

The weather and climate of the tropics:

Part 10 – Tropical agriculture

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This final part of the series contains a brief overview of agriculture in the tropics, as well as its effects, noting the increasing human population in all tropical climate zones. In many places, humans have altered the distribution of plant and animal species, in almost all areas using plants and animals for food or labour. These changes, in turn, change the climate as the appearance and, therefore, the characteristics of the environment alter significantly.

The sensitivity and effects of the tropics on global climate are important. Small changes in rainfall patterns, when experienced over a long period of years, have a great effect on the vegetation; this, in turn, affects populations dependent upon it. Small changes in temperature have changed rainfall patterns in the tropics within the past two million years, making some areas drier and others wetter (Burroughs, 2005). The global climate is regulated by conditions in the tropics: the source of energy for agriculture in the middle latitudes is partly supplied from the tropics, tropical forests absorb a large proportion of global carbon dioxide production, and protective ozone is created in the tropical stratosphere. It is thus increasingly important for us to study not only the weather and climate of the tropics, but also the interrelationship between tropical climates, agriculture and humankind.

Agriculture in the humid tropics and the effects of forest clearance

Agriculture has resulted in the clearance of forest in many parts of the humid tropics, although it is the semi-deciduous forest that has been subject to most clearance historically. In part, this is due to the relatively rich, but leached, red-brown (iron-rich) or grey (kaolin-rich) soils of the humid zone, but also due to patterns of settlement and the slightly favourable monsoon climate. Forests are ideally suited to the humid

tropics with roots able to tap dissolved minerals below the surface soil layer (Ellis and Mellor, 1995).

As the forest is cleared to open areas for agriculture and as a source of wood for construction and paper making, or to grow crops, there is a profound effect on the climate. Clearly, growing populations require more arable land, but the planting of cash crops remains a contentious issue. In the tropical rain forests of southeast Asia, many areas have been either cleared, or the forest changed to a secondary form, often of palm and fruit trees (Figure 1). Initially, the clearance was to provide wood for housing, but latterly it has been to grow subsistence crops. In semi-deciduous ('monsoon') forest, crops such as tea (originally brought from China to India and East Africa), coffee, and chocolate, grown largely for export, have often replaced the woodland. Elsewhere, oil crops, tropical fruit or groundnuts are the principal crops where forest has been cleared. (It seems likely that oil crops will become increasingly important in future, at the expense of the natural forest.)

Forest clearance has an unfortunate and significant effect on climate and the effects of weather (Figure 2). As crops or grassland replace woodland, the daily temperature range rises, transpiration decreases and lower surface humidity reduces cloud formation – most of which is a result of

convection in the tropics. Thus crops may require additional watering in the drier areas. The main feedback, however, is a reduced quantity of water carried through the hydrological cycle. Another feedback is an increase in cloud-base height of cumuloform clouds, which reduces the amount of rainfall that may reach the ground before evaporating.

As trees are cleared, there is a serious effect on the tropical latosols.¹ Without trees, leaf-fall and fallen trees cannot contribute to the recycling of minerals, so the soils are more easily leached of essential nutrients. The lack of a leaf canopy increases the intensity of rainfall at ground level, so that the thin humus layer can be washed away more easily. Where crops are grown commercially, it is often necessary for large amounts of fertilizer to be added, even where relatively nutrient-rich river waters from mountains such as the Himalayas are used to water them. Although the potential

¹ Latosols, as described briefly in Part 9 (Galvin, 2009b), are the characteristic soil of the humid tropics. They are formed by leaching of nutrients from the upper layers in heavy rainfall, so are generally deficient in many nutrients. However, rapid decomposition in the warm moist conditions of this zone, as well as nitrogen from rainfall does provide a good source of minerals in the humus layer, especially where trees provide some shelter.

