observed to rise from the steam fog up into a low cumulus cloud base. The air–sea temperature difference was more than 20 degC. Lyons and Pease suggest that steam devils are similar to dust devils over land since the rotation in them seems to be quite slow. They also suggest that steam devils extend to the cloud base only when wind speeds exceed 11 m s^{-1}, which is in contrast to our observation of funnel clouds reaching the cloud base with wind speeds of only 6 m s^{-1} or less. Bluestein (1990) has also noted that the wind speed does not appear to be a critical factor in whether steam devils form or not. The steam devils over lakes observed by Bluestein (1990) formed also in the presence of a large air–lake temperature difference. The steam devils lasted from 10 seconds to several minutes but they did not reach as high an altitude as the steam devils reported here or the steam devils observed by Lyons and Pease (1972).

We hypothesise that the weak vortex of the steam devil is able to shield the rising foggy thermal from mixing with the ambient air. Mixing could lead to evaporation of the condensed water and disappearance of the funnel. In contrast, the small wisps such as those in Fig. 3 may not have an associated vortex, as suggested by their appearance. Therefore, they might be more readily mixed with ambient air. This hypothesis would explain why these wisps were not observed to reach such high altitudes as steam devils.

Acknowledgements

The authors wish to thank Lea Saukkonen (Finnish Meteorological Institute) for discussions on the synoptic conditions.

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The Coriolis force and the subtropical jet stream

(Coriolis Part 8)

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"We're not going to listen to you. We're going up there and carry out our mission. We'll measure the *** winds and *tell* you what they are instead of asking you *** what they will be."

(US Air Force Brigadier General Emmett O'Donnell to the forecasters in autumn 1944 warning him about 170 kn winds over Tokyo (Fuller 1990, p. 202).)

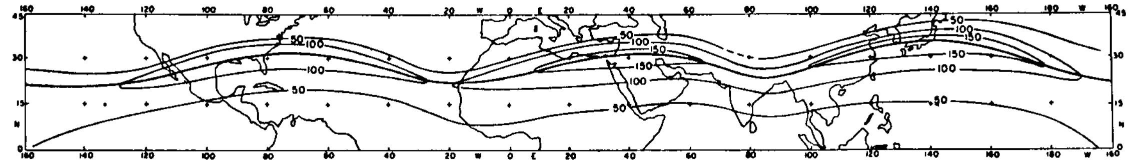

Fig. 1 Mean position and strength of the subtropical jet stream for winter 1955/56 according to a classic work by Krishnamurti (1961). Isotachs are drawn every 50 kn (25 m s^{-1}) at 200 mbar (c. 12 km). The mean latitude of the jet axis is between 25 and 30°. The subtropical jet stream constantly interacts with disturbances from the midlatitudes and frequently acquires a more irregular form or breaks up into more than three wind maxima.

The existence of midlatitude jet streams had been suspected since the late nineteenth century, when observations of the motion of cirrus clouds revealed strong upper-air currents, and was confirmed during World War II, when bomber aircraft encountered strong upper-tropospheric winds (see Phillips 1998, pp. 1110–1111 for further references). However, the existence in the subtropics of a separate band of strong westerly winds of 30–80 m s^{-1} at around 10 km* was not fully accepted by the meteorological community until the 1950s. One reason was scepticism about the quality of observational wind measurements in the area; these doubts were finally removed in 1961 with the comprehensive analysis by Krishnamurti (1961) (see Fig. 1). Meteorologists were also uncertain about the physical causes of the subtropical jet stream; it did not seem to be connected to any synoptic developments, as were the midlatitude jet streams. Curiously, even today, there does not seem to be any consensus about the mechanism behind the subtropical jet (Wiin-Nielsen and Chen 1993, p. 151) or why the jet winds are not stronger (Hartmann 1994, p. 153).

In spite of being the strongest large-scale wind system, the subtropical jet has a rather Cinderella-like existence in the meteorological literature. According to *Weatherwise*, the subtropical jet stream is "the most frequently slighted" of all the jet streams and is in need of "a new publicity agent" (Grenci 1997). Actually, an appreciation of how the Coriolis force functions makes it quite easy to get a good grasp of the subtropical jet stream.

