The weather and climate of the tropics, Part 9 – Climate, flora and fauna

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Much of this series has covered the weather types experienced in the tropics. Following on from the introduction to tropical climates in Part 1 (Galvin, 2007), this penultimate part describes the major climates and their relationship to the plants and animals of the tropics, including humankind, that have settled in all tropical environments. A map of the climatic zones of the tropics appears as Figure 1.

In many places, humans have altered the distribution of plant and animal species; in almost all areas they use plants and animals for food or labour. These changes in turn affect the climate, as significant alterations are made to the appearance of the environment. The zones discussed below are classified according to their natural vegetation, although settlement has often removed this.

The climates discussed include those that are only under the influence of the tropical air mass in summer (Galvin, 2007), including those along its poleward limits: the Caribbean, southern USA, northern Mexico, north Africa, southwest Asia, Tibet, central southern China, the southern tip of Africa, northern Argentina, Uruguay, Bolivia, Paraguay, southeastern Brazil, northern Chile and parts of southern Australia. In winter, these areas have weather dominated by mid-latitude weather systems, or are dry.

Tropical rainforest

This is the archetypal environment of the humid tropics and often what is thought of as *the* tropical environment (Af in Figure 1). However, there are many variations on a theme, based on seasonality of rainfall, distance from the meteorological Equator, and altitude.

In the non-seasonal tropics, areas of dense 'jungle' receive more than about 2000mm of rainfall every year and day length varies little. Mean temperatures are between 22 °C and 28 °C, with little variation throughout the year and a daily range of rarely more than 10 degC. Climate data for a typical location, Mactan, Cebu, Philippines, are shown as Figure 2.[1]

The high humidity, near-constant high temperature and high degree of shelter usually provided by the forest possibly make this the most uncomfortable tropical environment. It is hard to lose heat by perspiration and work rapidly causes tiredness, despite the shade from trees. Nevertheless, the high productivity of the rainforest supports a large number of people. In many areas, settlement is in the coastal zone, or along rivers, although there is increasing settlement in formerly inaccessible forest. Two of the world's ten largest cities, Jakarta and São Paulo, lie within the tropical rainforest zone.

Trees are broad-leafed and evergreen; many have so-called 'buttressed' trunks (a result of the leached soils, see below). They often live hundreds of years, since there is no frost and year-round rainfall allows the trees to grow throughout the year. The leaf canopy is very dense in much of the zone with lianas growing between and up tree trunks, so the jungle floor is relatively dark, even around midday. As a result, much of the forest floor has relatively thin vegetation, except near areas where more light can penetrate, such as along riversides, or where trees have fallen, or along coasts (Figure 3).

Along the poleward edges of the forest zone, where rainfall is lower and the temperature range is greater, the forest thins and there is greater development in the under-storey.

The typical soil of the tropical rainforest is the latosol[2] (FAO-UNESCO, 1989). The soils are often well developed and up to 30m deep, but are critically leached of fertilizing nitrate and phosphate. They are usually oxidized and have a shallow humus

[1] It should be noted that the data for most stations mentioned in this article are recorded at an open site (on an airfield), as are most across the world, so it could be argued that they do not fully reflect the temperature and rainfall of their climatic zone. In the case of tropical rainforest, the true climate is probably somewhat cooler by day, warmer by night and wetter (http://www.endangeredspecieshandbook.org/pdfslive/esh_chapter5.pdf).

[2] A description of the soil types of the tropics is given in Box 1.

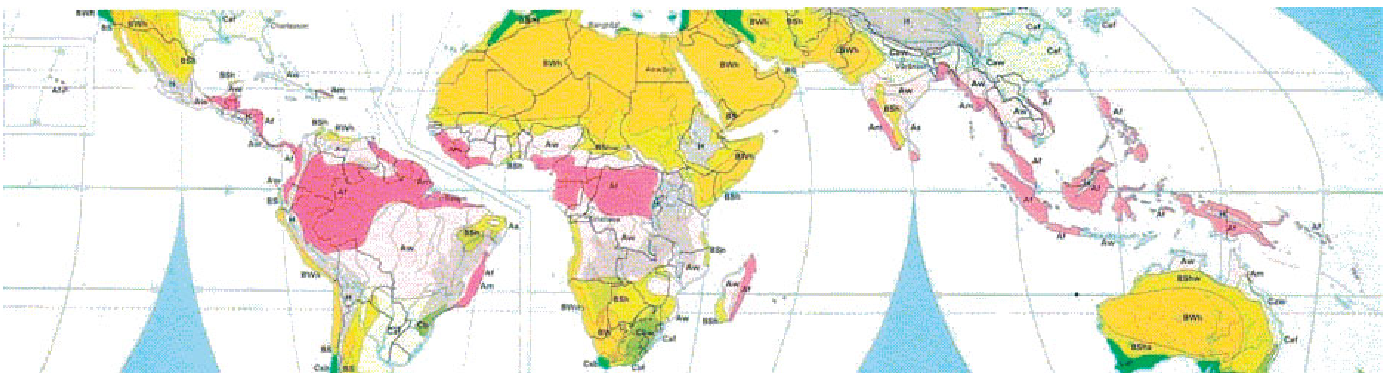

Figure 1. Climatic zones of the tropics: Af-tropical rainforest; Am-monsoon; Aw/Caw-savannah; BSh-tropical steppe; BWh-tropical and sub-tropical desert; H-highlands; stippled-modification due to altitude.

