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PART I

Contemporary atmospheric change in the tropics



Late twentieth-century patterns and trends in the climate of tropical forest regions

Yadvinder Malhi and James Wright

We present an analysis of the mean climate and climatic trends of tropical rainforest regions over the period 1960–98, with the aid of climatological databases. Up until the mid-1970s most regions showed little trend in temperature, and the western Amazon experienced a net cooling probably associated with an interdecadal oscillation. Since the mid-1970s all tropical rainforest regions have experienced a strong warming at a mean rate of $0.26 \pm 0.05^\circ\text{C}$ per decade, in synchrony with a global rise in temperature that has been attributed to the anthropogenic greenhouse effect. Over the study period precipitation appears to have declined sharply in northern tropical Africa (at 3–4% per decade), declined marginally in tropical Asia, and showed no significant trend in Amazonia. There is no evidence to date of a decline in precipitation in eastern Amazonia, a region thought vulnerable to climate-change induced drying. The strong drying trend in Africa suggests that this should be a priority study region for understanding the impact of drought on tropical rainforests. Only African and Indian tropical rainforests appear to have seen a significant increase in dry season intensity. The El Niño-Southern Oscillation is the primary driver of interannual temperature variations across the tropics, and of precipitation fluctuations for large areas of the Americas and Southeast Asia.

Introduction

The global atmosphere is undergoing a period of rapid human-driven change, with no historical precedent in either its rate of change, or its potential absolute magnitude (IPCC 2001). There is considerable concern at how this change may affect Earth's ecosystems, and in turn how these system responses may feed back to accelerate or decelerate global change. This threat is spawning considerable laboratory and field research into ecosystem responses to climate. This research gains its justification from the global change agenda. However, there is a gap between global context and local research that can sometimes feel unsatisfactory.

On one hand, global warming trends over the twentieth century have been examined compre-

hensively at global or regional levels (e.g. Jones *et al.* 1999; New *et al.* 2001; Giorgi 2002), particularly through the work of the IPCC (e.g. Folland *et al.* 2002). Among other issues, this has prompted concern at how ecosystems may respond to such trends. Yet there have been few attempts to examine climate trends at the level of specific biomes, and in particular the tropical rainforest biome.

On the other hand, there has recently been a surge of research aimed at understanding the interactions between climate change and tropical rainforest ecology and function, which is reflected in several of the chapters in this book. However, in their justification of their research agenda, tropical forest researchers generally have had to rely on broad or global climatic trends reported by the

IPCC, or generalities about warming or drying climates. But what are the recent trends in the climate of the region or biome being studied, and how do these trends compare with general trends in tropical rainforest regions, and with projections from global climate models?

In Malhi and Wright (2004), we presented a detailed analysis of spatial patterns and recent trends in the world's tropical forest regions since the 1960s. In this chapter, we present a summary of the results presented there, with updates where new studies and literature have appeared. For colour maps of the patterns described the reader is referred to the original paper.

We use recent global climatic datasets to examine the spatial variability of tropical rainforest climates. In public imagination, the climate of the tropical rainforest is frequently characterized as 'ever-warm and ever-wet'. In reality, however, although the 'ever-warm' is generally true (but not always), tropical rainforest regions can span a wide range of intensity and seasonality of rainfall. Moreover, many regions can experience significant interannual, interdecadal, and perhaps intercentennial variability in rainfall, and the regularity and intensity of drought can have a major impact on forest structure and adaptation. In the face of this spatial and temporal heterogeneity, there can be a danger of extrapolating too much from intensive studies of tropical rainforest in one locale; thus a global synthesis of tropical rainforest climate helps to put the climate of any particular site into context. The new global observational climatologies can be a powerful tool with which to address questions in tropical rainforest ecology.

We focus on three climatic parameters: temperature, precipitation, and dry season intensity. There are other atmospheric parameters that are varying and may have a direct effect on tropical forests, the principal examples being carbon dioxide concentrations, direct and diffuse solar radiation, and nitrogen deposition. Their possible influences are reviewed by Lewis, Malhi, and Phillips in Chapter 4, this volume. We also examine in particular detail the role of the El Niño-Southern Oscillation, which is the primary driver of interannual climate variability in the tropics.

In this chapter we address the following questions:

1. What is the spatial heterogeneity of the contemporary climate of tropical rainforest regions, and the representativeness of particular study regions?
2. How is interannual variability in temperature, precipitation, and drought stress in different regions related to the El-Niño-Southern Oscillation, the primary driver of present-day climatic variability in the tropics?
3. What are the trends in temperature, precipitation, and drought stress in the last 40 years, and how do we interpret these trends in terms of possible artefacts, longer-term oscillations, and net anthropogenic trends?

Methods

Before embarking on this analysis, we emphasize one important caveat: the ocean-atmosphere system may exhibit a number of multi-decadal internal oscillations, and trends observed over a 39-year period may not reflect longer-term variations. Hence caution must be applied in attributing these short-term changes to a longer-term trend caused by anthropogenic influences. Malhi and Wright (2004) illustrated this feature by demonstrating a century-long record of precipitation from Manaus in central Amazonia. In this record there was an evidence of a multidecadal oscillation in precipitation, which resulted in the precipitation trend in the last 40 years ($-0.5 \pm 5.5\%$ per decade) being different from the century-long trend ($2.6 \pm 1.2\%$ per decade).

The datasets and analysis procedures used in this chapter have been described in Malhi and Wright (2004) and this description is not repeated here. However, we do review briefly our definition of a dry season index. In most tropical terrestrial ecosystems, the most evident climatic factor is the duration and intensity of the dry season. The mean evapotranspiration rate (E) of a fully wet tropical rainforest is about 100 mm per month (Shuttleworth 1989; Malhi *et al.* 2002a); hence a common definition of dry season is when the precipitation (P) is less than 100 mm per month (i.e. when the forest is

in net water deficit), and a common parameter for dry season length is the number of months per year with $P < 100$ mm. However, this does not capture the importance of degrees of intensity: a dry season where P drops to 10 mm per month is more severe than one where it hovers at 90 mm per month. Similarly, many regions (particularly in Africa) experience a 'double-dip' pattern in rainfall, with two short dry seasons, which are less severe than one long dry season of equivalent total duration. Similarly, the dry season length does not capture the importance of soil 'memory'—that is, whether a soil is fully hydrated or only partially hydrated in the months preceding a dry month.

