Coffee and climate change in the Central Highlands of Vietnam

Dr. Peter S. Baker

July 2016

Summary

Q: Has the climate changed in the Central Highlands (CH) during recent years?

A: Yes, both temperature and rainfall have changed.

Q: How has temperature changed?

A: Overall, temperatures have risen by about 0.25C/decade over the past three decades. Increases are greatest in the dry season, where 0.5C/decade is not uncommon. The reason for this differential response is not clear. At least some of the meteorological stations are situated in towns, so a heat-island effect may be operating, but this is unlikely to be the only reason.

Q: How have maxima and minima changed?

A: Minimum temperatures have risen much faster than maxima – the results from the most detailed study suggest that annual maxima are falling, perhaps due to longer spells of cloudy weather.

Q: Why are minima rising so fast?

A: This is to be expected under anthropogenic global warming: CO_2 absorbs radiation during the day and releases it at night, hence greater concentrations lead to greater warming, especially at night.

Q: So diurnal temperature range has fallen?

A: Yes and this may be detrimental for coffee and other crops, since this could favour certain pests and diseases. E.g. Coffee Leaf Rust prefers a 'not-too-hot; not-too-cool' regime that reduces periods of low humidity and hence likelihood of drying out and low temperature inhibition of the delicate germination process. This is likely to be true for other fungal diseases as well.

Q: Has rainfall increased?

A: Although there seems to be a general tendency for increased rainfall over the whole of southern Vietnam, in CH rainfall changes are mixed with no clear trends – i.e. some stations are wetter, others drier.

Rainfall has increased in almost all CH in the late months of dry season (March, April). At the end of the wet season (Oct-Nov), trends differ between north and south CH. In the north, there is a more pronounced decline in October rainfall whereas in the south there is a general increase in November.

Q: Has rainfall intensity increased?

A: Yes, as widely seen in other countries because of global warming, but there is considerable variation. The Simple Precipitation Intensity Index suggests an increase in south and east CH but a decline in the north and west. However, there are cases where stations close together display opposite tendencies, suggesting that the true situation may be highly heterogeneous and subject to local influences.

Q: Is the increase in rainfall confined to the wet season?

A: No, there seems to be some extra rainfall in the dry season. In fact the wet season is starting earlier by about 2d/decade.

Q: Why is the wet season starting earlier?

A: This is not understood.

Q: Is the earlier start, related to the monsoon season?

A: Apparently not, the monsoon onset varies widely from year to year and is affected by external factors such as ENSO **(El Niño)**.

Q: Is the rainy season therefore getting longer?

A: No, the rainy season is ending sooner at about the same rate as the onset is changing: 2d/decade.

Q: Why is it ending earlier?

A: This is not understood. It seems to be a widespread phenomenon across Indochina. It has been suggested that deforestation is responsible, i.e. that when the monsoon declines, local rainfall recycling is reduced, but this is disputed and it may well be due to external factors including changing large scale circulations and sea surface temperatures.

Q: Are droughts increasing?

A: there is no clear evidence that they are.

Q: Are the droughts related to ENSO (El Niño)?

A: There is clear evidence that the 1997 ENSO phenomenon caused widespread drought across stations. However weaker events showed little correlation with data from individual stations. Hence droughts at different points in CH seem unconnected and therefore maybe due to local causes and not due to large scale exogenous causes.

Q: What is the evidence that deforestations affect rainfall?

A: Globally there is now abundant evidence that deforestation affects rainfall. Evidence comes both from measurements and modelling. Paradoxically it has been found that moderate amounts of deforestation can lead to increased rainfall, but as deforestation area increases, eventually a decline is seen.

Q: Is there evidence about deforestation effects from Indochina and Vietnam?

A: Very little, one modelling study suggests that deforestation over Indochina has indeed affected rainfall as far away as E China and this so-called 'teleconnection' effect is reported for other parts of the world. One study in the Be River catchment recorded high deforestation and high rainfall increase – larger than expected from CH meteorology. Generally, the wide (and widening) range of CH rainfall variation (e.g. stations in the same sub region that show opposite rainfall intensity changes) is consistent with what is now understood about the climatic effects of local land use change.

Q: How serious are the climate changes seen in CH?

A: Difficult to say: on the one hand CH seems to be changing at a moderate rate compared with other parts of Indochina. On the other hand the unexplained shifts in the rainy season are perplexing and need further study. Perhaps the most worrying aspect is the strong temperature rises in the dry season that may lead to increased evapotranspiration and increased need for irrigation.

Q: How do the changes affect coffee production?

A: Increasing temperatures will tend to stress plants more in the dry season, when the increases are most pronounced. This may lead to increasing demand for irrigation. Unseasonal rainfall may make coffee drying more difficult and are likely to exacerbate the effects of pests and diseases.

Q: What measures should be taken to improve understanding of climate change in CH?

A1) A greatly enhanced system of weather monitoring, including soil humidity measurements, to evaluate the true status of climate change in CH: the few existing stations are unlikely to be capturing the full range of changes occurring. Such measurements are now more feasible thanks to the development of less expensive measurement and recording devices. This allows for the possibility of establishing a large number of sensors across the region, including forested, coffee and arable lands to measure differences that are due to land use change.

A2) Monitoring of a range of coffee agro-systems, including shade, windbreaks etc. to determine the resilience of different growing styles to climate variables; studies of evapotranspiration of these systems and the effect of irrigation would help understand what role they might play in recycling rainfall within the CH region.

A3) The climate has already been changing in CH, by about 0.75C in the past 30 years. A lot might be learnt by studying how farmers have coped in the most marginal (i.e. lowest altitude and therefore warmest) coffee areas, the extent to which they might already have moved out of coffee and the extent to which they are determined to remain as coffee farmers.

coffee & climate
enabling effective response

Table of Content

1. Rationale for this study

a) In recent years there has been a surge of studies that model how the climate may change in the future. However, global temperatures have risen by about 1C since 1950 and very few studies have looked at what might be learnt from how the climate has already changed during the past few decades – the rate of change and geographical variation and how the changes might relate to production of commodities such as coffee.

b) There are an increasing signs that governments, companies and individuals are underestimating the rate at which climate risks are increasing for agriculture and other industries.

c) Recent events in Colombia, Central America, Brazil, Indonesia and other places suggest that climate change is already negatively affecting coffee production.

d) Vietnam is the world's second largest coffee producer, with the great majority produced in the Central Highlands (CH). At 28 to 30 million 60 kg bags of production (20% of global production), CH produces about the same as the largest coffee state of Minas Gerais (MG) in Brazil, but CH's area is about 5.5 million ha, roughly a tenth the size of MG. Accurate statistics on CH coffee area are lacking, but the most recent estimate is 668,200 ha (GAIN, 2016). Therefore as much as 15% of CH is covered by coffee, making it the most intensive and concentrated area of coffee production in the world. Climatic and environmental data for this zone however is scant and wholly incommensurate with its importance.

e) Hence the purpose of this study is to examine the available data to determine the extent to which the climate of this greatly transformed zone may have already changed. The main rationale is to discover if recent trends can help practitioners develop effective adaptive strategies.

2. The many faces of climate change

Climate change impacts in various ways, which vary according to location. There are a range of factors that need to be quantified, including:

Warming: how fast are temperatures rising? Are minima and maxima rising equally fast? Are there more temperature extremes which could affect tree health and production?

Precipitation: Has precipitation changed? Does it rain harder or longer, or less and more intermittently? Are there more droughts?

Climate change includes long term slow changes (e.g. mean temperature rise), short to medium term changes (such as El Niño) and very short change (e.g. change in intensity of storms). Shi *et al* (2014) suggest there are nine different categories of climate change (Fig. 1) and a primary aim therefore should be to indicate for each variable, what the recent tendencies have been and whether these have already impacted on coffee growing.

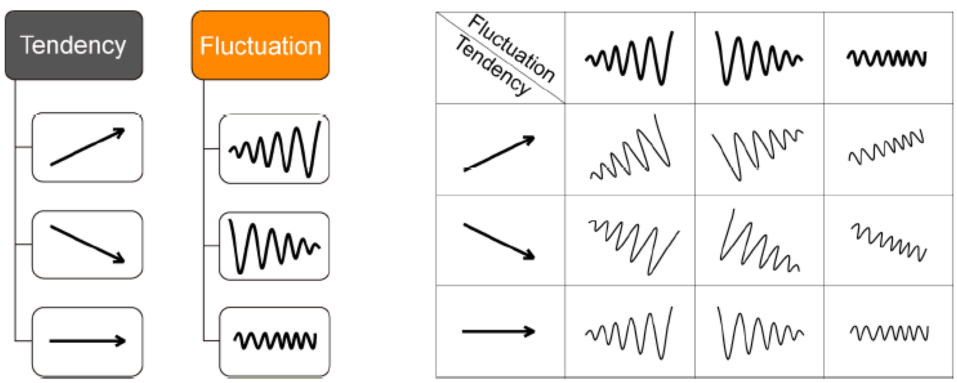


Figure 1 The nine modes of climate change (Shi et al. 2014)

Climatological terms and abbreviations

AII; aridity intensity index. Average precipitation on dry days - the ratio between total rain on dry days and the number of dry days, where a dry day is defined as RR<10mm

CDD; annual maximum length of a dry spell or maximum number of consecutive days with rainfall <1 mm

CWD; annual maximum length of a wet spell or maximum number of consecutive days with RR ≥ 1 mm

ENSO; El Niño Southern Oscillation (includes La Niña)

IRE; intermittent rainfall event in the rainy season with no less than 5 consecutive days with daily rainfall not exceeding (in the case of CH) 3mm/day.

ORD; outbreak rainfall day in the dry season over the CH region is defined as a day in the dry season (from 15 November of the current year to 30 April of the next year) where daily rainfall exceeds 10 mm.

RR; rain rate

RX1; annual maximum 1-day rainfall

RX5; annual maximum consecutive 5-day rainfall
R95pTOT; annual precipitation (mm) due to daily rainfall >95th percentile
SM; summer monsoon
RS; rainy season
SDII; simple precipitation intensity index: annual precipitation divided by the number of days with daily rainfall ≥1 mm/d
SST; sea surface temperature
TNn; monthly or annual minimum value of daily minimum temperature
TX90p; warm days – the percentage of time when daily max temperature > 90th percentile
TXx; monthly or annual maximum value of daily maximum temperature

2.1 Temperature

According to Nguyen *et al.* (2013), mean surface temperatures in Vietnam have warmed at a rate of 0.26C per decade over the last 40 years, a rate that is similar to northern hemisphere land rates, which vary from 0.29 to 0.34C per decade (IPCC Ar4 3.2.2, Table 3.2). The authors state that rises in the CH region are less, at 0.24C ±0.15 (MJJA) and 0.29C ±0.17 (DJFM). These seasonal differences follow a broad trend over Vietnam however, where it is winter (dry season) temperatures that have risen 25 to 40% higher than those of summer over the same period. Hence, dry season warming has been the principal driver of Vietnam's average annual temperature increases over recent decades.

