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World-wide extreme wind speeds
Part 1: origins and methods analysis

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Wind Engineering Panel. This Panel, which took over the work on wind engineering previously monitored by the Fluid Mechanics Steering Group, first met in 1979 and now has the following membership:

Chairman

Mr T.V. Lawson	—	Bristol University

Members

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Prof. J.E. Cermak*	—	Colorado State University, USA
Dr N.J. Cook	—	Building Research Establishment
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Dr G.A. Mowatt	—	Earl and Wright Ltd
Mr J.R.C. Pedersen	—	Independent
Mr C. Scruton	—	Independent
Mr R. E. Whitbread	—	British Maritime Technology Ltd
Mr G. Wiskin	—	British Broadcasting Corporation.

* Corresponding Member

The construction and subsequent development of the Data Item was undertaken by

Mr N. Thompson	—	Group Head, Wind Engineering.

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WORLD-WIDE EXTREME WIND SPEEDS. Part 1: origins and methods of analysis

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1. NOTATION AND UNITS

		SI Units	*British*
A_m, B_m	Lieblein best linear unbiased estimators (Section 5.4)		
c	constant in Weibull distribution (Equation (5.1))	m/s	ft/s
f	Coriolis force = $2\Omega \sin\phi$	rad/s	rad/s
K_s	terrain factor, $K_s = V_{10}/V_{10ref}$		
k	exponent in Weibull distribution (Equation (5.1))		
k_a	anemometer gust response factor (Section 7.2.1)		
L	distance constant of anemometer	m	ft
M	wind speed record length	yrs	yrs
m	order value within set of annual wind speed maxima with $m = 1$ denoting smallest value and $m = M$ denoting largest value		
m_s	order value within set of individual storm maxima		
N	exposure period or anticipated structure life	yrs	yrs
n_s	number of independent storms in complete record		
P_V	probability of wind speed being less than a value V		
P_x	probability of an extreme value being less than a value x in any one year		
P_{xN}	probability of an extreme value being less than a value x in N years		
R	radial distance from storm centre	km	mile
r	radius of curvature of isobars	m	ft
S_X	standard deviation of all maxima x_m		
T	mean recurrence interval or return period: $T = 1/(1 - P_x)$	yrs	yrs
U	mode or most likely value of x in data set	units of x	
V	extreme value of V corresponding to $P_x = 1 - 1/T$	m/s	ft/s

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V_z	mean or hourly-mean wind speed at height z	m/s	ft/s
$\ddot{V}_z$	gust speed averaged over time τ	m/s	mile/h
v_{10}, $V_{10_{ref}}$	V_z at z = 10 m for terrain z_0 and z_{0ref} respectively	m/s	ft/s
x	equated to individual maximum values such as V^2 or $\hat{V}^2$		
x_m	m^{th} ranked value in data set ($m = 1$ and M for smallest and largest values respectively)		
y	reduced variate, $y = -\ln(-\ln P_x)$		
z	height above ground	m	ft
z_0, $z_{0_{ref}}$	terrain roughness parameter and reference value for site where wind speed measurements made respectively	m	ft
α	dispersion parameter (see Section 5.3)	$(s/m)^2$	$(s/ft)^2$
ϕ	local angle of latitude	degree	degree
ρ	air density	kg/m^3	$slug/ft^3$
σ_x	standard deviation of x at given value of y		
τ	gust averaging time	s	s
Ω	angular rate of rotation of Earth $= 72.9 \times 10^{-6}$ rad/s		

1.1 Conversion Factors

1 km = 0.621 mile
1 m = 3.281 ft

m/s	km/s	mile/h	knots	ft/s
1	3.600	2.237	1.943	3.281
0.278	1	0.621	0.540	0.911
0.447	1.609	1	0.868	1.467
0.515	1.853	1.152	1	1.689
0.305	1.097	0.682	0.592	1

Wind speed in knots $\approx 1.63\, B^{3/2}$ where B = Beaufort scale number

2. PURPOSE AND SCOPE OF THIS DATA ITEM

This Data Item describes the weather systems giving rise to wind speeds of sufficient strength that they are important in the context of design wind loads on buildings and structures. Meteorological stations around the world record wind speeds at regular intervals although the form of the data records varies from place to place. The prime purpose of this Item is to provide guidance for engineering use on the analysis of such

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records and to give detailed calculation procedures for the evaluation of extreme winds associated with a probability or risk of occurrence in a particular exposure period. Further information is then presented on the extrapolation of these wind speeds to heights and terrain roughness that are different from those applicable to the wind speed record. Such methods must be considered in the light of the various storm mechanisms.

The purpose and scope of this Data Item is thus as follows

(1) To provide a background to the origins and nature of the world wind climate (Section 3).

(2) To explain the mechanisms of the storms giving rise to high wind speeds (Section 4).

(3) To provide information on corrections to wind speed records due to instrumentation inadequacies (Section 7).

