1
Setting the Scene

1.1 Introduction

Much of what we know about the weather has been focused on mid-latitude weather systems, first because most early researchers came from rapidly developing western Europe and eastern North America, and second because of the risks and consequences of weather systems prevalent in these zones. However, although there are simple non-scientific descriptions of weather events from the tropics and tropical climates going back hundreds or thousands of years, it is only since the late 1960s that much scientific research has been carried out within the tropical zone, although observational networks were established in many populous areas as early as the 19th century. What we know of the weather (and, to some extent, the climate) of the tropics remains limited and has typically focused on severe weather events, such as tropical revolving storms (Emanuel 2005) or data from a limited range of observing stations. This is partly because upper-air networks, in particular, are thinly spread with weather balloons launched rarely more than once per day. Of necessity, desert regions have few observing stations. Weather observations are often the first 'casualties' of economic hardship (see Appendix 1).

However, many factors of the day-to-day weather are important in the tropics, not least for aviation and public safety. It is also important for holiday-makers to know what to expect. In recent years, tropical resorts have become readily available and popular for their warmth and sunshine, but travellers often know comparatively little about seasonal weather variation or the effects of exposure to sunshine in the tropics.

For instance, the primary purposes of forecasting for aircraft operations in the tropics are safety and the maximization of efficiency for the benefit of passengers and aircraft operators. The most accurate and appropriate forecasts will achieve this goal using a mixture of numerical weather prediction products, observed data and good forecasting knowledge. It is the effects of the weather, in other words its outcomes, which must be considered.

In order to maintain observational networks and co-ordinate the exchange of atmospheric and hydrological data and numerical forecasts, the World Meteorological Organization (WMO) – an agency of the United Nations (UN) – has established various programmes, not least the World Weather Watch (WMO 2013). This agency has more members worldwide than any other UN agency, emphasizing the importance of meteorology and hydrology. The research carried out as part of the World Climate Research Programme since the early 1970s is very important in allowing us to

An Introduction to the Meteorology and Climate of the Tropics, First Edition. J F P Galvin.

understand many of the processes and associated weather of the tropical zone (Gates & Newson 2006). Knowledge continues to grow through more recent research programmes, such as Tropical Ocean Global Atmosphere (TOGA), which investigates the important links between the tropical ocean and the global atmosphere (Fleming 1986). It is clear that the tropics have an important effect on weather systems throughout the globe, providing much of their energy.

1.2 What do we mean by 'the tropics'?

In order to examine tropical weather and climate we need to define what we mean by 'the tropics'. Although most of us have some concept involving warmth, the definition is not straightforward and it is possible even for meteorologists and climatologists to have different views of what constitutes the tropical zone.

The most commonly used definition of the tropics is the zone within which the sun is directly overhead at some time during the year: the zone between the Tropics of Cancer and Capricorn (23.45°N and 23.45°S, respectively). However, a weather-related definition, rather than the elevation of the sun at midday, is probably more useful to the weather forecaster.

1.2.1 Climatological methods

The range of temperature is often large over land in the tropics. This is because the high sun brings high daytime temperatures, but the loss of temperature by long-wave radiation overnight is also large, the rate of loss of radiation increasing exponentially with absolute temperature (Stefan's law). Because condensation and a high water-vapour content reduce the loss of temperature, its range is also governed by humidity, so the mean daily temperature range is greatest across the deserts (15°C) and lower in the humid zone, in particular close to the oceans. However, even in humid coastal areas and on mountains the range is rarely less than 5°C. Temperature varies little over the ocean surface, where most solar radiation is absorbed rather than re-radiated, although daily variation is larger in many (but not all) parts of the tropics than it is at higher latitudes.

We could define our 'tropical' zone as, say, the region within which the mean temperature is above some nominal value, say, 20°C, throughout the year. However, this has the disadvantage of excluding even relatively modest high ground and, for part of the year, continental areas that are relatively close to the equator. Whilst this failing could be corrected by adjusting the nominal value to a specific level,[1] this is not the most satisfactory method as it can include high mountain areas well north and south of zones normally considered as tropical.

