An analysis of the weather and climate conditions related to the 2012 epidemic of coffee rust in Guatemala

Technical report

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Summary of results from analysis of weather and climate conditions in Guatemala

Guatemalan weather conditions in 2012 displayed considerable variations from the climatological data, as was the case for the larger Central American picture. A key finding from our research is that in general the minimum daily temperatures were higher than the corresponding climatology while the maximum temperatures were lower. As a result, the daily diurnal temperature range was generally lower than the corresponding climatological range, leading to an increased number of days where the temperatures fell within the optimal range for coffee rust development during the dry season, or for the development of lesions on the coffee leaves during the wet season. The coffee rust latency period was probably shortened as a result, and farms at high altitudes were impacted due to these increases in minimum temperature. A seasonal analysis of temperature accumulation at farm locations found a direct correlation between temperature accumulation and rust severity.

Overall, compared with the climatology, there was less rainfall than usual in Guatemala during the 2012 wet season. Additionally, at a number of case study farms with high rust severity, there were differences observed in the rainfall pattern during the year. There was a period of heavy rainfall between mid March and mid April, in contrast with the climatology, and before the usual start of the rainy season. During the 2012 dry season, there was a weak La Niña signal, followed by a weak El Niño signal during the wet season, which could explain the observed anomalies from the climatology. There was also a shift in the timing of the mid rainy season drought period to earlier in the season. Despite there being a general pattern of lower rainfall during the wet season when compared with the climatology, a number of the five day precipitation periods included very high rainfall events when compared with the climatology. The wet season came to an earlier end than usual in Guatemala.

Acknowledgements

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1 Introduction

The weather and climate indicators that favoured the high incidence of coffee rust disease in Central America in 2012 have been investigated using daily temperature data available from 81 ANACAFE/ INSIVUMEH weather stations located in Guatemala. Additionally, CHIRPS five day (pentad) data has been used to assess the anomalies between the 2012 and the climatological average precipitation data. The temperature data were interpolated to determine the corresponding daily data at 1224 farms located across Guatemala, between 400 and 1800 m elevation (figure 1.1).

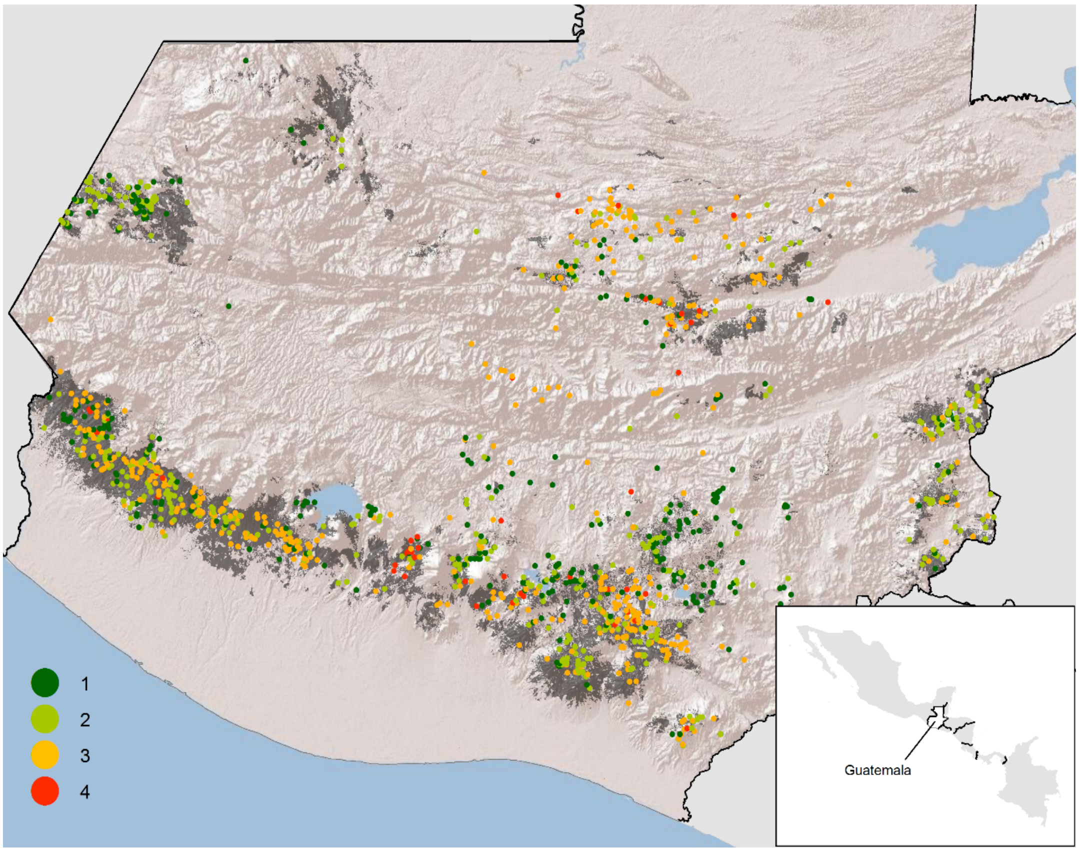


Figure 1.1. Map of Arabica coffee farm locations, marked by their coffee rust severity (1 = low to 4 = high severity) in 2012. Coffee producing regions are marked in grey (2003 data – MAGA, 2006).

The aim of this research is to propose recommendations for the development of a set of indicators to link weather conditions with the potential for coffee rust development at a particular location. Factors taken into consideration in developing indicators for coffee rust development include: seasonal and monthly temperature accumulations and anomalies from the climatological values; the diurnal temperature difference; altitude; El Niño/ La

Niña effects; the environmental lapse rate; and correspondence with the phenology of coffee.

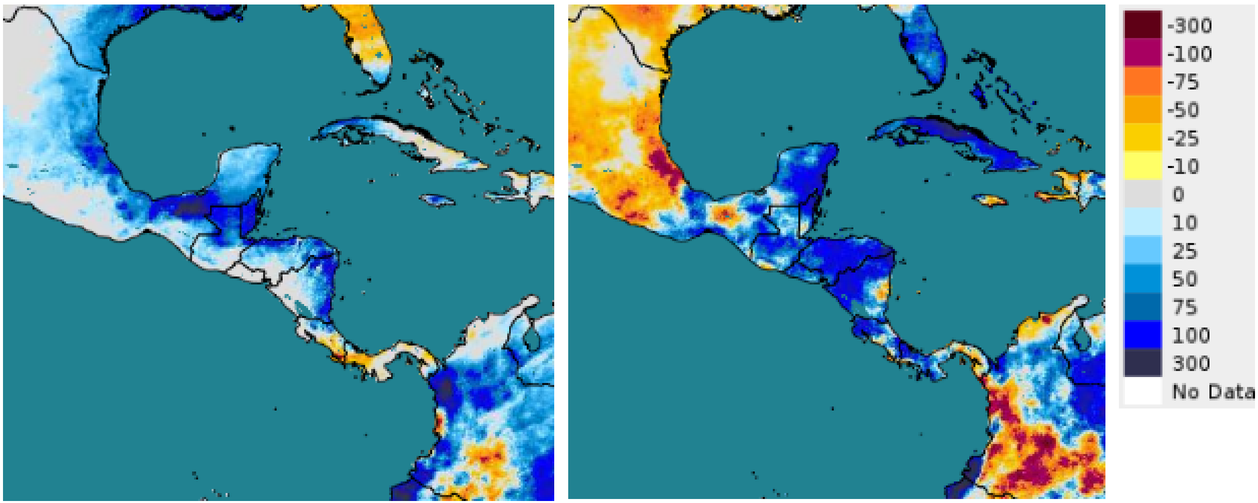
Described within this report are the results of this study, and the potential for each of the potential weather/ climate indicators to be used within risk assessments and to eventually be considered for use within an early warning system for coffee rust disease.

At the end of this report, a number of recommendations for further investigation are described.

Summary of the Central American weather conditions in 2012

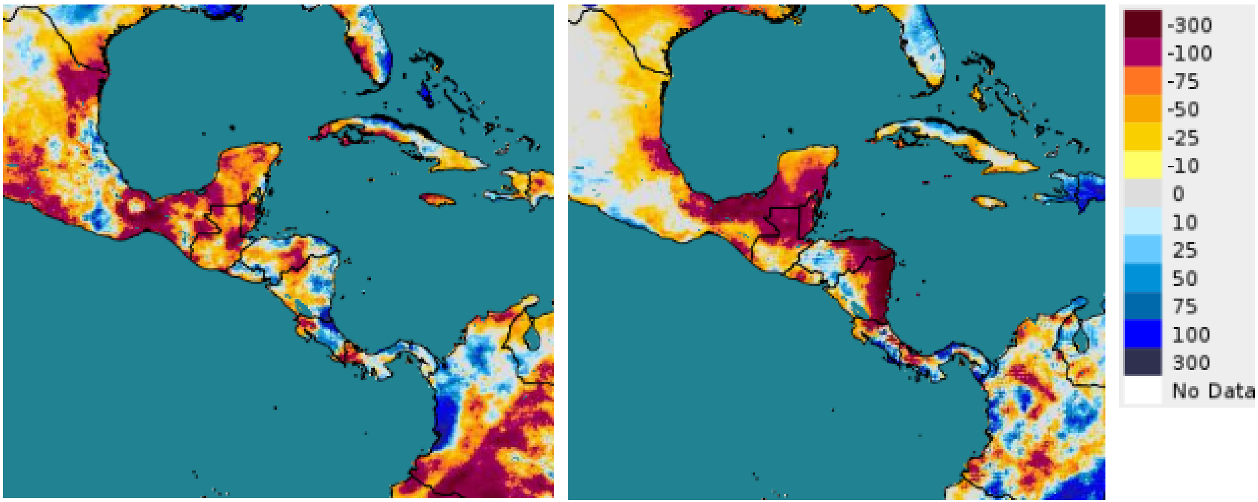
The annual mean temperature in 2012 was close to the long term mean values (1981 to 2010) but with reduced variability due to higher values of minimum temperature and lower values of maximum temperatures according to weather station data across the region (Amador et al., 2013). Similar findings were reported for the number of dry five day (pentad) periods and wet season mean precipitation and variability in 2012 (Amador et al., 2013).

A seasonal analysis from CHIRPS (gridded precipitation data based on remotely sensed precipitation data merged with weather station data) shows a different scenario with positive anomalies for the second trimester (end of the dry season and start of the rains and particularly in the highlands of northern countries) and negative during the second semester (most of the rainy season) for Guatemala. Honduras, Nicaragua and the Costa Rican highlands show some positive anomalies during the fourth trimester (fig. 1.2). The Northern part of the Central American region had increased precipitation during the March-May period in parallel with decreased values for Costa Rica which also had a lower precipitation peak in October (Amador et al., 2013). The Pacific watershed showed a shorter than usual rainy season with a later start and earlier end of the rains (Amador et al., 2013). Stronger than normal winds occurred in July due to El Niño conditions during the second and third trimesters. This should also have reduced cyclone activity (Amador et al., 2013).



January to March

April to June



July to September

October to December

Figure 1.2. 3 month precipitation anomalies (mm) in 2012 compared to CHIRPS (Climate Hazards Group Infrared Precipitation with Station data) climatology (1981-2010) for Central America. Data from http://chg2.geog.ucsb.edu/.

2 Description of data availability

The analysis is based on the use of the available weather, climate and coffee rust incidence data described in the following sections.

2.1 Temperature and precipitation data

2.1.1 Weather station data

Daily maximum and minimum temperature and precipitation data provided from 35 INSIVUMEH and 46 ANACAFE weather stations have been used (table 2.1). A plot with the locations of these stations is shown in figure 2.1.

Table 2.1. Description of weather station data availability

	No. of stations	Data availability
INSIVUMEH	35	1 Jan 1970 to 31 Dec 2012
ANACAFE	46	1 Jan 2008 to 30 Sept 2013
Total	81	-

2.1.2 The CHIRPS precipitation dataset

Guatemala has highly variable topography. As a result, spatial interpolation of the station rainfall data to the farm locations has demonstrated inaccuracy due to the limited number of stations and lack of accounting for topographic effects such as the orographic enhancement of rainfall. Taking this into account, the CHIRPS dataset, developed by USGS (Funk et al., 2014) has been used within our study. It is derived using satellite imagery combined with weather station observed rainfall. These data have been combined to form 5 day accumulations (pentads) for the period 1981 to present.

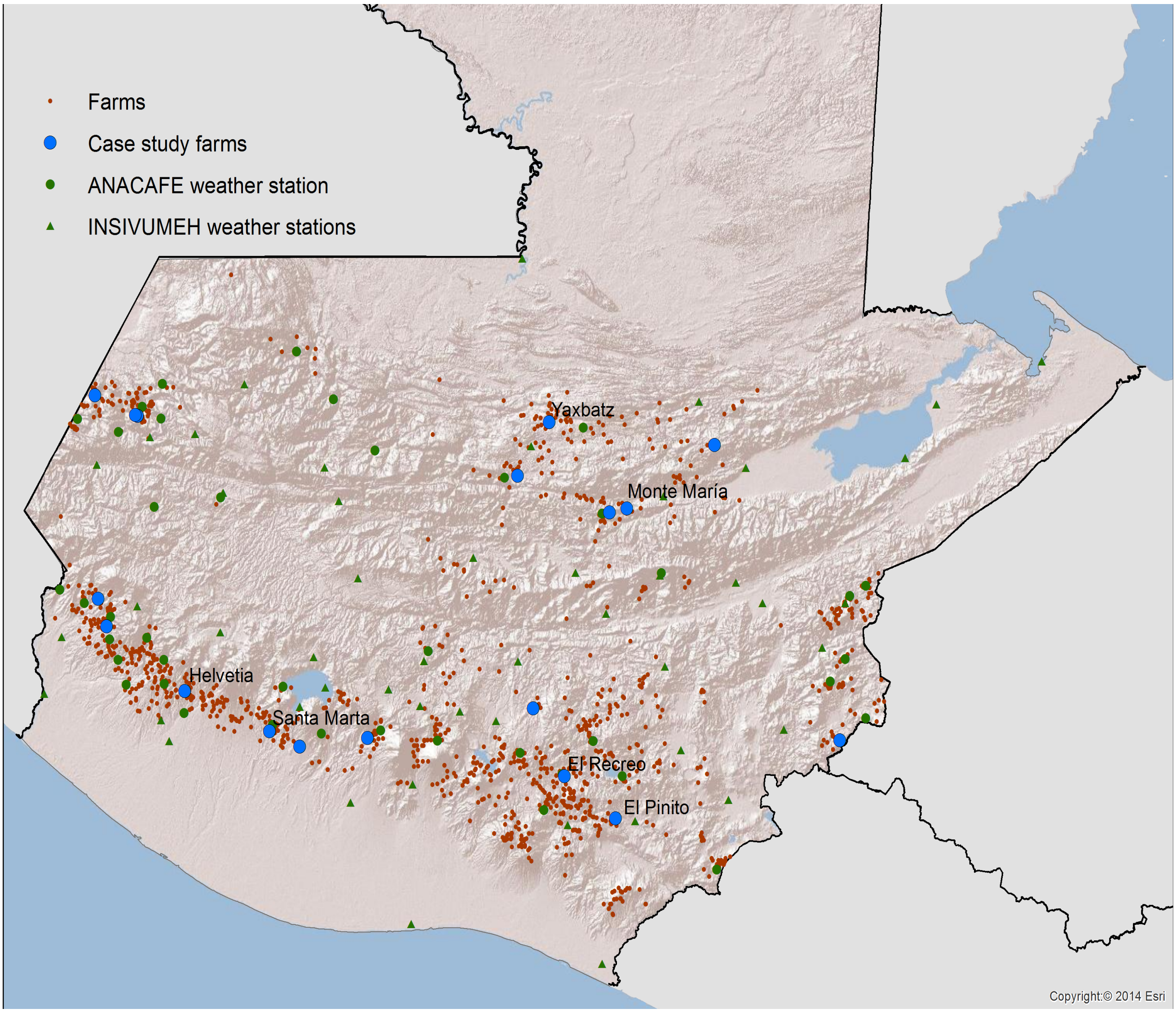


Figure 2.1 Map showing the locations of the ANACAFE and INSIVUMEH weather stations, the farms, and with the farms used within the case study analysis (section 5.3) highlighted with blue circles and named.

2.2 Coffee rust incidence data – 2012

Details about the coffee rust severity in 2012 are available from an impact assessment carried out over 1224 Guatemalan farms. This data includes information about: the area of each coffee farm; the area affected by coffee rust; crop loss and the potential for further crop loss. Using this data, the severity of the coffee rust disease at each farm has been graded on a scale of 1 to 4 (table 2.2). This categorisation represents the overall impact during the year, and does not provide any information about the progression of the severity of the disease during the year.

Within the analysis, this data has been used to assess how coffee rust severity varies with changes in the weather conditions between different locations and from the climatological averages.

Table 2.2 Description of rust severity categories

Rust category	Qualitative description of rust severity
1	Low impact
2	Low to medium impact
3	Medium to high impact
4	Severe, high crop loss

2.3 Case study data – 2013

A detailed impact assessment of coffee rust disease is available for 18 of the farm locations during the 2013 season. This includes time series information in the period April to December about the progression of rust incidence, rust severity and defoliation. An example for the El Pinito farm is shown in figure 2.2. This information has been used along with time series of temperature and precipitation data, and comparisons with climatological means to assess the factors that affect the progression of coffee rust disease (section 5.4).

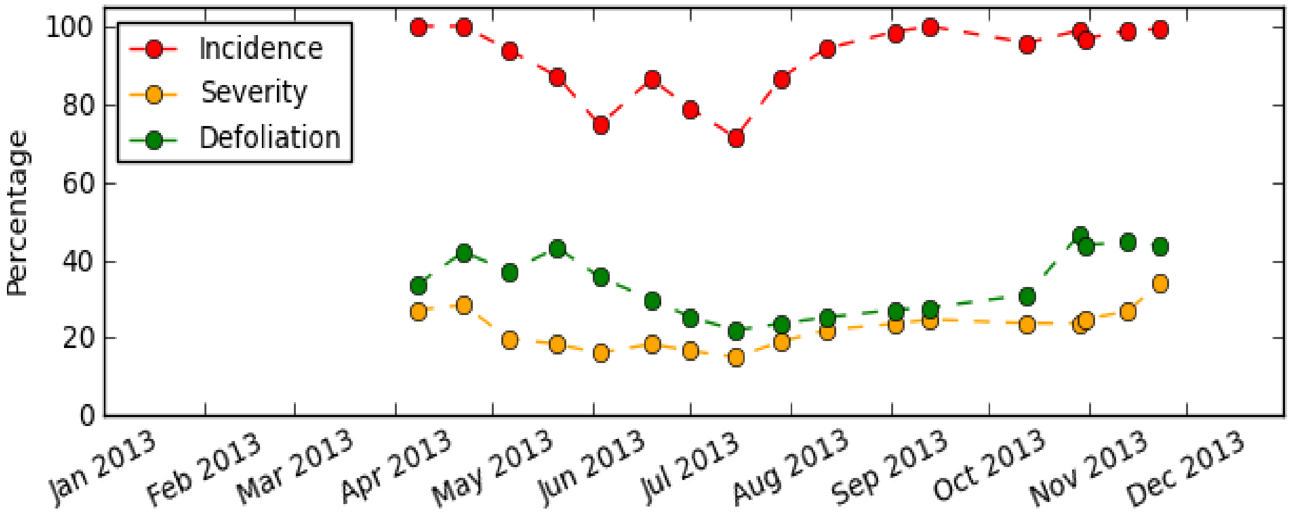


Figure 2.2. An example time series of 2013 case study data at the El Pinito farm which is located at an altitude of 1354m.

2.4 Additional data

To assess the weather and climate conditions at each of the farm locations, it was necessary to interpolate the available station data. Details about the method of interpolation used are provided in section 4.2. A 270m digital elevation model was used to find the altitudes of each of the weather stations and farms, and also for re-gridding within the interpolation.

New datasets were derived using the data described above. These include: daily environmental lapse rates, which can provide some information about the precipitation distribution; accumulated temperature datasets over various time periods; and daily climatologies calculated at station locations, and interpolated to the farm locations. An analysis of these data is provided in section 5.

3 Summary of parameters assessed

The parameters listed in table 3.1 have been investigated within the analysis detailed in section 5.

Table 3.1 Description of parameters assessed within the analysis described in section 5.

Parameter	**Description**
1. Seasonally accumulated minimum, maximum and mean temperature (^{0}C)	Used to decide if a rust degree day indicator could be a valid means for assessing the likelihood of coffee rust. Accumulated periods used: (a) the dry season – Jan to March (b) the wet season – April to December
2. Diurnal temperature range (^{0}C)	(a) inter-seasonal variations (b) monthly variations (c) comparison with climatology
3. Altitude considerations	(a) variations in rust severity with elevation (b) variations in temperature and temperature accumulation with elevation (c) Anomalies between observations in the period 1981 to 2012 and the climatological averages, categorised by elevation.
4. El Niño/ La Niña	Comparison between El Niño/ La Niña events and 1981 to 2012 station observations.
5. Quadratic weighting equation applied to temperature filtered data	Involves taking biological considerations into account through initial testing of the application of a weighting factor to the accumulated temperature values.
6. Monthly/ seasonal accumulations	Analysis of the following accumulated parameters: (a) Maximum temperature (b) minimum temperature (c) mean temp (d) precipitation (e) average diurnal temperature range

7. Daily environmental lapse rate (maximum temperature, minimum temperature, diurnal range)	(a) Relation of synoptic conditions to lapse rates. (b) Comparison between 2012/ 2013 and climatological patterns. (c) Statistical analysis comparing 2012 lapse rates with the climatology

4 Overview of methods used

Before the analysis was carried out, the station data was cleaned by identifying and removing anomalies. However, it is difficult to remove all possible anomalies without an understanding of the systematic errors at each station throughout the long term observation period. To minimise the impact of these systematic errors on our analysis, the statistics have been calculated on averaged values over a number of stations and farms.

Described within this section is an overview of the analysis methods that have been applied to the data. The results and analysis associated with each description is provided in section 5.

4.1 Initial analysis of station time series to visualise trends

The full time series of data available for each of the 35 INSIVUMEH stations (table 2.1, row 1) were plotted to visually assess the continuity of data availability, and to get a first idea of any major trends/ changes in the weather patterns since 1970. An example is shown in figure 4.1 for the Camantulul weather station. This particular station has close to full data availability for the climatological period from 1970 to 2012. It shows a trend of increasing minimum temperature during the period. The mean of the maximum temperatures remains quite consistent throughout the period, however in recent years there have been increases in the range of maximum temperatures, in parallel with increased variation in the daily precipitation.

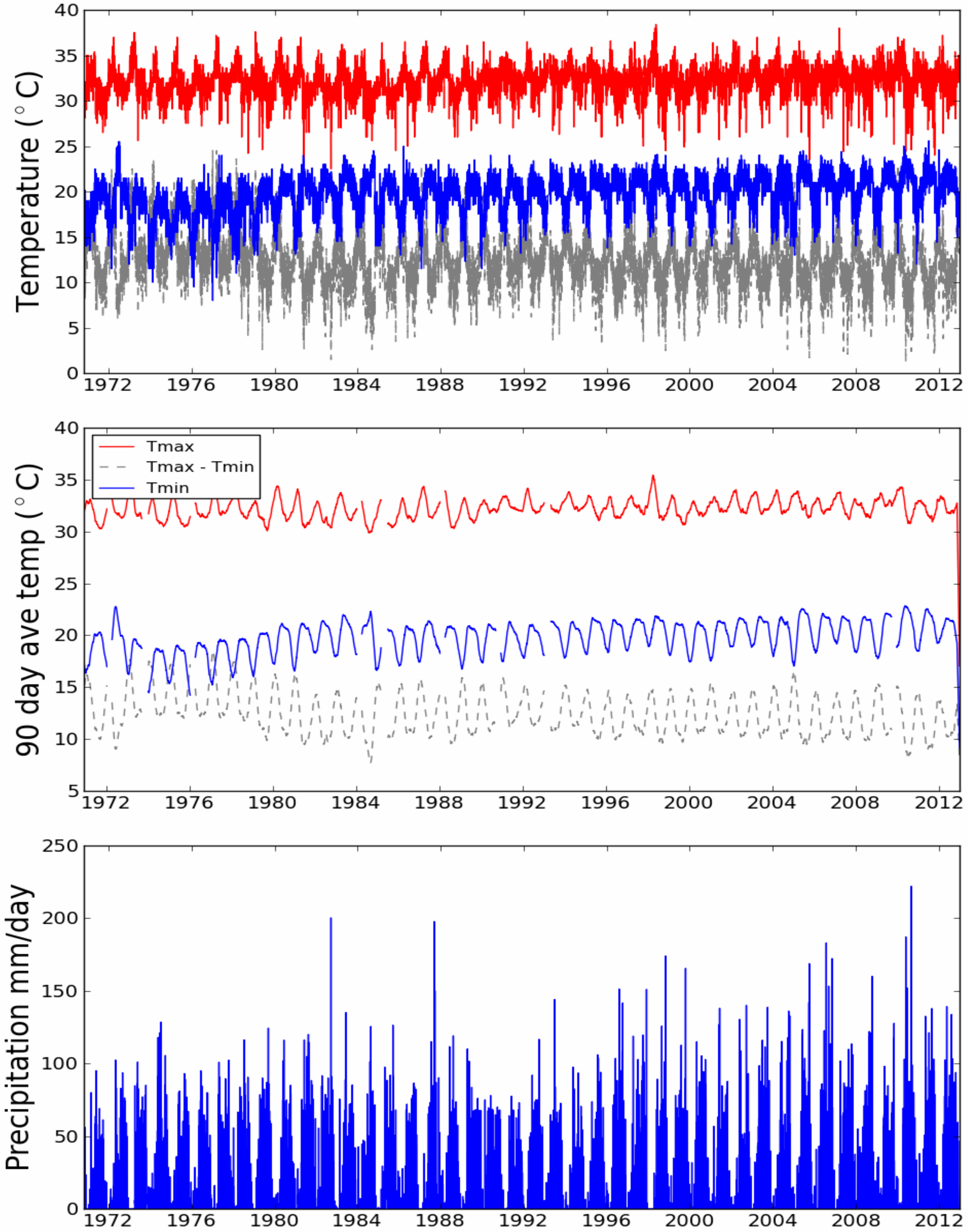


Figure 4.1. Long term time series of maximum, minimum temperature, diurnal temperature difference and precipitation data for the Camantulul weather station.

4.2 Analysis of anomalies between the station data and the climatological averages

A 30 year climatology (1981 to 2010) was calculated at each station location using the daily observed data. This was done for the maximum, minimum and mean temperatures, and the precipitation data. The anomalies between the two datasets have been calculated for each station. Additionally, the averaged anomalies over all stations, and within defined altitude ranges have been calculated, and compared between years for the period 1981 to 2012. These data are presented in section 5.2.

4.3 Interpolation of weather station data at farm locations

To assess the rust severity at each of the farms in relation to the co-located weather and climate data, it is necessary to first interpolate the weather station data to the farm locations. The topography of Guatemala is highly variable (figure 4.2) and it is important to take elevation into consideration when interpolating temperature data from weather stations.

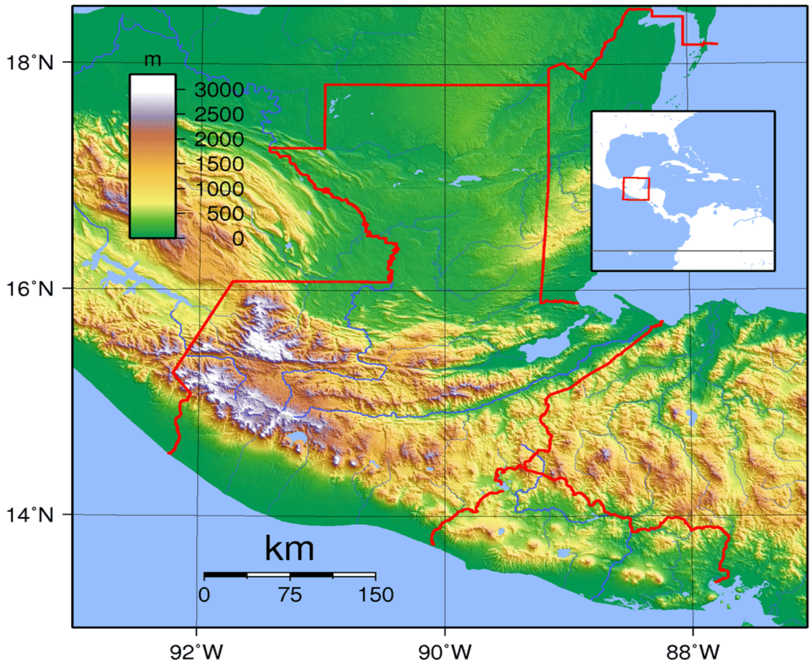


Figure 4.2 Map showing Guatemala topography – source: mapsof.net

A polynomial surface was fitted to the input daily maximum and minimum temperatures, and from this the corresponding daily lapse rates were calculated. Using these lapse rates, a map of sea level points, corresponding with the station locations, was produced. A linear Splines interpolation was then performed to create maximum and minimum sea level temperature grids, at the 270 metre resolution of the digital elevation model (DEM). By multiplying these base level grids by the lapse rate, taking into consideration the gridded DEM altitude data, it was then possible to map the temperatures according to elevation. An example of the resulting maps for maximum and minimum temperature is shown in figure 4.3. The resulting gridded temperature data were used to derive temperature time series and subsequent analysis at each of the farm locations. Global statistics were produced by averaging over the data derived at each farm, and an analysis of these results is included in section 5.

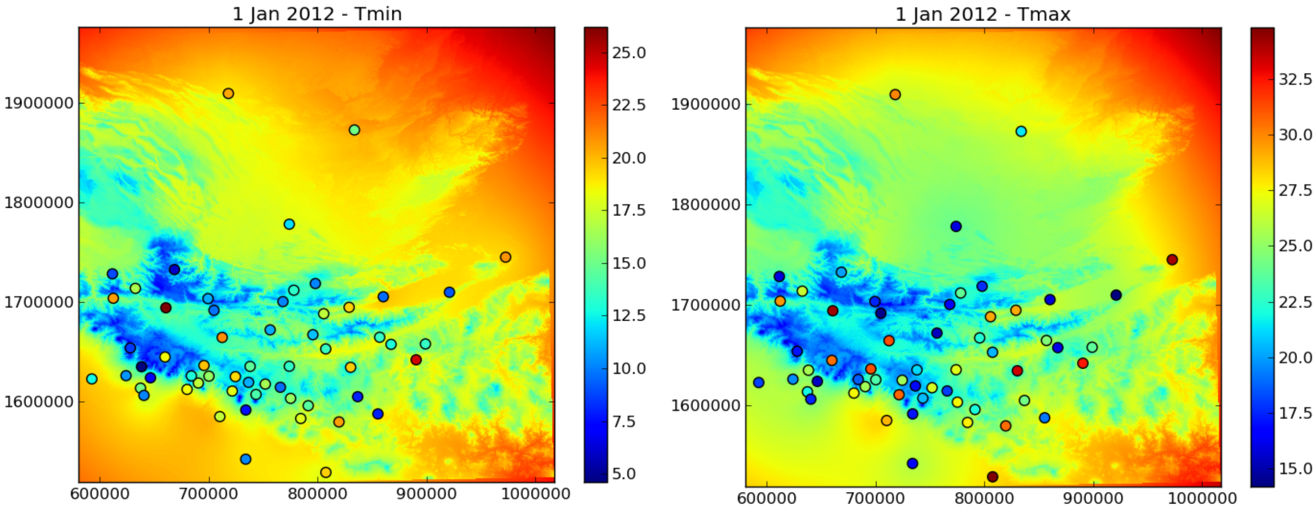


Figure 4.3. Examples of the interpolated maximum and minimum temperature maps for 1 January 2012. Over plotted are the locations of the 81 ANACAFE/ INSUVUMEH stations. The colours of the plotted stations are on a different scale from that shown in the legend. It should also be noted that the range associated with the colour bars differs between the maximum and minimum temperature plots.

