

## Essay 1

# The climates of the Tropics, and how they are changing

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Many features combine to make up the diverse climates of the Tropics. It is a warm region; mean annual temperatures exceed 20°C almost throughout the Tropics, except at high elevations, and exceed 25°C in many parts of the tropical zone. The tropical zone encompasses some of the wettest locations on Earth, as well as some of the world's driest deserts. It also includes some of the world's communities most vulnerable to natural disasters; population pressures drive settlement of flood- or drought-prone areas, and less developed countries lack the resources to create resilience to extremes of climate. Limitations in physical and human infrastructure also contribute to limited capacity to warn of, or respond to, major disasters, although this is an area where great strides have been made in many countries in recent decades.

### What makes up a tropical climate?

The classical definition of a tropical climate is one in which the mean temperature of the coolest month exceeds 18°C (see Figure E1.1), although

this is a relatively narrow definition; on most continents, the poleward boundary of the zone thus defined is some distance within the Tropics of Cancer and Capricorn, even at sea level. Such a definition also excludes high-altitude areas within the Tropics, as mean temperatures typically decrease at a rate of about 6°C per 1000 metres.

A small annual range of temperature is characteristic of the Tropics. Near the Equator, the difference in mean temperature between the warmest and coldest months is rarely more than 4°C, and at some locations (such as Quito, Ecuador) it is less than 1°C. Annual ranges of temperature become larger as one moves further from the Equator, but even at the limits of the tropical zone, few locations have an annual range of more than 15°C.

This low annual range of temperature makes traditional mid-latitude definitions of seasons of limited value; while it is possible to define "winter" and "summer" in any location that is not actually on the Equator, in many tropical locations, it is

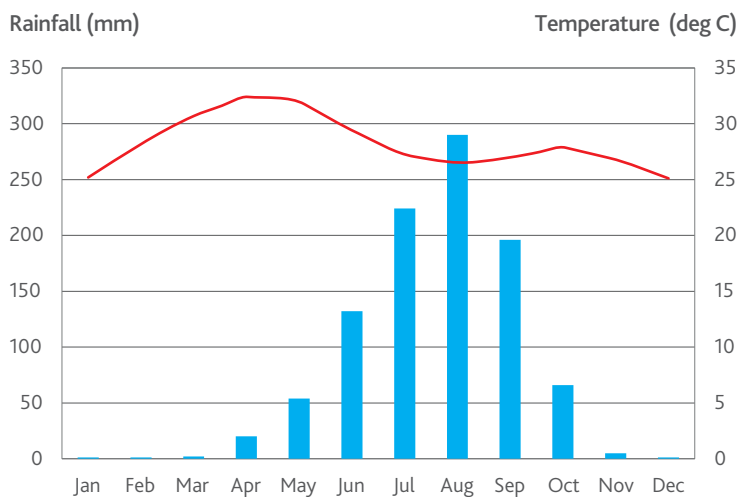
more common to speak of seasons in terms of the monsoon, "warm" and "cool" or "wet" and "dry" seasons. Outside the immediate proximity of the Equator, the coolest month is usually in "winter" (most often January in the Northern Hemisphere and July in the Southern Hemisphere), but the hottest month is not necessarily in "summer". In continental regions where there is a sharp, well-defined wet season – the African Sahel, much of the Indian subcontinent, and to a lesser extent northern Australia – the hottest weather occurs in the weeks prior to the onset of the wet season, sometimes with a smaller secondary peak at the end of the wet season (see Figure E1.2).

The equatorial zone is also characterised by consistent warmth and very small day-to-day temperature fluctuations; for example, at Singapore, the highest temperature on record is 36°C, and the lowest 18.9°C. Many locations within 15° latitude of the Equator, especially on islands or near the coast, have never reached 40°C and have highest recorded temperatures less than 5°C above the average daytime maximum temperature of the warmest month. This is in part due to island and coastal temperatures being largely controlled by ocean temperature, although in equatorial regions, even continental interiors (such as the Amazon basin) rarely, if ever, reach 40°C. Extreme temperatures are higher further from the Equator, although they still fall short of the world's highest extremes, most of which have occurred slightly outside the Tropics (including most of the instances of temperatures measured under standard conditions of 50°C or above).

While tropical climates are characterised by small variations in temperature, they include an immense variety of rainfall regimes. The Tropics include the driest parts of the world, the Atacama Desert on the west coast of South America where mean annual rainfall is less than 1 millimetre, as well as some of the wettest, locations in western Colombia and in Hawaii which receive more than 10,000 millimetres a year.

The classical model of tropical rainfall is one of an equatorial zone where rain occurs all year, transitioning to a "monsoon" or "savanna"

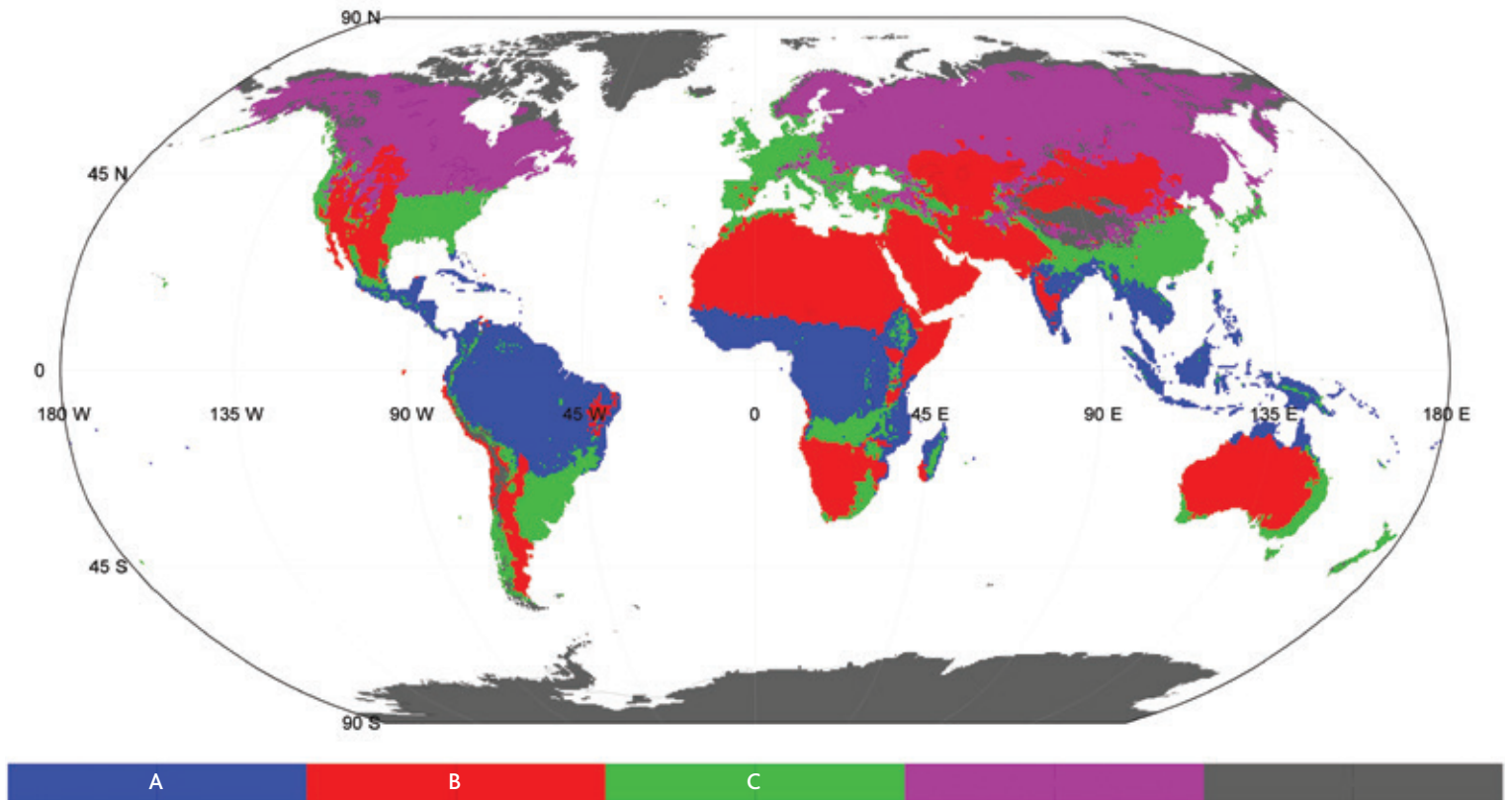
Figure E1.2 Mean monthly rainfall and temperature at Bamako, Mali.



