CHAPTER 6 — TURBULENCE AND GUSTS

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6.1 Turbulence in the free atmosphere

The sources are deep convection, wave motion and clear air turbulence (CAT).

6.1.1 Turbulence due to convection

This occurs at the boundaries of vertical convective currents:

(i) in cloud; cumulonimbus clouds can extend above 40,000 ft (12,200 m) in the United Kingdom, and above 60,000 ft (18,300 m) in the USA and some tropical areas;

(ii) outside cumulonimbus clouds, especially in clear air around the anvil and just above a storm top;

(iii) in dry thermals below cloud base, or in a cloudless region over any heated land mass (over deserts, dry convection may extend up to 15,000–20,000 ft (4600–6100 m)).

The magnitude of typical vertical currents in convective clouds, based on aircraft reports, are (**Table 6.1**):

Table 6.1.

Regime	Vertical velocity ($m\ s^{-1}$)	Description of turbulence
Stratocumulus		Light/moderate, occasionally severe over rugged terrain or due to instability
Altocumulus		Light/moderate, occasionally severe in unstable medium-level layers
Cumulus (humilis/mediocris)	1–3	Light
Cumulus (congestus)	3–10	Moderate
Cumulonimbus	10–25	Severe
Severe storm (USA)	>>25	Extreme
Dry thermals	1–5	Light/Moderate
Downdraughts	3–15	Moderate/Severe
Downdraughts (USA)	up to 40	Extreme

6.1.2 Wave-induced turbulence

Both *trapped* and *untrapped* waves may induce turbulence (see 1.3.2.1). Although both types are characterized by smooth, laminar flow, severe turbulence is often associated with convective instability or shearing instability of these waves. Turbulence due to mountain waves will be found:

(i) throughout middle and lower troposphere in the lee of a mountain range experiencing a severe downslope windstorm;

(ii) above the main tropospheric jet during conditions of strong mountain flow (with little change of wind vector with height);

(iii) at an elevated layer of very light winds (or flow reversal) when surface flow is strong and stably stratified;

(iv) in a layer of strong stability (or inversion) when surface flow is strong and stably stratified.

Bailey (1970) **Shutts & Broad (1993)**
Bradbury (1989) **Stull (1988)**

6.1.2.1 Inferring turbulent areas from imagery

High mountains with steep lee slopes may generate turbulence indicated on imagery by a narrow stationary clearing of jet cirrus to the lee (**Fig. 6.1(a)**); this will contrast with the cloud pattern with turbulence absent (**Fig. 6.1(b)**).

Bader et al. (1995), Chapter 8

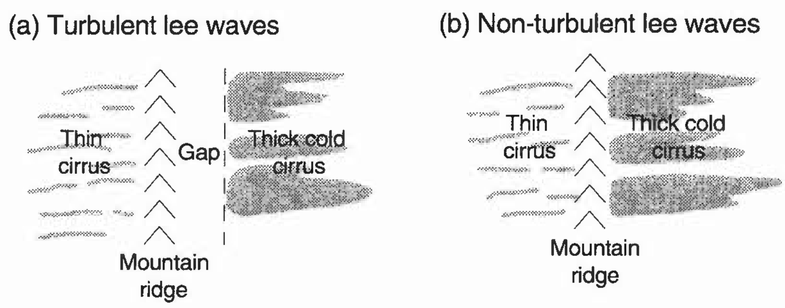

Figure 6.1. The relation between cloud patterns and possible turbulence, (a) pattern associated with turbulence and (b) pattern associated with turbulence absent.

6.1.3 Clear Air Turbulence (CAT)

Although this term can refer to any turbulence not associated with cloud, it is usually applied only to medium- and high-level disturbances.

Table 6.2(a). Typical dimensions of regions within which CAT may be encountered

Horizontally:	80–500 km (50–300 miles) along the wind direction, but only 20–100 km (12–60 miles) across the wind flow.
Vertically:	500–1000 m (1600–3300 ft), but they may be as shallow as 25 m (80 ft), or as deep as 4500 m (15,000 ft) near mountains.

