The Synoptic-aerological Conditions for the Occurrence of Clear Air Turbulence

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Summary

These are the results of CAT measurements under jet stream conditions based on in-flight registrations and observations made by the Deutsche Lufthansa over the North Atlantic and on occasion on some other special flights. Vertical acceleration as a measure of bumpiness has been related to certain meteorological situations and different atmospherical parameters.

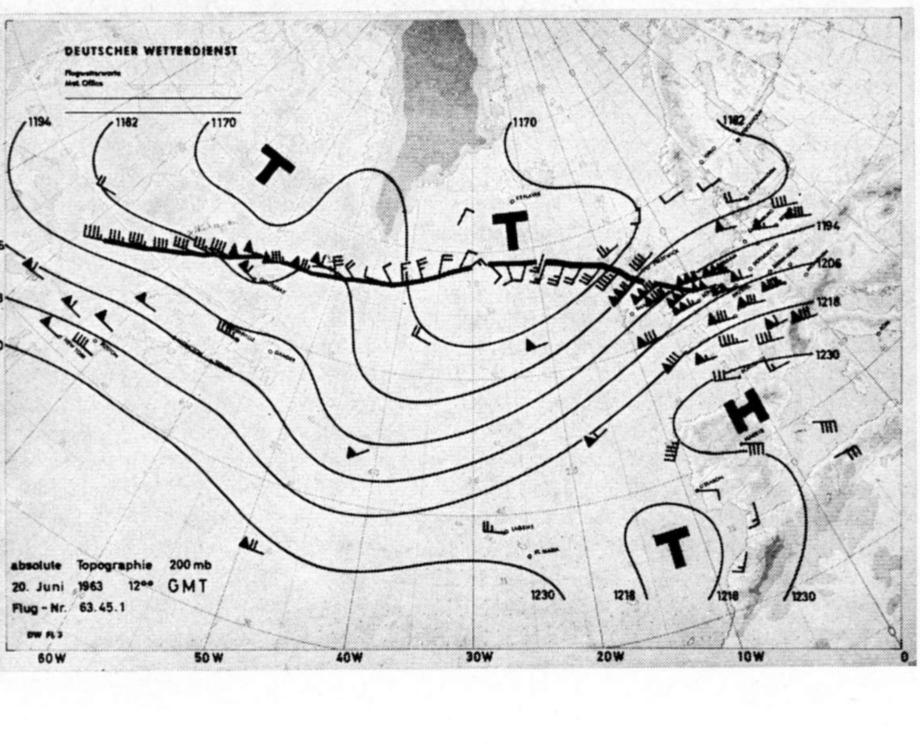
The special synoptic-aerological conditions on which heavy or moderate CAT can be expected are indicated by means of typical cases. These studies have proved that a definite localisation of areas imperilled by turbulence within the Polar Front jet streams is possible with the aid of the actual flight-meteorological material of the Meteorological Office as well as of meteorological flight data received on board the aeroplane.

The occurrence of the so-called Clear Air Turbulence (CAT) in free atmosphere particularly within the area of jet streams has always been one of the most important problems of aviation meteorology. For more than fifteen years research workers have made noteworthy efforts to discover the conditions on which CAT is possible, that is, the physical roots of CAT. These attempts and the quite expensive research programmes have been conducted with essentially one aim: to develop a method of forecasting CAT, and thus to be able to give well-timed warning of its occurrence. The change in vertical acceleration caused at an airplane by gusts is directly proportional to the true airspeed. Therefore, the problem of turbulence becomes more urgent with respect to the planned use of supersonic planes for passenger transport.

Definition of Clear Air Turbulence

In the United States nowadays any occurrence of turbulence at altitudes of more than 20 000 feet outside convection clouds is called CAT. In the Soviet Union the term «CAT» is used to describe bumpiness above 6,000 metres (i.e. the same altitude) outside clouds of any kind.

Ex. 1
Absolute topography 200 mb, 20. 6. 1963, 12.00 GMT.



The Conditions of Occurrence of Turbulence

It is well known that one can distinguish between various kinds of turbulence in the atmosphere:

1. Convection or convective turbulence is found on conditions of dry-unstable or moist-unstable thermal stratification.
2. We speak of dynamic turbulence when the source of the turbulence is not of a convective nature.
3. Bumpiness can also be caused by wave motions in the atmosphere. We must distinguish between mountain waves on certain atmospheric conditions within the region of mountains and gravitation waves at atmospheric inversions, as for example the tropopause. An airplane crossing such a wave and not adapting itself to the current will experience both positive and negative acceleration changes. The effects on the airplane are like those of real turbulence. Therefore, one should perhaps talk of bumpiness rather than of CAT.