Source: WMO (2012)

Note: Blue bars are monthly rainfall averages and the red line is mean temperature.

Figure E.11 Map of the major global climatic zones



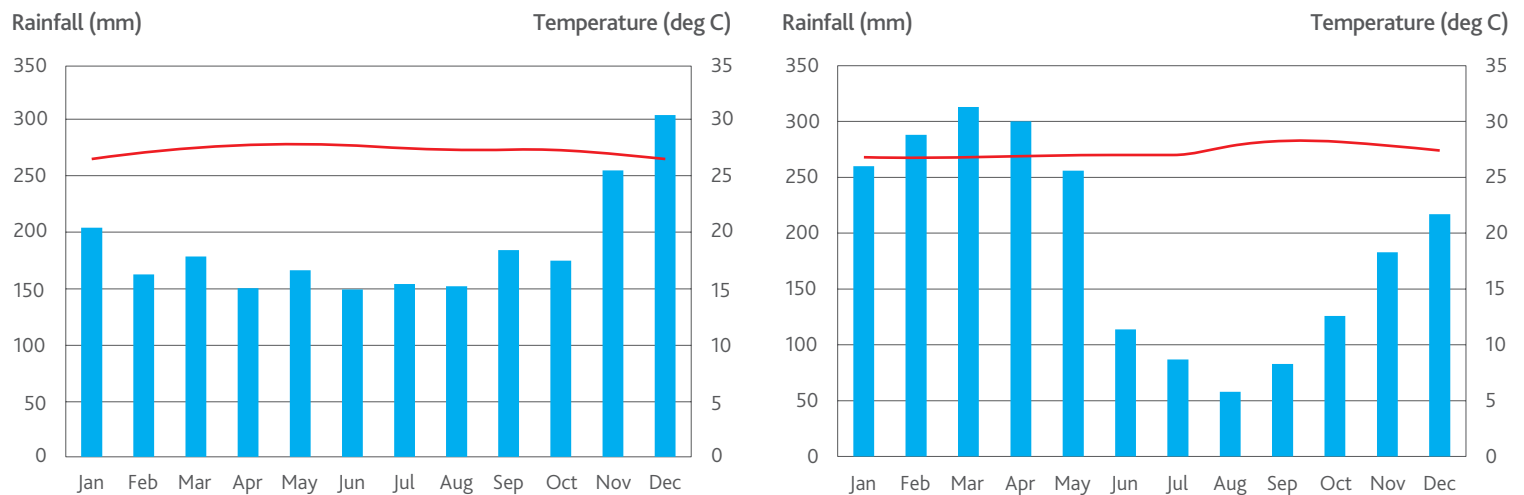
Source: Chen & Chen 2013

Note: Major global climatic zones include tropical zones (blue, type A), according to the Köppen climatic classification. In this classification tropical zones are defined by the mean temperature of the coolest month, and by rainfall (A: Tropical, B: Dry, C Mild temperate, D: Snow, E: Polar). WHO/ UNICEF (2012).

Figure E1.3 Mean monthly rainfall and temperature at four near-equatorial locations:

(A) Singapore, Singapore;

(B) Manaus, Brazil;



Source: WMO (2012)

Note: Blue bars are monthly rainfall averages and the red line is mean temperature.

climate with a well-defined wet and dry season (in summer and winter respectively), with the wet season becoming shorter with increasing latitude before it disappears altogether as one moves into the arid zone near the Tropics. This structure exists most clearly in west and central Africa north of the Equator, and in the Indonesian/Australian region.

Reality is a good deal more complex than that, but strong seasonal variations of rainfall are a common feature of tropical climates. Even near the Equator, a wide range of rainfall regimes exist. Regions such as the equatorial parts of the Indonesian archipelago, parts of equatorial Africa, and western Colombia are wet all year, but some other equatorial regions have a distinct drier season – sometimes relatively but not totally dry (as with the mid-year period over much of the Amazon), but in some regions, the near-total seasonal dryness of the savanna zone extends all the way to the Equator, as in western Africa. Highland East Africa has a more complex pattern still, with two rainy seasons (March-May and October-November), and dry conditions in between,

especially on the north side of the Equator. Some examples of rainfall regimes in near-equatorial locations are shown in Figure E1.3.

Moving away from the Equator and into the 10–20° latitude range, climates where there is a single, clear-cut wet season, most commonly in that hemisphere's summer, become the norm. In some parts of the world, such as west and central Africa (both north and south) and much of northern Australia, almost all the year's rain falls within four or five months with the remainder of the year being almost completely dry (e.g. Figure E1.2). Elsewhere, especially within reasonable proximity of east coasts (e.g. southern coastal China, the east coasts of Africa and South America south of the Equator, large parts of India, and much of the Queensland coast in Australia), rain can occur in all months of the year but there is still a clear distinction between the wetter and drier months. A variation on this theme comes in some parts of the world where coasts are at right angles to the trade winds; many of these locations are relatively rainshadowed during the summer monsoon and

receive their heaviest rain when the monsoon retreats in autumn and the trade winds become re-established. Examples include the central coast of Vietnam and the east coasts of southern India and Sri Lanka (all of which have their peak rainfall in October and November), and parts of coastal Brazil whose rainfall peaks between April and June. Figure E1.4 illustrates some climates of this type.