Table 6.2(b). Mean percentage duration of CAT encounters experienced by jet transport aircraft on North Atlantic flights

Light or greater	10%
Moderate or greater	1.25%
Severe	0.013%

Conditions for unusually prolonged, intense CAT are noted in 6.1.3.2(iv).

HAM, Chapter 5.8

6.1.3.1 Synoptic indicators of CAT

Marked wind shear

(i) Both vertical and horizontal wind shears are important for the physical generation of the turbulent eddies that cause turbulence, and stability (or instability) of the air suppresses (or enhances) the effect.
(ii) The relative magnitude of the stability to the kinetic energy due to the vertical wind shear (Richardson number, *Ri*) is used in theoretical calculations.
(iii) The theoretical threshold for turbulence initiation is as *Ri* drops below 0.25; a value of 0.5 is more appropriate for layers resolved by a radiosonde.

Jet streams

About 60% of CAT reports are near jet streams. The most probable regions are those where rapid changes or development are occurring **(Fig. 6.2(a))**:

(i) on the cold side, near and below the core;
(ii) on the warm side, above the core;
(iii) near exits with marked curvature and diffluence;
(iv) at a confluence or diffluence of two jet streams;
(v) near sharp upper troughs;
(vi) around sharp ridges on the warm side of jets;
(vii) where one jet undercuts another;
(viii) where the tropopause height fluctuates.

Moderate/severe CAT is often associated with certain cirrus (Ci) boundaries and cloud patterns which identify jet streams accompanied by strong temperature gradients, shears, deformation, atmospheric waves and instability.

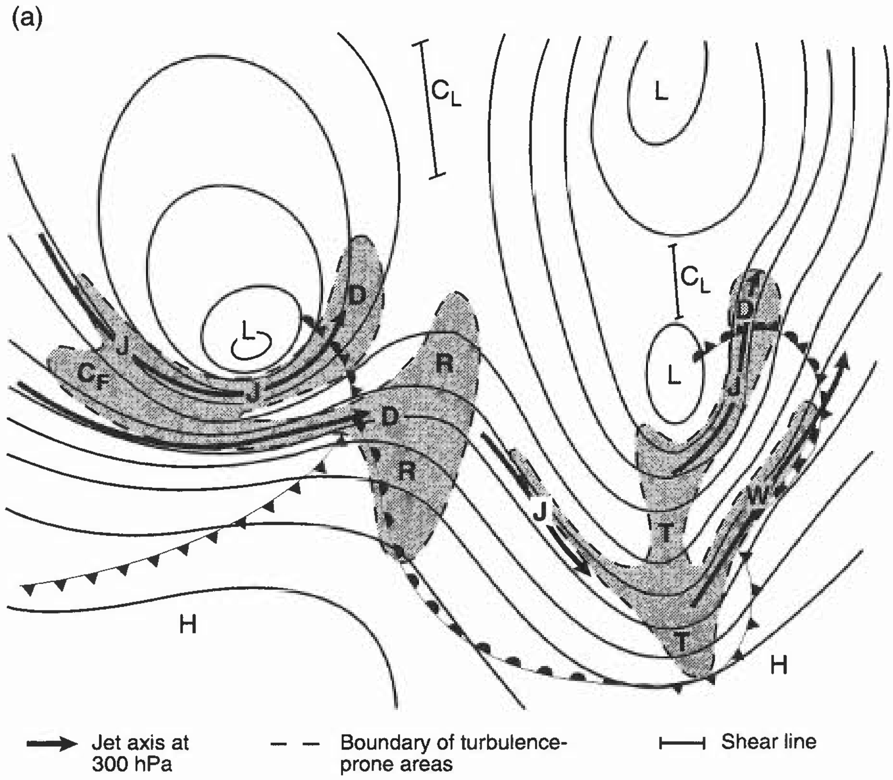

Figure 6.2(a). Main turbulence-prone areas between 500 and 200 hPa as related to features of the 300 hPa chart.

