The weather and climate of the tropics:
Part 7 – Tropical revolving storms

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In earlier parts of the series, there was much discussion of broad-scale convection in the near-equatorial humid tropics. The development of areas of deep cumuliform and layer clouds associated with low-pressure systems, however, is often a major cause of disruption due to flooding, landslip, wind damage and high seas. As a result, much effort is put into forecasting the development and motion of these tropical revolving storms. Such storms can be forecast evermore accurately, particularly up to about 48 hours in advance, not least by the UK Met Office (McCallum and Heming, 2006) and considerable effort is put into the improvement of these forecasts (Elsberry, 2006).

The forecasts of tropical revolving storms are co-ordinated by a number of designated Regional Specialized Meteorological Centres (RSMCs) of the World Meteorological Organization (WMO) to produce a single official forecast to be used worldwide. These centres are at Honolulu (central-north Pacific), La Réunion (southern Indian Ocean), Miami (north Atlantic and north-east Pacific), Nadi (south-west Pacific), New Delhi (northern Indian Ocean) and Tokyo (north-west Pacific). Forecasts are also prepared at various forecasting centres in Australasia, as well as Pretoria and Mauritius, although these are not officially RSMCs, but regional Tropical Cyclone Warning Centres. These centres are shown in Figure 1.

Most numerical weather prediction centres running global forecast models contribute to the global tropical-storm forecasting effort. The reliability of the Met Office global model has led to the development of a web-based seasonal storm forecast for the North Atlantic, based on the Hadley Centre GloSea seasonal climate model (http://www.metoffice.gov.uk/weather/tropicalcyclone/northatlantic.html). Useful seasonal forecasts are also produced by the Benfield Hazard Research Centre of University College, London (http://forecast.mssl.ucl.ac.uk/shadow/tracker/dynamic/main.html).

Tropical storm development and decline

Tropical revolving storms form initially as a cloud mass to one side of the equator, over sea temperatures greater than or equal to 27 °C. Mass ascent causes pressure to fall, forming a tropical depression. However, further development is possible only where there is sufficient vorticity to develop the depression (Emanuel, 2005) and then, where conditions are suitable for continued development, tropical storms (Cornish and Ives, 2006). The centre of the depression is normally required to be at latitude 5° or more for such development, although very rarely deepening occurs closer to the equator. Winds that cross the equator may assist in the generation of tropical storms, in particular in the north-west Pacific (Verbickas, 1998), since the convergence is from directly opposing directions. Layer clouds usually extend to great depth in these cloud masses and certainly several thousand metres more than is generally the case in the inter-tropical convergence zone (Galvin, 2008b).

It also appears to be necessary for air temperatures to be cooling aloft for development to occur, so the area ahead of an upper trough (though not too close to it) is well suited. This typically occurs when there is a cold front at higher latitudes and at a similar longitude to that of the depression. (In this respect, the area off the Brazilian coast may seem ideal, but as explained later, this is not the case!) Dynamical ascent generated by mid-level vorticity, such as that associated with easterly waves, also aids the development of these storms (Jones and Thorncroft,

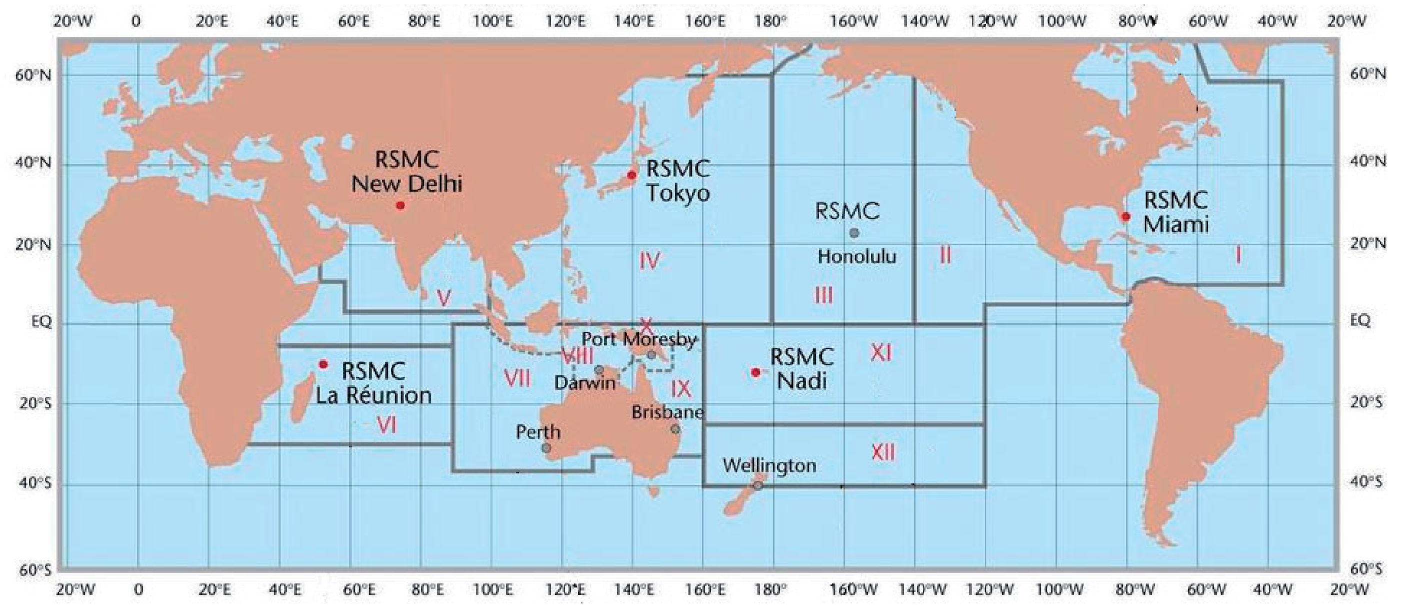

Figure 1. The location and areas of responsibility of designated tropical–cyclone warning centres.

