HIGH ALTITUDE CLIMATE OF THE ISLAND OF HAWAI'I

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Sara Couto Da Silva

Thesis Committee:

Steven Businger, Chairman

Tom Schroeder

Thomas Giambelluca

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Meteorology.

THESIS COMMITTEE

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Chairman

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Abstract

This thesis describes the results of a climatological investigation of observations taken at the Mauna Loa Observatory from 1958 through 2010 and observations taken at the summit of Mauna Kea from 1982 through 2010. In addition to diurnal and annual cycles, and the inter-annual variability associated with ENSO, the extremes in temperatures and wind are also presented. Finally, the relationship between the climates of Mauna Loa and Mauna Kea is described. It is observed that both Mauna Kea summit and MLO have two seasons, Hoo-ilo and Kau. During the Hawaiian summer the temperatures are warmer, the trade wind pattern dominates the wind flow and dry weather is likely. During Hawaiian winter, the passage of mid latitude fronts, Kona storms and also the weakening of the trades, bring wetter conditions, lower temperatures, and stronger winds to the islands. The wind blows the majority of the time from the Northeast through the East at Mauna Kea summit while it blows mainly from the Southeast at MLO. During the Hawaiian winter the wind shifts at both sites to directions to a westerly direction, influenced by the passage of frontal systems and storms, while during Hawaiian summer the wind blows mainly from easterly directions, influenced by the enhanced Hawaiian High Pressure. A strong mountain – valley circulation is observed at MLO that is not observed at the Mauna Kea summit. Both sites are influenced by ENSO phases. During El Niño the winters are drier and warmer, and during La Niña the winters are wetter and cooler when compared to climatological values. The prevailing wind directions change with ENSO phases as well, being more from the easterly directions during La Niña and westerly during El Niño.

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Chapter 1: Introduction

The island of Hawai'i has two massive mountains that shape the weather and climatology of the whole island. Mauna Kea and Mauna Loa, meaning "the white mountain" and "the wide mountain," respectively, were the home of the gods in ancient Polynesian religion and culture (Fig. 1). Due to their altitude they were seen to belong to the realms of the heavens and Hawaiians kept them as sacred places. Nowadays these two sites are ideal locations for astronomy and atmospheric research.

The summits of Mauna Kea and Mauna Loa are classified as polar tundra climate according to Koppen's climate classification (James, 1922). Temperatures below freezing can occur at any time of the year. The summits are arid, without vegetation or animal life, even though a variety of small bugs inhabit these summits year round (Eiben and Rubinoff 2010).

Mauna Kea summit, at the altitude of 4,206 meters (13,799 feet, 19.8°N latitude, 155.5°W longitude), is home for more than thirteen ground based astronomical observatories (Fig. 2). Two of these observatories provided the data for a recent climatology study (Da Silva and Businger 2006). The results for CFHT and UKIRT show that the temperature at Mauna Kea summit varies between -5°C to 5°C. The relative humidity is low at every month of the year, never reaching an average value higher than 40%. Cold, cool and dry weather year round make Mauna Kea summit the perfect location for astronomy observations.

The Mauna Loa Observatory (MLO) is not located on the summit of Mauna Loa, but on the north slope of the mountain at an altitude of 3397 meters (11,141 feet, 19.3°N latitude, 155.3°W longitude). Thus, MLO presents warmer weather and a warmer climatology than Mauna Kea's summit. Because MLO is located on the north slope of Mauna Loa, it experiences diurnal mountain-valley circulations, with upslope flow during the afternoon and downslope flow at night (Price, and Pales, 1963).

The Hawaiian Islands are at a distance >3000 km from a continental mass, and therefore, the ocean acts as a thermostat for temperature and relative humidity variations throughout the year over Hawaii. The subtropical latitude of the islands reduces the amplitude of the annual cycle in temperature. The result for Mauna Kea summit and MLO is that the diurnal variation in temperature is larger than the annual variation.

High – Altitude Climate of the Island of Hawai'i

The northern hemisphere branch of the Hadley circulation dominates the weather of the Hawaiian Islands. The Hadley circulation, starting from 5°N to 10°N, depends on the location of the ITCZ (Inter – tropical Convergence Zone) march following the sun. It is characterized by convergence at the surface and rising motion. This air descends north of Hawai'i at around 30°N. The Hadley cell is driven by solar radiation and its northward extension reaches the Tropics (Riehl, 1958). Its causes subsidence in air over the Islands of Hawai'I and this subsidence influences the main weather and climate patterns of the islands.

The trade wind inversion is observed to be present over Hilo 82.3% of the time, with a base height of 2255 meters and a thickness of 281 meters (Cao et al, 2006). Cao has also found that the inversion base and presence have strong annual cycle and also are influenced by the inter-annual variability phenomenon ENSO, that oscillates between El Niño (warm) and La Niña (cold) phases.

Mauna Kea summit and MLO are located above the trade-wind inversion, which caps moisture below, frequently resulting in fair skies over both places. Since the moisture is trapped below the inversion, clouds and precipitation are generally restricted to lower slopes of the volcano. The summit of Mauna Kea, which has a relatively easy access road, and is characterized by clear skies, makes it a preferred site for astronomical observations.

The prevailing Hawaiian anticyclone moves with the sun, northward during northern hemisphere summer and southward during northern hemisphere winter. The motion of the Hawaiian high results in two main seasons in Hawai'i. These are Hoo-ilo (cool season) and Kau (warm season). During Hoo-ilo (November – April), the semi-permanent high is weakened, and the weather in Hawai'i is influenced by winter storms crossing the north Pacific, Kona storms, cold fronts and upper level lows. During Kau (May - October) the anticyclone has shifted north and trade winds dominate the weather, the temperature is warmer and the rainfall is even more infrequent.

The weather at Mauna Kea summit and MLO are subject to significant inter – annual variability associated with ENSO (Da Silva, 2006). During El Niño (warm phase) the weather at both Mauna Kea summit and MLO is drier, warmer and the winds blow in a more westerly direction. During the cold phase of ENSO, La Niña, the weather is cooler, wetter and easterly winds prevail.

Giambelluca et al. (2008) have looked at secular temperature changes in diverse locations in Hawai'i and concluded that over time temperature has been increasing since the 70's, and this increase is greater at higher elevations. Giambelluca et al. (2008) also show that Hawai'i temperature variations are coupled with Pacific Decadal Oscillation of sea surface temperatures over the North Pacific Ocean. The overall drought trend for precipitation is on the Island of Hawaii upward, meaning drier conditions will become more frequent in time (Chu et al., 2010), meanwhile the trends present local and regional variations.

The high mountains of the Island of Hawai'i, above 2000 feet of altitude are known for clear skies and scant precipitation. It is in these regions that the lowest temperatures of the state are observed. Also precipitation does not happen often and it is likely to be in the form of snow or ice commonly. The annual mean for Mauna Kea rainfall is said to be around 204mm per year (Department of Geography, 2011, Rainfall Atlas of Hawai'i). Mauna Loa Observatory is observed to be located at a region in which rainfall mean values are in between 500 and 1000 inches contour lines described by Giambelluca and Schroeder, 1996 (Rainfall Atlas of Hawai'i) and (Nullet, et al, 1995).

There are two main seasons in Hawai'i, Hoo-ilo or Hawaiian winter, a seven months season usually, from October through April, and Kau or Hawaiian summer, a five months season, from May through September. There is a steady trade wind pattern in Hawaiian summer that prevails 80 – 95% of the time, while in the winter this pattern is observed to prevail as 50% or less (Bluemenstock and Prince, 1967).

In the winter the weather is affected by winter storms, upper-level lows, Kona storms, and the displacement southward of the jet stream.

In Tropical regions the most variable climate component is precipitation, because it varies abruptly in time and space. Temperature gradients are spatially small. Wind patterns are spatially variable as well because geography and orography play an important role in their formation and maintenance.

Motivations and Goals

The high-altitude ecology on Mauna Loa and Mauna Kea is unique. The Islands of Hawaii contemplate vast regional and spatial variability in climate and ecology. This happens partly due to the orographic nature of the islands. The orography of the islands changes abruptly from seas side to mountaintops in only several miles of extension. Local climate plays an important part in defining this ecology. As the summit of Mauna Kea experiences continued and expanded use from the astronomy community and the general public (Price, 1993) it is increasingly important to understand and protect this fragile ecosystem. This study is a step towards understanding the variability of the weather and climate and potential trends by analyzing the available observational record at the summit of Mauna Kea and on the north slope of Mauna Loa. It is known that some fragile animal life is sustained at the summit of Mauna Kea, such as Wekiu Bug. To understand how this bug survives arid conditions it is necessary to know about the climate and the weather of such regions (Eaton, 2012). Several questions arise regarding the climate of the Islands. We know about the climate of the sea level localities, what about high altitude climate? How do the climates of Mauna Kea and Mauna Loa evolve in time and how are they related? These two mountains play an important role in the weather and climate of the islands, how do they relate to each other? Are they evolving in the same way in time?

These are some of the questions that have inspired to develop this thesis. A comprehensive relationship between both places is important and useful to future studies and research.

Chapter 2. Data and Methods

The data used in this report were made available to us by the Mauna Kea UH 88 telescope and Mauna Loa Observatory (MLO). The available variables and dates in the data sets are provided in Table 1. For Mauna Kea we have used the longest data record available, which goes back to 1982. No data were collected before 1982 and even though the record is limited, containing only temperature, wind speed and direction, and relative humidity, the data are still useful as the results will show in Chapter 3. MLO data extend back to 1958 in monthly average precipitation and back to 1968 in daily average temperature. The more complete data set provided by MLO starts in 1977 and contains ten-minute data (see Table 1).

The data were quality controlled for each variable separately. There were non-valid values for each of the variables and also out of range values. Non-valid values include for example, negative wind speeds, relative humidity over 100%, dew points lower than negative 50°C, wind direction values over 360° or lower than 0. Out of range values include values that out of the range of variation for that specific variable. Examples of that is temperature of 200°C which is clearly a fault in the measurement of the temperature by the device itself. This validation was undertaken for all available data, removing the bad values for each variable.

After removing from the data sets, the non-valid values for each variable, another data control was implemented. In fact, many variables have default and error corrected values. These values were removed as well. Some variables needed to be validated and data controlled in pairs and groups such as horizontal wind. For these, such as wind speed and wind direction pairs of values, the validation needs to occur simultaneously. A valid wind value needs to contain both wind speed and wind direction for the same time and date; otherwise wind roses cannot be plotted correctly.

After the data were validated and data control was done, the next step was to work with the data and obtain results. For this several different methods were applied to the data. It is convenient to mention that MLO data was of better quality than Mauna Kea data. MLO data sets are temporal homogenous and of great density, while Mauna Kea data was scant and sparse at times, specially before 2007 when the collection of data started being automatic and analog instead of manually as from 1982 – 2003.

Standard deviation

Standard deviation is a measure of the variability of the data and it is important when working with averages and temporal data sets. Standard deviations were used when calculating yearly averages and monthly mean values (Eq. 1).

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \qquad (1)$$

Interpolating Missing Values, linear interpolation

When the observatories implemented changes in the collecting method, gaps occurred in the data record. The method used to estimate these missing values was by interpolation. This method was used for missing annual values only. It was not used for daily missing values or hourly missing values. The method used calculates missing data by estimating the following linear equation (Eq. 2).

$$y = y_a + \left(y_b - y_a\right)\frac{\left(x - x_a\right)}{x_b - x_a} \qquad \text{at point (x,y)} \qquad (2)$$

Statistics

In this thesis several statistical methods were used, diurnal, annual, inter-annual and also ENSO. We have used composites for the available data to study ENSO and the weather differences in El Niño and La Niña years. Composites are combinations of data that were collected under the same circumstances, meaning all El Niño years were combined, all La Niña years were combined and then compared to the climatology calculated from all available data. We have also used linear equations for the trends and least – square fit robust methods to obtain linear trends for each variable. For the ENSO composites, the index used was ONI used by

NOAA. The composites were constituted by weak, moderate and strong intensities for both phases of ENSO (warm and cold).

For weak El Nino, three years were considered, 1977, 2004, 2006. For moderate El Nino, there were considered six years, 1986, 1987, 1991, 1994, 2002, 2009. For strong El Nino we have considered two years, 1982 and 1997. For weak La Nina, three years were considered, 1984, 1995, 2000. For moderate La Nina, two years were considered, 1998 and 2007. For strong La Nina three years were considered, 1988, 1999 and 2010.

Chapter 3. Results for Mauna Kea

This Chapter and Chapter 4 describe the results of the research for Mauna Kea and Mauna Loa, respectively. For both Mauna Kea and MLO the study includes long-term variability and trends, annual and diurnal cycles, year-to-year variability and relationship with SST variability (ENSO). Therefore, these two Chapters of the thesis are organized in a similar manner.

The Mauna Kea UH 88 telescope is located at latitude of 19.8°N, longitude of 155.5°W and altitude of 4206 meters (12,799 feet). The UH88 data set extends from 1982 through 2011, with a period of missing data from 2004 to 2007, after which the observatory switched from hand-written to automated observations.

On Mauna Kea, the telescopes collect weather data, mainly because they are ultimately interested in knowing when the weather is dry and clear so astronomical observations can be done in the best of their abilities. Meanwhile the objectives of the astronomical observatories is sustained in the clear and dry weather and not much about precipitation, since when it's cloudy and rainy, the astronomers cannot observe space.

3.1 Long-term variability and trends

Temperature

The summit of Mauna Kea is cold year round. With an average temperature of 1.3˚C, the summit exhibits little variation throughout the twenty-nine years of collected data. In fact the standard deviation for the whole data set is very small, close to the unit value, δ = 0.8°C. For this time period the annual temperature minimum was in 2007, T_{min} = -0.8°C, while the maximum was found in 2010, T_{max} = 2.8°C. It is easy to see that the amplitude between these two values is ΔT = 3.5°C (Fig. 3), showing that temperature at the summit of Mauna Kea does not present large year-to-year variability. In fact, when the variability is studied in detail and regression analysis is applied, we see that the trend for the summit's temperature is practically flat, and does not show any particular trend of variation for the temperature. Applying a five-year running mean, in order to extract possible low frequency noise from the data, smooths the trend even more, making a tendency for the temperature something impossible to discern from the data.

Dew Point

Mauna Kea's summit is known for its arid climate. Even though the temperatures at the summit are fairly low the dew point temperatures are much lower. The dew point depression (difference between temperature and dew point temperature values at a given time) tends to be large all through the available data record. The average value for the dew point temperature for the twenty-nine year record is, dp = -17.4°C. The average dew point depression is more than 20˚C, indicative of the dry alpine climate at the summit. The dew point temperature does not vary much from year to year, with a standard deviation, δ = 2.9°C,. The highest annual average was found in 2007, dp = 11.8°C and the lowest in 2010 with dp = -24.2°C.(Fig. 4).

When the five-year running mean is applied to remove low-frequency variations, we observe that there is slight decreasing trend with time. Dew point temperature appears to be decreasing at a rate of – 1°C / decade, that indicates a very slight drying trend.

Horizontal Wind

At the top of Mauna Kea, the average wind speed is observed to be small. However, extreme high-wind events occur at times, particularly in winter when the polar jet comes nearer the island (see Appendix). The high elevation of the summit is in the free atmosphere, above the trade wind inversion. For the nearly thirty years of available data the wind speed at Mauna Kea's summit shows low variability. The maximum annual average wind speed was in 2010 at 9.2 m/s, while the minimum was in 1989 at 4.2 m/s, and the standard deviation of 1.3 m/s is small for the whole set of years (Fig. 5). The average wind speed for the entire data set from 1982 through 2012 is 5.8 m/s. When the five-year running mean and the regression analysis are applied we see an increasing trend for the wind speed over time.

The wind blows mainly from the east, which was expected since Hawaii is located in the trade belt of the Pacific. The prevailing directions observed are between NE and SE 56% of the time, leaving 44% of time for all other directions of the wind rose. The wind blows from the East around 8% of the time, spreading all other frequencies throughout the remaining directions (Fig. 6). Although the prevailing wind is trades, the wind variation at Mauna Kea's summit is sensitive to seasonal and ENSO influences more than year-to-year variability.

3.2 Annual Cycle and Diurnal Cycle

For each variable the annual cycle figures and diurnal cycle figures were calculated. They show us the mean variation for each variable and also the minimum and maximum. We have also included the tables that show the record maximum and the record minimum of each variable for the year period and the day / night period.

Temperature

In the tropics the annual solar radiation totals vary less than the diurnal solar radiation does. Therefore, temperature can vary more during a day than during a whole year in the tropics. The average annual cycle amplitude is smaller than the average diurnal cycle amplitude. In the data for Mauna Kea and Mauna Loa, the annual cycles are observed to change less than diurnal cycles.

Mauna Kea's summit has an annual temperature cycle, that peaks in September at 3°C, hottest month, and peaks in March at -0.5°C, the coolest month (Fig. 7), for an annual amplitude of only 3.5°C. The summer peak is delayed relative to the maximum solar forcing (June) by the proximity of the Pacific Ocean. The slowly varying sea surface temperature acts as a thermostat, dampens the air temperature variation, and delays the seasonal cycle.

During the day the solar radiation goes through a large range and this forces a large temperature diurnal cycle. In fact, we observe that the average diurnal amplitude is of 4.4°C, with the temperature peaking at 4.8°C at 1:00 PM, and then decreasing to 0.4°C at 3:00 AM (Fig. 8).

Dew Point

The dew point temperature is a measure of the moisture in the air and has application for assessing precipitation at the Mauna Kea summit. Cloud formation happens when dew point temperature and temperature reach the same value, meaning that the air becomes saturated. The difference between temperature and dew point at a certain time and place is called the dew point depression and it is a measure of the dryness of the air. Large dew point depressions occur when the air is dry and small dew point depressions occur when the air is moist.

Dew point temperature has a pronounced annual cycle, peaking in October at -15.4°C and with a minimum in January of -20.0°C. The average of the dew point temperature at Mauna Kea's summit is -17.4°C. Dew Point temperature increases from January through October, decreasing afterwards with the coming Hawaiian winter. Since the temperature of Mauna Kea's summit also decreases during the winter months, the dew point depression decreases for the coolest months of the year as well. Dew point temperature has a diurnal cycle that peaks during the hottest hours of the day and dips down at the coolest hours. The average for hourly dew point temperature is -20.7°C. The maximum of the hourly dew point temperature occurs at 2:00 PM,-14.3°C, while the minimum occurs at 5:00 AM, -23.3°C. Yearly, the amplitude for the average of daily temperature is 4.6°C, while the amplitude for the average of hourly temperature is 9.8°C (Fig. 9). The difference between the two values indicates that moisture in the air varies more in a day than through the year.

The diurnal dew-point temperature cycle ranges from -23˚C to -14˚C, with a mean of only -20˚C, indicating very dry conditions at the summit in the mean (Fig. 10), since the dew point depression is large and condensation requires temperature and dew point to be the same.

Wind

The wind at Mauna Kea is influenced by the Hawaiian High and the trade winds but also by storms that cross the Pacific Ocean especially in the winter when the polar vortex expands southward. The wind can change speed and direction very rapidly because local and synoptic weather patterns can influence Mauna Kea's wind circulation on a given day. Also, at Mauna Kea summit, the topography of the place influences local circulations. Pu'us spatial location, height and exposure to solar radiation affect local wind.

At Mauna Kea's summit, the wind blows at an average speed of 6 m/s. The average wind speed is does not change much during the year, with a fairly small amplitude of variation of 2.6 m/s (Fig. 11a). The daily average wind speed reaches a maximum in January at 7.6 m/s and slows down in September to 5.1 m/s.

The diurnal cycle of the wind speed at the summit of Mauna Kea exhibits a small amplitude and not a well defined structure. During the day the wind is likely to peak at around 6:00 AM at 7.7 m/s and to slows down around 12:00 AM to a minimum of 6.6 m/s, for a diurnal variation of only 1.1 m/s (Fig. 11b).

At the summit of Mauna Kea, the wind blows mainly from the east. The wind blows from the directions NE to SE 45 % of the time, and 8 % of the time the wind is blowing from due East (Fig. 12). The strongest winds occur in these eastern quadrants. A secondary region of enhanced wind speeds occurs from Northwest through Southwest. The wind blows from the North through SW 23 % of the time, showing that these directions of the wind rose have a relatively lower frequency of occurrence compared with easterly wind directions.

3.3 Year to Year variability and relationship with SST variability

EL Niño Southern Oscillation (ENSO) is a quasi-periodic coupled air-sea interaction phenomenon that influences the weather patterns and climatology all around the globe. ENSO has two phases, a warm one called El Niño and a cold one called La Niña. Both warm and cold phases represent a departure in the temperature of the Central Pacific Ocean. Usually ENSO recurs on a 2 to 8 years interval. The deviation from the climatological value for SST in Central Pacific Ocean determines the phase of ENSO. When the departure is positive, meaning SST is warmer than the climatological value then El Nino (Warm Phase) occurs. When the departure is negative then La Nina (Cold Phase).

During El Niño the temperature of the ocean is warmer than usual (climatology) which generates convection and precipitation over the central Equatorial zone, while in the periphery of this zone subsidence increases and air becomes more stable than climatology values. Hawaii is located in this drier area over the subtropical North Pacific.

During La Niña the temperature of the ocean is cooler than usual (climatology) the Hadley cell is weakened. Over equatorial regions the precipitation is less than climatology values while the periphery of this zone becomes wetter than climatology values. Hawaii is contained in this wetter area on the North Pacific (Trenberth, 1998).

We expect both alpine sites to be influenced by ENSO cycle, due to the proximity of the Islands to the central Pacific, where the anomalies occur. Chu (1995) has mentioned that the reason for Hawaii to experience dry events influenced by El Niño phase is due to the fact that during El Niño winters the jet stream extends to the east. The sinking motion during El Niño episodes is enhanced, which inhibits the propagation of frontal systems into the archipelago (Chu and Chen, 2005). This tendency is reversed when a La Niña episode is active, enhancing precipitation over the Islands. Meanwhile, there have been dry and wet winters in Hawai'i not associated with ENSO phases, but for the purposes of research we will focus on the influence of ENSO in the available variables.

Chu (1995) has conducted a study in which he observed that drought usually occurs in Hawaii in the Winter and Spring of the year immediately following the start of an El Niño event. The mechanism responsible for this is said to be the stronger Hadley Cell circulation at the times of warm ENSO phase. Because Hawaii is located at the subsidence branch of this general circulation, the stronger than usual subsidence is not favorable to the formation of Kona storms or the passage of midlatitude frontal rain bands, responsible for most of the winter rainfall across the Islands, specially in the drier areas.

ENSO classification depends on the intensity of the Oceanic Nino Index (ONI). This index is the departure in temperature from the climatologic values for the SST at Central Pacific. SOI < -1.5 corresponds to strong a El Niño. ONI (Oceanic Nino Index) between -1.0 to -1.4 corresponds to a moderate El Niño. An ONI smaller than -0.9 corresponds to weak El Niño. The same values are used in classifying La Niñas, but with positive anomalies. ONI is the index used by NOAA.

For the purpose of this study, we are interested in observing the relationship between the inter-annual variability of the alpine data in reference to SST variability. For this report, composites of strong ENSO years available were calculated and compared with the climatology values. Based on previous research, four different sets of winter months were used. November through April, November through March, December through March, December through February were the four sets of composites used. The comparisons were done for overall values (meaning the averages over these sets and respective climatology value for the same temporal range), annual cycle and diurnal cycle.

ENSO years and Climatology comparison

Temperature

The results show a clear departure from the climatology values and this departure is the greatest when the events are strong (Fig. 14). The departures from the climatologic values for the different sets of time ranges increase as the time set approach the three months, December, January and February.

For the strong El Niño and for the three months December through February the average temperature was 2.4°C while the climatologic value is 0.2°C and La Niña was -1.8°C.

For strong El Niño events composite the temperature was 2.4°C warmer than the climatologic temperature, and for strong La Niña events the temperature was 1.6°C cooler (Fig. 15). The departures in temperature diminishes in intensity as we enlarge the studied time set, and for November through April, El Niño departure was 1.8°C warmer and for La Niña the temperature was 1.4°C cooler than the climatology temperature for the same period of time.

The departures also vary with the intensity of the events, meaning that moderate and weak events for El Niño and La Niña the departures from climatology are smaller.

Dew Point

Dew point temperature departs from the climatology values in both El Nino and La Nina events. The departure is the greatest when the events are strong. For strong El Niño and for the three months December through February the average dew point temperature was -27.3°C while the climatological value is -19.9°C and La Niña was -14.8°C. For strong El Niño events composite the dew point temperature was 5.1°C cooler than the climatological temperature, and for strong La Niña events the dew point temperature was 7.4°C warmer (Fig. 16). For November through April composite, El Niño departure was 5.7°C warmer and for La Niña the dew point temperature was 5.1°C cooler than the climatology dew point temperature for the same period of time (Fig. 17).

Wind

The average of wind-speed departures from climatology increases as the time range approaches the three months, December, January and February. For the strong El Niño and for the three months December through February the average wind speed was 9.6 m/s while the climatological value is 7.3 m/s and La Niña was 5.1 m/s. For strong El Niño events composite for wind speed was 2.3 m/s stronger than the climatologic wind speed, and for strong La Niña events the wind speed was 2.3 m/s weaker (Fig. 18).

The departures for moderate and weak events are less than the results for strong events. Which leads us to suggest that the influence of ENSO is observed at Mauna Kea as early as November and lasts through April (Fig. 19).

The climatology wind directions between SE and NE occur with a frequency of 35%, of which 6% blows from due East. The secondary wind direction is between SW and NW and these occur with a frequency of 20%, of which 4% is due west (Fig. 20). These directions change with ENSO events. With the enhancement of the surface trades during El Niño, the winds aloft and at the summits comes more consistently from the west quadrant. The wind directions between NW through SW occur with a frequency of 46% from which 6 % blow from the west (Fig. 21). During La Niña the wind is blowing from NE through SE 40% of the time, of which 20% is from due East (Fig. 22).