—	300 hPa contours. Fronts marked are at surface.
C_F	Region of confluence between two jet streams.
C_L	Upper-air col. Turbulence occurs in narrow bands along marked shear line.
D	Diffluent region of jet stream.
J	Jet-stream turbulence on low-pressure side.
R	Developing upper ridge.
T	Sharp upper trough.
W	Developing wave depression.

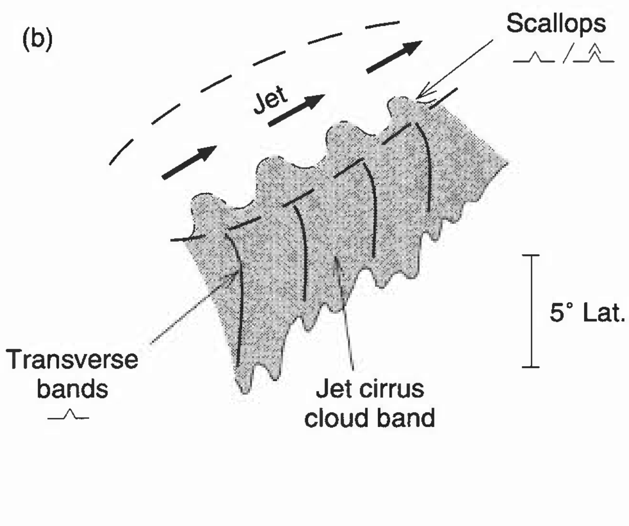

Figure 6.2(b). Model showing the relationship of turbulence to transverse bands and scallops in a jet cirrus band. Dashed lines enclose regions where moderate turbulence is likely.

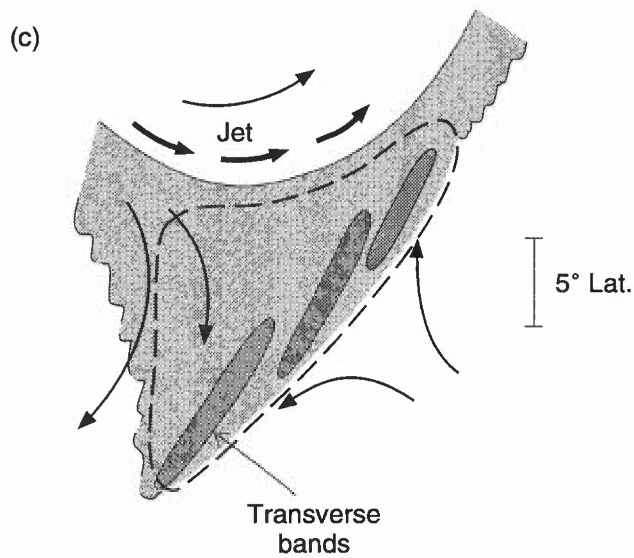

Figure 6.2(c). Model showing the relationship of turbulence to transverse bands in a delta cloud formation. The dashed line encloses a region where turbulence is likely, and thin arrows are streamlines.

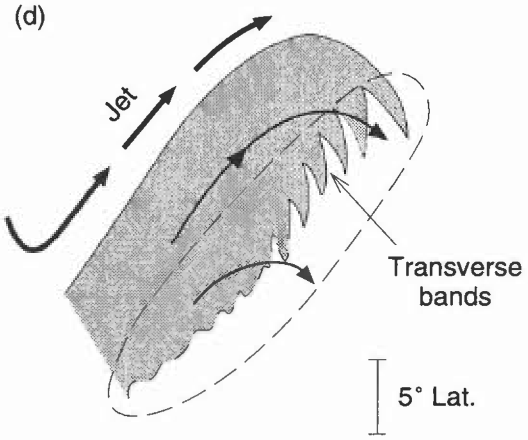

Figure 6.2(d). Model showing the relationship of turbulence to transverse bands (cirrus streamers) along the leading edge of ridge cirrus. The dashed line encloses a region of turbulence. Thin arrows are high-level streamlines.

Turbulence is usually within 3° latitude of the cloud or moisture edge. Transverse Ci bands, Ci 'scallops' and billows may indicate CAT at jet aircraft cruising level **(Fig. 6.2(b))**.