4.4 Creation of interpolated climatological datasets

Climatological temperature and precipitation datasets were created by finding the daily means over the period 1981 to 2010, at each of the 35 INSIVUMEH weather stations. These data were interpolated to allow for comparisons to be made with the interpolated 2012 and 2013 daily temperature data at each of the 1224 farm locations.

4.5 Daily diurnal environmental lapse rate

The environmental lapse rate is a measure of the temperature decrease with elevation, and is used in the interpolation of temperature data to account for variations in elevation. A fixed lapse rate with a value between 6 and 6.5 ^{0}C km^{-1} is commonly used when creating gridded temperatures for hydrological modelling (Li et al., 2013). However, in reality there can be large seasonal and spatial variations in the lapse rate depending on the amount of solar radiation, convection and condensation. Blandford et al. (2008) found that the value of 6.5 ^{0}C km^{-1} is only applicable to lapse rates associated with maximum temperatures and its use with minimum and average temperature interpolation would not be valid. They investigated daily and seasonal variations in the lapse rate for an area of South Central Idaho, and found that, in general: warmer air masses are associated with larger maximum temperature lapse rates (i.e. greater temperature decrease with increasing altitude); drier air masses are associated with lower minimum temperature lapse rates (i.e., lower temperature decrease with increasing altitude) and that a large diurnal range in the lapse rate (the difference in calculated lapse rate between the times of day with the maximum and minimum observed temperatures) can be indicative of dry tropical conditions.

The temperature interpolation (described in section 4.3) makes use of daily calculated maximum and minimum lapse rates. Yearly time series of daily lapse rates have been produced. These correspond with the maximum and minimum temperature surfaces for the years 2012, 2013 and for the daily climatological data. The daily diurnal variations have also been calculated, and variations in these values have been investigated, along with the corresponding temperature and precipitation data.

The daily precipitation data available from the stations provides information about the daily precipitation accumulation, but it doesn't provide information about rainfall intensity, or the duration of time during the day for which there was rainfall at each location.

Use of the lapse rate information in combination with the temperature and precipitation data could provide useful information about the structure of the precipitation. For example it could provide some additional insight into whether the total daily rainfall accumulation can be attributed to heavy convective rainfall during a small period of the day, or whether the rainfall was lighter, but perhaps continuous for much of the day.

The development of coffee rust lesions requires the continuous availability of water to the leaf during an extended period. Lapse rate information could be used to better assess whether the daily rainfall accumulation was well distributed throughout the day (providing continuous moisture availability), or at the other end of the scale, if the day was characterised by extended dry, sunny periods with perhaps some intense convective activity.

4.6 Biological considerations

The optimal air temperatures for coffee rust lesion development during the wet season are a minimum temperature of 18^0C and a maximum of 28^0C.

In section 5.5 an analysis is described which applies these thresholds to the data, and a subsequent weighting. The weighting applied uses the coefficients of the equation of the curve (figure 4.4) presented by Nutman and Roberts (1963) to explain how coffee rust lesion development varies with temperature within the defined threshold range.

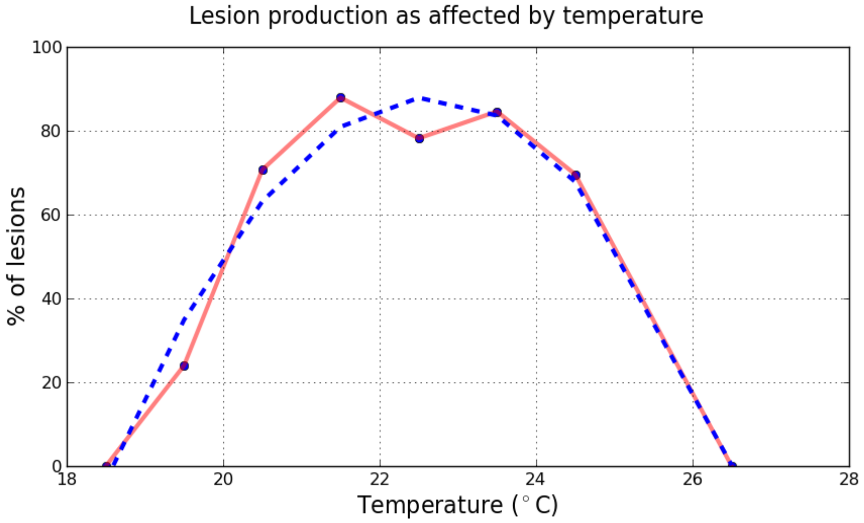


Figure 4.4 Lesion production as affected by temperature – source of data: figure 8 in Nutman and Roberts (1963)

5 Analysis

Within this section an analysis is described based on the application of the methods described in section 4. An overview of the methods used for the analysis of long term station temperature and precipitation data is provided in section 4.1.

5.1 Analysis of long term station temperature and precipitation data

Initial analysis of station time series to visualise trends

Long term maximum, minimum temperature and precipitation data, from 1970 to 2012, is available for the 35 INSIVUMEH stations (table 2.1). The full set of plots showing time series data at each farm can be found in Appendix 1. Arabica coffee generally grows between 400 and 1800m elevation. Within the analysis, we look at the weather conditions within different altitude ranges, to try to isolate weather and climatic features that may affect coffee rust progression to a greater or lesser extent at different elevations (section 5.2). Table 5.1 shows the altitude ranges used, and the number of INSIVUMEH stations within each.

Table 5.1: Altitude of Insivumeh stations

Altitude range	No. of Insivumeh stations within this range
< 800m	13
800 to 1000m	4
1000 to 1200m	2
1200 to 1400m	2
1400 to 1800m	7
> 1800m	7

Within this section the time series profiles for a selected station from each of the altitude ranges (defined in table 5.1) will be looked at to ascertain any recent changes in the long term trends that may have led to an increased likelihood of the farms at that altitude range being affected by coffee rust. This introductory evaluation of the data is very qualitative in nature, and aims to provide a picture of the changes in recent weather relative to the longer term observations. There is a lot of topographical variation in Guatemala, and due to differences in altitude and locality between the station and case study farm locations, a more quantitative analysis has been carried out using interpolated temperature data and CHIRPS rainfall data at the exact farm locations. This is presented in section 5.5.

Asuncion Mita station – 472 m elevation

The mean yearly value for the maximum temperature at Asuncion Mita has been fairly consistent during the period 1971 to 2012 (figure 5.1, top). However, there has been a clear increase in the mean yearly value of the minimum temperature over the long term period, this is particularly marked since around 2007. A corresponding decrease in the diurnal temperature difference is evident since then. The precipitation pattern shows increased fluctuations from its mean value in recent years (since 2007), with extended periods of lower rainfall accumulations, when compared with the historical data. The rainfall pattern has been very variable, with periodic highs and lows in intensity. Recently (2009 to 2013) there have been significant spikes in periods of very heavy rainfall when compared with the long term record. These years are also characterised by longer rainfall seasons than usual.

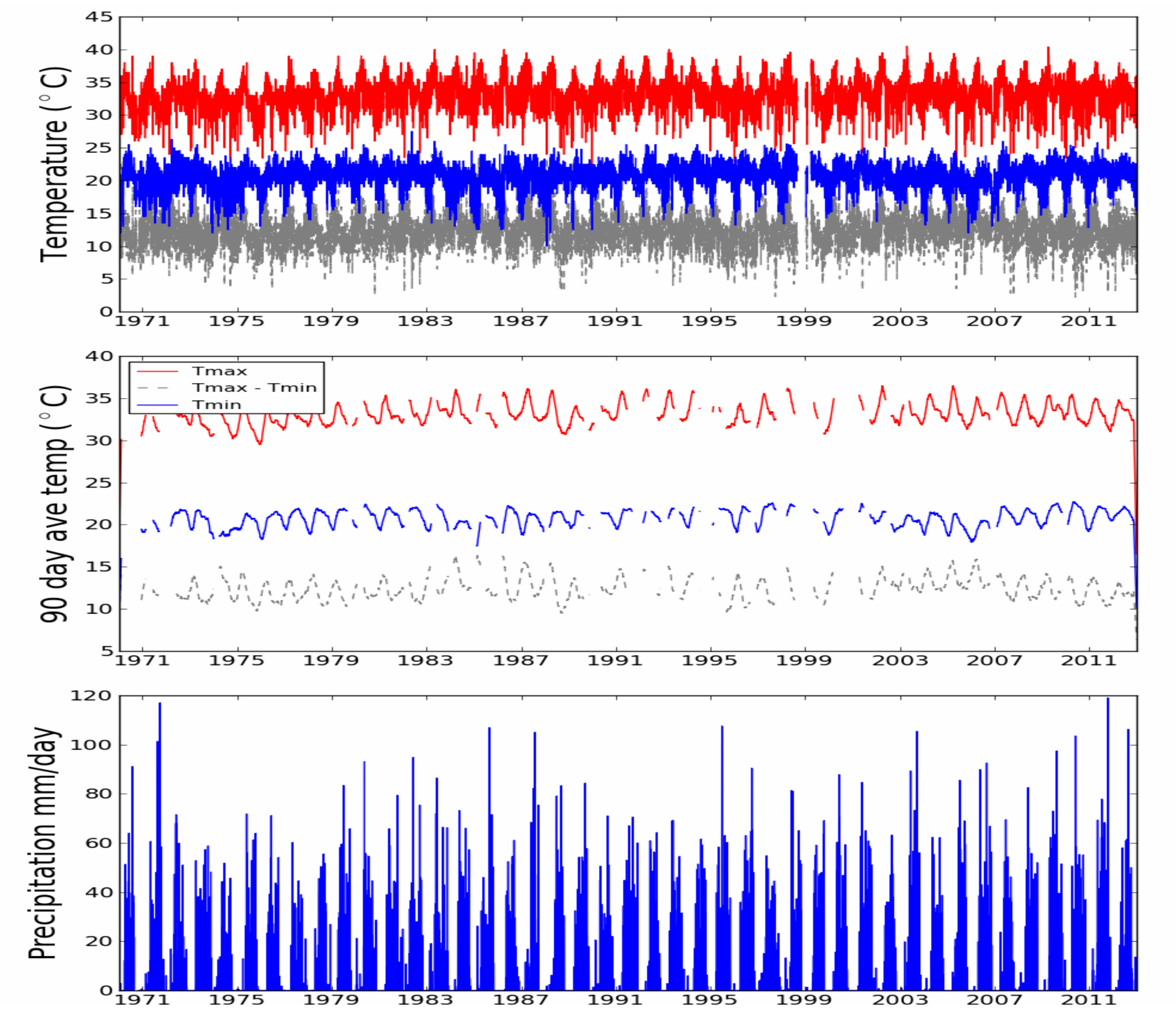


Figure 5.1.1 Long term maximum/ minimum/ diurnal temperature and precipitation time series for the Asuncion Mita weather station.

Esquipulas station – 895 m elevation

At this station, the maximum temperature has again been fairly consistent during the long term period, while a gradual increase in the minimum temperature has been observed. As with the Asuncion Mita station, there is a lot of variability between years in the maximum observed precipitation and also in the length of periods of high rainfall intensity. At this station, the maximums in the last few years have been consistent with the longer term average, and there have not been major spikes in high intensity rainfall events

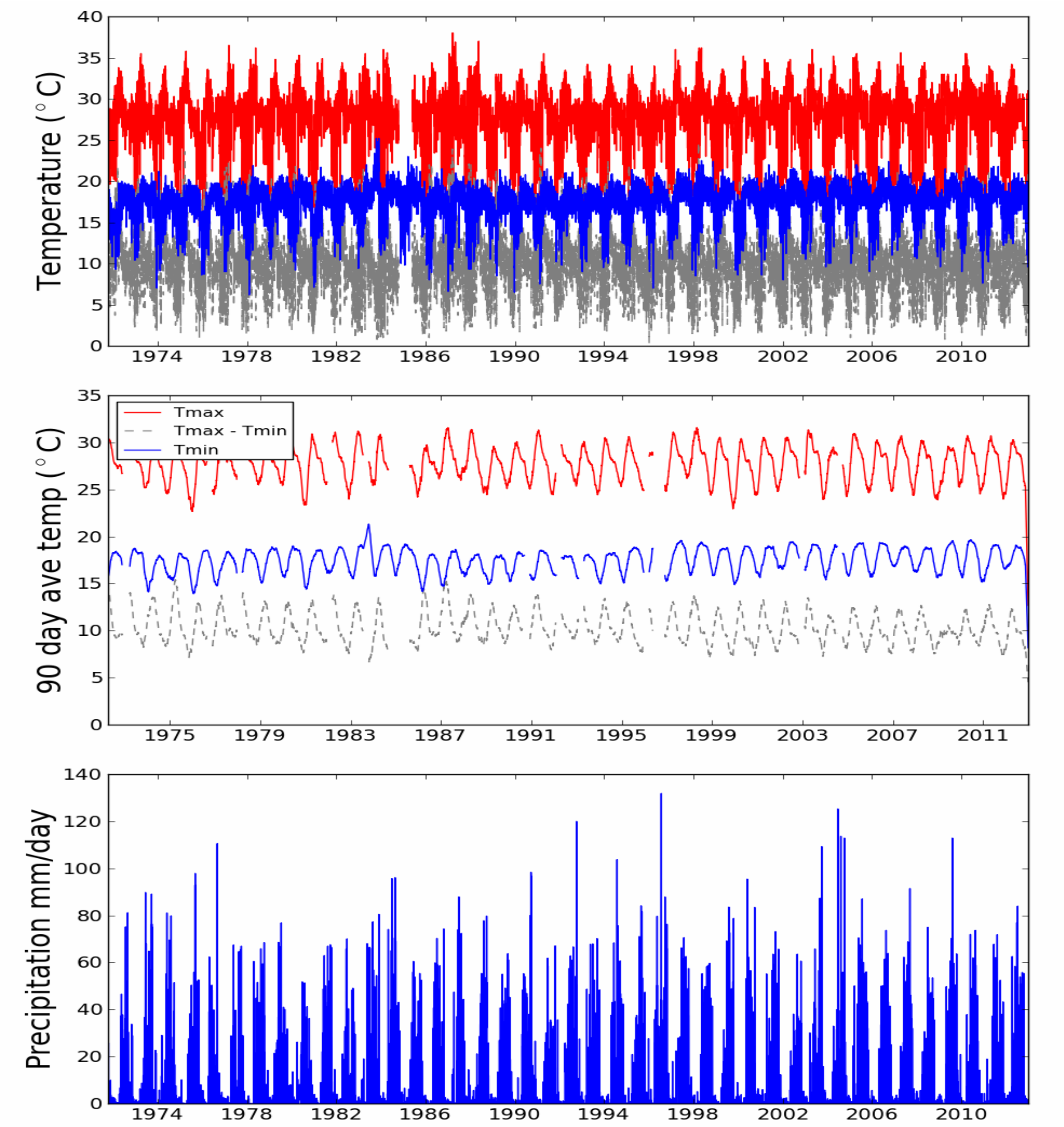


Figure 5.1.2 Long term maximum/ minimum/ diurnal temperature and precipitation time series for the Esquipulas weather station

Cuilco station – 1163 m elevation

The mean values of the minimum and maximum temperatures have stayed fairly consistent over the long term period, however in the last 10 years there has been an increasing trend for the minimum temperature.

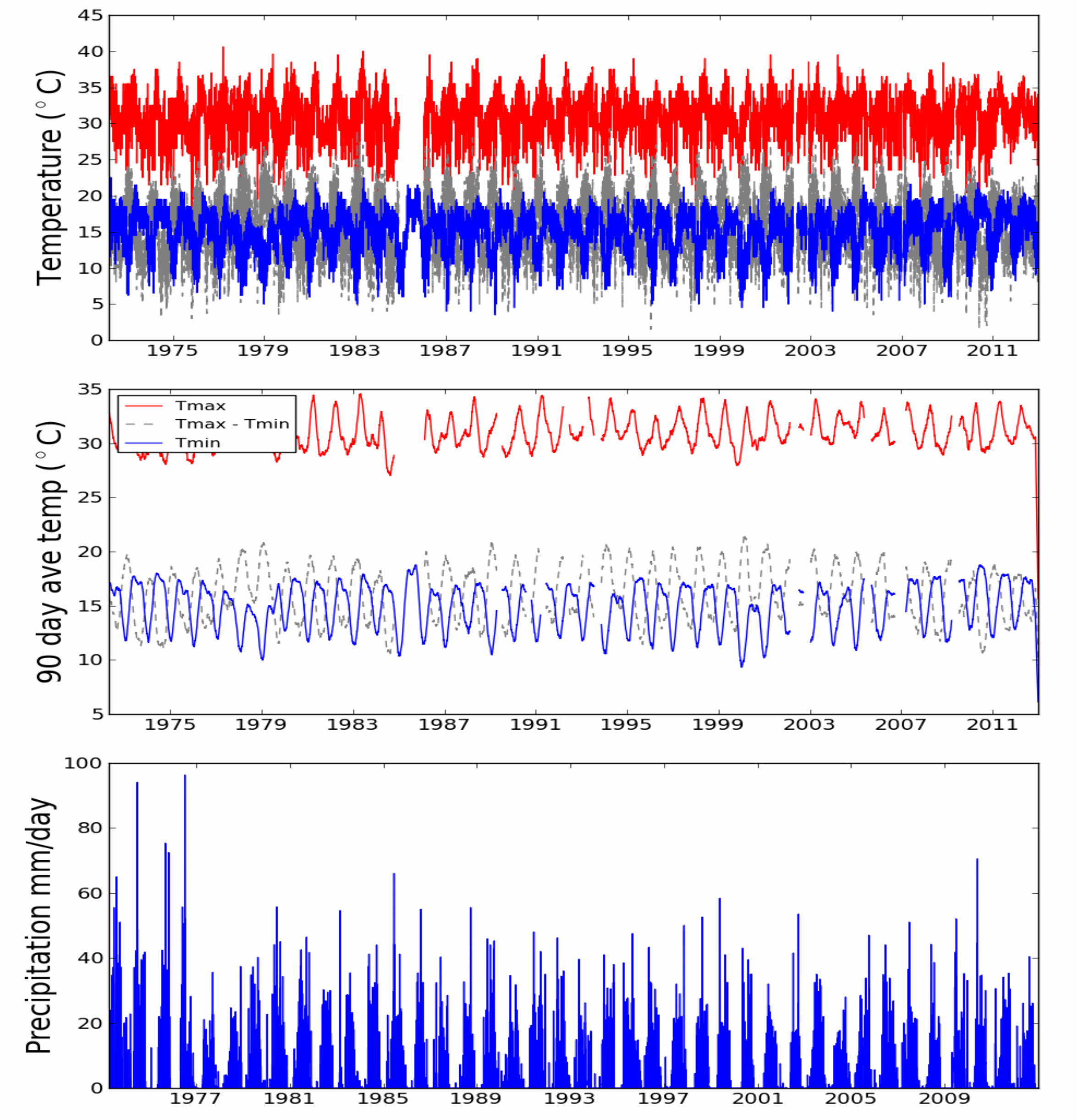


Figure 5.1.3 Long term maximum/ minimum/ diurnal temperature and precipitation time series for the Cuilco weather station

Coban station – 1318 m elevation

There has been an overall trend towards higher minimum and maximum temperatures. In the latter half of the time series (since ~1990), there have been fewer fluctuations towards temperatures below 5^{0}C. In this same period there have been significantly more periods of higher intensity rainfall, with maximums being observed during the 2007 rainy season. Compared with the other stations looked at so far, there is more variability in the temperature at this location. As the time series progresses, there are longer periods with higher minimum temperatures. This is particularly evident from 2000 onwards.

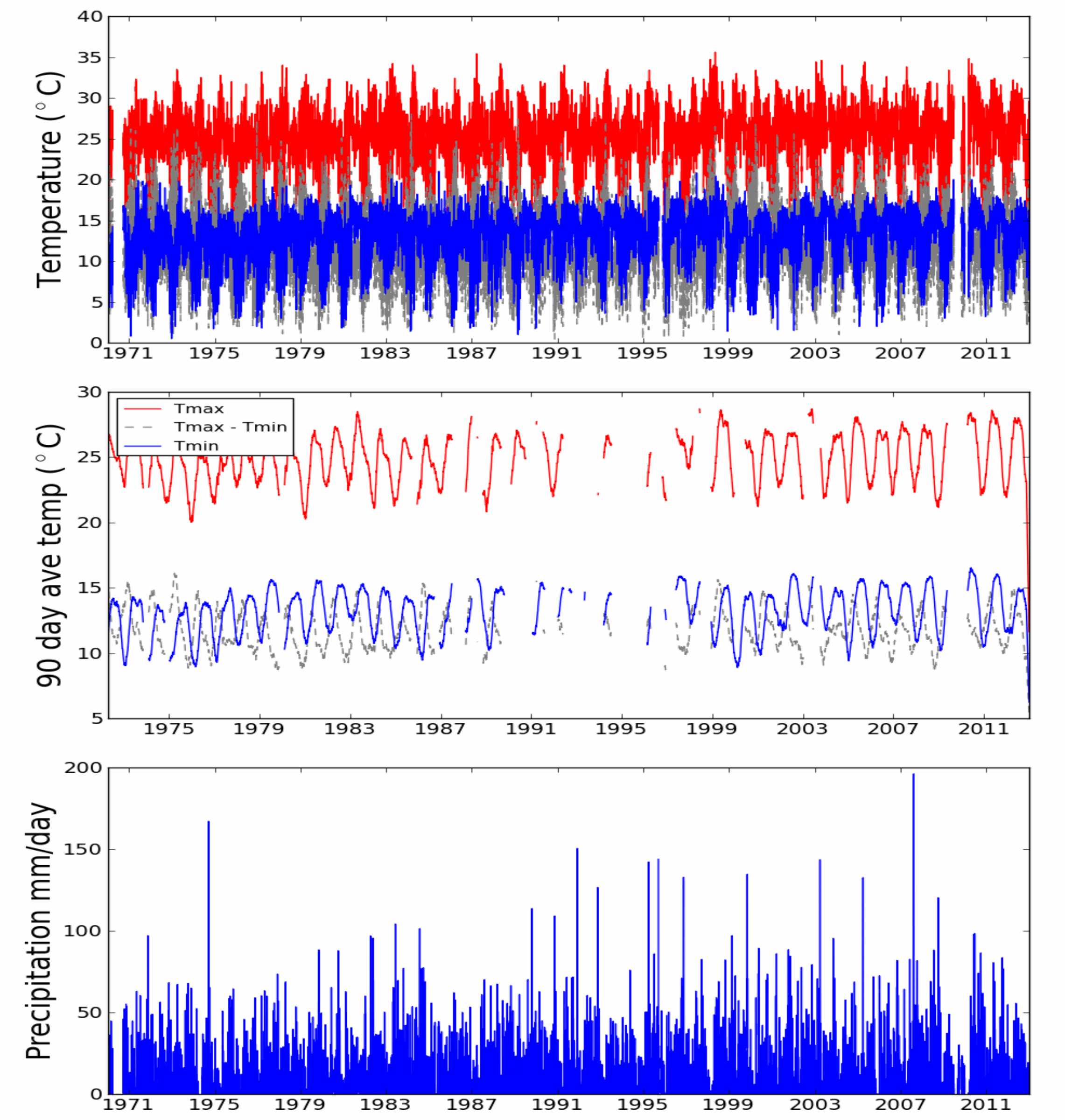


Figure 5.1.4 Long term maximum/ minimum/ diurnal temperature and precipitation time series for the Coban weather station.

Insivumeh station – 1505 m elevation

At this weather station increases are observed over the long term period for both the minimum and maximum temperatures. As a result the diurnal temperature range has remained pretty consistent.

The precipitation pattern has been fairly consistent throughout the period, although since 1999 there have been an increase in the number of high accumulation events.

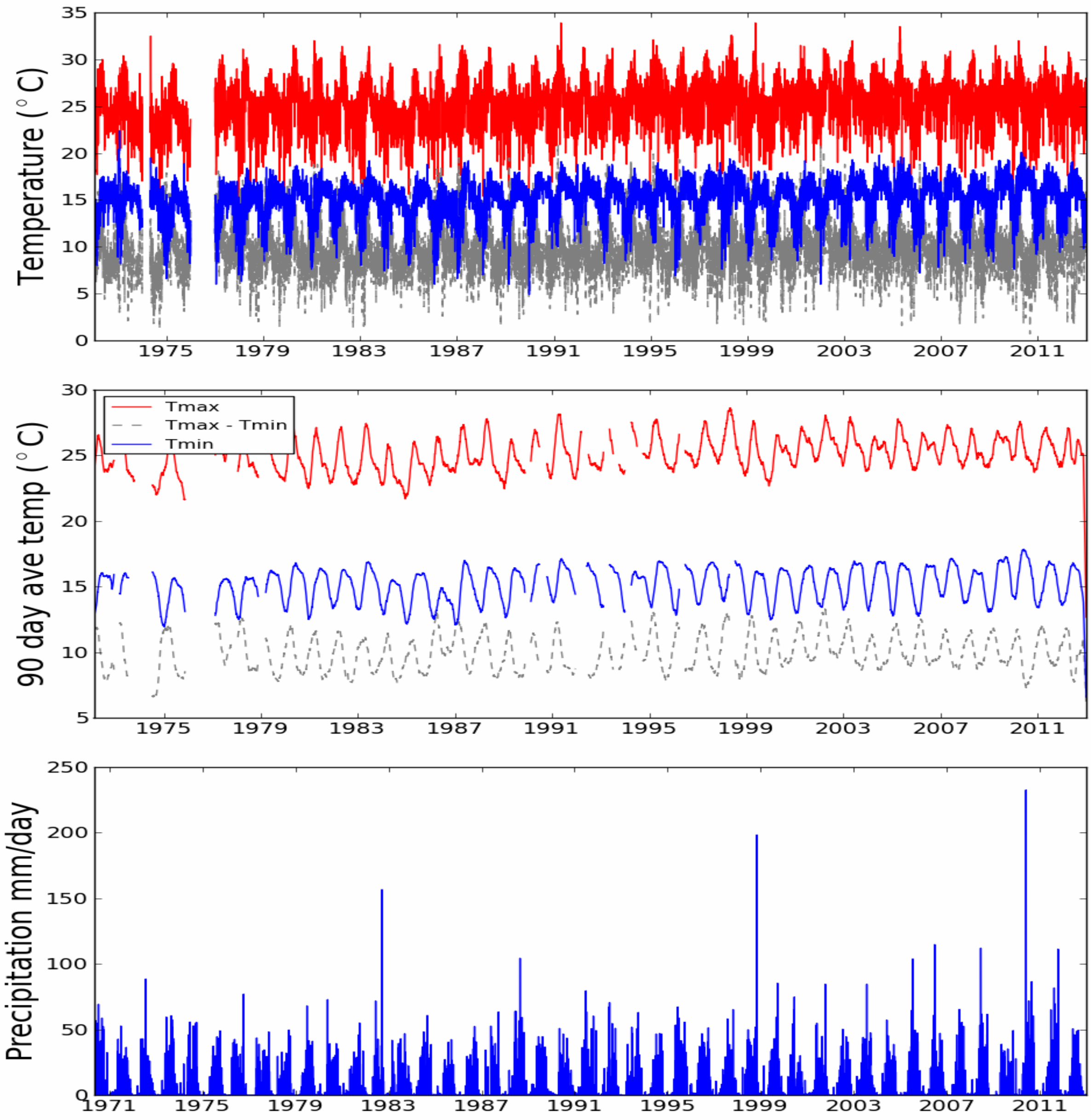


Figure 5.1.5 Long term maximum/ minimum/ diurnal temperature and precipitation time series for the Insivumeh weather station.

<u>San Martin Jilotepeque station – 1769 m elevation</u>

At this location, increases in both the minimum and maximum temperatures have been observed over time. There appears to have been a period when significantly lower temperatures than usual were observed between 2007 and 2009. The temperatures observed during this period are not unprecedented, but the length of time that they persisted for is. This period requires some further investigation, and verification that the measuring equipment was working well at the time. Since then, there has been a pronounced increase in the average minimum temperature (2009 to 2012). This recent period corresponds with an increase in rainfall.

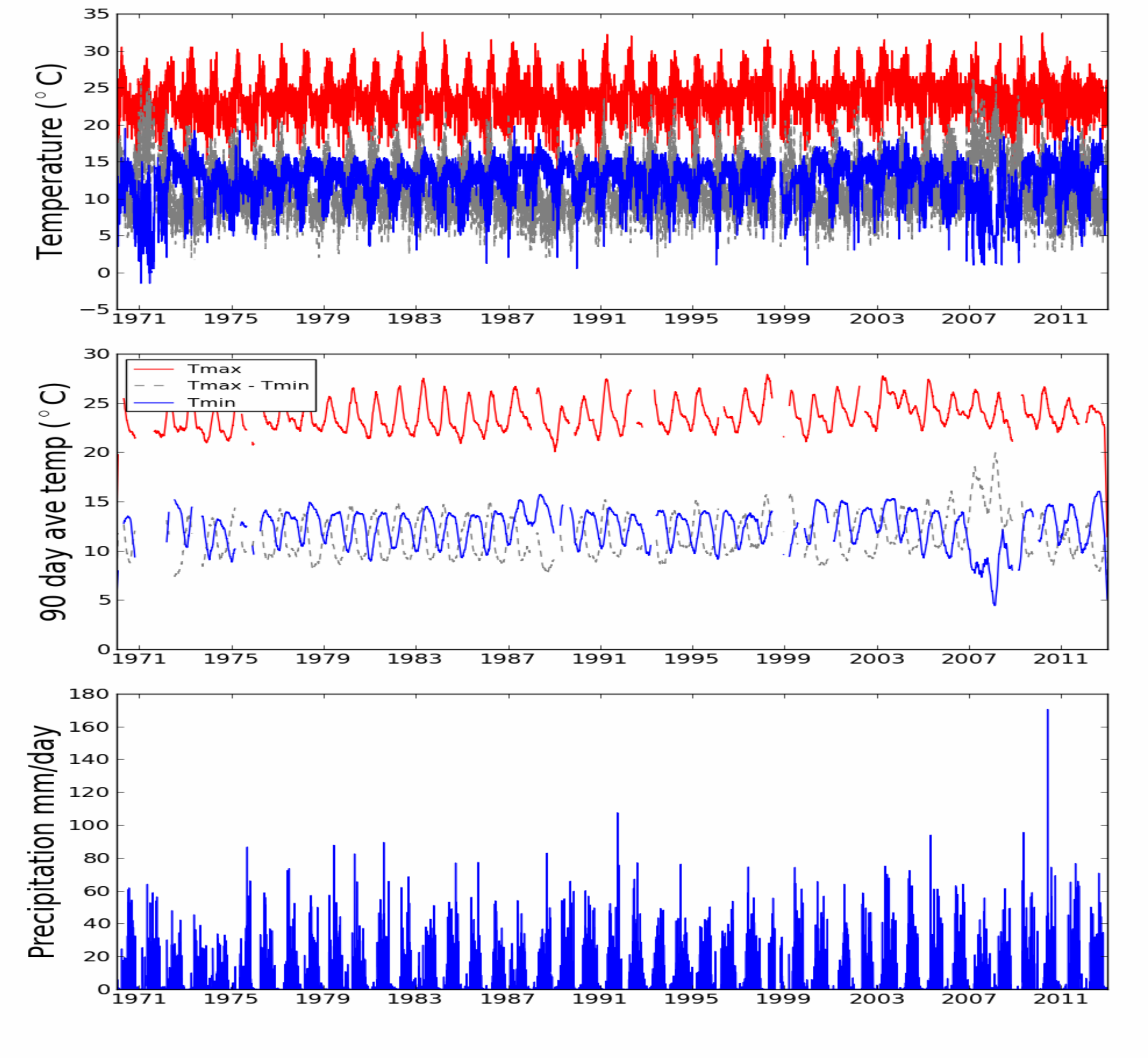


Figure 5.1.6 Long term maximum/ minimum/ diurnal temperature and precipitation time series for the San Martin Jilotepeque weather station.