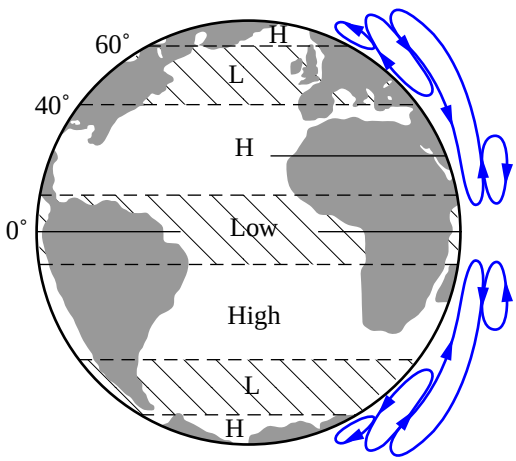
(4) To detail methods of extreme value analysis applicable to annual maxima or individual storm maxima (Section 5).

(5) To give guidance on the extrapolation of extreme wind speeds to other heights and terrains (Section 6).

Further Data Items in this series will give the results of applying the methods described to wind speed records from various parts of the world. In particular, ESDU 88037[47] contains examples of applying these methods to some practical problems.

3. ORIGINS AND NATURE OF WORLD-WIDE WINDS; CORIOLIS FORCE

The air in the atmosphere is constantly circulating powered by vast quantities of energy from the sun. In the absence of surface friction effects and rotation of the Earth, the heating of the atmosphere by the sun near the equator would set up an ideal cell of circulating air with hot air rising over the equator (resulting in a belt of low pressure), descending over the polar regions (high pressure) and returning to equatorial regions close to the Earth's surface. In reality the combined effects of rotation of the Earth and the effect of surface friction breaks up the ideal cell into three principal cells as illustrated in Sketch 3.1. These cells are further influenced by the relative seasonal movement of the sun and by the uneven coverage of the Earth's surface by land and water masses.



Sketch 3.1 Global circulation pattern

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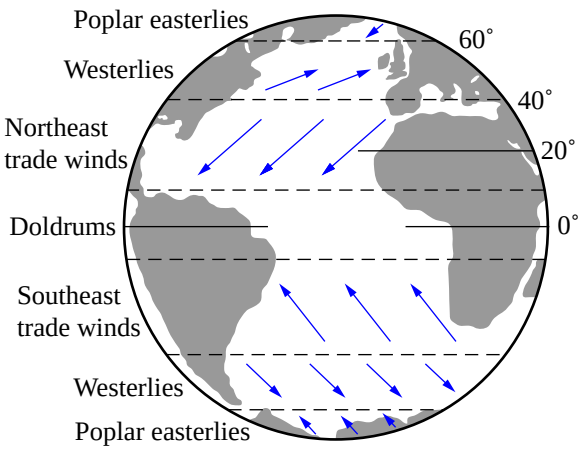

Sketch 3.2 World wind systems

Additionally, the rotation of the Earth causes an apparent deviating force (called the Coriolis Force) to act on a mass of air travelling across the Earth's surface. This force arises from the fact that an element of air moving initially in a straight line across the globe will also be subject to a rotational movement along a meridian due to the rotating Earth. To an observer on Earth this will cause the element of wind to take a curved path. In the northern hemisphere the wind will be deflected to the right of its original path and vice versa in the southern hemisphere.

The Coriolis forces within the three circulation zones in each hemisphere set up the general pattern of winds illustrated in Sketch 3.2. The pattern of these wind belts is affected by seasonal changes and by the geographical arrangement of large masses of land and sea. In the northern hemisphere the effect of differential heating of the surface between land and sea masses has a significant influence on the position of these bands; in the southern hemisphere, which is mainly open sea, the bands are distributed more uniformly around the Earth. These effects are illustrated in Sketches 3.3a and 3.3b which show a more detailed distribution of winds in each zone for the seasons corresponding to January and July respectively in each hemisphere.

The world pattern of weather that develops from this (albeit simplified) model is exceedingly complex. Sections 3.1 to 3.5 briefly describe the wind systems that occur in each of these bands and other strong winds that derive from local geographic effects. The bands are described in terms of latitude belts but particular geographic areas may be located on the world map in Sketch 3.3. The nature and origin of the major storm mechanisms are described in Section 4.

3.1 Polar Region: Easterlies (approximate latitudes: 90° to 60°)

This region includes northern parts of Scandinavia, and the northern parts of Canada and the USSR.

The dynamic pressure $(\frac{1}{2}\rho V^2)$ of the easterly winds in the polar regions is enhanced by the increased air density due to the intense cold (by as much as 10% over middle latitudes). Furthermore, strong but steady katabatic winds (see Section 4.5) are produced by the flow of cold air down steep slopes, particularly in the Antarctic.

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3.2 Middle or Temperate Latitudes: Westerlies (approximate latitudes: 60° to 40°)

This region covers much of Europe, North America and Asia in the Northern Hemisphere and parts of South America and the southern part of Australia, Tasmania and New Zealand in the Southern Hemisphere.

