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THE WINTER JET STREAM OF AUSTRALIA AND ITS TURBULENCE

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1. INTRODUCTION

One of the discoveries from the enormous increase in flying during the 1939-45 War was that the winds in the upper atmosphere are not uniformly strong. Rather is the kinetic energy of the atmosphere concentrated in comparatively narrow meandering belts, which have been given the name of jet streams. Their intensive study since the war has shown that in addition to the jet streams created by the temperature differences in frontal regions ('polar front jet streams'), there are at least two large permanent jet stream systems that arise from the major thermal contrast between the tropical and polar regions.

The most important of these planetary strong wind belts is the 'subtropical' jet stream, which in winter dominates the wind field over Australia at heights above 20,000 ft. Velocities of 200 knots and more have been observed in this jet stream, especially at times when it is reinforced by a polar front jet stream moving up from the south. A perspective representation of the mean wind field over Australia during July is given in Fig. 1, while Fig. 2 shows its average cross section in a north-south plane between meridians 120°E and 160°E.

Figure 1 also shows the projections on the earth's surface of the latitudinal extreme positions of the mean isotach surfaces of 60, 80 and 100 knots, and the heights of these mean surfaces above selected stations. For example, a vertical line above Brisbane will intersect the mean isotach surface of 60 knots at 23,000 and 52,000 ft, the 80 knot surface at 27,000 and 48,000 ft, and the 100 knot surface at 33,000 and 42,000 ft; whereas at Perth a vertical line will intersect the 60 knot surface at 30,000 and 52,000 ft, and the mean July winds above Perth are not more than about 90 knots at any level.

The climatological information in these diagrams has immediate and obvious relevance to the operation of high-flying aircraft. This information can be supplemented by statistical data on the wind variability at a point and on the mean wind along an air route, of the kind published by Sawyer (1950), Brooks et al. (1950) of the British Meteorological Office, and by Phillpot and Reid (1952) of the Australian Bureau of Meteorology. However, for a better understanding of the jet stream as a meteorological phenomenon and for optimum flight programming, it is necessary to study the average location and variability of the jet stream core in space and the temperature and wind fields relative to the jet core. This jet stream 'structure' is important when considering the distribution of turbulence in the atmosphere. Here we shall examine the Australian jet stream, first as it appears from routine observations at the Australian network of upper air stations, and then through the results of a special high-level flight project aimed at the study of Clear Air Turbulence over Australia.

2. SUBTROPICAL AND POLAR FRONT JET STREAM STRUCTURES

Two American meteorologists, Endlich of the Stanford Research Institute and McLean (1965) of the Air Force Cambridge Research Laboratories, have shown that winds expressed as percentages of the jet core speed and mapped relative to the jet core, exhibit only minor variations with season and position along the polar front jet (i.e. between the troughs and ridges of the waves in the band of strong winds). Their observations were made over North America, but agree well with jet structures determined for Western Europe by Briggs and Roach (1963) of the British Meteorological Office. Their results thus appear to have general validity for the polar front jet streams of the Northern Hemisphere.