However, a more recent Hanoi University study for The Initiative for Coffee & Climate (c&c) (Tan et al., 2013) finds faster rates of warming over the CH region for the period 1979-2012. They discovered increases of 0.4-0.5C per decade for Nov to Feb, an insignificant decrease of about 0.05C per decade in Mar and Apr (explicable as a consequence of increasingly early rains, see below) and an increase of 0.2-0.4C per decade in the other months. For some dry season months in a few stations, temperature rises seem to exceed 0.7C/decade, a very fast rise. Possible reasons for this will be discussed below.

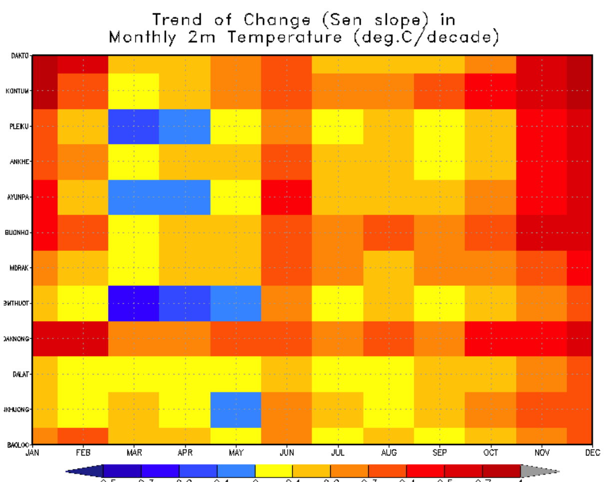


Figure 2 Trend of monthly mean temperature at stations in the Central Highlands (stations listed north to south).

Surprisingly however, the annual maximum temperature (TXx) shows a clear decreasing tend, especially in the southern CH region and at the Dak To station (up to -0.78C per decade). The decrease in TXx may relate to more cloud during early afternoon (when the daily maximum temperature occurs), stronger wind speed, or changes in atmosphere moisture content. It may also be possible that increased continent-wide air pollution, spreading from major centres of industry as well as deforestation could reduce maximum temperatures.

Additionally, the number of warm days (TX90p – those days where the maximum temperature is hotter than the 90th percentile of maxima from the climatological reference period) does not show consistent increase or decrease; changes range from ~ -19 to ~ +10 days per decade.

However, research over the longer period 1961–2007, suggests that CH temperature extremes have increased more than other regions. Ho *et al*. (2011) found that the 95th percentile threshold of maximum temperature rose strongly for JJA in CH (CH=R6, five stations only analyzed) compared to other regions. Fig. 3 suggests that CH maxima rose very strongly from 1960 to 1980.

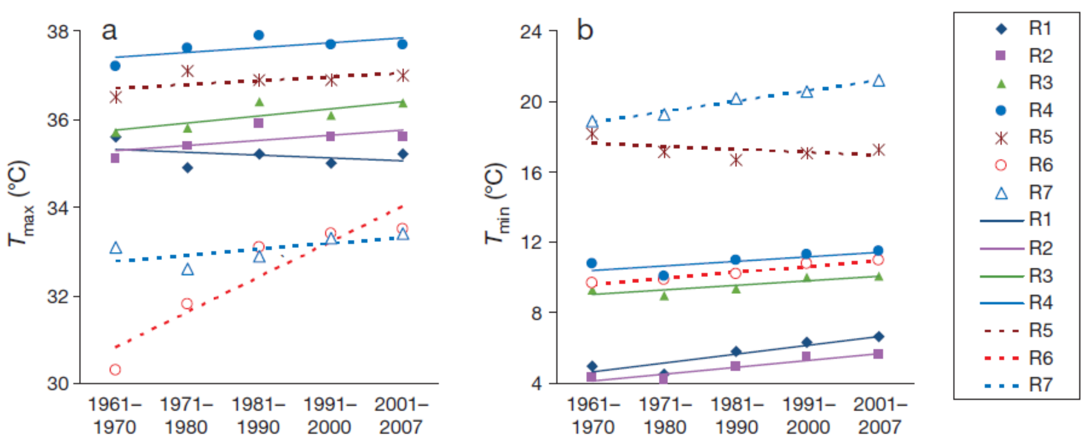


Figure 3 a) 95th percentile threshold of maximum temperature in summer (JJA); b) 5th percentile threshold of minimum temperature in winter (DJF). Region R6 = CH. From Ho et al. (2011).

Unsurprisingly, all CH stations show clear increasing trends of annual minimum temperature (TNn) with the warming rate of about 0.2 to 1.6 °C per decade. Under climate change caused by increased GHGs, it is expected that minimum temperatures will rise more than maxima.

Mostly because of rapidly rising minimum temperatures, the CH diurnal temperature range has significantly decreased at up to -0.64C per decade.

2.2 Rainfall

Rainfall in Vietnam is dominated by a monsoon system (Box 1).

Box 1 Monsoon Basics

A monsoon is a seasonal reversing wind due to the heating contrast between land and ocean, caused by solar radiation. As the sun moves north in summer, it draws in moist oceanic winds (the monsoon) that lead to heavy rainfall as it crosses land masses.

Global: over the twentieth century, global land monsoon precipitation changes show an overall increasing trend from 1901 to 1955, and then a decline up to the present time; the reasons for which are not clear (Zhang & Zhou, 2011).

India: Guhathakurta *et al*. (2014) also find this long term rise and fall to be true for India. The intensity of extreme rainfall events has also decreased significantly in the central region but increased in peninsular India and other regions. Lower rainfall intensities also show decreasing trends in most of the subdivisions of the country. Zhou et al. (2008) have suggested this weakening is due to tropical ocean warming but others (see Section 3.2.1) give evidence that deforestation plays a role.

Panda & Kumar (2014) emphasize clear increases in dry spells and moisture stress situations in the Indian monsoon, as evident from the significance of the trends in continuous dry days (CDD) and Aridity Index (AII) along with their spatial coherence. At the same time, there has been a large inter-annual variability of the monsoon over recent decades, with many nonsignificant trends in rainfall indices as well as a lack of large scale spatial uniformity in terms of the presence of both the increasing and decreasing trends. In several countries changes in rainfall extremes have become spatially less consistent in contrast to an apparent change in temperature extremes, which lends support to the hypothesis that global warming-induced accelerated hydrological cycle intensifies inter-annual variability (Seager *et al*., 2012).

Indochina: Zhang et al. (2002) point out that Indochina is a unique region where the monsoon activity reflects a transitional feature of two distinct monsoon subsystems: the S Asian and E Asian monsoons. The former is a typical tropical system, whereas the latter is a combined tropical–mid-latitude system. Hence the processes controlling the weather over Indochina are complex during monsoon onset in late spring to early summer.

Zhang *et al.* (2002) note a close relationship between the interannual variations of the monsoon onset and ENSO. Years with warm sea surface temperature (SST) anomalies in the W Pacific and cold SST anomalies in the central E Pacific in the preceding spring have an early monsoon onset. When SST anomalies are reversed, the monsoon arrives later, which would coincide with the El Niño phase of ENSO. Some recent studies suggest both that ENSO has become stronger and more frequent in recent decades (Lee & McPhaden (2010); Cai *et al.* (2014)) and that, from modelling, this tendency may continue in the future. If this is true, then the monsoon rains in Vietnam should also become more variable.

China: Zhao *et al*. (2010) show that monsoon rain has increased over recent decades in S China, however Ding *et al.* (2008) suggest that there are cycles of up to 80 years duration, based on a 123-year (1880–2002) time-series of summer (June, July and August) for S China. Simulations by Jun & Jan (2015) show that dust aerosol tends to weaken the East Asia summer monsoon by reducing the land-sea-temperature contrast.

Hence it seems likely that monsoon systems are driven by a number of interacting factors which are still incompletely understood; global warming may be contributing to this variability but this is by no means certain.

2.2.1 The monsoon

The Vietnam monsoon is a SW/NE system. Major droughts and forest fires coincide with failure of monsoon rains, which are associated with ENSO events (Fig. 4, from Katzfey *et al*, 2014).

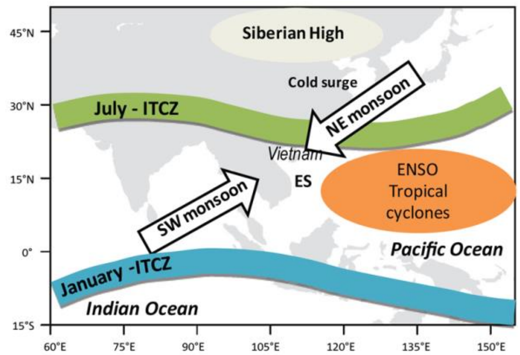


Figure 4 Principal factors affecting the rains in Indochina (Katzfey *et al*. 2014).

However the basic monsoon system shown in Fig. 4 is more complex because the Vietnam monsoon is transitional between the Indian and E Asian monsoon systems (Zhang *et al*., 2002). During mid-April to mid-May, three branches of the prevailing winds with different sources and properties may affect the weather regime over Indochina:

1. The subtropical westerly stretching from the N Indian subcontinent to the Indochina Peninsula;
2. The southeasterly associated with the subtropical ridge over the western Pacific;
3. The westerly over the equatorial eastern Indian Ocean, which stretches NE in early May.

Kajikawa *et al.* (2012) found monsoon onset earlier in May along 10°N; decreasing rainfall trends in June along 10°N were also detected. These changes they attributed to changing heat contrast between the Asian landmass and the tropical Indian Ocean. It is suggested that the accumulation of desert dust and soot aerosols over N India and Himalayan foothills can enhance the heating in the mid-upper troposphere.

Katzfey *et al.* (2014) give the mean observed Vietnam monsoon onset date as May 18 for the period from 1979 to 2011, with a range of 53 days between the earliest (April 20) and the latest (June 12) onset date. There is a negligible difference when the onset dates are calculated for the period from 1980 to 2000, with an onset date of May 20 and a range of 50 days between the earliest (April 21) and the latest (June 10).

Evidently the monsoon onset tends to be late during El Niño years and earlier during La Niña years. Fig. 5 suggests such a relationship is strong before 1993 and weak thereafter, with onset date tending to be earlier in most years after 1993.

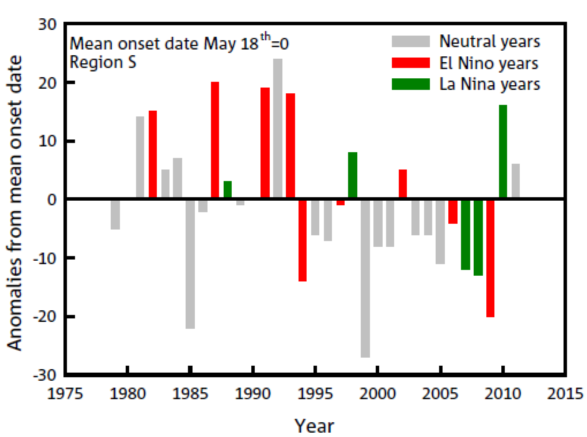


Figure 5 Inter-annual variability (days) of the onset (date) of the South West Monsoon over the South region of Vietnam from 1979 to 2011. Grey, red and green bars depict neutral, El Niño and La Niña years, respectively (Katzfey *et al.* 2014).

2.2.2 Rainfall changes in Vietnam and CH

An analysis by Vietnam's Ministry of Natural Resource and Environment (Schmidt-Thome *et al*., 2015) suggests that rainfall has generally increased over much of southern and central Vietnam during the past 50 years (Fig. 6).

