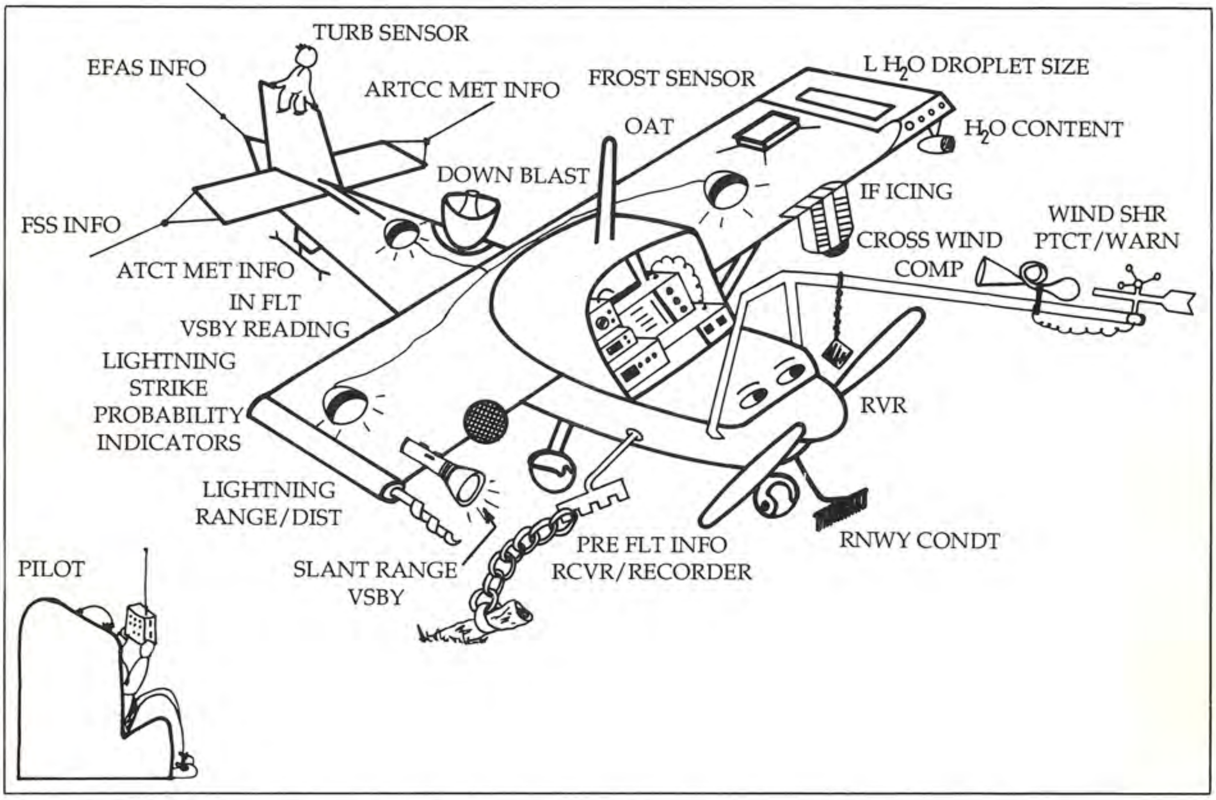
SMHI METEOROLOGI

Nr 74, 1988

AERONAUTIC WIND SHEAR AND TURBULENCE

A review for forecasters



A WELL-EQUIPPED WEATHER-INSTRUMENTED AIRCRAFT

Rapport SMHI

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AERONAUTIC WIND SHEAR AND TURBULENCE
A review for forecasters

Tage Andersson

Front cover picture after L Spencer

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1. INTRODUCTION

'Turbulence' in flight operations means all inhomogeneities in the wind field which cause unexpected deviations from the aircraft's intended flight path. It utters itself as bumpiness, which in extreme cases also may cause severe discomfort to passengers and crew, and even be dangerous because persons and loose objects may be tossed around. Even more serious is that in extreme cases the pilot may lose his control of the aircraft, and/or the aircraft may be damaged.

This is most serious when an aircraft is heavy loaded and flying at a speed just above its stalling speed, as in take-off.

'Turbulence' is related to the shear of the wind. A sharp wind shear by itself affects the aircraft; due to its inertia the aircraft tries to keep its speed relative to the ground also when the surrounding air has changed it. This affects the lifting forece, causing an acceleration and a change in the aircraft's attitude.

If the air flow is laminar, shear does not produce turbulence. However, even if turbulence needs not to be present in strong shear at low altitudes (NCR, 1983, after Lee and Beckwith, 1981) laminary flow belongs to the laboratory, not the atmosphere. In this manual we will mainly talk about wind shear, since this is a meteorological parameter that at least in principle is possible to measure. It has to be understood that wind shear is nearly always accompanied by turbulence (or bumpiness).

Some forecasting hints will be given in the text. The most important one will, however, be given already here:

ASK THE PILOT

as often as possible about the prevailing flight conditions. In a flight he is in the middle of what you are working with; after a flight he has just experienced it.

Table 1 summarizes the weather condition in 27 aircraft accidents/incidents related to low-level wind shear in the U.S. between 1 March 1964 and 28 July 1982 (Johnston, 1986, after NRC, 1983).

Table 1
Weather conditions in 27 shear-related accidents/incidents in the U.S. between 1 March 1964 and 28 July, 1982. Johnston, 1986, after NRC, 1983.

WEATHER CONDITION	EVENT NUMBER 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	TOTAL
Mountain Wave	•																											1
Snow	•																											1
Fog										•					•						•							3
Frontal Shear							•			•					•								•					4
Thunder		•						•	•		•		•	•			•	•	•			•		•	•		•	13
Shower		•			•	•		•	•		•	•	•	•		•	•	•	•	•	•	•		•	•	•	•	20
Microburst																	•	•	•			•		•	•	•	•	8
Outflow													•	•		•												3
Pressure Rise		•											•															2
Gust Front				•																								1

This manual will describe simple conceptual models of turbulence, and discuss the meteorological watch and forecasting of these phenomena. The wind shear and turbulence will be divided into two groups, low-level and high-level. The reason for this division is that at low levels the take-off and landing are affected, and that the friction of the ground always plays an important role as a producer of wind shear. At higher altitude the effect of friction has disappeared or at least decreased, and the climb, cruising and descent phase of the flight are concerned. It must, though, be understood that wind shear and accompanying turbulence occur at ALL altitudes.

2. DEFINITIONS, CRITERIA OF WIND SHEAR AND ITS EFFECT ON AIRCRAFTS

Though wind shear has long been recognized a major problem in aviation safety there are no international accepted criteria for its severity. This only demonstrates the complexity of the problem.

2.1 Definitions, criteria

Wind shear is the (vector) difference of wind velocity at two points, divided by the distance between them. Since the wind is 3-dimensional there may be horizontal as well as vertical shear of both the horizontal and vertical wind. We can thus have the following types of shear shown in Fig 2.1.

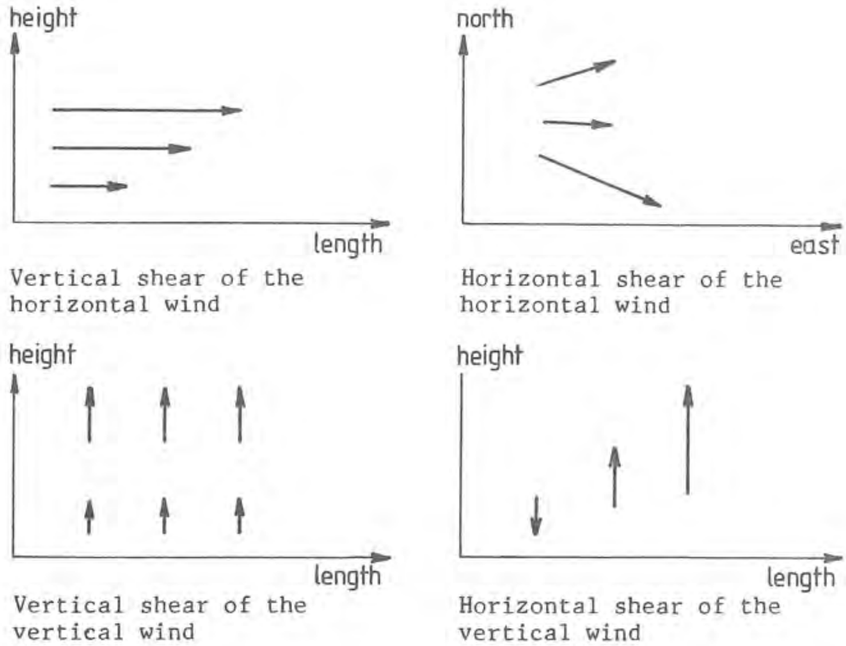


Figure 2.1
Types of wind shear. If the horizontal wind is divided into north and east directions there will be six types.

The shear may thus be a change in speed and/or direction.

The word 'wind' in this paper will mean the horizontal wind (component). Thus 'vertical wind shear' will mean the vertical shear of the horizontal wind.

Criteria for low-level wind shear were recommended by the 5th Air Navigation Conference in Montreal (1967). Though these criteria evidently have not been accepted and more elaborate ones have been proposed, for instance by WIST (Low Level Wind Shear and Turbulence Study Group, 1986) the Montreal criteria will be given here as a reference.

Table 2.1
Interim criteria for wind shear intensity recommended by the 5th Air Navigation Conference, Montreal, 1967

Light	- 0 to 2 m/s/30 m	(0-4 kt/100 ft)
Moderate	- 2 to 4 m/s/30 m	(5-8 kt/100 ft)
Strong	- 4 to 6 m/s/30 m	(9-12 kt/100 ft)
Severe	- above 6 m/s /30 m	(above 12 kt/100 ft)

WMO has estimated the worldwide frequencies of a 2-minute average vector wind shear for the layer 10-40 m above ground given in Table 2.1.

Table 2.2
Estimated worldwide frequencies of wind shear 10-40 m above the ground (WMO, 1976)

1.5 m/s/30 m	50%
2.6 m/s/30 m	17%
4.1 m/s/30 m	2%
5.1 m/s/30 m	0.4%

The term low-level wind shear should be understood to apply to the final approach path and initial climb-out one, i e below 500 m.

As to turbulence its severity is classified in Table 2.3 from ICAO, Doc 8812, AN-CONF/6, 1969.

Table 2.3
Severity of turbulence (ICAO)

Moderate - There may be moderate changes in aircraft attitude and/or altitude but the aircraft remains in positive control at all times. Usually, small variations in air speed. Changes in accelerometer readings of 0.5 g to 1.0 g at the aircraft's centre of gravity. Difficulty in walking. Occupants feel strain against seat belts. Loose objects move about.

Severe - Abrupt changes in aircraft attitude and/or altitude; aircraft may be out of control for short periods. Usually, large variations in air speed. Changes in accelerometer readings greater than 1.0 g at the aircraft's centre of gravity. Occupants are forced violently against seat belts. Loose objects are tossed about.

'Light' may be reported when effects are present but less than quoted for 'moderate'.

'Extreme' may be reported when the effects are greater than those appropriate to 'severe'.

2.2 Effects on aircraft in flight

In fact it is now known that the vertical wind shear as defined here is not entirely satisfactory for the following reasons (WIST, 1986):

"a) It is found that the same wind shear intensity (as proposed in Table 2.1)can affect each aircraft type differently; what might be considered 'severe' for one type of aircraft is only considered 'moderate' for another. This is especially true in respect of aircraft in widely different mass categories;

b) the effect that wind shear has on an aircraft is, inter alia, dependent upon the speed of passage through and hence time of exposure to the shear;

c) information on wind shear intensity in units of speed/distance is not of direct assistance to the pilot flying a 3^{o} glide slope, because a pilot does not think in such units and they do not relate to any of the usual flight deck instruments. A pilot thinks in terms of airspeed, and thus, changes in airspeed are accelerations in kt/sec or 'g' units;

d) the most hazardous wind shear is that associated with thunderstorms such as microbursts where all three components of the wind are changing at the same time; and

e) the boundary values of the intensity classes relating to shear in the horizontal components of the wind given in Table 2.1 (i e excluding downdrafts) do not seem to have been substantiated following the analysis by the RAE Bedford of AIDS data from over 9000 landings worldwide of British Airways B747 aircraft. In this context, the aircraft encountered wind shear conditions classed as 'severe' in accordance with the criteria in our Table 2.1 but which in fact had evidently presented little or no problem for the pilot in landing the aircraft."

An effect of this is that the terms 'light', 'moderate', 'strong' and 'severe' are not used in Annex 3 to the ICAO Convention - Meteorological Service for International Air Navigation. Therefore, the provisions in Annex 3 which require reports, forecasts and warnings of wind shear do not require intensity. Nevertheless, it is recognized in Annex 3 that 'pilots when reporting wind shear, may use the qualifying terms 'moderate', 'strong' or 'severe', based to large extent on their subjective assessment of the intensity of the wind shear encountered'.

Let us consider separately the effect of changes in each of the three components of the wind vector on aircraft in flight;

- the cross-wind component
- the head/tail wind component
- the vertical component (updraft/downdraft)

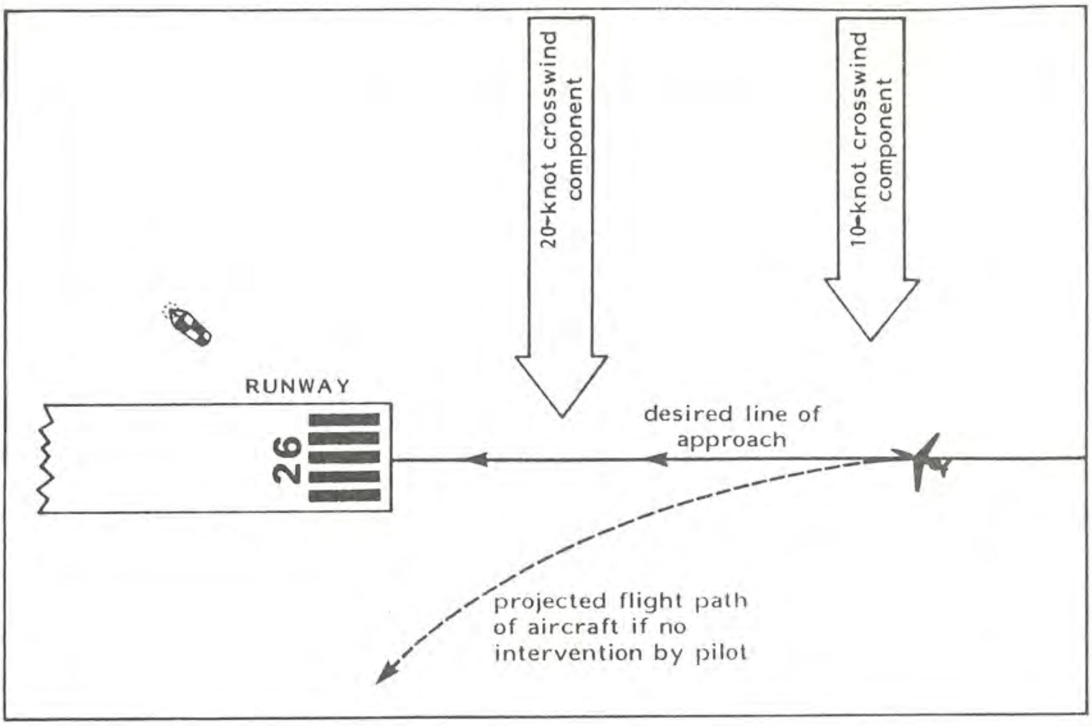


Figure 2.2a
Landing in increasing cross-wind component can result in a lateral deplacement of the aircraft, if not corrected. May be serious if the cross-wind limits of the aircraft are approached and/or the runway is wet or icy. Cross-wind effects are usually accompanied by the two others, complicating the matter for the pilot (after Fox, 1982).

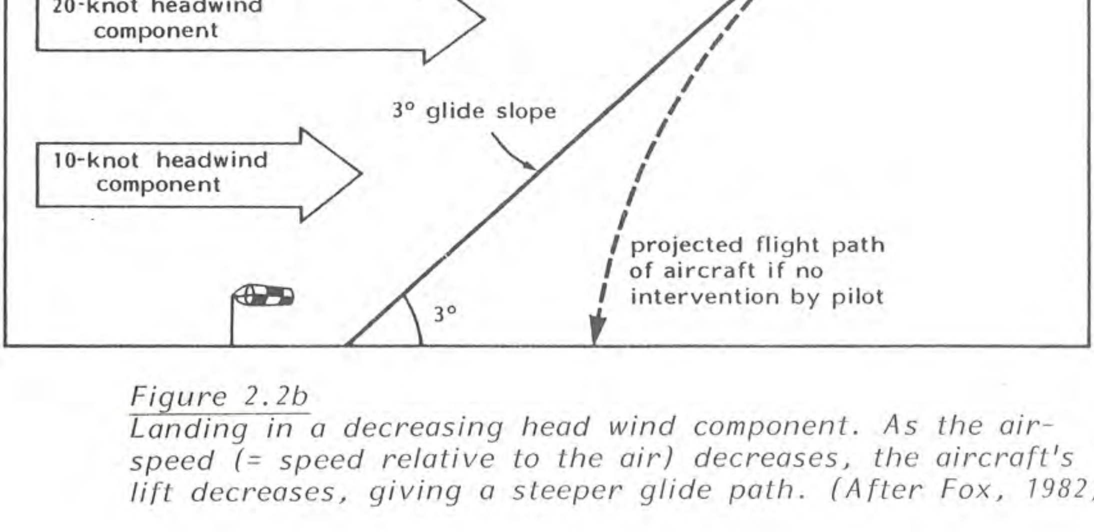


Figure 2.2b
Landing in a decreasing head wind component. As the airspeed (= speed relative to the air) decreases, the aircraft's lift decreases, giving a steeper glide path. (After Fox, 1982).

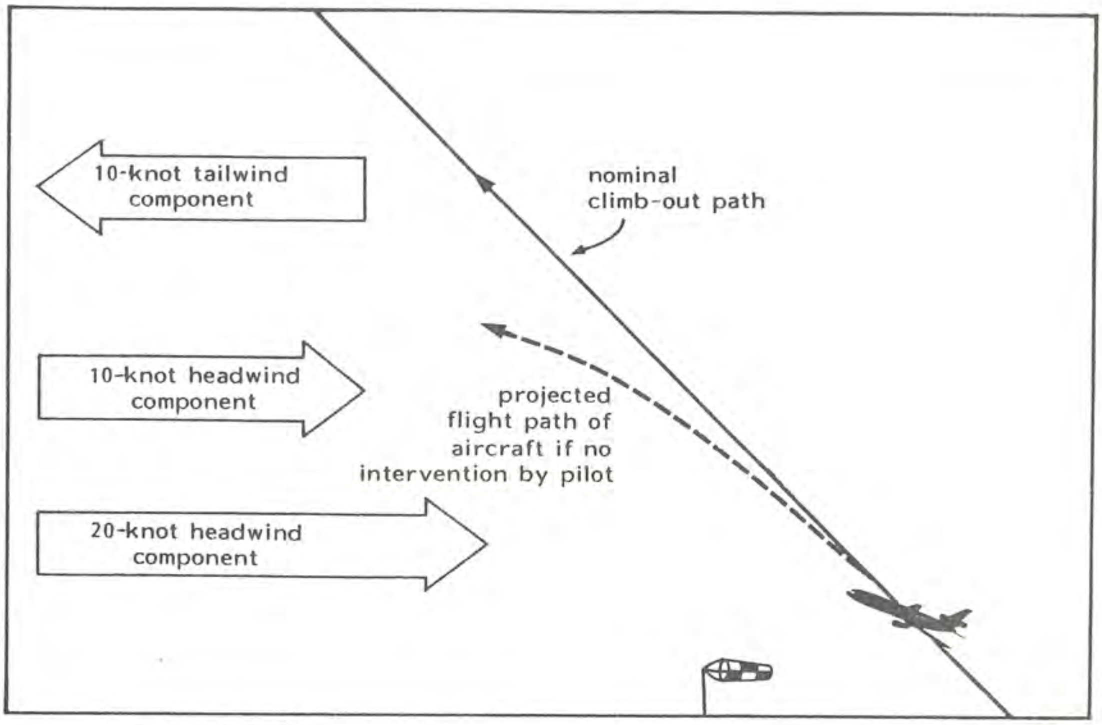


Figure 2.2c
Taking-off in a decreasing head-wind component. (After Fox, 1982).

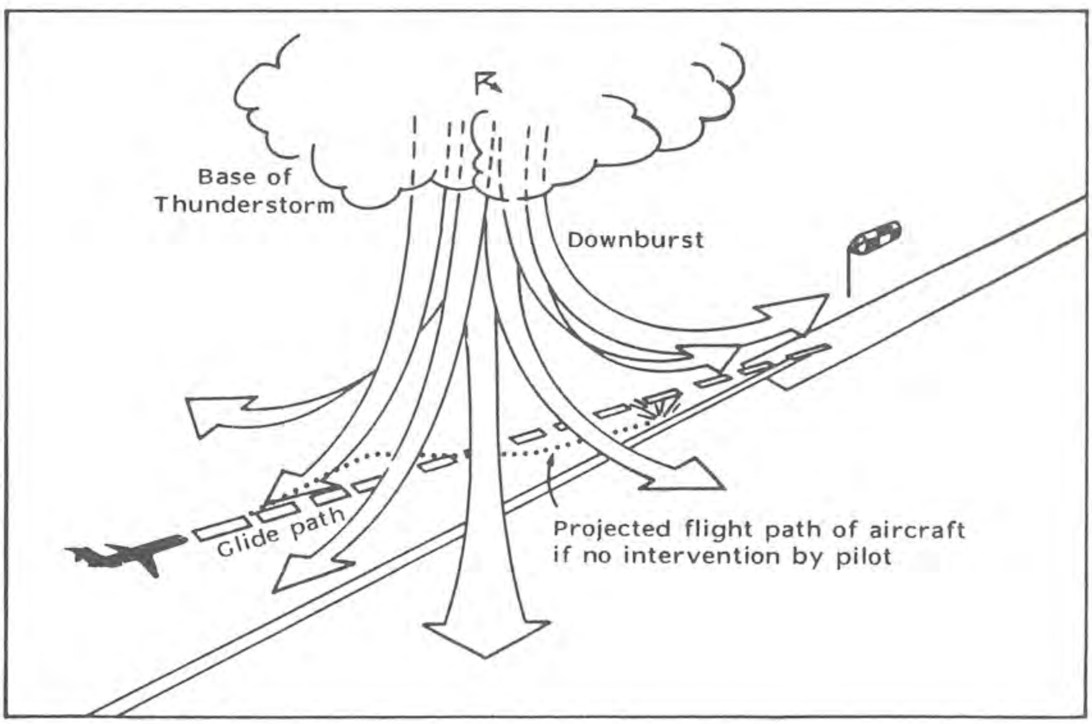


Figure 2.2d
Landing in a downburst results in several changes in lift and thus in flight path. Starting in a downburst is analogous. Since very high wind speeds and sharp velocity gradients can occur, this is the most dangerous case, known as 'THE KILLER'. (After Fox, 1982).