We developed a dry season index (DSI) in Malhi and Wright (2004) to represent the strength and duration of the dry season, calculated from precipitation data using a simple water balance model that incorporates seasonal variations of precipitation and field-calibrated evapotranspiration. The DSI as defined here does not take into account seasonal variations and long-term trends in temperature and solar radiation, except as implicitly correlated terms for the particular central Amazonian calibration site. Any net warming trend would be expected to increase actual water stress. Hence our DSI should be thought of as a descriptor

of dry season length and intensity, rather than a measure of water stress.

To maintain simplicity in the summary charts we have divided the tropical rainforest area into sub-regions (not always contiguous), which are shown in Fig. 1.1. The names ascribed to each region are convenient geographical terms, rather than referring to political entities. The climate results were overlaid with masks of tropical forests cover which were derived from FAO Global Forest Resources Assessment 2000 (FAO Forestry Paper 140, available online at www.fao.org/forestry/fo/fra) and coarsened to 0.5° resolution to match the climate data.

The mean climate of tropical rainforest regions

Globally, the mean annual precipitation of the tropical rainforest region is 2180 mm, the mean temperature is 25.4°C , and the mean insolation is 16.5 GJyr^{-1} (Table 1.1). There is considerable variation in precipitation around this mean, with east Malesia and north-west Amazonia the wettest tropical rainforest regions with about 3000 mm of rain per year, and almost all of Africa much drier than the mean. There is less variation in mean temperature and solar radiation, although the

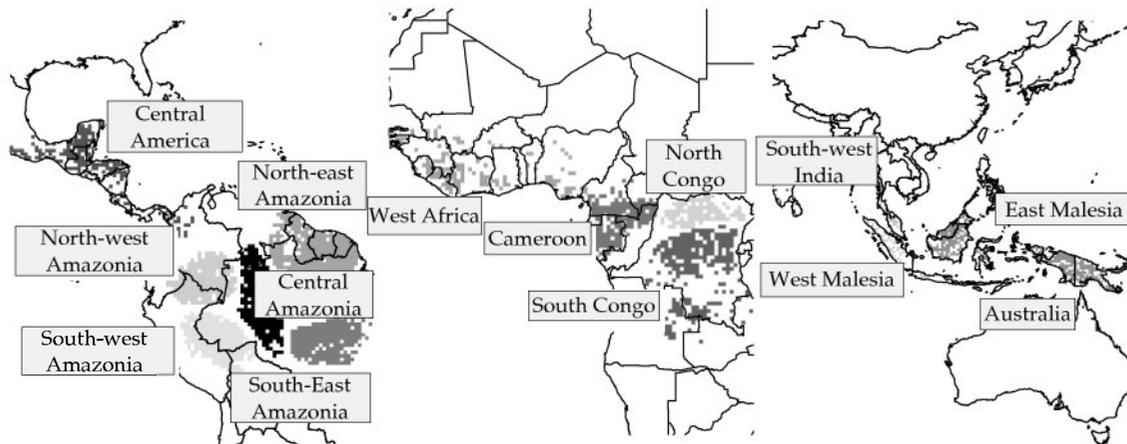


Figure 1.1 A map of the tropical rainforest sub-regions allocated for this analysis. Names of sub-regions are convenient geographical descriptors rather than reflecting political identities. (See Plate 1(a–c)).

Table 1.1 The mean climate of tropical rainforest regions over the period 1960–98 (1960–95 for solar radiation)

Region	Mean			Seasonal Variation			Dry Season		SD Peak DSI (mm)
	<i>P</i> (mm)	<i>S</i> (GJ yr ⁻¹)	<i>T</i> (°C)	<i>P</i> Fractional	<i>S</i> Fractional	<i>T</i> (°C)	Length (months)	Peak DSI (mm)	
<i>Central America</i>	2206	17.3	24.0	2.4	0.42	4.4	4.7	126	15.2
North-west Amazonia	2962	15.6	25.9	1.2	0.13	2.3	0.6	15	13.9
South-west Amazonia	2194	16.3	25.7	1.8	0.17	3.2	3.3	89	25.1
Central Amazonia	2420	15.6	26.2	1.6	0.23	2.4	2.3	56	15.2
North-east Amazonia	2260	16.6	26.0	2.0	0.26	2.2	3.7	82	26.7
South-east Amazonia	2103	16.1	25.5	2.3	0.31	2.9	4.5	149	21.8
West Africa	1601	16.6	26.3	2.7	0.28	4.6	5.8	165	14.4
Cameroon	1782	15.2	24.6	2.1	0.18	3.0	4.3	82	13.5
North Congo	1689	17.6	24.5	1.7	0.14	2.5	3.6	104	21.4
South Congo	1530	16.5	23.8	1.8	0.26	2.7	4.3	118	12.1
South-west India	1993	18.3	25.9	3.2	0.32	4.0	5.9	148	22.7
West Malesia	2584	17.1	25.3	2.1	0.31	3.2	2.9	72	9.2
East Malesia	3094	16.7	25.4	1.4	0.18	1.6	1.2	23	15.3
Australia	1702	20.1	24.2	3.5	0.22	6.7	7.0	193	24.1
Pantropical mean	2178	16.5	25.4	2.0	0.24	3.2	3.7	—	—

Notes: *P* = precipitation, *S* = solar radiation, *T* = temperature. Seasonal variation in precipitation and temperature is normalized by dividing by annual mean values. SD Peak is the standard deviation of the annual peak DSI values.

equatorial African forests are generally cooler by virtue of being at high elevation, and outer tropical rainforests tend to have slightly cooler annual means. For a given dry season regime, these cooler forests suffer less water stress.

