WORLD METEOROLOGICAL ORGANIZATION

AVIATION HAZARDS

EDUCATION AND TRAINING PROGRAMME

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TABLE OF CONTENTS

Page

1 INTRODUCTION

This document is to guide forecasters working for the aviation community. Its intention is to discuss the many and varied phenomena which, unfortunately, can prove hazardous to aviation.

At the very least, the phenomena discussed can cause delays and thus reduce the efficiency of the aviation. But they also lower the safety of air operations and, at their worst; they can cause the loss of equipment, and more importantly the loss of life.

Whilst some forecasting techniques are mentioned, of itself this document is not a forecasting ‘textbook’. It is intended that the reader is familiar with some quite technical terms used in meteorology. Practicing forecasters reading this document should have ready access to more involved texts on the various subjects. For illustration, some reference is made to forecasting techniques at the UK-Met Office.

2 TURBULENCE AND WINDSHEAR

Windshear can be defined as ‘layers or columns of air, flowing with different velocities (i.e. speed and/or direction) to adjacent layers or columns’. Windshear is a major hazard for aviation especially when operating at low levels. Even when flying within a layer with a laminar flow and the flight is smooth and uneventful, the sudden crossing of the boundaries between different laminar streams will accelerate the aircraft to a greater or lesser degree. Depending on the flight direction relative to the velocity changes, shear may be felt as turbulence, but also as a sudden tail or head wind with respective consequences.

Besides convection, shear is the second major source for turbulence. Basic fluid dynamics tells us that any fluid such as the atmosphere can support only a maximum of shear between laminar flow layers before breaking down into turbulent flow.

Some aircraft are more susceptible to the effects of turbulence than others. Light aircraft are prone to be buffeted, and are significantly affected even by light turbulence. Relatively few reports of turbulence are received from fast military jets which are designed to give a high degree of tolerance.

The intensity of turbulence is categorised by the ICAO as follows:

- ***Light***
  - Effects are less than those of 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 0.5-1.0g 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 (but note, Military aviators regard +4g/-2g as severe)
    - Objects are forced violently against seat belts. Loose objects are tossed about.
- ***Extreme***
    - Effects are more pronounced than for severe intensity.

From the above, we note that the only criterion that is not subjective is that of airborne accelerometer readings. Converting the 'standard' parameters available to forecasters such as wind speed, gusts, stability etc., to such values would necessarily be very difficult and would require a specific calculation for each aircraft separately. Bench forecasters, therefore, have to largely rely upon more general, empirical rules and relationships.

Windshear, of itself, is not categorised in the same way, although when it ultimately makes its presence felt, the above turbulence categories may become applicable. We will consider each of the following topics in turn.

- convective turbulence
- mechanical, mostly low-level turbulence
- orographically induced turbulence
- clear air turbulence (CAT)
- low level jets
- wake turbulence/wake vortices

2.1 Turbulence due to Convection - Convective Turbulence

2.1.1 Description

Convection is always associated with turbulence, which for that reason is referred to as convective turbulence. The origin and physical cause of the latter may vary:

- The vertical currents within and around convective clouds are turbulent;
- Growing convective towers may generate gravity waves which propagate either radially away, for instance within the anvil or may also propagate vertically;
- Dry thermals (i.e. non-saturated ascending air);
- Downdraughts associated with precipitation or mid-level cold layers of air. These can produce line squalls near showers.

Thermal turbulence over land has a marked diurnal variation, with a maximum during the afternoon and a minimum overnight. Thunderstorms, in contrast, may last during the whole night and propagate over large distances of several hundred kilometers.

2.1.2 Effects on Aircraft

At its simplest, convective turbulence will result in 'bumpiness' in flight. Of course, as the intensity of turbulence increases, its effect will increase in accordance with the ICAO categories. Ultimately, depending on aircraft type, severe turbulence may cause structural damage to an aircraft. Airlines are most concerned with injuries to passengers which may lead to costly compensation claims. One should also note that updraught speed usually varies strongly across an updraught. Thus an aircraft flying through a convective updraught will feel not only the convective turbulence within the cloud, but also the acceleration due to the varying vertical wind speed along its cloud transect. Usually we find in a thunderstorm updraught even more hazards such as hail, lightning, heavy rain and icing.

Additionally, in association with large storms, strong downdraughts or micro-bursts can occur producing a violent outflow of air which spreads outward on hitting the ground. Those downdraughts usually are caused by cool air sinking in the surrounding rising warmer updraught air. The lower temperatures might either be caused by evaporating precipitation, visible in a virga, or the mostly mid-level air by itself is cooler. Though downdraughts originate very often from deep in the cloud, the associated risk is highest below cloud base. Here we find not only a negative vertical wind speed, which by itself pushes the aircraft down; we also observe significant horizontal windshear. The downdraught forces the air air close to the ground to spread radially outwards. Figures 1a shows a typical scenario, while Figure 1b illustrates the escape route. The aircraft first experiences a headwind, lifting the aircraft up, then a sudden downdraught, followed by a strong tailwind. Both latter winds lead to a substantial loss of height if not counterbalanced. Downdraughts, therefore, can result in fatal accidents, particularly for small aircraft.

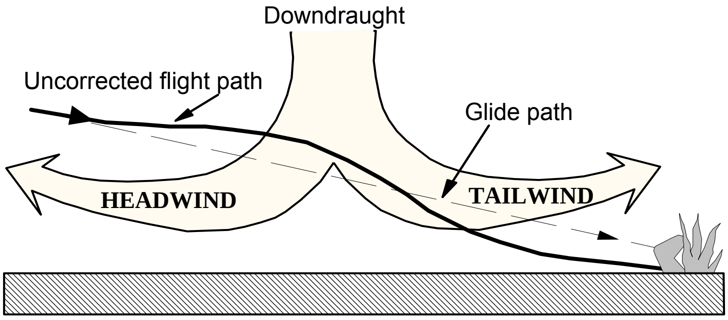


Figure- 1(a). Windshear. How a downdraught would affect the flight path of an aircraft if the pilot failed to correct for the gain and loss of lift.

In the above example of a micro-burst we see how turbulence and windshear can be inter-related. There will be windshear between ascending and descending columns of air in and around the Cumulonimbus, and windshear across the boundary of the outflow from the micro-burst on hitting the ground.

Updraught strength varies from 1 m/s in fair weather cumuli, to 5 m/s in shower clouds up to 65 m/s in severe Cumulonimbus. Downdraughts vary in a similar way with a maximum observed value of -25 m/s in CB (see Table 1).

Dry thermals are felt as light to maximum moderate turbulence.

The gravity waves close or above convective towers may either lead to related up- and downwards motions, or they may be felt as turbulence, especially if their wave-lengths is on the order of 100 m or less, or, more significantly if the gravity waves break and cause turbulence. Prior to breaking, waves overturn which may lead to significant and immediate height losses.

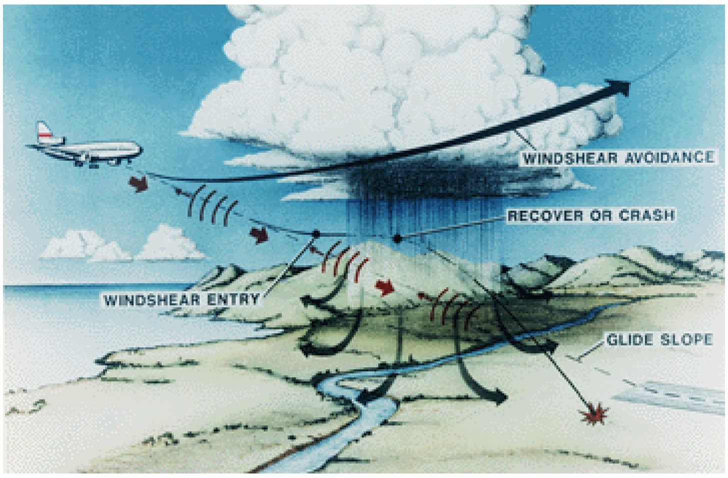


Figure- 1(b). Windshear and windshear avoidance (from http://www.nasa.gov/centers/langley/news/factsheets/Windshear.html)

2.1.3 Diagnosis of Hazard Using Appropriate Imagery

Satellite technology allows the monitoring of convective cloud development through the use of looping infrared and visible imagery – thus essentially through nowcasting. Water vapour imagery can be used to diagnose areas of likely development where upper levels of Positive Vorticity Advection (PVA) may engage with diurnal/orographic triggers. Indeed, PVA regions may well trigger convection. Monitoring water vapour imagery can give predictive results over a longer period of time.

The most recent geostationary satellites (such as Meteosat Second Generation (MSG), now renamed Meteosat 8, or GOES-10), will provide much more information to the forecaster. In addition to a much higher resolution across the visible channels, a more rapid scan of 15 minutes will allow closer monitoring of developing systems. There are also techniques in combining wavelengths to create false colour schemes to determine glaciation of cloud tops, and formation of CB anvils.

Radar imagery is invaluable for the short term forecasting (nowcasting) of developing storms. That noted, the formation of daughter cells must always be considered, including new cells unrelated to existing systems.

Doppler radar systems may be able to help diagnose the system relative flows around convective systems. Doppler radars will become increasingly useful as updated radar systems are commissioned over the coming years.

Lighting location and plotting systems (such as Sferics or SAFIR) are available in many forecast offices to assist the monitoring of storms.

2.1.4 Empirical Forecasting Techniques

There are many techniques available to the forecaster to assist in the prediction of convection – be it weak or intense. To avoid too much repetition, the reader is referred to the Cumulonimbus and Thunderstorms section of these Aviation Hazards notes. Many other meteorological texts describe the convection techniques in detail.

Criteria for forecasts of hazardous low-level windshear/turbulence

One or more of the following to be satisfied:

1)- Mean surface wind ≥ 20 kt

2)- Magnitude of vector difference between mean surface wind and gradient (2000 ft) wind ≥ 40 kt.

3)- Thunderstorms or heavy showers within 10 km.

4)- Significant windshear has already been reported by aircraft in the vicinity.

The table below gives a guide to the intensity of turbulence typically associated with various types of convective motions.

Table- 1. Typical vertical currents due to convection

Regime	Vertical velocity			Turbulence
	(m/s)	~kt	~ft/min	
Small/medium Cumulus	1–3	2-6	200-600	Light
Towering cumulus	3–10	6-20	600-2000	Moderate
Cumulonimbus	10–25	20-50	2000-5000	Severe
Severe storms (eg in USA)	20–65	40-130	4000-13000	Extreme
Dry thermals	1–5	2-10	200-1000	Light/Moderate
Downdraughts	3–15	6-30	600-3000	Moderate/Severe
Downdraughts	up to -25	up to 50	up to 5000	Extreme

However, as a recap, the forecaster should consider all aspects ranging from basic air mass theory, through actual and forecast tephigram analysis, up to the conceptual models of Mesoscale Convection Systems and daughter cell formation.

2.1.5 Associated NWP products

Computer assistance is often useful to examine the mesoscale forecast surface streamlines to find convergence zones.

See also the section Cumulonimbus and Thunderstorms within these Aviation Hazards notes.

2.1.6 A Brief Study of Two Cases

a) Micro-burst

On the 9th July 1982, a Boeing 727-235 crashed shortly after take-off at New Orleans International Airport. The ultimate cause was a microburst in the vicinity and over the airfield.

Synoptic Situation

High pressure was centred over the Gulf of Mexico, resulting in a hot, humid afternoon. The forecast was of scattered cloud fields at various heights, moderate showers and thunderstorms. There were no fronts or areas of low pressure within 180 km of New Orleans.

Take off and accident

After a period of calm, heavy rain began to affect the area and the surface wind became gusty. The airport had a windshear alert system, and this system alerted controllers, and the alert was duly passed to the pilots. In addition, a 767, on landing, reported 10 kt windshear at 100 ft.

The Boeing 727-235 took off on runway 28 and climbed to 100 ft before it descended and crashed beyond the airport boundary, and into a residential area.

The headwind component at take-off was 18 kt. At a distance of 3500 ft from take-off point the aircraft was subjected to a downdraught of 510 ft/min (≈2.5 m/s). 4000 ft after take-off the aircraft had a tail wind of 36 kt.

The cause

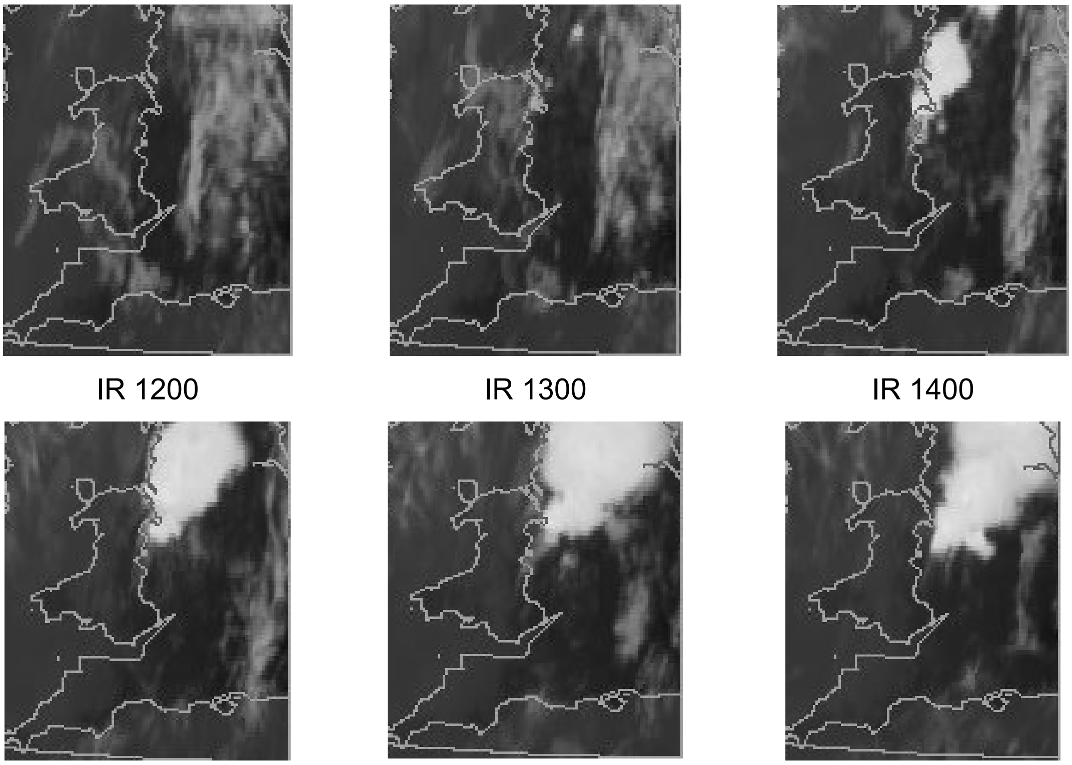
Thunderstorm activity crossing the airfield initiated a micro-burst that caused the aircraft to lose altitude, due to physical downdraught and loss of airspeed due to rapid change in wind direction and strength.

The duty forecaster had contacted the airport, prior to the accident, to advise of the possibility of ‘very strong to intense thunderstorms, with severe turbulence, lightning and wind gusts’. 152 people, including 8 on the ground, were killed in the accident.

b) Intense Thunderstorm and Rainfall

Satellite imagery from the Yorkshire (19th June 2005) storm

The following satellite imagery sequence shows how quickly deep cumulonimbus cells can develop when medium level instability is released.

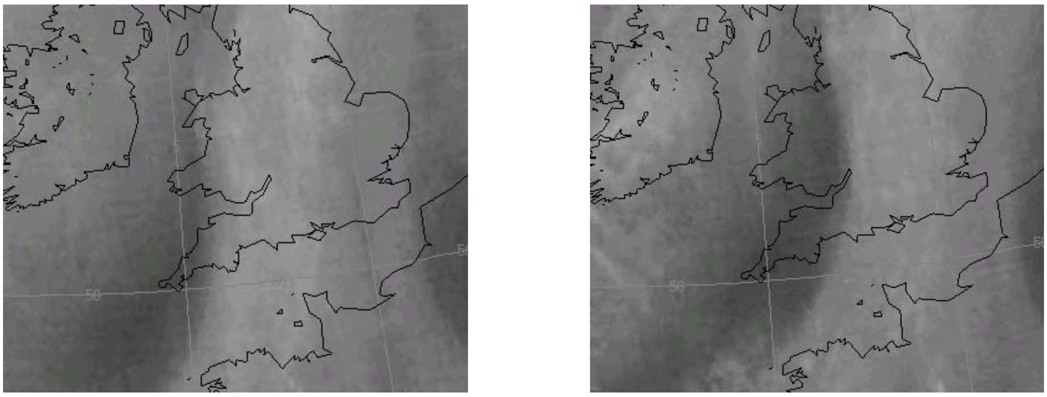


IR 1200 IR 1300 IR 1400

IR 1500 IR 1600 IR 1700

Figure- 2. Sequence of IR imagery for 19th June 2005

IR images (Figure 2) show the rapid development of the cumulonimbus cells. From water vapour imagery (Figure 3) it is concluded that at 0900 Z a region of high relative vorticity (dark region) was set to cross an area where orographic and heat triggers later initiated convection.



WV 0900

WV 1200

Figure- 1. Sequence of WV imagery for 19th June 2005

The synoptic chart for 19 June 1200 Z is shown below (Figure 4).

Essentially a split front was tracking east across the UK. The shallow moist zone that had been very evident over the Irish Sea and to the west of Wales dried out as it came up against the mountain barriers of Wales. Enhanced insolation due to clear skies over Cheshire, and/or the forced ascent over the mountains, combined with potential instability at height generated vigorous convective ascent.

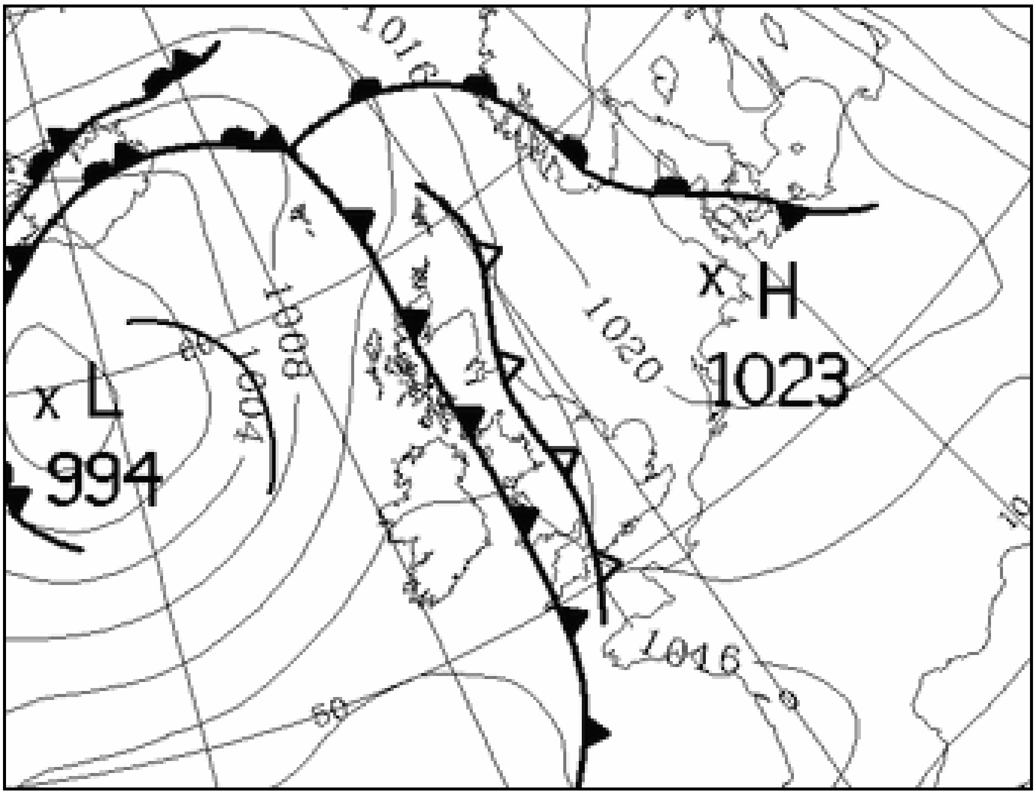


Figure- 2. Synoptic chart for 1200 Z on 19th June 2005

The cells indicated in the satellite imagery (Figure 2) were responsible for torrential rain across Yorkshire, and local flooding.