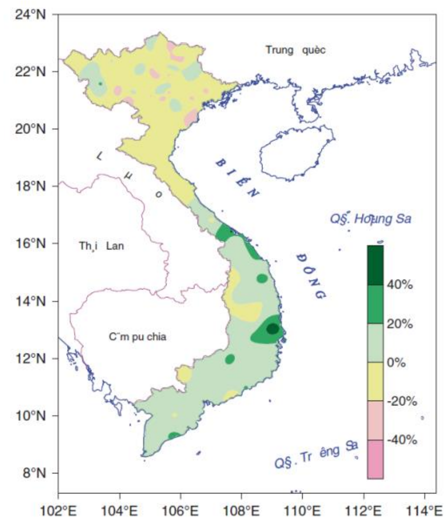


Figure 6 Change in precipitation (%) during the last 50 years in Vietnam (from Schmidt-Thome et al., 2015)

Katzfey *et al.* (2014) give a more complex version, with trends in rainfall showing both increases and decreases. They state that the NW, NE, North Delta (ND, Red River) and northern stations of North Central (NC) and stations in the South Region show decreases, with region ND showing stronger decreases than the others. Stations in SC, CH and the southernmost stations in NC show large increases during the past 40 years.

Katzfey *et al.* (2014) also reported more extreme rainfall events in CH during the past 50 years except at Ayunpa. Both RX1 and RX5 have generally increased for most stations by about 5-10% per decade. The R95p trend is positive by up to nearly 12 mm day-1. The observed trend in consecutive wet days (CWD) is generally negative but not significant, with only Dalat having increases. The number of consecutive dry days (CDD) shows little significant trend.

Rainfall in CH: from previous published studies as well as the commissioned Hanoi University studies, the following information is resumed (Box 2):

Box 2. CH rainfall – facts and trends (mostly from Tan et al. 2013, 2015)

General: from rather few stations, average rainfall in CH is 1888 mm per year, of which the rainy season rainfall is 1568 mm (83% of annual); spatial variation is large: station totals range from about 1100 to 3000 mm. The duration of the rainy season tends to be longer in the south and shorter in the middle CH sub-regions.

Rainfall in the rainy season (May to October) is relatively high – more than 200 mm per month; wettest months are July, August, and September (monthly rainfall > 250 mm per month).

Dynamics: in north and mid CH sub-regions, the daily rainfall increases fast and suddenly during the early days of rainy season, and decreases slowly and variedly towards the end of the wet season. In south CH, daily rainfall increases slowly in the early days of the rainy season and decreases suddenly from rainy season to dry season, but then with a small and unexplained upsurge again around mid-November.

Rains onset date: varies widely from year to year. It first starts in south CH and then spreads northwards. Earliest onset is middle March (day 73 to 75), the latest in the middle May (day 130 to 135). Mean onset is day 109 (19^{th} April, standard deviation of 16-17 days). Rainy season onset is earlier than the summer monsoon onset by about three weeks,

Trends: since 1979 rainfall has:

- increased in March, April, July, September, November and December
- decreased in the January, February, June, and October.

The CH rainy season is starting and ending earlier by about 2-4 days/decade.

Rainfall distribution trend: rainfall trends are very mixed over the region.

Number of annual rainy days (RR ≥ 0.1mm) has increased in the northern parts of CH and decreased in the SW.

More extreme rainfall events have been observed during the past 50 years (CSIRO), but since 1979, number of ≥ 50 mm rain days has decreased in the northwest but slightly increased in the SE regions (range of -5 days to 2.2 days/decade). Rainfall intensity (SDII) has tended to decrease in the NE and increase in the SW part of CH.

Total days with rainfall exceeding the 95^{th} percentile (R95pTOT) has tended to increase in the SE region and decrease in NW part of CH.

Number of intermittent rainfall events (IRE) during the CH rainy season is about 4-7 spells/year (an intermittent rainfall event occurs in wet season when there is no rain or negligible rainfall for a determined period during the rainy season – in the present case < circa 3mm). The number of these events has remained stable over time.

For the opposite case, i.e. outbreaks of wet weather in the dry season (ORD) these mostly range between five and ten spells per year, but for the southernmost stations (Dak Nong, Dalat, Lien Khuong, Bao Loc) the number is significantly higher, with up to 20 episodes per year.

At the same time, for most CH stations, there is a trend towards a shorter maximum annual dry spell (CDD) as well as a shorter maximum annual wet spell (CWD); both these trends seem to be more marked in the southern part of CH. The reason and significance of this however is unclear, but may be regarded as another indication that rainfall patterns are changing.

Hence taking ORD, CDD and CWD together, there is some indication that changes in rainfall are happening more in the southern part of CH.

Dry season: the number of days with daily rainfall exceeding 10mm/day during dry season (15th Nov to 30th Apr) in CH has a large annual variation. In the early months of the dry season, rainfall has slightly decreased or is unchanged in north CH, whereas in south CH it has increased, especially in November.

The number of rainy days in the dry season shows a clear increasing trend, especially at stations in Dak Lak; this is reflected too in the greater monthly total rainfall for March, April, November and December.

Drought: CH drought severity is highest for Mild Drought (D1, ~20%) and Moderate Drought (D2, ~10%). Frequencies of Severe (D3) and Extreme Droughts (D4) are low and mostly at the Ayunpa and Buon Ma Thuot stations. Prolonged droughts with duration of 10-12 weeks usually occur over a small area. There is no clear drought trend over time from the available data. A salient feature is that droughts of all severities seem to be local events, rather than correlated across a region or sub-region.

There are a number of difficulties with understanding rainfall changes in CH. Most importantly for a mountainous region, the number of stations is small, hence a detailed picture is not available and extrapolation from the few points is problematic. It is possible too that some of the stations, now located in large town environments, may be subject to a 'heat island' effect and even local rainfall changes (e.g. Shepherd *et al.* 2002). Nevertheless some tendencies are fairly clear, though the reasons behind them are still obscure:

Onset and retreat: the rains start and finish earlier than previously, but it is important to note that the rains start about three weeks before the true monsoon season, which is heralded by a change in prevailing wind direction. There is no indication that the onset of the monsoon itself is changing, so the earlier increase requires another explanation. Is it possible that increased temperatures lead to more convective rain and even that large scale irrigation is a contributory factor, as has been seen in other countries (e.g. Alter *et al.* 2015a,b). The effect of local land changes will be discussed in the following section. The rains also finish earlier and again, this change remains unexplained (though is a phenomenon widely seen across Indochina).

The summer monsoon: the monsoon period seems to have become more dynamic, with widespread declines in rainfall totals over parts of May, June, July, early August and October, but increases in late August and September. These changes are particularly notable for north and central CH and especially noteworthy are the steep increases in late July and an equally steep fall in mid- August (Fig. 7).

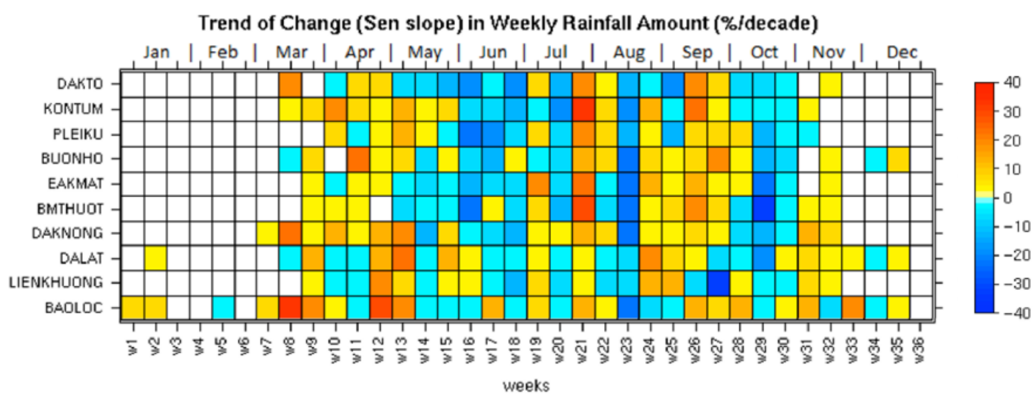


Figure 7 Trends of change in rainfall amount over CH for 10-day periods from 1981-2014. Coloured squares signify significant (P<0.1) rises (yellow-red) and falls (blue) in rainfall amount for each interval over the 1981-2014 period (Tan et al. 2016).

Intensity: heavy rainfall has broadly but sporadically increased, which is expected under climate change since warmer air can hold more moisture which eventually must fall as rain.

Unseasonal: rainfall may also be changing in the dry season as evidenced by the increased number of outbreaks of wet weather in the dry season (ORD) in south CH. Drought periods still occur, but their frequency seems to have changed little though there is some indication that weekly drought indices are becoming more variable and extreme.

Intermittence: the number of intermittent rainfall events (IRE, a minimum of 5 days where rainfall is less than about 3mm/day) during the rainy season in CH is about 4-7 spells/year and this shows very little change over recent decades.

Dry and wet spells: for most CH stations, there is a trend towards shorter maximum annual dry spells (CDD) as well as towards a shorter maximum annual wet spell (CWD) (Fig. 8); both these trends seem to be more marked in the southern CH. The reason and significance of these changes is not clear, but is an indication that weather patterns are becoming less stable.

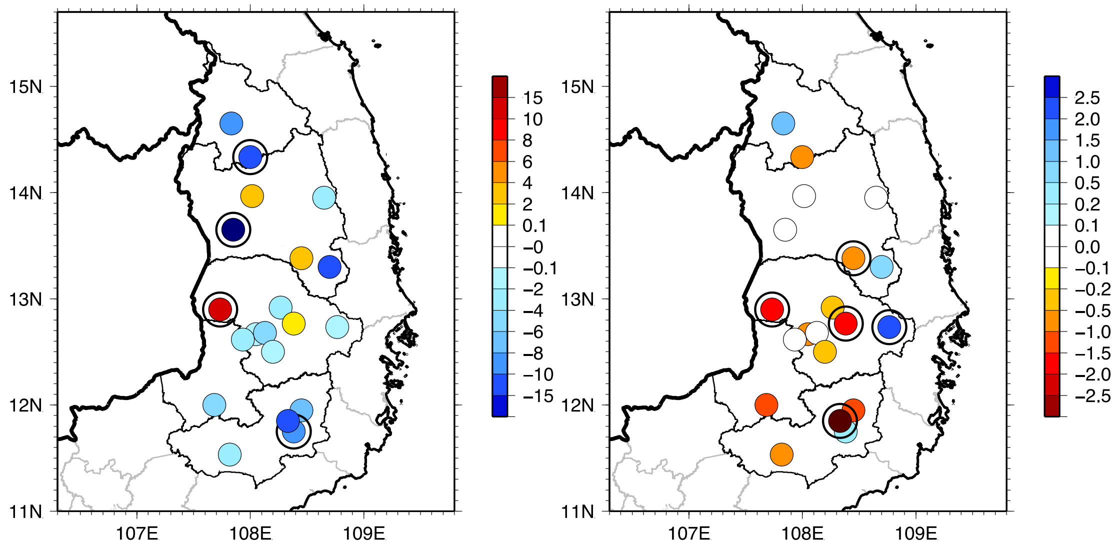


Figure 8. The trend (days per decade) of left: CDD (annual maximum length of a dry spell); right: CWD (annual maximum length of a wet spell) for the 1979 -2012 period. Magnitude of trend is shown by the color scale. Stations with trend satisfying the 10% significance level is indicated by an outside black circle.

