Possible Criteria of an Explanation of the Phenomenon of Clear-air Turbulence Encountered by Aircraft

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Abstract

Investigation has shown that the clear-air turbulence encountered by aircraft appears to occur (1) below the jet isotach-max and on its north, or cyclonic, side; and (2) above the jet isotach-max and on its south, or anticyclonic, side. Through the use of two stability criteria which have been given by the present author, one might hope to arrive at an explanation for the phenomenon of clear-air turbulence.

Past studies on the high-level clear-air turbulence present many interesting features. British and American investigators [BANNON (1951, 1952), SHAEFER and HUBERT (1955), LAKE (1956)] made one of the earliest extensive studies of this problem. Recently, Project Cloud Trail has been established within the USAF Air Defense Command, and the observational phase of the project ran for the one-year period from December, 1954 to December, 1955. The analysed results of Project Cloud

LEGEND:

HORIZONTAL

VERTICAL

Fig. 1 Vertical and horizontal cross sections of the typical distribution of turbulence around the jet-stream Max-Isotach Center of 1500 Z, January 24, 1955. After LeROY H. CLEM (1957).

Trail by CLEM (1957) are of interest in conjunction with the jet-stream situation. In Fig. 1, vertical and horizontal cross sections are reproduced to illustrate the typical distribution of turbulence around a jet-stream max-isotach center. There appears to be a greater probability of occurrence of the intense turbulence (1) below the jet isotach-max and on its north, or cyclonic, side; and (2) above the jet isotach-max and on its south, or anticyclonic, side. The synoptic situation in this case is reproduced in Fig. 2.

Fig. 2 Distribution of observed turbulence in relation to the jet stream—1500 Z, January 24, 1955. Dashed lines are isotachs (in knots) at 300 mb. Solid lines are the jet stream axes. Number above the station circle is the altitude (in thousands of ft) of the most pronounced turbulence during climb of aircraft. Intensity of turbulence is indicated by appropriate symbols. After LeROY H. CLEM (1957).

RICHARDSON (1920) has developed a criterion for the increase or decrease of atmospheric turbulence where there is wind shear in the vertical. He postulates that turbulent flow will continue if the rate of supply of energy by eddy stresses is equal to or greater than the work done to maintain the turbulence against any stabilizing force. The RICHARDSON number is given by

$$(1) \quad R_i = \frac{g}{T} \frac{\frac{\partial T}{\partial z} + \Gamma}{\left(\frac{\partial v_x}{\partial z}\right)^2 + \left(\frac{\partial v_y}{\partial z}\right)^2},$$

where g is the acceleration of gravity, T the absolute temperature, $\partial T/\partial z$ the observed lapse rate, Γ the adiabatic lapse rate and $\partial v_x/\partial z$ and $\partial v_y/\partial z$ are the components of the vertical wind shear. The critical value to the RICHARDSON number has been assigned ranging from 1/4 to unity.

SOLBERG (1939) has discussed the vanishing of the absolute vorticity in the case of transition to instability. The vertical component of the absolute vorticity in a zonal current η is given by

$$(2) \quad \eta = -\frac{\partial u}{\partial y} + 2\omega \sin \phi + \frac{u}{R} \tan \phi,$$

where y is the meridional coordinate pointing northward, ω the angular velocity of the earth, ϕ the latitude, u the west wind speed and R the radius of the earth. If η is negative, the motion is dynamically unstable. This type of instability is possible on the south side of strong jet streams.

Another criterion for dynamic turbulence in the zone of cyclonic shear to the north of strong jet streams, has been given by ARAKAWA (1951 a). According to his theory the critical cyclonic shear, again for zonal flow, is given by

$$(3) \quad -\frac{\partial u}{\partial y} = \omega \sin \phi + \frac{2u}{R} \tan \phi.$$

This critical value is often realized in a narrow region just north of well-developed jet streams. As shown in Figs. 1 and 2, most of the cases of clear-air turbulence have, in fact, been from this zone of strong cyclonic shear.

The last criterion for dynamic turbulence [ARAKAWA (1951 b, 1957)] is related to the vertical gradient of the wind speed. The critical negative wind shear (wind speed decreasing with height) is given approximately by

$$(4) \quad \frac{\partial u}{\partial z} = -2\omega \cos \phi - \left(\frac{\partial T}{\partial z} + \Gamma \right) \frac{g}{2\omega \cos \phi \cdot T}.$$

As shown in Fig. 1, clear-air turbulence has, in fact, been associated with negative shear while no turbulence with positive shear in the narrow zone just south of the jet stream.

The definition of the jet stream recommended by the Commission for Aerology of the World Meteorological Organization [Abridged Final Report of the Second Session, Paris, 18th June—5th July 1957, p. 48] is "The vertical shear of wind is of the order 5~10 m/s per kilometre and the lateral shear of the order 5 m/s per 100 kilometres." There are, therefore, narrow belts near any jet stream characterized by strong vertical and lateral wind shears satisfying Equations (3) and (4).

References

- ARAKAWA, H., 1951 a: Possible heavy turbulent exchange between the extratropical tropospheric air and the polar stratospheric air, *Tellus*, 3, 208-211.

- ARAKAWA, H., 1951 b: The criterion of dynamic stability of zonal motion including the vertical shear, *Geofis. pura e Appl.*, 20, 56-61.
- ARAKAWA, H., 1957: Clear-air turbulence associated with negative vertical wind shear, *Journ. Met.*, 14, 188-189.
- BANNON, J.K., 1951: Meteorological aspects of turbulence affecting aircraft at high altitudes (Meteorological Office, London), Professional Notes, No. 104.
- BANNON, J.K., 1952: Weather systems associated with some occasions of severe turbulence at high altitudes, *Met. Mag.*, London, 81, 97-101.
- CLEM, LeROY H., 1957: Clear-air turbulence over the United States, *Aeronautical Engineering Review*, 16, No. 11, 63-68.
- LAKE, H., 1956: A meteorological analysis of clear air turbulence, *Geophys. Res. Pap.*, No. 47, 63, pp.
- RICHARDSON, L.F., 1920: The supply of energy from and to atmospheric eddies, *Proc. Roy. Soc.*, (A), 97, 354-373.
- SHAFFER, V.J. and W.E. HUBERT, 1955: A case study of jet stream clouds, *Tellus*, 7, 301-307.
- SOLBERG, H., 1939: Le mouvement d'inertie de l'atmosphère stable et son rôle dans la théorie des cyclones, *Procès-Verbaux de l'Assoc. de Météorologie*, UGGI, Edinburgh (1936), II. Mémoires et discussions, 66-82.

ク リ ア ・ エ ア ・ タ ー ビ ュ レ ン ス

荒 川 秀 俊

最近、イギリス及びアメリカで経験されたクリア・エア・タービュレンスに関する事実は、RICHARDSON および著者によつて示された基準によつて説明できることを示そうとしたものである。RICHARDSON の基準によると鉛直方向の風のシアが大きいところで乱れがおこる筈であり、著者の基準によると (1) ジェット気流の極側で、低気圧性の風のシアの強いところと、(2) 最強風のあらわれる高さよりも高いところ、いわば負のシアが大きいところで乱れがおこる筈である。これらの三種のシアのつよいところでは実際にクリア・エア・タービュレンスは頻発しているようである。