Table 2.4
Horizontal scale, lifetime and maximum wind speed of wind shear disturbances, associated with convective storm. (Fox, 1982, after Fujita, 1979)

Wind shear disturbance	Horizontal dimensions	Life-time	Maximum wind speed
Gust front	10-100 km	1-10 h	40 m/s
Downburst	4-10 km	10-60 min	50 m/s
Microburst	1-4 km	2-20 min	60 m/s

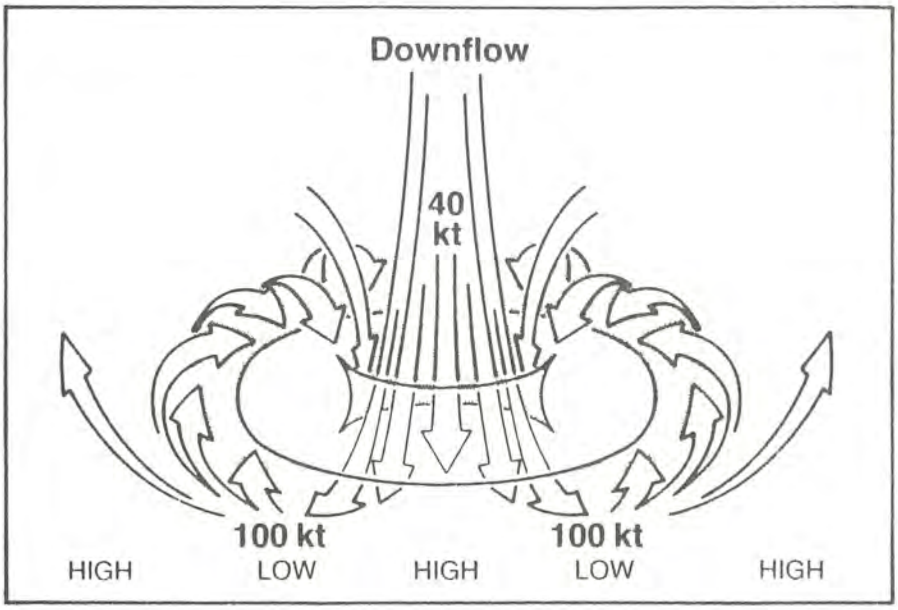


Figure 2.3
Simplified picture of a microburst and its horizontal vortex (Johnston, 1986)

When an aircraft is flying well above the ground changes in lift are not so serious and the aircraft accelerates or decelerates to recover the original airspeed. The airspeed is also much above the stalling speed, so it is possible to control the aircraft. In landing and take-off, with an airspeed just above the stalling and close to the ground, a change in lift can be very serious.

In dealing with a loss of lift in a wind shear encounter in a propeller-driven aircraft, the pilot increases the engine power which almost immediately results in an increased propeller slipstream over the wings and increased lift. The jet aircraft response to an increase is much slower due to the relatively longer 'spool-up' time of the jet engine and the corresponding slower recovery as the airspeed builds up.

3. OBSERVATIONS AND MEASUREMENTS OF WIND SHEAR

There are still no satisfactory instruments or systems for routine measurements of low-level wind shear. This is hardly surprising. Such a system should give continuous measurements of the horizontal as well as the vertical wind components along the climb-out and landing paths.

Remote sensing equipments to achieve this aim are not impossible, but too expensive to be realized in a near future. The situation is improving, however, since more and more aerodromes are being equipped with instruments as doppler radar and sodar, who immensely increase the possibilities of measuring wind shear.

3.1 Observations

Clues to the wind shear may be given by visual observation. The wind shear itself is of course invisible but its effects may be observed (WIST, 1986):

"- adjacent cloud layers moving in different directions;
- smoke plumes sheared and moving in different directions;
- roll cloud ahead of an approaching squall line;
- strong, gusty surface winds affecting trees, flags, etc);
- windsocks around an aerodrome responding to different winds;
- dust (especially in the form of a ring) raised by downdrafts beneath convective cloud;
- dust raised in gust fronts ahead of squall line;
- virga especially associated with convective clouds;
- lenticular clouds indicating standing waves, etc;
- funnel clouds (waterspouts and tornadoes).

Not all of these wind shear effects would necessarily have any significance for aircraft landing and taking-off; this would need to be assessed on a case-by-case basis in the light of local circumstancies at the time. Many of the effects would be visible both from the ground and in the air and could be useful clues to warn the pilot of possible wind shear."

It must, however, be noted that a continuous watch of these phenomena by the forecaster or observer is impossible at least in Sweden. The reason being that these officers have too many other duties. Besides it is beyond human capability to keep a continuous watch over whole the horizon or over the landing and climb-out path, even if the visibility is good enough and there is an unobstructed field of vision. Nevertheless, using the clues given above helps the forecaster to cope with the problem.

3.2 Ground-based measurements

There are three main types of ground-based measurements:

1 Direct, several anemometers either spaced horizontally around the airport, or vertically on a nearby mast.

2 Several pressure gauges around the airport to catch an anticipated pressure jump associated with the wind shear.

3 Remote sensing, doppler radar, acoustic sounders.

3.2.1 Direct measurements

Horizontally spaced anemometer

This method measures of course horizontal shear. A vertical wind shear may be reflected close to the ground as a horizontal shear of the wind. This is true for, for instance, the sloping front accompanying a gust front, but not for the wind shear connected to a horizontal inversion. One such system, the LOLA (LOw Level Alert), see Fig 3.1, is now operational at 80 major U.S. airports (Baker et al, 1986). It consists of a number of anemometers mounted above (10-60 feet) the ground at and around the airport. Usually, there are five anemometers around the airport (about 3 km from its centre) and one at the centre. The anemometers are interrogated at short time intervals (10 sec). The reference value is a mean wind vector from the centre gauge (2 min average. The difference between the centre value (2 minutes mean) and outer gauges (10 seconds mean) are computed and when the vector difference exceeds a threshold (15 knots) an alert is given to the tower.

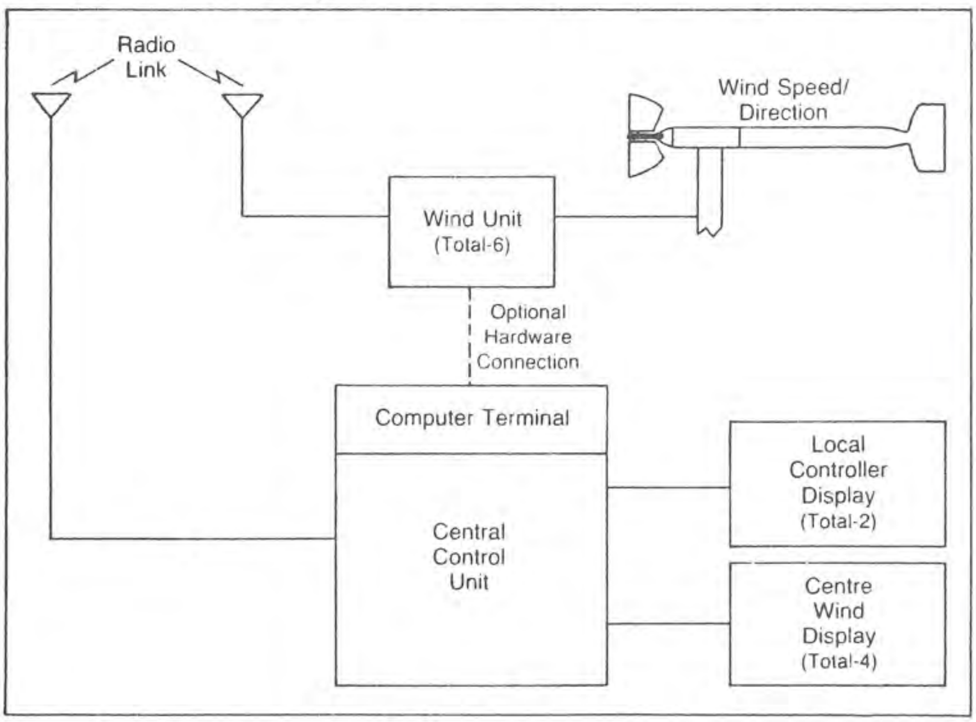


Figure 3.1
The LOLA-system (after Baker et al, 1986).

The LOLA system is primarily intended to detect wind shear connected to gust fronts in thunderstorms outflows, that is fairly large systems. As such it seems to work well, but there are smaller violent phenomena as microbursts, whose detection requires a denser network and higher time resolution.

Vertically spaced anemometers

An obstruction as a 100-300 m high mast on an airfield is impossible. Such systems therefore have to be placed several kilometers from the airfield. Then they are of little use for small-scale violent phenomena as microburst but well adopted for larger scale ones. Simply comparing values (winds, temperature) from the mast with those from the airfield give valuable information.

Such systems are working at the airports of Helsinki and Sundsvall, and have been found very useful in our climate.

3.2.2 Pressure gauges

Active thunderstorms may show 'pressure jumps' caused by the vertical motions of the air in the storm. The cold, outrushing air in the gust front moving away from the storm may also produce a 'pressure jump'. This is often associated with the wind shift. Networks of pressure gauges have been tested around airports in the U.S., but the results seem not conclusive, though there are indications that the pressure gauges may give warnings up to 3 minutes earlier than anemometers would.

3.2.3 Remote sensing

Doppler radar

A doppler radar measures a o the radial velocities, i e the velocity vector away from or towards the antenna. There have to be targets in the atmosphere to measure against. Such targets are not only precipitation particles, but also insects and turbulence-produced discontinuities in the air's refractive index. These clear-air-echoes are weak, but occur often during the warmer seasons out to a range of some tens of kilometers and up to the top of the boundary layer. That is, up to 1-2 km during summer in our climate.

A qualitative analysis of wind shear may be made manually by the operator. The vertical wind shear, both in wind direction and wind speed, has a characteristic pattern on a PPI (Plan Position Indication) using a suitable elevation angle. Also, small-scale cyclones and downbursts have characteristic patterns.

Quantitative analysis is possible if the wind pattern is not too complicated. For instance, supposing the wind field is only linearly varying, the VAD (Velocity Azimuth Display) technique can be used. This technique gives the horizontal as well as the vertical wind for an area around the radar. Mapping of the wind over an area is possible with a single radar, using the uniform wind technique, Fig 3.2, if the wind field is not too complicated and only a low resolution in space is needed. Analysis of small-scale phenomena as microbursts needs at least two doppler radars fairly close to the airport.

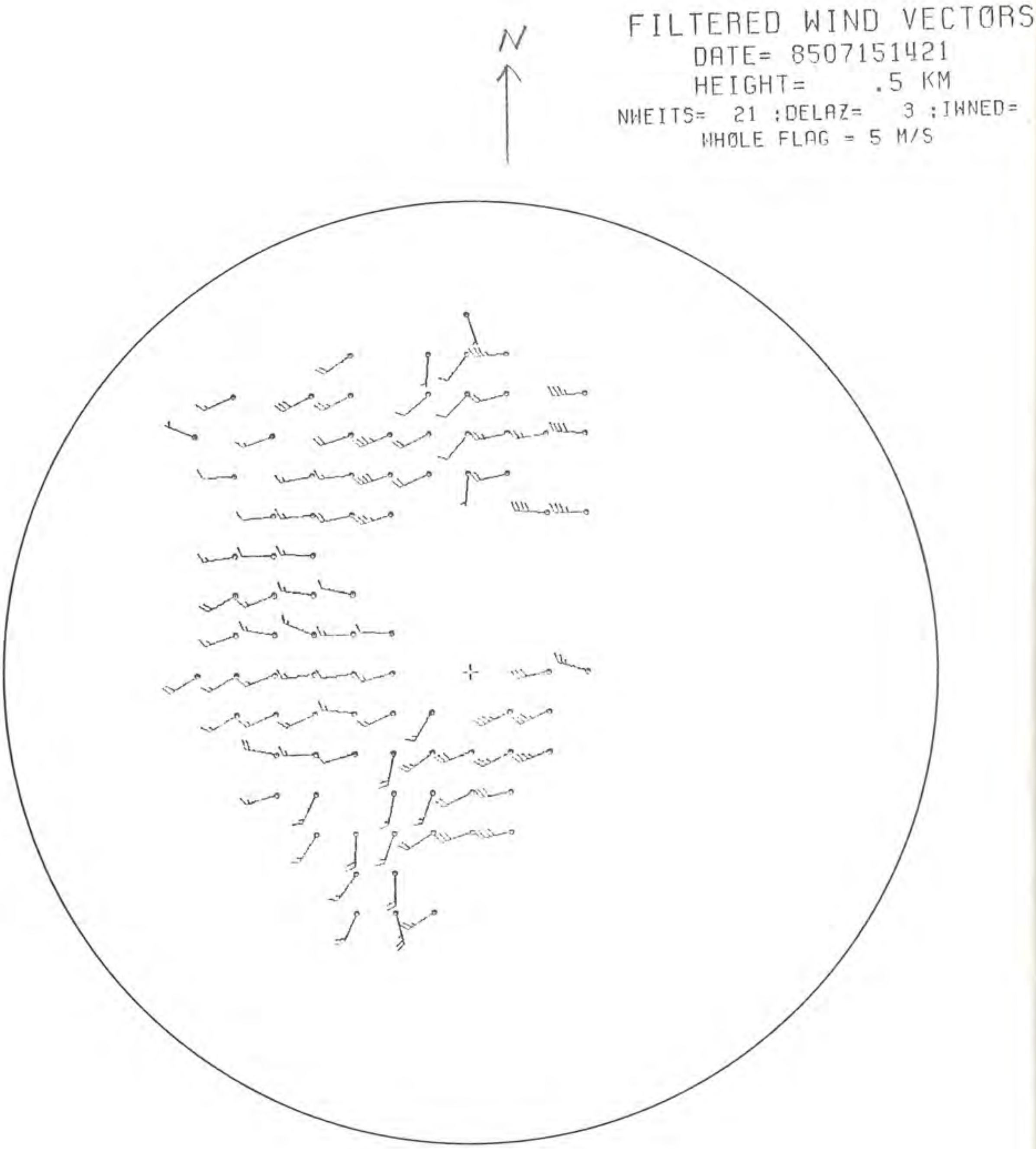


Figure 3.2
Wind field at 500 m derived from the Norrköping radar using uniform wind technique. The radius of the circle is 60 km. A squall line with very irregular winds, at some spots strong enough to fel trees. 850715, 14:21 UTC. Whole flag = 5 m/s.

Though this has been accomplished in research projects in the U.S., see Fig 3.3, the technique is expensive and complicated and has not become operational.

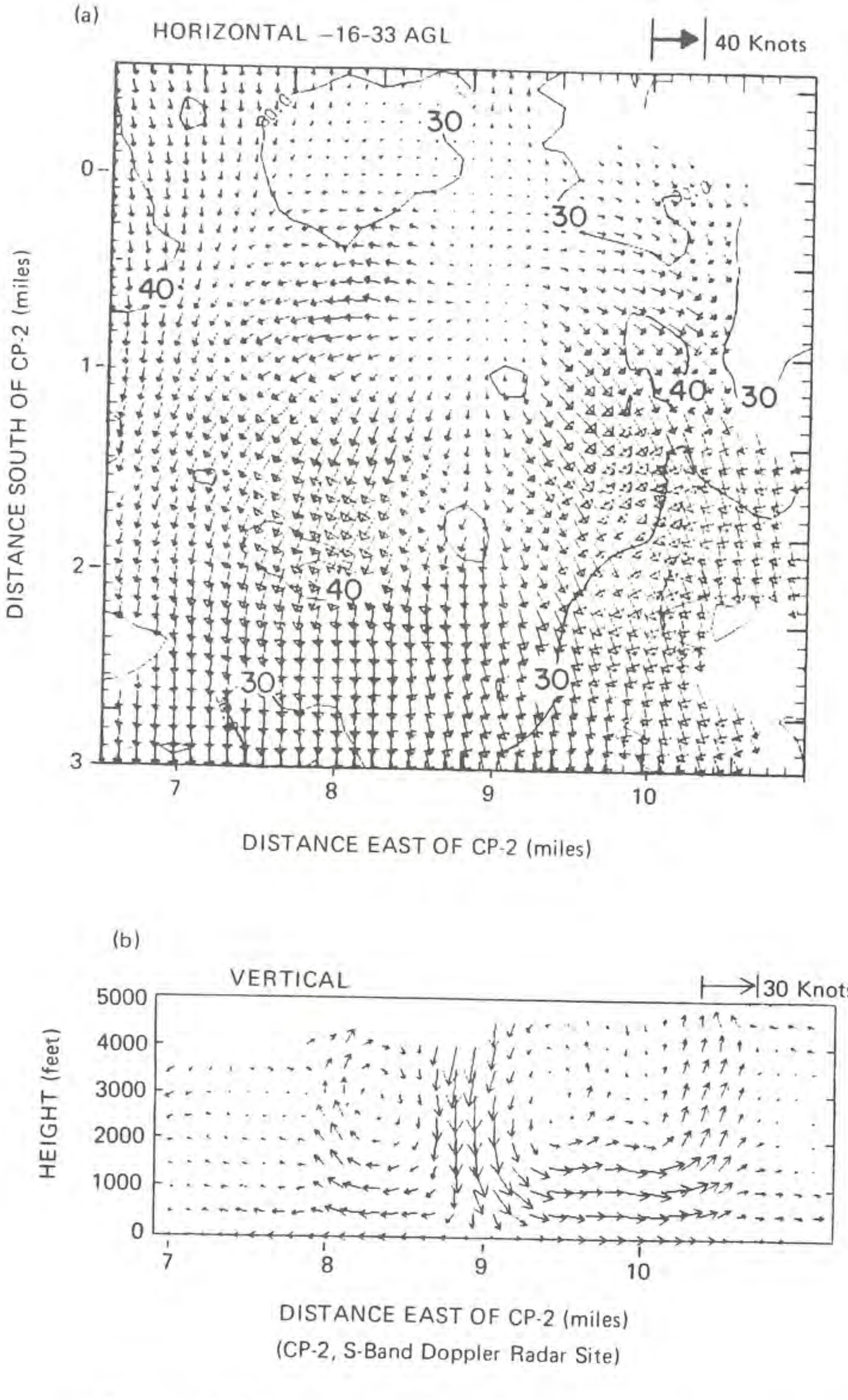


Figure 3.3
Velocity fields with respect to the ground, based on a dual doppler analysis for a microburst occurring at 1452 MDT on July 14, 1982. Contours are radar reflectivity factors (dBZ_e). (Wilson and Roberts, 1983).

It must be noted, that in order to detect small short-lived phenomena as microbursts, a very high resolution in both time and space is needed. Besides the radar has to automatically detect and warn, since a human operator can hardly be expected to detect phenomena having a lifetime of only a few minutes.

Acoustic sounder, SODAR

Doppler sodar gives a vertical wind profile over a small area up to some hundreds meters. The signals may be disturbed both by natural audio-noice, as high wind speeds and precipitation, and man-made noice. However, it is more sensitive in clear air than a radar though it usually only reaches a few hundreds meters up. The measurements can be compared to those from a doppler radar using VAD-technique. A doppler radar being at its advantage in precipitation when the sodar has difficulties.

Mapping of the wind-field around an airport requires several sodars, since each in principle gives only one vertical profile.

An example of a sodar wind profile is given in Fig 3.4.

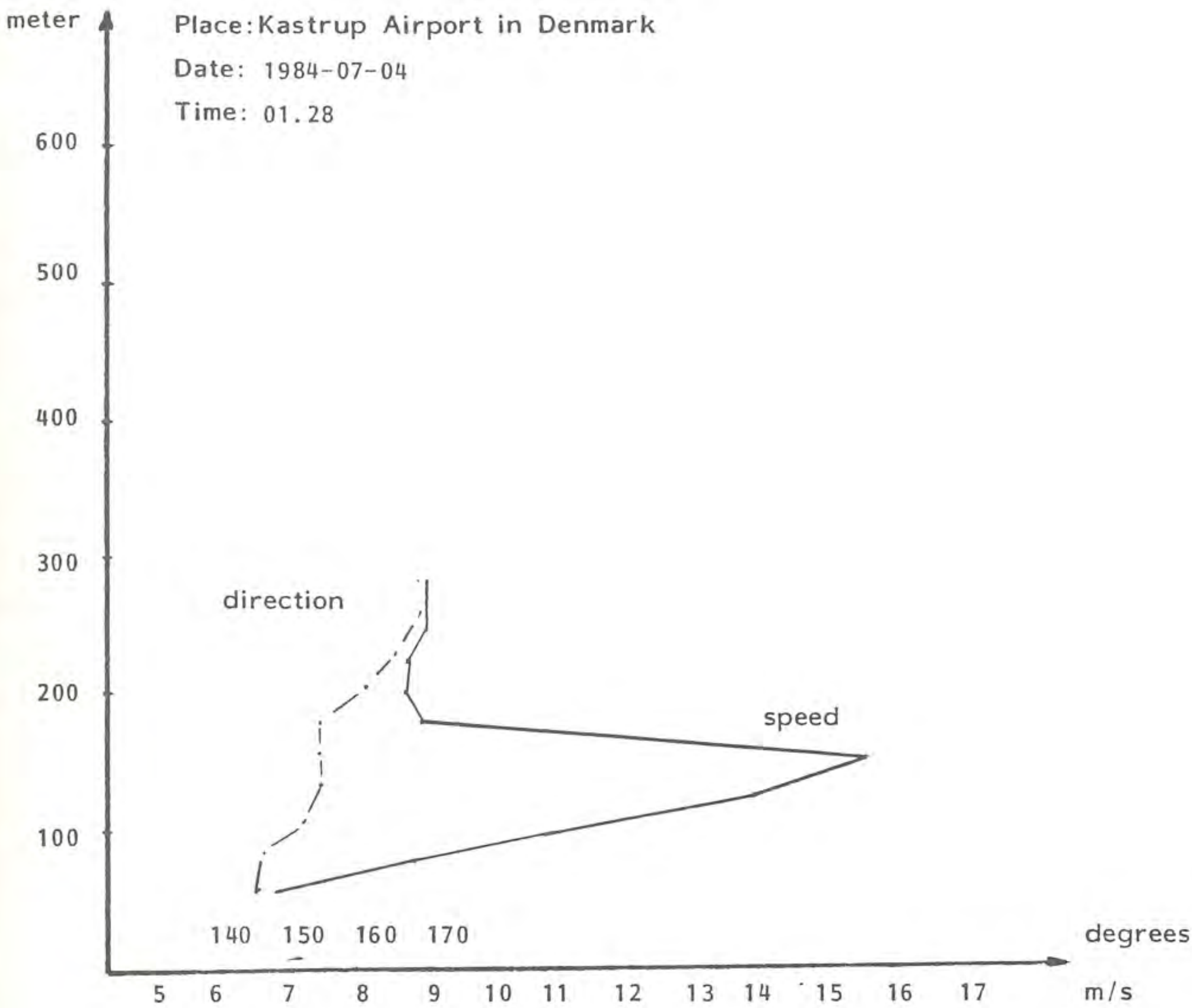


Figure 3.4
A low-level jet, depicted by a doppler sodar. (Courtesy of Sensitron AB).

3.3 Airborne measurements

The advantage of measuring from the aircraft itself is that it measures where the aircraft is or even better, some distance before it, thus giving the pilot a lead time to prepare the right maneuvres or even better, avoid an hazardous area. The disadvantages are that few instrument types are available, they are advanced and probably only heavy aircrafts are and will be equipped with them.

These measurements may be divided into two classes.

1 Monitoring of aircraft performance.

2 Remote sensing

3.3.1 Monitoring of aircraft performance

One commercially available system uses input data from the conventional aircraft sensors of airspeed, pitch attitude and angle of attack + data from special horizontal and vertical accelerometers. The system computes continuously the shear in the vertical and horizontal components of the wind. Taking into account any compensatory actions by the pilot it displays the energy loss or gain due to the shear and at a preset threshold gives an audio alert. The threshold is set at a headwind loss/tailwind gain of 3 kt/sec or a decrease in angle of attack of 0.15 radians or any combination of the two which provides a threshold deceleration (0.15 g), (WIST, 1986).