Summary of general findings from long term weather station analysis

A small sample of the available weather station data within the different altitude ranges (defined in table 5.1) has been looked at for the period 1970 to 2012. The time series from all 35 INSIVUMEH stations are included in appendix 1, and through analysis of these, we see the trends discussed here are prevalent at many of the locations. From this brief and qualitative analysis the following points have been noted:

- There have been increases in the average minimum temperature at all stations over the study period.

- Observations from the stations below 1200m elevation do not generally show increases in the average maximum temperature. As a result these stations show a decrease in the observed diurnal temperature range.

- Observations from the Coban station (1318m) and those at higher elevations have shown increases in the average values of both the minimum and maximum temperatures. As a result there has been no overall change in the diurnal temperature range.

- There is high variability in the precipitation pattern at all stations over the time period, and also variations between stations for the timing of extreme events.

- It is recommended that the rainfall patterns are studied more on a regional basis (e.g. Pacific/ Caribbean area), in combination with reference to the effects of el Niño and la Niña events.

5.2 Analysis of yearly station data anomalies from the climatology

A statistical analysis of the station data with respect to the climatological averages has been carried out. The daily weather station data was averaged within the altitude ranges specified in table 5.1, for monthly and dry/ wet season periods. A 30 year climatological period has been used, 1981 to 2010. A precipitation climatology has been calculated over the same period at each of the station locations using the CHIRPS dataset (Funk et al., 2014). Within this section, the anomalies from the climatology for the maximum, minimum and mean temperatures and the precipitation are described for the years 1981 to 2012, taking into consideration El Niño and La Niña effects.

5.2.1 El Niño/ La Niña effects

The Oceanic Niño Index (ONI) is the standard that the National Oceanic and Atmospheric Administration (NOAA) uses for identifying El Niño (warm) and La Niña (cool) events in the tropical Pacific. Figure 5.2.1 shows a graph of the 3 month averaged SST anomalies in the Niño 3.4 region (5^0N - 5^0S, 120^0W – 170^0W). Table 5.2.1 provides information about the strength in El Niño/ La Niña for the years between 1970 and 2012. This information is used in conjunction with the time series analysis to help distinguish between inter-annual variability in the weather conditions resulting from El Niño and La Niña periods. Generally El Niño events are associated with less precipitation in Guatemala, and an extended period of canícula (a dry period during the wet season) which usually lasts for around 10 days but can last for up to 20 days under such events. There can also be changes in the timing of the start of the rainy season, cooler weather, and an increase in hurricanes in the Pacific, while there is a decrease in the Atlantic, Caribbean and the Gulf of Mexico.
In contrast, years in which there are La Niña events are usually characterised by heavier rainfall in Central America.

Figure 5.2.2 shows plots of the seasonally calculated Oceanic Niño Index for the dry/ wet season periods, January to March and April to December, in the years 1981 to 2012. This data is used for direct comparison with the anomalies in the maximum and minimum temperatures and the precipitation (see figure 5.2.5). During the 2012 dry season, there was a weak La Niña signal, followed by a weak El Niño signal during the wet season. This could explain the 2012 positive rainfall anomaly during the dry season, and the negative anomaly during the wet season. 2006 and 2009 are the only other years in the time series 1981 to 2012 that show a similar pattern between the 2 seasons (figure 5.2.2).

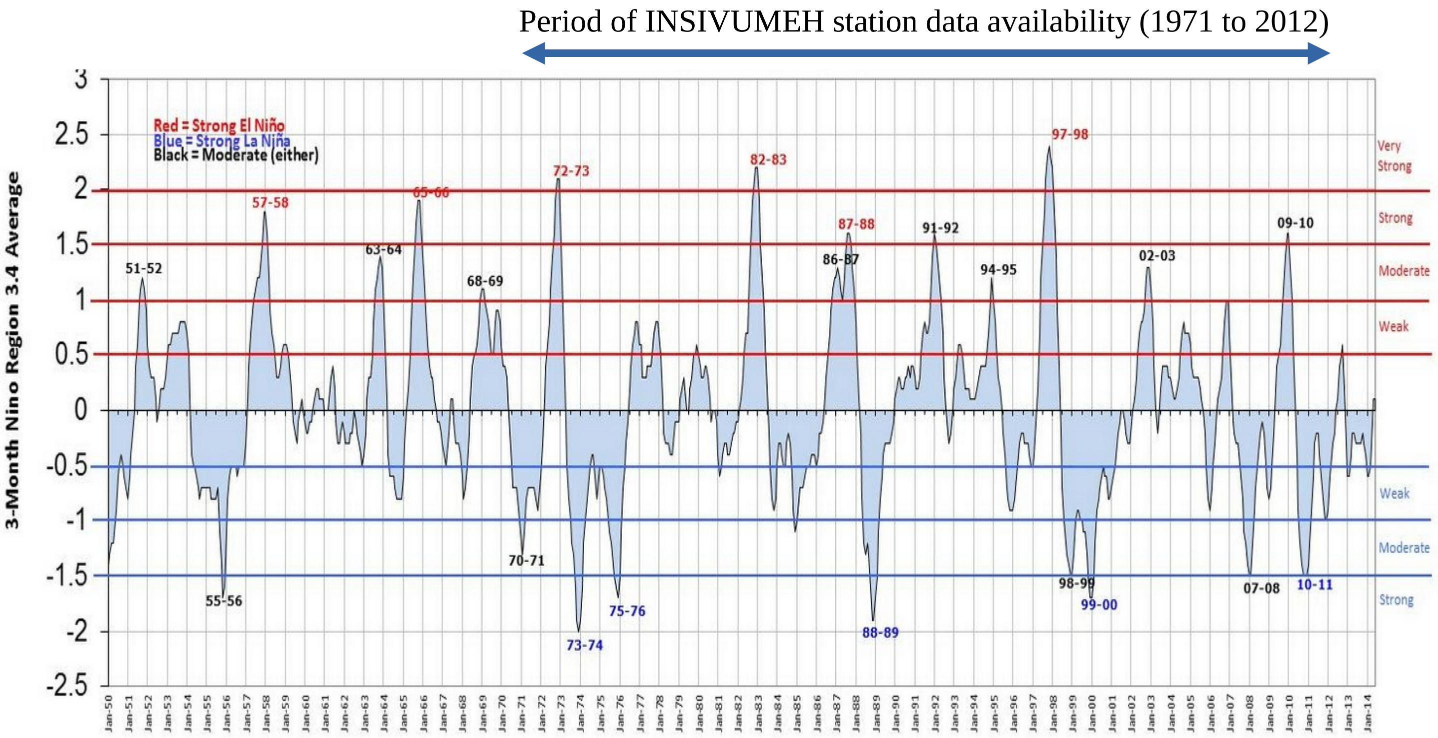
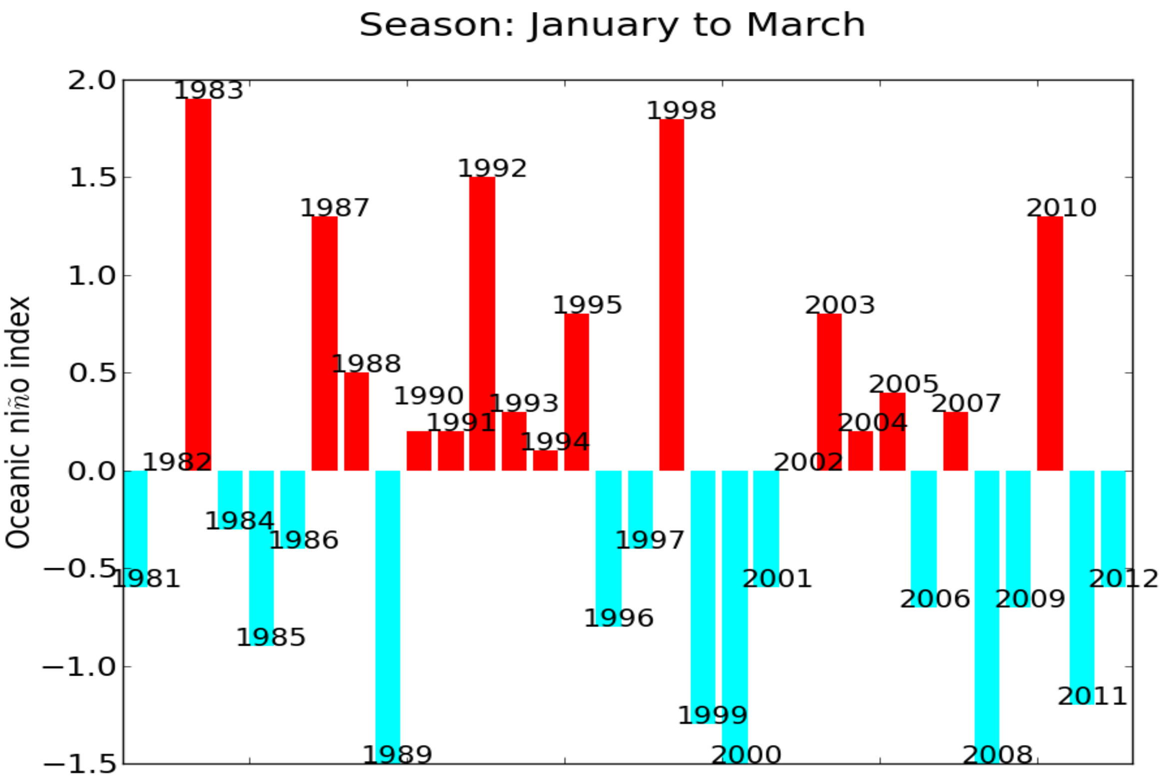


Figure 5.2.1 The Oceanic Niño index. Values are averaged over 3 month periods, and plotted between January 1950 and January 2014. Data source - http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml
Image source - http://ggweather.com/enso/oni.htm

Table 5.2.1 Categorisation of El Niño/ La Niña years by their strength between 1970 and 2012, corresponding with the available weather station data period. Data source - http://ggweather.com/enso/oni.htm

El Niño			**La Niña**		
Weak	**Moderate**	**Strong**	**Weak**	**Moderate**	**Strong**
1976 - 1977 1977 - 1978 2004 - 2005 2006 - 2007	1986 - 1987 1991 - 1992 1994 - 1995 2002 - 2003 2009 - 2010	1972 - 1973 1982 - 1983 1987 - 1988 1997 - 1998	1971 - 1972 1974 - 1975 1983 - 1984 1984 - 1985 1995 - 1996 2000 - 2001 2005 - 2006 2008 - 2009 2011 - 2012	1970 - 1971 1998 - 1999 2007 - 2008	1973 - 1974 1975 - 1976 1988 - 1989 1999 - 2000 2010 - 2011



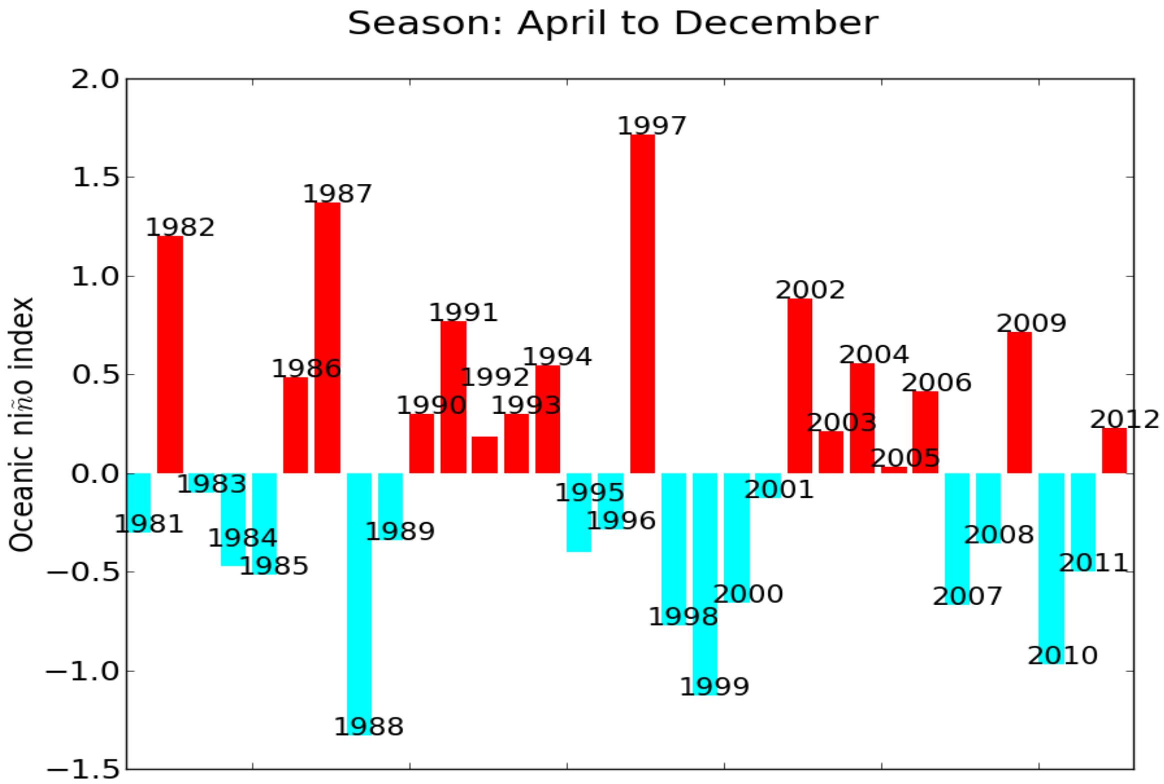


Figure 5.2.2. The Oceanic Niño Index averaged over the seasonal periods January to March (top) and April to December (bottom) for the years 1981 to 2012. Positive values indicate El Niño events, and negative La Niña.

5.2.2. 1981 to 2012 analysis

The analysis described within this section looks at the variations in the anomalies between the yearly data (1981 to 2012) and the climatology data for the 35 Insivumeh stations. Comparisons are made on a monthly and seasonal basis, and take elevation range into consideration. The use of average station data values helps to iron out inconsistencies in the station data due to systematic or technical errors that may have affected some weather station observations.

Seasonal averages

The dry (January to March) and wet season (April to December) average daily values and anomalies from the climatology have been calculated for minimum, maximum and mean temperature over each of the elevation ranges detailed in table 5.1.

Figure 5.2.3 shows the variability with elevation of the seasonal anomaly for maximum and minimum temperature between the 1981 to 2012 station averaged values and the corresponding climatology over the dry season period. The data used have been averaged for each elevation range using the time series data from the relevant Insivumeh stations.

At most elevations there is large variability observed in the anomaly throughout the time series. Additionally, there is a lot of variability between elevation ranges for each year.

During the dry season, there is a very clear positive trend of increasing maximum temperature over time for the elevation ranges between 1000 and 1400m. The picture is less clear for the other elevations where there is a lot of variability between years. There is a clearer increasing trend for the minimum temperature where there have been positive anomalies for the majority of years in the 10 year period between 2002 and 2012. For the stations at high altitudes (>1000m) there have been particularly high anomalies in the minimum temperature since 2005.

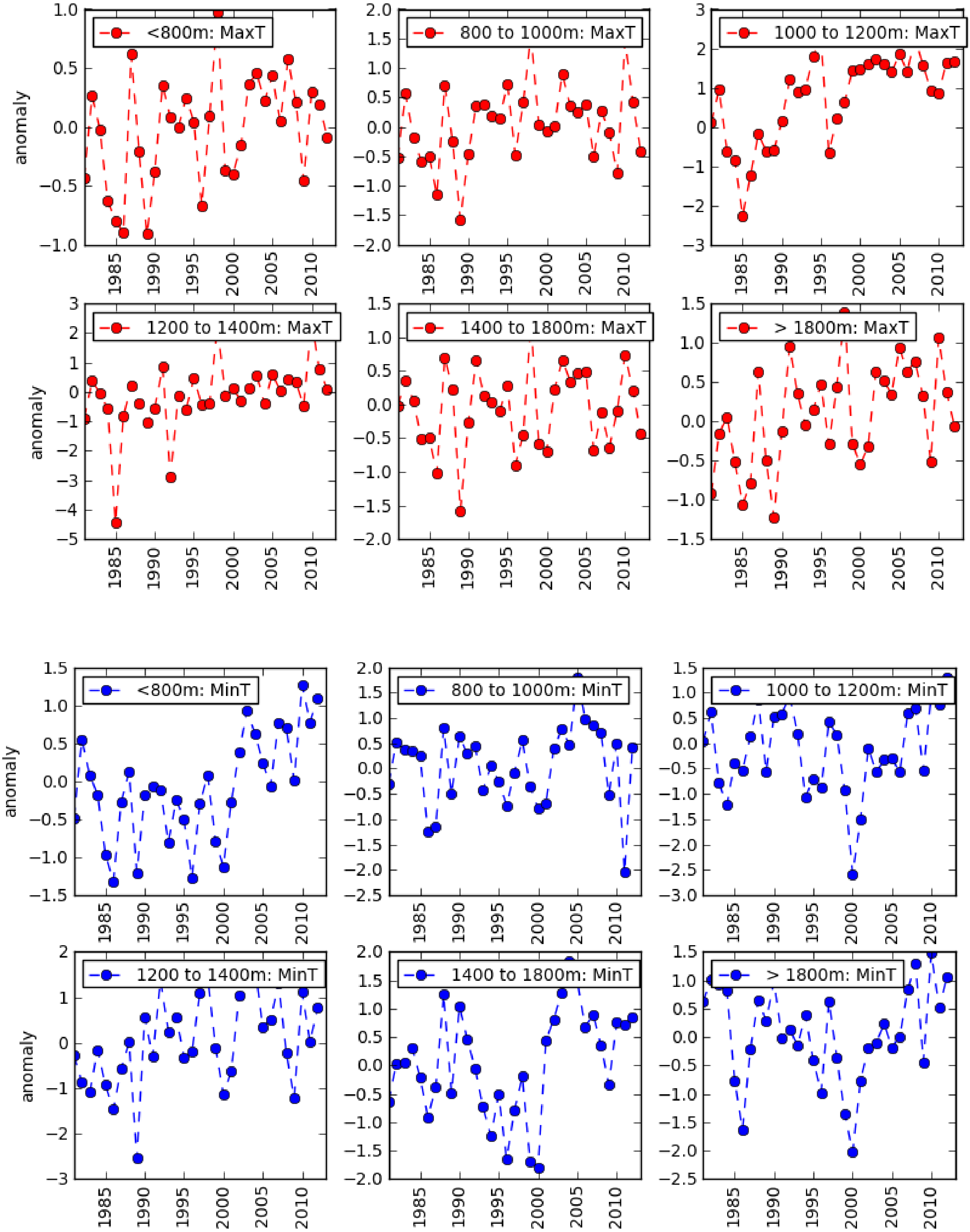


Fig. 5.2.3. Seasonal anomaly between yearly and climatology data calculated for 6 elevation ranges for the averaged daily maximum (top) and minimum temperatures (bottom) over the 35 Insivumeh stations during the dry season period January to March.

With reference specifically to the 2012 anomalies, the stations in the range 1000 to 1200m recorded the highest positive anomalies for the minimum temperature over the whole time series. Anomalies were also significantly higher than in other years for the stations in the altitude ranges below 800m and above 1800m. During the dry season period, there were positive anomalies at all elevation ranges for the minimum temperature in 2012. Overall there was a slightly negative anomaly for the maximum temperature. This is significant as it indicates that the diurnal temperature range was lower than usual at most elevations. A lower diurnal temperature range can have significant impacts for farm sites which may be more likely to experience the optimal temperature range criteria conducive to the development of coffee rust lesions. Within later sections of this study, we look more in depth at the farm weather data for 2012.

Figure 5.2.4 shows the variability with elevation of the anomalies between the 1981 to 2012 maximum and minimum temperatures and the corresponding climatology data averaged over the wet season period. Compared with the dry season, there is a clearer positive trend with time for the maximum temperature. In 2012 there were positive anomalies for the maximum temperature at all elevations where Arabica coffee can grow (400 to 1800m). There was a particularly large anomaly for stations in the elevation range 1000 to 1200m with an average daily increase in maximum temperature of 1.8^{0}C. This is the elevation range in which a large amount of the farms in Guatemala are sited.

It should be noted that this range analysis was performed using data from just 35 stations, sited in different regions of Guatemala, which are likely to also be affected by local climatological effects such that the elevation range anomalies calculated may not be very representative of the actual weather patterns for individual farms within each elevation range.

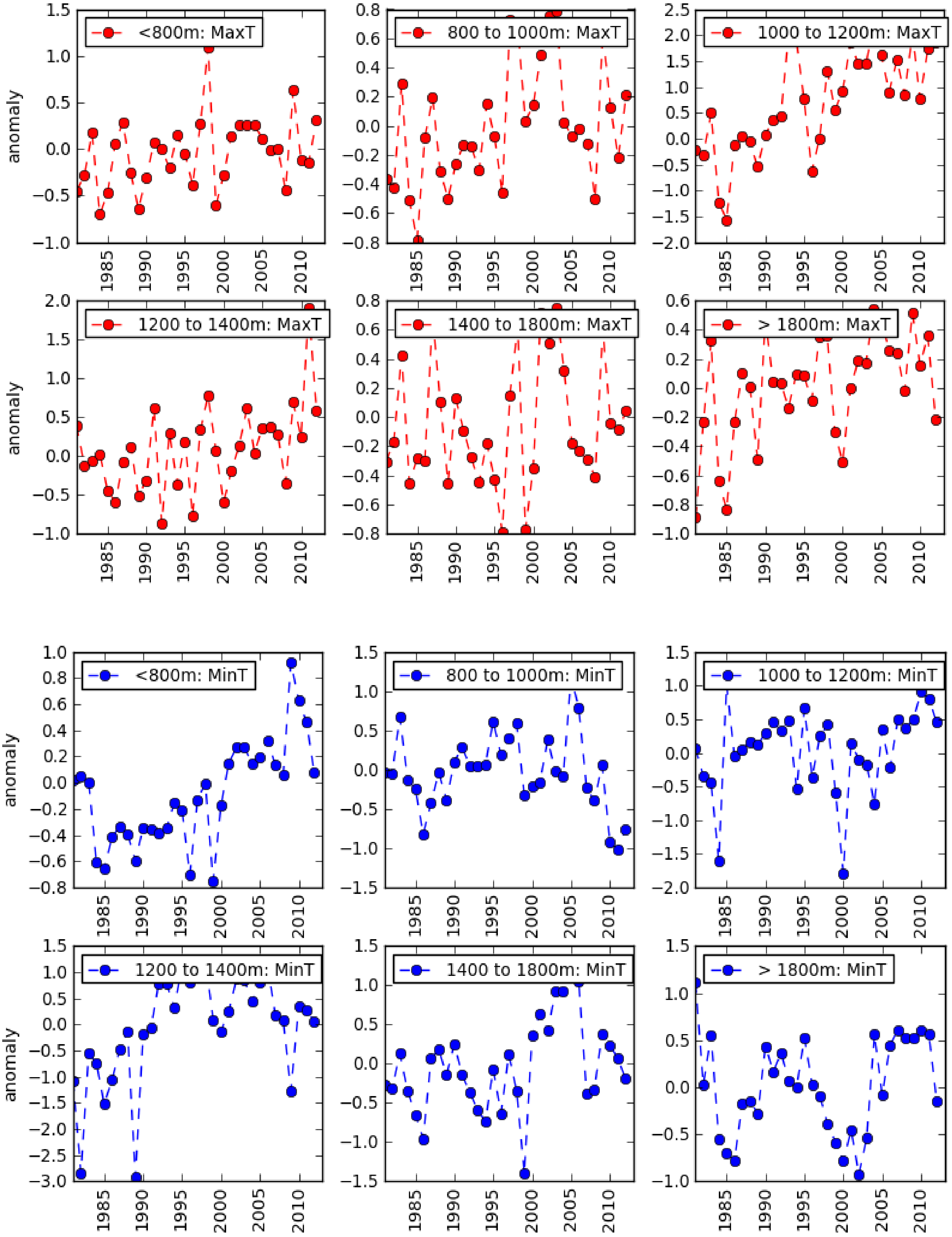


Fig. 5.2.4. Seasonal anomaly between yearly and climatology data, calculated for 6 elevation ranges, for the averaged daily maximum (top) and minimum temperatures (bottom) over the 35 Insivumeh stations during the wet season period April to December.

Figure 5.2.5 shows the 1981 to 2012 seasonal anomalies from the climatology data for the averaged daily maximum and minimum temperatures and rainfall over the 35 Insivumeh stations during the dry and wet season periods. Graphs of the averaged Oceanic Niño Index are also shown for each season for comparison. During the 2012 dry season there was a La Niña event, followed by a weak el Niño event during the wet season. As is typically characterised by La Niña events for Central America, there was a slight positive anomaly for the rainfall during the 2012 dry season. This was much smaller than the positive anomaly that coincided with the stronger La Niña event during the 2011 dry season. Looking at the correspondence between El Niño/ La Niña events for previous years and the rainfall anomaly, the expected pattern of anomalies is generally followed, especially for the more prominent events. For example there is a high positive anomaly in the rainfall during the 1989 dry season, and again in 2010 during the wet season when there were strong La Niña events. In contrast, in 1992 and 1998 there were strong El Niño events, and significantly lower precipitation than usual. However, this pattern is not always followed with reference to our averaged station data. This is likely to be related to a combination of the strength of the La Niña/ El Niño events, and also the locations of the weather stations. The distribution is such that some of them are closer to the Caribbean, while others are closer to the Pacific. These stations will therefore experience different precipitation regimes, which are affected in different ways by changes in the Oceanic Niño Index. By averaging rainfall values over all stations, the true signals in relation to this index may have been obscured in some years, particularly if the El Niño/ La Niña signals were weak. Overall there are general positive trends over time for both the maximum and minimum temperature, which is to be expected in line with the overall climate change warming signal. 2012 differed from previous years in that the maximum temperatures for both the dry and wet seasons were closer to the climatological values than in the previous 10 years, breaking with the upwards trend. It can also be seen that the minimum temperature trend has broken with the previous trend since 2003. Between 1981 and 2003, the anomaly was most often negative, however the trend has been for it to become increasingly positive since then. There has been less of a dramatic shift in the maximum temperatures. In 2012, the diurnal temperature range was less than the climatological average (see table 5.2.6). If the trend of the minimum temperature bias being greater than the maximum temperature bias from the climatology continues, then there is a greater likelihood for the temperature values to fall within the optimum range for lesion development of the coffee leaves.

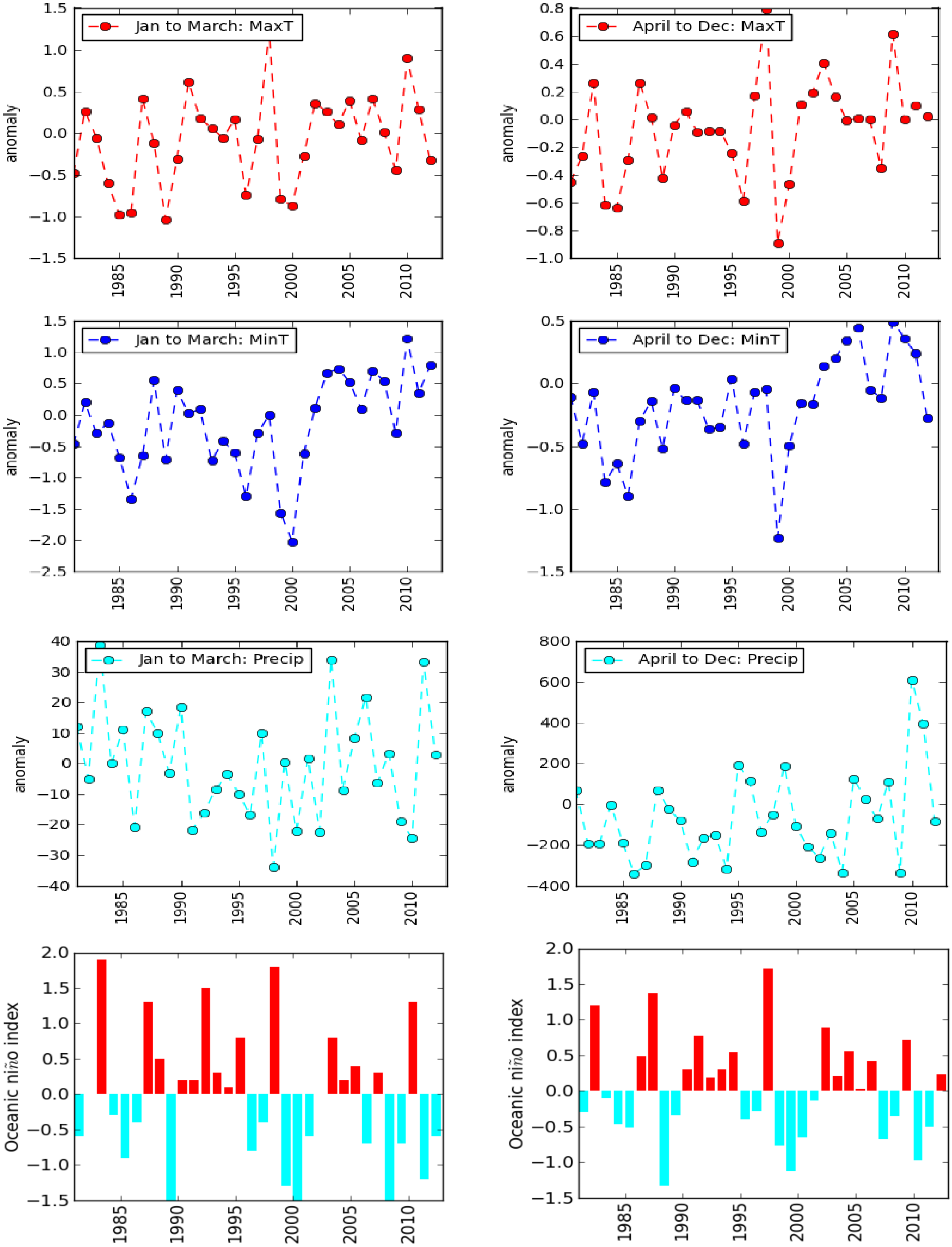


Fig. 5.2.5. Seasonal 1981 to 2012 anomalies from climatology for the averaged daily maximum and minimum temperatures and rainfall over the 35 Insivumeh stations. Dry season (left), wet season (right). Oceanic Niño Index is also shown for each season.

Another point of interest is the correspondence between the Oceanic Niño Index and the minimum and maximum temperatures. 2002 to 2006 were characterised by El Niño events. During the dry period, there were positive anomalies for both the minimum and maximum temperatures. During the wet period there was a positive anomaly for the minimum temperature and little anomaly for the maximum temperature. In contrast, the years 1991 to 2001 were characterised by La Niña events and there were negative anomalies for both the minimum and maximum temperatures.