Curved flow

(i) In areas of anticyclonic curvature, where the actual wind speed approaches the critical value of twice the geostrophic wind speed.
(ii) Within 150 n mile or so of the axis of a sharp upper trough where the wind shift is over 90°.
(iii) Occasionally, across shear lines in cols where the wind direction reverses rapidly.

Turbulence in deformation zones is often associated with a transverse banding signature in Ci **(Fig. 6.2(c))**; delta- and comma-shaped clouds are a reliable indicator of moderate or severe turbulence (particularly as the comma system transforms into a vortex).

Thermal gradients

Cloud edges may provide clues as to thickness gradients; near a ridge axis transverse bands (Ci streamers indicate a turbulence area **(Fig. 6.2(d))**.

Topography

CAT is reported twice as often over land as over the sea, and is possibly ten times more frequent over mountains as over flat land.

Bader et al. (1995), Chapter 3
Ellrod (1990)
Hisscott (1986)
Sparks et al. (1976)
WMO (1977)

6.1.3.2 Empirical prediction of CAT

Useful empirical rules are:

(i) Horizontal wind shear:
If shear ≥20 kn deg^{-1} of latitude, forecast moderate CAT
If shear ≥30 kn deg^{-1} of latitude, forecast severe CAT.
(ii) Vertical wind shear:
If shear ≥6 kn/1000 ft, forecast moderate CAT
If shear ≥9 kn/1000 ft, forecast severe CAT
(iii) Jet streams:
If the core speed exceeds 100 kn, and vertical wind shear 4 kn/1000 ft, forecast moderate CAT within 150 n mile.
(iv) An unusually persistent and extensive incidence of moderate to severe CAT reported over the UK in September 1985, was associated with diffluence and anticyclonic turning below a warm-frontal zone.
(v) CAT is rare above a well-defined tropopause.

CAT probability forecasts are available from numerical prediction model output.

Hisscott (1986) **WMO (1977)**

6.1.4 Intensity of turbulence and aircraft response

(i) The intensity of the turbulence reported by aircraft ('bumpiness') will be a function of the strength of the vertical currents and of various aircraft characteristics.

(ii) Individual aircraft will experience different effects, depending on their track, speed, flown profile and physical characteristics. **Table 6.3** (ICAO definitions) refers to civil aircraft while not discussing the origin of the turbulence.

Table 6.3. Definitions (ICAO) of turbulence

Description	Effect on civil aircraft
Light	Effects are less than those for Moderate intensity.
Moderate	There may be moderate changes in aircraft attitude and/or height but the aircraft remains in control at all times. Air-speed variations are usually small. Changes in accelerometer readings of 0.5–1.0 g at the aircraft's centre of gravity. Occupants feel strain against seat belts. There is difficulty in walking. Loose objects move about.
Severe	Abrupt changes in aircraft attitude and/or height. The aircraft may be out of control for short periods. Air-speed variations are usually large. Changes in accelerometer readings greater than 1.0 g at the aircraft's centre of gravity. (Military aviators regard +4 g/−2 g as severe). Occupants are forced violently against seat belts. Loose objects are tossed about.
Extreme	Effects are more pronounced than for Severe intensity.

CAA (1991, 1992)
HAM (1994), Chapter 12.3
HWF (1975), Chapter 23.3

6.2 Turbulence near the surface

The sources will be frictional and orographic; there will also be effects due to deep convection and severe storms. Forecasts required will depend on what is at risk and the nature of the wind /gust hazard.

Hunt, 1995

6.2.1 Turbulence, gusts and squalls

(i) As a rough guide: the intensity of turbulence expected in the lowest few hundred feet in windy conditions increases as surface roughness increases **(Table 6.4(a))**.

(ii) Strong sunshine added to strong wind may increase the difficulties of controlling aircraft, especially on landing and take-off.

Violent turbulence creates a most dangerous low-level hazard to aircraft. It may occur:

(i) during or preceding the passage of an active cold front;
(ii) during or preceding a thunderstorm;
(iii) in hilly or mountainous country (1.3.2, 1.3.3);
(iv) with a steep lapse rate.