Anothersystem, becoming available in 1986, in principle compares the aircraft's inertial and air-mass accelerations. A large difference between these two indicates a wind shear. By comparing the rate of change of the two accelerations an estimate of the shearing conditions is made. This is used to provide warning to the crew before deep penetration into the wind shear. A third computation is the monitoring of the total acceleration vector, see Fig 3.5, showing an aircraft crossing a microburst.

At point W the total, inertial and airmass accelerations are all zero. When the aircraft approaches the microburst it encounters a headwind giving an upward acceleration and a horizontal deceleration and the total acceleration vector A (point X). A lamp on the instrument panel will display a steady WIND SHEAR message to alert the crew of wind shear conditions.

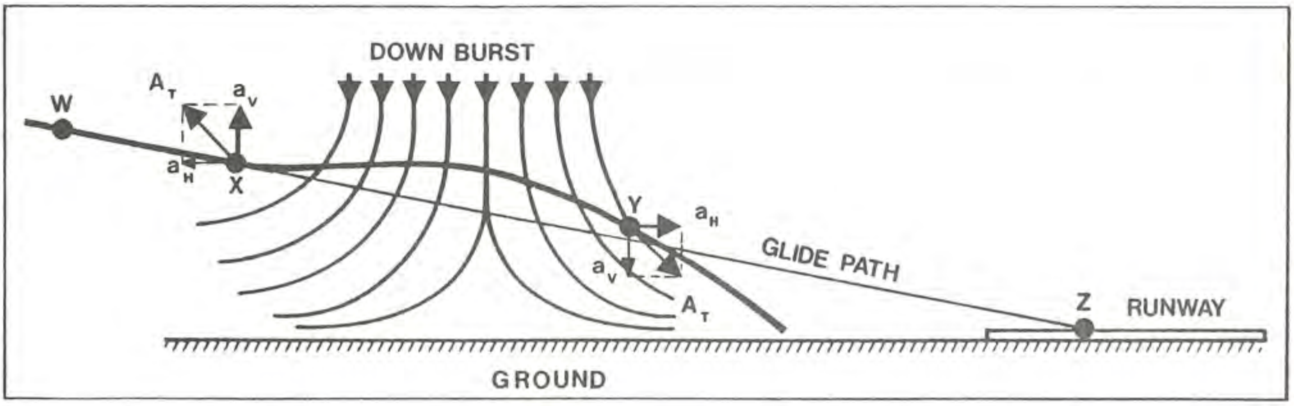


Figure 3.5
A microburst along the glide path of a landing aircraft. (Johnston, 1986).

As the aircraft proceeds the head-wind will decrease and the downdraft increase giving a significant difference between the air-mass and inertial acceleration and a rapid counter-clockwise rotation of the acceleration vector. Both these events will be detected, giving an audio warning, illuminating the flashing red wind shear warning lamp and displaying a flashing WIND SHEAR message. (Point Y).

In a second stage of development the system will also give information on how to best exit the wind shear.

These systems have the limitation that they do not warn for wind shear until the aircraft has encountered it. However, they are said to detect the wind shear a few seconds before a pilot normally would. It is argued that this is enough for a pilot, provided he has got wind shear training and knows what to do.

Automatic systems can at best work properly under conditions anticipated by the designer. If something outside these conditions happen the system cannot give a proper response. An innovative human being at least has a chance.

3.3.2 Remote sensing

The airborne Doppler radars of today appear to be insufficiently sensitive and have too low spatial resolution to address the low-level wind shear problem.

A continuous-wave Doppler Lidar, focused to measure the wind at a range of about 300 m before the aircraft has been developed in England. Lidar systems, however, suffer heavy attenuation in clouds and precipitation.

Airborne remote sensing of wind shear still remains in the research stage of development.

4. LOW-LEVEL WIND SHEAR

4.1 Small-scale obstacles

When the surface wind is strong obstacles such as close-planted stands of tall trees, buildings and low hills create localized areas of wind shear and turbulence.

Runways are often 'carved out' of forests consisting of 20-30 m high trees. The wind at the runway below the height of the treetops is then 'steered' along the runway and often bears little resemblance to the wind above the treetops, see Fig 4.1 a.

The same applies to a runway in a narrow valley or alongside a range of low hills, see Fig 4.1 b. Hills may also cause downdrafts over the runway, see Fig 4.1c. In such conditions there also may appear thermal winds, as valley and mountain winds, katabatic wind and lee waves with rotors.

Buildings in the vicinity of the runway may cause horizontal wind shear which is usually very localized, shallow and turbulent, Fig 4.1 d. It is likely of most concern to small aircrafts.

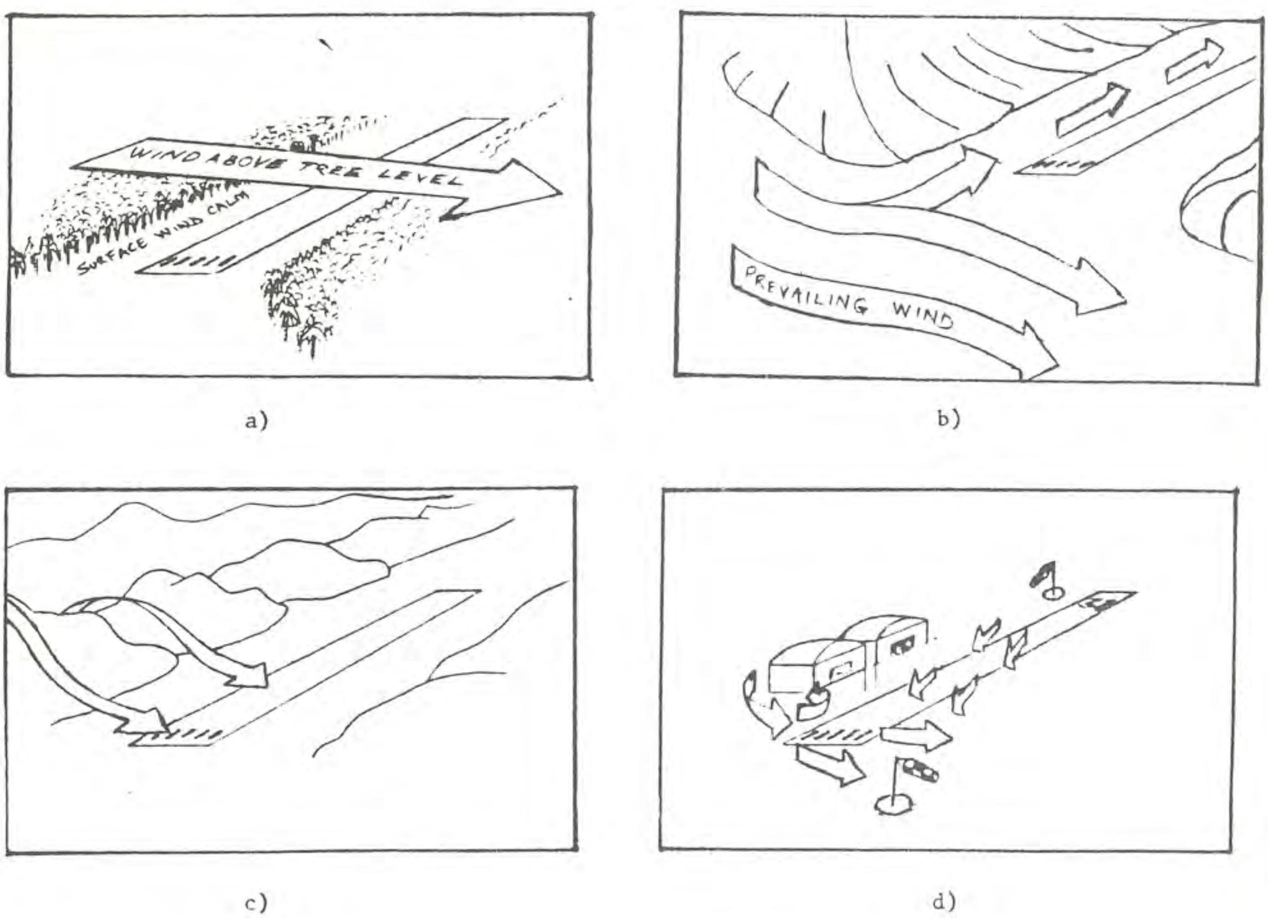


Figure 4.1
Wind flow around obstacles, WIST 1986.

4.2 Friction and thermals

Due to surface friction there is always a wind shear close to the surface. Schematically the wind speed from about 10 to 200 meters height may be given by the power law

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^m$$

u = wind speed at height z

u_1 = " " " " z_1

m = parameter, constant with height, dependent on lapse rate, surface roughness and geostrophic wind speed

Over smooth open country and neutral lapse rate an approximate value of m is 1/7.

In the lowest 30 meter interval, from 10 to 40, a wind speed of 20 m/s at anemometer level will then give a vertical wind shear of 4.4 m/s/30 m i e strong wind shear according to Table 2.1.

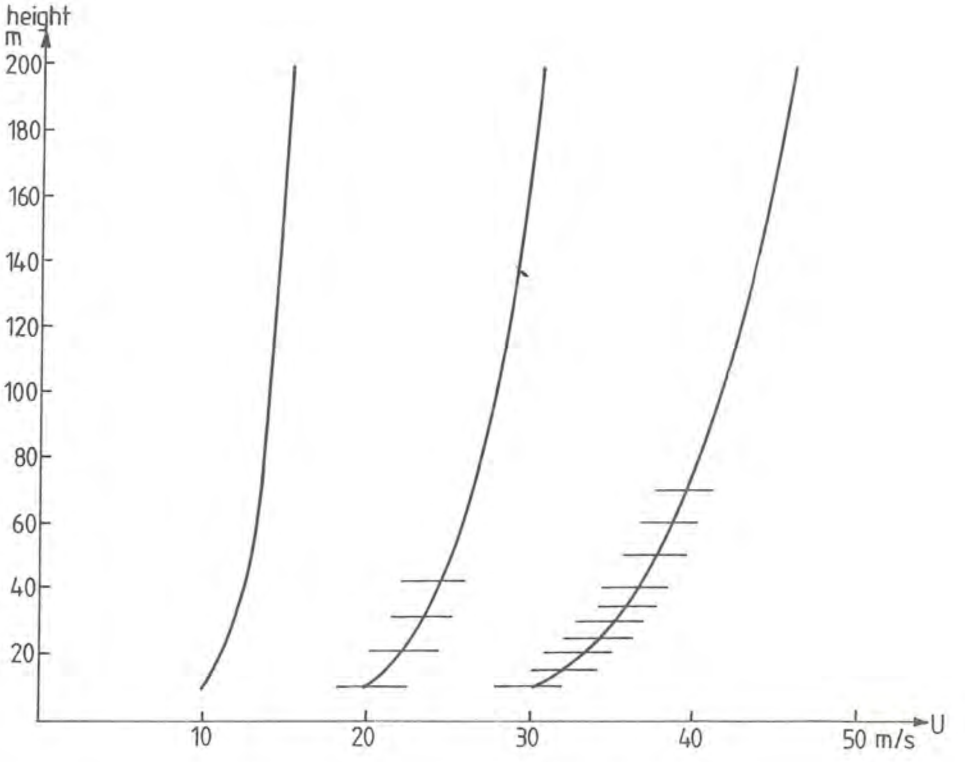


Figure 4.2
Wind profiles according to the power law

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^m$$

m = 1/7, i e neutral lapse rate and smooth surface.

—— *Strong wind shear (4-6 m/s/30 m)*
═══ *Severe wind shear (>6 m/s/30 m)*

The three most important factors determining the wind shear are

* Wind speed
* Lapse rate near the surface (stability)
* Surface roughness

Schematically they influence the vertical wind shear as follows:

Increasing wind speed
Increasing stability
Increasing roughness
} Increasing vertical wind shear

Decresing wind speed
Decreasing stability
Decreasing roughness
} Decreasing vertical wind shear

If the air is unstable close to the surface we should thus expect low vertical wind shear. This does NOT mean smooth flying. The horizontal shear of both the vertical and horizontal wind will increase giving turbulence and bumpiness.

The surface roughness and wind speed are reponsible for mechanical turbulence: The stratification of the air determines the thermal or convective turbulence.

The convective turbulence is associated with cumuliform clouds, whether in cloud or clear air close to the clouds. This turbulence reaches much higher altitude than the mechanical one. The convective turbulence will also be treated in chapter 4.5.

Analysis and forecasting

A simple parameter can be used to get an idea of the vertical wind shear. This parameter is the difference between the geostrophic wind and the wind at anemometer level. Combining this with the vertical temperature profile gives a possibility to more exactly pinpoint the altitude of the wind shear. If there is an inversion the wind shear should be expected at the top of the inversion. If there only is a stable lapse rate the wind shear is more evenly distributed over the friction layer. It must, however, be remembered that in low-level jets the wind may be super-geostrophic.

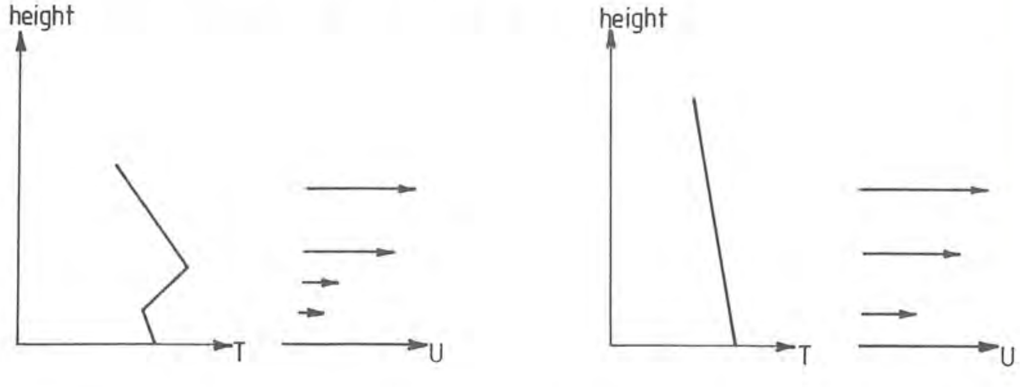


Figure 4.3
If the geostrophic wind speed is high and the wind speed at anemometer level is low a high vertical wind shear is expected at the top of inversions.

The following table (Met Office, 1975) gives some useful 'thumb rules' for analyzing and forecasting turbulence in the lowest few hundred meters.

Table 4.1
Thumb rules for low-level mechanical turbulence .

SURFACE WINDS m/s	Sea	Flat country	Rugged terrain
8-20	light-moderate	moderate	severe
>20	moderate-severe	severe	extreme

Note the big difference between sea and rugged terrain. A wind speed giving only light turbulence over the sea may give severe over rugged terrain. True the surface wind speed is higher over the sea than over land, but the abrupt onset of bumpiness when crossing a coast at low altitude is well-known.

During summer days this difference is enhanced by convective turbulence. The convection is damped or even prevented by the relatively cool sea.

The convective clouds give useful information of the turbulence.

Table 4.2
Thumb rules for thermal turbulence

CLOUD TYPE	TURBULENCE
Cumulus humilis	Light
Cumulus congestus	Moderate
Air-mass cumulonimbus	Severe
Cold front/ Squall line cumulonimbus	Extreme
Dry thermals	Light/moderate

4.3 Low-level jets

The low-level jet is in many respects analogous to the high-level one, though there are differences in extent and life-time, and also in our knowledge of them. The high-level jet is well-known since many years, but our knowledge of the low-level one is scarce. Low-level jets are probably much more common than we anticipate. The main reason being that due to their size and altitude, usually below the air routes and the 850 hPa chart, they easily escape detection. Moreover, some of them are shortlived and have a pronounced daily march so they may occur between Rawind soundings.

Table 4.3
Order of magnitude for some properties of the high-level and low-level jet. The high-level jet criteria are those given by Reiter (1961) and used by WMO. As to the low-level jet there are no accepted criteria. The figures given are an attempt to summarize their properties according to the literature.

	The high-level jet	The low-level jet
Horizontal extent km		
Length	>1000 km	>100 km
Width	>100 km	
Vertical extent	1 km	100 m
Height above ground	10 km	1 km
Duration	Days	Some hours to 2-3 days
Max wind speed	>30 m/s	>15 m/s
Vertical wind shear	>0.5 m/s/100 m	>1 m/s/100 m or expressed as umax-umin >some limit
Horizontal wind shear	>0.05 m/s/100 m	

Table 4.4
Classification of low-level jets

Though there are no firm criteria to distinguish between different types of low-level jets a classification is useful. (Sladkovic and Kanter, 1977)

Classification of low-level jets

1 Nocturnal
2 Orographic
3 Thermal
4 Synoptic scale

Of course, all types are connected to synoptic weather systems. But the nocturnal jets show a clear diurnal variation having no counterpart in synoptic weather systems. The orographic ones are confined to certain areas.

The nocturnal jet usually develops during evening and dissolves just after sunrise. Its formation is tied to radiative inversions close to the ground. Though not generally giving high wind speeds, they often exceed the geostrophic ones.

Orographic low-level jets are found in local wind systems as Föhn and Bora. They may attain very high wind speeds.

Thermal low-level jets are found in sea breeze, mountain and valley winds.

Synoptic scale low-level jets may have a length of several hundred kilometers. They often occur in warm sectors, before active cold fronts. Maximum wind speeds above 30 m/s have been observed.

Though usually low-level jets, as the nocturnal ones, are connected with temperature inversions there is no unambigous connection between the temperature and wind profile. The wind maximum may appear above, below and within inversions. Low-level jets may, however, occur without any inversions. This is especially the case for low-level jets connected to cold fronts (Mix, 1981).

4.3.1 The nocturnal low-level jet

This is perhaps the most well-known low-level jet. The one of the Great Plains was the first to be described in more detail. The jet is usually at about 500 m above the ground, above a strong radiation inversion at nights with clear skies.

During daytime with convection momentum from higher levels is transported downwards. This retards the wind speed just above the friction layer and there is a very low vertical wind shear from the anemometer level and some hundred meters upward, see Fig 4.4 and 4.5. Towards sunset, when the convection ceases, the downward transport of momentum decreases. The wind above the friction layer accelerates. A radiation inversion forms close to the ground, cutting off the friction drag from the surface, and above the inversion the wind still accelerates and due to an inertial oscillation reaches supergeostrophic speeds.

After sunrise the ground inversion dissipates, and when convection begins the downward momentum transport rapidly dissipates the jet.

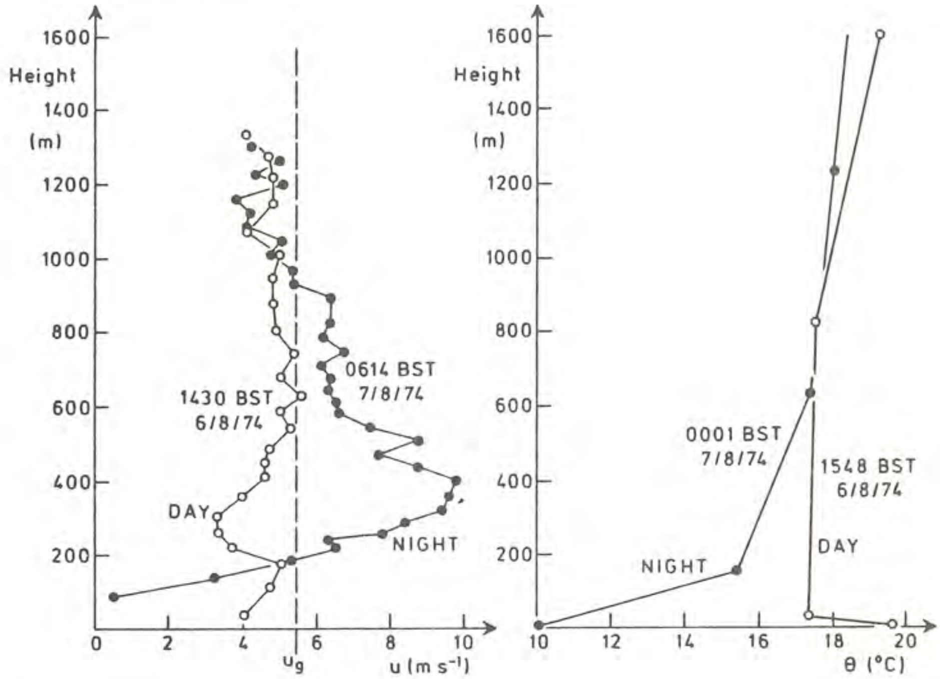


Figure 4.4
The profile of the wind component resolved along the geostrophic wind (u_g) showing a nocturnal jet on 7 August, 1974, compared with the profile of the previous afternoon. Nearest available potential temperature profiles are also shown. Data obtained near Ascot, England. (BST = British Summer Time = GMT + 1 hour).

Note that the wind speed below 500 m is subgeostrophic during afternoon with a very irregular vertical wind shear. During night the vertical wind shear between 80 and 300 m is 1.3 m/s/30 m. Though a wind shear of this magnitude is unlikely to cause acute loss of lift near touchdown or lift it can be an embarrassment to aircraft having been advised of calm surface winds. (After Thorpe and Guymer, 1977).

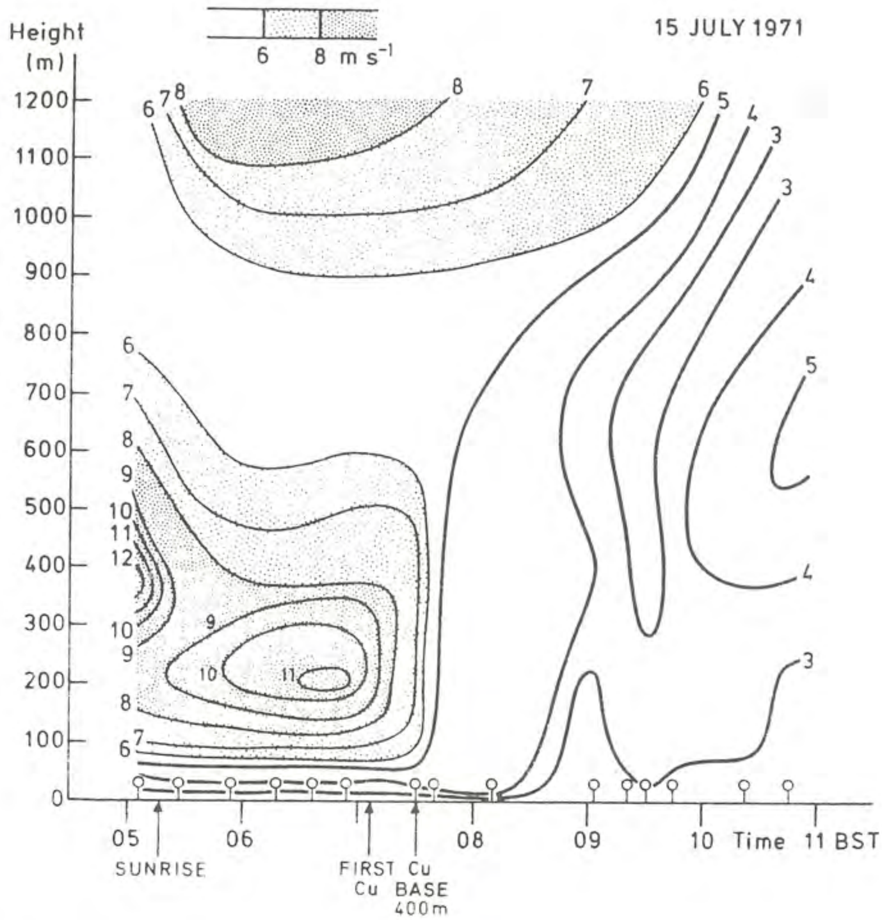


Figure 4.5
Time-height section of wind component along the surface geostrophic wind (circles denote pibal wind soundings). Note the rapid breakdown of the nocturnal jet just after the formation of Cumulus. (After Thorpe and Guymer, 1977).