Figure 1.1 demonstrates the difficulties of using mean temperature as the main method of definition of climatic zones. It is readily apparent that some of what most meteorologists or climatologists would call the tropics – albeit along the poleward extremes – is classified by Köppen as 'temperate' (zone C), largely due to altitude or the presence of cool air over the coasts of cool oceans. His scheme defines the tropics in two zones: A, wet climates and B, dry climates. However, this results in a narrowing of the tropical zone to within 25° of the equator in places and an expansion as far poleward as 50° (in the dry zone) elsewhere. One result of this classification scheme is to place northern parts of the monsoon zones in the temperate zone and the dry (often cold) deserts of central Asia in the tropics.

A geographical method could be to use the limits to growth of a particular characteristic crop: bananas or fruiting pine trees might be considered ideal crops in this respect. This approach is useful in many ways, especially if adjustment is made for areas that are too dry to grow the crop, such as deserts. However, some parts of these dry lands are susceptible to frost (which would kill sensitive plants, such as

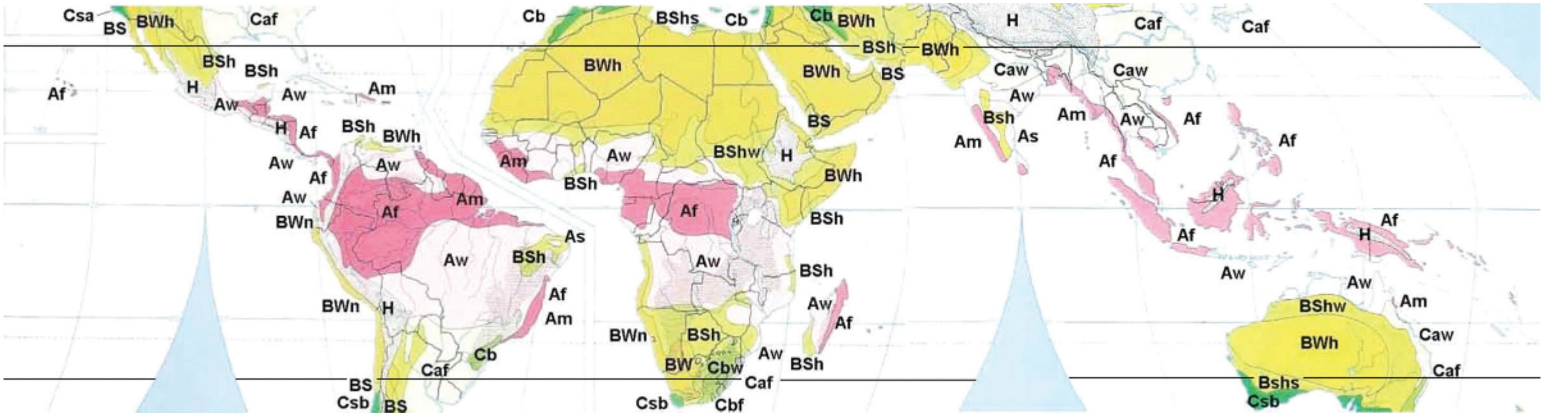

Figure 1.1 Climatic zones of the tropics: Af/Am, humid tropical; Aw, savanna; BS/BSh/BShw, tropical steppe; BWh, tropical and sub-tropical desert; Cf, warm temperate with no dry season; Cs, warm temperate with dry summer; Cw, warm temperate with dry winter; Cb, temperate climate with cool summer months; H, highlands; stippled, modification due to altitude (using the system devised by Wladimir Köppen (McKnight & Hess 2000)). The effect of high ground has a profound influence on climate in the tropics, particularly above about 2 km. The black lines indicate latitudes 30°N and 30°S.