Indices of seasonality are also shown in Table 1.1. These are defined as (mean annual maximum value – mean annual minimum value)/mean annual value for precipitation and solar radiation. For temperature they are not normalized by dividing by the mean.

The estimates for Australia and south-west India need to be treated with particular caution, as these are small areas of tropical rainforest in areas with strong spatial gradients in climate associated with mountains. This spatial variability is probably not adequately sampled, and the 0.5° scale of the interpolated climate data may not distinguish between tropical rainforest areas and adjoining drier areas.

The spatially averaged maximum DSI for each region is also shown in Table 1.1. As would be expected, the outlying tropical rainforest regions

show the greatest seasonality and dry season intensity (Australia, west Africa, south-west India, Central America), and the 'core' tropical regions the weakest dry seasons (north-west and central Amazonia, all of Malesia). However, there are significant longitudinal trends, and the core regions of tropical Africa (north and south Congo and Cameroon) are still fairly water-stressed, as is north-east Amazonia. As a whole, African tropical rainforests are the most water-stressed, and Asian forests the least. Maximum DSI is not shown for the global tropics, as the asynchrony of dry seasons across such a large area make this term meaningless.

A plot of the maximum DSI against the dry season length shows a general linear relationship between these two terms (not shown). North-east Amazonia and Cameroon fall significantly below this line; here dry seasons are 'shallower' than the mean and hence the peak DSI is lower than would be expected. South-east Amazonia falls significantly above this line, and experiences more intense dry seasons than the mean.

Variation in temperature 1960–98

Interannual variability in temperature

The pantropical temperature anomaly for the tropical rainforest regions for the period 1960–98 is shown in Fig. 1.2. The multivariate El Niño index is also shown in the same figure. Over this time-scale, the interannual variability of temperature in tropical rainforest regions is clearly greater than any net trend. This variation clearly shows a strong correlation with the ENSO, with mean temperatures about 1°C higher during El Niño events

(positive ENSO index) than during La Niñas. The Pearson correlation between mean temperature and the multivariate ENSO index for various lag times is shown in Fig. 1.3. Globally, the mean temperature of tropical rainforests lags behind the ENSO index with a mean lag time of two months, and a correlation coefficient $r=0.64$. The correlation is greatest in Southeast Asia ($r=0.64$, lag = 4 months), intermediate in Africa ($r=0.57$, lag = 4 months), and least in the Americas ($r=0.52$, lag = 1 month). Considering sub-regions, the greatest correlations are in western Malaysia ($r=0.62$, lag = 3 months),

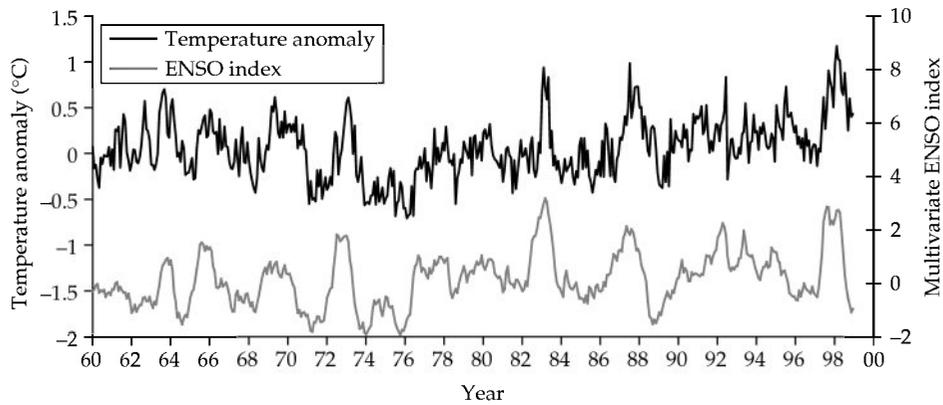


Figure 1.2 Time series of pantropical temperature anomaly relative to the period 1960–98 and the multivariate ENSO index.

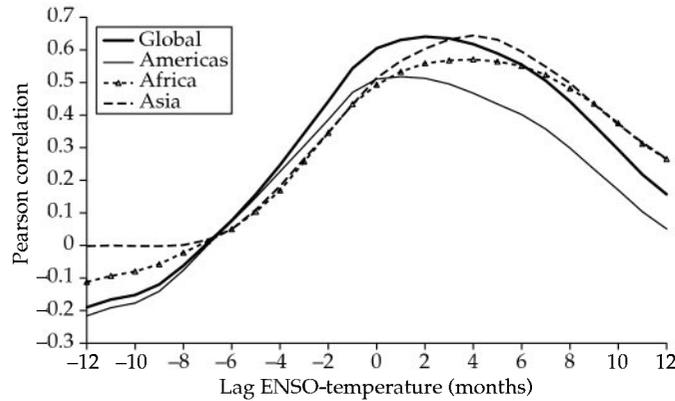


Figure 1.3 The cross-correlation function between mean temperature in each tropical rainforest continent and ENSO.

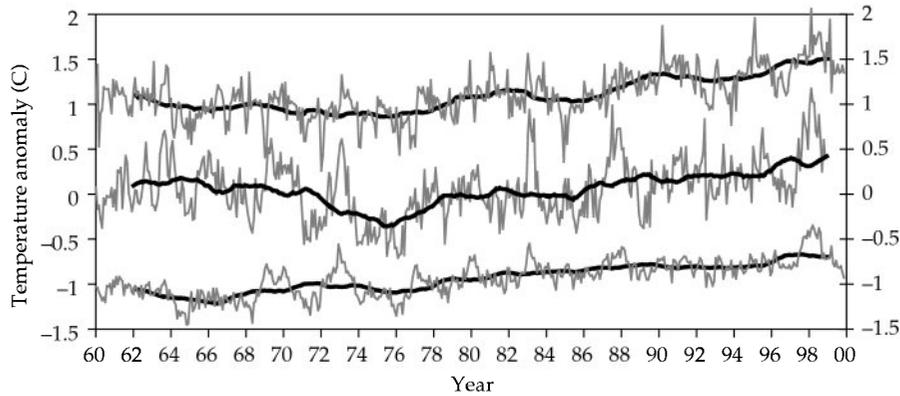


Figure 1.4 Time series of the tropical rainforest temperature anomaly (centre line), compared with the global (land and sea) temperature anomalies for the same period for the Northern (top line) and Southern (bottom line) Hemispheres. The thicker lines are 4-year moving averages.

north-east Amazonia ($r=0.60$, lag = 2 months), and south-west India ($r=0.60$, lag = 2 months) (not shown); the lowest correlations are in south-west Amazonia ($r=0.24$, lag = 0 months).