Nocturnal low-level jets occur over Scandinavia, but little is known of them. Examples are given in Figs 3.4 and 4.6.

4.3.1.1 Analysis and forecasting

Nocturnal low-level jets are very difficult or impossible to detect with ordinary observations. Remote sensing, doppler sodar and doppler radar should improve this situation. A doppler sodar should be able to give vertical wind soundings throughout the year. The doppler weather radars of today are so sensitive that during the warmer seasons insects and inhomogeneities in the refractive index of the air often give echoes up to about 1 km (in our climate) and out to 20-30 km.

A technique for forecasting of low-level jet wind shear was suggested by Blackaddar and Reiter (1958). Some of their conclusions are probably valid also in our climate:

* Daytime instability near the surface promotes restraint on the wind speed between 300 and 450 m.

* A reasonable strong pressure gradient and, therefore, relatively strong geostrophic wind is required.

* Cloud cover must not interfere with the normal cycle of daytime heating and nocturnal cooling.

The following criteria have been tried by the British Met Office.

Low-level jet criteria

Criteria to be tested at observation times 2100, 0000, 0300 and 0600 GMT.

A low-level (nocturnal) jet should be suspected if all the following criteria are satisfied:

1 Time is in the range (sunset + 3 hours) to (sunrise + 1 hour)

2 A ground-based inversion or isothermal layer is present, and has been present for at least the preceding three observations, and

$$T_a T_a(\text{max}) - T_a T_a \geqslant 10^{o}C$$

3 $V_{10} \leqslant 10$ kt and V_{10} (max) > 10 kt

4 $V_G \geqslant 10$ kt and V_G (sunset) $\geqslant 10$ kt

5 No surface front has passed through since 1200 GMT.

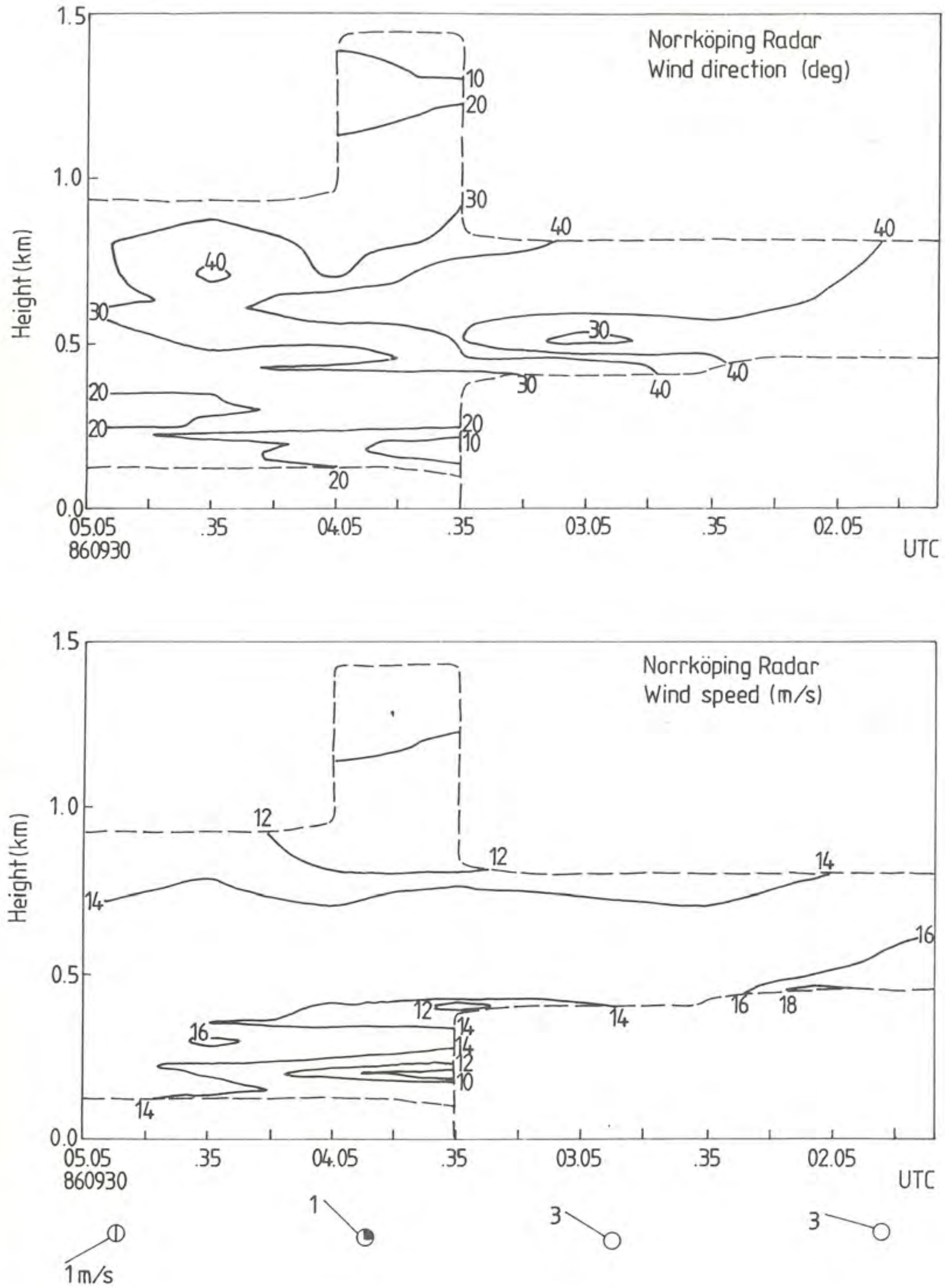


Figure 4.6
Nocturnal jet observed with SMHI's doppler weather radar. The winds are obtained from clear air echoes. The observations plotted below the wind speed diagram give wind speed (m/s) and cloudiness at Bråvalla, 4 km northwest of the radar. The vertical wind shear is 3.3 m/s/30 m in the lowest layer at 5:50 local time. Broken line delimits the area with sufficient echoes to compute the wind using VAD (Velocity Azimuth Display) technique.

Notes

1 V_{10} (max) and T_aT_a (max) are the maximum reported values of V_{10} and T_aT_a from 1300 to 1800 GMT inclusive previous afternoon.

2 If all the criteria are satisfied, then a low-level jet should be suspected for the current hour and the succeding two hours, and the warnings will be issued throughout the three-hour period.

V_G = geostrophic wind speed

V_{10} = wind speed 10 meters above ground

T_aT_a = air temperature

4.3.2 Orographic low-level jets

Local winds as Föhn, Bora and Mistral often have wind profiles with a low-level maximum and may reach extremely high speeds, if the wind is channelled into narrow valleys, as for instance the Mistral in the Rhone valley or the fjord winds in Norway. The Bora and the Mistral are also called katabatic winds. The air on high plateaus is cooled through radiation losses, during night at southerly latitudes, also during winter at northerly. When the isobars get a favourable orientation the cold air starts flowing downwards and accelerates. Over Antarctica and Greenland these wind systems become very large, see Fig 4.8. Examples of low-level jets in Föhn are given in Fig 4.7.

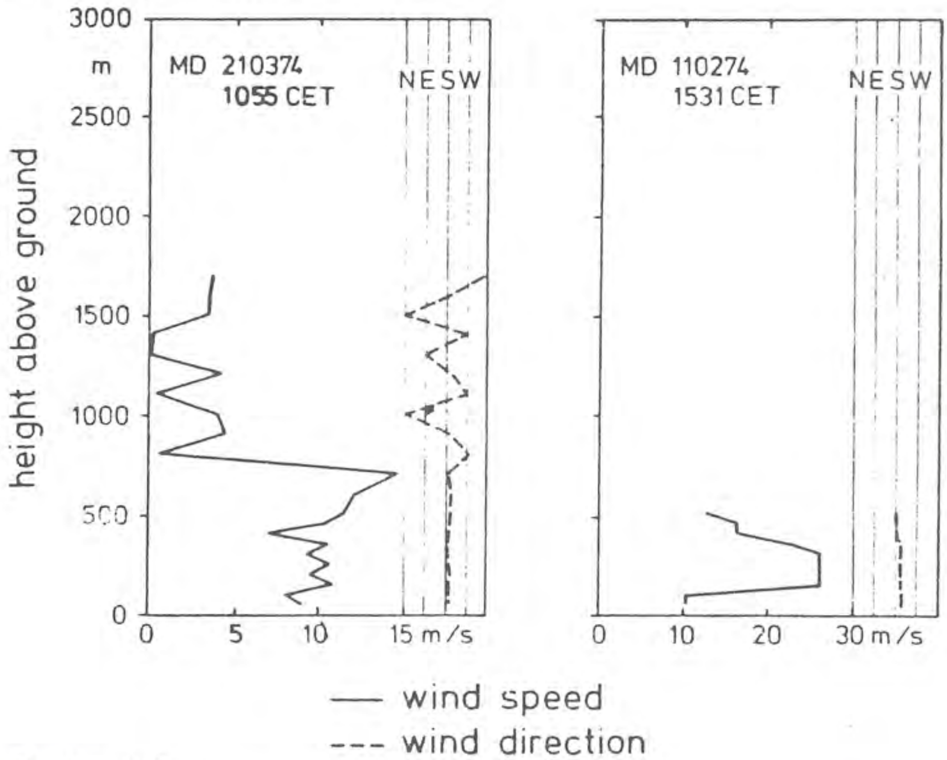
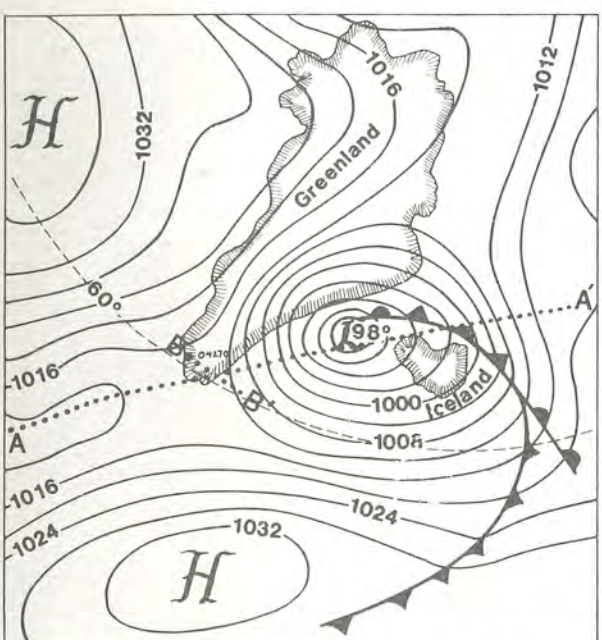


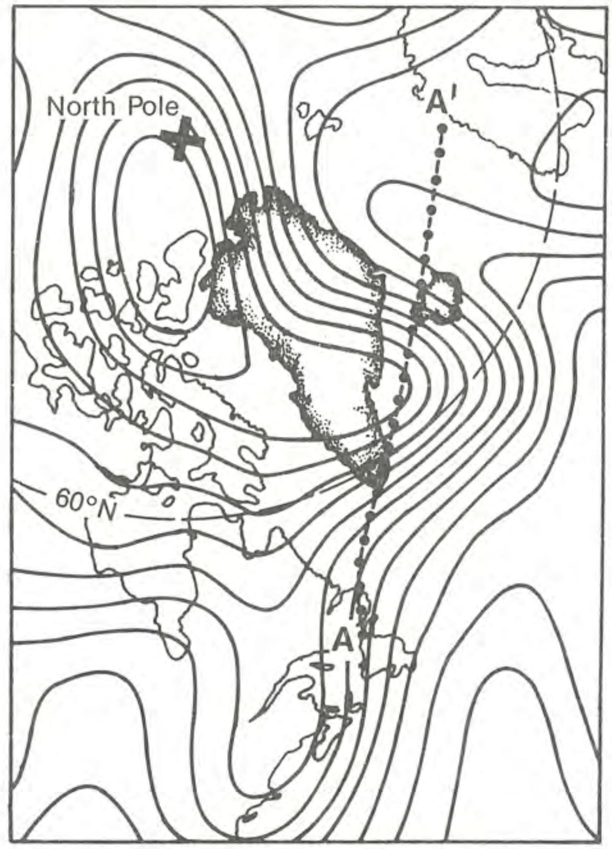
Figure 4.7
Two cases of low-level jets associated with Föhn winds at Mittenwald, Bavaria. After Sladkovic and Kanter, 1977.

a) *NOAA-7 satellite-visible image at 1718 GMT, 11 April, 1983.*



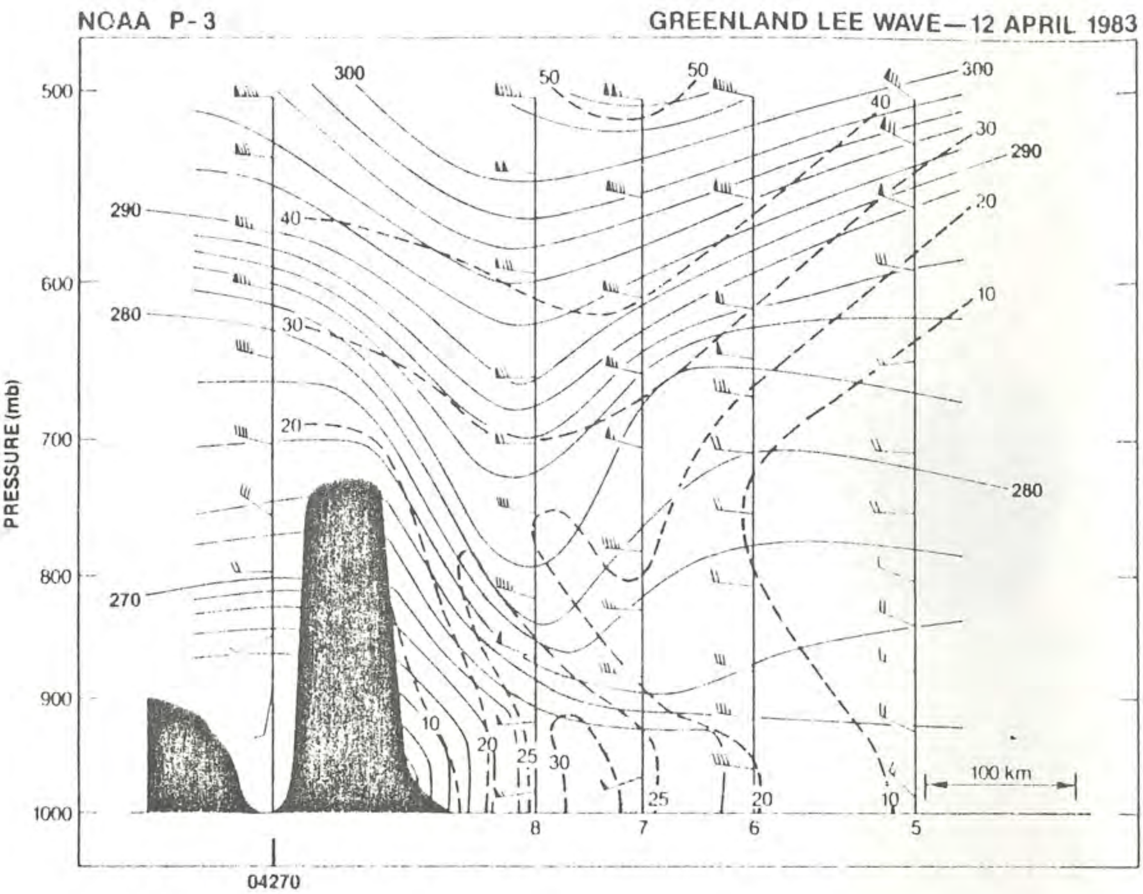
Surface pressure 1200 GMT 12 April 1983

b) *Surface pressure (mb) analysis at 1200 GMT, 12 April, 1983. Line AA' (dotted) is the flight track of the NOAA P-3 research aircraft. Line BB' (dashed) is the projection line for Fig 4.9d.*



500mb 1200 GMT
12 APRIL 1983

c) *500 mb height analysis (60 m contour interval) at 1200 GMT, 12 April, 1983. Line AA' (dot-dashed) is the flight track as in 4.9b.*



d) Cross section along the line BB' of Fig 4.9b taken through the Greenland lee wave of 12 April, 1983. Solid lines are potential temperature (^{o}K). Broken lines are wind speed (m/s). Flag = 25 m/s. Full barb = 5 m/s. Half barb = 2.5 m/s.

Figure 4.8
Katabatic winds formed over Greenland. After Schapiro, 1985.

4.3.3 Thermal low-level jets

Large wind shear close to the surface may also occur in thermal wind systems, as mountain and valley winds, see Fig 4.9.

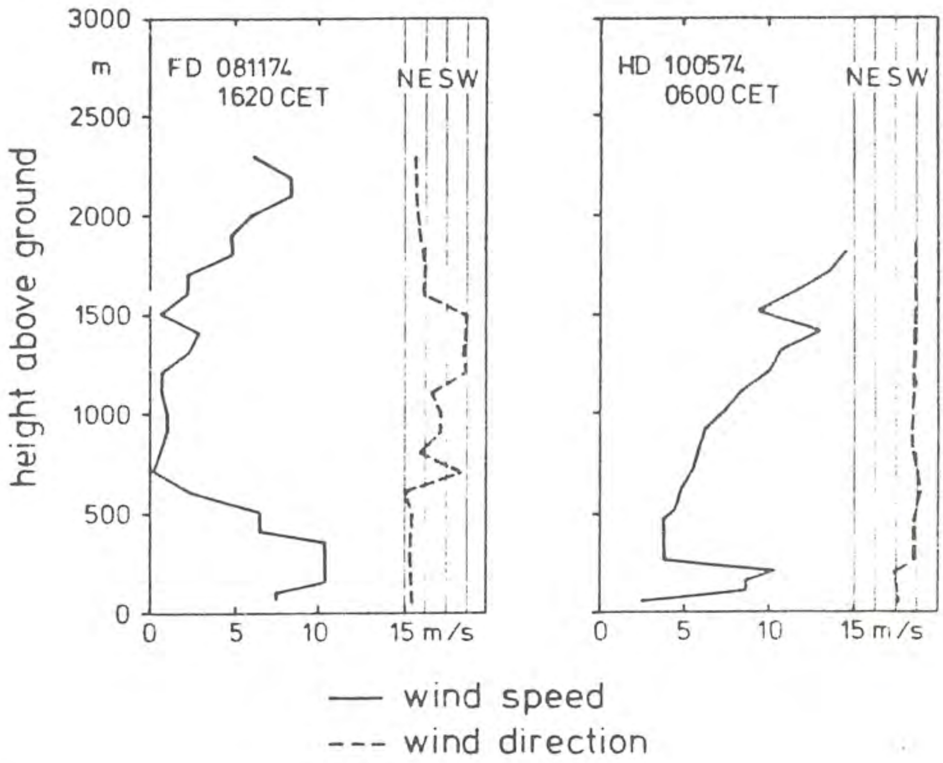


Figure 4.9
Thermal low-level jets.
To the left: daytime valley wind in Farchant, Bavaria.
To the right: nighttime mountain wind in Hofheim, Bavaria.

4.3.4 Synoptic scale low-level jets

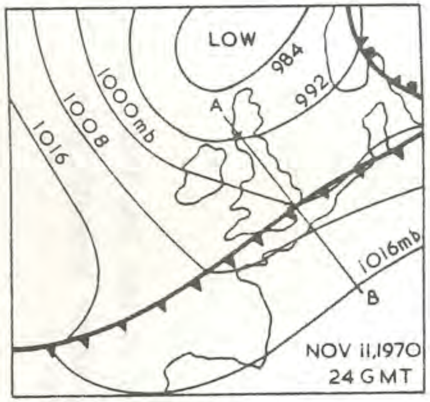
Low-level jets in association with mid-latitude fronts are probably much more common than generally anticipated. As to their frequencies some data from the Soviet Union (Mix, 1981) are available. Snitkovskij and Kuselkova analyzed 1460 Rawind soundings from the Moscow area and found low-level jets in 6% of the cases (criteria $u_{max} > 15$ m/s, vertical shear > 4 m/s/300 m). Some of their findings can be summarized:

* u_{max}: 18-23 m/s. Higher values autumn/winter. Lower spring/summer.
* Connection to inversions: About 75% of the jets are connected to inversions. Wind speed maximum usually at the lower part of the inversions.
* Connection to fronts: About 2/3 of all low-level jets appear together with fronts, most of them with warm fronts: usually up to 150-200 km from cold fronts and up to 400 km from occluded fronts.
* Frequency: About 2/3 in autumn and winter and about 2/3 during night.
* Duration: Mostly less than 12 hours. Some up to 24 hours. Highest durations at warm fronts.
* Cloudiness: About 2/3 of the jets together with deep layer clouds. 16% with clear sky.

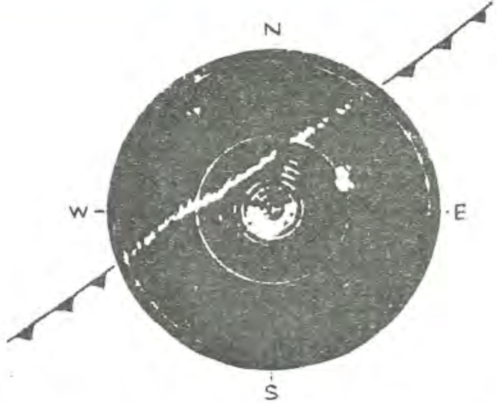
Studies from the European part of the USSR have also shown that when the wind speed at anemometer level is high (>20 m/s) there is often a wind speed maximum at about 1000 m altitude with supergeostrophic wind speeds (+20 to 80% of the geostrophic wind speeds).

Browning and Pardoe (1973) studied the structure of six ana-cold fronts with a narrow band of shallow but vigorous convection (line convection) at the surface cold front. In each case the line convection was bounded on its forward side by a low-level jet, reaching 25-30 m/s. Behind the line convection the winds decrease abruptly. The low-level jet lies in a tongue of anomalously warm air and there is warm air advection before the surface cold front. The horizontal temperature is thus reversed ahead of the surface cold front and the geostrophic wind decreases with height since it is opposed by the thermal wind component. That the wind maximum does not occur at ground level is explained by the friction. The jet maximum is displaced 100-200 hPa upwards.

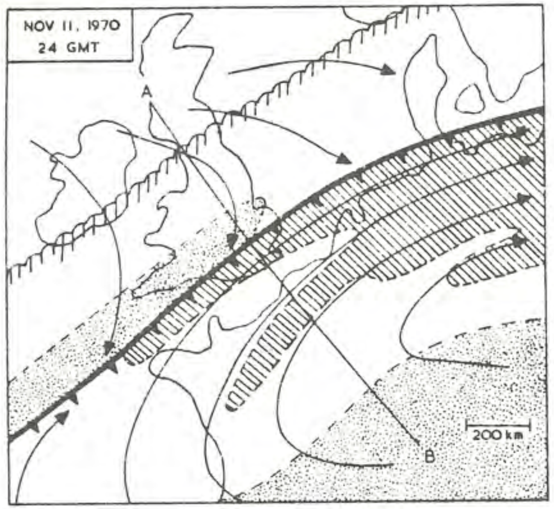
Browning and Pardoe also found that there may be more than one low-level jet. The most intense one occurred just ahead of the surface cold front, cf Figs 4.11 and 4.12. The low-level jets are often thousands of kilometers long. This, and the fact that there may be several parallel jets, may expose an airport for the wind shear beneath them for several hours or even 1-2 days.



