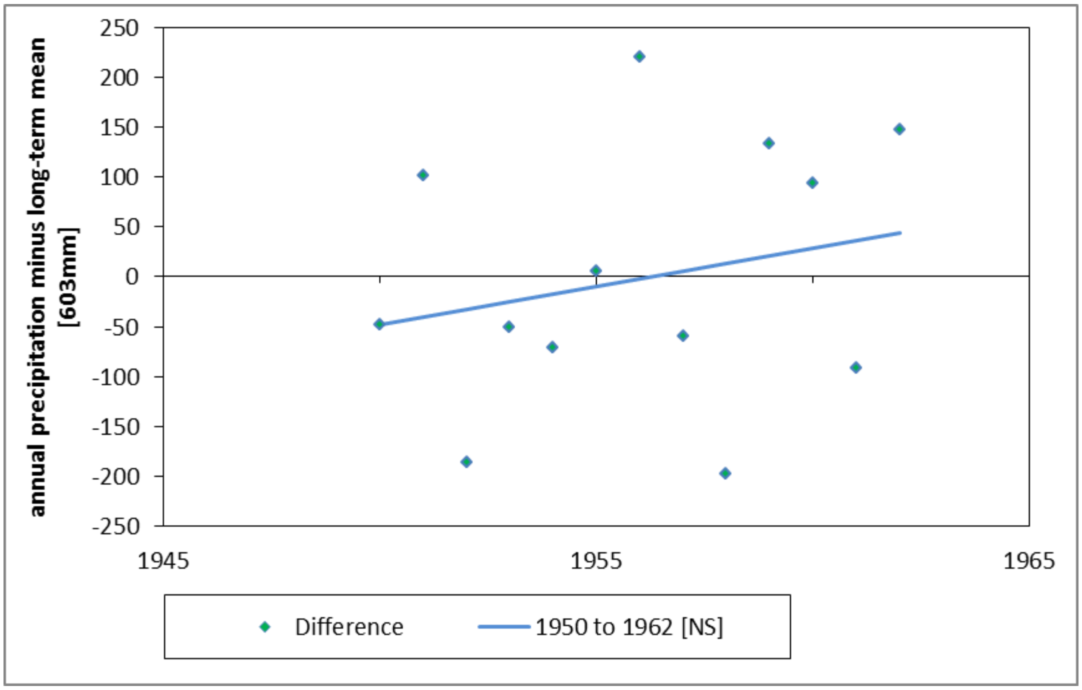

Figure C.20 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (603mm) for the station, Puu Anahulu 93a. The zero line represents the mean calculated over the period of record, 1950 to 1962.

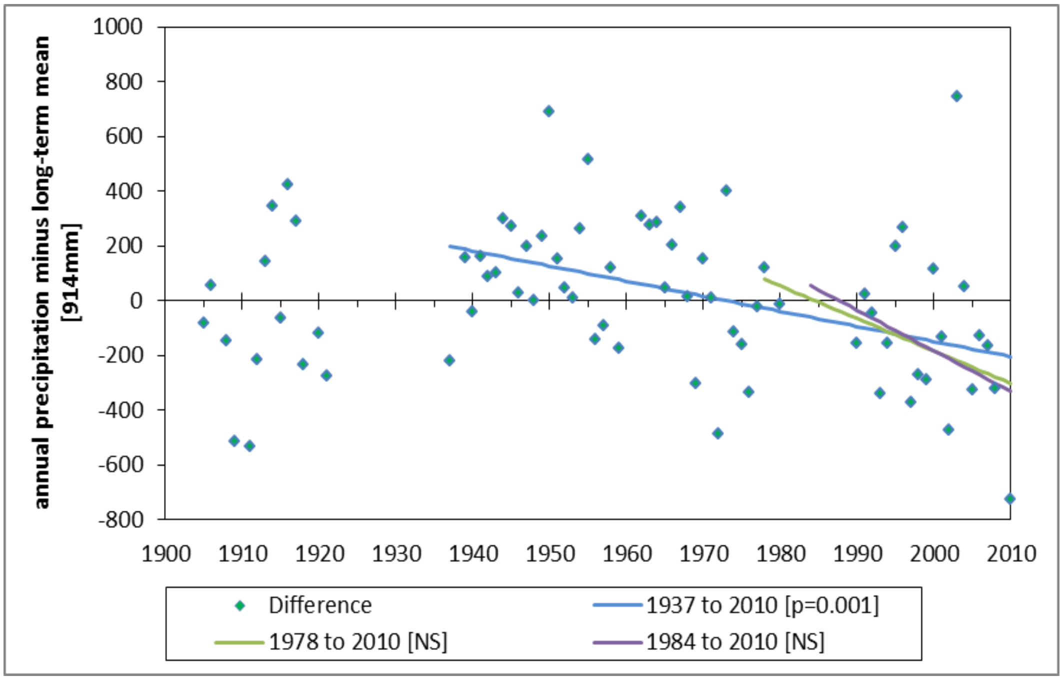

Figure C.21 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (914mm) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1937 to 2010.

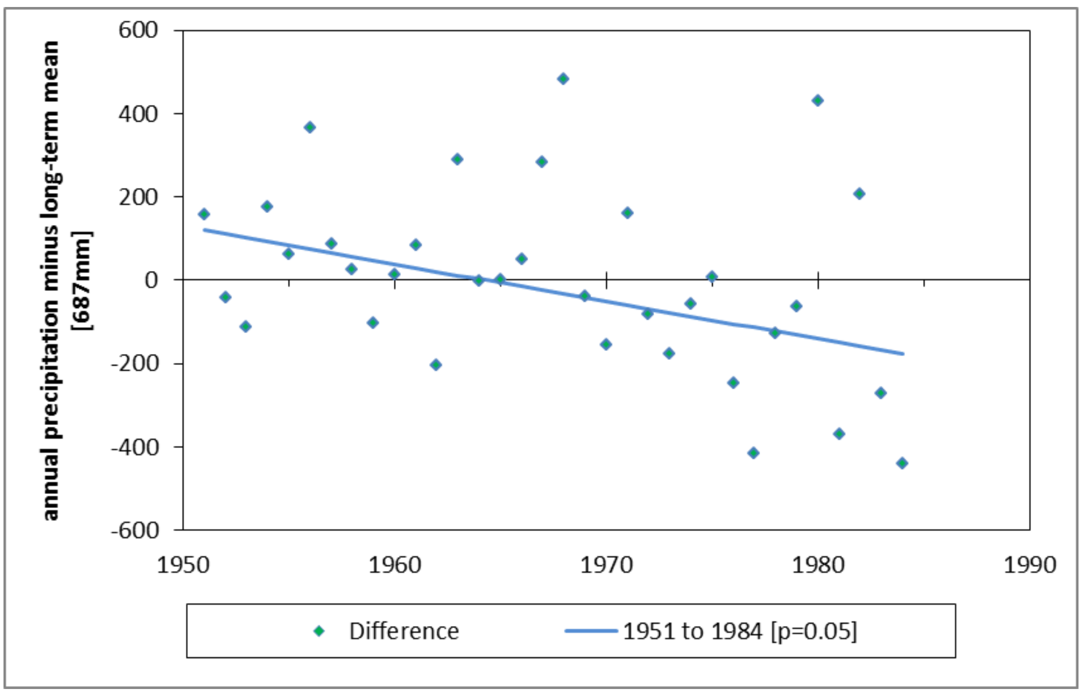

Figure C.22 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (687mm) for the station, Puu Lehua 73. The zero line represents the mean calculated over the period of record, 1951 to 1984.

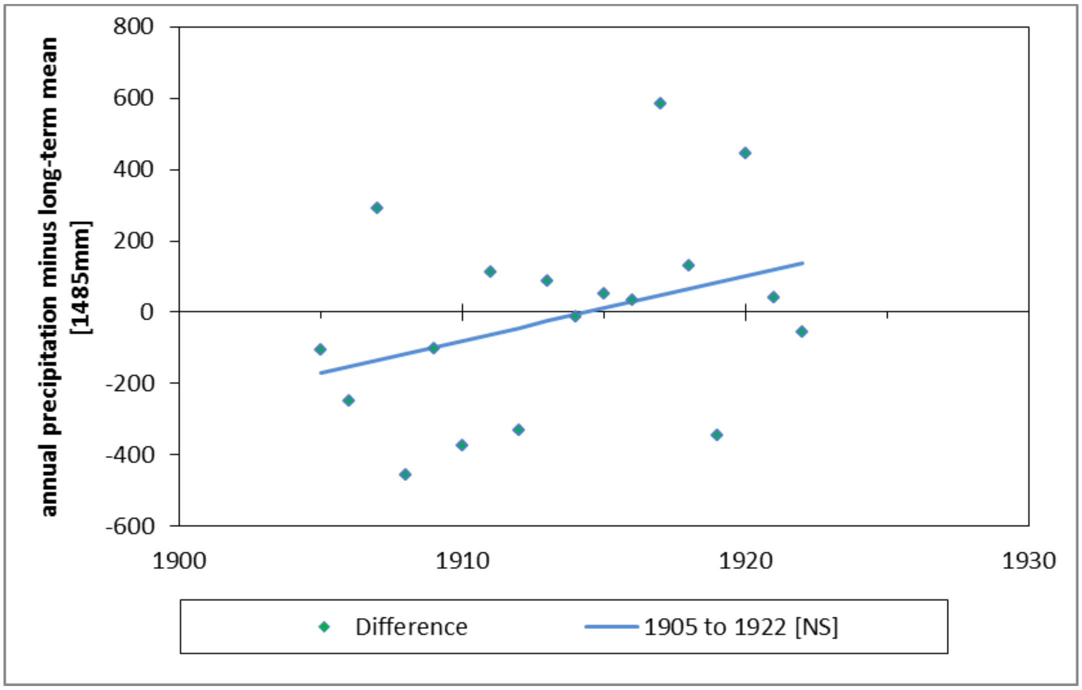

Figure C.23 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1485mm) for the station, Kealakekua 2 28.7. The zero line represents the mean calculated over the period of record, 1905 to 1922.

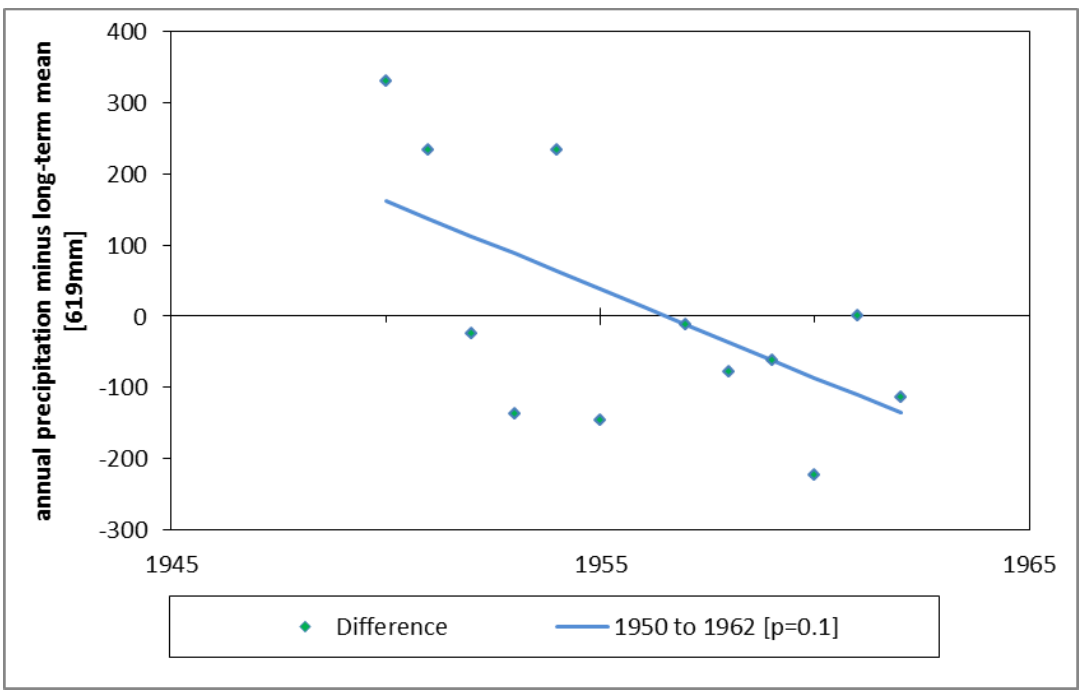

Figure C.24 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (619mm) for the station, Kanahaha 74. The zero line represents the mean calculated over the period of record, 1950 to 1962.

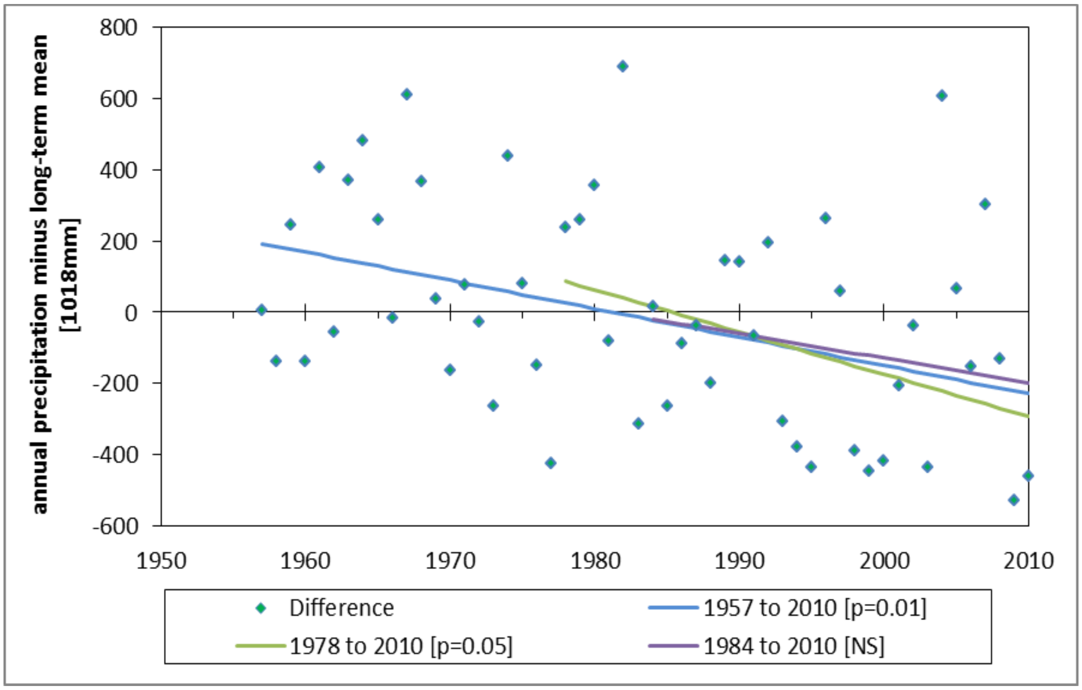

Figure C.25 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (1018mm) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1957 to 2010.

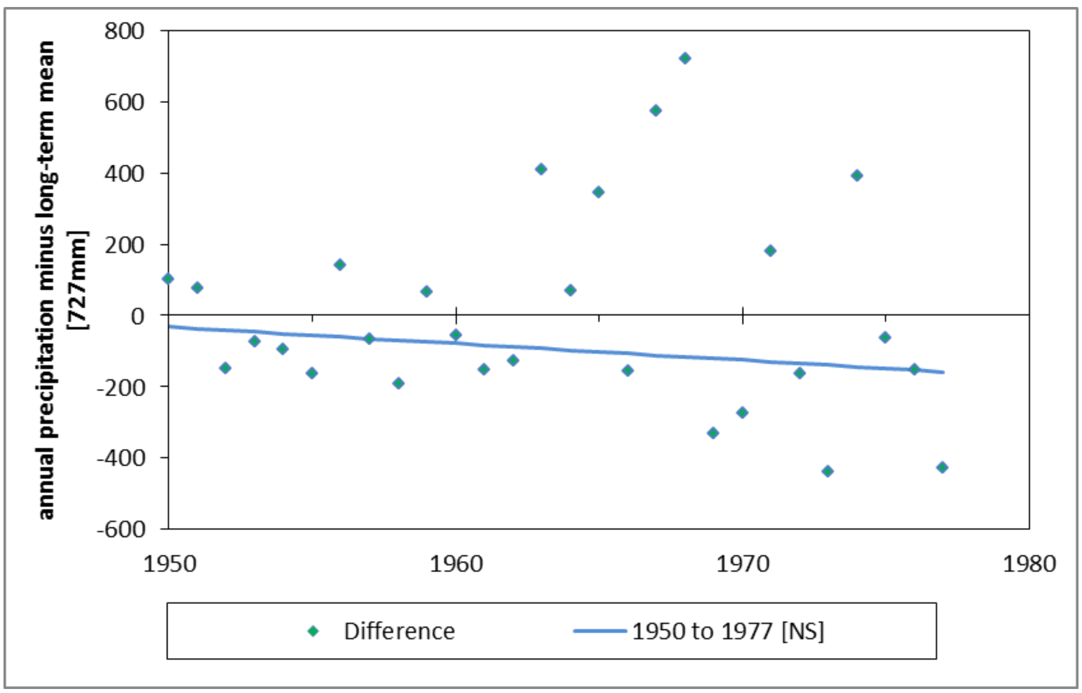

Figure C.26 Trend results from the Mann-Kendall tests and annual precipitation differences when compared to the mean (727mm) for the station, Puu Waawaa 94.1. The zero line represents the mean calculated over the period of record, 1950 to 1977.

APPENDIX D: SUMMER MANN-KENDALL TREND TEST RESULTS

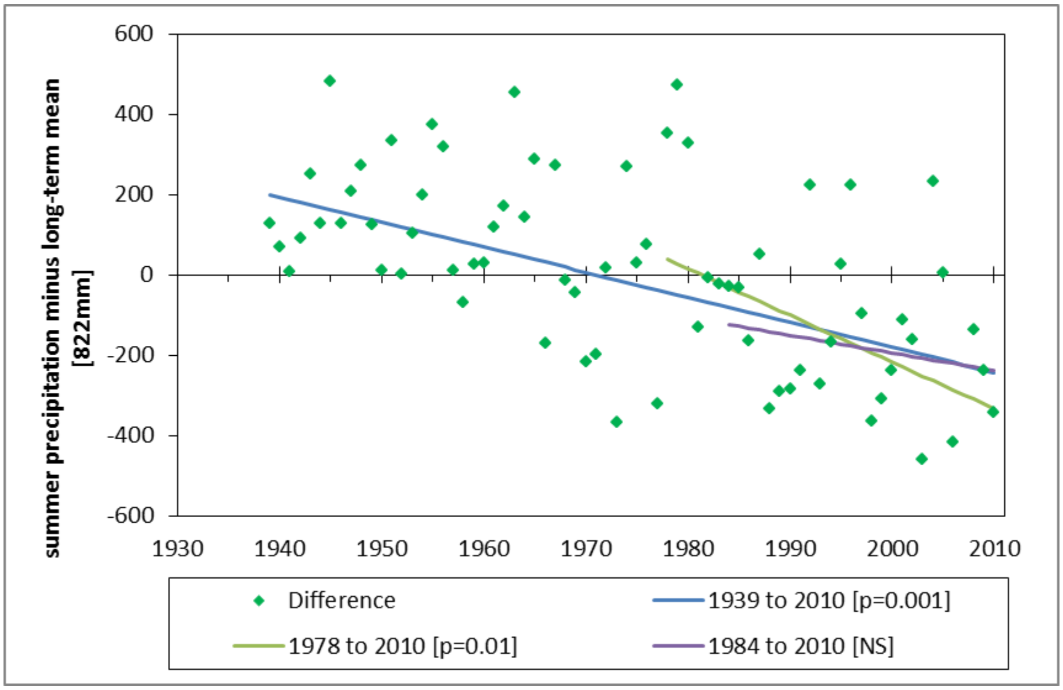

Figure D.1 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (822mm) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1939 to 2010.

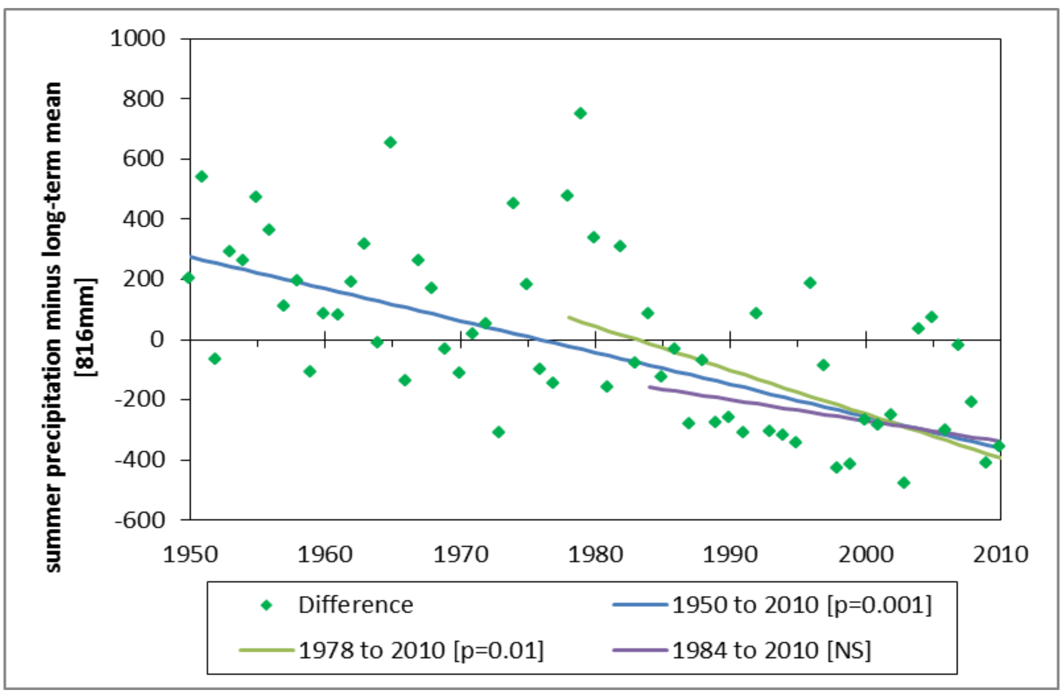

Figure D.2 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (816mm) for the station, Lanihau 68.2. The zero line represents the mean calculated over the period of record, 1950 to 2010.

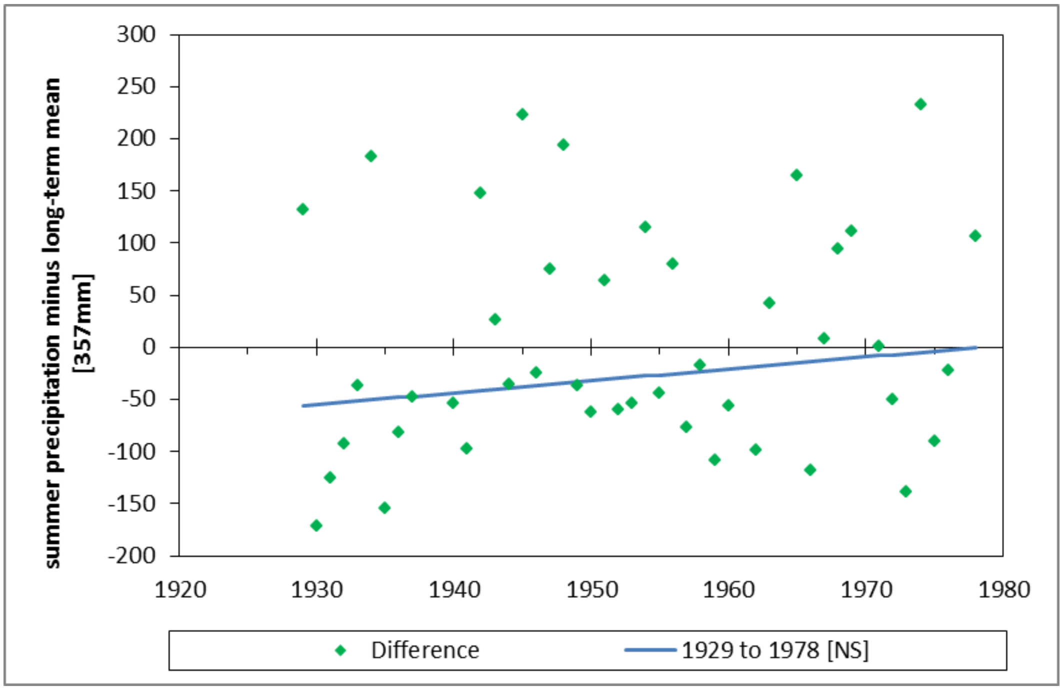

Figure D.3 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (357mm) for the station, Holualoa Beach 68. The zero line represents the mean calculated over the period of record, 1929 to 1978.

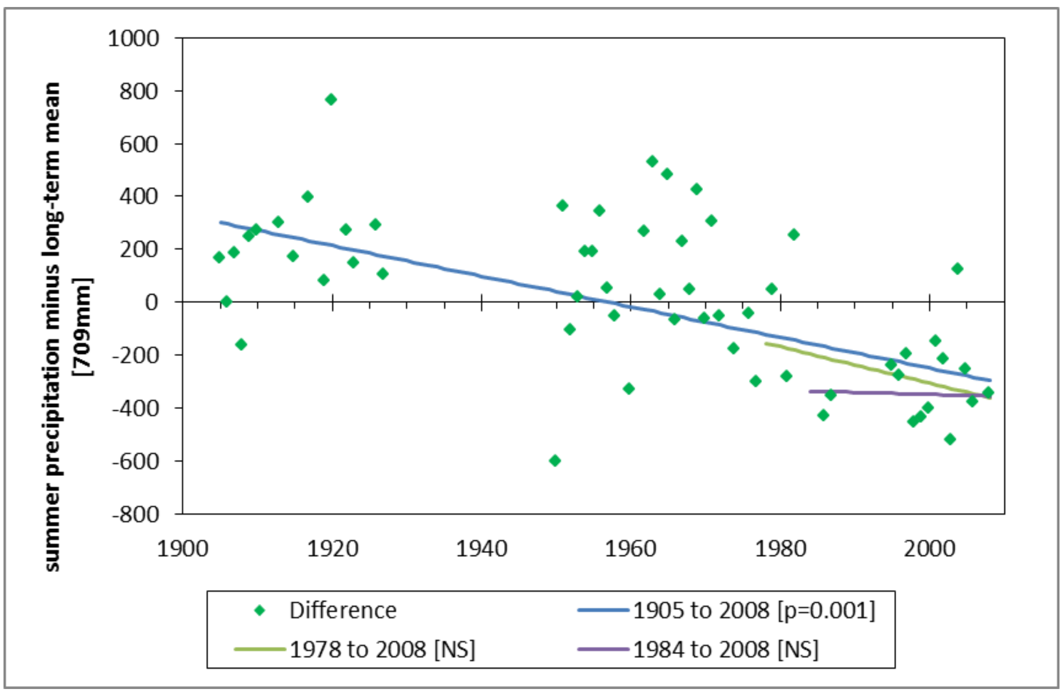

Figure D.4 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (709mm) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1905 to 2008.

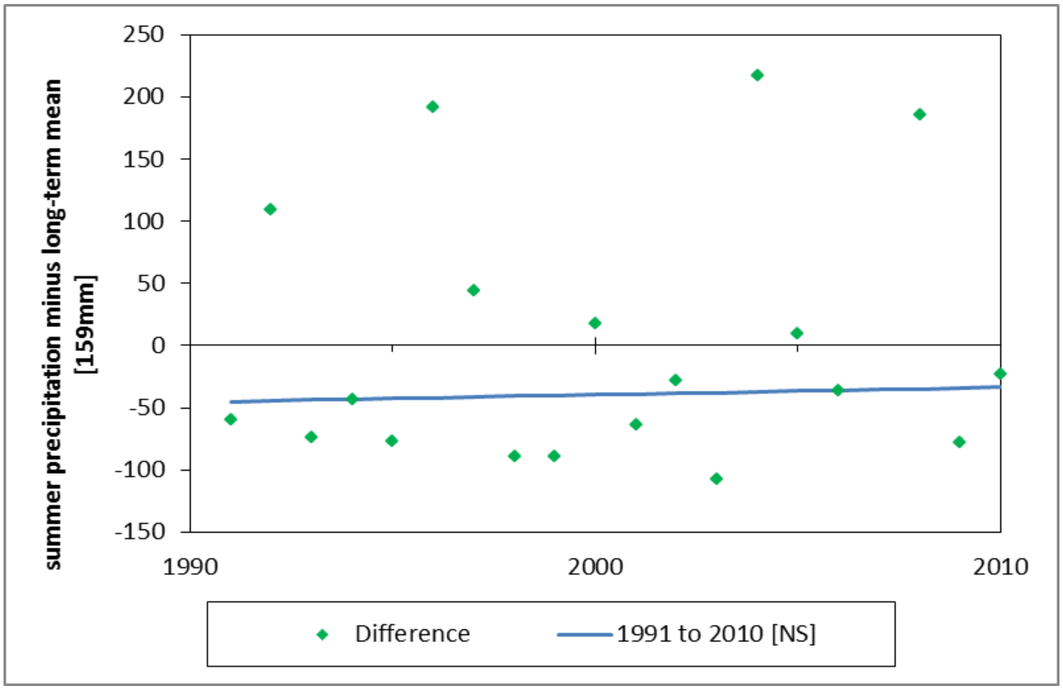

Figure D.5 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (159mm) for the station, Honokohau Harbor 68.14. The zero line represents the mean calculated over the period of record, 1991 to 2010.

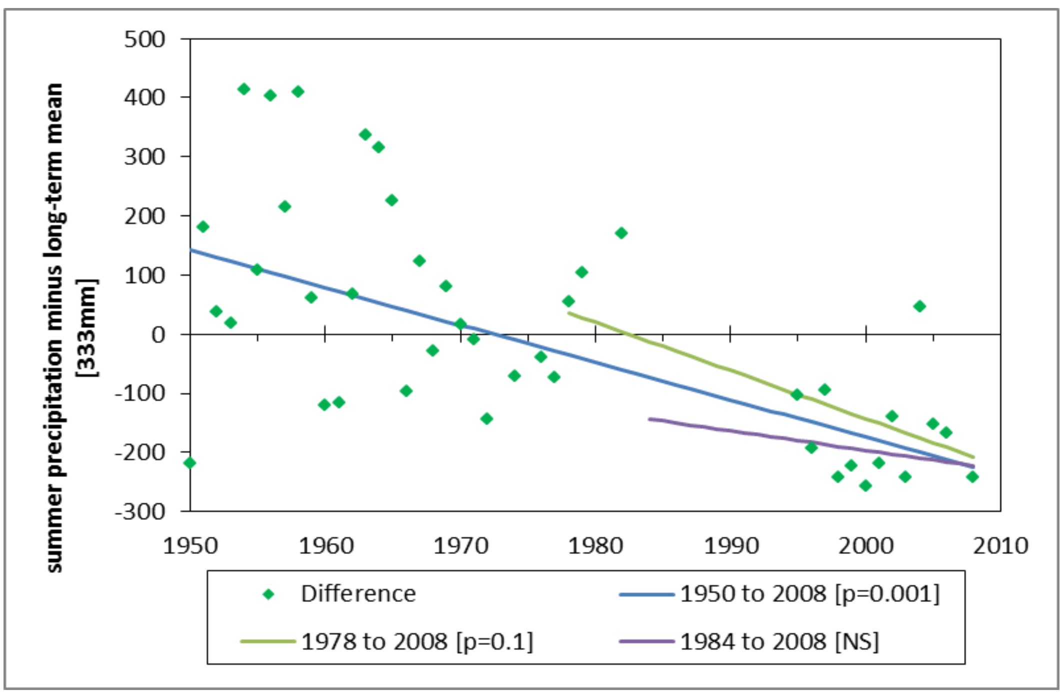

Figure D.6 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (333mm) for the station, Honuaula 71. The zero line represents the mean calculated over the period of record, 1950 to 2008.

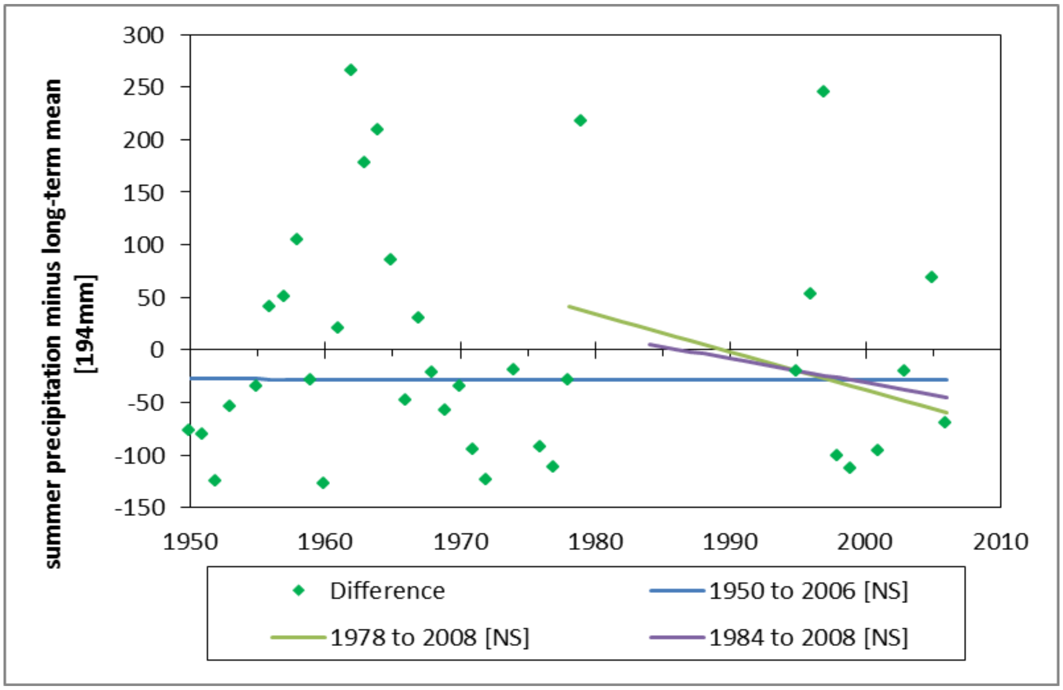

Figure D.7 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (194mm) for the station, Hualalai 72. The zero line represents the mean calculated over the period of record, 1950 to 2006.