Island climates can be more complex still, with substantial changes in the seasonal regime over short distances depending on aspect. In the southwest Pacific, windward southeast sides of islands receive significantly more rainfall than leeward sides during the “dry” season, and thus have a more even spread of rainfall than leeward sides or island interiors. On the larger islands the heating of land and convergence of sea breezes during the warmest months of the year causes the development of convective cloud and showers in the late afternoon.

At the outer limits of the Tropics, in areas sufficiently far from east coasts, the wet

(C) Nairobi, Kenya and

(D) Lambarene, Gabon.

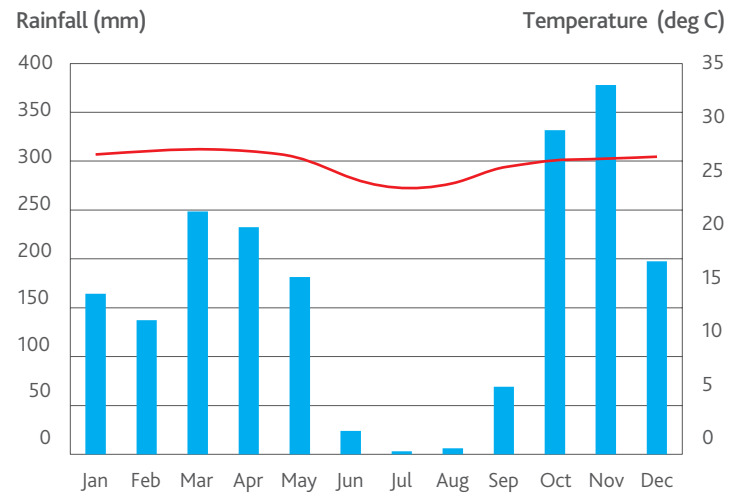
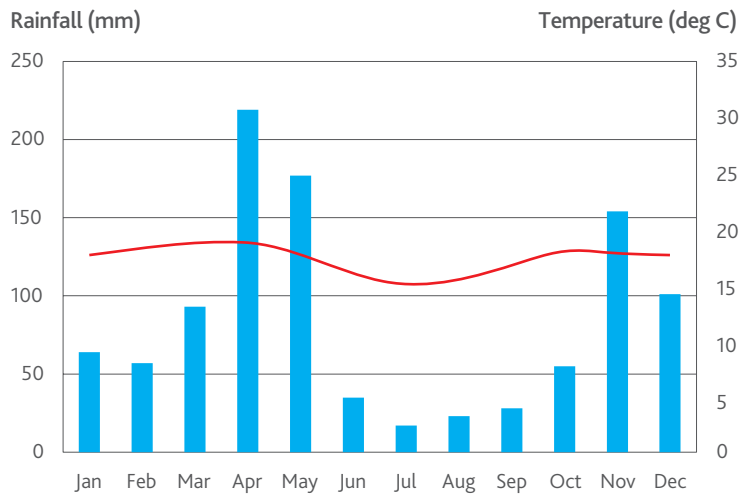
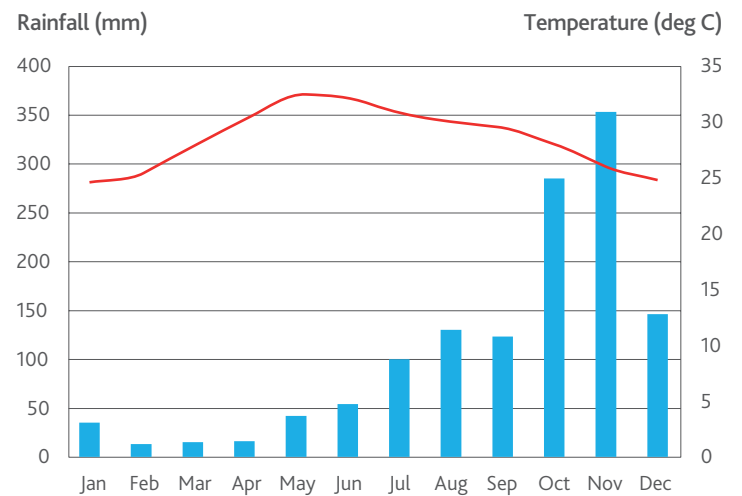
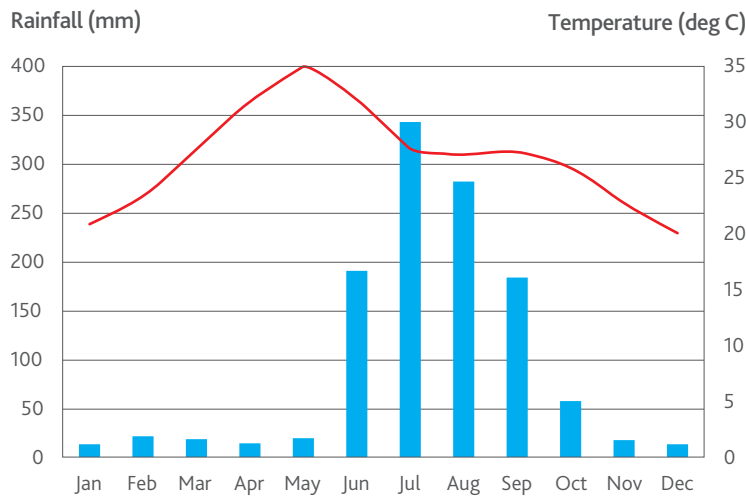


Figure E1.4 Examples of monsoonal climates in India:

(A) Nagpur, in central India

(B) Chennai, on the southern east coast.



Source: WMO (2012)  
 Note: Blue bars are monthly rainfall averages and the red line is mean temperature.



## Box E1.1 Climatic definitions of the Tropics

The traditional definition of the Tropics is the area between the Tropics of Cancer and Capricorn (approximately latitude 23°N and 23°S respectively).

The most widely used system of climatic classification, the Köppen classification (Chen and Chen, 2013), has two major classifications within the Tropics, humid tropical climates and arid/semiarid climates. The main temperature criterion for humid tropical climates is that the mean temperature of the coolest month is above 18°C, with various rainfall-based criteria distinguishing humid tropical climates from arid/semiarid climates. In regions where humid tropical climates transition to moist temperate climates rather than arid/semiarid ones, the boundary of humid tropical climates is generally fairly close, in low-altitude areas, to the Tropic of Cancer/Capricorn, although it is a little closer to the equator in east Asia.