Surface analysis for 24 GMT on 11 November 1970.



PPI display showing the thin line of echo associated with the line convection at the SCF as it approached a radar located on the Isles of Scilly on 11 November 1970. The radar sensitivity has been reduced to show only the narrow belt of heavy rain at the SCF. The two main range markers are at 50 and 100 km. The intense echo towards the east-north-east, at 50 km is from the mainland of south-west England near Lands End. Weaker echo at close ranges is mainly from the sea surface. The small gap in the echo line towards the north is due to blocking of the radar beam. The echo line is intensified where it intersects faint range markers spaced at 5 km intervals.



900 mb analysis for 24 GMT on 11 November 1970 showing low-level jets with total windspeed in excess of 20 m s⁻¹ as hatched shading and regions with winds less than 10 m s⁻¹ as stippled shading. Streamlines represent flow at 900 mb relative to the cold frontal system. The rear edge of the cold front cloud deck aloft is drawn partly hatched.

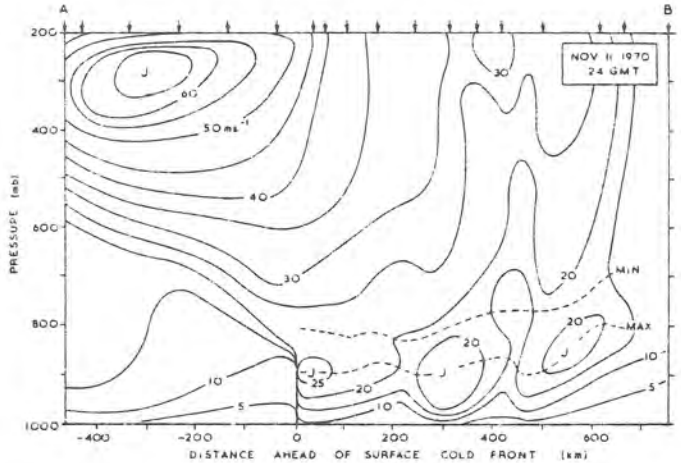
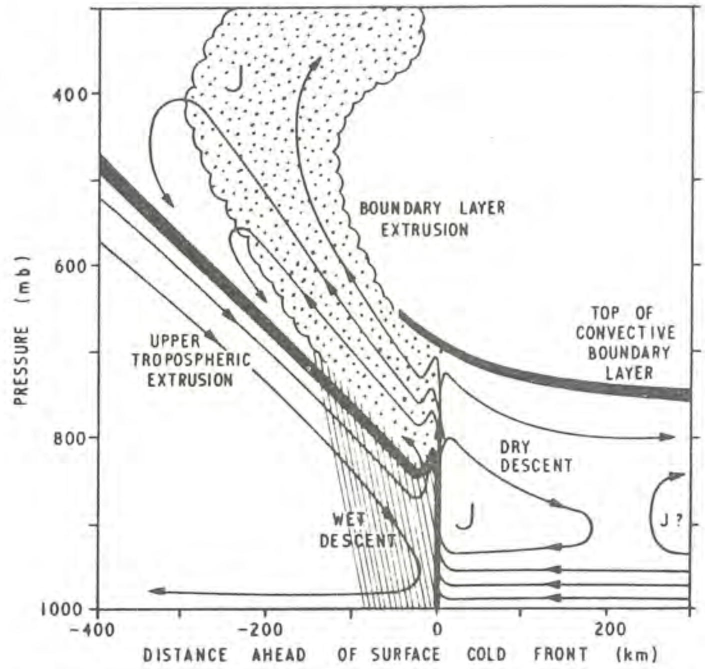


Figure 4.10

An ana-cold front preceded by low-level jets. The isopleths in the lower right figure give the wind speed along the front. After Browning and Pardoe, 1973.



Schematic model of the airflow associated with an ana-cold front. Thin lines are streamlines relative to the moving system. Thick lines represent the cold frontal zone and the top of the convective boundary layer. Regions of saturated ascent are stippled.

Figure 4.11
The Browning-Pardoe model of a low-level jet. After Browning and Pardoe, 1973.

One of their cases is illustrated in Fig 4.10.

The ana-cold front model suggested by Browning and Pardoe is shown in Fig 4.11.

Table 4.5
Characteristics of the low-level jets preceding ana-cold fronts. The statistics are computed over cross-sections perpendicular to the cold front. After Browning and Pardoe, 1973.

	(a) 3 Oct 1967	(b) 6 Feb 1969	(c) 11 Nov 1970	(d) 12 Jan 1972	(e) 9 Nov 1972	(f) 27 Nov 1972	Average
Maximum jet velocity (m s^{-1})	31	25	26	27	30	26	27:5
Height of velocity maximum (mb)	900	850	900	850	900	900	880
Velocity half-width in the horizontal at the level of the maximum wind (km)	700	320	700	200	1000	650	600

Table 4.5 gives some characteristics of the low-level jets.

All the jets had the strongest wind shear beneath them.

An investigation of low-level jets using the Ericsson doppler weather radar in Norrköping November 1986 to August 1987 showed that low-level jets (defined as $V_{max} > 15$ m/s, V_{max} shall occur below 2 km, $V_{max} - V_{min} > 5$ m/s. V_{min} is the lowest wind speed between 3 km and the height of V_{max}) occurred in 12 cases, during 3% of the time. These numbers are an underestimate since jets may appear without any radar echos. Moreover there were some malfunctions of the radar and the wind computing programs. The longest case occupied 1.5 days, during which there was a low-level jet fulfilling the conditions above 23 hours and a low-level wind maximum also during the remaining hours.

Common for all these cases was that below the jet the wind turned to the right with height, i e there was warm air advection.

The thermal wind below the jet did not oppose the 1000 hPa or anemometer wind but inforced it. Above the jet maximum the wind generally still veers (turns to the right with height) but the thermal wind component opposes the jet maximum wind. The wind hodograph for 861222, 00:04 UTC is typical, Fig 4.12b. This jet north of a semistationary low over the Baltic countries, 4.12a persisted with short interruptions for 1.5 days. Timeheight cross sections for wind speed and direction are given in Figs 4.12 c,d showing that the winds changed very little with time.

Of the thirteen cases found, two long-lasting ones occurred north to northwest of semipermanent lows over the southern Baltic or over Balticum. Five occurred ahead of and one behind occluded fronts. Two were ahead and one behind warm fronts. One was found at a developing cyclone and one east of a decaying one.

It is remarkable that no coldfront low-level jet of the type described by Browning and Pardoe was found.

Fig 4.12: A low level jet (over leaf)

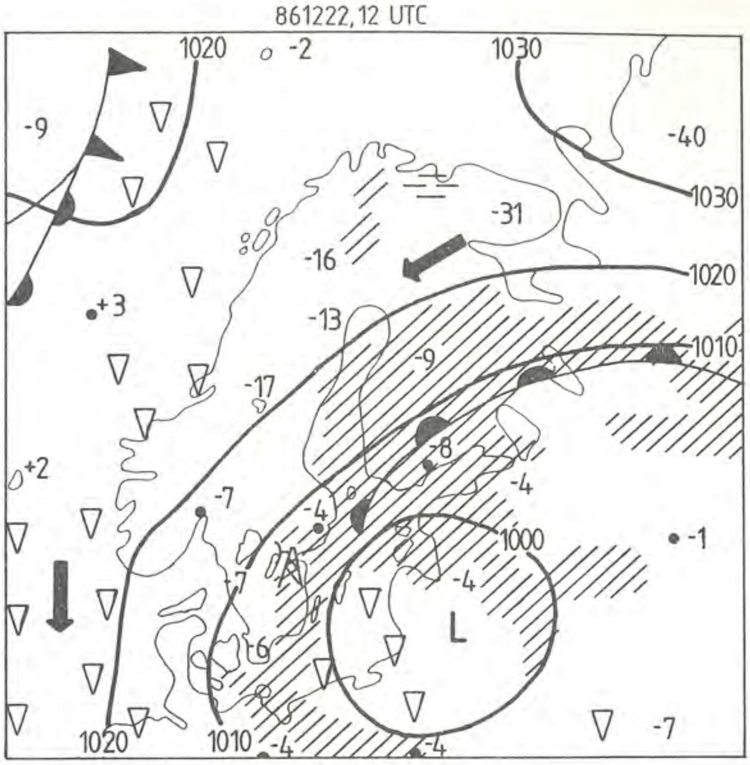
a) Surface map 861222, 12UTC

b) Wind hodograph 861222, 00:05

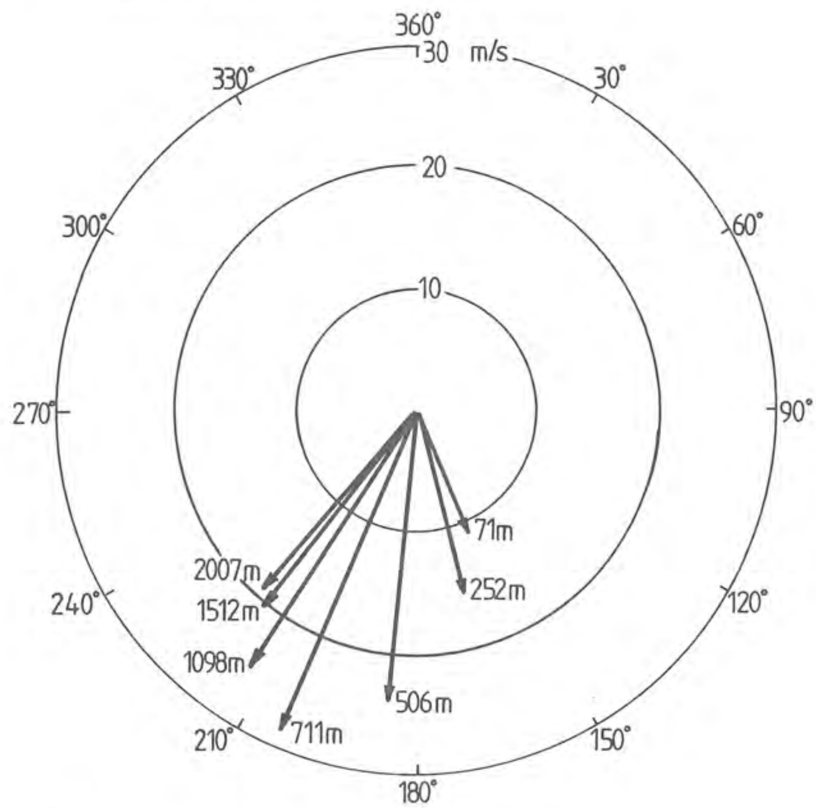
c) Time-height cross section of wind direction, 861221, 21:19 to 861222, 00:49

d) Time-height cross section of wind speed, 861221, 21:19 to 861222, 00:49

Pictures b-d originate from the Ericsson Doppler Weather Radar in Norrköping. Local times (UTC + 1 hr).

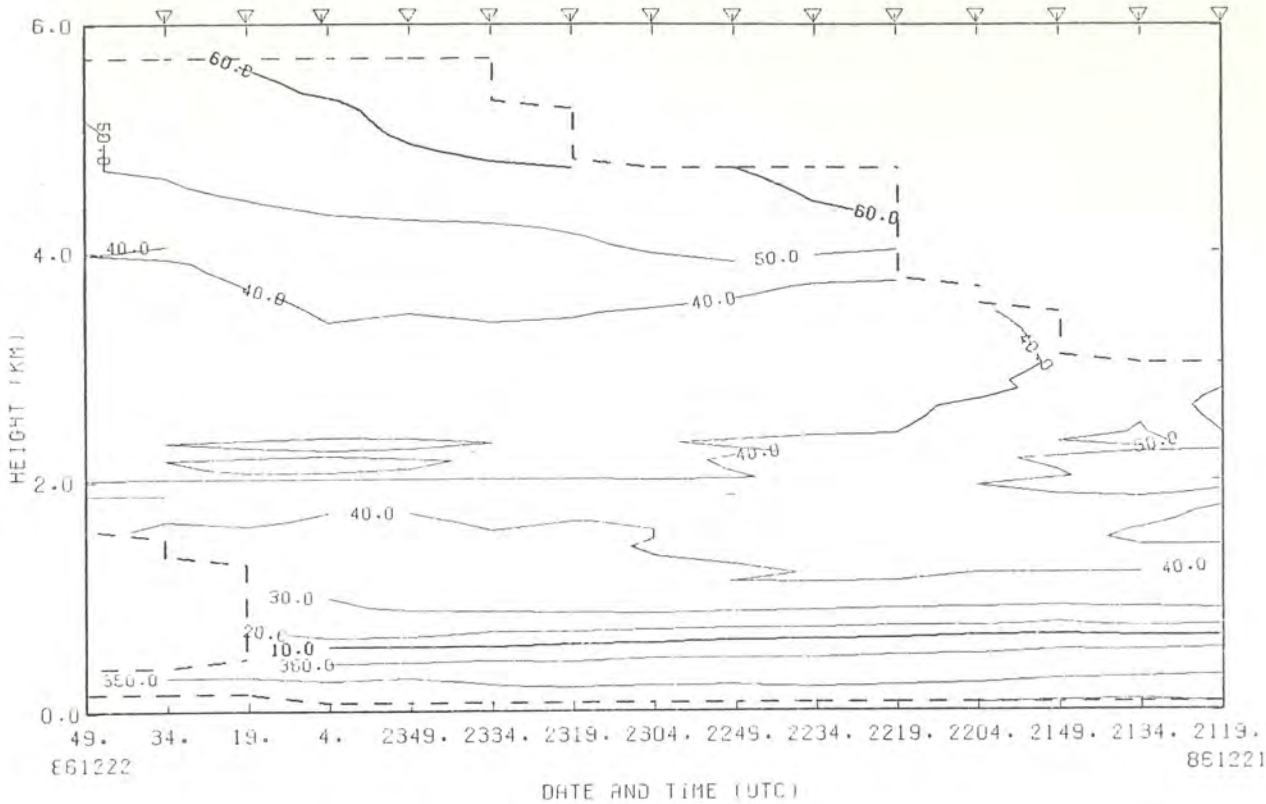


a) Surface analysis 861222, 12 UTC

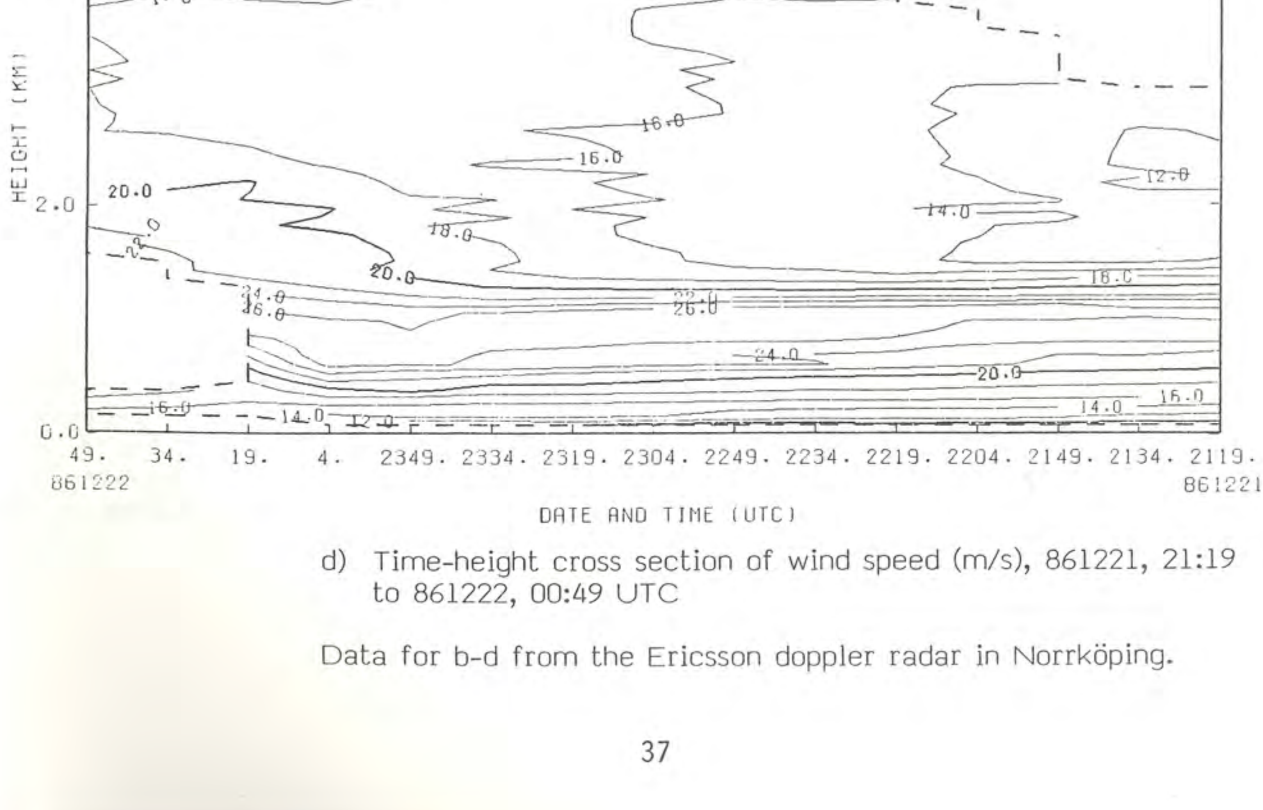


b) Wind hodograph 861222, 00:04 UTC

cont.



c) Time height cross section of wind direction, 861221, 21:19 to 861222, 00:49 UTC. Note the pronounced veering of the wind with height below the jet axis



d) Time-height cross section of wind speed (m/s), 861221, 21:19 to 861222, 00:49 UTC

Data for b-d from the Ericsson doppler radar in Norrköping.

A formation scheme for low-level jets in extratropical cyclones over USA is given Djuric and Ladwig (1983), Fig 4.13.

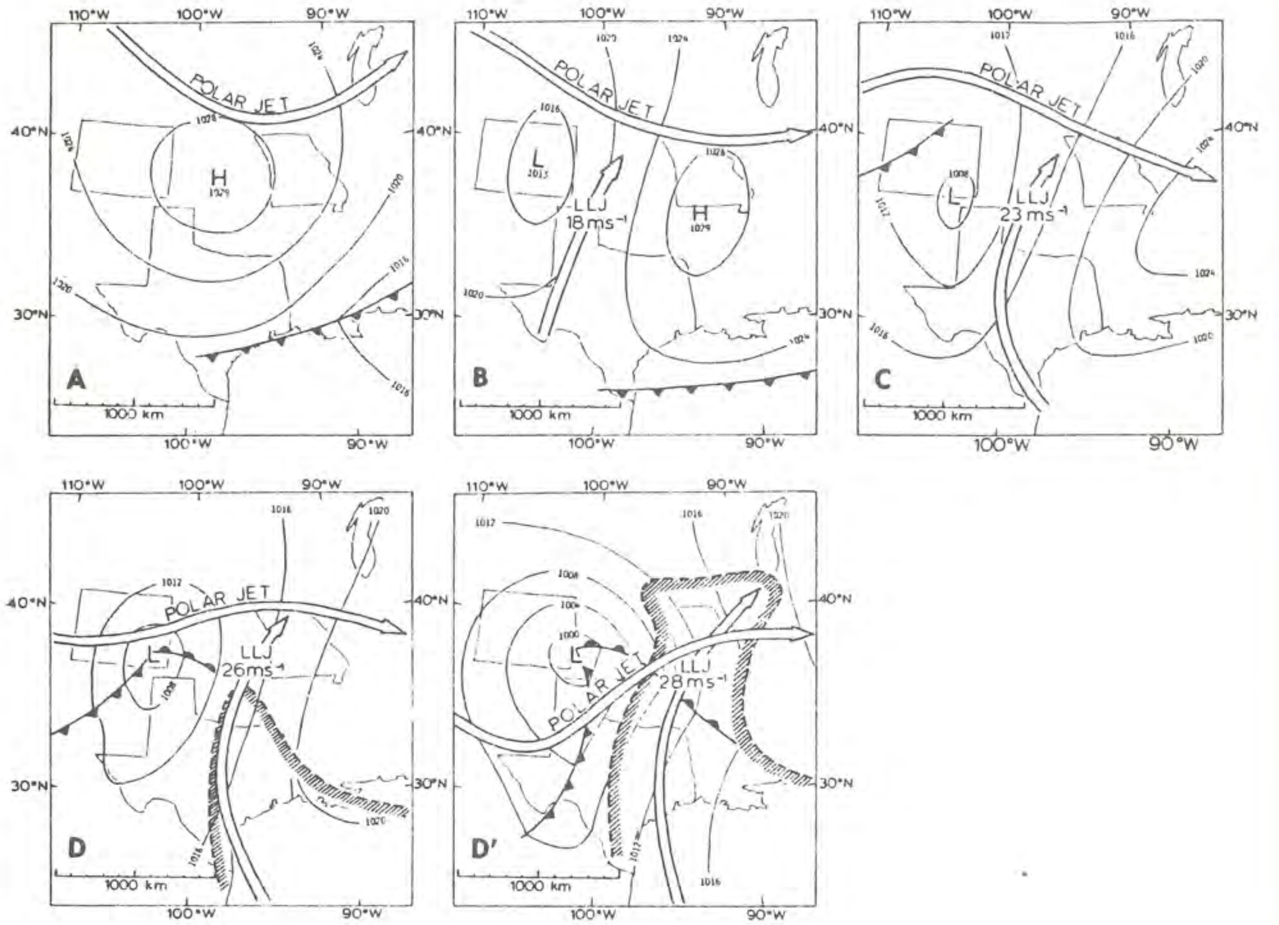


Figure 4.13
The formation of the low-level jet (LLJ) in an extratropical cyclone.

The polar jet is at 9 km above the sea level. The LLJ is at about 1 km above the ground. The polar front is indicated at the earth's surface. Humidity over 70 percent at the LLJ level is enclosed by a broken line with shading. Typical maximum wind in the LLJ is entered at the LLJ core. After Djuric and Ladwig, 1983.

As to the synoptic situation, this jet is often found in tongues of warm, moist air on the forward side of troughs crossing the Great Plains. Though the jet has its maximum frequency during early morning it also occurs during daytime. According to Wexler (1961) the primary cause of this jet is the large-scale air motion. A shallow layer of air flowing westward along the boundary of a large pressure area is deflected northward by the Rocky Mountains.

4.4 Fronts

A front has always wind shear. However, for the shear to reach the strong or severe category the frontal zone has to be narrow and the wind speeds high. Suppose a frontal zone having a horizontal width of 60 km. If the front has a slope of 1/100 the frontal zone has a vertical extent of 0.6 km. If the vertical wind shear is evenly distributed within this the (vector) difference in speed between the two air masses has to be 40 m/s to reach moderate vertical wind shear. Thus to get strong/severe wind shear the frontal zone must be extremely narrow or the wind change be concentrated to a narrow part of it. An extreme case of shear at a warm front is given by Sowa (NRC, 1983), Fig 4.14.