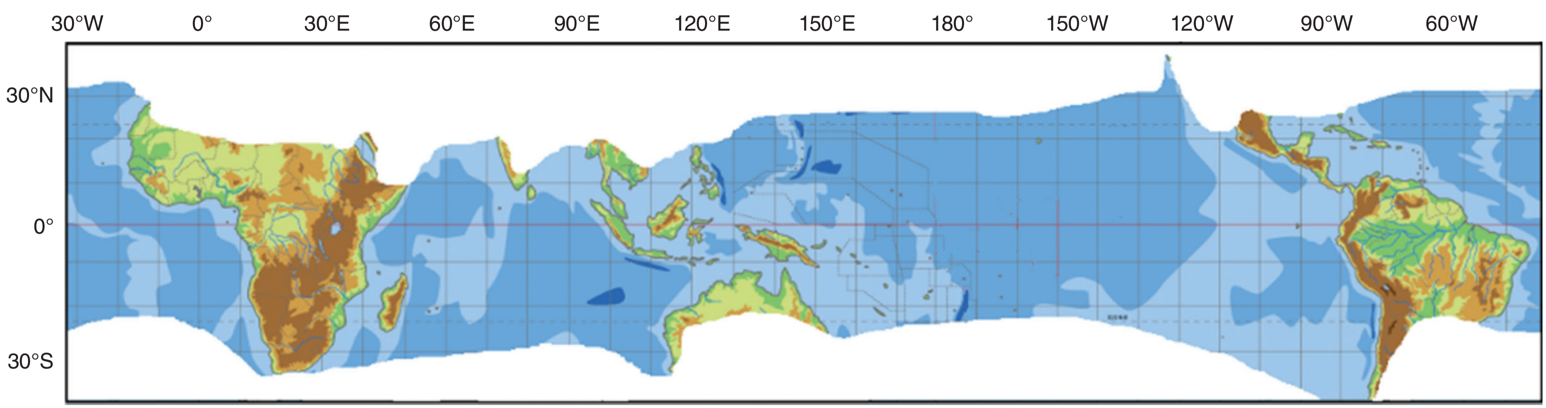

Figure 1.2 Area fitting Riehl's scheme for the definition of the tropics. From all available data, areas where the diurnal temperature range exceeds the annual range of mean temperature are included in the tropical zone. Some notable peculiarities can be seen: much of Arabia, India and South-East Asia, locally as far south as 10°N, is excluded, but some cool-water coasts of the Americas and Africa are included. Much of the mountainous tropics would also be likely to be excluded, as high ground has a low diurnal temperature range (a few degrees), exceeded by the seasonal mean-temperature change. (This is further complicated by the difference in the climatology of valleys, which have a high diurnal range, and exposed mountaintops, where the diurnal range is low.)

banana bushes) and the cold of high mountains would also exclude their growth (rather than latitude constraints). However, both crops are grown in many sunny frost-free parts of the extra tropics, such as south-western coastal Cyprus, so perhaps an agricultural indicator has too many limitations?

A simple method is to divide the globe into fixed tropical and extra-tropical zones. This method is often employed for the verification of numerical forecasts (WMO 1982; Fuller 2004). One such form divides the globe into two equal-sized halves with somewhat arbitrary dividing lines at 30°N and 30°S (marked on Fig. 1.1). Conveniently, this latitude range includes the area within which near-surface winds are predominantly easterly and all of the climatic zones that can be regarded as tropical: humid, savanna, semi-desert and tropical desert. However, part of some of these climate zones, notably the tropical desert and semi-desert, frequently lies north or south of 30°, in the margin of the extra-tropical zone and some zones that do not have tropical characteristics extend equatorward of 30°N and 30°S. In addition, as we will see in Chapter 2, the area between these latitudes on average receives a surplus of incoming solar radiation (insolation) over that lost by long-wave radiation. This surplus is carried poleward into a more readily defined extra-tropical zone (Fig. 2.5).