Drought (Box 3): mild and moderate droughts (referred to here as D1 (PDSI score between -1 to -2)[1] and D2 (PDSI -2 to -3) are common (Fig. 9). From Fig. 9, it seems that drought frequency, of whatever severity, shows no clear trends across the region or over time. What is surprising is that apart from the extreme El Niño/ La Niña event of 1997/8 onward, ENSO events are not particularly evident in the record of drought frequencies. Even the 1997/8 event, although correlated across the region's stations, was not long-lasting in respect to drought, but the subsequent La Nina period was drought-free for the whole of 1999 across all stations. Hence it seems that drought periods mostly depend on local factors, being neither closely correlated between stations, nor major external events such as ENSO.

[1] PDSI = Palmer drought severity index

Box 3 Drought

"The first 13 years of the twenty-first century have begun with a series of widespread, long and intensive droughts around the world. Extreme and severe-to-extreme intensity droughts covered 2%-6% and 7%-16% of the world land, respectively, affecting environment, economies and humans. These droughts reduced agricultural production, leading to food shortages, human health deterioration, poverty, regional disturbances, population migration and death." (Kogan & Guo, 2016).

Drought must now be considered a principal global threat to coffee production. Recent ENSO related droughts, as well as others still not fully understood (e.g. the Minas Gerais (Brazil) drought of 2014) caused very substantial losses and hardships. Some studies suggest that ENSO events have been getting more frequent during the 20th century and through modelling it seems possible that more extreme events will occur in the 21st century.

According to a drought assessment by the Vietnamese Ministry of Agriculture and Rural Development, in 1997–1998, about three million people were affected and total agricultural production losses were about 400 million US dollars (Vu *et al*. 2015).

According to Nguyen & Shaw (2011) CH and South Central districts are the most drought-prone parts of Vietnam which are becoming more common. Ty *et al*. (2009), studying the Srepok river basin in the heart of CH concluded that there were no water shortages at basin level whereas there were severe water scarcities at the district level. This observation tends to bear out the localized nature of droughts depicted in the current report from Tan et al. (2016.).

In recent years, research suggests that mega-droughts have occurred occasionally in past centuries. It is now suspected for instance that the collapse of the 'hydraulic city' of Angkor, the capitol of the Khmer Empire in Cambodia, was at least partly caused by decades-long droughts interspersed with intense monsoons in the 14th and 15th centuries. The evidence comes from detailed tree-ring studies of rare Po Mu (*Fokienia hodginsii*) conifers including those from the Bidoup Nui Ba National Park in CH (Buckley *et al*. 2009).

With similar data from N Vietnam (Sano *et al*. 2009) there is also good evidence for mid 18th and late 19th century droughts that may have extended across the Indochina peninsula. Hence it is feasible that there will be similar major 'mega' drought episodes in the future – but in that eventuality they will have to be endured under a record high temperature regime and without the buffering capacity of much of the region's forests.

Only weekly PDSI shows some signs of change over recent decades, with stations showing signs of increasing heterogeneity (Fig. 10).

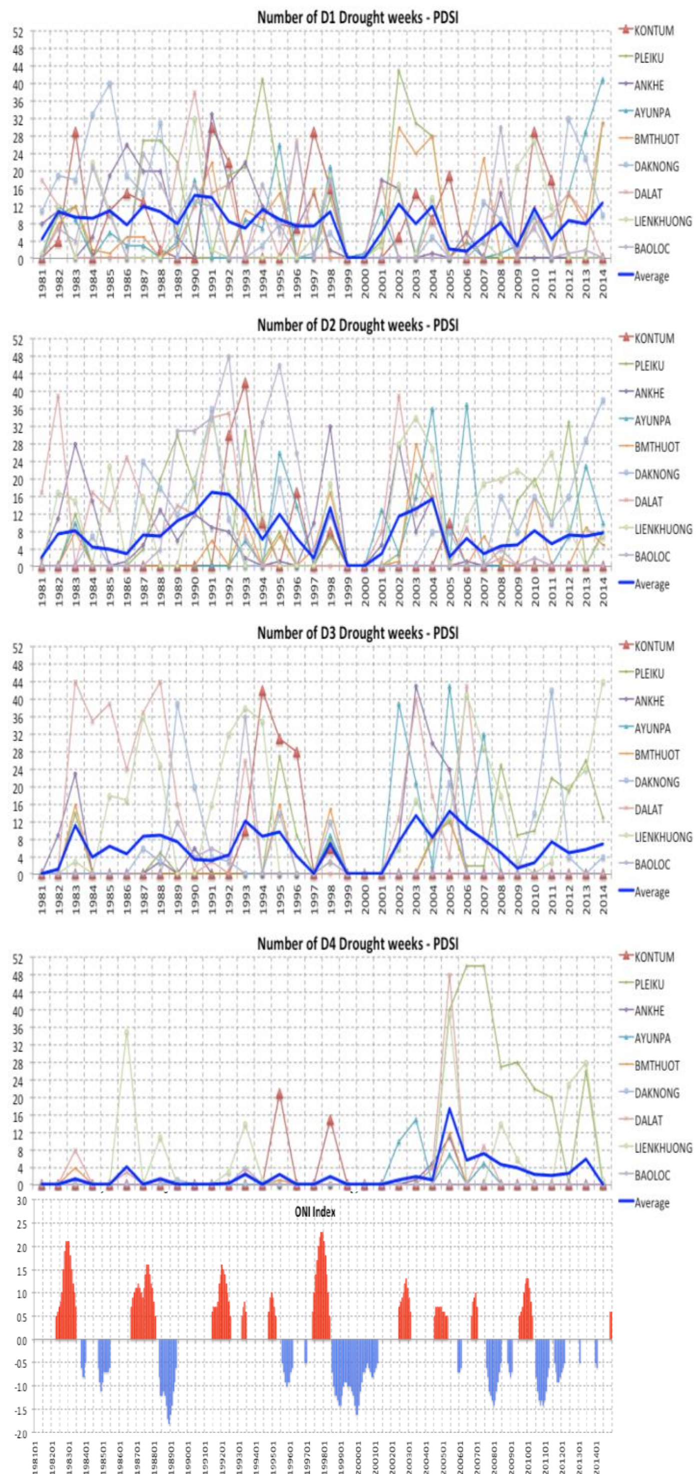


Figure 9. Number of drought weeks for different severe droughts at each station as functions of time. Compared to an El Niño (red) La Niña (blue) index. Note the lack of a clear relationship between the index and drought events at the local level.

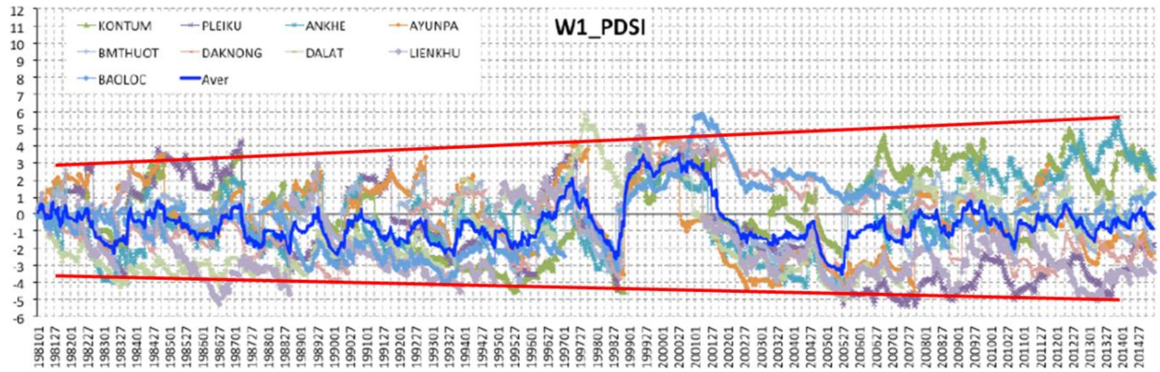


Figure 10. Weekly PDSI for each station and mean value over all station (blue line); red bounding lines drawn manually.

Vu *et al.* (2015) however, using the standardized precipitation index (SPI) as a measure of drought, registered a CH 2004 drought of equal/worse severity than that of the 1997 ENSO event (Fig 11). The discrepancies with the above measurements must be due to the differences between SPI and PDSI.

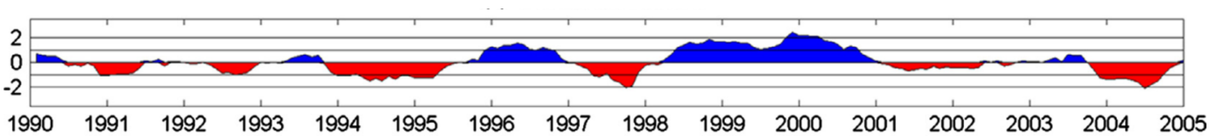


Figure 11. Standardized Precipitation Index (SPI) measures of the 13 CH met stations showing major droughts for 1994-5, 1997 and 2004 (from Vu et al. 2015).

Vu *et al.* (2015) also found mixed trends in drought tendency across CH since 1961, with 4 stations (Dak To, Kon Tum, Dak Nong, Bao Loc) showing a significant wetter trend, 3 stations (An Khe, Ayunpa, Eakmat) a significant drier trend. The wetter trend stations were those at the higher altitudes. These authors also hint that improved observational data will be needed to facilitate improved prognostications.

3. Locally caused climate change

The rationale for considering local causes of climate change is as follows:

- CH climate changes are complex, with signs of increased heterogeneity across the region, in terms of temperature changes and rainfall (temporal and spatial);
- The Indochina and CH biomes have become greatly modified through agricultural expansion over recent decades (Box 4);
- Research from several tropical countries gives very strong evidence that land use change can substantially affect the local climate, causing increased temperatures and either increased or decreased rainfall according to local conditions.

Temperature rises seen across CH and Vietnam are without doubt caused by global GHG rises, but the quite rapid increases seen in the dry season are less easy to explain, as are the very local droughts and changes in rainfall patterns. It is likely that some of the changes observed are not due to global warming but instead to some extent to local climate change caused by deforestation, urbanization, air pollution or some combination of these.

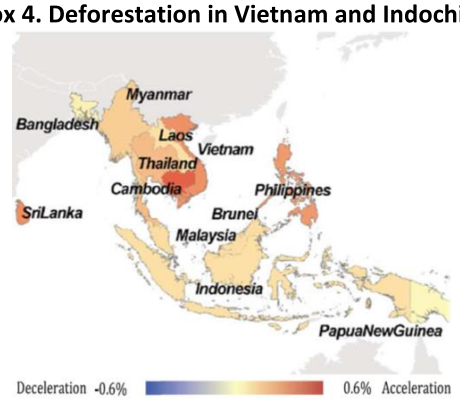
A brief review of the literature reveals the following:

3.1 Temperature rises

Deforestation leads to local temperature rises and the observational evidence is now overwhelming. E.g. a recent study of Nicaragua (Gourdji *et al.* 2015) shows that the meteorological station temperatures in deforested zones have risen significantly more than those in still forested areas.