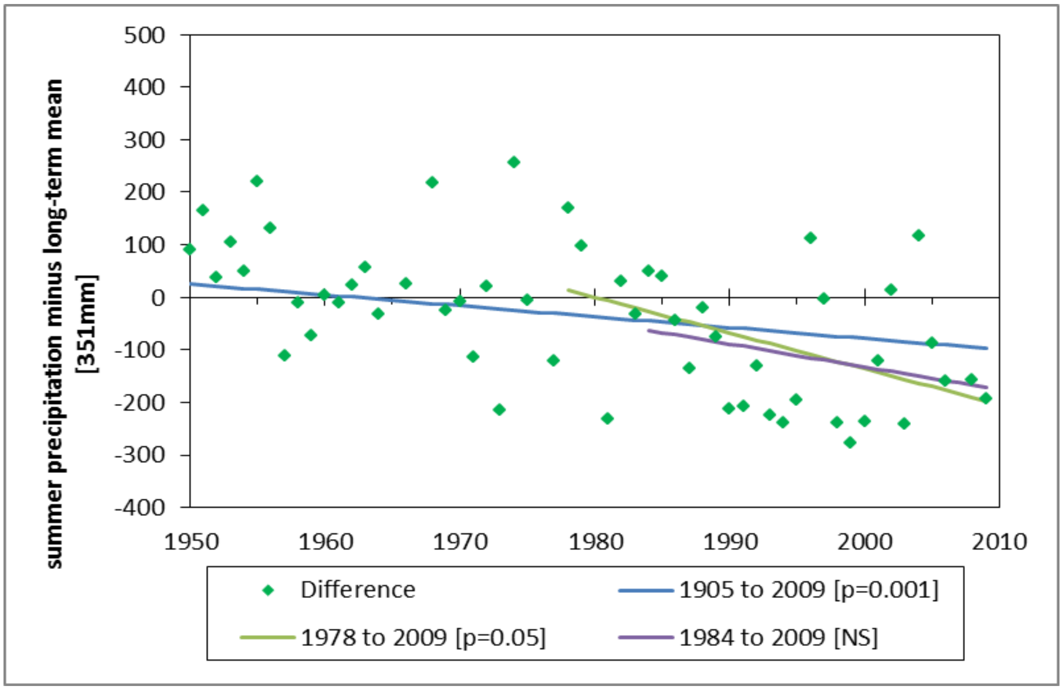

Figure D.8 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (351mm) for the station, Huehue 92.1. The zero line represents the mean calculated over the period of record, 1905 to 2009.

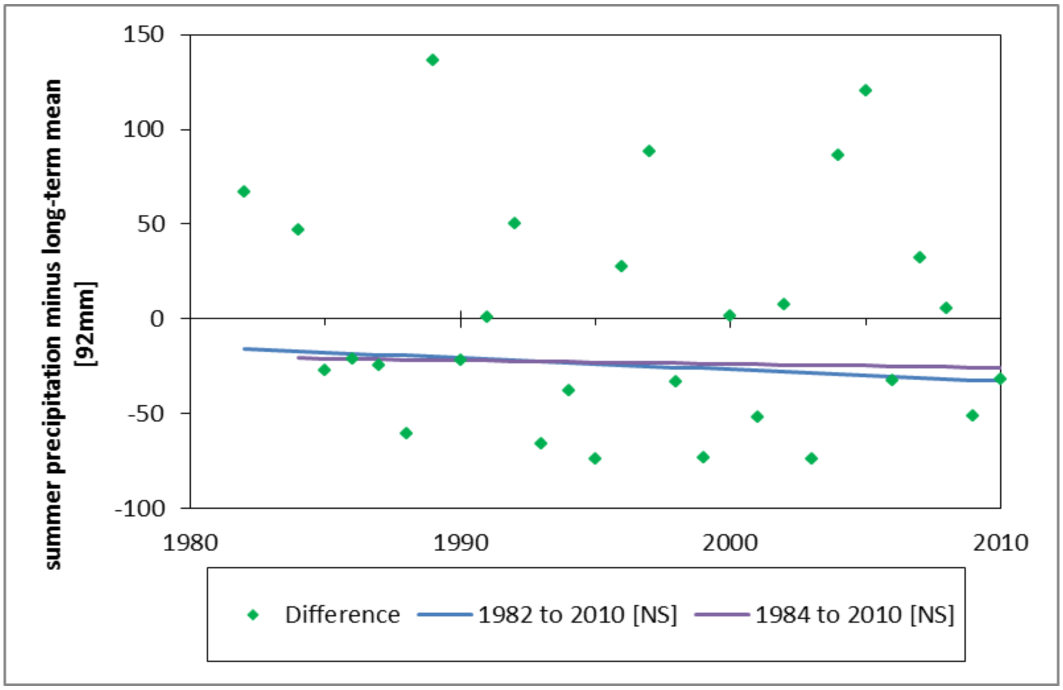

Figure D.9 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (92mm) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1982 to 2010.

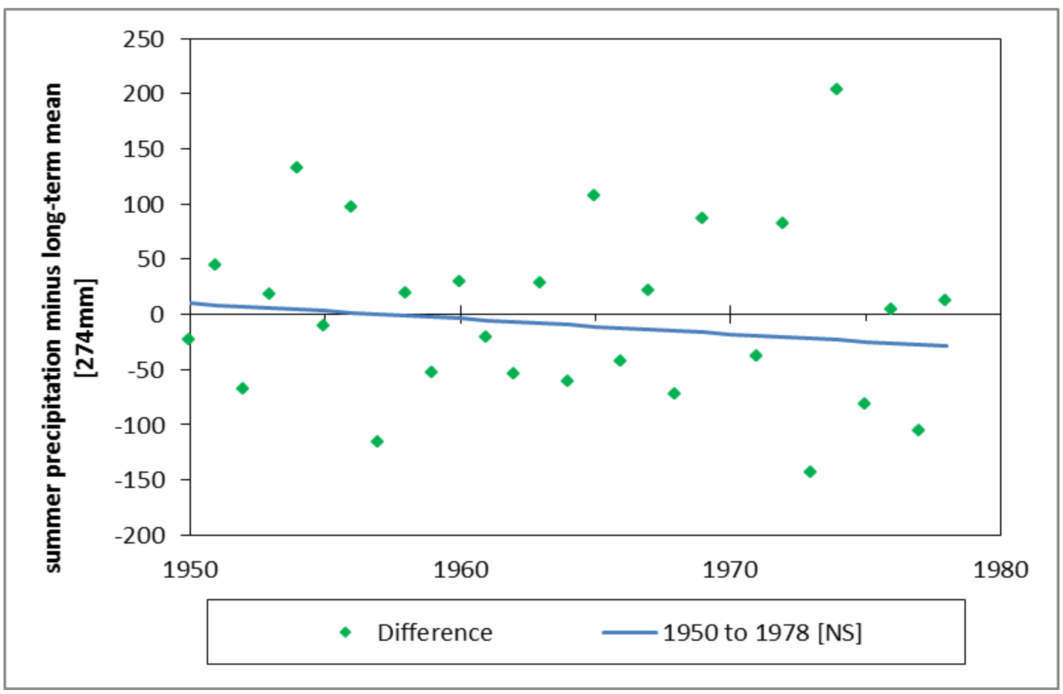

Figure D.10 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (274mm) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1978.

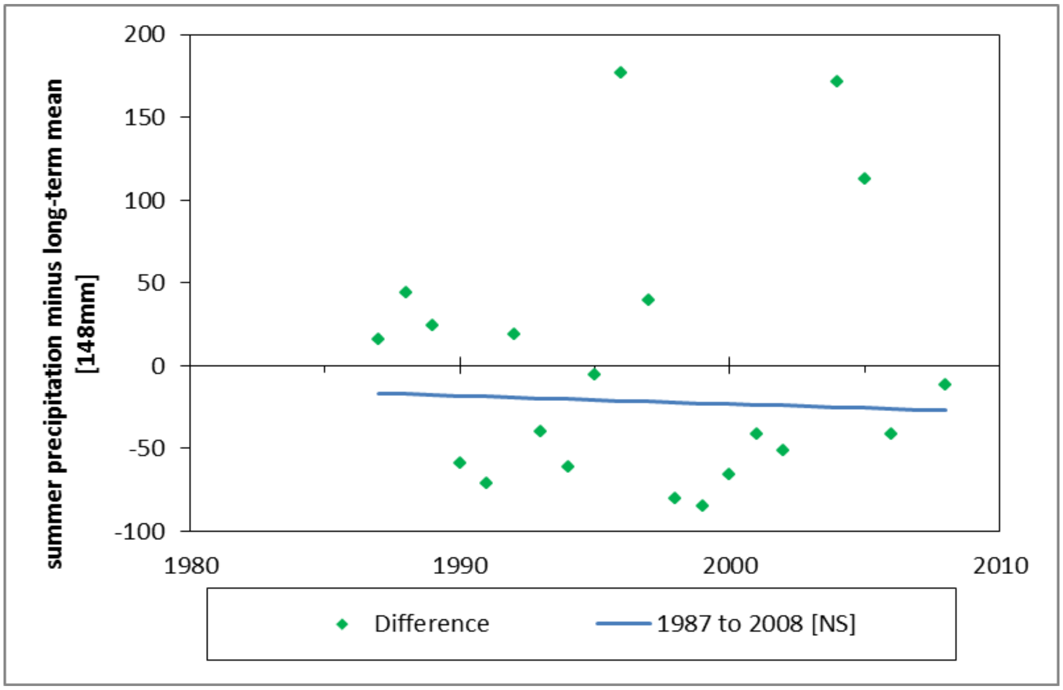

Figure D.11 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (148mm) for the station, Mahaiula 92.7. The zero line represents the mean calculated over the period of record, 1987 to 2008.

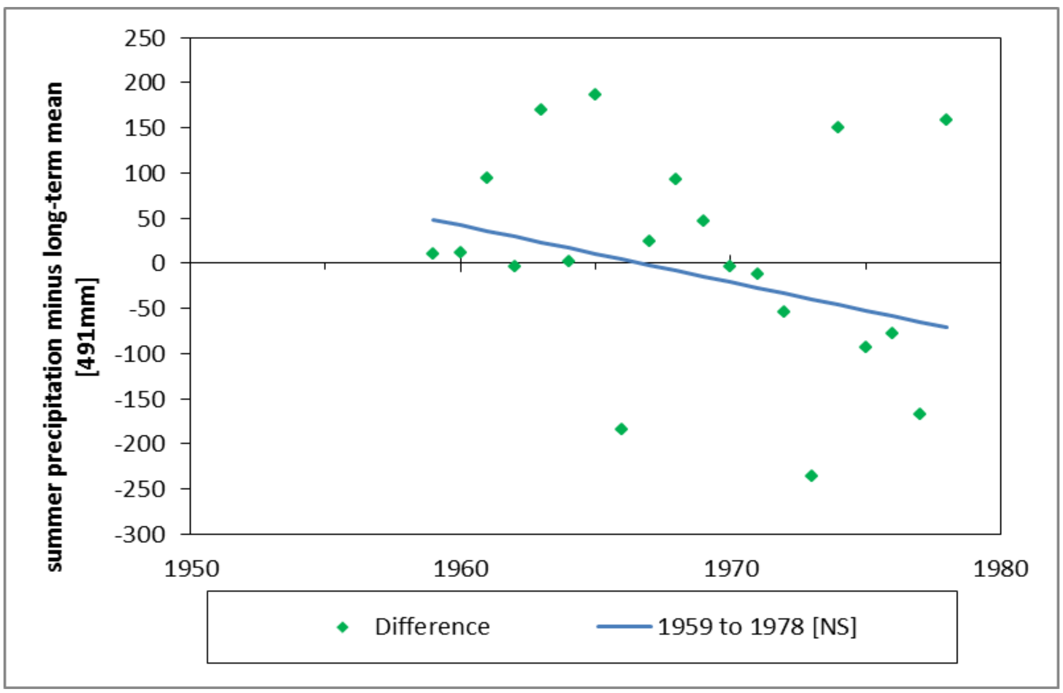

Figure D.12 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (491mm) for the station, Middle Holualoa 68.1. The zero line represents the mean calculated over the period of record, 1959 to 1978.

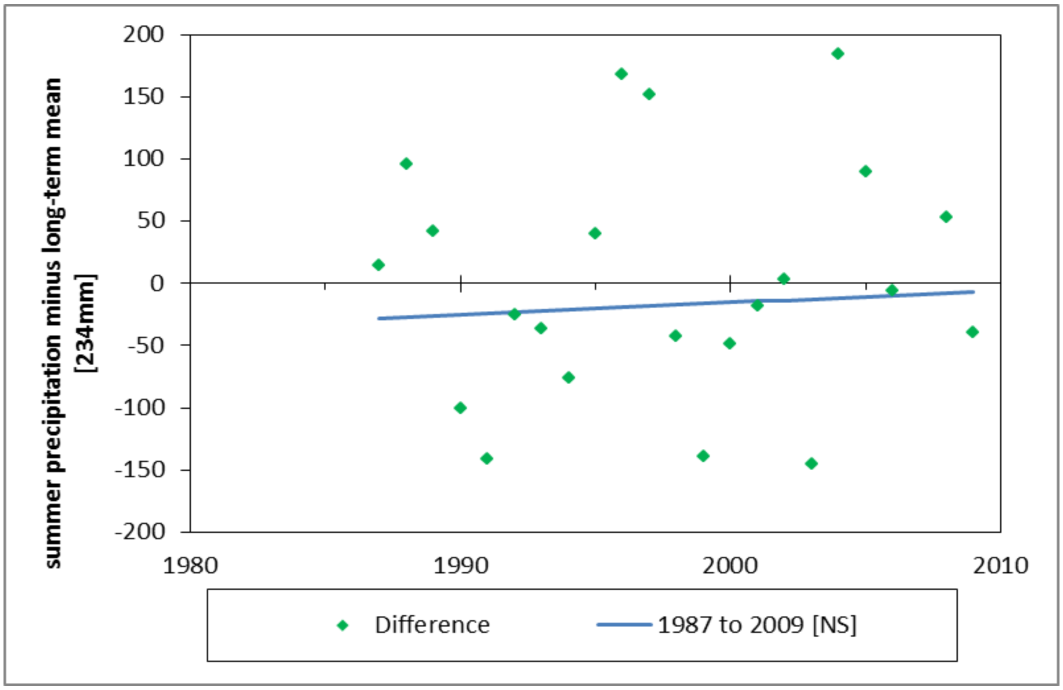

Figure D.13 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (234mm) for the station, Moanuiahea 69.24. The zero line represents the mean calculated over the period of record, 1987 to 2009.

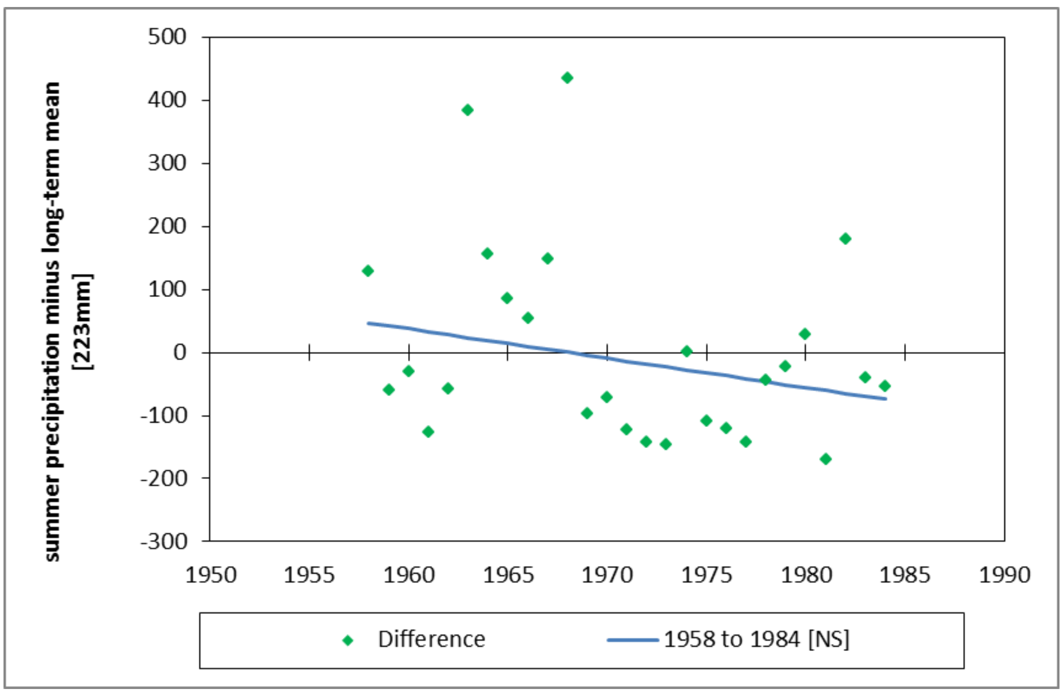

Figure D.14 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (223mm) for the station, Ahua Umi 75. The zero line represents the mean calculated over the period of record, 1958 to 1984.

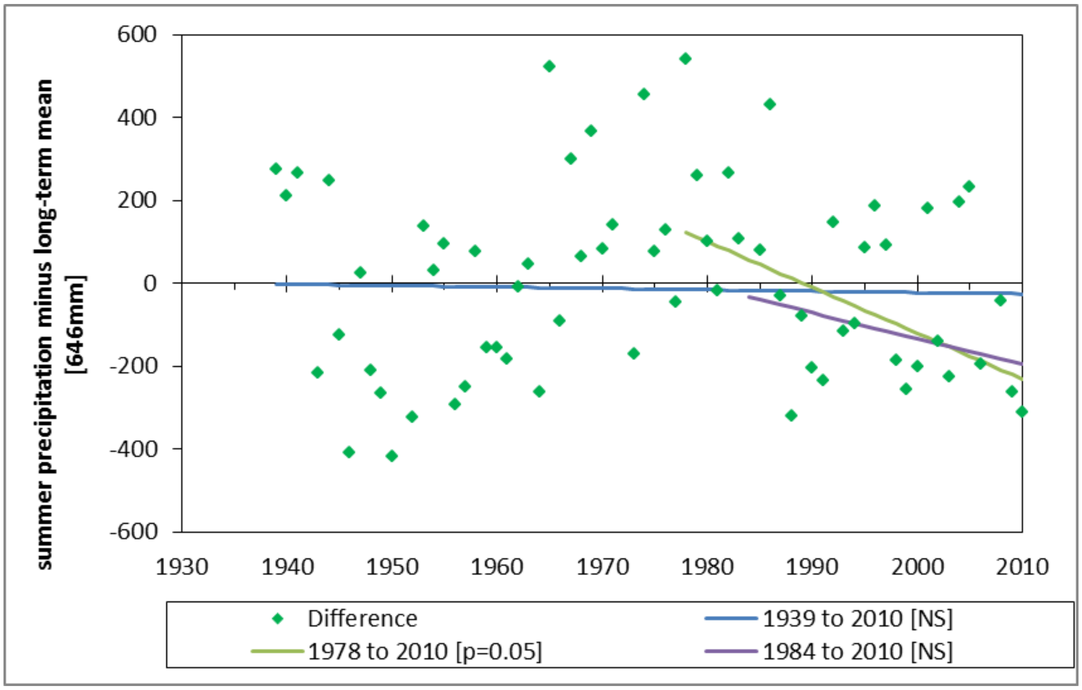

Figure D.15 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (646mm) for the station, Honaunau 27. The zero line represents the mean calculated over the period of record, 1939 to 2010.

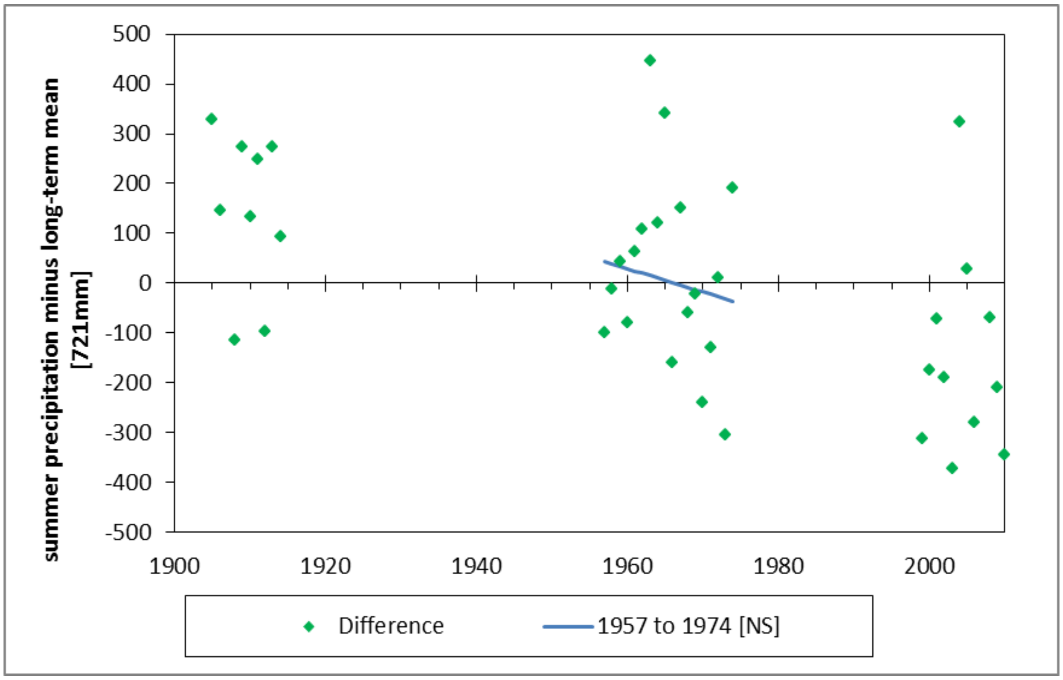

Figure D.16 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (721mm) for the station, Kealakekua 26.2. The zero line represents the mean calculated over the period of record, 1905 to 2010.

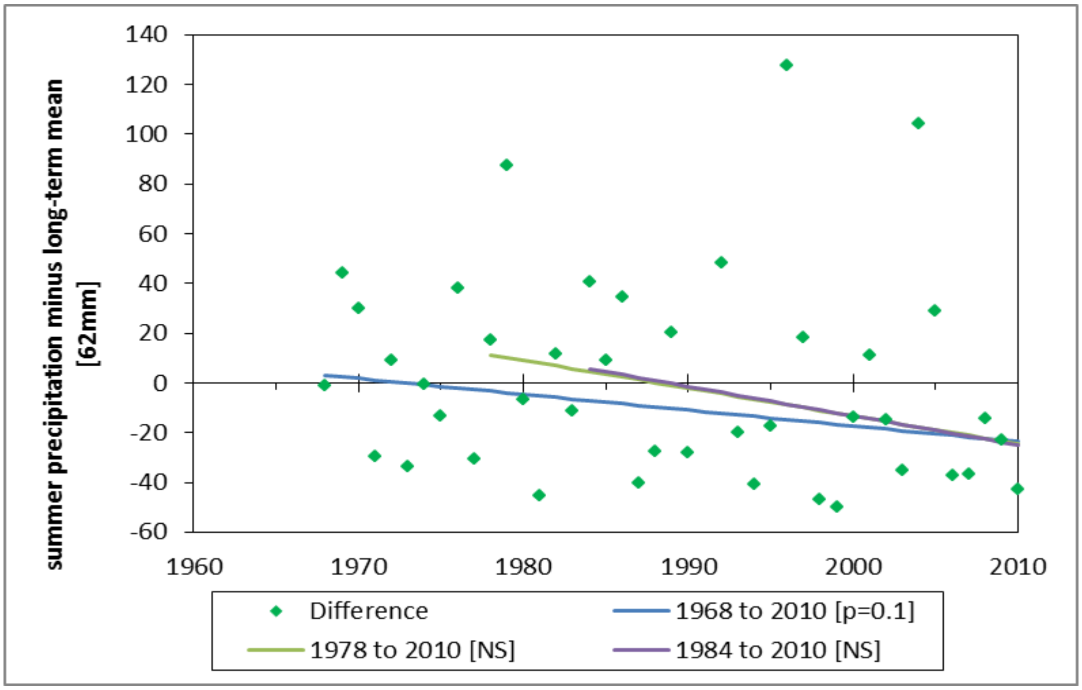

Figure D.17 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (62mm) for the station, Kona Village 93.8. The zero line represents the mean calculated over the period of record, 1968 to 2010.

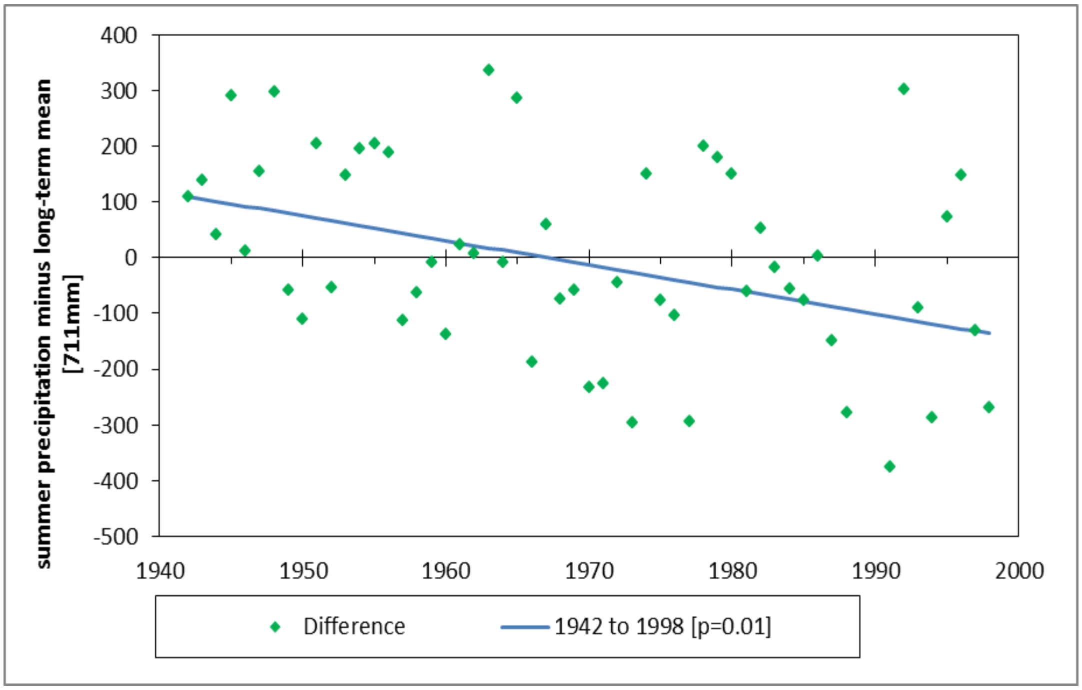

Figure D.18 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (711mm) for the station, Kaawaloa 29. The zero line represents the mean calculated over the period of record, 1942 to 1998.

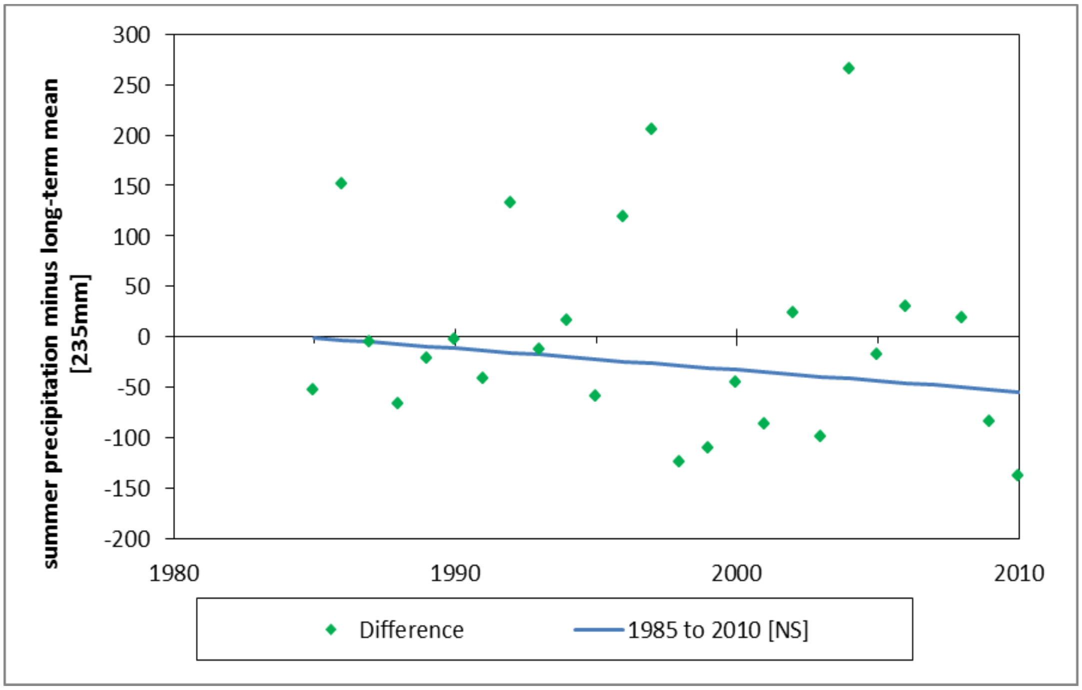

Figure D.19 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (235mm) for the station, Milolii 2.34. The zero line represents the mean calculated over the period of record, 1985 to 2010.

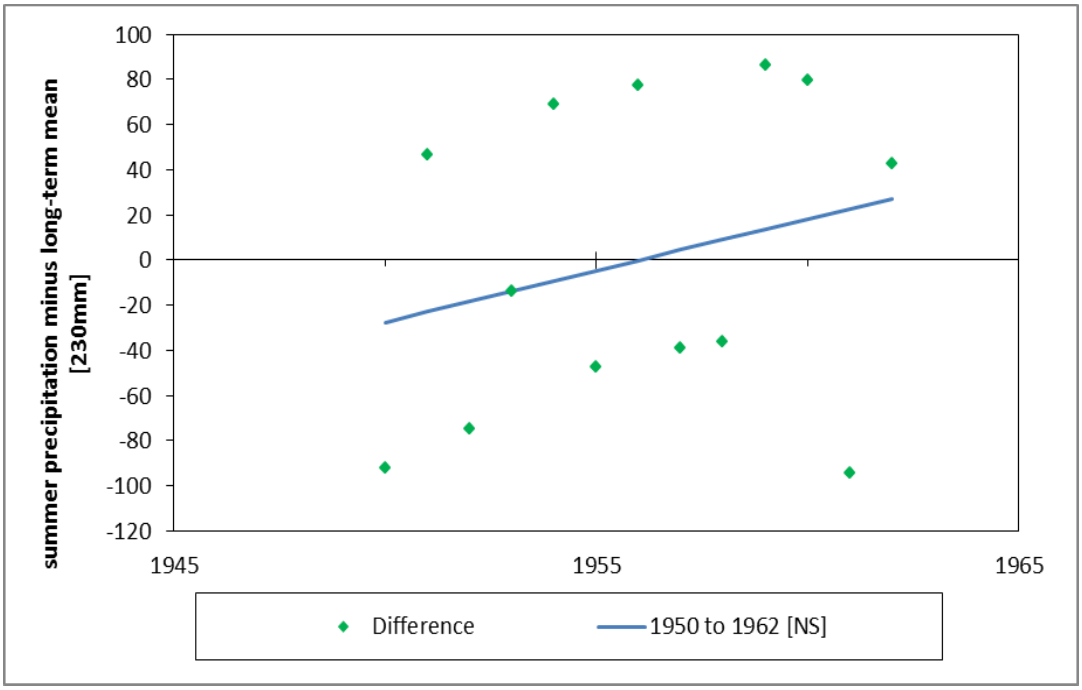

Figure D.20 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (230mm) for the station, Puu Anahulu 93a. The zero line represents the mean calculated over the period of record, 1950 to 1962.

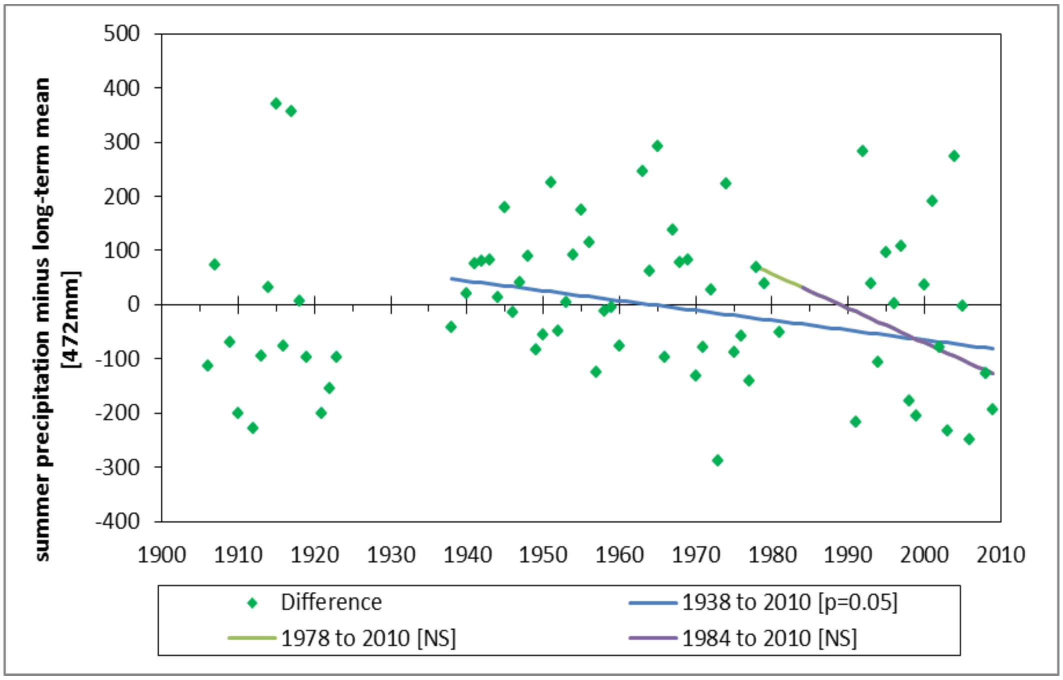

Figure D.21 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (472mm) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1938 to 2010.

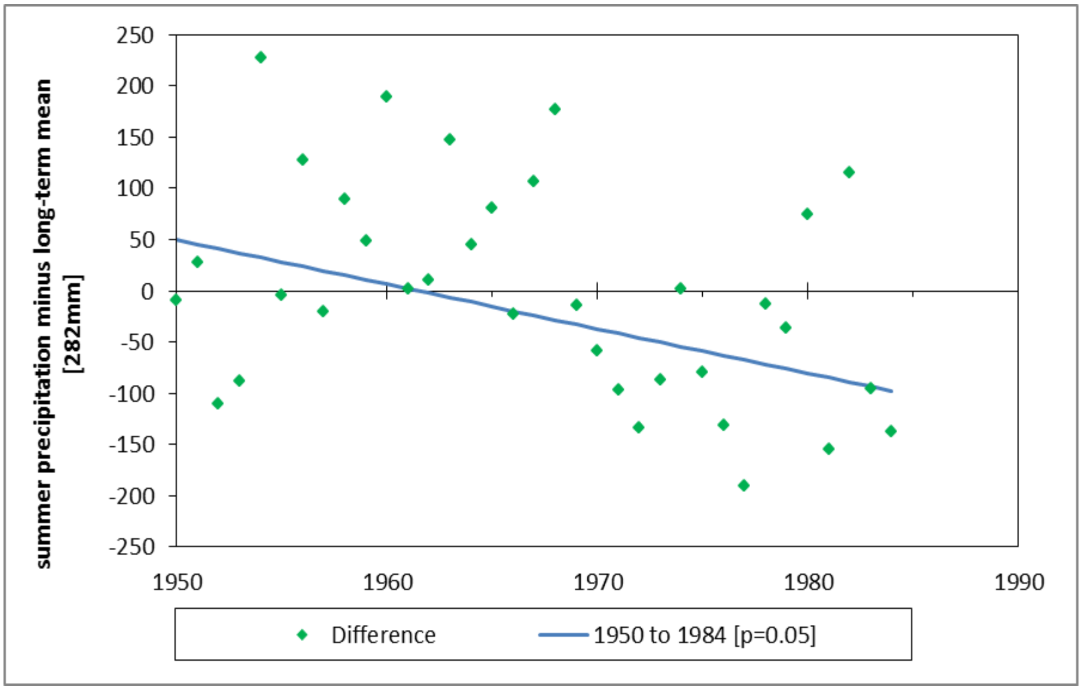

Figure D.22 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (282mm) for the station, Puu Lehua 73. The zero line represents the mean calculated over the period of record, 1950 to 1984.