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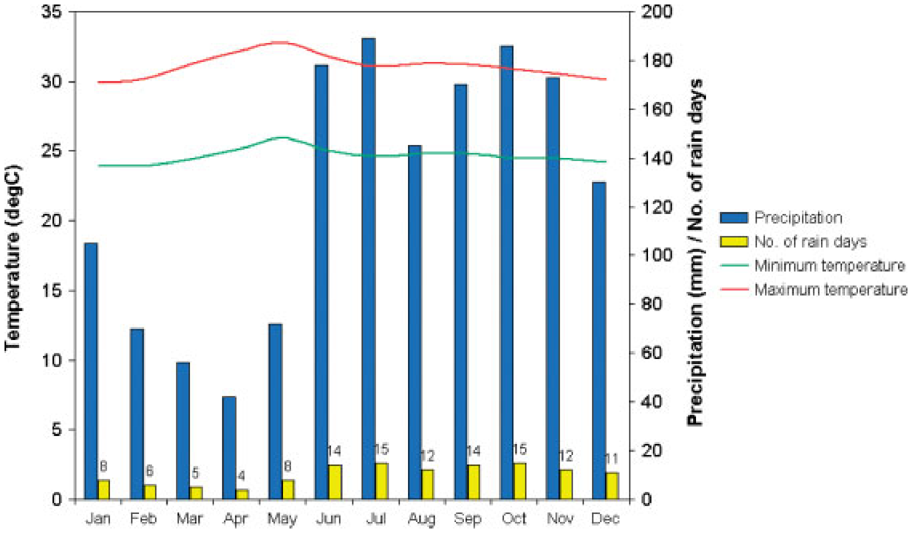

Figure 2. The climate of Mactan, Cebu, Philippines (10.3°N, 124.0°E, 24m) in the tropical rainforest zone. It is wet throughout the year, although monthly totals vary as the ITCZ moves north through the Philippines in June and July then returns south between September and November. Drier weather occurs as northeast Trade Winds make occasional incursions south between January and May. The number of rain days is high, in particular between June and December, when there is rain on more than half the days. Note the small daily and annual temperature range, < 10 degC (sourced at http://www.pagasa.dost.gov.ph/cab/cab.html).

Figure 3. Typical dense tropical rain forest at Latak waterfall, Lambir National Park, Sarawak. (© Richard Young.)

layer (http://uk.encarta.msn.com/media_121627758/Typical_Latosol_Soil_of_the_Tropical_Rainforest.html), so that trees tend to spread their roots laterally rather than downwards to make use of humus nutrients. The leaching concentrates acid minerals, including iron and, in particular within this zone of high rainfall, aluminium (Ellis and Mellor, 1995). Interestingly, however, the forest canopy itself reduces the rainfall that reaches the ground, reducing leaching. Studies at the Centre for Ecology and Hydrology, Wallingford, suggest that the reduction is as much as 30% (Overton and Strangeways, 2007).

Productivity is highest of all the world's environments in these forests (Table 1). The total productivity[3] (plants and animals) reaches 4.5kg C $m^{-2} yr^{-1}$; 50% of the world's species of plants and animals live in these forests. The low level of available mineral nutrients, however, has had an interesting effect: the diversification of plant and animal species, which must find ways to extract nutrient from the environment (Fothergill *et al.*, 2006). This is mainly because growth occurs throughout the year. The jungle teems with insects and these provide plentiful food for mammals and reptiles. Fruit-bearing trees also support some larger animals, including monkeys and apes. Amongst many insects, the mosquito is particularly well-adapted to tropical rainforest. With it comes the malaria parasite – bringing one of many diseases that flourish in the warm, wet, equatorial environment.

On the leached soils, new growth is very dependent on the death of older trees, which can be decomposed in a matter of months or years in this high-temperature, moist environment. Thus beetles, as well as other insects, bacteria and fungi, which do not depend on sunlight, but use undecomposed organic matter for food, are important inhabitants of this biome.

The archetypal tropical rainforest, however, is sensitive to temperature, humidity and rainfall changes. As a result, it soon gives way to other forms of tropical forest where temperatures are lower, or where rainfall is seasonal. As a result, it is usually found within 200–500m of sea level where there is no long dry season. As a result, the main areas in which it is found are the islands and peninsulas of southeast Asia, the Congo and Amazon basins, and the Irrawaddy river system. Poleward of the main equatorial zone, upland areas of modest altitude may maintain dense evergreen forest, because rain falls throughout the year.

At high altitudes, the trees are better adapted to changes in temperature. The fall in humidity with altitude discussed in Part 3 (Galvin, 2008a) allows temperature to vary much more during the day, even though it remains above freezing to altitudes of 3000m or more. On higher mountains, where occasional frosts risk damaging

[3] This is expressed in terms of the annual mass of carbon fluxed from the environment (i.e. the amount of carbon dioxide changed to plant material) in a given area: primarily by vegetation, which may then be eaten by animals. Total productivity includes production of carbon by animals.

Table 1

Typical productivity (measured as the fixing rate of carbon by plants/phytoplankton) in tropical environments (from Fothergill et al.*, 2006 and Lalli and Parsons, 1993).*

Climatic zone	*Productivity (kg C m^{-2} yr^{-1})*
Tropical forest	1–3.5
Savannah	0.2–2
Arid zones	~0.3
Mountain	≤0.02
Ocean – barrier reefs	1.5–5
Ocean – coastal zones	~0.1
Ocean – continental western margins	~1
Ocean – subtropical gyres	<0.03

Box 1. Soil types of the tropics

Alfisol. Formed of clay with nutrient-enriched subsoil, typical of monsoonal and semi-arid regions. Those in monsoonal regions, however, have a tendency to acidify when heavily cultivated, especially when nitrogenous fertilizers are used.

Andosol. A highly porous, dark soil developed from volcanic rocks: ash, tuff or pumice. It typically occurs in highland areas.

Grumusol. A brown, calcium-rich soil of dry environments. It forms over limestone or dolomite bedrock.

Latosol. A soil rich in iron, alumina, or silica formed in areas of tropical rainforest. The iron and aluminium enrichment is a result of high rainfall, which leaches the soil of soluble minerals, such as calcium and phosphorus.

Leptosol. A very shallow soil (indicating little influence of soil-forming processes), often containing large amounts of gravel. It typically remains under natural vegetation, as cultivation makes it especially susceptible to erosion and desiccation.