In the Xingu region of the Amazon, Silvério *et al.* (2015) show that forest-to-crop and forest-to-pasture transitions in the 2000s decreased the net surface radiation and latent heat flux giving rise to land surface warming by 0.3 °C compared with surrounding forest reserves, where no significant temperature rises were recorded.

Box 4. Deforestation in Vietnam and Indochina



Accelerated deforestation in the humid tropics from the 1990s to the 2000s (Kim et al., 2015)

Understanding the true extent and rate of deforestation in many countries is problematic. As Fitzherbert *et al.* (2008) put it: "*The usefulness of the most widely cited land-cover data sets (FAO) is undermined by changing definitions of forest, minimal independent monitoring of government statistics and a lack of information on the subnational patterns and causes of land-cover change.*"

Indochina: according to FAO (2015) forests for the six Indochina countries (Cambodia, Laos, Malaysia, Myanmar, Thailand, Vietnam) have declined by only 4.3 % since 1990 – a rate of about 200,000 ha/yr. However according to Global Forest Watch (GFW), tree cover losses since 2001 are up to 1 million ha/yr, with recovery rates of about 350,000 ha/yr.

Vietnam: FAO (2015) suggests that Vietnam's forests have increased by 58% since 1990, whereas GFW estimates tree cover loss at 1 to 1.5 million ha since 2001, with about 0.5 million ha of regrowth over the same period.

Taking the whole of Vietnam, Meyfroidt & Lambin (2008) show that forest coverage declined from about 60% at the start of the 20th century to reach a low of between 25 and 31% in the early 1990s. The decline was then reversed to reach 32 to 37% by 2000 and as high as 38% in 2005, due to both natural forest regeneration and new plantations. According to Tuan (2015), between 2002 and 2013, nearly 390,000 ha of natural forests were officially converted to the other land uses, accounting for 40 % of the total natural forest loss. The policy of the government on rubber plantation development (up to 800,000 ha by 2020) allowed so-called "poor and degraded" natural forests to be converted to rubber plantations, and many natural forests have hence been clear-cut. By the end of 2012 almost 910,500 ha (over 100,000 ha more than the maximum proposed area by 2020) had been converted to rubber plantations.

Over the Vietnamese part of the Lower Mekong Basin, which includes part of CH, Leinenkugel *et al.* (2015) find that the deforestation rate continued at the highest rates for the region. They show for the period 2001-2011 it was particularly the dense evergreen forests in Cambodia and CH that suffered losses at rates of 0.7% and 1.1% per year. When considering continuous forest losses, annual gross loss rates were highest for Vietnam for the categories '10%+ canopy cover (-1.1%), 40%+ canopy cover (-1.2%), and 60%+ canopy cover (-0.9%). This suggests that deforestation is continuing unabated for agricultural expansion.

CH: Neilson *et al.* (2012) conclude that anywhere between 235,000 and 1,000,000 ha of forest has been cleared for coffee in the CH since the 1970s. Meyfroidt *et al*. (2013) found that thanks to coffee and rubber booms, rates of clearance of natural forests in the CH increased during the period 2005 to 2009 compared to 1999 to 2005, while natural forest regeneration in the rest of the country slowed down. The authors point out that most primary forests remnants are in CH and ongoing deforestation has important impacts on biodiversity and carbon storage. Studying an area of 747,800 ha of CH provinces, they found that forest cover (excluding open deciduous forests) declined from 27% in 2000 to 22% in 2010.

Vu et al. (2014) delineated areas of about 63,900 km2 of land (19% of the national land) that showed a persistent decline in biomass productivity that was mainly caused by non-climate (i.e., anthropogenic) factors; CH comprised 21% of these degraded areas.

Alkama & Cescatti (2016) show quite pronounced tropical warming due to deforestation even over the past few years (2003 to 2012) which seem to be particularly marked over Indochina (Fig. 12).

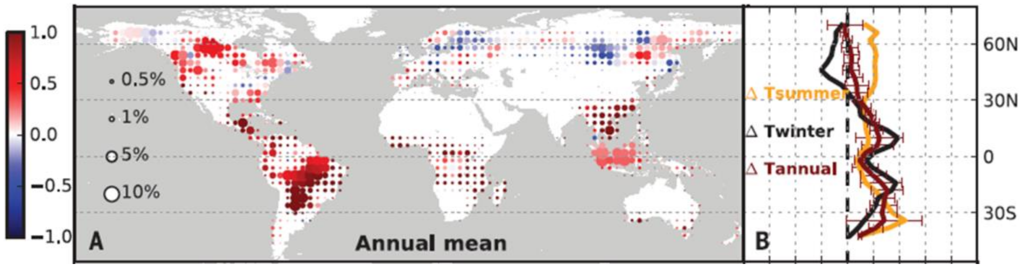


Figure 12. Regional changes in air surface temperature due to losses in forest cover between 2003 and 2012. Changes in mean annual air temperature due to forest losses are shown. The symbol size indicates the magnitude of forest cover losses, and the colour specifies the average temperature sensitivity to total deforestation (Alkama & Cescatti, 2016).

Furthermore the same authors found that mean and maximum temperature rose as a result of 5.5km^2 deforested areas and these are seen during similar months to those found in the meteorological record of CH (Fig. 13).

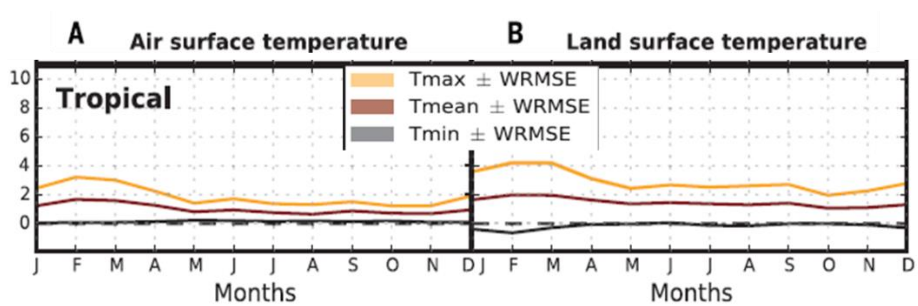


Figure 13. Seasonal changes in air and land surface temperature due to losses of forest cover. Expected changes in the monthly maximum, minimum, and mean air (A) and land (B) surface temperature due to the total clearing of a 0.05° grid cell in the different climate zones are shown (mean ± weighted root mean square error,WRMSE). Alkama & Cescatti (2016).

Additionally, modelling of diurnal temperature range (DTR) changes due to deforestation (Hua & Chen, 2013) shows significant reductions over Indochina, suggesting that the observed DTR changes for Vietnam may be at least partially due to deforestation (Fig. 14).

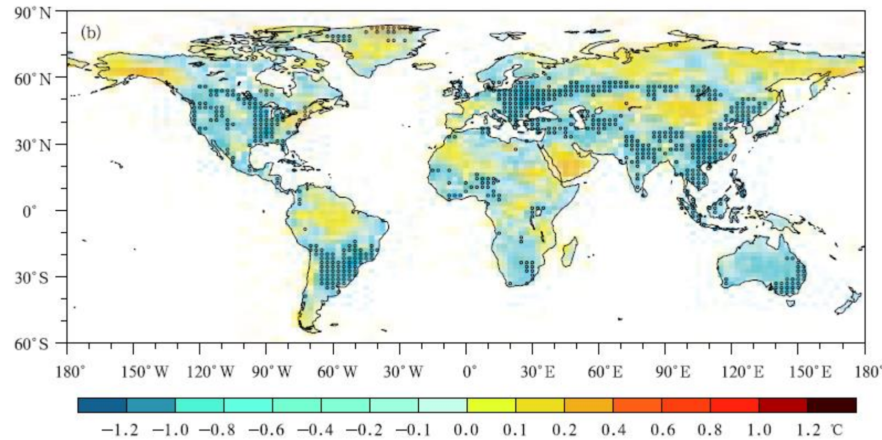


Figure 14. Changes in diurnal temperature range due to LUCC (hollow circles denote significance at the 0.05 level) as modelled by Hua & Chen (2013) using NCAR CAM4.0 general circulation model and comparing 1850 vegetation to the present day.

3.2 Rainfall changes following deforestation

Rainfall origin, local or oceanic? Without doubt, much of CH rain originates directly from the summer monsoon, i.e. the rain was very recently evaporated from the surrounding seas and transported across the land by large pressure differences between land and sea. However, not all rainfall originates directly from this source; for instance Li and Fu (2004) found that land surface latent heat flux (i.e. through evapotranspiration) is a more important source of atmospheric moisture than large-scale moisture transport during the dry season and early stages of the transition season in the Amazonas. Indeed through isotope studies it has long been known that inland rainfall in the Amazon is up to 50% derived from re-evaporation rather than direct transport from the sea (Salati *et al*., 1979; Eltahir *et al*., 1994)).

Recent work by Kuricheva *et al*. (2015) shows that Vietnamese monsoon forests produce similar quantities of atmospheric water vapour as their Amazonian counterparts, hence the role of local and regional forests as a source of rainfall is likely to be important.

The published evidence taken together suggests that the effects of deforestation on rainfall are complex and that precipitation can increase or decrease depending on local circumstances.

3.2.1 Deforestation leading to decreased local rainfall

Spracklen *et al.* (2012) note that when forests are replaced by pasture or crops, evapotranspiration of moisture from soil and vegetation is often diminished, leading to reduced atmospheric humidity and potentially supressed precipitation. From their study, they found that for more than 60% of the tropical land surface, air that passed over extensive vegetation in the preceding few days produced at least twice as much rain as air that has passed over little vegetation.

Silveiro *et al.* (2015) suggest that large-scale agricultural expansion over tropical forests warms land surfaces and may reduce regional rainfall via several mechanisms:

- Loss of forest cover increases surface reflectance and decreases the energy available to drive the hydrological cycle.
- It reduces evapotranspiration and increases sensible heat flux, thus reducing humidity and potentially cloud formation.
- It decreases surface roughness, which reduces the transfer of heat between the biosphere and atmosphere, thus potentially warming land surfaces and decreasing convective overturning.

Satellite imagery of lowland Costa Rica and Nicaragua suggests that deforested areas remain relatively cloud free during the dry season while forested areas have well-developed cumulus cloud fields (Lawton *et al*. 2001). Similarly, rainfall in the cloud forests of Costa Rica is sensitive to upwind vegetative cover.

Tree cover was a good predictor of the annual number of rain days, but not total annual rainfall in Atlantic Forest remnants of Brazil from 1962–1992 (Webb *et al*. 2005). By implication, although fewer rain events occurred in deforested sites, they were of higher intensity, compared with forested sites.

Seasonality changes: seasonality of rainfall has shifted due to deforestation in Rondônia, Brazil where the wet season has been delayed by ~11 days in deforested regions while it has not changed in forested areas over the last 30 years (Butt *et al.* 2011). This would suggest that the CH advance in the rainy season is unlikely to be linked to deforestation.