The mechanism behind the subtropical jet stream

On average, the equatorial region receives more heat from the sun than higher latitudes. Since pressure falls off more slowly with height in warm air than it does in cold air, the same pressure in the atmosphere is found at a higher elevation in the tropics than elsewhere. From this upper-level high-pressure belt, air is accelerated away from the tropics. This is the main driving mechanism behind the so-called 'Hadley circulation' which transports air at high altitude polewards and air at low altitude equatorwards.

In old textbooks (*e.g.* Haurwitz 1941, p. 259) the student is invited to calculate this upper-level poleward acceleration, assuming a thermal difference between pole and equator of 40 degC. After some arithmetic the student arrives at a value of 0.7 mm s^{-2}. This does not sound much, but after 24 hours this small acceleration would result in a velocity of 60 m s^{-1} and would cover a distance of 2580 km, corresponding to 22.5° latitude. When the air is accelerating polewards it is of course affected by the Coriolis force trying to force it back in a clockwise trajectory towards the equator and higher pressure (Fig. 2(a)).

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* The Polish–Swedish–Australian meteorologist Andrzej Berson (1991; personal communication, 1994) claims that the subtropical jet was first identified when the upper-air unit at the Meteorological Office had to brief the pilots taking Winston Churchill to and from the Teheran conference via Cairo. The period of interest is 22 November–6 December 1943. The 300 mbar charts at the National Meteorological Archive support the essence of Berson's account, although not the details. The period around 24 November was characterised by a strong westerly flow over the Mediterranean with Malta reporting winds of west-south-west 144 kn. (See also the autobiography of Petterssen (2001, p. 127) where Berson's wartime interest in jet streams is confirmed.)

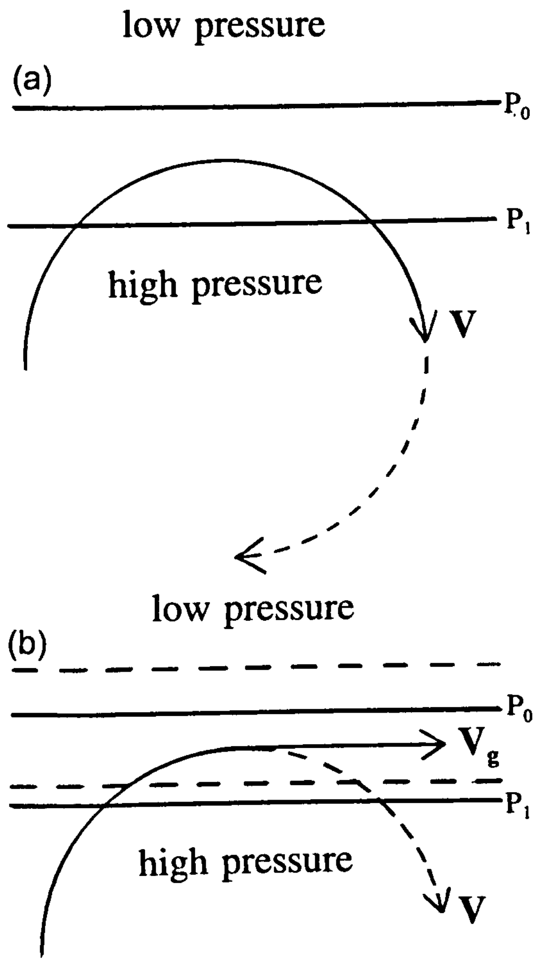

Fig. 2 Schematic illustrations: (a) How the wind is accelerated into a pressure gradient, and the Coriolis force, when the wind is stronger than the geostrophic wind, tries to drive it to the right, back towards high pressure. (b) How the Coriolis force, by driving air towards higher pressure, strengthens the pressure gradient until a geostrophic balance is reached.

This transport of air from low to high pressure strengthens the pressure gradient. Eventually, a geostrophic balance is established where the air is, on one hand, prevented from moving further polewards by the Coriolis force and, on the other, from returning towards the equator by the strengthened pressure gradient force* (Fig. 2(b)).