At 250 feet (75 m) AGL mean winds >30 to 35 kn in unstable conditions might preclude a low-level training flight, primarily due to the dangers of parachute-induced drag should ejection be necessary. Thus a 35 kn wind can be a forecast 'threshold'. Low-level convective turbulence has been reported by aircrew to be over-forecast; the very turbulent conditions encountered by them in mountain-wave and rotor streaming conditions are reported in 1.3.3.

Cashmore (1966) **HAM (1994)**
Förchtgott (1949) **Klemp (1978)**

6.2.1.1 Criteria for forecasts of hazardous low-level wind shear/turbulence

One or more of the following to be satisfied:

(i) Mean surface wind ≥20 kn.
(ii) Magnitude of vector difference between mean surface wind and the gradient (2000 ft) wind ≥40 kn.

(iii) Thunderstorms or heavy showers within 10 km.
(iv) Significant wind shear has already been reported by aircraft in the vicinity.

MO, Heathrow(198?)

6.2.1.2 Effect of turbulence, lapse rate and wind shear
Turbulent mixing, lapse rates and wind shears are interlinked; the net result of turbulent mixing, starting with a surface inversion, is to warm the lower layers and cool the upper layers until a dry adiabat is established, sometimes forming an inversion at the top of the friction layer. If initial conditions are superadiabatic, the lapse rate will decrease. Section 5.5 discusses the case when the mixing air becomes saturated.

Criteria for forecasting low-level wind shears likely to hazard aircraft are in 6.2.1.1.

6.2.2 Gusts
Empirical and theoretical procedures have produced estimates for 'gust ratios' and gusts which are defined both in terms of the mean hourly wind, and relative to the gradient wind.

Table 6.4(a). Ratio of maximum (3-second) gust to mean hourly speed (for strong, steady 10 m winds)

Surface type	Range of ratios	Estimated average
Open sea	1.3	1.3
Isolated hill tops	1.4–1.5	1.4
Flat open country	1.4–1.8	1.6
*Rolling country (few wind-breaks)	1.5–2.0	1.7
Rolling country (numerous wind-breaks), forest areas, towns, outskirts of large cities	1.7–2.1	1.9
Centres of large cities	1.9–2.3	2.1

*Local variations, using this commonly used category, often give gusts varying widely in space and time from the estimated values, making airfield forecasting difficult, especially under isallobaric surging.

Table 6.4(b). Maximum wind speeds relative to the gradient wind, V_{grad}, in neutral conditions

	V_{grad} units: m s^{-1} (kn)		
Surface type	10 (19)	20 (39)	30 (58)
Open sea	8.8 (17.0)	17.0 (33.1)	24.9 (48.1)
Flat open country	7.8 (14.8)	15.0 (27.3)	21.6 (41.8)
Rolling country (few wind-breaks)	7.1 (13.5)	13.4 (26.1)	19.5 (37.7)
Rolling country (numerous wind-breaks) forest areas, towns, outskirts of large cities	6.8 (12.9)	12.8 (25.0)	18.3 (35.4)
Centres of large cities	6.4 (12.1)	12.0 (23.4)	17.4 (33.6)

Maximum wind speed V_{max} is here defined statistically as: the mean wind speed V_{mean}, plus the fluctuating component in the direction of the mean wind speed (3 times the standard deviation).

These tables may be combined to give an estimate of the mean wind and the ratio of max/mean wind over different surfaces in neutral conditions in terms of the gradient wind **(Table 6.4(c))**.

Table 6.4(c). Estimate of the mean wind and the ratio max/mean wind over different surfaces in neutral conditions in terms of the gradient wind

	V_{grad} units: m s^{-1} (kn)			
Surface type	10 (19)	20 (39)	30 (58)	V_{max}/V_{mean}
Open sea	6.8 (13.2)	13.1 (25.4)	19.2 (37.2)	1.3
Flat open country	4.9 (9.5)	9.4 (18.2)	13.5 (26.2)	1.6
Rolling country (few wind-breaks)	4.2 (8.1)	7.9 (15.3)	11.5 (22.3)	1.7
Rolling country (numerous wind-breaks) forest areas, towns, outskirts of large cities	3.6 (7.0)	6.7 (13.0)	9.6 (18.6)	1.9
Centres of large cities	3.0 (5.8)	5.7 (11.1)	8.3 (16.1)	2.1