Chapter 4. Results for Mauna Loa

Mauna Loa Observatory (MLO) is located at latitude of 19.3°N, longitude of 155.3°W and altitude of 3397 meters (11,141 feet). The MLO data runs from 1977 through 2011. For precipitation, a longer data set was available, from 1958 through 2008, as in monthly totals. A complementary data set was used, from 1968 through 2008, with daily averages.

Long-term variability and trends

Pressure

Pressure is a function of altitude and density of the air. Therefore, the pressure at MLO is substantially lower than at the sea level. At an altitude of 3397 meters, the annual mean pressure of MLO is 680.4 mbar. Calculating an estimate for the MLO pressure using temperature mean annual value (T = 7.1°C), altitude of MLO (z = 3397 m), a mean sea-level surface pressure (P = 1023 mbar), and with the hypsometric equation, we obtain

$$p_{MLO} = p_{surf} \times e^{\left(\frac{-g}{RT} \times \left(z_{MLO} - z_{surf}\right)\right)} \quad \text{(Eq. 7)}$$

Substitution gives, which is a good estimative of the mean annual pressure for MLO.

At MLO the average value for pressure over the ~thirty five years record is 680.4 mbar. Pressure varies very little during the year, and this is confirmed by the low standard deviation based in annual means, found in the available record, δ = 0.6 mbar. The maximum yearly average pressure value found was 682 mbar in 1983 and the minimum yearly average pressure value was 679.5 mbar in 2009. The amplitude of variation is Δ = 2.8 mbar (Fig. 23). Pressure does not vary too much from year to year. When a 5-year running mean is applied,

the tendency for pressure is decreasing at - 0.3 mbar / decade which is significant. Meanwhile, when we observe the ten-year and twenty-year trends we see that the slope of the trend oscillates. There are episodes during which the trend is positive and episodes during which it is negative, depending on the ten or twenty-year periods that have been chosen.

Temperature

At MLO, the average of temperature for the data set from 1977 through 2011 is 7.2°C. The temperature changes very little from year to year, presenting a small standard deviation of δ = 0.8°C. The warmest year was found to be 2010 at 8.7°C and the coolest year was 1978, 6 °C. For the data set the temperature variation between the warmest and the coolest years is 2.8°C (Fig. 24). When we apply the five-year running mean to remove the influence of low frequency variations from the data set we see that the temperature variations become smoother in time. Also, after applying regression analysis, temperature shows a warming trend of 1.5°C per decade or 0.15˚C per year.

Dew Point

MLO is a dry place, with a low average dew point temperature of -9.1°C. Even though dew point temperature varies more than temperature, this variation is still fairly small, δ = 1.8 °C. The average dew point depression is 16.2°C. The highest dew point temperature was found in 1982 at -5. 8°C and the minimum in 1983 of -13.3°C (Fig. 25). After applying five-year running mean and regression analysis, we observe that the trend over time is for dew point to slowly decrease at a rate of –0.02°C per decade.

Horizontal Wind

The average of annual wind speed for the Mauna Loa is 4.5 m/s. On average, wind speed changes little from year to year, resulting in a low standard deviation, of 0.3 m/s (Fig. 26). The windiest year was found to be 1996, 5.1 m/s, while the calmest was found to be 2007, 3.9 m/s. when applying five-year running mean and regression analysis we see that the trend for wind speed is practically flat, not being accurate to infer or conclude in this matter. At MLO, the wind blows mainly from

ESE through SSE, 25% of frequency. Of these 25% of frequency, 8% of the time the wind blows from Southeast (Fig. 27).

Precipitation

Precipitation is the most variable of the data sets. Not only is precipitation influenced by orography and mesoscale weather systems, it is also influenced by ENSO. For the available date set, from 1958 through 2008, precipitation shows high variability from year to year. Precipitation totals change abruptly from year to year. The wettest year was 1982 during which 1241 mm fell, while the driest was 1998 with only 65 mm. The amplitude of variation for the whole data set is 1176 mm, while the average precipitation is 447 mm (Fig. 28). When we apply the five-year running mean and regression analysis to the whole data set we see that precipitation shows a decreasing trend in time of -34.5 mm per decade which is a significant trend. The major peaks for precipitation were found 1982 and 1990 while the minimum were 1983, 1991 and 1998. This suggests that precipitation at MLO is becoming less frequent in time, but intense rain fall events still occur.

3.2 Annual Cycle and Diurnal Cycle

Pressure

At MLO the annual average pressure is 680.4 mbar, being the maximum average 681.5 mbar observed in August and the minimum in February, 678.9. The annual amplitude is 2.6 mbar. The diurnal amplitude at the same location is of 11.7 mbar, being the maximum 680.8 mbar observed at 10:00 AM and the minimum, 679.2 mbar at 4:00 AM (Fig. 29).

Pressure has a semi-diurnal cycle (Fig. 30). The average of hourly pressure maxima is 680.7 mbar, which occurs at 10:00 AM. The minimum is 679.2 mbar which occurs at 4:00 AM.

Temperature

Temperature follows a well-defined annual cycle, peaking during the summer months and with a minimum in winter for an amplitude of 4°C. At MLO, the average daily temperature is 7.2°C, the average maximum is 9.1°C in June and the minimum is 5.1°C in February (Fig. 31). The diurnal amplitude at the same location is of 6.8°C, the maximum is 11°C observed at noon and the minimum, 4.2°C at 5:00 AM (Fig. 32).

The average of daily temperature maxima is 11.1°C. The maximum occurs at 12:00 PM while the minimum, 4.5°C at 5:00 AM. The amplitude for the maximum temperatures is 6.6°C (Fig. 32).

Dew Point

At MLO, dew point temperature annual daily average is -9°C (Fig. 33). Dew point temperature peaks in September at -5.8°C , and dips down in January at -12.1°C. (Fig. 33). The annual amplitude of the average values is 6.3°C. The average hourly temperature peaks at -2°C, at 2:30 PM, dipping down at 5:00 AM to -14.7°C. The diurnal amplitude is 12.7°C (Fig. 34).

Wind

The wind speed at MLO blows at annual average of 4.5 m/s (Fig. 35). With stronger winds and more variability during the cool season. The diurnal cycle shows only small variation in the mean hourly winds, ranging from 3.9 to 4.7 m/s in a semi-diurnal pattern during the course of the day.

The average of daily wind speed is maximum in January at 5.4 m/s (Fig. 36) and the minimum in September at 3.6 m/s (Fig. 37). The amplitude of variation for the average of daily wind speed is 1.8 m/s.

Wind speed does not exhibit a well-defined diurnal cycle. The wind speed tends to be the highest during transition times, sunrise and sunset, and then the wind is likely to be mild all day long, except during passing synoptic disturbances. The average of hourly wind speed is maximum at 5:00 AM at 4.9 m/s and minimum 3.9 m/s occurs at 6:00 PM. The diurnal amplitude of variation is 1 m/s. The minimum wind speed average is 1.7 m/ while the diurnal minimum wind speed average is 0.01 m/s. The absolute maximum wind speed recorded is 21,9 in January while the absolute minimum is 0 m/s.

Precipitation

Precipitation shows significant variation through the year. It has a well-defined annual cycle. The average precipitation annual maximum value observed occurs in January, with 59 mm, and the minimum average value was found in June, at 12 mm (Fig. 38). March is the month where the maxima values are located, 396 mm while the month when the maxima were the lowest was June, with 61 mm (Fig. 39). The totals plot shows that January is the wettest month for the whole period of data with a total precipitation exceeding 3000 mm, while June was the driest month with a total of 600 mm. it is visible that the wettest months go from November through May with the exception of September and October that can be wetter than the common summer months (Fig.40).

ENSO years and Climatology Comparison

Pressure

For the strong El Niño and for the three months December through February the average pressure was 679.4 mbar while the climatologic value is 679.0 and La Niña was 678.7 (Fig. 41). For strong El Niño events composite the pressure was stronger 0.4 mbar than the climatologic value, and for strong La Niña events the temperature was 0.3 mbar weaker (Fig. 42). The departures increase as we increase the months included to November through April. The departures also vary with the intensity of the events, meaning that moderate and weak events for El Niño and La Niña the departures from climatology are less intense. From November through April the pressure departures for El Niño are larger than from December through February. This is not visible under La Niña conditions.

Temperature

The most significant changes occur during strong ENSO events (Fig. 43). For the strong El Niño and for the three months December through February the average temperature was 7.6°C while the climatologic value is 5.5°C and La Niña was 3.4°C. For strong El Niño events composite the temperature was 2.1°C warmer than the climatologic temperature, and for strong La Niña events the temperature was 2.0°C cooler (Fig. 44).

The departures diminish in intensity as we enlarge the studied time set, and for November through April, El Niño departure was 1.3°C warmer and for La Niña the temperature was 1.0°C cooler than the climatology temperature for the same period of time. The departures also vary with the intensity of the events, meaning that moderate and weak events for El Niño and La Niña the departures from climatology are less intense.

Dew Point

For the strong El Niño and for the three months December through February the average dew point temperature was -15.8°C while the climatologic value is -11.7°C and La Niña was -6.3°C (Fig. 45). For strong El Niño events composite the dew point temperature was 4.1 °C lower than the climatologic temperature, and for strong La Niña events the temperature was 5.5°C higher (Fig. 46). The departures diminish as we increase the time window. For November through April, El Niño departure was 2.6°C warmer and for La Niña the dew point temperature was 5.7°C cooler than the climatological dew point temperature for the same period of time.

Wind

For the strong El Niño and for the three months December through February the average wind speed was 4.5 m/s while the climatologic value is 4.8 m/s and La Niña was 5.4 m/s (Fig. 47). For strong El Niño events composite for wind speed was 0.3 m/s weaker than the climatologic temperature, and for strong La Niña events the wind speed was 0.9 m/s (fig. 48). The departures for moderate and weak events fluctuate little around the results for strong events, and there is not really a trend for the different time sets used.

The climatology wind directions comprised between SE and SW occur with a frequency of 50% from which 6 % blows from SE and 6% from SW (Fig. 49). El Niño events wind blows mainly from the directions compromised between S and W from which SW blows with a frequency of 10% (Fig. 50). During La Niña the wind is blows from S and E 48% of the time from which 10 % is from the East (Fig. 51).

Precipitation

Precipitation changes significantly with ENSO events. For the strong El Niño and for the three months December through February the average precipitation was 12.1 mm while the climatologic value is 50.6 mm and La Niña was 50.3 mm (Fig. 52). For strong El Niño events composite the precipitation was 38.4 mm less than the climatologic precipitation, and for strong La Niña events the precipitation was 0.3 mm more (Fig. 53).

Precipitation is highly influenced by ENSO. In fact the influence of EL Nino and La Nina in the winter months is greatly visible through the whole data set. The stronger the events the more likely it is to influence precipitation, even though there might be droughts and wet winters that are not coupled with ENSO influence and might be due to other atmospheric events. Winter storms and also Kona Lows are two of the major precipitation sources during Hawaiian weather. El Nino forces the winter storms to move away from the islands, while La Nina allows them to move more southerly bringing moisture and precipitation to the islands.

Chapter 5. Comparison between Mauna Kea and Mauna Loa

Mauna Kea summit and MLO have common geographic features, latitude, longitude. However, their altitudes differ as Mauna Kea observations are made at the summit, whereas Mauna Loa observations are from several thousand feet lower on the north slope of the mountain. Therefore, the results provided in this report show that they have different weather and climatology. In this Chapter we compare both locations in order to understand what the differences are.

Inter-annual Variability, Annual Cycle and Diurnal Cycle

The variables that are compared in this section include temperature, dew point temperature and horizontal wind.

Temperature

The inter-annual variability for both Mauna Kea summit and MLO are similar. The fluctuations of temperature values coincide with few differences; the hottest year for both was 2010 while the coldest year for Mauna Kea was 1989. The trend lines for both are in opposite directions, since MLO presents a slow warming over time while Mauna Kea summit presents stability in the trend and no tendency can be diagnosed at the moment (Fig. 54).

The temperature increases from the coolest month, February, for both Mauna Kea and Mauna Loa Observatory through June (Mauna Loa) and September (Mauna Kea). June, July, August and September are the hottest months, but the peak of summer for Mauna Kea and MLO are different, having Mauna Kea a delay in relation to Mauna Loa. Late winters are visible in both when the temperatures diminish for both places reaching the lowest value at February. The coldest months run from December through March (Fig. 55). The maximum for temperature also follow the annual cycle for temperature, being the maximum during June, July, August and September and there is not a month in which the temperature is highest than the other months, even for both locations the peak value occurs in June. The coolest maximum temperatures are February and March. The minimum temperatures peak in September for Mauna Kea and in June for Mauna Loa, while the minimum for minimum temperatures are observed in March for both sites.

The amplitude of the diurnal cycle is higher than the annual amplitude for both Mauna Kea and MLO and they both share the daily minimum at 5 AM before the sun rises. The maximum for MLO is around noon while for Mauna Kea has a delay to be observed around 1 PM (Fig. 56).

Dew Point

The changes in dew point at both MLO and Mauna Kea summit are related, even though the amplitude of the changes is larger at Mauna Kea. The lowest value for dew point temperature was 1982 while the highest was for Mauna Kea 2007 while for MLO was 1988. The trend show at both sites slow decrease in time for dew point temperature, and at Mauna Kea that decrease is slightly larger than for MLO (Fig. 57).

Dew point temperature follows the march of the sun having a pronounced annual cycle, the highest values for dew point are found in the summer months and later in the year when compared to temperature. The highest dew point temperature occurs at July, August, September and October for both sites. The maximum are found at July and August. The minimum occurs during the winter, particularly at January and February where the minimum are found. The maximum dew point temperatures are found to be in September and the minimum at January. The minimum dew point temperatures happen to peak at July, August and the minimum occur in January (Fig. 58).

The amplitude for the diurnal cycle of dew point temperatures is larger than the annual cycle amplitude as expected in the Tropics. The minimum occurs right before sunrise, at around 5 AM for MLO and Mauna Kea and the maximum occurs at 1 PM for both locations (Fig. 59).

Temperature Extremes

Temperature, at both Mauna Kea summit and Mauna Loa Observatory, show well defined annual and diurnal cycles, with warmest temperatures happening in the summer months, and the coolest ones in the winter months. The temperature extreme for Mauna Kea is 14.97°C, 2011 while for Mauna Loa it reaches 19.9°C in each of 2007, 2009, 2010. See Appendix for tables of extremes.

Horizontal Wind

The wind speed inter-annual variability shows more stability for MLO than for Mauna Kea, the differences in annual averages are more pronounced for Mauna Kea than for MLO. The trend line show opposite directions, implying a slow increase in time for Mauna Kea, while MLO is experiencing slower decrease. At both sites the trends are slow and the rates are fairly low (Fig. 60).

The wind speed peaks during winter months for both sites. The maximum is clearly visible in January. The slowest wind is observed in September in both locations (Fig. 61).

The diurnal cycle for the wind speed is irregular and shows that there are two daily minimum value and two daily relative maximum that occur later at MLO than at Mauna Kea (Fig. 62).

Diurnal Cycle Extremes

The diurnal cycle temperature has a very well defined diurnal cycle and annual cycle for both locations, with the extreme values of 6.72°C for Mauna Kea and 18.1°C at Mauna Loa Observatory. These values are substantially different between both locations, the altitude specially and geography are the major diverse factors for this discrepancies in the found values.

Wind Speed Extremes

Even though the wind speed at the summit of Mauna Kea presents a weak or small diurnal cycle, and a weak annual cycle, it can reach extreme values of over 80m/s. The wind gusts at the summit can be very strong, these may happen when storms are crossing the Hawaiian Islands. The extreme wind speed recorded at the summit is 99m/s. At MLO the wind speed does not reach such extremes values, the highest value being 24.1m/s.

Chapter 6. Discussion and Conclusions

This thesis describes the results of a climatological investigation of observations taken at the Mauna Loa Observatory from 1958 through 2010 (precipitation), from 1977 – 2010 (all other variables) and observations taken at the summit of Mauna Kea from 1982 through 2010. In addition to diurnal and annual cycles, the inter-annual variability associated with ENSO was also investigated. Finally, the relationship between the climates of Mauna Loa and Mauna Kea was described.

The results presented in this report suggest that the climate variability of the sites explored is determined in large measure by the altitude of the sites, their location (latitude, longitude), and proximity of the surrounding ocean. Mauna Kea summit and Mauna Loa have two main seasons, Kau and Hoo-Ilo. Kau, Hawaiian word for summer runs from May through September while Hoo-ilo, Hawaiian word for winter runs from October through April.

The summit winds are weaker during the summer, blowing mainly from the East (MK) and South East (MLO) due to the strong influence of the Hawaiian High and the trade winds. At MLO the south component comes from the mountain – valley circulation that is typical on the slope of the mountain. The temperatures are warmer peaking in June for MLO and September at Mauna Kea. The summer is drier, when dew point depression is the largest, meanwhile the dew point temperature reaches its annual maximum around August and September for MLO and September, October to Mauna Kea. The wind is generally stronger at Mauna Kea than at Mauna Loa.

The Hawaiian winter, Hoo-ilo, running from October through April has stronger winds with stronger maxima and also blows from other directions than East (MK) or South East (MLO). The temperature is cooler and the dew point is cooler as well. The winter brings Kona storms and fronts that cross the Pacific with winds that blow from directions other than prevailing NE trades. The dew point depression is smaller during these months, and precipitation happens more frequently.

The climate is influenced significantly by ENSO. During El Niño years with the lowering of the equatorial thermocline and the increase in SST along the equator, the Hadley cell becomes reinforced and the subsidence over Hawaiian Islands is enhanced and therefore stability increased which prevents precipitation and formation of clouds. This enhancement in the subsiding branch of the Hadley Cell increases the dew point depression at Mauna Kea and Mauna Loa. A lower dew-point depression makes it less likely for the air to reach saturation.

The Walker cell is a transversal circulation cell over the equator driven by a difference in the pressure values between Darwin (semi-stationary low pressure) and Tahiti (semi-stationary high pressure) (Trenberth, 1998). The Walker cell drives the easterly winds along the equator and during El Niño events these winds become weaker, reducing upwelling and resulting in warmer SSTs.

At MLO the winds are predominantly from the southwest during El Niño events, the southerly component resulting from the diurnal mountain-valley circulation. At the Mauna Kea UH 88 site westerly winds are reinforced during El Niño conditions as a result of enhanced westerlies aloft associated with the upper branch of the Hadley circulation. Strong ENSO events are more likely to cause significant climatic impacts over the islands than moderate and weak events. Although, how moderate and weak events are differentiated varies by investigator.

La Niña events happen when the Hadley cell becomes weaker and the Walker cell becomes stronger. This means that the upwelling near the equator is reinforced and cooler water weakens the Hadley circulation over the central Pacific Ocean. The subsiding branch of the Hadley cell over the Hawaiian Islands becomes weaker and convection is more likely to rise up to reach MLO and Mauna Kea, bringing precipitation more frequently. Aloft, a weaker southwesterly outflow produces a larger easterly wind component over the summits. At Mauna Kea the wind is predominantly from the East. The temperature decreases at both sites and the dew point increases. The composites that refer to December – February show the strongest deviations from climatological values. This is in agreement with previous studies conducted by Gregory Taylor (Taylor, 1984) when he shows that the sharpest El Nino and La Nina transitions occur between December and January, due to a marked change in the upper tropospheric circulation at this time.

Knowing that MLO and Mauna Kea are at similar alpine altitudes, we might assume that the weather patterns and climates are similar. The analysis shows that the major weather patterns are indeed related, and it is suggested that the main differences can be explained as a result of summit versus slope influences.

The trends for MLO and Mauna Kea are somewhat different in tendency, even though the observed trends are relatively small. The temperature time series shows a warming trend for MLO while at Mauna Kea it shows no discernable trend over the short period of record. A slight cooling trend observed at Mauna Kea is the result of low temperatures observed in 2007. The dew point over MLO shows a decreasing trend over time that may be indicative of slow drying. This trend is inconclusive for Mauna Kea. The wind speed shows a different trend for both locations. MLO shows decrease in the wind speed, while Mauna Kea shows increase in wind speed over time. So these two are in opposition with each other. The precipitation shows slow decrease over time at MLO, which is consistent with previous research (Chu et al. 2010; Giambelluca 2011), in which it is mentioned that Hawai'i will over time experience fewer and more intense rain events. These results are also in agreement with those predicted in Rainfall Atlas of Hawaii, 2011.

The heterogeneity of the data for Mauna Kea data makes the calculated trends insignificant, since the data was not consistent and homogenous. Therefore, we do not conclude these trends to be significant for the time period they are related to and further studies need to be conducted to obtain conclusive and robust trends. The homogeneity of MLO data therefore predicts the calculated trends to be significant and in agreement with previous studies.

Our analysis shows that the mountain valley circulation in terms of wind speed, wind direction and temperature fluctuations significantly influences MLO. Temperature maxima occur earlier at MLO than at Mauna Kea summit, due to solar radiative heating on the northern slope of Mauna Loa, other than that we know that the skin temperature of the soil at these locations can be in the order of tens higher than the temperature measured by the instruments available. It would be interesting to manage a study in which skin temperature is compared to the air temperature collected in these data sets. This would makes us conclude about the vertical structure of the atmosphere especially in the turbulent layer.

The major results of this thesis infer that MLO precipitation tends to decrease in time while MLO dew point decreases and temperature slightly increases. The results for MLO are significant due to homogeneity in the data collected. This means that the atmosphere at MLO is tending to be more stable with time (lower dew point and higher temperature), which will inhibit in time precipitation from happening. This is in agreement with the decreasing precipitation trend found in the results.

Due to scarcity of data, gaps in the data (absence of data from 2003 – 2007) at Mauna Kea data sets, the trends are not significant and more studies need to be conducted to accurately predict which way the temperature is varying in time and if global warming is observable at this location. Also, it would be important to collect precipitation data at the summit, even if not interesting to the Observatories, because precipitation data from the summit of Mauna Kea will constitute a big step towards the understanding of the climate and weather at this region.

El Niño 1982 / 83

ENSO events cause both sites to experience anomalies. The 1982 / 83 El Niño was considered to be one of the strongest events in recent years (Murakami, 1989). This El Niño event was considered short and the averaged anomaly for SST in January was observed to be 5.6°C (McPhaden, and Stanley, 1990). It would be expected to observe major changes and variations to the climatological values for both Mauna Kea and MLO.

The years of 1982 and 1983 show opposite anomalies in all variables except wind speed. At Mauna Kea, the temperature was cooler during 1982, 0.7°C, and warmer for 1983, 2.4°C. At Mauna Loa, the annual-average temperature was 6.9°C for 1982, and 7.9°C for 1983. The dew point reached a maximum of -5.8°C in 1982, and then a minimum of -13.3°C in 1983, reflecting very dry conditions during 1983. The wind speed did not show much variation over both years. The total annual precipitation available for MLO shows remarkable variation, with 1241 mm recorded in 1982 and only 155.5 mm in 1983. In summary, the strong 1983 El Niño caused warmer and dryer conditions at both sites. These results are in agreement with previous studies conducted by Meisner (1976) in which he finds a negative correlation between the expected rainfall and the observed rainfall for ENSO events.

As mentioned before in this thesis, the variations in precipitation are likely to be easily observed at the sites. It is remarkable that over 1982 and 1983 the precipitation totals show amplitude of more than 1000 mm for MLO.

In 1983 was also the year in which the most Wekiu bugs were collected so far, year of uncommon drought. The bugs are considered to enjoy dry weather more than overly wet weather. There is not a particular study at the moment that can conclude about the origin of the enlarged amount of bugs collected at 1983 at the summit of Mauna Kea, but the relationship between rain fall amount and number of bugs is quite visible and revealing about the favorable conditions for survival.

Conclusions

The uniqueness of the environment of Mauna Kea summit and Mauna Loa Observatory is a field for more research in the future. The conclusions are presented first in terms of groups related to the geography of Mauna Kea and Mauna Loa, secondly with ENSO influence and thirdly with the comparison between both sites.

Features Associated with the latitude of Mauna Kea and MLO

- Inter-annual variability in annual temperature is small, 3.5°C (MK), 2.8°C (MLO)
- Seasonal lag in temperature associated with latitude and ocean environment, maximum temperature in September (MK)
- Annual amplitude in monthly temperature is smaller than diurnal amplitude,
    - 3.5°C (annual), 4.4°C (diurnal) Mauna Kea;
    - 4 °C (annual), 6.8 °C (diurnal) MLO;

- Wind direction has a strong component of easterly flow due to the presence of trade wind weather pattern
    - 45 % NE – SE 45, Mauna Kea, 8 % E
    - 25 % ESE – SSE, MLO, 8 % SE

Features Associated with the altitude and geography of Mauna Kea

- Monthly mean is low, smaller than 5°C .
- Mean value of dew point temperature is more than 10°C than of temperature, large dew point depression
- Complex and weak wind speed diurnal cycle
- Rainfall is infrequent, large dew point depression
- Very large wind speed extreme values (up to 80 m s^{-1}).