The zones of predominantly westerly winds make incursions equatorward of these lines of latitude, particularly in winter. In order to keep within a zone of predominantly easterly winds at most levels, a narrower north–south zone must be used.

We might also define the tropical zone as the area within which there is more solar energy (short-wave radiation) received at the surface than that emitted from it (long-wave radiation). The energy balance is discussed in Chapter 2 and is an important aspect of our definition of the tropical zone. However, even this has its problems: whilst there is an excess of energy available to drive the 'tropical heat engine' (Pidwirny 2013; Lindsey 2009) close to the equator all the way around the world, areas of relatively cold ocean extend near to the equator (within 10° latitude of the equator), in particular in the eastern Pacific Ocean. In these areas there is a deficit of energy and all of the incoming short-wave radiation is absorbed in the surface ocean layers. Over land, the excess of available energy is more evident, but varies seasonally, driving the major monsoon circulations, as described in Chapter 8.

A more useful definition for the climatologist is based on the small annual variation of climate typical in the tropics. Riehl (1979, Ch. 2) proposed the definition as the area within which the diurnal temperature range exceeds the range of annual mean temperature. This method allows both continental (inland) climates, where temperature range is high, and coastal climates to be included, as there is some compensation for the combination of high diurnal range with a tendency for a larger annual range of continental areas. It has great value, since data can easily be sorted using this definition, although, theoretically at least, data needs to be available at a relatively high resolution, which is little more than a pipe dream in most of the tropics. Nevertheless, there are some drawbacks to this method, as Fig. 1.2 shows. The tropical area thus defined approximates to the astronomical tropics, in particular in the northern hemisphere. However, it includes some extra-tropical areas, such as a small part of the cool coast of California around San Francisco, and in the southern hemisphere it extends further poleward than in the northern hemisphere, just including all of South Africa, coastal western Australia and the Chilean coast north of 40°S. Although accommodating these areas, it excludes notable areas dominated by monsoon flows, including much of India and the south of China – areas that are rarely, if ever, outside the tropical air mass, which is discussed in section 1.2.2.

1.2.2 The tropical air mass

Day to day, the weather forecaster usually needs something more closely related to the day-by-day weather, without reference to seasonal variations.

Using the current state of the atmosphere in depth, treating tropical air as a single air mass, it is possible to define the tropical zone on a daily basis. The characteristics of the tropical troposphere are discussed in the following sections. The temperature difference between the tropics and middle latitudes causes a jet stream to develop at the poleward limit of the tropics. This sub-tropical jet stream (STJ) is a generally broad belt of winds, often extending across a latitude range of 10° or more. It has a core close to 30°N and 30°S and has little high-amplitude wave development along it (see Fig. 4.1). The area between these jet streams has a tropospheric depth characteristic of the tropical zone. This depth allows us to define the periphery of the tropics, even when the STJ weakens or is absent, as occurs in summer in both hemispheres and is usually the case in the northern hemisphere summer. Furthermore, the equatorward edge of the STJs coincides (albeit weakly) with the transition from westerly lower tropospheric winds to poleward and easterly trade winds nearer the equator.[2] The subtropical jet stream is described in more detail in Chapter 4.

Although use of the STJ as the northern and southern limits of the tropics means that the tropical zone extends north of 40°N over Asia during the northern summer, it is appropriate, since the air to the south of it retains tropical characteristics. Thus, to provide consistency, in this book some areas poleward of the mean latitude of the STJ will be discussed, since these areas are often within the meteorological tropics. For instance, it allows inclusion of areas frequently affected by troughs in the STJ and upper troposphere (Chapters 4, 10 and 11). The incursion of extra-tropical air has important effects on the weather of the tropics, in particular in the monsoon zones, as well as within upper-tropospheric troughs, notably in winter.

1.3 The geography of the tropics

To understand the weather of the tropics we need first to understand the geography and its controls on the movement of weather systems.