A wide variety of definitions are in use for various applications; for example, the UK Meteorological Office report on temperatures in the region between 30°N and 30°S, while NASA report on a zone bounded by 24°N and 24°S. The IPCC Fifth Assessment Report also reports various results for the region between 30°N and 30°S.

Some characteristic features of tropical climates can extend well beyond the Tropics. The Indian monsoon's influence extends throughout the subcontinent, including those areas north of the Tropic of Cancer, and monsoon-type features can also extend well beyond the Tropics in other regions, particularly east Asia. Most tropical cyclones form within the Tropics, but many of them move well outside the Tropics during their lifetime, particularly in the North Atlantic where destructive tropical cyclones have occurred as far north as Newfoundland.



Papua New Guinea. Image: Mark Ziembecki.

season peters out altogether and the climate becomes consistently arid under the fringes of the subtropical high pressure belt. Many of the world's major deserts have their equatorward limit between latitude 15° and 20°, including the Saharan and Arabian deserts, the Australian deserts, and Africa's Kalahari. South America is too narrow in this latitude range to support a major continental desert, but does have the world's most extreme example of a coastal desert dominated by the stabilising influence of cool ocean currents offshore; the narrow Atacama Desert along the west coast of Peru and northern Chile. A similar mechanism governs the Namib Desert on the west coast of southern Africa.

## Major features of the tropical circulation

The most fundamental feature of the tropical atmospheric circulation is a zone where warm air rises from the surface to the upper atmosphere (a process known as convection), creating a zone of low pressure at the surface. Once in the upper atmosphere, this air moves towards the poles before descending in the subtropics, the descending air creating a zone of high surface pressure (the subtropical high or ridge). To complete the process, air then flows at surface level from the high-pressure area in the subtropics towards the low-pressure zone near the Equator. The whole structure is known as the Hadley Cell (see Figure E1.5).

The zone of near-equatorial low surface pressure is variously known as the Intertropical Convergence Zone (ITCZ), or the monsoon trough; the former term is derived from the fact that it is where surface winds flowing in from the subtropical ridges of the Northern and Southern Hemispheres converge. The ITCZ moves with the seasons, being centred (on a global-mean basis) north of the Equator during the Northern Hemisphere summer, and south of the Equator during the Southern Hemisphere summer (although it generally stays closer to the Equator when in the Southern Hemisphere due to the lesser influence of the continents, and in the central and eastern Pacific

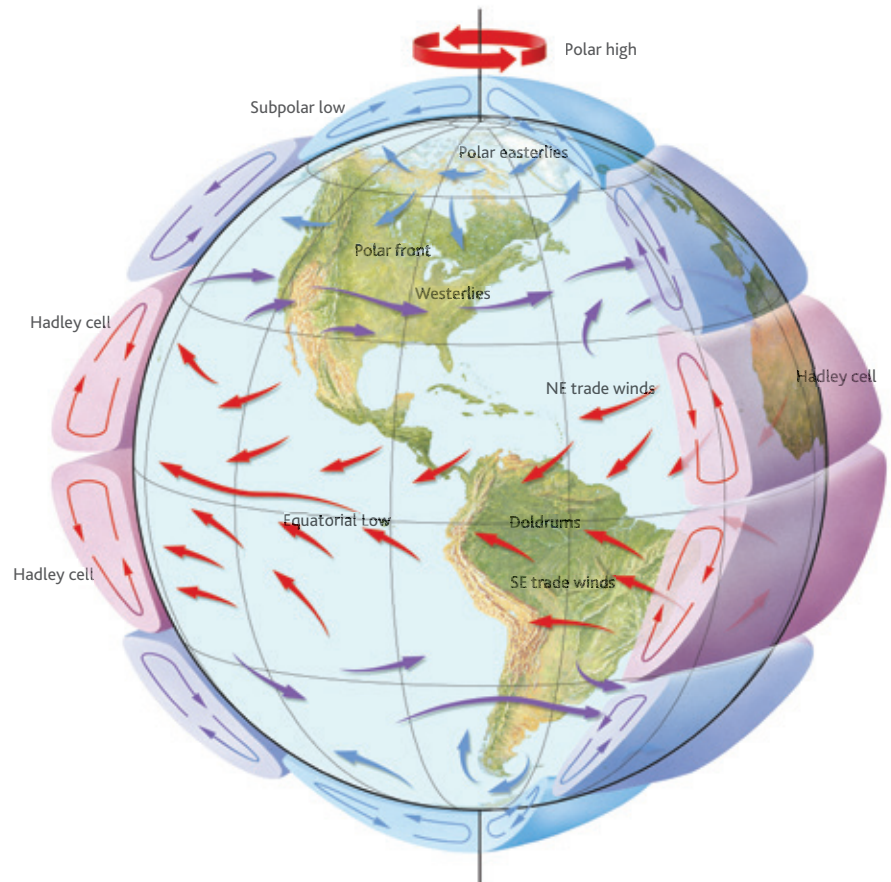
remains north of the Equator all year). As an active area of convection it also tends to be the most favoured zone for the formation of storms.

The winds between the subtropical ridge and the ITCZ are referred to as the “trade winds”. Due to the effect of the Earth’s rotation, these winds are deflected to the left in the Southern Hemisphere and to the right in the Northern Hemisphere, and hence generally blow from the southeast and northeast respectively. If the ITCZ is some distance from the Equator, the trade winds from the opposite hemisphere will cross the Equator and thus shift direction – so, for example, during the Northern Hemisphere summer, winds originating in the Southern Hemisphere turn from southeast to southwest as they cross the Equator. In some parts of the world, the trade winds interact with circulations around subtropical high-pressure systems and troughs to generate additional convergence zones. The South Pacific Convergence Zone (SPCZ), which typically runs southeast from the tropical western Pacific to French Polynesia (and is a very strong influence on the climate of many South Pacific island countries), is the best-known example.

In those areas which are crossed by the ITCZ during the course of the year, the result of this is seasonally reversing winds (the original definition of the monsoon); for example, over the Indian subcontinent, winds are generally southwesterly when the ITCZ is to the north (normally between June and September) and northeasterly when the ITCZ is to the south. Similarly when the SPCZ is to the north of Fiji (Southwest Pacific) the winds are generally southeasterly and cool due to their high latitude origin. When the SPCZ is to the south of Fiji the winds are northerly and warm with more moisture content.

Cold and warm fronts, which are regular features of the circulation at higher latitudes, are generally absent from the Tropics. Mid-latitude systems can, however, have an indirect influence on the Tropics, particularly through driving surges of cool, dry air into the Tropics as a result of high pressure building behind cold fronts passing at higher latitudes. South America, where the Andes

Figure E1.5 The global circulation, including an illustration of the Hadley Cell



Source: Gary Hicks, Science Photo Library

act as a barrier to westward diffusion of cold air at low levels, is particularly noted for this, with such surges occasionally reaching the Equator, but it is also a feature of regions such as northern Australia, eastern parts of central America, and east Asia. In the latter two cases, the relative proximity of very cold continental air masses to the north means that such surges can bring low temperatures into the Tropics; for example, locations such as Hong Kong and Hanoi occasionally have mid-winter daytime maximum temperatures below 10°C.