3.2.1 Deforestation leading to increased local rainfall

Modelling by Castillo and Gurney (2013) has simulated more realistic deforestation scenarios at the regional scale, incorporating different patterns, rates, and scales of deforestation. Climate impacts of slow, prolonged, and incomplete deforestation differ from the impacts of sudden, complete deforestation. They found that a gradual decline in forest cover resulted in a modest increase in annual rainfall for SE Asia from -22 to +123 mm/yr. When Saad *et al*. (2010) modelled deforestation in rectangular patches (from 4,500 to 63,000 km2) in northern Amazonia, precipitation increased downwind and decreased upwind in deforested patches. In smaller patches, precipitation downwind increased more than precipitation upwind declined, resulting in a net increase in rainfall over the entire deforested patch.

Lawrence & Vandecar (2015) conclude that small clearings modelled at regional scales can result in enhanced local rainfall over the deforested area. Along borders between forested and deforested regions, mesoscale models predict enhanced convection and, potentially, enhanced rainfall over deforested areas. The reason for the increase is that rising hot air over the deforested area causes an influx of moist air from the adjacent forested area. Thus, although a clearing lowers evapotranspiration, winds bring moisture into it. Following convection and cloud formation, rainfall may ensue (Fig. 15).

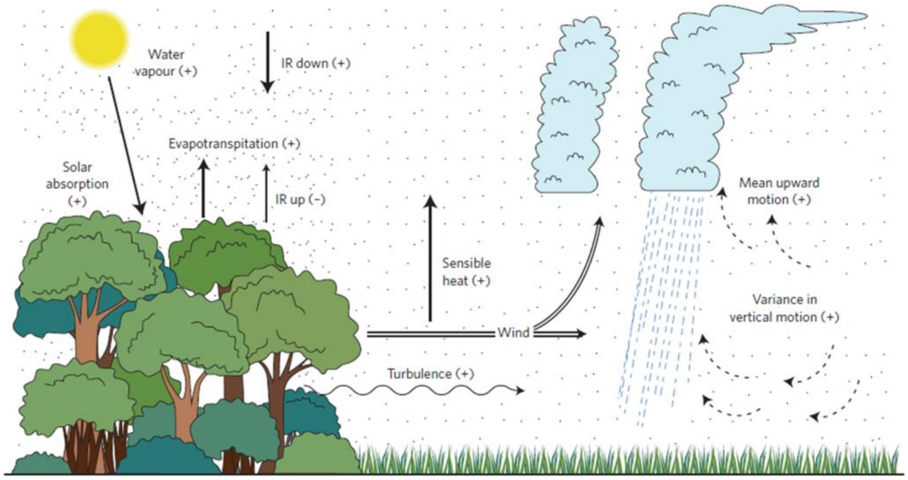


Figure 15. Atmospheric dynamics induced by the boundary between forest and non-forest. Rainfall may be caused by convection that develops at the edge of forest vegetation. Rising hot air over the deforested area causes an influx of moist air from the adjacent forested area (from Lawrence & Vandecar 2015).

The cumulative impact of small-scale deforestation on mean regional rainfall may be small (with enhancement initially), as increases in some areas balance declines elsewhere. However, Lawrence and Vandecar clearly indicate that, as the size of the cleared area grows, a net increase is likely to switch to a decrease, with the magnitude of the decline increasing as deforestation expands. This is potentially an important finding, since the decline might be difficult to reverse by modest reforestation schemes.

3.2.2 Land use change effects in Indochina (modelling)

Lawrence and Vandecar (2015) emphasize that it is unwise to infer general rules from studies in just one locality, hence it is important to look at evidence more local to CH.

Simulations of the Indochina peninsula (Sen *et al*., 2004) suggest that local deforestation tends to increase rainfall on the downwind side and decrease it on the upwind side. Locally it causes increases in wind speed and temperature and a decrease in water vapour mixing ratio from surface up to about 1500 m above sea level. Surprisingly perhaps, these authors also found far-reaching effects on the East Asia summer monsoon that included a weakening of the monsoonal flow over east China and a strengthening over the neighbouring seas to the east. These changes yield sandwich-type dryer and wetter bands that are elongated along the main flow path of the East Asia summer monsoon. The authors found that the changes in modelled rainfall appear to be in broad qualitative agreement with observed trends in the Indochina Peninsula and southern China and hence that deforestation in the Peninsula could be one of the major factors causing changes in the climate of the region.

Schneck and Mosbrugger (2011) confirm the findings of Sen *et al.* (2004) through simulation of remote as well as local changes in climate as a result of deforestation in SE Asia. They report that, despite reductions in precipitation on the deforested grid cells, enhanced moisture convergence increased regional precipitation. Recently Halder *et al*. (2015) also show that observed declines in moderate rainfall over India during recent decades can be explained in part by deforestation. Their modelling of the effect of the difference between present and past land cover on rainfall, suggests falls that extend over the Indochina peninsula as well (Fig. 16).

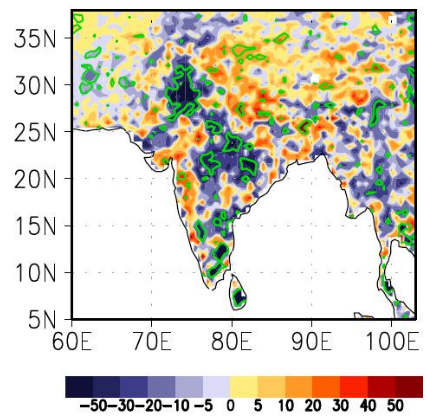


Figure 16. Changing moderate rainfall. Difference (Present minus Historical Land Cover) in moderate rainfall (in mm/day, 1982–2008). Green contour shows differences significant at the 90% confidence level (Halder *et al*. 2015).

3.2.3 Land use change effects in Indochina (observational evidence)

Kanae *et al.* (2001) examined monthly precipitation data for the past 40 years from all over Thailand and found a strong decrease in precipitation only in September (by ~100mm per month) following the monsoon. Strong monsoon westerlies provide moisture from the ocean to the Indochina Peninsula until the end of August and the authors suggest that they mask local impacts of deforestation until the winds disappear in September. However Takahashi *et al.* (2009) modelled this effect over Indochina and concluded that the September decline was more likely due to weakening tropical cyclone activity.

In the case of Vietnam, Kuricheva *et al.* (2015) and Kurbatova *et al.* (2015) accurately measured remarkably high levels of evapotranspiration in monsoon forest of south of Vietnam (in a reserve just south of CH) which is only moderately reduced throughout the dry season. They estimate that water vapour flux from these monsoon forests is approximately equal to that of the rain forests of Central Amazonia (Kurbatova *et al*. 2015), hence their continued removal (Box 4) is likely to affect local rainfall.

Khoi & Sugetsugi (2014) indicate how dominant land-use types in the Be River catchment (in SW CH) have changed, with 40% agricultural land and 51% forest in 1990 which had changed to 55% agricultural land and 37% forest only 11 years later. From the late 1970s, their results show rises in annual temperature, precipitation, and streamflow (by 0.035°C/yr, 20.6 mm/yr, and 3.1 m^3/s/year) at the 5% significance level. This precipitation increase exceeds the largest found by Yazid *et al*. (2015) for the Indochina region (16.4mm/yr) suggesting large heterogeneity across the region which is consistent with locally caused change.

As Lawrence & Vandecar (2015) point out, a number of modelling studies that incorporate various levels of deforestation suggest that tropical forest clearing beyond about 30–50% may constitute a critical threshold for Amazonia, beyond which reduced rainfall triggers a significant decline in ecosystem structure and function. However, the threshold may differ in SE Asia, where the land–ocean balance is very different. Rainfall reduction is reduced when deforestation is modelled as patches rather than continuous belts.

All this implies that there could be a limit to what can be learnt from precipitation from a few land-based meteorological stations in Vietnam, some of which may be located in centres of habitation – they may give an overall poor understanding of countrywide rainfall change. Nevertheless, the apparent high heterogeneity in rainfall parameters changes seen in CH (Fig. 17) is not inconsistent with a land use change effect and the observational and modelling results from many sources suggest that at the very least, this possibility needs to be better monitored in the future.

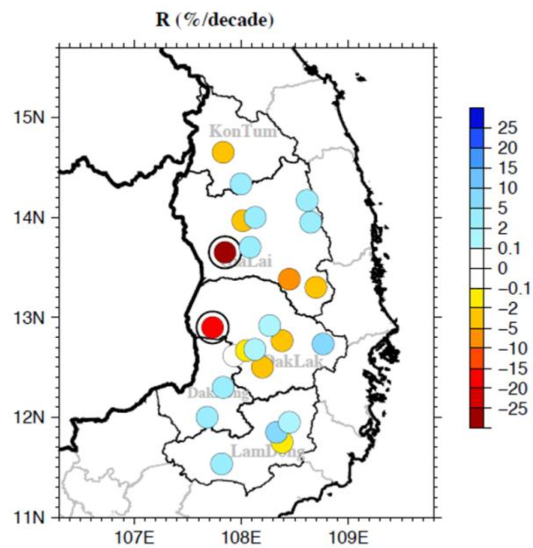
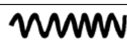
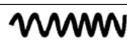
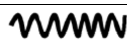
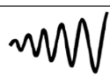
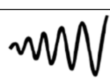
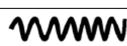
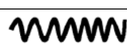


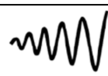
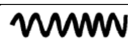
Figure 17. Sen slope of the linear trend of annual rainfall (mm change/decade). Note the marked differences in trend between some adjacent stations. The outside black circle indicates the Sen slope at the station satisfies the 10% significance level (Tan *et al.* 2013).

4. Synopsis of changes

Any change in climate is likely to be a complex mix of global, regional and local effects. The several influences of the monsoon systems, the topography of the Central Highlands and major land use change may all add to this complexity. A relative paucity of data (both number of point sources and length of record) make it doubly difficult to draw firm conclusions. However, from observational and modelling data from a number of sources the following are resumed in Table 1 according to the categories of Shi *et al.* (2013):

Table 1. Tendencies and variation of climate over Central Highlands in recent decades.

Climate variable	Tendency	Variation	Potential effect on coffee
Min temp	↗		Pest and disease increases
Max temp	→		
Diurnal temp range	↘		Pest and disease increases
Total annual ppt	→		Increased variation makes planning farm work and processing more difficult
Length of wet season	→		
Heavy rain	↗		Possible effects on flowering and tree damage
Continuous dry day maxima (CDD)	↘		
Continuous wet day maxima (CWD)	↘		

Outbreaks of wet weather in the dry season (ORD)	Mixed		Post-harvest drying problems
1-week Palmer drought severity index			
Other drought severity indices	Mixed		

4.1 Temperature overview

It is clear that temperatures are rising across CH at mean rate of 0.2 to 0.4C/decade in the wet season and substantially higher than that for the dry season. It is minimum temperatures that are rising especially fast, with mostly little increase in maximum temperatures, except in JJA, which may be related to reduced rainfall during parts of that trimester. It is possible that increased air pollution from regional industrial, agricultural and forest activities could limit increases in maxima (Makkonen *et al*. 2012).

Recent studies strongly link deforestation to temperature increases and the most recent (Alkama & Cescatti, 2016) suggest that Indochina is a ‘hotspot’. Hence a *prima facie* case can be made that the temperature rises recorded are at least partly linked to deforestation. It is therefore very likely that the temperature rises will also be affecting rainfall.