The Polar Easterlies and the more temperate Westerlies converge along a shear line called the Polar Front. The position of this Polar Front varies with the seasons, moving polewards in the summer. It also veers polewards over the sea and towards equatorial regions over land; in particular, over the North Atlantic, the Polar Front stretches from Florida in the south west to Norway in the north east. Sketches 3.3a and 3.3b indicate the respective positions of the Polar Front in each hemisphere.

The polar front is inherently unstable and it is along this line of shear that frontal depressions develop, as described in Section 4.1, travelling in an easterly direction. It is these depressions which, in the winter season, give rise to the highest mean wind speeds for these latitudes. Such winds generally decrease in strength with increasing fetch over land and are highest in western Europe and along the west coast of North America; in the southern hemisphere this region is mainly over the sea except for part of South America and the southern parts of Australia and New Zealand.

Smaller scale systems such as thunderstorms and tornadoes will also produce high local wind speeds in these regions (see Section 4.2). Tornadoes in particular, although less intense than those originating in sub-tropical regions, can give rise to high, short period, wind speeds. However, because they are only dominant for mean recurrence intervals greater than about 500 years[10], their occurrence is usually sufficiently rare to ignore in design apart from extreme safety considerations necessary, for example, in nuclear power plant siting.

3.3 Sub-tropical High Pressure Region (approximate latitudes: 30° to 40°)

In a corridor between the Westerlies and the Trade Winds, a region of high pressure exists in each hemisphere where the large scale weather systems such as frontal depressions are far less likely to develop. However, the greater influx of solar energy leads to the development of more intense, but smaller scale, systems such as severe thunderstorms (see Section 4.2) and tornadoes (Section 4.4). This region includes southern parts of the United States and the USSR, central South America, central parts of Australia and across the Velt of southern Africa.

Their intensity is much greater than those occurring in the more temperate middle latitudes. Whilst the more intense tornado systems are more likely to occur on plains (such as the mid-west of the United States), thunderstorm winds can be significantly enhanced in high mountainous regions where gravity effects on downslope katabatic winds (see Section 4.5) may also produce severe winds. Coastal areas in this region (where the sea temperature is greater than about 26°C) are susceptible to occasional tropical cyclones originating from tropical regions.

3.4 Tropical Regions; Trade Winds (approximate latitudes: 10° to 30°)

Sea temperatures in this zone are sufficiently high (greater than about 26°C to 27°C) for tropical storms (see Section 4.3) to develop. Where these destructive storms cross the coast extremely high wind speeds are possible but they will decay rapidly as they move inland (see Section 4.3.3).

The northeast and southeast Trade Winds in these regions are a direct result of large cells in the global circulation system. The seasonal winds produced are called monsoons and are only moderate in strength but they persist for many days at a time. They are most notable over the Asian land mass.

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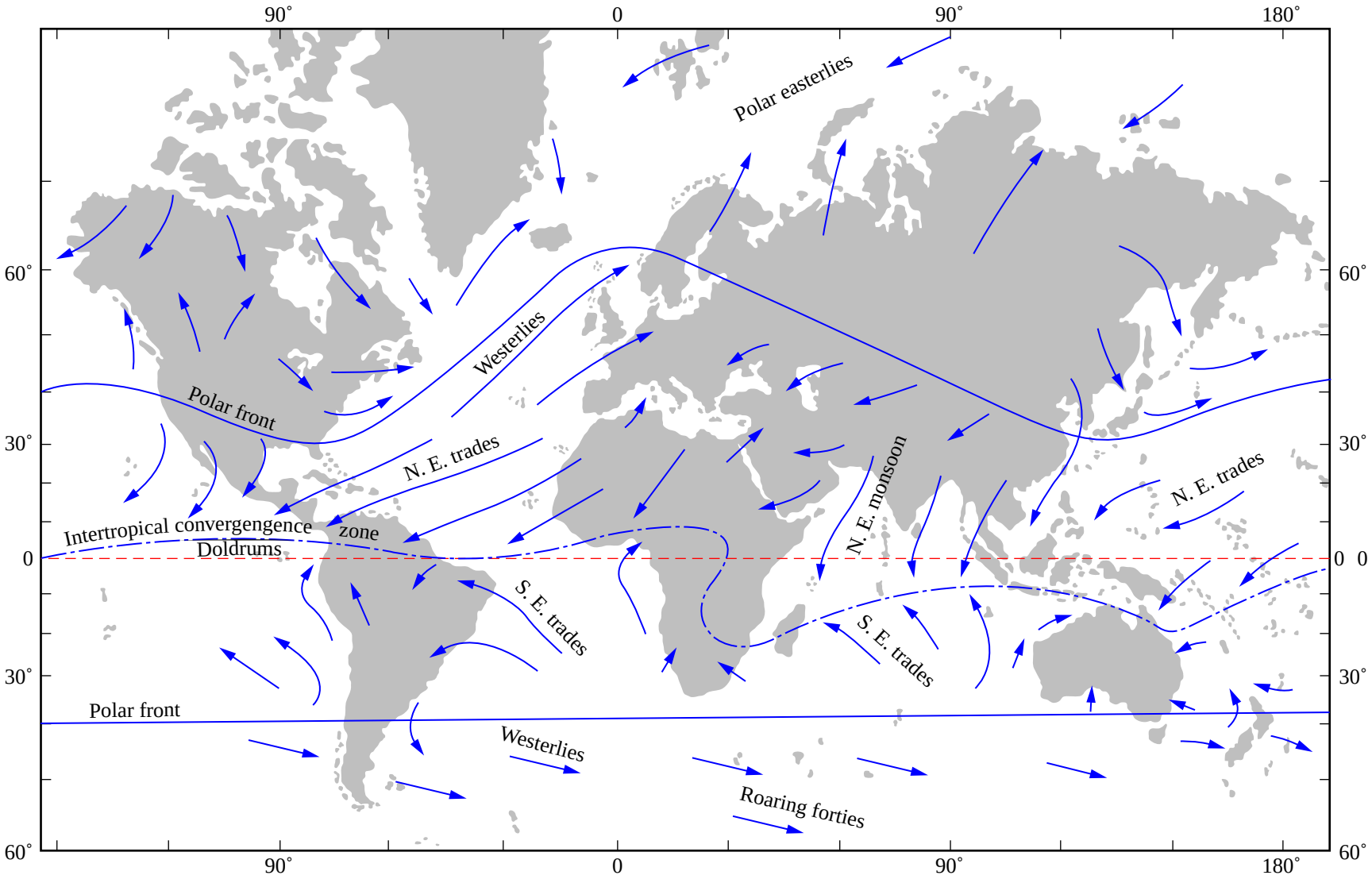