Bradbury et al. (1994) **HWF (1975), Chapter 16.7.1**

6.2.2.1 Gusts over hills

Limited UK observations suggest that the structure of the flow over hills associated with strong, steady winds is similar to that over flat terrain, the difference between hilly and flat terrain being the magnitude of the roughness length. The gust factor appears almost independent of hill height for hills greater than 100 m. Assuming a wavelength of hills to be 1.5 km (e.g. gust ratios representative of the Welsh hills), the geostrophic gust ratio at hill height is estimated as about 0.75.

6.2.2.2 Rotor streaming

Associated with large amplitude *trapped lee waves* and *severe downslope winds (1.3.3.4)*:

(i) Surface winds often fluctuate between low and high values. The effect is considered not to extend more than 15 n mile downwind (**Fig. 6.3**).

(ii) The vertical wind/temperature profiles associated with rotor streaming are of the form:
  - strong winds (over 25 kn) near the ground;
  - a sharp decrease in wind speed, which may be accompanied by a large change in direction, at a height of 1.5 to 2 times the height of the hills;
  - an inversion within 1000–3000 feet of the hill tops.

Some severe cases of turbulence affecting airfields (e.g. in NW Wales) may be due to 'rotor streaming'. Initially there is a marked upwind acceleration over the hill/ridge top to 1.5 to 2 times gradient speed; speeds of some 70 kn have been encountered by helicopters. Dark lee areas in water vapour imagery can indicate the presence of hazardous, downslope surface winds.

Bader et al. (1995) Chapter 8 **Förchtgott (1949)**
Bradbury (1989) **Stull (1988)**

6.2.2.3 Gust forecasting in strong wind situations

The gales that disrupted the 1979 Fastnet Yacht Race, and the Burns' Day storm of 1990 are examples of convection occurring in the presence of strong geostrophic winds in a mid-latitude depression. Damaging winds also occur in association with thunderstorms in such depressions. Convectively generated gusts in both cases are produced by two mechanisms:

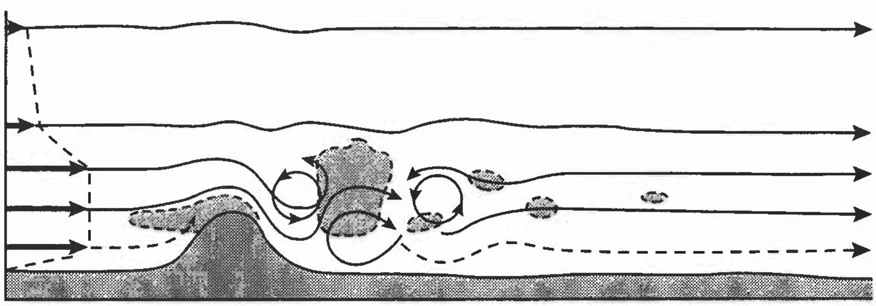

Figure 6.3. Rotor streaming (after Förchtgott). The vertical profile of the wind is shown by the bold arrows on the left.

(a) the production of horizontal momentum by pressure gradient forces as convective downdraughts are blocked by the surface and spread out horizontally,
(b) the downward transport of horizontal momentum by convective downdraughts in the presence of vertical shear.

The relative importance depends on the strengths of the vertical wind shear and the intensity of the downdraughts.

An effective approach to forecasting strong gusts is:
Are showers likely?
(i) *No*: use **Table 6.4(b)**
(ii) *Yes*: use gradient wind speed at 900 hPa as first guess of likely maximum gusts at exposed locations.
If showers are expected to be moderate or heavy, squalls (expected in association with a trough or front) or gusts might significantly exceed the gradient wind.

As a rule of thumb: $V^2_{gust} = V^2_{convection} + V^2_{gradient}$

where $V_{convection}$ is estimated using Fawbush and Miller (**Fig. 6.4**), or $V_{convection} = (gh\ \Delta T/T)^{0.5}$ and, ΔT is the surface temperature deficit in the downdraught, T the average absolute temperature and h the depth of the downdraught in metres.