2.2 Mechanical Turbulence

Mechanical turbulence results solely from shear. The latter is always found close to the surface where wind speed vanishes. Within the boundary layer and typically at night a low-level-jet may be found, which also might produce turbulence. Furthermore, turbulence may also be found close to the edge of the jet-stream at tropopause heights.

2.2.1 Description

Close to the ground mechanical turbulence is also often referred to as low-level turbulence. Surface friction is the primary cause of the vanishing wind at the surface. Thus the intensity of mechanical turbulence depends upon:

- wind strength
- terrain roughness
- atmospheric stability near the surface.

In general, the stronger the wind and the rougher the terrain, the more intense the turbulence experienced. Light winds over a smooth sea give the least turbulence.

The steeper the lapse rate, the more readily vertical gusts develop and thus the more vigorous the turbulence is. In more stable air, vertical eddies are suppressed and turbulence is more damped – but very stable air and a sufficient displacement over large obstacles (hills/mountains) may lead to mountain or lee wave development, see Orographic Turbulence in this section of notes.

2.2.2 Effects on Aircraft

At its simplest, mechanical turbulence will result in ‘bumpiness’ in flight. The intensity of turbulence will increase in accordance with the above mentioned criteria and flight speed. For any given intensity of turbulence, the faster the aircraft flies, the more it will be accelerated. The closer it is to the ground, the less time there is available to react to those accelerations. Ultimately, depending on aircraft type, severe turbulence may cause structural damage to an aircraft, especially when combined with inadequate, strong rudder movements.

2.2.3 Diagnosis of Turbulence Using Appropriate Imagery

Diagnosis of the surface wind is difficult using standard imagery. Loops of satellite and radar imagery can help in the following of cloud/showers, but generally the steering flows are at levels and strengths greater than the ‘gradient wind’ and therefore are not directly applicable to surface/near surface wind flows. Characteristic shapes in convective cloud patterns can give an indication of gradient flow, but these are only applicable to maritime areas and break down overland.

The most effective way of monitoring wind speed, and therefore having some idea of resultant turbulence, is to regularly check surface wind reports. Such information can then be used to verify and modify model winds.

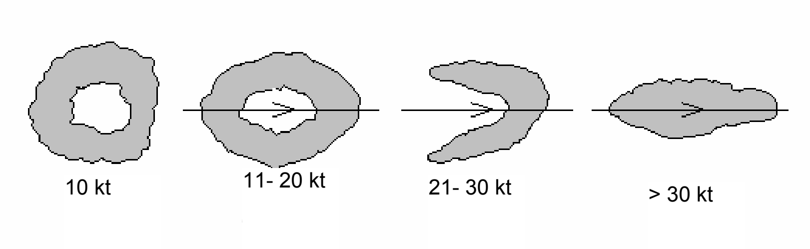


Figure- 3. **Maritime Convective Cell patterns, and related surface wind speed. From Pearson and Stogaitis, 1998.**

2.2.4 Empirical forecasting techniques

Given that the forecaster is confident in the forecast of wind speed, an estimation of likely turbulence is possible, and is indicated in the table below.

Table- 1. **Rough guide to intensities of turbulence associated with different wind speeds and surface types.**

Surface wind (kt)	Sea	Flat country	Hilly country
15 to 35	Light to moderate	Moderate	Severe
Over 35	Moderate to severe	Severe	Extreme

The forecaster should also consider the stability of the air, and determine the likely surface speed from a given gradient for a given situation, and apply a gust factor to determine gusts. In convective situations with showers, gusts may approach gradient strength. In very unstable situations with heavy showers and thunderstorms, gusts may be in excess of the gradient wind and may reach that of the 5000 ft wind.

When forecasting gale force surface wind, forecasters should by default expect low level turbulence to be severe.

2.2.5 Associated NWP products

Model winds are often very good guidance, but the forecaster must be aware of the limitations in the resolution of model orography. It is often useful to take the 925 hPa wind as gradient, and work out a corresponding surface wind manually. But beware when surface pressure is significantly above or below 1013 hPa, since the 925 hPa value will be much less representative of the 'gradient' wind.

2.3 Orographic Turbulence

2.3.1 Description

If surface roughness increases and characteristic roughness heights increase as well, eg over cities, forests, small hills and larger hills, and finally mountains, the airflow suffers large corresponding displacements from its original level. Dependent upon the stability of the air mass, this may result in triggering convection, with its attendant turbulence; it also may generate gravity waves, referred to in that case as mountain waves, or may tend to return the airflow to its original level giving 'standing waves' and rotors. Orographic structure might be arbitrary complex and so is the associated flow pattern. One finds the airflow be funnelled along valleys creating marked deviations from what might be expected from the undisturbed 'gradient wind', one might find blocking of the flow by mountains or hills, one might also found increased turbulence close to the ridges.

Forecasters must be aware of being caught out under ‘calm’ scenarios. Katabatic and anabatic winds may develop to give a flow of wind where none was expected. Strong katabatic winds may be found along and at the foot of glaciers, and valley wind systems enhanced by cold air to be considered.

Mountain waves are generated by a flow across the mountains and can develop in stable atmospheric conditions. These wave motions may persist for hundreds of miles downstream:

- in warm sectors;
- in strong winds around the periphery of anticyclones;
- ahead of warm fronts.

More specifically, the signals for mountain wave formation would be

- strong winds (>20-25 kt), at the top of the boundary layer, typically just below a sharp inversion;
- the wind blowing within 30 degrees of normal to the ridge axis;
- a low level neutral layer capped by a marked inversion 1.5 to 2 times the height of the hills.

Mountain waves are nothing more than gravity waves and thus we can classify them ‘trapped’ or ‘un-trapped’. The latter ones are also known as vertically propagating.

Trapped waves are defined as forming when wind speeds increase with height and/or a less stable layer overlies a stable layer. Wave energy is then trapped within respective horizontal layers at mostly low levels and propagates downwind.

Un-trapped waves form if stability is high and/or wind speed low, or the hill width large. The wave energy is propagated upwards so that these waves are often routinely observed in the stratosphere, having there sometimes a characteristic orographic cirrus signature with a well defined boundary.

Turbulence may be experienced in association with mountain wave motions, particularly if the vertical currents are strong and the wave length is short. Turbulence-prone areas are most likely to be near wave crests and troughs, while at mid-levels, the flow may be quite smooth and laminar. As with all gravity waves, mountain waves may also break causing then severe turbulence.

Rotors

Turbulent rotors in the lower troposphere are usually associated with high-amplitude lee waves. Two types of rotors have been observed. The first type, often visible as harmless-looking cumulus or cumulus fractus lines paralleling the mountain range, comprises a well-defined circulation under the crests of resonant mountain waves. This type of rotor contains moderate or severe turbulence and is often confined below the height of a frequently-observed upstream, near-mountain-top inversion. A second, less common, rotor type extends much higher than the upstream inversion. This type has been observed to contain severe or extreme turbulence, and is thought to be associated with a high-amplitude mountain-wave system resembling a hydraulic jump. Both rotor types present a hazard to aviation, although the second type of rotor is far more dangerous.

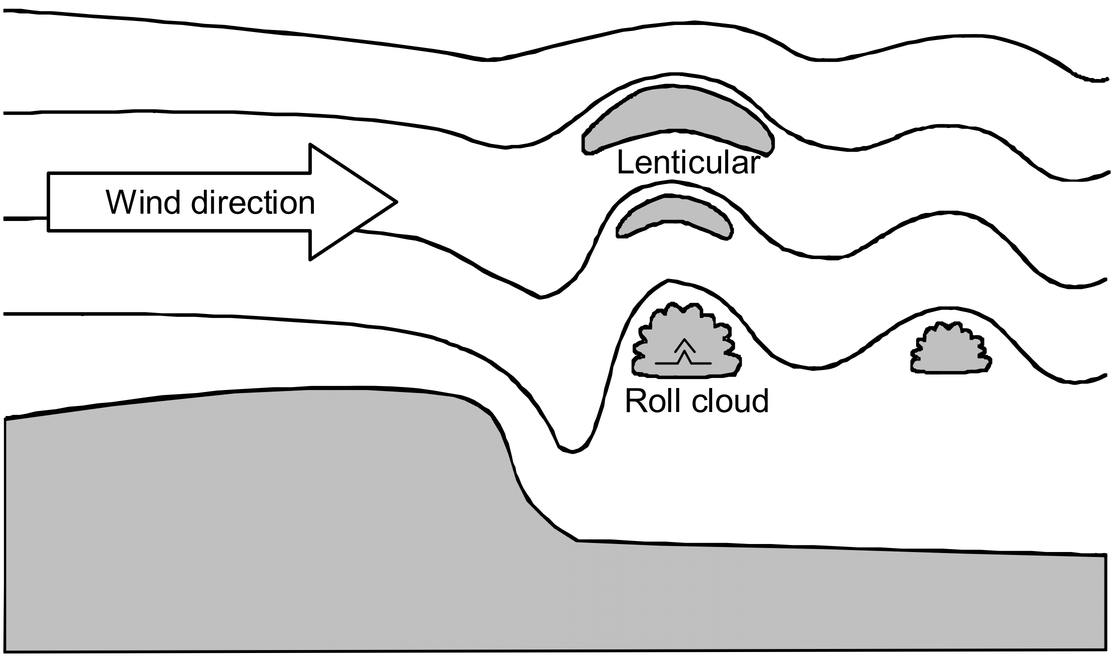


Figure- 4. Standing wave and rotor activity to lee of a mountain range

Rotor streaming

The term "rotor streaming" is used by forecasters to describe recirculations associated with lee waves. This is an idealisation of a local wave-induced adverse pressure gradient. These gradients are observed to cause rapid near-surface deceleration; they are associated with strong turbulence and a high degree of wind variability.

To generate rotor streaming the required conditions are:

- strong winds (>20-25 kt), at the top of the boundary layer, typically just below a sharp inversion;
- the wind blowing within 30 degrees of normal to the ridge axis;
- a low level neutral layer capped by a marked inversion 1.5 to 2 times the height of the hills;
- a marked decrease in wind speed, accompanied by a large change in direction, at a height 1.5 to 2 times the height of the hills;
- a stable air mass, above the well mixed lowest layer.

A good indication of rotor streaming can be seen by surface observations downwind of the mountain range showing a light or even a strong wind, often from the opposite direction to the gradient wind flow.

Note that the inversion on the lee side of the ridge may be lower than the windward side, due to forced descent and resultant adiabatic warming.

Note also that even in situations where mountain wave activity or rotor streaming are not present, strong winds can give rise to severe turbulence in hilly areas due to the roughness of the surface (as described in 3.2, above).

2.3.2 Effects on Aircraft

Mountain waves can be both an advantage and a disadvantage to aviation, mostly however the latter is the case.

Experienced glider pilots look for the updraught side of mountain waves in order to gain altitude. With ascent rates of around 500 ft per minute they can be very useful in gaining height quickly. Within such updraughts the flight may well be very smooth.

There are several inherent dangers.

1) The rapid change in height can mean that a pilot caught unawares may very quickly conflict with aircraft at different flight levels, and more importantly, if caught in a downdraught may rapidly erode any terrain clearance margins, and ultimately cause impact with the ground. Such effects will be most pronounced if the aircraft track is parallel with the ridge. Mountain wave activity is noted on aviation charts when vertical velocities reach and exceed 500 ft per minute – the maximum climb rate of some models of Cessna light aircraft are of the order of 700 ft per minute. Clearly, higher powered commercial and military aircraft will normally be able to climb more rapidly, but it does give an indication of how important a 500 ft per minute downdraught can be to the pilots of light aircraft.
2) The laminar and smooth flow will break down to give rotors in the crests of the first one or two lower level waves of the flow – turbulence should be expected to be severe in these regions, and may or may not be marked with ‘roll cloud’.
3) If the wavelength is short, then an aircraft travelling swiftly through and perpendicular to the wave-train will experience a prolonged series of rapid fluctuations of vertical velocity. This will result in turbulent flight.

Rotorstreaming, and surface rotors are extremely hazardous to aircraft. Aircraft may simply not be able to stabilise their approach. Not only may wind direction change abruptly (windshear) causing marked changes in lift and drift, but the aircraft also may be affected by strong updraughts and downdraughts. The turbulent flow can quickly be replaced by the very strong flow of air on the leeside, often well outside cross wind limits of aircraft. It is possible for windsocks at different locations within the perimeter of an airfield to all indicate markedly different wind directions and strengths.

2.3.3 Diagnosis of Hazard Using Appropriate Imagery

Mountain wave activity is often very apparent on satellite imagery. Trapped waves are often easily diagnosed, with very clear wave-like patterns in both infra-red and visible imagery. Untrapped, or vertically propagating waves, are often indicated by ‘orographic cirrus’ signatures. There are recognised cirrus patterns that indicate turbulence under such conditions.

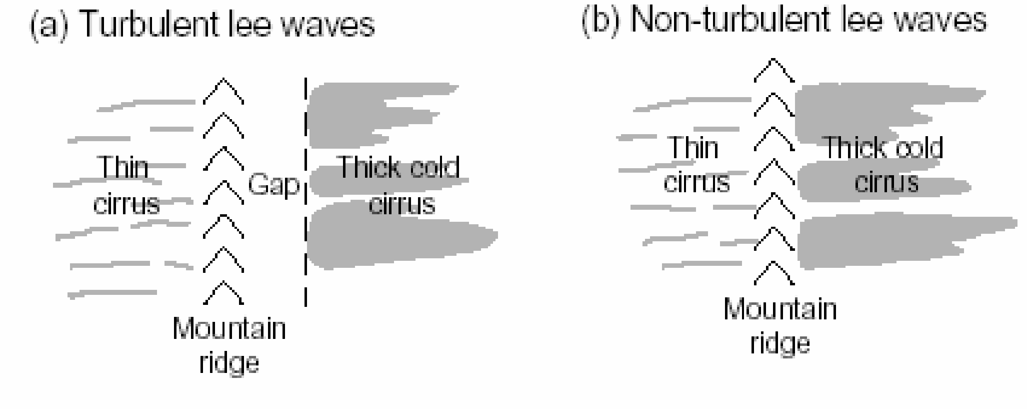


Figure-5. Cirrus signatures indicating turbulence/no turbulence scenarios

Surface plots of wind speed and direction can often 'give away' the effects of rotors at surface level. On such occasion surface flow may often be very light, and from a direction completely at odds to the normal gradient/surface relationship - sometimes the reciprocal direction.

2.3.4 Empirical Forecasting Techniques

The synoptic situations where orographic turbulence tends to be marked are:

- around a deep low pressure, due to the strength of the wind;
- ahead of a warm front, where stable air aloft causes air to be squeezed over extended mountain ridges. This can give wind speeds of more than twice the gradient wind at the hill top, and may generate rotor activity;
- in strong winds in a stable warm sector with intense summer heating.

2.3.5 Associated NWP products

As a first approximation the 925 hPa and 850 hPa wind fields are usually good guidance for the general flow across the mountainous areas, but remember that the model orography has limitations. The forecaster should have a good grasp of the country's topography.

Stability of the atmosphere is of course a major influence upon the development, or not, of mountain wave activity. The forecaster should therefore pay close attention to appropriate tephigrams (actual and forecast).

2.3.6 Brief Case Study

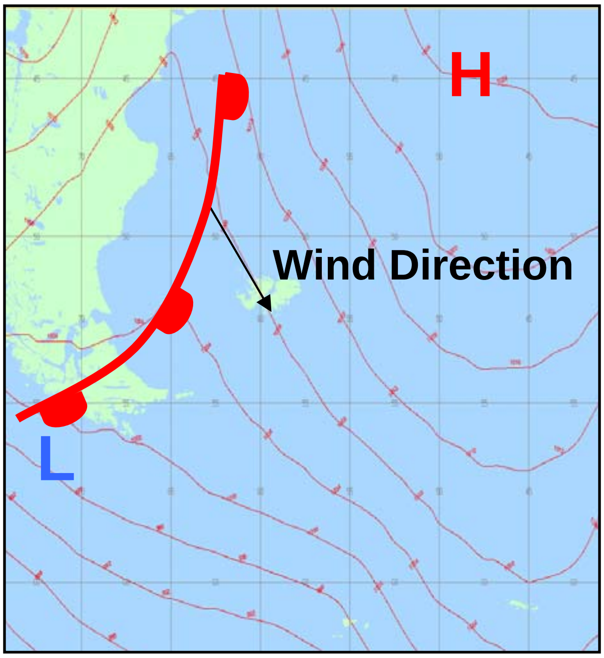


Figure- 6. Sea level pressure map covering the Falkland Islands. High pressure is to the northeast (southwest flank of the South Atlantic subtropical high).

The map above shows a classic, stable, NW gradient affecting MPA. It is often the case that such scenarios have either a low subsidence inversion; or a low inversion ahead of an approaching warm front. The tephigram below shows the resultant temperature and wind profiles, and is again the classic indicator for rotors to develop over/around the airfield. The hills generating the affect run approximately east to west, a few miles to the north of the airfield. Although Mt Wickham is some 2000 ft high, the ridges are generally between 1000 and 1500 ft high.

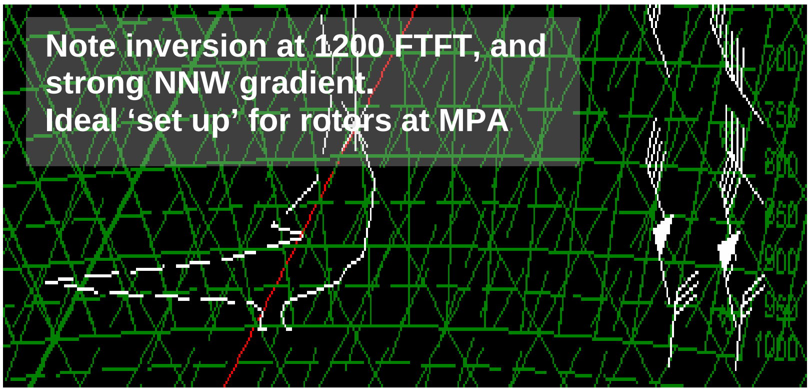

Note inversion at 1200 FTFT, and strong NNW gradient.
Ideal 'set up' for rotors at MPA

Figure- 7. Tephigram indicating inversion, hydro-lapse and winds at MPA

Looking at the resultant METARs during the period, we can see;

- the strong flow, with gusts to 50 kt,
- the variability in speed/gusts. Look at the change in wind/gust speed between 0850 Z and 1350 Z.
- Small patches of low stratus, likely to be indicative of rotor zone.

