Turbulence

Turbulence occurs when airflow becomes chaotic and apparently random, rather than smooth and laminar. It occurs as eddies of varying size and intensity travel as vortices in the general airflow before dissipating due to friction.

The Bureau of Meteorology forecasts moderate (MOD) and severe (SEV) turbulence. Forecasts of severe turbulence include the extreme intensity given in the table opposite.

Introduction

Atmospheric turbulent eddies occur in a range of scales from hundreds of kilometres down to centimetres. Aircraft bumpiness is most pronounced when eddies are about the size of the aircraft, i.e. in the order of one hundred metres or so for commercial aircraft, to tens of metres for smaller aircraft. The reactions of aircraft are dependent on their type, configuration and the speed at which they encounter turbulent zones. Turbulence encounters can result in delays, extra fuel costs, aircraft damage, injuries to passengers and, in worst cases, fatalities and loss of aircraft.

Turbulence Intensity

Turbulence intensity is specified according to the perceived effect upon aircraft and occupants, as indicated in the following table:

Intensity	Airspeed Fluctuat-ions (kt/s)	Vertical Gust (ft/s)	G Load	Aircraft Reaction	Reaction Inside Aircraft
Light	5 – 14	5 - 19	0.15 – 0.49	Momentary slight and erratic changes in attitude and/or altitude. Rhythmic bumpiness.	Little effect on loose objects.
Moderate	15 – 24	20 - 35	0.50 – 0.99	Appreciable changes in attitude and/or altitude. Pilot remains in control at all times. Rapid bumps or jolts.	Unsecured objects move. Appreciable strain on seatbelts.
Severe	≥ 25	36 -49	1.0 – 1.99	Large abrupt changes in attitude and/or altitude. Momentary loss of control.	Unsecured objects are tossed about. Occupants violently forced against seatbelts.
Extreme	≥ 25	≥ 50	> 2.0	Very difficult to control aircraft. May cause structural damage.	

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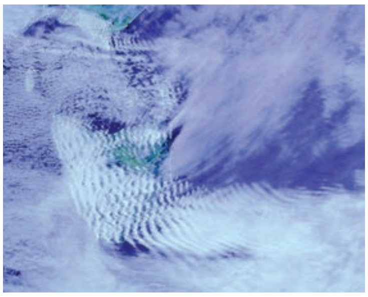
Types and Causes of Turbulence

The basic causes of turbulence are wind shear and thermal instability which, working together or independently, produce a local random variation in wind velocity.

Turbulence may be characterized as being:

- terrain-induced turbulence, i.e. mechanical and orographic turbulence, including mountain waves
- convective turbulence
- frontal turbulence
- low-level jet turbulence
- clear air turbulence (CAT)
- wake turbulence.

More than one type may contribute to any single turbulence event.



Satellite image of mountain waves over Tasmania, 3 December 2002.

Von Karman vortices forming in a stratocumulus field downwind from the volcanic island of Rishiri-to in the northern Sea of Japan. Image courtesy of NASA.

Turbulence may disturb an aircraft's attitude about its major axis, and cause rapid bumps or jolts to be experienced, but in most cases it does not significantly alter the aircraft's flight path.

This compares with wind shear which can cause a change in an aurcraft's headwind or tailwind that can displace the aircraft abruptly from its intended flight path, requiring substantial control action to be taken.

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Mechanical turbulence occurs due to frictional forces on the surface wind creating turbulent eddies. The intensity of mechanical turbulence is primarily dependent on wind speed, surface roughness and atmospheric stability near the surface. The intensity increases as both overlying wind speed and surface roughness increases, and when air flow is forced by obstacles to diverge around, or converge through gaps in, barriers. Winds over the ocean are subject to less frictional stress than winds over land.

Orographic turbulence is initiated by large-scale displacement of airflow by hills, mountains and islands. In general, upward displacement and consequent gravitational forcing lead to the development of mountain waves, downslope winds and rotors. Mountain waves form above and downwind of topographic barriers when strong winds blow with a significant vector component perpendicular to the barrier in a stable environment. If air is being forced over terrain, it will move downward along the lee slopes, then oscillate in a series of waves as it moves downstream, sometimes propagating long distances downwind. Aircraft may encounter severe turbulence in the wake of isolated islands when the atmosphere is stable. In these instances, air is forced around the obstacles rather than over them, producing both horizontal and vertical vortices and thereby adding to the complex turbulent motions in the obstacles wake. These lee side horizontal disturbances are called von Karman vortices and can rotate in both clockwise and anticlockwise directions.