With the typical heating and rotation of our earth, the balance between the poleward-directed pressure gradient force and the Coriolis force is established around 30° latitude (Fig. 3). This large-scale geostrophic balance also sets the poleward limit of the Hadley circulation. With a faster rotation of the earth and/or weaker Hadley circulation (*e.g.* due to weaker insolation) the subtropical jet would be weaker and closer to the equator. A slower rotation and/or stronger Hadley circulation (*e.g.* due to stronger insolation) would result in a stronger jet further away from the equator.

Geographical variations of the subtropical jet

On average there are three semi-stationary cores of the jet stream, geographically coupled polewards from areas with the strongest heating: the Caribbean and the Amazon Basin, the Sahel and the African rainforests, and the Indonesian archipelago and Australia. Because of instabilities that develop within the jet stream and/or interactions with midlatitude

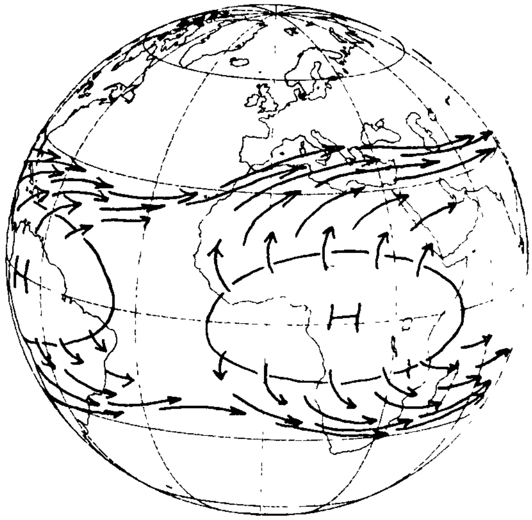

Fig. 3 Schematic illustration of the formation of the subtropical jet stream. Air accelerated by the upper tropospheric pressure gradient force gains speed polewards, but is simultaneously affected by the Coriolis force, which always, by deflecting it clockwise in the Northern Hemisphere (anticlockwise in the Southern Hemisphere), tries to bring it back towards the equator. A balance is reached around 30° latitude.

• For a similar, but quantitative, explanation see Gordon and Shaw (1954). The 'resistance' or 'friction' that the pressure gradient force exerts on the winds is often referred to in the meteorological literature as 'eddy stresses' or 'Reynolds stresses', a concept borrowed from classical turbulence theory.