Features Associated with the altitude and geography of MLO

- Visible valley and mountain breeze circulation
- Daytime upslope breeze
- Nighttime downslope breeze
- Weak wind speed diurnal cycle
- Low monthly pressure
- Rainfall is infrequent, large dew point depression

Features Associated with Global warming at Mauna Kea

- Inconclusive and insignificant flat trend for temperature

Features Associated with Global warming at MLO

- Slow warming
- Slow decrease in dew point temperature
- Increase in dew point depression, implying slow decrease in precipitation

Features Associated with ENSO at Mauna Kea and MLO

- Warmer winter during El Niño events winters
    - + 2.4°C, Mauna Kea
    - + 2.1°C, MLO
- Cooler winter during La Niña events winters
    - - 1.6°C, Mauna Kea
    - - 2.0°C, MLO
- Drier winter during El Niño events (less precipitation at MLO), (larger dew point depression at Mauna Kea)
    - - 5.1°C El Niño, +7.4°C La Niña, dew point mean, Mauna Kea
    - - 4.1°C El Niño, +5.5°C La Niña, dew point mean, MLO

- Wetter winter during La Niña events (more precipitation at MLO), (smaller dew point depression at Mauna Kea)
- Westerly winds during El Niño event (West at Mauna Kea), (SW at MLO)
- Easterly winds during La Niña event (East at Mauna Kea), (SE at MLO)

Changes Associated with the Annual Cycle of Solar Forcing

- Climate at Mauna Kea and MLO can be characterized by two seasons: warm season, May through September (Kau), and cool season, October through April (Hoo-ilo)
- May – September – highest temperatures and weaker winds, strong influence of the trade wind pattern, east fro Mauna Kea and southeast for MLO
- October – April – lowest temperatures and stronger winds, influence of winter storms, fronts and Kona storms, west for Mauna Kea and southwest for MLO
- Diurnal cycles for temperature and dew point are larger than annual cycle

Comparison between Mauna Kea and MLO

- Even though the monthly means, inter annual variability, diurnal cycles, and behaviors under ENSO influence are similar and comparable between Mauna Kea and Mauna Loa, the trends for temperature, wind speed are not in agreement. They are both practically flat which suggests that either the weather is not influenced by global warming at Mauna Kea as much as it is at MLO, or that there are not enough data to see the predominant trend if any.
- Dew point depression is decreasing in both sites, but the conclusion for a decrease in precipitation is premature.
- MLO is under the influence of valley – mountain breeze, while Mauna Kea has local wind circulations, not affected by diurnal heating circulation typical of mountains.
- MLO presents a strong component of southerly flow, coming from the mountain – valley circulation
- Mauna Kea and MLO winters are more influenced by ENSO when the events are considered to be strong and they behave similarly

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Table 1: Available Data After Validation

variable	MLO data	UH 88 data
wind speed	1977 - 2011	1982 - 2003 2008 - 2011
wind direction	1977 - 2011	1982 - 2003 2008 - 2011
pressure	1977 - 2011	NA
dew point	1977-2007 2007-2011*	1982-2003* 2008-2011*
temperature	1968-2009 1977-2011	1982 - 2003 2008 - 2011
relative humidity	1977 - 2011	1983-2003 2008 - 2011
wind (wind speed and direction)	1977 - 2011	1982 - 2003 2008 - 2011

- these values were computed using the available weather data

Table 2: MLO long period average and variation range results

Variable	Mean	Range	Units
Pressure	680.36	±0.6	mbar
Temperature	7.075	±0.83	Celsius
Dew Point	-9.12	±1,75	Celsius
Relative Humidity	74.28	±26.14	%
Wind Speed	4.49	±0.283	m/s
Temperature 1968 - 2010	6.9	±0.56	Celsius

Table 3: MK (UH 88) long period average and variation ranges results

Variable	Mean	Range	Units
Temperature	1.309	±0.788	Celsius
Dew Point	-17.43	±2.92	Celsius
Relative Humidity	29.73	±8.32	%
Wind Speed	5.83	±1.33	m/s

Table 4: MLO 5-yrs running mean averages and standard results

Variable	Mean	Range	Units
Pressure	680.38	±0.376	mbar
Temperature	7.175	±0.83	Celsius
Dew Point	-9.15	±0.773	Celsius
Relative Humidity	81.66	±12.59	%
Wind Speed	4.49	±0.166	m/s

Table 5: MK (UH 88) 5-yrs running mean averages and variation ranges results

Variable	Mean	Range	Units
Pressure	680.38	±0.376	mbar
Temperature	7.175	±0.83	Celsius
Dew Point	-9.15	±0.773	Celsius
Relative Humidity	81.66	±12.59	%
Wind Speed	4.49	±0.166	m/s

Table 6: MLO Regression Analysis results, trends

Variable	Trend	Units	Decade Change	Units
Pressure	-0.0276 yrs + 735.73	mbar/yr	- 0.3	mbar / dec
Temperature 1977 - 2010	0.014 yrs – 21.04	C / yr	0.1	C / dec
Temperature 1968 - 2010	0.038 yrs – 68.52	C / yr	0.3	C / dec
Relative Humidity	0.14 yrs – 192.16	% / yr	1.4	% / dec
Precipitation	-3. 45 yrs + 7.29 * 10 ^ 3	mm / yr	- 34.5	mm / dec
Wind Speed	- 0.0112 yrs – 26.78	(m/s) / yr	- 0.1	(m/s) / dec

Table 7: MK (UH 88) Regression Analysis results, trends

Variable	Trend	Units	Decade Change	Units
Temperature 1982 - 2010	-0.02 yrs + 40.14	C / yr	- 0.2	C / dec
Temperature 1982 - 2003	- 0.0198 yrs – 40.73	C / yr	- 0.2	C / dec
Relative Humidity 1983 - 2010	0.22 yrs – 405.8	% / yr	2.2	% / dec
Relative Humidity 1983 - 2003	- 0.553 yrs + 1.13 e ^3	% / yr	- 5.5	% / dec
Dew Point 1983 - 2010	- 0.09 yrs + 171.19	C / yr	-0.9	C / dec
Dew Point 1983 - 2003	- 0.1966 yrs + 375.5	C / yr	- 2	C / dec
Wind Speed 1982 - 2010	0.053 yrs – 101.44	(m/s) / yr	0.5	(m/s) / dec
Wind Speed 1982 - 2003	0.018 yrs – 30.397	(m/s) / yr	-0.2	(m/s) / dec

Table 8: Temperature annual cycle (Celsius), amplitudes of variation

T MK	A	B	C	AA	CC	C-A	CC-AA
	min	mean	max	recmin	recmax	deltaCA	deltaCCAA
1.00	-4.58	0.16	4.91	-7.42	7.41	9.49	14.83
2.00	-4.55	-0.46	4.49	-6.67	6.73	9.03	13.40
3.00	-4.85	-0.53	3.90	-6.94	5.83	8.76	12.78
4.00	-3.61	0.15	4.42	-6.94	9.44	8.03	16.39
5.00	-2.96	1.41	5.75	-5.56	7.78	8.72	13.33
6.00	-1.60	2.50	6.43	-5.00	10.59	8.03	15.59
7.00	-1.64	2.69	6.78	-4.44	8.55	8.42	13.00
8.00	-0.75	2.88	5.99	-2.22	8.89	6.74	11.11
9.00	-0.36	3.02	6.85	-2.41	8.61	7.20	11.02
10.00	-1.48	2.17	5.54	-6.67	6.82	7.02	13.49
11.00	-2.68	1.19	5.21	-8.22	13.33	7.89	21.56
12.00	-4.04	0.34	4.43	-8.33	7.50	8.46	15.83
mean	-2.76	1.29	5.39	-5.90	8.46	8.15	14.36
max	-0.36	3.02	6.85	-2.22	13.33	7.20	21.56
min	-4.85	-0.53	3.90	-8.33	5.83	8.76	11.02

Table 9: Dew Point Temperature annual cycle (Celsius), amplitudes of variation

dp MK	A min	B mean	C max	AA recmin	CC recmax	C-A deltaCA	CC-AA deltaCCAA
1.00	-35.88	-20.02	-6.09	-46.28	0.00	29.79	46.28
2.00	-35.15	-19.48	-4.62	-43.61	-1.35	30.53	42.26
3.00	-35.78	-19.82	-5.64	-46.13	0.00	30.14	46.13
4.00	-33.00	-18.72	-6.31	-46.58	-1.20	26.69	45.38
5.00	-32.32	-17.29	-5.56	-42.71	-1.81	26.76	40.90
6.00	-30.04	-16.95	-6.04	-43.05	-1.11	24.01	41.94
7.00	-31.37	-16.05	-3.17	-42.01	2.20	28.20	44.21
8.00	-33.19	-15.94	-2.50	-40.29	6.51	30.69	46.80
9.00	-33.32	-15.69	-1.88	-45.04	1.38	31.44	46.42
10.00	-31.16	-15.40	-2.16	-39.75	1.76	29.00	41.51
11.00	-37.05	-16.61	-2.31	-49.87	2.22	34.74	52.09
12.00	-33.69	-17.46	-2.96	-44.36	0.53	30.73	44.89
mean	-33.50	-17.45	-4.10	-44.14	0.76	29.39	44.90
max	-30.04	-15.40	-1.88	-39.75	6.51	28.17	46.26
min	-37.05	-20.02	-6.31	-49.87	-1.81	30.73	48.06

Table 10: Wind Speed Annual Cycle (m/s) and amplitude of variations

ws	A min	B mean	C max	AA recmin	CC recmax	C-A deltaCA	CC-AA deltaCCA A
1.00	1.58	7.62	13.13	0.00	14.75	11.55	14.75
2.00	1.44	7.45	13.21	0.00	14.75	11.77	14.75
3.00	0.67	6.95	13.12	0.00	14.75	12.45	14.75
4.00	0.47	5.80	12.49	0.00	14.75	12.03	14.75
5.00	0.70	5.52	12.78	0.00	14.75	12.08	14.75
6.00	0.53	5.39	12.22	0.00	13.86	11.69	13.86
7.00	0.56	5.48	11.70	0.00	14.01	11.14	14.01
8.00	0.44	5.08	11.48	0.00	14.08	11.04	14.08
9.00	0.36	5.07	11.29	0.00	14.30	10.93	14.30
10.00	0.64	5.42	11.88	0.00	13.86	11.25	13.86
11.00	0.52	6.22	12.62	0.00	14.30	12.10	14.30
12.00	1.26	6.63	12.46	0.00	14.08	11.20	14.08
mean	0.76	6.05	12.37	0.00	14.35	11.60	14.35
max	1.58	7.62	13.21	0.00	14.75	11.63	14.75
min	0.36	5.07	11.29	0.00	13.86	10.93	13.86

Table 11: Temperature Diurnal Cycle (Celsius) and amplitude of variations

T MK	A	B	C	C - A
	min	mean	max	deltaAC
0.00	-6.40	0.66	8.24	14.64
1.00	-5.75	0.50	6.45	12.20
2.00	-5.95	0.45	6.05	12.00
3.00	-5.86	0.37	5.98	11.84
4.00	-6.57	0.48	8.31	14.89
5.00	-5.94	0.39	6.54	12.48
6.00	-5.75	0.62	6.43	12.18
7.00	-5.46	1.43	8.14	13.60
8.00	-4.91	2.38	9.09	14.00
9.00	-3.94	3.29	10.34	14.28
10.00	-3.14	4.06	11.31	14.45
11.00	-2.37	4.54	11.77	14.14
12.00	-2.03	4.77	12.14	14.17
13.00	-1.90	4.81	11.93	13.83
14.00	-2.37	4.56	11.74	14.11
15.00	-2.51	4.10	11.16	13.66
16.00	-3.31	3.41	10.29	13.60
17.00	-3.72	2.44	8.95	12.67
18.00	-4.93	1.59	9.51	14.44
19.00	-5.85	1.02	8.28	14.14
20.00	-5.13	0.77	6.93	12.06
21.00	-5.66	0.72	6.14	11.81
22.00	-5.39	0.68	6.27	11.67
23.00	-5.16	0.61	6.19	11.34

mean	-4.58	2.03	8.67	13.26
max	-1.90	4.81	12.14	14.89
min	-6.57	0.37	5.98	11.34

Table 12: Dew Point Temperature Diurnal Cycle and amplitude of variations

dp MK				C - A
	min	mean	max	deltaAC
0.00	-50.35	-21.39	1.40	51.76
1.00	-50.03	-22.87	0.48	50.51
2.00	-50.02	-22.96	0.36	50.38
3.00	-49.85	-22.92	-0.12	49.72
4.00	-50.77	-21.82	0.58	51.34
5.00	-50.11	-23.05	-0.49	49.61
6.00	-50.30	-23.04	-0.52	49.78
7.00	-49.68	-22.78	0.09	49.77
8.00	-49.03	-21.95	1.02	50.05
9.00	-48.08	-20.52	1.65	49.74
10.00	-47.04	-18.88	2.40	49.44
11.00	-46.10	-16.96	3.51	49.61
12.00	-44.54	-15.31	3.85	48.39
13.00	-44.62	-14.44	3.59	48.22
14.00	-45.31	-14.29	3.54	48.85
15.00	-45.93	-15.08	3.15	49.08
16.00	-47.90	-16.85	2.66	50.56
17.00	-48.36	-18.61	2.02	50.38
18.00	-49.82	-20.02	1.30	51.12
19.00	-49.98	-20.88	1.40	51.38
20.00	-49.81	-22.12	0.51	50.32
21.00	-49.79	-22.32	0.57	50.35
22.00	-49.79	-22.39	0.61	50.41
23.00	-50.19	-22.59	0.43	50.62

mean	-48.64	-20.17	1.42	50.06
max	-44.54	-14.29	3.85	51.76
min	-50.77	-23.05	-0.52	48.22

Table 13: Wind Speed (m/s) Diurnal Cycle, and amplitude of variation

ws	A	B	C	C - A
	min	mean	max	deltaAC
0.00	0.00	6.63	14.79	14.79
1.00	0.45	7.17	14.77	14.32
2.00	0.40	7.17	14.77	14.37
3.00	0.43	7.13	14.75	14.32
4.00	0.00	6.66	14.81	14.81
5.00	0.52	7.36	14.77	14.26
6.00	0.82	7.69	14.75	13.93
7.00	0.95	7.69	14.75	13.80
8.00	0.91	7.57	14.75	13.84
9.00	1.07	7.42	14.75	13.68
10.00	0.91	7.31	14.76	13.85
11.00	1.01	7.33	14.77	13.76
12.00	0.97	7.25	14.75	13.79
13.00	1.00	7.21	14.75	13.75
14.00	1.08	7.17	14.75	13.67
15.00	1.07	7.17	14.77	13.70
16.00	0.91	7.21	14.75	13.84
17.00	0.68	7.28	14.75	14.07
18.00	0.00	6.92	14.75	14.75
19.00	0.00	6.75	14.75	14.75
20.00	0.20	7.09	14.76	14.56
21.00	0.32	7.09	14.77	14.46
22.00	0.36	7.10	14.75	14.40
23.00	0.30	7.15	14.75	14.45

mean	0.60	7.19	14.76	14.16
max	1.08	7.69	14.81	14.81
min	0.00	6.63	14.75	13.67

Table 14: Pressure Annual Cycle (mbar) and amplitude of variation, MLO

p	A	B	C	AA	CC	C-A	CC-AA
	min	mean	max	recmin	recmax	deltaCA	deltaCCAA
1.00	673.86	679.12	682.98	668.75	684.47	9.12	15.72
2.00	673.02	678.96	683.14	668.93	684.88	10.12	15.94
3.00	674.29	679.57	683.58	670.49	685.45	9.30	14.97
4.00	675.88	679.91	683.02	673.62	684.80	7.13	11.19
5.00	677.21	680.66	683.75	673.88	684.81	6.54	10.93
6.00	678.70	681.33	683.96	677.40	685.15	5.26	7.74
7.00	679.03	681.42	683.98	678.18	685.67	4.95	7.49
8.00	679.22	681.48	683.93	678.00	684.96	4.71	6.96
9.00	678.44	680.92	683.37	677.03	684.17	4.93	7.14
10.00	678.07	680.87	683.57	676.61	684.86	5.50	8.25
11.00	676.31	680.46	683.69	671.35	685.10	7.38	13.75
12.00	674.53	679.87	683.44	671.23	685.16	8.91	13.94
mean	676.55	680.38	683.53	673.79	684.96	6.99	11.17
max	679.22	681.48	683.98	678.18	685.67	10.12	15.94
min	673.02	678.96	682.98	668.75	684.17	4.71	6.96

Table 15: Temperature (Celsius) Annual Cycle and amplitude of variation, MLO

p	A	B	C	AA	CC	C-A	CC-AA
	min	mean	max	recmin	recmax	deltaCA	deltaCCAA
1.00	673.86	679.12	682.98	668.75	684.47	9.12	15.72
2.00	673.02	678.96	683.14	668.93	684.88	10.12	15.94
3.00	674.29	679.57	683.58	670.49	685.45	9.30	14.97
4.00	675.88	679.91	683.02	673.62	684.80	7.13	11.19
5.00	677.21	680.66	683.75	673.88	684.81	6.54	10.93
6.00	678.70	681.33	683.96	677.40	685.15	5.26	7.74
7.00	679.03	681.42	683.98	678.18	685.67	4.95	7.49
8.00	679.22	681.48	683.93	678.00	684.96	4.71	6.96
9.00	678.44	680.92	683.37	677.03	684.17	4.93	7.14
10.00	678.07	680.87	683.57	676.61	684.86	5.50	8.25
11.00	676.31	680.46	683.69	671.35	685.10	7.38	13.75
12.00	674.53	679.87	683.44	671.23	685.16	8.91	13.94
mean	676.55	680.38	683.53	673.79	684.96	6.99	11.17
max	679.22	681.48	683.98	678.18	685.67	10.12	15.94
min	673.02	678.96	682.98	668.75	684.17	4.71	6.96

Table 16: Dew Point temperature (Celsius) Annual Cycle and amplitude of variations, MLO

dp	A	B	C	AA	CC	C-A	CC-AA
	min	mean	max	recmin	recmax	deltaCA	deltaCCAA
1.00	-27.03	-12.06	1.81	-34.48	4.91	28.84	39.38
2.00	-26.50	-11.20	1.63	-37.64	4.68	28.13	42.32
3.00	-26.13	-10.31	2.23	-30.86	3.52	28.36	34.38
4.00	-25.48	-10.24	1.47	-30.29	4.30	26.95	34.59
5.00	-22.36	-8.78	2.53	-27.00	6.34	24.90	33.33
6.00	-22.20	-9.24	1.71	-28.19	4.61	23.91	32.80
7.00	-20.29	-7.10	4.11	-27.67	7.00	24.40	34.67
8.00	-19.46	-5.84	4.82	-32.34	8.00	24.28	40.34
9.00	-19.03	-5.84	5.06	-28.48	7.27	24.09	35.75
10.00	-22.06	-7.55	4.16	-26.78	6.51	26.22	33.28
11.00	-24.06	-8.57	4.68	-28.62	7.45	28.75	36.07
12.00	-27.38	-11.72	2.79	-33.63	7.64	30.17	41.26

mean	-23.50	-9.04	3.08	-30.50	6.02	26.58	36.51
max	-19.03	-5.84	5.06	-26.78	8.00	30.17	42.32
min	-27.38	-12.06	1.47	-37.64	3.52	23.91	32.80

Table 17: Wind Speed (m/s) Annual Cycle, and amplitude of variations, MLO

ws	A	B	C	AA	CC	C-A	CC-AA
	min	mean	max	recmin	recmax	deltaCA	deltaCCAA
1.00	1.97	5.36	13.76	1.22	21.86	11.79	20.64
2.00	1.75	5.22	12.79	0.00	21.20	11.04	21.20
3.00	1.76	4.89	12.15	0.94	15.66	10.38	14.72
4.00	1.71	4.38	11.06	1.19	15.25	9.35	14.06
5.00	1.73	4.36	11.30	1.28	15.41	9.57	14.13
6.00	1.75	4.36	10.62	1.15	14.88	8.87	13.73
7.00	1.63	4.36	10.19	0.91	13.56	8.56	12.65
8.00	1.59	4.04	9.35	0.95	13.92	7.76	12.96
9.00	1.60	3.64	7.87	1.35	11.29	6.27	9.94
10.00	1.65	3.95	9.04	1.05	13.16	7.39	12.12
11.00	1.52	4.57	10.84	0.83	15.92	9.32	15.10
12.00	1.76	5.07	13.01	1.06	17.78	11.25	16.73

mean	1.70	4.52	11.00	0.99	15.82	9.30	14.83
max	1.97	5.36	13.76	1.35	21.86	11.79	21.20
min	1.52	3.64	7.87	0.00	11.29	6.27	9.94

Table 18: Pressure Diurnal Cycle (mbar) and amplitudes of variation

p	A	B	C	C-A
	min	mean	max	deltaAC
0	673.35	680.19	685.21	11.86
1	673.10	679.80	684.86	11.76
2	672.91	679.42	684.48	11.57
3	672.76	679.21	684.29	11.53
4	672.71	679.21	684.24	11.53
5	672.90	679.39	684.53	11.63
6	673.38	679.71	684.85	11.48
7	673.91	680.07	685.32	11.41
8	673.96	680.43	685.68	11.72
9	674.28	680.70	685.88	11.60
10	674.33	680.76	685.86	11.53
11	674.00	680.57	685.63	11.63
12	673.57	680.20	685.23	11.67
13	673.26	679.78	684.76	11.50
14	673.03	679.48	684.47	11.44
15	672.81	679.34	684.38	11.57
16	672.81	679.36	684.43	11.63
17	672.87	679.54	684.64	11.78
18	673.13	679.82	684.89	11.76
19	673.40	680.16	685.28	11.88
20	673.73	680.49	685.65	11.92
21	674.00	680.69	685.79	11.79
22	673.95	680.71	685.80	11.85
23	673.75	680.52	685.53	11.78
mean	673.41	679.98	685.07	11.66
max	674.33	680.76	685.88	11.92
min	672.71	679.21	684.24	11.41

Table 19: Temperature Diurnal Cycle (Celsius), and amplitude of variation

T	A	B	C	C-A
	min	mean	max	deltaAC
0.00	-1.58	5.05	11.37	12.95
1.00	-1.53	4.81	11.33	12.87
2.00	-1.94	4.58	11.13	13.07
3.00	-2.14	4.40	11.16	13.30
4.00	-2.11	4.28	10.80	12.91
5.00	-2.15	4.21	10.72	12.87
6.00	-1.68	4.83	11.22	12.90
7.00	-0.10	6.92	13.78	13.88
8.00	0.77	8.91	15.72	14.95
9.00	1.59	10.06	17.06	15.47
10.00	1.90	10.74	18.07	16.17
11.00	2.09	11.02	18.70	16.61
12.00	2.12	11.03	18.70	16.58
13.00	1.99	10.84	18.59	16.60
14.00	1.23	10.56	18.43	17.20
15.00	0.98	10.17	17.88	16.89
16.00	0.42	9.66	17.56	17.14
17.00	0.18	8.87	16.23	16.05
18.00	0.09	7.79	14.47	14.38
19.00	-0.33	6.91	13.28	13.61
20.00	-1.20	6.37	12.33	13.53
21.00	-1.10	5.96	11.74	12.84
22.00	-1.06	5.61	11.82	12.88
23.00	-1.32	5.30	11.37	12.68

mean	-0.20	7.45	14.31	14.51
max	2.12	11.03	18.70	16.58
min	-2.15	4.21	10.72	12.87

Table 20: Dew Point Temperature (Celsius) and amplitude of variation

dp	A min	B mean	C max	C-A deltaAC
0	-35.19	-13.63	6.57	-21.57
1	-35.07	-13.88	6.15	-21.19
2	-35.15	-14.11	5.77	-21.04
3	-35.32	-14.23	5.67	-21.09
4	-35.39	-14.48	5.63	-20.91
5	-35.23	-14.66	5.46	-20.57
6	-35.08	-14.52	5.58	-20.56
7	-35.02	-13.72	6.58	-21.30
8	-35.67	-12.33	8.21	-23.33
9	-34.10	-10.47	8.67	-23.63
10	-32.67	-8.01	9.71	-24.66
11	-30.56	-5.44	10.98	-25.12
12	-28.98	-3.52	11.14	-25.47
13	-31.31	-2.34	11.07	-28.97
14	-29.08	-1.85	11.27	-27.24
15	-29.45	-2.11	10.87	-27.33
16	-30.21	-3.21	10.66	-27.00
17	-31.08	-5.17	10.08	-25.92
18	-33.02	-7.69	9.06	-25.33
19	-34.54	-9.81	7.84	-24.73
20	-34.73	-11.25	7.15	-23.47
21	-34.90	-12.30	7.29	-22.60
22	-35.17	-12.99	6.79	-22.17
23	-35.18	-13.32	6.93	-21.86

mean	-33.42	-9.79	8.13	-23.63
max	-28.98	-1.85	11.27	-20.56
min	-35.67	-14.66	5.46	-28.97

Table 21: Wind Speed (m/s) Diurnal Cycle, and amplitude of variation

ws	A	B	C	C-A
	min	mean	max	deltaAC
0	0.03	4.71	17.91	-4.69
1	0.00	4.70	17.77	-4.70
2	0.00	4.73	18.17	-4.73
3	0.03	4.76	17.62	-4.73
4	0.00	4.83	17.31	-4.83
5	0.04	4.89	16.90	-4.85
6	0.07	4.76	17.28	-4.70
7	0.03	4.16	18.02	-4.13
8	0.00	4.02	17.78	-4.02
9	0.00	4.19	17.72	-4.19
10	0.00	4.31	17.36	-4.31
11	0.00	4.46	17.33	-4.46
12	0.00	4.53	17.10	-4.53
13	0.00	4.55	17.05	-4.55
14	0.00	4.53	16.66	-4.53
15	0.00	4.45	16.83	-4.45
16	0.00	4.31	16.50	-4.31
17	0.00	4.09	16.41	-4.09
18	0.00	3.89	16.82	-3.89
19	0.00	3.95	17.05	-3.95
20	0.00	4.14	17.10	-4.14
21	0.00	4.38	16.51	-4.38
22	0.00	4.59	16.84	-4.59
23	0.02	4.68	17.36	-4.66

mean	0.01	4.44	17.22	-4.43
max	0.07	4.89	18.17	-3.89
min	0.00	3.89	16.41	-4.85

Figures:

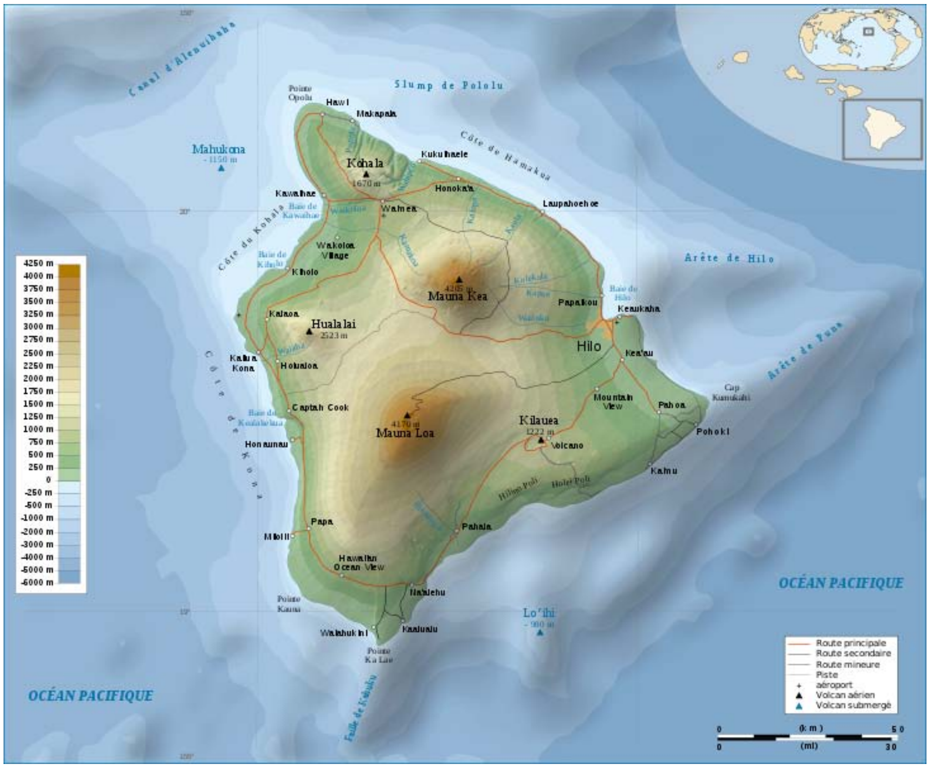


Fig. 1: Map of the Island of Hawai'i, Mauna Kea and Mauna Loa

Fig. 2: Mauna Kea and astronomical Observatories

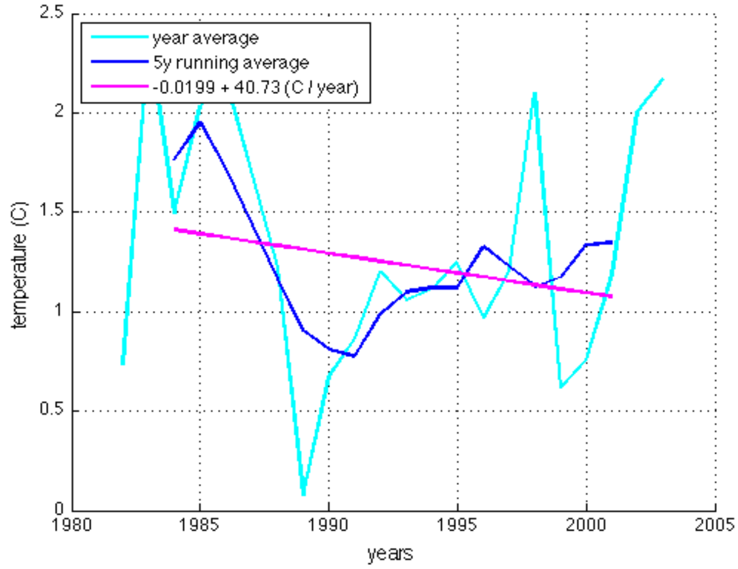


Fig.3: Temperature (° C) inter-annual variability (light blue line), Temperature (° C) 5-yr running mean (dark mean line), Temperature (° C) trend (pink line) of the 5-yr running mean

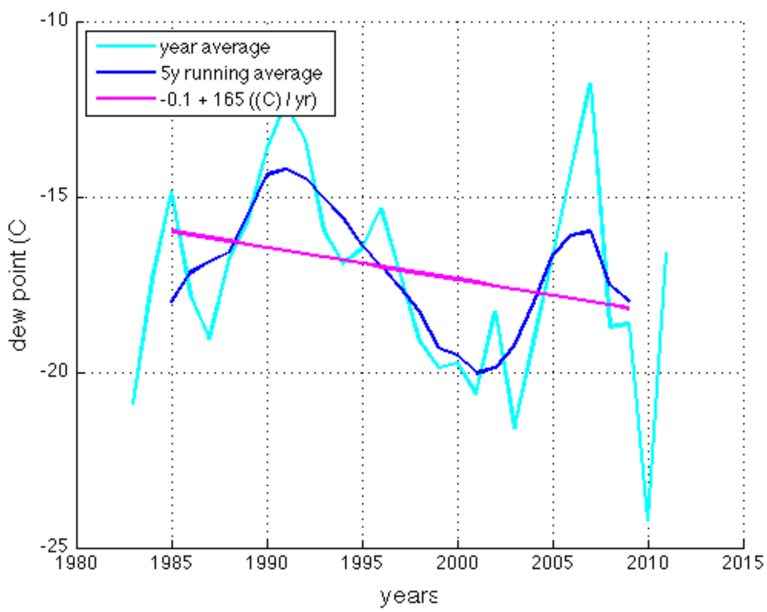


Fig.4: Dew Point temperature (° C) inter-annual variability (light blue line), dew point temperature (° C) 5-yr running mean (dark mean line), dew point temperature (° C) trend (pink line) of the 5-yr running mean

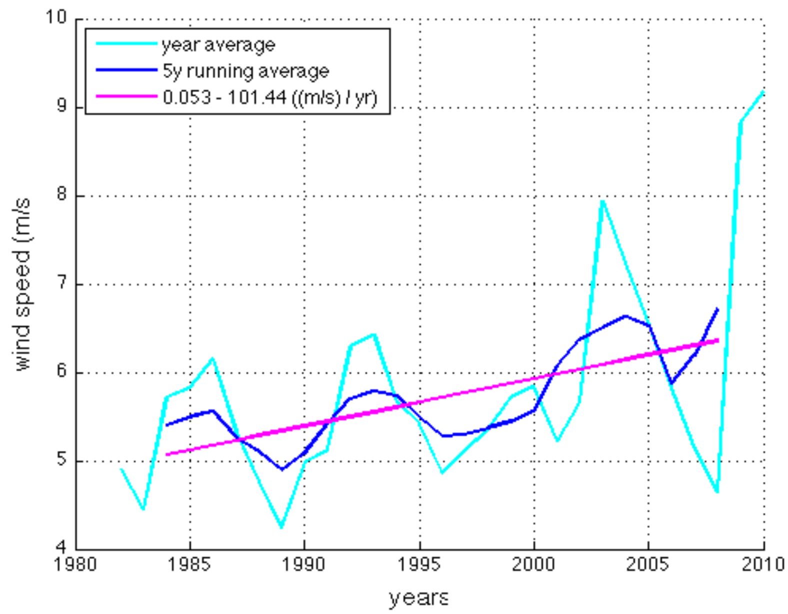


Fig. 5: Wind speed (m/s) inter-annual variability (light blue line), wind speed (m/s) 5-yr running mean (dark mean line), wind speed (m/s) trend (pink line) of the 5-yr running mean

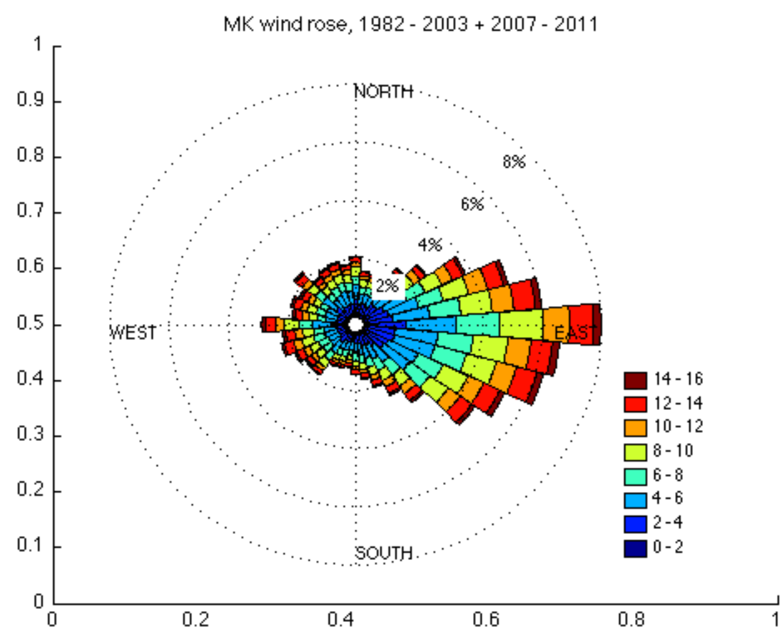


Fig. 6: Wind Rose 1982 – 2010, Mauna Kea, wind speed in m/s

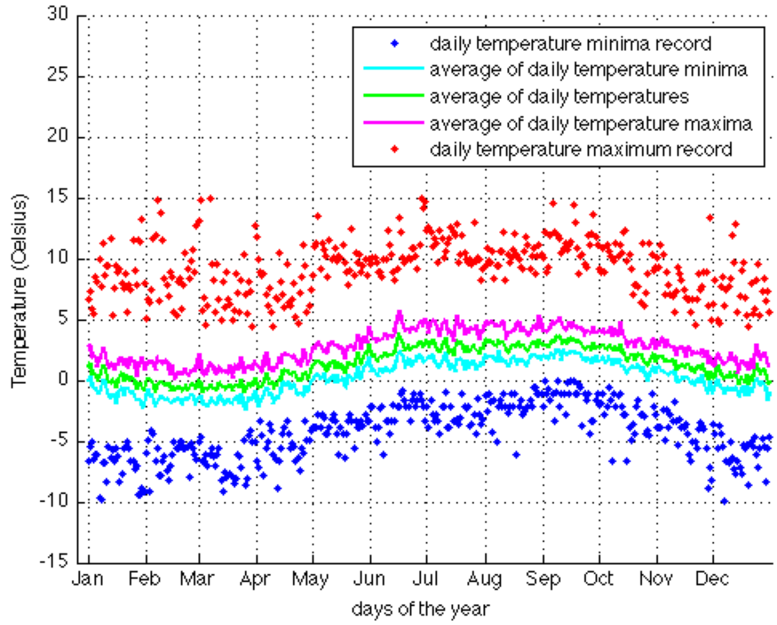


Fig. 7: Temperature (° C) Annual Cycle for Mauna Kea, 1982 – 2010, daily temperature (˚C) maxima record (red dots), average of daily temperature (˚C) maxima (pink line), average of daily temperature (˚C) (green line), average of daily temperature (˚C) minima (light blue line), daily temperature (˚C) minimum record (dark blue dots)

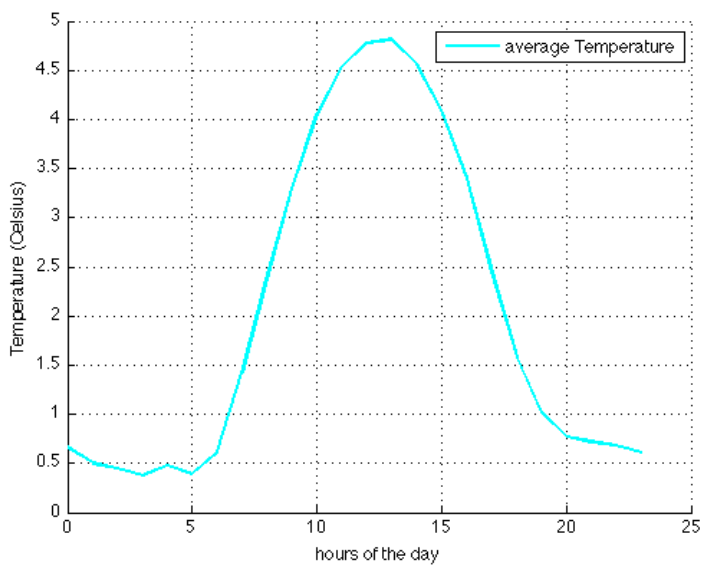


Fig. 8: Temperature (° C) Diurnal Cycle for Mauna Kea, 1982 – 2010.

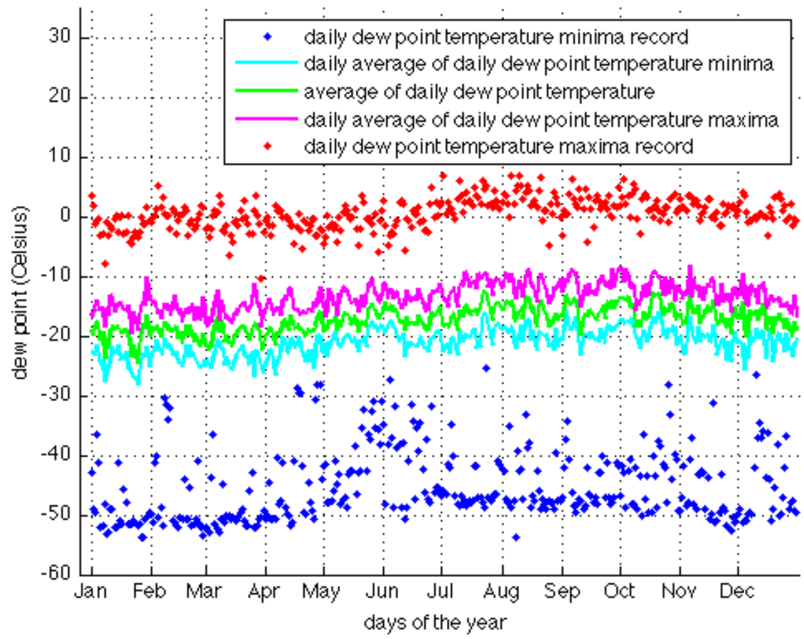


Fig. 9: Dew Point Temperature (° C) Annual Cycle for Mauna Kea, 1982 – 2010, daily dew point temperature (˚C) maxima record (red dots), average of daily dew point temperature (˚C) maxima (pink line), average of daily dew point temperature (˚C) (green line), average of daily dew point temperature (˚C) minima (light blue line), daily dew point temperature (˚C) minimum record (dark blue dots).

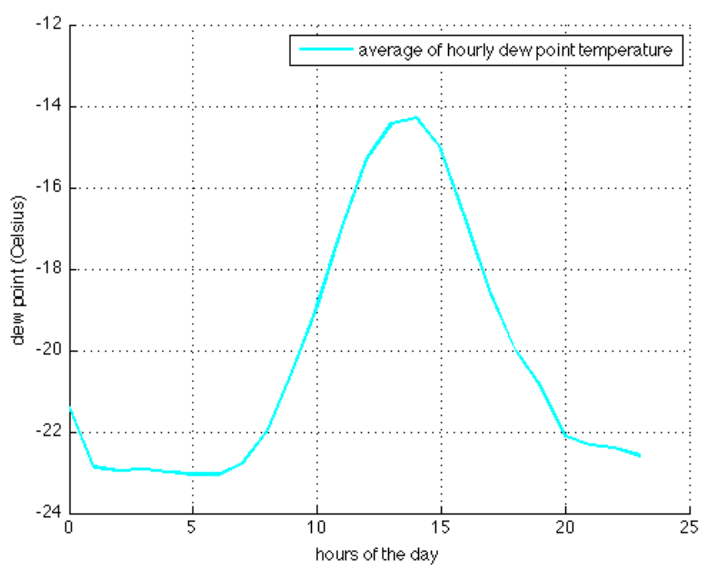


Fig. 10: Dew Point Temperature (° C) Diurnal Cycle for Mauna Kea, 1982 – 2010.

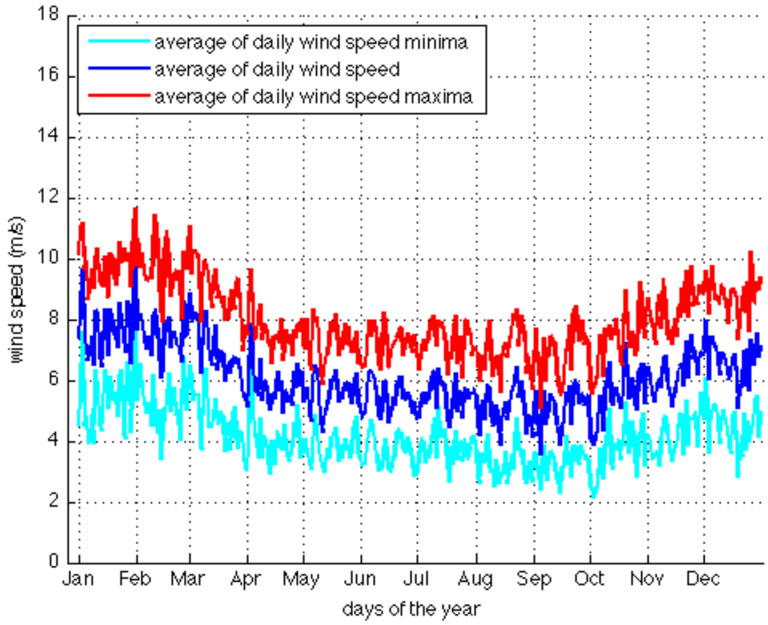


Fig. 11a: Wind Speed (m/s) Annual Cycle for Mauna Kea, 1982 – 2010, average of daily wind speed (m/s) maxima (red line), average of daily wind speed (m/s) (dark blue line), average of daily wind speed (m/s) minima (light blue line).

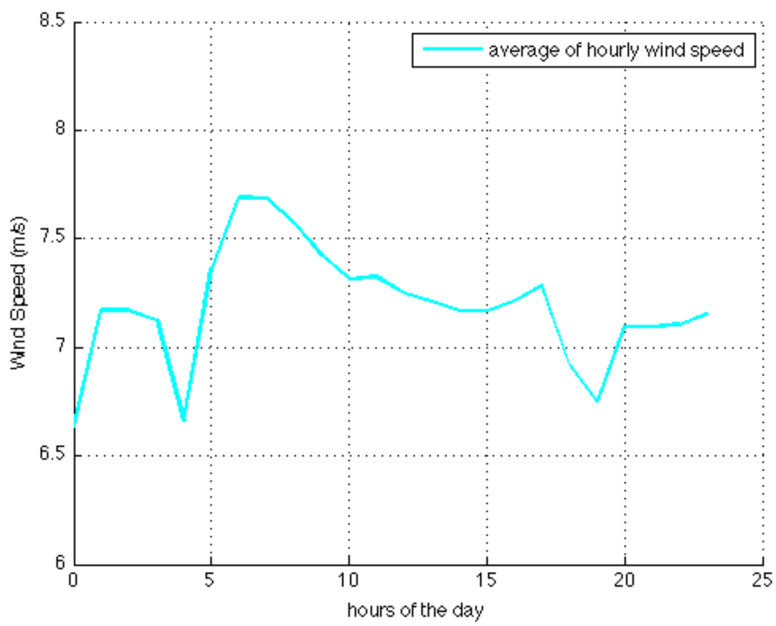


Fig. 11b: Diunal cycle of the wind speed for Mauna Kea, 1982-2010. Average of the hourly wind speed (m/s).

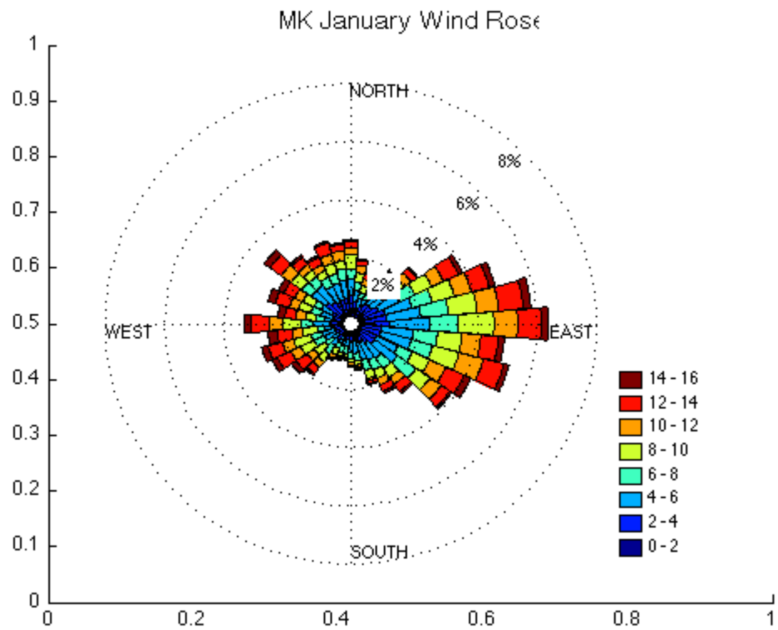


Fig. 12: January 1982 – 2010 Wind Rose for Mauna Kea, wind speed in m/s

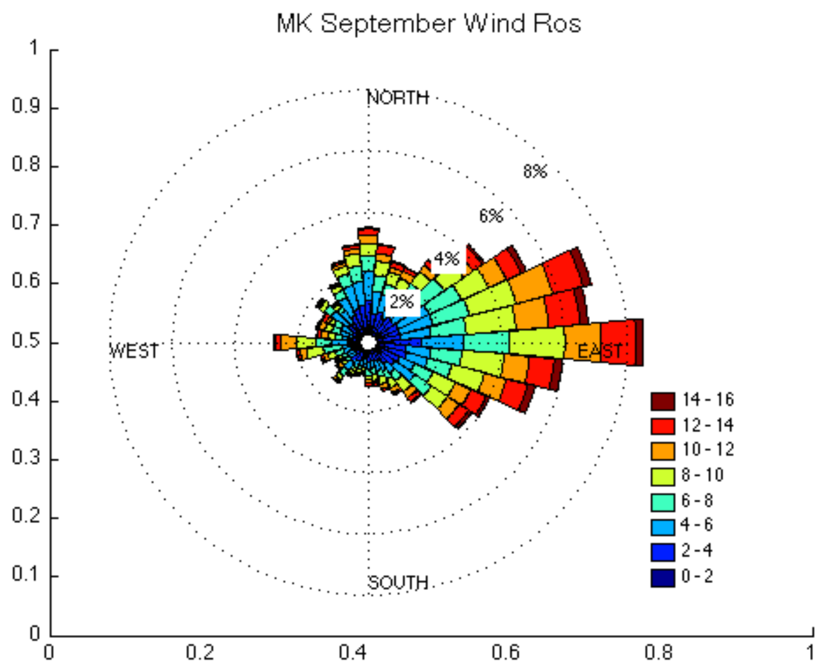


Fig. 13: September 1982 – 2010 Wind Rose for Mauna Kea, wind speed in m/s

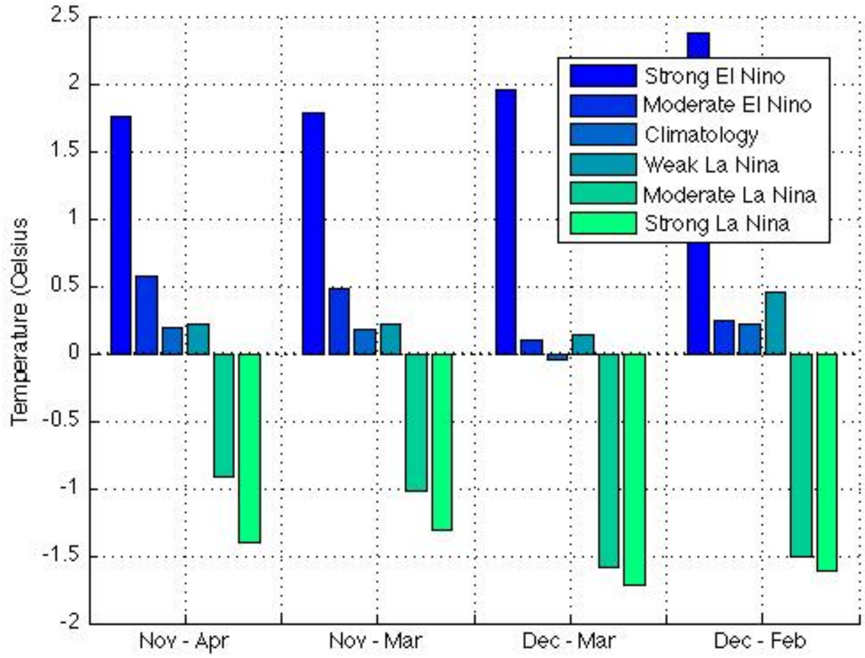


Fig. 14: Temperature (˚C) composite for climatology, moderate and strong ENSO events, Mauna Kea, 1982 - 2010

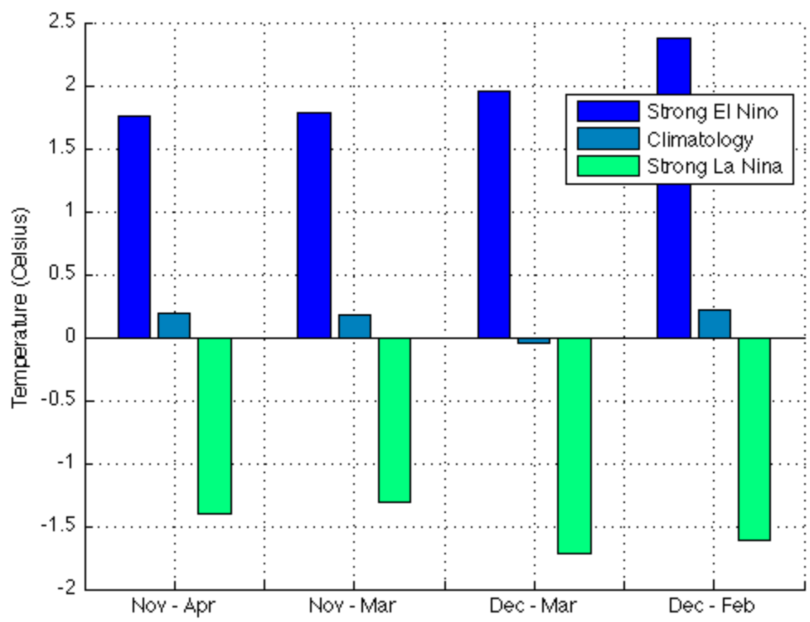


Fig. 15: Temperature (˚C) composite for climatology, strong El Niño and strong La Niña events, Mauna Kea, 1982 - 2010