Nevertheless, opinions still vary as to what extent bumpiness is caused by real turbulence or by wave motion. In theory, however, it can be shown that oscillations of the air in short wave lengths, that is, between 100 and 2,000 ft, become easily unstable and therefore can develop into a real turbulent form.

The Results of the Turbulence Research at the Atmospheric Physics Institute of the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR)

From April to October 1963 the Deutsche Lufthansa made in cooperation with the DFVLR recordings on their North Atlantic route, using a normal airliner Boeing 707, investigating the so-called Clear Air Turbulence effects in the sphere of Polar Front jet streams. In a total of 95 journeys across the ocean the following atmospheric data were registrated analogically:

1. vertical acceleration
2. air temperature (total air temperature and static air temperature)
3. pressure altitude
4. dynamic pressure
5. ground speed
6. drift angle
7. compass heading.

From these data one can also calculate the direction and velocity of the wind as well as the true airspeed. Contrary to the still common subjective estimates one can thus deduce objective values for the intensity of bumpiness from the following formula:

$$U_{de} = \frac{2 \; \triangle n \; G}{\varrho_o \quad v \; F \; C'_A \; k}$$

U_{de} = equivalent vertical gust velocity
Δn = n − 1 = increment in acceleration in g units
n = total acceleration in g units
$\frac{G}{F}$ = wing loading
ϱ_0 = standard air density at sea level
v = airspeed
C'_A = wing lift-curve slope
k = alleviation factor

In subjective estimates normally 3–5 degrees of bumpiness are distinguished; they correspond to the following objective values for the change of vertical acceleration and respective calculated vertical speeds:

very light	0.0 to ±0.05 g		0.0– 1.5 m/s
light	>0.5 to ±0.2 g	>	1.5– 6.0 m/s
moderate	>0.2 to ±0.4 g	>	6.0–10.0 m/s
severe	>0.4 to ±1.0 g	>	10.0–15.0 m/s
extreme	>1.0 g	>	15.0 m/s

Frequency of Occurrence of Clear Air Turbulence and the Dimension of the Turbulence Zones

In 95 flights across the Atlantic with a total cruising time of 612 hours excluding ascent and descent there was a total of some 86 hours of turbulence. This can be divided among the various degrees of turbulence as follows:

degree of turbulence	time	
	in hours	in %
very light	49.9	8.15
light	31.1	5.08
moderate	5.0	0.81
severe	0.2	0.03
	86.2	14.07

The first surprise was the small proportion of severe and moderate turbulence at 0.03 and 0.81 % of the total flying time. This was considerably lower than the proportion of turbulence found on the occasion of other investigations.

The reason for this: The experiments of the Lufthansa took place during the summer months, and it is well known that one can expect less turbulence, particularly CAT, during that half of the year. Furthermore, the flights were conducted on any weather conditions and not only when jet streams occurred. However, the recordings have shown that the pilots had made manoeuvres to avoid turbulence as soon as they noticed severe or moderate turbulence.

The horizontal extension of turbulence zones on the North Atlantic air route was in 86% of cases less than 50 km and in 95% less than 100 km. The greatest recorded extent of one turbulence zone was 660 km.

As to the vertical thickness of turbulence zones no information has been gained from the results of Lufthansa flights. A measurement programme carried out in South Germany by the Institute of Atmospheric Physics showed in 50% of the cases examined a vertical expansion of less than 200 m and in 95% one of less than 900 m. Our statistical statements concerning the dimensions of turbulence zones closely agree with the results obtained in the Soviet Union.

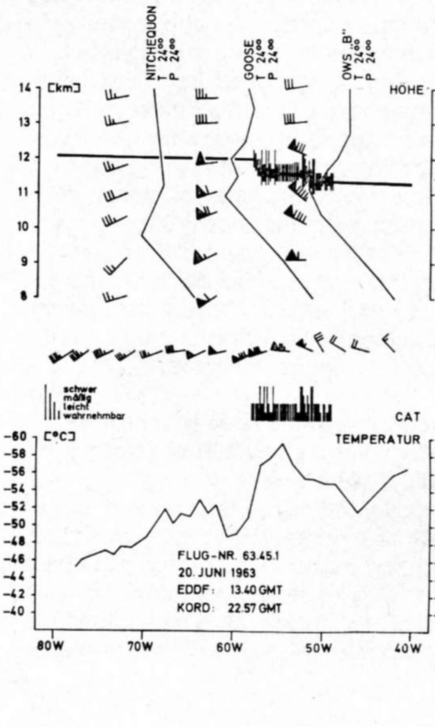
The Synoptic-aerological Conditions for the Occurrence of Clear Air Turbulence

These experiments were, as already explained, primarily based on the flight recordings over the North Atlantic as well as on measurements and observations during some further special flights on jet stream conditions. The data thus obtained were evaluated in connection with the available synoptic-aerological material. Thus unambiguous information has been obtained concerning typical synoptic-aerological situations in which severe or moderate turbulence tends to occur. In all the analysed cases stronger bumpiness has only been encountered within the region or at the edge of Polar Front jet streams.