It is recommended that this analysis is replicated using interpolated values of the station temperature data for the 1224 farm locations, and the corresponding CHIRP precipitation values for the period 1981 to 2012. The relationship between precipitation, temperature and the Oceanic Niño Index can then be examined in more detail. This could be done by separating the farms by both region to remove the bias introduced by the influence of the Caribbean/ Pacific precipitation patterns, and by altitude for a good assessment of temperature biases. This could potentially form the basis for the development of a regional specific coffee rust indicator, related to the expected seasonal weather patterns.

Monthly averages

The monthly average daily values and anomalies from the climatology have been calculated for minimum, maximum and mean temperature over each of the elevation ranges detailed in table 5.1. Presented here is an analysis of the month to month variability for each of these parameters, using averaged values over all stations. Figures 5.2.6 to 5.2.9 show the monthly anomalies for the maximum, minimum and mean temperatures and the precipitation respectively.

The maximum temperature anomaly (fig. 5.2.6) has high variability between years, and trends are clearer for some months than for others. Between July and October there has been a clear upward trend over the years. For the other months, the maximum temperature has generally fluctuated between positive and negative anomalies. For most months in 2012, the maximum temperature anomaly broke with the upward trend, and there was a negative anomaly for the first half of the year.

The minimum temperature positive anomaly trends (fig. 5.2.7) are much clearer to see in the months January to October. There has generally been a positive anomaly in relation to the climatology since around 2003 for this parameter. Contrasting with the maximum temperature data, it can be seen that there was a positive anomaly for the minimum temperature in January and February 2012, followed by a slightly negative anomaly for most other months.

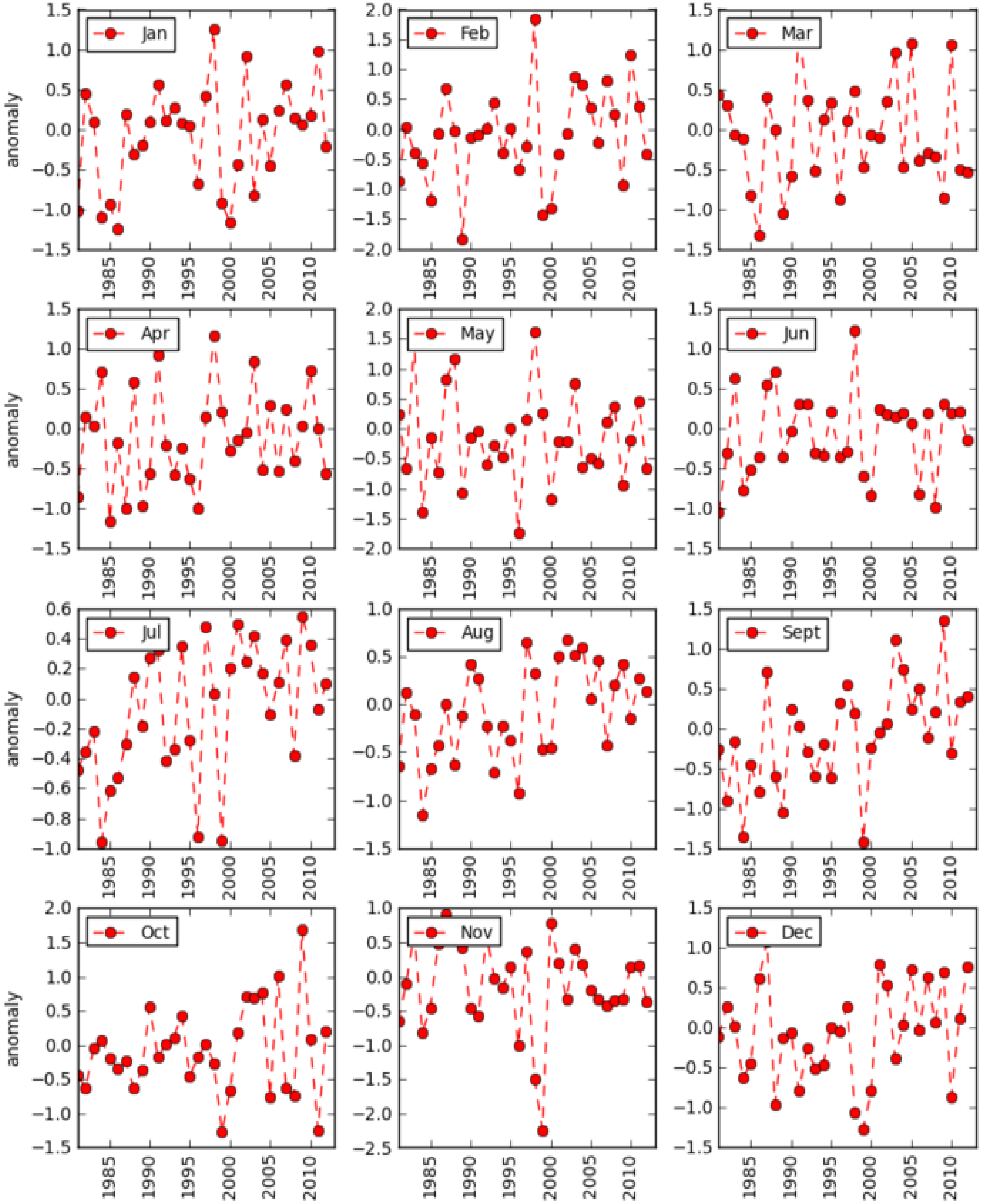


Fig. 5.2.6. Monthly maximum temperature anomalies for the period 1981 to 2012, using averaged data from the 35 Insivumeh stations.

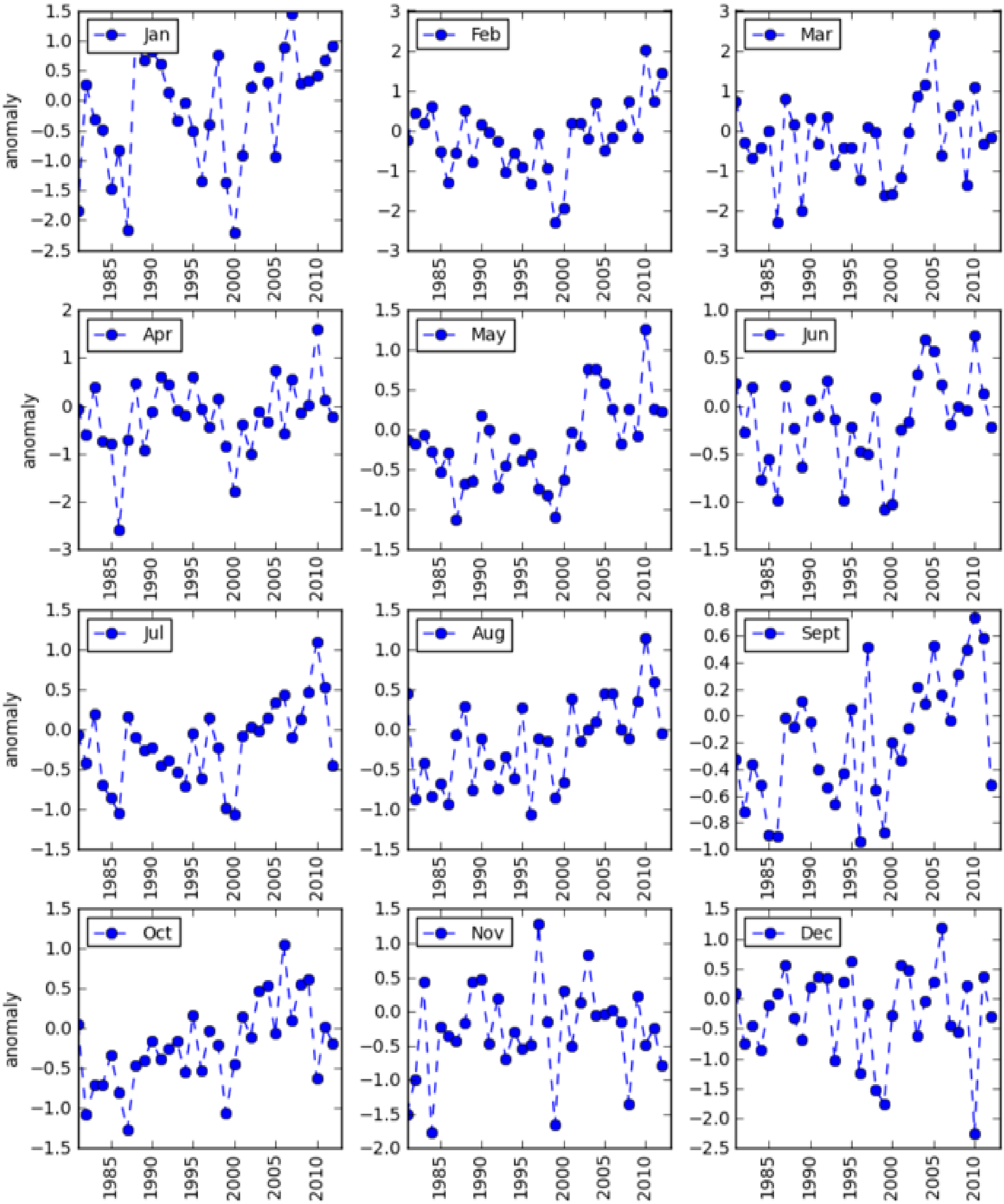


Fig. 5.2.7. Monthly minimum temperature anomalies for the period 1981 to 2012, using averaged data from the 35 Insivumeh stations.

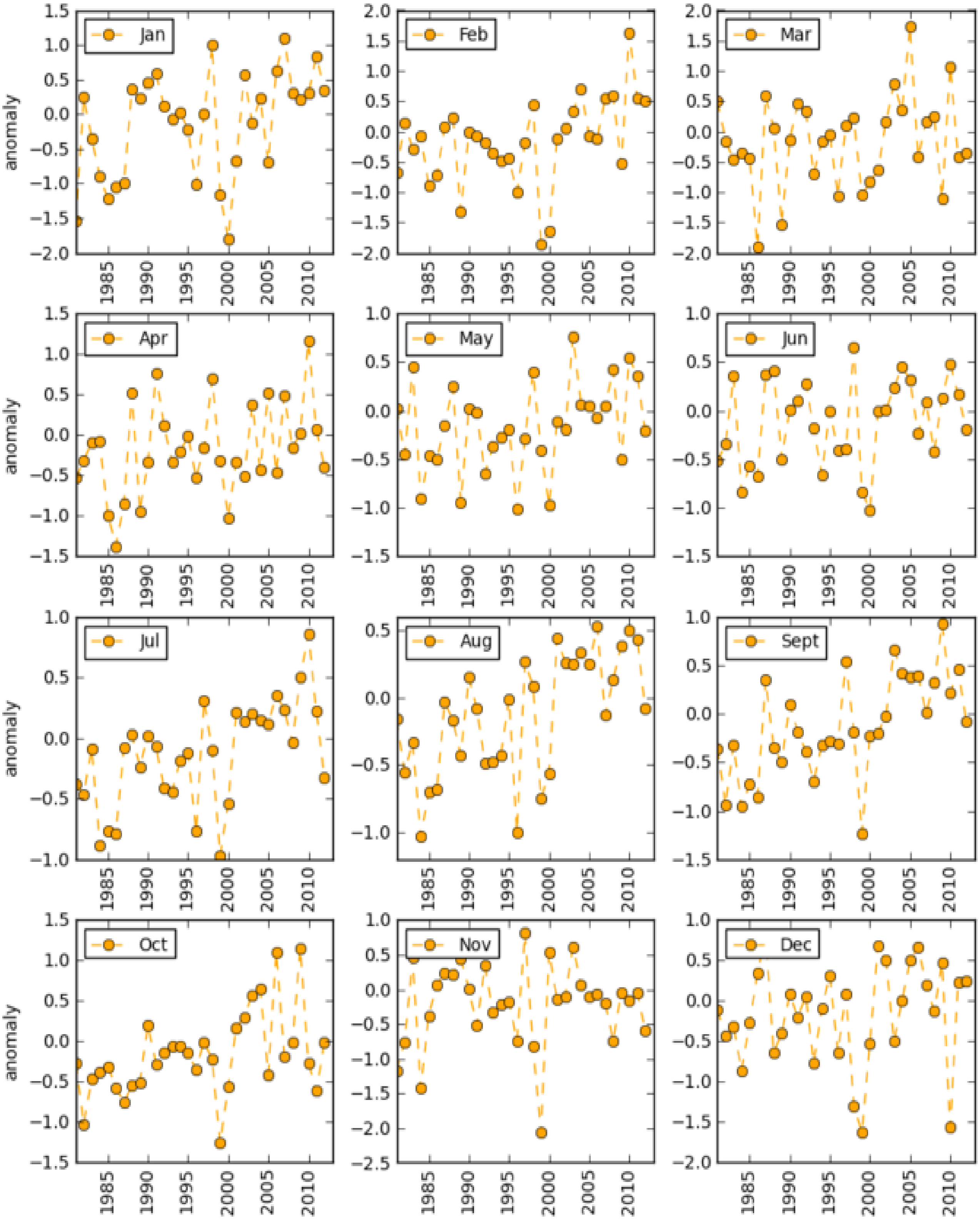


Fig. 5.2.8. Monthly mean temperature anomalies for the period 1981 to 2012, using averaged data from the 35 Insivumeh stations.

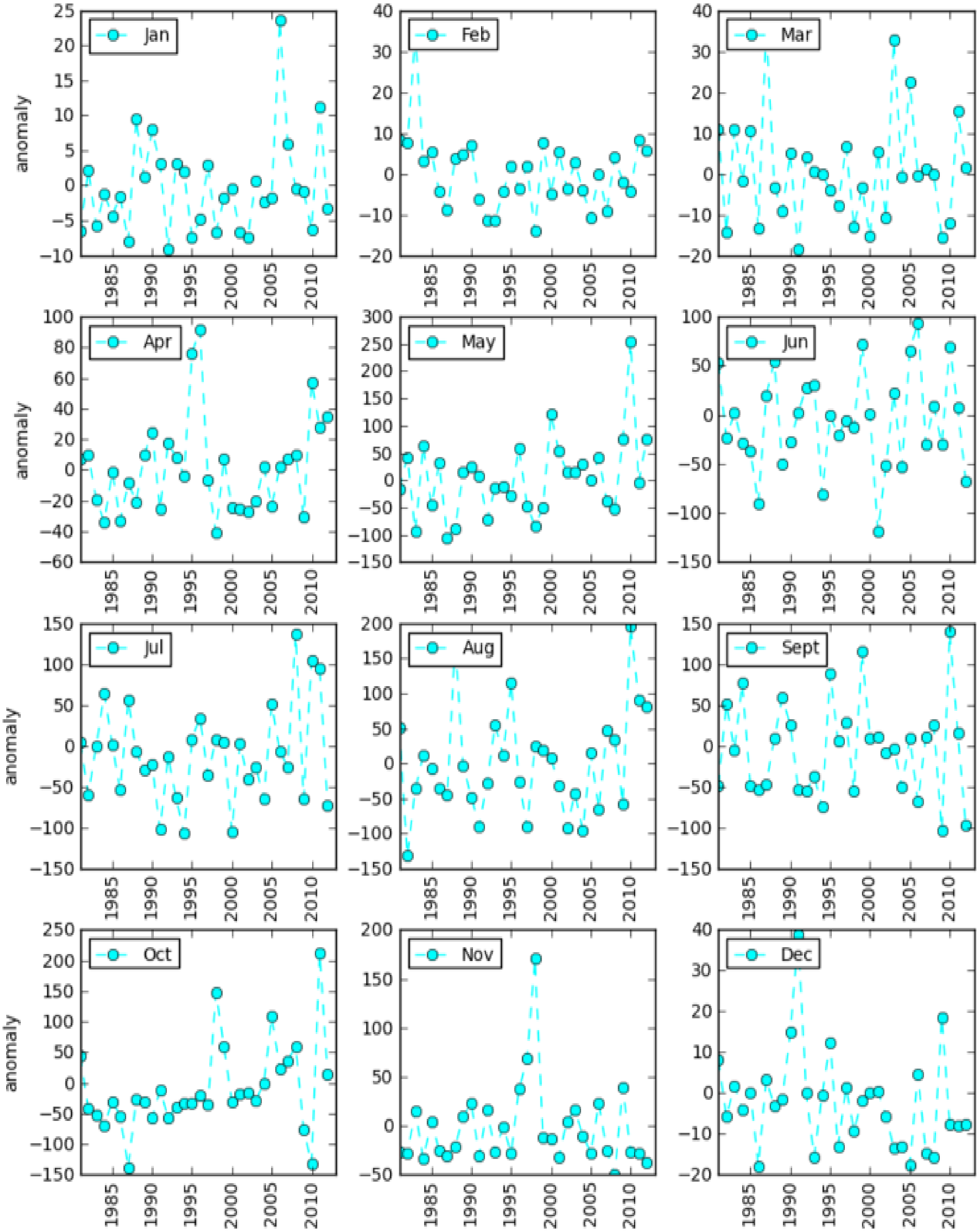


Fig. 5.2.9. Monthly precipitation anomalies for the period 1981 to 2012, using averaged data from the 35 Insivumeh stations.

In line with the increases in maximum and minimum temperatures, there is also an increasing trend for the mean temperature (fig. 5.2.8). 2012 observations broke with this trend, when mean temperatures were calculated to be closer to the climatological average. This is particularly evident for the months April to October.

Table 5.2.7 shows the difference between the average monthly accumulated rainfall over all sites for 2012. The overall rainfall accumulation for the year was 71 mm below the climatological average. The picture throughout the year was mixed, with 6 months (Feb to May, Aug and Oct) all experiencing increased rainfall. The largest bias by rainfall amount was in September. Figure 5.2.10 shows how the bias for this month has varied in the 1981 to 2012 period for each of the elevation ranges described in table 5.1. There is a strong negative bias for stations at all elevation ranges, and in comparison with past years, this ranks amongst the greatest 5 negative biases over all ranges in the period 1981 to 2012.

Overall, the weather in 2012 in Guatemala seems anomalous when compared with the overall trends of increasing mean temperature in the period 1981 to 2012, and also with the climatological average of rainfall.

A recommendation is to continue this analysis by comparing the monthly temperature and rainfall values with the Oceanic Niño Index monthly values to ascertain further dependencies, and to calculate the 1981 to 2012 anomalies over all farms, as was recommended for the seasonal analysis.

Table 5.2.7. Average CHIRPS precipitation monthly accumulated data averaged over the 35 station locations (^{0}C)

Year	**Monthly rainfall accumulation (mm)**												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**All**
2012	12.6	20.9	24.5	89.8	236.9	227.2	167.8	325.4	199.5	221.4	24.1	18.9	1569
Climatology	16.0	15.4	23.1	54.6	160.6	294.5	240.9	244.4	296.6	206.3	61.8	26.4	1641
Bias	-3.4	5.6	1.4	35.2	76.3	-67.2	-73.0	81.0	-97.1	15.2	-37.7	-7.4	-71.3
%	79.0	136.3	105.9	164.4	147.5	77.2	69.7	133.1	67.3	107.4	39.0	71.8	95.7

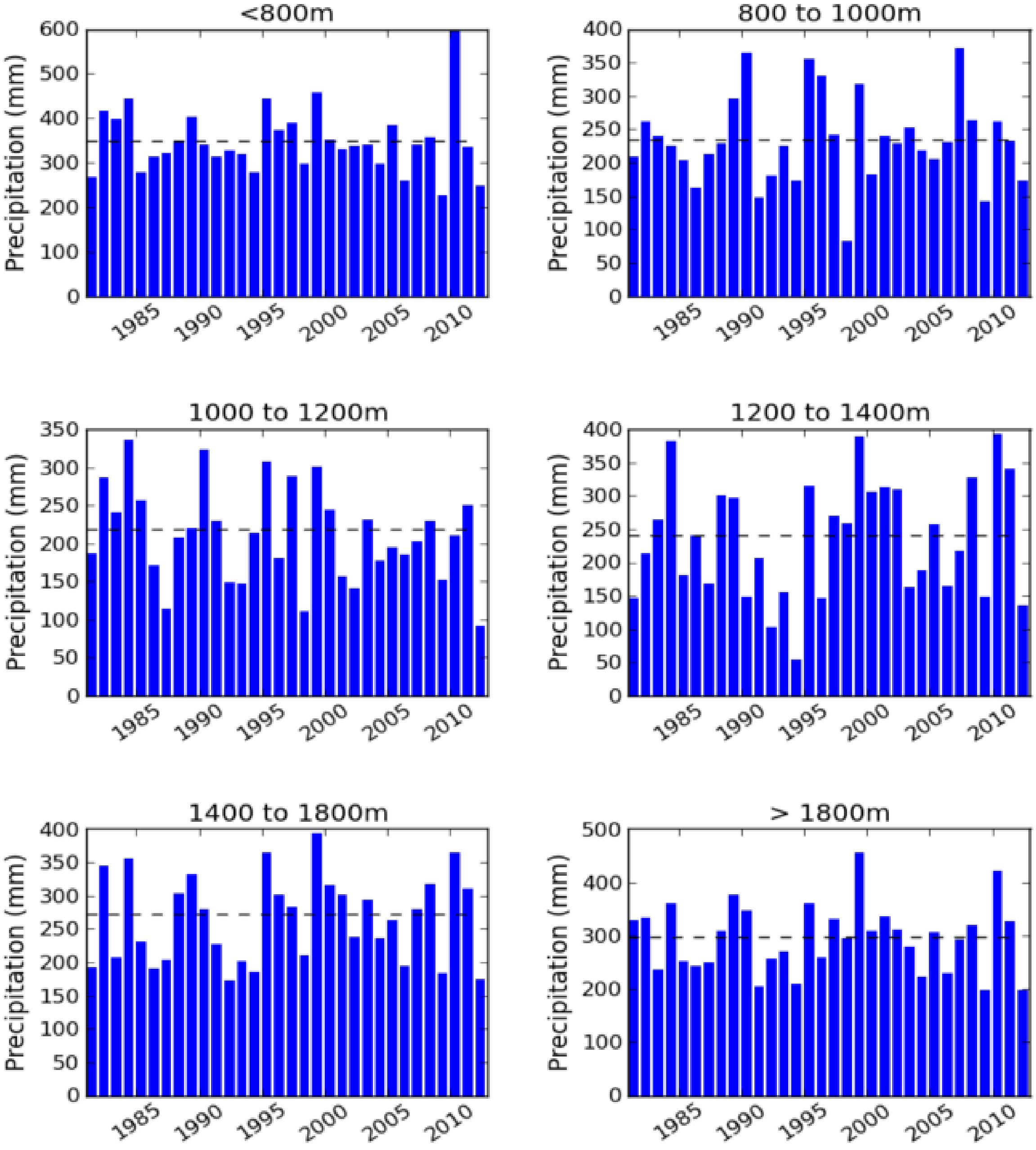


Fig 5.2.10. September precipitation accumulations for the period 1981 to 2012 (blue bars) for stations at different elevation ranges. The dashed line represents the climatological average (calculated as the average Sept accumulation over the 30 yr period 1981 - 2010).

5.3 Comparisons between 2012 and climatological data

Described in this section are the key observations from comparisons between the 2012 temperature and precipitation data at the same stations as described in section 5.1. These stations are in proximity to the farm case studies described in section 5.3, and are referenced from that analysis.

5.3.1 Assuncion Mita station – 472 m elevation

- Increases in the minimum temperature during the dry season, when compared with the climatology.
- Slight decrease in the maximum temperature during the dry season (end of Jan to Feb) and early in the wet season (April to June)
- Decreased diurnal temperature range during the dry season and early wet season (Jan to June)
- The maximum and minimum temperatures are in closer agreement with the climatology during the wet season.
- Heavy rainfall events during May and August, but lower than usual rainfall between mid June and July.

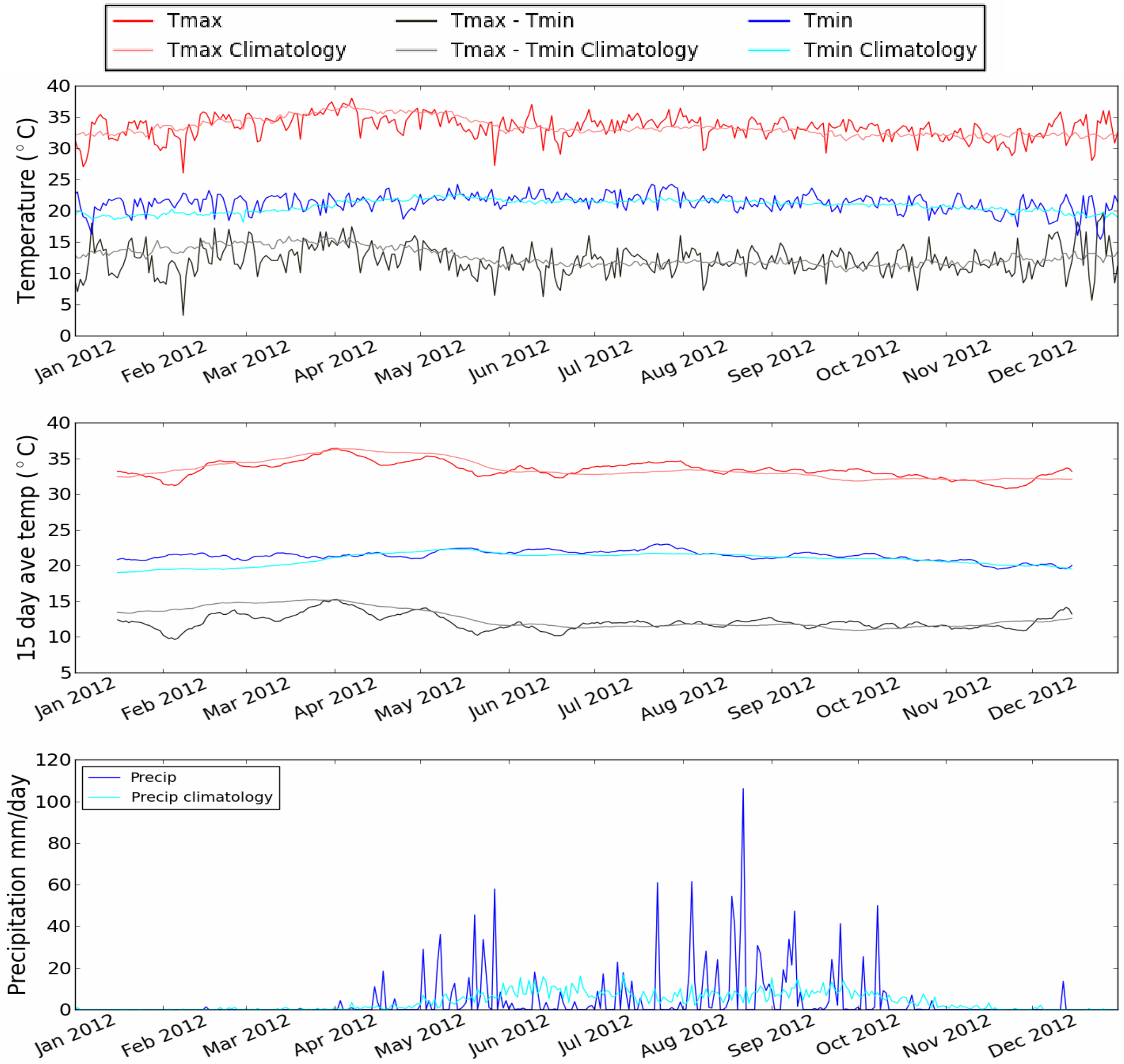


Figure 5.3.1. Assuncion Mita weather station. Time series comparisons between (a) daily maximum, minimum and mean temperatures (b) 15 day averaged temperature values and (c) precipitation for 2012 and climatological data.

5.3.2 Esquipulas station – 895 m elevation

- Positive anomaly in the minimum temperature during the dry season.
- Large variations in daily maximum temperature between January and May
- Negative anomaly for the diurnal temperature range during the dry seasonal
- Maximum and minimum temperatures are in closer agreement with the climatology during the wet season.
- Isolated high rainfall events in June and August to October.

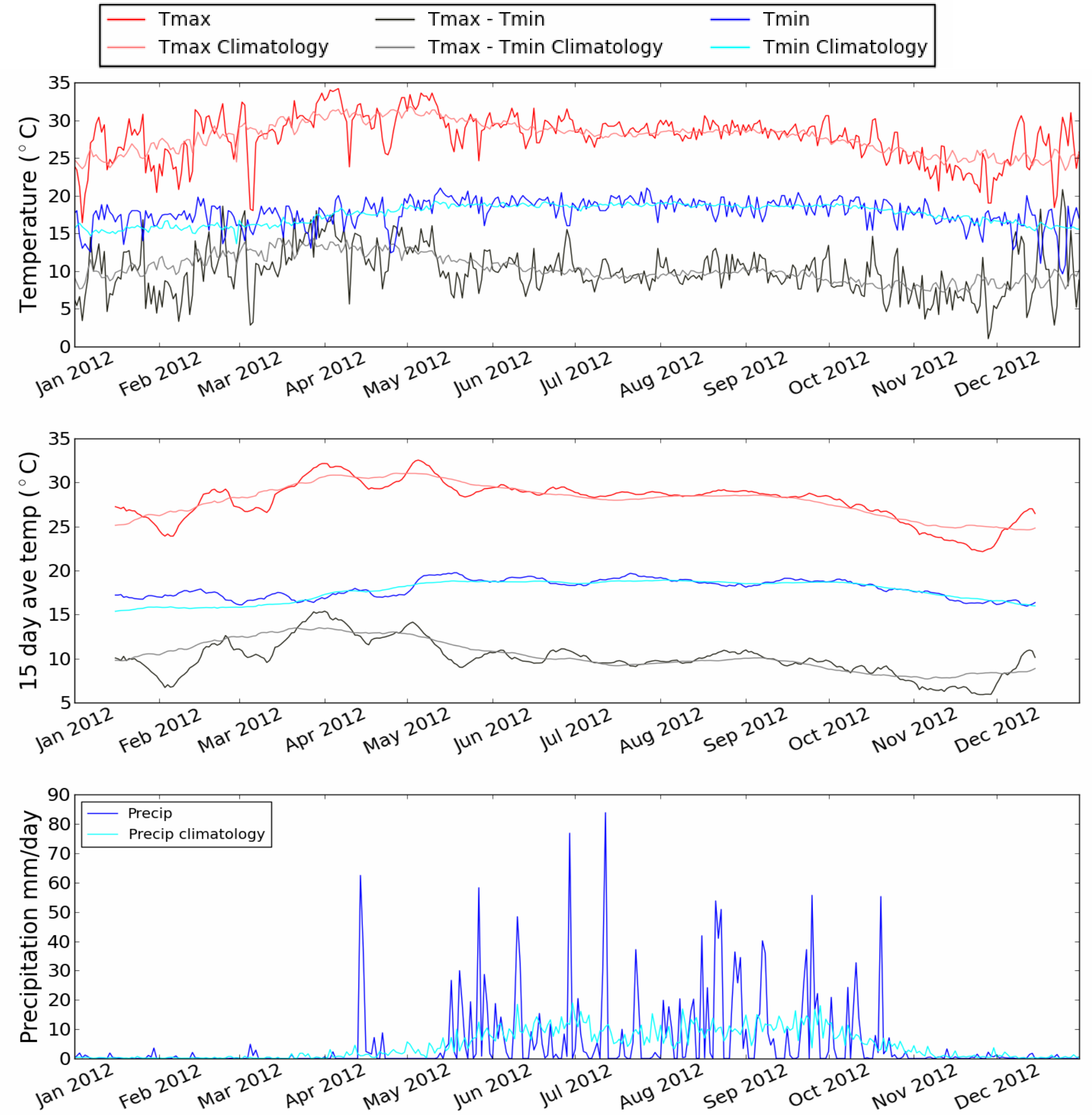


Figure 5.3.2. Esquipulas weather station. Time series comparisons between (a) daily maximum, minimum and mean temperatures (b) 15 day averaged temperature values and (c) precipitation for 2012 and climatological data.