221650	33015KT	9999 FEW010 SCT100 BKN120
221550	33027G39KT	9999 –RA FEW012 SCT100 BKN120
221450	34031G42KT	9999 FEW012 BKN100 BKN120
221350	35036G47KT	9999 FEW008 SCT012 BKN100
221250	34009G19KT	6000 VCSH FEW007 BKN012
221150	01016KT	9999 –RA FEW007 BKN014
221134	36015G25KT	9999 FEW008 BKN014
221050	33010KT	9999 FEW008 BKN018 BKN100
220950	35016G29KT	9999 FEW011 SCT019 BKN150
220850	35036G48KT	9999 FEW045 SCT130 OVC160
220750	35024G36KT	9999 FEW045 SCT080
220650	36033G46KT	9999 FEW010 SCT090 BKN200
220550	35033G47KT	9999 FEW010 SCT090 BKN200
220450	36036KT	9999 FEW010 BKN220
220350	36039G50KT	9999 FEW008 SCT080 BKN120
220250	36028G38KT	9999 FEW008 SCT080 BKN120
220150	03023KT	9999 FEW008 SCT180 BKN120
220050	01031G41KT	9999 FEW008 SCT120
212350	01038G49KT	9999 FEW007 SCT120
212250	01028KT	9999 FEW007 SCT120
212150	36037G50KT	9999 FEW007 SCT050 BKN220
212050	01028G39KT	9999 FEW003 BKN100 BKN120

2.4 Clear Air Turbulence (CAT)

2.4.1 Description

CAT is the term used to describe medium- or high-level turbulence produced in regions of marked windshear. As its name suggests, this often - though not necessarily- occurs in the absence of cloud, making it difficult to detect visually.

2.4.2 Effects on Aircraft

As with all turbulence types, the degree of turbulence is categorised by the ICAO definitions. Although the aircraft is at height on most occasions, severe turbulence must never be trivialised. In extremes, structural damage may occur.

For civil aviation, passengers may be made uncomfortable, or suffer injuries when not wearing their seat belts. In recent years, also fatalities occurred.

2.4.3 Diagnosis of Hazard Using Appropriate Imagery

Certain cloud signatures in satellite imagery may help identify areas of likely CAT. AIREPs should also be monitored for reports of in-flight turbulence.

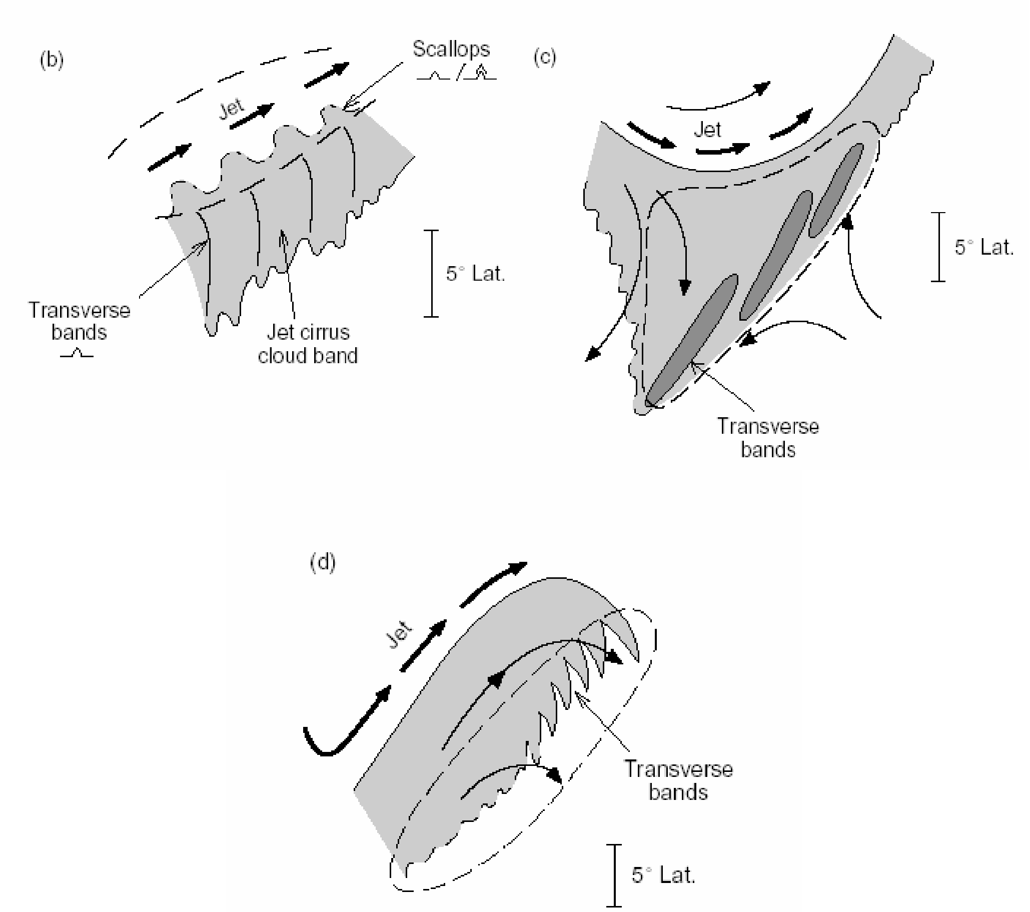


Figure-8. Figures b, c (previous page), and d (a not shown) indicate cloud signatures indicative of turbulent areas. From Bader et al, 1995.

A characteristic pattern of cirrus clouds, known as ‘billows’, is a signal of a region of CAT. The billows are an indication of breakdown into turbulent flow in the form of Kelvin-Helmotz instability.

Kelvin-Helmholtz instability can be evaluated via reference to the Richardson number Ri which itself is the ratio of the turbulence production by static instability to the one by shear:

$$Ri = \frac{N^2}{\left(dUdz\right)^2}$$

where

$$N^2 = \frac{\left(g/\theta\right)}{d\theta/dz}$$ (N being the Brunt-Vaisala frequency)

In the above equations U is the wind speed, g the gravitational acceleration (about 9.8 ms-1), θ the potential temperature, and z height. Note, that even in the stratosphere where static stability is high, turbulence and breaking waves can still be generated if the windshear is of sufficient magnitude. Values of Ri less than 0.25 will allow the production of ‘breaking waves’. Values of between 0.25 and 1.0 will allow the persistence of turbulence, whereas values greater that 1.0 will tend to cause any existing turbulence to subside.

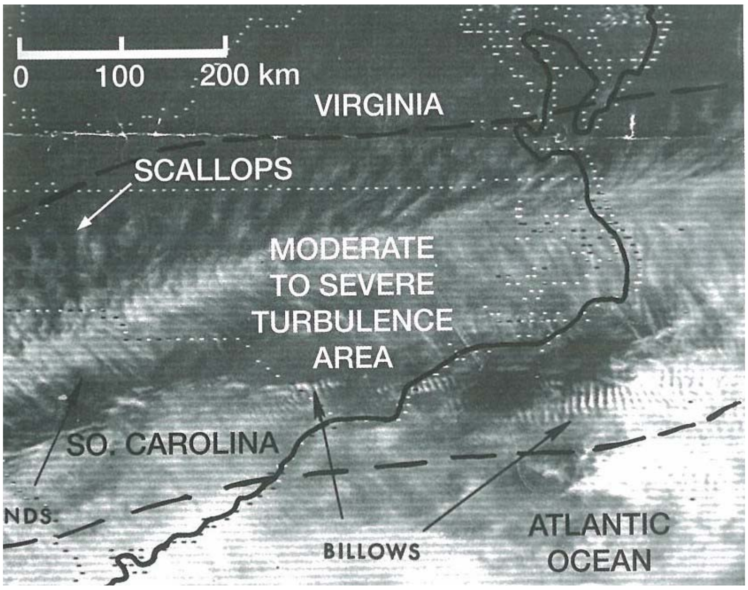


Figure- 9. Note the Billows as indicated marking breakdown into turbulent Kelvin-Helmholtz instability

Water vapour and infra red are invaluable in locating jet-streams, and may indicate that the model has a positional error. In such instances the regions of CAT can be adjusted accordingly.

Aireps should be monitored, and can help assess and adjust jet-stream strength.

2.4.4 Empirical Forecasting Techniques

CAT is often reported;

- on the cold (pole-ward) side of a jet-stream, near and below the core where the windshear is greatest;
- on the warm (equator-ward) side of a jet-stream , above the core. The stronger the jet, the more likely that CAT will be present;
- in developing upper ridges where the speed of the wind flow around the ridge approaches its limit due to curvature;

- in sharp upper troughs where wind direction changes abruptly;
- in regions of confluence and diffluence in jet-streams;
- in cold areas where a narrow but marked line of CAT may occur.

Some more characteristics:

- If the core speed exceeds 100 kt and vertical windshear 4 kt/1000 ft, forecast moderate CAT within 150 nautical miles.
- CAT is rare above a well defined tropopause, due to the Richardson number (Ri) being greater than 0.25.
- CAT may occur, or be intensified, over a region of convection, especially embedded frontal convection.

CAT occurs more often over land, especially over mountainous land, than over the sea. 60% of CAT reports are near jet-streams. The severity of CAT may be estimated if the horizontal and vertical windshear values are known (see Table 4). CAT probability is also predicted automatically by the forecast model.

Table- 2. Subjective guide relating CAT to horizontal and vertical windshear.

	Moderate	Severe
Horizontal windshear	20 kt per degree of latitude	30 kt per degree of latitude
Vertical windshear	6 kt per 1000 ft	9 kt per 1000 ft

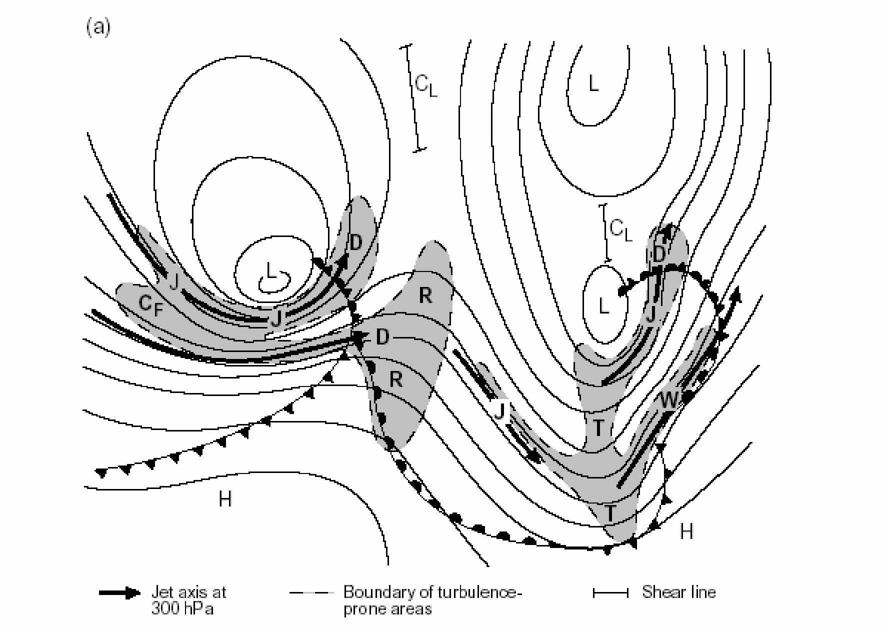


Figure- 10. Schematic showing areas prone to CAT

Solid lines	300 hPa contours
CF	Region of confluence between two jet-streams.
CL	Upper air col. Turbulence occurs in narrow bands along the 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.

2.4.5 Associated NWP products

For high level jet-streams appropriate gph fields, combined with isotach and streamline analysis can help diagnose areas of likely CAT. Consider how ridges and troughs are developing in the model, and apply the empirical techniques above to the model fields.

The Dutton Index is a value obtained from model data, and is therefore a raw NWP product that can provide guidance for CAT forecasting.

$$\text{Dutton Index} = \frac{5(HorizontalWindShear) + (VerticalWindShear)^2 + 42}{4}$$

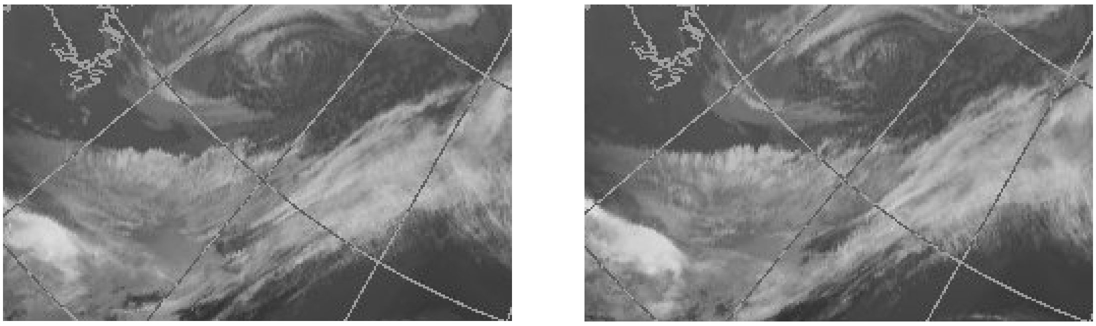
CAT is probable when DI >4.

It may be possible at some locations to obtain copies of the 'jet-plan' (a flight specific calculation of route winds, timings, fuel burn, flight level temperatures etc) and assess the 'shear' value provided as part of the dataset.

Remember that jet-cores may not be correctly resolved by the model because of grid-length/vertical separation between model levels.

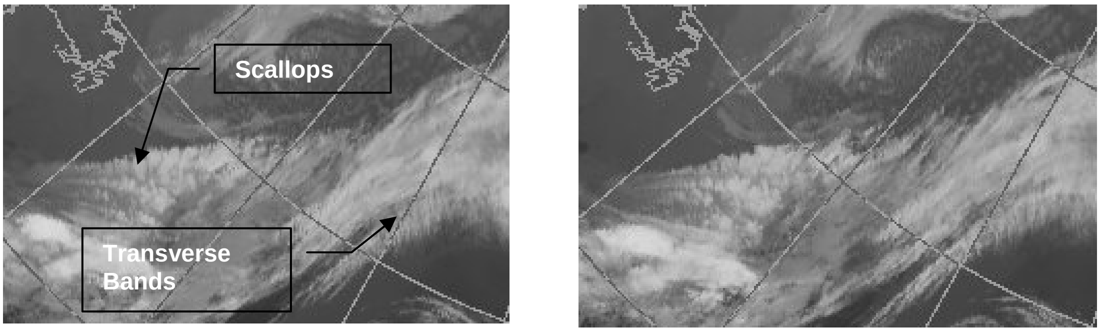
2.4.6 Brief Case Study

Imagery of Scallops and Transverse Bands



IR 0500 Z

IR 0600 Z



IR 0700 Z

IR 0800 Z

Figure- 11. Sequence of images showing developing scallop cloud and developing transverse bands on 06/06/2005

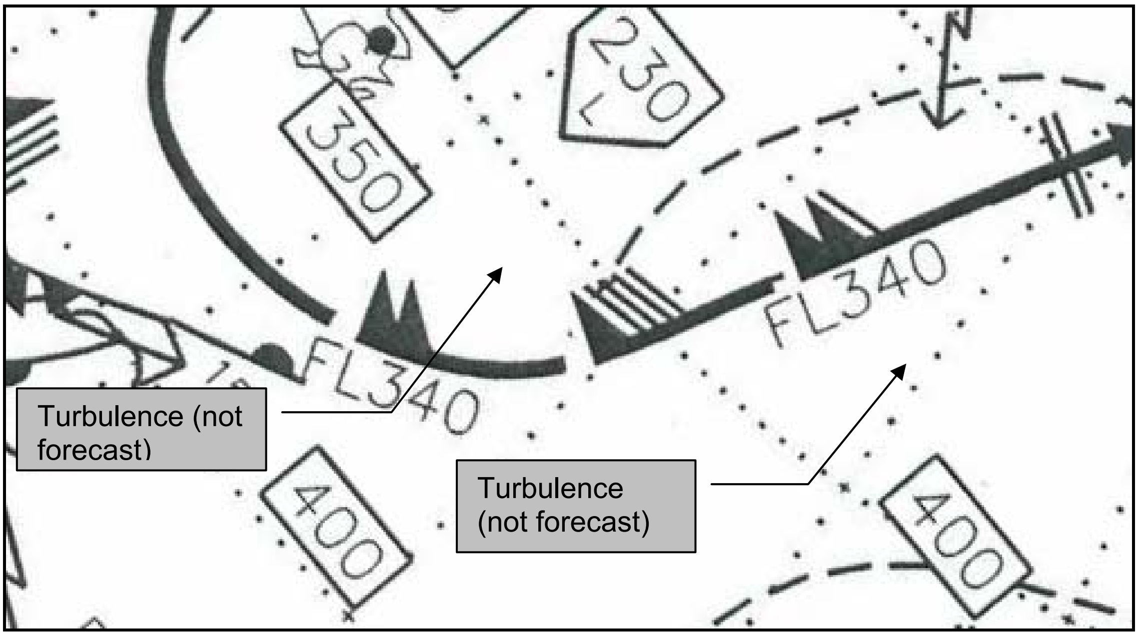


Figure- 12. Verifying NAT Significant Weather Chart, 0600 Z, 06/06/2005

The NAT Significant Weather chart (for 0600 Z) did not quite predict the areas of turbulence associated with the scallops or the transverse bands. It is probable that moderate turbulence would have been encountered in these areas The area alluded to on the chart along the 110 kt jet at FL340 suggested moderate CAT between FL280 and FL390.

What ought to be remembered is that the WAFC charts are issued 24 hours in advance, and certain cloud signatures may not be apparent that far in advance - particularly when systems are developing. Also, the model may be in error, and the data from which the forecaster works may of itself not fully capture events.

Nonetheless, it is such imagery that can allow a forecaster to add value to a product, when briefing aircrew immediately prior to a long distance flights.

2.5 Low Level Jets

2.5.1 Description

There are several forms of low level jets.

One form of low level jet can be described as a tube of enhanced low level wind flow along and ahead of a cold front. As such, it is associated with the front, and will move with it.

Another form of low level jet can be described as increased wind flow caused by the formation of a nocturnal inversion and associated de-coupling of the gradient and surface wind regime. When the flow is de-coupled, the surface flow becomes very much lighter, but the flow immediately above the discontinuity is no longer affected so much by friction (or viscous drag), and so becomes stronger.