4.2 Rain overview

Although there has been no clear change in rainfall amounts across the region, this is not unexpected given the heterogeneity of the CH and the small number of data points.

From all the evidence, it is concluded that rainfall is changing, becoming more variable during the rainy season with both increases and decreases at different phases during the rains. Onset is earlier and there are also more rainfall events during the dry season. The monsoon itself however shows no overall trend in onset or retreat dates (as evidenced by changing wind direction), being very variable and controlled by a number of large scale exogenous factors, not least of which is ENSO. It is surprising nonetheless those ENSO events, apart from the severe 1997/8 event, seem to exert relatively little impact on CH, as seen in a complex pattern of droughts that seem to be more of local origin than externally driven.

There have been fairly small but significant changes in rainfall patterns, which have become more varied throughout the year, with signs of significant and sometimes abrupt waves of increase and decrease (Fig. 7).

The trends observed in CH could be regarded as unusual in that they partly contravene the widely accepted principle with climate change precipitation that the wet seasons get wetter and the dry seasons drier. E.g. Chou *et al.* (2013), using Global Precipitation Climatology Project data clearly show the tendency for wet seasons getting wetter (by 0.94 ± 0.20 mm /day/century) and dry seasons getting drier (by -0.53mm ±0.10 mm/day/century). Li *et al.* (2015) confirms an increase in total precipitation, especially it seems for latitudes that include Vietnam

However rainfall in the second trimester (AMJ) has increased so that by different measures the rainy season has advanced. The reason for this is not clear, it could be that the increases in temperature have led to a more unstable atmosphere and increased convective rain (more heavy showers). This could be also fed by greatly increased irrigation in the zone – it has been shown in other countries that rainfall increases in the vicinity of irrigation schemes (Alter et al. 2015a,b). It could also be partly due to deforestation, which can have marked and sometimes unexpected local effects.

Drought is the principal concern for the stability of the region; the lack of apparent change over recent decades could be considered reassuring, were it not for growing evidence that ENSO-like phenomena may become more frequent and/or severe in the coming years. The science also suggests that as deforestation progresses, rainfall increases might quite quickly disappear and be replaced by declines. The historical record also points to the possibility of a mega-drought such as those of past centuries – a future event of this nature would have to be faced with land much more exposed than the previous events.

It is remarkable that per unit area of annual evapotranspiration in monsoon forest in southern Vietnam is approximately equal to that of the central Amazonian forests (Kurbatova *et al.* 2015). It seems very likely that the amount of deforestation in the region over recent decades has caused significant declines in local water vapour flux that is equally likely to have had impacts on rainfall.

5. Implications for coffee growing

Dry season rainfall: an increased number of wet weather outbreaks in the dry season in south Central Highlands is likely to affect flowering patterns, possibly affecting pollination success.

Increasing temperatures (especially through the dry season): coffee lands that were optimal for production 20 years ago may now become more marginal. Higher temperatures stress the plant, reduce photosynthesis and yield and increase susceptibility to pests and diseases.

Diurnal temperature change: higher minima and less change in maxima lead to a reduced diurnal range. This is very likely to favour some pests and diseases.

Diseases: fungal diseases mostly prefer a 'not-too-hot; not-too-cool' regime that reduces likelihood of drying out and low temperature inhibition of the delicate germination process.

Pests: higher average temperatures mean that insects like the coffee berry borer may be able to complete an extra life-cycle and therefore exert greater economic loss. Higher temperatures may also stress the trees – it is well established that many insects find it easier to overcome the defences of weakened trees. Cicadas have become abundant in CH in recent years – a possible reason for this is that they find it easier to attack trees stressed by drought and/or higher temperatures.

Soil pests: increasing temperatures, together with high fertilizer use, may accelerate the breakdown of organic matter and provoke changes in the microbial balance of the soil which may affect a range of 'friendly' microbes that tend to control soil pests and diseases such as nematodes and mealybugs.

A reduced diurnal range also means that shade as a response to increased warming might not work, because shade tends to enhance minimum temperatures by retaining warmth at night under the canopy, which with longer wet periods could give rise to fungal disease outbreaks.

'Longer' rainy season: The rainy season is deemed to now start and finish earlier by about the same amount, however because of an upsurge of rain in November (albeit still small amounts) there is now a longer period subject to rainy conditions, which may extend from March to the start of December. This could be advantageous to agriculture in general, especially as it seems that droughts are not increasing nor are intermittent rainfall periods in the wet season. Wetter conditions however may favour fungal disease outbreaks, especially if there are prolonged cloudy, low-light conditions. E.g. the recent rust outbreaks in Central America seem to have been exacerbated by quite small increases in dry season rain, which may have been enough to provoke a rise in spore inoculum.

Early warning: The year-to-year variations of the onset dates and the rainfall amount within the rainy season (RS) and summer monsoon (SM) season are closely linked with the preceding winter and spring sea surface temperature (SST) in the central-eastern and western Pacific. It was also found that the onset dates were significantly correlated with the RS and SM rainfall amount. Hence the preceding winter and spring SST and the onset information could be good predictors for seasonal rainfall forecasts over the Central Highlands

6. Recommendations

6.1 Monitoring and research

Given that the CH climate is definitely changing, but in quite complex and heterogeneous ways across the region, it would be important to:

- Greatly extend the number of meteorological measurement points, to get a much better understanding of local climate change as it may relate to local land use change. Modern miniaturized measurement recording devices are quite inexpensive, so a large number could be deployed to gain a much better idea of local climate change.
- Enhanced instrumentation would help to map out areas that are optimal, sub-optimal and marginal for coffee growing. Such mapping would assist future activities to assist farmers to adapt and diversity.
- Carry out detailed studies with satellite data to observe rainfall and temperature changes and where possible to relate these to land use change.
- Determine the extent to which coffee differs from forest in terms of evapotranspiration – i.e. to complement the studies of Kurichova *et al.* (2015) in CH. Perhaps Robusta coffee and/or rubber are reasonable replacements that generate substantial water vapour flux to maintain rainfall circulation. But this needs to be evaluated to determine the true picture and if there are situations where a mix of coffee and trees might offer a better substitute.
- Carry out isotope studies to determine the provenance of rain throughout the year – what proportion is from land evapotranspiration?
- Climate change will very likely increase some pest and diseases, including new or previously rare ones. It would be advisable therefore to carry out routine pest and disease surveys, so as to detect changes in a timely fashion.

6.2 Farmers

Much of the findings in this Working Paper will be unknown to farmers and other rural stakeholders. It is suggested that training curricula should in future include teachings on climate change and the effects of land use change and what this means for present and future production challenges.

Farmer/commune leaders/local schools should be canvassed on their interest to host mini-weather stations or other sensors, which are becoming ever more affordable, accurate and easier to use.

6.3 Traders

Traders have very detailed knowledge of coffee production in a particular district as well as information about recent weather-related production problems (e.g. poor quality through cherry drying difficulties, flood damage, etc.). They are therefore a potentially valuable source of information and early warning of difficulties, Hence ways to tap into this knowledge should be considered.

6.4 Government

CH is a vitally important strategic production and ecoservice resource to the nation; enough evidence has been presented here to suggest that there are significant climate changes taking place. However more detailed monitoring is required to quantify and explain the nature of these changes; due investment in a range of environmental monitoring devices will be a rewarding investment.

Greater education and training for many CH stakeholders, about its climate and potential fragilities is also advisable.

7. References

Alkama R., Cescatti A., (2016). Biophysical climate impacts of recent changes in global forest cover. Science, 351: 600-604.

Alter, R. E., Im, E. S., & Eltahir, E. A. (2015a). Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation. Nature Geoscience.

Alter, R. E., Fan, Y., Lintner, B. R., & Weaver, C. P. (2015b). Observational evidence that Great Plains irrigation has enhanced summer precipitation intensity and totals in the Midwestern US. Journal of Hydrometeorology, (2015). 16: 1717-1735

Buckley, B. M., Anchukaitis, K. J., Penny, D., Fletcher, R., Cook, E. R., Sano, M., ... & Hong, T. M. (2010). Climate as a contributing factor in the demise of Angkor, Cambodia. Proceedings of the National Academy of Sciences, 107(15), 6748-6752.

Butt, N., de Oliveira, P. A. & Costa, M. H. (2011). Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. J. Geophys. Res. Atmos. 116, D11120 (2011).

Cai, W., Borlace, S., Lengaigne, M., Van Rensch, P., Collins, M., Vecchi, G., ... & England, M. H. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. Nature climate change, 4(2), 111-116.

Castillo, C. K. G. & Gurney, K. R. (2013). A sensitivity analysis of surface biophysical, carbon, and climate impacts of tropical deforestation rates in CCSM4-CNDV. J. Clim. 26, 805–821.

Chou, C., Chiang, J. C., Lan, C. W., Chung, C. H., Liao, Y. C., & Lee, C. J. (2013). Increase in the range between wet and dry season precipitation. Nature Geoscience, 6(4), 263-267.

Dai, A., Trenberth, K. E., & Qian, T. (2004). A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. Journal of Hydrometeorology, 5(6), 1117-1130.

Ding, Y., Wang, Z., & Sun, Y. (2008). Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. International Journal of Climatology, 28(9), 1139-1162.

Eltahir, E. A., & Bras, R. L. (1994). Precipitation recycling in the Amazon basin. Quarterly Journal of the Royal Meteorological Society, 120: 861-880.

FAO, 2015. Global Forest Resources Assessment 2015. FAO Forestry Paper No. 1. Food and Agricultural Organization of the United Nations (FAO). Rome.

Feng, X., Porporato, A., & Rodriguez-Iturbe, I. (2013). Changes in rainfall seasonality in the tropics. Nature Climate Change, 3(9), 811-815

Fitzherbert, E. B., Struebig, M. J., Morel, A., Danielsen, F., Brühl, C. A., Donald, P. F., & Phalan, B. (2008). How will oil palm expansion affect biodiversity? Trends in ecology & evolution, 23: 538-545.

Fu, R., Yin, L., Li, W., Arias, P. A., Dickinson, R. E., Huang, L., ... & Myneni, R. B. (2013). Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. Proceedings of the National Academy of Sciences, 110(45), 18110-18115.

GAIN (2016). Vietnam Coffee Report. USDA Agricultural Service Global Agricultural Information Service Foreign. Report No: VM6033 May 2016, 11pp.

Gourdji, S., Läderach, P., Valle, A. M., Martinez, C. Z., & Lobell, D. B. (2015). Historical climate trends, deforestation, and maize and bean yields in Nicaragua. Agricultural and Forest Meteorology, 200, 270-281.

Guhathakurta, P., Rajeevan, M., Sikka, D. R., & Tyagi, A. (2014). Observed changes in southwest monsoon rainfall over India during 1901–2011. International Journal of Climatology.

Guo Jun; Yin Yan (2015). Mineral dust impacts on regional precipitation and summer circulation in East Asia using a regional coupled climate system model. Journal of Geophysical Research: Atmospheres 2015 Vol. 120 No. 19 pp. 10378-10398

Ha, D. T., & Shively, G. (2005). Coffee vs. cacao: A case study from the Vietnamese central highlands. Journal of Natural Resources and Life Sciences Education, 34, 107-111.