Two main factors affect the development and motion of weather in the tropics: the distribution of land and sea and the effect of mountain chains on this motion (Chapter 11). Between 30°N and 30°S the proportion of land to sea is about 1:4. There is much less land in the tropics than at higher latitudes. Not only does this generate the great monsoon flows of the tropical zone (Chapter 8), but it also provides the moisture that drives the tropical heat engine. With much more land there would be significant differences in the tropical weather systems and the tropical winds. The diurnal and seasonal heating and cooling of land are much greater than that of the sea, generating weather systems on a variety of scales. In the tropics there is more land north of the equator than in the southern hemisphere; this brings more rain to the north of the equator than to the south.

The tropical zone also has a disproportionately large amount of high ground, including parts of the Himalayan and the South-East Asian mountains, much of the Andes and all of the Central American sierras. These mountains help to guide and block the motion of weather systems. However, they also generate their own weather.

These effects will be described in detail in succeeding chapters.

1.4 The tropical troposphere

The atmosphere is composed of a number of layers and almost all weather occurs in the lowest of these: the troposphere. In general, temperatures fall with altitude within this layer, although locally there are layers of warmer air overlying cooler, forming shallow layers where temperature rises (inversions). Both the overall

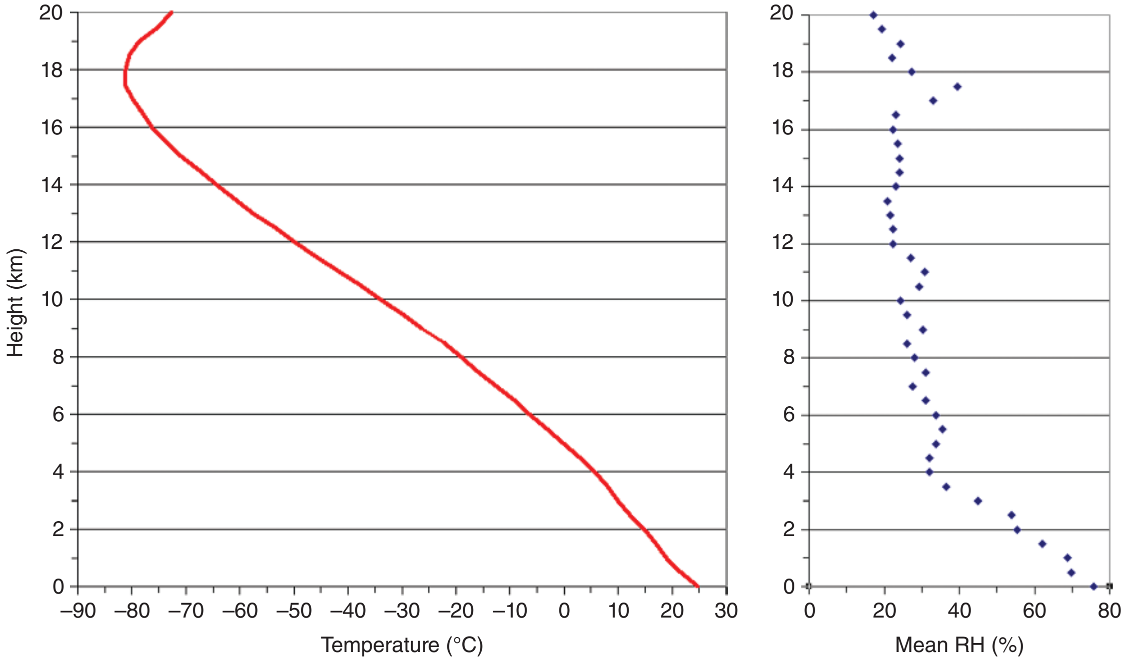

Figure 1.3 The mean change of temperature and humidity with height in the tropics from a selection of radiosonde ascents made across the range of tropical weather regimes. RH, relative humidity. In practice there is considerable variability in these figures: the profiles are much drier over the deserts and during the winter monsoon, where the upper troposphere tends to be somewhat cooler than in the humid zone. However, the height of the tropopause – the level at which temperature stops falling quickly, marking the transition into the stratosphere – is remarkably constant (unlike in the higher latitudes), near 17 km.

