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FLIGHT OVER AND IN THE VICINITY OF HIGH GROUND

1 The aim of this Circular is to remind pilots of the basic theory of airflow over high ground, to describe the effect of the airflow on aircraft in flight and to offer advice on avoiding or minimising the various hazards that may be encountered. This Circular is divided into three parts accordingly :

Part 1 - Meteorology

Part 2 - Flying Aspects

Part 3 - Advice to Pilots

Part 1 - Meteorology

1.1 **Introduction**

1.1.1 The expression 'high ground' is used here to describe mountains, hills, ridges etc which rise to heights in excess of about 500 ft above nearby low lying terrain.

1.1.2 Air flow is more disturbed and turbulent over high ground than over level country and the forced ascent of air over high ground often leads to the formation of cloud on or near the surface, which sometimes extends through a substantial part of the troposphere if the air is moist enough.

1.1.3 Forced ascent also increases instability so that thunderstorms embedded in widespread layer cloud may occur over high ground, even when no convective clouds form over low ground. When the air is generally unstable, cloud development will be greater, icing in the clouds will be more severe and turbulence in the friction layer and in cloud will be intensified over high ground.

1.1.4 The air flowing over high ground may be so dry that, even when it is forced to rise, little or no cloud is formed. The absence of cloud over high ground does not imply the absence of vertical air currents and turbulence.

1.1.5 Strong down currents are caused by the air descending the lee slope and it is, therefore, especially hazardous to fly towards high ground when experiencing a headwind.

1.1.6 On some occasions the disturbance of a transverse airflow by high ground can create an organised flow pattern of waves and large scale eddies in which strong up-draughts and downdraughts and turbulence frequently occur. These organised flow patterns are usually called mountain waves but may also be referred to as lee waves or standing waves and can be associated with relatively low hills and ridges as well as with high mountains.

1.2 **Mountain Waves**

1.2.1 Conditions favourable for the formation of mountain waves are:

(a) A wind blowing within about 30° of a direction at right angles to a substantial ridge;

(b) the wind must increase with height with little change in direction (strong waves are often associated with jet streams). A wind speed of more than 15 kt at the crest of the ridge is also usually necessary;

(c) a marked stable layer (approaching isothermal, or an inversion), with less stable air above and below, between crest level and a few thousand feet above.

1.2.2 Mountain wave systems may extend for many miles downwind of the initiating high ground. Satellite photographs have shown wave clouds extending more than 250 nm from the Pennines and as much as 500 nm downwind of the Andes. However, 50 to 100 nm is a more usual extent of wave systems in most areas. Wave systems may, on occasions, extend well into the stratosphere.

1.2.3 The average wave length of mountain waves in the troposphere is about 5 miles, but much longer waves do occur. A good estimate of the wave length λ (nautical miles) can be derived from the mean troposphere wind ϖ (knots) by using the simple formula $\lambda = \varpi/7$. Disturbances in the stratosphere are often irregular features located very near or just over the initiating mountains. However, when waves to the lee of the high ground are evident, their length is usually greater than in the troposphere; 15 nm is probably a typical wave length but wave lengths of 60 nm have been measured.

1.2.4 The amplitude of waves is much more difficult to determine from meteorological observations. In general, the higher the mountain and the stronger the airflow, the greater is the resulting disturbance; but the most severe conditions occur when the natural frequency of the waves is 'tuned' to the ground profile and conditions for wave motion are only just satisfied. This makes the prediction of wave amplitude uncertain.

1.2.4.1 In the troposphere the double amplitude (peak-to-trough) of waves is commonly 1500 ft with vertical velocities about 1000 ft/min but double amplitudes of about 20,000 ft and vertical velocities over 5000 ft/min have been measured in the USA. Even over the UK vertical velocities up to 2000 ft/min have been recorded, ie well beyond the climbing capability of many light aircraft.

1.2.4.2 Waves in the stratosphere have been measured with double amplitudes up to 1300 ft over the UK and more than 8000 ft over the western USA. Vertical velocities up to 2000 ft/min have been recorded in these waves. In the stratosphere above the Rocky Mountains, disturbances which have been interpreted as rotors, with amplitudes up to 9000 ft, have been observed. A pilot flying in such a disturbance has reported an accelerometer reading of minus 1g.