Strong mid-latitude systems can also interact with tropical systems such as the SPCZ on occasions to amplify rainfall in those regions.

As many of the weather features which formed the basis of the development of weather forecasting at higher latitudes are absent in the Tropics, the science of forecasting took longer to develop in the Tropics; in particular, surface pressure gradients are not as reliable a guide to surface wind speed and direction as they are at mid-latitudes.

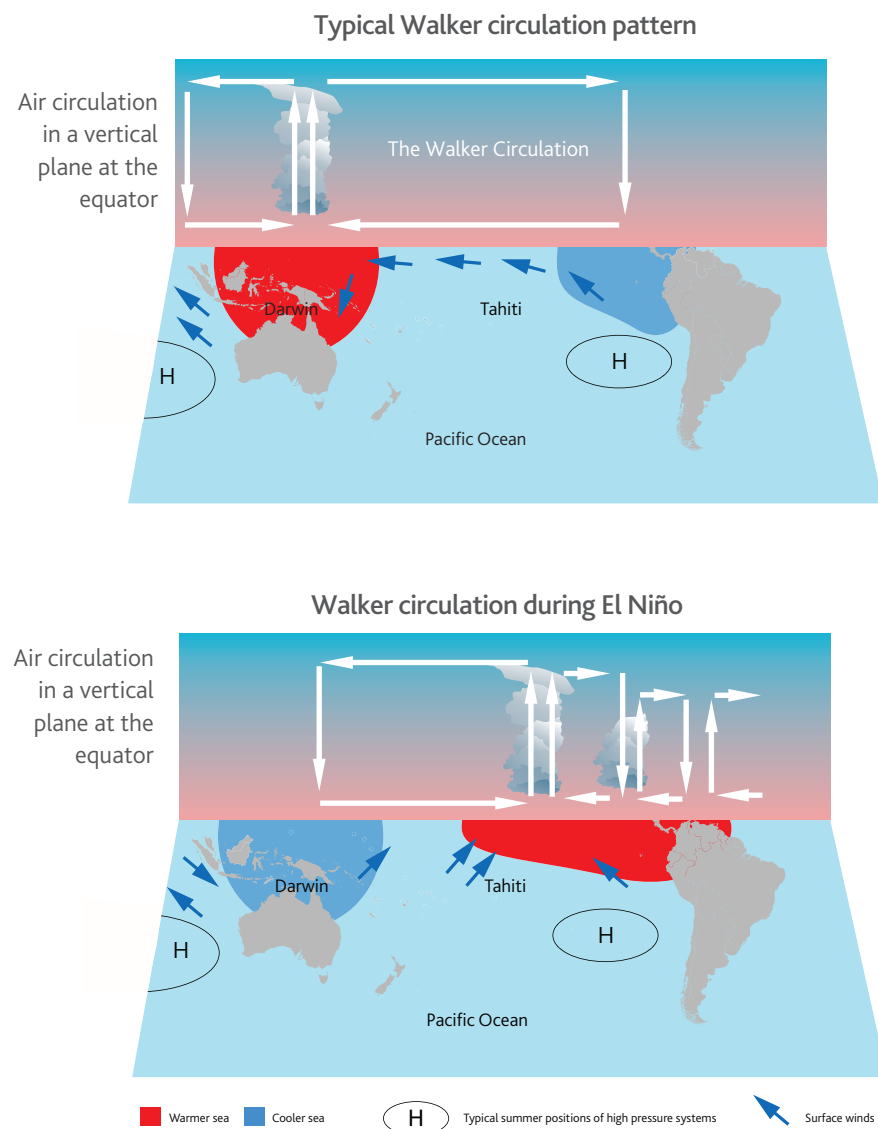
## Key drivers of climate change and variability in the Tropics

There are many factors which influence variations of climate in the Tropics on a variety of timescales, from those which operate on a timescale of weeks, to long-term changes over a period of decades or centuries. These interact to create complex patterns of variability overlying longer-term trends.

The most significant long-term driver of climate change in the Tropics over the last century, as elsewhere on the globe, has been the increased concentration over time of greenhouse gases such as carbon dioxide (CO<sub>2</sub>) in the atmosphere. Successive assessments have given an increasing level of confidence that observed increases in temperature over the last 50 to 100 years are primarily attributable to increased concentrations of greenhouse gases driven by human activity. Regional attribution of temperature trends cannot be done with quite the same level of confidence in the Tropics that it can in some other regions because of more limited observations, but nevertheless, the IPCC AR5 (IPCC, 2013) concluded that it is likely that human influence has made a substantial contribution to the observed warming since 1950 in each of the inhabited continents, including those located primarily or partly in the Tropics.

Other changes in radiative forcing can affect climate globally or regionally. In contrast with the influence of greenhouse gases, aerosols can have a measurable cooling effect (especially in heavily polluted areas) and may also be linked to changes in atmospheric circulation – for example, some studies have linked increased aerosols in east Asia to changes in the north Australian monsoon which have led to increased rainfall in north-western Australia. Natural forcings, such as variations in solar activity or major volcanic eruptions, can also have an influence on global climate. The 1991 eruption of Mount Pinatubo in the Philippines suppressed mean global temperatures by up to 0.4°C over a period of several years, while 19th century eruptions such as those of Tambora (1815) and Krakatoa (1883) are believed, from the available data, to have had even larger impacts.

Figure E1.6 The typical atmospheric circulation pattern in the tropical Pacific Ocean and how it changes during an El Niño year.



Source: Australian Bureau of Meteorology (2008)



The climate also has numerous internal modes of variability. The most prominent of these is the El Niño-Southern Oscillation (ENSO). This phenomenon is characterised by changes in ocean temperatures in the eastern and central equatorial Pacific but has impacts on climate over many parts of the world. During an El Niño event, the waters in this region (which are normally substantially cooler than other equatorial waters, due to the influence upwelling from below the ocean surface off the west coast of South America) are warmer than normal (by 1 to 2°C in a typical event, although in the strongest events, such as 1982-83 and 1997-98, anomalies have reached 4°C) (see Figure E1.6). This results in a weakening of the easterly (equatorial) trade winds in the Pacific (the surface part of what is known as the Walker Circulation) on both sides of the Equator, with flow-on consequences for the atmospheric circulation over a large part of the world. El Niño events are associated with a high risk of dry conditions over areas such as the western Pacific including eastern Australia, southern Africa, much of the Indian subcontinent, and northeast Brazil, while they are associated with high rainfall in east Africa and on the west coast of South America. Through their influence on the location of the ITCZ and SPCZ (Australian Bureau of Meteorology and CSIRO, 2011), El Niño events also have a strong influence on the rainfall on many Pacific Islands (positive or negative, depending on island location). La Niña events are the near reverse of El Niño – that is, waters are cooler than normal in the eastern and central equatorial Pacific – and have broadly opposite climatic impacts.