fall in temperature and the presence of inversions are necessary components of the formation of cloud and rain, particularly in the tropics. The tropopause is at the top of the troposphere and above it is a near-isothermal layer, the stratosphere. Convective cloud locally reaches into the lowest part of this layer, but with temperatures no longer falling quickly with height, the cloud can no longer rise, as its density becomes equal to (or below) that of the surrounding environment. The cloud tops readily evaporate because of the very low humidity of much of the stratosphere. The temperature and humidity profiles of the tropical troposphere and lowest part of the stratosphere are shown diagrammatically in Fig. 1.3.

Within a single air mass, temperatures (and humidity) vary most in the layer just above the surface: the boundary layer. The balance of incoming and outgoing radiation changes the temperature of the surface and convection carries these temperature changes into the lower layers of the troposphere. By day the development of instability carries warmth to a much greater depth by convection than overturning can when the air is cool and stable by night. The greater the instability, the more heat can be carried to depth away from the surface. However, the entrainment of heat (and moisture) becomes comparatively small above about 2000 m and the boundary layer is generally considered to exist below that level, even by day.[3] By night the boundary layer may be little more than a few tens or hundreds of metres deep.

On a broader scale, radiation is the main source of energy exchange in the atmosphere. Although most outgoing long-wave radiation is emitted from the earth's surface in response to heating by the sun, the atmosphere also radiates long-wave radiation to space. Most atmospheric radiation is emitted by the troposphere, proportional to its mean temperature. As there must be a balance of outgoing and incoming radiation, where the lower troposphere is warm, the upper troposphere and lower stratosphere are cold (and vice versa). To accommodate this, the tropopause must be high where the air is warm and lower where it is cool. Thus, the height of the tropopause may be used as a marker of a particular air mass (although cooler air may make incursions at low levels, so that a particular air mass may not extend all the way to the surface from the tropopause).

The height of the tropopause varies little in the tropics, but changes as the mean temperature of the troposphere changes and although there are significant differences in weather within the tropical zone, there is only a single tropical air mass. Nevertheless, differences in mean tropospheric temperature, humidity and dynamics cause some variation within the air mass, so that the highest tropopause is generally found close to the equator. The troposphere rarely extends above about 18 km and is most often close to 17 km altitude. Within the tropical air mass, height gradients are usually small, but increase somewhat near the sub-tropical jet streams. Indeed, the association of the STJ with a tropospheric depth[4] of about 15 km provides a definition of tropical air.

Despite its relatively uniform depth for much of the year, some variation occurs with the changing of the seasons and these variations are notably marked in the northern hemisphere summer. Between May and September, the tropopause is higher over northern Africa, and southern and eastern Asia than it is close to the equator. The intense warming of these land masses causes the troposphere to expand and the tropopause occasionally reaches a height of 18 km or more over northern India, Nepal and Tibet. Smaller expansions occur over Australia, southern Africa and South America during the southern summer. The expansion is a key element in the development of the summer monsoon circulations described in Chapter 8.

The density of tropical air is low because it is warm, so the heights of pressure levels are high in the deep tropical troposphere and the thickness between fixed (standard) levels is high. Globally, this is usually measured in terms of the height difference between a pressure of 1000 hPa and 500 hPa. This height difference generally has a minimum around 580 decametres[5] (dam) along the northern and southern boundaries of the tropical zone and may reach 590 dam or more.

The height of the freezing level can also be used as a marker for tropical air. Although night-time frosts sometimes occur at lower levels on high ground within tropical air, the free-air freezing level is never below 4000 m in the tropical air mass and is usually found between 4500 and 5500 m.