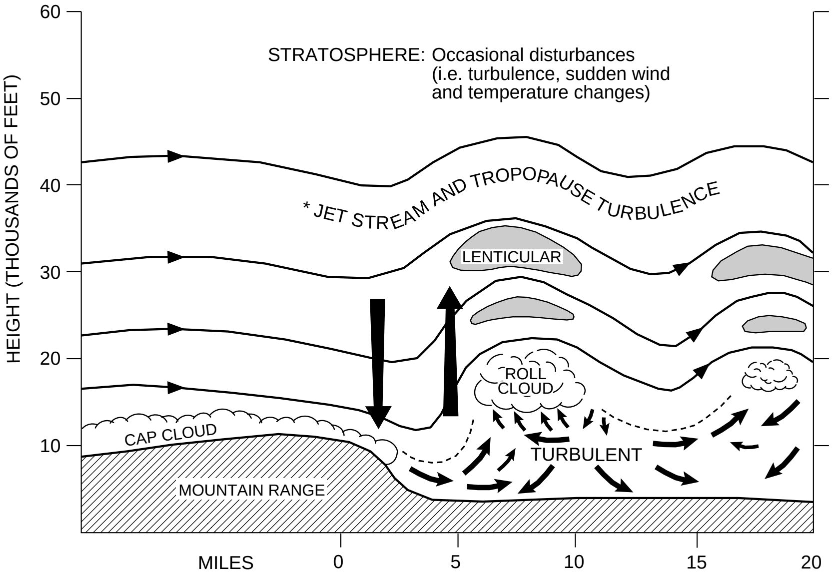
1.2.4.3 In extensive mountainous areas the wave system generated by one ridge is disturbed by further ridges downwind. Furthermore, the characteristics of an airstream are always changing with time, and occasions when small changes in the airstream give rise to large changes in mountain wave characteristics can be envisaged, but not forecast. Such changes may generate a transient but severe disturbance resulting in violent turbulence (eg due to a wave 'breaking').

1.3 Visual Detection of Mountain Waves

1.3.1 The special clouds which owe their appearance to the nature of wave flow are a valuable indicator to the pilot of the existence of wave formation. Provided there is sufficient moisture available the ascent of air will lead to condensation and formation of characteristic clouds. These clouds form in the crest of standing waves and therefore remain more or less stationary.

1.3.2 They may occur at all heights from the surface to cirrus level and are described briefly in the following paragraphs, to be read in conjunction with the diagram below, which shows the characteristic distribution of clouds and turbulence to the lee of the Sierra Nevada in North America. This is an area in which mountain wave phenomena are exceptionally marked, but the diagram has a fairly general application.

MODEL OF A WELL-DEVELOPED MOUNTAIN WAVE SHOWING TYPICAL FEATURES



* The tropopause and level of maximum wind are usually located somewhere within this layer

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(a) Lenticular clouds provide the most unmistakable evidence of the existence of mountain waves. They form within stable layers in the crests of standing waves. Air streams through them, the clouds forming at their up-wind edges and dissipating downwind. They have characteristically smooth lens shaped outlines and may appear at several levels, sometimes resulting in an appearance reminiscent of a stack of inverted saucers. Lenticular clouds usually appear up to a few thousand feet above the mountain crests, but are also seen at any level up to the tropopause and even above. (Mother-of-pearl clouds, seen on rare occasions over mountains, are a form of wave-cloud at an altitude of 80,000 ft or so). Air flow through these clouds is usually smooth unless the edges of the cloud take on a ragged appearance which is an indication of turbulence.

(b) Rotor or roll-clouds appear, at first glance, as harmless bands of ragged cumulus or stratocumulus parallel to and downwind of the ridge. On closer inspection these clouds are seen to be rotating about a horizontal axis. Rotor clouds are produced by local breakdown of the flow into violent turbulence. They occur under the crests of strong waves beneath the stable layers associated with the waves. The strongest rotor normally forms in the first wave downwind of the ridge and is, therefore, usually near or somewhat above the level of the ridge crest, but may occasionally be much deeper (rotor clouds have been reported to extend to 30,000 ft over the Sierra Nevada). There are usually not more than one or two rotor clouds in the lee of the ridge.

(c) Cap clouds form on the ridge crest and strong surface winds which are commonly found sweeping down the lee slope may sometime extend the cap cloud down the slope producing a 'cloud fall' or 'föhn wall'.