5.3.3 Cuilco station – 1163 m elevation

- Large positive anomaly in minimum temperature during the dry season, and a positive anomaly through much of the dry season.
- Maximum temperature fluctuates around the climatological mean
- Diurnal temperature range has a negative anomaly during the dry season and start of the wet season (May) and a positive anomaly towards the end of the year. This varies from the stations at lower elevations.
- Some heavy rainfall events observed before the start of the rainy season (Feb to March)

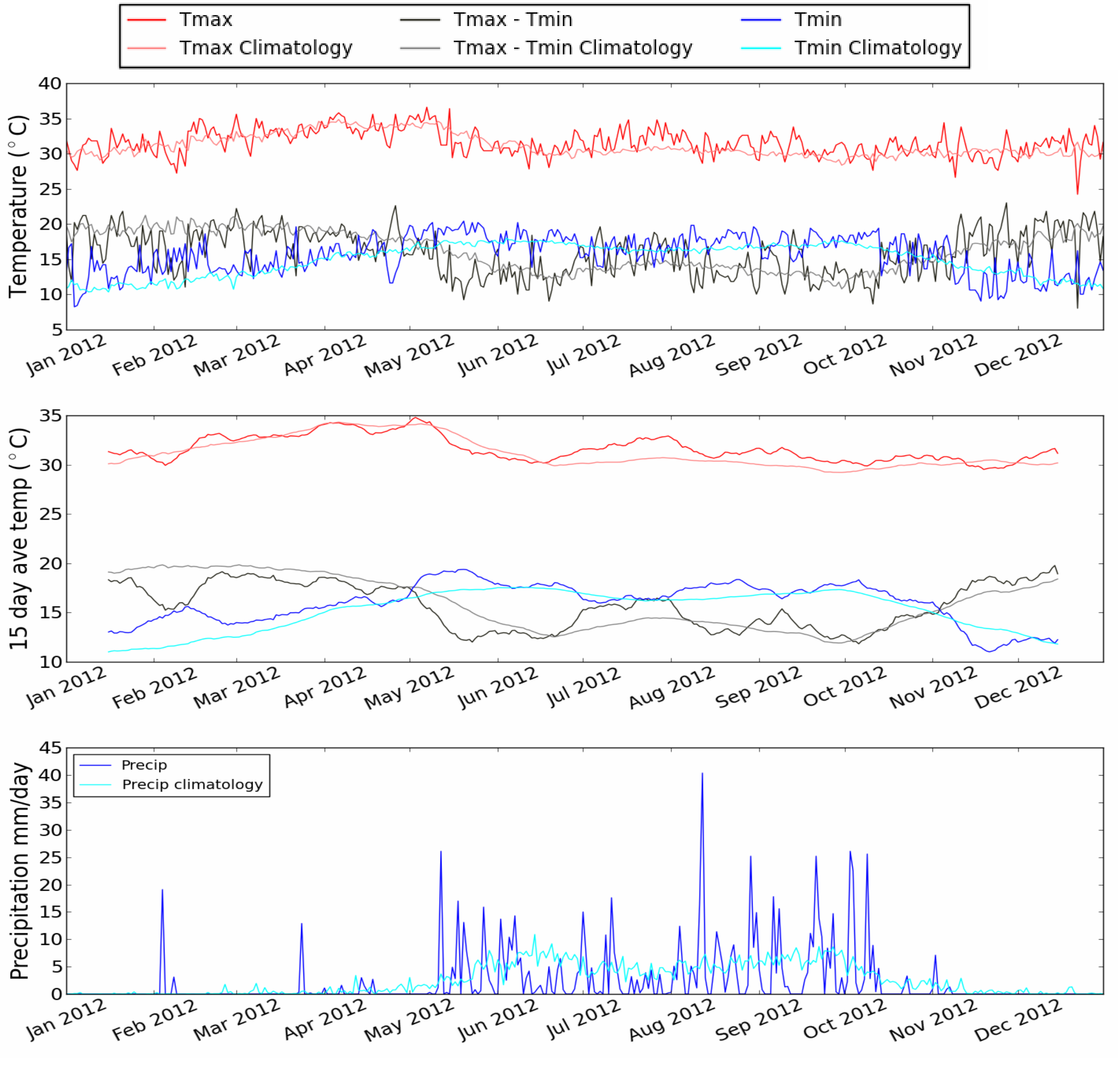


Figure 5.3.3. Cuilco weather station. Time series comparisons between (a) daily maximum, minimum and mean temperatures (b) 15 day averaged temperature values and (c) precipitation for 2012 and climatological data.

5.3.4 Coban station – 1318 m elevation

- The mean values of the maximum and minimum 2012 temperatures are in close agreement with the climatology, however there are a lot of fluctuations from these values.
- Overall there is a larger diurnal temperature difference when compared with the climatological data.
- During the period January to March, the minimum temperatures are higher than the climatology.
- There are precipitation peaks in April and May, that occur before the climatological precipitation peak.

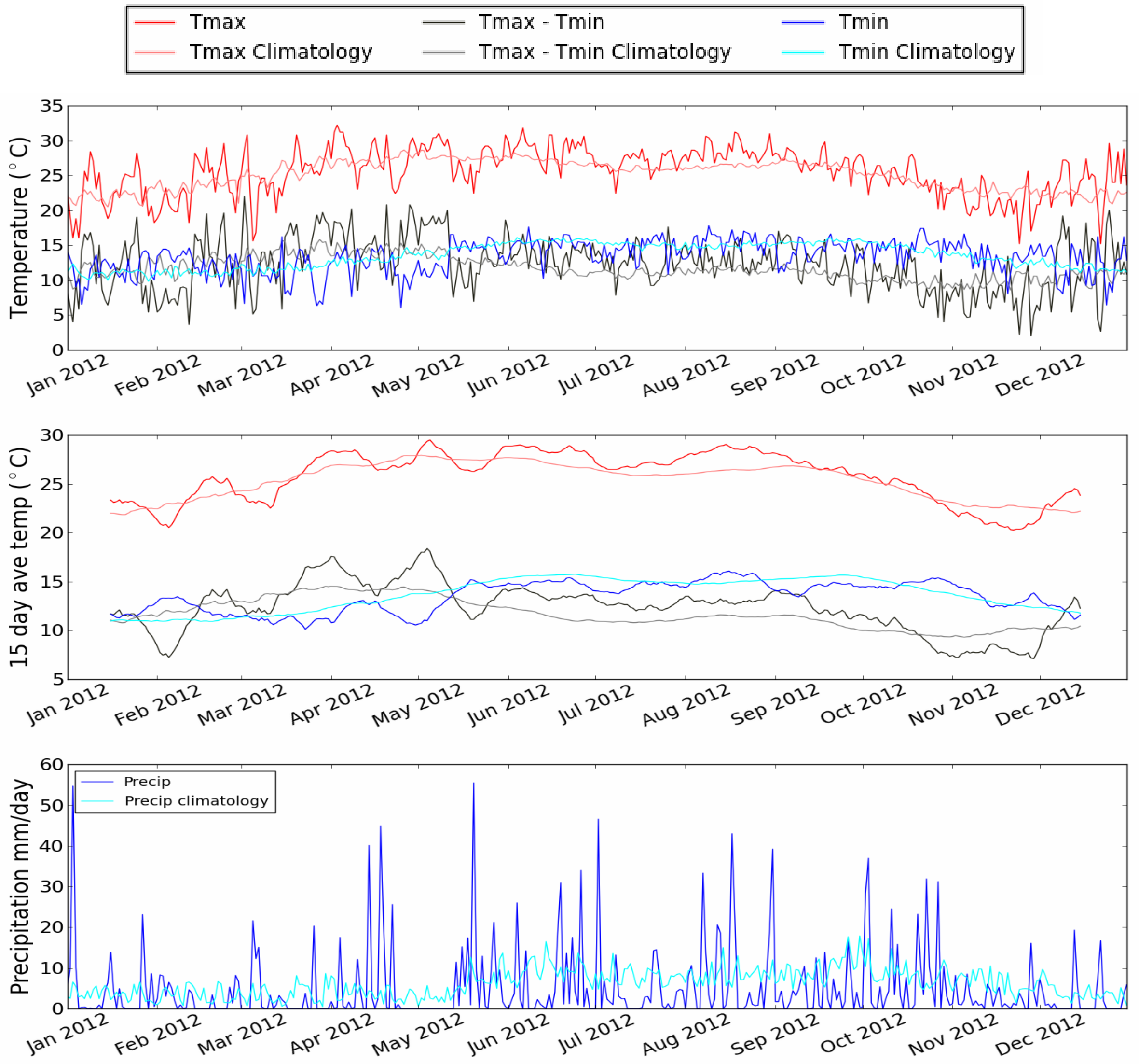


Figure 5.3.4. Coban weather station. Time series comparisons between (a) daily maximum, minimum and mean temperatures (b) 15 day averaged temperature values and (c) precipitation for 2012 and climatological data.

5.3.5 Insivumeh station – 1505 m elevation

- Overall the 2012 data is in good agreement with the climatological data.
- There is one anomalous period between June and July 2012 where the maximum temperature dipped below the climatology by ~ 6^0C. This corresponds with a period that began and ended with high rainfall events, but was characterised by lower than average rainfall in the intervening period. This seems anomalous, perhaps being the result of technical errors in the observing equipment, and requires further investigation.

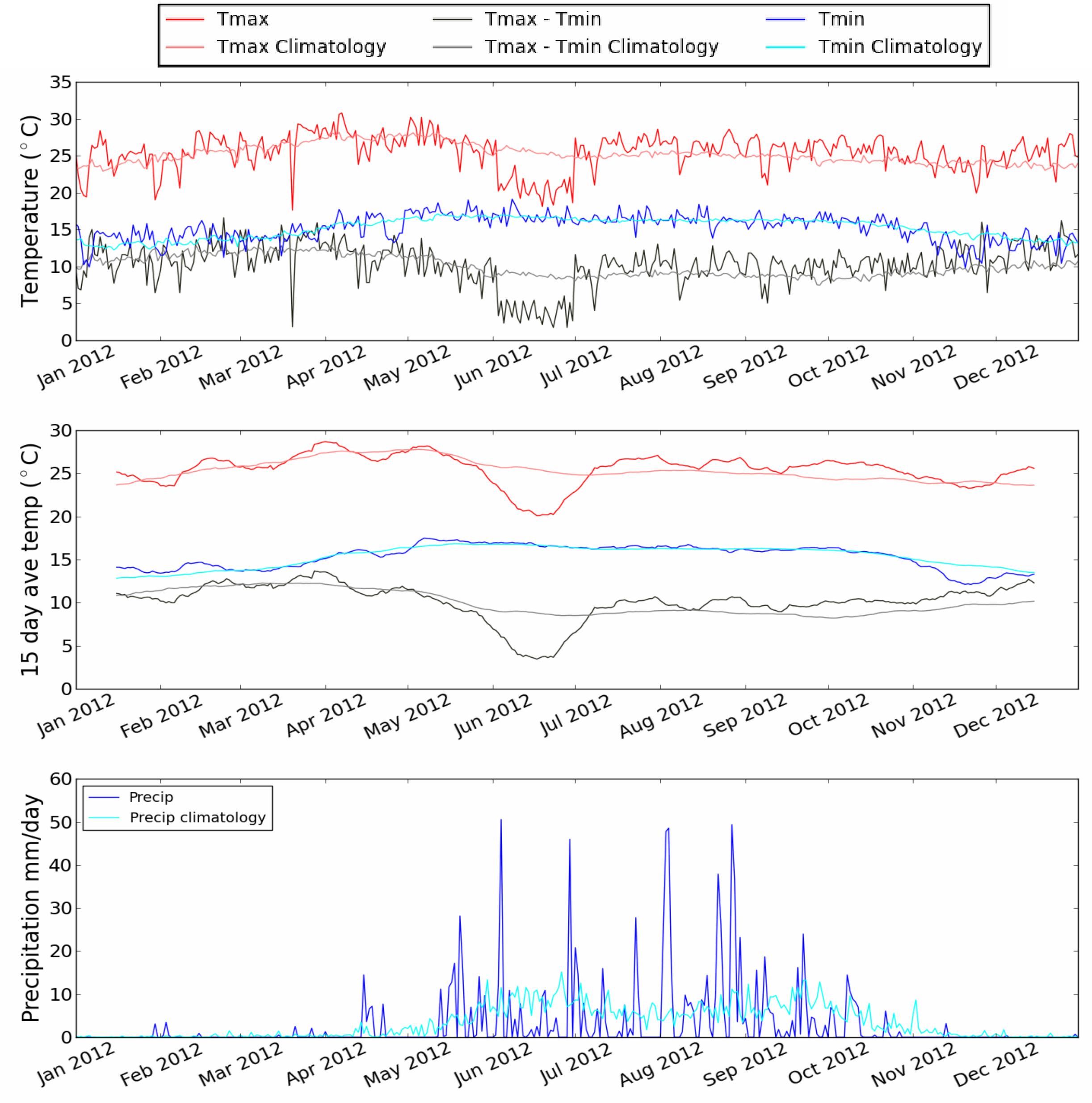


Figure 5.3.5. Insivumeh weather station. Time series comparisons between (a) daily maximum, minimum and mean temperatures (b) 15 day averaged temperature values and (c) precipitation for 2012 and climatological data.

5.3.6 San Martin Jilotepeque station – 1769 m elevation

- Negative anomaly in the maximum temperature (Jan to Jun)
- Positive anomaly in the minimum temperature during the wet season
- Reduction in the diurnal temperature range for most of the year
- Large spikes in precipitation data – lots of high rainfall events, including in the March to April period, before the climatological start to the rainy season.

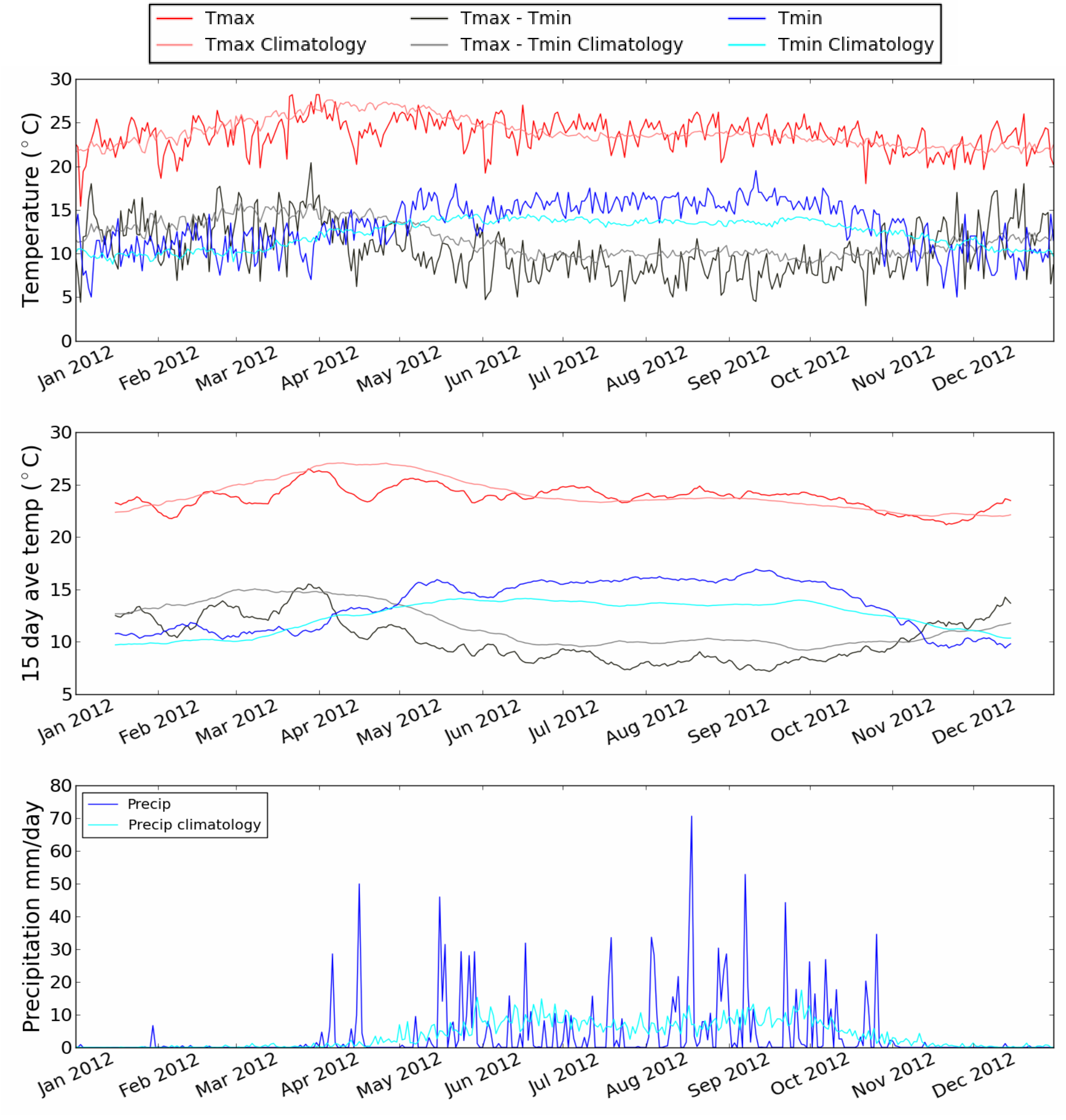


Figure 5.3.6. San Martin Jilotepeque weather station. Time series comparisons between (a) daily maximum, minimum and mean temperatures (b) 15 day averaged temperature values and (c) precipitation for 2012 and climatological data.

5.4 Case studies at farm locations

There are 18 coffee farms for which 2013 time series data of the rust incidence, severity and leaf defoliation is available. The full set of time series plots for these farms is included in appendix 2.

This analysis serves to give an overview of the anomalies in the weather conditions from the climatological averages at selected farms (table 5.4), and how these may relate to the development of indicators for identifying the susceptibility of the coffee crop at a location to coffee rust disease.

The temperature data used has been derived from interpolation of the INSIVUMEH station data. Additionally, CHIRPS five day (pentad) precipitation data has been used at these farm locations to look at anomalies from the 30 year climatology (1981 to 2010).

Details of the case study locations that were badly affected by coffee rust in 2012 are highlighted on the map in figure 2.1 and included in table 5.4.

Table 5.4 Details of case study farms within different altitude ranges that were affected by coffee rust

Case study	Farm name	Altitude (m)	Region	2012 Rust severity
1	Finca Monte Maria	528	6	4
2	Santa Marta	564	2	3
3	Helvetia	852	2	3
4	El Recreo	986	4	3
5	Finca Yaxbatz	1107	6	3
6	El Pinito	1354	4	3
7	La Soledad y Anexo	1443	3	2

Case study 1 – Finca Monte Maria, 528m elevation

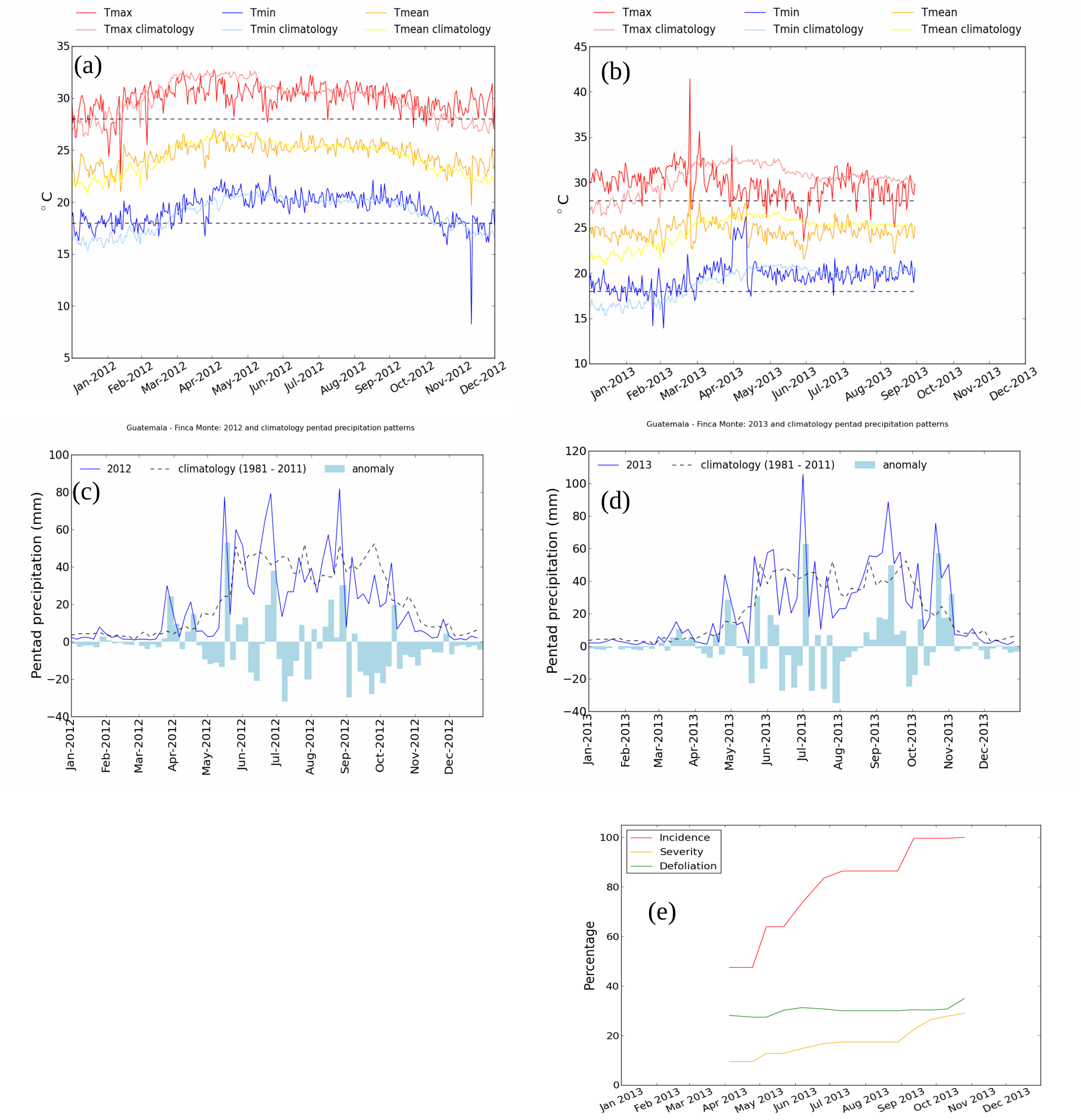


Figure 5.4.1. Finca Monte Maria, 528 m elevation, 2012 rust severity = 4.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values overplotted
(e) 2013 coffee rust incidence, severity and leaf defoliation

A comparison between the 2012 precipitation pattern and the climatology (figure 5.4.1) shows that the significant increases in rainfall, associated with the beginning of the wet season, began much earlier in the year than the climatological average for this location (March to April). There is no time series data available for rust incidence in 2012, but the overall impact assessment of coffee rust was high at this farm during this year (rust category 4). The 2013 rainy season more closely followed the climatological pattern in terms of when the rainfall increases were observed at the beginning of the wet season. However, the accumulations in 2013 were significantly higher. To assess how rainfall changes affect the progression of coffee rust incidence, the time series plots in figure 5.1(a) and (c) can be compared directly. A key observation is that the coffee rust incidence appears to respond quickly to increases in rainfall. This can be seen around the incidence assessments taken in May, June to July and August to September.

If this same pattern of increasing incidence with increases in the rainfall was followed in 2012, then the earlier start to the 2012 rainfall season at this farm's location could be a major factor in explaining the high coffee rust severity.

Overall, the maximum and mean temperature patterns were similar to the climatological averages in 2012. There was a large positive anomaly of around 2.5^{0}C for the minimum temperature observations during the dry season, and a small positive anomaly of between 1 and 1.5^{0}C during the wet season. The optimal temperature for the formation of lesions on the coffee plant is around 22^{0}C. This positive anomaly for the minimum temperature therefore provided an improved environment for the development of coffee rust disease.

Case study 2 – Santa Marta, 564 m elevation

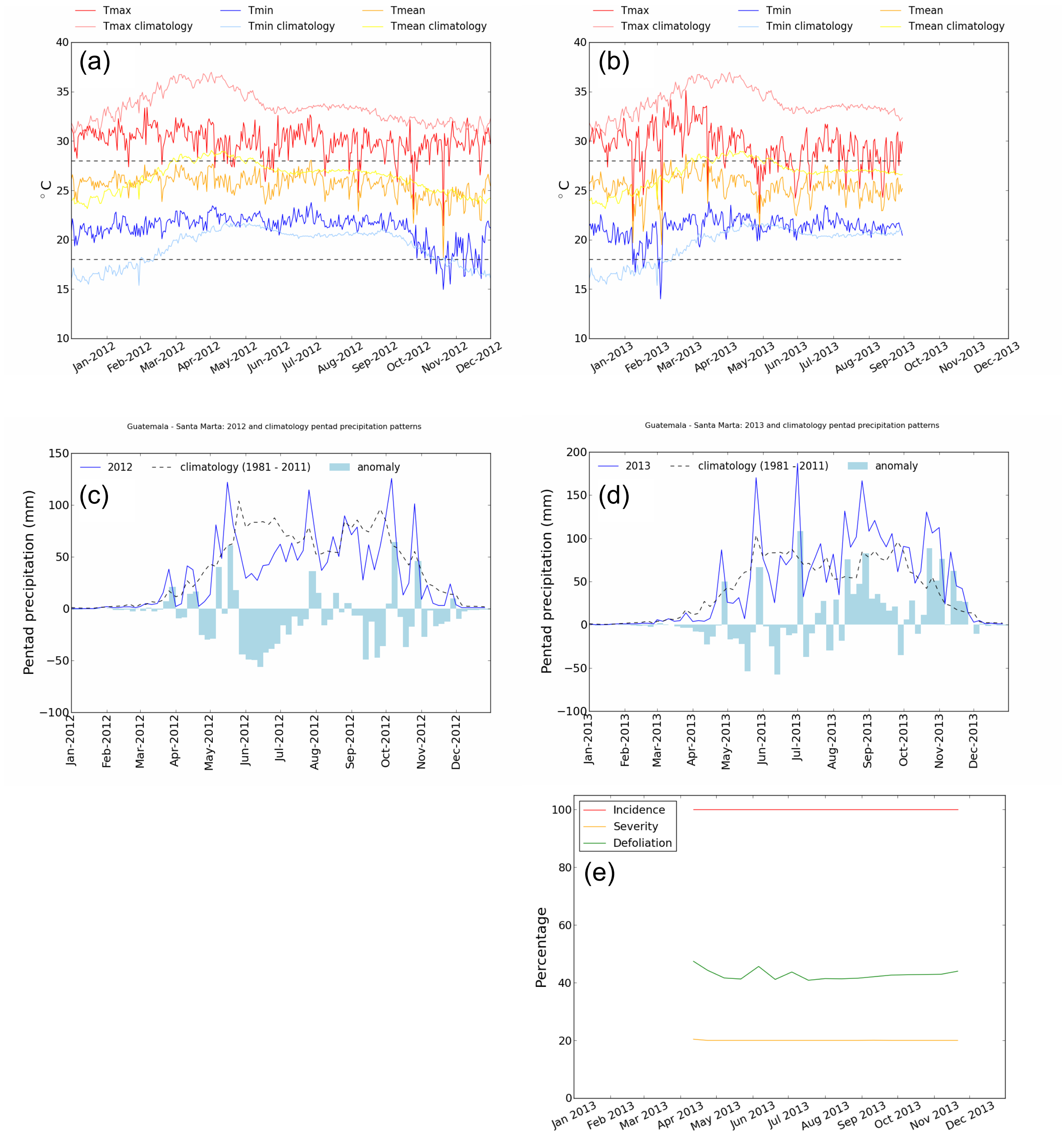


Figure 5.4.2. Santa Maria, 564 m elevation, 2012 rust severity = 3.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values overplotted
(e) 2013 coffee rust incidence, severity and leaf defoliation.

This farm is located around the same elevation as Finca Monte Maria, and the two locations show similarities in the early start to the rainfall season when compared with the climatology (figure 5.3.2a). However, at this farm, a similar pattern is observed in both the 2012 and 2013 rainfall data. The corresponding coffee rust incidence is at 100% throughout the observed period in 2013 (figure 5.3.2). By comparison with the incidence at Finca Monte Maria (figure 5.4.1), it is clear that this farm was more severely affected by coffee rust much earlier in the season. This is perhaps related to a quick response of lesion development in response to the sharp increase in rainfall before the incidence evaluations began in 2013.

In both years, the minimum temperatures were higher than the climatological average, and the maximum temperatures were lower. The mean temperature was also slightly lower than the climatological mean, and remained quite consistent around 24^0C – close to the optimal temperature for lesion development on coffee leaves. In this case, the weighting method described in section 4.5 would lead to an increased weighted temperature accumulation within the optimal range for the progression of coffee rust.

Case study 3 - Helvetia, 852m elevation

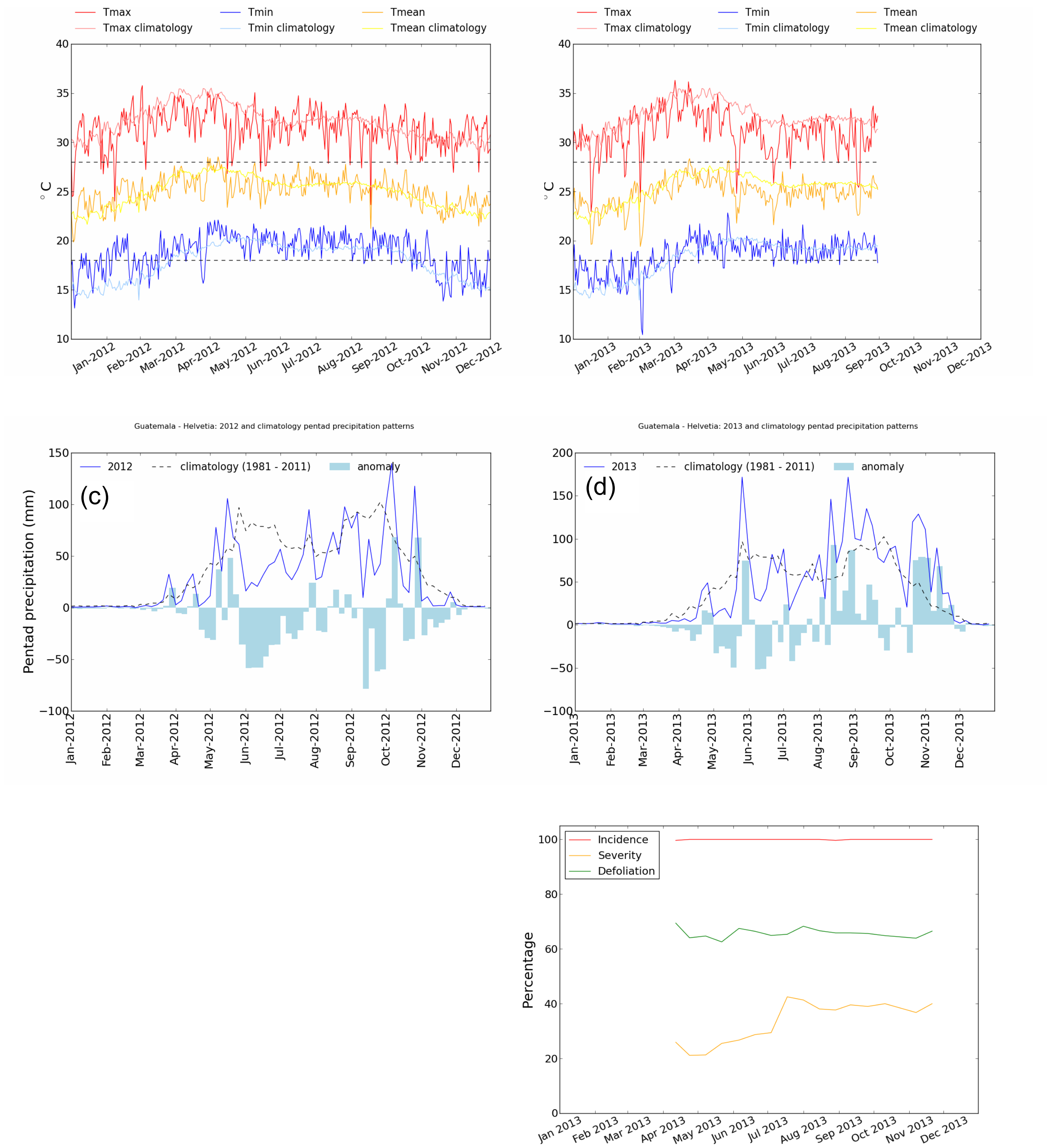


Figure 5.4.3. Helvetia, 852 m elevation, 2012 rust severity = 3.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values over-plotted.
(e) 2013 coffee rust incidence, severity and leaf defoliation.