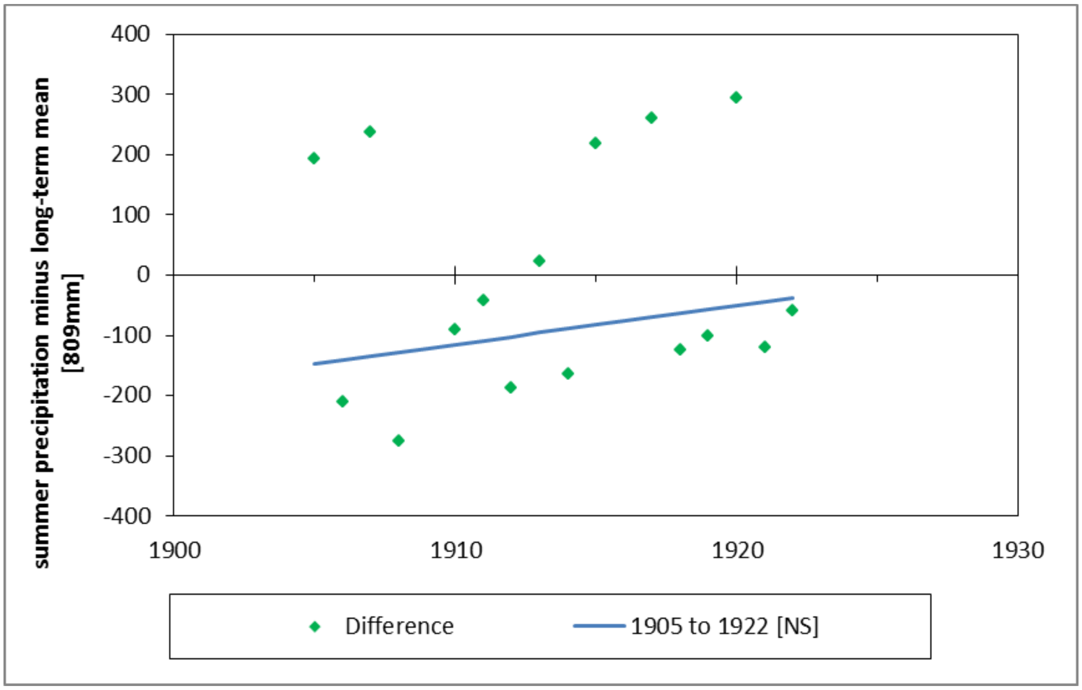

Figure D.23 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (809mm) for the station, Kealakekua 2 28.7. The zero line represents the mean calculated over the period of record, 1905 to 1922.

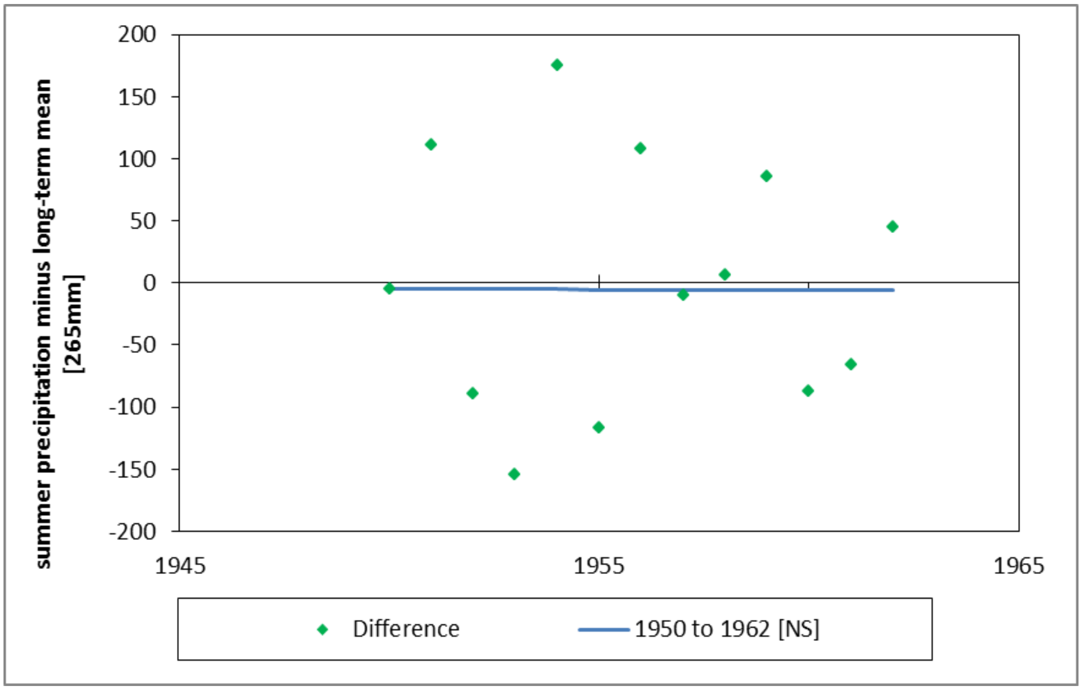

Figure D.24 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (265mm) for the station, Kanahaha 74. The zero line represents the mean calculated over the period of record, 1950 to 1962.

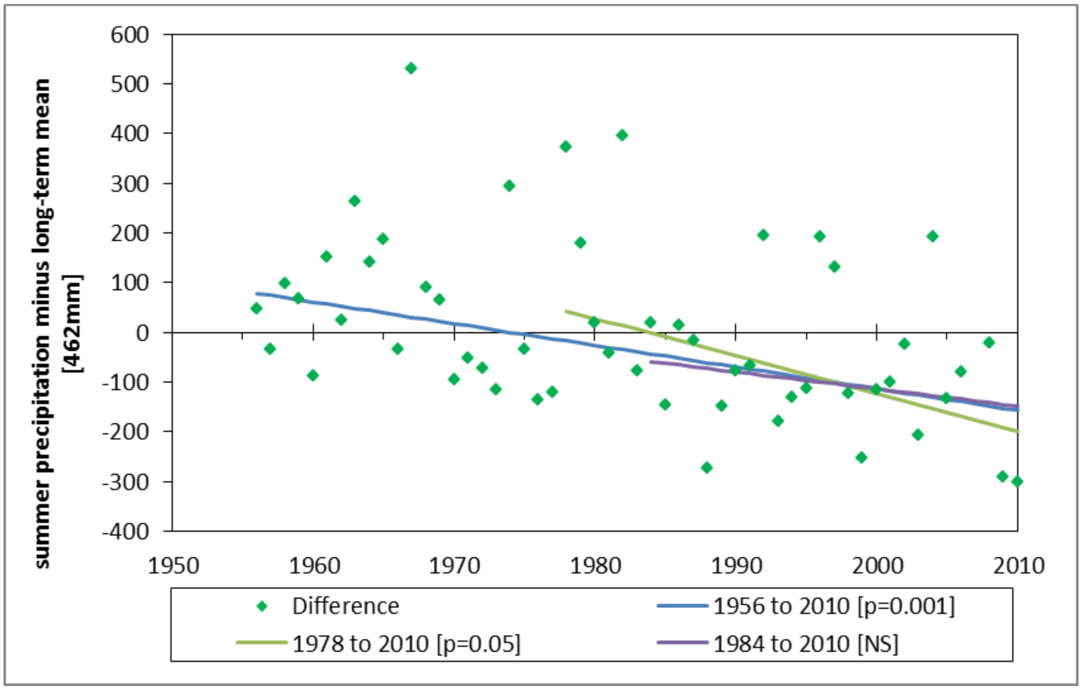

Figure D.25 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (462mm) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1956 to 2010.

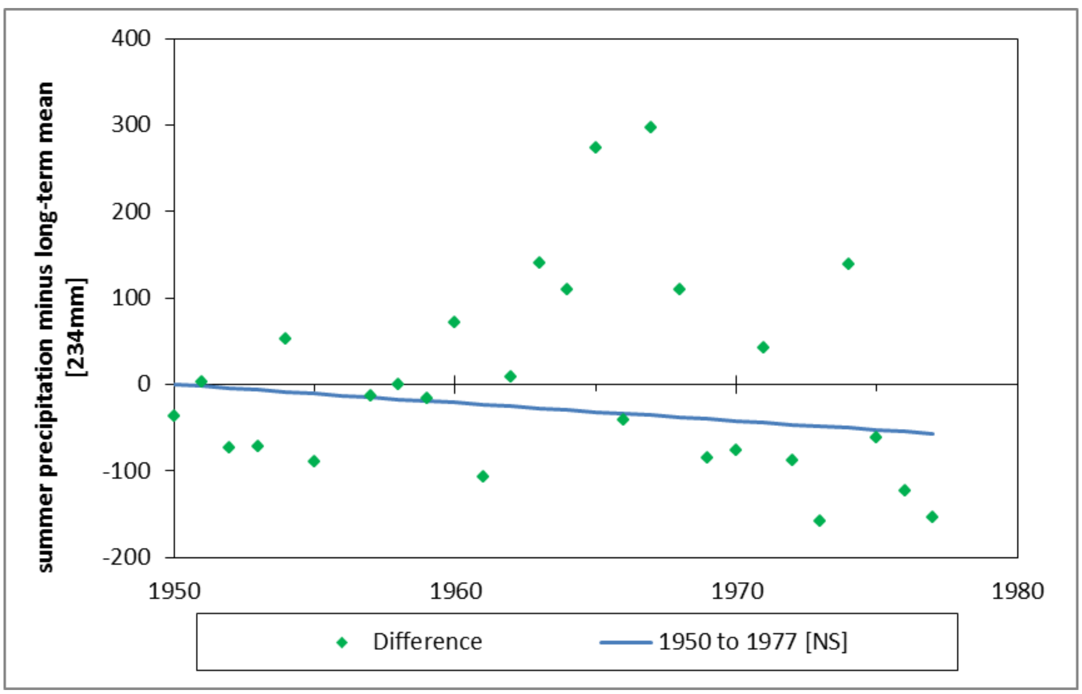

Figure D.26 Trend results from the Mann-Kendall tests and summer precipitation differences when compared to the mean (234mm) for the station, Puu Waawaa 94.1. The zero line represents the mean calculated over the period of record, 1950 to 1977.

APPENDIX E: WINTER MANN-KENDALL TREND TEST RESULTS

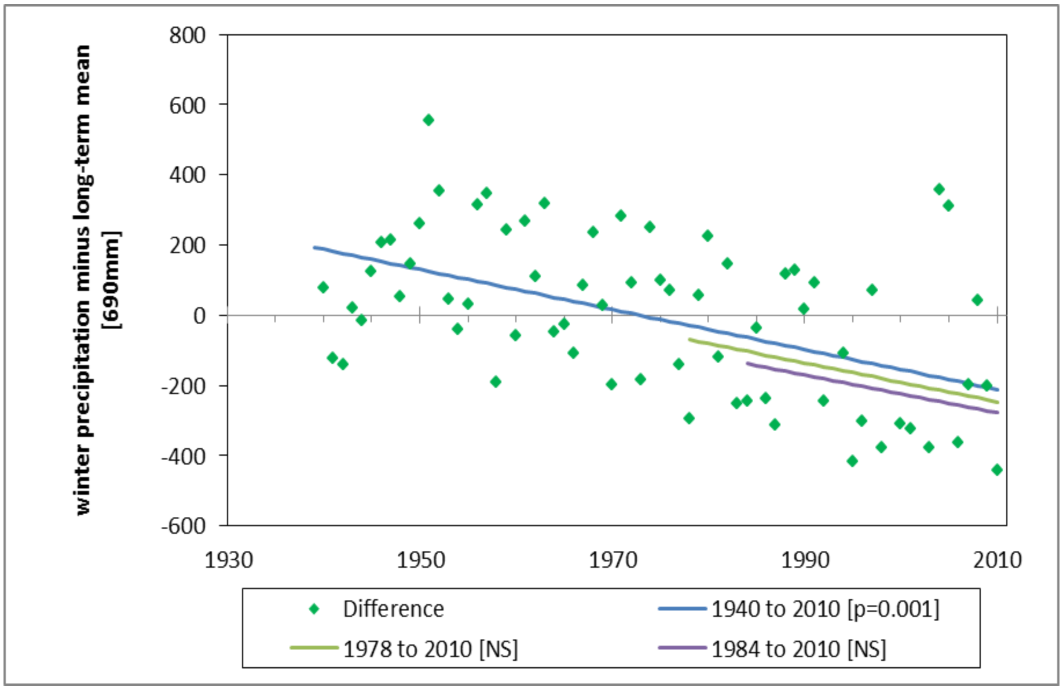

Figure E.1 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (690mm) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1940 to 2010.

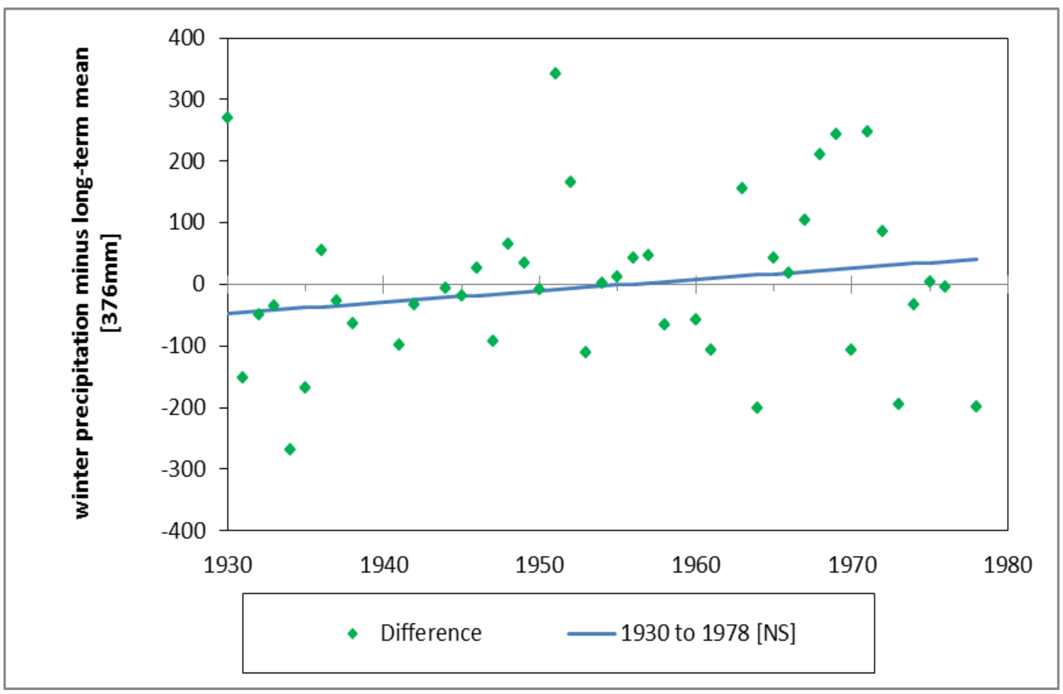

Figure E.2 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (376mm) for the station, Holualoa Beach 68. The zero line represents the mean calculated over the period of record, 1930 to 1978.

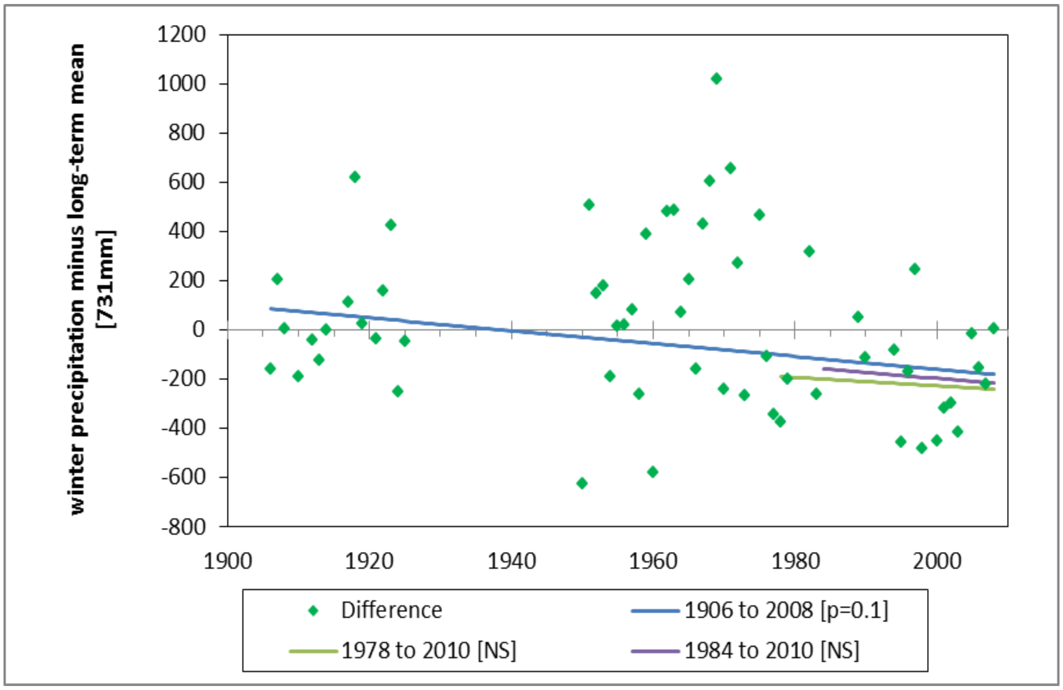

Figure E.3 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (731mm) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1906 to 2008.

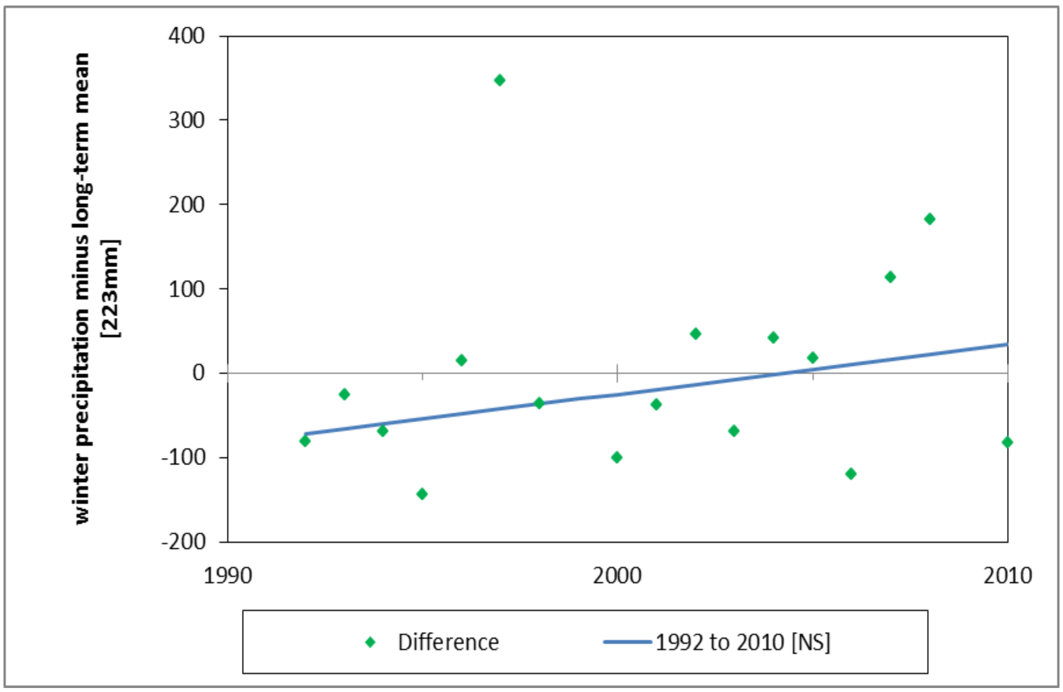

Figure E.4 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (223mm) for the station, Honokohau Harbor 68.14. The zero line represents the mean calculated over the period of record, 1992 to 2010.

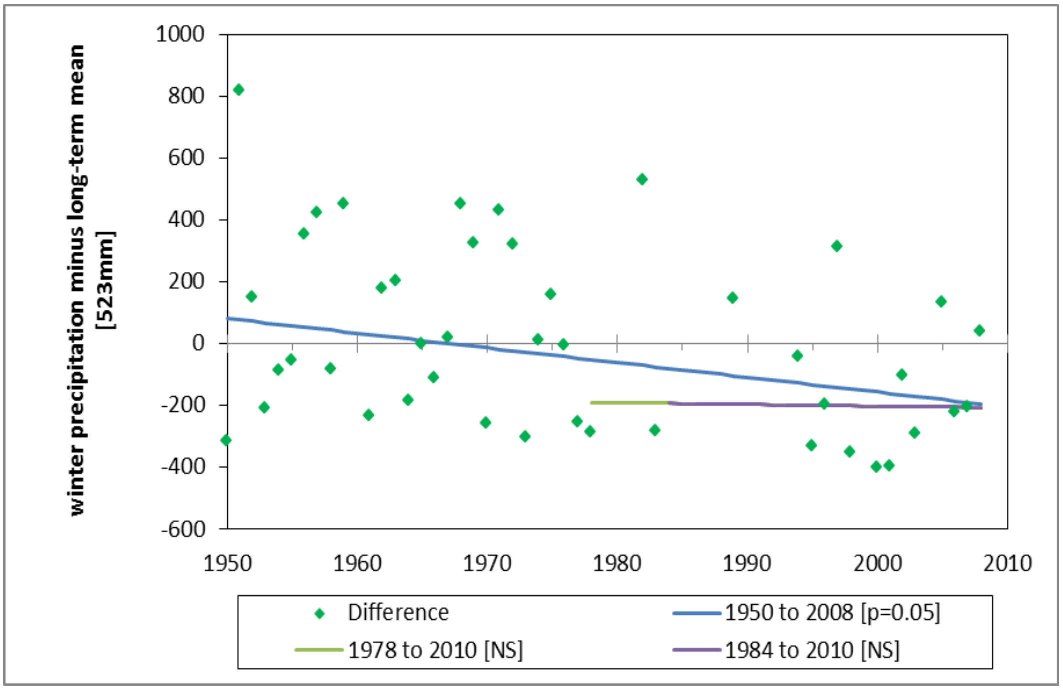

Figure E.5 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (523mm) for the station, Honuaula 71. The zero line represents the mean calculated over the period of record, 1950 to 2008.

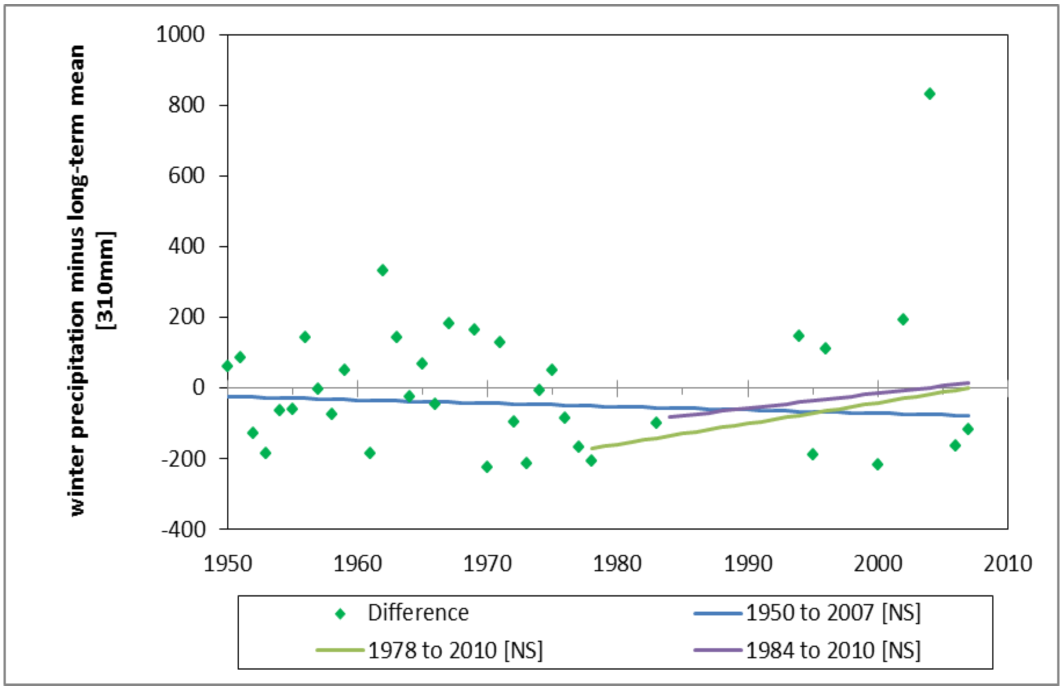

Figure E.6 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (310mm) for the station, Hualalai 72. The zero line represents the mean calculated over the period of record, 1950 to 2007.

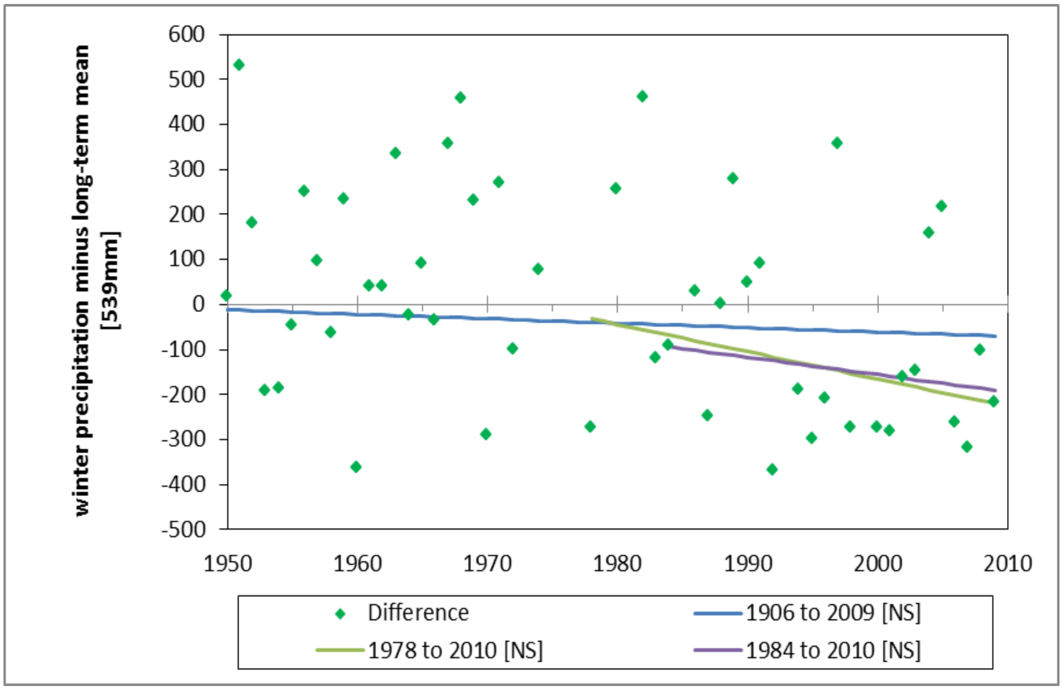

Figure E.7 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (539mm) for the station, Huehue 92.1. The zero line represents the mean calculated over the period of record, 1906 to 2009.

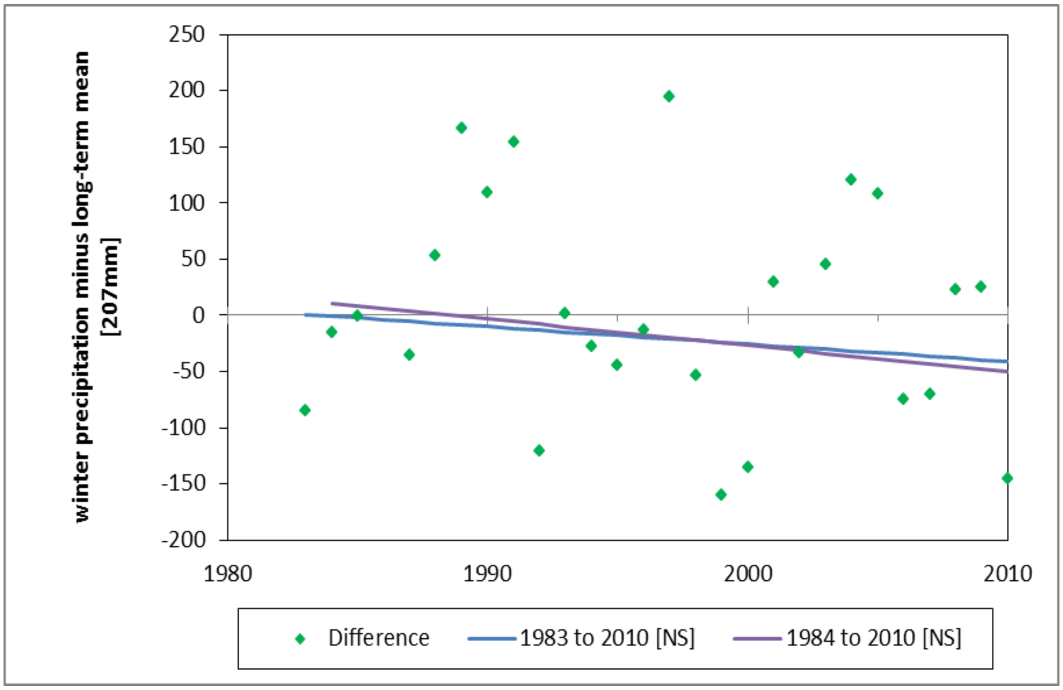

Figure E.8 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (207mm) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1983 to 2010.

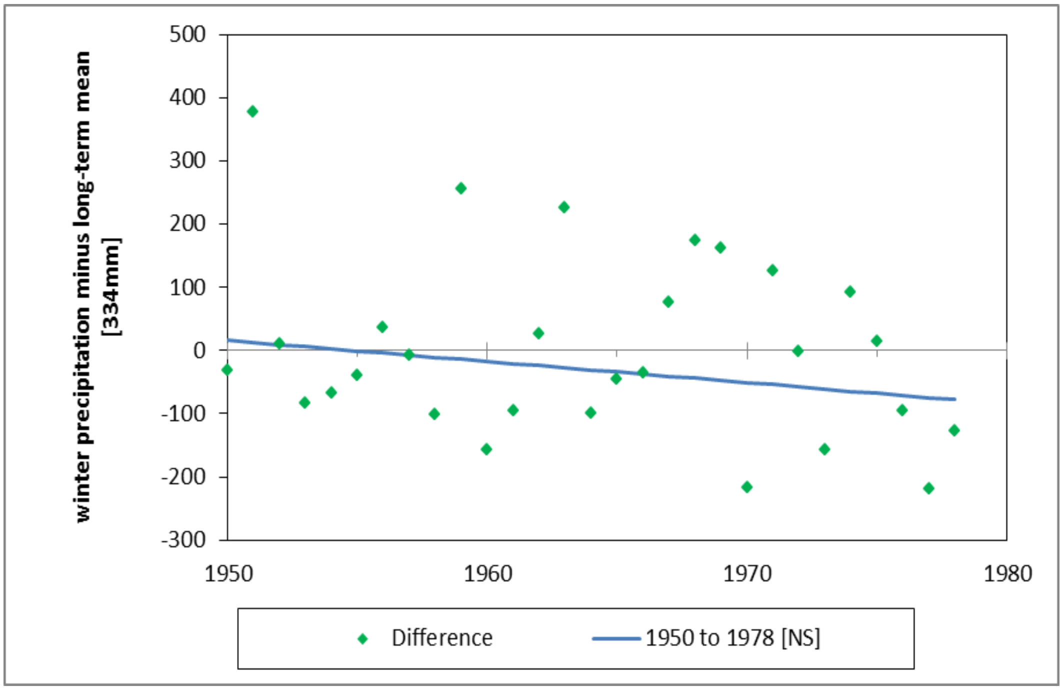

Figure E.9 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (334mm) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1978.

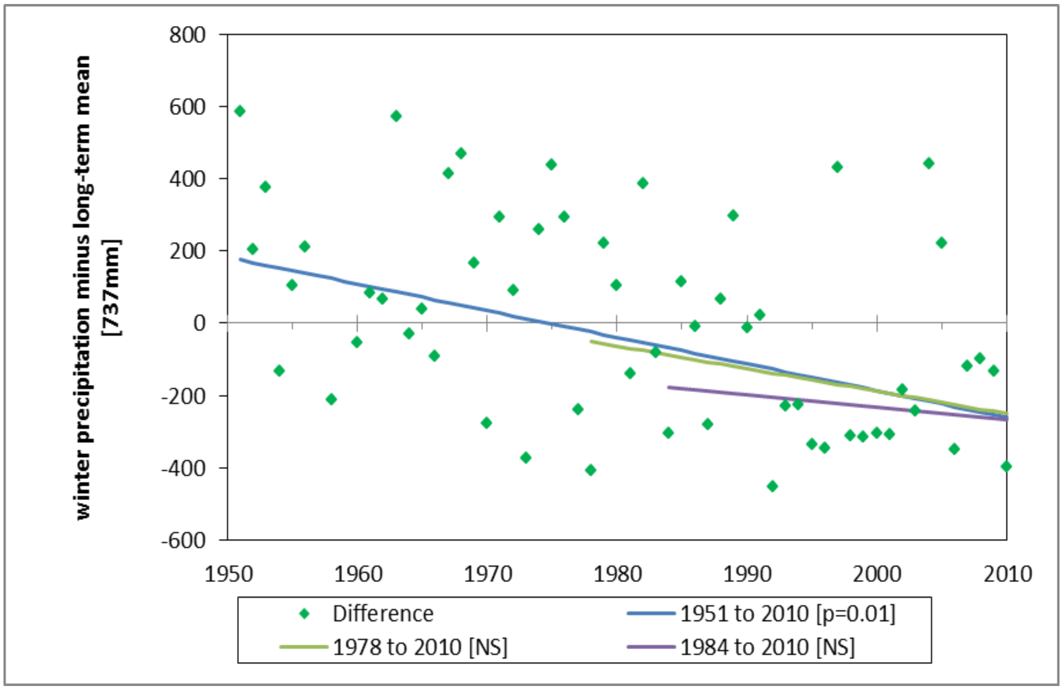

Figure E.10 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (737mm) for the station, Lanihau 68.2. The zero line represents the mean calculated over the period of record, 1951 to 2010.