Table 1(a)

The Saffir-Simpson scale of tropical revolving storm damage.

Category	*Level*	*Maximum sustained wind (1-min. mean)*	*Damage*	*Example*
1	MINIMAL	33–42 ms^{-1}	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery and trees. Some coastal-road flooding and minor pier damage.	Hurricane *Earl* (1998)
2	MODERATE	43–49 ms^{-1}	Some roofing material, door and window damage. Considerable damage to vegetation, mobile homes and piers. Coastal and low-lying escape routes flood 2–4 hours before arrival of centre. Small craft in unprotected anchorages break moorings.	Hurricane *Georges* (1998)
3	EXTENSIVE	50–57 ms^{-1}	Some structural damage to small houses and other buildings. Mobile homes are destroyed. Flooding near coast destroys smaller structures with larger structures damaged by floating debris. Land less than 1.5 m above sea level may be flooded 13 km or more inland.	Hurricane *Fran* (1996)
4	EXTREME	58–68 ms^{-1}	More extensive building failures with some complete roof-structure failure on small houses. Major damage to lower floors of buildings near the shore. Major erosion of beach. Land less than 3 m above sea level may be flooded, requiring mass evacuation of residential areas inland as far as 10 km.	Hurricane *Andrew* (1992)
5	CATASTROPHIC	>68 ms^{-1}	Complete roof failure on many houses and industrial buildings. Some complete building failures with some small buildings blown over or away. Major damage to lower floors of all structures less than 5 m above sea level and within 500 m of the shoreline. Mass evacuation of residential areas on low ground 8–16 km from the shoreline may be required.	Hurricane *Camille* (1969)

Tropical cyclones not on this scale can produce extensive damage from flooding. Categories 3, 4 and 5 hurricanes are collectively referred to as major (or intense) hurricanes. These major hurricanes cause over 83% of the damage in the USA even though they account for only 21% of tropical cyclone landfalls. Sourced at http://www.aoml.noaa.gov/general/lib/laescae.html

1998). Indeed, few storms develop without the presence of these waves and they are a key indicator of likely development. All the factors conducive to the formation of a depression and its associated deep convection, with layer clouds throughout the troposphere, need to be present for development. Even where the sea-surface is warm enough, there is sufficient vorticity and there is an upper trough present to aid development, storms may not occur (Emanuel, 1988). This may explain the fact that only one hurricane has been observed off the Brazilian coast (*Catarina* off Brazil in March 2004), where wind shear in the troposphere is usually too strong to allow a tropical storm to develop, preventing storms developing in depth. (Indeed, the inter-tropical convergence zone is not usually seen to migrate south with the sun over the South Atlantic Ocean.)

As a tropical depression develops, although initially in relatively cool air, convective heating is so powerful that the depression gains a warm core as it becomes a tropical storm (Emanuel, 2005). Most convection occurs near the centre and this may allow an 'eye' to develop, due to convective subsidence. This 'eye' is surrounded by a ring of cumulonimbus clouds. The tops of these clouds will often reach the tropopause at around 16 km, in part because of cooling due to over-shooting convection through the convective 'lid' described in Part 3 (Galvin, 2008a). Combined with dynamical forcing, altostratus and nimbostratus often form in association with the cumulonimbus clouds, frequently forming a 'wall' around the centre. Outside the eye-wall region, convection is more limited, convergence reducing with distance from the eye wall.

As pressure falls and the surface wind speed of a tropical depression reaches gale force (mean speed 18 ms^{-1} or more), it becomes known as a tropical revolving storm. With further development, the system becomes known by a variety of names: hurricane in the north-east Pacific, North Atlantic and Caribbean; typhoon in the western Pacific; and tropical cyclone in the Indian Ocean and south-west Pacific. These storms have surface wind speeds of 33 ms^{-1} or more.

Further deepening of the low pressure at the heart of a tropical revolving storm can generate stronger winds still. Major hurricanes are defined in the Americas when wind speeds are 50 ms^{-1} or more (Emanuel, 2005) and super typhoons in the north-west Pacific when mean wind speeds reach 65 ms^{-1}. Table 1(a) shows the Saffir-Simpson scale of tropical revolving storm intensities and their likely effects. The corresponding classification by the Japan Meteorological Agency is shown as Table 1(b). The significant

Table 1(b)

Japan Meteorological Agency classification of tropical revolving storms in the north-west Pacific Ocean.