The nocturnal low-level jet is a boundary layer feature in heights between 50 and 1000 m. It may be confined to shallow layers of a few decameter depths. Shear may be significant with values of 20 m/s per 50 m. The nocturnal low-level jet is a typical inertial flow occurring under weak pressure gradients. The wind direction turns during the night according to the inertial frequency $2\pi/f$. Due to the shear at the lower and upper part of the jet, turbulence may be generated there and/or gravity waves may be excited. Nocturnal low-level jets are a frequent feature in certain areas of the world, especially over the lower plains of Australia, of Northern Central Europe and over the Great Plains in North America.

There is a type of low level jet, referred to as a ‘sting jet’, that can form around low centres during explosive cyclogenesis. Such jets are regions of enhanced windflow, caused by descending air accelerating as it is cooled (and therefore becoming denser) due to precipitation evaporating as it (the precipitation) falls through the already descending air. It should be noted that the ‘sting jet’ is still being studied, and its precise method of formation will be more complex than the simple description above.

An example of a ‘climatological’ low level jet would be the seasonal development and subsequent decay of the ‘Somali Jet’. The Somali Jet is a feature of the northern hemisphere summer, and the development of the Asian Monsoon. When fully developed a SE’ly low level flow crosses the northern tip of Madagascar, before veering S’ly and then SW’ly across the Horn of Africa to become a SW’ly flow running parallel to the coasts of Yemen and Oman. The jet has important climatological effects, but with maximum winds of some 40 or 50 kt at the 850 hPa level, there is an aviation aspect to always consider.

2.5.2 Effects on Aircraft

Turbulence effects on the low level cold front jet can be marked, and unexpected. Windshear across the boundaries of the jet will need corrective action on the part of the pilot. By definition, the low level jet implies that terrain clearance may be compromised, and difficulties during the landing phase may be encountered.

Nocturnal jets may not have any apparent turbulence associated with them whilst the pilot remains on one side of the discontinuity. Crossing the boundary may result in a period of turbulence, but it is the change of airflow across the wings at low level that may adversely affect lift – especially in the landing and take off phase.

2.5.3 Diagnosis of Hazard Using Appropriate Imagery

Low level jets on cold fronts may not always be resolvable on satellite imagery. However, it may be possible to spot areas of enhanced convection, indicating line convection on the front and as a result, an implied low level jet.

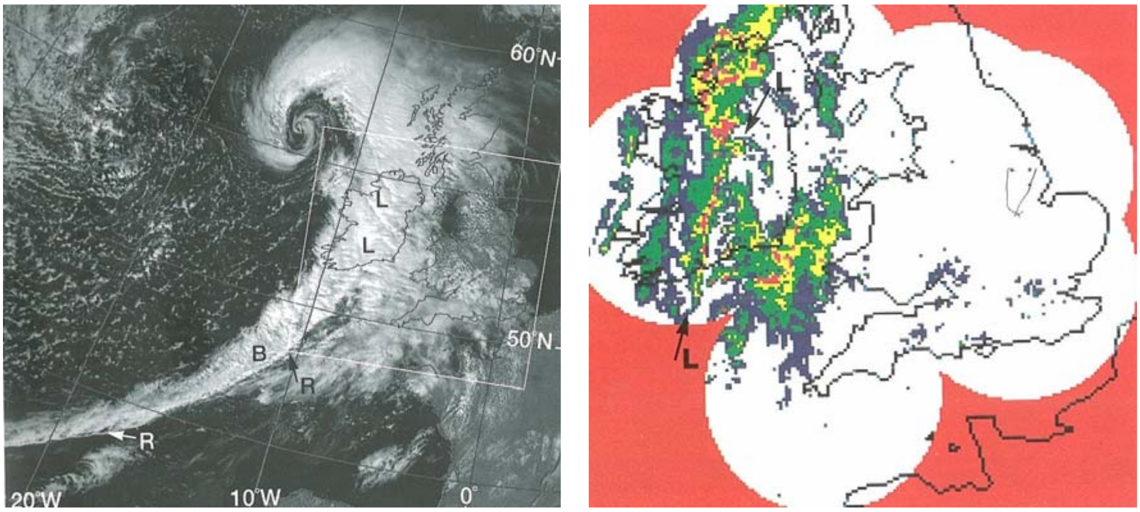


Figure- 13. Satellite and radar imagery indicating rope cloud (RR) and line convection (LL)

Split fronts may signal low level jets in the shallow moist zone.

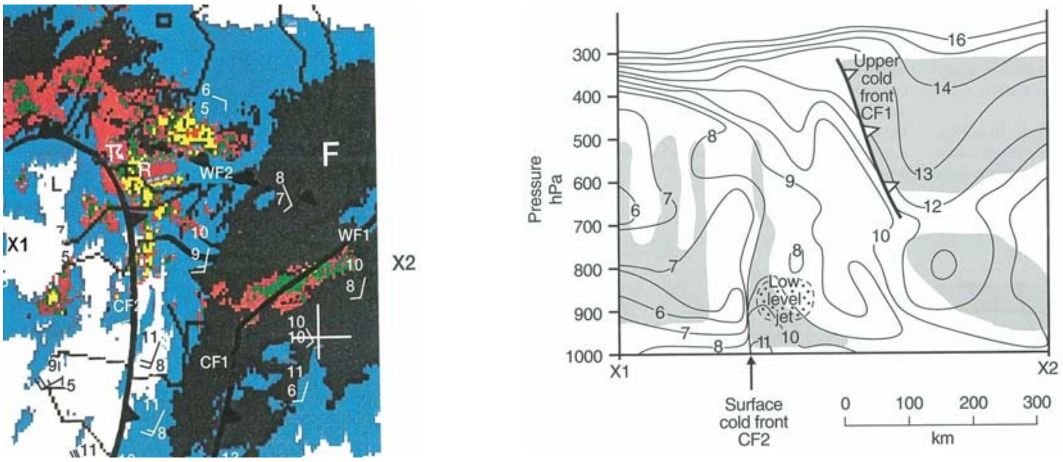


Figure- 14. **Radar and satellite composite, with corresponding cross section, illustrating low level jet relationship to upper and surface frontal positions**

Radar imagery may indicate the line convection on a cold front, and by inference suggest a low level jet.

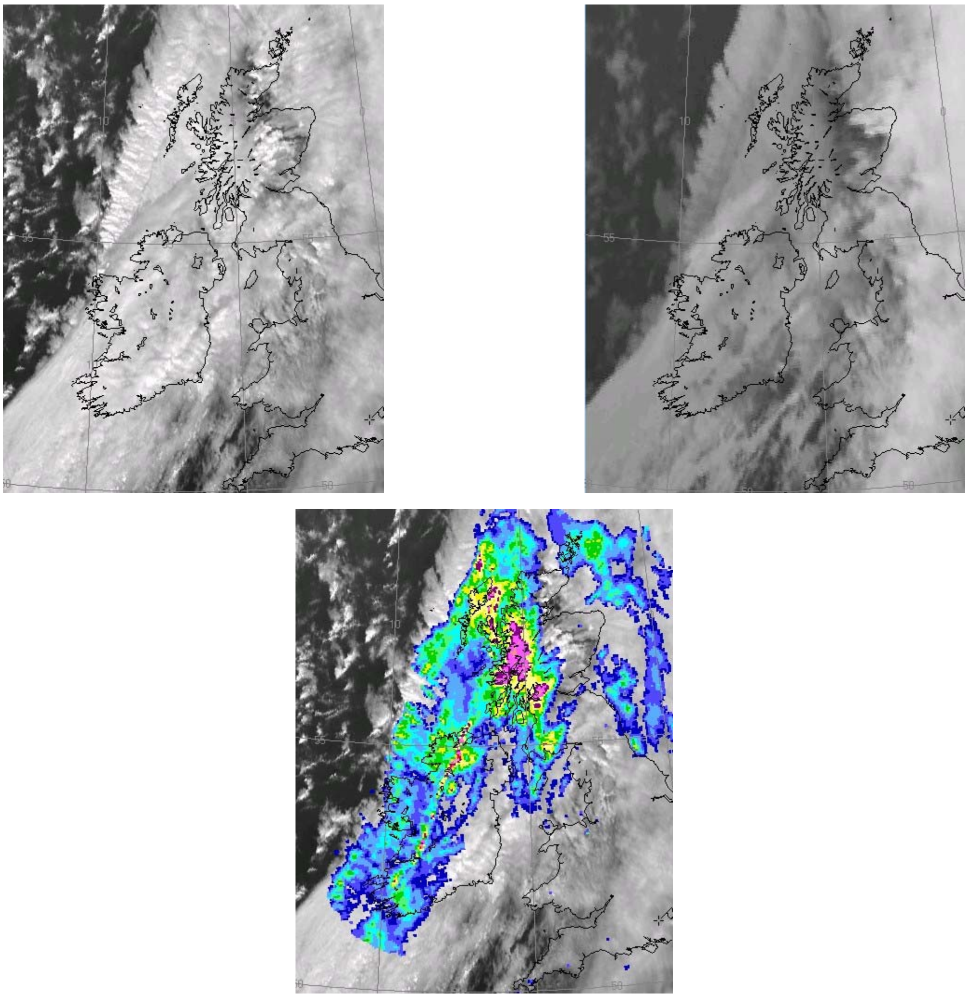


Figure- 15. **In this series of imagery taken at 1200 Z on 26 September 2005, the Vis and IR imagery does not reveal the line convection. Radar imagery (at far right) reveals the line convection running from Limerick to Enniskillen. An enlarged radar/vis image is shown below.**

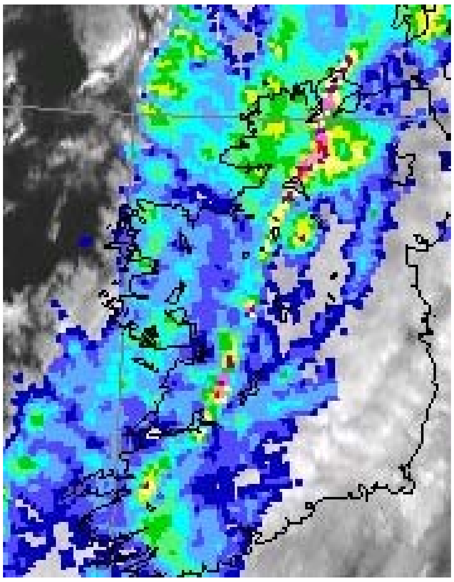


Figure- 16. Enlarged image revealing the line convection over Ireland

2.5.4 Empirical Forecasting Techniques

Forecasters should be aware of the conceptual models behind all of the low level jet scenarios. Not all low level jet forms lend themselves to reliable empirical techniques.

However, an example of a locally developed method would be the nomogram developed for forecasting the nocturnal jet strength and height in the Persian Gulf – see case study.

A diagram is reproduced below which visualises the relationship between frontal zone, line convection and the low level jet.

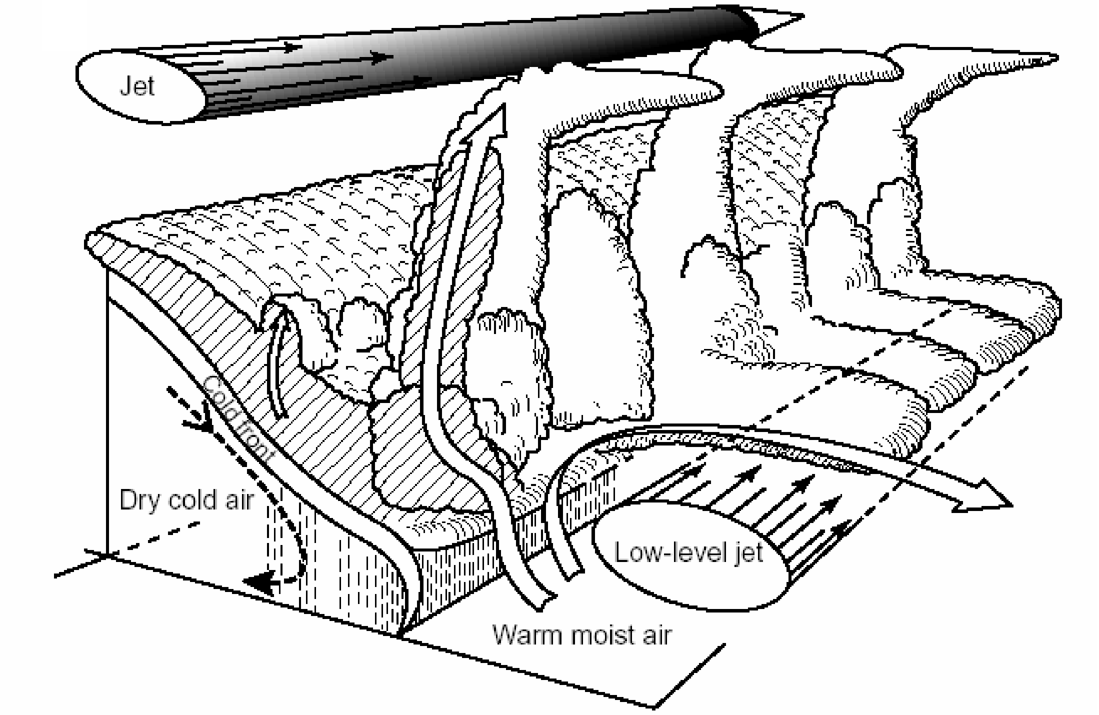


Figure- 17. Conceptual model of Low Level jet forward of surface cold front

2.5.5 Associated NWP products

NWP forecast winds may not fully capture low level jets.

Cross-referencing of actual against forecast tephigrams may be the only way to spot an enhanced region of low level wind where none had been expected. Of course, this relies upon real ascents being released at the right time and place to capture the low level jet! AMDAR profiles could be used to identify such features.

Tight gradients in the 850 θw plume in the vicinity of the cold front, especially if there is other evidence suggesting the feature has split, may imply a scenario similar to the example given by Bader above.

NWP forecast ascents will often indicate surface inversions, but may not fully resolve the sharpness of that inversion. Forecasters should be alert to the signals and consider the effect of near surface wind flow should the surface and gradient windstreams become de-coupled.

2.5.6 Brief Case Study

A nocturnal jet is frequently observed between midnight and dawn along southern shore of the Arabian Gulf. Here, in conditions of light and variable surface wind, and less than 20 kt north-westerly geostrophic flow, a low-level jet maximum in excess of 40 kt may be observed below 1000 ft. This presents a particular windshear hazard to aircraft on take-off or landing.

Figure 20 shows three cases where a marked temperature inversion is present, and winds reach a super-geostrophic maximum of around 40 kt at a height well below 1,000 ft.

Membery (1983) has devised a simple nomogram for predicting the speed and height of the jet, given the magnitude of the temperature inversion (Figure 21). This may be applied when conditions are favourable for the development of a nocturnal jet, i.e.:

- clear skies allowing sufficient radiative cooling at the surface to set up a stable layer near the ground;
- anticyclonic synoptic-scale north-westerly flow with a substantial pressure gradient.

The nocturnal jet disappears during the early morning as daytime heating breaks down the temperature inversion.

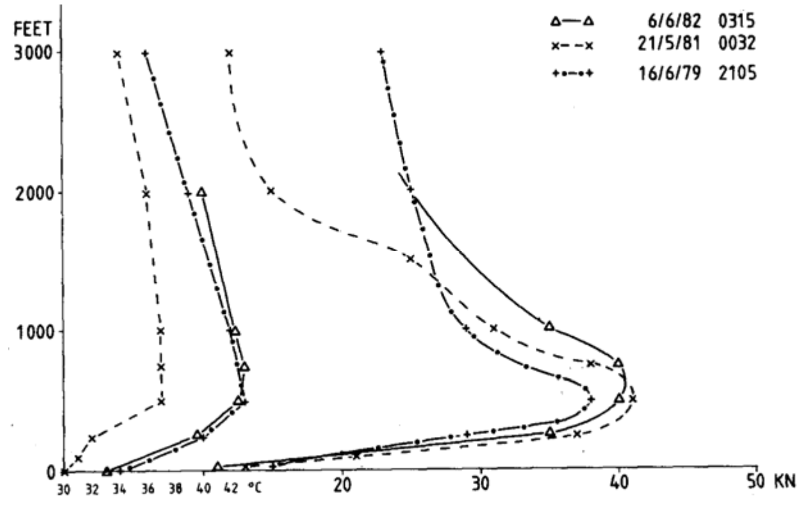


Figure- 18. Low-level profiles at Bahrain with marked temperature inversions present (from Membery,1983)

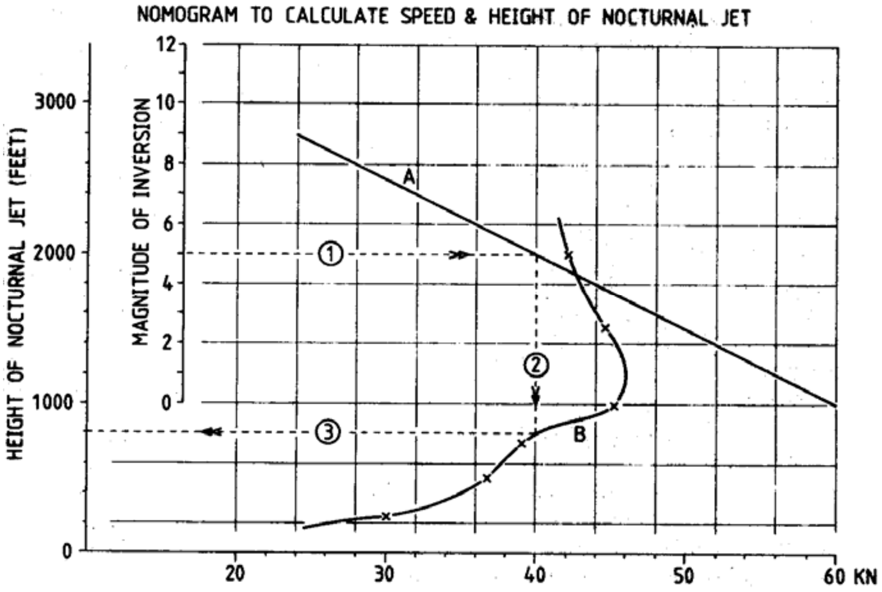


Figure- 19. Nomogram for forecasting speed and height of nocturnal jet

Step 1: Forecast magnitude of inversion, e.g. 5°C and locate intercept at A.
Step 2: Read of speed of low-level max (40 kt).
Step 3: Read off most probable height of max (800 ft).
Valid for inversions of 3 to 9°C and jet wind speeds of 24 to 46 kt (from Membery, 1983).

2.6 Wake Turbulence/Wake Vortices

2.6.1 Description

Wake turbulence is a result of the vortices formed in the wake of aircraft. Vortices form on the top surface of each wing, and are left in the aircraft's wake. Helicopters also produce wake turbulence, with vortices generated from the main rotor blades.

In their formation, they are not of 'meteorological' origin as they serve to keep the aircraft fly. and transport momentum downwards Primarily, they are a function of the weight, size, and aerodynamic properties of the aircraft. However, once formed, they are known to sink with a speed of 1-2 m/s, and will be transported with the general wind flow.

2.6.2 Effects on Aircraft

As with all forms of turbulence, encounters at low level can prove fatal, with little room or time for recovery. It might be considered that the worst case scenario would be that of two aircraft taking off. All other things being equal, the lead aircraft is likely to be full, in terms of passengers, cargo and fuel. Because of its weight it will generate more intense wake vortices/turbulence. The second aircraft takes off, and it too will likely be full and heavy. On encountering the turbulence, because of its high weight, it will be less responsive to control input and engine power settings, and may well impact the ground. Experienced turbulence together with improper rudder reactions proved to be disastrous as the design load limits might be exceeded.