More explicitly the gust is well estimated by: $V^2_{gust} = [(gh\ \Delta T/T) + V(h)^2 + 2gq_r h]$ in SI units

where h = 2000 m, T = 300 K, q_r = Rainfall rate (mm h^{-1})/(3600 × air density × precipitation fall velocity).
Air density = 1 kg m^{-3}, and fall velocity is about 5 m s^{-1} for rain and up to 10 m s^{-1} for hail. (This term is only of importance at high rainfall rates.)

It follows that a 10 m s^{-1} gust could be produced by either a ΔT of 1.7 °C, or by a rainfall rate of 45 mm h^{-1}, or by an initial wind speed at the top of the downdraught of 10 m s^{-1}.

Bradbury et al. (1994)
Nakamura et al. (1996)

6.2.2.4 Forecasting peak gusts in thunderstorms
The peak gust can be estimated using Fawbush and Miller, which relates gust strength to the negative buoyancy force in a downdraught. It is thus based mainly on the first mechanism ((a) in 6.2.2.3) (although, by its empirical nature, Fawbush and Miller may encompass elements of the second process).

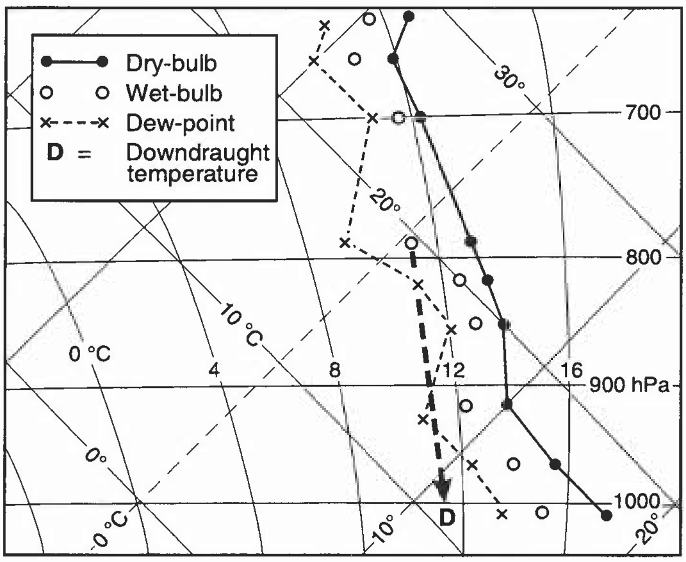

Figure 6.4. Example of a tephigram, illustrating the computation of the downdraught temperature in non-frontal thunderstorms in the USA (after Fawbush and Miller).

Procedure, in particular for summer thunderstorms when the downdraught originates near the wet-bulb freezing level (i.e. melting point for precipitation), is as follows:

(i) Peak wind speeds depend largely on the temperature difference between this cooler downdraught air and the surrounding warmer air at the surface.

(ii) Downdraught temperature may be estimated from an upper-air sounding by drawing a saturated adiabat from the level where the wet-bulb curve cuts the 0 °C isotherm to the surface pressure. **Fig. 6.4** illustrates the construction on a tephigram. **Fig. 6.5** shows the relationship between the temperature difference and the peak wind speed. A correlation coefficient of 0.86 was found in the USA (for non-frontal thunderstorms).

In wintry conditions the downdraught may originate well above the freezing level, being driven by the evaporation of snow or graupel. Such thunderstorms are usually associated with a front or trough in a depression, in which case the gust forecasting technique in the previous section is recommended.