Convective turbulence in the absence of cloud is commonly referred to as thermal turbulence. Convection occurs when air parcels are differentially heated by different earth surfaces, resulting in the warmer parcels rising as they will be less dense than the surrounding air. Thermals usually do not cause serious problems for aircraft, but the ride can be rough. While gliders seek out thermals to provide lift, light aircraft (travelling faster than gliders) may experience bumpiness sufficient to cause discomfort to passengers. Fast aircraft will experience more frequent bumpiness but will be in the turbulent area for a shorter time and the larger aircraft will have greater inertia due to larger mass to partially offset the extra bumpiness.

Thermals that produce significant turbulence are generally confined to the period of most intense insolation (generally late morning to mid afternoon), depending on the surface type, slope and angle to the sun and the depth of the mixing layer. Thermal turbulence frequently occurs in clear air with no visual signs. On other occasions dust and dust devils mark strong upward motion. Over flat surfaces and in light winds (~10 knots) thermals tend to occur in a honeycomb pattern. With stronger winds (>20 knots) they often form lines along the wind direction. In strong wind, thermals become chaotic and combine with mechanical turbulence to produce significant turbulence.

Convective turbulence in association with cloud is initiated by surface heating and/or low-level convergence, but later on in this process the convection is enhanced by the release of latent heat during the process of condensation and subsequent warming and destabilisation of the cloud environs.

Detection & Monitoring

Turbulence is one of those hazards where, in the absence of cloud, there are little or no visual clues to notify pilots of the presence of turbulence. Therefore pilots need to be aware of the situations in which turbulence is most likely, and monitor the forecasts, warnings and observations accordingly.

Visual clues for the presence of turbulence include:

- Cloud in the form of waves (Kelvin-Helmholtz waves), ripples or billows
- Roll clouds
- Lenticular clouds above mountains
- Thunderstorms or enhanced convection
- Raised dust or dust devils

A pilot in command of an aircraft must advise Air Traffic Services (ATS) of any encounter with severe turbulence.

Kelvin-Helmholtz wave clouds over Laramie, Wyoming, USA. Image courtesy of Brooks Martner, NOAA Forecast Systems Laboratory, 2001

It is not confined to the cloud mass. Its full force can extend around, over and below the cloud, and as such, it poses one of the biggest threats to safe aviation operations.

All cumulonimbus clouds should be considered to be turbulent. Hence within an aviation weather forecast the mention of cumulonimbus flags severe turbulence, though some are more turbulent than others. The most likely turbulent areas in cumulonimbus clouds are:

- the updraft/downdraft boundaries within the cloud
- the leading edge of the gust front
- above the cloud tops
- in any funnel clouds extending from the cloud base (sometimes reaching the ground as tornadoes and water spouts)
- in the upper parts of the updraft within the cloud

Updrafts are generally stronger than downdrafts, and tend to be strongest in the middle and upper parts of the cumulonimbus. The main impact on aircraft caused by updrafts and downdrafts is the rapid altitude change.

Beneath the cumulonimbus cloud, when a downdraft strikes the ground, it rushes outward in all directions. The leading edge is known as the gust front. The outward flowing cold air undercuts the warmer environmental air, much like a cold front, and continues to move outward, forced by the downdraft. As it spreads horizontally, it causes the warm air to rise and can lead to the formation of new convective clouds and thunderstorms. The strongest turbulence is at the leading edge of the gust front.

When the atmosphere is strongly unstable, vigorous updrafts can reach the upper troposphere, above the cumulonimbus tops. The resultant perturbation can induce severe wind shear and turbulence across short boundaries in clear air.

Note that turbulence associated with towering cumulus clouds may also have similar characteristics to those associated with cumulonimbus clouds.

Frontal zones, i.e. cold fronts and sea breeze fronts, may be associated with significant turbulence. The intensity of the turbulence in these regions is determined by:

- the speed of movement of the front
- the degree of any mechanical contribution
- vertical and horizontal wind shear across the frontal zone at both low and high-levels
- any thunderstorms generated on the front
- stability of the atmosphere
- temperature differences across the front

In vigorous cold fronts, a narrow zone of turbulent air will extend several thousand feet above the surface. In the absence of cloud and weather along a front, aircraft flying at low levels through this zone will encounter turbulence for only a short time. However, because frontal zones generally slope back and become broader with height, an aircraft flying well above and behind the surface front might be caught in a turbulent zone for some time.