JMA Category	*Maximum sustained wind (10-min. mean)*	*International Category*	*Class*
Tropical Depression	≤17 ms^{-1}	Tropical Depression (TD)	2
Typhoon	18–24 ms^{-1}	Tropical Storm (TS)	3
	25–32 ms^{-1}	Severe Tropical Storm (STS)	4
Strong Typhoon	33–43 ms^{-1}	Typhoon (TY) or hurricane	5
Very Strong Typhoon	44–53 ms^{-1}		
Extreme Typhoon	≥54 ms^{-1}		

The definition of typhoon is different between the Japanese standard and the international standard. A tropical storm with the wind speed of more than 17 ms^{-1} is called a typhoon in Japan, while in the international standard, that with the wind speed of 33 ms^{-1} or more is called a typhoon.

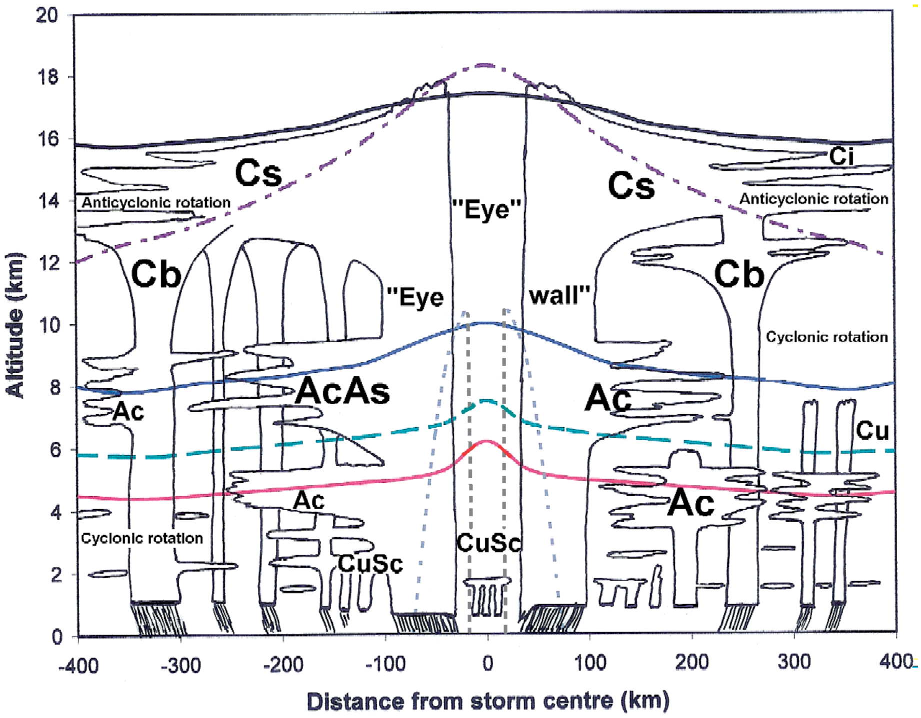

Figure 2. Cross-section of a mature typical tropical revolving storm. The effect of vigorous convection on the freezing level (—), 500-hPa height (------), –20 °C isotherm (—) and tropopause height (–) can be seen easily. Cloud types are indicated: Cb – cumulonimbus; Cu – cumulus; Sc – stratocumulus; Ac – altocumulus; As – altostratus; Cs – cirrostratus; and Ci – cirrus. The division between cyclonic and anticyclonic rotation is indicated —-—. Only within the area ----- do wind strengths reach more than 17 ms^{-1}. (© J F P Galvin, drawn using data from Hawkins and Imbembo, 1976; Frank, 1977; Anthes, 1982; and National Hurricane Research Laboratory, 1970.)

difference between these scales and the local classification of tropical storms is evident.

Tropical depressions deepen most commonly over the north-west Pacific (mostly between March and December), south Indian Ocean (between November and April), the north-east Pacific, North Atlantic and Caribbean (between June and November), as well as the south-west Pacific (between December and April). Fewer occur over the north Indian Ocean (rarely during the south-west monsoon and during the change of monsoon circulation). No tropical revolving storms form in the south-east Pacific, where sea-surface temperatures are always too low. The need for a very warm water source is evidently crucial, as can be seen by the rapid dissolution of these storms as they run ashore, even when temperatures are high over land. The immense constant supply of latent heat from a warm ocean surface provides the energy to develop and then maintain the storm as long as it remains over water.

The heat, humidity and associated convection of tropical revolving storms lift the freezing level locally – typically to more than 5500 m in the area immediately around and above the eye. In this area, the –20 °C isotherm (the level at which icing in cloud becomes less significant) rises above 9500 m (Figure 2). The widespread convection warms the troposphere, which expands, creating an upper high above the storm, the tropopause often lifting above 17 km. As a result, cirrus and cirrostratus clouds rotate anticyclonically away from the centre of the storm – see, for example, Figure 3. Occasionally, the anticyclonic circulation around this high may generate winds of jet-stream strength.

Inspection of Figure 2 shows that cyclonic rotation occurs throughout the eye-wall region, although wind speeds are greatest up to about 4 km and decrease in the upper troposphere (Frank, 1977; Anthes, 1982). Studies reveal that most warming occurs above 4 km; temperature anomalies of 11 degC or more have been measured (Hawkins and Imbembo, 1976).