The great disadvantage of defining the tropics by means of an air mass is that its area changes day by day, so that, locally, we must discuss extra-tropical air that affects areas in winter to include areas under the influence of tropical air in summer. However, this is an inclusive method, including all areas, such as the monsoon zones, which remain within the tropical air mass in winter despite having cool (or even cold) air near the surface. There is comparatively little expansion and contraction of the tropical air mass (between the sub-tropical jet streams) from winter to summer. The waves in the STJ are comparatively modest and move slowly, upper troughs of sub-tropical air tending to fill as they move.

1.5 Climate and population in the tropics

On average, population density is low in the tropics, typically around 10 km^{-2}. However, in India, Bangladesh, southern China and parts of South-East Asia the population density is much higher, reaching 100 km^{-2} or more.

Away from rivers, the hot-desert environment is not able to support large populations and tropical rainforest is a dark foreboding environment with trees that are difficult to clear unless heavy machinery is available. Thus populations are found mainly along coasts or rivers, where transport has been available for centuries or millennia. It is near the mouths of the larger rivers that the largest cities are found.

The savannas are moderately populated, the land easy to clear for agriculture and road building. However, in some areas the population density is close to the ability of the land to support it. In Africa and parts of South America this presents a problem, since populations have grown rapidly during the late 20th century and the rainfall is not sufficiently reliable in these areas for there to be confidence that populations can survive without a major risk of drought and famine.

The degree of urbanization, by contrast, varies considerably from continent to continent. In South America it is generally above 50%, the proportion in Venezuela above 90% and in Australasia 80%. However, in much of Asia and Africa it is below 45%; Ethiopia, Uganda, Malawi and Nepal have fewer than 15% of their populations living in towns. This stresses the relative importance of agriculture in these countries, even those that are rapidly industrializing, such as India and China. However, there are significant variations from country to country, as well as within countries.

1.6 Question

List the main factors determining climate, considering why the tropics differ from the higher latitudes.

Notes

1 In meteorology we can use the standardized physical properties of air to describe air masses, which may be compared or grouped. In this case the observed (or interpolated) mean temperature could be assumed to be its equivalent at, say, the 1000 hPa level (i.e. very near the surface). The change in altitude would compress and warm the air at a standard rate of 0.0098 km^{-1}, so that air originally at 3000 m with a pressure of 695 hPa and a temperature of 0°C in the Andes of Brazil would be warmed to 28.5°C as the pressure rose to 1000 hPa. Similarly, air at 25°C with a pressure of 1025 hPa in Death Valley (85 m below sea level) in the western desert of the USA would cool to 22.5°C as its pressure reduced to 1000 hPa.

2 A careful examination reveals that the core of the STJ usually lies above the margin of the cooler air of the sub-tropics, which, as is the case along the frontal zones of the high latitudes, undercuts the warmer lower-density air. However, the 'true' tropical air is found all the way to the surface close to the equatorward margin of the jet-stream belt (which is usually several hundred kilometres wide).

3 There are some problems with this somewhat arbitrary approach. Areas of high ground, such as inter-montane plateaux, will develop their own boundary layers. If the altitude of the plateau is near or above 2000 m, the top of the boundary layer will often be much higher than the broadly accepted level given here. Although mountains also affect the temperature of the air in contact with them, the effects are generally rather small, with temperature changes affected more by advection than the exchange of radiation.

4 In winter, as cool sub-tropical (sometimes polar) air undercuts the tropical air mass, a tropopause may be found below the level of the STJ and, indeed, a second jet-stream core (a cut-off from the polar-front jet stream) may be found below this secondary tropopause.

5 Atmospheric height and thickness are, in fact, measured in geopotential metres, which allows for the difference in potential energy in air at different distances from the centre of the earth, geopotential being a measure of the work required to lift a fixed mass of gas to a new altitude. Geopotential height (Z) uses gravity to calculate altitude, so that where acceleration due to gravity $g = 9.79$ ms^{-2} (the value near sea level at the equator), true height $h = gZ/0.979$ m.