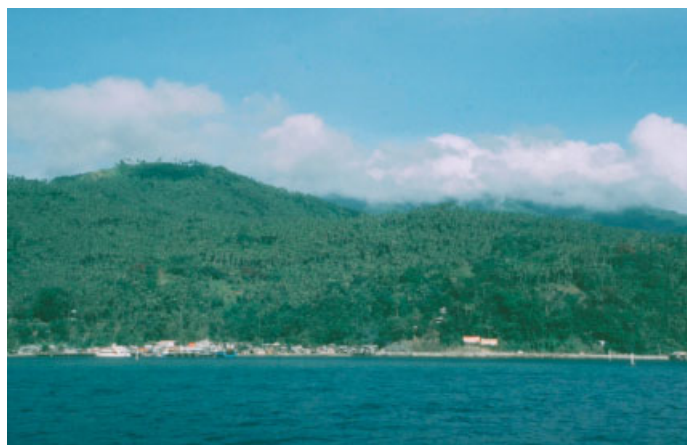


Figure 1. Much of the humid tropical zone has now lost much of its primary forest (darker shades), in particular in coastal populated areas, such as here at Benoni, Camiguin, Philippines, where coconut palms form a secondary forest (lighter shades) with relatively easy access and much altered local radiation balance. (© J.F.P. Galvin.)



Figure 2. In mountainous areas, the removal of many trees (often precariously clinging to mountainsides) has unfortunate effects in heavy rain. Here, in the valley of the Bued River, near Baguio, Benguet, Philippines, soil erosion is evident on the distant, east-facing sides of the valley above the maize fields of the valley bottom. (© J.F.P. Galvin.)

for productivity is very good, especially where there is a continuous growing season, the costs can be high.

Clearance and degradation of forests also emit carbon to the atmosphere, further affecting global climate. Net deforestation has contributed around a quarter of the historical rise of CO_2 , mainly from deforestation in the tropics (de Forster *et al.*, 2007). Tropical forest cover declined by 250 million hectares between 1980 and 1990. The forestry sector is currently the third-largest contributor of global greenhouse gas emissions and is a larger emitter than transport.

Tropical forests are also vulnerable to climate change with some models predicting widespread loss of the Amazon rainforest due to climate change (Betts *et al.*, 2004; Cox *et al.*, 2004), although any such impacts are highly uncertain. Severe impacts of climate change on tropical forests may be more likely if the forest is already affected by forestry activities (Betts *et al.*, 2007). Forest degradation may therefore increase the likelihood of climate–carbon cycle feedbacks, accelerating the rise of CO_2 . Protecting tropical forests

and the carbon they store is now being discussed as one possible measure to combat climate change through a mechanism called ‘REDD’ (Reducing Emissions from Deforestation and Degradation) (Gullison *et al.*, 2007).

Rice is perhaps the characteristic crop of the tropics, in particular across Asia, where 90% of the population is dependent on it as a staple diet. It feeds more than 3×10^9 people worldwide, approximately 45% of the global population, and so is the world’s most important crop (www.irri.org). It grows well in hot and moist climates with plentiful rainfall during the growing season (mean temperature $> 15^\circ\text{C}$ for germination, $> 22^\circ\text{C}$ for grain maturation² but $< 33^\circ\text{C}$ (Stansel and Fries, 1980) and no frost). About 150

² These temperatures are ‘typical’ values and vary according to grain cultivar. They must be sustained over a period of weeks, although the plants can usually withstand brief colder weather, over a period of a few days. The maximum temperature most grain crops can endure is around 32°C and most need plentiful soil water for growth.

million hectares of land are devoted to rice production – more than any other crop. Two growth stages are normally used, the first exploiting the plant’s water tolerance to restrict weed growth. However, this method of growth produces methane – a very powerful greenhouse gas. Up to three crops of rice may be grown annually, provided there is sufficient water. The need for water for the crop to grow – up to 5000kg^{-1} – can be critical in areas of periodic drought (ABC Radio National, 2008).

Even where the commercial planting is of trees grown extensively (e.g., fruit, oil palms, or coconut for copra), the damage to the environment can be serious, removing the habitat of the great diversity of flora and fauna of these forests.