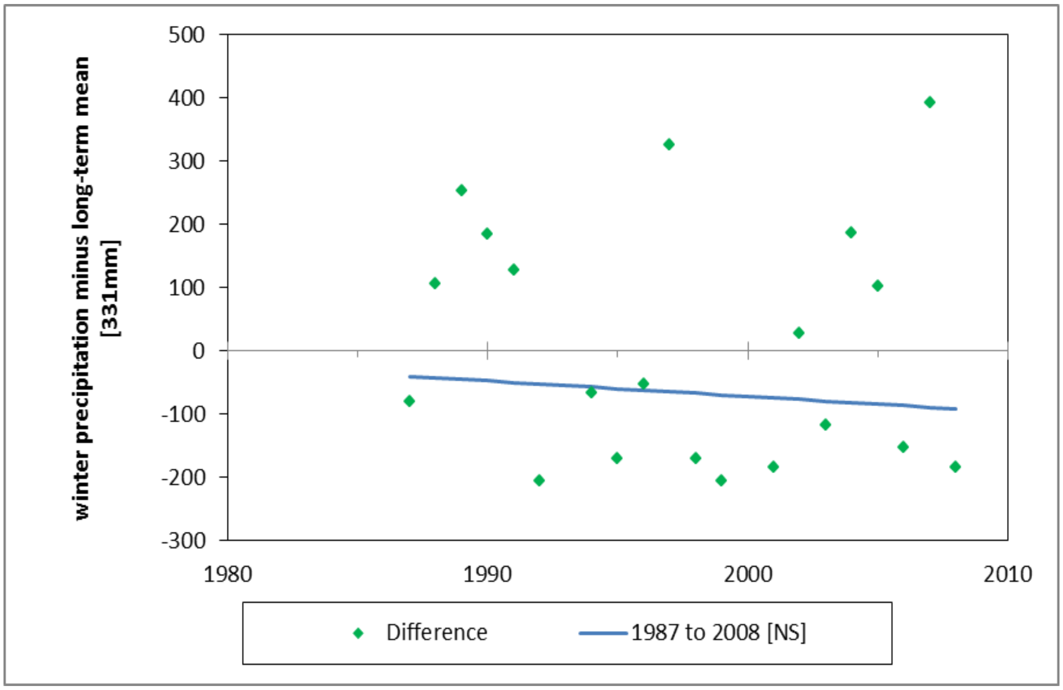

Figure E.11 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (331mm) for the station, Mahaiula 92.7. The zero line represents the mean calculated over the period of record, 1987 to 2008.

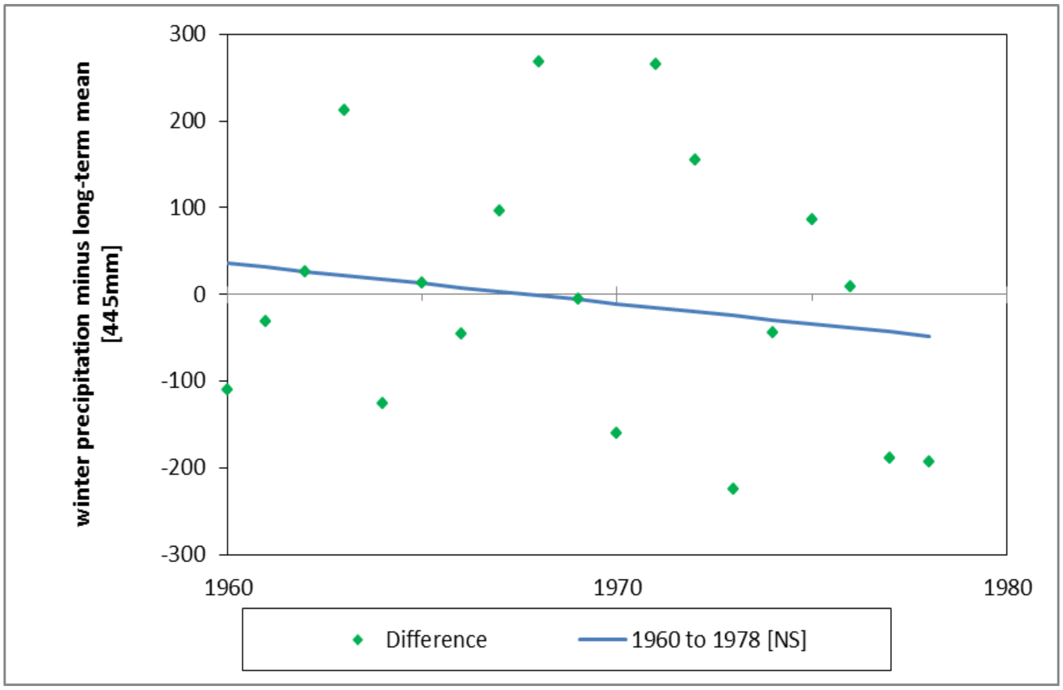

Figure E.12 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (445mm) for the station, Middle Holualoa 68.1. The zero line represents the mean calculated over the period of record, 1960 to 1978.

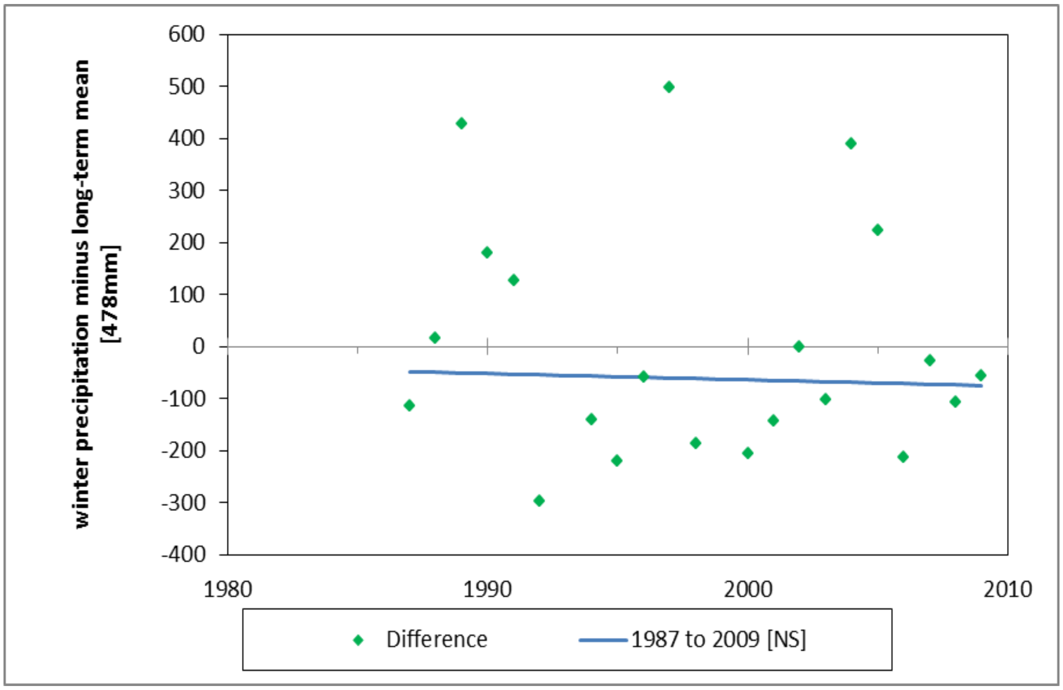

Figure E.13 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (478mm) for the station, Moanuiahea 69.24. The zero line represents the mean calculated over the period of record, 1987 to 2009.

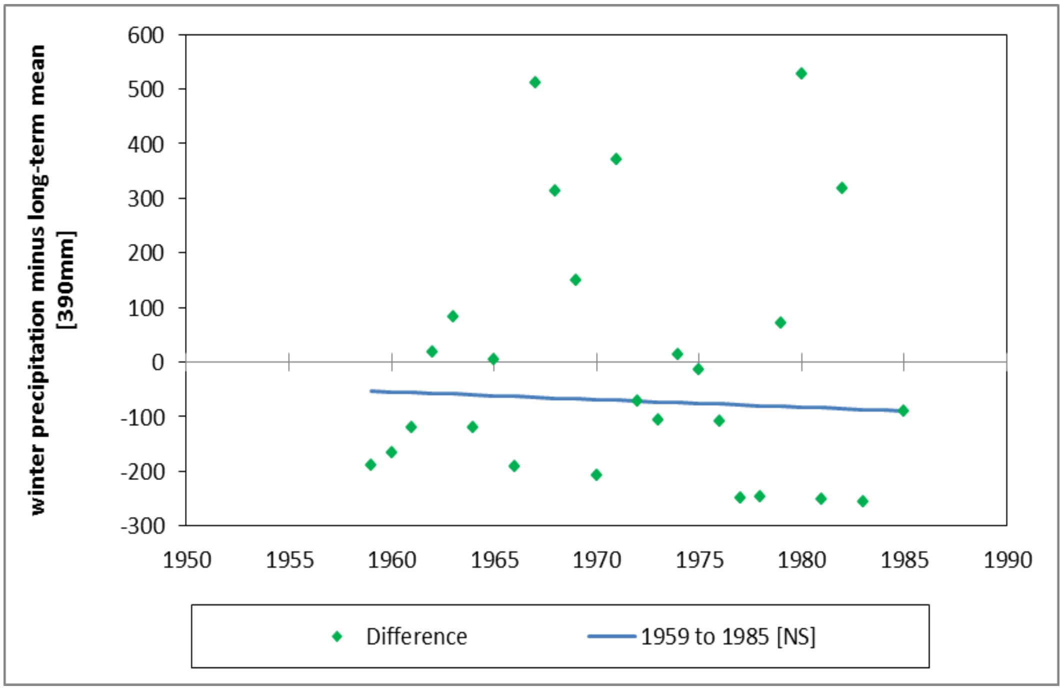

Figure E.14 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (390mm) for the station, Ahua Umi 75. The zero line represents the mean calculated over the period of record, 1959 to 1985.

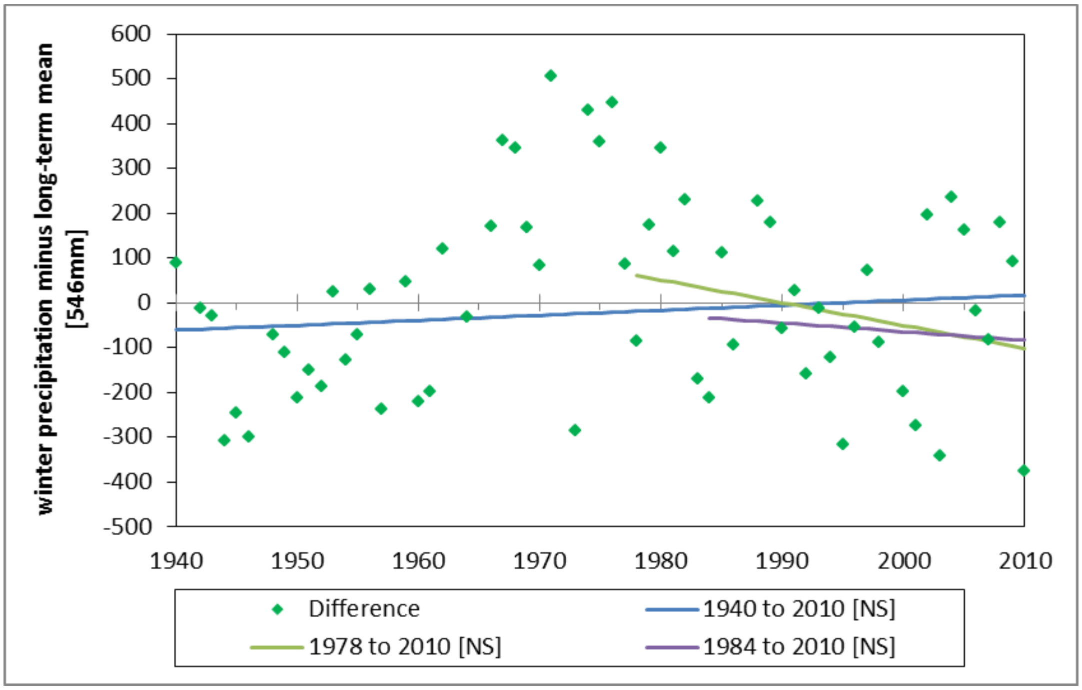

Figure E.15 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (546mm) for the station, Honaunau 27. The zero line represents the mean calculated over the period of record, 1940 to 2010.

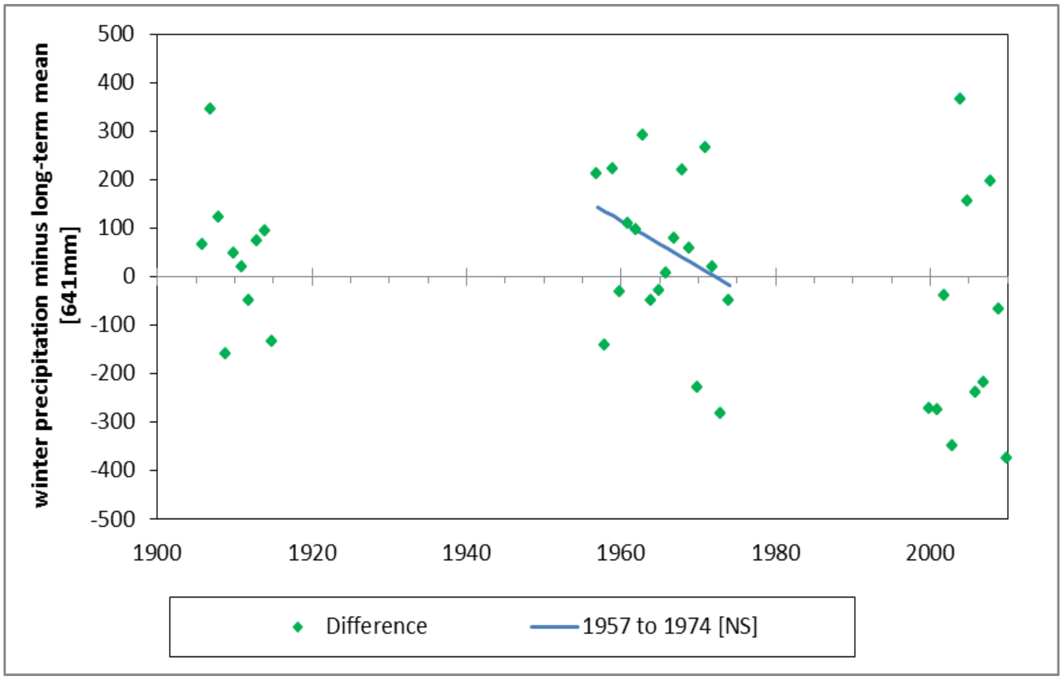

Figure E.16 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (641mm) for the station, Kealakekua 26.2. The zero line represents the mean calculated over the period of record, 1905 to 2010.

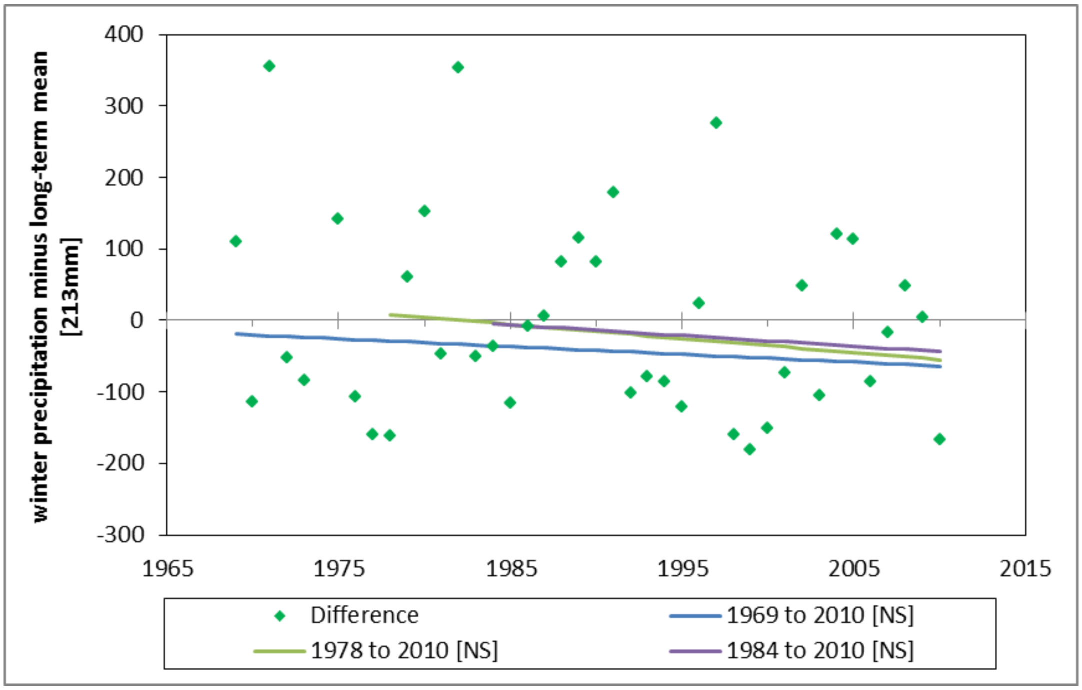

Figure E.17 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (213mm) for the station, Kona Village 93.8. The zero line represents the mean calculated over the period of record, 1969 to 2010.

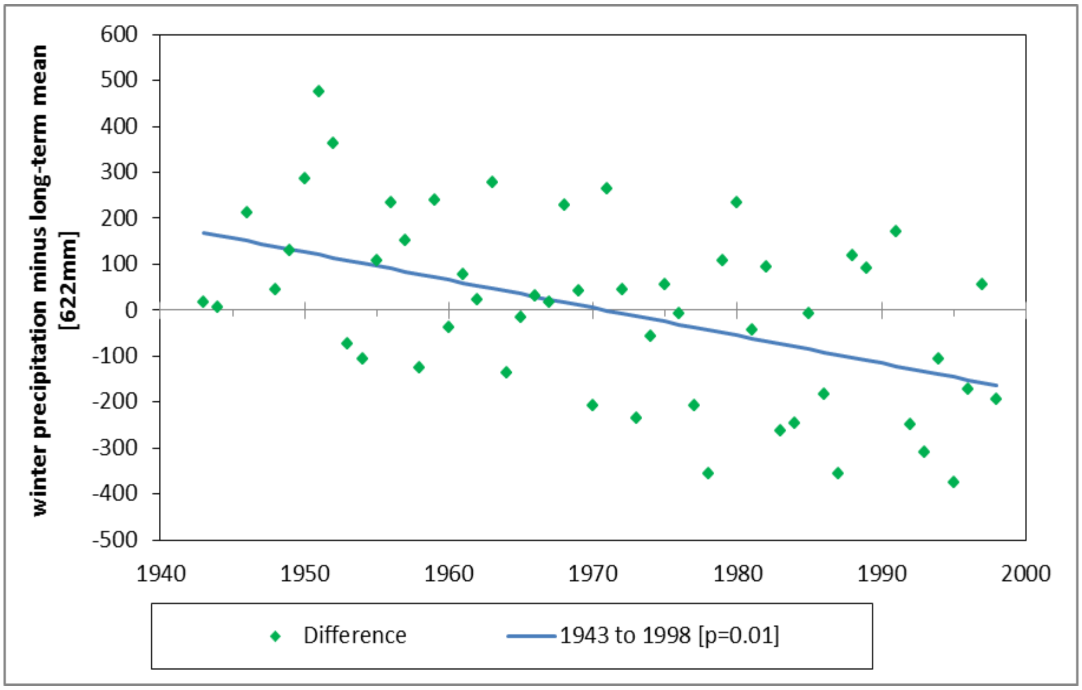

Figure E.18 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (622mm) for the station, Kaawaloa 29. The zero line represents the mean calculated over the period of record, 1943 to 1998.

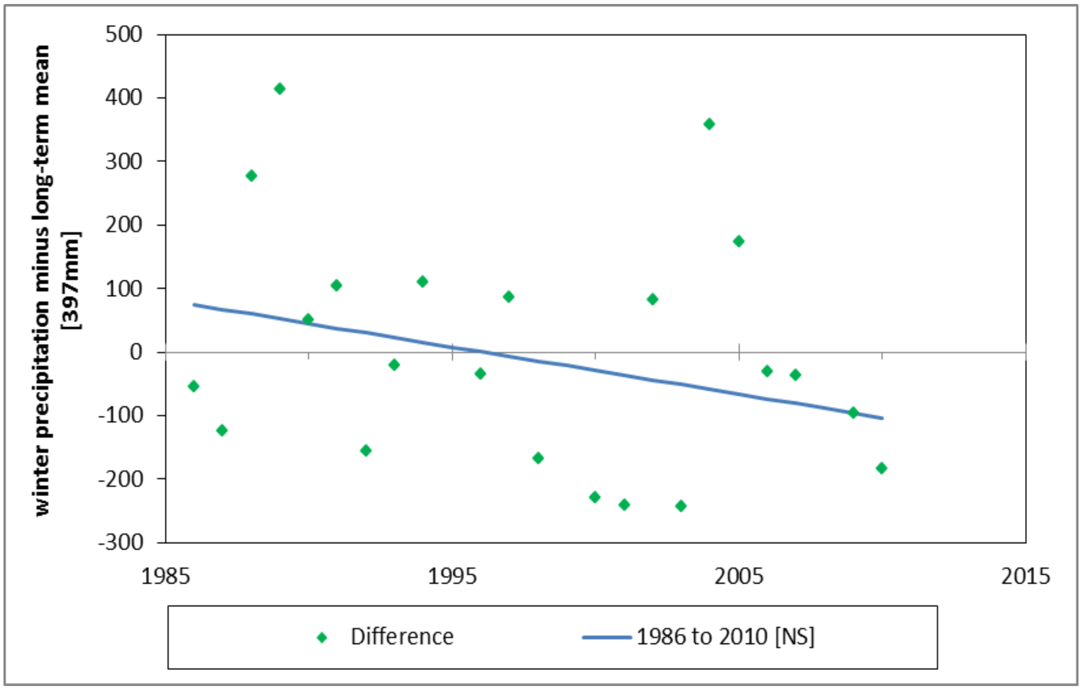

Figure E.19 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (397mm) for the station, Milolii 2.34. The zero line represents the mean calculated over the period of record, 1986 to 2010.

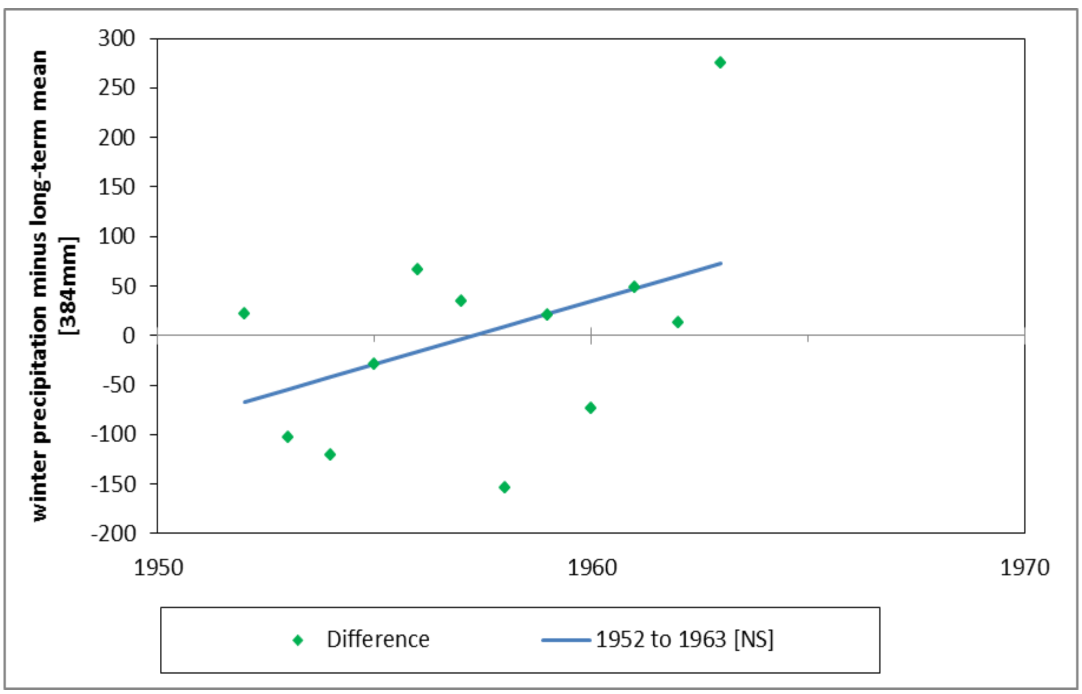

Figure E.20 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (384mm) for the station, Puu Anahulu 93a. The zero line represents the mean calculated over the period of record, 1952 to 1963.

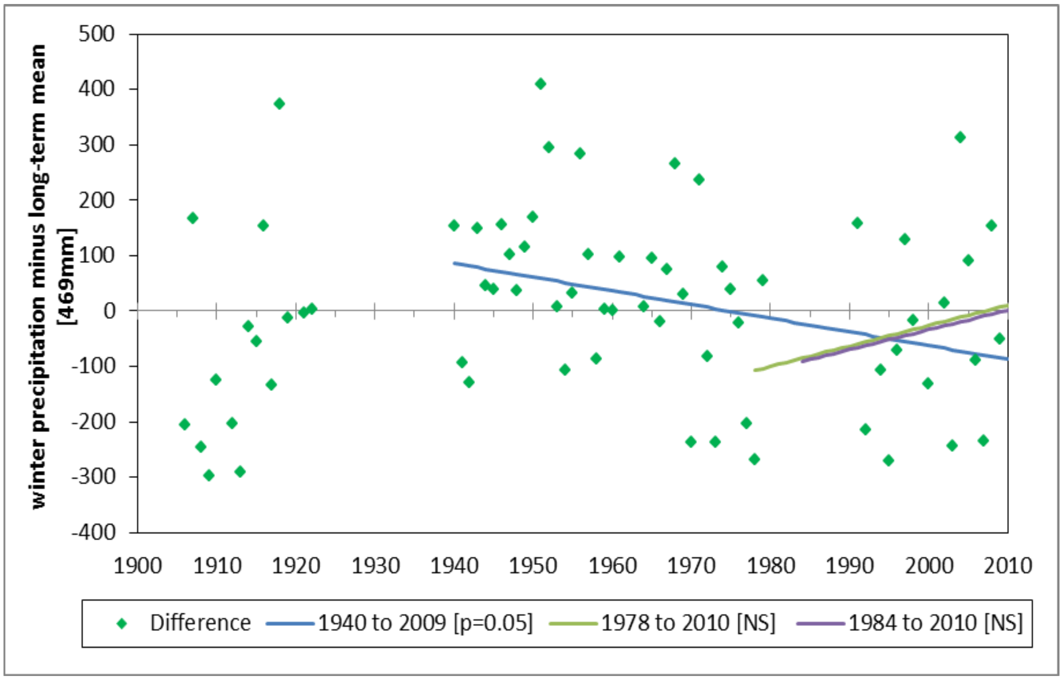

Figure E.21 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (469mm) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1940 to 2009.

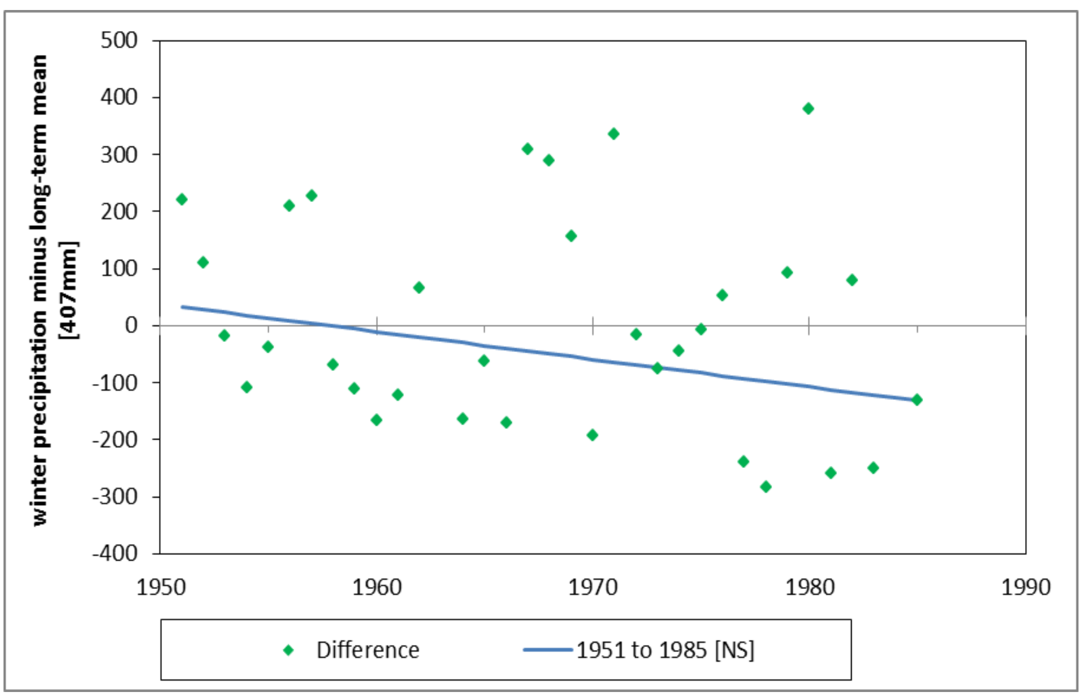

Figure E.22 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (407mm) for the station, Puu Lehua 73. The zero line represents the mean calculated over the period of record, 1951 to 1985.

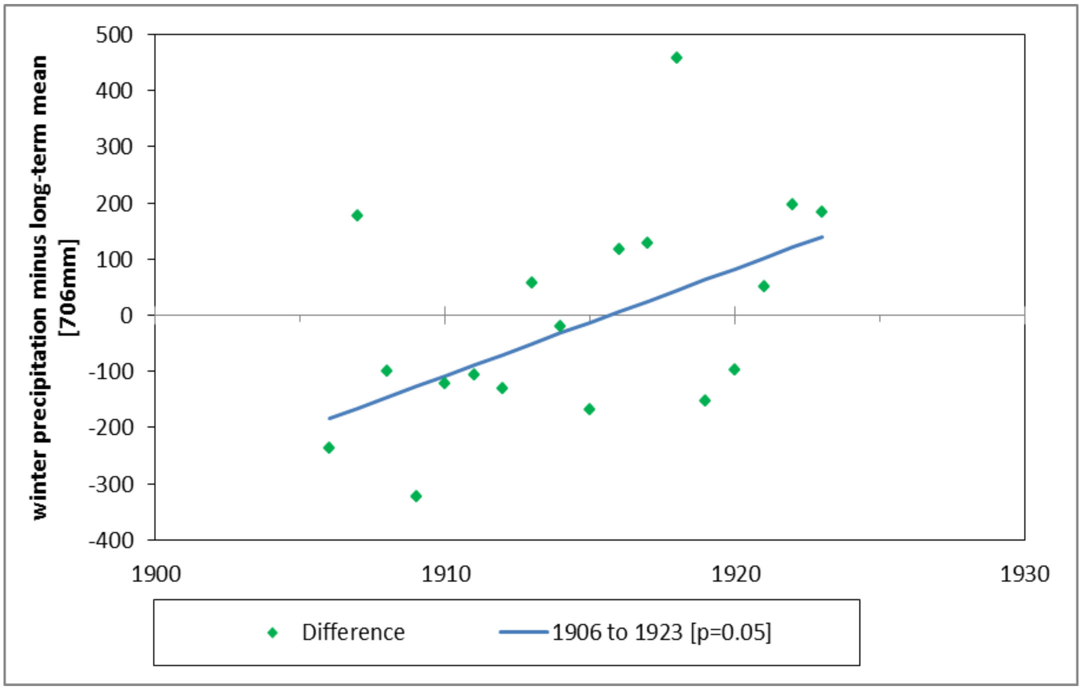

Figure E.23 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (706mm) for the station, Kealakekua 2 28.7. The zero line represents the mean calculated over the period of record, 1906 to 1923.

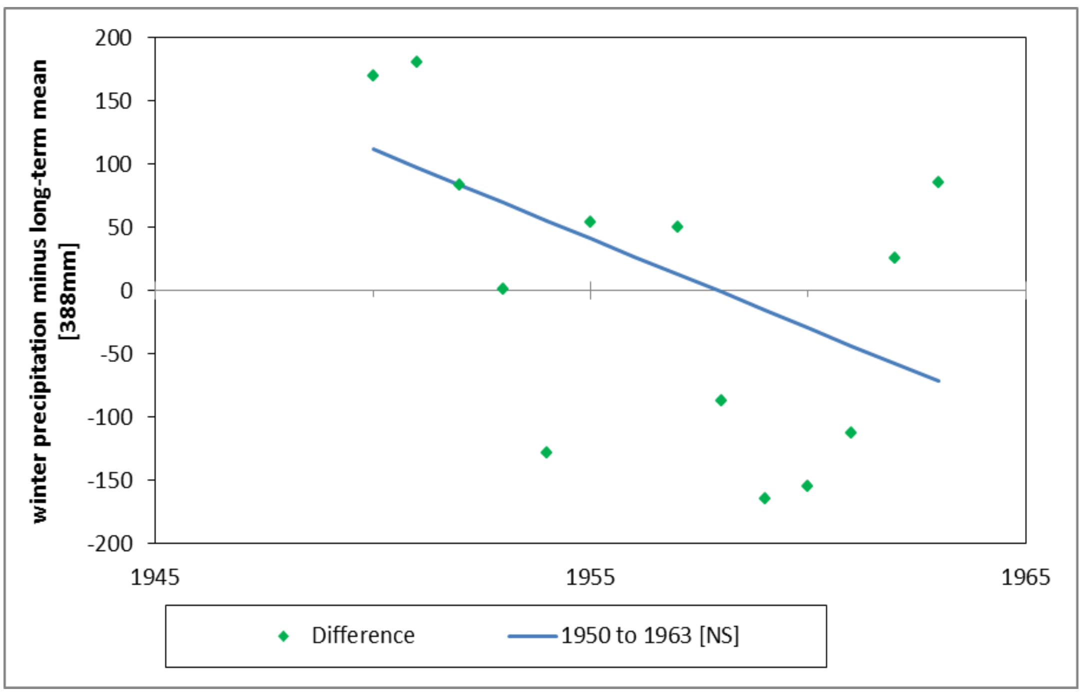

Figure E.24 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (388mm) for the station, Kanahaha 74. The zero line represents the mean calculated over the period of record, 1950 to 1963.