1.3.3 Although cloud often provides the most useful visible evidence of disturbances to the airflow, the characteristic cloud types may sometimes be obscured by other cloud systems, particularly frontal cloud. On the other hand, the air may be too dry to form any clouds at all, even in strong wave conditions.

1.4 **Turbulence**

1.4.1 Turbulence at low and medium levels.

1.4.1.1 A strong wind over irregular terrain will produce low level turbulence which increases in depth and intensity with increasing wind speed and terrain irregularity.

1.4.1.2 In a well developed wave system, the rotor zone and the area below are strongly turbulent and reversed flow is often observed at the surface. Strong winds confined to the lower troposphere, with reversed or no flow in the middle and higher troposphere, produce the most turbulent conditions at low levels, sometimes accompanied by 'rotor streaming' comprised of violent rotors which are generated intermittently near lee slopes and move downwind. These low level travelling rotors are distinct from the stationary rotors which form at higher levels in association with strong mountain waves.

1.4.2 **Turbulence in the rotor zone**

1.4.2.1 Rotors lie beneath the crests of lee waves and are often marked by roll clouds. The most powerful rotor lies beneath the first wave crest downstream of the mountains. Rotors give rise to the most severe turbulence to be found in the air flow over high ground. On occasions it may be as violent as that in the worst thunderstorms. Gliders flying in rotor zones in both Europe and the USA have found accelerations of 2g to 4g quite common and 7g has been exceeded in the USA. Several gliders suffered structural damage and one disintegrated.

1.4.3 **Turbulence in waves**

1.4.3.1 Although flight in waves is often remarkably smooth, severe turbulence can occur. The transition from smooth to bumpy flight can be abrupt. Very occasionally violent turbulence may result, sometimes attributed to the wave 'breaking'.

1.4.4 **Turbulence at high levels (near and above the tropopause)**

1.4.4.1 **Turbulence near the jet stream**

1.4.4.1.1 Turbulence in jet streams is frequently greatly increased in extent and intensity over high ground. Strong vertical wind shears are often concentrated in a few stable layers just above and below the core of the jet stream. Distortion of these layers when the jet stream flows over high ground particularly when mountain waves form, can produce local enhancements of the shears so that the flow in those regions breaks down into turbulence. Usually the cold side of the jet stream is more prone to turbulence, but mountain waves may be more pronounced on the warm side.

1.4.4.2 **Turbulence in the stratosphere**

1.4.4.2.1 Flight experience has shown that in the stratosphere moderate or severe turbulence is encountered over high ground about four times more frequently than over plains and about seven times more frequently than over the oceans.

1.4.4.2.2 Evidence from research flying over the Rocky Mountains has shown that strong rotors and/or waves may occur well into the stratosphere on days favourable for strong wave formation in the troposphere. The associated severe turbulence can cause serious difficulties to an aircraft flying near its ceiling.

1.5 **Downdraughts**

1.5.1 Whether or not a well developed wave system exists, if the air is stable a strong surface air flow over high ground will produce a substantial and sustained downdraught and/or turbulence on the lee side. Such downdraughts may on occasions be strong enough to defeat the rate of climb capability of some aircraft. In a wave system, a series of downdraughts and updraughts exists, the most powerful being those nearest the high ground.

1.6 **Icing**

1.6.1 Adiabatic cooling caused by the forced ascent of air over high ground generally results in a lowering of the freezing level and an increase of liquid water concentration in clouds. Thus airframe icing is likely to be more severe than at the same altitude over lower ground when extensive cloud is present. This hazard is at a maximum a few thousand feet above the freezing level, but in general is unlikely to be serious at altitudes above 20,000 ft, except in cumulonimbus clouds.

Part 2 - **Flying Aspects**

2.1 The effects of the airflow over high ground on aircraft in flight depend on the magnitude of the disturbance to the airflow, the performance of the aircraft, its altitude and the aircraft's speed and direction in relation to the wave system. A broad distinction may be made between low level hazards (below about 20,000 ft) and high level hazards (above 20,000 ft).

2.2 **Low Altitude Flight**

2.2.1 The main hazards arise from severe turbulence in the rotor zone, from downdraughts and from icing. The presence of roll-clouds in the rotor zone may warn pilots of the region of most severe turbulence, but characteristic cloud formations are not always present or, if they are present, may lose definition in other clouds. Similarly, the updraughts and downdraughts are, in general, not visible. If an aircraft remains for any length of time in a downdraught (eg by flying parallel to the mountains in the descending portion of the wave), which may be remarkably smooth, serious loss of height may occur.