This case was characterised by rainfall more similar to the climatology for both 2012 and 2013 (figure 5.3.3a). The dry season minimum temperatures were higher than the climatological average, and were more within the optimal range for lesion development. The maximum temperature was also lower, and the mean temperature around 24.5^{0}C. There were not large differences from the climatological means at this farm.

Case study 4 – El Recreo, 986m elevation

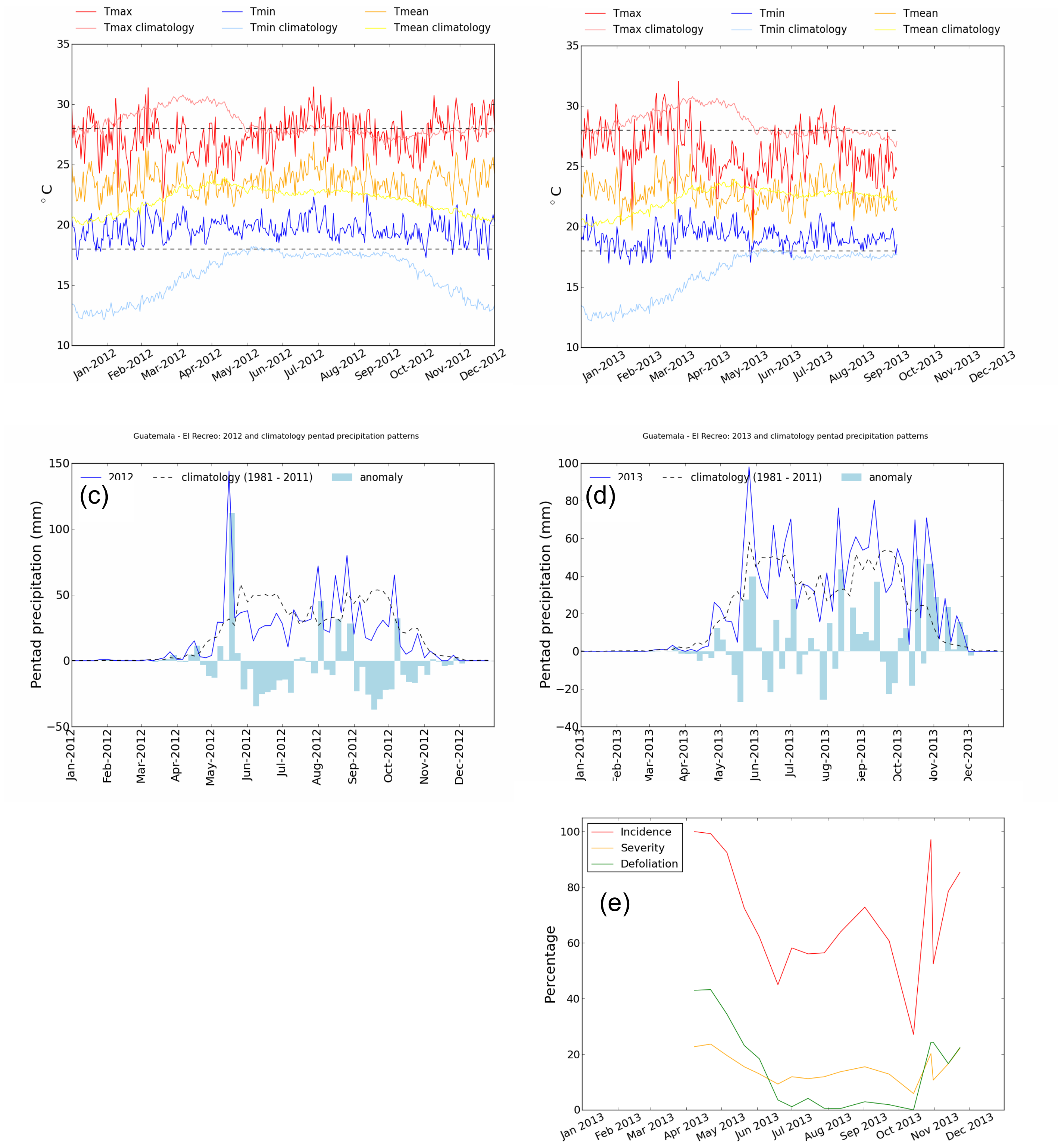


Figure 5.4.5. El Recreo, 986 m elevation, 2012 rust severity = 3.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values over-plotted.
(e) 2013 coffee rust incidence, severity and leaf defoliation.

This farm is at a similar elevation to Helvetia and the rainfall pattern was also similar to the climatology in both 2012 and 2013.

The minimum temperature was higher throughout the year. This temperature difference was particularly significant during the dry season period when there was on average a 6^0C difference. Between February and June, the maximum temperature was lower than the climatological average (figure 5.3.4b). These anomalies resulted in both the minimum and maximum temperatures existing within the threshold limits for lesion development throughout the dry season as well as the wet season. Similar anomalies were observed in the 2013 data (figure 5.3.4d). Additionally, the mean temperature for 2012 was around 24^0C and 23^0C for 2013. With reference to the rust incidence plot (figure 5.3.4c), the incidence was highest at the start of the wet season. Taking into consideration that there are similar weather profiles for both 2012 and 2013, this indicates that the temperature anomalies during the dry season were likely to have contributed to the high level of coffee rust observed in both 2012 and 2013.

Case study 5 – Finca Yaxbatz, 1107m elevation

At this farm (figure 5.4.6), the climatological profiles for both temperature and rainfall were closely followed for the 2012 data (figure 5.3.5). The mean temperature was around 22^0C. In 2013 the minimum temperature was on average 3^0C higher than the climatology. As with El Recreo farm (case study 4) the corresponding incidence of coffee rust in 2013 was very high from the start of the evaluated period. This again may indicate that a positive anomaly in the minimum temperature during the dry season may in some way prime the leaves for the development of coffee rust.

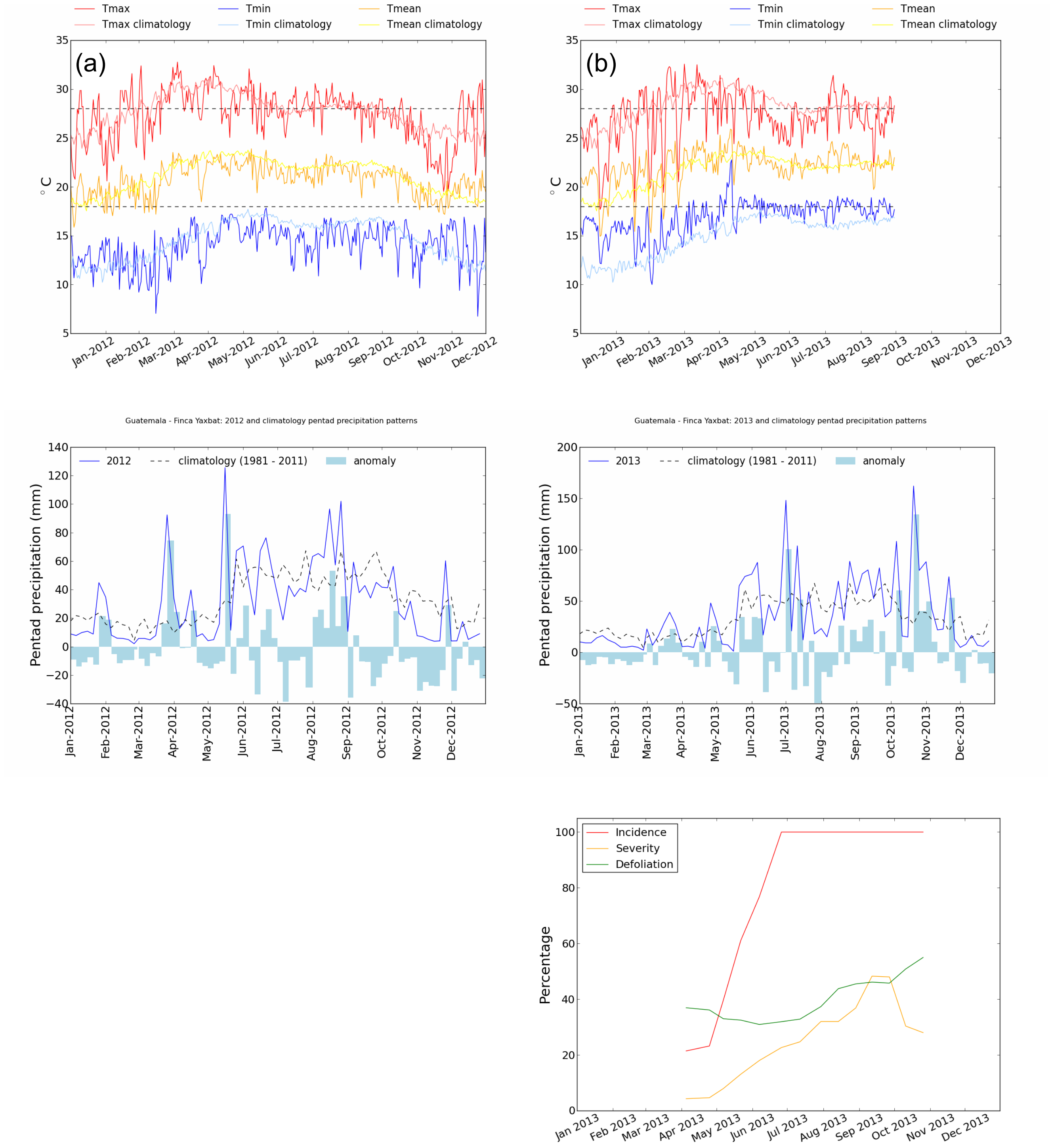


Figure 5.4.6. Finca Yaxbatz, 1107 m elevation, 2012 rust severity = 3.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values over-plotted.
(e) 2013 coffee rust incidence, severity and leaf defoliation.

Case study 6 – El Pinito, 1354 m elevation

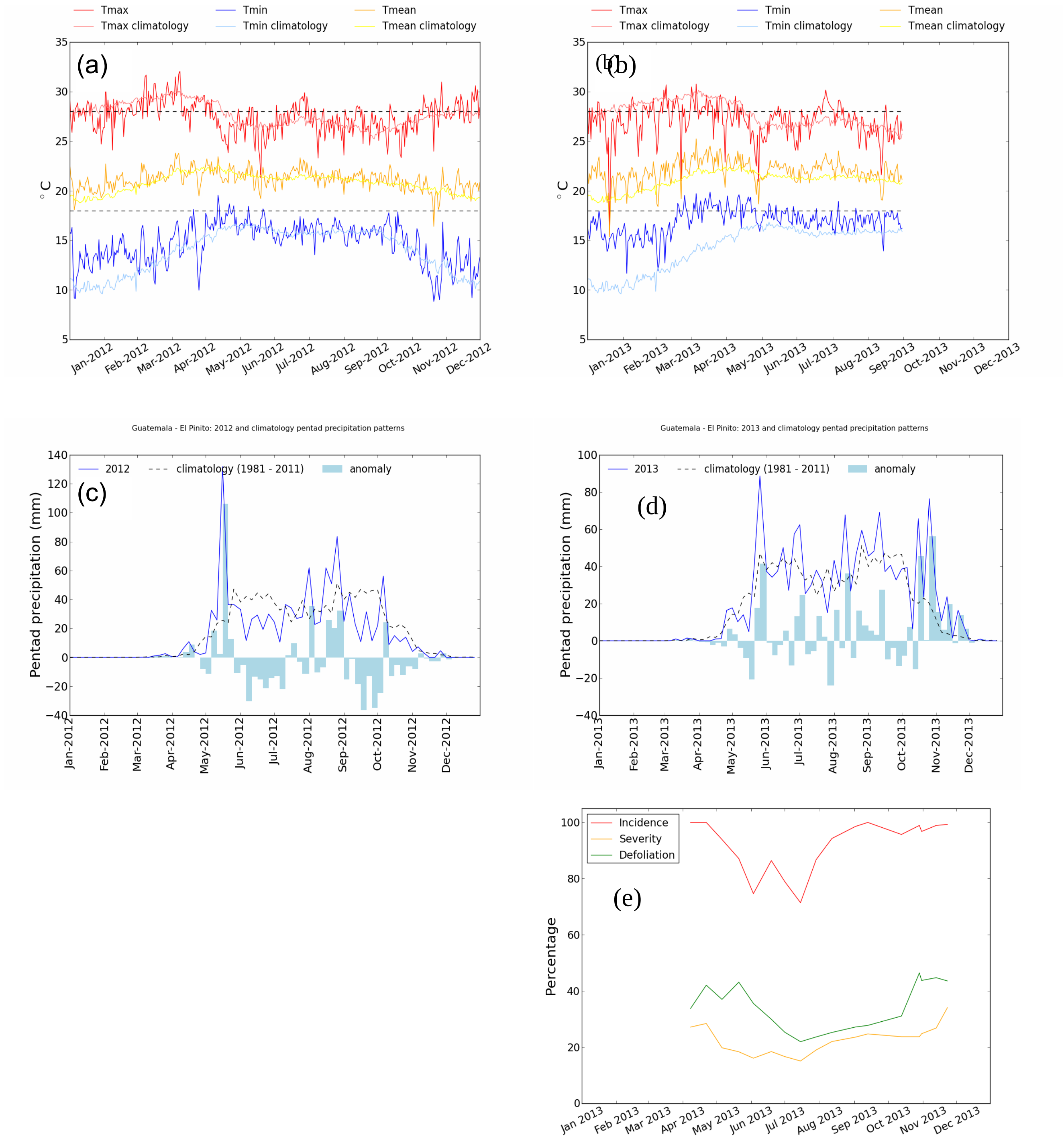


Figure 5.4.7. El Pinito, 1354 m elevation, 2012 rust severity = 2.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values over-plotted.
(e) 2013 coffee rust incidence, severity and leaf defoliation.

In this case there were earlier peaks in the rainfall seasonal maximums (figure 5.3.6), providing a source of moisture to the coffee leaves from earlier in the season. As in the previous two case studies, the minimum temperature was higher during the dry season than the climatological average for both 2012 and 2013. The maximum temperature was also lower in both years, enabling the threshold criteria to be better met for lesion development. In 2013 the observed incidence of coffee rust was again high from the start of the observed period. This indicates that the weather prior to this period is an important consideration. This factor may be particularly important for the development of a coffee rust indicator for farms above 900m elevation.

Case study 7 – La Soledad y Anexo (1443m elevation)

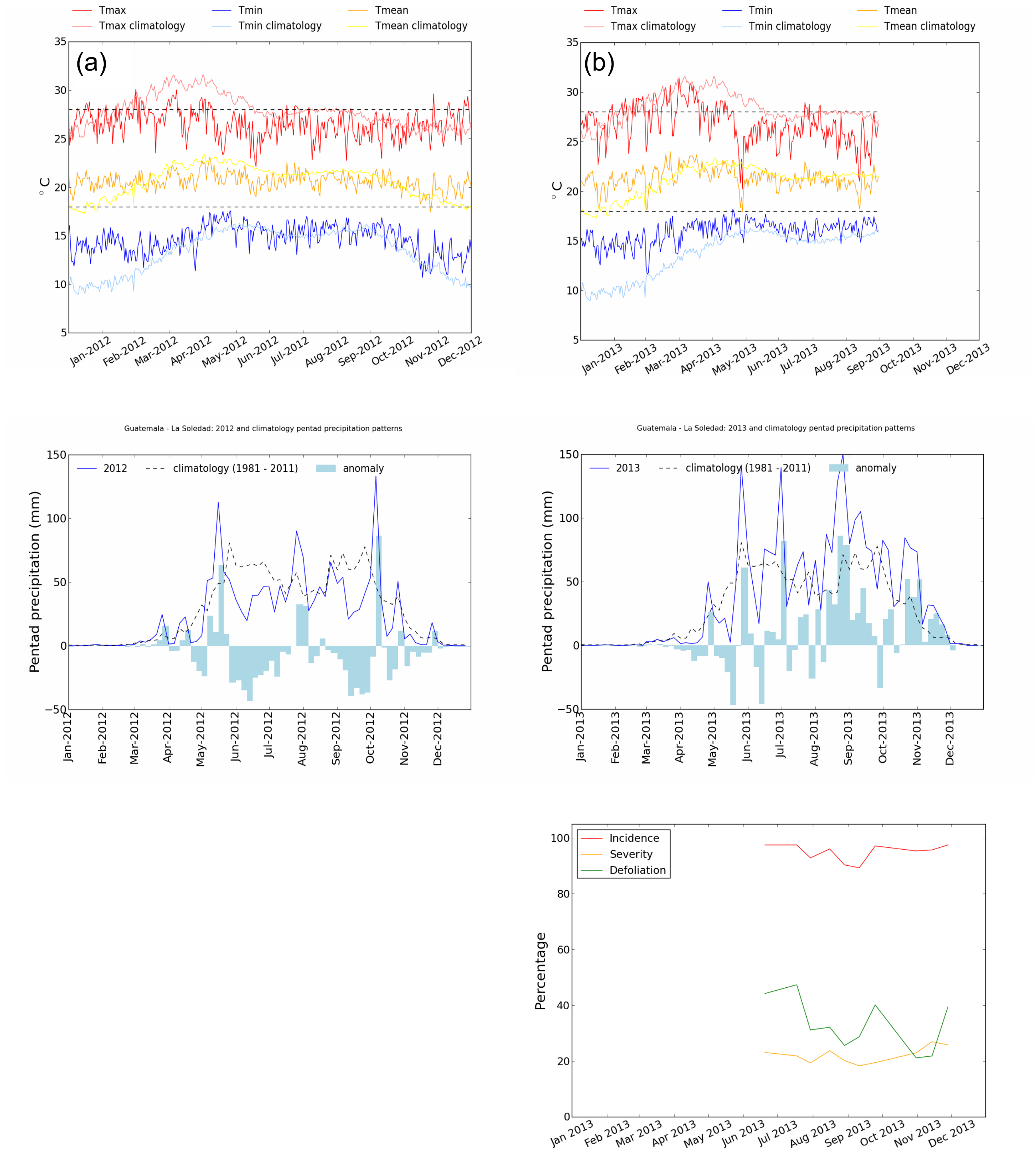


Figure 5.4.8. La Soledad y Anexo, 1443 m elevation, 2012 rust severity = 4.
(a) and (b) 2012 and 2013 respectively - minimum, maximum and mean temperature profiles with the threshold range for coffee rust and the climatology data over-plotted.
(c) and (d) 2012 and 2013 pentad precipitation anomaly from climatology (bars) with the actual values over-plotted.
(e) 2013 coffee rust incidence, severity and leaf defoliation.

La Soledad y Anexo is the highest elevation farm included in the case study analysis. There were negative anomalies in the maximum temperature data for the period February to September 2012. During the dry season there was a high positive anomaly for the minimum temperature, resulting in increased mean temperatures during this period, as with El Pinito farm which is at a similarly high elevation. There is a negative anomaly for the precipitation during much of the 2012 rainy season. However, there was an earlier start to the rainfall season, with a positive rainfall anomaly in the period March to April. This farm was affected by the lowest category of rust. It is rarer for such high altitude farms to be badly affected by coffee rust due to the lower temperatures, and the necessary minimum temperature that's conducive to coffee rust lesion development not being met.

Summary of the case study analysis and potential indicators for coffee rust disease

- An early start to the wet season (e.g. figure 5.4.8) can provide additional moisture to the coffee plants for an extended period, and lead to an early start of the epidemic. The success of the epidemic depends on the application of fungicide before the coffee rust increases. Fungicide applications can be too late with respect to an unexpected early start to the epidemic, resulting in little control over the coffee rust's development.
- At elevations between 500 and 700m, coffee rust incidence reacts quickly to increases in rainfall accumulations.
- There were very high positive anomalies in the minimum temperature observed during the dry season in both 2012 and 2013 at the highest elevation case study locations (> 1300 m), bringing the mean temperature within the optimum threshold range for coffee rust lesion development.
- Comparisons between the positive anomalies in the minimum temperature during the dry season and the coffee rust incidence in 2013 show that this anomaly can lead to a high incidence of coffee rust being observed early in the wet season.
- Mean temperatures of between 22 and 24.5^{0}C may provide optimal heat accumulation for the development of coffee rust. This is in agreement with the range
- specified by Nutman and Roberts (1963) of minimum/ maximum temperatures of 18/ 28^{0}C respectively (figure 4.4).
- Increases in the minimum and decreases in maximum temperature correspond with an increased likelihood of the optimal temperature thresholds being met.

5.5 Rust severity distribution with altitude

The distribution of the 2012 rust severity with altitude was analysed for the 1224 farms between 400 and 1800m elevation. Table 2.2 provides qualitative descriptions of the rust severity associated with each category. An initial overview of the overall farm distribution with altitude for all rust categories, including farms which experienced low impacts, is shown in figure 5.5.1(a). Figure 5.5.1(b) shows the distribution with altitude of the more heavily affected farms (rust categories 2 to 4). By comparison between these two figures it can be seen that for farms above 1400m there is a drop in rust severity. There are peaks in the number of farms affected by severe rust between 1000 and 1400m altitude.

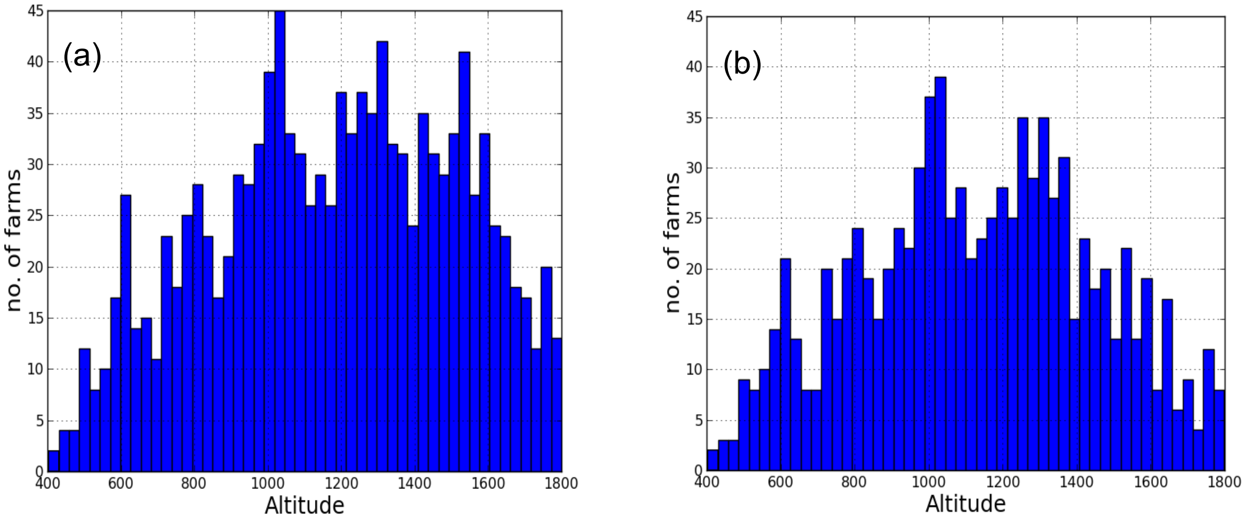


Fig 5.5.1. The distribution of (a) all rust severity categories (1 to 4) across the 1224 farms and (b) rust categories 2 to 4.

Figure 5.5.2 shows the farm distribution with altitude for each of the individual rust categories. The distribution for rust category 1 (low impact) is fairly low and evenly spread below 1400m altitude, and has a peak at around 1500m. By comparison between figure 5.5.1(a) and figure 5.5.2(a), the largest percentage of farms affected between 1400 and 1800m is characterised by category 1 severity rust. The distribution at this elevation range is also similar in shape. This is also the case for farms that experience other levels of rust severity within this altitude range (comparison between figure 5.5.1(a) and figures 5.5.2 (b) to (d). This indicates that farms in the range 1400 to 1800m altitude can be treated as being similar with regards to how changes in weather affected coffee rust development in 2012. The distribution for low to medium impact rust (category 2) has its main peak at around 1300m, and there are many farms that fall into this category between 900 and 1350m. Rust category 3 has its main peak around 1000m and a high distribution between 700 and 1400m. It is clear that the histogram peaks are shifting to lower altitudes with increased rust severity. The overall pattern for the majority of farms is that the level of rust severity varies inversely with altitude.

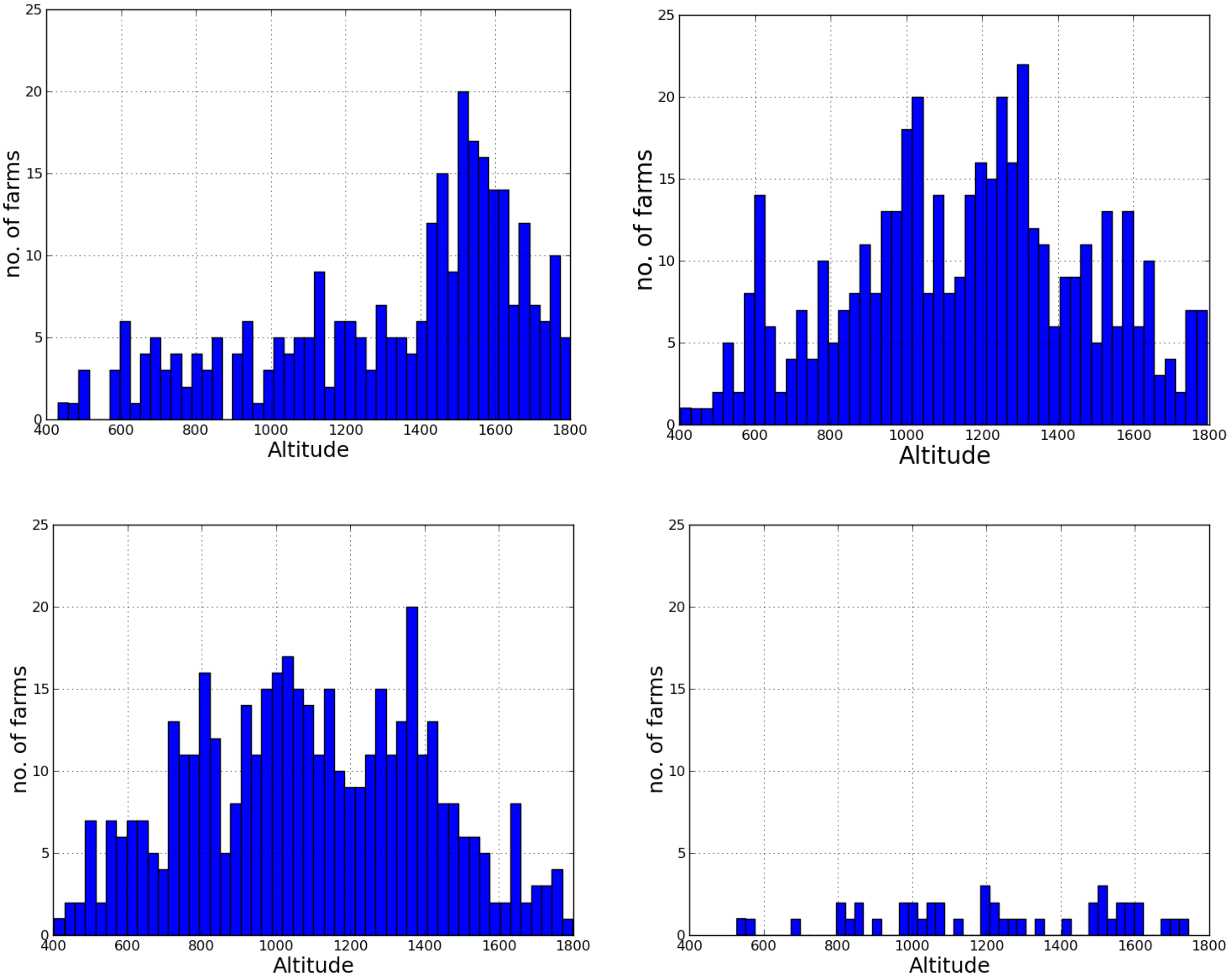


Figure 5.5.2. The distribution of farms for each of the rust severity categories.

Only 43 out of the 1224 farms experienced the most severe level of coffee rust (category 4). The distribution for this category is fairly spread out between altitudes. It is of interest to note that approximately 40% of category 4 rust assessments were made at farms between 1400 and 1800m elevation. This is significant as farms at these altitudes have not historically been affected by coffee rust due to having lower temperatures.

Figure 5.5.3 shows the distribution of farms with rust severity within defined altitude categories. The general pattern observed is that rust severity varies inversely with altitude, with the highest proportion of low severity rust (category 1) at elevations above 1400m. The Chi-square statistics were calculated for this distribution, and it was found that there's less than a 0.001% probability that the observed relationship could be a consequence of chance alone (further information about the calculation of the Chi-square statistic is provided in section 5.6.1).

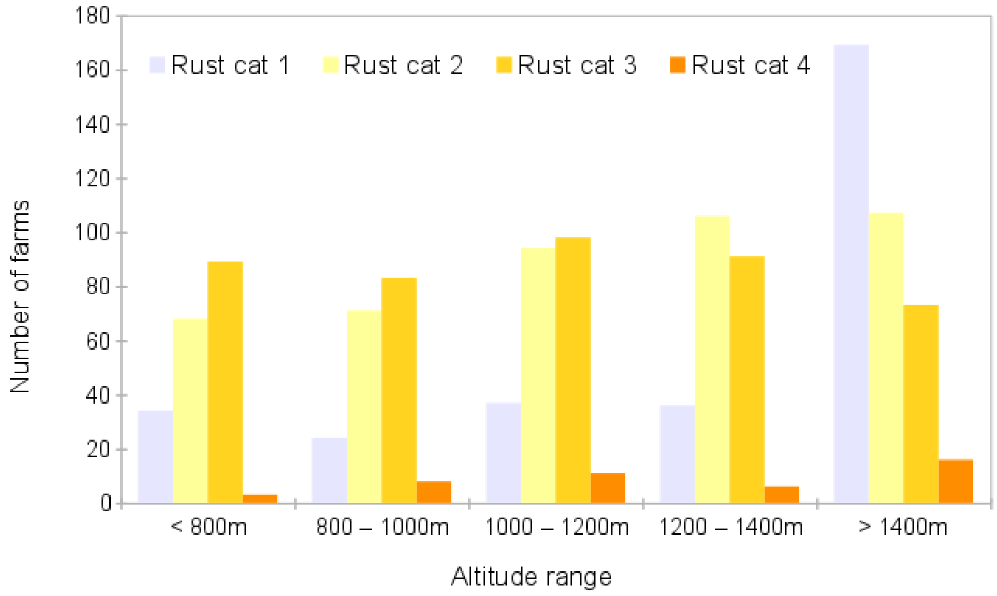


Fig 5.5.3 The distribution of farms with rust severity within defined altitude categories. The Chi-square statistic for this distribution is 153.5, and the p-value is < 0.00001. There are too few farms that experienced category 4 rust for conclusions to be drawn from their distribution with rust category.