Light aircraft which encounter the wake turbulence of heavy airliners may be violently tossed around.

Even after take-off, aircraft can encounter wake turbulence unexpectedly. Consider an aircraft taking off in a northward direction, and departing the area. If the wind is from the west, then the wake will drift eastward. A second aircraft may take off, turn towards the west and subsequently catches up with, and encounters the previous aircraft's wake.

The simplest precaution for pilots to take is to remain a safe distance behind the leading aircraft. A light aircraft must remain at a greater distance behind a heavy aircraft, than the distance that a heavy aircraft must remain behind a similar heavy aircraft. Currently, it is the responsibility of Air Traffic Control and the captain of the following aircraft to maintain such separation and to comply with prescribed internationally agreed separation distances. There is increased pressure these days to reduce such separations to a still safe minimum, and meteorology may play a part in this.

Contrails forming at the exit of aircraft engines will be incorporated in the wing tip vortices. Thus from a four engine contrails only two separate ones remain after one aircraft length behind. Subsequently the behaviour of the wake vortices may be monitored by the contrails marking the former. Usually, wake vortices exhibit a longitudinal variation which finally leads to a break-up of the vortices. This break-up is enhanced and, therefore, occurs earlier if ambient turbulence is high.

2.6.3 Diagnosis of Hazard Using Appropriate Imagery

There is no imagery available to the meteorologist to enable wake vortices to be diagnosed.

Long living contrails require a supersaturated atmosphere with respect to ice. Very often, therefore, contrails perform prior to the onset of natural cirrus clouds. Contrails, however, might live for hours, while the wake vortices usually are dissipated after few minutes.

2.6.4 Empirical Forecasting Techniques

As noted above, the main factors are the weight, size, and aerodynamic properties of the aircraft. However, once formed, they are known to sink, and will be transported with the general wind flow. Their persistence and strength is affected by the stability of the air through which the aircraft flies, and the strength of the wind. Vortices tend to decay most quickly in highly stably stratified and unstable air masses. They persist for longer when the atmosphere is more neutrally stratified. There is little, if anything, that bench forecasters can usefully add at the current time with regard to persistence.

The vortices, once formed, tend to sink at between 300 ft and 500 ft per minute, eventually levelling off some 1000 ft below the level of formation, or some 5 to 9 nautical miles behind the aircraft. Helicopters also form wake vortices or a down-wash, and a helicopter of a given weight may generate more powerful vortices than a fixed wing aircraft of similar weight. When vortices are generated on the ground during take of or landing, clearly they cannot sink but will tend to persist essentially at the surface and move sidewards from the aircarft track. This depends, however, on the surface wind. It, therefore, might happen that sideward motion and advection in the opposite direction lead to a stationary wake vortex. When descending to the surface from above, they may 'bounce and move upwards again. .

Forecasters may be asked for more detailed information on wind direction where several, especially parallel, runways are in use. Controllers may have concern about wake vortices (and attendant turbulence) drifting in the wind across other runways.

Wind direction, and the resultant track of wake vortices, may influence the choice of circuit direction (right hand or left hand). Again, the information provided by the forecaster will assist the controller under such circumstances.

2.6.5 Associated NWP Products

There are no current operational NWP products available that will predict wake turbulence specifically, or its persistence. Research is ongoing and wake vortex models are under development, which allow for a given aircraft and a given environment to determine where and when and for what time wake votices from that aircraft might be observed.

With regard to the drifting of wake turbulence, low level winds are important and model winds will usually provide a good first approximation. Forecasters should be particularly wary in light wind scenarios. The limitations of the models may mean that more can be usefully added by the forecaster by determining the most likely direction of the light drift and therefore if wake vortices may or drift onto adjacent runways.

Brief Case Study

On the 12th November 2001, an Airbus 300 crashed into Queen’s District, New York, after taking off from JFK airport. The aircraft is believed to have encountered wake turbulence from a Boeing 747 that had departed shortly before.

Whilst there is controversy regarding the details of the crash, it is believed that the encounter with the 747’s wake, and the subsequent attempts at recovering the aircraft, set up destructive forces on the aircraft’s vertical stabiliser, resulting in loss of control and subsequent impact with the ground. Whilst the wake turbulence itself would not have destroyed the tailfin, its encounter and the pilots reaction could be considered contributory.

3 ICING

Icing occurs if pecipitation aggregates on the aircraft or at or within parts of it. There are several impact mechanism. The dominant one is that super-cooled liquid water impinges on the aircraft and freezes instantaneously. Icing may occur

- in-flight

or at the surface:

- ground icing.

One might also categorize icing into:

- airframe icing
- engine icing.

Normally, forecasts of icing are for airframe icing only.

There are three strategies to cope with aircraft icing: (i) aircraft must be certified for icing, (ii) aircraft have to be cleaned of ice prior to take-off (clean wing princip), (iii) aircraft are equipped with de-icing equipment. Each aircraft is certified up to a certain category of icing severity: light, moderate, severe.

3.1 Airframe Icing

3.1.1 Description

Airframe icing normally occurs when the ambient air temperature is below 0° C and super-cooled water droplets are present. However, when an aircraft dives steeply and moves into air with positive temperatures, icing may occur while the aircraft skin, especially close to the tanks, is still below freezing point – this is known as ‘cold soak’.

There are five types of airframe icing:

- Rime Ice – white, porous, opaque, brittle and rough, so disruptive to airflow. This occurs at low temperatures (<10°C) and/or low liquid water contents as under those circumstances the released heat during the freezing process can be transported immediately to the enviropnment.
- Clear Ice (also known as glaze ice) – clear, tough, adhesive, dense and heavy, smooth so little effect on airflow. It occurs usually at warm temperatures >10°C and/or high liquid water contents, as then, during the freezing process, an ice-water mixture is formed which remains semi-liquid for about several seconds. Due to the relatively warm temperatures the released heat needs a longer time to be carried away by the ambient air flow.
- SLD- super-cooled large drops or drizzle drops- with diameters ranging between 50 and 500 µm. SLD may flow after impingement behind the protected zones on the wing and freeze then there. Cerification regulations, in the past, ignored this hazard, and meteorologists are requested to carefully forecast SLD (freezing drizzle).
- Mixed Ice – impingement of super-cooled water and ice.
- If superooled rain drops with diameter larger 500 µm hit the aircraft, extreme accretion of ice may occur (freezing rain).
- Hoar frost – thin 'coating' occurring in the absence of rain or cloud usually when aircraft is parked outside on cold winter nights.
- Snow accreted on the fuselage has to be removed prior to take-off.
- Rain and snow mixed (sleet) is similar to freezing rain and can also lead to 'pack snow' that can block air intakes and other aircraft openings – see the section headed Snow from within these *Aviation Hazards* notes.

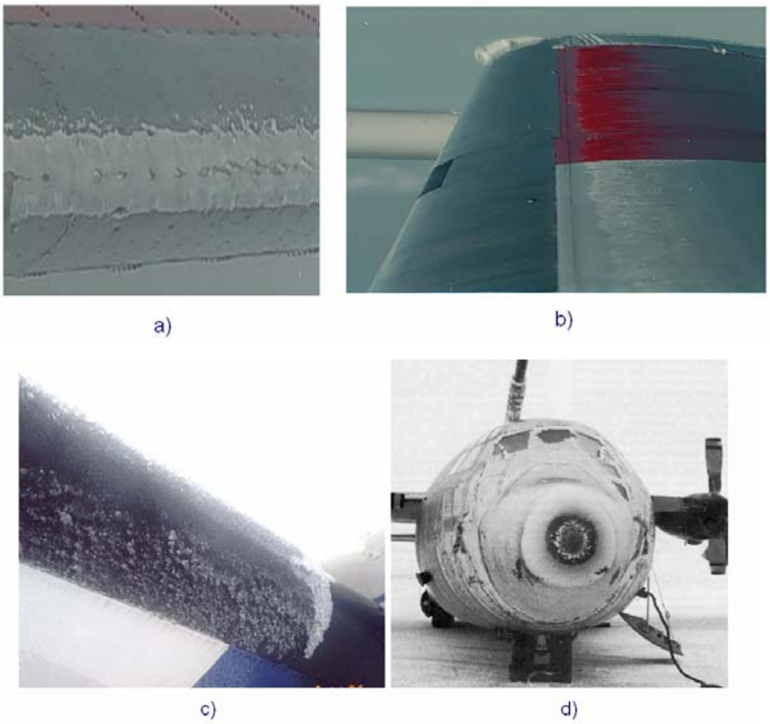


Figure- 20. Examples of: a) rime icing; b) clear (glaze) icing; c) mixed icing; d) freezing rain.

3.1.2 Effects on Aircraft

Small super-cooled cloud droplets freeze rapidly on contact with the aircraft, trapping in the ice to give a deposit of white rime on forward-facing surfaces. Larger droplets take longer to freeze, spreading out across the airframe before solidifying.

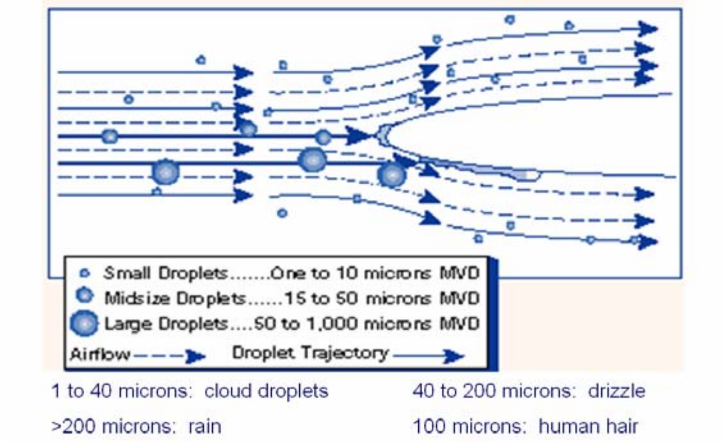


Figure- 21. Droplet trajectories in the vicinity of an airfoil

The intensity of icing is defined as follows:

Light	Accumulation rate may create a problem if flight in this environment exceeds 1 hour.
Moderate	Rate of accumulation is such that even short encounters are potentially hazardous. Anti-icing equipment must be used.
Severe	Rate of accumulation is such that use of anti-icing equipment fails to reduce or control the hazard. Immediate diversion from the region is necessary.

Aside from meteorological factors, the rate of ice build-up on the airframe also depends on the characteristics of the aircraft. Fast aircraft with thin wing cross-sections are more susceptible to deteriorating aerodynamics, and hence are more susceptible to ice accretion.

Helicopters are particularly vulnerable to icing, since build-up of ice on the rotors can lead to imbalance, de-stabilising the aircraft.

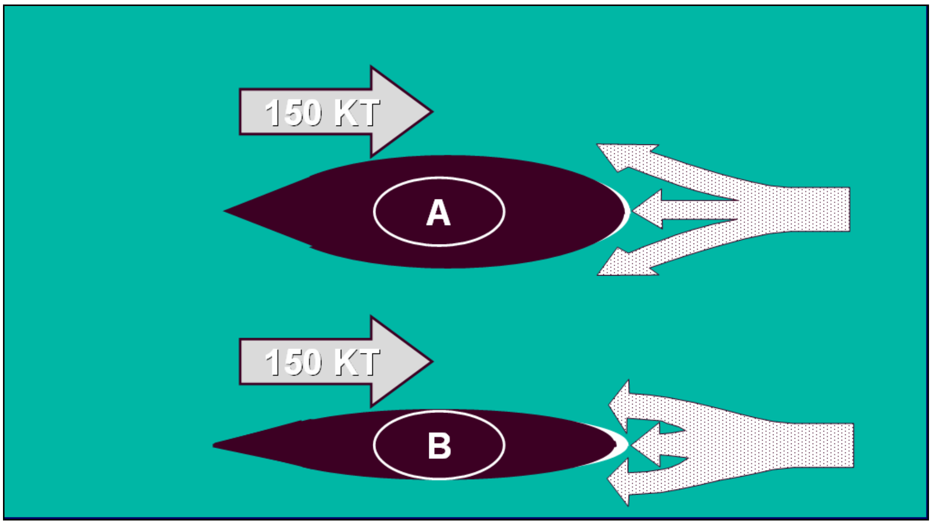


Figure- 22. Icing accumulation in relation to wing cross-section

Airframe icing is a serious aviation hazard. The possible range of effects on an aircraft are listed below:

- Reduction in the aerodynamic properties
- Change in flight performance
- Increase in weight and uneven loading
- Engine intakes become blocked
- Undercarriage retraction/extension problems
- Control surfaces jam or become stiff
- Pitot tubes become blocked
- Communications affected
- Vision impaired

Engin or piston icing occurs under conditions of high elative humdity close to freezing when the underpressure in a piston causes the humdity to condensate and freeze within the engine (see section below).

3.1.3 Diagnosis of Hazard Using Appropriate Imagery

A fundamental requirement of airframe icing is the presence of sub-zero cloud droplets. The real-time diagnosis of such cloud is most easily achieved through the use of ‘colour-slicing’ techniques on IR satellite imagery, typically MSG Channel 9 (10.8 microns). This enables the forecaster to determine actual cloud top temperatures from an infra-red satellite image. This facility is available on Nimbus.

The MSG series of satellites also have the capability to discriminate between super-cooled water droplets and ice. At 1.6µm (MSG channel 3) ice crystals and water droplets behave differently to incoming 'visible' light. Ice crystals absorb strongly, leading to areas of ice appearing darker then water droplet clouds on MSG Channel 3 imagery. Combining this property with cloud top temperatures from the conventional Channel 9 IR, particularly with the use of RGB colour composites can lead to identification of super-cooled water droplets at the cloud top. Although this method may prove a useful way to monitor cloud tops it obviously does not give information regarding the cloud beneath.

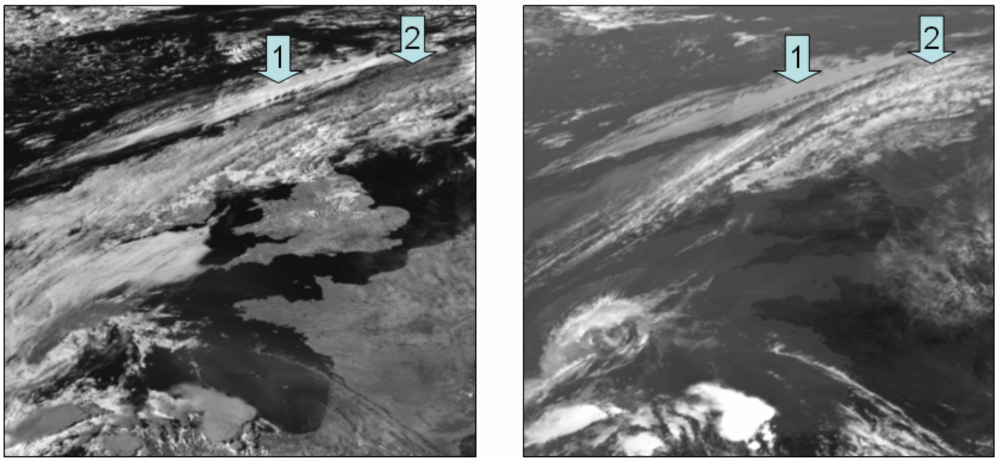


Figure- 23. Imagery for the 5/9/04 1500 Z, left 1.6 mm right 10.8 mm. Note the difference in reflection in areas 1 and 2. 1 – water droplets, high reflectance, 2 – ice crystals, lower reflectance. While in both these areas the IR picture indicates cold cloud.

3.1.4 Empirical Forecasting Techniques

Severity of airframe icing is dependent on temperature, liquid water content, droplet size and vertical motion. To determine the above, it is necessary to utilise actual and forecast vertical profiles of the atmosphere, rainfall radar and satellite imagery together with knowledge and understanding of the characteristics of different types of cloud.

Forecast considerations

In considering the likelihood of icing, the following factors should be considered:

- For icing to occur super-cooled water must be present in the atmosphere (liquid water droplets with a temperature below 0° C).
- The more super-cooled water there is present (Super-Cooled Liquid Water Content), the more significant is the icing risk. SLWC decreases with decreasing temperature.
- The larger the super-cooled water droplet, the more significant the risk.
- Only very small droplets seem to remain super-cooled below -20° C, hence the worst icing is likely between 0 C and -15 C.
- Super-cooled water droplets cannot exist with temperatures below -40° C.

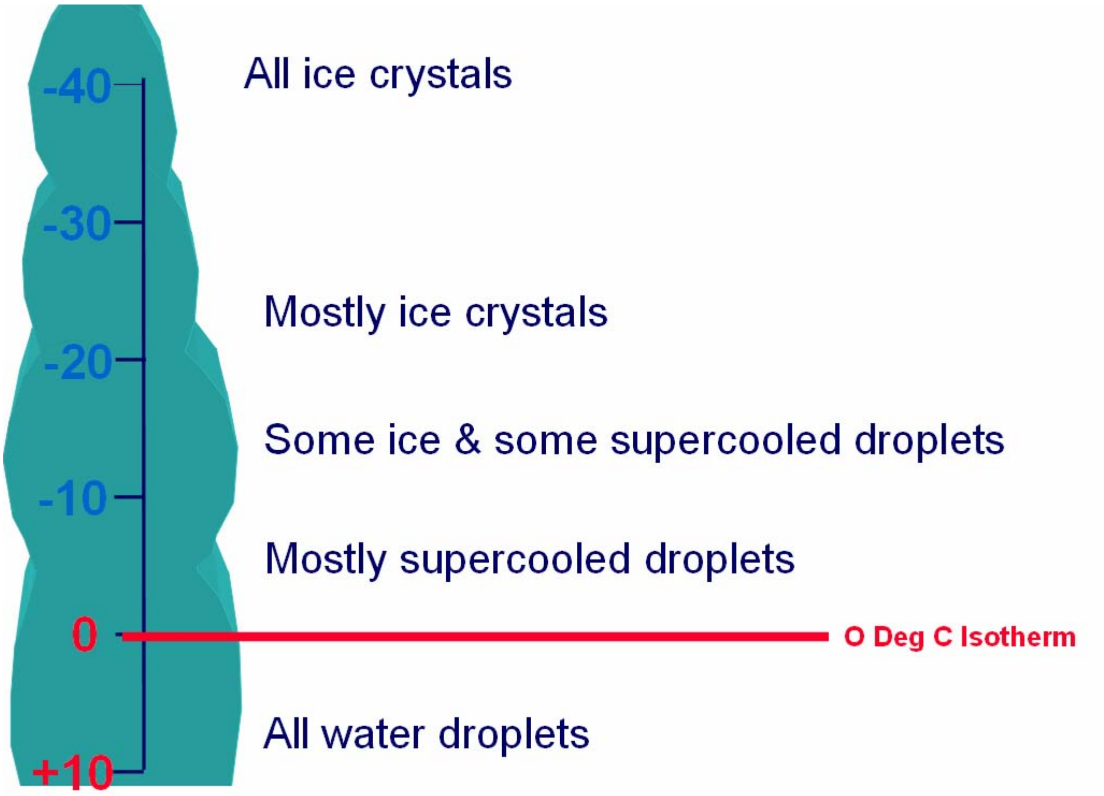


Figure- 24. Water phase changes in relation to falling temperature with height

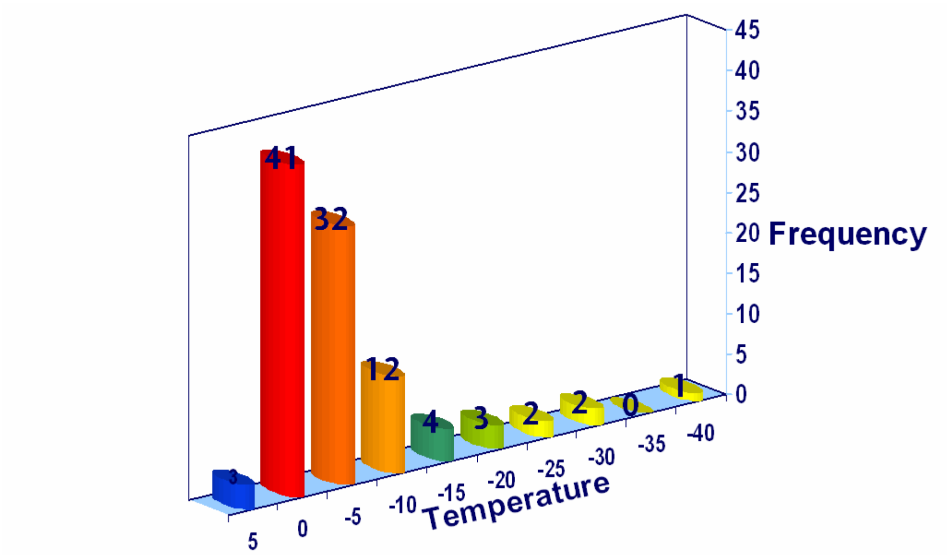


Figure- 25. Percentage frequency of airframe icing (800 reports)

- Super-cooled droplets freeze on impact with a solid surface but may spread out before completely freezing. The amount of spreading depends on the size of the droplets (large droplets spread out more), the ambient air temperature and the temperature of the surface.
- Vertical motion of cloudy air will increase the liquid water content of the cloud. The most severe icing is associated with updraughts in cumuliform cloud, but the vertical motions in frontal and orographic cloud can also lead to severe icing.