Agriculture in the savannahs

The savannahs are very important for humankind and many crops have replaced the climax vegetation of this climatic zone, in particular in India, the Americas and Africa.

Perhaps most important of the crops grown in many savannah lands are the grains: rice, wheat, barley, oats, maize and millet. These plants, developed from grasses, feed a large proportion of the population of the tropics, although the cultivated area remains relatively small, compared with the natural grasslands used principally for pastoral farming. Many of these grains are ground to form flour for baking or bread-making. In general, tropical grains (apart from rice) contain little gluten, so bread does not rise well. Many grains are also used as animal-fodder supplements. In countries where alcohol may be produced, malted barley is used to make beer. The crop type depends partly on climate, but also on its familiarity to the population. Among the cereals, oats and barley are resistant to periodic cold, including frosts, whereas maize requires warmer, wetter conditions and millet is adapted to drier environments. Barley is salt-tolerant and oats can grow in very wet climates.

To germinate, the mean temperature (in a sufficiently moist soil) must be above $\sim 4^\circ\text{C}$ for oats, $\sim 9^\circ\text{C}$ for wheat and $\sim 11^\circ\text{C}$ for maize (Petr, 1991).² These temperatures are only a limit at altitude in most of the tropical zone, or at the periphery of the tropics in winter.

Beans are also important crops, helping to preserve soil fertility by fixing nitrogen from the atmosphere, whilst providing valuable vegetable protein. The most significant root crop is cassava, grown mainly in Africa.

In the savannahs, animals and plants must be adapted to dry and hot weather for part of the year, whilst able to withstand the very wet weather of the summer.

Dry-land agriculture

Most desert settlement is near rivers that, in some cases, are ephemeral (Figure 3). But



Figure 3. The Hugh River, south of Alice Springs in the Simpson Desert, Australia. Although most rain falls during the summer (monsoon) season, this was taken following winter rain. The scrub vegetation grows sustained by rains of the previous summer. (© J.F.P. Galvin.)

where there is sufficient water, agricultural productivity can be high, since the lack of rainfall restricts leaching of the soils. The soils may be thin and poorly formed, so that their mineral content has not been broken down to be readily used by plants but is still held within immature clays or bedrock. Nutrients may be rapidly consumed or leached when water is added, however, as soils are usually loose and friable. Irrigation water is readily transpired in the low humidity and daytime warmth of this zone.

Irrigation was traditionally seasonal, provided by great rivers, such as the Nile. Alluvial soils, largely of fine porous but impermeable clays, store water and help make agriculture productive (Ellis and Mellor, 1995). More recently, the building of dams and irrigation has allowed the greening of drier areas. The fertility of desert soils is also dependent on the geology of the surroundings. Where this is limestone, poorer soils are likely to form than from, say, claystones (Open University, 1986). Other areas may be largely bare rock, unsuitable for anything other than hardy animals that can live on the scrubby vegetation growing in cracks in the rocks. Almost everywhere in the dry environment, soils are thin and poorly developed.

The effects of desert irrigation over a long period can have a serious effect in dry lands. Soils naturally contain minerals, including salts. Addition of water gradually denudes the soil of essential phosphate and nitrate by leaching and as plants grow, whilst increasing many salts, in particular sodium chloride and calcium carbonate present in the water, due to evaporation. Sodium chloride is poisonous to many plants, so tolerant species may need to be grown.

In many parts of southern Asia, scrublands have long been irrigated. Groundnut is an important crop grown usually for its oil in central India, between the Eastern and Western Ghats, as well as in Indo-China.

The Sahel of Africa has come to prominence, mainly due to the effects of a growing population and the ephemeral nature

of the rainfall. The human effect on water resources has been important in these marginal zones, in particular for agriculture, where inhabitants have become increasingly settled, rather than nomadic. However, there are also signs that these zones have become drier during human history. This change may well be due to changes in the environment of the Sahel and of the neighbouring savannah, as well as larger scale climate changes and global sea-surface temperatures (Folland *et al.*, 1986). As studies continue, no doubt our understanding will increase.