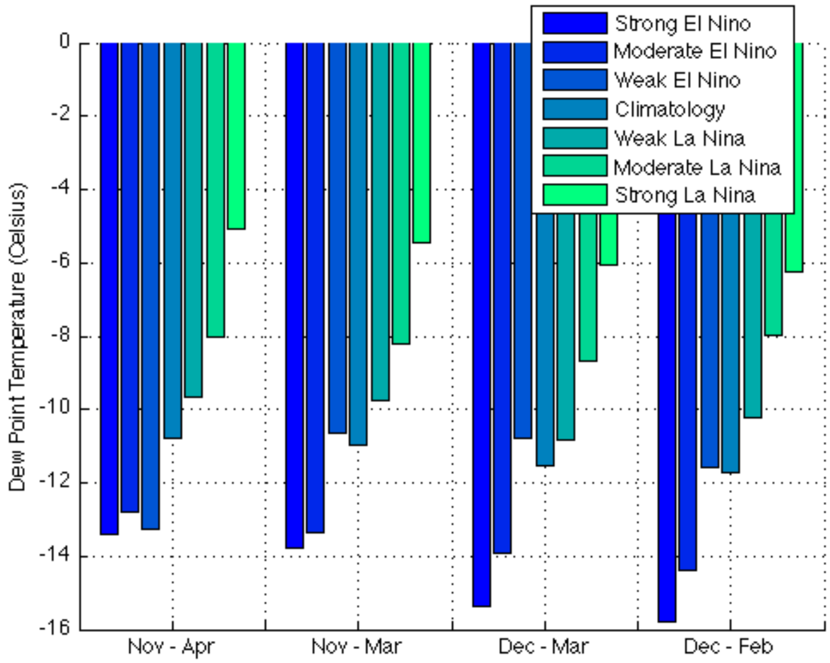


Fig. 16: Dew Point Temperature (˚C) composite for climatology, weak, moderate and strong ENSO events, Mauna Kea, 1982 - 2010

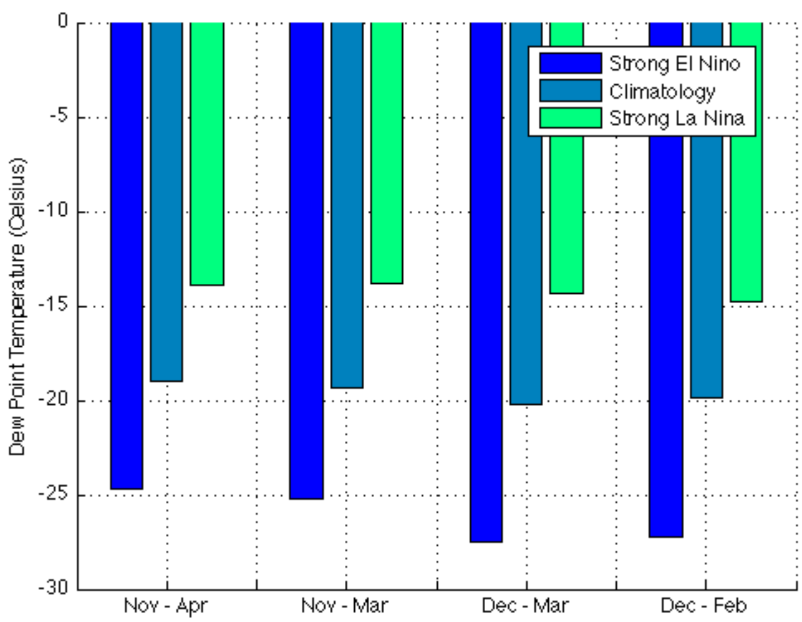


Fig. 17: Dew Point Temperature (˚C) composite for climatology, strong El Niño, strong La Niña, Mauna Kea, 1982 - 2010

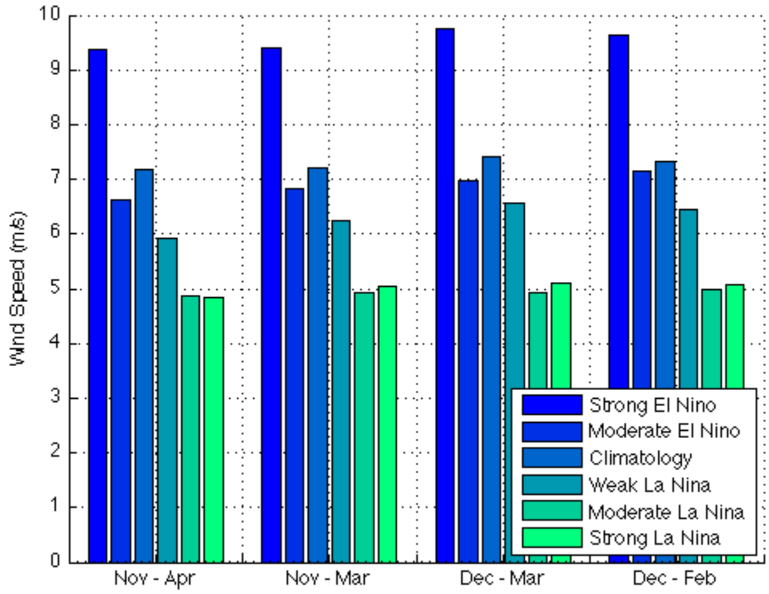
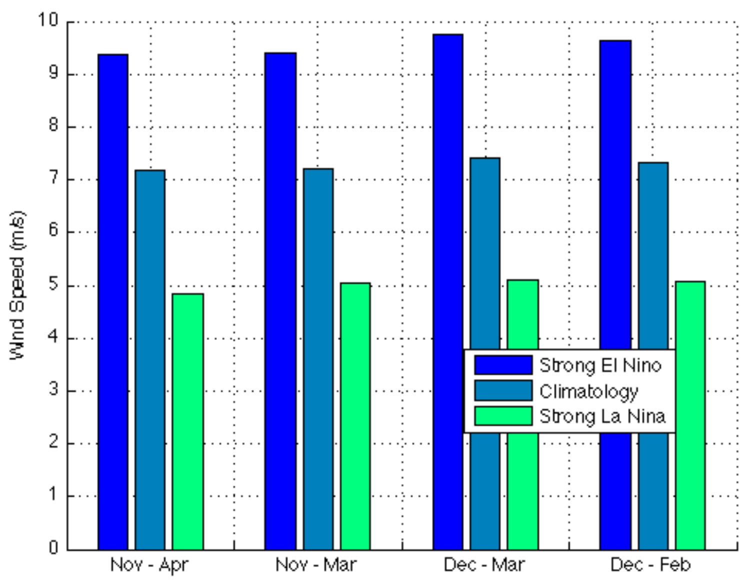


Fig. 18: Wind Speed (m/s) composite for climatology, weak, moderate and strong ENSO events, Mauna Kea, 1982 - 2010



Fig, 19: Wind Speed (m/s) for climatology, strong El Niño and strong La Niña, Mauna Kea, 1982 - 2010

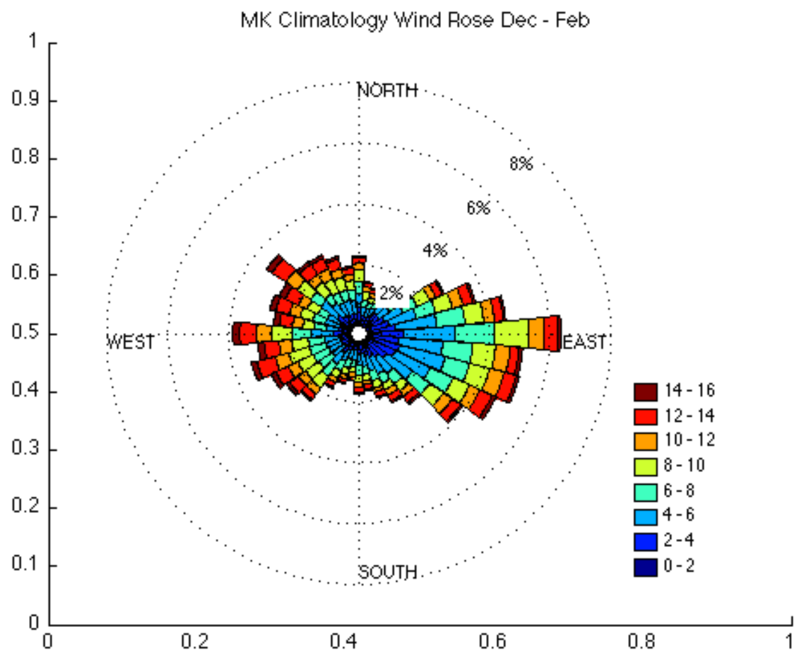


Fig. 20: Climatology Wind Rose , 1982 – 2010, Mauna Kea, wind speed in m/s

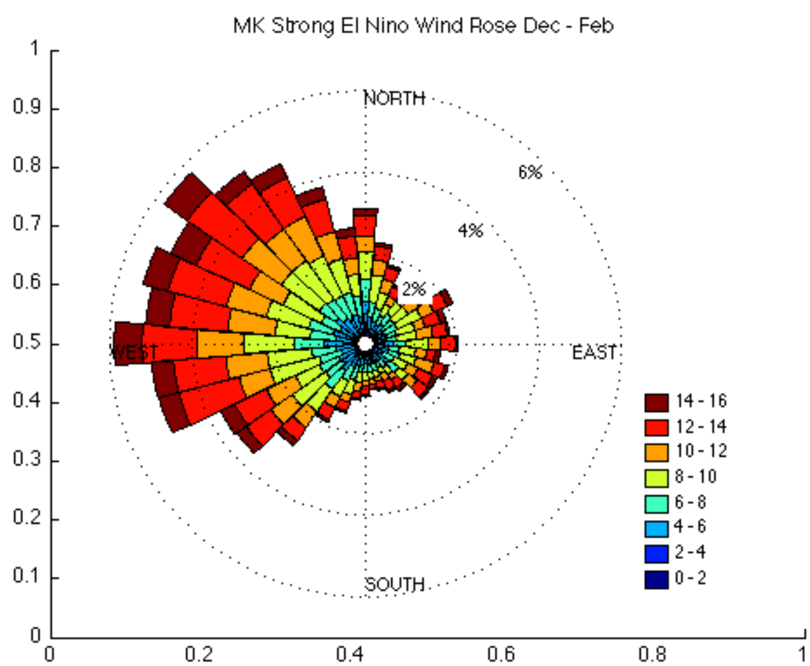


Fig. 21: Strong El Niño Wind Rose composite, Mauna Kea, 1982 – 2010, wind speed in m/s

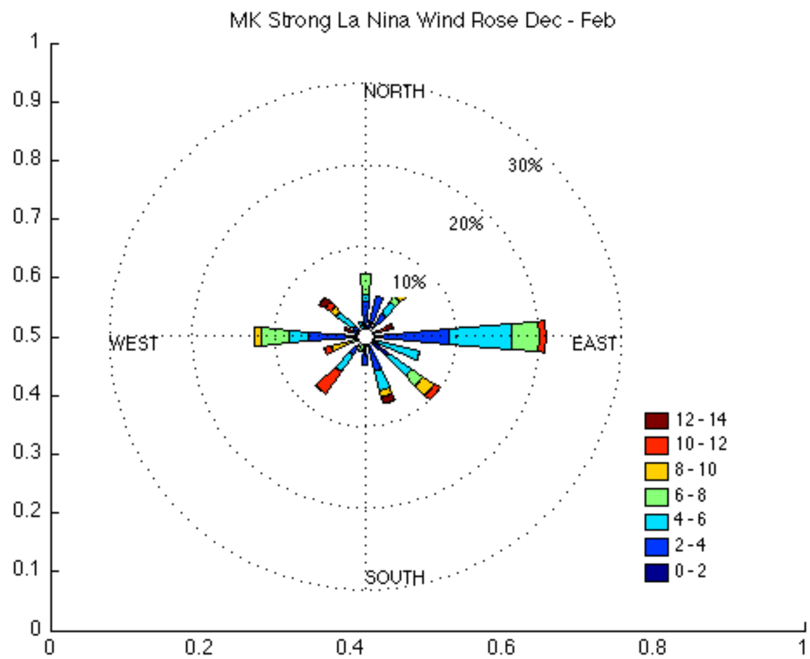


Fig. 22: Strong La Niña Wind Rose composite, Mauna Kea, 1982 – 2010, wind speed in m/s

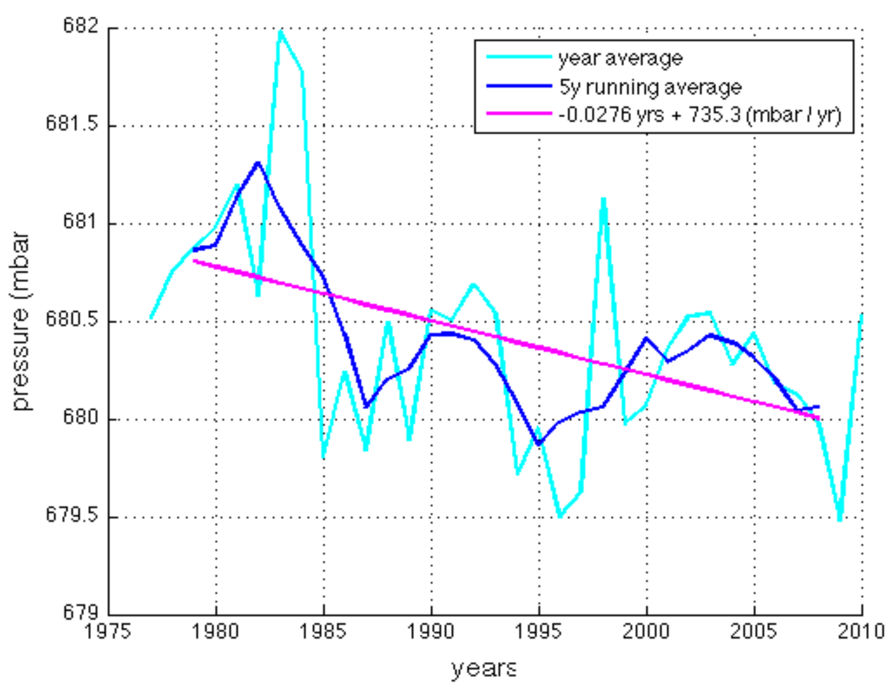


Fig. 23: Pressure (mbar) inter-annual variability (light blue line), Pressure (mbar) 5-yr running mean (dark mean line), Pressure (mbar) trend (pink line) of the 5-yr running mean

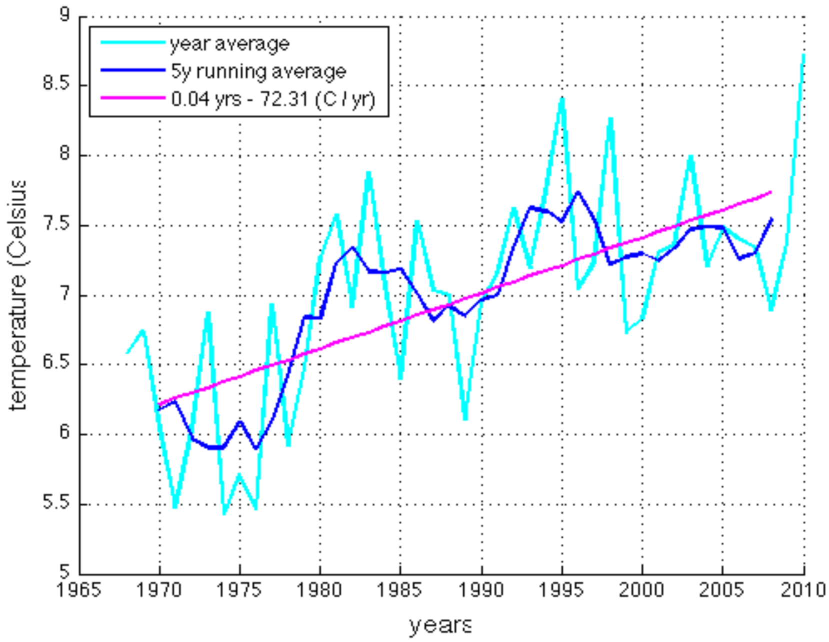


Fig. 24: Temperature (° C) inter-annual variability (light blue line), Temperature (° C) 5-yr running mean (dark mean line), Temperature (° C) trend (pink line) of the 5-yr running mean

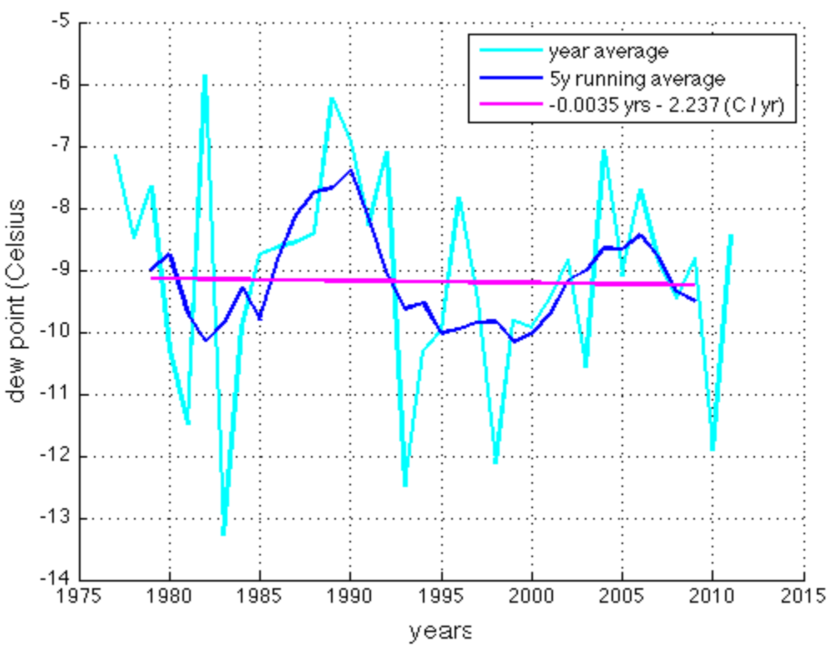


Fig. 25: Dew Point Temperature (° C) inter-annual variability (light blue line), Temperature Dew Point (° C) 5-yr running mean (dark mean line), Temperature Dew Point (° C) trend (pink line) of the 5-yr running mean

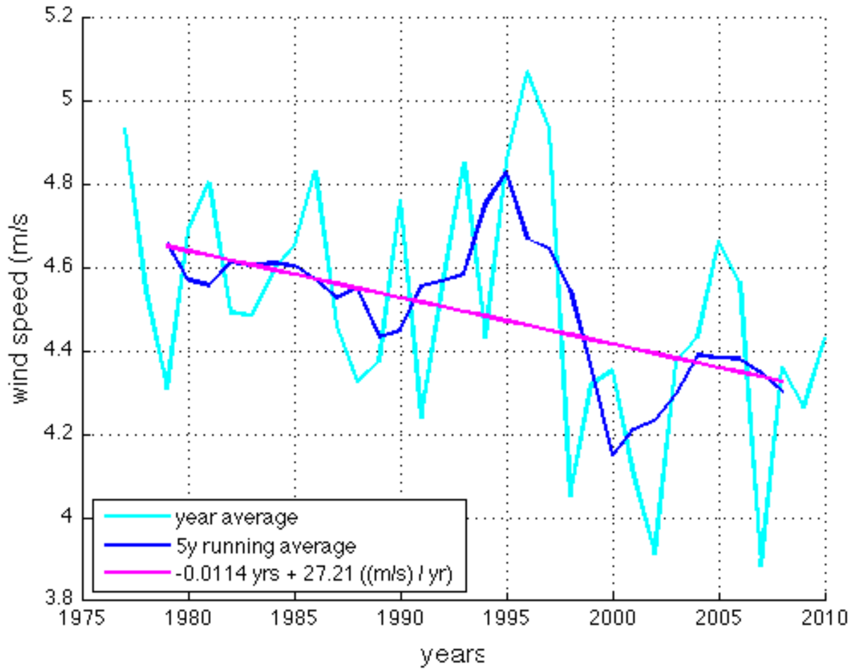


Fig. 26: Wind Speed (m/s) inter-annual variability (light blue line), Wind Speed (m/s) 5-yr running mean (dark mean line), Wind Speed (m/s) trend (pink line) of the 5-yr running mean

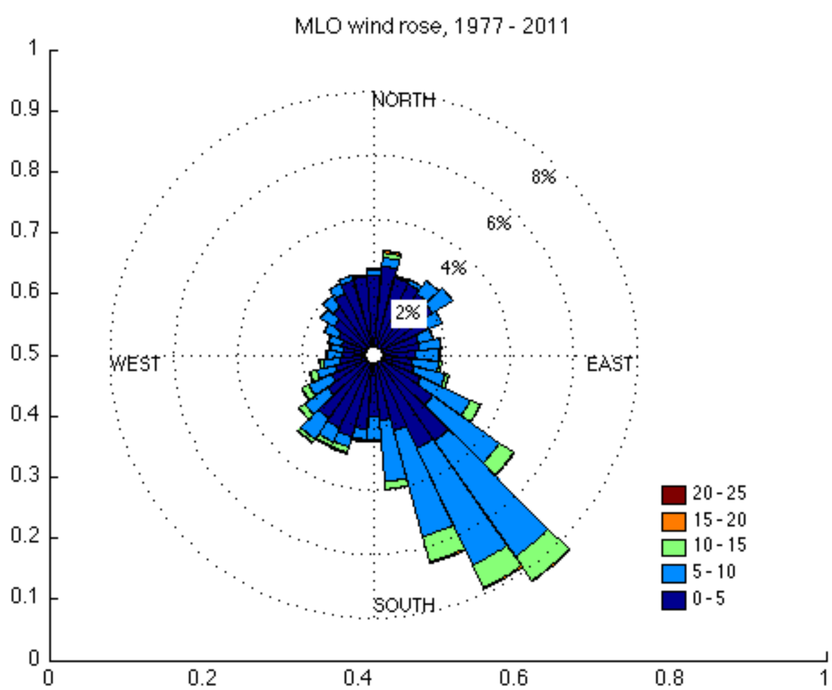


Fig. 27: Wind Rose 1977 – 2010, MLO, wind speed in m/s

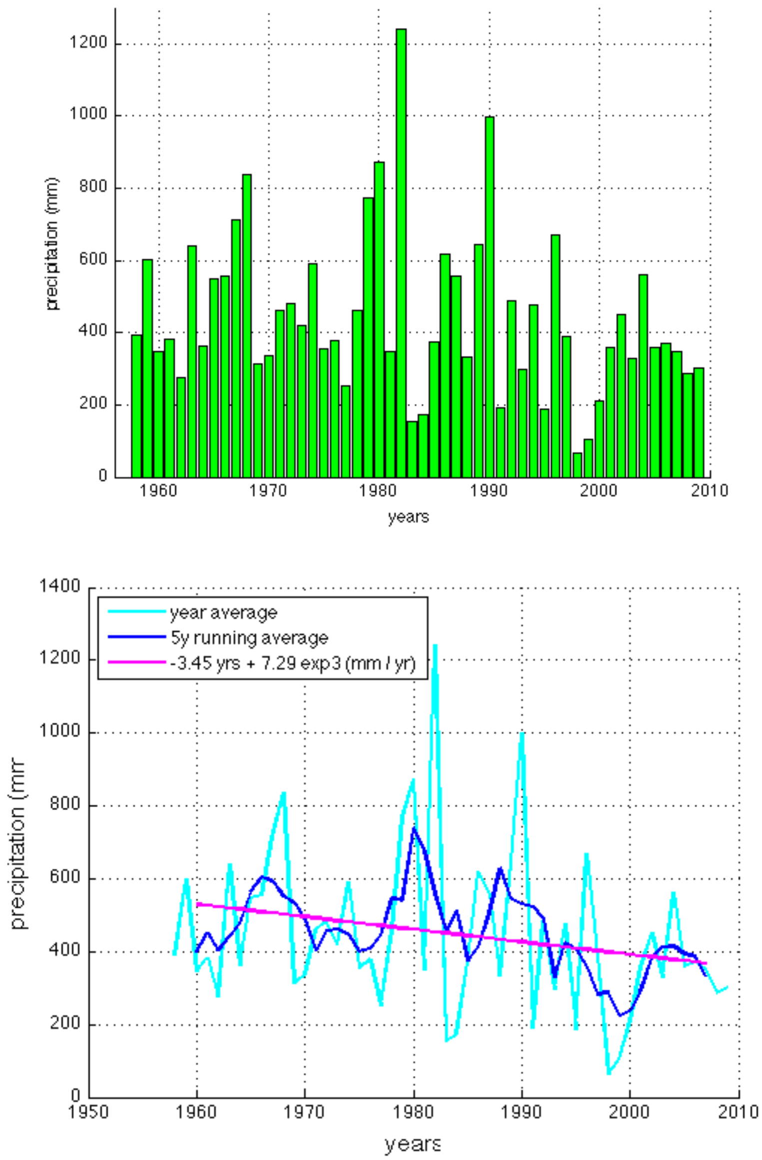


Fig. 28: (top) Histogram of annual total precipitation. (bottom) Precipitation (mm) inter-annual variability (light blue line), 5-yr running mean (dark mean line), trend of the 5-yr running mean (pink line).