The typical lifecycle of El Niño and La Niña events is 9-12 months; they tend to form between March and May, when the temperature gradient across the equatorial Pacific is at its weakest, and break down early in the following years. It is rare for an event to continue into a second year (although more common for La Niña to do so than El Niño). On average 2-3 events of each type occur each decade, but there is no consistent cycle; in some periods, such as the 1950s and 1970s, La Niña predominated and El Niño events were rare, whereas for much of the 1980s and 1990s El Niño events occurred regularly and La Niña events were

few and far between. This interdecadal variation in the relative frequency of El Niño and La Niña events contributes to a pattern referred to as the Interdecadal Pacific Oscillation (IPO), although the extent to which the IPO functions independently of ENSO is a matter of some debate.

Conditions in the equatorial Indian Ocean also vary on seasonal timescales in a way which has broader influences on the tropical climate. There is a tendency for below-normal temperatures in the eastern Indian Ocean, off the south coast of Java and Sumatra, to be associated with above-normal temperatures off the African coast, and vice versa. This is referred to as the Indian Ocean Dipole (IOD), with its positive phase denoting warm conditions in the western Indian Ocean and cool conditions in the east. The positive phase of the IOD, which is more likely to occur during El Niño years but can also occur during other ENSO phases, tends to be associated with wet conditions in east Africa, and below-normal rainfall over large parts of Australia, especially in the Southern Hemisphere winter and spring. The dynamics of the IOD are less well-understood than those of ENSO and seasonal prediction of its behaviour is still in its infancy.

On longer timeframes, the tendency of temperatures in the North Atlantic to persist above (or below) the long-term trend over periods of 20-30 years has been referred to as the Atlantic Multidecadal Oscillation (AMO). During warm phases of the AMO, one of which has been in progress since the mid-1990s, there are a number of impacts on tropical climate, including a tendency towards increased tropical cyclone activity in the North Atlantic, and increased rainfall in the Sahel and the Indian subcontinent. Climate models suggest that AMO phases are linked with small shifts in the broader ocean circulation but the mechanisms of this are still poorly understood, and no demonstrated predictability currently exists.

An influence which operates on shorter timeframes is the Madden-Julian Oscillation (MJO) (Wheeler and Hendon 2004). This can be characterised as an eastward-moving “pulse” of

cloud and rainfall near the Equator which typically recurs every 30 to 60 days, and is most visible over the Indian Ocean and the western Pacific. Active phases of the Indian and Australian monsoons are most likely to occur when the MJO pulse passes local longitudes, something which is also associated with a higher risk of tropical cyclone formation. The MJO is predictable with useful skill over periods up to about three weeks, supporting forecasting of wet and dry periods on timescales longer than those feasible with conventional weather-forecasting methods.

## Long-term temperature trends and variability in the Tropics

Like the rest of the world, the Tropics have warmed over the last century (see Figure E1.7), with steady warming from the early 20th century to about 1940, then a levelling off until the mid-1970s, then a rapid rise to the end of the century. Depending on the data set used, the total warming over the 1910-2012 period in the Tropics and near-Tropics has been 0.7-0.8°C, about 0.1°C less than that over the globe as a whole. Warming over the Tropics has been slower than over higher latitudes of the Northern Hemisphere, but faster than over mid- to high latitudes of the Southern Hemisphere.

Finer geographic patterns of warming over the century are challenging to assess, due to very limited pre-1950 data over continental Africa, the Amazon and much of the tropical Pacific. In the last 30 years, the Sahara, Sahel and Arabian Peninsula have been amongst the most rapidly-warming parts of the world, whilst large parts of the eastern and central tropical Pacific have seen weak cooling, associated with decadal variability in the El Niño-Southern Oscillation (ENSO).

Temperatures averaged over the Tropics show more interannual variability than those averaged over the globe as a whole. This partly reflects the smaller area over which averaging is being done, but also reflects the fact that the bulk of ENSO's influence on temperature is felt in the Tropics. A strong El Niño year will typically be about 0.2°C warmer in the Tropics than the years around it, and

a strong La Niña year about 0.2°C cooler, whereas for the globe as a whole the signal is about half that size (WMO, 2012). The most recent strong El Niño year, 1998, is clearly the warmest year on record in the Tropics to date, whereas globally it is closely matched with 2005 and 2010. Recent years have seen La Niña predominate over El Niño, with particularly strong events in 2008 and 2011, and hence tropical temperatures in the last few years have been relatively low compared with global means.

## How has tropical rainfall changed over time?

Rainfall in many tropical regions of the world has shown marked fluctuations from year to year, and from decade to decade. Many of these fluctuations are associated with ENSO, which has a marked influence on rainfall in many parts of the Tropics. Over land, there are more tropical regions where El Niño has a drying influence than there are regions where it is associated with increased rainfall (the reverse is true over the oceans), and hence total tropical rainfall on land is generally substantially higher in La Niña years, and lower in El Niño years.

The IPCC 5th Assessment Report (AR5) (IPCC, 2013) reported that downward trends in total tropical rainfall which had prevailed from the 1970s to the 1990s had reversed in the last decade, and that there was now no significant trend over either the 1901–2008 or 1951–2008 periods. This reversal is largely associated with decadal fluctuations in ENSO, with the dominance of El Niño through the 1980s and 1990s replaced by a number of major La Niña events in the years from 1999 onwards. The IPCC also cautions that confidence in reported rainfall trends in the Tropics is low in the first half of the 20th century, and medium from 1950 onwards, due to limitations in the available data.

Focusing on the most recent 30 years, rainfall has increased significantly since 1979 in a number of tropical regions, including the Sahel (which was affected by chronic drought from the mid-1970s to the 1990s but has been quite wet in recent

years), southern Africa from Zambia southwards, the western tropical Pacific and much of northern Australia, especially the Northern Territory and northern Western Australia. The only large areas showing significant decreases over that timeframe are Brazil south of about 10°S and the central equatorial Pacific. Few tropical areas show significant trends over the 20th century as a whole, partly because few areas have consistent data over that length of time.