Regosol. A soil formed from unconsolidated silt or clay that may be of alluvial origin and that has a lack of a significant soil horizon because of a dry or cold climate.

Vertisol. A soil containing immature (swelling) clays, commonly found in the wet or seasonally wet tropics where chemical erosion affects the bedrock, which is usually of volcanic origin. The soil is regularly overturned by wetting, due to its high proportion of swelling clay.

Desert surfaces. The surfaces of arid lands are composed of exposed bedrock outcrops and fluvial deposits including alluvial fans, playas, desert lakes and oases. Bedrock outcrops commonly occur as small mountains surrounded by extensive plains. Where soils occur, they are poorly developed and shallow, although they may contain a high concentration of minerals, since the low rainfall does not leach them. Where developed on limestone, they form *rendzinas*. However, they are also high in salts, since any rainfall is evaporated rapidly. Deserts have highly specialized salt-tolerant natural vegetation.

(Courtesy *Encyclopædia Britannica* and *Wikipedia*.)

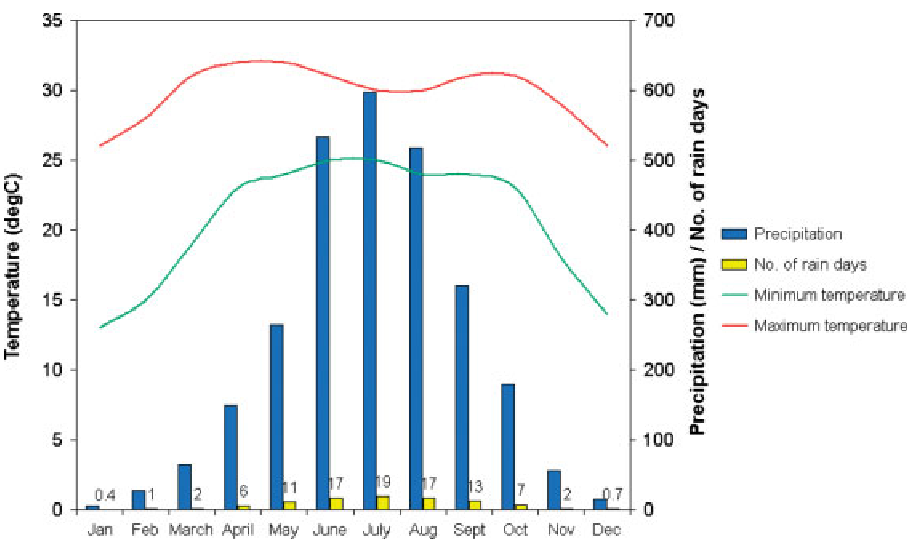

Figure 4. The climate of Chittagong, Bangladesh (22.3°N, 91.8°E, 6m) in the tropical deciduous forest zone. In this monsoon climate, there is little rain between late October and early April. During this period potential evaporation exceeds precipitation. Thus trees 'hibernate' through the winter and make use of the very high rainfall between June and September for rapid growth. Agriculture has replaced natural forest in much of this zone. The temperature range is high between November and March (>12 degC), but comparatively low during the wet summer season.

trees in leaf and which is usually above the humid tropical boundary layer, needle-leaf conifers predominate. At these altitudes there is often less rainfall available, placing greater stress on trees that are not adapted to steep slopes, thin soils and, at times, low temperatures.

Seasonal tropical forest

In the lower-lying tropics dominated by monsoons (Galvin, 2008c), where there is sufficient precipitation to support extensive forest (an annual rainfall more than about 1000mm; zone Am in Figure 1), trees must withstand dry, periodically hot weather for a substantial part of the year. In the wet season, foliage must be able to withstand very wet humid weather.

Deciduous trees, such as teak, are well adapted to this regime, as they shed their broad leaves at the beginning of the dry season, so are present in much of this zone, although evergreen species are also seen. The rate of carbon fixing is somewhat lower than in the predominantly wet rainforests, but the annual leaf fall allows the soils to be somewhat more fertile, with more nutrients returned to the soil, although the heavy rains of the monsoon wash them out for a proportion of the year. Seasonal forests are the climax vegetation of much of West Africa and eastern Brazil, parts of the Indian subcontinent, China, Central America and northern Australia.

Although these forests have an annual mean temperature range similar to that of the equatorial forests, the daily range is high during the dry season, reaching 12 degC or more. At times inland, the temperature may reach 40°C or more. Climate data for Chittagong, Bangladesh, reflecting this zone, are shown in Figure 4.

Seasonal tropical forest supports a variety of plants as an under-storey; evergreen bamboo varieties are perhaps the most notable. The woodland is locally interspersed with grassland, in particular towards its poleward limit, and so also supports a wide variety of fauna – in particular larger animals of a great variety of species. The forest thins where the annual rainfall is less, reflecting the relatively large amounts of water required for trees to grow. The trees themselves, however, maintain a relatively moist environment, providing some protection from desiccation.

The savannahs

Where rainfall is regular, but insufficient to support extensive forests – usually below an annual total of about 800mm – grassland is the climax vegetation. The savannahs (Aw, Caw in Figure 1) thus mainly lie to poleward of the monsoon forest zone, although in East Africa, altitude and shelter extend the zone across the Equator. Although defined as grassland, trees are also a characteristic

Figure 5. Blaze in stands of trees in the savannah of Australia's Northern Territory. The dry conditions make fire a near-constant hazard, Australian 'gum' trees easily burning. (© D. & B. Pettigrew.)