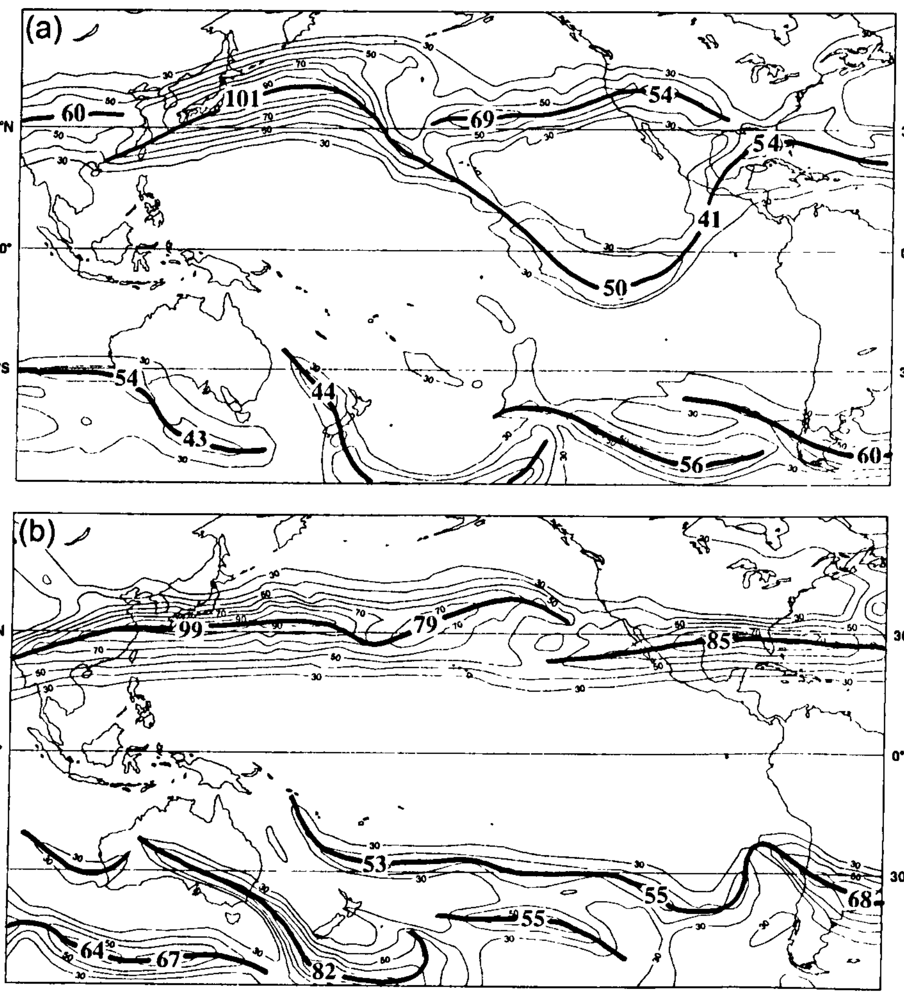

Fig. 4 Typical upper-tropospheric flow patterns with wind speed in metres per second: (a) Over the Pacific during a Northern Hemisphere winter. The subtropical jet stream over eastern Asia is almost permanently positioned over southern Japan. Halfway across the North Pacific, due to the action of the Coriolis force and the reduced heating from below, the wind becomes deflected over the equator. Since the Coriolis force deflects to the left in the Southern Hemisphere, the jet wind is normally deflected back to the Northern Hemisphere. (b) Over the Pacific during El Niño. The two subtropical jet streams are clearly separated in either hemisphere by the extra heat source over the east Pacific. Bold values show local maxima. (Analyses from the European Centre for Medium-Range Weather Forecasts.)

systems, the subtropical jet often breaks up into six or seven individual jet streams (Fig. 4(a)).

Because of the irregular distribution of continents and oceans, the three main regions of maximum heating are not evenly distributed longitudinally. The maximum over east Asia and Australia around 120°E is far upstream from the next downstream maximum over the Americas, around 80°W – almost half the circumference of the earth. During the long passage over the Pacific the Coriolis force has plenty of time to affect the jet wind, trying to drive it into a circular motion towards the equator. As the temperature of the ocean's surface water decreases eastwards, the pressure gradient force weakens and allows branches of the subtropical jet occasionally to cross the equator from either hemisphere. During El Niño this does not happen. Then the cold sea surface water over the central and eastern Pacific is replaced by warm water. The extra heat source creates an upper-air high pressure area which effectively prevents the Coriolis force from deflecting the wind across the equator (Fig. 4(b)).