Maps of the correlation between deseasonalized temperature and the ENSO index are presented in Malhi and Wright (2004). In Africa the strongest temperature influence is felt in the Congo basin, and in Asia across peninsular and insular Southeast Asia, with a weaker correlation in New Guinea. The Americas show the most striking spatial gradients, with a strong ENSO influence on temperatures in northern and eastern Amazonia, and in Central America, and almost no ENSO influence in south-west Amazonia. No tropical rainforest region is cooler during El Niño events.

Pantropical trends in temperature

A simple linear trend through the global tropical rainforest temperature time series yields a significant ($p < 1\%$) temperature trend of $+0.08 \pm 0.03^\circ\text{C}$ per decade (i.e. a net increase of 0.31°C between 1960 and 1998).¹ The pantropical mean time series shows a net cooling during the period from 1960 to 1974 ($-0.08 \pm 0.11^\circ\text{C}$ per decade) and a subsequent strong warming; since 1976 the net warming has been at a rate of $0.26 \pm 0.05^\circ\text{C}$

per decade ($p < 0.001\%$). This post-1976 warming is observed in all three major tropical rainforest regions (Americas $0.26 \pm 0.07^\circ\text{C}$ per decade, Africa $0.29 \pm 0.06^\circ\text{C}$ per decade, Asia $0.22 \pm 0.04^\circ\text{C}$ per decade).

The results reported here are in agreement with the general trends observed by the IPCC (Folland *et al.* 2002) using a variety of climate datasets. For the tropics as a whole (land and seas), surface temperature increased by 0.08°C per decade between 1958 and 2000, a trend which can be divided into a cooling period from 1958 to 1978 ($-0.09 \pm 0.12^\circ\text{C}$ per decade), and a warming period since 1978 ($+0.10 \pm 0.10^\circ\text{C}$ per decade). The pattern of relatively invariant or slightly cooling global temperatures between the 1940s and 1970s, followed by a rapid warming since the mid-1970s, is a feature of the global temperature pattern in both Northern and Southern Hemispheres, and the warming trend over tropical rainforests appears to fit this global pattern (Fig. 1.4). The rates of warming in tropical rainforest regions between 1976 and 1998 ($0.26 \pm 0.05^\circ\text{C}$ per decade) compares with a global mean land surface temperature rise of $0.22 \pm 0.08^\circ\text{C}$ per decade between 1976 and 2000, and lie between the rates observed for the Northern Hemisphere ($0.31 \pm 0.11^\circ\text{C}$ per decade) and the Southern Hemisphere ($0.13 \pm 0.08^\circ\text{C}$ per decade) as a whole (Jones *et al.* 2001).

¹ All significant values calculated in this manuscript are estimated from the two-tailed Mann-Kendall rank statistic.

Regional trends in temperature

The mean temperature trends in each region are summarized in Fig. 1.5, for the overall period (Fig. 1.5(a)), and the period 1976–98 (Fig. 1.5(b)). All regions showed a net warming over the overall period except central and western Amazonia, and all regions showed strong warming since 1976 of between 0.15 and 0.4°C per decade. The cooling in western Amazonia occurred in the early 1970s and was followed by steady warming, and it is this cooling that causes the dip in global mean tropical

rainforest temperatures over the same period. Close examination of individual station time series shows that this cooling–warming in western Amazon is real and not an artefact of station switching (Malhi and Wright 2004). The overall positive trend is partially influenced by positive temperature anomalies of 1.0–1.5°C during the 1983 and 1998 El Niño events, but the trend is only reduced by 0.03°C per decade when these peaks are removed.

Victoria *et al.* (1998) conducted an analysis of 17 stations in the Brazilian Amazon from 1913