Low-level nocturnal jets frequently form with nocturnal temperature inversions and ahead of cold fronts and windward of barriers when winds are blocked. Temperature inversions are effective in shielding the flow above from surface frictional effects, allowing the wind speed to increase in a narrow band near the top of the inversion.

Such a jet extends over southern Queensland and the Northern Territory during the cooler months. The core of this jet is often located from Daly Waters to the southeast of Tennant Creek with a maximum speed around 50 knots occurring at around 3000 feet. It is usually strongest around dawn and dissipates by late morning.

Low-level jets are also frequently observed on a much smaller scale just ahead of cold fronts and windward of physical barriers such as hills and escarpments when the

Forecasts & Warnings

Forecasting turbulence is a complicated issue due to the wide range of temporal and spatial resolutions at which it is observed, and because causes are not always clearly defined. More than one mechanism may contribute, or one may dominate the other, e.g. with strong winds, even if significant mountain waves exist ,it may be mechanical turbulence, rather than orographic (mountain waves), that has the most significance to aircraft flying close to terrain.

Turbulence forecasts are included in Area Forecasts, AIRMETs, Trend Forecasts (TTF), Aerodrome Forecasts (TAF), Significant Weather (SIGWX) charts and SIGMETs.

SIGMETs for thunderstorms and tropical cyclones do not include reference to turbulence as its presence is implied. TAF and TTF do not include turbulence associated with cumulonimbus or towering cumulus as the turbulence is implied.

Wake Vortex Study at Wallops Island. The air flow from the wing of this agricultural plane is made visible by a technique that uses colored smoke rising from the ground. Image courtesy of NASA. traces the aircraft's wake vortex, which exerts a powerful influence on the flow field behind the plane.

boundary is stable due to the presene of a surface temperature inversion. Funnelling of the wind through valleys and ravines may produce similar effects on a local scale.

The wind shear-induced turbulence associated with these jets can be hazardous to light aircraft operating at low levels, especially during take-off and landing.

Clear air turbulence (CAT) is defined as turbulence that occurs outside of convective cloud (mostly) at high altitudes. CAT creates a hazard for air navigation mainly because:

- aircraft experience sudden and unexpected changes in speed and/or altitude as they rapidly cross invisible bodies of air which are moving at different speeds
- it is impossible to detect either with the naked eye or with conventional radar.

CAT is more prevalent in regions of:

- Vertical and horizontal wind shear
- Convergening winds
- Horizontal wind deformation
- Temperature lapse-rate discontinuities
- Strong horizontal thermal gradients

The major synoptic features of the wind and temperature fields that have been found to be associated with CAT are:

- high altitude jet streams (sub-tropical and polar jets), particularly when they have anti-cyclonic curvature, and when the two types of jets are in close proximity.
- high altitude lows or troughs
- the tropopause

Wake turbulence is produced by all aircraft, including helicopters, when aerofoils are producing lift. Circulations are shed from the wing tips and evolve into a pair of counter-rotating vortices behind the aircraft. Each vortex is a mass of rotating air and consists of a core and a flow field about the core. The cores of these spinning currents can reach speeds of 180 knots and when moisture levels are high enough they become visible, shooting from the wings as thin strands of condensed water vapour. The strength of the vortex is governed by the weight, speed and shape of the wing of the generating aircraft.

Typically, for each nautical mile behind the generating aircraft, the vortices will have descended between 100 and 200 feet. These vortices generally persist for up to 80 seconds over the runway, but in light or calm air this period may be up to three minutes. In calm wind situations, the trailing vortices slowly descend and roll apart. Crosswinds can shift vortices over adjacent runways, and, under certain atmospheric conditions, vortices may rebound off the ground. A tail wind can move the vortices forward into the touchdown zone. The dissipation rate of the vortices, the path they travel and whether or not they rebound or drift across runways, is dependent on the atmospheric stability and wind velocity.

Aircraft encountering these powerful swirling vortices will experience some degree of turbulence, with short wingspan aircraft being most susceptible. At cruise levels, encounters are unlikely to be severe, but at low levels they are particularly dangerous to aircraft in takeoff and landing phases. Air Traffic Control apply minimum separation between aircraft to avoid encounters with wake turbulence. Wake turbulence is not forecast.

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