Summary of rust severity with altitude analysis:

- The overall pattern for the majority of farms is that the level of rust severity varies inversely with altitude.
- Farms between 1400 and 1800m altitude were similarly affected by weather (and possibly other) factors that led to occurrence of coffee rust at these altitudes.
- Farms that experienced high rust severity were found at all altitudes, including above 1400m, which breaks from previous understanding that these locations are too cold to support the development of coffee rust.
- Farms with rust severity category 4 are rare at all altitudes, and it is therefore

difficult to derive correlations between the weather conditions and this category of rust severity.

5.6 Seasonal analysis

To assess the impact of accumulated heat in relation to the severity of coffee rust, the temperature data was accumulated over the periods:
(i) Dry season - January 1st to March 31st
(ii) Wet season - April 1st to December 31st

5.6.1. All data analysis

The temperature accumulation was calculated using daily temperature data at the 1224 farm locations for the dry and wet seasons. Figure 5.6.1 shows the correspondence between rust category and mean temperature accumulation. For both seasons, there is a direct correlation between rust category and accumulated temperature (indicated by the density of farms that experienced each rust category).

The Chi-squared statistical test is a non parametric test and provides a measure of the likelihood of variables to be related. It's calculated as:

$$X^2 = \sum \left(\frac{(observed - expected)^2}{expected} \right)$$

The larger the X^2 value, the more likely that the variables are related. The p-value is the probability that the deviation of the observed value from the expected can be the result of chance alone. The relative standard used here for comparison is $p > 0.05$, which means that any deviation is the result of chance alone only 5% or less of the time.

A Chi-squared statistical test (X^2) was carried out for the minimum, maximum and mean accumulated temperatures using both the dry and wet season data (table 5.6). In this case, the relationship between accumulated temperature and rust category are being tested. It was found that for each of the tested parameters, the p-value was less than the required criteria for significance (0.05). This confirms that there is a relationship between accumulated temperature and rust severity. This relationship is most evident for the minimum and mean temperature data, which have very large X^2 statistics. This is to be expected as these parameters experienced the largest anomalies from the climatological data. All parameters tested have p-values of less than 0.00001 for both seasons (i.e. less than a 0.001% probability that the variation could be due to chance alone).

Table 5.6 X^2 statistical test results to demonstrate the relationship between rust category and the minimum, maximum and mean accumulated temperatures during the dry and wet seasons. Significance is at $p < 0.05$.

Accumulated parameter	**X^2 statistic**	**P-value**	**Related? (p <0.05)**
Min T (Jan to Mar)	113.3	< 0.00001	Yes
Min T (Apr to Dec)	128.2	< 0.00001	Yes
Max T (Jan to Mar)	76.2	< 0.00001	Yes
Max T (Apr to Dec)	93.6	< 0.00001	Yes
Mean T (Jan to Mar)	135.1	< 0.00001	Yes
Mean T (Apr to Dec)	115.4	< 0.00001	Yes

This relationship between accumulated temperature and rust severity indicates that sustained increases in daily temperatures, when compared with the climatology, could indicate an increase in the likelihood of a farm to experience more severe coffee rust than in the past. Increased minimum temperatures were observed at high altitude stations (>1200m) in 2012, particularly during the dry season. This will have resulted in increased temperature accumulations, perhaps shifting the farm location to within a hypothetical optimal accumulated temperature threshold, such that these high altitude farms became more predisposed to the development of coffee rust. This effect should also be considered in combination with changes in the rainfall patterns and accumulations.

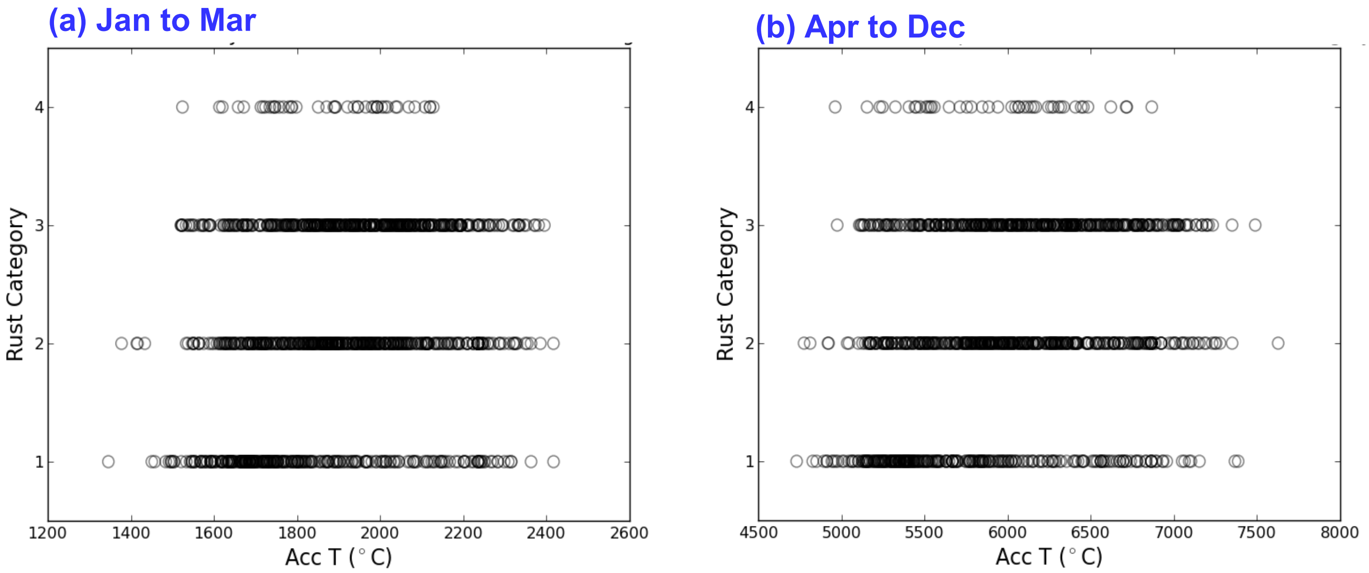


Fig 5.6.1. Correspondence of rust categories 1 to 4 with accumulation of mean seasonal temperatures at each farm for the dry and wet seasons. Blue bars show the accumulated temperature range with a dense population of farms for that particular rust category.

Figure 5.6.2 shows the overall normalised histograms for the climatology and 2012 data during each season. These examples were calculated over all rust categories for the accumulated minimum temperature. Minimum temperatures have been highlighted in this example as the largest anomalies were found in these values during the 2012 dry season, and these anomalies may contribute usefully to the development of an indicator for coffee rust disease. Probability distribution functions (PDF) have been applied to each histogram.

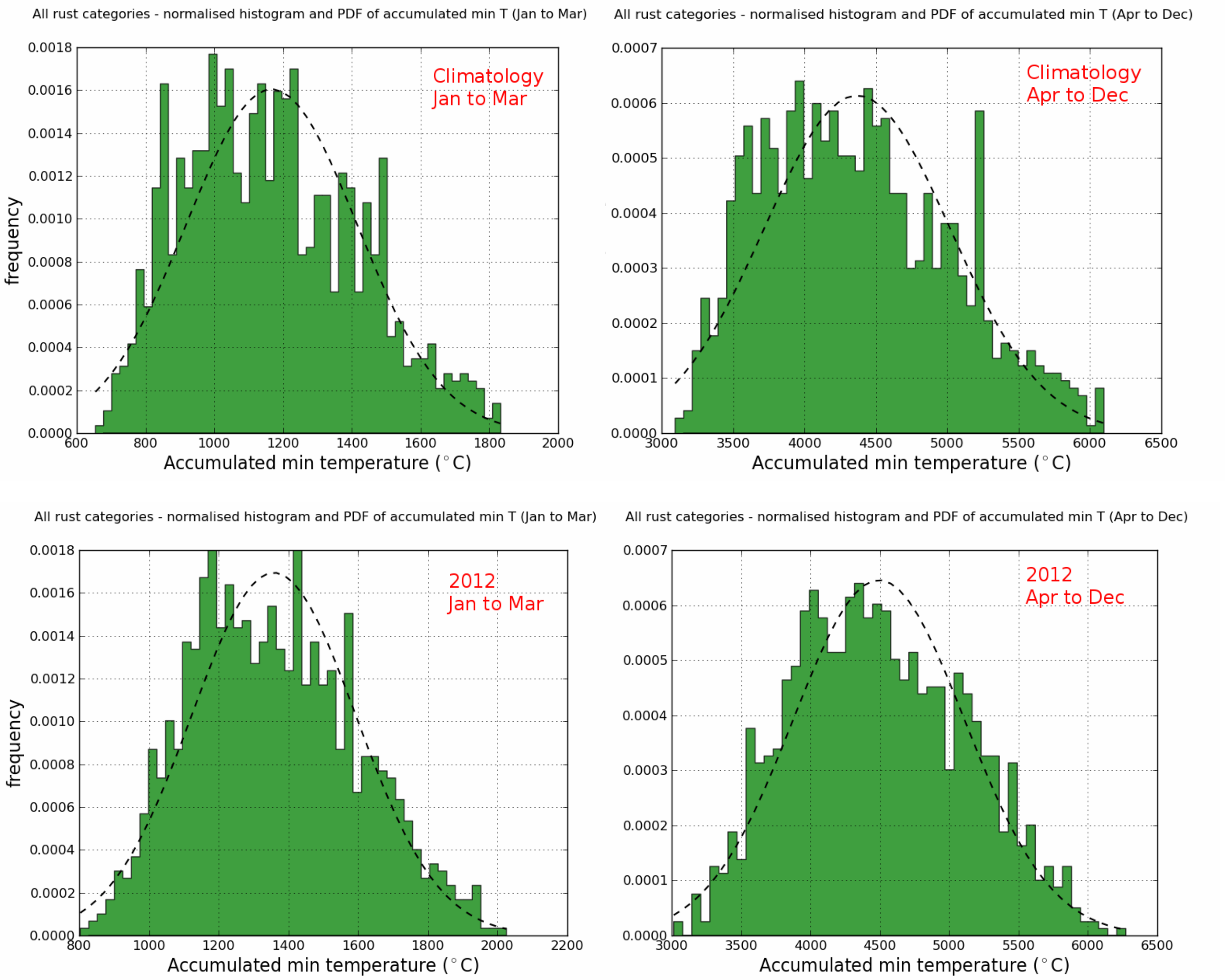


Fig 5.6.2. Normalised histograms and over-plotted probability density function for the climatology and 2012 accumulated minimum temperature data over all 1224 farms and for all rust categories.

For the minimum temperature parameter, the climatological peak of the PDF is around 1150^{0}C temperature accumulation in the period January to March. The 2012 value is ~17% higher at around 1350^{0}C. During the wet season, the accumulated peak values are 4400^{0}C for the climatology and 4500^{0}C for the 2012 data, a difference of only around 2%. This assessment includes farms that experienced low impact rust severity. Figure 5.6.3 shows the same information, specifically for farms that experienced rust of category 3 severity. In this case, the accumulated minimum values for the 2012 dry season were approximately 14% higher than for the climatology, and ~4% higher for the wet season.

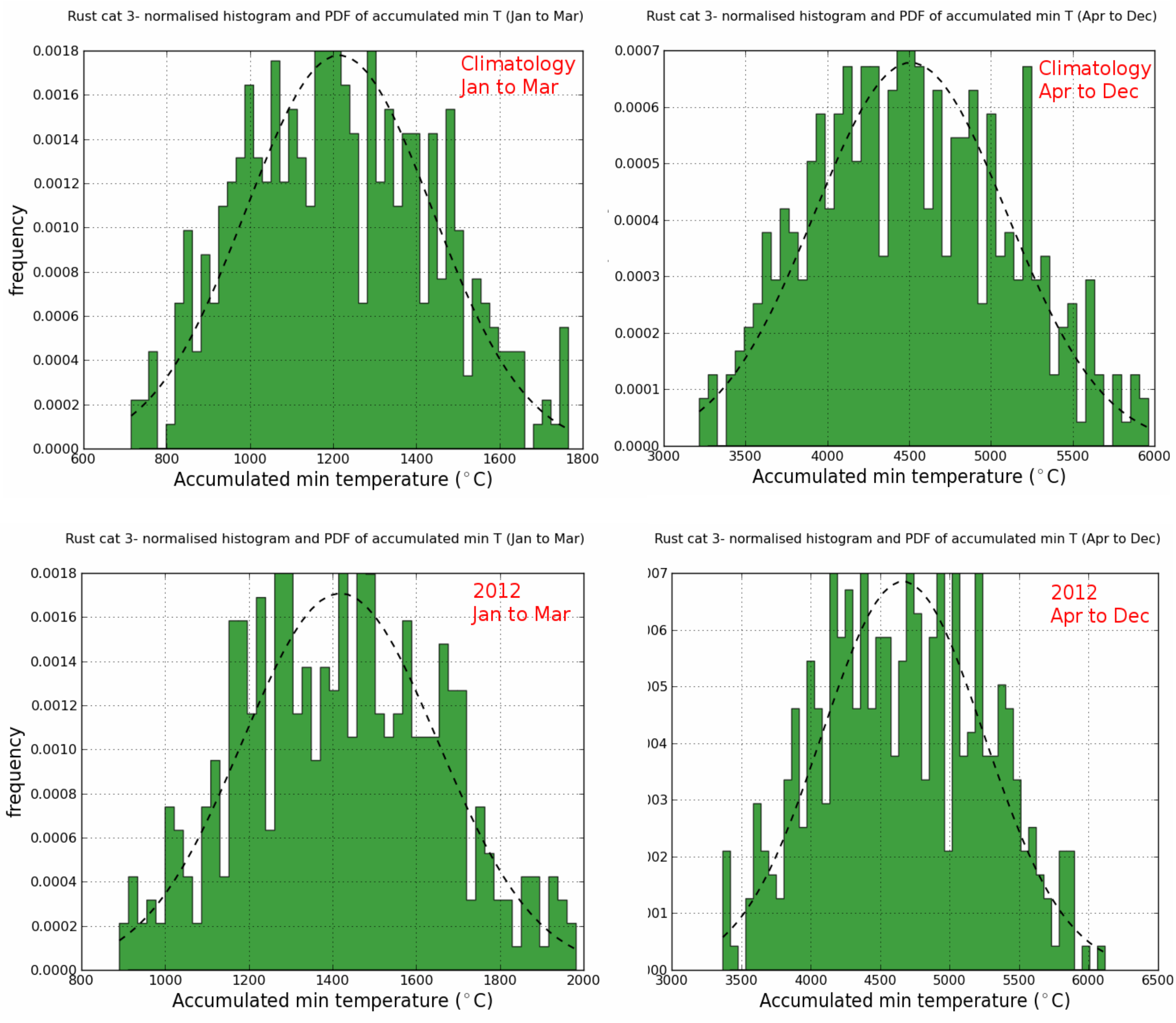


Fig 5.6.3. Normalised histograms and over-plotted probability density function for the climatology and 2012 accumulated minimum temperature data over farms that experienced coffee rust of severity 3.

Figure 5.6.4 shows the correspondence between the number of farms that were affected within each rust category and the accumulated minimum, maximum and mean temperatures for 2012. These graphs should be considered in conjunction with the corresponding Chi-square statistics shown in table 5.6. We can see generally a decrease in the proportion of farms experiencing rust category 1 (the mildest impact) with increasing temperature accumulation, and conversely an increase in the proportion of farms experiencing category 2 and 3 rust.

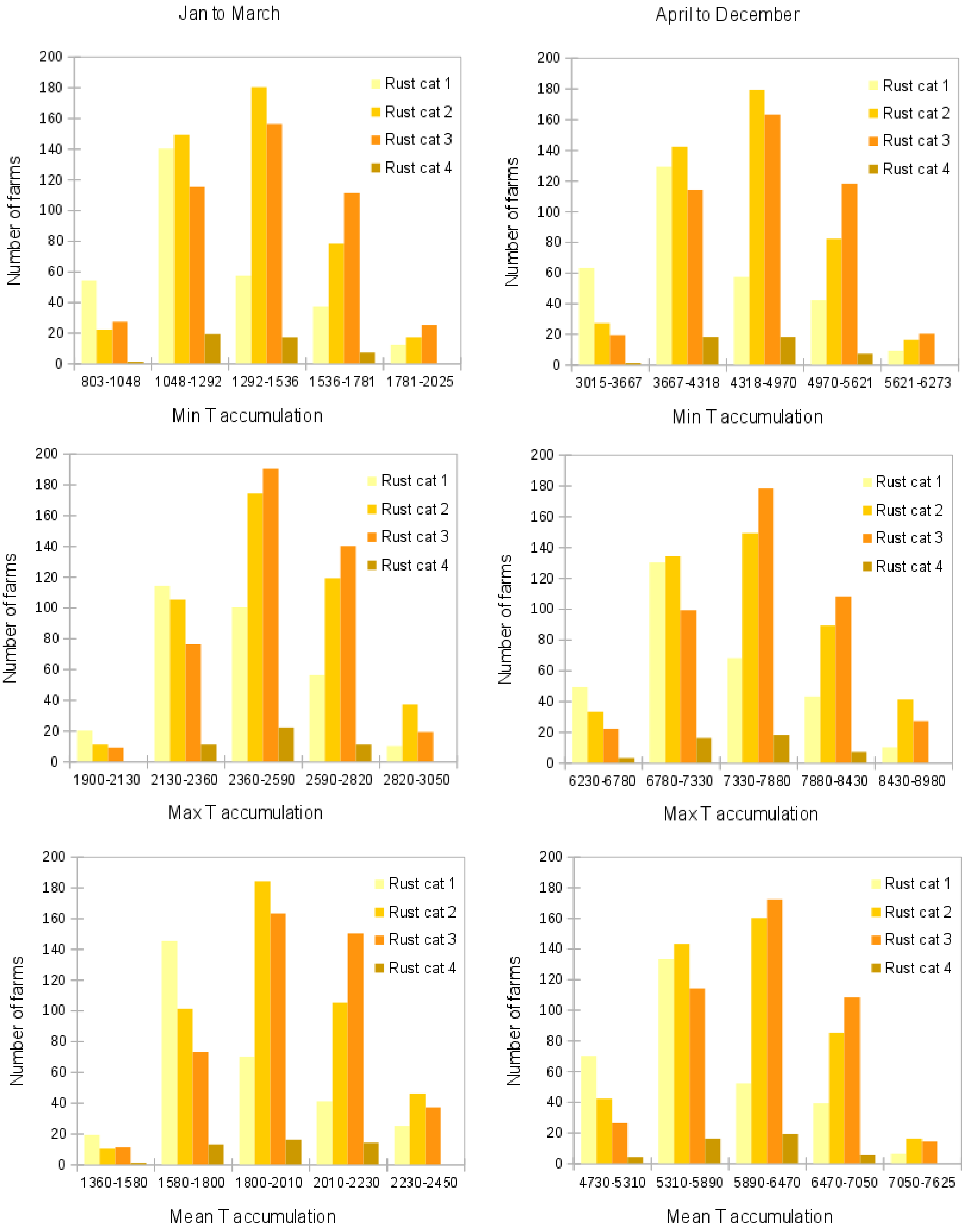


Figure 5.6.4 The number of farms that experienced each level of rust severity, categorised by minimum (top), maximum (middle) and mean (lower) accumulated temperatures, and for the dry season (left) and wet season (right). In all cases the p-value associated with the Chi-square statistic is less than 0.0001.

It can be seen that at lower temperature accumulations, higher altitude farms are still affected within the highest rust severity categories. This indicates that there are additional factors that it is important to consider when determining the vulnerability of a farm to coffee rust disease.

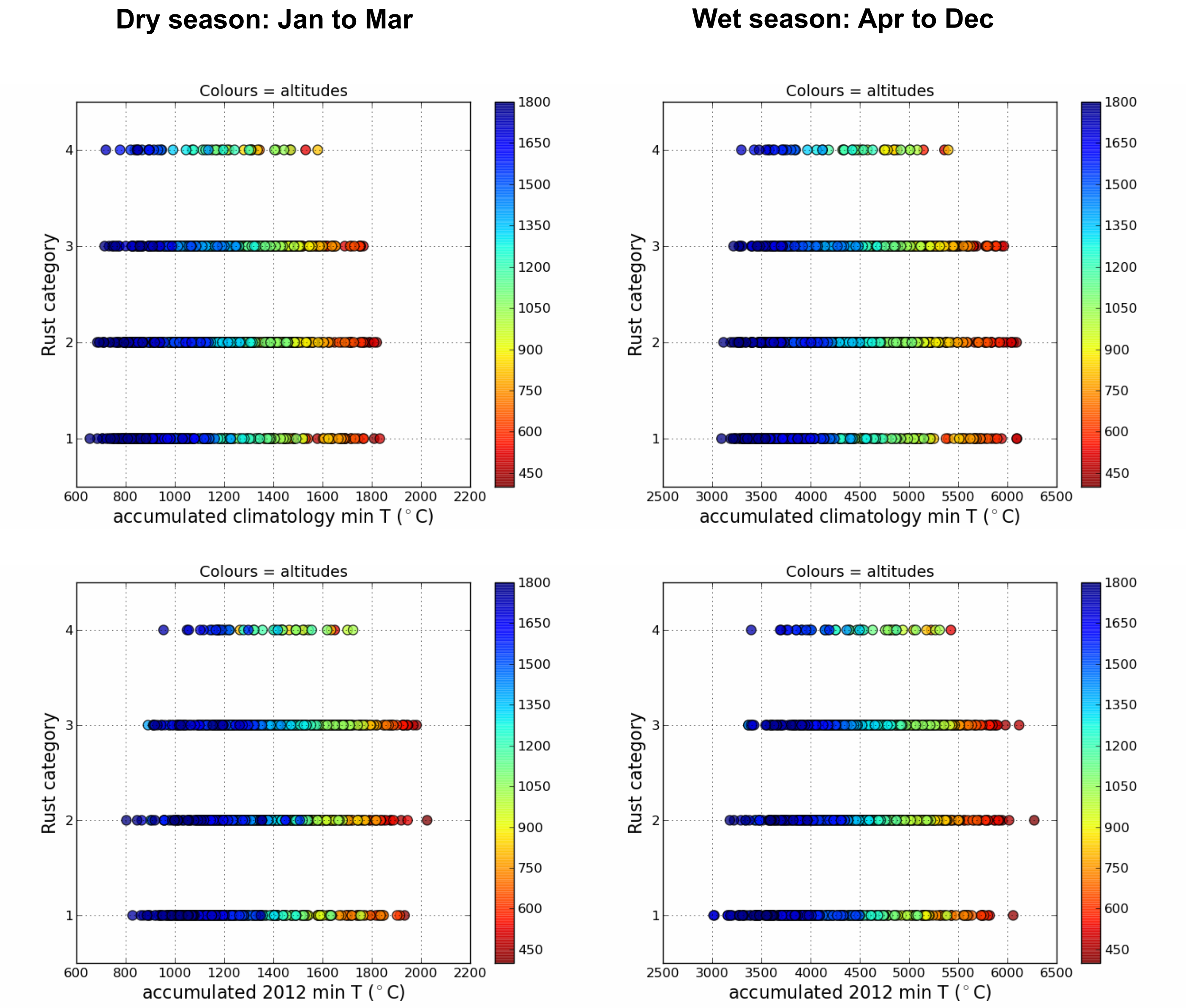


Figure 5.6.5. Correspondence between the number of farms that were affected within each rust category and the accumulated minimum temperature for the climatological data (top and 2012 data (bottom).

Figure 5.6.5 shows the correspondence between accumulated minimum temperature and rust category for both the climatological and 2012 data. With reference to the wet season skew between rust severity levels in the accumulated minimum temperatures for the climatology data (fig. 5.6.5 – top right), there is a slight skew to higher accumulated temperatures with increased rust level. This is believed to be due to some farms that experienced rust categories 2 to 4 in 2012 being more predisposed due to their locations or other contributing factors. However, this skew is small in comparison to that observed during the 2012 wet season for each rust level (the minimum temperature accumulations for the same farms are indicated for each rust category).

From these plots, it's also clear that higher altitude farms were far more affected by increases in minimum temperature than low altitude ones (point colour indicates the altitude). This is indicated by the lack of increase in accumulated temperatures at the higher end of the range for each rust level. This difference in range of accumulated temperatures with the climatological average range could be useful for defining an indicator for coffee rust disease related to average change in minimum temperature accumulation, particularly for higher elevation farms.

5.6.2 Filtered data

The accumulated mean temperature data was then filtered using the following temperature threshold criteria (see section 4.5 for further background):

maximum temperature, $Tmax \leqslant 28^{0}C$

and minimum temperature, $Tmin \geqslant 18^{0}C$

This temperature range represents the optimum conditions for the formation of coffee rust lesions on the leaf of the plant (Nutmann and Roberts, 1963). Additionally, the data was weighted according to the curve equation method described in section 4.5, to account for the biological response to air temperature.

Figure 5.6.6 shows how the variations in altitude and rust severity (point size) at the filtered farms vary with accumulated temperature. Use of the filtering and weighting method results in a clearer signal than applying the analysis over all farms. Using this approach, it is observed that some of the most severely affected farms exist in the areas with the highest weighted accumulated temperatures. By analysis of the wet season plot (April to December) in figure 5.6.5, it can also be noted that the farm locations that best suited the optimal conditions for rust development in 2012, according to these weighted criteria, are sited at between 900 and 1100m elevation. For 2012 data, there is a peak around 1000m altitude in the number of farms that optimally meet both the temperature range and weighting criteria.

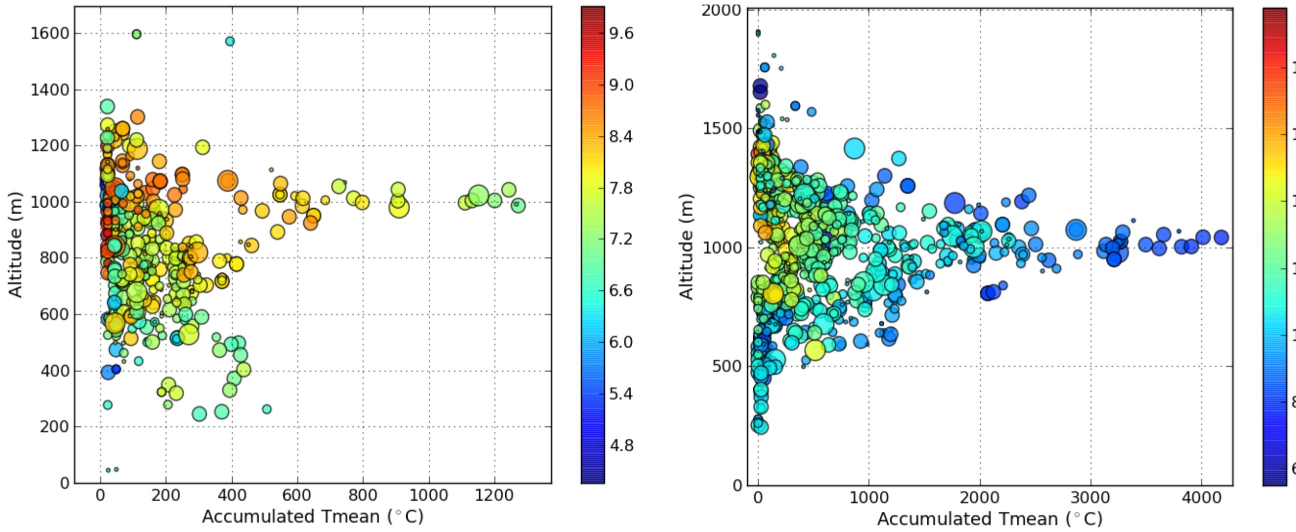


Figure 5.6.6 Variation in 2012 accumulated mean Temperature with altitude for filtered and weighted data. The colour bar relates to the diurnal temperature difference, and the point size to the rust severity.

Referenced by the colour bar in figure 5.6.6 is the average diurnal temperature range over the two seasonal periods. It can be seen that in the dry season period, the filtering and weighted criteria are optimally met when the diurnal temperature range lies between 7 and 8^0C. During the wet season period, these criteria are optimally met when the diurnal temperature range lies between 8 and 13 degrees. Diurnal temperature range should additionally be considered for use as a combined indicator in assessing the likelihood of a farm to be affected by coffee rust.

5.7 2012 statistics corresponding with the seasonal analysis

The anomalies between the seasonal temperatures in 2012 and the climatological data are described in table 5.7.1. These were calculated using the seasonally averaged temperatures over all farms for the dry season period, Jan to March, and the wet season, April to December. There was a large increase in the average minimum temperature during the dry season of 16.2% and a smaller increase during the wet season of 2.8% (table 5.7.1a), while there were negative anomalies in the average maximum temperature of -4.8% and -4% during the dry and wet seasons respectively (5.7.1b). As a result of the larger positive anomaly in the minimum temperature during the dry season, and conversely the larger negative anomaly in the maximum temperature during the wet season, an increase in the mean temperature averaged over the 1224 farms of 1.7% was observed for the dry season and a decrease of 1.6% during the wet season. The diurnal temperature difference was reduced significantly as a result of the increased minimum temperatures (5.7.1d) with negative anomalies of 21.7% during the dry season and 12.8% during the wet season.

At higher altitudes, the positive minimum and mean temperature anomalies would bring the temperature at farm locations into a range that is more commonly observed at lower elevation farms. Additionally, at lower elevation farms (< 1000m), the negative anomaly in the maximum temperature would also act to bring the maximum temperature to within an optimal range that is suitable for the development of coffee rust lesions. A decrease in the diurnal thermal amplitude (table 5.7.1d) means that temperatures were often close to the optimum temperature for coffee rust. In section 5.4, the case study analyses described how coffee rust incidence appears to respond to increased dry season rainfall, and increases in the mean temperature during the same period, perhaps by means of increasing the plant's susceptibility to the disease rather than initiating lesion production. Taking this into consideration, higher elevation farms are likely to have been more prone to experiencing the effects of coffee rust than usual due to these anomalies. There were also similar positive biases in the mean precipitation recorded for the dry season. This increased precipitation during the dry season indicates that there was increased moisture availability to the plant at an earlier point in the season than usual. This is likely to have been one of the contributing factors for farms which experienced an earlier onset of rust development.

Table 5.7.1 Seasonal 2012/ climatology temperatures averaged over all 1224 farms and corresponding anomalies (standard error < 0.04).