Liquid water content of clouds

The liquid water content of the cloud depends on a variety of factors. Some import considerations are given below:

- From a value of zero just below the cloud base, the liquid water content of a cloud increases roughly linearly for the first 600–1000 ft. In the absence of orographic uplift, embedded cumulonimbus or precipitation little icing occurs in this bottom 600-1000 ft.
- There is a wide variation of cloud liquid water within each cloud: mixing with dry air at the cloud top may reduce the cloud water content to half the maximum value, while maximum values are only approached in a tiny fraction of the cloud volume.
- In what appears to be a uniformly layered cloud, there may be significant spatial changes in the severity of icing if some part undergoes vertical motion due to orographic effects.

Forecasting Icing Types

- Rime Ice – small super-cooled water droplets, relatively low SLWC along flight path, temperature range typically 0 C to -40 C, rapid freezing due to small latent heat release thus trapping air.
- Clear Ice (also known as glaze ice) – large super-cooled water droplets, relatively high SLWC along flight path, temperature range typically 0 C to -15 C, slow freezing due to large latent heat release thus allowing run-back.

- Mixed Ice – variable super-cooled water droplet size, variable SLWC along flight path, temperature range typically -10° C to -15° C, different rates of freezing.
- Freezing rain – As clear ice but very large super-cooled water droplets (SVLD) otherwise known as freezing rain. Freezing rain consists of super-cooled raindrops that freeze on contact with a surface. This can cause severe airframe icing very rapidly. It is most common when raindrops fall from a warm layer of the atmosphere into a much colder layer below, causing the water droplets to become super-cooled. The most likely weather situation for this is just ahead of a warm front in winter, especially if the warm air is over-riding cold continental air. Note the “warm nose” in the sounding.

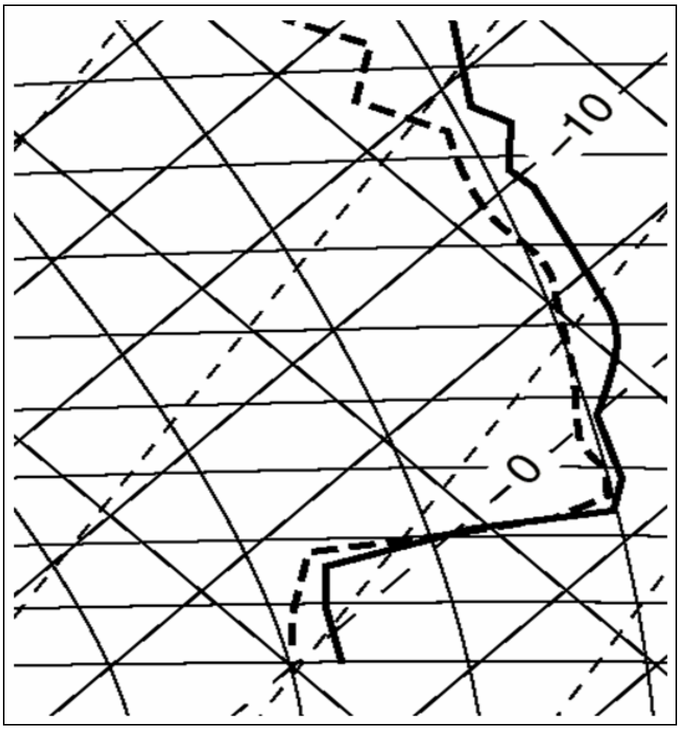


Figure- 26. Example of a typical freezing rain temperature sounding

SLD superooled large drops, drizzle drops, freezing drizzle. Drops in the size range 50-500 µm . A typical scenario is a supercooled fog layer. The pure coalescence process lead to the formation of drizzle drops after a couple of days. If temperature at the surface is below 0°C, freezing drizzle can easily be diagnosed by (a) liquid precipitation, and, (b) below zero temperatures aloft.

Hoar frost – dewpoint higher than sub-zero airframe. Three scenarios: a) aircraft parked on cold winter’s night ; b) rapid descent from sub-zero environment into warmer, moist air otherwise known as ‘cold soak’; c) take-off on frosty morning with warmer, moist air above due to nocturnal surface inversion.

Forecasting the severity of Icing

Table 1 gives a guide as to the probability, intensity and type of airframe icing. Convective clouds tend to result in worse instances of icing than layer cloud due to a higher water content, larger droplet size and greater vertical velocities. If the advection of supercooled drops from below is stronger than the freezing of drops, especially if there is a lack of freezing nuclei, then the amount of supercooled liquid water increases. That is why one may find severe icing in any part of a CB or CU. The risk of icing is also likely to be greatest in a cloud that is only just below freezing (high SLWC).

Table- 3. Probability and intensity of icing with different cloud types

Cloud type	Probability of icing	Intensity of icing	Likely Icing Type	Water content gm-3
CB	High	SEV	All	0.2– 4.0
CU	MOD/High	MOD/SEV	Clear	0.2-0.6
NS	High	SEV	All	0.2-4.0
SC, AC	MOD	Rarely more than MOD*	Mixed	0.1– 0.5
AS	Low	MOD/light	Rime	0.1– 0.3
ST	Low	Light	Rime	0.1– 0.5

**Note that: a) prolonged flight within a super-cooled, layered cloud can give rise to a greater degree of icing than suggested here. b) stratocumulus (SC) can sometimes give unexpected severe icing, particularly when it lies in a sub-zero layer just below an inversion over the sea. A special risk exists in embedded convection, and especially there near the overshooting tops. Pilots do not recognize the embedded cumuli when flying through the stratus clouds. Ice accretion rates of up to 3 m/min may be found in those convective clouds.*

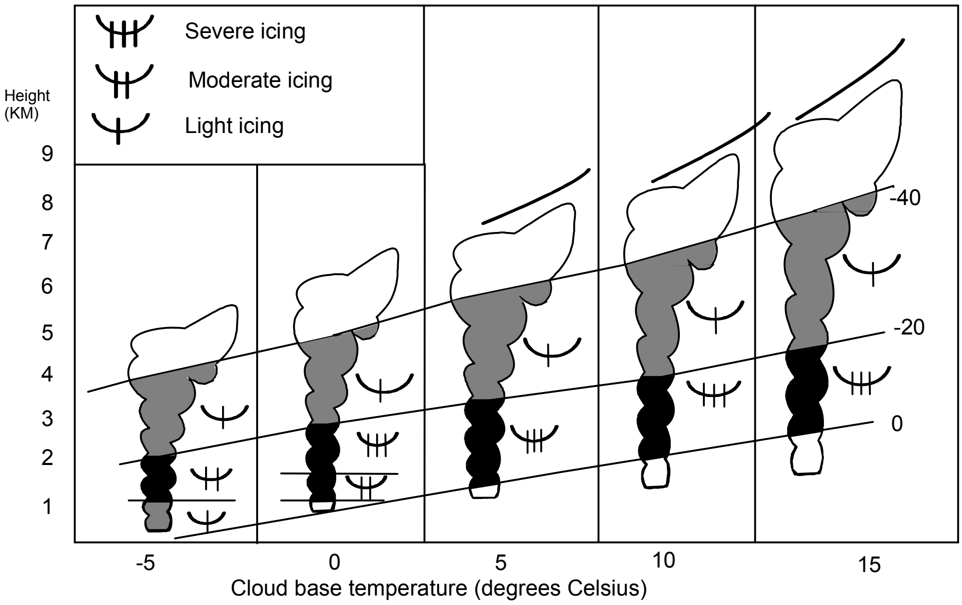


Figure- 27. A guide to severity of icing in convective clouds

The time actually spent flying in an icing environment is also an important consideration. Icing layers in clouds are usually only 2000-3000 ft thick and rarely greater than 5000 ft. Cumulus-type clouds can usually be flown around whilst icing in layer clouds can usually be dealt with by altering height, either upwards or, if terrain permits, downwards. If, however, significant mass of ice has accreted already, the aircraft might be unable already to leave the cloud upwards. Decisions, therefore, especially for light aircraft, have to be made on short time scales of often only a few minutes.

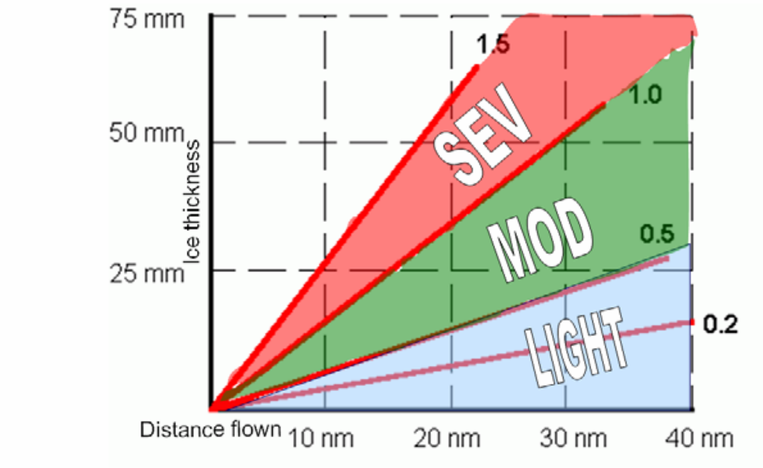


Figure- 28. SWLC (gm-3) rate of ice accretion

Non-meteorological or other factors

- Risk and severity of icing increases in sub-zero clouds over hills and mountains due to vertical motion.
- The source and nature of SLD is still under investigation. But observations tell that shear layers close to the top of a cloud supercooled cloud are prone for SLD.
- The same holds for overshooting cumulus tops.
- The impact of SLD on aircraft performance varies with type. Typically, smaller aircraft, such as turboprop, are more susceptible to SLD icing.
- Risk and severity of icing increases in sub-zero clouds over and downwind of significant bodies of (non-frozen) water due to higher SWLC and larger super-cooled water droplets.
- Friction induced kinetic heating raising airframe temperature. Eg +1° C at 100 kt and +25° C at 500 kt.

There are specific icing diagnosing and warning models under development. Some of them are already in an experimental test phase and may be accessed officially. Look for instance for CIP/FIP at NCAR, for SIGMA at METEO France, for ADWICE at the German Weather Service (DWD) and for the icing algorithm of the Unified Model UM at UK Met Office. Those models are essentially expert system, which make use of large set of observational and model and derive from them where, when, what type of, and with what strength icing occurs.

3.1.5 Icing Case Study

The following is an excerpt from an Australian Transport Safety Bureau (ATSB) report on a Saab 340 in-flight loss of control on 28th June 2002. It occurs after the aircraft had levelled out at its minimum descent altitude of 3810 ft as a result of airframe icing encountered during final descent of a flight from Sydney to Bathurst, New South Wales. The aircraft initially rolled to the left and pitched down without warning and during the recovery from the first stall, the aircraft rolled to the right and descended to 112 ft before altitude was recovered.

The final investigation ATSB report into that serious incident has found that pilots lost control because of low airspeed, airframe icing and the operation of the aircraft autopilot system, and that they did not receive a prior stall warning. One might further conclude that ice accretion must have been slightly asymetric on the aircraft such that the autopilot could not cope any more with the generated roll moment.

Using a representative temperature sounding and available IR satellite imagery, the following meteorological conditions for the Bathurst area were determined (all heights are AMSL):

- The 0° C isotherm was 3500 ft.
- The cloud was broken or overcast, base was 3000 ft, cloud top 7500 ft.
- Cloud top temperatures ranged between –7° C and -9° C.
- Cloud formation was in part due to orographic effects.
- Ice accretion was observed on the windshield during descent through cloud.

As a result of a 1994 fatal accident involving airframe icing to an ATR-72 at Roselawn, the US FAA issued an airworthiness directive, which applied also to US Saab 340s, requiring that flight manuals warn that autopilot operations may mask problems in severe icing conditions.

3.2 Carburettor and Engine Icing

Some aircraft are prone to icing in the carburettor and air intakes. This is caused by a reduction in pressure leading to adiabatic cooling as the air expands.

Carburettor icing is by far the most common form of ice-related problem affecting piston-engined aircraft. When humid air enters the venturi in the carburettor, ice crystals are deposited. This constricts the venturi and causes progressive power reduction. Carburettor icing frequently occurs when the ambient air temperature is above 0 C, the dominant factor being the moisture content of the air. The more humid the air, the higher the risk; hence engine icing is more likely on a warm, humid, cloudy summer's day, than on a cold, dry, clear winter's day. In very moist air, adiabatic cooling can result in a temperature reduction of up to 5 C.

The cooling may be enhanced in the carburettor by the evaporation of fuel. This refrigeration cooling can in itself lead to a temperature reduction of around 10° C.

An additional problem for the engine is the build-up of ice on the rims and struts of intakes at, however, different conditions. In extreme cases large pieces of ice can break off and cause damage to the engine.

Some aircraft may require forecasts of the heights of specified temperatures (e.g. the PS 03 and MS 01 levels) in order to avoid flying at heights where engine icing may be a problem.

Engine icing is most common when the air temperature is a few degrees above 0° C and the relative humidity is greater than 60%. Pilots, therefore, use forecasted temperature data and an estimate of humidity to assess the engine icing risk. Typical high humidity scenarios are mist post heavy rain and just below stratiform cloud.

4 CUMULONIMBUS AND THUNDERSTORMS

Cumulonimbus (CB) clouds are a severe hazard to aviation, due to the likelihood of:

- severe turbulence,
- severe icing,
- micro-bursts, generating squalls or gust fronts giving severe low-level turbulence;
- lightning,

- high liquid water content, eg rain water content,
- hail.

Because Cumulonimbus clouds can generate many different types of hazards at the same time and location, they must never be underestimated. Aircraft should avoid flying into areas of known CB activity, especially when such activity may be hidden by obscuring cloud layers.

Whilst individual Cumulonimbus clouds may have a lifetime of 1½ hours, the most intense Cumulonimbus development and thunderstorm/lightning activity is associated with Multi Cell Convective systems which may develop further into Supercells. Such systems are long lived due to the spawning of daughter cells and may last for many hours.

Forecasters must always be aware of the various typical synoptic scenarios that are likely to generate thunderstorm activity. It is impractical to discuss such scenarios in detail here, and the reader is referred to the many and varied texts on the subject, including Met Office College notes.

4.1 Severe Turbulence

The reader is referred to the section on Turbulence within these Aviation Hazards notes, and should regard CB cloud as being capable of generating the most hazardous of turbulent conditions.

4.2 Severe Icing

The reader is referred to the section on Icing within these Aviation Hazards notes, and should regard CB clouds as being capable of generating the most hazardous of icing conditions. One should keep in mind that severe icing may occur at heights close to the -40° level, that is in the upper part of the cloud and might be well above 30000 ft. In the past, several incidents occurred where CBs were embedded into a large frontal cloud system and an aircraft entered a CB from above without being aware of it. Icing was such that both pitot tubes were completely blocked despite of their functioning heating.

4.3 Microbursts

The reader is referred to the section on Turbulence within these Aviation Hazards notes, where the phenomena of microbursts and CB are discussed. Also refer to the Sandstorms and Duststorms section and the discussion of the haboob phenomenon.

4.4 Thunderstorms and Lightning

4.4.1 Description

Lightning can occur in and near Cumulonimbus clouds including the anvil layers and the sub-anvil atmosphere.

The Meteorological glossary describes lightning as an electrical discharge of some 20 coulombs and a potential difference of some 108 or 109 volts. Electrical discharges may occur within the cloud, referred to as intra-cloud lightning, and between cloud and ground, referred to as cloud-to-ground-lightning. Generally, intra-cloud lightning is weaker than cloud-to-ground-lightning, but still may reach the same strength.

Thunder is the audible manifestation of the electrical discharge, caused by the violent heating and expansion of the atmosphere surrounding the path of the lightning strike.

4.4.2 Effects on aircraft

The effects of lighting on an aircraft (and its crew and passengers) are many.

If lightning strikes a previously sound, metal bonded structure, the aircraft will remain structurally sound, and the passengers and crew will not be directly affected by the strike's voltage and current, due to the Faraday Cage effect. However, entrance and exit burn marks will be evident on the skin of the aircraft. This results from the temperature of 3000 – 32000 K within the lightning channel. If the discharge is adjacent to or through structures such as aerials, then these structures may be destroyed. The effect of a lightning strike on both passengers and crew will induce shock, and possibly fear. At night a lightning strike may cause the crew to suffer temporary blindness, or degraded vision.

Lighting strikes on modern composite materials will cause de-lamination of the material. If such strikes are upon structurally important areas of the aircraft, its integrity may be compromised. For this reason, lightning strikes on composite helicopter blades are particularly hazardous.

Following a lightning strike, electrical/electronic systems may fail, with circuit breakers tripping. Magnetic compasses will become untrustworthy.

Radio communications and navigation equipment may be adversely affected.

The Automatic Direction Finder (ADF) will often point into the storm's centre.