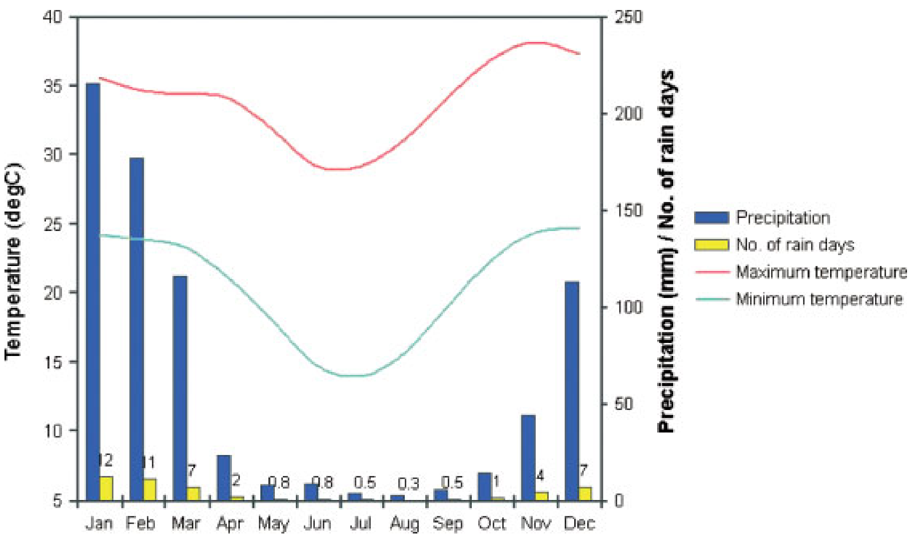

Figure 6. The climate of Croydon, Queensland, Australia (18.2°S, 142.2°E, 116m) in the savannah zone. The temperature range is high in winter (>12 degC). Rainfall is plentiful in summer and has the potential to support highly productive agriculture, even though year-round potential evaporation is very high; winter is generally dry (sourced at http://www.bom.gov.au/climate/averages/tables/cw_029012.shtml).

Figure 7. Chamber's Pillar – a sandstone outcrop with vertical sides in the western Simpson Desert, Northern Territory, Australia. This landform can only exist in deserts and indicates a lack of regular rainfall. However, meagre rainfall seeps gradually through the rock and supports the scrubby trees around its base. (© J. F. P. Galvin.)

of much of this land, often occurring as small stands among large areas of grass. The zone usually has a pronounced dry 'winter' season and a wet 'summer' season characterized by large falls of rain in short periods.

The mean temperature range of these grasslands often exceeds 12 degC with the highest temperatures and largest temperature range occurring during the dry season, maxima reaching 35 °C or more. Although frosts are rare, they sometimes occur in winter in upland valleys within this zone. Typical climate data for the savannahs, recorded at Croydon, Queensland, Australia are shown as Figure 6.

The grassland characteristically supports many herds of large animals, but also a variety of smaller ones. Indeed, fauna abound: there is about 200 times the mass of animal life on the savannahs, compared with that in the tropical rainforest (Fothergill *et al*., 2006). The large herds of animals, in their turn, support predator species in most tropical continents and have been a traditional source of food for humans. Reptiles often live well in this environment too.

Where there is plentiful water, there is a greater variety of species in the savannahs and this is often from rivers that flow throughout the year in this climatic zone, even though rainfall is seasonal – almost all falling in a wet summer period. Not only is this water important for vegetation, it also supports many animal species.

Winds can be strong over this zone, flat grasslands exerting little friction on the airstream. Dry Trade Winds predominate in winter, although the summer brings predominantly moist equatorial flow.

Although dry for a large part of the year with much less growth than more humid areas, in terms of carbon fixing rate, the savannahs deserve the title of the world's most efficient environment. Between 0.2 and 2kg C m^{-2} yr^{-1} (Table 1) are fixed from relatively scant resources by just a tenth of the biomass of the tropical rainforest (Fothergill *et al*., 2006): a rate up to about four times that of tropical rainforest.

The soil types of the savannahs vary between vertisols, alfisols (Natural Resources Conservation Service, United States Department of Agriculture, 1999, 2006) and, in areas of limestone bedrock, grumusols.[2] However, most have a form characteristic of the zone. Leaching reduces the organic and mineral content of the surface layer, but these soils are less leached than the latosols of the rainforest zone. They are formed both by leaching in the wet season and mineral differentiation during the dry season, when capillary action brings lighter dissolved minerals towards the surface. Much of the rainfall of the savannahs occurs in short-period heavy downpours, however, increasing the potential for wash out, although the presence of grass cover helps to reduce the impact

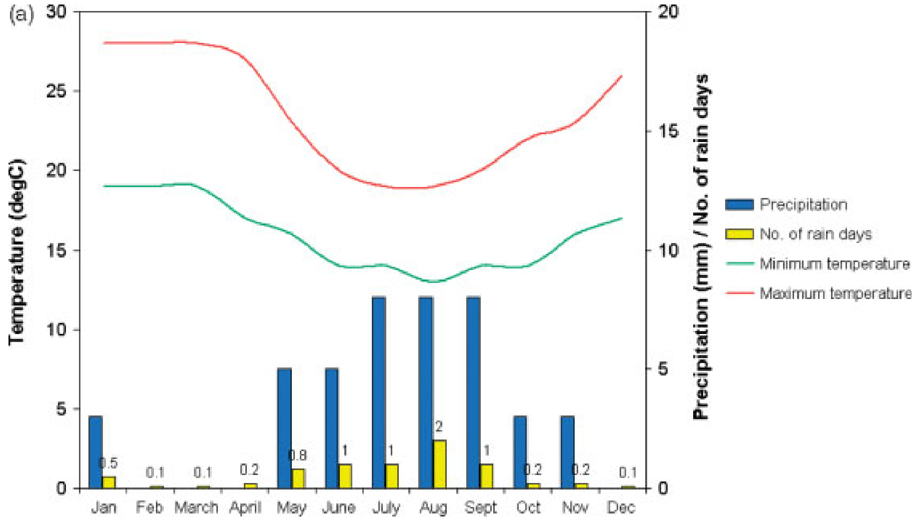

Figure 8. (a) The climate of Lima, Peru (12.0°S, 77.1°W, 13m) in the coastal Atacama desert. Most rain falls in winter as upper troughs bring occasional mid-latitude disturbances from higher latitudes. Note the limit to maximum temperature through the summer, due to sea breezes from the neighbouring cool water of the Peru Current.