The great benefit of mountains in arid areas is demonstrated by the growth of the staple cereals on high ground: rye, oats and barley on the mountains of Saudi Arabia and Yemen. Elsewhere, the orographic rains supply water to surrounding low ground, some of which may be in rain shadow. Notably, potatoes first grew on the slopes of the tropical Andes. Although humidity is low on the highest ground, these areas are seen often to be cloudy in satellite imagery. Settlement in upland valleys is dependent on rain- and snowfall from these clouds. This is particularly important in northeast Afghanistan, Iran and Pakistan. Relatively large populations live in these countries of dry climate, where hardy crops are grown by irrigation from great rivers such as the Helmand, Indus, Chenab and Sutlej. Rain and snow fall on the Reshte-ye Alborz–Paropamisus–Kuh-e Bābā–Hindu Kush–Karakoram, Brahui and Sulaiman ranges to feed these areas (Galvin, 2008b).

Weather and locust swarms

Locust infestation, which has a serious effect on agriculture in marginal desert areas, is related to the climate of these areas. Although different areas are affected in different years, locusts hopping and then flying in their millions destroy crops and thus livelihoods in the areas they land. Their pestilence is dependent on both weather

and wind. Rain, usually associated with incursions of westerly winds, provides suitable conditions, promoting the growth of plants and the successful hatching of locusts (Dubey and Chandra, 1991). Plagues may develop following insect maturation once the wind returns into the east. This change of wind direction is typically seen in the transition from summer to winter. However, many factors determine the occurrence of locusts, on all meteorological scales. A text in the Bible (*Exodus* 10:13–15) readily suggests the serious effect of such plagues.

Over the Middle East and North Africa, locusts are carried from the northeast to reach the southern periphery of the Sahara – the Sahel. Eventually, provided sufficient surface vegetation is available, southwest monsoon winds may carry locusts northeast, into northwest African countries. Southwest Asia, Pakistan and northwest India are also affected by locust plagues.

The effects of agriculture in the tropics

Figure 4 shows the distribution of the natural vegetation types in the tropics. Humans have altered this environment, mainly by agriculture (Turner and McCandless, 2004). The appearance of tropical lands, as modified by humankind, is shown in Figure 5. At first sight, the modification appears minimal, as the area under agricultural production is small (less than 10%). A closer look, however, comparing this figure with Figure 4, reveals that the areas of natural vegetation vary significantly – in particular the area covered by tropical woodland. This is likely to have been a direct result of agriculture over the centuries.

It is now generally accepted that areas formerly forested, but at the margins of arid areas, have become drier since the last ice age, some 10 000 years ago (Burroughs, 2005). This drying is probably caused, in part, by the spread of agriculture, although importantly the drying in itself reduces the tree cover. As discussed above, this, in turn, reduces rainfall, since evapotranspiration is reduced – and so on.

Clearly, humans must have the ability to grow sufficient food in the areas where it is needed: types that will grow well and that are familiar (IRRI, 2004). There is also a need to grow crops that will bring an income (e.g. tea, coffee, cocoa, copra, fruit) to provide cash and supplement the staple diet, thus generating sufficient wealth to allow education and health care. Although this has an effect on the environment (as seen very clearly in Europe or North America), this is generally small in the tropics (notwithstanding the changes discussed above). The lowland humid tropical zone has potential to produce vast crops from a small area, given its plentiful rainfall and sunshine, although supplements in the form