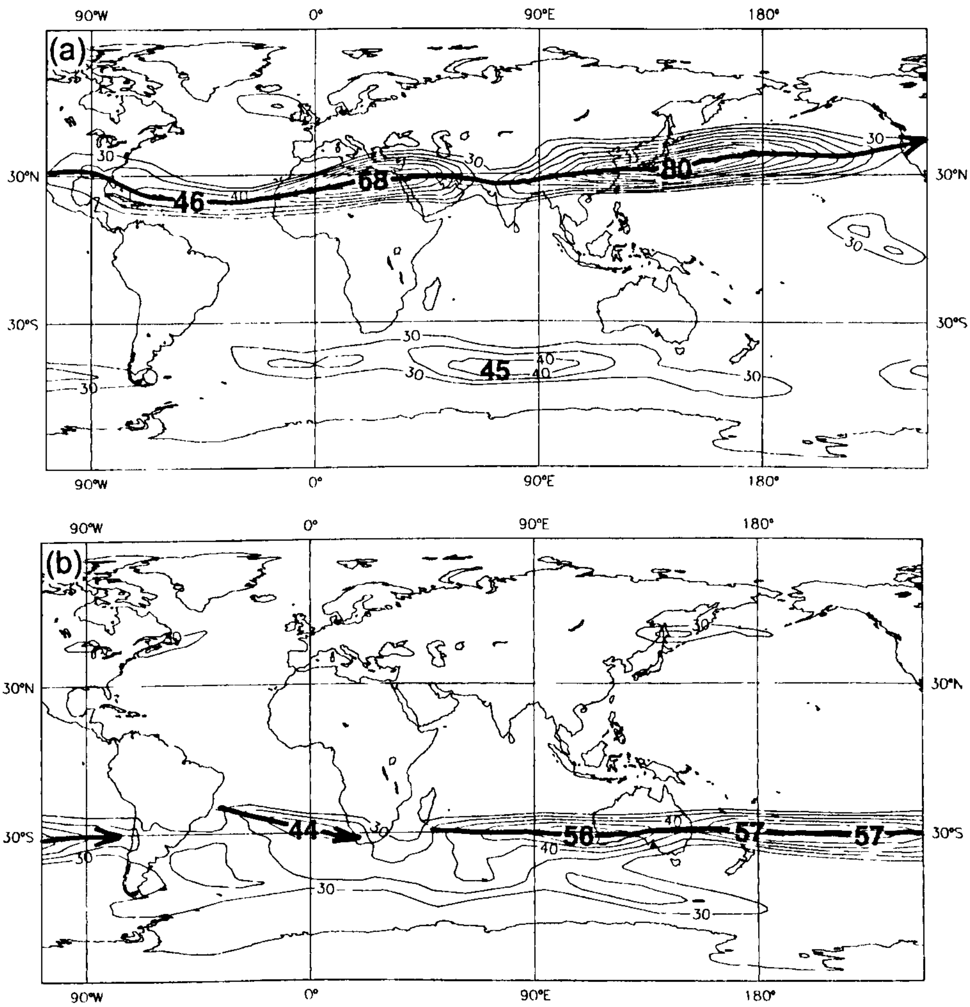

Fig. 5 (a) The mean wind speed at 200 mbar (c. 12 km) during February 1999. Isolines are drawn at 5 m s^{-1} intervals. The Northern Hemisphere subtropical jet stream is clearly seen around 30°N, whereas its counterpart in the Southern Hemisphere is weak. The mid-latitude jet streams around 50°N do not feature strongly in the monthly averages due to their great day-to-day variability. (b) As (a) but for August 1999. The subtropical jet stream in the Northern Hemisphere has disappeared, but its counterpart in the Southern Hemisphere is clearly seen around 30°S. The midlatitude jet streams around 50°S are still visible due to their strength and interaction with the subtropical jet. Bold values show local maxima.

For medium-range forecasts in Europe, El Niño normally heralds high skill, since influences from the very data-sparse area over the South Pacific are effectively blocked; influences come mainly from the data-dense area over eastern Asia.

Seasonal variations of the subtropical jet

The subtropical jet streams show large seasonal variations, in particular over the Northern Hemisphere. Indeed, there is nothing that shows the close connection between the subtropical jet stream and large-scale heat sources better than the extraordinary change in the subtropical jet that regularly occurs from winter to summer. When summer approaches, the large mass circulation of winter that transports heat towards the north pole is greatly weakened, the heat source for the atmosphere is extended well into the middle latitudes and, due to strong insolation over the large subtropical land masses of the Northern Hemisphere, the westerly subtropical jet stream disappears as a circumpolar phenomenon (Fig. 5).

The subtropical highs

The subtropical jet streams not only affect air traffic and the occasional balloon cruise, but also have a profound effect on weather conditions in the subtropics. Air entering the subtropical jet stream is on one hand prevented from moving further poleward by the Coriolis force, and on the other prevented from returning equatorward by the pressure gradient force. This causes a 'congestion' of air in the upper troposphere which is felt at lower levels as a small, 1–2%, increase in pressure. This is not much, but is quite enough to create the subtropical high pressure belts around 30° latitude, just underneath the subtropical jets. Individual high pressure centres are formed over the relatively colder subtropical oceans due to a combination of dynamic and thermal effects (Fig. 6).