Bumpiness above the Tropopause

Ridges of high pressure in the upper atmosphere with a considerable anticyclonic wind rotation have proved to be particularly liable to turbulence. Here waves and the connected bumpiness occur above the tropopause, which on such weather conditions is nearly always a layer of strong negative temperature gradients. At however the same time instability of current in ridges of high pressure in the upper atmosphere can also be caused by anticyclonic wind rotation and curvature of trajectories. For example:

Ex. 2
Temperature and spot winds at flight altitude as well as radio soundings around the flight route and CAT.



Flight on 20th June 1963

The synoptic-aerological conditions on the day of the flight are reproduced in example 1. The flight route has been drawn into the absolute topography which corresponds best to altitude and time of flight. The spot winds are indicated on the flight route. During this flight severe turbulence was observed within the region of the anticyclonic recurvature of a ridge of high pressure in the upper atmosphere which stretched from Newfoundland to South Greenland. The aerological conditions within the region of the ridge of high pressure can be seen in example 2. Turbulence is marked by vertical lines. The most noticeable phenomenon here is the strong inversion of the tropopause, the anticyclonic wind rotation and the vertical shearing of wind of around 1 m/sec/100 m.

The possible reasons for the severe bumpiness observed here may be:

1. gravitation waves at the tropopause inversion,
2. inertia instability.

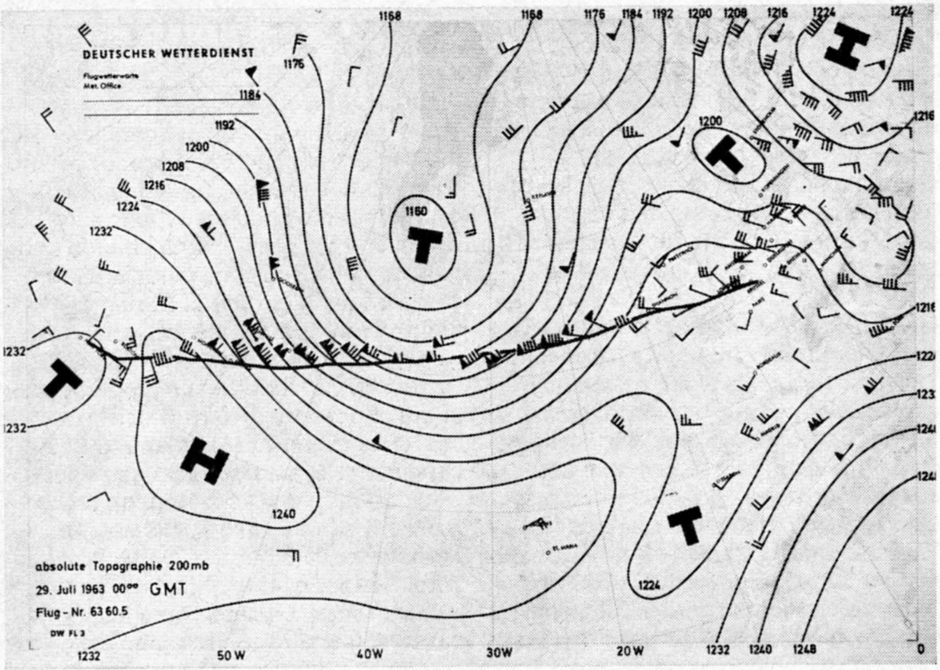
A. F. Crossely (1962) showed that the vertical component of absolute vorticity must be positive if the current is to remain stable. It is true that:

$$\frac{V}{r} - \frac{\partial V}{\partial n} + f > 0$$

V = wind velocity
r = radius of curvature of the streamlines
$\frac{\partial V}{\partial n}$ = horizontal wind shear along the normal to the streamline, the positive direction of the normal being taken to the left of the flow
f = Coriolis parameter