2.2.2 During upwind flight the aircraft's height variations are normally out of phase with the waves; the aircraft is, therefore, liable to be at its lowest height when over the highest ground. The pilot may also find himself being driven down into a roll-cloud over which ample height clearance previously appeared to be available.

2.2.3 Downwind flight may be safer. Height variations are usually in phase with waves, but it must be appreciated that the relative speed of an accidental entry into the rotor zone will be greater than in upwind flight because the rotor zone is stationary with regard to the ground. Thus, the structural loads which may be imposed on the airframe when gusts are encountered are likely to be greater and there will probably be less warning of possible handling difficulties.

2.3 **High Altitude Flight**

2.3.1 The primary danger at high altitude is that of a sudden encounter with localized disturbances (ie turbulence, sudden large wind and temperature changes) at high penetration speeds, this is particularly relevant at cruising levels above FL 300 where the buffet-free margin between the Mach number for 1g buffet and the stall is restricted. In this respect flight downwind is likely to be more critical than flight upwind, especially when the wind is strong. As in the case of low altitude flight the waves are stationary relative to the ground, and the higher relative speed on accidentally encountering a standing wave while flying downwind is likely to place greater loads on the airframe. There will often be no advance warning of the presence of wave activity from preliminary variations in flight instrument readings, or from turbulence. Although downdraughts are present they are unlikely to be hazardous and icing and rotor zone turbulence are unlikely.

2.4 **General**

2.4.1 While flying through strong mountain waves, large fluctuations in wind velocity may be encountered, with associated turbulence; and an aircraft entering a wave system with its auto-pilot (including height and airspeed locks) fully engaged may begin to oscillate in the pitching plane as it attempts to maintain the selected height and airspeed. This oscillation can become unstable and, if unchecked, may put an aircraft into a dangerous flight condition as a result of excessive tailplane deflection. If the aircraft is being flown manually and the pilot chases height or airspeed, a similar result may occur. In either case there is a risk of an upset developing with catastrophic results. This emphasises the importance of the well established technique of flying 'attitude' in these conditions.

Part 3 - Advice to Pilots

3.1 When planning a flight over or close to high ground, pilots should ensure that the possibility of mountain wave conditions is considered in their meteorological briefing, particularly if frontal conditions are present in the area and a jet stream is expected at altitude. Although areas of turbulence associated with mountain waves cannot be forecast with accuracy, Meteorological Offices can help pilots to assess the possibility of mountain waves being encountered and can give advice on the probable height of layers of marked stability. Careful attention should be paid to warnings given in SIGMET messages broadcast during the flight.

3.2 If mountain wave conditions are forecast or known to be present:

(a) Do not attempt to approach or penetrate rotor clouds or likely rotor zones adjacent to mountain ran

(b) when flying over high ground, maintain a clearance height above the highest ridge at least equal to the height of the ridge above terrain. This should avoid the worst of the lower altitudes hazards;

(c) choose cruising altitudes well away from the base of layers of marked stability where severe turbulence is most likely to occur (present information suggests that, while there may be more than one stable layer, a margin to 5000 ft on either side of the base of a stable layer, including the tropopause, is advisable);

(d) be prepared for the occurrence of icing if cloud formations are present.

3.3 When flying in an area in which mountain wave conditions are suspected, always be prepared for turbulence, even in clear air, and take precautions accordingly. These precautions should include:

(a) Setting up the recommended speed for flight in turbulence;

(b) re-trimming the aircraft and noting the trim position so that any changes that may occur (due to auto trim action when using the auto-pilot) can be quickly detected;

(c) ensuring that crew and passengers are securely strapped in and that there are no loose articles;

(d) following the recommendations on the use of auto-pilot, height and airspeed locks and stability aids (yaw dampers etc) as appropriate;

(e) do not attempt to chase the gust induced lateral rocking, but aim to keep the aircraft laterally level to within reasonable limits, yaw dampers should remain engaged however;

(f) try to make all control inputs smoothly and gently.

3.4 Take-Off and Landing Manoeuvres

3.4.1 Pilots should be aware of the danger and severity of turbulence which may be encountered in the lee of high ground during take-off and approach to land maoneuvres, when performance margins may be small.

This Circular is issued for information, guidance and necessary action.

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