The level of the tropopause, –20 °C isotherm and freezing level all decrease quickly with increasing radius from the centre of a storm. Near the outside of the circulation, the levels are typically 16 km, 8200 m and 4500 m, respectively (Asnani, 1993). A typical radius for the main area of frequent cumulonimbus clouds is rarely more than 2° (Riehl, 1979), suggesting that the main convection area is rarely more than about 450 km across. Figure 3 shows the main areas of cloud in a large vigorous mature tropical revolving storm. Nevertheless, many tropical revolving storms are smaller than this and a few are considerably larger.

Spiral rain bands are often seen in association with tropical revolving storms (Galvin, 2005). Formed in cooler air, outside the main core, spiral rain bands are often very vigorous, bringing copious rainfall and frequent thunderstorms (Asnani, 1993). In many cases, the rainfall of a tropical storm is heaviest within these bands (Emanuel, 2005). They spiral cyclonically towards the storm centre and, although no measurements appear to have been made of their motion, are likely to move at about 8 ms^{-1}, a typical speed of the 500 hPa wind 700 km from the storm centre. These bands take approximately six days to complete one revolution around the core.

Tropical revolving storms decline as they reach cooler water or land. Their decline may be relatively slow in the former case, but is rapid over land, the energy and wind speed of the system soon reducing. Nevertheless, where a storm runs inland over a swamp or relatively deep warm lakes, or when it

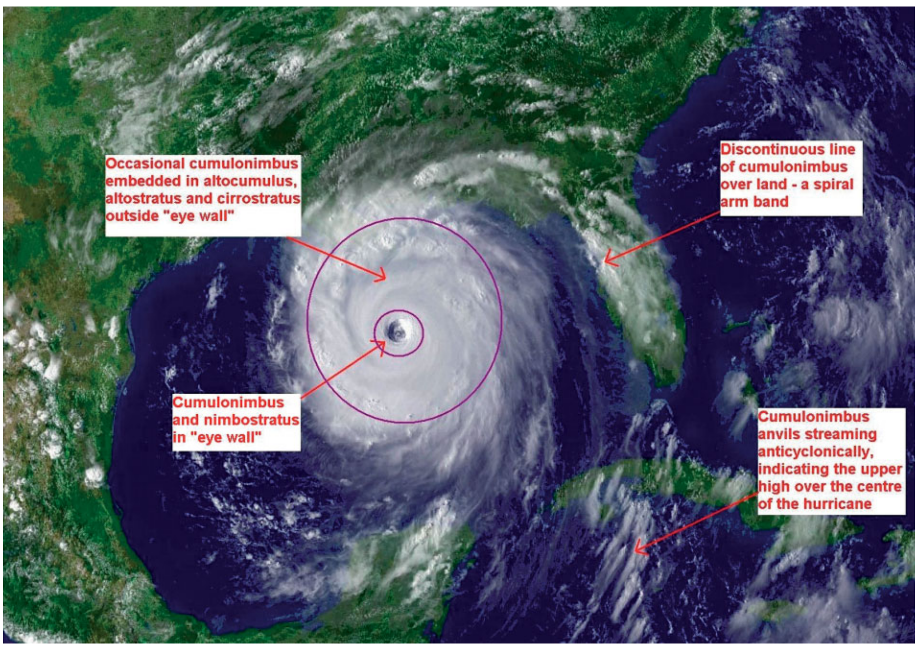

Figure 3. Cloud masses associated with a mature tropical cyclone (Hurricane Katrina *on 28 August 2005.)*

reaches another area of warm sea before the depression has filled, it may regenerate, regaining its power. Hurricane *Andrew* crossed Florida's Everglades swamp on 24 August 1992 and lost little of its power, allowing it to develop further as it reached the Caribbean Sea. The *San Felipe* hurricane on 17 September 1928 retained its energy as it moved north through Florida, sustained by the warmth of Lake Okeechobee (Emanuel, 2005). The potential vorticity associated with any storm may be carried long distances over land, such that westward-moving tropical revolving storms over the South China Sea may re-form as depressions over the northern Bay of Bengal. Occasionally, storms that originally formed over the southern Bay of Bengal may regenerate over the Arabian Sea, having crossed southern India early in the season, while the sea-surface temperature remains sufficiently high (Galvin, 2008a).

In most ocean basins, tropical revolving storms are given names. Where a storm causes major damage and destruction, its given name will never be used again.

The annual average, maximum and minimum number of tropical storms in each ocean basin is shown in Table 2. However, there is considerable variation from year to year and there was a notable 28 storms in the North Atlantic in 2005 (the season ending in January 2006!), compared with 10 in 2006 (Table 2).

The effects of tropical revolving storms

A tropical revolving storm or depression is at its most vigorous while it is developing and during its mature stage; declining storms are relatively weak. Convection causes strong turbulent updraughts and there is strong wind shear at high levels, where the outflow from the storm is strongly anticyclonic. The risk from icing in cumulus and cumulonimbus clouds is high. Rain in tropical revolving storms may be locally torrential and accompanied by hail. Tornadoes and waterspouts may also form. These factors are the most crucial for aviation, and aircraft must attempt to fly around these storms, as they are deeper than the maximum altitude at which most commercial jets can fly. It is the turbulence from convection and strong horizontal wind shear, as well as the high probability of severe icing in the cumulonimbus and nimbostratus clouds near the core of the storm that are the main risks, in particular at medium levels. The radius of the strongest winds close to the surface within a tropical revolving storm is usually small – rarely more than a few tens of kilometres (Figure 2), gale-force winds extending into the mid troposphere.