4.4.3 Diagnosis of Hazard Using Appropriate Imagery

Satellite imagery, especially loops, can help identify developing convective cloud. Infra red imagery can give estimates of cooling tops, and an approximate value for the cloud top temperature. Water vapour imagery can help identify areas of high Positive Vorticity Advection which may favour Cumulonimbus, and thunderstorm/lightning, development.

The monitoring with a weather radar is an essential tool in monitoring the development of convective cells. The colour code representing rainfall rates can be used as an assessment of the likelihood of lightning. Polarimetric radars allow for the dicrimination of precipitation particles, eg graupel and hail. Dual Doppler radars indicate inflow regions, shear layers and may give the updraught strength.

Lightning detection systems identify the electrical active part of a cloud and thus allow the discrimination on the radar image between the non-hazardous stratiform rain areas and the active convective cells. Detection systems of intra-cloud activity indicate very early developing thunderstorm cells prior to the first ground flash. Their first occurrence is strongly correlated with the onset of glaciation within the cloud.

4.4.4 Empirical Forecasting Techniques

There are many techniques to assist the forecaster in assessing the likelihood, or not, of thunderstorm and lightning activity. A summary of some of the main techniques is given below.

- Tephigram constructions, both on actual and forecast profiles.
- Examine depth of convection and check thunderstorm occurrence according to local criteria.
- Convection ascending to and through the minus 20° C isotherm.
- Consideration of instability indices, Boyden, Modified Rackliff, Jefferson (Potential instability index), Bradbury (K-Index), or others.

- Monitoring for regions of decreasing θw with height to diagnose areas of Potential Instability.
- 'Shallow moist' zones associated with split cold fronts are always worth studying.
- Consider the effects of nil, uni-directional, or directional windshear through the cloud depth.

There are several other indices commonly used, such as CAPE values and Lifted Indexes. The calculation of CAPE depends on the prediction systems operated in the Services, but the graphical 'equal area' properties of the tephigram allow very meaningful constructions in order to determine convective depth to be easily made. Lifted Index values (such as 850hPa) can be used, but these will not take into account any marked suppressing inversions just above the sample height, nor do they take into account freezing levels.

For completeness, the units of CAPE are Jkg-1

0	stable
0-1000	marginally unstable
1000 – 2500	moderately unstable
2500 – 3500	very unstable
≥ 3500	extremely unstable.

Lifted Index (500 hPa)

11	extremely stable	TS unlikely
8-11	very stable	TS unlikely
4-7	stable	TS unlikely
0-3	mostly stable	TS unlikely
-3 - -1	slightly unstable	TS possible
-5 - -4	unstable	TS probable
-7 - -6	highly unstable	Sev TS possible
<-7	extremely unstable	Violent TS. Tornadoes possible.

Convective cells can be moved, or steered, with the windfield at a height equivalent to 1/3 of the cloud's depth, measured upwards from the clouds base.

The 700 hPa (~10000 ft) wind is a often a good first approximation of a UK thunderstorm's trajectory – but be aware of occasions when cloud is excessively low/shallow or high/deep.

4.4.5 Associated NWP Products

Overlapping with the empirical techniques, NWP forecast ascents can be used to determine the various instability indices. The usual convective constructions can be applied to tephigrams, and conclusions drawn. Most NWP output will give some indication of convective precipitation, and its intensity. It may be considered that the 'heaviest' such indicators are implicitly suggesting the possibility of CB and thunderstorm activity.

4.5 Heavy rain

4.5.1 Description

There is no agreed international definition regarding rainfall intensity. Some use the following criteria:

- Heavy rain is defined as rates in excess of 4 mm per hour.
- Heavy showers are defined as rates in excess of 10 mm per hour.

Showers are further classified as being violent if the rate exceeds 50 mm per hour, although these are normally considered to be rates typical for tropical regions.

Terms such as ‘very heavy’ have no official definition, but they, and terms like them, will be used below to describe rainfall rates that are much greater than normally expected, and would be associated with thunderstorm activity. Please note for aviation purposes rain rates are essentially a measure of rain water content.

4.5.2 Effects on Aircraft

Heavy or very heavy rates of rainfall will clearly have a detrimental impact upon general visibility. However, in addition to any true meteorological reduction of visibility, raindrops impacting the windscreen/canopy will additionally reduce visibility. Windscreen wipers (if fitted) may not be able to fully cope with the rainfall rate.

Light, non pressurised aircraft may find the heaviest rain rates allow water ingestion into the cabin/cockpit/engine compartments with subsequent risks to electronic equipment.

Civil airliner engines are tested and certified to ensure that engines will normally not ‘flame out’ under conditions of intense rainfall and water ingestion. Hurricanes are a different issue.

Runway flooding, or areas of deep standing water will affect braking action, and may result in asymmetric braking and possible sliding off runways.

Low cloud (stratus pannus) may form in periods of moderate or heavy rain, when it had not previously been expected (see below).

4.5.3 Diagnosis of Hazard Using Appropriate Imagery

Rainfall radar is invaluable for diagnosing areas of rainfall and the intensity of that rainfall, although the limitations of radar imagery must always be borne in mind.

Satellite imagery can assist in showing areas of cooling (and therefore ascending and developing) cloud tops. Combining the various wavelengths sensed by a meteorological satellite (RGB products) may prove increasingly useful in determining areas of precipitation, and general development. Refer to the section on Icing with these Aviation Hazards notes.

Lightning detection systems will indicate where the most frequent and organised of thunderstorm activity exists, and also some support the movement estimation.

When analysing such data the forecaster should always be mindful of the development of daughter cells, and the triggering of quite separate cells elsewhere, i.e. storms may not appear to move with the general wind flow or ‘steering level’.

4.5.4 Empirical Forecasting Techniques

Look out for and consider those occasions where high values of Positive Vorticity Advection and Warm Advection coincide as being the most likely areas to generate heavy rainfall – both from stratiform and convective cloud.

Remember that orography will enhance rainfall on the windward side of hills and mountains.

Prolonged periods of heavy, or moderate rain, will increase the humidity at low level through the process of evaporative cooling. After only half an hour of very heavy rain the ambient temperature may be reduced to a temperature close to that of the wet-bulb, whilst it may take some 1-2 hours of continuous moderate rain to produce the same effect. Ragged, stratus pannus is often the result, and the following guide is reproduced from the Forecasters' Reference Book (Source).

- 2 hours continuous rain – base 800 ft.
- 4 hours continuous rain – base 400 ft.

4.5.5 Associated NWP Products

Basic model output data will provide values for expected dynamic rainfall/convective rainfall rates at specified times, and for accumulated totals over specified periods.

Always be aware of the limitations of model data and that such rates will be averaged over a gridbox. Consider the effects of enhanced rainfall on windward slopes.

4.6 Hail

4.6.1 Description

Small hail (METAR code GS) is hail or gaupel of less than 5 mm in diameter. True hail (METAR code GR) is hail of 5 mm or more in diameter. GS and GR may fall from Cumulonimbus. GS (not GR) may fall from Cumulus congestus (TCU). The phenomena should not be confused with Ice Pellets (METAR code PE) that originates from stratiform cloud.

Hail is formed in the updraughts of convective (TCU or CB) cloud. The stronger the updraught, and the greater the cloud vertical extent, the larger the hailstone that can be sustained.

4.6.2 Effects on Aircraft

Hail of small size will have little effect on the structure of an aircraft, merely bouncing off the airframe. However, even small hailstones have a marked detrimental affect upon visibility. The onset can be rapid, surprising the pilot.

Hailstones can attain sufficient size to cause damage to the skin of aircraft, which may affect the aircraft's aerodynamics, and possibly shatter windscreens.

Hail may severely damage propellor blades and engine blades. Hail may block air inlets or may be deposited somewhere within air intakes.

Sudden hail showers may leave an extremely slippery surface on runways and taxiways. So, even if the shower has passed and the visibility and cloud may be described as fit for attempting a landing, breaking action may be adversely affected.

4.6.3 Diagnosis Using Appropriate Imagery

Intense returns from radar imagery may indicate the presence of hail within a given convective system. Doppler radar may provide information of updraughts of sufficient strength to maintain hailstones, and polarimetric radar allow for the identification of hail within the clouds. Generally, hail can be expected within or close to the main thunderstorm updraught.

4.6.4 Empirical Forecasting Techniques

As a guide, hail might be expected if

- Cumulonimbus tops are colder than -20° C.
- The parcel path curve is warmer than the environment curve by 4° C at some level, and gives cloud tops in excess of 15000 ft.

Examining the parcel curve more carefully, the following technique may be used:

- At the point where the curve reaches -20° C, measure the difference between this temperature and the environment temperature.
- If the difference is ≥ 5° C, forecast hail; from 5° to 2.5° C, forecast soft hail or rain; if the difference is ≤ 2.5° C, forecast rain.

It is further stated that large hail requires a ‘steady state’, but not necessarily slow moving storm.

Vertical windshear is required between the base and top of the Cumulonimbus.

4.6.5 Associated NWP Products

The main NWP product to make use of under such scenarios would be the forecast tephigrams. From such it is then possible to apply the usual convective constructions, and make judgements upon the likelihood or not of hailstones.

‘Raw’ model output in the form of heavy shower symbols may be considered as indicative of possible hail formation, but generally this is a very course tool. Rather more detail of the atmosphere structure is required, hence the study of NWP forecast ascents.

4.6.6 Brief Case Study

The following image indicates the damage that large hail can do to an aircraft in flight.

Figure-31. Military plane after exposure to hail

5 HEAVY RAIN

See the discussion of heavy rain within the Cumulonimbus and Thunderstorm section of these *Aviation Hazards* notes.

Note, that heavy rain may occur without the presence of a Cumulonimbus cloud. On such occasions, the cause will be due to thick, deep layers of frontal cloud, perhaps enhanced by orographic forcing. Nimbostratus ought to be reported (and indeed forecast) if such rainfall is expected to fall from non-convective clouds.

There is no fundamental reason why Cumulonimbus clouds may not be embedded within Nimbostratus.

6 SNOW

6.1 Description

Snow is solid precipitation in the form of individual, usually branched, ice crystals, or an agglomeration of those ice crystals. The precise nature will depend upon the temperature and conditions in which they develop. At temperatures warmer than about -5 C the crystals tend to agglomerate.

6.2 Effects on Aircraft

Even slight rates of snowfall have a serious detrimental effect upon visibility.

Non-melting snow flakes at sub-zero temperatures will be largely deflected in the airstream and not adversely affect the majority of the airframe. However, where snow is deflected into engine nacelles or into cavities such as open wheel wells, the snow may collect and ‘pack’ to create obstructions. Such obstructions may restrict airflow into engines, or prevent retraction of landing gear.

On the ground, whilst stationary or taxiing, snowfall may accumulate on the airframe, disturbing the aerodynamics and adding to the all up weight of the aircraft. Windscreens may become obscured with snow, with windscreen wipers becoming ineffective (if fitted).

Pitot tubes may become blocked, with resultant errors in airspeed and altitude indication.

Wet (melting) snow may not be so easily deflected by airflow, and may more readily ‘pack’ against blunt surfaces of the airframe. As noted above, when snow packs into and against engine nacelles, wheel wells, or engine intake grilles, significant consequences may result.

Runway contamination by snow will significantly degrade braking action. Snow accumulations will also obscure runway lights and possibly make it difficult to discern the runway from the adjacent grass areas, especially given that visibility will be anyway degraded.

There are occasions when precipitation is of rain at the surface of the aerodrome, but may be of snow at approximately 1000 ft above. Under these circumstances aircraft ‘in the circuit’ or on approach will be affected by snow.

Snow must be removed completely from an aircraft prior to take-off by appropriate means, ususally through the application of a de-icing fluid. It is a fatal error to assume that snow on the aircraft, respectively on the wing, will be removed by aerodynamic forces during start and take-off.

6.3 Diagnosis Using Appropriate Imagery

Radar and satellite imagery do not, specifically, by themselves diagnose snow at the surface. Cloudtops visible to satellites will necessarily obscure the ground below, although visible imagery may reveal recent snowfall through breaks in cloud.

The Radar returns from snow and rain are calibrated to be essentially similar for a given intensity, but melting snow does give a much larger return. It is this phenomenon that produces the ‘bright band’ effect on rhi radar imagery.

6.4 Empirical Forecasting Techniques

Forecasters must be familiar with the synoptic scenarios that lend themselves to surface snow fall. A cold blast of polar air giving wintry showers would be one such scenario. Cold, continental air ahead of an approaching warm front may cause precipitation to fall as snow at low level, including the surface.

Without engaging in the detailed use of the techniques here, the forecaster may consider the use of:

- Boyden’s 1000-850 hPa technique
- Height of 0 C isotherm
- Surface temperature
- 1000-500 hPa thickness
- Hand’s Rule
- Initial wet bulb potential temperature
- Screen wet bulb temperature
- Booth’s snow predictor
- Varley snow predictor

Forecaster’s should be aware of the limitations of such techniques, and where appropriate make quantitative adjustments when considering the effects of orography, or the lowering of the freezing level during periods of continuous falling snow.

Forecasters may also wish to consider the likelihood of drifting or blowing of lying snow.

6.5 Associated NWP Products

NWP generally provides good guidance with regard to the general synoptic situation, and the forecaster should therefore be able to assess the general likelihood, or not, of snowfall.

Some model fields give specific advice. Plotted precipitation symbols will often differentiate between liquid and solid, but these will relate to the precipitation type falling at the surface, based upon the model’s internal representation of orography. Under such circumstances, snowfall expected down to 3500 ft say, may not be plotted by the model as snow if internally it represents the area as being no higher than 3000 ft against real peaks of 4000 ft.

In addition, snow probabilities are often provided and these refer to the probability of snow falling at sea level. As such, snow symbols may (correctly) be plotted over mountainous terrain, when the sea level probability of snow is nil.

Some forecaster hints from the UK Met Office perspective. Indirect indicators from model output would be the following of 850hPa 2 θw marker, or the 528 decametre thickness value to determine regions where precipitation could be expected to be 'wintry' at sea level. Snow probability lines, 2 θw lines, and 528 thickness lines should be used with caution. They may not always reveal shallow undercuts of sub-zero surface airflow, which will result in snow at low level.

Forecast tephigrams are extremely useful but again the limitations of model data always needs to be considered. Model tephigrams may not capture sub-zero layers. Forecasters also need to be on guard to the effect of cooling due to the phase change of snow to rain, and subsequent lowering over time of the freezing level. The lowering of the freezing level, and the extraction of heat energy from the lower layers due to the phase change from solid to liquid, can lead to the destabilising of an initially stable low level layer. This will result in the formation of cumulus fractus in snow conditions.

6.6 Brief Case Study

On the 13 January 1982, an Air Florida 737 crashed on take off from Washington DC's National Airport into the Potomac river.

Under conditions of snowfall and blowing snow, and after de-icing activity, the aircraft had failed to remain airborne after take off.

Notwithstanding the de-icing activity, snow had been seen to have settled on the wings prior to take off. Contributory to the accident had been the use of reverse thrust as an attempt to taxi away from the terminal when tow trucks had been unable to pull the aircraft back. The reverse thrust is believed to have drawn snow and ice into the engines, adversely affecting a sensor that gave cockpit indications of engine power.

To that end, the aircraft took off with snow covered wings and with insufficient thrust from the engines.

7 FOG

7.1 Description

Fog is the suspension of microscopic droplets of water with Ø ≤ 10 μm, or in the case of ice fog, particles of ice. For aviation purposes, it is a condition that the horizontal visibility due to such phenomena is reduced to less than 1000 m.

Fog may be further classified as being formed by advective processes or radiative cooling processes. Hill fog and frontal fog are also descriptors commonly used.

Fog may cover a large, continuous area or it may form in patches possibly only covering small parts of an airfield. If the fog layer is less than 2 meters deep overland it is termed shallow fog.

7.2 Effects on Aircraft

Fog seriously degrades visibility, to such a degree that landing may be impossible. Only the most expensive of aircraft (Civil Airliners/military aircraft) may be able to 'auto land' under such circumstances, and then only at suitably equipped airports. Even allowing for the technical ability, airline and military procedures may prohibit 'auto landings' under certain conditions.

Ice fog has similar visibility restrictions, but in addition untreated taxiways and runways may be coated with a thin layer of ice.

Pilots may be given a false sense of security when over-flying an airfield, since structures and runways may be quite clear to the pilot when looking down from directly above the airfield. However, when descending onto the approach, and trying to view the airfield at a slant angle through the fog, the pilot may very quickly lose all visual cues and find themselves in very serious difficulty.

7.3 Diagnosis Using Appropriate Imagery

Fog can be best diagnosed by comparison between visible and infra red imagery taken by the same satellite at the same time. Usually the temperature of the fog top will have a temperature similar to the surface temperature, and will therefore be invisible on infra red. However, the fog will strongly reflect sunlight, and will appear clearly on the visible image. Such comparison techniques are only possible during daytime.

A technique of combining two infra red channels (10.8 μm, and the 3.7 μm), and taking advantage of slightly different return values, allows detection of fog overnight. The resultant image is commonly referred to as the ‘fog channel’. This process can only be applied at night.

Both daytime and night-time detection of fog will be impossible if higher level cloud obscures the surface.

Surface observations of fog should be monitored closely.

7.4 Empirical Forecasting Techniques

The primary task is to determine what form of fog, if any, will affect the area. Terrain, frontal movement, warm air masses advecting over a colder surface, or clear skies/light wind radiative cooling are all aspects that need to be considered. Local knowledge is important. Knowing the location and size of any adjacent marshes or large bodies of water, including reservoirs, helps the forecaster fine tune the forecast for a specific location. Low lying areas affected by katabatic drainage may also be prone to fog formation.

There are several techniques available to assist the forecaster in determining the formation and clearance of fog, and the most appropriate should be used by the bench forecaster.

Forecast surface temperatures are an essential pre-requisite. Fog points for radiation fog situations can be determined from Saunders’ method. Craddock and Pritchard have a regression technique that provides a fog point, and in combination with their minimum temperature methods provides an estimation of fog likelihood.

Relatively warm air masses advecting over colder surfaces (whether sea or land) should alert the forecaster to the possibility of advection fog formation, especially when the ambient dew point is higher than the surface temperature. Such occasions are common over the maritime areas to the southwest of the UK in ‘Warm Sector’ scenarios.

7.5 Associated NWP Products

Visibility fields are available from NWP models. As with all model data, they should be critically assessed, and as much value added as possible by applying empirical techniques and local knowledge.

8 LOW CLOUD/POOR VISIBILITY

8.1 Description

Low cloud and poor visibility may be overlooked as being potentially hazardous. They are also quite difficult to define since they will depend upon aircraft type, pilot skill and experience, the precise role the aircraft is performing, and the navigation aids available en route or at the departure/destination/alternate airfields.

Whilst the precise values may differ under the many varied possibilities, perhaps low cloud and poor visibility might best be described as having values that fall below the operating minima of either or both that of the aircraft and pilot.

Small amounts of low cloud (1 or 2 oktas say) may not generally be hazardous. As cloud amounts increase, then the risk to aircraft also increases. That noted, even a small patch of low cloud may cover a small peak (indeed may be caused by the peak).