Nakamura et al. (1996)
Fawbush & Miller, 1954

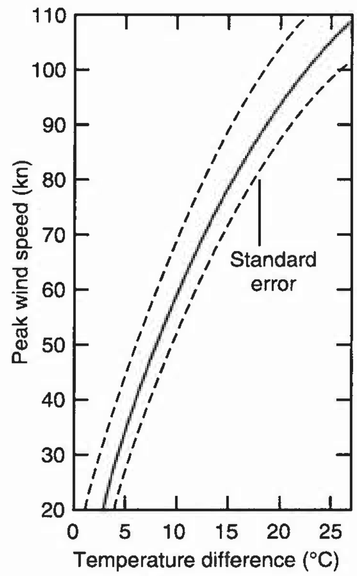

Figure 6.5. Peak wind speed at the surface related to the temperature difference between cold downdraught air and the warm surface air, during non-frontal thunderstorms in the USA.

6.2.2.5 Wind-direction changes associated with gusts

Although there is widespread belief among, for example, yachtsmen that during a surface gust the wind may veer (in the northern hemisphere) by up to 20° to 30°, studies at Cardington and elsewhere have failed to show any significant tendency for this happening at low wind speeds likely to be encountered by yachts. However, there may be a conceptual difference here; for the yachtsman a gust has to last several minutes rather than a few seconds to be of interest.

However, severe *convective gusts* (>65 kn) occasionally occur from a substantially different direction; veers of 60° have been recorded. In high gusts of convective origin at Manston between 1980 and 1990, the mean and standard deviation veers were 40° and 65°, respectively.

Bradbury et al. (1994)
Brettle (1994, 1996)
Houghton (1984)
Singleton (1981)

6.2.3 Squalls

See 6.2.2.3; also 4.7.6.

HWF (1975), Chapter 16.7.2
Ludlam (1980)

6.2.4 Tornadoes and microbursts

6.2.4.1 Tornadoes

(i) These are usually associated with the strong low-level convergence and intensification of vorticity of severe convective storms (4.7.7).
(ii) Pressure falls and wind speeds within the narrow funnel rise to exceptional levels.
(iii) In the United Kingdom modest tornadoes occur mainly in association with vigorous cold fronts or during heavy showers or thunderstorms and with convective potential vorticity advection (PVA) features (8.8).
(iv) Tornadoes normally require:
  considerable depth of convective instability;
  high values of θ_w (18–23 °C) in lowest layers;
  marked potential instability (θ_w falling 5 °C or more up to 500 hPa);
  marked vertical wind shear with winds increasing and veering with height.

HAM (1980)
Ludlam (1980)

6.2.4.2 Microbursts (downbursts)

Strong flows associated with thunderstorm downdraughts (4.7, 6.2.2.4) pose severe risks to aircraft at take-off and landing.

(i) The flows can become organized such that the aircraft encounters a 'ramp pair', on take-off/landing, a sudden headwind component being replaced by a vertical downdraught, followed by a tailwind component — all over a few kilometres.
(ii) The damaging winds are highly divergent, vertical momentum being converted to horizontal momentum; the surface outflow speed ranges from 10 m s^{-1} (19 kn) to over 25 m s^{-1} (49 kn) over a horizontal distance of 2 to 4 km (1.1 to 2.2 n mile).
(iii) The maximum speed occurs usually around 100 m above the ground.
(iv) Horizontal shears of 12.5 m s^{-1} (25 kn) km^{-1} have been measured.
(v) Radar often gives a characteristic 'spearhead-shaped' echo which may contain several potential microburst cells.
(vi) *'Wet' microbursts* are associated with shafts of intense, frozen thunderstorm precipitation falling through the melting layer. Negative buoyancy is enhanced with a high lapse rate below the melting layer.
(vii) *'Dry' microbursts* have virga visible but do not reach the surface. Evaporative cooling of the air may intensify the dry microburst downdraught, particularly if lower θ_w air at middle levels is entrained into the downdraught.

Summary of indicators for thunderstorm microbursts:
  Large positive CAPE.
  Little or no capping inversion.
  At least 1500 m of unsaturated air beneath the convective cloud base.
  A moist mid-tropospheric layer between 1500 m and 4500 m above the ground.
  An elevated dry layer above an altitude of 4500 m.

Bader et al. (1995), Chapter 6.5.6.5
CAA (1991)
Caracena et al. (1989)
HAM (1994)
McCarthy & Serafin, 1984
Naylor (1995)
Waters & Collier (1995)

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