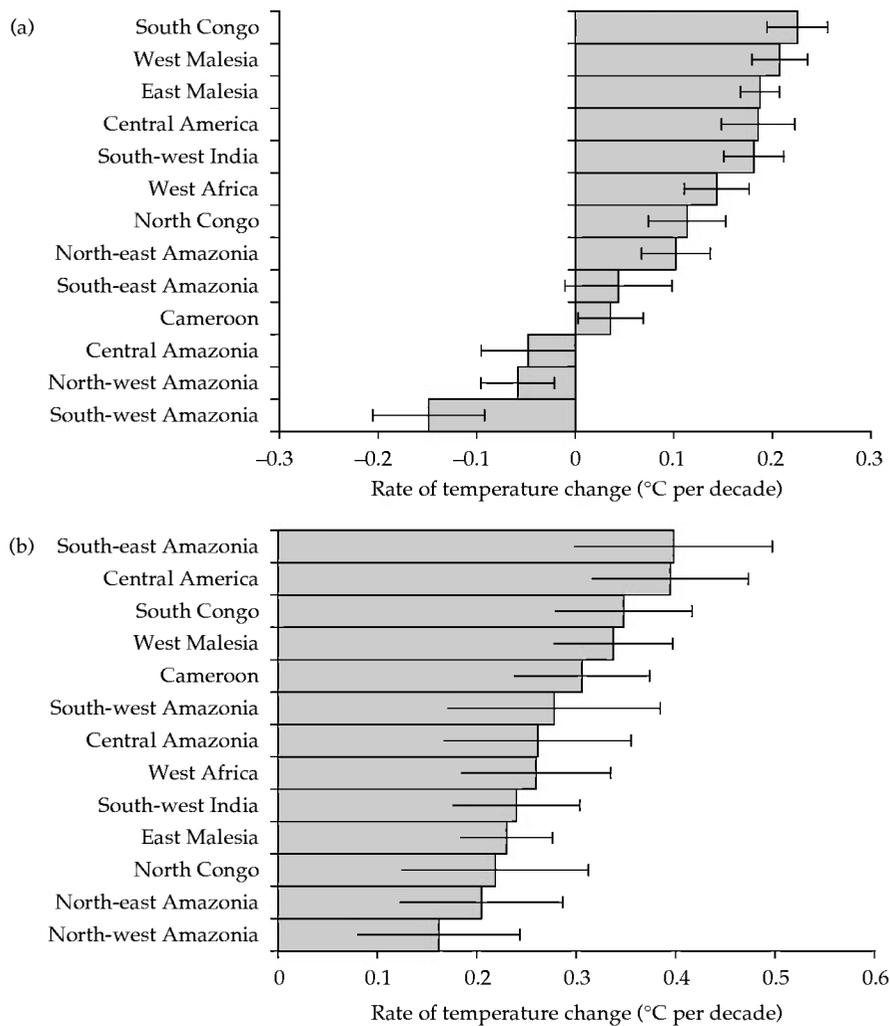


Figure 1.5 Temperature trends in each tropical rainforest sub-region (a) for the period 1960–98; (b) for the period 1976–98.

to 1995, taking care to eliminate stations with discontinuities in methodologies. They report little variation in the period 1910–40, a decade-long dip by 0.3°C in the 1950s, and a period of rapid warming since the mid-1970s at a rate of about 0.25°C per decade. New *et al.* (2001) analysed the temperature trends for the whole African continent over the twentieth century, and observed a warming up to the 1940s, a slight cooling up to the mid-1970s, and a rise of about 0.8°C since then. Hence the overall pattern of rapid and pantropical recent warming is confirmed, but in the longer-term trends there can be significant regional differences.

Variations in precipitation 1960–98

The mean monthly precipitation anomaly over tropical rainforest regions for the period 1960–98 is shown in Fig. 1.6, calculated using the same procedure as for temperature. Compared to temperature, the precipitation record is much more variable, both spatially and temporally.

Interannual variability in precipitation

As with the temperature time series, the interannual variability of precipitation in tropical rainforest regions is greater than any net trend. Globally, this variation shows a reasonably strong

inverse correlation with the ENSO, with less precipitation during El Niño events. This reduction in precipitation is principally caused by the warming of the eastern Pacific causing enhanced convection in this region and compensatory zones of air subsidence in northern South America and Southeast Asia, which suppress rainfall in these normally highly convective regions. The correlation between the precipitation anomaly and the ENSO index for various lag times is shown in Fig. 1.7. Globally, the mean precipitation of tropical rainforests does not lag behind the ENSO index (lag time 0 or –1 months) and the correlation is weaker than that for temperature ($r = -0.44$, compared to $r = 0.64$ for temperature). The correlation is greatest in Southeast Asia ($r = -0.48$, lag = –3 months), intermediate in the Americas ($r = -0.35$, lag = 0 months), and very weak for Africa ($r = -0.12$, no distinctive lag). The comparison with temperature in Africa is particularly noteworthy: although African forests are consistently warmer during El Niño events, they are not generally much drier; hence the higher temperatures are not induced by local drought, but perhaps by more general atmospheric and oceanic changes, such as increases in surface temperatures in the Indian and Atlantic Oceans. In almost every tropical rainforest region, the peak changes in precipitation precede

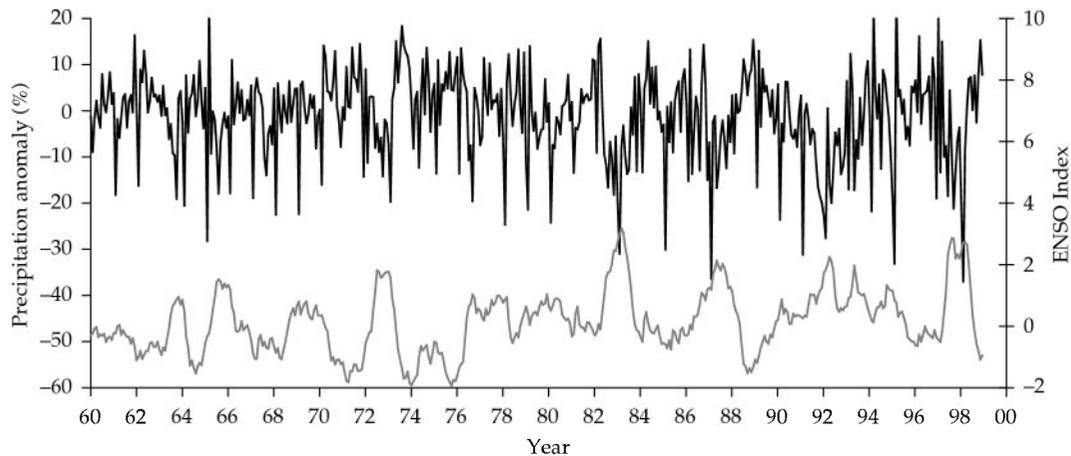


Figure 1.6 Monthly time series of pantropical precipitation anomaly for the period 1960–98 (top line) and the multivariate ENSO index (bottom line). The percentage is calculated relative to the pantropical mean precipitation for tropical rainforests ($181.5 \text{ mm per month}$, or 2177 mm yr^{-1}).

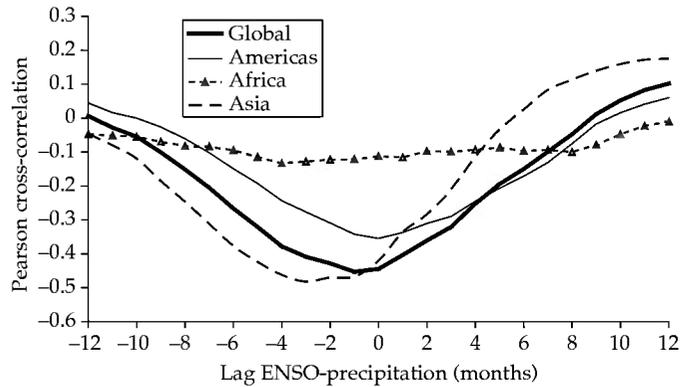


Figure 1.7 Cross-correlation function of the precipitation anomaly and the ENSO index for the three tropical rainforest continents.

changes in temperature, and often also precede peaks in the ENSO index.