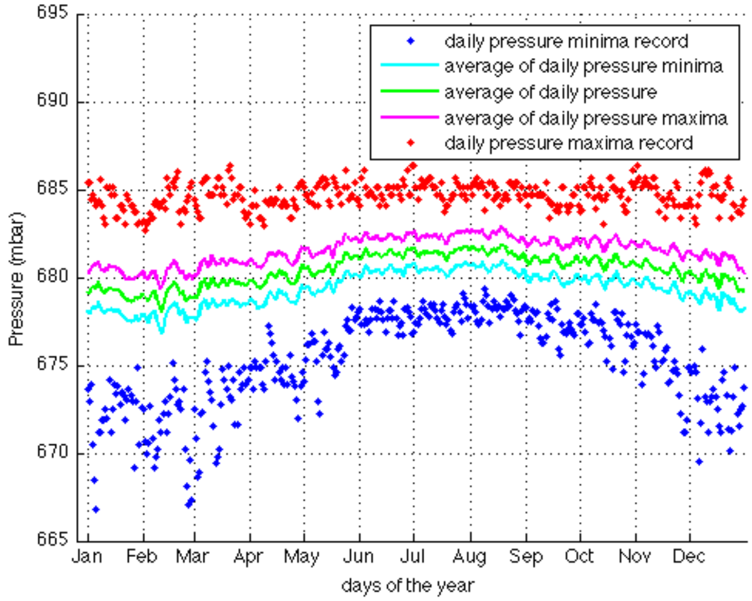


Fig. 29: Pressure (mbar) Annual Cycle, MLO, 1977 – 2010, daily pressure (mbar) maxima record (red dots), average of daily pressure (mbar) maxima (pink line), average of daily pressure (mbar) (green line), average of daily pressure (mbar) minima (light blue line), daily pressure (mbar) minimum record (dark blue dots)

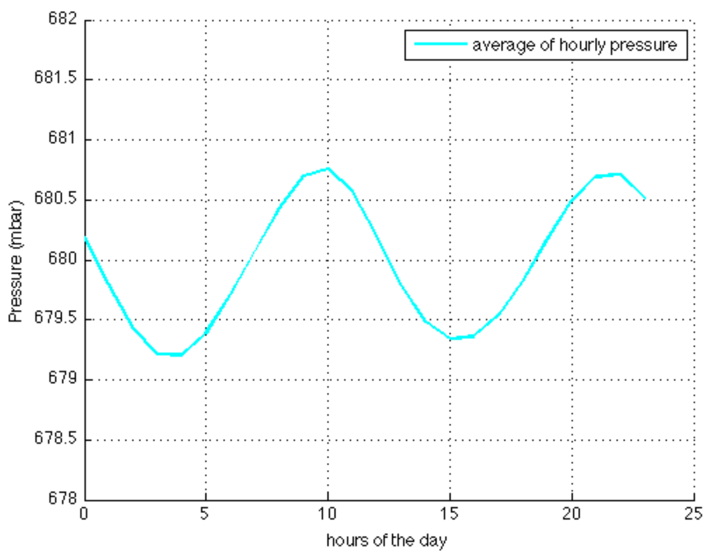


Fig. 30: Pressure (mbar) Diurnal Cycle, MLO, 1977 – 2010, average of hourly pressure (mbar) maxima (pink line), average of hourly pressure (mbar) (light blue line), average of hourly pressure (mbar) minima (dark blue line)

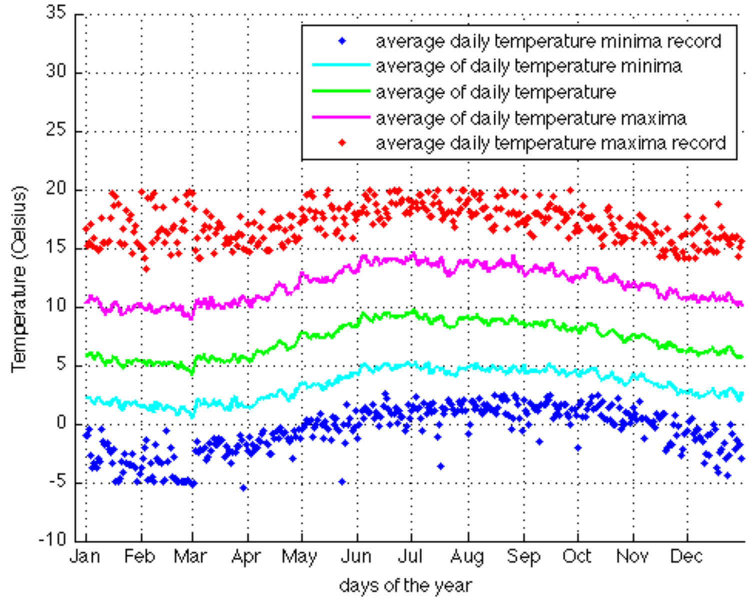


Fig. 31: Temperature (° C) Annual Cycle, MLO, 1977 – 2010, daily temperature (˚C) maxima record (red dots), average of daily temperature (˚C) maxima (pink line), average of daily temperature (˚C) (green line), average of daily temperature (˚C) minima (light blue line), daily temperature (˚C) minimum record (dark blue dots)

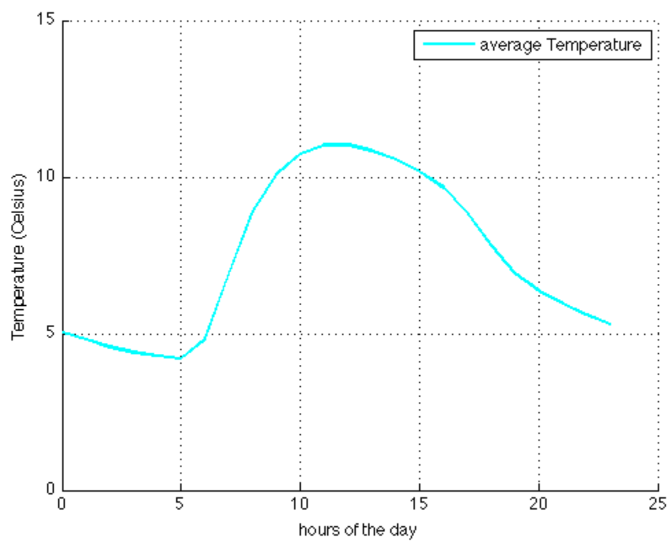


Fig. 32: Temperature (° C) Diurnal Cycle, MLO, 1977 – 2010, average of hourly temperature (˚C) maxima (pink line), average of hourly temperature (˚C) (light blue line), average of hourly temperature (˚C) minima (dark blue line)

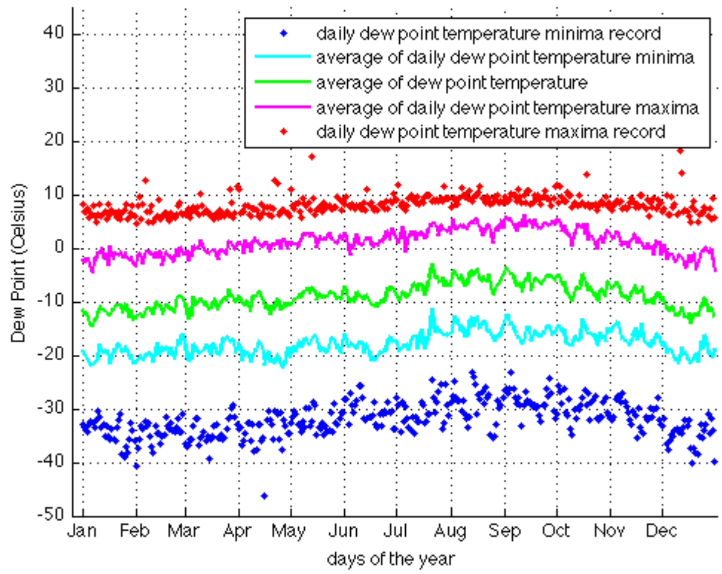


Fig. 33: Dew Point Temperature (° C) Annual Cycle, MLO, 1977 – 2010, daily dew point temperature (˚C) maxima record (red dots), average of daily dew point temperature (˚C) maxima (pink line), average of daily dew point temperature (˚C) (green line), average of daily dew point temperature (˚C) minima (light blue line), daily dew point temperature (˚C) minimum record (dark blue dots)

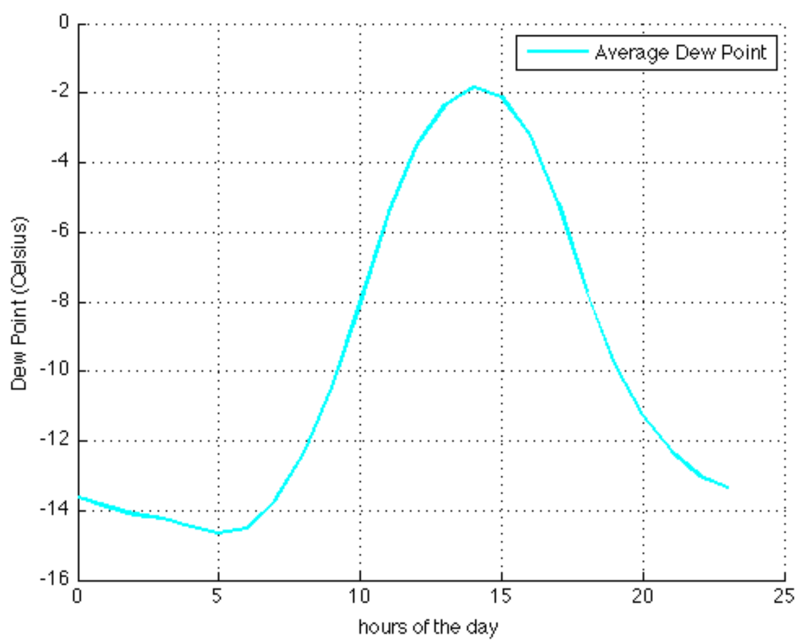


Fig. 34: Dew Point Temperature (° C) Diurnal Cycle, MLO, 1977 – 2010, average of hourly dew point temperature (˚C) maxima (pink line), average of hourly dew point temperature (˚C) (light blue line), average of hourly dew point temperature (˚C) minima (dark blue line)

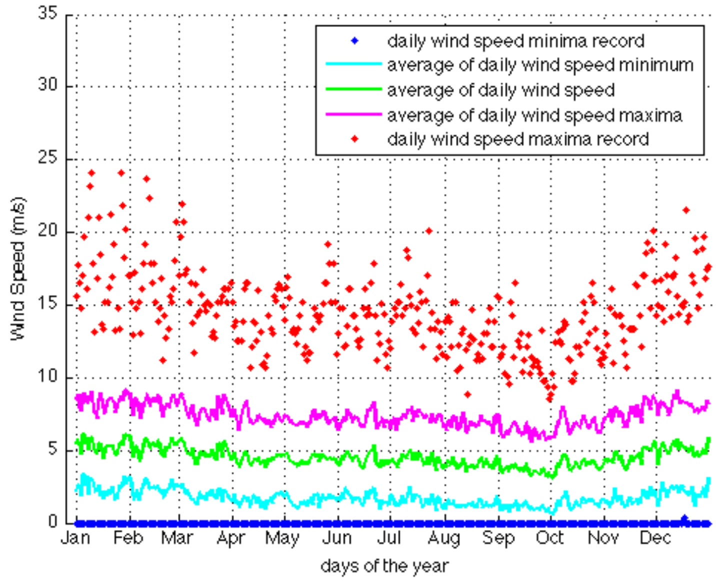


Fig. 35a: Wind Speed (m/s) Annual Cycle, MLO, 1977 – 2010, daily wind speed (m/s) maxima record (red dots), average of daily wind speed (m/s) maxima (pink line), average of daily wind speed (m/s) (green line), average of daily wind speed (m/s) minima (light blue line), daily wind speed (m/s) minimum record (dark blue dots)

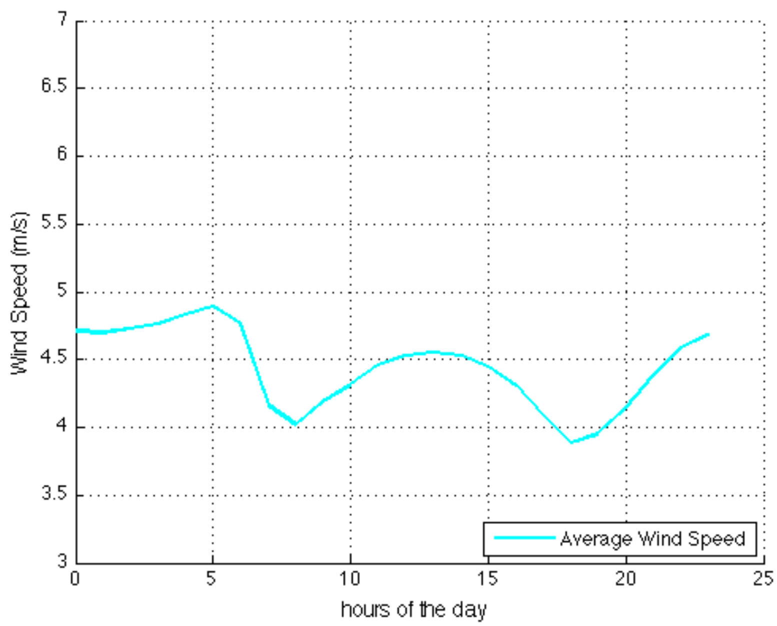


Fig. 35b: Diunal cycle of the wind speed for Mauna Kea, 1982-2010. Average of the hourly wind speed (m/s).

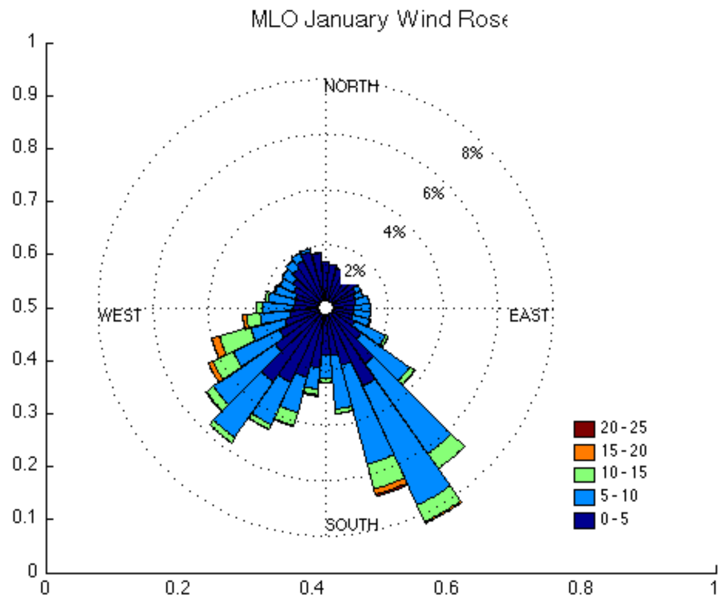


Fig. 36: MLO January Wind Rose, 1977 – 2010, wind speed in m/s

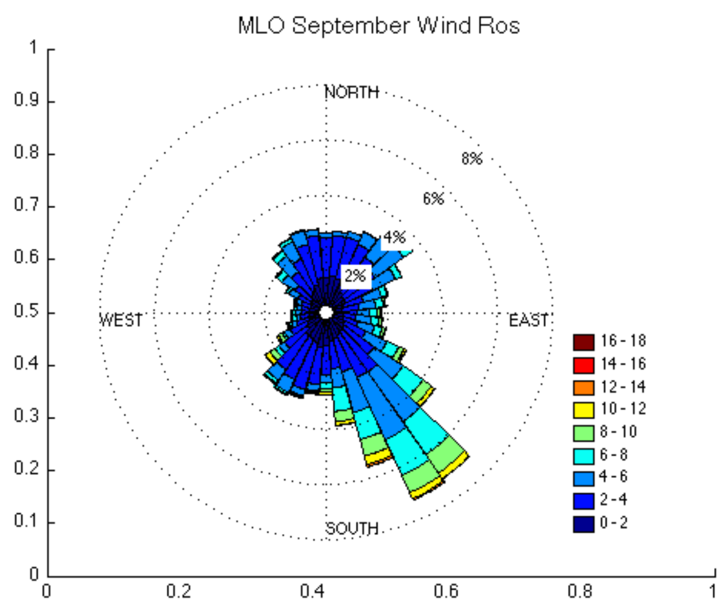


Fig. 37: MLO September Wind Rose, 1977 – 2010, wind speed in m/s

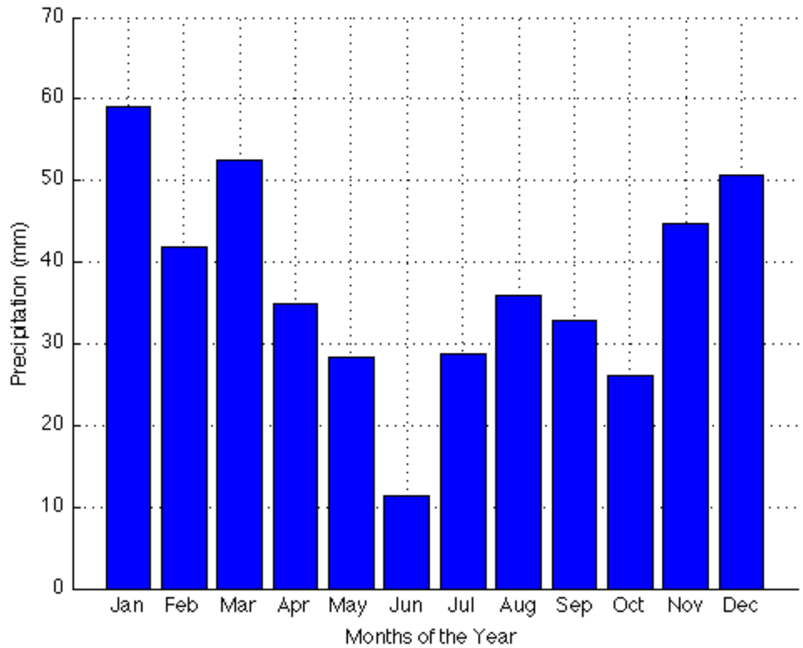


Fig. 38: MLO average precipitation annual cycle (mm).

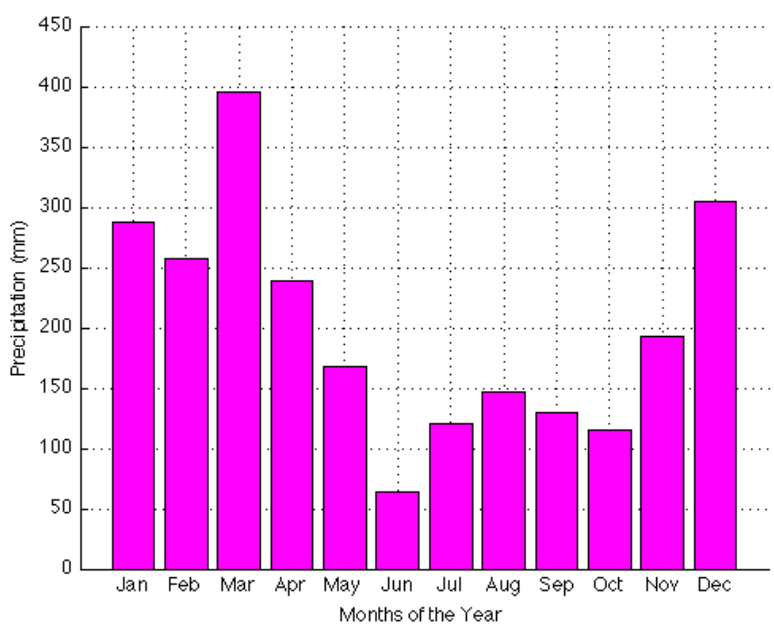


Fig. 39: MLO precipitation maxima annual cycle (mm).

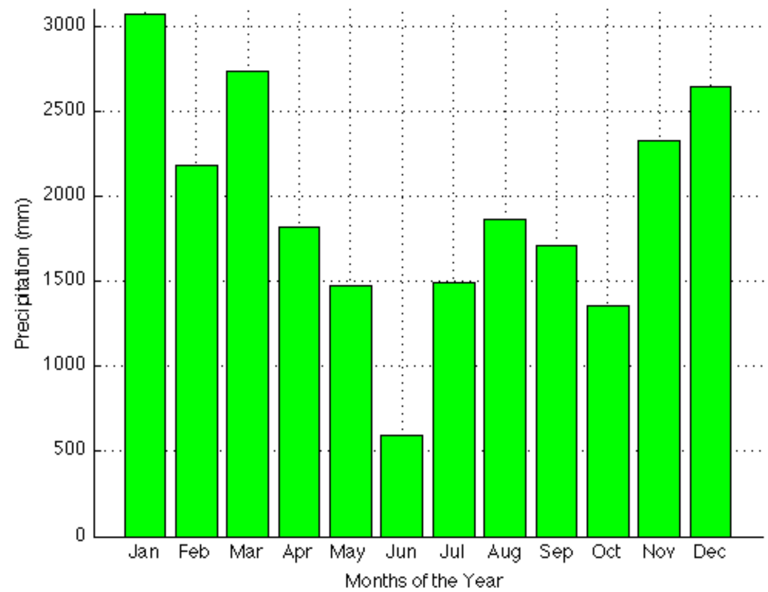


Fig. 40: MLO precipitation totals annual cycle (mm).

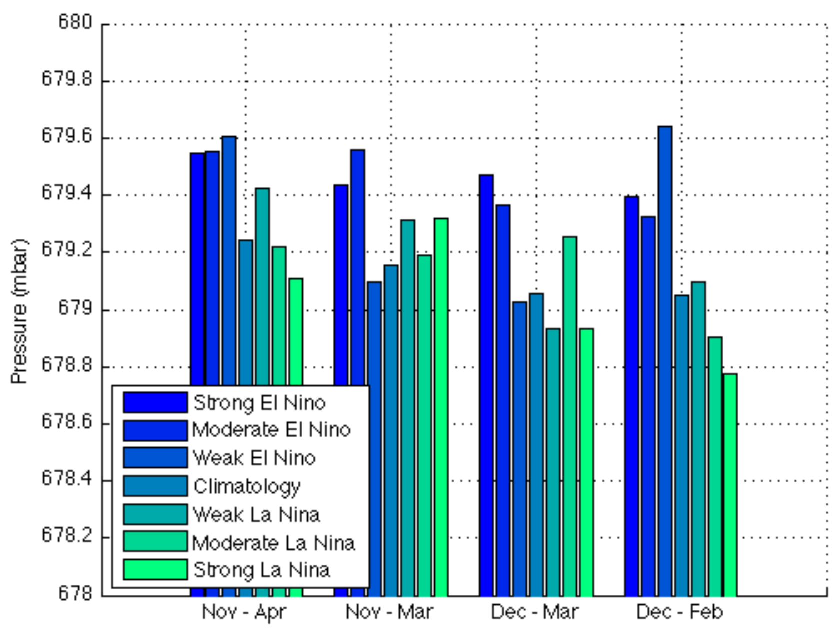


Fig. 41: Pressure (mbar) composites for climatology, weak, moderate and strong ENSO events, MLO, 1977 -2010

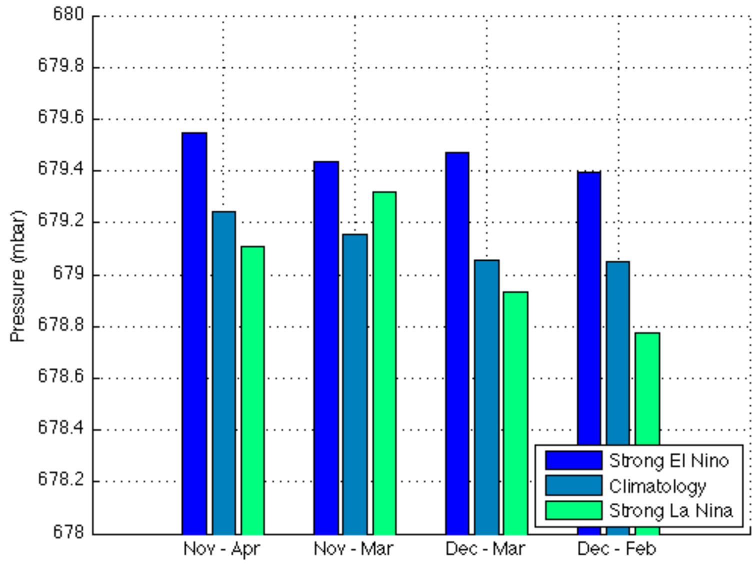


Fig. 42: Pressure (mbar) composites for climatology, El Niño and La Niña strong events, MLO, 1977 - 2010

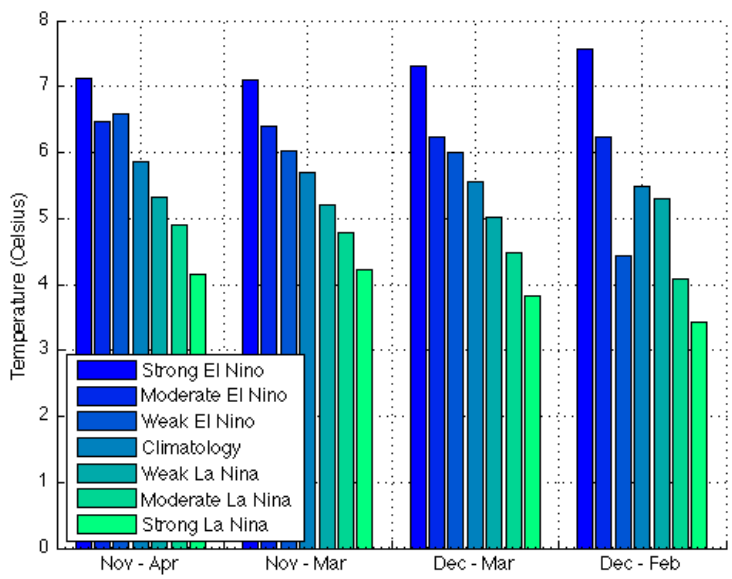


Fig. 43: Temperature (˚C) composites for climatology, weak, moderate and strong ENSO events, MLO, 1977 - 2010