Sketch 3.3a Mean front locations and wind systems for January

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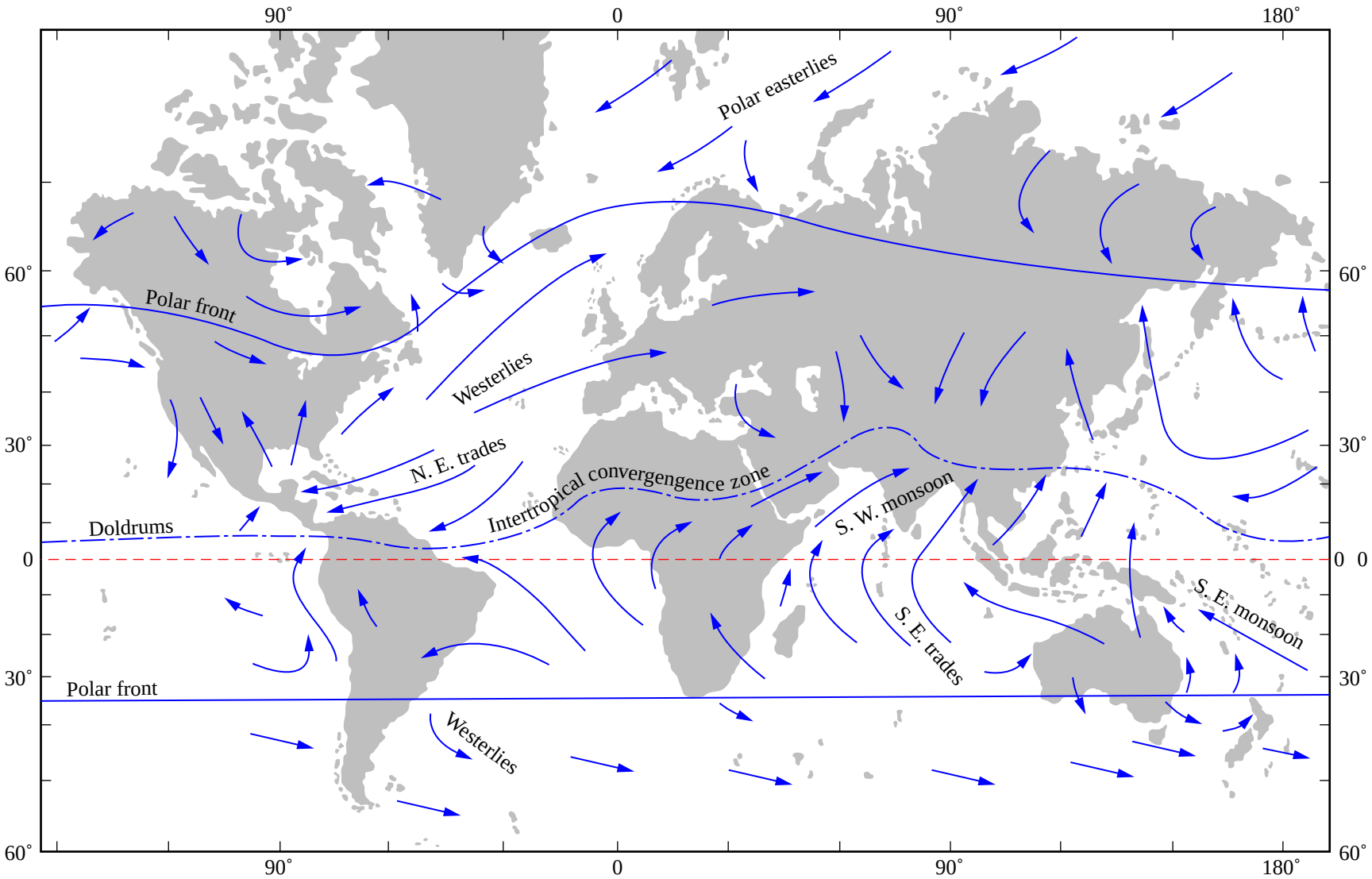