Although wind speeds are the most dramatic element of severe tropical storms, they do not usually cause the most damage associated with the system. Rainfall and storm surge are most likely to cause loss of life and livelihood (Elsberry, 2006) as a result of flooding and landslides.

Rainfall rates often reach more than 50 mm h^{-1} from both the spiral arms and the eye wall (see Galvin, 2005 and http://www.weather.org.au/tolga/larry.htm). Such heavy rain can overwhelm streams and rivers, causing flash floods and inundation of low ground. Settlements on either side of rivers are often flooded following rainfall from tropical storms; large populations commonly live close to these rivers. Still more damaging are the landslides that may follow this rainfall. This was very evident when volcanic mud from the Mayon Volcano in the Philippines buried and destroyed many homes around Legaspi, following the passage of Super-typhoon *Durian* on 30 November 2006. Deforestation of hillsides for agriculture or quarrying has increased the risk of landslides and many people sheltering from a tropical revolving storm have been buried by landslides, in particular in recent years. A typhoon that affected Hong Kong in 1937 killed 137 000 people, most of whom drowned.

Further inundation of low ground can occur due to storm surge. With large populations living on coasts, floodplains, deltas or coral atolls, loss of life may be high, in particular where there is no high ground, as seen in New Orleans in 2005, Bangladesh in 1971 (Emanuel, 2005) and 2007. Inundation also brings longer-term effects. Farmland may be polluted or suffer salination from a storm surge, the effects lasting years. Water may become undrinkable and, in the worst cases, may not even be suitable for crop irrigation.

Many beaches in areas where tropical storms occur indicate the level of surge from these storms. There is usually a step in the beach, raised by recent surges. Figure 4 shows the beach at Cayawan, Surigao del Norte, Philippines, where this step is evident.

Due to the high risks associated with tropical storms, many nations in south-east Asia now have warning mechanisms in place, using telephones, radio and television. In the Philippines, radio and television bulletins interrupt other programming and instruct people to flee to high ground, or other places of safety, from areas that are expected to be affected. Although the Internet, with its ability to disseminate warning emails and graphics, is potentially a powerful warning tool, in the less-developed economies in this worst-affected area its availability is restricted to relatively few.

The extreme wind speeds at low levels generate very high waves and swell that may travel thousands of miles. Occasional waves in excess of 15 m high may be generated, particularly in the poleward semicircle, where winds are strongest (Cornish and Ives, 2006). Constructive interference may even produce an occasional wave more than 30 m high. Such seas can inflict severe damage and are capable of capsizing ships, even those of frigate or destroyer size (Figure 5). Indeed, it is thought that typhoons inflicted

Table 2

Annual number of tropical revolving storms for each ocean basin (using data from Landsea, 2007; Emanuel, 2005; and Heming, personal communication).

	Tropical revolving storm or stronger (>17 ms^{-1} sustained winds)			Hurricane/typhoon/severe tropical cyclone (>33 ms^{-1} sustained winds)		
Basin	**Most**	**Least**	**Average**	**Most**	**Least**	**Average**
Atlantic	28 (2005)	4 (1983)	10	15 (2005)	2 (1982)	6
North-east Pacific	27 (1992)	5 (1976)	17	14 (1990&92)	4 (many)	9
North-west Pacific	39 (1964)	17 (1998)	26	26 (1964)	9 (1998)	16
North Indian Ocean	10 (1976)	1 (1986)	5	6 (1972)	0	2
South-west Indian	15 (1996/7)	6 (1982)	10	10 (1970/1)	0	4
South-east Indian	11 (1981/2)	1 (1987/8)	7	7 (1979/80)	0	3
South-west Pacific	16 (1971/2)	2 (1981/2)	9	11 (1971/2)	1 (1979/80)	4
Globally	100 (1992/3)	70 (1990/1)	85	65 (1971/2)	34 (1977/8)	44

Data in this table are updated from statistics for 1968–1989 (Northern Hemisphere) and 1968/69–1989/90 (Southern Hemisphere). Averages are rounded to the nearest whole number.