Maps of the ENSO correlation with deseasonalized precipitation have been shown in Plate 1. Throughout Africa the correlation is negative but weak. It appears that some El Niños do significantly affect Africa, but the teleconnection from the tropical Pacific is variable, and appears to be dependent on the exact seasonal timing of the El Niño, and the extent to which it influences Indian and Atlantic Ocean temperatures (Nicholson *et al.* 2000). In contrast, in both the Americas and Asia many tropical rainforest regions show a strong response to ENSO. The largest inverse correlations (reduced precipitation during El Niños) are seen in north-eastern Amazonia and in a band running from Borneo to New Guinea. In contrast, many regions at the dry fringe of the tropical rainforest belt (southern and northern tips of Amazonia, northern Central America, northern fringe of Congo, parts of Southeast Asia) show a weak positive correlation, with increased precipitation during El Niño events.

Trends in precipitation

A simple linear trend through the pantropical anomaly time series yields a decline in annual precipitation rates of -22 ± 17 mm per decade, or $-1.0 \pm 0.8\%$ per decade ($p < 0.05$). This is a net decrease of about 86 mm between 1960 and 1998. There is little pantropical trend between 1960 and the mid-1970s, and a more marked decline since then. Because of the high interannual variability, the

trends are generally of low significance. It must be emphasized that the trend over four decades may not necessarily be indicative of a longer-term trend.

In the three tropical rainforest continents, there is no overall significant trend in precipitation in the American tropical rainforests ($-0.6 \pm 1.1\%$ per decade), a moderately significant drying trend in Asia ($-1.0 \pm 1.1\%$ per decade, $p < 0.05$), and a strong drying trend in Africa ($-2.4 \pm 1.3\%$ per decade, $p < 0.0001$). It is this strong drying trend in Africa that drives the overall pantropical decline.

A map of spatial variations in the linear trends is presented in Malhi and Wright (2004). Most tropical regions show a drying trend over this period, with the exception of north-east Amazonia and Central America. However, at a regional level the interannual variation is non-significant in many regions. The only significant trends are in eastern Malesia ($-1.0 \pm 1.4\%$ per decade; $p < 0.05$), much of Africa (West Africa $-4.2 \pm 1.2\%$ per decade ($p < 10^{-5}$); north Congo $-3.2 \pm 2.2\%$ per decade ($p < 0.05$), south Congo $-2.2 \pm 1.8\%$ per decade ($p < 0.1$)), and south-west India $-3.5 \pm 2.9\%$ per decade ($p < 0.05$). One noteworthy feature is that the drying trends tend to be strongest in regions which are least directly affected by El Niño events, whereas the trends are small or even reversed in some of the El Niño susceptible regions (Malesia, north-east Amazonia). A highly significant drying trend in north-west Amazonia is most likely a station-switching artefact (Malhi and Wright 2004) and is not shown here.

In Asia, a modest drying trend is observed over the entire period, with few regional anomalies, again suggesting that station switching is not a major problem. Because of the interannual variability, in most areas of Africa and Asia the trends are not significant at sub-regional level, but the broad spatial consistency makes the overall trend marginally significant for Asia ($p < 0.05$), and highly significant for Africa ($p < 10^{-4}$).

The most noteworthy feature in the precipitation results is the strong drying trend in northern African tropics. This pattern is confirmed by Nicholson *et al.* (2000), who examined meteorological data from a much larger dataset in Africa (1400 weather stations, including many in the Congo Basin). They demonstrated a strong drying trend in northern sub-Saharan Africa, centred on major droughts in the Sahel but extending into the tropical rainforest belt of west Africa and north Congo. The drying peaked in the 1980s, when most of west Africa and the Congo basin were anomalously dry (the non-rainforest regions of east Africa, on the other hand, were anomalously wet). In the 1990s there are hints of some recovery, particularly in the eastern most sectors (east Nigeria, Cameroon, Gabon) but in most regions

rainfall was still well below the long-term mean. Rainfall trends in equatorial Africa appear more spatially variable, and do not show the same strong net drying. The drying trend appears to have started in the mid-twentieth century: overall in the west Africa/north Congo tropical rainforest belt, rainfall levels were about 10% lower in the period 1968–97 than in the period 1931–60 (Nicholson *et al.* 2000).

For Brazilian Amazonia, Marengo *et al.* (2004) conducted an analysis of extensive rain gauge data. They reported regionally a significant decline in rainfall in northern Amazonia since the mid-1970s. River data from northern Amazonia indicate wetter periods in the mid-1970s, and drier periods in the 1980s. Multi-decadal variations in precipitation in Amazonia seem to be dominating over any long-term trend. This was also demonstrated by an analysis of a long term rainfall record from Central Amazonia by Malhi and Wright (2004).