Poor visibility may likewise only affect small areas (in the form of showers, or in fog patches), and may be caused for many reasons (rain, mist, haze, smoke etc). Under such circumstances a pilot may be able to 'navigate around' the problems. Conversly, reductions to visibility can and often do affect very large areas and as such dealing with the problem can be much more difficult.

8.2 Effects on Aircraft

When cloudbase and/or visibility fall below acceptable values, the pilot is in a situation where there will not be sufficient time to take avoiding action should an obstacle be sighted. That obstacle may be natural (hill, or simply the ground), a structure (building/tower), or another aircraft. To that end collisions are possible. Pilots who are not qualified to use instruments, or flying poorly equipped aircraft, may become disorientated when confronted with poor visibility and/or low cloud.

Elevated layers of haze can mislead pilots, since reported (and correct) values of visibility are those assessed horizontally at the surface. The pilot flying in the haze layer does not perceive the visibility to be as good as reported.

When a pilot is flying above a low level haze layer (which may effect the surface), the pilot will often be able to see further than the reported airfield visibility. On such occasions the pilot may be led into a false sense of security, and on descending into the haze layer suddenly find that their visibility is much reduced.

8.3 Diagnosis Using Appropriate Imagery

Low clouds, which are not obscured by higher cloud layers, may be determined by appropriate comparison of visible and infra red imagery. Refer to the section on Fog within these Aviation Hazards notes for further information.

Surface observations of visibility and cloud bases are the most immediate resource available to forecasters.

8.4 Empirical Forecasting Techniques

Low Cloud

With regard to the forecasting of low cloud, forecasters should use appropriate actual and forecast tephigram data, applying standard constructions where relevant. Forecast surface temperatures, and surface wind speeds are fundamental in relation to forecasting low cloud bases. Cloud bases may fall to lower than expected values under circumstances of continuous moderate or heavy rain, or in downdraughts from convective cloud, or due to orographic uplift.

Poor Visibility

Allowing for the many and varied causes of reduced visibility, forecasters should be aware of all factors involved, and apply the most appropriate techniques to assess likely visibility values. Fog techniques are discussed in the Fog section of these Aviation Hazards notes. Visibility values related to various intensities of rainfall and snowfall should be considered.

Whilst not something that forecasters specifically determine, it is appropriate to at least alert aircrew to reduced values of slant visibility. Forecasters should also advise of elevated haze layers if expected.

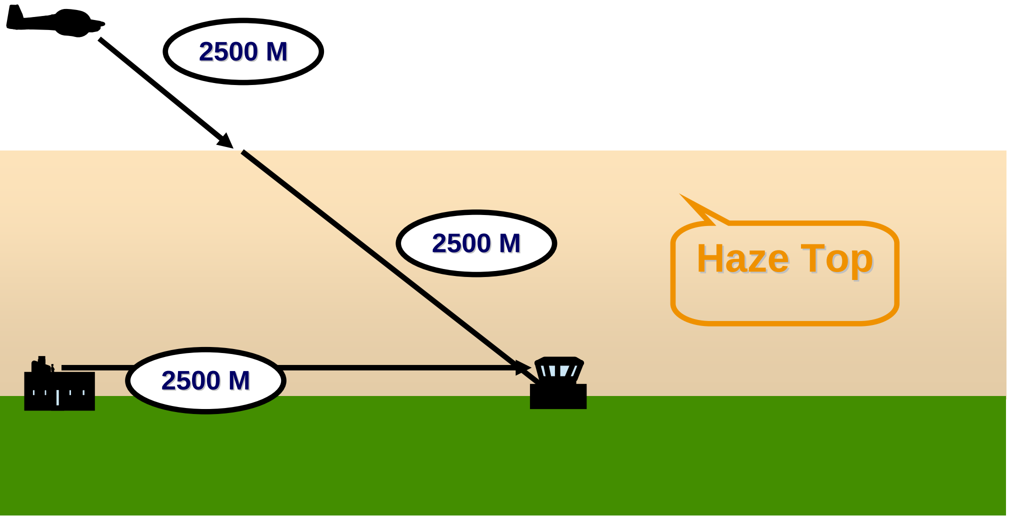


Figure-32. **Example of pilot above a haze layer, experiencing a greater visibility than reported by the observer**

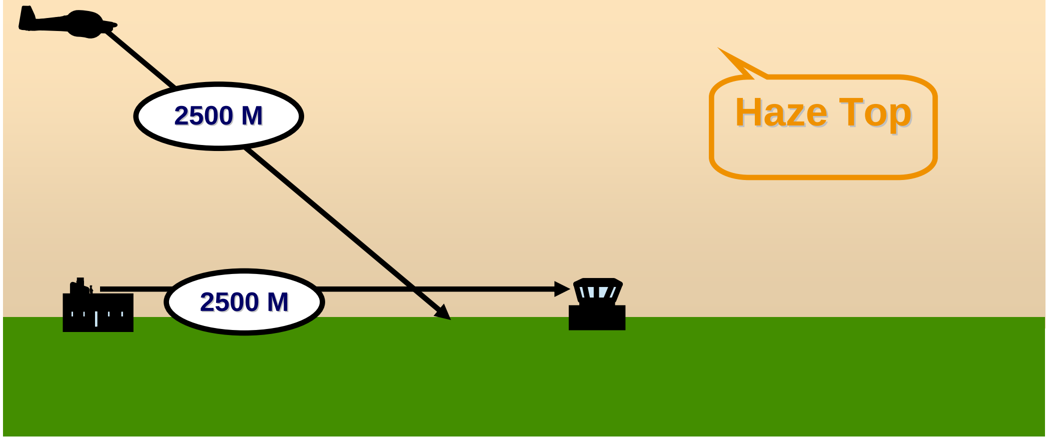


Figure-33. **Example of a pilot within a haze layer, perceiving a lower visibility than reported, due to the slant visibility**

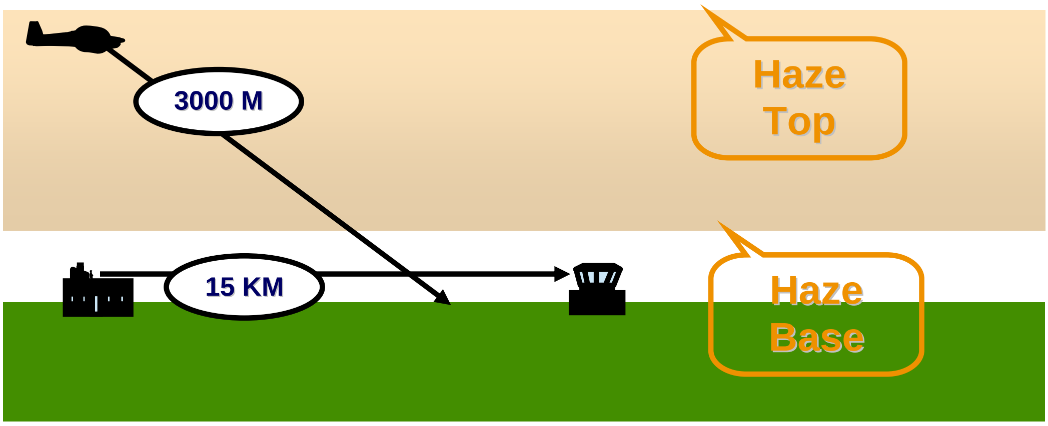


Figure-34. **Example of a pilot in an elevated layer of haze, experiencing very much lower visibility than (correctly) reported**

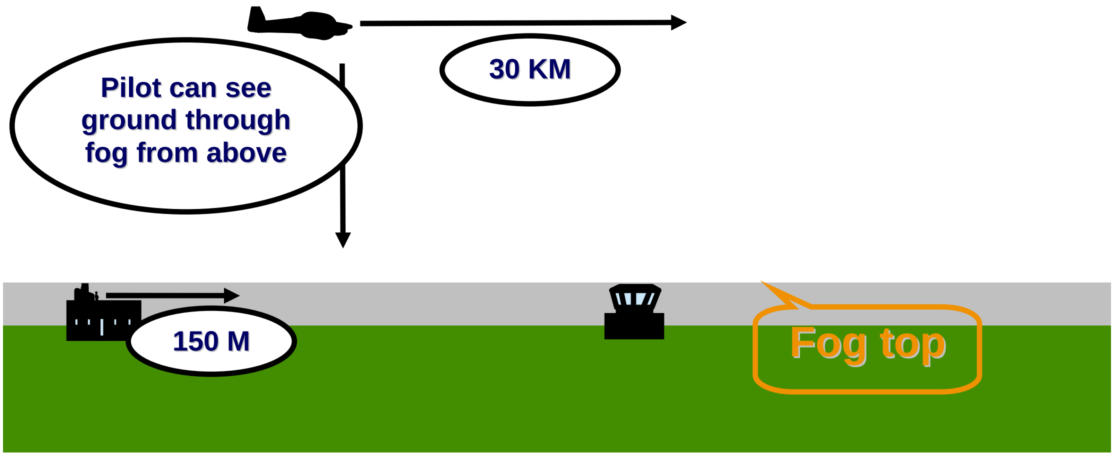


Figure-35. **Example of a pilot overflying a layer of fog. The pilot may see the ground and building from above, possibly quite clearly. However, on approach to land and on descent into the fog the pilot will experience a rapid reduction of visibility into fog limits.**

8.5 Associated NWP Products

As discussed in the section on Fog, visibility fields are available from NWP models. As with all model data, they should be critically assessed, and as much value added as possible by applying empirical techniques. They are generally 'air mass' visibilities based on aerosol content. Whilst they do take into account humidity and subsequent condensation onto the aerosol (nuclei), they do not necessarily provide visibility values that are directly related to rainfall or snowfall rates. NWP forecast ascents can give valuable indication of inversions that will indicate the likely haze tops. Standard convective constructions can be applied to determine whether or not haze layers will lift, and whether they will disperse completely should convection break through the entire layer of haze.

Model ascents will not have the fine resolution to diagnose several low level inversions and possibly distinct haze layers that sometimes develop under prolonged periods of high pressure. The distinct layers form as the air mass below the main inversion is repeatedly heated and cooled over several days.

9 SANDSTORMS AND DUSTSTORMS

9.1 Description

Duststorms and sandstorms are regions of raised dust and sand. The dust and sand are essentially raised by the wind, and are lofted to various heights dependent upon turbulence and instability and persistency of the flow that lifted the particles.

The size of dust and sand particles ranges from slightly sub-micron to several hundreds of micron. Clearly, smaller and lighter particles will be lifted more readily and to greater heights, and take longer to settle out, while the larger particles may remain airborne only for short distances of a few hundred meters..

9.2 Effects on Aircraft

Drastic reductions in visibility are likely to accompany dust and sand storms. Effective visibility may very likely be close to zero in some circumstances.

Dust and sand ingestion into aircraft engines may cause reductions in power till complete engine failure.

Should dust and sand find their way into cockpits, then problems with electrical equipment may occur.

9.3 Diagnosis Using Appropriate Imagery

Sand and duststorms can be observed using standard visible and infra red imagery. As is nearly always the case, comparison between wavelengths; and looping of images will provide for the best diagnosis.

9.4 Empirical Forecasting Techniques

As a rule of thumb, 15 kt is considered sufficient to raise dust. Stronger winds will lift larger particles.

Desert regions are not all ‘loose sand and dust’, and some areas may be largely bare rock. From this it is a requirement that forecasters are aware of the primary source regions of dust and sand for the areas in which they are expected to forecast.

More difficult to assess is the level to which dust and sand may be lifted to. Whilst dust and sand has been known to be lifted to above 15000 ft, the more common values are between 3000 ft and 6000 ft. A first estimate to the likely top of raised dust and sand would be the height to the top of the expected dry adiabatic lapse rate.

When considering the movement of the plume of dust and sand, higher level winds at the various levels within the plume of sand and dust will affect its trajectory – so surface winds may not always provide the best indication of where the majority of the dust and sand may go.

Once raised, and assuming that the wind eases below 10 kt, and that turbulence and instability decay, dust settles at some 1000 ft per hour. So, dust raised to some 6000 ft will take 6 hours to settle. The larger particles of sand will settle more quickly.

Rainfall has two effects on dust and sand.

- Generally, after a period of rainfall the raising of dust and sand will be inhibited for some 24 hours.
- Rainfall will also ‘wash’ out dust and sand from the atmosphere.

Haboob

A type of dust/sandstorm generated by convective downdraughts is known as a haboob. Simply stated, the surface outflow from the downdraught raises the dust and sand. The mechanism is similar to the microburst discussed in the Turbulence section of these Aviation Hazards notes. In this scenario, the general windspeeds may not be considered sufficient to raise dust or sand, but the local speed up of wind due to the downdraught, and its related instability provide the mechanism.

Figure- 36 Sand and dust mark a downdraught outflow.

9.5 Associated NWP Products

NWP products can help the forecaster in predicting dust and sandstorms over prone areas.

At the very simplest, monitoring of surface windspeed forecasts will alert the forecaster to areas where dust and sand may be raised. Monitoring of forecast tephigrams data will allow some assessment of the likely depth of dust and sand.

Consider the possible effects of Cumulonimbus clouds and the subsequent generation of downdraughts and 'haboobs'.

Consider the effects of forecast rain, and the hinderence of dust formation/dispersal, but note that model rain may not actually reach the surface from medium level instability, due to very dry air below.

The NWP models of some countries include parameters to allow for the transport of dust. The University of Athens has such a product, and can be viewed on the Internet.

9.6 Brief Case Study

The images below illustrate blowing dust and sand. The dust and sand was sourced from Syria and Iraq, and was driven south east on a strong 'shamal' wind. As always, looping imagery provides the eye with more clues, but hopefully the main signals can be seen from these images.

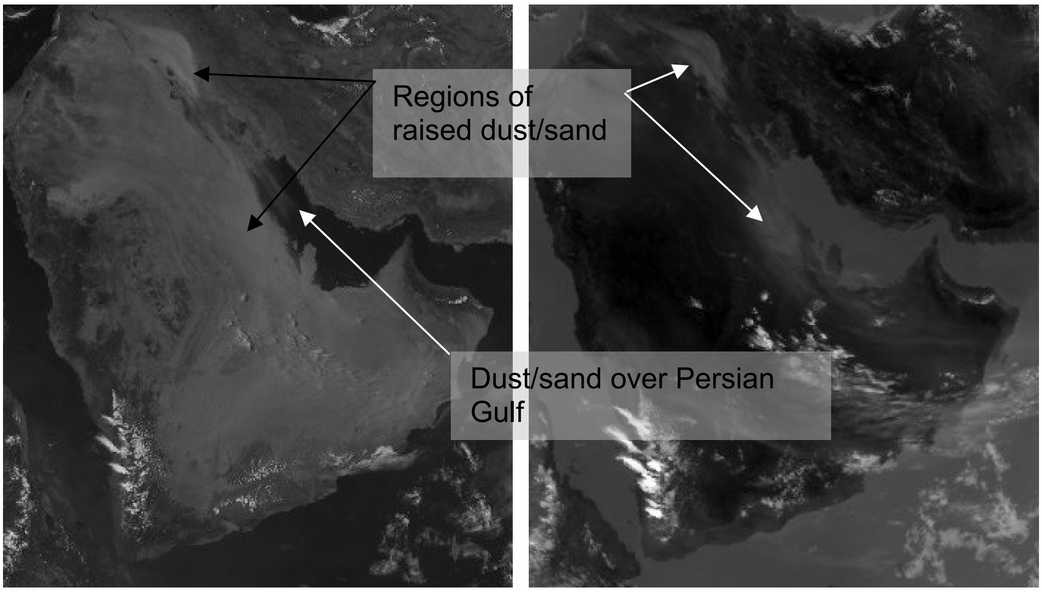


Figure- 37 Visible (left) and infra red (right) images for 1200 Z, 7th August, 2005

10 SQUALLS/LINE SQUALLS

10.1 Description

A squall is simply defined as a sudden, temporary increase of the wind. It is specified as an increase in the mean wind by at least 16 kt, to a minimum value of 22 kt, and sustained for a period of 1 minute, then dying away comparatively suddenly.

Squalls may be associated with the gust front/microburst from a individual Cumulonimbus cell. They are the cause of the haboob discussed in the previous section.

They may occur in a more organised fashion on the passage of a cold front, when they are known as a 'line squall'.

10.2 Effects on Aircraft

Refer to the Turbulence section of these Aviation Hazards notes, particularly the microburst and low-level jet sections.

10.3 Diagnosis Using Appropriate Imagery

Refer to the Turbulence section of these Aviation Hazards notes, particularly the microburst and low-level jet sections.

10.4 Empirical Forecasting Techniques

Refer to the Turbulence section of these Aviation Hazards notes, particularly the microburst and low-level jet sections.

10.5 Associated NWP Products

Refer to the Turbulence section of these Aviation Hazards notes, particularly the microburst and low-level jet sections.

10.6 Brief Case Study

Refer to the Turbulence section of these Aviation Hazards notes, particularly the microburst and low-level jet sections.

11 'HOT AND HIGH'

11.1 Description

Aircraft performance is degraded under conditions of high temperature and low density. Such scenarios are factors at airfields that are 'hot' due to the general climate (seasonal or otherwise), and 'high' by virtue of being located at high elevation.

11.2 Effects on Aircraft

Quite simply, when the ambient air temperature is greater than the International Standard Atmosphere the performance of an aircraft's engines and wings are hindered. Specifically, engine performance is degraded and the lift from wings is degraded.

When pressure is less than the International Standard Atmosphere, the performance of an aircraft's engines and wings are also hindered. Again, thrust and lift are degraded.

When both conditions occur simultaneously, quite significant limitations to aircraft performance may result.

All aircraft will have different criteria with regard to the limitations that high temperatures and low pressure place upon them. Forecasters should be aware that aircraft will require longer take off runs and/or have restrictions placed upon their maximum take off weight. It is up to the captain of the aircraft to determine the effects on the aircraft and make appropriate allowances. Forecasters may be asked to give quite precise forecasts of temperature and pressure under such circumstances.

A typical scenario is a too high temperature for take-off and the requested forecast of cooling effects, such as the onset of the sea breeze. Such a scenario as was reported from Melbourne, Australia.

Another scenario is the decrease of density limiting the ceiling of an aircraft, eg when attempting to fly over passes in the Rocky Mountains, USA.

11.3 Diagnosis Using Appropriate Imagery

Operational imagery is not appropriate for diagnosing conditions of ‘hot and high’ conditions.

Monitoring of surface observations such as METAR and SYNOP will be an essential tool to assist forecasting temperatures and pressures.

Monitoring of upper air observations and tephigrams will also be essential in understanding the vertical temperature structure of the region’s air mass.

Empirical Forecasting Techniques

Forecasters should make reference to locally produced empirical methods.

11.4 Associated NWP Products

Model forecasts of temperatures, at all levels in the model, are available. They should be treated with caution for high areas, since often the model resolution is limited and the grid point/height may not accurately represent the point/height of the airfield.

This has the dual effect in that the model may not accurately calculate temperatures because it fails to resolve the effects of elevated heating at such levels, and also because it actually forecasts a temperature for a height that is not that of the airfield.

Given that a forecaster has allowed for these effects, or in cases where they are considered minimal, the parameter that the pilot may be most interested in will be the Density Altitude.

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