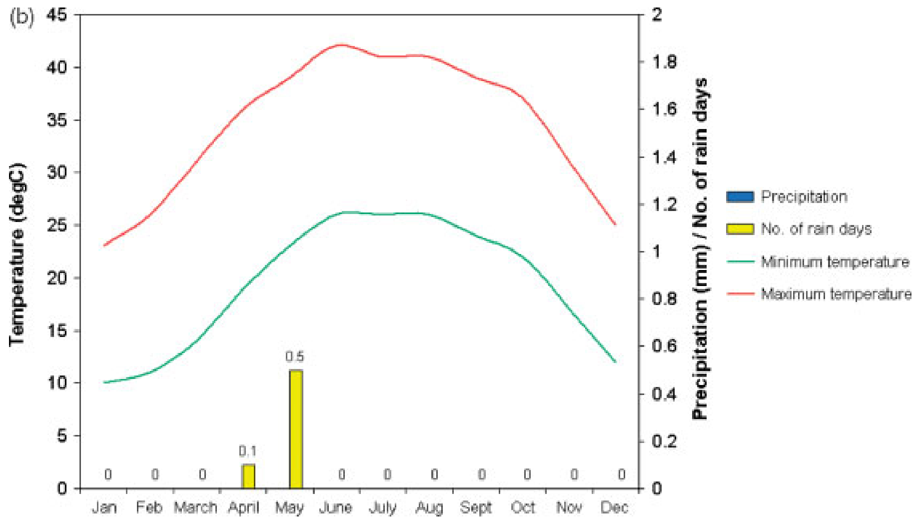

Figure 8. (b) The inland desert environment at Aswān, Egypt (24.0 °N, 32.8 °E, 194 m) in the eastern Sahara desert. No more than a trace of rain can be expected to fall here. Note that the rainfall scales in these diagrams are very much smaller than in the other figures. The difference in temperature range between the two desert environments is notable: large inland at Aswān (~15 degC) and small at Lima (5–10 degC), moisture from a cold ocean limiting both maxima and minima at the latter.

of the rain. Crops, as they grow, provide similar – or better – shelter, but when the ground is clear following the harvest, soils may be more open to leaching. As the harvest usually occurs at the beginning of the dry season, however, the risks are relatively small. Savannah soils can be hard to cultivate, due to leaching and so favour pastoral farming, although arable farming is also very important in this zone, in particular where soils are rich in minerals and water is available for irrigation.

Fires are another characteristic of this zone, in particular towards the poleward edges. Following the dry season, vegetation may be desiccated and, in particular as more humid air begins to return, 'dry' thunderstorms occur, their lightning typically setting fire to trees (Figure 5).

Three of the world's ten largest cities: Mumbai, Delhi and Shanghai, have developed in these seasonally dry zones, reflecting the benefit to humans of seasonal climates with adequate rainfall during a warm growing season.

Tropical deserts and scrublands

These environments (BSh and BWh in Figure 1) cover more than one-third of the Earth's surface and support a remarkably high population, despite their aridity. Throughout the year, evaporation exceeds precipitation, which is generally below 300mm yr^{-1} and more typically below 50mm yr^{-1} in the desert plains. Rainfall is very variable, however: in some years there is relatively high rainfall locally, whilst in most years there is none. The usual lack of cloud cover and very low humidity (away from the cool-ocean coasts of Namibia, Angola, Chile and Peru, as well as, seasonally, those of Somalia, Yemen and Oman) bring a daily temperature range of 15 degC or more. Sunshine totals may be more than 80% of the maximum possible. Many aspects of harsh dry environments were presented in Part 5 (Galvin and Membery, 2008).

Most scrublands along the fringes of the deserts see occasional monsoon rain. Many have their own peculiar environments and ecosystems. Ephemeral rivers, such as the Okavango at the edge of the Kalahari, may not drain into the sea, but can support a variety of animals that must travel hundreds of kilometres to find water, following seasonal rainfall.

In many areas, especially over higher ground and in its rain shadow, the tropical forests and savannahs give way to semi-desert scrublands composed mainly of stubby drought-tolerant trees and hardy grasses. Parts of southern and eastern Africa, India and the Australian Outback are characterized by this vegetation.

Scrubland has mainly short, needle-leafed trees growing near ephemeral streams or in stands where sufficient water is available. Some hardy grasses are also seen, although there is a large amount of bare soil, especially at the edge of the deserts. In Africa and Australia, close to the furthest poleward burst of the summer monsoon, are scrublands (Figure 7). In Africa, this land is known as the Sahel.

Rain, when it falls, is often intense and may be accompanied by hail. Indeed, it is estimated that much of the rainfall of the Sahel comes from mesoscale convective complexes, as described in Part 8 (Gaye *et al*., 2005; Galvin, 2009).

Life must be very hardy to survive in the arid lands. Animals usually retain water, or can make their own water metabolically. Nevertheless, all major types of animal are represented in desert or semi-desert environments and humans live in many tropical areas subject to drought. Perhaps surprisingly, two of the world's ten largest cities are in dry environments. The trading ports of Karachi and Lima were founded on rivers to supply plentiful fresh water from glaciers on neighbouring mountains to support populations of 10.8 million and 8.9 million, respectively. As these glaciers have declined in recent years, however, there is a growing need to find alternative sources of drinking water (Aquino and Ford, 2008; Asif, 2008).

The climates of Lima, Peru and Aswān, Egypt are typical of the world's tropical deserts, as shown in Figure 8. The scrubland (semi-desert) climate is illustrated by data from Timbuktu, Mali (Figure 9).