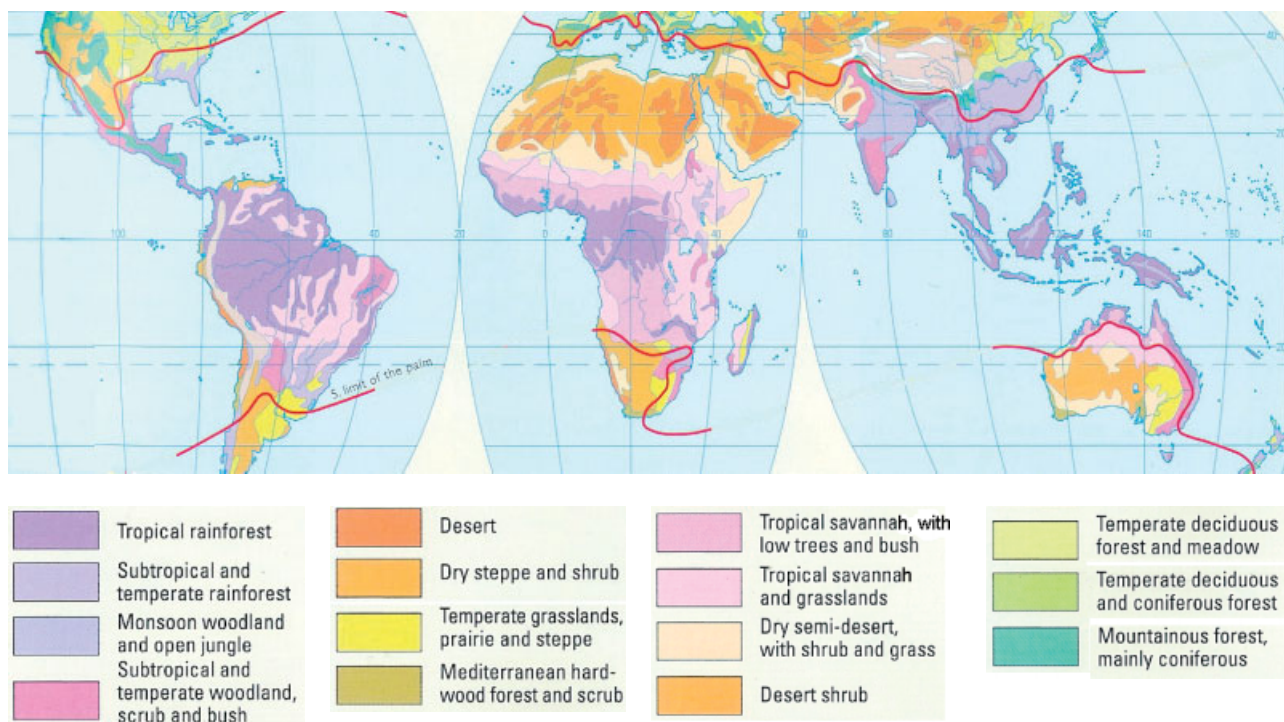


Figure 4. The natural vegetation of the tropics. The red lines indicate the northern and southern limits of palm tree growth (approximately equivalent to the area within which frosts are rare or absent). Where these lines are closest to the Equator, there is either high ground or the incursion of dry winter continental air.