Sketch 3.3b Mean front locations and wind systems for July

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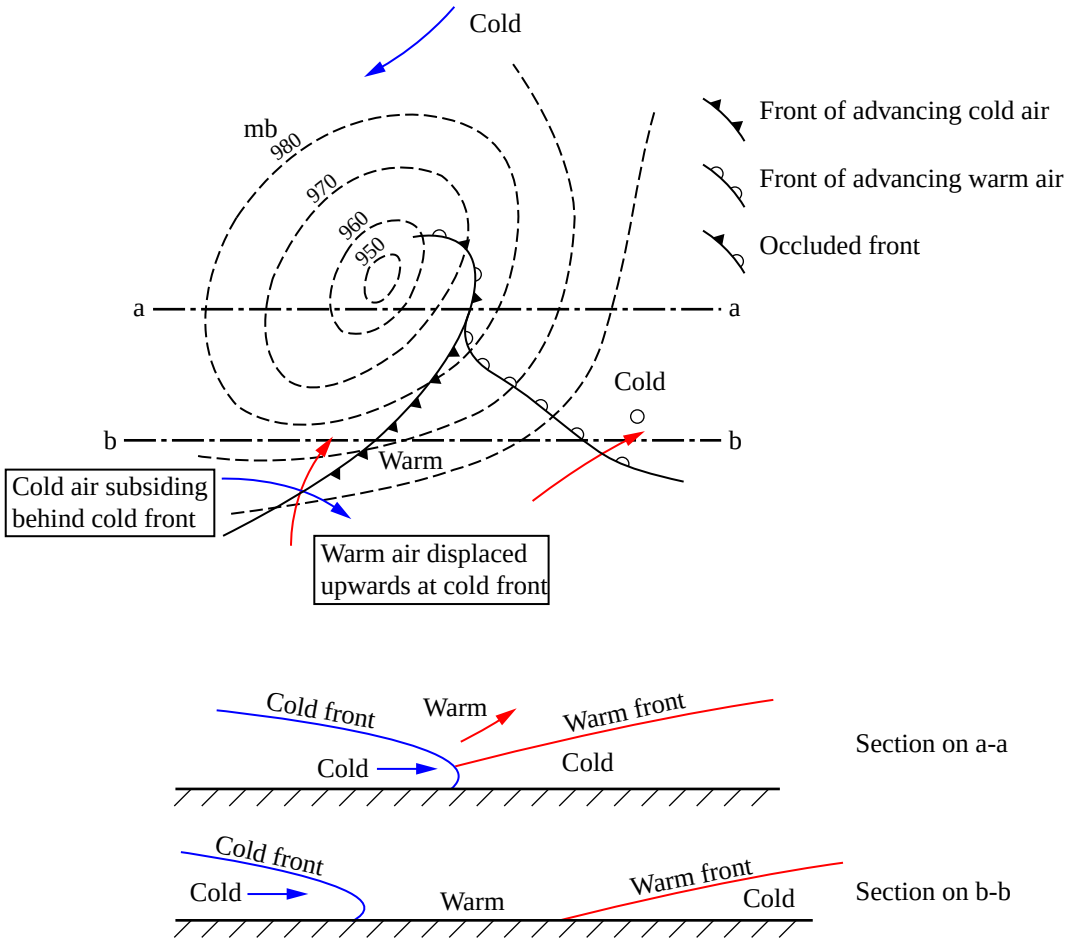
3.5 Equatorial Regions; Doldrums (approximate latitudes: 10°S to 10°N)

With the exception of the occasional remnants of tropical storms drifting toward the equator, this region is characterised by generally low wind speeds (or at least extensive periods of calm). It is where the northeast and southeast Trade Winds converge but because the Coriolis Force (Section 3) is small the resulting tendency to form cyclonic or anticyclonic systems (as along the Polar Front) is small. The convergence zone is called the Intertropical Convergence Zone which varies in position with the seasons as shown in Sketches 3.3a and 3.3b.

4. MECHANISMS LEADING TO HIGH WIND SPEEDS

The purpose of this Section is to provide a description of the various types of storm and other mechanisms leading to the production of high wind speeds near ground level. An understanding of these mechanisms is important because it is usually necessary to extrapolate wind speed measurements to other conditions than those relevant to the measured value. In particular, the following Sections will assist in assessing the extent to which the well-established model giving the variation of wind speed and turbulence with height and terrain roughness for frontal-depression winds can be applied to other storm mechanisms.