Natural vegetation, where it can survive at all, is characterized by water-retaining

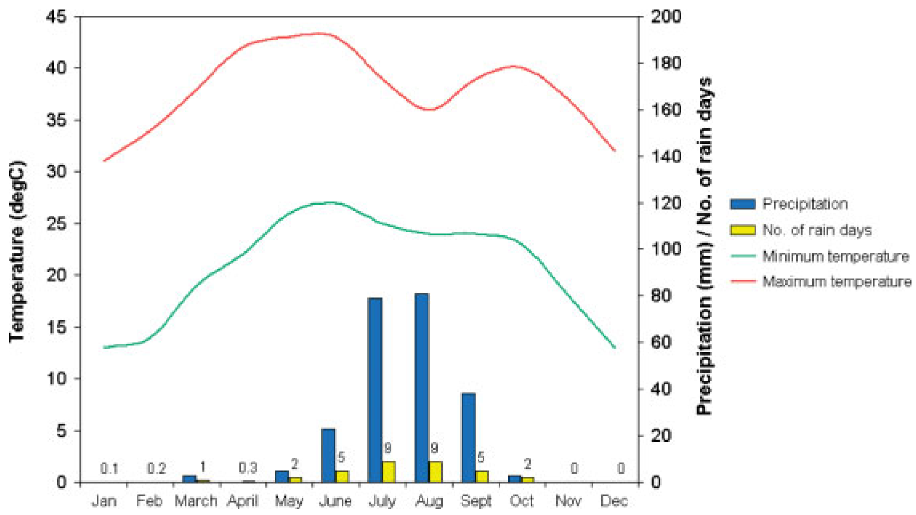

Figure 9. The climate of Timbuktu, Mali (16.7°N, 3.0°W, 264m) on the desert fringe of the Sahel. Almost all the rainfall comes from northward excursions of the summer monsoon from late June to early September. It occurs on only a few days during the summer, often in heavy bursts and about half comes from squall lines, associated with easterly waves (Laing and Fritsch, 1997). The dramatic reduction in temperature range during the rainy season is notable.

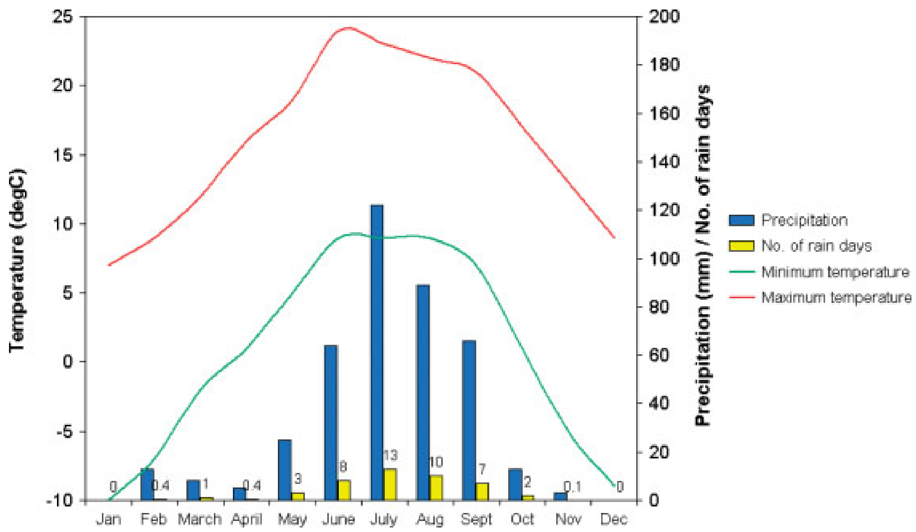

Figure 10. The climate of Lhasa, Tibet, China (29.7˚N, 91.1˚E, 3650m), typical of tropical highlands with cold winters (under the influence of extra-tropical air streams) and hot summers (considering the altitude) with rainfall mainly from locally formed convection in summer. Many days are wet, but rain occurs over relatively short periods, mainly late in the day.

plants. Other plants survive drought as dormant seeds that germinate rapidly following rain that may fall only one year in six. Characteristically, these are flowering plants and short-lived seas of colour are the beautiful result.

Cool-water desert coasts – in particular those of the Namib and Atacama – have an unusual vegetation, dependent on dew and fog in humid, cool air carried ashore.

Low rainfall and high evaporation make productivity low in the deserts (Table 1), although there is considerable variation, dependent on the variability of annual rainfall and potential soil fertility.

For much of the year, these zones have relatively strong Trade Winds, blowing across relatively flat land with little vegetation, although summer brings periods of moist monsoon flow poleward from their equatorward fringes (see Figures 4 and 5 of Part 8: Galvin 2009). The return of the Trade Winds may bring plagues of locusts across areas of seasonal growth, moistened in summer, whilst mosquitoes and the associated risk of malaria may occasionally be brought by the moist equatorial flow of high summer.

Mountain climates

Mountain climates are particularly important across the tropics; drainage of the rainfall they generate often helps to maintain populations on dry, or seasonally dry lands around them. These areas are stippled or designated H in Figure 1.

One of the most extraordinary climates of the tropical zone, as it expands poleward in the northern summer, is that of the Tibetan plateau. Although much of the zone is a plain, its altitude brings it into the realm of mountains. Almost all the plateau lies above 4000m and so, even in high summer, it remains cold with surface temperatures barely above freezing at night and reaching more than 20 °C by day. It is cold enough for the ranges of mountains (the Tangula Shan) that cross the plains to remain ice-covered throughout the year. Climate data for Lhasa, Tibet (at one of the lowest points on the plateau) are shown as Figure 10.

At 4000m above sea level, the air is very thin, containing barely 60% of the oxygen available near sea level. Still more limiting for life is the lack of water. The plateau is sheltered on all sides: monsoon rains cannot cross the Himalaya and clouds from more northern latitudes deposit meagre rainfall mainly on the Kunlun Shan, which forms a rim along its northern border. Apart from a few deep narrow passes, mountains reaching 7000m or more surround the plateau. What little rain and snow that does fall mostly occurs in summer, mainly from isolated cumulonimbus clouds. With a base near 5000m, convective clouds contain little precipitable water, even though they may be 11 000m deep. The humidity mixing ratio for saturated air at 5000m and 0 °C is only 9g kg^{-1}, the air density little more than half that at sea level. A lowland cumulonimbus cloud in the ITCZ, with a base at 750m and 15 000m deep, may contain five times as much water! Humans, plants and animals living in this environment must adapt to drought in the dry air and low oxygen levels, as well as to the cold.