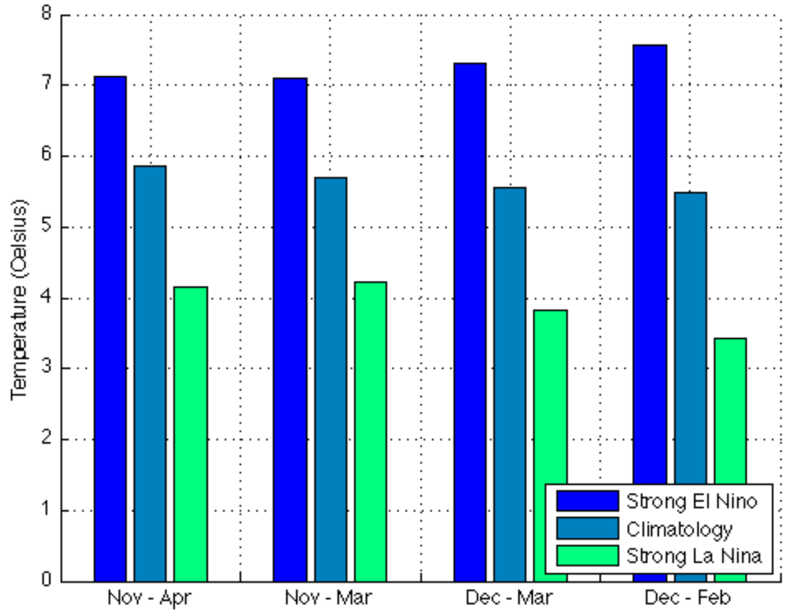


Fig. 44: Temperature (˚C) composites for climatology, strong El Niño and strong La Niña, MLO, wind speed in m/s

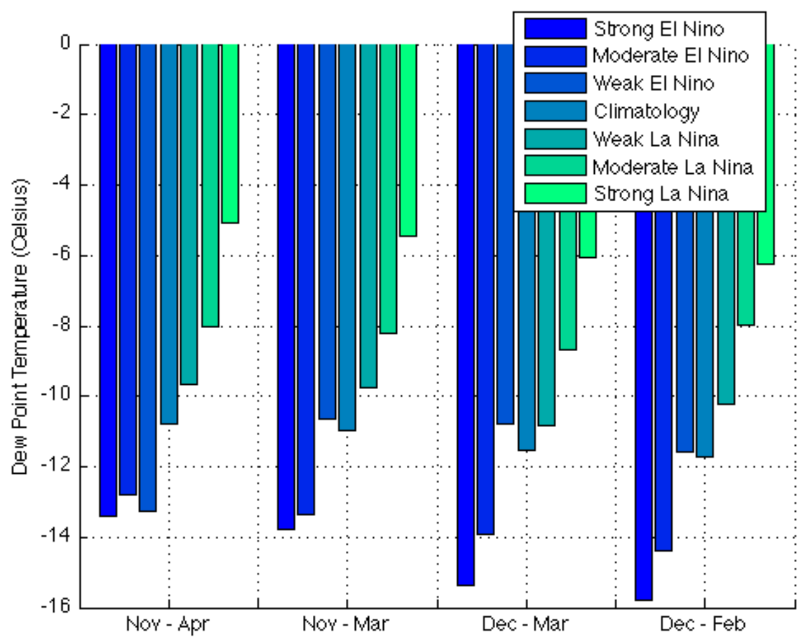


Fig. 45: Dew Point Temperature composites (˚C) for climatology, weak, moderate and strong ENSO events, MLO, 1977 - 2010

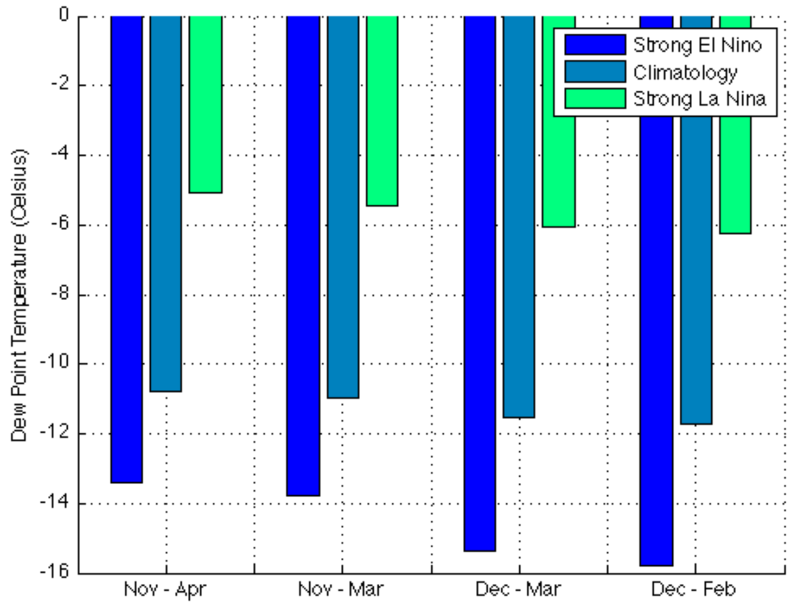


Fig. 46: Dew Point Temperature composites (˚C) for climatology, strong El Niño and strong La Niña, MLO, 1977 - 2010

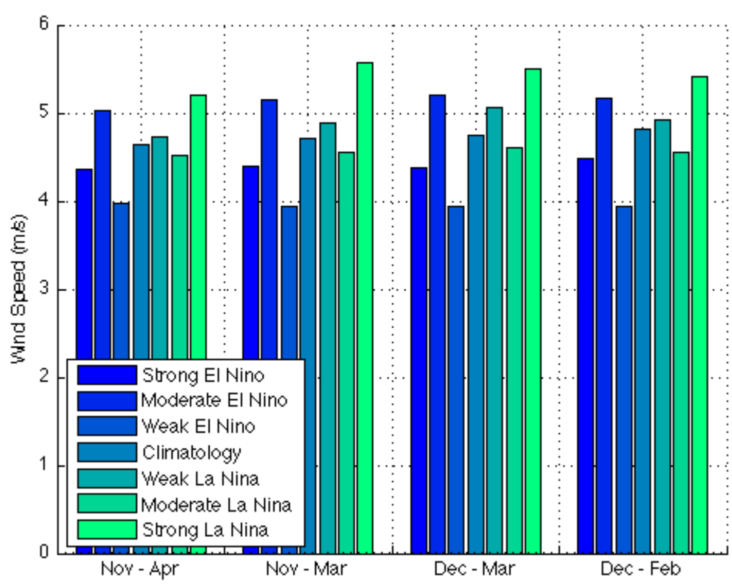


Fig. 47: Wind Speed (m/s) composites, weak, moderate and strong ENSO events, MLO, 1977 - 2010

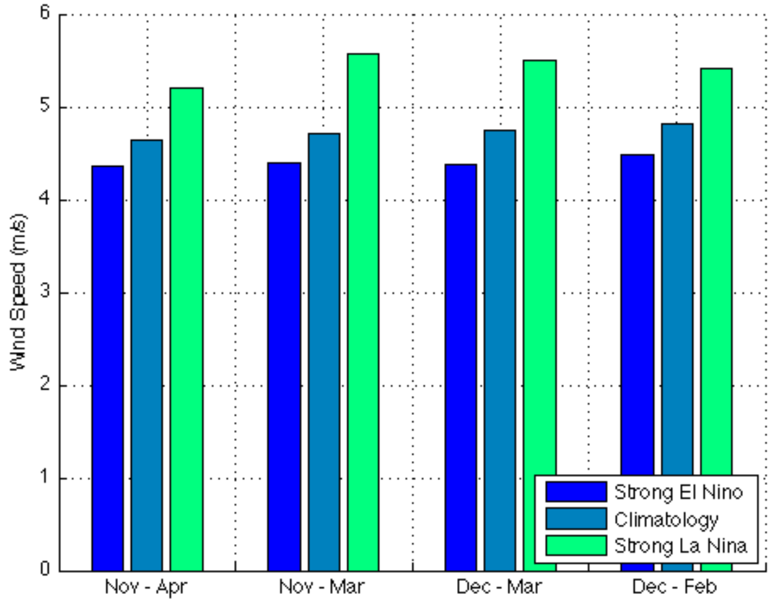


Fig. 48: Wind Speed (m/s) composites for climatology, strong El Niño and strong La Niña, MLO, 1977 – 2010

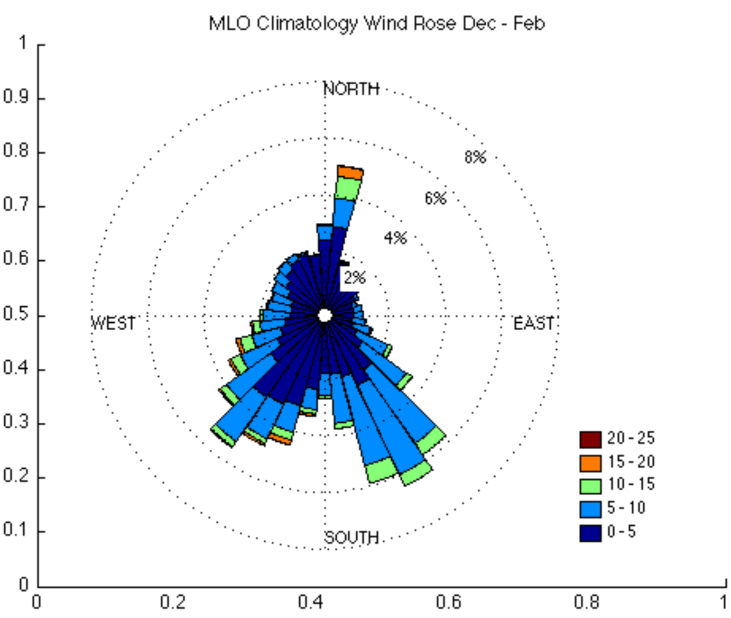


Fig. 49: Climatology Wind Rose , 1977 – 2010, MLO, wind speed in m/s

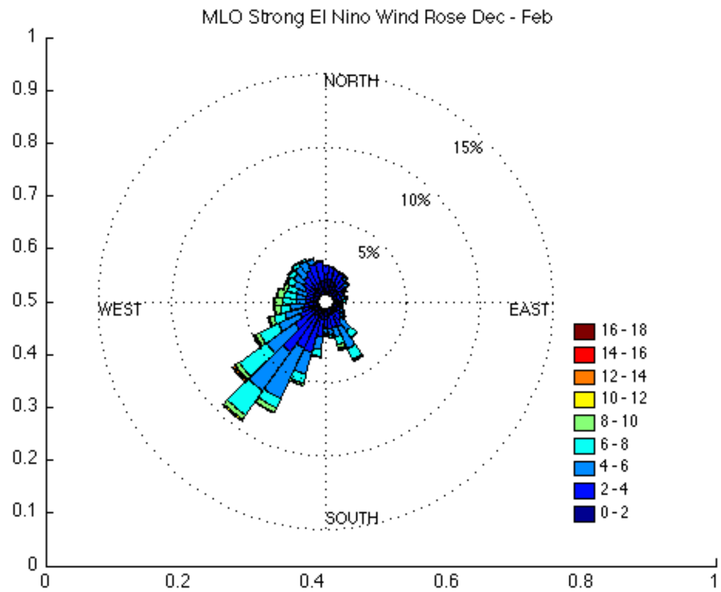


Fig. 50: Strong El Niño Composite Wind Rose , 1977 – 2010, MLO, wind speed in m/s

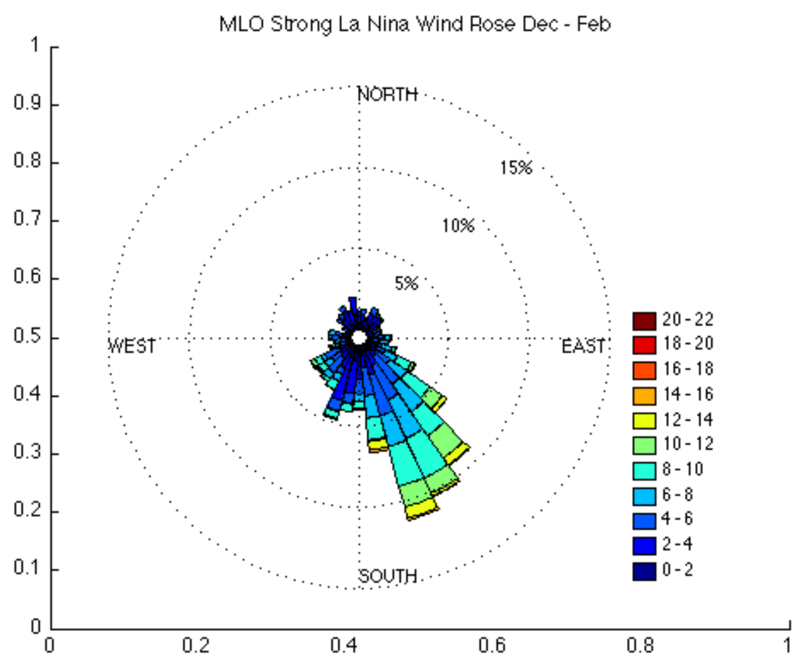


Fig. 51: Strong La Niña Wind Rose, 1977 – 2010, MLO, wind speed in m/s

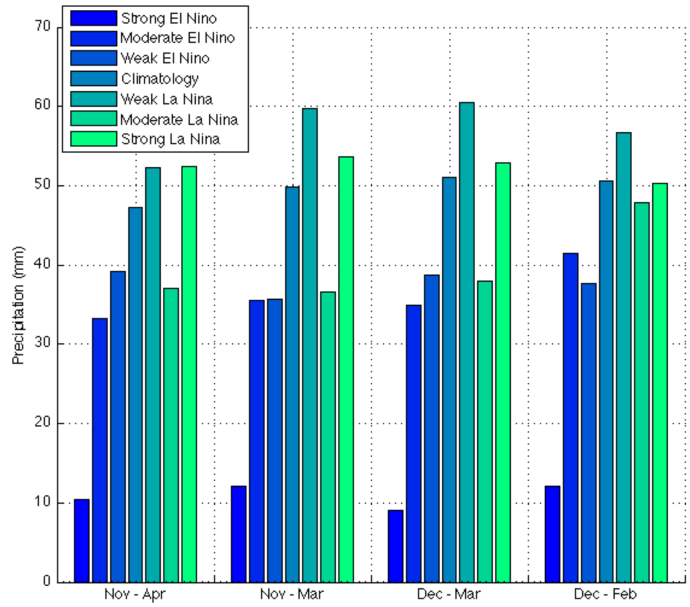


Fig. 52: Precipitation (mm) composites for climatology, weak, moderate and strong ENSO events, MLO, 1977 - 2010

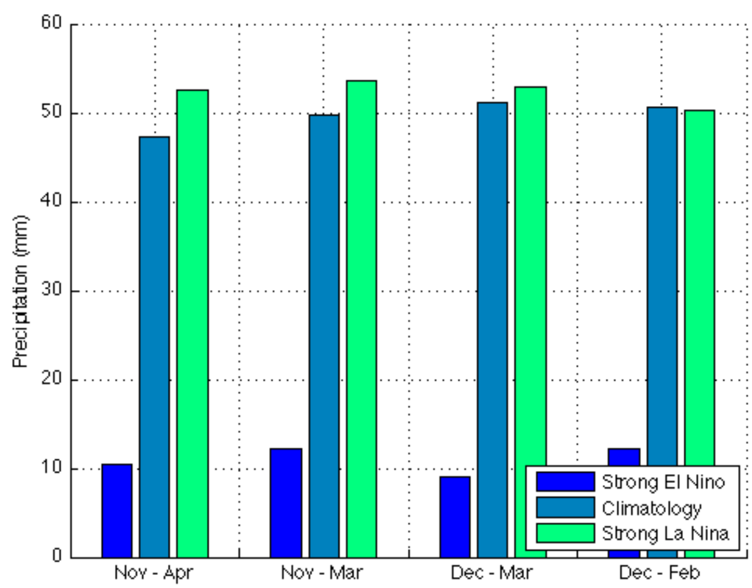


Fig. 53: Precipitation composites (mm) for climatology, strong El Niño and strong La Niña, MLO, 1977 - 2010

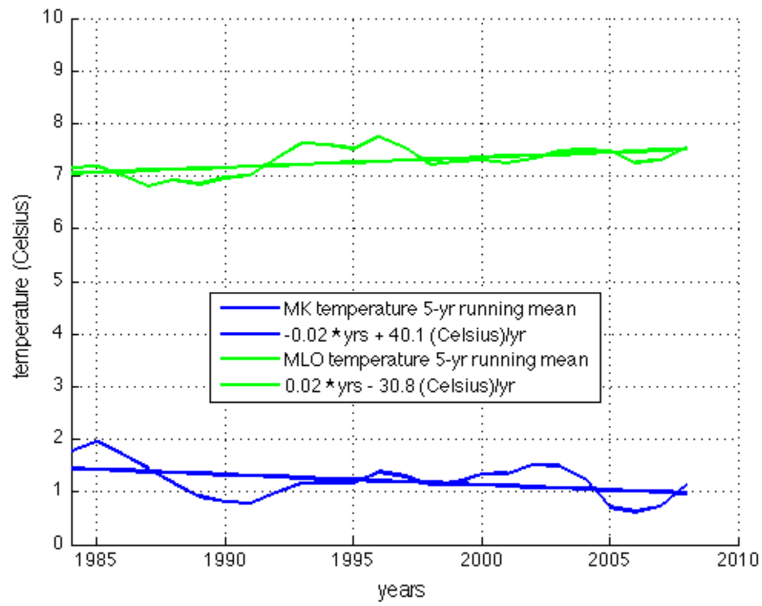


Fig. 54: Temperature (°C) inter-annual variability comparison, trends for temperature (° C) 5-yr running mean, Mauna Kea (dark blue line) and MLO (green line), 1982 - 2010

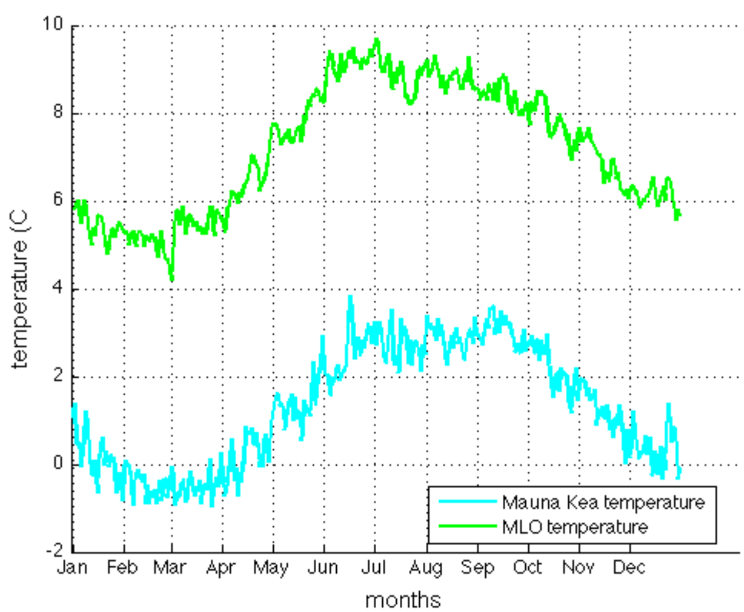


Fig. 55: Temperature (° C) Annual Cycle comparison, Mauna Kea (light blue line) and MLO (green line), 1982 - 2010

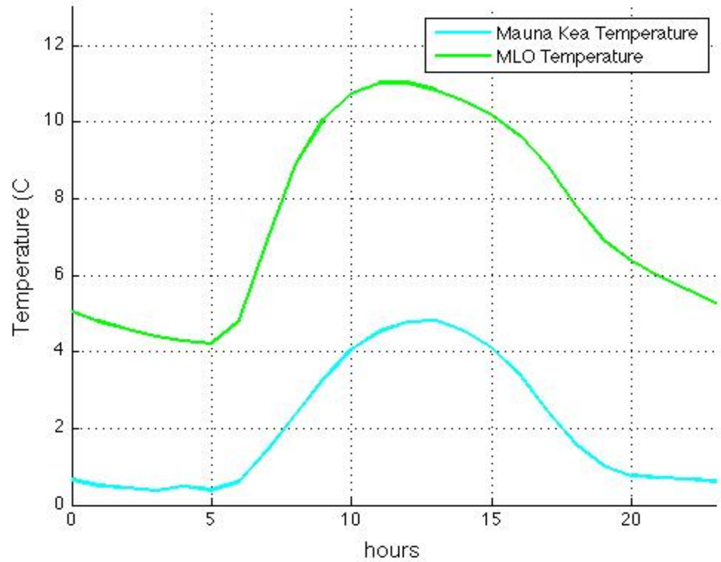


Fig. 56: Temperature (° C) Diurnal Cycle comparison, Mauna Kea (light blue line) and MLO (green line), 1982 - 2010

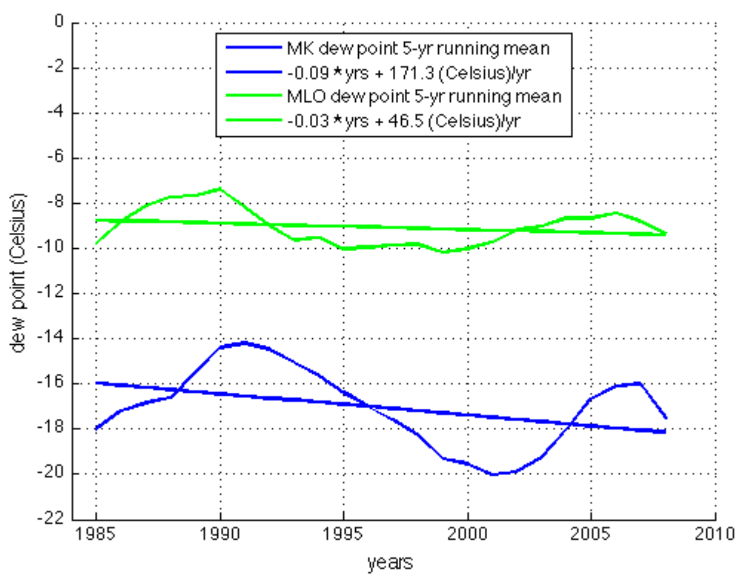


Fig. 57: Dew Point Temperature (° C) inter-annual variability comparison, Mauna Kea (dark blue line) and MLO (green line), 1982 - 2010

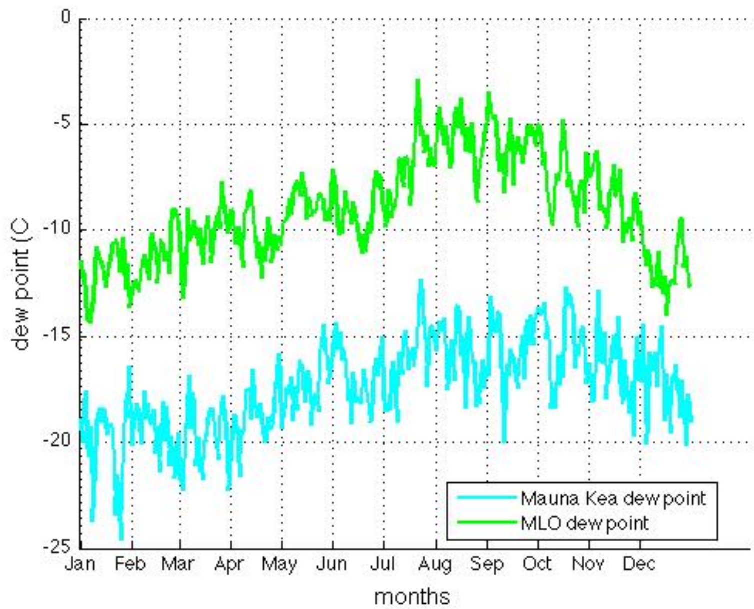


Fig. 58: Dew Point Temperature (° C) Diurnal Cycle comparison, Mauna Kea (light blue line) and MLO (green line), 1982 - 2010

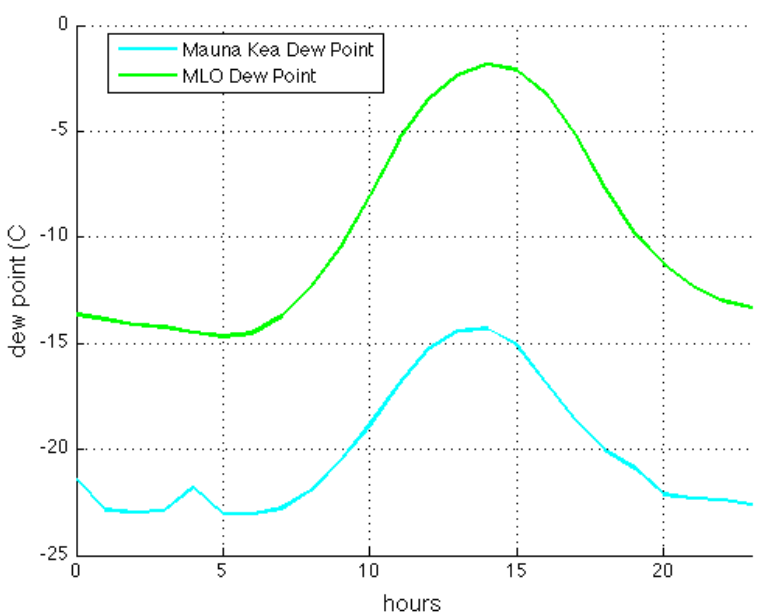


Fig. 59: Dew Point Temperature (° C) Diurnal Cycle comparison, Mauna Kea (light blue line) and MLO (green line), 1982 - 2010