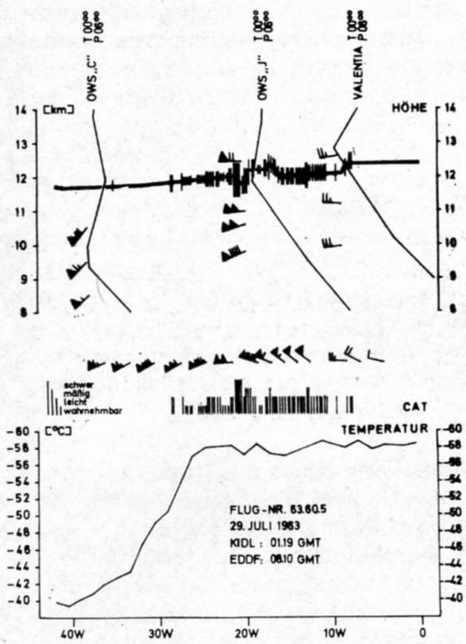
Bumpiness above the Tropopause and in the Highest Troposphere within the Area of Frontal Disturbances

Our investigations have furthermore shown that moderate and severe turbulence was mostly connected with the existence of frontal disturbances. Here it must particularly be the zone of upslide in the warm front area which is liable to turbulence. Such areas can be analysed by the pilot with the help of «Significant Weather Charts» as well as of cirrus formed clouds which are typical for the upslide process. In these cases the strong vertical wind shearing particularly seems to be the reason for serious turbulence as will be shown below. In temperate latitudes intensive warm air advection in front of a dynamic cyclone in respect of a trough in the upper atmosphere very often leads to the time frontal disturbances are usually building up of a ridge of high pressure in the upper atmosphere. At the same

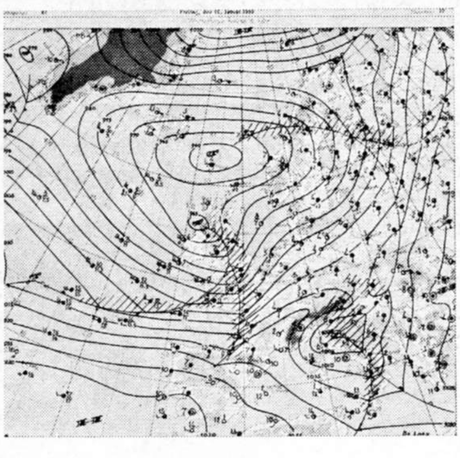


Ex. 3
Absolute topography 200 mb, 29. 7. 1963, 00.00 GMT.

Ex. 4
Temperature and spot winds at flight altitude as well as radio soundings around the flight toute and CAT.



Ex. 5
Surface weather chart for 12. 1. 1962, 06.00 GMT.



time frontal disturbances are usually present in this warm air current so that in many cases a ridge of high pressure in the upper atmosphere and a warm front immediately appear beside one another. In these cases it is difficult to decide which of the causes mentioned is to be considered responsible for the turbulence observed. Here is an example to illustrate this:

Flight on 29th July 1963

On this flight from New York to Frankfurt (example 3) severe and moderate turbulence was encountered at around 20° W at a height of approximately 12 km. At the front of a large dynamic low an intensive warm air advection from the south-west is created in which frontal disturbances are set up. The severe turbulence of two minutes duration occurred just above the tropopause inversion within the region of the ridge of high pressure in the lower stratosphere with a distinctive anticyclonic wind rotation (example 4). Here, according to the Air-Report, the aircraft was above an almost closed cirrostratus blanket. Shortly afterwards the flight led at the same flight level from the stratosphere to the troposphere. Here the aircraft was moving within the area of high frontal cloud; moderate turbulence occurred.

Turbulence in the Area of a Frontal Disturbance as a Result of Strong Vertical Wind Shear

As explained above the cause of moderate or even severe turbulence in the area of a frontal disturbance must be sought in the strong vertical wind shear. This in turn, as is well known, is connected with an extreme horizontal temperature gradient as can be shown in the following manner:

$$\frac{\partial v_y}{\partial z} = \frac{g}{2\omega \sin \varphi} \frac{1}{T_m} \frac{\partial T}{\partial x}$$

$\frac{\partial v_y}{\partial z}$ = vertical wind gradient
g = acceleration due to gravity
$2\omega \sin \varphi$ = Coriolis parameter
T_m = mean temperature, °C absolute
$\frac{\delta T}{\delta x}$ = isobaric change of temperature vertical to wind direction

The flight, analysed here, which is part of the above mentioned research programm in South Germany, provides an example for this.