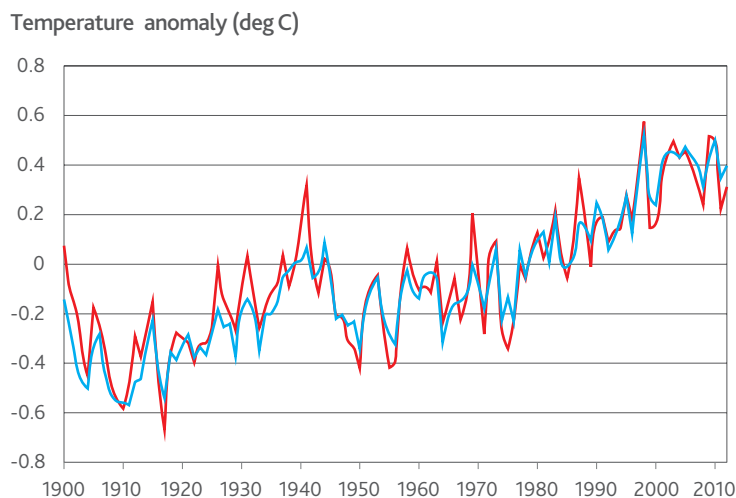
There are also few coherent signals of changes in rainfall extremes, at either end of the scale. The IPCC reports indications of an increase in the frequency of high precipitation extremes in parts of South America, but mixed or inconclusive changes in other tropical land areas. There is low confidence in assessment of changes in flooding, and also for drought in many areas. (In part, this is because of a wide range of indicators used for drought – some are purely rainfall-based, others attempt to incorporate other variables such as temperature and soil moisture). The strong increases in rainfall

since 1960 in north western Australia have been accompanied by a decrease in drought, while west Africa shows a likely increase of drought since 1950 (although this signal is dominated by the protracted late 20th century drought in the Sahel).

## Tropical cyclones – their occurrence and long-term changes

Tropical cyclones (generally referred to as hurricanes in the Atlantic and Northeast Pacific, and typhoons in the Northwest Pacific) are amongst the most significant atmospheric phenomena in the Tropics. They can be exceptionally destructive, through a combination of extreme winds, very heavy rain leading to freshwater flooding and landslides, and storm surges causing dangerously elevated sea levels in coastal areas near landfall. In the most extreme cases (Figure E1.8), maximum wind gusts have exceeded 300 km/h, daily rainfalls have occurred in excess of 1000 millimetres in 24 hours, and

Figure E1.7 Mean annual temperatures (anomalies from 1961–90 mean) for the globe (blue line) and for areas between latitudes 30°N and 30°S (red line)



Source: HadCRUT data set, Brohan et al. 2006

## Box E1.2 How do we monitor climate in the Tropics?

One of the major challenges in monitoring climate change and variability is that of obtaining appropriate long-term observations to do so.

On land, much of our information comes from "conventional" meteorological observing stations, set up under the auspices of meteorological authorities in the countries where they are located. These stations measure a range of variables, most often temperature and rainfall. Few of these were set up with the primary intention of assessing climate change; more commonly, they were established to support weather forecasting, or for purposes such as tracking seasonal rainfall for agriculture.

In the ocean, observations such as those of winds, pressure and sea surface temperature have been made from ships since the 19th century. These have been supplemented over time by a range of moored and drifting buoys, which are particularly valuable in ocean regions away from shipping lanes. More recently, subsurface information has become available through tools such as the Argo floats, which spend most of their lives drifting about 1500 metres below the surface but rise to the surface, taking measurements on the way, every few days; this information is especially important in monitoring and predicting El Niño and La Niña events, as changes in the subsurface of the equatorial Pacific are often a precursor to changes at the surface.

Remotely sensed data sets, mostly from satellites, are becoming increasingly important in climate monitoring. Satellites and, for systems near land, radar are especially critical in monitoring tropical cyclones, as cyclones spend the bulk of their lives over oceans with few or no conventional observations (only in the North Atlantic are aircraft routinely used for tropical cyclone monitoring), and even when they make landfall, instruments often fail to capture the cyclone's full intensity (either because there are no instruments in the right place, or because those which are there fail to survive the cyclone). Prior to the satellite era, some tropical cyclones which stayed out to sea throughout their lives are likely to have been missed altogether, especially in the Southern Hemisphere and the central North Pacific. Satellites are also used to track elements such as cloud cover, rainfall – an especially

valuable tool has been the Tropical Rainfall Measurement Mission (TRMM), a joint US/Japan satellite launched in 1997 – and sea surface temperature.

All of these data sets have their challenges, and these challenges are particularly acute in many tropical areas. In many less developed countries – which are disproportionately located in the Tropics – maintaining conventional land-based observation networks over time has been difficult, due to factors such as a lack of funds, a lack of personnel with suitable technical expertise, and armed conflict or civil unrest, and while the situation is improving in some countries, it is deteriorating in others. Even where observations are being made, they are often not accessible in a timely manner because of poor communications, while many historical observations are available only in hard-copy documents (often held by former colonial powers) and are thus effectively unavailable for analysis. Some countries also limit the sharing of their data for commercial or military reasons. Work is ongoing amongst many national and international institutions (e.g. Thorne et al 2011) to address these issues, but progress is slow. Elsewhere, regions such as northern Australia and the Amazon basin in Brazil are in countries with well-developed national meteorological services, but have very sparse populations and hence sparse observation networks. The consequence of all of this is that stations with 100 years or more of continuous reliable observations, relatively common in Europe and North America, are few and far between in the Tropics, especially in Africa and parts of South America.

Satellite observations have been very useful for ongoing climate monitoring, and are now routinely used for tracking seasonal rainfall, especially in Africa where they have been critical in providing real-time information from regions such as the Sahel and the Horn of Africa where such information is difficult to obtain from more traditional sources. The main disadvantage of satellite-based data sets is their relatively short length, normally insufficient for assessments of long-term climate change. Few satellite-based data sets go back further than the late 1970s, although with careful analysis, satellite data suitable for tropical cyclone analysis extends into the late 1960s.

storm surges have driven coastal waters 10 metres or more above their normal levels. In particular, cyclone-related storm surges have caused catastrophic loss of life on a number of occasions along heavily-populated, low-lying coastlines, especially around the coast of the Bay of Bengal.

To obtain sufficient energy to form or maintain intensity, tropical cyclones normally need to be over water with a sea surface temperature of at least 26°C. They also require sufficient Coriolis force to generate initial rotation, so do not normally occur within about 4° latitude of the equator. Once formed, their intensity and longevity is governed by numerous factors, including sea temperatures, the available moisture in the surrounding environment, and the presence or absence of wind shear (differential wind speed/direction at different elevations), which if present to an excessive degree can rapidly weaken a cyclone. Tropical cyclones will normally weaken quickly once they move over land (although the moisture associated with cyclones can penetrate inland for very long distances, especially over continents with few topographic barriers such as western and central Australia). They will also normally lose intensity as they move over cooler waters, although under certain conditions they can transition into intense extratropical cyclones (which are distinguished from tropical cyclones by having a cold rather than warm core in the upper levels, and by their typically larger size) as they move to higher latitudes – something especially common in the North Atlantic and Northwest Pacific. Tropical cyclones are typically smaller than mid-latitude systems, especially at low latitudes; some highly destructive systems, such as Tracy (which largely destroyed Darwin in 1974), have had fields of gale-force winds only a few tens of kilometres across.