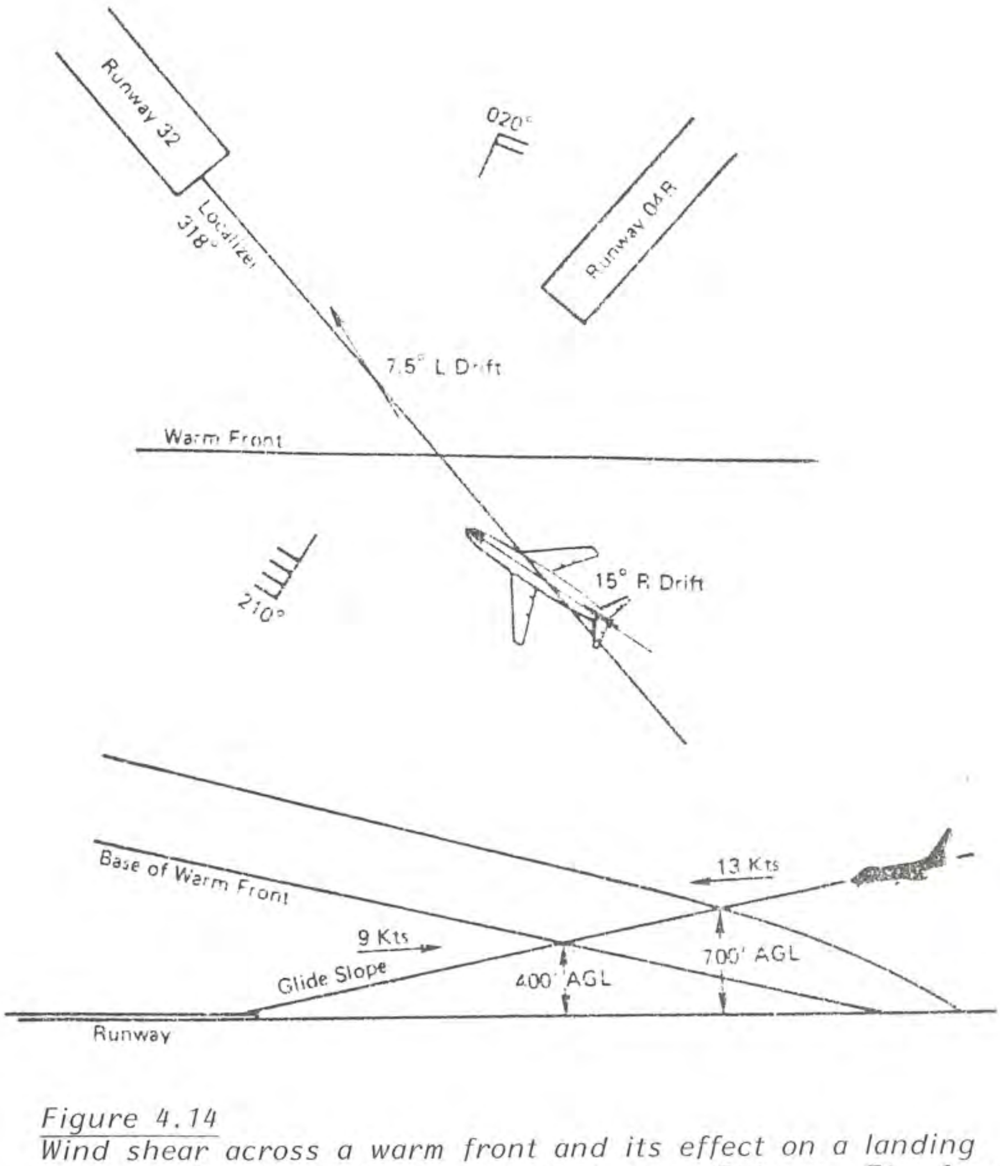


Figure 4.14
Wind shear across a warm front and its effect on a landing Boeing 747. O'Hara International Airport, Chicago. The frontal zone was extremely narrow, only 100 m high. The change in wind velocity was abrupt and accompanied by moderate/severe turbulence. NRC (1983, after Sowa, 1974).

Analysis and forecasting

Rawinsonde winds are of course one of the best means to estimate vertical wind shear. Since they are rare both in time and space they are, however, not sufficient. Moreover, it must be remembered that these winds already represent mean winds for successive layers. A wind for a specific level has been obtained through interpolation and may give a bad estimate of the actual shear between two levels. Careful synoptic analyses give a possibility to estimate the wind shear. The vector difference between the geostrophic winds in the cold and warm air can be used to give an estimate of the wind shear. It may be more difficult to estimate the distance, horizontal or vertical, over which this shear occurs.

Remote sensing provides excellent help in these cases. A doppler sodar can give a wind profile up to some hundred meters above the instrument. A doppler radar can give a vertical wind profile as well as a mapping of the wind field, see Figs 3.2 and 4.13. Consideration must also be paid to the fact that one or more low-level jets may be connected to the front without being situated just in the frontal zone.

The following rules for issuing warnings of low-level wind shear have been tried by the British Met Office:

- There shall be a frontal zone below 600 m on the approach/climb-out area with
  * a vector wind change across it of at least 10 knots magnitude (noted either locally or at a neighbouring station during the passage of the front

  or
  * a temperature difference across is of at least 5^{o}C

  or
  * a speed of at least 30 kt.
- Significant low-level jet suspected below 600 m.
- Aircraft report(s) of low-level wind shear received during the previous hour.

The temperature and 30 kt speeds criteria seem to originate from Sowa (Badner, 1977). A front with a speed of 30 knots can only affect an airport for a very short time and an accurate timing certainly needs radar and/or frequently updated detailed satellited pictures.

4.5 Cumulonimbus

Many Cumulonimbus produce cold downdrafts causing low-level wind shear. The downward moving air spreads out over the ground preceded by a GUST FRONT, see Fig 4.15. When investigation damages caused by a superoutbreak of 148 tornadoes in USA 3-4 April, 1974, Fujita (1985) found that hundreds of fallen trees were blown outward in a starburst pattern, not in the swirling pattern found in the wake of tornadoes. He suggested that the starburst pattern was due to down-directed jet spreading out when hitting the ground and called them DOWNBURSTS. Remarkable is that the downdrafts do not weaken to low speeds before hitting the ground. According to size these downbursts were later divided into macrobursts and microbursts. The microburst has damaging winds extending less than 4 km and a lifetime less than 10 minutes, but the wind speed in it may reach 60 m/s.

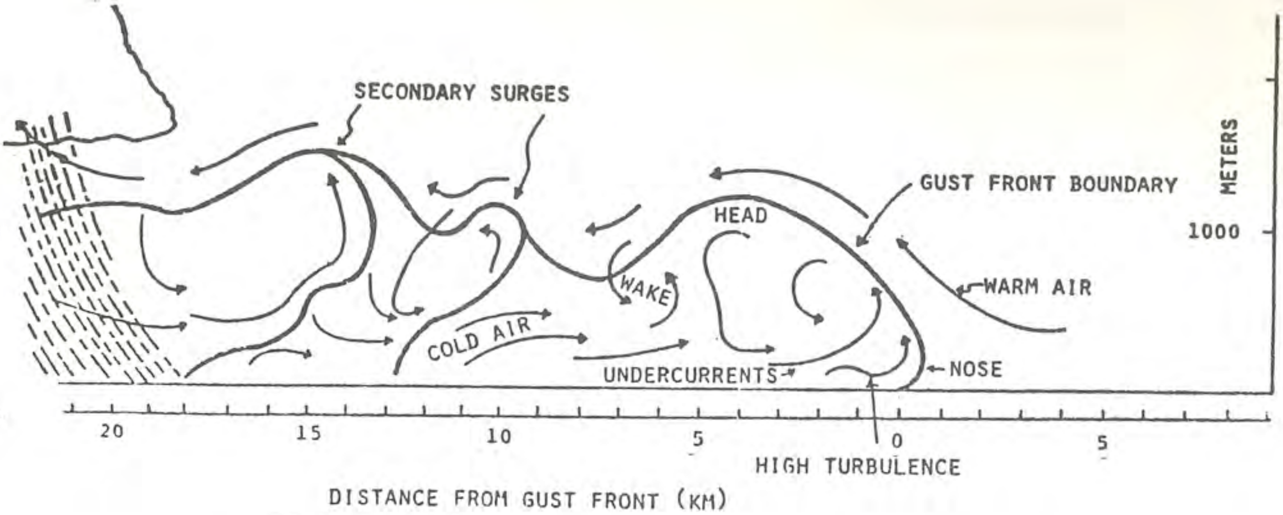


Figure 4.15
Common features of a gust front (Badner, 1979).

4.5.1 The Gust Front

The gust front is the leading edge of the downdraft, see Fig 4.15. The cool air near the front has strong turbulent winds. If the prevailing winds are light and change little with height the gust front is nearly circular around the storm that produced it. If there is a vertical wind shear through the atmosphere, the gust front is displaced in the direction of the shear, see Fig 4.16.

A gust front from a single Cumulonimbus cell may move 10-20 km ahead of the parent cell. If the thunderstorms form a squall line the gust front may move further away from the parent cells.

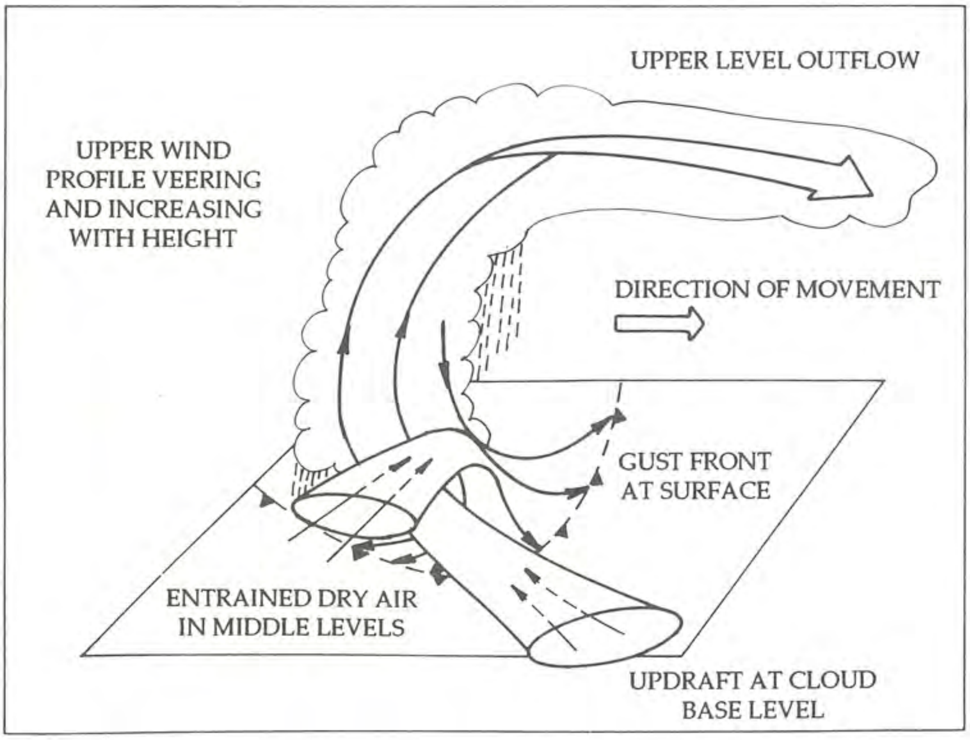


Figure 4.16
Diagrammatic structure of a 'supercell' thunderstorm. (WIST, 1986, after A J Thorpe).

4.5.2 The Downburst

In a developing Cumulonimbus the droplets in the updraft grow by condensation and coalescence until eventually the updraft ceases or the droplets become so large (they may then be frozen) that their fall velocities exceed the updraft. They can begin to fall, becoming even larger by sweeping up smaller rising droplets. This is the origin of the downdraft. If dry air is entrained from outside the cloud when the downdraft reaches lower levels the drops may start evaporating. This cools the air, accelerating the downdraft. The cooling is enhanced below the $0^{o}C$ isotherm when hail start melting. The water droplets not having completely evaporated fall down as rain accompanied by strong, gusty winds. If the droplets or hail particles evaporate before reaching the ground, we get a downburst without rain (or hail). So we can distinguish between wet and dry downbursts, Fig 4.17 (Fujita 1985). In a dry downburst the air warms dry adiabatically after the raindrops have evaporated. Such a downburst may therefore be accompanied by a temperature increase.

Some radar echo types are according to U.S. investigations (Badner, 1979, after Fujita and Byers, 1976, and Fujita, 1978) accompanied by downbursts. The spearhead echo appears when there are Cumulonimbus in a strong vertical shear, see Fig 4.19. Hook, bow and comma echoes, Fig 4.20, are also associated with strong downbursts. The hook echo is also considered one of the best indicators of tornadoes.

The wind pattern of downbursts is illustrated by Fig 4.18 (Fujita 1985).

Often a microburst is encircled by a vortex ring, see Fig 2.3. The downbursts' hazard to aircraft is serious and is illustrated by Fig 2.2 d).

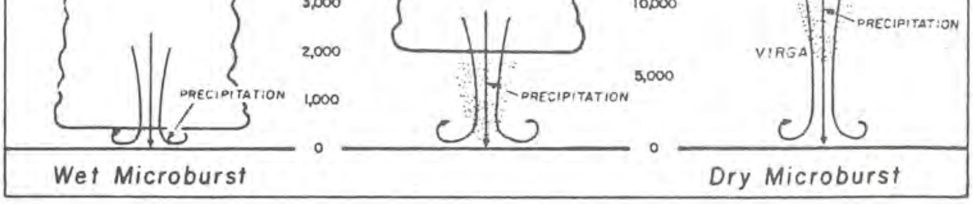


Fig 4.17 ***Schematic views of wet and dry microbursts. Wet microbursts are expected to occur in the wet regions of the world, while dry microbursts are commonly seen in the dry regions with high bases of convective clouds.*** After Fujita, 1985.

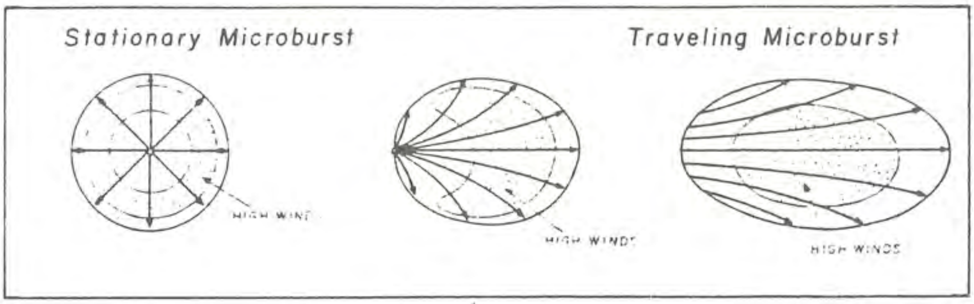
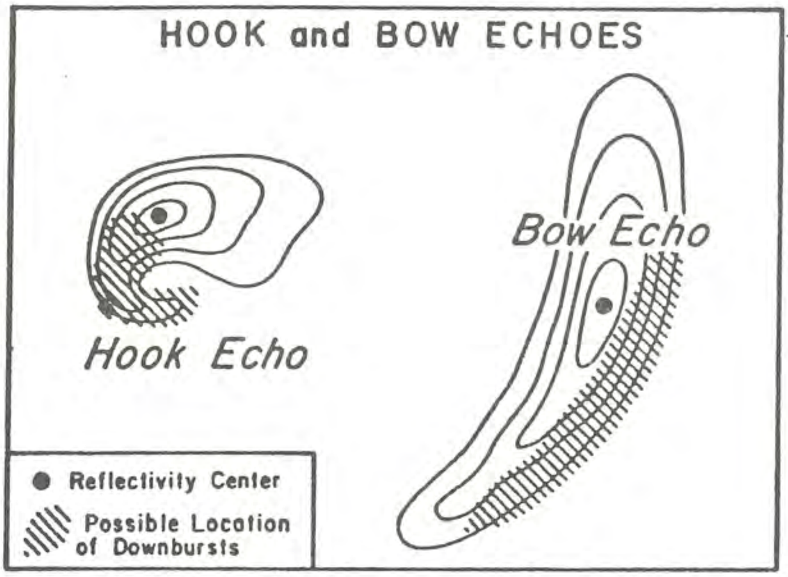
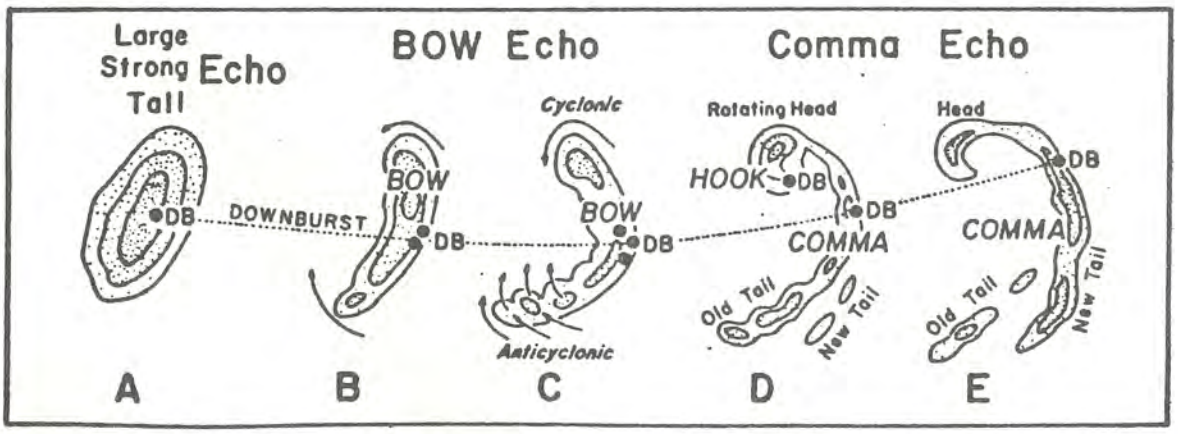


Fig 4.18 *The variation of airflow inside microbursts with different traveling speeds. A stationary microburst shows a starburst airflow with an annular ring of high winds.* After Fujita, 1985.



a) Hook and bow echoes commonly observed during downbursts. A line echo wave pattern (LEWP) often includes a fast moving bow echo. The maximum reflectivity within a bow echo is frequently seen on the left side of the bow center.



b) A typical morphology of radar echoes associated with strong and extensive downbursts. Some bow echoes disintegrate before turning into comma echoes. During the period of strongest downbursts, the echo often takes the shape of a spearhead or a kink pointing toward the direction of motion.

Figure 4.19
Characteristics of radar echoes which produce downbursts (WIST, 1986, after Fujita, 1978).

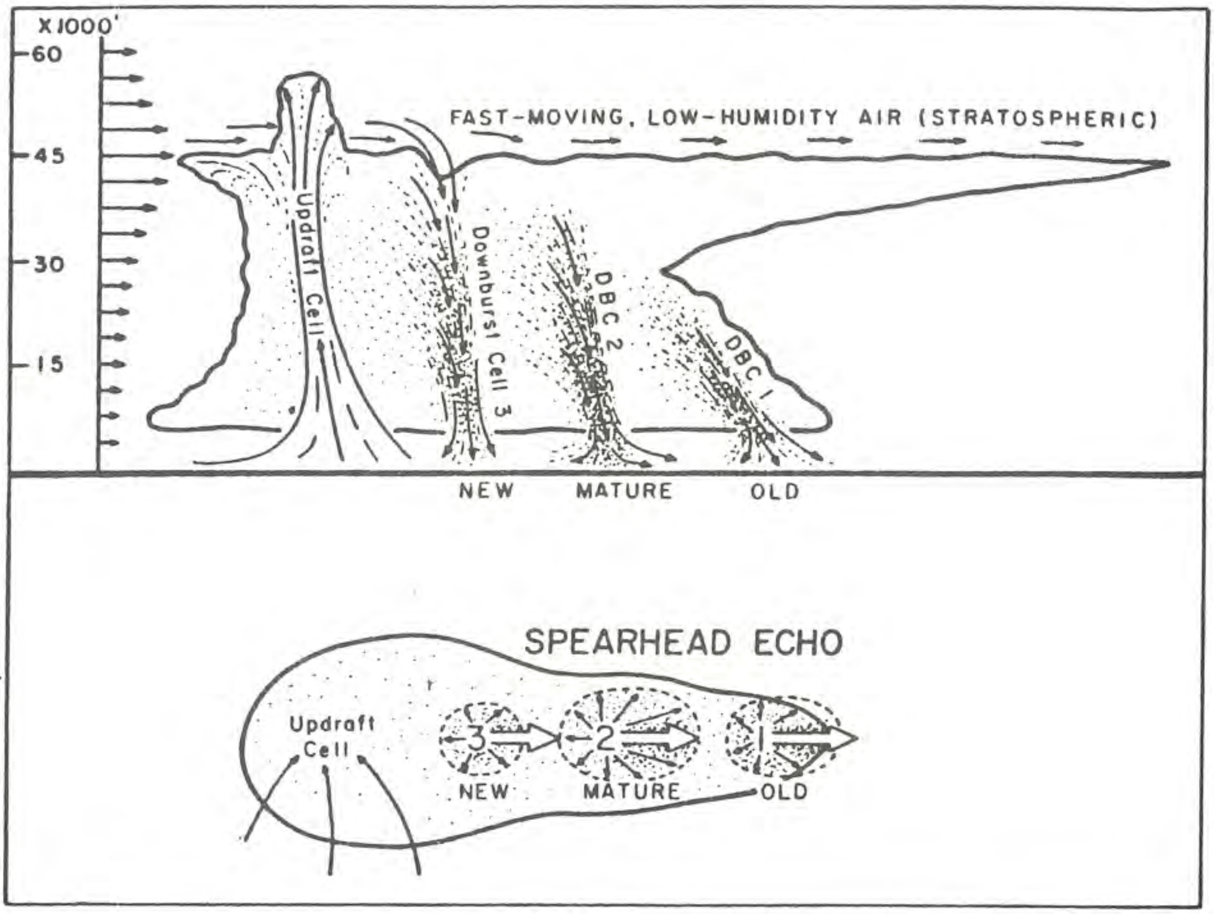


Figure 4.20
The Fujita-Byers model of spearhead echo.

They assumed that the fast-moving air is brought into the source region of the downburst when an overshooting top collapses into the anvil cloud. By virtue of large horizontal momentum drawn into a downburst cell, the cell moves faster than other portions of the echo. In effect, downburst cells run away from the parent echo and weaken, resulting in a pointed shape on the advancing end of the echo. At close range, especially below the cloud base, the radar paints small circular echoes. (WIST, 1986, after Fujita and Byers, 1976).

4.5.3 Why are Downbursts and Gust Fronts rare in our climate?

It is quite common in our climate that we have heavy showers without downdrafts and strong, gusty winds. The information given earlier stems from U.S. Over some U.S. states the downdrafts and accompanying phenomena are both common and violent during summer. But also in our climate do we have big Cumulonimbus with downbursts though they are much less common. An accident which is remarkable a o since it occurred in snow-showers during winter will be shortly referred.

The accident occurred Dec 6, 1977, at the Swedish Air Force base at Hässlö. There were Cumulonimbus giving snow-showers and a nearby synoptic station had reported thunder. The Cumulonimbus top reached only 5 km. Two aircrafts J35 Draken made an instrument (PAR) landing in the shower. About 3 km from the runway the leader found that he was losing height rapidly and therefore began to climb. The pilot of the second aircraft tried to follow, but lost control of his aircraft and had to jump. Fig 4.21 shows his path. A downburst was considered the most likely cause of the accident.