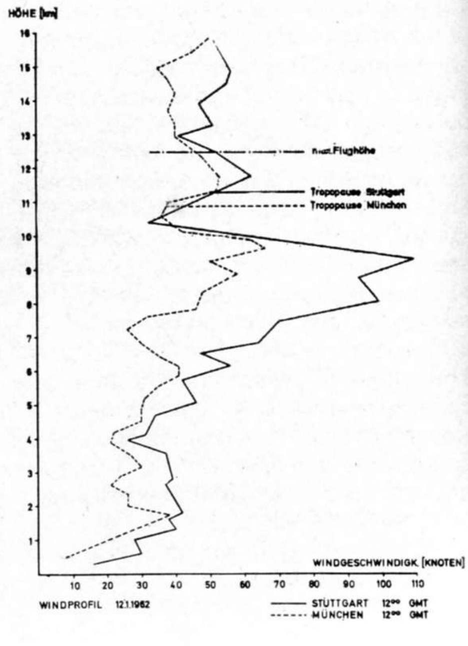
Turbulence Measuring Flight on 12th January 1962

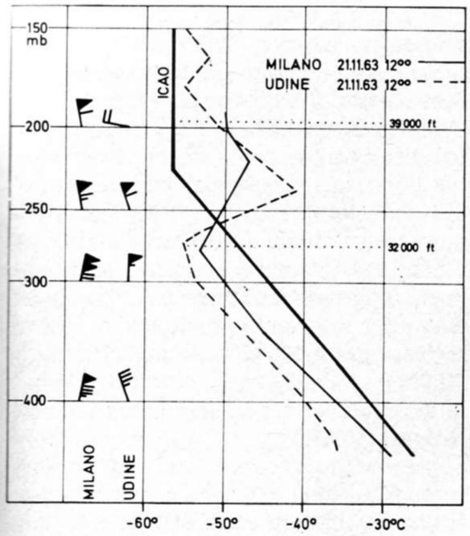
The surface chart of 11th January 1962 (example 5) shows several fronts crossing Western Europe and Germany on the day of the flight. High up a pronounced frontal zone combined with a jet stream crosses the Atlantic towards Europe. The wind measurements in the area of flight at the upper edge of the jet stream show maximum shear values of 3.6 to 3.9 m/sec/100 m (example 6). Over Stuttgart this shear zone has a vertical thickness of 1,000 m. In this area moderate to severe turbulence was observed.

Turbulence as a Result of Gravitation Waves or Mountain Waves

Often severe or moderate turbulence also occurs within the region or on the lee-side of mountains if at high wind speeds the air current is approximately vertical to the obstacle. Under certain circumstances most violent bumpiness can be encountered here, for example in the area of a strong tropo-

Ex. 6
Wind profiles from Stuttgart and Munich on 12. 1. 1962, 12.00 GMT.





Ex. 7
Radio soundings from Milan and Udine on 21. 11. 1963, 12.00 GMT.

pause inversion. This is a matter of gravitation waves or of air oscillations which are stimulated by the obstacle of the mountains. Again an example:

Lufthansa Flight of 21st November 1963 across the Alps

On that day the aircraft flew from Athens to Munich. South of the Alps it entered an area of severe turbulence.
The bumpiness was so strong that the Boeing was actually dancing in the air. The high weather chart of 21st November 1963 shows a trough in the upper atmosphere which reaches from a low over Finland down over Italy to North Africa. South of the edge of the Alps north winds dominate behind the trough. The radio soundings from Milan and Udine show marked tropopause inversions (example 7). The tropopause itself is located at both points at an altitude of 32,000 ft. The severe turbulence was encountered between 39,000 ft and 32,000 ft. With the aeroplane beginning to descent the bumpiness suddenly stopped below the tropopause.
A turbulent layer above the tropopause has on simular weather conditions already been found by J. Kuettner and C. F. Jenkins (1953).

Final Remarks

Because of limitations of space, out of a multitude of examples it has only been possible to explain briefly a few individual cases in which severe or moderate turbulence has been observed. Hereby it was made obvious that CAT of a greater intensity appeared in connection with Polar Front jet streams on certain synoptic-aerological conditions, namely within the region of ridges of high pressure with considerable anticyclonic wind rotation, in areas with frontal disturbances and in the neighbourhood of mountains when the air current is directed perpendicular to the obstacle. In the latter case especially the tropopause inversion will become dangerously turbulent.

Crossely, A. F.: Extreme of Wind Shear (Scientific Paper Meteorological Office, No. 17, London 1962).

Kuettner, J. and Jenkins, C. F.: Flight Aspect of the Mountain Wave (Air Force Surveys in Geophysics, No. 35, 1953).