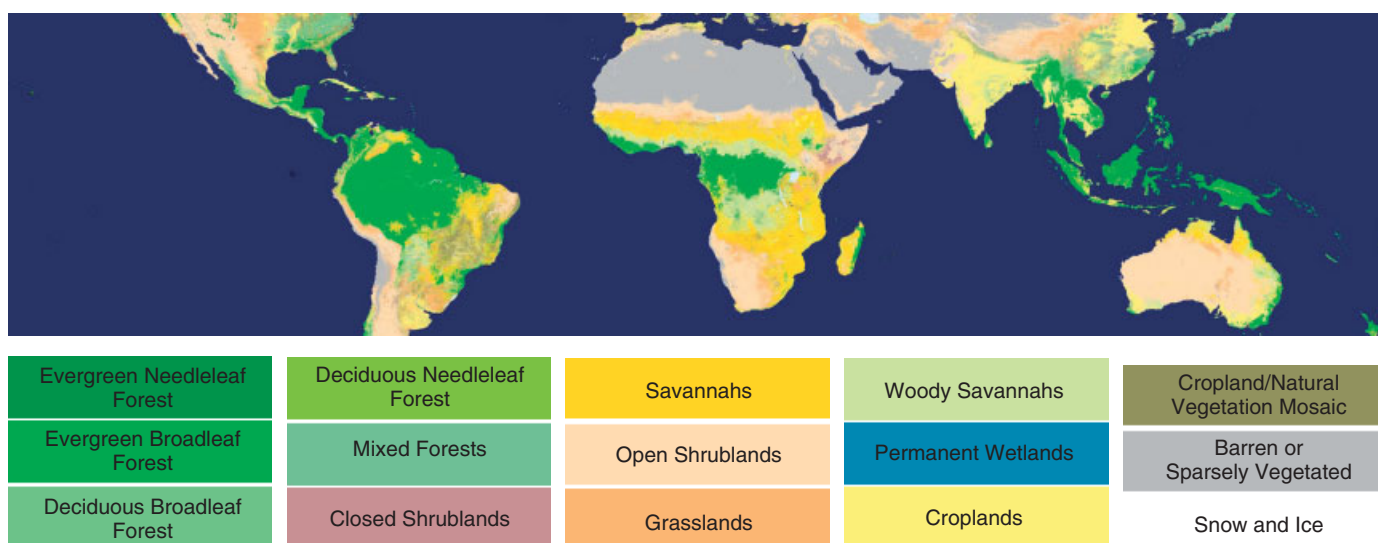


Figure 5. Present-day land cover of the tropics, as seen by the TERRA/MODIS satellite. (© Courtesy NASA/University of Boston.)

of fertilizers (natural or manufactured) will be needed to sustain this growth and the growing population.

Agriculture and climate change

The fact of increased greenhouse gas concentrations in the atmosphere and resultant warming is now well established (Le Treut *et al.*, 2007). The Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC, 2007) gives warming between about 2 and 4 degC in the tropics by the end of the twenty-first century compared with 1980–1999, the greatest warming over land, mainly in areas of dry climate. Over the sea,

the likelihood is that the greatest warming will be close to the Equator (Figure 6).

Any change of climate can take one of two forms as temperatures rise. Either the new climatic state has a similar variability as the current climate, or the variability changes. In the first case, the number of extreme weather events will change little, but in the latter case, it is likely that variability will increase. More extreme events would be likely, posing a risk of greater danger: more torrential rain, more droughts, more (or more extreme) tropical revolving storms, more forest fires, even above the increase to be expected as temperatures rise (IPCC, 2007). Clearly, these scenarios could have very different

outcomes and much research now goes into discovering which is more likely.

Also, there remain some uncertainties about regional effects, in the tropics as elsewhere. Studies increasingly focus on the regional scale, however, and, as knowledge and the resolution of models increase, studies will assess likely effects more locally. The Met Office Hadley Centre, using versions of the Unified Model, plays an important part in this work.

Deforestation and forest fires, as well as increases in greenhouse gas concentrations in the atmosphere will change the climate of the tropics (Andreae *et al.*, 2004), continuing the pattern observed since the

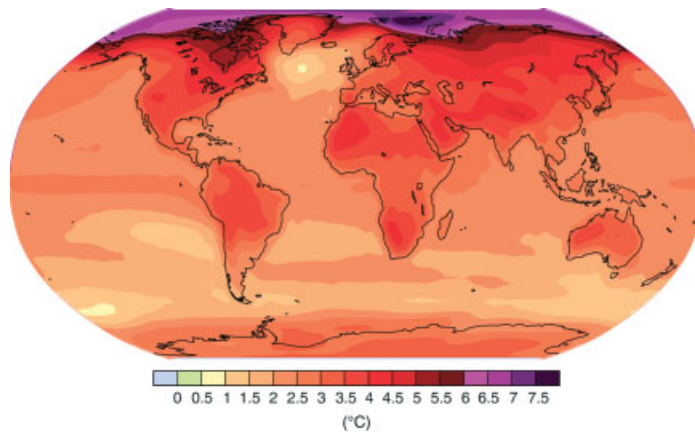


Figure 6. Projected surface temperature changes for the late twenty-first century (2090–2099). The map shows the multi-AOGCM average projection for the A1B SRES scenario. Temperatures are relative to the period 1980–1999. (Figure SPM.6 of IPCC, 2007.)