Sketch 4.1 Development of wave-like instability along a front

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4.1 Fronts, Depressions, Extratropical Cyclones

The interface between the large masses of cold and warm air which make up the cells of the global circulation is called a front, an example of which is the Polar Front in Sketch 3.3. The temperature and moisture content of the two masses of air on either side of the front are different and where they meet very rapid changes in their properties occur and this causes instabilities to develop in wave-like patterns. Along the Polar Front, for example, cold polar air moving into the warmer zone will abruptly push the warmer air upwards as illustrated in Sketch 4.1. An unstable situation results; the natural circulation of the air mass increases forming the characteristic vortical motion of a depression with mean wind speeds at a height of 10 m above the ground of up to about 25 m/s inland and 35 m/s over the open sea.

The severe storm which passed over southeast England in October 1987 was an example of a frontal depression of extreme intensity formed when warm air moving north from sub-tropical regions was confronted with much colder polar air. The larger than normal temperature differences led to a rapid exchange of potential energy for kinetic energy resulting in the development of a comparatively small, but very intense, storm with extreme winds gusting up to about 45 m/s (100 mile/h) over land.

The pressure gradient $(\mathrm{d}p/\mathrm{d}x)$ across the isobars results in a pressure force being exerted on a parcel of air, acting from a region of high pressure towards a region of low pressure. Additionally, due to the curvature of the isobars, a force due to radial acceleration acts away from the low pressure centre. In practice, above a certain level, called the gradient height (h), where retarding forces due to surface friction are negligible, the wind speed is determined by a balance between these two forces and the Coriolis force (Section 3) acting normal to the resultant wind direction, *i.e.*,

$$V_h^2/r + V_h f = (\mathrm{d}p/\mathrm{d}x)/\rho\,. \tag{4.1}$$

The Coriolis force gradually turns the wind until its direction is parallel to the isobars. Below the gradient height (*i.e.* in the atmospheric boundary layer which is of the order 1 km thick) surface friction extracts energy from the wind so that wind speed (and its direction) vary down through this layer with wind speed decreasing to zero at the Earth's surface.

Typically, a deep depression can be up to about 4000 km in diameter and travels at speeds of between about 15 and 25 m/s. It is sufficiently large for it to influence the wind patterns at locations along its path for up to about three days. In middle northern latitudes, depressions tend to move in a northeasterly direction over the sea and in a southeasterly direction over land with the strongest winds from the southwesterly and northwesterly directions respectively. In the southern hemisphere the winds tend to be from the northeasterly direction.

Tropical storms that meander into more temperate regions and lose their identity can often be regenerated as extratropical storms when they combine with a growing disturbance along a front to form a frontal system of extreme ferocity.

A cold front moves typically 25% more quickly than a warm front and, because it is associated with rapid vertical movements of air, can cause severe weather conditions such as frontal squalls, thunderstorms and tornadoes. On the other hand, a warm front is less steeply inclined, moves more slowly and is not usually associated with severe weather. When a cold front catches up with a warm front it becomes an 'occluded' front.

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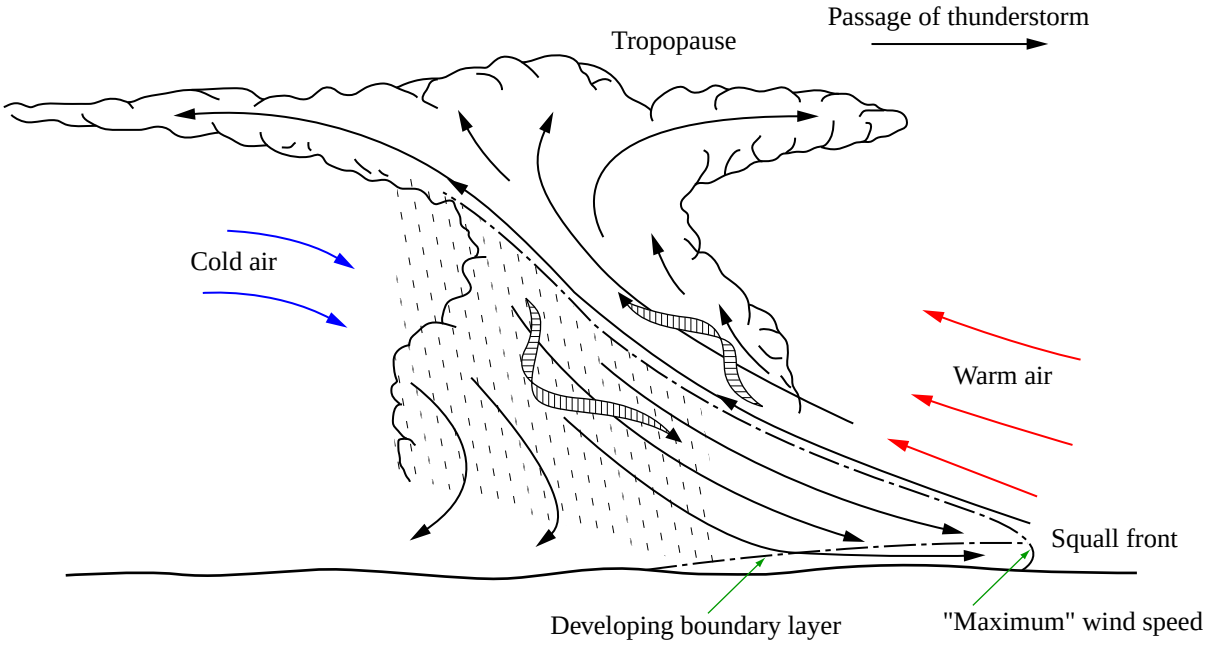
4.2 Thunderstorms

