Clear-air turbulence

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Clear-air turbulence (CAT) is the turbulent movement of air masses in the absence of any visual cues such as clouds, and is caused when bodies of air moving at widely different speeds meet.[1]

The atmospheric region most susceptible to CAT is the high troposphere at altitudes of around 7,000–12,000 metres (23,000–39,000 ft) as it meets the tropopause. Here CAT is most frequently encountered in the regions of jet streams. At lower altitudes it may also occur near mountain ranges. Thin cirrus cloud can also indicate high probability of CAT.

CAT can be hazardous to the comfort, and, though very infrequently, even the safety, of air travel. An increase in clear-air turbulence is an expected effect of global warming. In the journal *Nature Climate Change* Paul Williams of the University of Reading and Manoj Joshi of the University of East Anglia reported moderate to severe transatlantic turbulence would be 40 to 170 percent more frequent in a world that had twice as much atmospheric carbon dioxide as pre-industrial times did.[2][3][4][5][6]

Contents

Detection

Clear-air turbulence is usually impossible to detect with the naked eye and very difficult to detect with conventional radar,[7] with the result that it is difficult for aircraft pilots to detect and avoid it. However, it can be remotely detected with instruments that can measure turbulence with optical techniques, such as scintillometers, Doppler LIDARs, or N-slit interferometers.[8]

Although the altitudes near the tropopause are usually cloudless, thin cirrus cloud can form where there are abrupt changes of air velocity, for example associated with jet streams. Lines of cirrus perpendicular to the jet stream indicate possible CAT, especially if the ends of the cirrus are dispersed in which case the direction of dispersal can indicate if the CAT is stronger at the left or at the right of the jet stream.

Factors that increase CAT probability

↑ вероятност

Detecting and predicting CAT is hard for meteorologists because it is at such heights that even when caused by factors that can be measured, intensity and location cannot be determined precisely. However because this turbulence affects long range aircraft that fly near the tropopause, CAT has been intensely studied. Several factors affect the likelihood of CAT. Often more than one factor is present. 64% of the non-light turbulences (not only CAT) are observed less than 150 nautical miles (280 km) away from the core of a jet stream.[9]

Jet stream

A jet stream alone will rarely be the cause of CAT, although there is horizontal wind shear at its edges and within it caused by the different relative air speeds of the stream and the surrounding air.

Rossby waves caused by this jet stream shear and the Coriolis force cause it to meander.

Temperature gradient

A temperature gradient is the change of temperature over a distance in some given direction. Where the temperature of a gas changes, so does its density and where the density changes CAT can appear.

Vertical

From the ground upwards through the troposphere temperature decreases with height; from the tropopause upwards through the stratosphere temperature increases with height. Such variations are examples of temperature gradients.

Horizontal

A horizontal temperature gradient may occur, and hence air density variations, where air velocity changes. An example: the speed of the jet stream is not constant along its length; additionally air temperature and hence density will vary between the air within the jet stream and the air outside.

Wind shear

Wind shear is a difference in relative speed between two adjacent air masses. An excessive wind shear produces vortices, and when the wind shear is of sufficient degree the air will tend to move chaotically. As is explained elsewhere in this article, temperature decreases and wind velocity increase with height in the

troposphere, and the reverse is true within the stratosphere. These differences cause changes in air density, and hence viscosity. The viscosity of the air thus presents both inertias and accelerations which cannot be determined in advance.

Vertical

Vertical wind shear above the jet stream (i.e., in the stratosphere) is sharper when it is moving upwards, because wind speed decreases with height in the stratosphere. This is the reason CAT can be generated above the tropopause, despite the stratosphere otherwise being a region which is vertically stable. On the other hand, vertical wind shear moving downwards within the stratosphere is more moderate (i.e., because downwards wind shear within the stratosphere is effectively moving against the manner in which wind speed changes within the stratosphere) and CAT is never produced in the stratosphere. Similar considerations apply to the troposphere but in reverse.

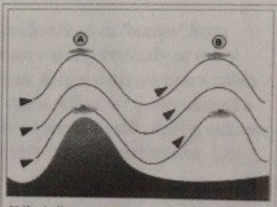
Horizontal

When strong wind deviates, the change of wind direction implies a change in the wind speed. A stream of wind can change its direction by differences of pressure. CAT appears more frequently when the wind is surrounding a low pressure region, especially with sharp troughs that change the wind direction more than 100°. Extreme CAT has been reported without any other factor than this.

Mountain waves

Mountain waves are formed when four requirements are met. When these factors coincide with jet streams, CAT can occur:

- A mountain range, not an isolated mountain
- Strong perpendicular wind
- Wind direction maintained with altitude
- Temperature inversion at the top of the mountain range



Wind flow over a mountain produces oscillations (A), (B) etc.

Gravity wave wind shear

The tropopause is a layer which separates two very different types of air. Beneath it the air gets colder and the wind gets faster with height. Above it the air warms and wind velocity decreases with height. These changes in temperature and velocity can produce fluctuation in the altitude of the tropopause, called gravity waves.

Effects on aircraft

In the context of air flight, CAT is sometimes colloquially referred to as "air pockets".

Standard airplane radars cannot detect CAT, as CAT is not associated with clouds that show unpredictable movement of the air. Airlines and pilots should be aware of factors that cause or indicate CAT to reduce the probability of meeting turbulence.

Aircraft in level flight rely on a constant air density to retain stability. Where air density is significantly different, for instance because of temperature gradient, especially at the tropopause, CAT can occur.