nineteenth century. Overall, climate models predict that temperatures will rise, although some parts of the tropics may see only small increases.³ The changes, however, are likely to affect both the Hadley Circulation (which brings warm air poleward) and the Walker Circulation, changing areas of broad scale ascent and descent in the tropical zone. Increasing variability is likely and the climate is likely to be less stable with greenhouse gas concentrations increasing (Cox *et al.*, 2000).

If the climate and the oceans, in particular, are warmer, more rainfall may result. Some parts of the tropics, however, are likely to become drier and others wetter. In general, the humid tropics are likely to become wetter, whilst drier parts of the tropics are likely to suffer more water shortages than occur at present (IPCC, 2007). In Asia, it seems likely that the southwest monsoon will become wetter and that monsoon rain will be heavier (Lowe *et al.*, 2005). On a regional scale, however, patterns of rainfall are likely to become more complicated. The Hadley Centre mesoscale climate model, running with a 25km grid length, suggests that there will be more rain on the highest ground, but areas in rain shadow in southern India, as well as the relatively cool ocean areas, are likely to become much drier (Met Office, 2004). Changes, although subtle, are likely to favour some crops over others.

Increasing rainfall is likely to increase river flow, although in many drier areas, any increase is likely to be minimal, the extra rainfall being used by plants, in particular in areas of marginal agriculture (Lowe *et al.*, 2005). Although generally of benefit to the population of these zones, there is a risk that the additional rainfall will be mainly in the form of heavy rain and hail, posing a threat of damage to crops, either directly or from floods and landslides. Some other,

unexpected, changes may also occur, as is already apparent in the western Pacific during the La Niña phase of the Southern Oscillation. In southeast Asia, when increased rainfall runs off high ground, rice terraces are often inundated, the rice seed washed away, or young rice plants drowned in deep water. Plants such as maize may not be able to germinate, or may suffer fungal infections when fields become waterlogged.

In areas of increased run-off and river flow, nutrients are likely to be more easily washed away, reducing natural fertility, as well as poisoning the sea, reducing oceanic productivity and fish stocks.

A warming world is also likely to bring changes to the El Niño–Southern Oscillation – the main control of climate variability in the tropics. Whilst some researchers suggest that El Niño will become more common, however, ice-core studies for 10 000–5000 years ago, when the global climate was warmer than at present, suggest that El Niño will be less common, decreasing tropical climate variability (Burroughs, 2005). Overall, the eastern equatorial Pacific is expected to warm, as shown in Figure 6 (IPCC, 2007). If tropical climate variability is reduced, some of the hazards of tropical agriculture will either lessen, or can be allowed for.

Warmer oceans might reasonably be expected to produce a greater likelihood of tropical storms and there is some evidence of an increase in storm activity over warming waters (Saunders and Lea, 2008). However, many studies suggest an overall reduction in storm number, some areas seeing fewer storms, while others experience more. Where they occur, they are likely to become more intense (Burroughs, 2005; Emanuel, 2005). Coastal and island populations are likely to bear the brunt of a warmed world as sea level rises, due to melting ice caps and ocean expansion (IPCC, 2007).

Given the key role played by the oceans in the development of weather systems bringing vital rainfall for agriculture, it is important that we use the best possible system to

predict the likely sea-surface temperature changes in a warming world. In the Hadley Centre, ensemble and deterministic climate modelling are improving our understanding, using the Met Office Operational SST and Sea Ice Analysis (OSTIA: see http://ghrsstpp.metoffice.com/pages/latest_analysis/ostia.html), incorporating climate-change feedback into ocean surface temperatures at a horizontal resolution of 5km.