Thunderstorms are relatively small-scale, unpredictable systems (typically 10 km wide and 10 km high). Those producing the strongest winds usually develop along cold fronts as illustrated in Sketch 4.2. However, thunderstorms may also be generated when a mass of warm air is displaced upwards by mountain ranges or by solar heating particularly on the slopes of hills facing the sun or by diurnal winds from the sea.

In the thunderstorm shown in Sketch 4.2 cold air moving forwards is displacing warm air upwards in a cyclonic motion causing the formation of boiling, cumulonimbus cloud topped by the characteristic anvil-shaped cloud which is elongated in the downwind direction by the outflow of warm air. In the cooling expanding air, precipitation takes place forming rain and ice crystals and releasing latent heat which accelerates the upward motion of air. The falling rain cools the inflowing air, partly by evaporation, accelerating the downdraught towards the ground where it then bursts out in all directions, but principally in the direction of the storm passage. This advancing cold air often extends far ahead of the storm and at ground level a sudden squall, often of considerable force, will be experienced as the front arrives.



Sketch 4.2 Structure of a thunderstorm cell

In the region of the downburst very rapid wind speed changes occur. An aircraft that flies into a downburst at low altitude usually encounters a headwind, followed by a downdraught and finally a tailwind resulting in a rapid loss of lift. This vicious sequence of events can be catastrophic to the control of the aircraft.

From the point of view of wind loading on ground-based structures the squall gusts can be very strong although of relatively short duration, lasting between about 5 and 30 minutes at particular locations. In subtropical zones these gusts contribute significantly to records of extreme winds (such as in the United States and Australia) but in more temperate latitudes the energy available is more limited and therefore thunderstorm winds are usually less strong than those associated with deep depressions.

In very severe thunderstorms, tornadoes may develop from vortices formed within the storm (see Section 4.4).

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4.3 Tropical Storms (Hurricanes, Typhoons, Cyclones)

Compared with cyclonic depressions, tropical storms are comparatively rare events at any particular location. An indication of their average annual frequency of occurrence is shown in Sketch 4.3. They are also much smaller in size than depressions, being about 400 to 800 km in diameter. However, they are most destructive events with very high wind speeds (surface gusts up to about 100 m/s and mean wind speeds up to about 65 m/s but typically about 50 m/s) and usually very heavy rainfall. At a typical speed of storm movement (5 to 15 m/s) a severe tropical storm system can take up to about two days to pass a particular location but the most severe weather there will only last about 4 to 6 hours.

When a tropical storm attains mean wind speeds at a height of 10 m in excess of 33 m/s (74 mile/h) it is identified as a hurricane (in the north Atlantic); alternative names are 'typhoon' in the far east and 'cyclone' in the regions of India and Australia.

4.3.1 Origin of tropical storms

The intense energy contained in a tropical storm is derived from solar heating of the ocean surface which in turn releases vast quantities of water vapour into the atmosphere. Under the right conditions this water vapour is convected upwards and the subsequent condensation releases enormous amounts of latent heat (and rain) which fuels the growth and sustenance of the tropical storm. It has been quoted that in an extreme tropical storm one day's rainfall is equivalent to the total flow of the Colorado River in the United States in an average year[23] and that the associated release of latent heat in one hour may be equivalent to the electrical energy used in the entire United States in one week[2] .

The birth of a tropical storm is not well understood but they are often seeded by cyclonic centres originating from the shear lines in the equatorial trough region. They originate in the summer months over the ocean in equatorial regions between about 5° and 15° on either side of the equator but only where the sea temperature is at least 26°C to 27°C and where the upper atmosphere is sufficiently divergent to create the outflow necessary to maintain the storm structure. Tropical storms will not form any closer to the equator because the Coriolis Force (Section 3) is too weak to impart the required circulation to sustain the storm. The characteristic parabolic tracks of tropical storms in their movement away from equatorial regions is illustrated in Sketch 4.4; however, individual tracks may vary considerably and they cannot be predicted easily.

Those tropical storms that follow a curved track over the oceans often become extratropical storms outside the tropical regions (such as in the northwest Atlantic) being regenerated as frontal depressions.