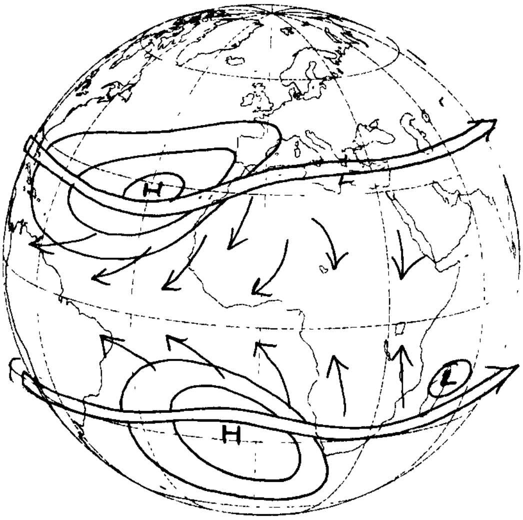

Fig. 6 Schematic of the flow and pressure distribution of the surface high-pressure belt beneath the subtropical jet streams

From the subtropical high pressure cells air flows outwards, mainly polewards and equatorwards. The wind, moving equatorwards, is affected by a rapidly decreasing Coriolis force and converges from both hemispheres in the Intertropical Convergence Zone, characterised by strong upward motion and heavy precipitation. Air moving polewards is affected by an increasing Coriolis force, and a strong adjustment between wind and pressure takes place in the midlatitudes.

The midlatitudes

Approaching the midlatitudes it is tempting to apply 'Coriolis thinking' to understanding the developments on the daily weather maps:

(i) The Coriolis force might help us to understand why midlatitude storms develop, why they are coupled to jet streams, why these jet streams look like bananas, or rather like contracted cycloids, and why there tend to be about six jet streams around the hemisphere.

(ii) We are well acquainted with the traditional picture of developing midlatitude storms where warm, light air rises, and cold, heavy air sinks; but almost as often strong storms develop because the cold air is rising and the warm air is sinking. In this process the Coriolis force plays a decisive role.

(iii) The action of the Coriolis force will, in turn, help us to understand how an upstream storm can affect a downstream one within a short time; for example, on 16 October 1987 Hurricane *Floyd* remained east of Florida, but its influence was clearly felt over southern England.

But all this has to wait. Already, to understand rather simple consequences of the Coriolis force, we have had to scrutinise traditional meteorological concepts, rather like sorting out cows in a cattle market: which ones can provide healthy milk and beef, which ones are holy and should be ignored, and which ones are mad and should be finished off? The scientific field of midlatitude atmospheric developments is filled with cows!

Acknowledgement

I am grateful to the late Adrian Gordon who encouraged me over the years to explain the general circulation and in particular the subtropical jet stream. Alan Heasman at the National Meteorological Archive, and Eric Harris and Dick Ogden in the Royal Meteorological Society's History Group helped me to find the upper-tropospheric maps used by the wartime forecasters in autumn 1943.

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UWERN* Report No. 5:

Quantitative precipitation forecasts

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Accurate forecasting of the location and the amount of precipitation is one of the major problems in operational meteorology. Its solution would be of considerable benefit to society, providing, for example, warning of flash floods so that action can be taken to mitigate their effects. Operational radar networks provide observations of precipitation with high resolution in space and time, typically 2 km and 5 minutes, which contrasts with current operational mesoscale models which have a resolution of about 12 km and are only run every 6 hours. Short-range forecasts based on the objective advection of radar echoes modified for growth and decay using model products show some skill, but what is needed is a higher-resolution mesoscale model which can be run more frequently and assimilate the latest observations, in particular the rapidly evolving radar data. In this article we concentrate upon the forecasting of convective precipitation on very short time-scales, as it is responsible for most flash floods, but we shall also consider the more widespread rainfall within frontal systems and any associated orographic enhancement.

An example of the challenges facing meteorologists aiming to provide quantitative short-range forecasts of precipitation is provided by the situation on 19 May 1999 in southern England. The midnight forecast was for isolated thunderstorms to break out in the afternoon, and the sequence of 5 km resolution images in Fig. 1 (p. 65), from the UK operational radar network, confirms that this did indeed happen – one single localised area of storms developed.

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* The Universities Weather Research Network (UWERN) is a consortium of UK universities funded by the Natural Environment Research Council to develop core strategic research relating to weather. It has several scientific focuses: mesoscale weather systems, including cyclonic and convective storm systems; convection in general; boundary-layer meteorology and dispersion; orographic processes; regional transport of atmospheric constituents; and, most recently, the science underpinning quantitative precipitation forecasting as discussed in this article.