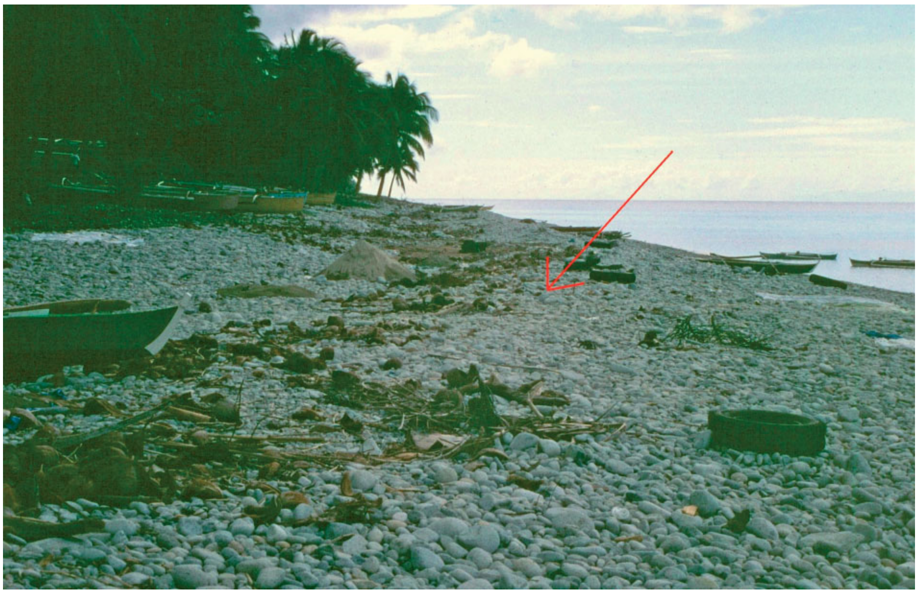

Figure 4. Stepped beach profile showing the level of storm surge (indicated by the arrow) with a slight hollow behind at Cayawan, Surigao del Norte, Phlippines. (© JFP Galvin.)

about the same amount of damage to the US Pacific Fleet during the Second World War as did the Japanese navy. Typhoon *Cobra*, which developed over the Philippine Sea at the end of the north-west Pacific typhoon season of 1944, was encountered by the US 3rd Fleet on 18 December. Three destroyers were capsized and lost; 146 aircraft were blown overboard or damaged beyond repair; 13 other vessels required major repairs; and 9 others needed minor repairs (Calhoun, 1981). Nearly 800 sailors lost their lives. Clearly, it is necessary for shipping to avoid tropical revolving storms, if at all possible. Sixty-four years ago, it was extremely difficult to predict the formation and movement of storms; radar, which can see the precipitation from these storms, had only just been added to ships' equipment (Emanuel, 2005).

At low latitudes, tropical cyclones move at speeds of the order of 5 ms^{-1} or less. It therefore follows that swell will propagate well ahead of the storm. In the days before satellite imagery and numerical weather prediction, it was the swell ahead of these storms, perhaps combined with careful observation of clouds, that gave the best indication of an approaching tropical revolving storm. Clearly, ships with engines can usually outrun these storms or steer around them, but in the days of sail, extreme care was needed if a ship was to avoid the hazards of these systems.

Storm tracks in the Pacific Ocean

In the Pacific, there are three main genesis regions. Most important is the north-west Pacific and South China Sea area, west of about 160 °E, south of about 20 °N. As they grow from a tropical depression, tropical revolving storms track initially west-north-west. Those over the open ocean may affect Micronesia and the Philippines, from north-east Mindanao northwards. The track usually curves north-west and, if sufficiently far away from land, north, then north-east. However, the so-called 're-curving' track takes a large number of storms ashore over, or near Taiwan. Those that complete the re-curving track can affect Korea or Japan. In this area, they may be absorbed into a mid-latitude weather system, imparting a great deal of energy that may be carried across the North Pacific to Alaska.

Those that form over the South China Sea have little time to re-curve. The coasts of southern China and northern Vietnam have occasional encounters with these storms. Typhoon *Xangsane*, which first brought destructive hurricane-force winds to the central Philippines on 26–28 September 2006, crossed the South China Sea to bring winds of 50 ms^{-1} to Vietnam on 30 September and 1 October. At least 200 deaths were associated with this storm.

In the north-east Pacific, under the influence of easterly waves (Berry *et al.*, 2007) warm waters also generate many storms and this area is second in importance only to the north-west Pacific (Table 1). Most form near 110 °W and 15 °N, but soon dissipate as they reach cooler water. Despite the frequency of storms, few affect land, since most are carried away from North America, although on occasion, storms may move northwards to reach the coast of Mexico. A small number of tropical storms forms west of 140 °W when the water temperature here reaches a peak. These relatively rare storms may affect Hawaii.

Despite very warm waters during the southern summer (Galvin, 2008a, Figure 1), fewer tropical revolving storms form over the south-west Pacific (Table 2), due mainly to the high level of wind shear commonly seen in this zone, associated with the formation of tropical upper-tropospheric troughs (Galvin, 2007a). Of these, most run close to the many islands of area, typically affecting Fiji and the Solomon Islands as they track east. A few remain over the cooler waters of the Coral Sea and begin to re-curve south, then south-west. Occasionally the north-east coast of Australia, or even New Zealand's North Island may be affected. The mountainous terrain of the latter can yield very large amounts of rainfall from these storms, which may result in flash flooding.