(a) Average minimum temperature

Parameter	Jan to Mar	Apr to Dec
2012	14.91	16.34
climatology	12.83	15.89
anomaly	2.08	0.45
% anomaly	+16.21%	+2.83%

(b) Average maximum temperature

Parameter	Jan to Mar	Apr to Dec
2012	27.37	27.34
climatology	28.74	28.50
anomaly	-1.37	-1.17
% anomaly	-4.77%	-4.07%

(c) Average mean temperature

Parameter	Jan to Mar	Apr to Dec
2012	21.14	21.84
climatology	20.78	22.20
anomaly	0.36	-0.36
% anomaly	+1.73%	-1.62%

(d) Diurnal temperature difference

Parameter	Jan to Mar	Apr to Dec
2012	12.46	11.00
climatology	15.91	12.61
anomaly	-3.45	-1.62
% anomaly	-21.68%	-12.77%

In summary, there was strong overall departure from the climatological pattern for the minimum, and mean temperatures and consequently for the diurnal temperature difference.

5.8 Monthly data statistical analysis

A statistical analysis of the monthly accumulated data was carried out for the mean, maximum and minimum temperatures. The average diurnal range over each month has also been investigated. This analysis was carried out over all farms included in the study. It's recommended that further statistical analysis is carried out by categorising the data into rust severity and altitude ranges.

5.8.1 Overall bias statistics for 2012

The overall bias with the climatology data was calculated for each parameter accumulated over monthly periods in 2012 (table 5.8.1). The monthly averaged value of the daily diurnal range over all farms is also included.

Table 5.8.1 Monthly accumulated temperature bias between 2012 and climatological data for mean, maximum and minimum temperatures, and average monthly diurnal range (standard error < 0.4 for each month and parameter).

Accumulated parameter	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temp	28	22	-5	-14	-12	-10	1	-1	-2	-10	-25	14
Maximum Temp	-26	-42	-49	-47	-56	-31	-12	-24	-13	-37	-57	-15
Minimum Temp	81	86	39	19	33	11	14	22	9	18	7	43
Diurnal range	-3.3	-4.5	-2.9	-2.2	-2.9	-1.4	-0.8	-1.4	-0.8	-1.7	-2.1	-1.9

With reference to table 5.8.1, there is an overall increase in the mean monthly accumulated temperature in January and February when compared with the climatological data. Subsequent months are characterised by negative temperature anomalies. Throughout the year there are large biases in both the maximum and minimum temperatures. The overall maximum temperatures in 2012 were lower than usual, while there were large increases in the minimum temperatures for all months.

A significant difference between the 2012 and climatological data is the negative bias in the diurnal temperature range throughout the year. Lower diurnal temperature ranges can be indicative of cloudier conditions overall, and such synoptic conditions may result in more consistent moisture availability to the coffee plants.

5.8.2 Monthly accumulations

The average monthly accumulated temperature and precipitation data was compared with the climatological accumulations (tables 5.8.2 to 5.8.5). These accumulations correspond well with the biases presented in table 5.7.1. They show that the mean monthly temperatures had a positive anomaly at the start of the year, before more closely following the climatological trend. The overall maximum and minimum temperatures follow similar monthly patterns for both the 2012 and 2013 data, with the maximum temperatures being lower throughout both years, and the minimum observed temperatures being higher than the climatological values. This indicates that farms were also at risk from a coffee rust epidemic in 2013, but the impacts were likely limited by lessons learned from 2012 and implementation of modified approaches to crop management (possibly including mitigation through earlier application of fungicide during the 2013 growing season).

Table 5.8.5 shows the average monthly diurnal temperature range. Both the 2012 and 2013 data showed similar patterns for this parameter, with a lower diurnal range observed than usual.

Table 5.8.2 Mean monthly accumulated daily temperatures averaged over all farms (^{0}C)

Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	633	611	670	676	709	669	689	691	663	659	592	627
2013	633	616	651	712	705	670	693	691	663			
Climatology	606	589	675	690	721	679	688	691	665	668	618	613

Table 5.8.3 Max monthly accumulated daily temperatures averaged over all farms (^{0}C)

Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	820	781	879	873	871	819	858	853	822	812	757	808
2013	793	791	838	893	860	808	847	846	796			
Climatology	846	823	927	919	927	850	870	877	836	849	815	838

Table 5.8.4 Min monthly accumulated daily temperatures averaged over all farms (^{0}C)

Year	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2012	447	440	461	479	547	519	520	528	503	506	427	431
2013	473	440	463	531	551	531	539	537	529			
Climatology	366	354	422	460	514	508	506	506	494	488	420	388

Table 5.8.5 Average diurnal temperature range, averaged over all farms (^{0}C)

Year	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2012	11.7	11.7	13.4	13.1	10.5	10.0	10.9	10.6	10.6	9.9	11.0	12.6
2013	10.0	12.6	11.9	12.3	9.9	9.3	9.8	10.0	8.8			
Climatology	15.0	16.2	16.3	15.3	13.4	11.4	11.7	12.0	11.4	11.6	13.1	14.4

5.8.3 Average daily parameter values for each month

The average daily parameter values are presented in tables 5.8.6 to 5.8.9. The optimal temperature range for lesion development during the wet season is 18 to 28^{0}C. At many farms, especially at lower altitudes the maximum temperature can be too high for effective lesion development, and conversely at higher elevations, the minimum temperature can be too low to meet the threshold criteria. These tables verify the 2012 pattern of higher minimum temperatures (table 5.8.6) and lower maximums (table 5.8.7) when compared with the climatology. As a result there was a negative bias in the diurnal temperature range (table 5.8.9) for all months, and many more days than usual in 2012 that met the threshold criteria for lesion development. There were only small changes in the mean temperature from the climatological average for each month (table 5.8.8) with an overall positive anomaly during the dry season, and a negative anomaly during the wet season.

Table 5.8.6 Min daily temperature for each month, averaged over all farms (^{0}C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2012	14.5	15.3	15.0	16.1	17.7	17.4	16.9	17.2	16.9	16.4	14.4	14.0
2012 Standard deviation	1.1	1.3	1.4	1.3	1.1	1.1	1.2	1.2	1.2	1.0	1.1	1.1
2012 Standard error	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Climatology	12.1	12.6	13.8	15.6	16.9	17.3	16.7	16.7	16.8	16.0	14.2	12.8
Climatology standard deviation	1.2	1.3	1.3	1.2	1.0	1.0	1.0	1.0	0.9	1.0	1.1	1.2
Climatology standard error	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Bias (2012 – Clim)	2.5	2.7	1.2	0.5	0.8	0.2	0.2	0.5	0.1	0.4	0.1	1.2

Table 5.8.7 Max daily temperature for each month, averaged over all farms (^{0}C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2012	26.6	27.0	28.5	29.2	28.2	27.4	27.8	27.6	27.5	26.3	25.4	26.7
2012 Standard deviation	1.1	1.1	1.1	1.3	1.2	1.1	1.0	1.0	1.1	0.9	1.5	1.2
2012 Standard error	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03
Climatology	27.5	28.7	30.0	30.9	30.1	28.6	28.2	28.5	28.1	27.6	27.3	27.2
Climatology standard deviation	1.2	1.1	1.0	1.1	1.2	1.3	1.1	1.1	1.1	1.1	1.2	1.2
Climatology standard error	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Bias (2012 – Clim)	-0.9	-1.6	-1.5	-1.6	-1.9	-1.2	-0.5	-0.9	-0.6	-1.3	-2.0	-0.6

Table 5.8.8 Mean daily temperature for each month, averaged over all farms (^{0}C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2012	20.5	21.2	21.7	22.7	23.0	22.4	22.3	22.4	22.2	21.3	19.9	20.4
2012 Standard deviation	1.1	1.1	1.2	1.2	1.0	1.0	1.0	1.0	1.0	0.9	1.2	1.1
2012 Standard error	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03
Climatology	19.8	20.6	21.9	23.2	23.5	22.9	22.5	22.6	22.4	21.8	20.8	20.0
Climatology standard deviation	1.2	1.1	1.0	1.1	1.0	1.0	1.0	0.9	1.0	1.0	1.1	1.1
Climatology standard error	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Bias (2012 – Clim)	0.8	0.5	-0.2	-0.6	-0.5	-0.5	-0.1	-0.2	-0.2	-0.4	-0.9	0.3

Table 5.8.9 Mean daily diurnal temperature range, averaged over all farms/ each month (^{0}C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2012	12.0	11.8	13.5	13.1	10.4	10.0	10.9	10.5	10.6	9.8	11.0	12.6
2012 Standard deviation	0.8	0.7	1.0	1.0	0.8	0.5	0.5	0.5	0.6	0.5	0.7	0.7
2012 Standard error	0.02	0.02	0.03	0.03	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.02
Climatology	15.4	16.1	16.2	15.3	13.2	11.4	11.5	11.8	11.3	11.6	13.1	14.4
Climatology standard deviation	0.6	0.5	0.5	0.5	0.8	1.0	1.0	1.0	1.0	0.8	0.6	0.7
Climatology standard error	0.02	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Bias (2012 – Clim)	-3.3	-4.4	-2.7	-2.2	-2.7	-1.4	-0.6	-1.4	-0.7	-1.7	-2.1	-1.8

5.9 Lapse rate analysis

The environmental lapse rate is the rate of decrease of air temperature as elevation increases. Variations in the lapse rate can be representative of varying synoptic conditions (this is described in more detail in section 4.4). It may be possible to derive a set of indicators relevant to the development of coffee rust, by researching how these variations correspond specifically with weather patterns in Guatemala and Central America. Initial analysis has been done within this study using the available precipitation and temperature data. Additionally, comparisons have been made with climatological data.

Figure 5.9.1 shows the variations in the daily lapse rates derived from the maximum and minimum temperature data, and the corresponding diurnal range. There was significantly greater variation in the range of each lapse rate pattern in 2013, compared with 2012.

By looking in more detail at the 2012 daily and time averaged data (figures 5.9.2 and 5.9.3 respectively), it can be seen that the diurnal lapse rate difference was significantly lower than the climatology for much of the year, apart from a period in June to August when it was higher. Overall the largest anomalies were observed in the lapse rate derived from the maximum temperature data, which was higher than the climatological value for most of the year. The greater the lapse rate, the greater the decrease in temperature with elevation. Larger maximum temperature lapse rates are generally associated with warm air masses. In the period January to June, the lapse rate associated with the minimum temperature was lower than the climatology. Previous studies have linked lower minimum temperature lapse rates with drier air masses.

Tables 5.9.1 and 5.9.2 show how the lapse rate varies between months and seasons (dry/ wet) respectively. With reference to table 5.9.1, it can be seen that there is significant variability between months for both the maximum and minimum lapse rates. The lapse rate is lower during the months with higher rainfall. This is related to the effects additional of cloud cover during the rainy season. In addition to inter-seasonal differences, there are also significant differences between the lapse rates associated with the minimum and maximum temperature data.

The links between lapse rate and synoptic conditions are tenuous and it's recommended that some further investigation is carried out, to determine how variations in the lapse rate are linked with synoptic conditions in Central America. Such a study would require more detailed information about the synoptic conditions for a number of case study events. Lapse rate variations have the potential to be a useful indicator for determining moisture availability to the crop.

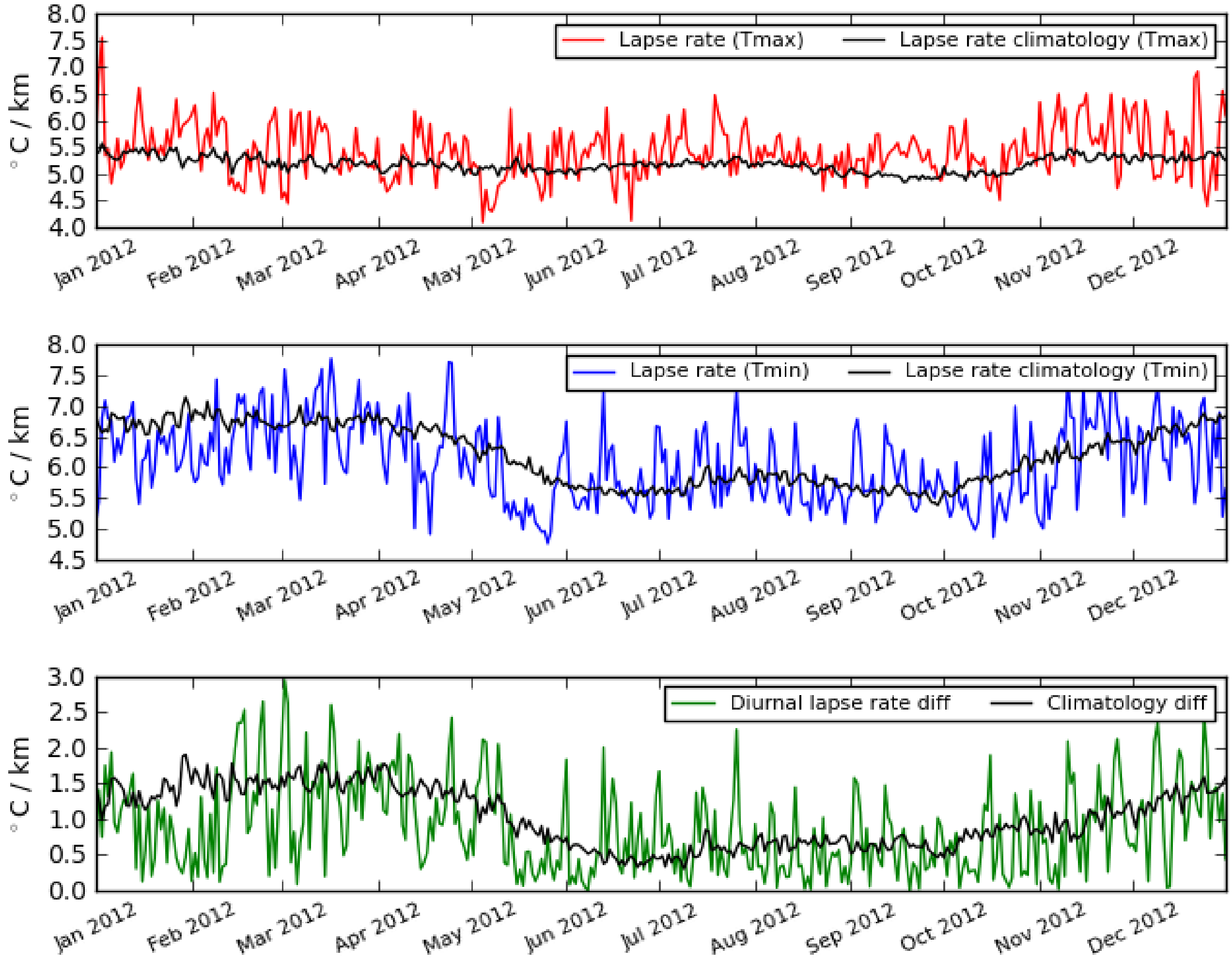


Figure 5.9.1 The daily environmental lapse rates in 2012 compared with the climatological data.

Table 5.9.1. 2012 and climatological monthly environmental lapse rates and their anomalies for the Guatemalan region

	Monthly lapse rates (^{0}C/km)												
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
2012 min lapse rate	-6.32	-6.47	-6.71	-6.35	-5.61	-5.74	-5.59	-5.65	-5.83	-5.62	-6.41	-6.32	**-6.05**
2012 max lapse rate	-5.73	-5.48	-5.39	-5.33	-5.03	-5.27	-5.24	-5.28	-5.32	-5.29	-5.77	-5.55	**-5.39**
2012 max - min difference	0.90	1.10	1.41	1.18	0.77	0.62	0.56	0.44	0.63	0.55	0.95	1.19	**0.66**
Climatology min lapse rate	-6.88	-6.96	-6.89	-6.76	-6.20	-5.75	-5.83	-5.94	-5.70	-5.99	-6.42	-6.71	**-6.34**
Climatology max lapse rate	-5.41	-5.29	-5.21	-5.17	-5.12	-5.13	-5.20	-5.13	-4.96	-5.03	-5.34	-5.35	**-5.19**
Clim max - min difference	1.48	1.67	1.68	1.59	1.08	0.62	0.63	0.81	0.74	0.96	1.08	1.37	**1.14**
Anomaly max (2012 - Clim)	0.56	0.49	0.18	0.42	0.59	0.01	0.24	0.28	-0.13	0.37	0.01	0.40	**0.29**
Anomaly min (2012 - Clim)	-0.32	-0.20	-0.18	-0.16	0.09	-0.14	-0.04	-0.15	-0.36	-0.26	-0.43	-0.20	**-0.20**

Table 5.9.2. 2012 and climatological seasonal environmental lapse rates and their anomalies for the Guatemalan region

	Seasonal lapse rates (^{0}C/km)	
Parameter	**Jan to March**	**April to December**
2012 min lapse rate	-6.50	-5.95
2012 max lapse rate	-5.54	-5.38
2012 max - min	1.14	0.78
Climatology min lapse rate	-6.91	-6.15
Climatology max lapse rate	-5.30	-5.16
Climatology max - min	1.61	0.99
Anomaly max (2012 - Clim)	0.41	0.20
Anomaly min (2012 - Clim)	-0.23	-0.22

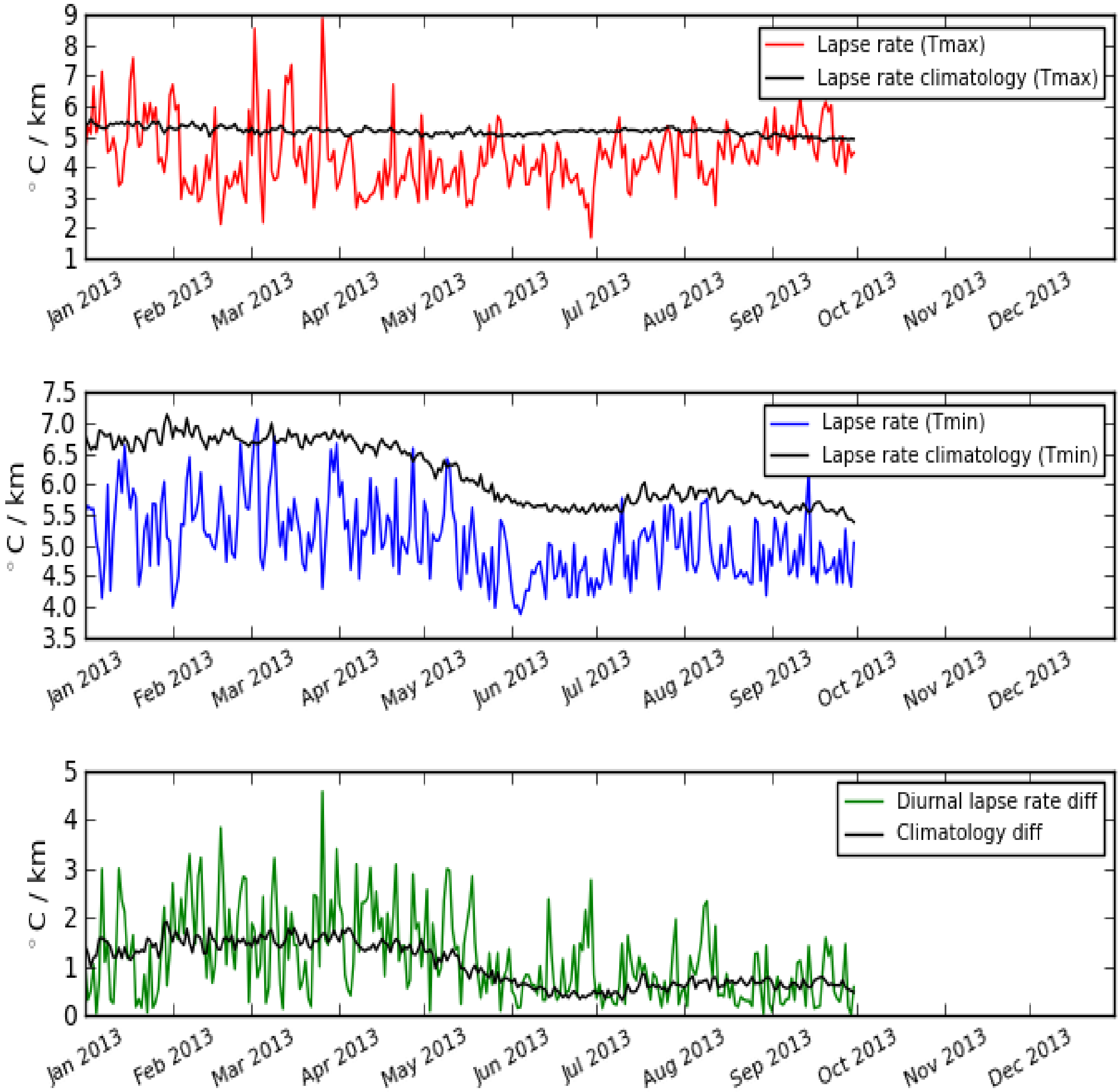


Figure 5.9.2 The daily environmental lapse rates in 2013 compared with the climatological data.

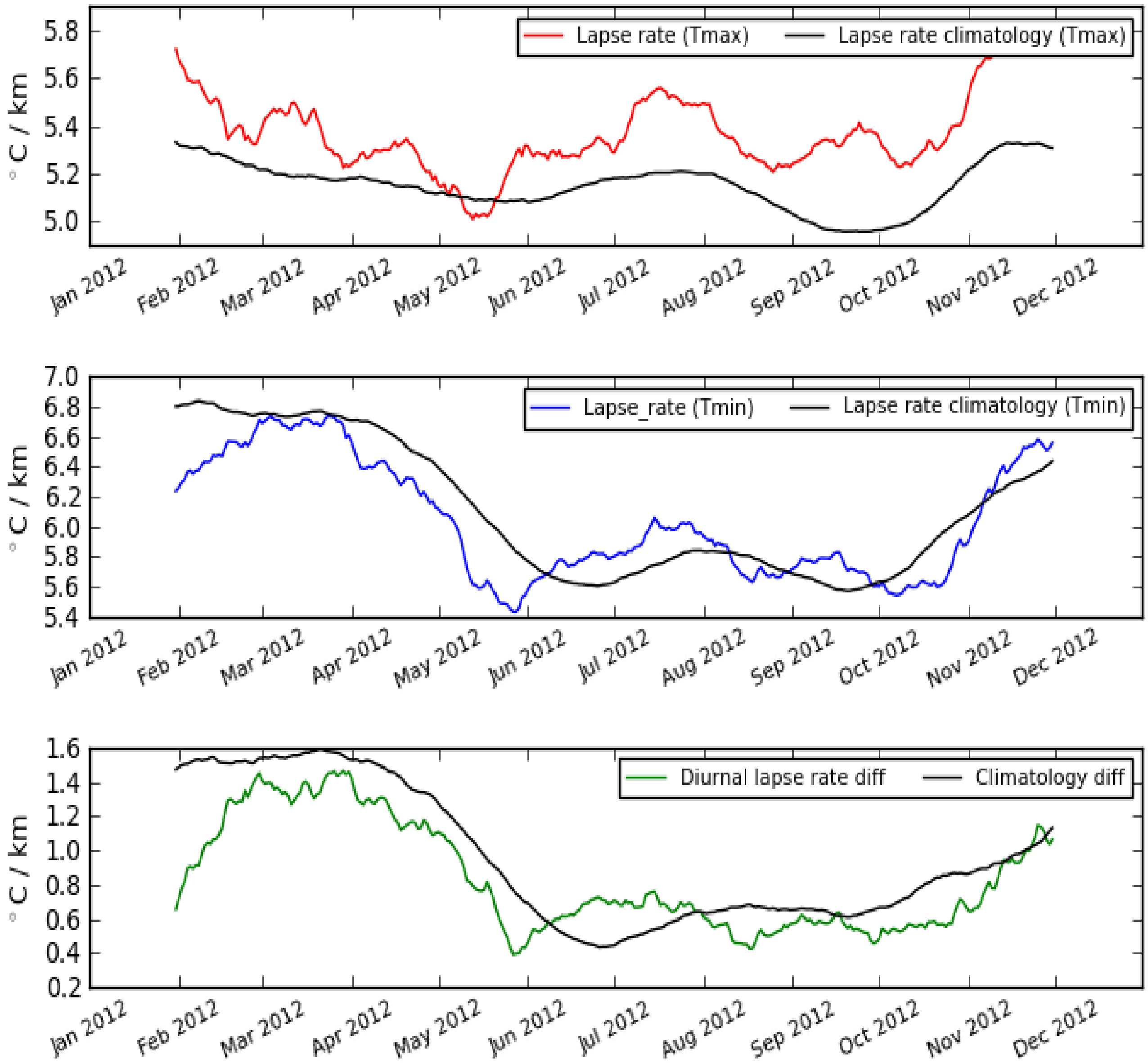


Figure 5.9.3 The 30 day time averaged environmental lapse rate data for 2012 and the climatology.

6 Results summary and conclusions

Described in this section are the key findings from the analysis, including a summary of potential coffee rust indicators, conclusions and recommendations for further work.

6.1 Summary of potential coffee rust indicators

Within this study a number of anomalies in the weather conditions from the climatological data have been considered. Described in table 6.1 is a summary of the potential coffee rust indicators derived from this study.

Table 6.1 Summary of potential coffee rust indicators derived from the analysis

Indicator	Description
1. Accumulated mean temperature	- accumulate temperatures that lie within the threshold temperature range of 18 to 28^{0}C - weight according to the phenological development of coffee rust lesions at varying temperature. - optimal usage at altitudes between 900 and 1100m (in 2012 case)
2. Diurnal lapse rate	- variations in this can provide information about the synoptic conditions and the daily precipitation pattern. - further investigation required - potential to link this parameter with moisture availability to the plant.
3. Date when larger rainfall accumulations begin	- the incidence of coffee rust closely follows increases in rainfall in many cases (see section 5.3 and appendix 2), especially at elevations between 500 and 700m, coffee rust incidence reacts quickly to increases in rainfall accumulations - coffee rust incidence is very high when the rainfall pattern begins earlier in the season than the climatological average. - this can provide additional moisture to the coffee plants for an extended time period.
4. Increased minimum temperature during dry season when compared with the climatology	- Positive anomalies in the minimum temperature during the dry season can lead to a high incidence of coffee rust being observed early in the wet season. - increased minimum temperatures enable greater heat accumulation within the range appropriate for coffee rust development or for increasing the plant's susceptibility to coffee rust development.
5. Reduced diurnal temperature range when compared with the climatology	- Lower maximum temperatures and higher minimum temperatures lead to more heat accumulation in the optimal temperature threshold range for lesion development.

6. Diurnal range thresholds	- in the dry season period, the filtering and weighted criteria are optimally met when the diurnal temperature range lies between 7 and 8^{0}C. - During the wet season period, these criteria are optimally met when the diurnal temperature range lies between 8 and 13 degrees.
7. Mean temperature	- Mean temperatures of between 22 and 24.5^{0}C provide optimal heat accumulation for coffee rust development within this analysis.

6.2 Conclusions from analysis

A number of weather and climate parameters have been assessed within this study (a summary of these is provided in table 3.1). The key finding from the analysis is that the weather conditions in 2012 displayed considerable variations from the climatological data. In general the minimum daily temperatures in 2012 were higher than the corresponding daily minimum temperature climatology. The maximum temperatures were generally lower than the climatology. The diurnal temperature range was generally lower than the climatology as a result of the higher minimum temperatures and lower maximum temperatures. These factors led to an increased number of days where the temperatures fell within the optimal range for coffee rust development during the 2012 dry season, resulting in an earlier start to the epidemic than would normally be observed. Farmers were likely unprepared for this early development of coffee rust and the need to apply fungicide earlier in the growing season than is usual, leading to the high severity impacts that were witnessed in 2012. Comparisons between the accumulated monthly and seasonal temperature data with the climatology added emphasis to the conclusion that significant anomalies existed between the climatology and 2012 data.

The coffee rust epidemic of 2012 differed from previous outbreaks in that it had an effect on the harvest in the same year. It is more common for leaf defoliation to happen after the harvest, such that the largest losses are observed in the following year. A case study analysis of farms where severe coffee rust existed has shown that particularly at low elevation farms (500 to 700m elevation) the wet season began earlier than usual. This provided additional moisture availability to the coffee leaves, and is likely to be responsible for the earlier lesion development and onset of coffee rust disease at some farms.

Through comparison of 2013 weather and climate data with time series data of the incidence of coffee rust, it was found that incidence closely follows sharp increases in precipitation. In particular, in cases where there was early onset of the wet season, the incidence of coffee rust was measured to be very high from the beginning of the climatological wet season.

A temperature threshold and weighting approach was applied to the accumulated data. From this, a positive correlation between heat accumulation and rust severity was arrived at. It was also observed that in 2012 the optimal altitude range for maximum heat accumulation was between 900 and 1100m elevation (in accordance with the threshold and weighting criteria).

A summary of key indicators has been produced as a result of this analysis, and it is recommended that these findings form the basis of a deeper analysis into how best to use each indicator, such that they can contribute usefully to producing early warnings of the susceptibility of each farm to coffee rust development.

6.3. Recommendations

The analysis within this study has resulted in recommendations for a number of potential indicators of coffee rust disease (detailed in table 6.1). Before these indicators can be implemented usefully within an early warning system it will be necessary to carry out a deeper analysis, taking into consideration the following points:

- An in depth assessment of the effects of each potential indicator at different altitudes and in different geographical locations (e.g. variation in rust severity impacts between farms located closer to the Pacific or Caribbean).
- Investigation into the optimal combination of indicators – this will generally vary with altitude.
- It is recommended that the El Niño/ La Niña analysis (section 5.2.2) is replicated using interpolated values of the station temperature data for the 1224 farm locations, and the corresponding CHIRP precipitation values for the period 1981 to

2012. The relationship between precipitation, temperature and the Oceanic Niño Index can then be examined in more detail. This could be done by separating the farms by both region to remove the bias introduced by the influence of the Caribbean/ Pacific precipitation patterns, and by altitude for a good assessment of temperature biases. This could potentially form the basis for the development of a regional specific coffee rust indicator, related to the expected seasonal weather patterns.

- It would be interesting to further develop the El Niño/ La Niña analysis by comparing the monthly temperature and rainfall values with the Oceanic Niño Index monthly values to ascertain further dependencies (section 5.2.2).
- Combine this research with other research into additional local effects that may affect the severity of coffee rust, e.g. shade, topography, aspect.
- There are some cases where farms at the same geographical location have experienced different levels of rust severity. These differences may arise due to the use of different farm management techniques, such as shading of plants, or application of fungicides. In refining a final set of indicators, it would be useful to incorporate the non-meteorological factors affecting the development of coffee rust disease.
- Creation of a rust degree day model with risk thresholds. The 2012 station and farm location data could be used to calculate how many days fitted the threshold filtering and weighting compared with the climatology.
- Investigation into the use of alternative weighting methods to apply to the accumulated temperature data. Possibly a combined temperature/ precipitation system would produce an optimal indicator at some altitude ranges.
- Further statistical analysis of the temperature and precipitation anomalies with the climatological data is also required. It would be useful to categorise the statistics according to farm altitude, rust severity and the percentage area of the coffee farm affected.
- Lapse rate anomalies from the climatology are significant, and this parameter has the potential to be a useful indicator. However, more research is required into the synoptic situations that are represented by variations in the lapse rate. It would be ideal if detailed synoptic information could be sourced for some case study locations.

- In the literature there are a number of studies that have looked at the relationship between leaf and air temperature - more consideration of this relationship should be included in subsequent analysis.
- It would also be useful to incorporate additional data into future research, possibly including the following data relevant to some case study locations:
    1. Weather data - solar radiation, humidity and wind data (especially during the dry periods).
    2. Biological data - latency periods between germination and sporulation, details of fungicide application, fruit load and inoculum residue from the previous station.
    3. Site data – soil moisture and information about shaded areas within the plot.
    4. The length of time between coffee rust plant flowering and harvesting for each different region. This could contribute to an analysis of the anomalies in this period, as related to anomalous weather conditions.

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