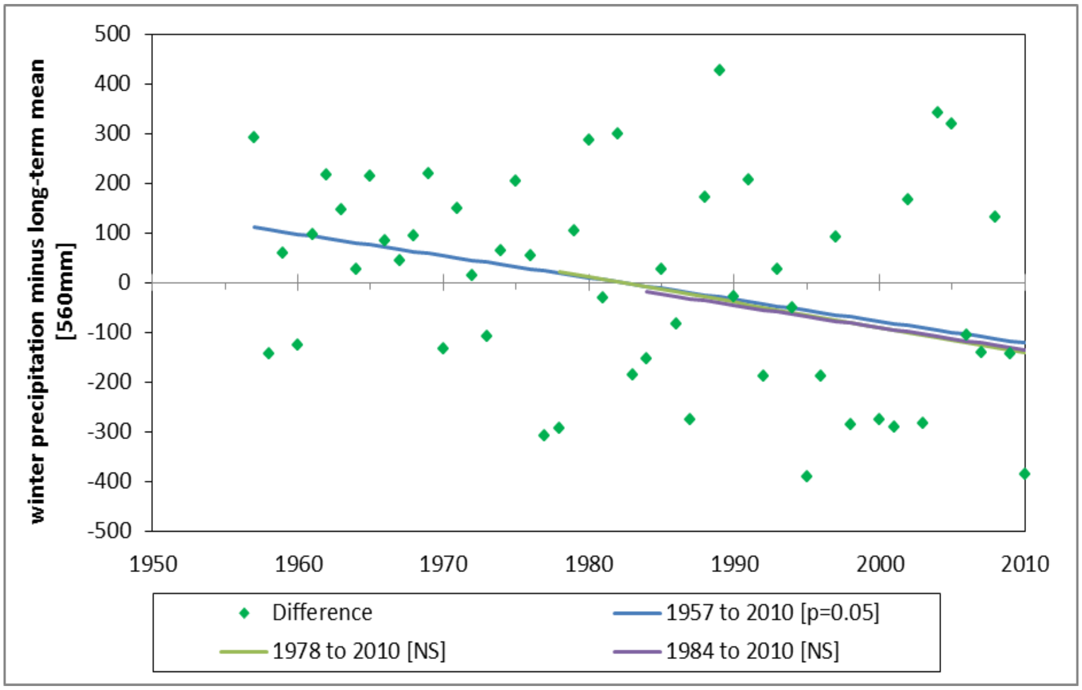

Figure E.25 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (560mm) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1957 to 2010.

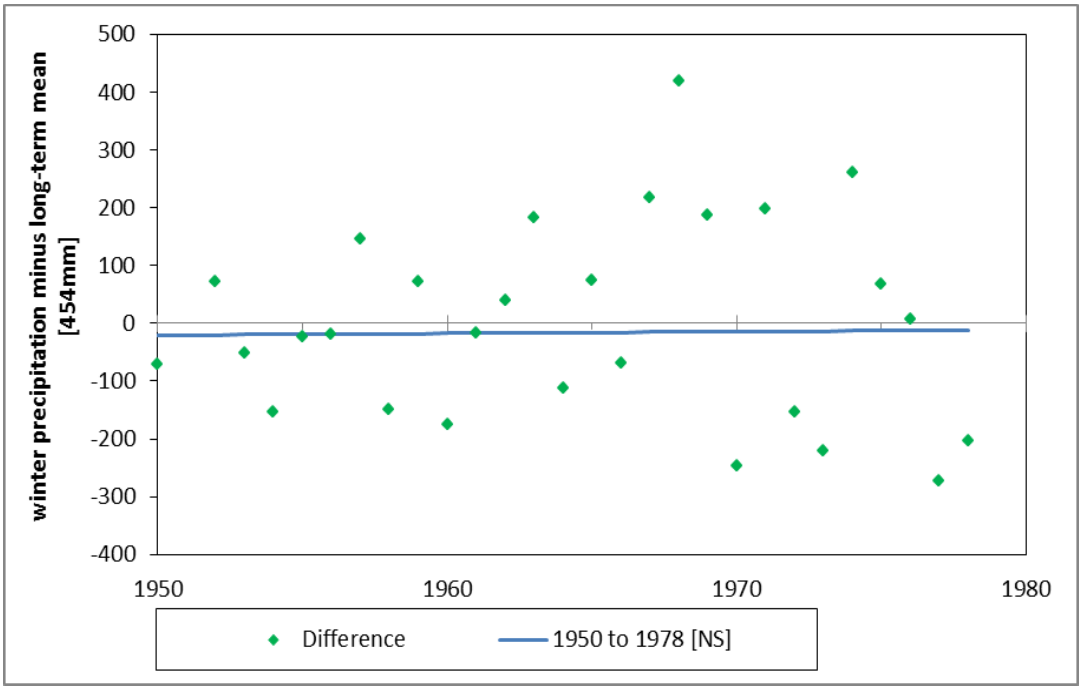

Figure E.26 Trend results from the Mann-Kendall tests and winter precipitation differences when compared to the mean (454mm) for the station, Puu Waawaa 94.1. The zero line represents the mean calculated over the period of record, 1950 to 1978.

APPENDIX F: TEMPERATURE MANN-KENDALL TREND TEST RESULTS

Table F.1: Results of Mann-Kendall test for trend and the estimated rate of change for the annual mean daily minimum temperature datasets. . (N equals the numbers of years tested.)

	Period Tested					Sen's Slope Estimate
Station Name	First year	Last Year	N	Significance		Rate of Change
Station Period of Record						
Holualoa 70	1906	1927	16	N		0.001
Kainaliu 73.2	1940	1984	43	Y	0.01	0.024
Ke-Ahole Point 68.13	1983	2003	21	Y	0.05	-0.029
Kona AP	1950	1969	20	Y	0.1	-0.069
Napoopoo 28	1921	1956	29	Y	0.001	-0.093
Opihihale 2 24.1	1958	2010	48	N		0.007
1978 to 2010						
Opihihale 2 24.1	1978	2010	30	N		-0.013

Table F.2: Results of Mann-Kendall test for trend and the estimated rate of change for the annual mean daily maximum temperature datasets. (N equals the numbers of years tested.)

	Period Tested					Sen's Slope Estimate
Station Name	First year	Last Year	N	Significance		Rate of Change
Station Period of Record						
Holualoa 70	1906	1927	18	N		0.016
Kainaliu 73.2	1940	1984	43	Y	0.01	-0.024
Ke-Ahole Point 68.13	1983	2003	21	Y	0.001	-0.132
Kona AP	1950	1969	20	N		0.018
Napoopoo 28	1921	1956	28	N		0.017
Opihihale 2 24.1	1958	2010	48	Y	0.05	0.017
1978 to 2010						
Opihihale 2 24.1	1978	2010	30	Y	0.001	-0.043

Table F.3: Results of Mann-Kendall test for trend and the estimated rate of change for the summertime mean daily minimum temperature datasets. (N equals the numbers of years tested.)

	Period Tested					Sen's Slope Estimate
Station Name	**First year**	**Last Year**	**N**	**Significance**		**Rate of Change**
Station Period of Record						
Holualoa 70	1905	1927	19	N		-0.030
Kainaliu 73.2	1939	1984	44	Y	0.05	0.019
Ke-Ahole Point 68.13	1982	2002	21	N		-0.024
Kona AP	1950	1969	20	Y	0.1	-0.067
Napoopoo 28	1919	1956	31	Y	0.001	-0.104
Opihihale 2 24.1	1957	2010	51	N		0.007
1978 to 2010						
Opihihale 2 24.1	1978	2010	32	N		-0.016

Table F.4: Results of Mann-Kendall test for trend and the estimated rate of change for the summertime mean daily maximum temperature datasets. (N equals the numbers of years tested.)

	Period Tested					Sen's Slope Estimate
Station Name	**First year**	**Last Year**	**N**	**Significance**		**Rate of Change**
Station Period of Record						
Holualoa 70	1905	1927	19	N		0.001
Kainaliu 73.2	1939	1984	43	Y	0.05	-0.024
Ke-Ahole Point 68.13	1982	2002	21	Y	0.001	-0.131
Kona AP	1950	1969	20	N		0.020
Napoopoo 28	1919	1956	31	Y	0.05	-0.028
Opihihale 2 24.1	1957	2010	51	N		0.008
1978 to 2010						
Opihihale 2 24.1	1978	2010	32	Y	0.001	-0.054

Table F.5: Results of Mann-Kendall test for trend and the estimated rate of change for the wintertime mean daily minimum temperature datasets. (N equals the numbers of years tested.)

Station Name	Period Tested		N	Significance		Sen's Slope Estimate
	First year	Last Year				Rate of Change
Station Period of Record						
Holualoa 70	1906	1927	16	N		0.036
Kainaliu 73.2	1940	1984	43	Y	0.001	0.034
Ke-Ahole Point 68.13	1983	2003	20	Y	0.1	-0.025
Kona AP	1950	1970	21	Y	0.01	-0.088
Napoopoo 28	1921	1959	31	Y	0.001	-0.087
Opihihale 2 24.1	1958	2010	49	N		0.005
1978 to 2010						
Opihihale 2 24.1	1978	2010	31	N		-0.010

Table F.6: Results of Mann-Kendall test for trend and the estimated rate of change for the wintertime mean daily maximum temperature datasets. (N equals the numbers of years tested.)

Station Name	Period Tested		N	Significance		Sen's Slope Estimate
	First year	Last Year				Rate of Change
Station Period of Record						
Holualoa 70	1906	1927	17	N		0.020
Kainaliu 73.2	1940	1984	44	Y	0.05	-0.018
Ke-Ahole Point 68.13	1983	2003	20	Y	0.001	-0.131
Kona AP	1950	1970	21	N		0.017
Napoopoo 28	1921	1959	31	N		0.005
Opihihale 2 24.1	1958	2010	49	Y	0.05	0.017
1978 to 2010						
Opihihale 2 24.1	1978	2010	31	Y	0.001	-0.037

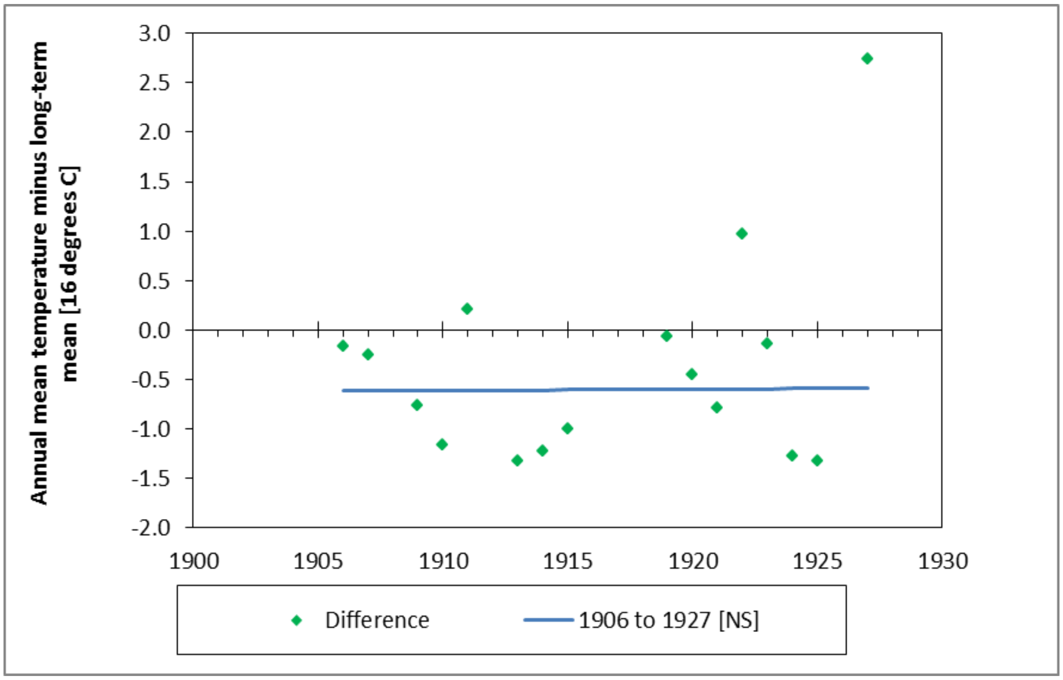

Figure F.1 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (16 degrees C) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1906 to 1927.

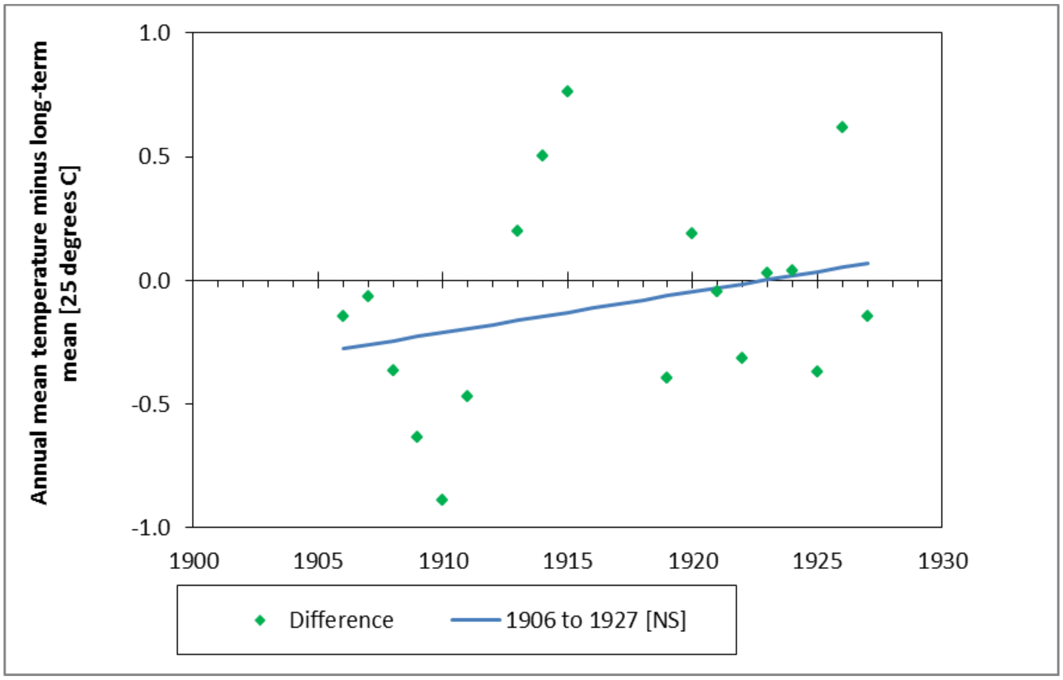

Figure F.2 Trend results from the Mann-Kendall tests and annual mean maximum temperature differences when compared to the mean (25 degrees C) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1906 to 1927.

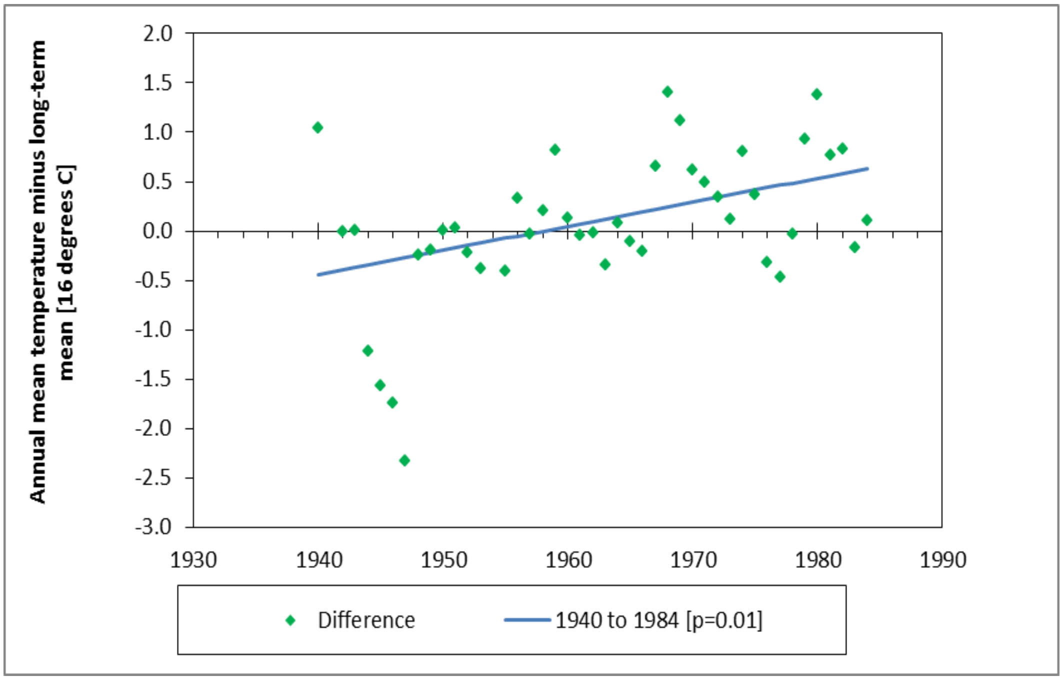

Figure F.3 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (16 degrees C) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1940 to 1984.

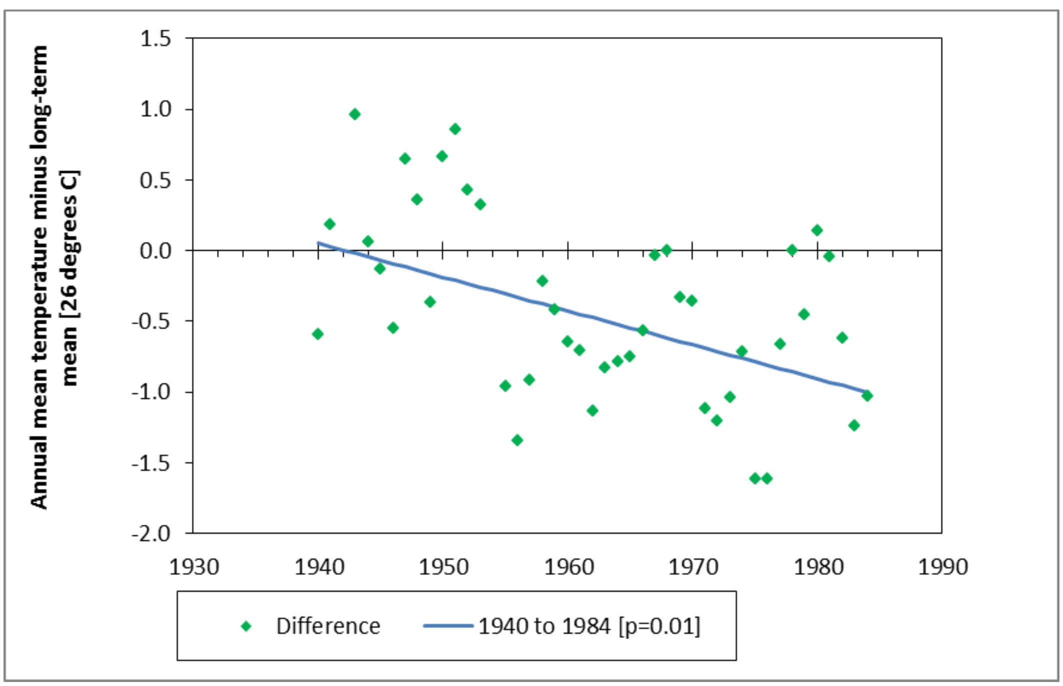

Figure F.4 Trend results from the Mann-Kendall tests and annual mean maximum temperature differences when compared to the mean (26 degrees C) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1940 to 1984.

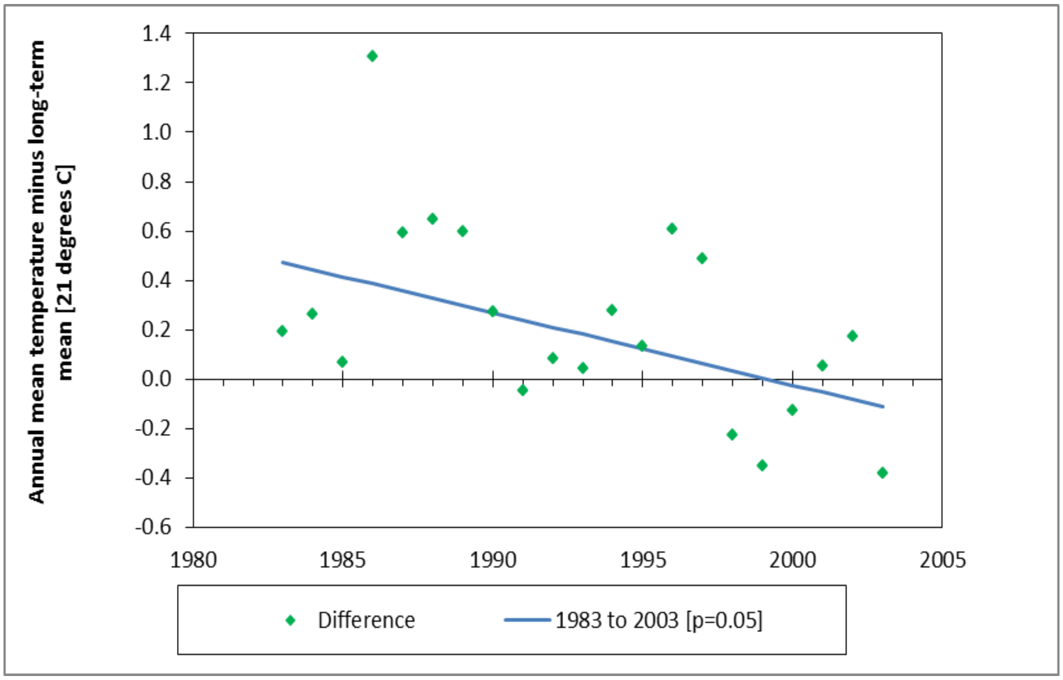

Figure F.5 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (21 degrees C) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1983 to 2003.

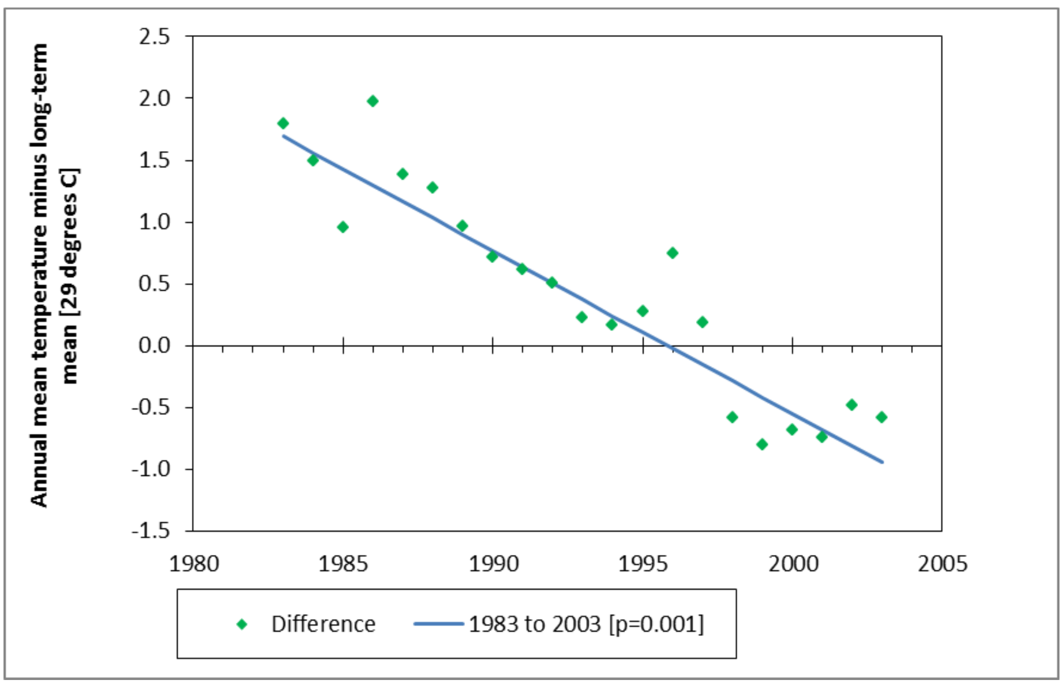

Figure F.6 Trend results from the Mann-Kendall tests and annual mean maximum temperature differences when compared to the mean (29 degrees C) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1983 to 2003.

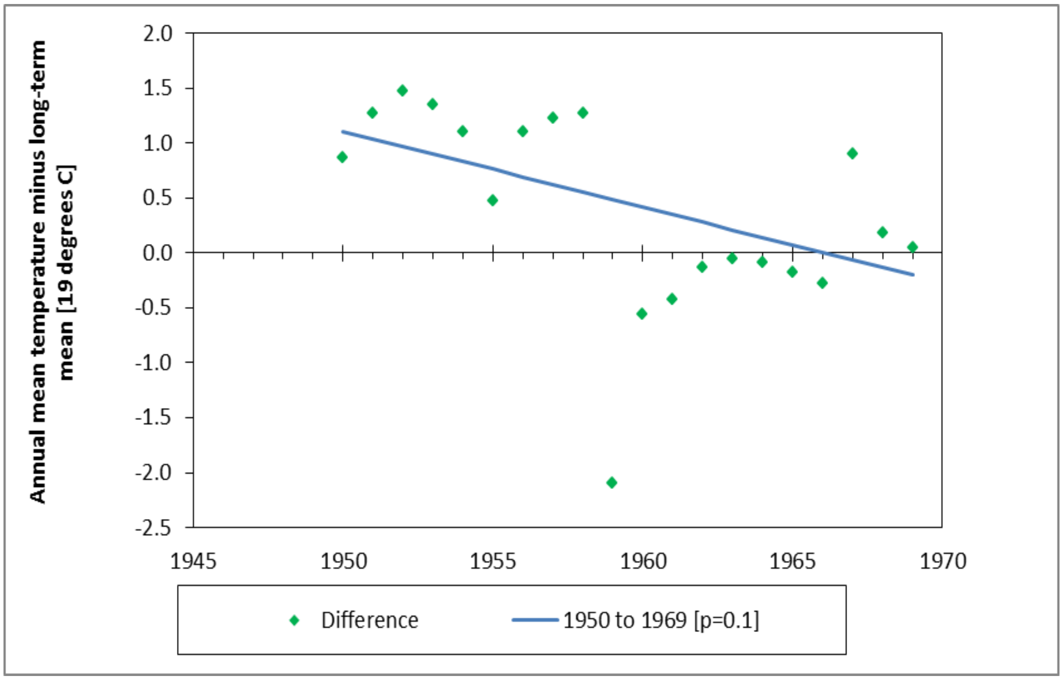

Figure F.7 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (19 degrees C) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1969.

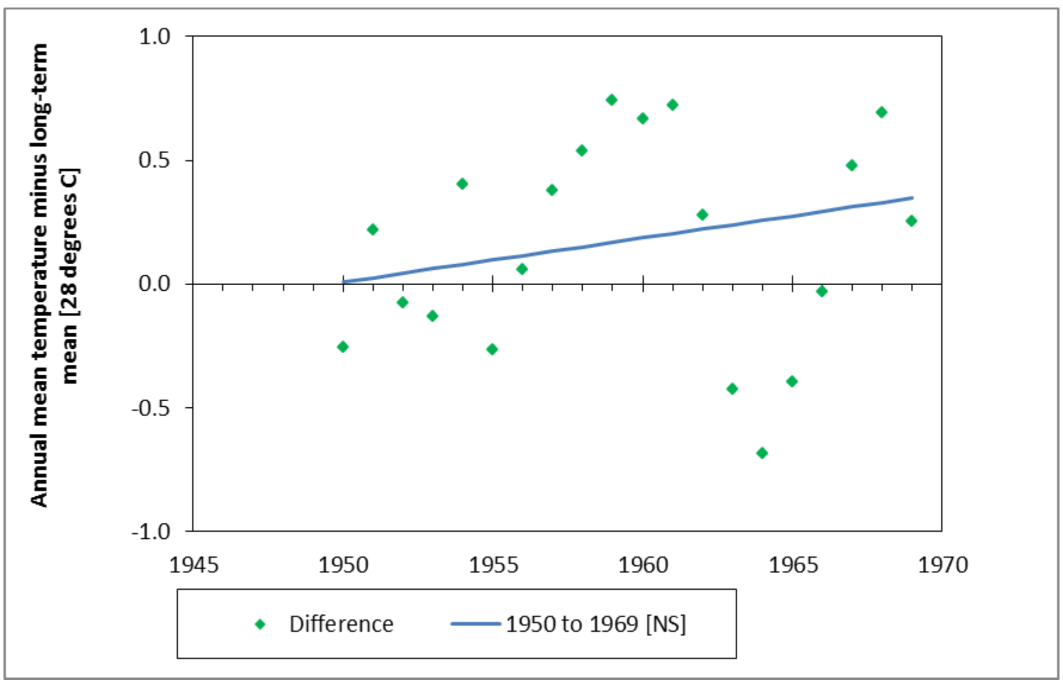

Figure F.8 Trend results from the Mann-Kendall tests and annual mean maximum temperature differences when compared to the mean (28 degrees C) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1969.

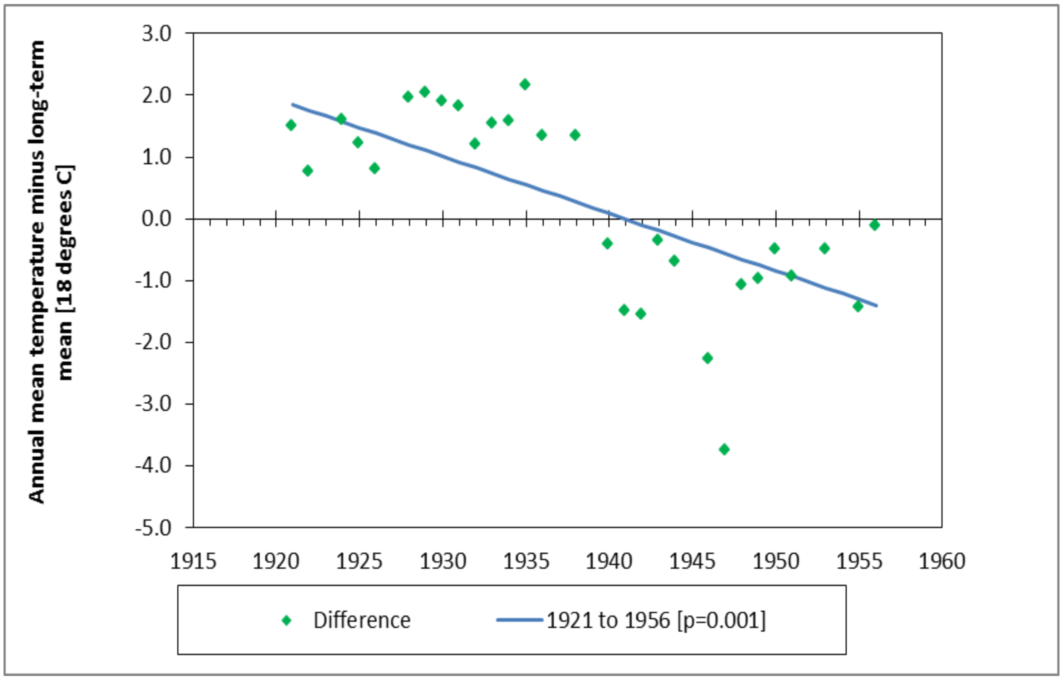

Figure F.9 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (18 degrees C) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1921 to 1956.

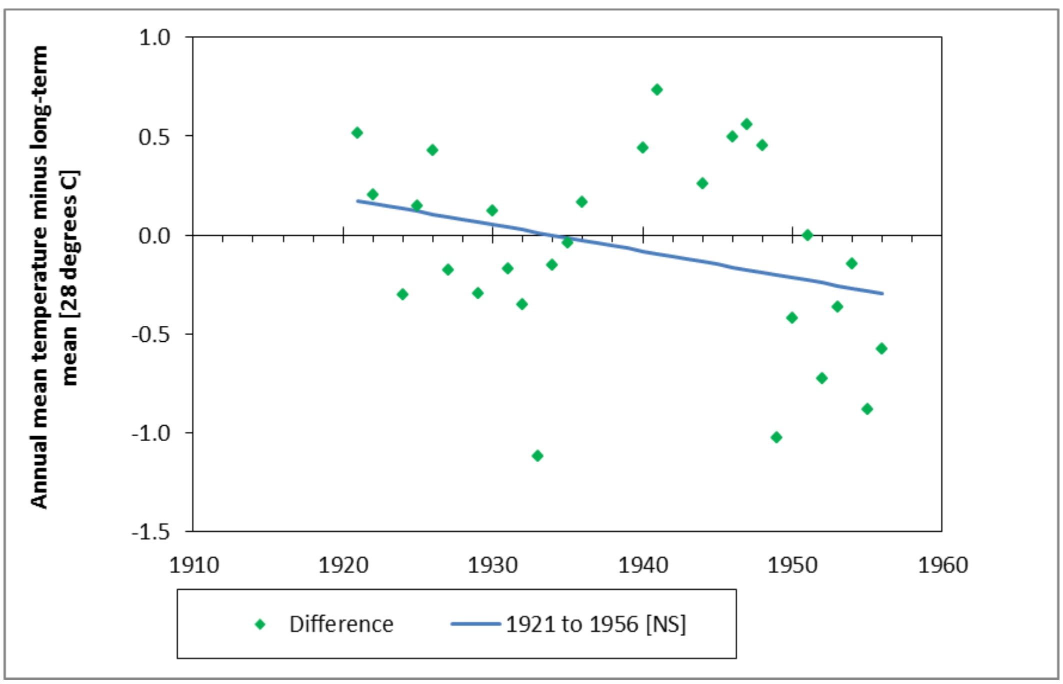

Figure F.10 Trend results from the Mann-Kendall tests and annual mean maximum temperature differences when compared to the mean (28 degrees C) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1921 to 1956.