4.3.2 Structure and winds of a mature tropical storm

The structure of a mature tropical storm is illustrated in Sketch 4.5. Under suitable conditions (when some vorticity around a region of low pressure is present) moist air is drawn inwards, expanding and cooling in a spiralling motion. The air is warmed by the sea and convected to high altitudes in a vortex motion forming towering clouds in the process. Condensation of water vapour occurs as the air expands, releasing vast quantities of rain and latent heat which further fuels the evaporation process at the sea surface. The air, after rising to heights near the tropopause (about 10 km) has cooled and flows outwards, sinking slowly in a vortex-like motion (viewed from above) to lower levels. At the centre of the vortex system is a region of relative calm called the 'eye' which is typically about 40 km to 60 km in diameter. It is this characteristic 'eye' that differentiates hurricane-like storms from less intense rain storms. It provides a central source of sufficiently low pressure (typically about 950 mb) to generate the inwardly spiralling streams of air which are cooled, by expansion, to temperatures below that of the sea thereby maintaining the self-regeneration.

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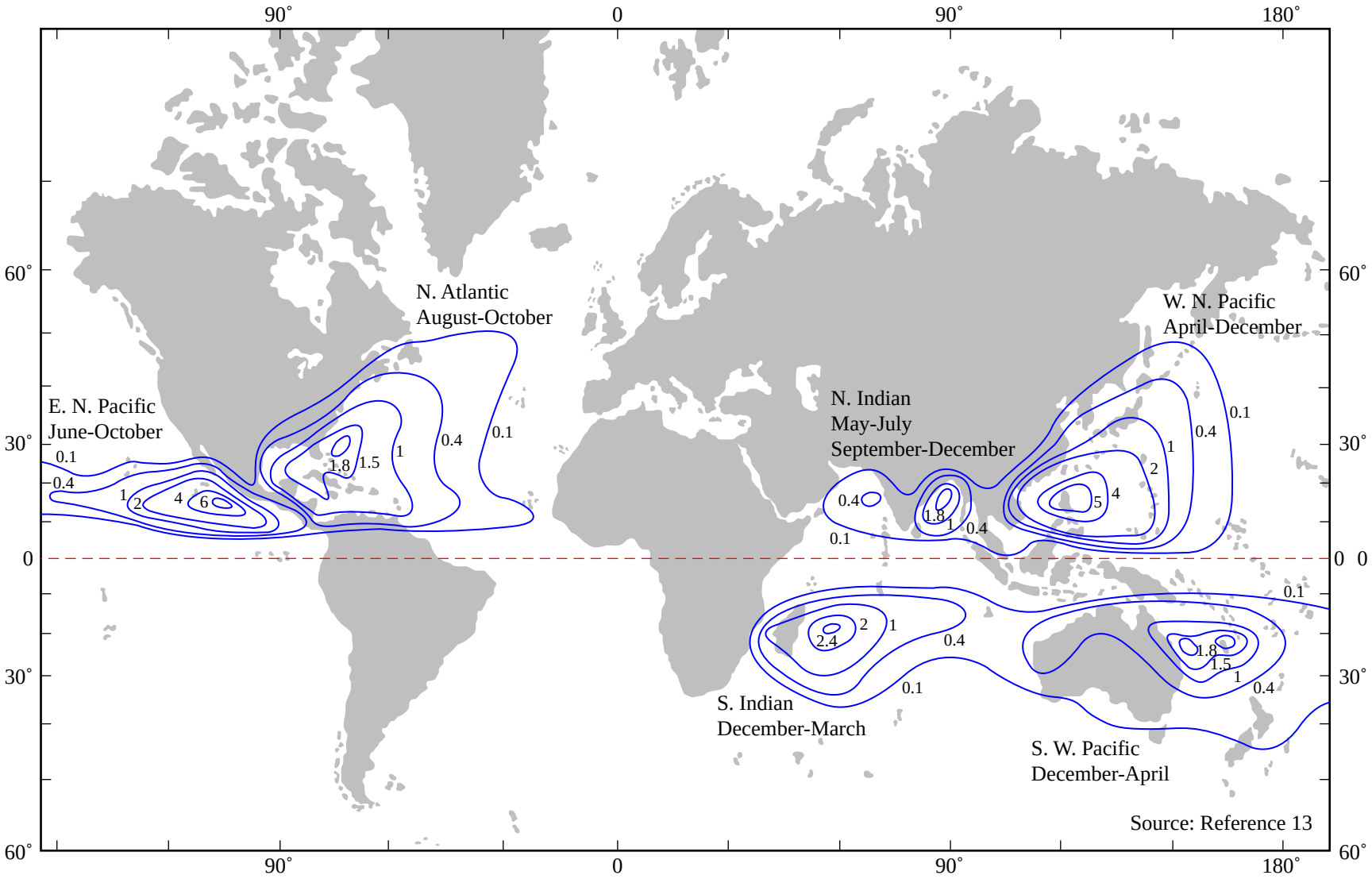

Sketch 4.3 Guide to the occurrence of tropical storms per year per 5° latitude and longitude square (Beaufort scale 8 (≈ 19 m/s) or stronger)

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