Strength and intensity of dry season

The mean annual maximum dry season index (DSI) over the three tropical rainforest continents is shown in Fig. 1.9. Globally, there is no significant

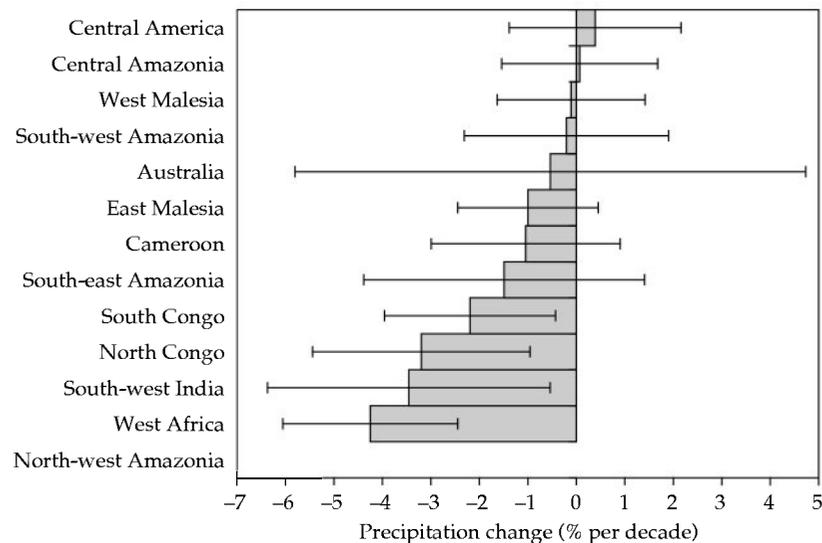


Figure 1.8 Bar chart of precipitation trends in each tropical rainforest sub-region for the period 1960–98. The trend for north-west Amazonia seems to be an artefact generated by the interpolation method and is not shown.

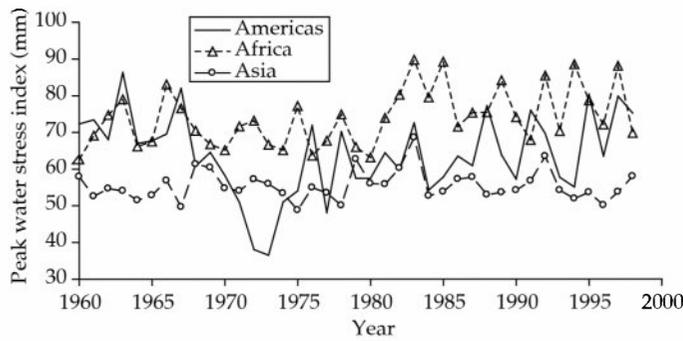


Figure 1.9 Time series of the dry season index over the three tropical rainforest continents.

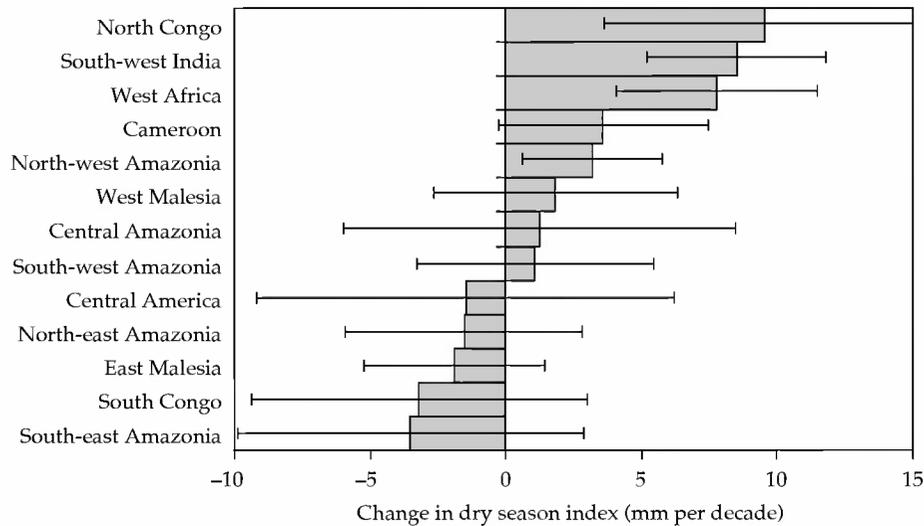


Figure 1.10 Bar chart of trends in dry season index for each tropical rainforest sub-region for the period 1960–98.

trend in maximum DSI (-0.5 ± 1.7 mm per decade). However, for DSI it is particularly important to consider local trends rather than pantropical averages, because of the asynchrony of the time of peak DSI in different regions. On a continental level, there is no significant trend in Asia (0.2 ± 1.2 mm per decade) or the Americas ($+0.4 \pm 3.2$ mm per decade), but there has been a moderately significant increase in dry season intensity in Africa ($+2.8 \pm 2.0$ mm per decade, $p < 0.05$).

A bar chart of trends in maximum dry season index in the various sub-regions is shown in Fig. 1.10. The drying trend in Africa is driven by a

steady increase in dry season intensity throughout the northern African tropics (west Africa $+7.8 \pm 3.3$ mm per decade, $p < 0.0001$; north Congo $+9.5 \pm 5.3$ mm per decade, $p < 0.01$; Cameroon $+3.6 \pm 3.7$ mm per decade, $p < 0.10$), perhaps slightly offset by a modest weakening of dry season in the southern Congo (-3.2 ± 3.3 mm per decade, $p < 0.05$). A similar drying trend is seen in south-west India ($+8.5 \pm 5.9$ mm per decade, $p < 0.01$). In contrast, a significant reduction in dry season index in this period is indicated for the Australian tropical rainforest belt (-8.4 ± 6.4 mm per decade, $p < 0.01$). Once again, on the basis of

the limited dataset used here, the trend for much of the DRC needs to be treated with caution. However, this pattern of general drying in northern sub-Saharan Africa is clearly observed in the more comprehensive analysis by Nicholson *et al.* (2000), as is the peak in drying throughout the African tropical rainforest belt in the 1980s.

The contrast between, for example, the hydrological regimes of north Congo (steadily dry, seasonal, and getting drier), Malaysian (generally very wet but occasionally very drought-stressed), and north-west Amazonian (almost always wet) tropical rainforests is marked, and suggests that successful trees in these regions need to adopt very different survival strategies.

Discussion

The climate of tropical rainforest regions clearly exhibits considerable variation in rainfall patterns, from no seasonality to high degrees of seasonality and interannual variability. The 'average' tropical rainforest (Table 1.1) can be said to have an annual rainfall of 2180 mm, a dry season of 3–4 months, a mean annual temperature of 25.2°C with a seasonal range of 3.2°C, and a mean insolation of 16.5 GJ, but there is considerable variation, particularly in the hydrological parameters. As a whole, African tropical rainforests are generally drier, at higher elevation, and cooler than those of other continents.