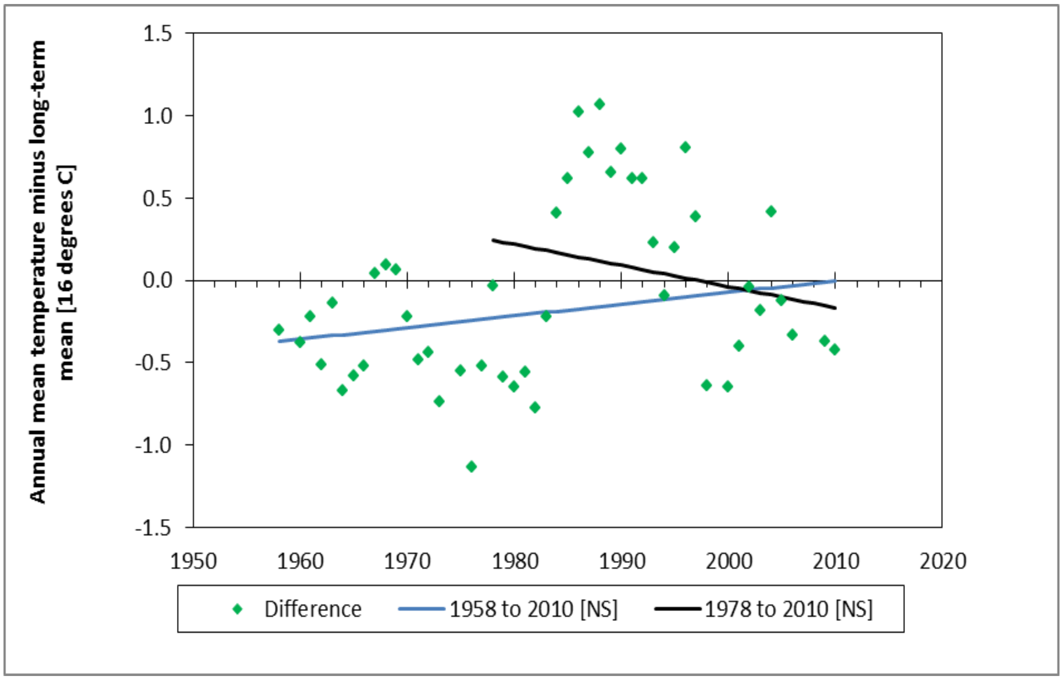

Figure F.11 Trend results from the Mann-Kendall tests and annual mean minimum temperature differences when compared to the mean (16 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1958 to 2010.

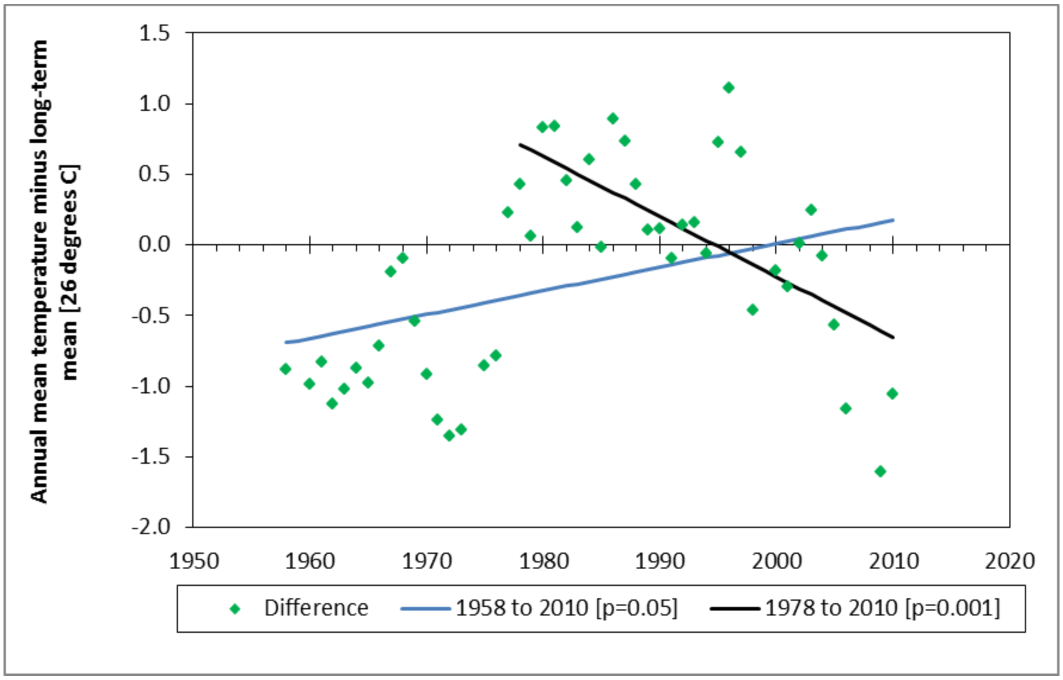

Figure F.12 Trend results from the Mann-Kendall tests and annual mean maximum temperature differences when compared to the mean (26 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1958 to 2010.

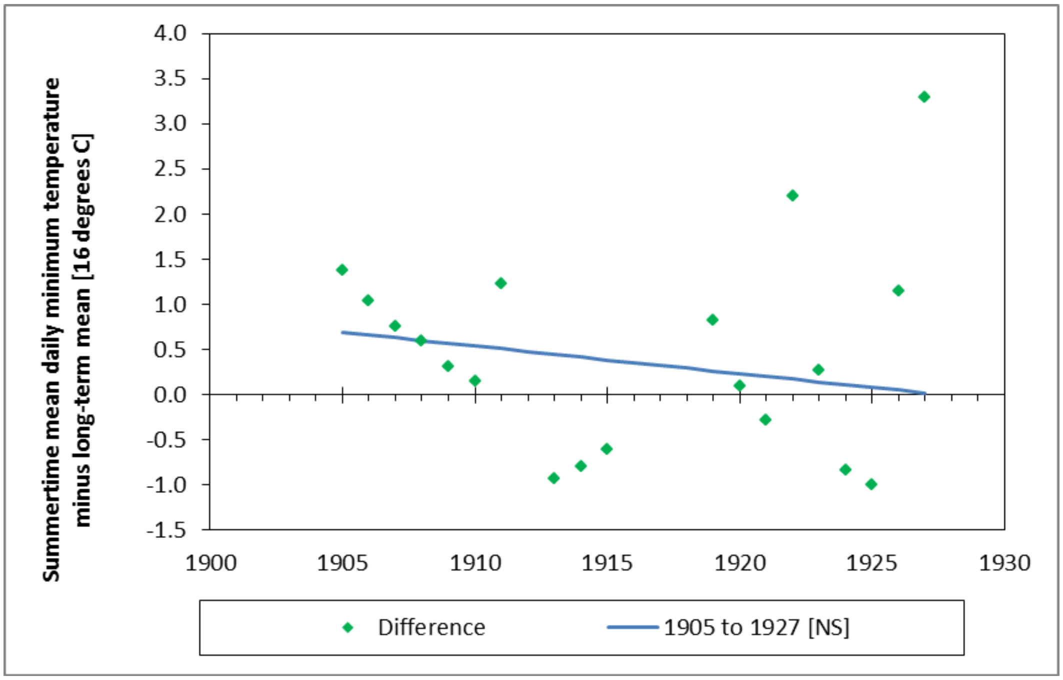

Figure F.13 Trend results and summer mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (16 degrees C) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1905 to 1927.

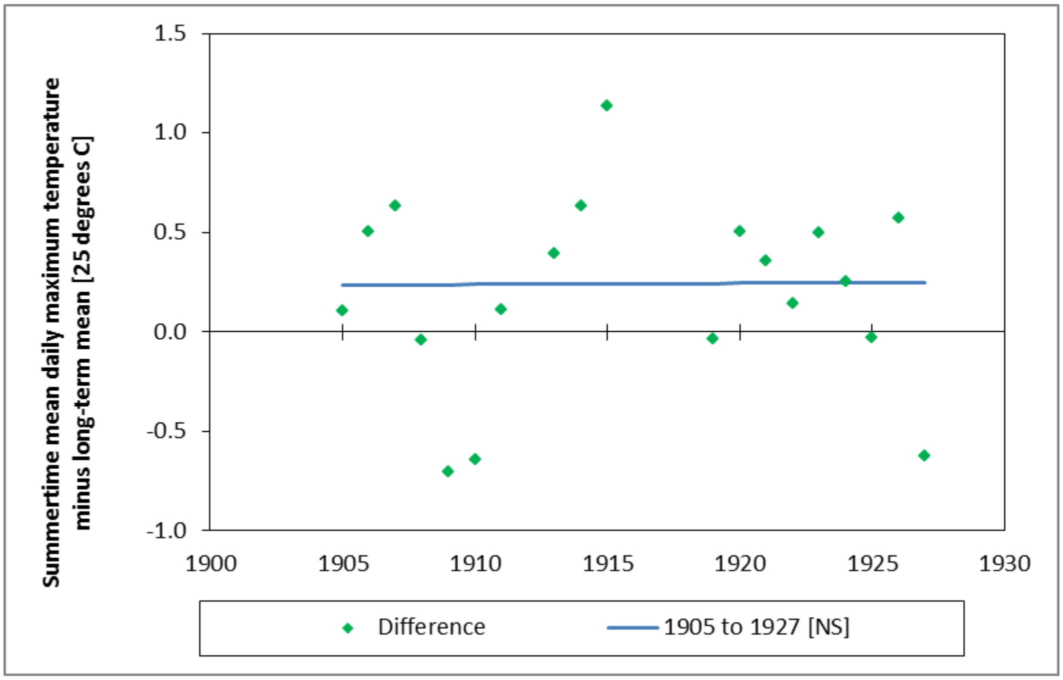

Figure F.14 Trend results and summer mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (25 degrees C) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1905 to 1927.

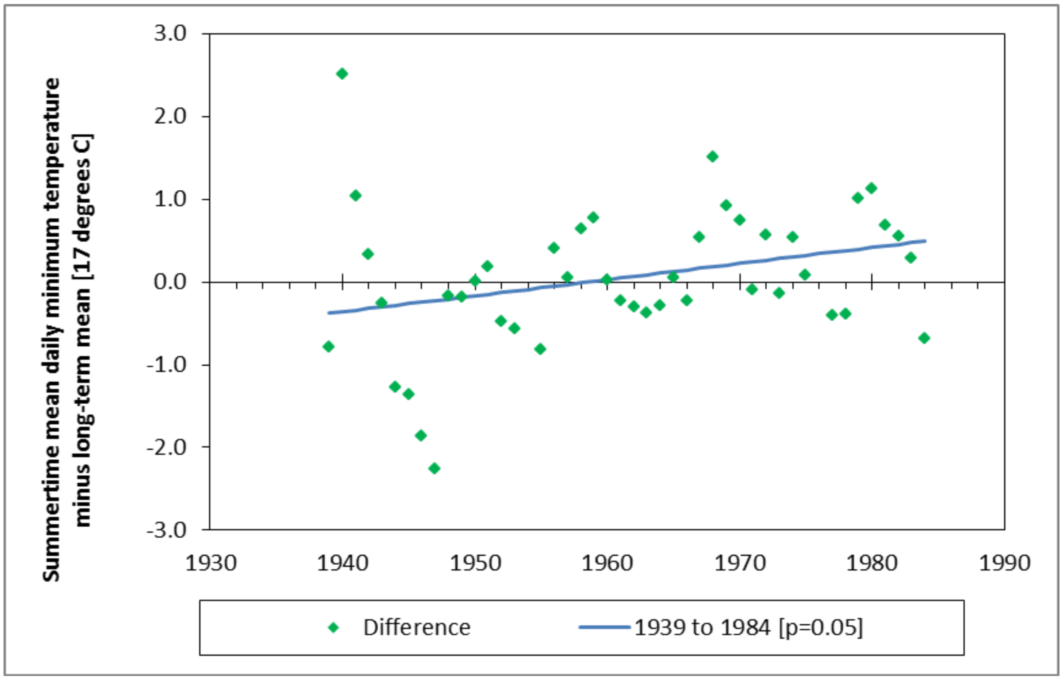

Figure F.15 Trend results and summer mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (17 degrees C) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1939 to 1984.

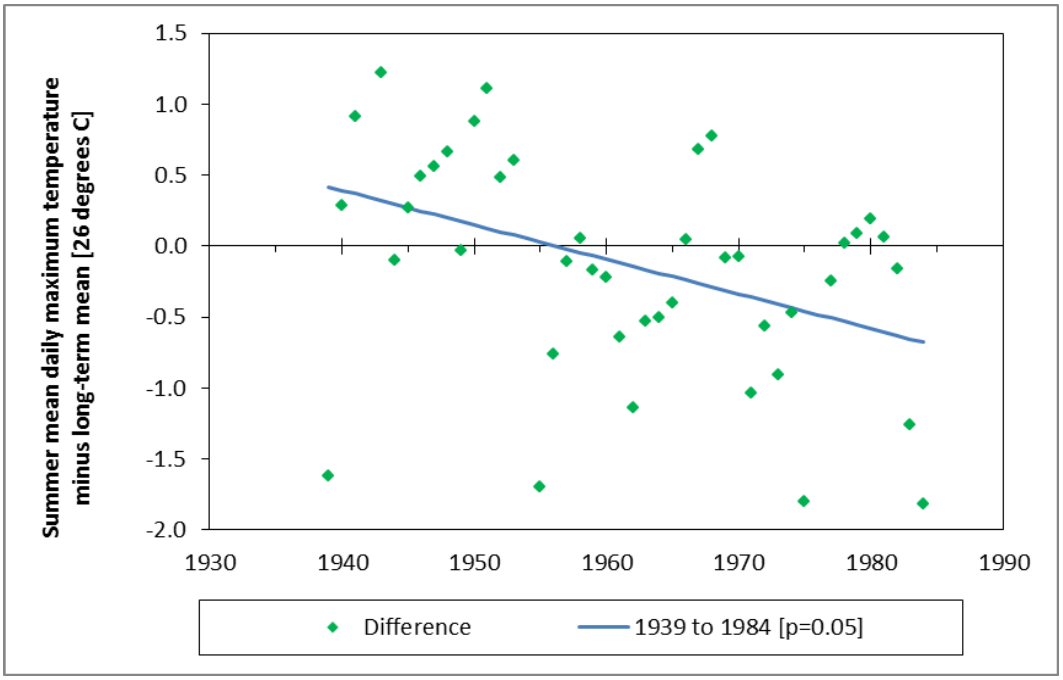

Figure F.16 Trend results and summer mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (26 degrees C) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1939 to 1984.

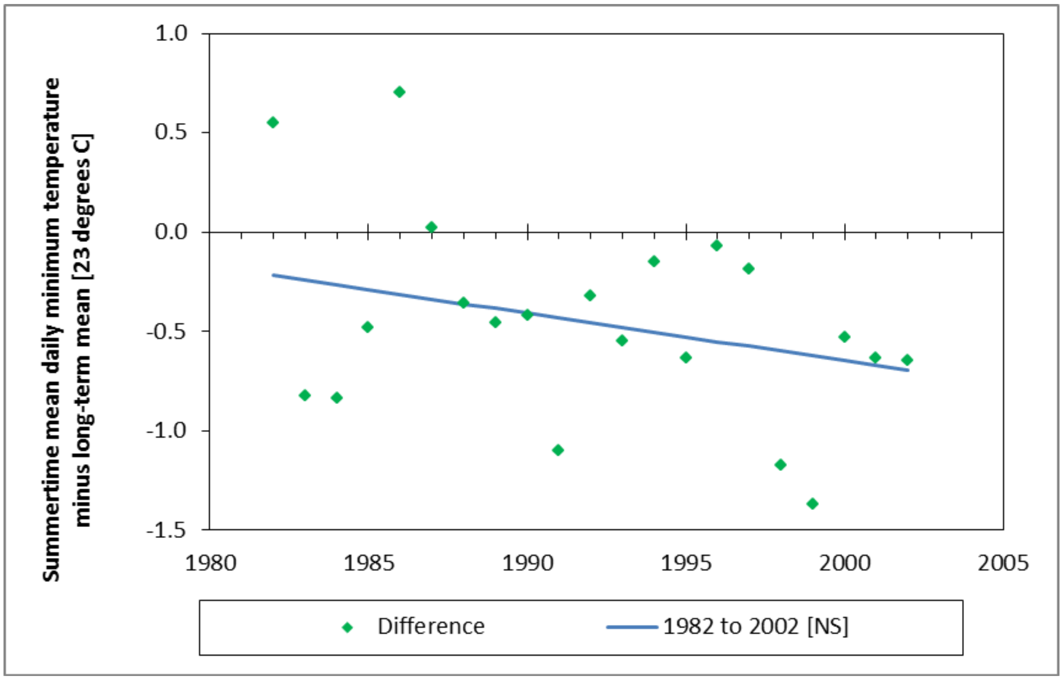

Figure F.17 Trend results and summer mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (23 degrees C) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1982 to 2002.

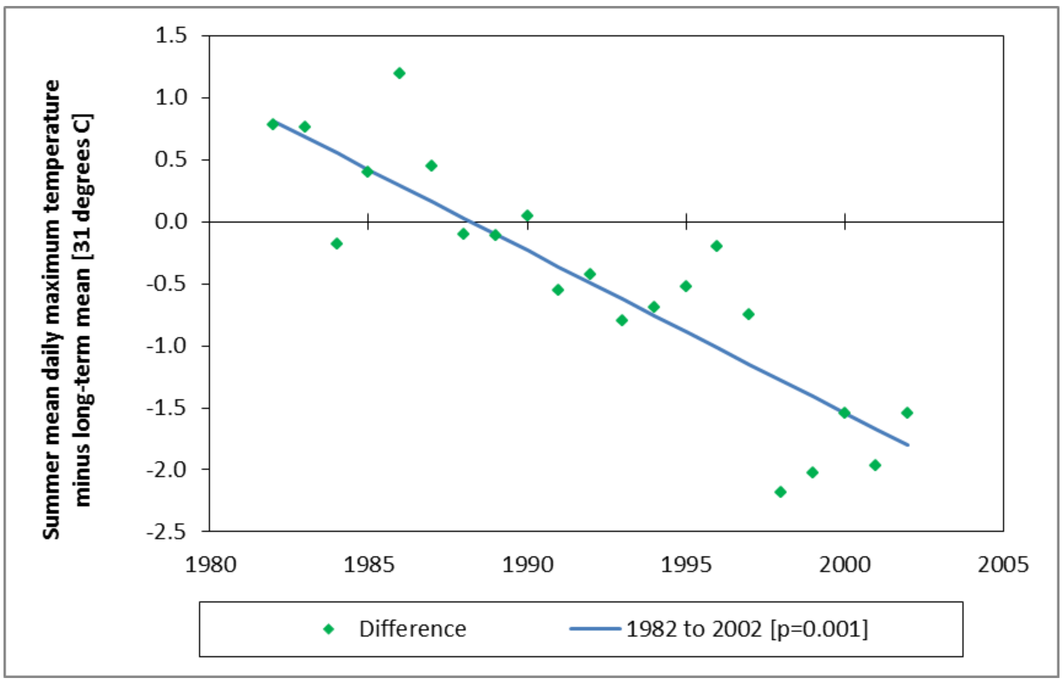

Figure F.18 Trend results and summer mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (31 degrees C) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1982 to 2002.

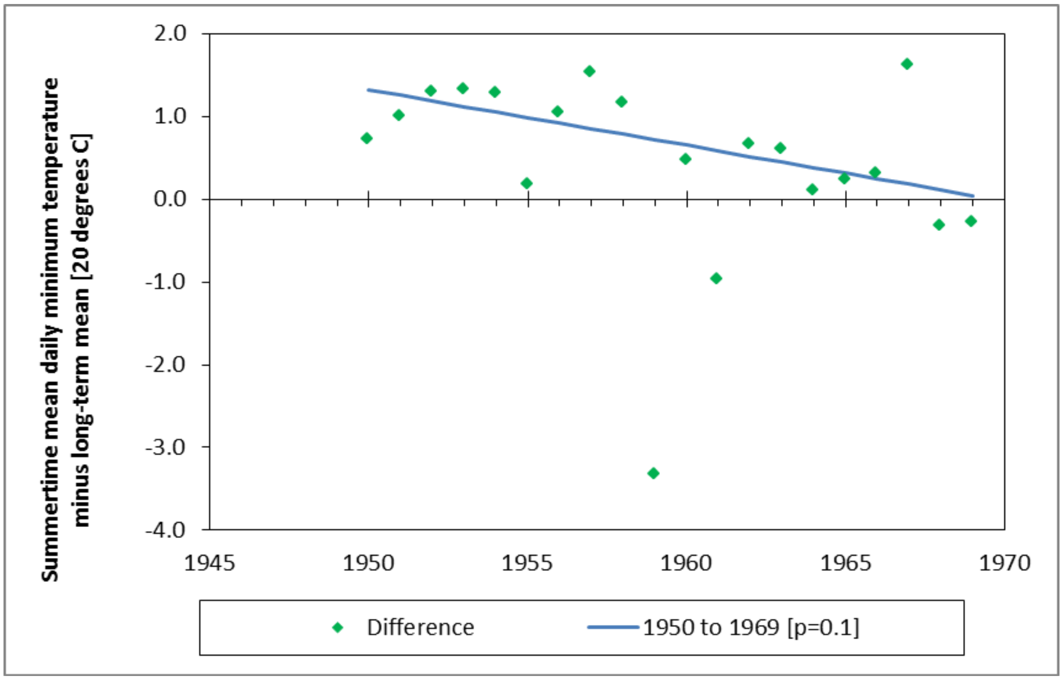

Figure F.19 Trend results and summer mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (20 degrees C) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1969.

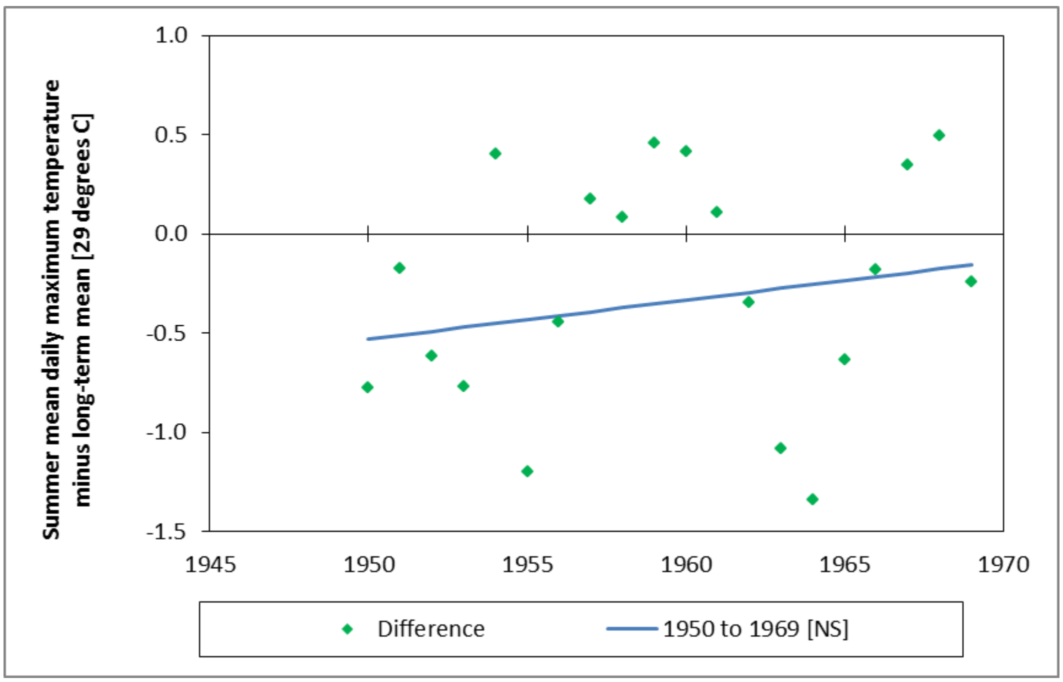

Figure F.20 Trend results and summer mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (29 degrees C) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1969.

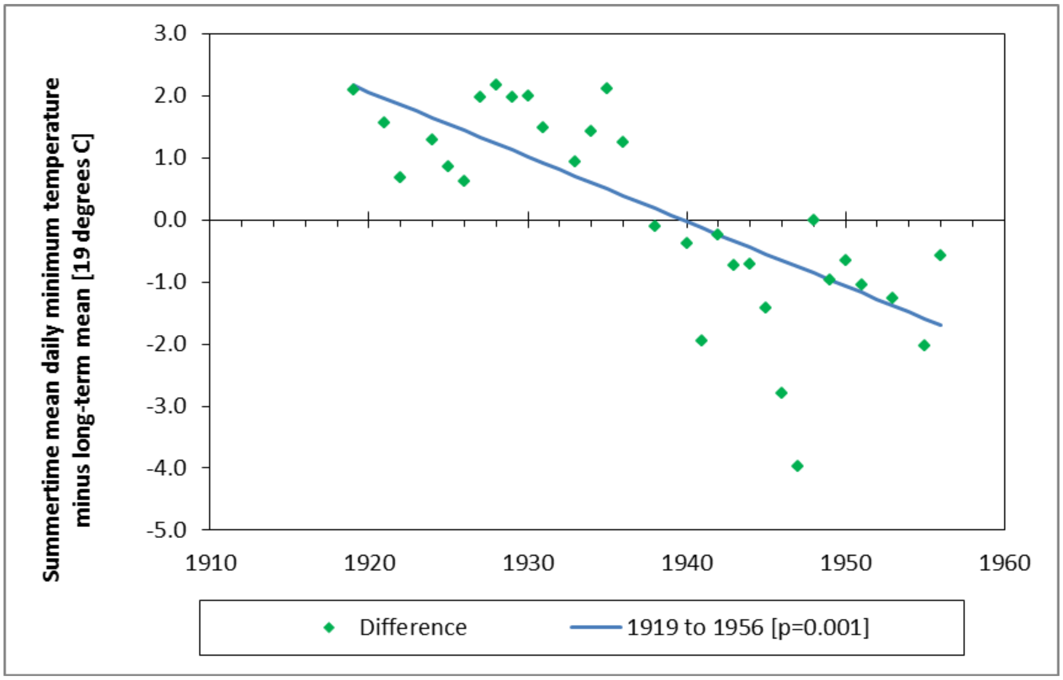

Figure F.21 Trend results and summer mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (19 degrees C) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1919 to 1956.

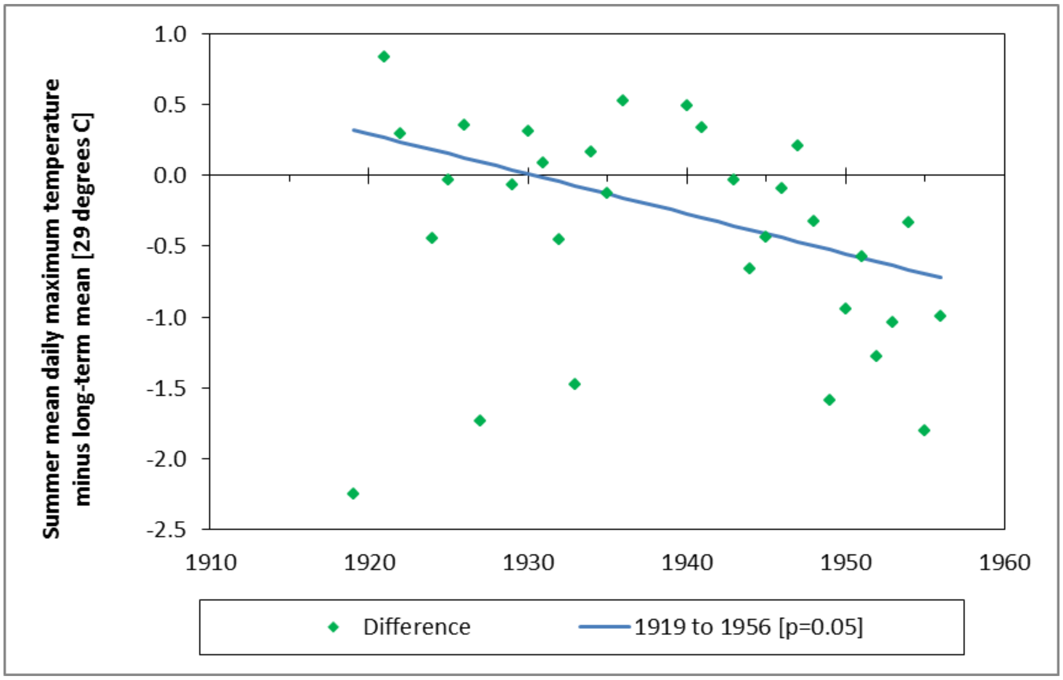

Figure F.22 Trend results and summer mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (29 degrees C) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1919 to 1956.

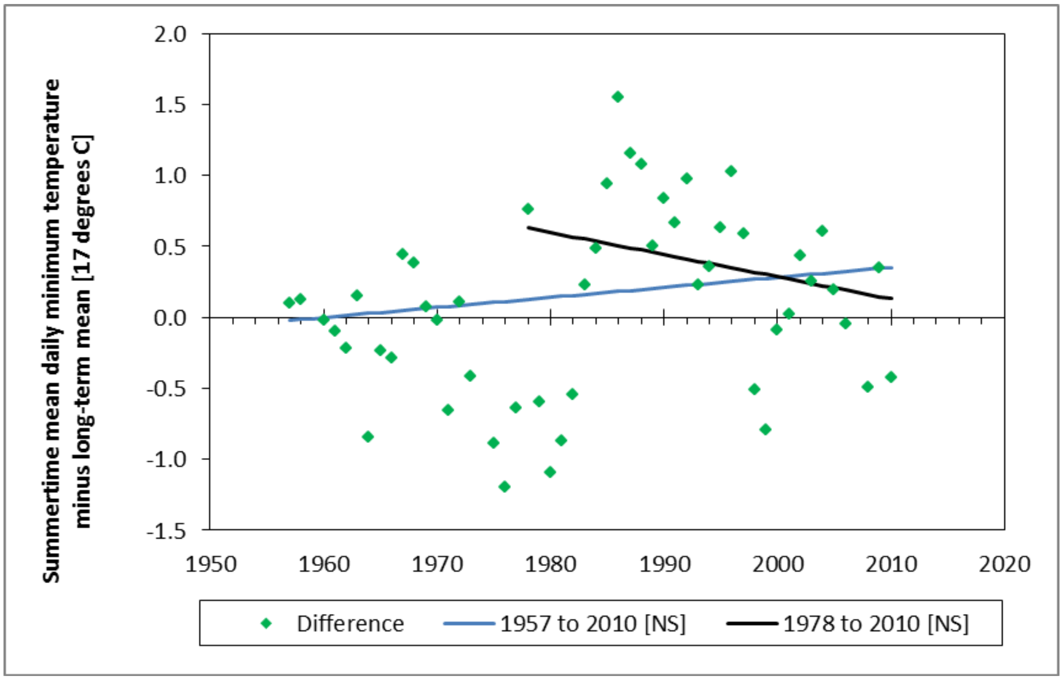

Figure F.23 Trend results and summer mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (17 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1957 to 2010.

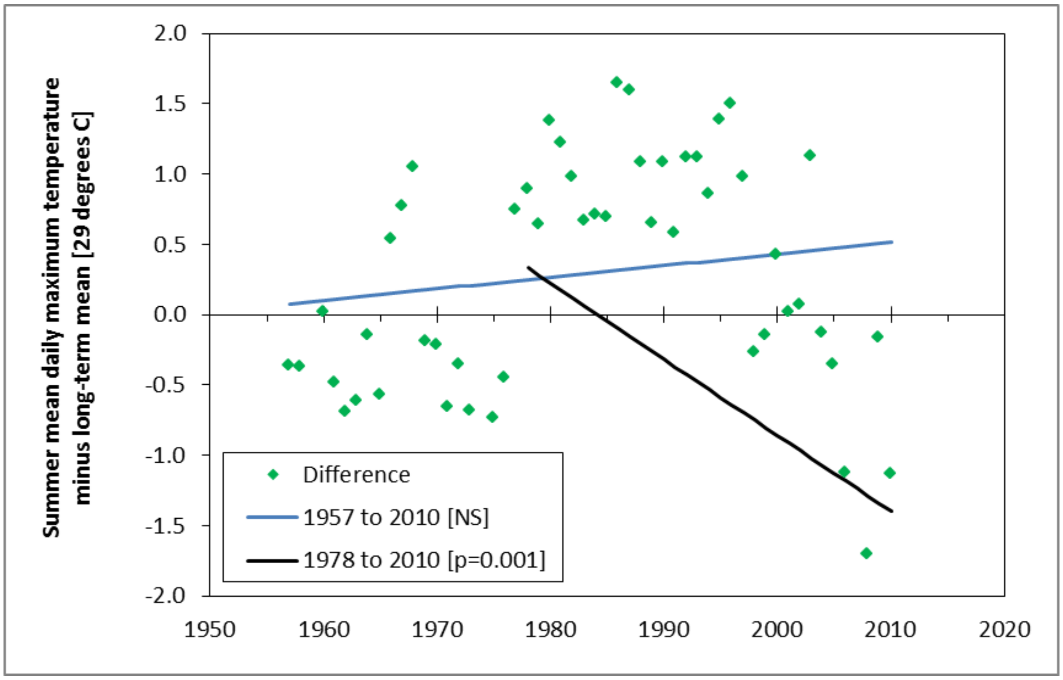

Figure F.24 Trend results and summer mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (29 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1957 to 2010.

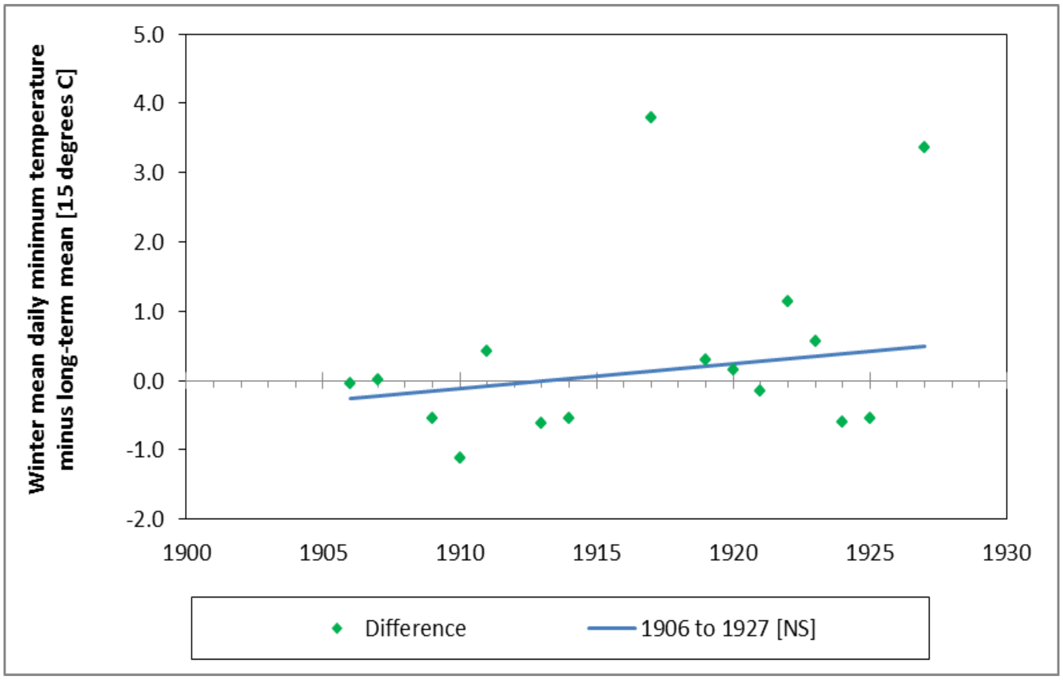

Figure F.25 Trend results and winter mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (15 degrees C) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1906 to 1927.