Figure 5. The aircraft carrier USS Lunga Point *in rough seas generated by a western Pacific tropical storm in October 1945. (Supplied courtesy US Navy Historical Center: Photo # NH 94876.)*

The formation and tracks of hurricanes in the North Atlantic-Caribbean

African easterly waves are now recognized as important in the formation of many of the tropical revolving storms of the North

Atlantic-Caribbean region, as well as elsewhere (Emanuel, 2005). These waves are found in the middle troposphere, usually most easily recognized at the 600 hPa level (~4,500 m). The waves carry positive vorticity and associated barotropic instability across the Atlantic (Berry *et al.*, 2007). In so doing, one of the ingredients for the development of tropical depressions is carried west. Indeed, when the forcing of these waves is absent, associated with a decrease in middle- and upper-tropospheric wind speeds, tropical revolving storms are usually absent, as was particularly noticeable in late July and for much of August 2006 in the Atlantic Basin.

Over the warm water of the western Atlantic and, in particular, the Caribbean, where the water is relatively shallow and can thus warm up more easily, tropical storms may develop near the base of an easterly wave.

Most storms that form in the open Atlantic re-curve north, then north-east and may affect the East Coast of the USA or occasionally Canada's Atlantic Provinces, if they are carried by upper winds rapidly across the cool waters north of Cape Hatteras. Those that reach 40 °N may become incorporated into a mid-latitude weather system – a process known as 'transition'.

More rarely, storms cross into the Caribbean, where they often strengthen. Hurricane *Katrina* of 2005 was one such storm.

The warmth of Caribbean waters frequently generates severe tropical storms. All the Caribbean island chains and the east coast of Central America, as well as the south coast of the USA, bear the brunt of these storms. Flash flooding and inundation may affect the mountainous Central American coasts, whilst the low-lying land of the southern USA, in particular around the Mississippi Delta, is at significant risk of both coastal and fluvial inundation. This does not seem to deter a growing population from moving to the sunshine of the southern US states!

Florida – a low-lying state – is particularly exposed to tropical revolving storms from both the Atlantic and the Caribbean and a large population is at risk from their effects.

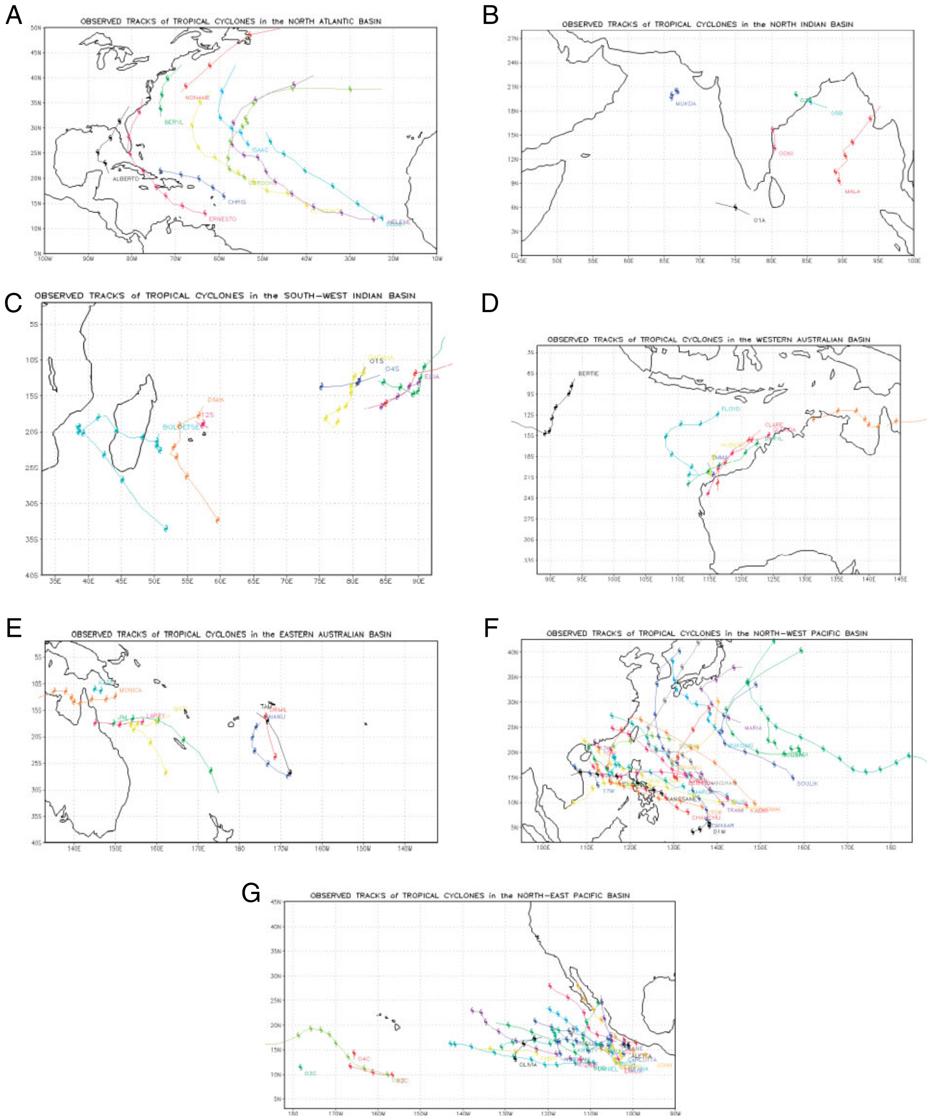

Figure 6. The tracks of tropical revolving storms in the 2006 (Northern Hemisphere) and 2005–06 (Southern Hemisphere) seasons: (a) North Atlantic Ocean; (b) northern Indian Ocean; (c) south-west Indian Ocean; (d) south-east Indian Ocean; (e) south-west Pacific Ocean; (f) north-west Pacific Ocean; (g) north-east Pacific Ocean.