A forecaster then ought to know when a Cumulonimbus may be expected to produce downdrafts. Unfortunately little is known. A dry middle level atmosphere may be needed to permit evaporational cooling of entrained air. The echo types given in the preceding paragraph originate from the U.S. and their applicability here has to be investigated.

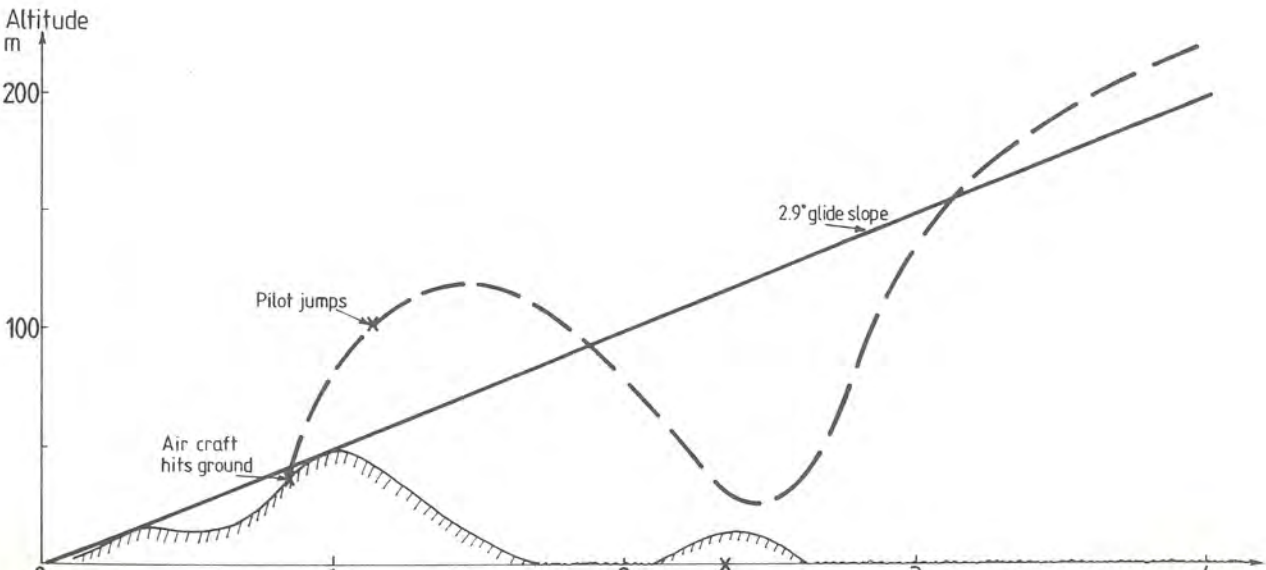


Fig 4.21
Probable path of an aircraft encountering a downburst from a snow-shower during landing. Försvarets haverikommission, Rapport 1978-04-14.

5. HIGH-LEVEL WIND SHEAR

5.1 Mountain waves

Mountain waves are notorious shear- and turbulence-producers, extending from low levels up to and into the stratosphere, see Fig 5.1. The rotor zone gives perhaps the worst turbulence found in the air flow over mountains. It is related to the size and height of the mountain range: The rotors of Sierra Nevada are known for turbulence comparable to that in thunderstorms. Outside the friction layer and the rotor zone, flight through mountain waves is often smooth. However, the smooth flow may break down and strong turbulence appear in lenticular clouds, which then have a rugged appearence.

Strong mountain waves often occur when a jet crosses the mountain range. Any turbulence normally associated with the jet may then be greatly increased in extent and severity.

Favourable for the formation of mountain waves are:

* a stable layer sandwiched between two less stable layers one near the ground and the other at a higher level.
* A wind blowing within 30^{0} of normal to the mountain range.
* A wind speed above 15-20 knots across the ridge line, with speed increasing with height, but with little change of direction.

5.2 Convective turbulence

Convective turbulence means turbulence connected to cumuliform clouds in the clouds or in clear air close to the clouds. This involves clouds of very different sizes, from small Cumulus with a depth of a few hundreds meters to giant Cumulonimbus, which in the tropics may reach up to nearly 20 km. Generally, the intensity of the turbulence to be expected in a cloud depends on its size, see Table 4.2.

Some interesting facts about Cumulonimbus in our climate are given by investigations over the British Isles.

The building of the Cumulonimbus consists of a rapid succession of large thermals, progressively penetrating to greater heights. Upwind velocities up to 30 m/s occur in the largest storms. The downdrafts may attain 20 m/s.

The most severe bumps occur in the entry of the main drafts. The gradients of vertical velocity (the horizontal gradient of the vertical wind) tend to be concentrated within horizontal distance of a few hundred meters at the peripheres of the drafts. These regions are also characterized by radar echoes with sharp edges.

The strongest drafts and gusts are found in the middle and upper parts of the cloud. Moderate to severe turbulence is also encountered at upper levels in clear air outside the Cumulonimbus, up to about 1 km above the anvil and to horizontal distances of about 10 km from the cloud boundaries.

In the middle troposphere (say 3-6 km) the turbulence in clear air outside the cloud seems to be light.

Fig 5.2 is an attempt to draw a model of a mature thunderstorm, summarizing literature data.

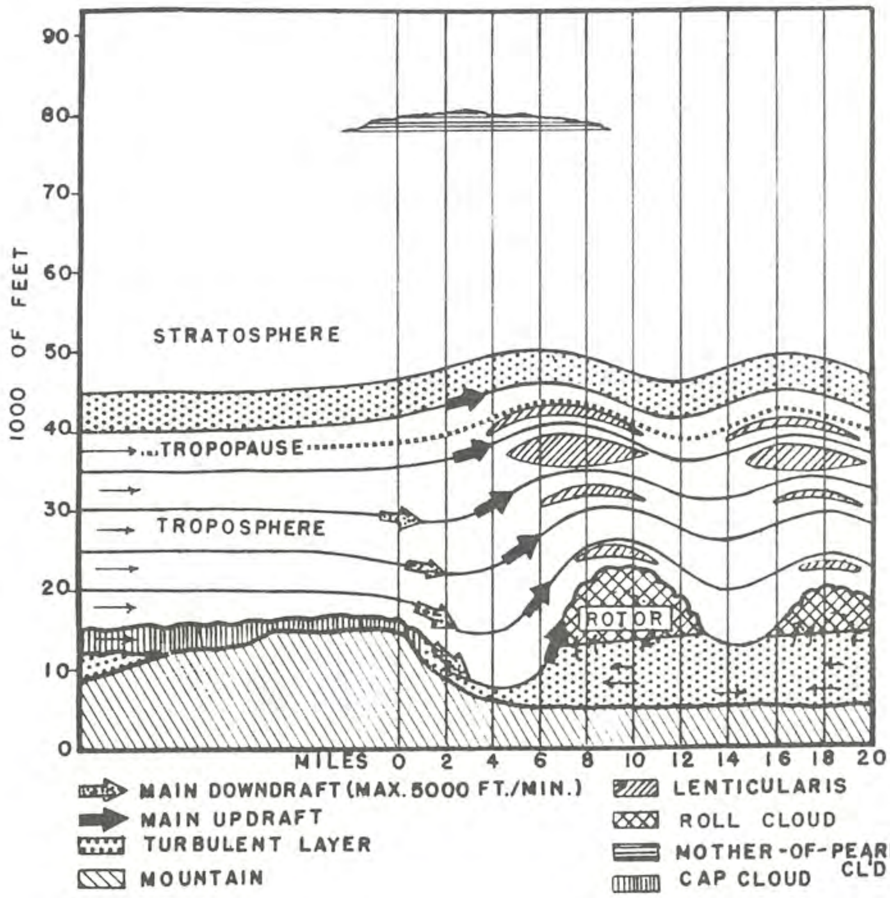


Figure 5.1
Cross-section of conditions associated with a typical mountain wave. George, 1960.

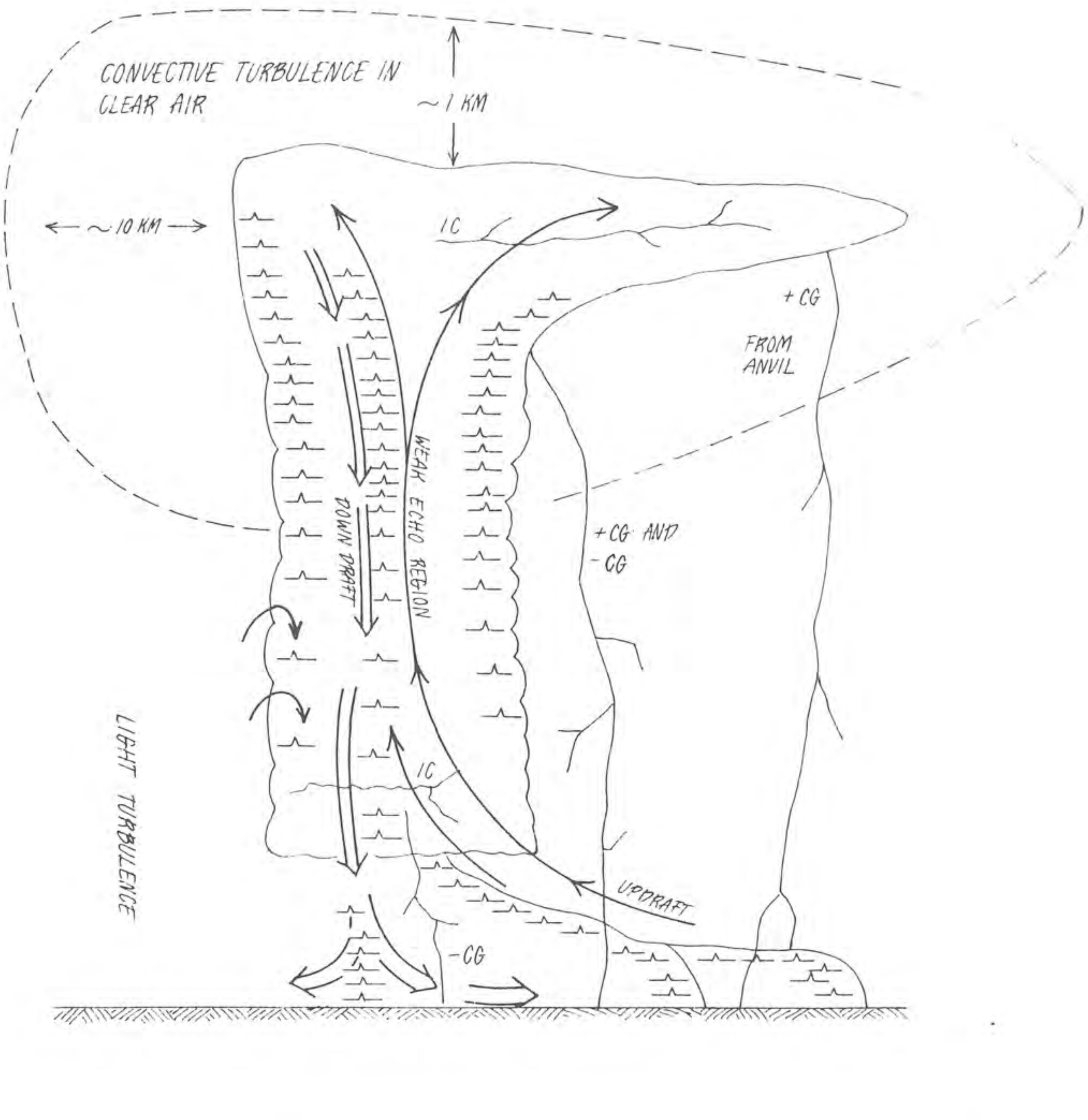


Figure 5.2
Schematic cross-section through a mature thunderstorm.

—^— turbulence and large reflectivity gradients
+ CG positive cloud-to-ground discharge (positive charge in the cloud, negative in the ground)
- CG negative cloud-to-ground discharge
IC intracloud discharge

5.3 Lightning

Lightning strikes are a common cause for aircraft weatherrelated mishaps. Clifford (1980) states that more than half of all U.S. Air Force weather-related aircraft mishaps are caused by lightning strikes. Commercial aircraft data from Fischer and Plumer (1977) show that reported strikes average 34 ones per 100 000 hours, that is about one strike to each airliner per year. That an airliner is struck by lightning once a year must be considered a very high rate, at least compared to ground-based vehicles. The reasons may be

* the ground strikes are highly outnumbered by strikes not hitting the ground
* the aircraft itself triggers strikes.

According to a 1965 United Airline Report (Clifford, 1980) experienced pilots agree that there are two kinds of lightning. The first, most common one, is actually a non-thunderstorm one which occurs while flying in precipitation at temperatures near freezing. It is preceded by a buildup of static noice in the communication gear and a corona (St Elmo's fire) can be observed if it is dark. The buildup may continue for several seconds before the discharge occurs. The discharge terminates the static and corona. Many pilots believe that this type is not a true lightning strike but rather a discharge of excess charge built up on the aircraft while flying through the precipitation.

The second kind occurs abruptly with no warning, and is mostly encountered in or near thunderstorms. Both kinds can create a brilliant flash and a boom.

There is evidently no satisfactory theory explaining how sufficient charge can be stored on an airplane to produce a discharge which looks and sounds like a lightning. Aircraft size is however important for the likelihood of being struck. Jumbo jets are logging more strikes than their smaller predecessors (Clifford, 1980). Also aircrafts carrying long antennas or towing gunnery targets report high number of strikes.

Most strikes occur in clouds and precipitation, see Fig 5.3. Notice however that some strikes occur in the clear. Strikes have been reported as far as 40 km from the nearest cloud and even with no clouds everywhere around. Though it is difficult to conceive how sufficient strong charge centers can be built up in clear air these reports cannot be wholly dismissed because they continue to appear.

According to earlier investigations using data from commercial aircrafts most strikes occur at lower altitudes at temperatures about 0^{0} C, see Fig 5.4, which also shows the typical charge distribution in a thunder Cumulonimbus. Evidently this Fig pays no account to the fact that (United Airline Report, 1965) most lightnings encountered by aircrafts are not connected to Cumulonimbus. The probable reason is that there evidently is no satisfactory explanation for the non-thunderstorm strikes.

Cruise altitude for piston aircrafts were about 5 km, while jets fly at about 10 km. Yet the altitude distributions of strikes are very similar for the two types. This indicates that for commercial aircrafts

* most strikes occur below 6 km
* jet aircrafts are likely to be struck below cruise altitude, that is during climb, descent or holding operations.

A large number of flights through Cumulonimbus have been undertaken in the Storm Hazard Program of NASA (Bohne and Chmela, 1985). The aircraft lightning strike events were correlated with

* aircraft penetration altitude
* air temperature
* precipitation
* turbulence structure

Peak strike rates were obtained at altitudes about 40 kilofeet, at air temperatures below -40^{o}C. Relatively few strikes were observed near the freezing level. These distribution of strikes differs markedly from that given in Fig 5.4. A possible explanation is that the NASA flights were confined to Cumulonimbus, while Fig 5.4. refers to all types of strikes. Furthermore that it is probably easier to avoid Cumulonimbus at higher than lower altitudes may contribute to the low strikes rates at higher altitudes in Fig 5.4.

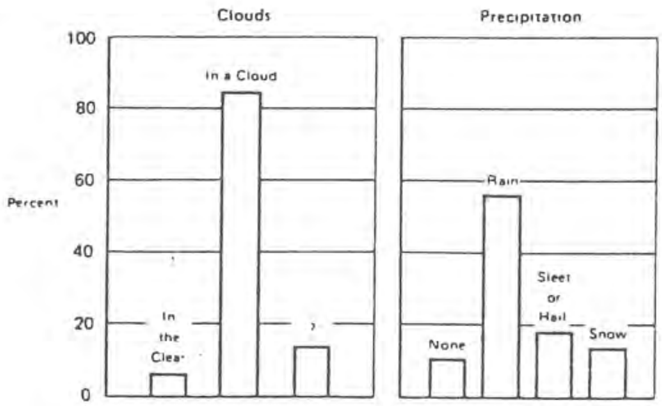


Fig 5.3
Environmental conditions at time of strike. After Fisher and Plumer, 1977.

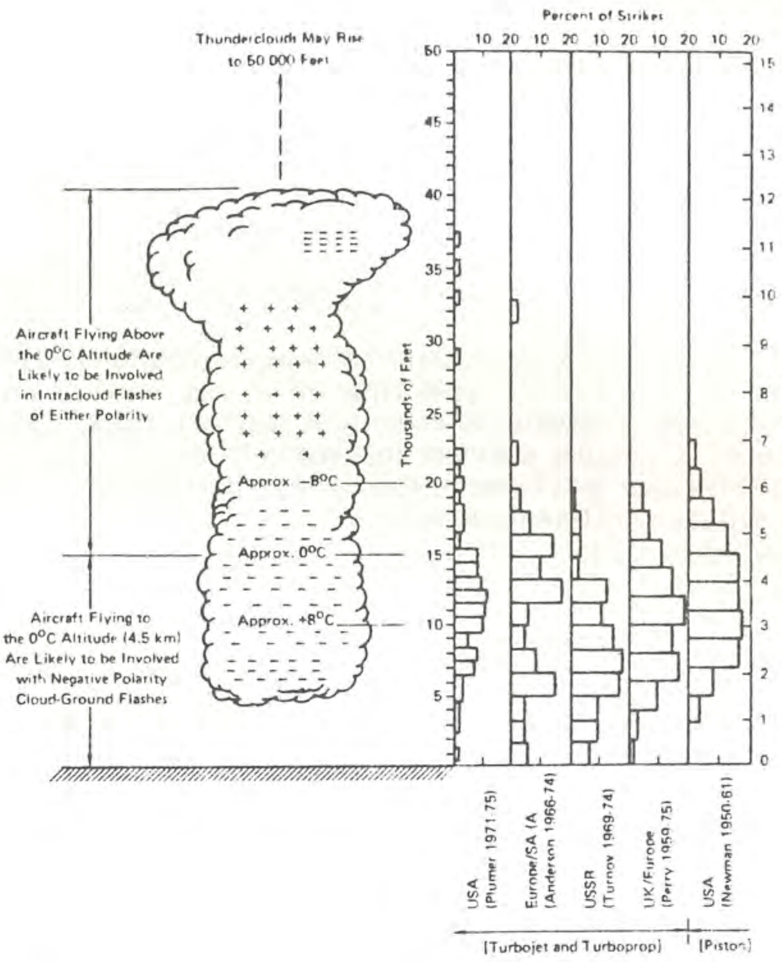


Fig 5.4
Aircraft lightning-strike incidents vs altitude. After Fisher and Plumer, 1977.

Several lightnings were triggered by the aircraft itself.

Lightning strikes were not well correlated with regions of heavy precipitation or turbulence. However, lightning activity seems to be concentrated to storm downdrafts, heavy precipitation core boundaries and strong turbulence regions.

Strikes generally occurred at a reflectivity factor of 35-45 dBz close to a precipitation core, that is where the reflectivity gradient was high. The strikes also occurred when the aircraft was in a region of vertically moving air, preferably near a downdraft edge. Furthermore the lightning events occurred near regions of heavy to severe turbulence.

This does not mean that every precipitation core, downdraft or region with severe turbulence is associated with lightning. In fact most regions with strong turbulence showed no lightning activity. This suggests that lightning location devices should not be used to locate areas of strong turbulence.

Now operative lightning location systems only record cloud-to-ground strokes and hence underestimate the frequency of lightnings in the atmosphere. For aircrafts this underestimation is even more accentuated since the aircraft itself may trigger lightning.

Clifford (1980) reports that the USAF aircraft F4 has considerably higher strike rates in Europe than in USA or Asia. The political air space constraints in Europe and the types of mission flown are likely contributors to this.

5.4 Clear Air Turbulence, CAT

The term CAT means according to the British Met Office (1975) turbulence in clear air at high levels, remote from convective and orographic effects. It is noted, though, that turbulence in clear air may occur at low levels in the boundary layer, in mountain waves and close to thunderstorms. Turbulence is also often reported in frontal cirrus.

The turbulence is commonly limited to shallow layers about 100 m thick, but may reach about 1000 m and reach about 1000 km in horizontal length.

An aircraft can expect to encounter moderate CAT about 1% of its flying time, and severe CAT much less, see Table 5.1.

Table 5.1
Percentages of distance flown in clear-air turbulence - all flights. 1976 Turbulence Survey, Dutton (1979).

Flight level	Light +	Reported CAT Moderate +	Severe +	Total distance flown (km)
100	9.17	1.09*	0.242*	13 245
100-149	8.29	0.44*	0.077*	38 816
150-199	8.29	0.53	0.061*	111 895
200-249	9.19	0.67	0.018*	236 872
250-299	10.72	1.43	0.006*	686 695
300-349	8.87	0.90	0.012*	1 385 671
350-399	10.92	1.72	0.005*	1 415 676
400	5.30	0.24*	0.236*	16 557

* Denotes that the percentage is based on fewer than 5 encounters with CAT. Flight levels are given in hundreds of feet.

Note that what is called CAT in Table 5.1 appears at all altitudes, not only high ones. The severe turbulence even seems more common at low altitudes though the very few cases with severe turbulence do not permit any definite conclusions about its frequency at different altitudes.

Most evidence, however, suggests that CAT has a tendency for maximum incidence near jet streams and the tropopause. The frequency tapers off in the stratosphere, but there may be a secondary maximum at about 15 km over mountainous areas.

Under certain simplifying assumptions it is possible to compute the probability of encountering turbulence as a function of the length of the flight. This supposes that the probability of encountering turbulence in a square of, say 100x100 km^2 is known. Dutton (1979) used data from the 1976 Turbulence Survey to calculate the abovementioned probability. He found that the probability of encountering moderate to severe turbulence in a square of 100x100 km^2 was

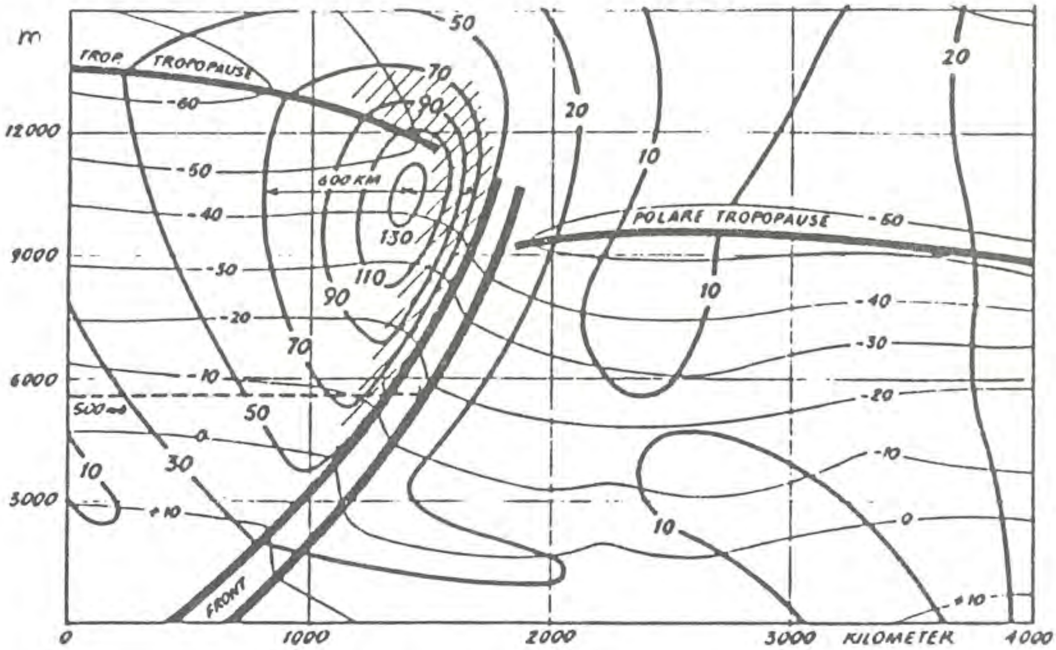
> 1.38% if NIL CAT was forecasted for the area
> 2.83% if MOD CAT or MOD OCNL SEV CAT was forecasted for the area

From these empirical probabilities the risk of encountering CAT over flights of different distances were calculated, see Table 5.2.