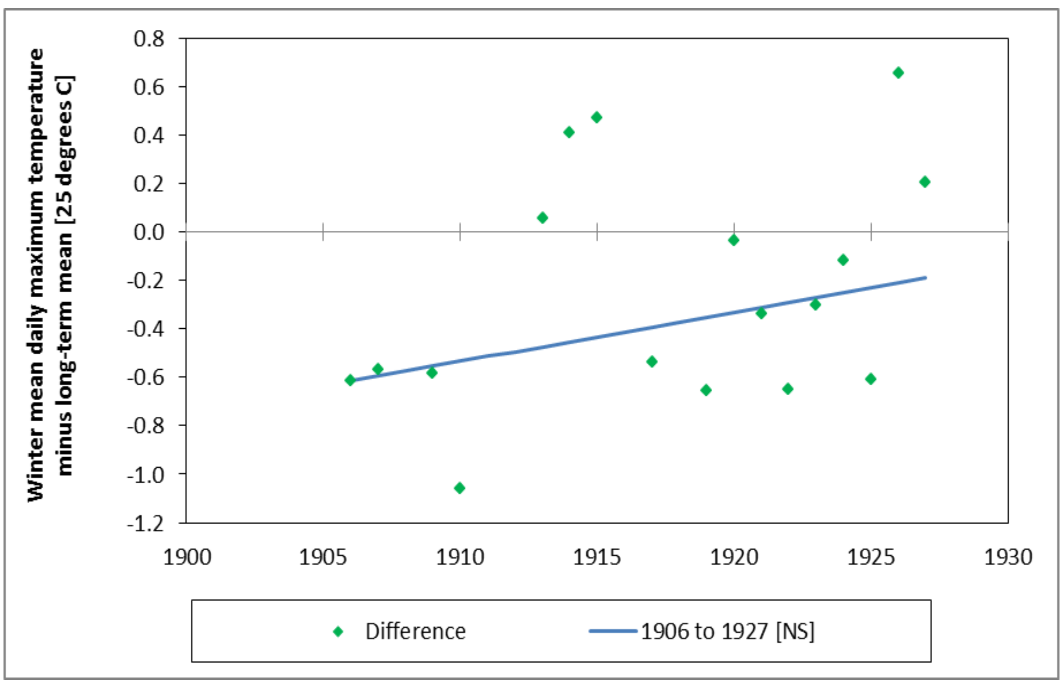

Figure F.26 Trend results and winter mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (25 degrees C) for the station, Holualoa 70. The zero line represents the mean calculated over the period of record, 1906 to 1927.

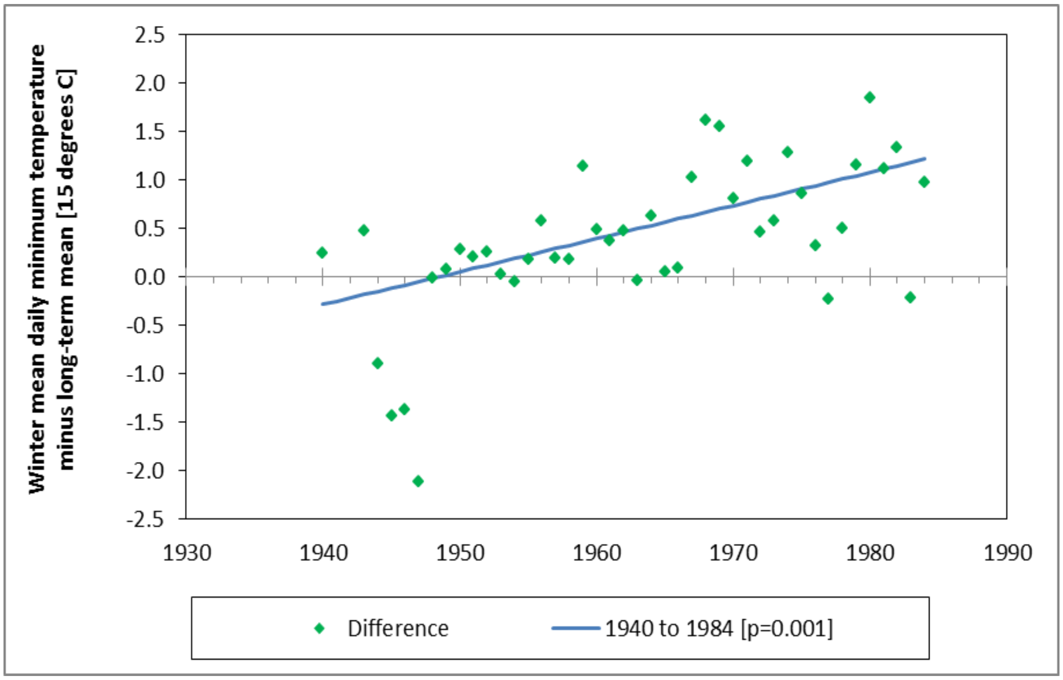

Figure F.27 Trend results and winter mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (15 degrees C) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1940 to 1984.

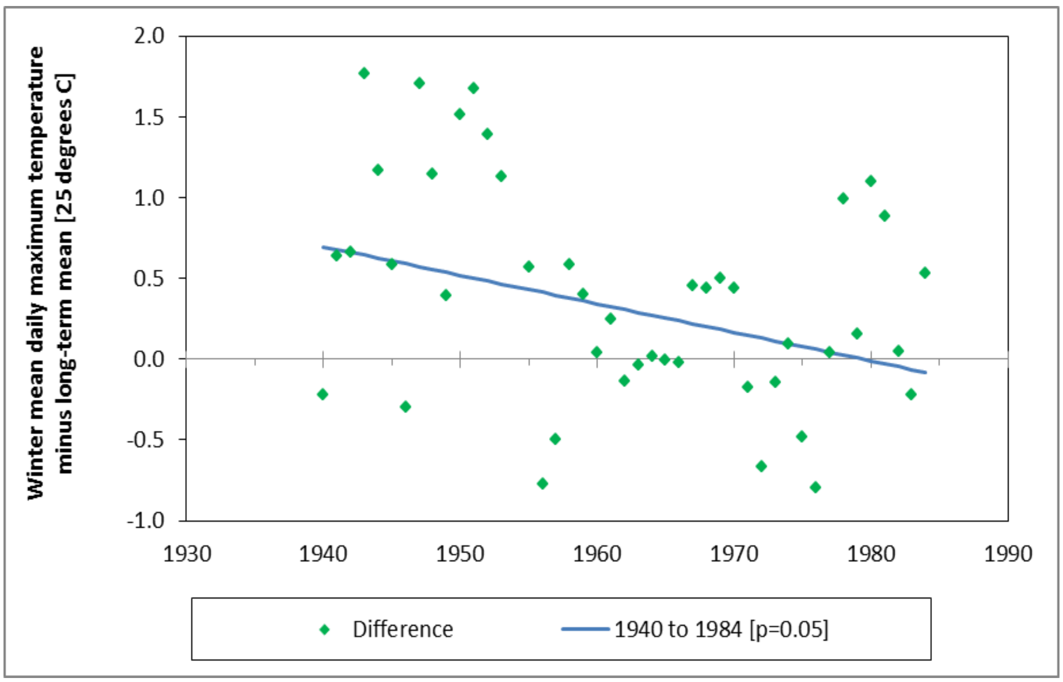

Figure F.28 Trend results and winter mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (25 degrees C) for the station, Kainaliu 73.2. The zero line represents the mean calculated over the period of record, 1940 to 1984.

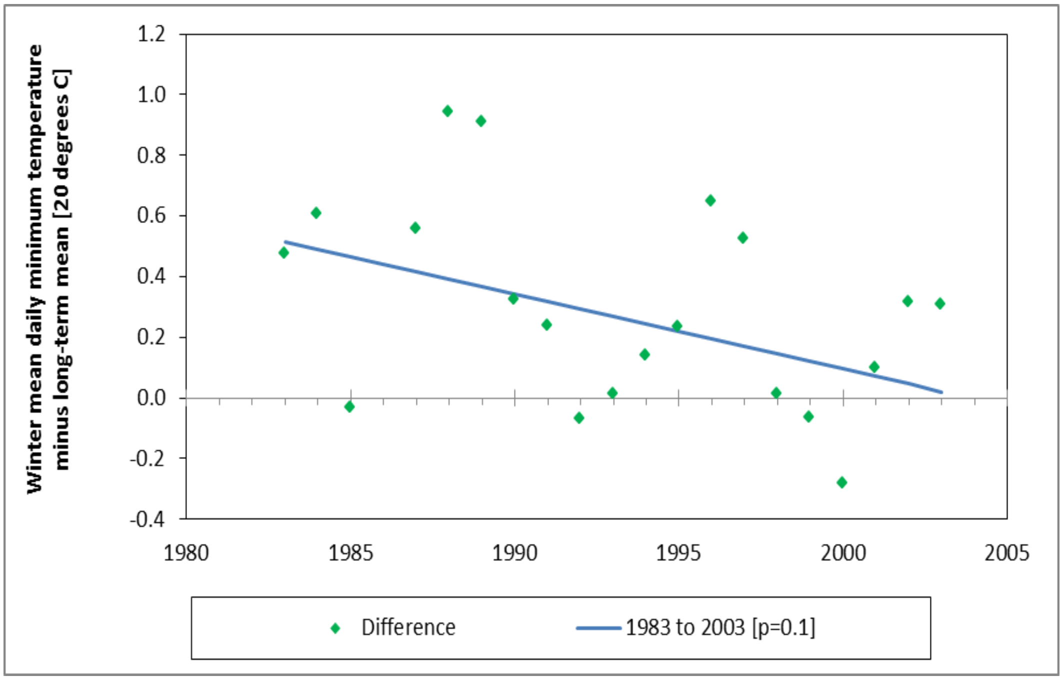

Figure F.29 Trend results and winter mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (20 degrees C) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1983 to 2003.

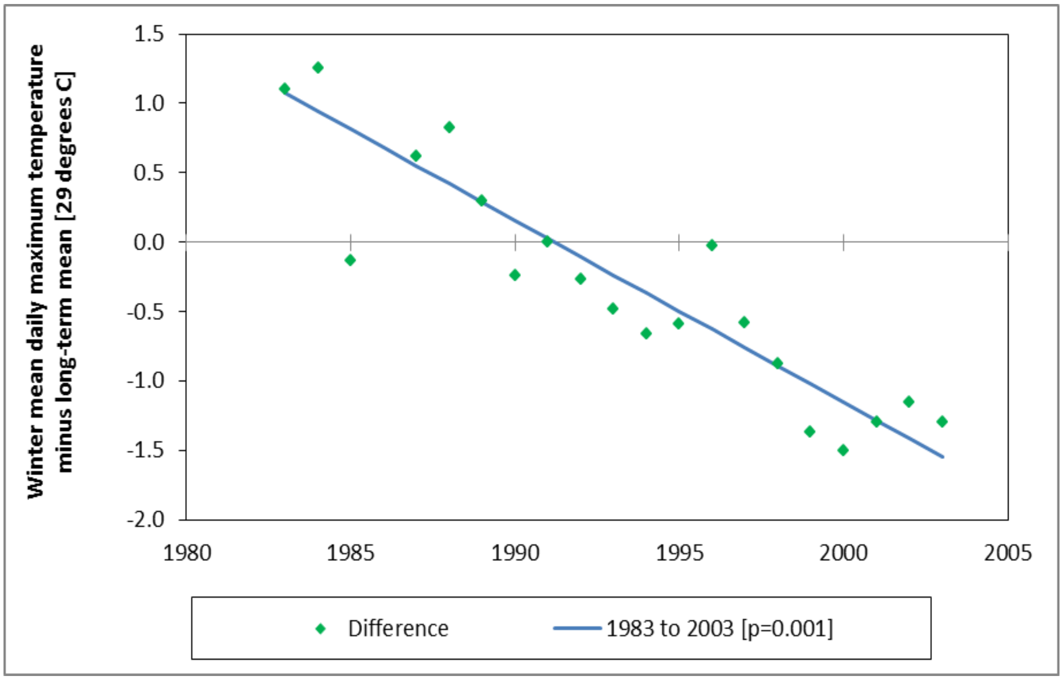

Figure F.30 Trend results and winter mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (29 degrees C) for the station, Ke-Ahole Point 68.13. The zero line represents the mean calculated over the period of record, 1983 to 2003.

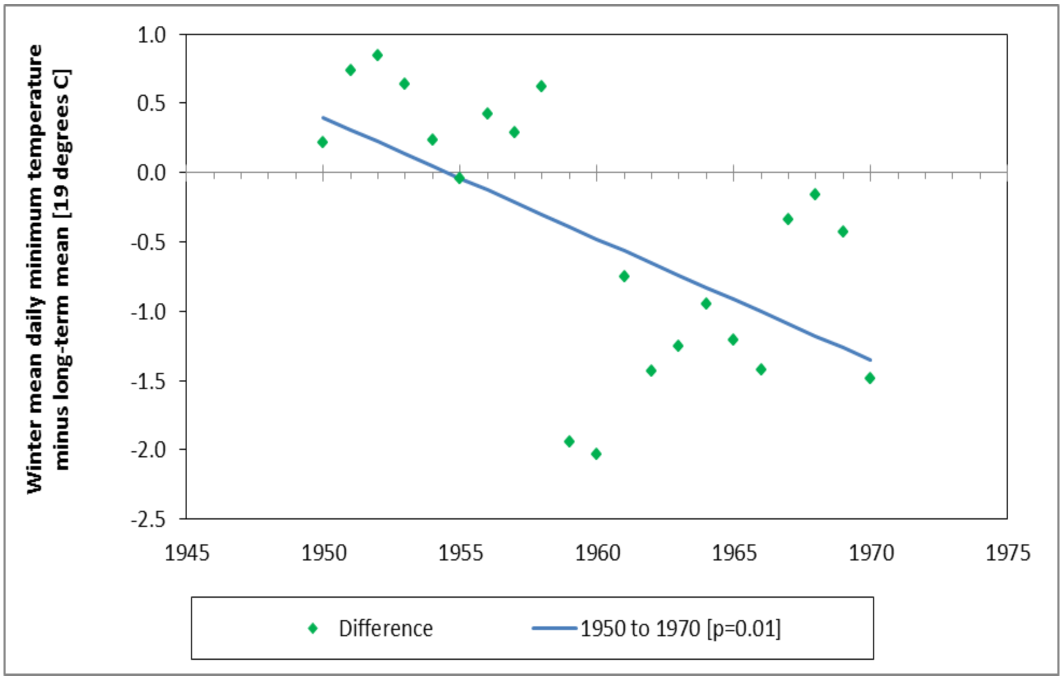

Figure F.31 Trend results and winter mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (19 degrees C) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1970.

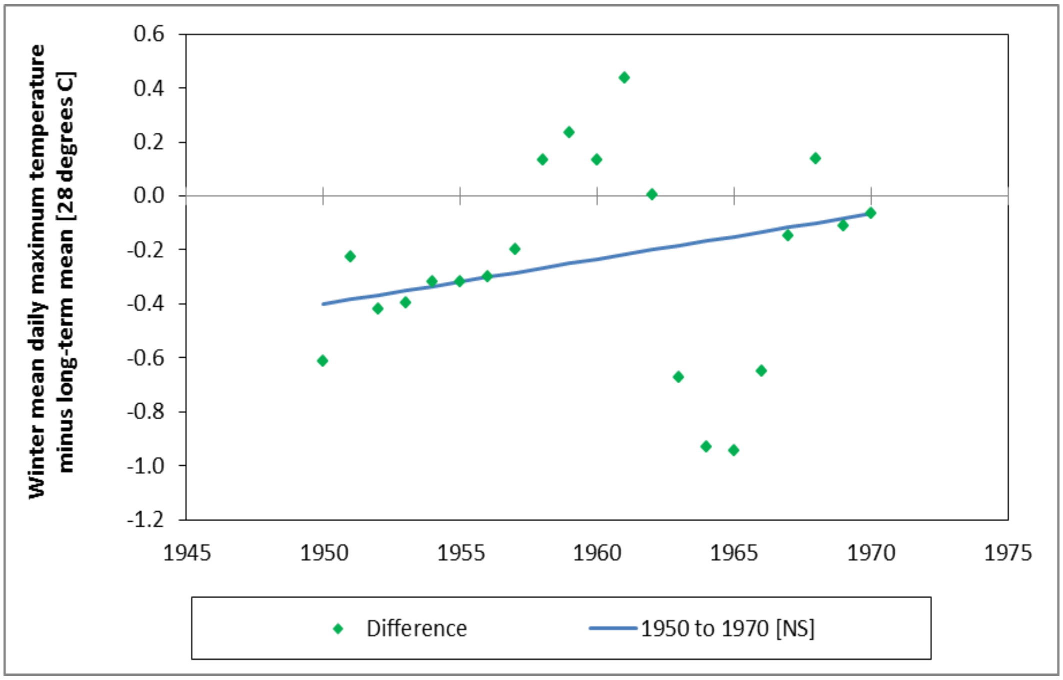

Figure F.32 Trend results and winter mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (28 degrees C) for the station, Kona Ap 68.3. The zero line represents the mean calculated over the period of record, 1950 to 1970.

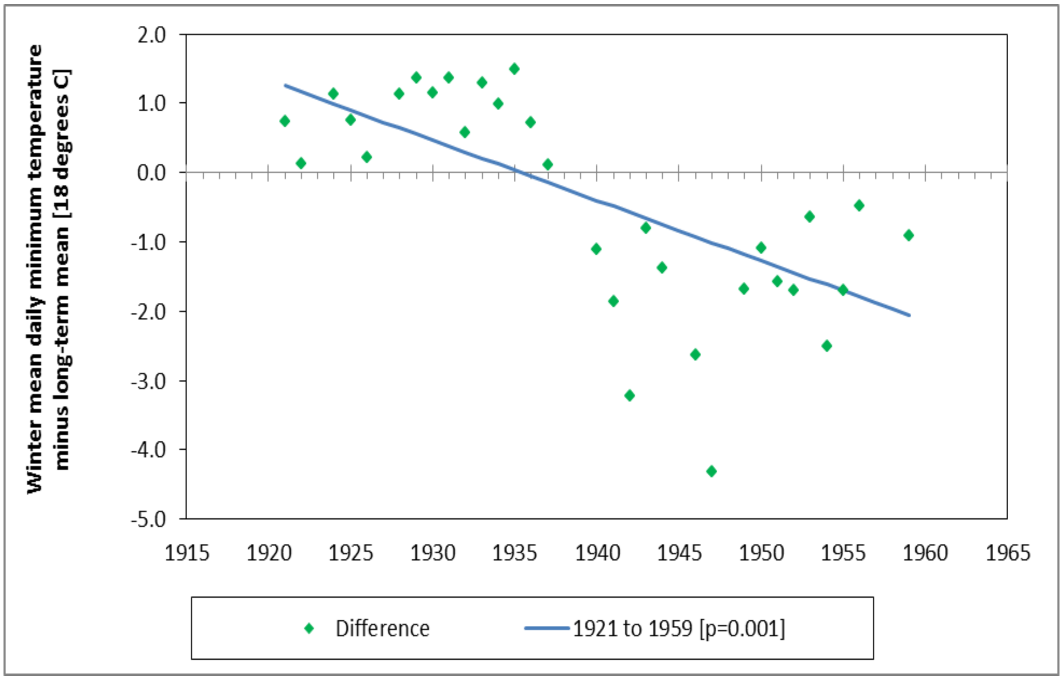

Figure F.33 Trend results and winter mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (18 degrees C) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1921 to 1959.

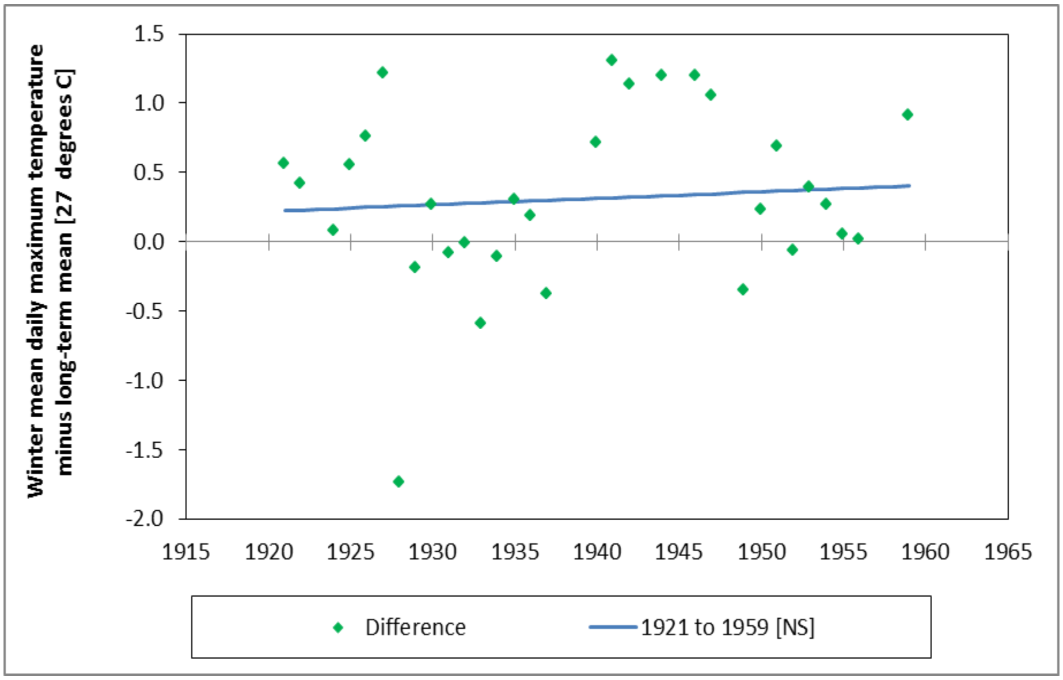

Figure F.34 Trend results and winter mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (27 degrees C) for the station, Napoopoo 28. The zero line represents the mean calculated over the period of record, 1921 to 1959.

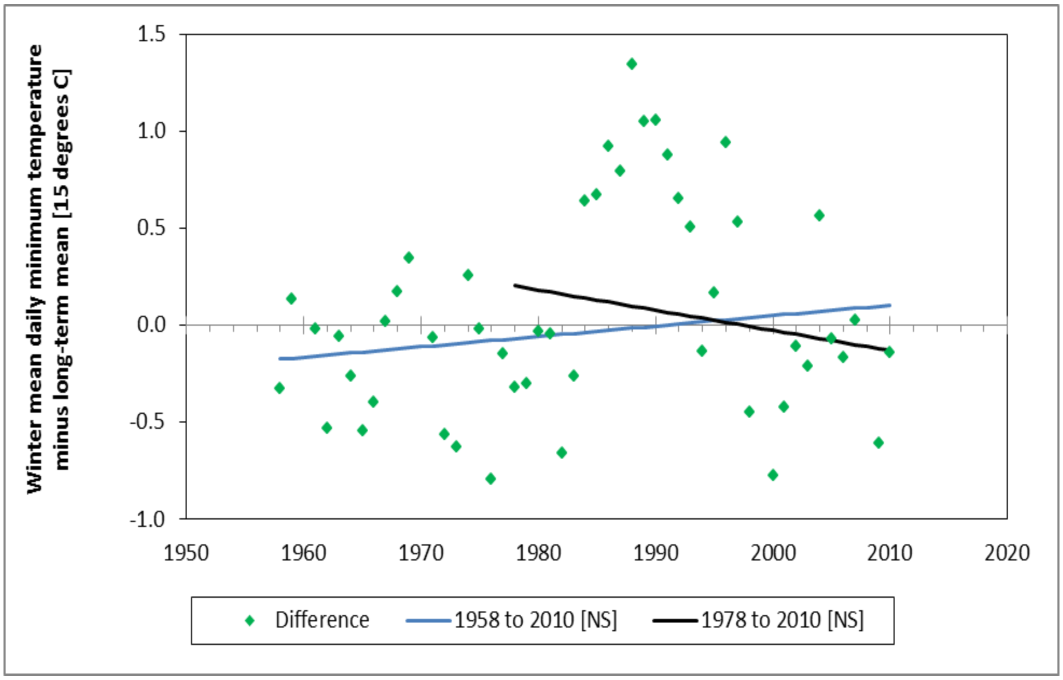

Figure F.35 Trend results and winter mean daily minimum temperature differences when compared to the long-term mean daily minimum temperature (15 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1958 to 2010.

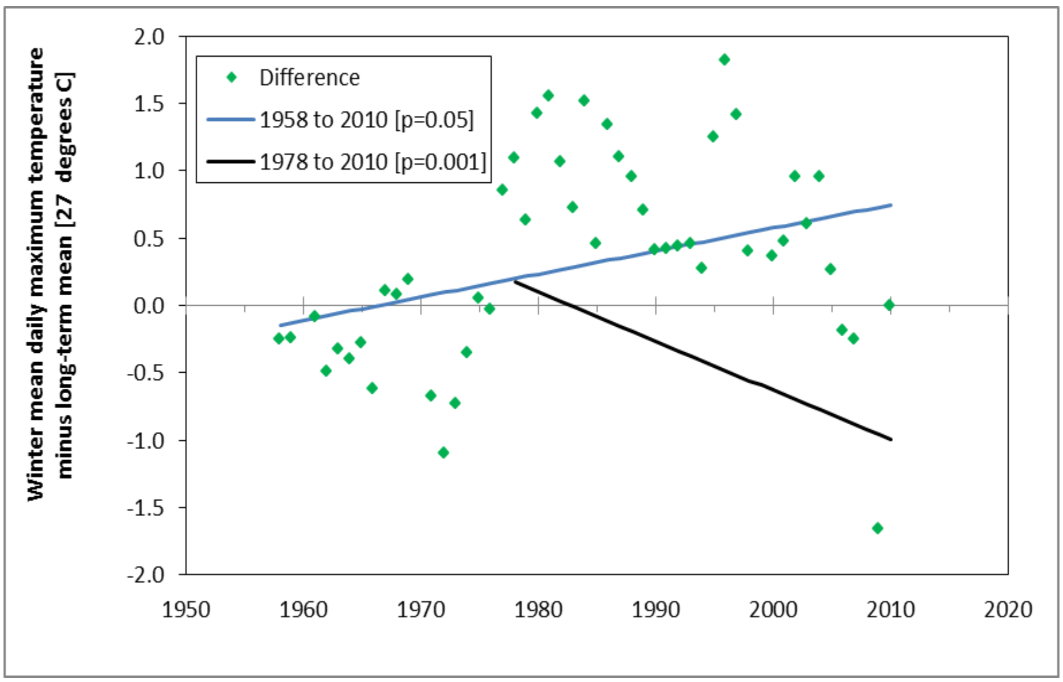

Figure F.36 Trend results and winter mean daily maximum temperature differences when compared to the long-term mean daily maximum temperature (27 degrees C) for the station, Opihihale 2 24.1. The zero line represents the mean calculated over the period of record, 1958 to 2010.

APPENDIX G: DOUBLE MASS ANALYSIS

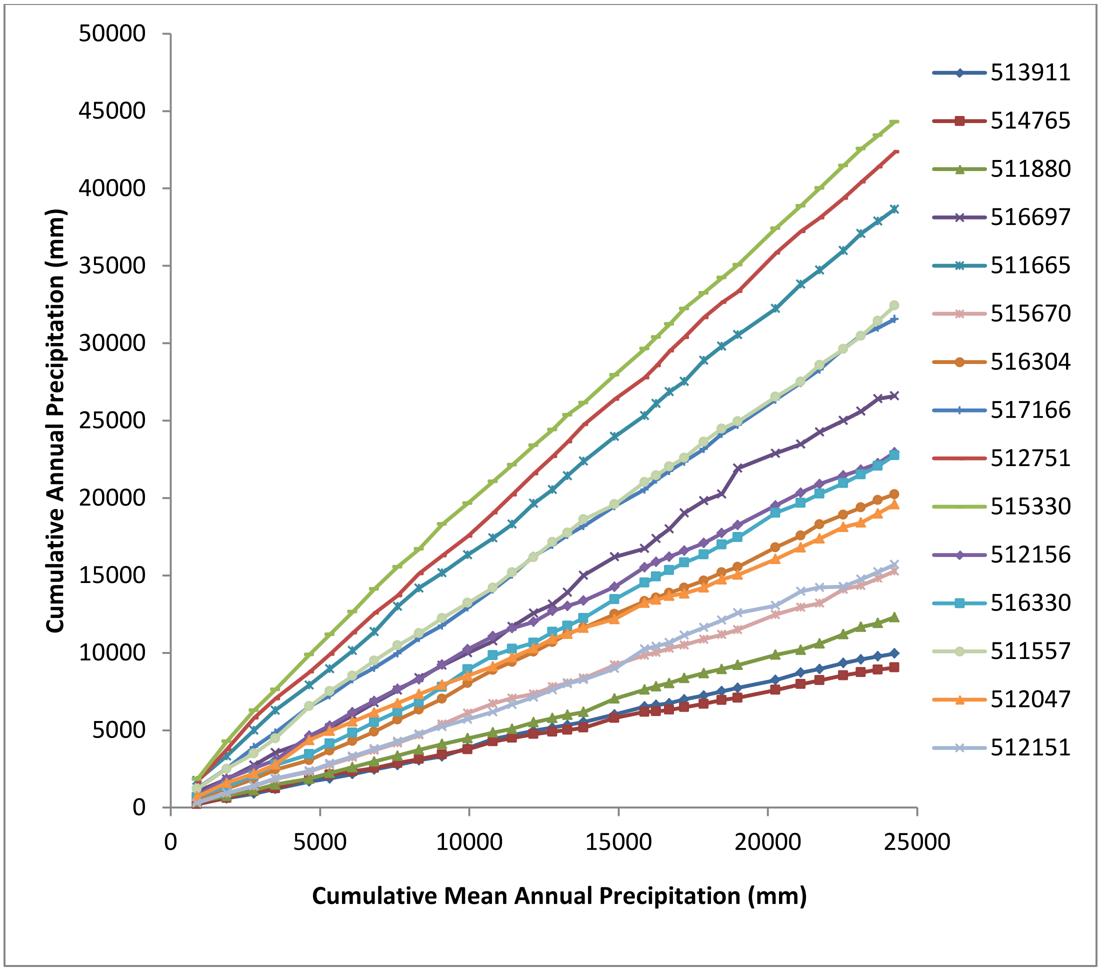

Figure G.1 Double mass analysis of precipitation from stations located within the Kona recharge area from 1978 to 2010. The stations range from 6 meters to 2354 meters in elevation. The stations in increasing elevation order are : Ke-Ahole Point 68.13 (513911), Kona Village 93.8 (514765), Honokohau Harbor 68.14 (511880), Napoopoo 28 (516697), Honaunau 27 (511665), Mahaiula 92.7 (515670), Milolii 2.34 (516304), Opihihale 2 24.1 (517166), Kainaliu 73.2 (512751), Lanihau 68.2 (515330), Huehue 92.1 (512156), Moanuiahea 69.24 (516330), Holualoa 70 (511557), Honuaula 71 (512047), and Hualalai 72 (512151). The mean annual precipitation is calculated using annual precipitation amounts for the stations being compared in the graph.

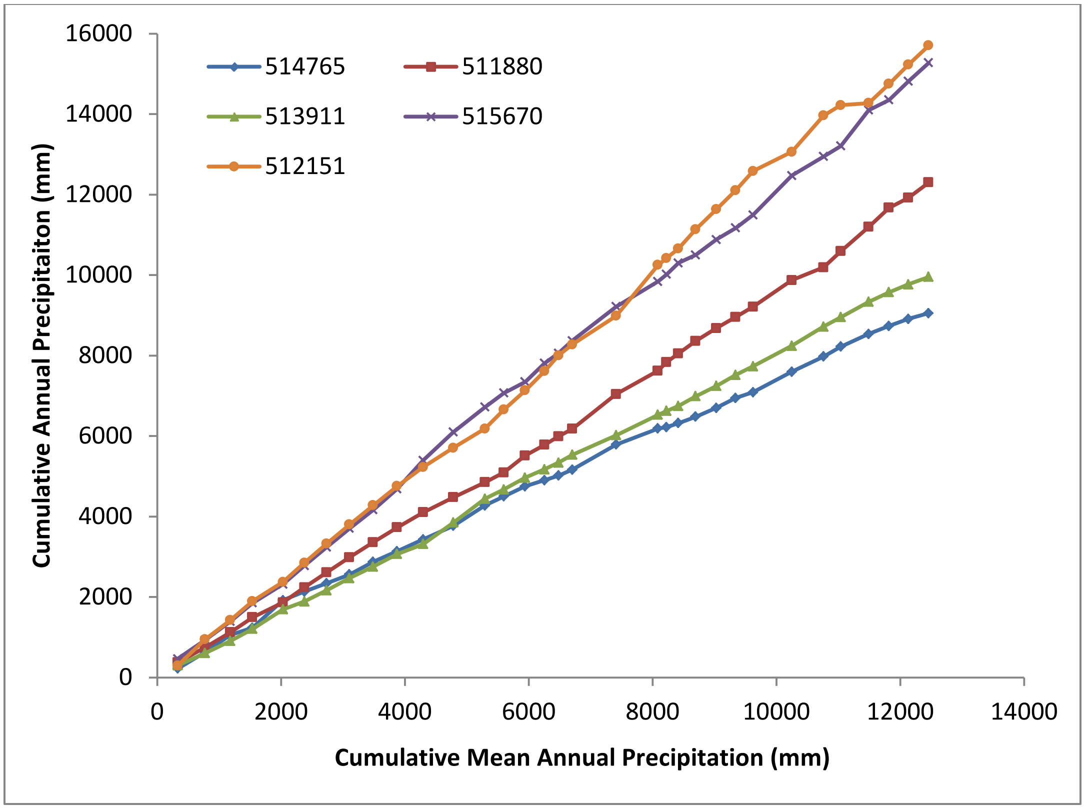

Figure G.2 Double mass analysis of precipitation from first subgroup of stations located within the Kona recharge area from 1978 to 2010. These stations are located at elevations between 6 meters and 2354 meters. The stations arranged in order of increasing elevation are Ke-Ahole Point 68.13 (513911), Kona Village 93.8 (514765), Honokohau Harbor 68.14 (511880), Mahaiula 92.7 (515670), and Hualalai 72 (512151). The mean annual precipitation is calculated using the annual precipitation amounts for the stations being compared in the graph.