Tropical cyclones in the Indian Ocean

Most tropical revolving storms of the Arabian Sea have a peculiar character, closely associated with the onset and recession of the south-west monsoon (Galvin and Lakshminarayanan, 2006). In late May or early June, a depression forms close to the Laccadive Islands (~11 °N, 73 °E), at the leading edge of the south-west monsoon flow. Where other factors are conducive (around 1 year in 4), a tropical storm forms from this depression and either moves north up the west coast of India, or north-west across the Arabian Sea (dependent on the mid-tropospheric flow). The latter very occasionally brings copious rainfall to the Arabian Peninsula (particularly Oman), Somalia, or southern Iran.[1] Crucially, once the monsoon sets in (Galvin 2008c), the strength of the wind overturns the ocean, bringing cool water to the surface, preventing further storms forming. Thus these pre-monsoon storms can form no more than once per year (Membery, 2001). Almost half the total number of tropical storms in the Arabian Sea form at this time. Nearly all the rest occur as the south-west monsoon recedes, over a longer season between September and November, so long as sufficient moisture remains in depth, after the strong winds of the south-west monsoon have decreased, allowing sea-surface temperatures to reach 27 °C. However, occasionally storms may also occur early in the summer season. David Membery (1998, 2002, 2008) has written interesting and useful reviews of some notable tropical cyclones in the Arabian Sea.

Formation is less well organized in the Bay of Bengal, allowing a somewhat longer season of onset, associated with increased boundary-layer humidity and sea-surface temperatures above 27 °C. The presence of the south Asian upper trough allows the development of tropical storms in May and June, when the waters of the northern Bay of Bengal are warm (c. 29 °C) and upper-atmospheric conditions remain conducive. Unusually, storms may continue after the monsoon flow becomes established, where the ocean remains warm and wind shear is conducive. This was the case in 2007, when a tropical revolving storm formed over the southern Bay of Bengal on 20 June

[1] Tropical Cyclone *Gonu* brought very heavy rain and flooding to Muscat and Oman on 5/6 June 2007. A total of 70 mm of rain fell at Seeb, Muscat, where the mean June rainfall is 1 mm. Twelve people were reported killed and 20 000 were evacuated. The severe, gale-force winds uprooted trees and damaged buildings. Electricity and water supplies were interrupted. This was the most damaging tropical revolving storm in the area for decades (Membery, 2008).

and moved north-west across India's Deccan plateau. Although surface winds soon decreased over India, sufficient vorticity remained within the system for the cyclone to re-form over the north of the Arabian Sea (where the ocean surface temperature was > 28 °C) on 24 June, later affecting Pakistan and Afghanistan.[2] An account of the development and motion of this storm appears as Galvin (2007b) and its position at 1200 UTC on 22 June appears as Figure 5 in Part 3 (Galvin, 2008a).

Later in the year, the season of recession of the south-west monsoon is sufficiently long over the Bay of Bengal to allow storms to form as late as December. As in the Arabian Sea, no tropical revolving storms form during the peak of the south-west monsoon season during July and August (Membery, 2001).

The Arafura Sea, north of Australia, is an important area for the formation of cyclones in the south-east Indian Ocean. The water is relatively shallow and can warm up readily during the southern summer. Cyclones can form here between December and April. The city of Darwin was destroyed on Christmas Eve 1974 by Tropical Cyclone *Tracy* that had formed rapidly over the Arafura Sea.

A similar season occurs in the south-west Indian Ocean and some cyclones affect La Réunion, Mauritius, Madagascar or the east African coast. However, the development is usually confined to a relatively narrow band south of the equator (compared with the northern-hemisphere zone of formation), where waters are warmer than 27 °C. However, the relatively shallow waters of the Mozambique Channel are also a good breeding ground for cyclones in the southern summer, easily warming above the required 27 °C as far south as 25°.

The tracks of the tropical revolving storms of 2006 are shown in Figure 6. Many can be seen to re-curve, where the ocean track is sufficiently long, but in the southern Indian Ocean this is rare.

Conclusion

The effects of tropical revolving storms are often serious – rainfall and storm surge, in particular – causing flooding and loss of life in prone areas of the tropics. However, throughout the world much effort is put into the prediction of these systems: their development, motion and expected effects (Saunders and Rockett, 2001). Accuracy has increased rapidly in recent years (http://www.metoffice.gov.uk/weather/tropicalcyclone/tcerrors/ nhem.html), especially where models may be improved by forecaster intervention and the use of ensemble techniques (Heming, 1999; personal communication; Met Office, 2004; John, 2006).

The Met Office verifies the accuracy of its predictions of the motion of tropical revolving storms; results can be found at http://www.metoffice.gov.uk/weather/tropical cyclone/ verification.html

[2] This storm was exceptional. It is only about once in 100 years (Membery, personal communication) that a storm affects the coast of Pakistan and runs north into southern Iran and Afghanistan.

Acknowledgements

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