Concluding the series

Throughout this series, we have tried to describe the variations of weather and climate in the tropics on the synoptic and, to some extent, mesoscale. Many of the local variations have been described from a forecaster's perspective. It was not possible to cover the subject in detail, however, and the articles are only a 'taster' for this vast subject, the tropics covering about half the world. Many specific texts are available for readers whose interest has been spurred by this series. These cover many details and often deal with the mathematics of the tropical atmosphere.

We have also attempted to show the way that the weather affects humankind and, in this part, how humans have modified the natural environment. What can be more important than to understand the weather across the globe and to predict its serious effects? As we have seen throughout the series, there is great potential for severe weather in most of the tropical zone. From the parched deserts to torrential downpours, marked seasonal changes to tropical revolving storms, squall lines with hail and thunder, the tropics has perhaps more than its fair share of severe weather (Galvin, 2008a, 2008c, 2008d, 2009a; Galvin and Membery, 2008). Associated with the weather are plague and pestilence. By improving our understanding, we can forecast the weather and minimize its effects to improve our prospects in this productive, but often fragile, environment.

Flying through the tropics can be very interesting, and at times hazardous. Vigorous convective currents and clear-air turbulence along the subtropical jet streams or over high tropical mountains can make flight uncomfortable, occasionally dangerous (Galvin, 2007, 2008a, 2008b). Lightning and hail can cause serious damage to airframes and the large temperature variations of tropical deserts can cause dangerous wind shear (Galvin and Membery, 2008; Galvin, 2009a).

More than 70% of the world's population lives in the tropics (i.e. about 4700 million people inhabited the tropics in

³ The assumptions about changing climate and its effects on agriculture assume that greenhouse gas concentrations will increase throughout the twenty-first century (*Special Report on Emissions Scenarios*, Scenario A).

⁴ This depends (to a small extent) on the way we define the tropics, as discussed in Part 1 (Galvin, 2007). However, as the tropical margins are predominantly dry areas, populations are mainly small.

2007),⁴ many of them along coasts or rivers, where transport and water resources have allowed populations to grow crops and flourish (http://en.wikipedia.org/wiki/World_population#Population_distribution). The extremity of most tropical climates – the discomfort of humidity, large desert temperature ranges, the cold of high mountains, copious rainfall – are well represented by the climate data (Galvin, 2009b).

The land area of the tropics is about 40% of the world total, although the habitable area is much less than half this. Clearly, there is a large and growing need for increased knowledge of the effects of the weather in all tropical countries.

In recent years, there has been increasing research into the weather of the tropics, both to aid our understanding and improve forecast models. As this research proceeds, our understanding grows and numerical models improve – in particular as model resolution is increased (Galvin, 2005; Glenn Greed, personal communication) – yielding benefit to all.

The Met Office provides many new services to assist tropical countries in dealing with the weather, adapting to the climate and assisting national development. These include south Asian and African mesoscale models, warning systems for tropical revolving storms, direct assistance to national meteorological services, as well as forecasts for medium- and long-haul aviation at medium and high levels from its World Area Forecast Centre. Climate prediction and adaptation strategies are produced by the Met Office Hadley Centre for Climate Prediction and Research.

Acknowledgements

Some elements of the text drew on figures in the *Britannica Atlas* (1989 edition) and *Philip's Universal Atlas of the World* (2005 edition).

Jim Galvin thanks all those who have provided help and advice during the writing of this series, or who have freely provided pictures, in particular Richard Young, David Membery (co-author of Part 5), Nigel Bolton, Barbara and David Pettigrew, Sue Wilson, Andy Dexter, Nick Grahame, Clive Jones, Fiona Smith, Chris Tyson, Clive Wilson and the members of the World Area Forecast Centre team, Met Office Operations Centre, Exeter. Julian Mayes saw the value of the series and, with reviewers, skilfully ensured focus throughout. Nige Emery drew Figure 4 of Part 2.

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DOI: 10.1002/wea.369