Alpine grasses have adapted themselves to this environment, but there are very few trees (Figure 11). The thin mountain soils: leptosols, andosols and regosols[2] (FAO-UNESCO, 1989) vary mainly in their mineral content and origin, but most remain under their natural vegetation. In the tropics there are trees to near 4000m (but highly variable), thin grassland scrub at higher altitudes giving way to bare ice-shattered rock on the highest peaks. Where rainfall does not erode the soil, it may be rich in organic matter (Ellis and Mellor, 1995). However, herds of antelope and horses typify the natural fauna of the plateau. With such a short growing season and a desert environment, productivity is very low in Tibet and similar highlands.

Although the Tibetan plateau provides an interesting area to study, the tropics have many other mountain areas, such as the Ethiopian plateau. Relatively modest areas of high ground are likely to be more wooded than great plateau lands and benefit from a high rainfall – well above that of surrounding lowlands. The towering peaks of the great plateaux are so high that they are above most rain-bearing cloud. The greatest increase in rainfall is between about 1000m and 3000m, the moisture content of the air reducing significantly above this level. High ground in the rain shadow of larger massifs remains almost as dry as its surroundings,

Figure 11. Vegetation of the Himalayan mountain zone, essentially an upland cold desert (above an altitude of about 3500m), with few trees and scant vegetation, Manang Himalaya, Nepal, October 1992. An effect of rural depopulation is visible as ruined buildings in the middle ground. (© Nigel Bolton.)

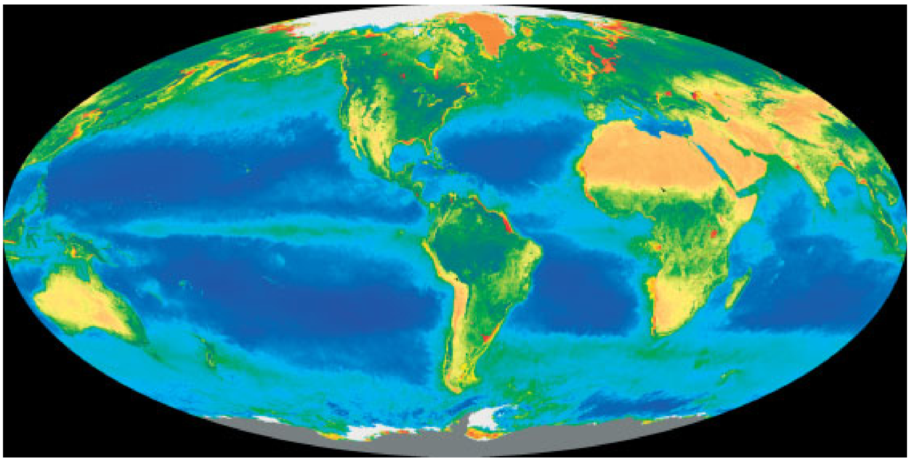

Figure 12. The global distribution of ocean chlorophyll concentration from satellite imagery - an indicator of productivity, September 1997 – August 1998. Note the low productivity of oceanic gyres (blue shades < 100mg C m $^{-2}$ day $^{-1}$) compared with the productive areas of upwelling - in particular along the western coasts of Africa and South America, where values reach more than 400mg C m $^{-2}$ day $^{-1}$ (yellow-orange). The slight increase in productivity (~200mg C m $^{-2}$ day $^{-1}$) near the Equator in the Pacific and Atlantic Oceans (green shades) is not present in the Indian Ocean, where the ocean gyre - and so convergent descending water - is present across the Equator. (Courtesy NASA-GSFC.)

but many dry or seasonal areas of the tropics between these heights have a significantly increased rainfall. Many of these areas of high ground were listed in Part 4 (Galvin, 2008b). Mexico City – one of the world's largest cities – at an altitude of about 2300m, is founded on the relatively equable climate of the Mexican Highlands.

Tropical oceans and coasts

For the purposes of this article, the tropical oceans are found between the relatively steep temperature and salinity gradients that occur close to 30° south and 35° north of the Equator (varying somewhat with season) and where the ocean surface has a temperature above about 22°C. However, the areas of upwelling cold water that lie along the western coasts of the continents, where temperatures are locally well below 22°C, are included (see Figure 1, Part 3: Galvin, 2008a).

Odd though it may sound, most tropical oceans are equivalent to the continental deserts. Their productivity is usually very low, since nutrients easily settle out. This is mainly due to the relatively light winds of much of the tropics, notwithstanding the moderate to fresh Trade Winds, which do ensure some essential minerals are retained in the surface layer.

The convergence and subsidence of surface water in the great ocean gyres, under the influence of the subtropical, high-pressure belt (Lalli and Parsons, 1993), along with the distribution of both rainfall and wind ensure that most nutrients soon sink below the surface layer. The windier areas receive little rainfall and the wetter areas (the doldrums) have light winds. Under clear skies, the intensity of radiation also reduces productivity near to the ocean surface (Table 1). This means that nitrogen, the main source of which is rainfall over the open oceans, is usually in short supply.

In the humid tropics, the drier season, dominated by Trade Winds, brings some increase in the maritime harvest, as does the weather following tropical storms (Galvin, 2008d). Large swell brings deep water to the surface and the tropical rainfall adds nutrients to the sea, some of it as run-off from the land.