On an interannual timescale, it is clear that the ENSO is the primary driver of temperature variations through most of the tropics, and of precipitation in the Americas and Southeast Asia. The correlation between tropical rainforest temperature and the ENSO index is particularly remarkable. The teleconnections between ENSO and rainfall in the tropical rainforest regions of Africa are less clear, and appear to depend on the seasonal timing of events. For example, the strong El Niño of 1998 appeared to have little influence on rainfall in African tropical rainforests (Nicholson *et al.* 2000). It is noteworthy that temperature in African forests still appears to respond to the ENSO signal even when there is no precipitation response; hence, the

rise in temperature does not seem to be driven by local drought, but by a general increase in mean tropical surface temperatures.

It is also clear that climatic oscillations on multi-decadal timescales are important in many tropical climates, and caution should be used in attributing many of the trends observed here to anthropogenic climate change. A particular example is the apparent multi-decadal oscillation in temperature in western Amazonia, a feature that was also noted by Botta *et al.* (2002). The strong drying trend in the northern African tropics may also be driven by an oscillation in Atlantic Ocean temperatures, but global warming may also be driving a secular shift in Atlantic temperatures.

A substantial and rapid warming of about 0.26°C per decade is evident in all tropical rainforest regions since the mid-1970s. The recent rise is highly significant and global in extent: the net increase of about 0.6°C in recent decades is comparable with the amplitude of temperature oscillation induced by the ENSO. This feature is remarkable and perhaps not noted sufficiently in discussions of century-long trends: on the physiologically relevant timescale of years to decades, tropical rainforests have experienced rapid warming. The pantropical extent of this rise suggests that it is not induced by a local climatic oscillation or by local land use change effects. This trend since the 1970s seems to be synchronous with, and consistent with, changes in the global climate over the same period that have been ascribed to the anthropogenic greenhouse effect (IPCC 2001). It thus seems likely that this recent trend is indeed a signal of the anthropogenic greenhouse effect. Climate models suggest that a warming by 2–5°C can be expected in tropical rainforest regions over this century (Cramer *et al.*, Chapter 2, this volume), a change that seems likely to have a substantial impact on tropical rainforest physiology (e.g. Cowling *et al.*, Chapter 16, this volume).

There is much greater uncertainty in how tropical precipitation regimes will respond to changes in the global atmosphere. Globally, evaporation rates are expected to increase, the atmosphere is

expected to become more humid, and rainfall rates to increase. Indeed, satellite observations of upper-tropospheric humidity from 1980 to 1997 show statistically positive trends of $0.1\% \text{ yr}^{-1}$ for the zone 10°N to 10°S . However, any pantropical trends in precipitation are expected to be eclipsed by strong regional variations as atmospheric circulation patterns shift. There is little agreement among climate models on the future pattern of rainfall in the tropics.

The results presented here confirm that regional trends in precipitation and dry season intensity do indeed dominate over any coherent pantropical trend. The high interannual variability of precipitation makes it difficult to detect any overall trend in the American tropics, but there is a hint of a marginally significant drying trend in the Asian tropics. In African tropical rainforest regions, however, the drying trend is very strong, particularly at the northern edge of the tropical rainforest zone. This trend appears to be associated with the general drying of the Sahel region in the second half of the twentieth century. This overall drying in the tropical forest belt contrasts with the general expectation that precipitation levels will increase with global warming. However, the net pattern of precipitation change projected for tropical rainforests (typically between -1 and $+2\%$ per decade; Giorgi 2002) is highly dependent on the spatial pattern of projected drying. The current drying trend may continue, or it may simply reflect natural oscillations, and reverse in coming decades. The reduction of rainfall in specific tropical regions seems to be decoupled from the recent pantropical warming. Regions that have not experienced drying (e.g. Amazonia) show similar rates of temperature increase to regions that have (e.g. Africa).

A frequently cited climate modelling scenario (Cox *et al.* 2000; Cowling *et al.*, Chapter 16, this volume), suggests that north-eastern Amazonia may be vulnerable to extreme drying in response to circulation shifts induced by global warming, and that the consequent die-back of tropical rainforest could substantially accelerate global warming. To date, there is little evidence of any drying trend; in fact, the region has become marginally

wetter (precipitation trend $+1.9 \pm 2.2\% \text{ yr}^{-1}$, $p < 0.10$; no significant trend in dry season index). However, this region is strongly influenced by ENSO; if the ocean-atmosphere system were to shift into a sustained 'El Niño-like' state in coming decades (as opposed to the ENSO simply increasing in frequency and amplitude), the region could be vulnerable to drying.

The apparent marginality of Africa's tropical rainforest zone stands out in this analysis. This is the driest tropical rainforest region, and in recent decades it has generally become drier. The extent of African tropical rainforest seems particularly vulnerable to small shifts in ocean-atmosphere circulation. The palaeo-record seems to confirm this: large areas currently covered by African tropical rainforest appear to have been covered by savanna in the last ice age (Morley 2001), and perhaps as recently as 2500 yrs ago (Maley and Brenac 1998), contrasting with the continuity of forest cover in most of Amazonia (Mayle and Bush, Chapter 15 and Maslin, Chapter 14, this volume).

With some caveats about biogeographical and paleohistorical differences between regions, it appears that a study of how surviving African forests have responded to the drying trends of recent decades may yield useful insights into how tropical rainforests in general may respond to future drying. If eastern Amazonia were to dry over this century, perhaps we can gain insights into the future of its surviving forests by examining what happened to Africa's forests over the last decade of the last century?

Finally, the phrase 'surviving forests' is important to keep in mind. The most important process to affect the northern African tropical rainforests over recent decades was probably not the reduction in rainfall, but fragmentation and clearance. The long belt of tropical rainforest at the southern edge of west Africa now largely consists of small, logged-over fragments. Climate and deforestation are coupled, in that drier regions are more likely to be deforested, and deforestation contributes to modifying local and global climate. The fate of many of the world's tropical rainforests are

not likely to be primarily determined by climate trends, but by human actions on forest use or protection.

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