Table 5.2
Expected probabilities in % of encountering moderate or severe CAT over flight distance L. Dutton, 1979

	L = 100	L = 500	L = 1000	L = 2000 km
NO CAT FORECAST	1.7	8.3	15.8	29.2
MOD CAT or MOD OCNL SEV CAT FORECAST	3.5	16.4	30.0	51.1

That is, the probability of at least one encounter with moderate to severe turbulence during a long flight is high.



Isotachen, Geschwindigkeit in Knoten
Isothermen, Temperatur in °C
///, Zone voraussichtlicher Turbulenz

Figure 5.5
Cross-section through a front-jet system, showing probable CAT areas.

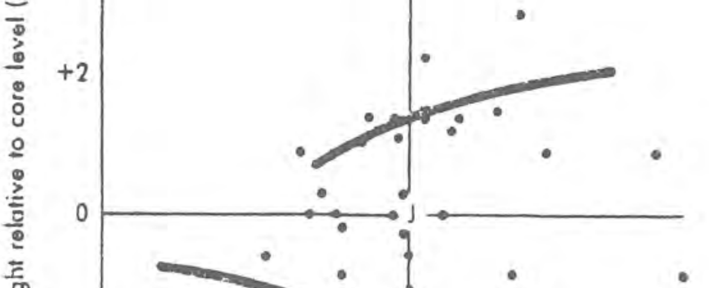


Figure 5.6
Positioning of occurrences of moderate turbulence in relation to the jet core (each point represents the centre of a reported zone of turbulence). Met Office, 1975.

average tropopause position

The turbulence probably appears in long filaments which usually move with the wind speed, which is high near a jet. Then, if one aircraft encounters turbulence at a certain spot, what is the probability that another aircraft at the same spot some time later also will encounter turbulence? This is no trivial question. Dutton (1980) has investigated this matter, see Table 5.3.

Table 5.3
Percentage probability of encountering moderate or severe CAT as function of the CAT experience of another aircraft flying in the same 100x100kmx1000ft box within 1 hour (Dutton, 1980)

	Report of other aircraft in same unit region		
	NIL	LIGHT	MOD or SEV
Probability %	1.24	5.15	23.13

Even if a turbulence report from one pilot to another is not a perfect forecast it is a very useful guide.

From the foregoing it should be clear that when we talk about areas of CAT we actually mean areas with an increased risk of CAT: In other words a CAT forecast generally gives no indication of whether a particular aircraft is likely to meet turbulence of a particular intensity.

5.5 Synoptic feature associated with CAT

There are some simple rules for finding areas of CAT on an upper chart (300 hPa):

* The low-pressure side of a jet stream, i e the baroclinic frontal zones, see Fig 5.5 and 5.6.
* Troughs.
* Sharp or disrupting ridges.
* Rapidly developing upper troughs and ridges.
* Above rapidly developing waves on the ground chart.

These and some other important rules are summarized in Fig 5.7.

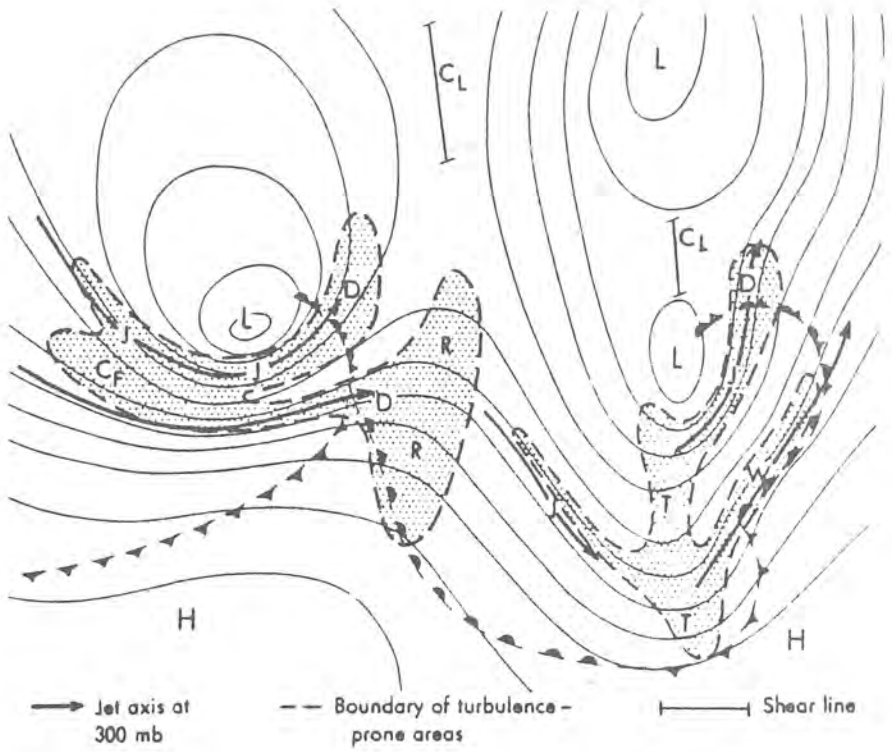


Figure 5.7
Main probable areas with turbulence between 500 and 200 hPa *as related to features of the 300* hPa*-chart.*

300 mb 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*

5.6 CAT and satellite pictures

There are often large Cirrus shields near midlatitude jet streams. The most distinguishing feature of jet stream Cirrus is its clear cut poleward edge. The jet stream axis is displaced about 100 km into the cold air. Jet stream Cirrus usually has a smooth, even texture on satellite imagery. A transverse pattern on the Cirrus shields cold air side indicates vertical shear through the cloud layer and greater turbulence than when the Cirrus texture is even. A more thorough discussion of jet stream clouds is given in Hagmarker's (1985) 'Satellitmeteorologi' which a.o. contains examples from Northern Europe.

5.7 Performance of conventional CAT forecasts

On a routine basis CAT is forecast on Significant Weather Charts.

An interesting verification of those forecasts during the 1976 Turbulence Survey is given by Dutton (1979).

Table 5.4 summarizes the result. The forecasts were issued by the Central Forecasting Office, Heathrow. The forecast area is shown in Fig 5.8.

The forecasts are reduced to two categories NIL (no turbulence) and MOD-SEV (moderate or moderate to severe). In the same way the pilots' reports are reduced to NIL or LIGHT resp MODERATE OR SEVERE. The table gives the total distance flown in each category. For instance, in 29614 km flight distance the pilots reported moderate or severe turbulence while the forecast was NIL. As a rule no turbulence was experienced when the forecast was MOD or MOD-SEV (794 925 or 97.94% of all forecasted). However, the empirical risk of encountering turbulence when turbulence is forecast is double that when no turbulence is forecast (2.06 resp 1.03%).

Table 5.4
Distance (km) flown in CAT: Central Forecasting Office forecasts versus reported bumpiness. 1976 Turbulence Survey. (After Dutton, 1979).

Pilots' report	Forecast CAT	
	NIL	MOD, MOD-SEV
NIL or LIGHT	2835510 98.97%	794925 97.94%
MOD or SEV	29614 1.03%	16679 2.06%

The number of 'successes' i e MOD or SEV CAT forecast and MOD or SEV CAT reported is extremely low (2.06%).

As emphasized earlier a forecast of CAT must be intepreted as a forecast of larger risk of CAT, not that CAT will occur over whole the CAT area.

The performance of one forecast is illustrated in Fig 5.6.

5.8 A numerical predictor of CAT

Dutton (1980) reports an attempt to select predictors for CAT. Output from the Met Office 10-level model was used to compute fields of eleven indices believed to have some association with the occurrence of CAT. These indices included the horizontal wind shear, the vertical wind shear, the wind speed. Forecast values of these indices were compared with pilots' reports of CAT. Horizontal and vertical wind shear were found to be the best predictors. The following empirical index (E) emerged as the 'best' predictor of CAT:

$$E = 1.25\ S_H + 0.25\ S_V^2 + 10.5$$

S_H = horizontal wind shear in m/s per 100 km

S_V = vertical wind shear in m/s per km

That is the wind shear itself was superiour to more complicated indices, as the Richardson number.

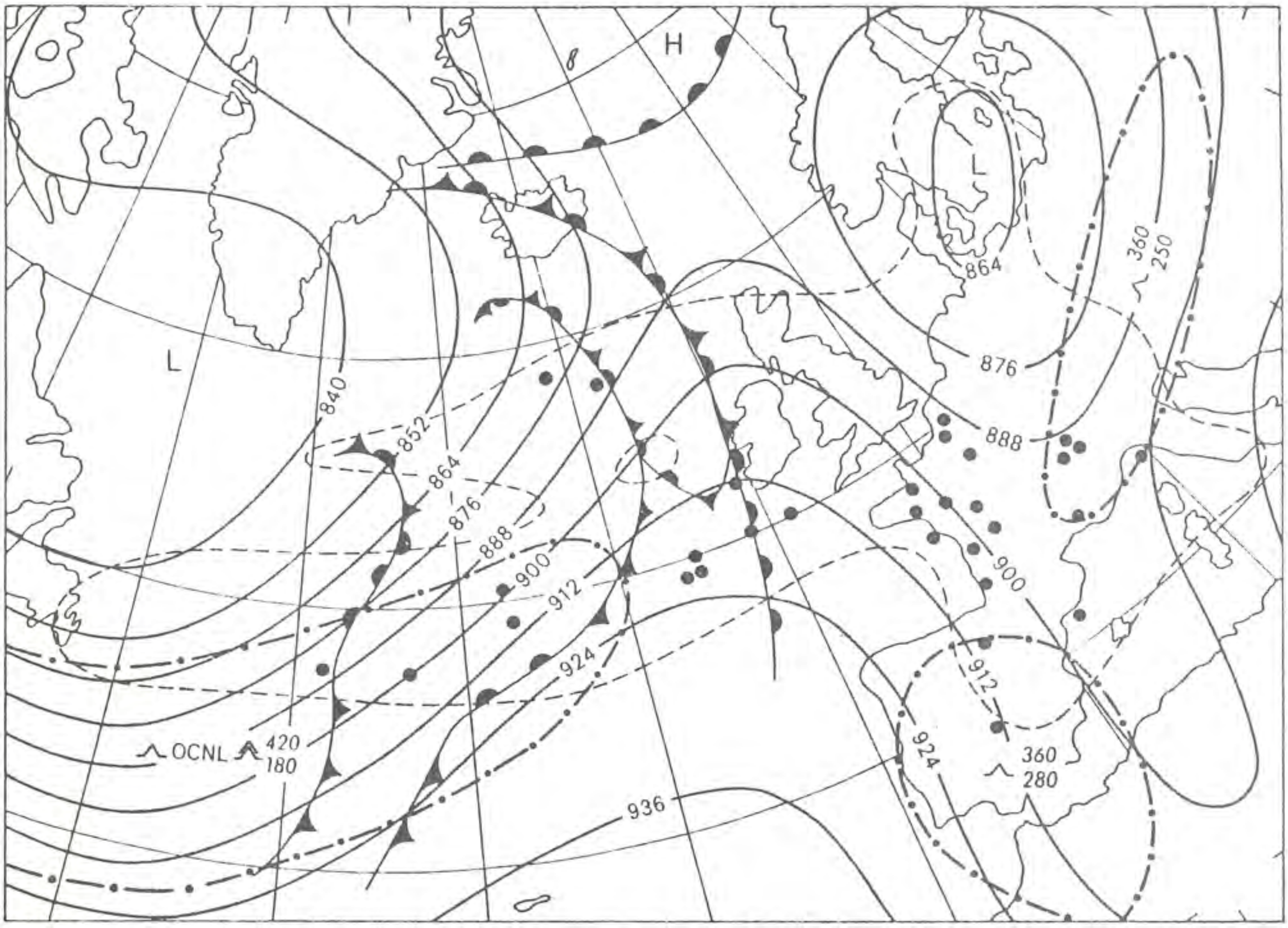


Figure 5.8

300 hPa contours at 12 GMT on 9 March, 1976.
Heights are in decageopotential metres. Surface fronts are indicated. Locations of encounters with moderate and moderate to severe CAT are indicated by black dots and those of encounters with severe CAT by encircled black dots. Areas of forecast CAT (verifying time 12 GMT) are indicated by symbols explained below. The adjacent figures represent flight levels in hundreds of feet. Pecked lines encircle areas for which at least ten aircraft submitted full reports and therefore highlight the areas of densest air traffic. After Dutton, 1979.

= Moderate turbulence
= Severe turbulence

5.9 A CAT probability chart

The British Met Office (1986) has developed a numerical CAT probability chart described by Forrester (1986). They use forecast fields from their 15-level (grid 150 km) global model. An example of such a chart is shown in Fig 5.7. This chart shows the CAT probability forecast averaged over the 4% and 6% probabilities of encountering moderate or severe turbulence per 100 km of flight path. The background value (= average value of encountering CAT) is about 2%. The risk of encountering moderate to severe turbulence over longer flights can be estimated in this way; If the risk of encountering turbulence on a 100 km flight is 4% then the chance of not encountering turbulence is 1 - 0.04 = 0.96.

The chance of not encountering turbulence on a 200 km flight then is (1 - 0.04)(1 - 0.04). Do for a 300 km flight (1 - 0.04)(1 - 0.04)(1 - 0.04) = 0.88.

The risk of encountering turbulence on a 300 km flight is then

$$1 - 0.88 = 0.12 \text{ i e } 12\%$$

In this way the risk of encountering turbulence on flights of different lengths through CAT areas can be estimated.

It was found that this method produced charts with smaller CAT areas than the manual methods, cf Fig 5.9.

As a test of the method,CAT probability charts were provided for British Airways flights over the North Atlantic and Europe during July 1984 - July 1985. During part of the time Pan American World Airways and Air Canada joined the trial.

The pilot was requested to annotate his turbulence experience on the flight and return the chart. The results of an analysis of 584 Atlantic flights are summarized in Table 5.5, where each count refers to a 100 km segment of flight.

Table 5.5
CAT probability forecast against reported turbulence for 584 North Atlantic flights

Reported turbulence	CAT probability forecast 0-4%	4%
NIL or LIGHT	33450 (98.6%)	3088 (92.7%)
MODERATE or SEVERE	473 (1.4%)	244 (7.9%)

It may be objected that a forecast of say 6% (that is high) risk of moderate or severe turbulence would give the pilot the adverse impression, viz that the risk of turbulence is low. But an experienced pilot knows that this phenomena is rare. Also the forecast could refer to climatology and be given not in percentages but as high, medium or low risk.

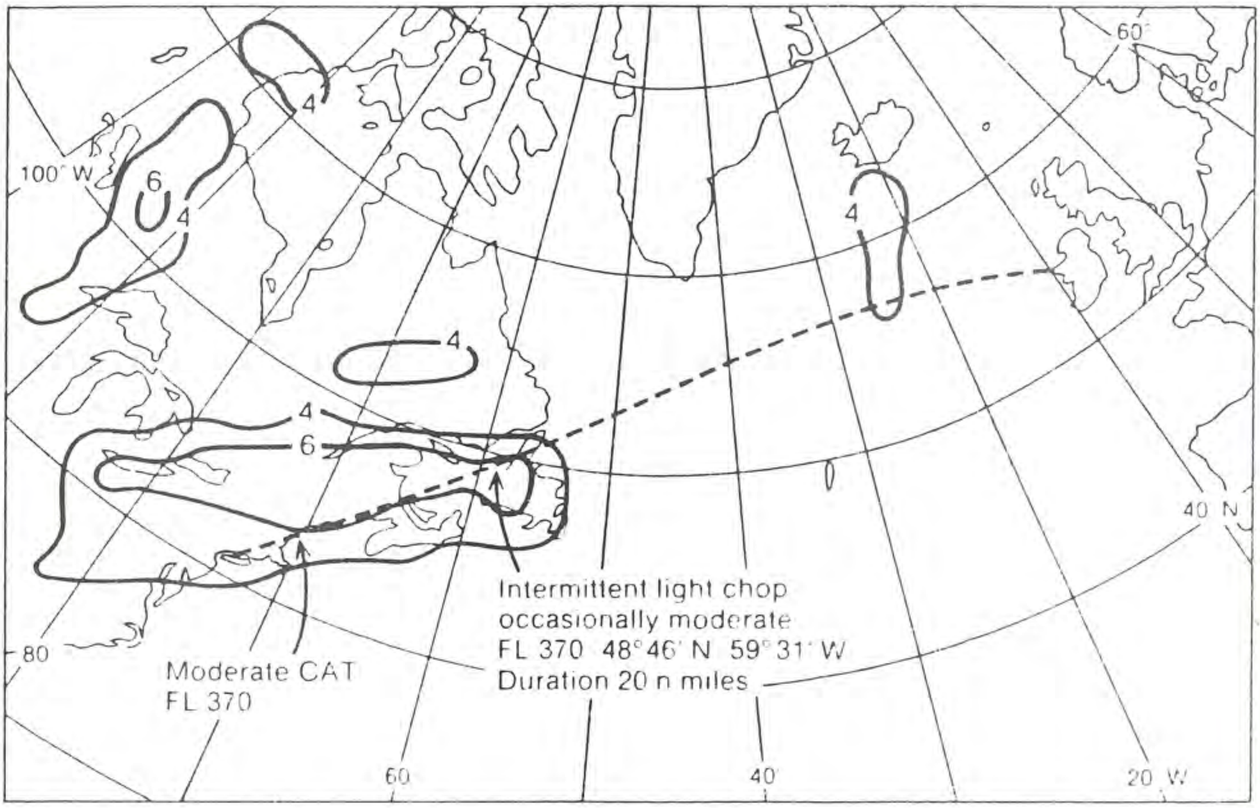


Figure 5.9
24-hour CAT probability (%) forecast chart for 0000 GMT on 3 January, 1985, with route of flight and pilot's remarks shown. Forrester, 1986.

6. WAKE VORTICES AND HEAVY RAIN

6.1 Wake vortices

Behind an aircraft in flight wing tip vortices are generated in the form of two counter-rotating cylindrical vortex tubes trailing behind the wing tips, see Fig. 6.1. These vortices are well developed behind large wide-bodied aircrafts and delta-winged ones. Vortices generated by starting and landing aircrafts may pose a serious hazard to smaller aircrafts following too close behind. Helicopters in forward flight form tip vortices.

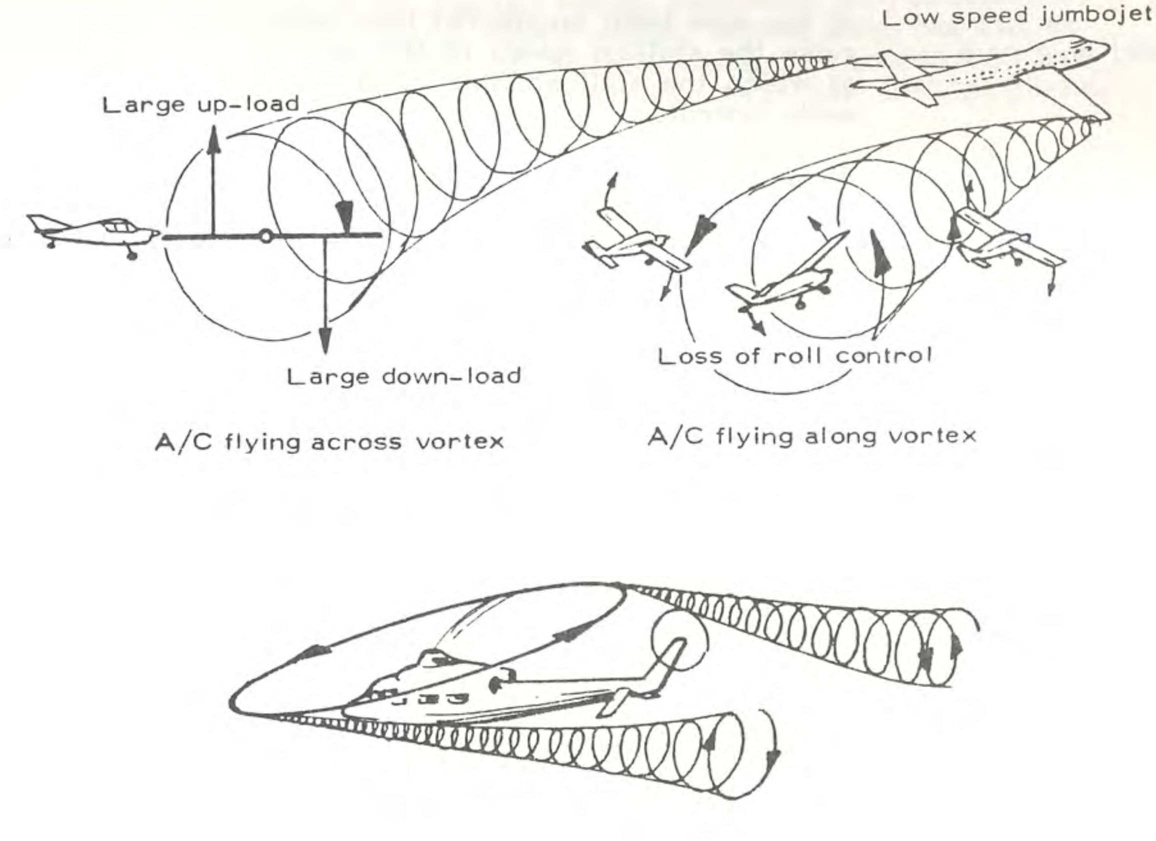


Figure 6.1
Wake vortices and their effects. Roed, 1972.

6.2 Heavy rain

In several aircraft accidents in the U.S. wind shear has been considered a major cause. There have, however, been suggestions that much of the loss in the aircraft performance was caused by heavy rain.

A theoretical analysis has given the following conclusions (WIST, 1986):

a) Momentum penalties become significant for rainfall rates approaching 500 mm/h (extremely heavy rain);

b) Drag/lift penalties could be very significant for rainfall rates exceeding 100 mm/h (heavy rain).

It has also been suggested that heavy rain could temporarily raise the stalling speed of the aircraft, possily above the speed at which the stall warning system (stick shaker) would normally operate.

Another suggestion is that the angle of attack sensors used on stall warning and shear warning systems can be affected by heavy rain. The sensor vanes should be aligned with the angle of the approaching rain (about 8^{o} from the horizontal at normal approach aircraft speed).

There have been cases when aircraft penetrating heavy thunderstorms have experienced a total loss of thrust from all engines. This has been attributed to the direct ingestion of massive amounts of water and/or hail.

It should also be noted that in an announcement in 1985 the Ministry of Civil Aviation in USSR has prohibited the landing/take-off of domestic aircraft under the following conditions (WIST, 1986):

- Landing: Visibility less than 1000 m in heavy showers.

- Take-off: Visibility less than 600 m in heavy showers.

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