The majority of tropical oceans are able to support tropical cyclone formation for at least some of the year. The world's most active tropical cyclone region is the Northwest Pacific, which on average has about 30% of the global total (which is normally 85-90 cyclones per year), with the Philippines being the world's most frequently hit country. The Northwest Pacific also has the highest

Figure E1.8 Satellite image of Typhoon Haiyan approaching the Philippines, 7 November 2013



Source: NASA Images.

frequency of intense tropical cyclones, and has had the majority of the world's most intense systems, and most intense landfalls. Northwest Pacific cyclones can occur at any time of year, although they are most common from July to October, and least common from January to April. The North Atlantic, Northeast Pacific, Southwest Pacific and North and South Indian Oceans also experience regular tropical cyclones, and regular landfalls on most of the surrounding coasts and islands (except for the African coast, where landfalls are rare on the east coast and almost unknown on the west). The Southeast Pacific is too cool to support tropical cyclones, and they are also exceptionally rare in the South Atlantic.

Whilst most tropical cyclones form within the Tropics, some go on to have significant impacts outside the Tropics, especially in the North Atlantic and Northwest Pacific, where sea surface temperatures near or above 26°C extend well north of the Tropics during summer and early autumn. Tropical cyclones regularly make landfall on the Japanese island of Honshu and on the Korean Peninsula, between latitudes 35 and 40°N, and have also done so at similar or higher latitudes in the northeast United States and the Atlantic provinces of Canada, causing major destruction as far north as 48°N in Newfoundland.

The total number of tropical cyclones globally remains remarkably stable from year to year; years with fewer than 75, or more than 100, cyclones are rare. However, the geographic distribution of cyclones shows more interannual variability, with ENSO acting as a strong influence. In general, El Niño years see an eastward displacement of cyclones in the Northwest and Southwest Pacific; fewer cyclones make or approach landfall on the coasts of Australia and China, and more occur in the central South Pacific and in longitudes near and east of Japan. El Niño years also tend to see fewer tropical cyclones in the North Atlantic, and more in the Northeast Pacific. La Niña years generally display the opposite pattern.

The IPCC Fifth Assessment Report (IPCC 2013) reported little evidence of significant trends in global tropical cyclone activity, with

low confidence in observed changes of most indicators, both in terms of total numbers and of intensity, although more confidence exists in a few regions for limited time periods (e.g. for an increase in the frequency and intensity of the most intense tropical cyclones in the North Atlantic since the 1970s, something to which the current warm phase of the AMO is at least partly contributing). To some extent, this reflects the large uncertainties which arise from changes in observing technologies over time; outside the North Atlantic, most tropical cyclone intensity assessment (Velden et al. 2006) depends on satellite data (see Box E1.2) which have only been consistently available since the late 1970s. The IPCC assessment of projections of future tropical cyclone activity is that it is likely that the total number of tropical cyclones will either decrease or remain essentially unchanged, while the number of intense cyclones is likely to increase, but at a rate which is sufficiently slow that it is unlikely to be statistically distinguishable from interannual variability for many years to come.

## What lies ahead for the tropical climate?

Like the rest of the world, the Tropics are projected to warm substantially over the coming 50 to 100 years. The actual amount of warming, particularly in the second half of the century, depends largely on the trajectory of greenhouse gas emissions; the lowest-emission scenarios considered by IPCC (IPCC 2013) indicate warming of global mean temperature (from a 1986–2005 baseline) of around 1°C by mid-century and 1–2°C by 2100, whereas under high-emission scenarios projected global temperature changes are 1–2°C by mid-century and 3–4°C by 2100.

Most model projections indicate that warming trends over the Tropics will be marginally smaller than those for the globe as a whole, continuing the 20th century pattern of the strongest warming being at high latitudes of the Northern Hemisphere and the weakest warming at mid- to high latitudes of the Southern Hemisphere. There is no clear indication of significant differences in

temperature trends within different parts of the Tropics, apart from a weak tendency towards stronger warming in continental regions than over the oceans. Because of the low day-to-day variability of tropical temperatures, however, the change in the frequency of extreme temperatures is expected to be larger over most of the Tropics than in other parts of the world; in many parts of the Tropics now, an individual day 3°C above the 20th century average is an unusually warm day and something only experienced a few times per year, but under the higher-range warming scenarios such conditions would become the norm in the later part of the 21st century.

There is low confidence in projected changes in annual rainfall over most of the Tropics. The majority of models simulate increased rainfall over the equatorial oceans, especially the Pacific, but there are few consistent signals over the tropical continents. There are indications of an intensification of the seasonal rainfall cycle and a lengthening of the monsoon season in many regions (particularly the Indian subcontinent), with the wet season becoming wetter and the dry season drier, as well as of an increase in extreme rainfall events at various timescales, but uncertainties are large.

More confidence can be attached to various changes in the atmospheric circulation – for example, it is considered likely that there will be a broadening of the Hadley cell which will lead to a poleward displacement of the tropical dry zones – but the most clear-cut rainfall impacts of this will be outside the Tropics. It is also considered likely that the eastern tropical Indian Ocean will warm more slowly than the west, indicative of a shift towards more positive modes of the Indian Ocean Dipole, but there is low confidence in changes in the intensity and spatial pattern of ENSO in a warmer climate.

A major area of uncertainty is the potential for feedbacks arising from changes in land cover. The best-known tropical scenario in this respect is the possibility of a major change in the vegetation over large parts of the Amazon basin – as a result of a more pronounced dry season, land use changes,

other changes such as altered fire regimes, or a combination of all of these – and a consequent reduction in moisture availability (and hence rainfall) through reduced transpiration. Whilst the possibility that such a (potentially irreversible) “step change” could occur is known, the critical thresholds which might result in such a change are largely unknown, and hence IPCC currently assigns low confidence to any assessment of possible changes of this type.

Future climate change is an issue of concern worldwide. Many tropical countries are particularly vulnerable to its impacts, because of the generally lower resilience of less developed countries to extreme events of any kind. In marginal areas, even minor changes in rainfall regimes can have a major impact on agricultural productivity. Some tropical countries also have heavily-populated areas on low-lying coasts which are highly vulnerable to sea level rise; in extremis, some low-lying coral atolls (such as those which make up the Maldives, Tuvalu and Kiribati) may be rendered uninhabitable should sea levels rise sufficiently far.

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