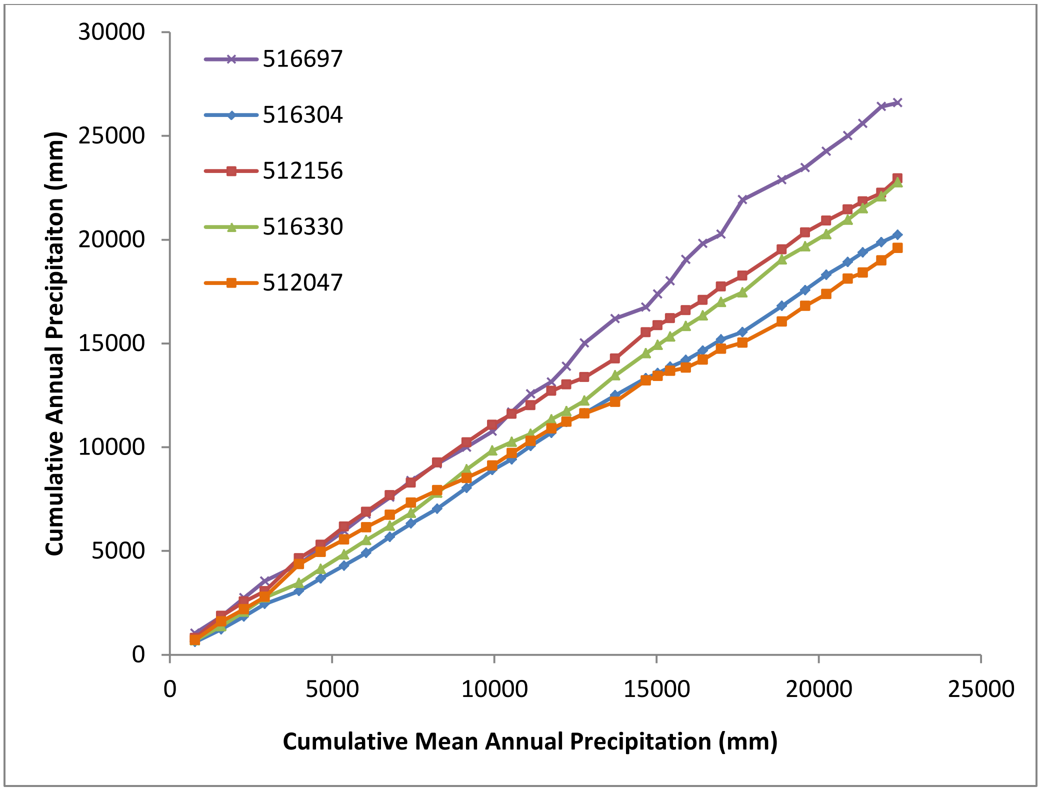

Figure G.3 Double mass analysis of precipitation from second subgroup of stations located within the Kona recharge area from 1978 to 2010. These stations are located at elevations between 122 meters and 1905 meters. The stations arranged in order of increasing elevation are Napoopoo 28 (516697), Milolii 2.34 (516304), Huehue 92.1 (512156), Moanuiahea 69.24 (516330), and Honuaula 71 (512047). The mean annual precipitation is calculated using the annual precipitation amounts for the stations being compared in the graph.

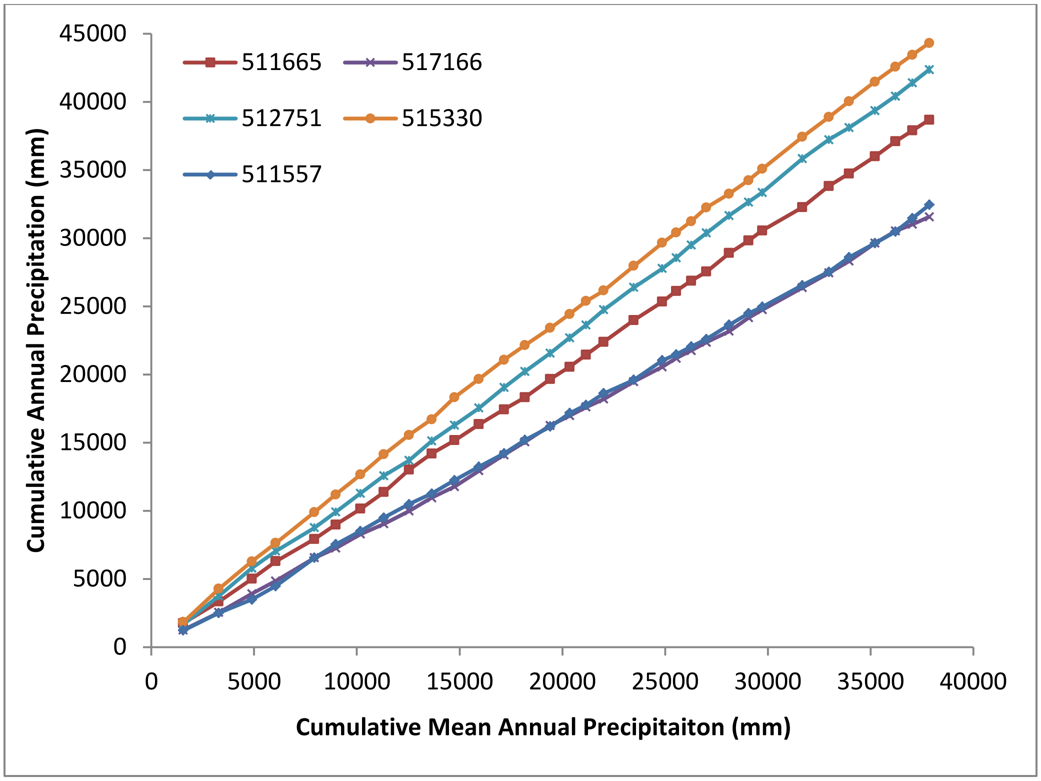

Figure G.4 Double mass analysis of precipitation from third subgroup of stations located within the Kona recharge area from 1978 to 2010. These stations are located at elevations between 287 meters and 982 meters. The stations arranged in order of increasing elevation are Honaunau 27 (511665), Opihihale 2 24.1 (517166), Kainaliu 73.2 (512751), Lanihau 68.2 (515330), and Holualoa 70 (511557). The mean annual precipitation is calculated using the annual precipitation amounts for the stations being compared in the graph.

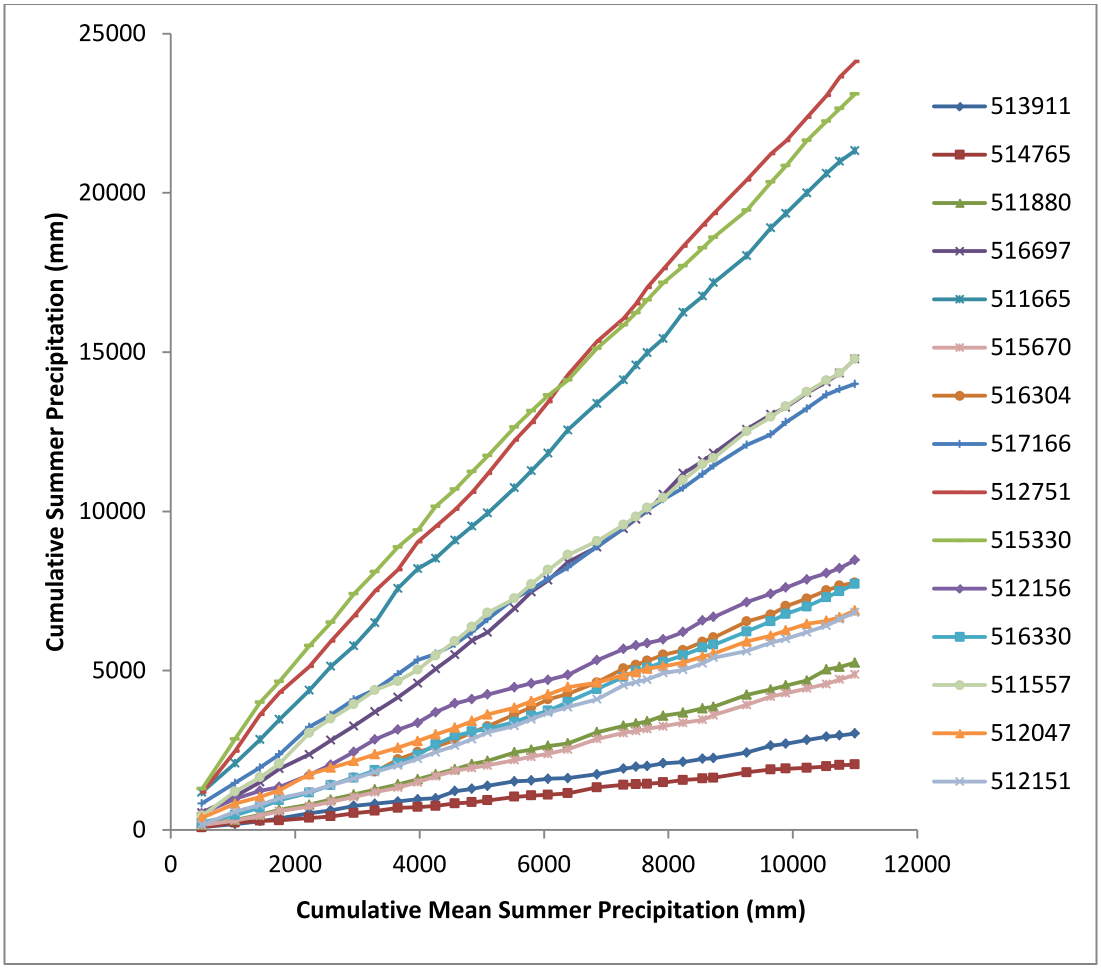

Figure G.5 Double mass analysis of precipitation from stations located within the Kona recharge area from 1978 to 2010. The stations range from 6 meters to 2354 meters in elevation. The stations in increasing elevation order are : Ke-Ahole Point 68.13 (513911), Kona Village 93.8 (514765), Honokohau Harbor 68.14 (511880), Napoopoo 28 (516697), Honaunau 27 (511665), Mahaiula 92.7 (515670), Milolii 2.34 (516304), Opihihale 2 24.1 (517166), Kainaliu 73.2 (512751), Lanihau 68.2 (515330), Huehue 92.1 (512156), Moanuiahea 69.24 (516330), Holualoa 70 (511557), Honuaula 71 (512047), and Hualalai 72 (512151). The mean summertime precipitation is calculated using summer precipitation amounts for the stations being compared in the graph.

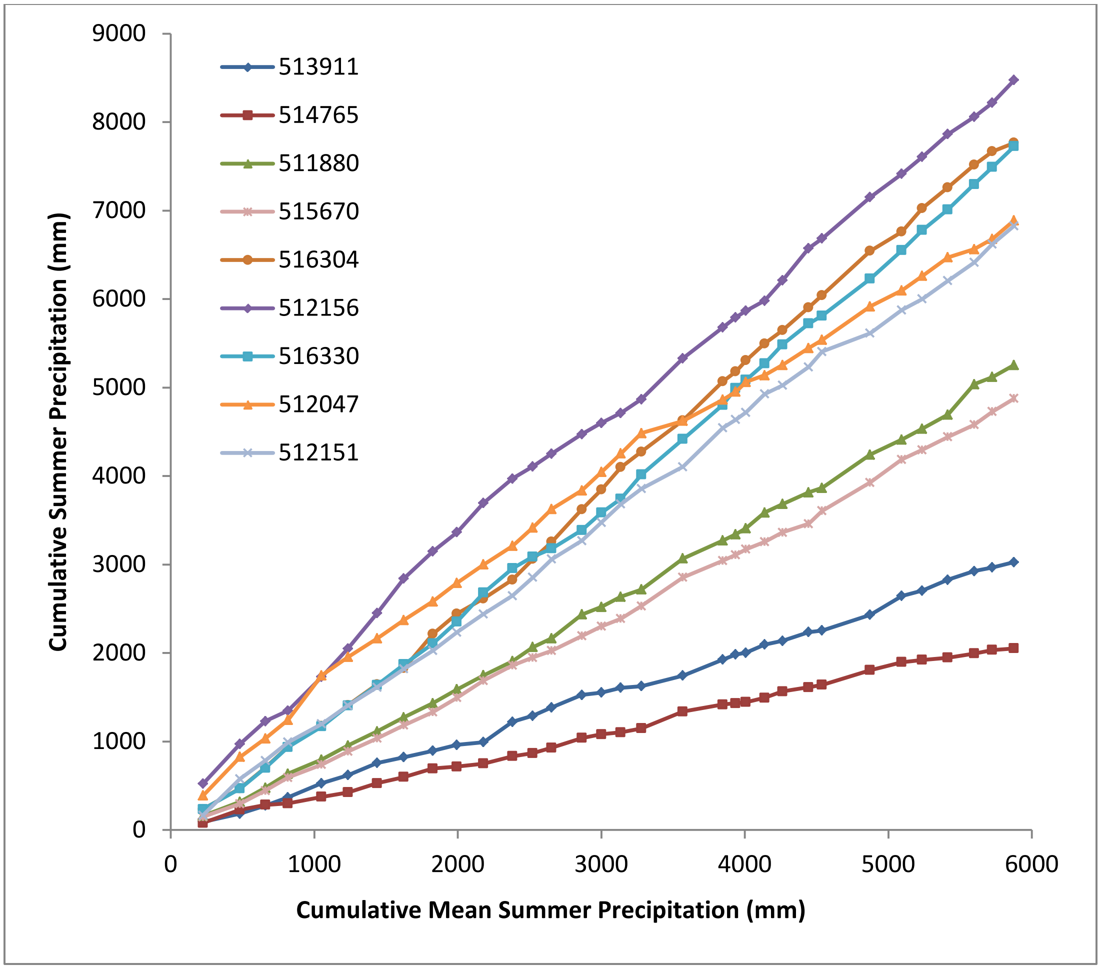

Figure G.6 Double mass analysis of precipitation from first subgroup of stations located within the Kona recharge area from 1978 to 2010. The stations range from 6 meters to 2354 meters in elevation. The stations in increasing elevation order are : Ke-Ahole Point 68.13 (513911), Kona Village 93.8 (514765), Honokohau Harbor 68.14 (511880), Mahaiula 92.7 (515670), Milolii 2.34 (516304), Huehue 92.1 (512156), Moanuiahea 69.24 (516330), Honuaula 71 (512047), and Hualalai 72 (512151). The mean summertime precipitation is calculated using summer precipitation amounts for the stations being compared in the graph.

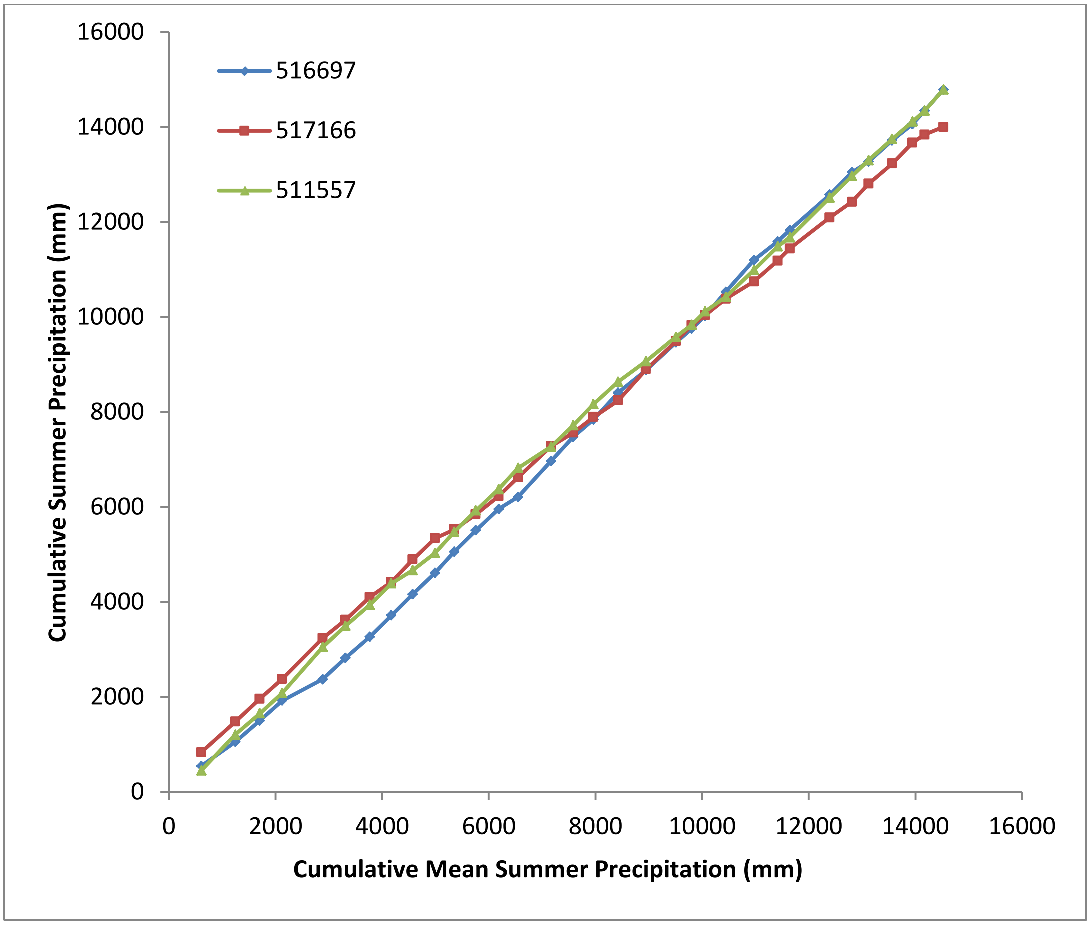

Figure G.7 Double mass analysis of precipitation from second subgroup of stations located within the Kona recharge area from 1978 to 2010. The stations range from 122 meters to 982 meters in elevation. The stations in increasing elevation order are : Napoopoo 28 (516697), Opihihale 2 24.1 (517166), and Holualoa 70 (511557). The mean summertime precipitation is calculated using summer precipitation amounts for the stations being compared in the graph.

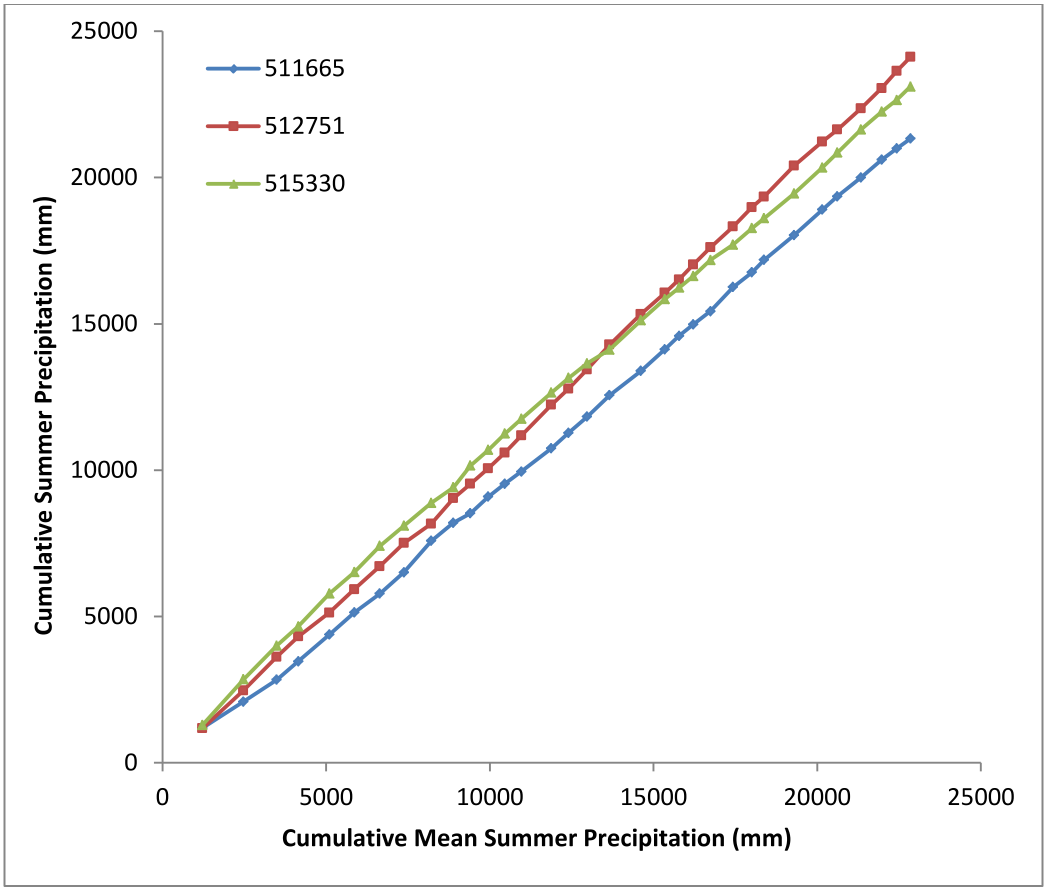

Figure G.8 Double mass analysis of precipitation from third subgroup of stations located within the Kona recharge area from 1978 to 2010. The stations range from 287 meters to 466 meters in elevation. The stations in increasing elevation order are : Honaunau 27 (511665), Kainaliu 73.2 (512751), and Lanihau 68.2 (515330). The mean summertime precipitation is calculated using summer precipitation amounts for the stations being compared in the graph.

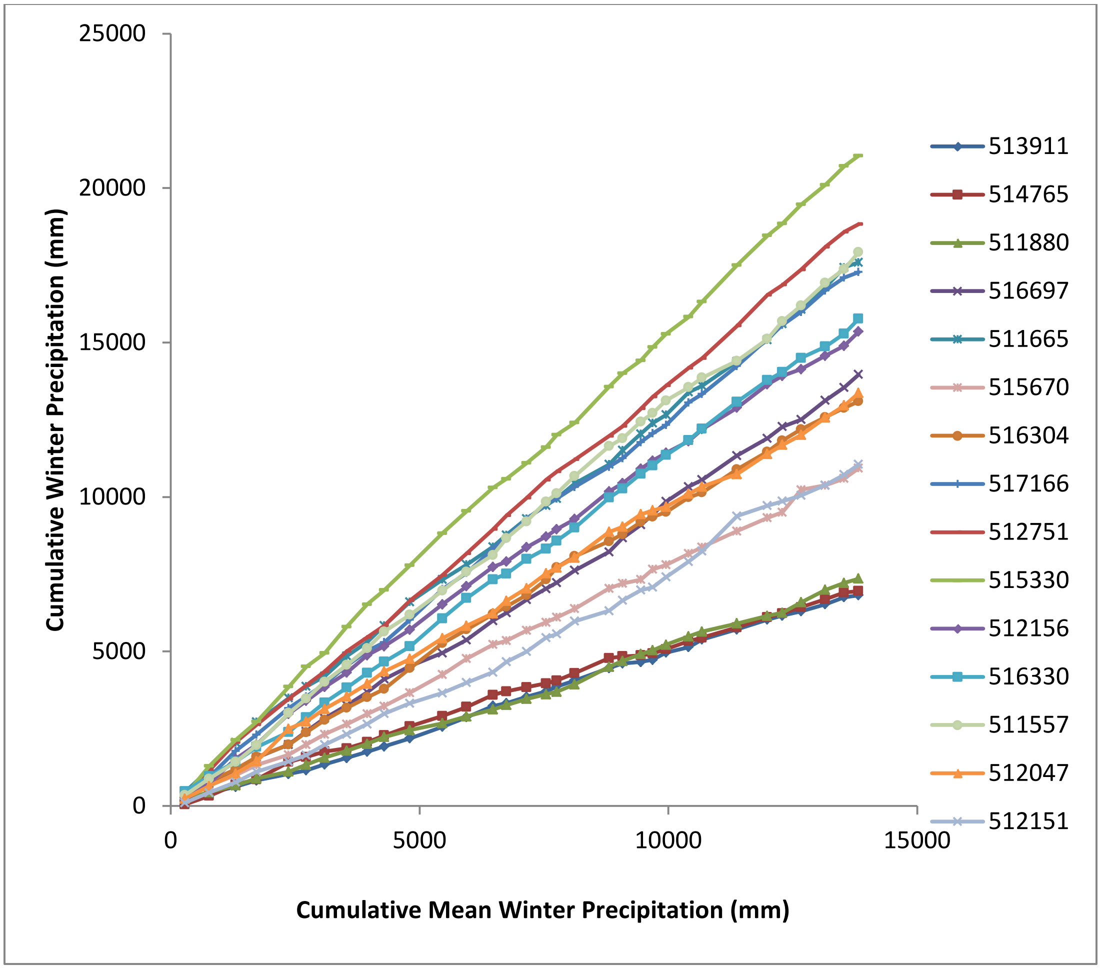

Figure G.9 Double mass analysis of precipitation from stations located within the Kona recharge area from 1978 to 2010. The stations range from 6 meters to 2354 meters in elevation. The stations in increasing elevation order are : Ke-Ahole Point 68.13 (513911), Kona Village 93.8 (514765), Honokohau Harbor 68.14 (511880), Napoopoo 28 (516697), Honaunau 27 (511665), Mahaiula 92.7 (515670), Milolii 2.34 (516304), Opihihale 2 24.1 (517166), Kainaliu 73.2 (512751), Lanihau 68.2 (515330), Huehue 92.1 (512156), Moanuiahea 69.24 (516330), Holualoa 70 (511557), Honuaula 71 (512047), and Hualalai 72 (512151). The mean wintertime precipitation is calculated using winter precipitation amounts for the stations being compared in the graph.

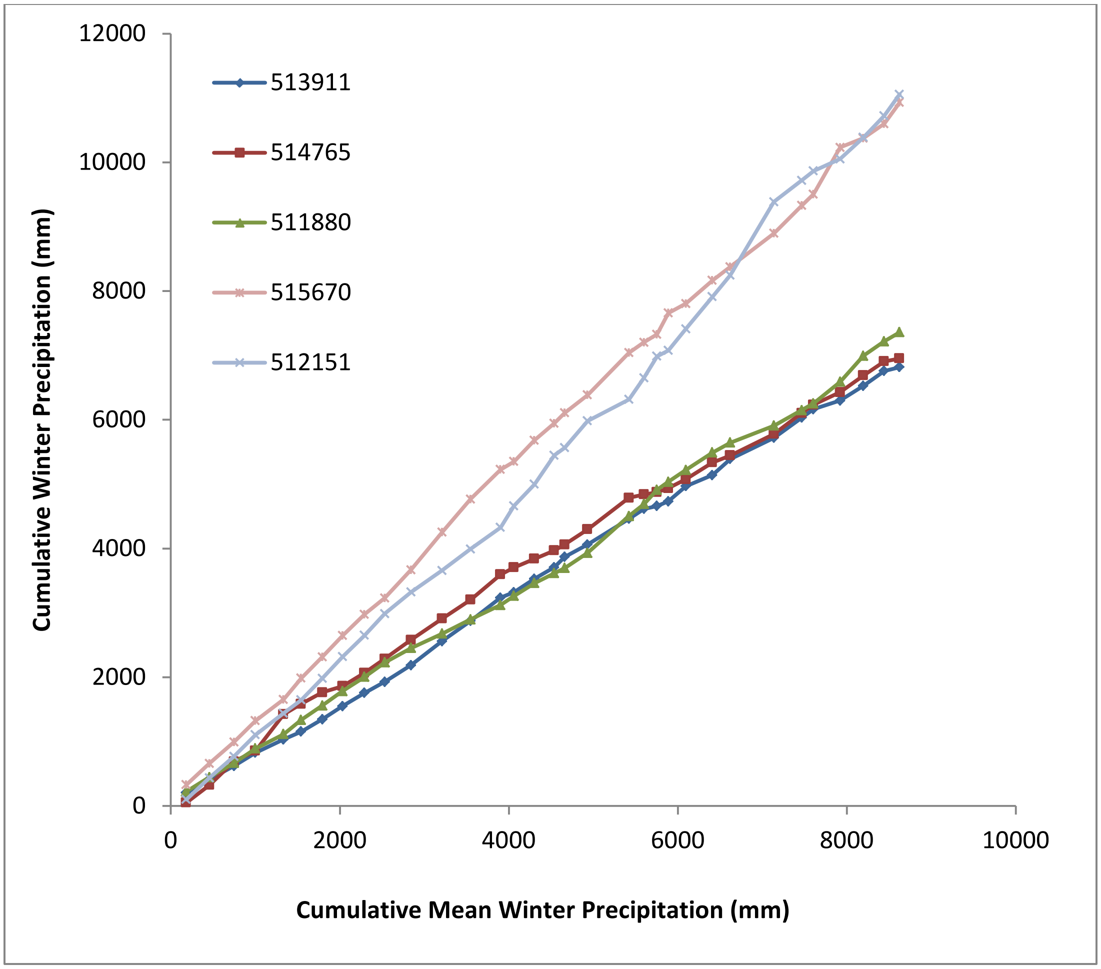

Figure G.10 Double mass analysis of precipitation from the first subgroup of stations located within the Kona recharge area from 1978 to 2010. The stations range from 6 meters to 2354 meters in elevation. The stations in increasing elevation order are : Ke-Ahole Point 68.13 (513911), Kona Village 93.8 (514765), Honokohau Harbor 68.14 (511880), Mahaiula 92.7 (515670), and Hualalai 72 (512151). The mean wintertime precipitation is calculated using winter precipitation amounts for the stations being compared in the graph.

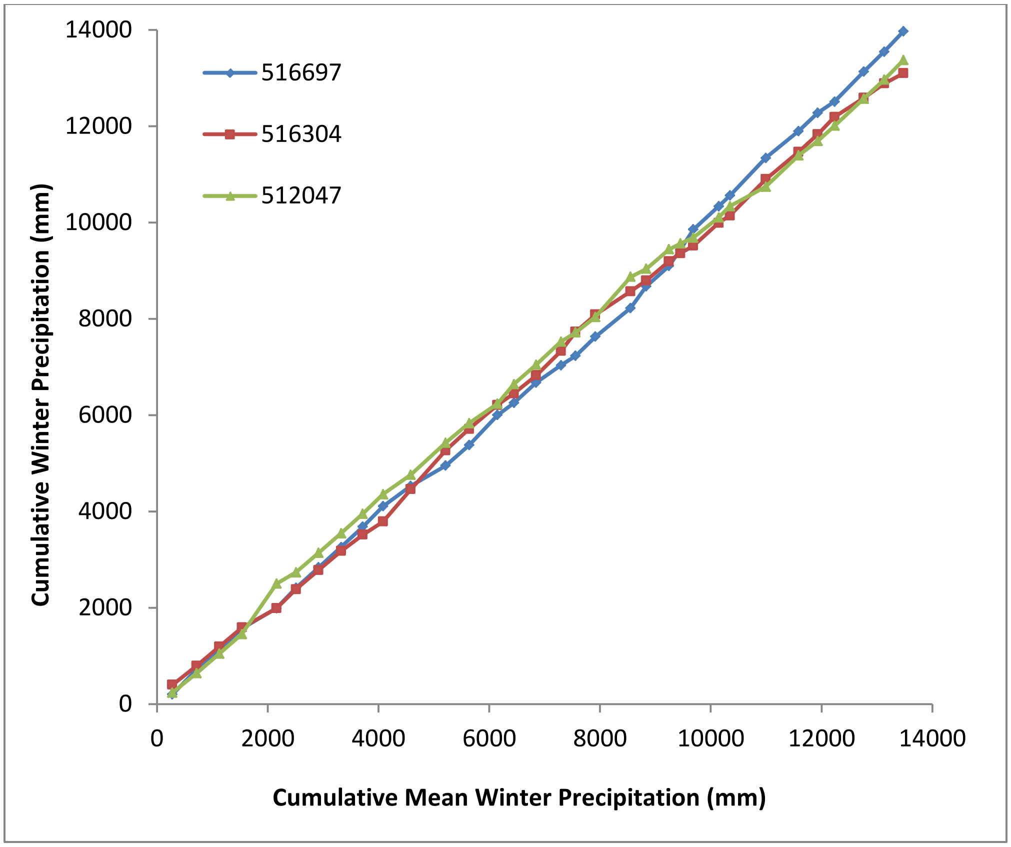

Figure G.11 Double mass analysis of precipitation from the second subgroup of stations located within the Kona recharge area from 1978 to 2010. The stations range from 122 meters to 1905 meters in elevation. The stations in increasing elevation order are: Napoopoo 28 (516697), Milolii 2.34 (516304), and Honuaula 71 (512047). The mean wintertime precipitation is calculated using winter precipitation amounts for the stations being compared in the graph.

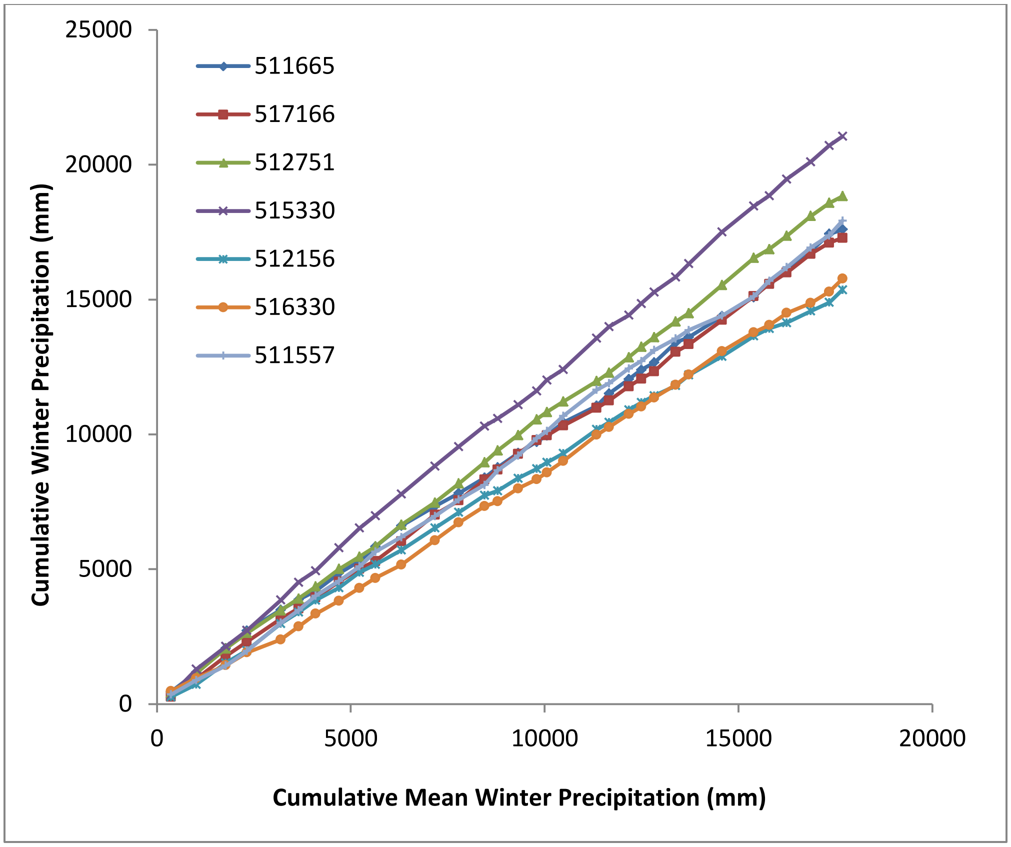

Figure G.12 Double mass analysis of precipitation from the third subgroup of stations located within the Kona recharge area from 1978 to 2010. The stations range from 287 meters to 982 meters in elevation. The stations in increasing elevation order are : Honaunau 27 (511665), Opihihale 2 24.1 (517166), Kainaliu 73.2 (512751), Lanihau 68.2 (515330), Huehue 92.1 (512156), Moanuiahea 69.24 (516330), and Holualoa 70 (511557). The mean wintertime precipitation is calculated using winter precipitation amounts for the stations being compared in the graph.