Of course, there is a great variety across the tropical oceans. In coastal areas, there is a much greater supply of minerals, resulting from run-off in streams and rivers (Table 1). Most remarkable, however, are areas where there is little run-off, but a shallow continental shelf. Here, in the dry tropical ocean environment, coral reefs blossom. These are incredibly productive, despite the poor nutrient supply (Table 1). (Due to the paucity of nutrients, this is not reflected in the chlorophyll concentration shown in Figure 12.) Indeed these animals, which grow together as a colony, depositing the coral mineral as they develop, are dependent for survival on warm, clear, still water with almost no suspended particulates. In the shelter of the corals live a variety of fish, shellfish and echinoderms (e.g. starfish, sea urchins).

An important exception to the usual paucity of fish in tropical oceans occurs in the areas of upwelling along the western coasts of the tropical continents. Trade Winds blowing offshore cause cool water from the ocean deeps to rise to the surface, bringing with them a high nutrient supply, as indicated by Figure 12. In this figure, the level of nutrients is proportional to the number of fish, since the nutrient feeds drifting plants (phytoplankton), the phytoplankton form food for floating animals (zooplankton), which are available as food for fish. The west coast of South America, south of the Equator, is particularly well-endowed. The waters rapidly deepen offshore, so that deep water can readily rise to the surface under the influence of the offshore Trade Wind flow. The result is a cooling of about 6 degC and fish stocks are usually high. They include anchovies, pilchards and jack mackerel. This coast, however, is periodically cursed. Close to the Equator in northern Peru and Ecuador, the supply of upwelling water periodically decreases at a time when it would normally be expected to reach a peak in December and January. This is the El Niño phenomenon. Without sufficient upwelling, the nutrient supply is limited and the fish

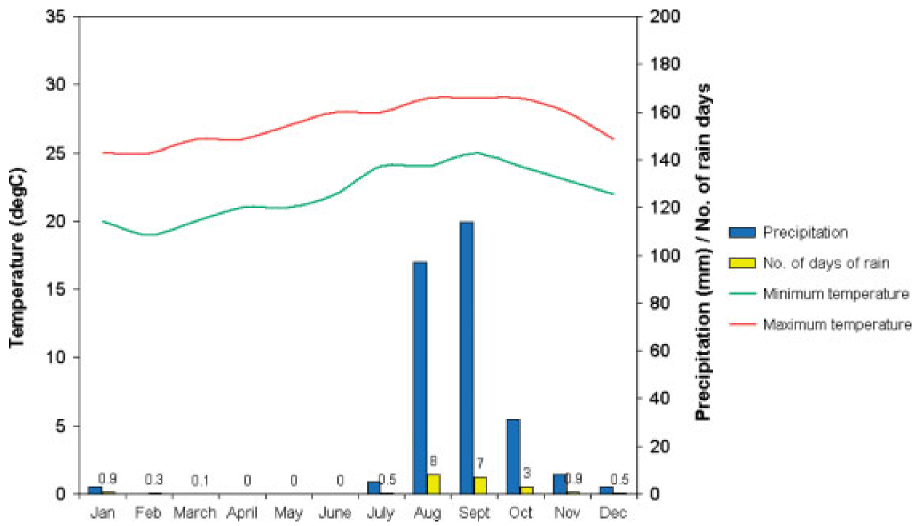

Figure 13. The climate of Praia, Cape Verde Islands (14.9°N, 23.5°W, 35m). This predominantly dry climate is typical of the oceanic anticyclones with most rainfall late in the summer when sea temperatures are highest, allowing heavy showery rain (on average, more than 10mm per rain day) to develop, often associated with easterly waves (described in Part 8: Galvin 2008e). The relatively scant rainfall must be stored to last through the dry season between December and July when evaporation remains high in the northeast Trade Wind regime. These winds, off the Sahara Desert, frequently bring outbreaks of dust.

stocks reduce – at times causing a failure of the ocean's harvest, typically around Christmastide. This gave the phenomenon its name – the Christ child.

Although the greatest stocks of fish are found along the South American coasts, those of the west coasts of Central America, southern Africa and North Africa are also important throughout the year (Table 1).

Periodically, there is upwelling along other tropical coasts – in particular those of the Gulf of Guinea, Somalia and Yemen, where the strong southwesterlies of the summer monsoon bring a good summer harvest from the Arabian Sea. Here, as in many parts of the world, fishing is a hazardous occupation – every bit as taxing as in the western European waters of winter with rough seas hindering the fishing effort.

A variation on tropical forest is found along its brackish coastal limit: the mangrove forest. Mangroves grow well semi-submerged in silt-laden waters and provide a defence against coastal inundation. The storm surges from tropical revolving storms can be much ameliorated by this dense, low-lying vegetation and its maintenance is regarded as a very important part of the protection of the prevalent coastal communities in areas affected by these storms. In addition, mangroves stabilize the foreshore and many can filter out poisonous chemicals from the water, helping to maintain its fertility.

The lack of rainfall in the oceanic deserts can make living conditions difficult on remote tropical islands – perhaps especially those that, because of their sunshine and dry weather, attract many tourists. Desalination remains a very expensive way to provide drinkable water, but can be the only way to provide sufficient for the population and local agriculture, even if tourists survive on imported bottled water. The climate of Praia, Cape Verde Islands (Figure 13) illustrates the predominantly dry weather of the oceanic anticyclones, where relatively scant rain falls for only a few months of the year.

Conclusion

In this part, it has been necessary to divide the tropics according to 'typical' climate parameters, established by long-term means. However, there is, of course, great variety within these discrete zones and the margins of climate zones are, in truth, zones of transition. Climate change is also likely to impose changes to the limits of particular climatic regions.

The final part will discuss tropical agriculture and the associated effects on climate in the tropics, both at present and as they are expected to change during the twenty-first century.

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Climate data for many world cities are available at http://www.bbc.co.uk/weather/world/city_guides/index.shtml. The descriptions of soil types are as given in the *Encyclopædia Britannica, The concise Oxford dictionary of earth sciences*, at http://uk.encarta.msn.com/medias_761576446/Soil.html and http://soils.usda.gov/technical/classification/osd/index.html.

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