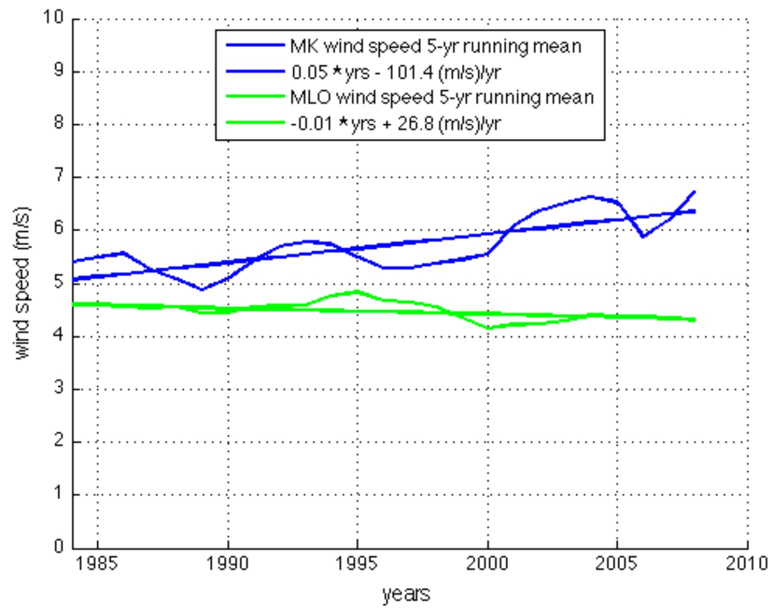


Fig. 60: Wind Speed (m/s) inter-annual variability comparison, Mauna Kea (dark blue line) and MLO (green line), 1982 - 2010

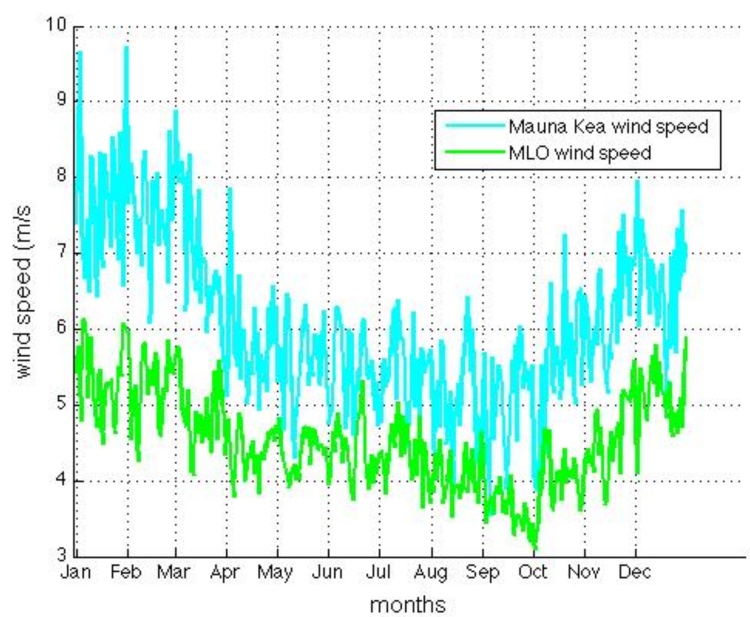


Fig. 61: Wind Speed (m/s) annual cycle comparison, Mauna Kea (light blue line) and MLO (green line), 1982 - 2010

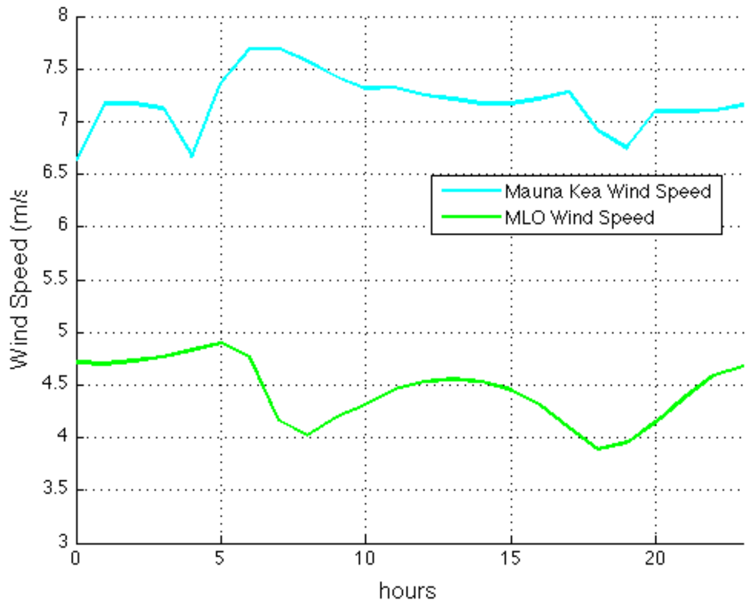


Fig. 62: Wind Speed (m/s) diurnal cycle comparison, Mauna Kea (light blue line) and Mauna Loa (green line), 1982 - 2010

Appendix

Table 22: MLO Pressure Yearly Averages and 5-Yrs Averages and respective standard deviations

Year	Yearly Av.	Range
1977	680.51	±1.79
1978	680.75	±1.70
1979	680.87	±2.06
1980	680.98	±1.98
1981	681.19	±1.75
1982	680.62	±2.15
1983	681.98	±1.64
1984	681.77	±1.87
1985	679.80	±1.95
1986	680.24	±1.78
1987	679.84	±2.10
1988	680.50	±1.80
1989	679.89	±2.03
1990	680.55	±2.16
1991	680.50	±1.83
1992	680.69	±1.87
1993	680.54	±2.36
1994	679.72	±1.72
1995	679.96	±1.99
1996	679.50	±2.47
1997	679.63	±2.11
1998	681.12	±1.56
1999	679.97	±1.54
2000	680.07	±1.48
2001	680.35	±1.75
2002	680.52	±1.67
2003	680.54	±1.89
2004	680.27	±1.96
2005	680.44	±2.04
2006	680.18	±1.87
2007	680.13	±1.62
2008	679.98	±1.59
2009	679.48	±1.89
2010	680.53	±1.66
2011	679.18	±2.01

Year	5 Yrs Av
1979	680.86
1980	680.88
1981	681.13
1982	681.31
1983	681.07
1984	680.88
1985	680.73
1986	680.43
1987	680.05
1988	680.20
1989	680.26
1990	680.43
1991	680.43
1992	680.40
1993	680.28
1994	680.08
1995	679.87
1996	679.98
1997	680.03
1998	680.06
1999	680.23
2000	680.41
2001	680.29
2002	680.35
2003	680.42
2004	680.39
2005	680.31
2006	680.20
2007	680.04
2008	680.06
2009	679.86

Table 23: MLO Temperature Yearly Averages, 5 – Yrs Averages and respective standard deviations

Year	Yearly Av.	Range
1977	6.94	±3.81
1978	5.92	±3.72
1979	6.51	±4.07
1980	7.28	±3.86
1981	7.58	±4.02
1982	6.93	±3.81
1983	7.89	±3.89
1984	6.93	±4.09
1985	6.36	±3.81
1986	7.54	±3.54
1987	6.99	±3.74
1988	7.03	±3.82
1989	6.12	±3.72
1990	6.97	±3.80
1991	7.12	±3.77
1992	7.63	±3.61
1993	7.06	±3.81
1994	7.05	±3.49
1995	7.87	±3.50
1996	7.01	±3.54
1997	7.03	±3.67
1998	8.17	±3.50
1999	7.16	±3.75
2000	7.09	±3.58
2001	6.70	±3.30
2002	6.49	±3.53
2003	8.00	±3.53
2004	7.23	±3.50
2005	7.50	±3.62
2006	7.43	±3.64
2007	7.50	±3.57
2008	6.98	±3.86
2009	7.40	±3.88
2010	8.73	±3.95
2011	5.83	±3.46

Year	5-Yrs Ave
1979	6.85
1980	6.85
1981	7.24
1982	7.32
1983	7.14
1984	7.13
1985	7.14
1986	6.97
1987	6.81
1988	6.93
1989	6.84
1990	6.97
1991	6.98
1992	7.17
1993	7.35
1994	7.32
1995	7.21
1996	7.43
1997	7.45
1998	7.29
1999	7.23
2000	7.12
2001	7.09
2002	7.10
2003	7.19
2004	7.33
2005	7.54
2006	7.33
2007	7.36
2008	7.61
2009	7.29

Table 24: MLO Yearly Averages and 5 – Yrs Averages (long data set, 1968 – 2010)

Year	Av. Temp.
1968	6.58
1969	6.74
1970	6.05
1971	5.47
1972	6.03
1973	6.88
1974	5.42
1975	5.71
1976	5.46
1977	6.94
1978	5.92
1979	6.48
1980	7.28
1981	7.58
1982	6.92
1983	7.88
1984	7.06
1985	6.40
1986	7.53
1987	7.03
1988	6.99
1989	6.10
1990	6.95
1991	7.16
1992	7.62
1993	7.19
1994	7.74
1995	8.41
1996	7.04
1997	7.23
1998	8.27
1999	6.73
2000	6.83
2001	7.31
2002	7.36
2003	8.00
2004	7.20
2005	7.48
2006	7.40
2007	7.33
2008	6.89
2009	7.38
2010	8.73

Year	5-Av temp
1970	6.18
1971	6.23
1972	5.97
1973	5.90
1974	5.90
1975	6.08
1976	5.89
1977	6.10
1978	6.42
1979	6.84
1980	6.83
1981	7.23
1982	7.34
1983	7.17
1984	7.16
1985	7.18
1986	7.01
1987	6.81
1988	6.92
1989	6.85
1990	6.97
1991	7.01
1992	7.33
1993	7.63
1994	7.60
1995	7.52
1996	7.74
1997	7.54
1998	7.22
1999	7.27
2000	7.30
2001	7.24
2002	7.34
2003	7.47
2004	7.49
2005	7.48
2006	7.26
2007	7.30
2008	7.55

Table 25: MLO Dew Point Yearly Averages and respective standard deviations, 5 – Yrs Averages

Year	Yearly Av.	Range
1977	-7.14	±8.39
1978	-8.48	±8.94
1979	-7.66	±8.27
1980	-10.28	±8.43
1981	-11.49	±9.71
1982	-5.84	±9.37
1983	-13.27	±11.46
1984	-9.90	±10.53
1985	-8.74	±8.95
1986	-8.62	±9.77
1987	-8.54	±9.92
1988	-8.39	±9.58
1989	-6.23	±8.87
1990	-6.94	±9.78
1991	-8.28	±10.36
1992	-7.08	±9.78
1993	-12.48	±11.41
1994	-10.31	±11.33
1995	-9.98	±9.81
1996	-7.82	±9.68
1997	-9.50	±11.00
1998	-12.13	±10.98
1999	-9.81	±9.62
2000	-9.92	±10.34
2001	-9.46	±10.15
2002	-8.83	±9.87
2003	-10.58	±10.53
2004	-7.07	±9.29
2005	-9.10	±9.33
2006	-7.70	±9.52
2007	-8.85	±9.71
2008	-9.47	±8.83
2009	-8.81	±8.87
2010	-11.90	±9.14
2011	-8.43	±8.51

Year	5-Yrs Av.
1979	-9.01
1980	-8.75
1981	-9.71
1982	-10.16
1983	-9.85
1984	-9.28
1985	-9.82
1986	-8.84
1987	-8.11
1988	-7.75
1989	-7.68
1990	-7.39
1991	-8.20
1992	-9.02
1993	-9.63
1994	-9.54
1995	-10.02
1996	-9.95
1997	-9.85
1998	-9.84
1999	-10.16
2000	-10.03
2001	-9.72
2002	-9.17
2003	-9.01
2004	-8.66
2005	-8.66
2006	-8.44
2007	-8.79
2008	-9.35
2009	-9.49

Table 26: MLO Wind Speed Yearly Averages and respective standard deviations, and 5 – Yrs Averages

Year	Yearly Av.	Range
1977	4.93	±3.33
1978	4.55	±3.04
1979	4.31	±2.84
1980	4.69	±3.21
1981	4.81	±3.29
1982	4.49	±3.30
1983	4.49	±2.71
1984	4.59	±2.96
1985	4.65	±3.19
1986	4.83	±3.09
1987	4.46	±2.88
1988	4.33	±2.62
1989	4.38	±2.66
1990	4.76	±2.94
1991	4.24	±3.00
1992	4.55	±2.80
1993	4.85	±3.24
1994	4.43	±2.89
1995	4.86	±3.30
1996	5.07	±3.58
1997	4.94	±3.27
1998	4.05	±2.75
1999	4.32	±2.77
2000	4.35	±2.79
2001	4.10	±2.78
2002	3.91	±2.59
2003	4.37	±2.84
2004	4.43	±3.01
2005	4.67	±3.14
2006	4.57	±2.96
2007	3.88	±2.08
2008	4.36	±2.54
2009	4.26	±2.52
2010	4.43	±2.52
2011	4.47	±2.56

Year	5 - Yrs Av.
1979	4.66
1980	4.57
1981	4.56
1982	4.61
1983	4.61
1984	4.61
1985	4.60
1986	4.57
1987	4.53
1988	4.55
1989	4.43
1990	4.45
1991	4.56
1992	4.57
1993	4.59
1994	4.75
1995	4.83
1996	4.67
1997	4.65
1998	4.55
1999	4.35
2000	4.15
2001	4.21
2002	4.23
2003	4.30
2004	4.39
2005	4.38
2006	4.38
2007	4.35
2008	4.30
2009	4.28

Table 27: MLO Precipitation Yearly Averages and 5 – Yrs Averages. Standard deviations are not available

Year	Year Total
1958	392.43
1959	600.96
1960	345.95
1961	381.76
1962	276.61
1963	641.35
1964	362.71
1965	547.88
1966	554.99
1967	713.99
1968	838.96
1969	313.94
1970	335.79
1971	462.53
1972	480.82
1973	420.88
1974	592.33
1975	355.85
1976	377.44
1977	253.24
1978	459.99
1979	772.92
1980	873.51
1981	348.49
1982	1241.04
1983	155.45
1984	172.47
1985	374.14
1986	618.74
1987	558.00
1988	332.00
1989	643.00
1990	999.00
1991	192.00
1992	487.00
1993	298.00
1994	477.00
1995	187.00
1996	671.00
1997	390.00
1998	65.00
1999	104.00
2000	212.00
2001	359.00
2002	452.00

Year	Year Totals
1960	399.54
1961	449.33
1962	401.68
1963	442.06
1964	476.71
1965	564.18
1966	603.71
1967	593.95
1968	551.54
1969	533.04
1970	486.41
1971	402.79
1972	458.47
1973	462.48
1974	445.47
1975	399.95
1976	407.77
1977	443.89
1978	547.42
1979	541.63
1980	739.19
1981	678.28
1982	558.19
1983	458.32
1984	512.37
1985	375.76
1986	411.07
1987	505.18
1988	630.15
1989	544.80
1990	530.60
1991	523.80
1992	490.60
1993	328.20
1994	424.00
1995	404.60
1996	358.00
1997	283.40
1998	288.40
1999	226.00
2000	238.40
2001	291.20
2002	382.60

2003	329.00
2004	561.00
2005	359.00
2006	371.00
2007	349.00
2008	287.00
2009	301.00

2003	412.00
2004	414.40
2005	393.80
2006	385.40
2007	333.40

Table 28: MK (UH 88) Temperature Yearly Average and respective standard deviations, 5 – Yrs Average

Year	Yearly Av.	Range
1982	0.74	±3.01
1983	2.40	±2.52
1984	1.50	±2.70
1985	2.03	±2.65
1986	2.16	±2.22
1987	1.71	±2.90
1988	1.22	±2.61
1989	0.08	±2.60
1990	0.70	±2.44
1991	0.86	±2.62
1992	1.22	±1.99
1993	1.06	±2.57
1994	1.11	±2.22
1995	1.53	±2.41
1996	0.99	±2.24
1997	1.20	±2.52
1998	2.10	±2.55
1999	0.62	±2.54
2000	0.75	±2.38
2001	1.19	±2.35
2002	2.01	±2.48
2003	2.17	±2.33
2004	1.44	±2.47
2005	0.71	±2.61
2006	-0.02	±2.76
2007	-0.75	±2.90
2008	1.73	±3.52
2009	1.96	±3.70
2010	2.78	±3.19
2011	0.26	±3.58

Year	5 - Yrs Av.
1984	1.77
1985	1.96
1986	1.72
1987	1.44
1988	1.17
1989	0.91
1990	0.82
1991	0.79
1992	0.99
1993	1.16
1994	1.18
1995	1.18
1996	1.39
1997	1.29
1998	1.13
1999	1.17
2000	1.33
2001	1.35
2002	1.51
2003	1.50
2004	1.26
2005	0.71
2006	0.62
2007	0.72
2008	1.14
2009	1.20

Table 29: MK (UH 88) Dew Point Yearly Averages and respective standard deviations, 5 – Yrs Averages

Year	Yearly Av.	Range
1983	-20.92	±9.06
1984	-17.36	±8.78
1985	-14.84	±6.78
1986	-17.77	±9.09
1987	-19.07	±9.48
1988	-16.85	±8.31
1989	-15.67	±6.88
1990	-13.65	±5.73
1991	-12.38	±5.17
1992	-13.36	±5.63
1993	-16.00	±7.44
1994	-16.92	±6.47
1995	-16.48	±5.03
1996	-15.35	±6.13
1997	-17.21	±5.77
1998	-19.12	±4.57
1999	-19.87	±6.88
2000	-19.76	±6.44
2001	-20.62	±6.43
2002	-18.28	±5.34
2003	-21.60	±10.53
2004	-19.14	±10.69
2005	-16.68	±10.84
2006	-14.22	±11.00
2007	-11.76	±11.16
2008	-18.71	±12.50
2009	-18.62	±13.04
2010	-24.24	±12.12
2011	-16.59	±12.18

Year	5-Yrs Av.
1985	-17.99
1986	-17.18
1987	-16.84
1988	-16.60
1989	-15.52
1990	-14.38
1991	-14.21
1992	-14.46
1993	-15.03
1994	-15.62
1995	-16.39
1996	-17.02
1997	-17.61
1998	-18.26
1999	-19.32
2000	-19.53
2001	-20.03
2002	-19.88
2003	-19.26
2004	-17.98
2005	-16.68
2006	-16.10
2007	-16.00
2008	-17.51
2009	-17.99

Table 30: MK (UH 88) wind speed yearly averages and respective standard deviations, and 5 – yrs average

Year	Yearly Av.	Range
1982	4.90	±3.45
1983	4.44	±3.34
1984	5.72	±3.39
1985	5.82	±3.43
1986	6.16	±3.60
1987	5.35	±3.43
1988	4.76	±3.01
1989	4.24	±2.90
1990	4.98	±3.42
1991	5.13	±3.40
1992	6.29	±3.44
1993	6.43	±3.52
1994	5.66	±3.49
1995	5.41	±3.81
1996	4.86	±3.86
1997	5.11	±4.05
1998	5.35	±4.00
1999	5.72	±4.19
2000	5.84	±4.17
2001	5.21	±3.96
2002	5.65	±4.04
2003	7.94	±3.37
2004	7.23	±3.11
2005	6.53	±2.85
2006	5.82	±2.59
2007	5.12	±2.33
2008	4.65	±2.19
2009	8.81	±3.19
2010	9.17	±3.18
2011	8.76	±3.23

Year	5 - Yrs Av.
1984	5.41
1985	5.50
1986	5.56
1987	5.27
1988	5.10
1989	4.89
1990	5.08
1991	5.41
1992	5.70
1993	5.79
1994	5.73
1995	5.49
1996	5.28
1997	5.29
1998	5.37
1999	5.45
2000	5.55
2001	6.07
2002	6.38
2003	6.51
2004	6.64
2005	6.53
2006	5.87
2007	6.19
2008	6.71
2009	7.30

Table 31: Diurnal Cycle for MK table

	T (Celsius)	dp (Celsius)	ws (m/s)
0.00	0.66	-21.39	6.63
1.00	0.50	-22.87	7.17
2.00	0.45	-22.96	7.17
3.00	0.37	-22.92	7.13
4.00	0.48	-21.82	6.66
5.00	0.39	-23.05	7.36
6.00	0.62	-23.04	7.69
7.00	1.43	-22.78	7.69
8.00	2.38	-21.95	7.57
9.00	3.29	-20.52	7.42
10.00	4.06	-18.88	7.31
11.00	4.54	-16.96	7.33
12.00	4.77	-15.31	7.25
13.00	4.81	-14.44	7.21
14.00	4.56	-14.29	7.17
15.00	4.10	-15.08	7.17
16.00	3.41	-16.85	7.21
17.00	2.44	-18.61	7.28
18.00	1.59	-20.02	6.92
19.00	1.02	-20.88	6.75
20.00	0.77	-22.12	7.09
21.00	0.72	-22.32	7.09
22.00	0.68	-22.39	7.10
23.00	0.61	-22.59	7.15

Table 32: Diurnal Cycle for MLO table

	P (mbar)	T (Celsius)	dp (Celsius)	ws (m/s)
0.00	680.19	5.05	-13.63	4.71
1.00	679.80	4.81	-13.88	4.70
2.00	679.42	4.58	-14.11	4.73
3.00	679.21	4.40	-14.23	4.76
4.00	679.21	4.28	-14.48	4.83
5.00	679.39	4.21	-14.66	4.89
6.00	679.71	4.83	-14.52	4.76
7.00	680.07	6.92	-13.72	4.16
8.00	680.43	8.91	-12.33	4.02
9.00	680.70	10.06	-10.47	4.19
10.00	680.76	10.74	-8.01	4.31
11.00	680.57	11.02	-5.44	4.46
12.00	680.20	11.03	-3.52	4.53
13.00	679.78	10.84	-2.34	4.55
14.00	679.48	10.56	-1.85	4.53
15.00	679.34	10.17	-2.11	4.45
16.00	679.36	9.66	-3.21	4.31
17.00	679.54	8.87	-5.17	4.09
18.00	679.82	7.79	-7.69	3.89
19.00	680.16	6.91	-9.81	3.95
20.00	680.49	6.37	-11.25	4.14
21.00	680.69	5.96	-12.30	4.38
22.00	680.71	5.61	-12.99	4.59
23.00	680.52	5.30	-13.32	4.68

Table 33: Temperature Extremes (C), Mauna Kea

year	temp
1983	12.78
1984	8.33
1985	8.89
1986	8.33
1987	11.11
1988	12.22
1989	9.44
1990	8.68
1991	8.89
1992	8.33
1993	13.33
1994	8.89
1995	10.00
1996	8.06
1997	10.00
1998	12.78
1999	8.89
2000	6.67
2001	13.33
2002	8.89
2003	8.00
2007	9.29
2008	14.77
2009	14.95
2010	12.99
2011	14.97

Table 34: Dew Point Temperature Extreme (C), Mauna Kea

year	max
1983	2.22
1984	4.44
1985	6.79
1986	1.76
1987	0.56
1988	2.22
1989	-0.04
1990	2.91
1991	1.38
1992	1.38
1993	6.51
1994	2.22
1995	3.33
1996	2.22
1997	2.22
1998	0.00
1999	1.11
2000	1.85
2001	3.33
2002	0.69
2003	2.20
2007	3.93
2008	6.72
2009	6.88
2010	3.82
2011	6.01

Table 35: Wind Speed Extreme (m/s), Mauna Kea

1982	56
1983	55
1984	55
1985	80
1986	90
1987	90
1988	38
1989	67
1990	96
1991	77
1992	65
1993	60
1994	55
1995	95
1996	99
1997	70
1998	65
1999	45
2000	50
2001	50
2002	51
2003	60
2007	56
2008	80
2009	79
2010	89
2011	70

Table 36: Pressure Extreme (mbar) Maxima, Mauna Loa

1977	685.1
1978	685.4
1979	686.4
1980	685.7
1981	686.1
1982	685.4
1983	686.4
1984	686.1
1985	684.7
1986	685.7
1987	685.1
1988	685.7
1989	685.4
1990	685.4
1991	685.1
1992	685.7
1993	686.4
1994	684.2
1995	685.1
1996	685.6
1997	685.1
1998	686
1999	684.7
2000	684.5
2001	685.6
2002	685.2
2003	684.8
2004	685.3
2005	685.2
2006	686.1
2007	684.6
2008	684.7
2009	683.9
2010	684.9
2011	683.7

Table 37: Temperature Extreme (Celsius), Mauna Loa

1977	17.4
1978	16.5
1979	18.2
1980	18.4
1981	19.8
1982	18.2
1983	18.5
1984	19.4
1985	18.9
1986	17.6
1987	17.6
1988	18.4
1989	18.1
1990	19.7
1991	18.9
1992	17.7
1993	19.2
1994	16.8
1995	18.3
1996	17.8
1997	18.2
1998	19.9
1999	18.1
2000	18.2
2001	16.7
2002	16.9
2003	17.5
2004	18.2
2005	17.8
2006	18.7
2007	19.9
2008	19.6
2009	19.9
2010	19.9
2011	19.8

Table 38: Dew Point Temperature Extreme (C), Mauna Loa

1977	10.6
1978	11.5
1979	10.9
1980	8.8
1981	8.6
1982	17
1983	9.3
1984	8.4
1985	9.4
1986	8
1987	8.7
1988	9
1989	9.8
1990	18.1
1991	13.7
1992	12.7
1993	11.4
1994	10
1995	9.9
1996	9.2
1997	10.7
1998	9.2
1999	11.6
2000	9.6
2001	9.5
2002	8.6
2003	9
2004	10
2005	8.6
2006	9.3
2007	10.9
2008	11.7
2009	10
2010	11.6
2011	12.7

Table 39: Wind Speed Extremes (m/s), Mauna Loa

1977	19.2
1978	18.8
1979	16.1
1980	24.1
1981	17
1982	23.7
1983	15.2
1984	14.8
1985	21
1986	20.1
1987	21.5
1988	20.1
1989	19.7
1990	19.2
1991	24.1
1992	16.5
1993	19.7
1994	17.1
1995	17.7
1996	22
1997	21.2
1998	16.1
1999	18.5
2000	16.8
2001	16.7
2002	14.8
2003	19.3
2004	20.7
2005	17.4
2006	15.9
2007	8.4
2008	9.0
2009	8.2
2010	8.5
2011	9.1