Halder, S., Saha, S. K., Dirmeyer, P. A., Chase, T. N., Goswami, B. N. (2015). Investigating the impact of land-use land-cover change on Indian summer monsoon daily rainfall and temperature during 1951–2005 using a regional climate model. Hydrol. Earth Syst. Sci. Discuss, 12, 6575-6633.

Hang Vu-Thanh & Thanh Ngo-Duc & Tan Phan-Van (2014) Evolution of meteorological drought characteristics in Vietnam during the 1961–2007 period. Theoretical and Applied Climatology, 118(3), 367-375.

Ho Thi Minh Ha, Van-Tan Phan, Nhu-Quan Le, Quang-Trung Nguyen(2011). Extreme climatic events over Vietnam from observational data and RegCM3 projections. Clim Res, 49, 87-100.

Hua, W. J., Chen, H. S. (2013). Impacts of Regional-Scale Land Use/Land Cover Change on Diurnal Temperature Range. Advances in Climate Change Research. 4: 166-172.

Huong Ngo-Thanh, Thanh Ngo-Duc, Hanh Nguyen-Hong, Peter Baker, Tan Phan-Van (2016) Evaluating rainfall characteristics over the Central Highlands of Vietnam (in preparation).

Kajikawa, Y., Yasunari, T., Yoshida, S., & Fujinami, H. (2012). Advanced Asian summer monsoon onset in recent decades. Geophysical Research Letters, 39(3).

Kanae, S., Oki, T., & Musiake, K. (2001). Impact of deforestation on regional precipitation over the Indochina Peninsula. Journal of Hydrometeorology, 2(1), 51-70.

Katzfey, JJ, McGregor, JL and Suppiah, R (2014). High-Resolution Climate Projections for Vietnam: Technical Report. CSIRO, Australia. 266 pp.

Khoi, D. N., & Suetsugi, T. (2014). Impact of climate and land-use changes on hydrological processes and sediment yield—a case study of the Be River catchment, Vietnam. Hydrological Sciences Journal, 59(5), 1095-1108.

Khoi, D. N., Thom Vu Thi (2015). Impacts of climate variability and land-use change on hydrology in the period 1981-2009 in the Central Highlands of Vietnam. Globalnest International Journal 17:870-881 · DECEMBER 2015

Kim, D.-H., J. O. Sexton, and J. R. Townshend (2015). Accelerated deforestation in the humid tropics from the 1990s to the 2000s, Geophys. Res. Lett., 42: 3495–3501.

Kogan, F.; Guo Wei (2016). Early twenty-first-century droughts during the warmest climate. Geomatics, Natural Hazards and Risk 2016 Vol. 7 No. 1 pp. 127-137.

Kurbatova, Y. A., Kuricheva, O. A., Avilov, V. K., Dinh, B. D., Kuznetsov, A. N. (2015). Fluxes of energy, H2O, and CO2 between the atmosphere and the monsoon tropical forest in Southern Vietnam. Doklady Biological Sciences 464: 235-238.

Kuricheva, O. A., Avilov, V. C., Dinh, D. B., & Kurbatova, J. A. (2015). Water cycle of a seasonally dry tropical forest (Southern Vietnam). Izvestiya, Atmospheric and Oceanic Physics, 51(7), 693-711.

Lawrence D, Vandecar K (2015). Effects of tropical deforestation on climate and agriculture. Nature Climate Change 5, 27–36.

Lawton, R. O., Nair, U. S., Pielke, R. A. & Welch, R. M. (2001). Climatic impact of tropical lowland deforestation on nearby montane cloud forests. Science 294, 584–587.

Lee, T., & McPhaden, M. J. (2010). Increasing intensity of El Niño in the central-equatorial Pacific. Geophysical Research Letters, 37(14).

Leinenkugel, P., Wolters, M. L., Oppelt, N., & Kuenzer, C. (2015). Tree cover and forest cover dynamics in the Mekong Basin from 2001 to 2011. Remote Sensing of Environment, 158, 376-392.

Li, W., & Fu, R. (2004). Transition of the large-scale atmospheric and land surface conditions from the dry to the wet season over Amazonia as diagnosed by the ECMWF re-analysis. Journal of Climate, 17(13), 2637-2651.

Li, X., Zhai, G., Gao, S., & Shen, X. (2015). Decadal trends of global precipitation in the recent 30 years. Atmospheric Science Letters, 16(1), 22-26.

Limsakul, A. et al. (2011). PDSI-based variations of droughts and wet spells in Thailand: 1951-2005.

Limsakul, A., & Singhruck, P. (2016). Long-term trends and variability of total and extreme precipitation in Thailand. Atmospheric Research, 169, 301-317.

Malhi, Y., Gardner, T. A., Goldsmith, G. R., Silman, M. R., & Zelazowski, P. (2014). Tropical forests in the Anthropocene. Annual Review of Environment and Resources, 39, 125-159.

Makkonen, R., Asmi, A., Kerminen, V. M., Boy, M., Arneth, A., Hari, P., & Kulmala, M. (2012). Air pollution control and decreasing new particle formation lead to strong climate warming. Atmospheric chemistry and physics, 12: 1515-1524.

Nair, U. S., Lawton, R. O., Welch, R. M. & Pielke R. A. Sr (2003). Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of cumulus cloud field characteristics to lowland deforestation. J. Geophys. Res. 108, 4206.

Nguyen D-Q, Renwick J, McGregor J (2013). Variations of surface temperature and rainfall in Vietnam from 1971 to 2010. Int. J. Climatol. (2013)

Nguyen, H., & Shaw, R. (2011). Drought risk management in Vietnam. In: Droughts in Asian Monsoon Region: Emerald Group Publishing Limited, 141-161.

Panda, D. K., & Kumar, A. (2014). The changing characteristics of monsoon rainfall in India during 1971–2005 and links with large scale circulation. International Journal of Climatology, 34(15), 3881-3899.

Saad, S. I., da Rocha, H. R., Silva Dias, M. A. F. & Rosolem, R. (2010). Can the deforestation breeze change the rainfall in Amazonia? A case study for the BR-163 highway region. Earth Interact. 14, 18 (2010).

Salati, E., Dall'Olio, A., Matsui, E., & Gat, J. R. (1979). Recycling of water in the Amazon basin: an isotopic study. Water Resources Research, 15: 1250-1258.

Sano, M., Buckley, B. M., & Sweda, T. (2009). Tree-ring based hydroclimate reconstruction over northern Vietnam from Fokienia hodginsii: eighteenth century mega-drought and tropical Pacific influence. Climate dynamics, 33(2-3), 331-340.

Schmidt-Thome, P., Nguyen, T. H., Pham, T. L., Jarva, J., & Nuottimäki, K. (2015). Climate Change in Vietnam. In Climate Change Adaptation Measures in Vietnam (pp. 7-15). Springer International Publishing.

Seager, R., Naik, N., & Vogel, L. (2012). Does Global Warming Cause Intensified Interannual Hydroclimate Variability?. Journal of Climate, 25(9), 3355-3372.

Sen, O. L., Wang, Y. & Wang, B. (2004). Impact of Indochina deforestation on the East Asian summer monsoon. J. Clim.17, 1366–1380.

Sen, O. L., Bozkurt, D., Vogler, J. B., Fox, J., Giambelluca, T. W., & Ziegler, A. D. (2013). Hydro-climatic effects of future land-cover/land-use change in montane mainland southeast Asia. Climatic change, 118: 213-226.

Shepherd, J. M., Pierce, H., Negri, A. J. (2002). Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. Journal of Applied Meteorology, 41: 689-701.

Shi P J, Sun S, Wang M, et al. 2014. Climate change regionalization in China (1961–2010). Science China: Earth Sciences, 57: 1–14, doi:10.1007/s11430-014-4889-1

Silvério, D. V., Brando, P. M., Macedo, M. N., Beck, P. S., Bustamante, M., & Coe, M. T. (2015). Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. Environmental Research Letters, 10(10), 104015.

Spracklen, D. V., Arnold, S. R., & Taylor, C. M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. Nature, 489(7415), 282-285.

Takahashi, H. G., Yoshikane, T., Hara, M., & Yasunari, T. (2009). High-resolution regional climate simulations of the long-term decrease in September rainfall over Indochina. Atmospheric Science Letters, 10(1), 14-18.

Tan Phan Van, Thanh Ngo Duc, Nguyen Van Hiep (2013). Climate Change Assessment for Risk Management of Hydro-meteorological Disasters in Coffee Cultivation and Trading in the Vietnam Central Highlands. Unpublished report 49pp.

Tan Phan Van, Nguyen Van Hiep, Thanh Ngo Duc (2016). Variations and Changes in Rainfall and Drought in the Central Highlands, Vietnam. Unpublished report 63pp.

Tran, P., Marincioni, F., & Shaw, R. (2010). Catastrophic flood and forest cover change in the Huong river basin, central Viet Nam: A gap between common perceptions and facts. Journal of environmental management, 91(11), 2186-2200.

Tuan, D.A., 2015. Study on Drivers of Change Affecting Mekong Forests: Towards the Formulation of Action Plans for Great Mekong Sub-region Countries: Vietnam. USAID-LEAF and FAO, pp 77.

Ty, T. V., Babel, M. S., Sunada, K., Oishi, S., & Kawasaki, A. (2009). Utilization of a GIS-based water infrastructure inventory for water resources assessment at local level: a case study in mountainous area of Vietnam. Hydrological Research Letters, 3, 27-31.

UNCCD, 2006. Vietnam National Report on the UNCCD Implementation 2006 (Ha Noi,Vietnam).

Webb, T. J., Woodward, F. I., Hannah, L. & Gaston, K. J. Forest cover–rainfall relationships in a biodiversity hotspot: the Atlantic forest of Brazil. Ecol. Appl. 15, 1968–1983 (2005).

Vu, Q. M., Le, Q. B., & Vlek, P. L. (2014). Hotspots of human-induced biomass productivity decline and their social–ecological types toward supporting national policy and local studies on combating land degradation. Global and Planetary Change, 121, 64-77.

Vu, M. T., Raghavan, S. V., Pham, D. M., & Liong, S. Y. (2015). Investigating drought over the Central Highland, Vietnam, using regional climate models. Journal of Hydrology, 526, 265-273.

Yazid, M. (2015). Regional Observed Trends in Daily Rainfall Indices of Extremes over the Indochina Peninsula from 1960 to 2007. Climate, 3(1), 168-192.

Yu, R., & Zhou, T. (2007). Seasonality and three-dimensional structure of interdecadal change in the East Asian monsoon. Journal of Climate, 20(21), 5344-5355.

Zhang et al. 2002 Onset of the Summer Monsoon over the Indochina Peninsula: Climatology and Interannual Variations. Journal of Climate 15: 3206

Zhang L, Zhou T. (2011) An assessment of monsoon precipitation changes during 1901–2001. Clim Dyn 37:279–296

Zhao, P., Yang, S., & Yu, R. (2010). Long-term changes in rainfall over eastern China and large-scale atmospheric circulation associated with recent global warming. Journal of Climate, 23(6), 1544-1562.

Zhou, T., Yu, R., Li, H., & Wang, B. (2008). Ocean forcing to changes in global monsoon precipitation over the recent half-century. Journal of Climate, 21(15), 3833-3852.