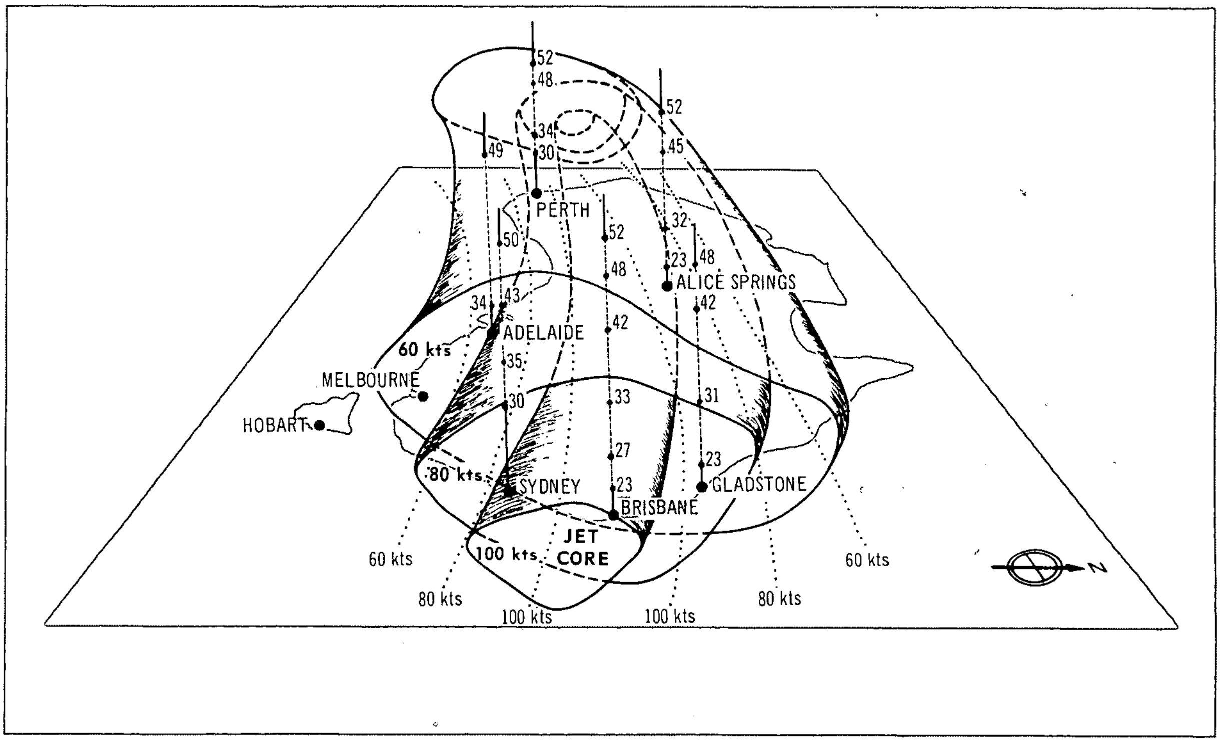

Fig. 1 Perspective diagram of mean July wind field over Australia (1956 – 61)

The isotach surfaces of 60, 80 and 100 knot westerly wind are drawn, and projections on the earth's surface of their latitudinal extremes are shown as dotted lines. The values in lines are the heights in 1000's of feet of the isotach surfaces above selected stations. (see text)

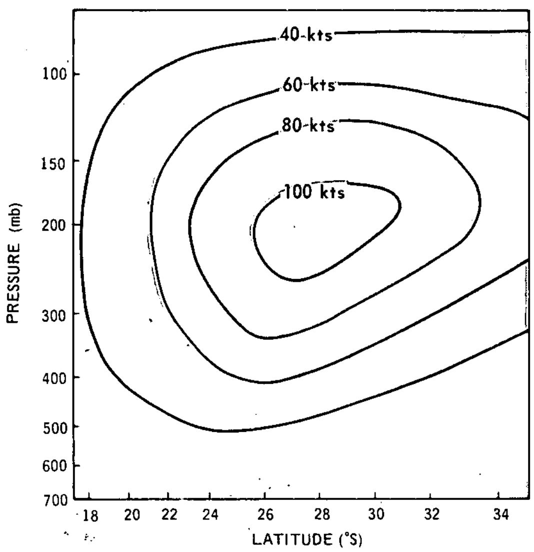

Fig. 2 Mean meridional cross section of average wind over region 120° E to 160° E.

The average core speed found by Endlich and McLean was 142 knots; yet in the mean wind field constructed in co-ordinates fixed to the earth, this jet stream, because of its transitory existence, limited longitudinal extent, and large meridional movement, does not appear as a recognisable entity as in the case of the subtropical jet stream. This illustrates the need to study the wind field relative to the jet core. Although as a planetary feature the subtropical jet stream is readily apparent in space co-ordinates, the salient features again emerge most clearly when jet stream co-ordinates are used - as was done for the Northern Hemisphere subtropical jet by Krishnamurti (1961) at the University of Chicago.

For the Australian region such an analysis has been carried out by Muffatti (1963) of the Bureau of Meteorology, but only for the 200 mb (40,000 ft) level. From Fig. 2 it can be seen that the height of the strongest mean wind is very close to the 200 mb level, which is also approximately the level of the subtropical jet core of the Northern Hemisphere. Thus, Muffatti's results provide the important structural features of the Australian jet stream.

He finds that July is the month of strongest mean flow, with a core speed of 143 knots nearly constant along the jet (between longitudes 120°E and 160°E) and a uniform standard deviation about this speed of nearly 30 knots. The average position of the core is at latitude $28\frac{1}{2}$°S, with a standard deviation of 3.7° latitude in longitudes 120 to 140°E, decreasing to 2.9° latitude at 160°E. Krishnamurti's Northern Hemisphere jet stream for the winter of 1955/6 showed a 120° longitude wave pattern centred at $27\frac{1}{2}$°N latitude, with a mean amplitude of $12\frac{1}{2}$° latitude.

The winds and horizontal variations in wind speed ('shears') over 5° of latitude on either side of the Australian jet core, are compared in Table 1 with those of the subtropical jet and polar front jets of the Northern Hemisphere.

Table 1. Winds across various jet streams at core level:

1. Northern Hemisphere polar front jet (Endlich and McLean)
2. Northern Hemisphere winter subtropical jet (Krishnamurti)
3. Southern Hemisphere winter subtropical jet (Muffatti)

	5° on Equatorial side	Jet Core	5° on Polar side
1. Speed (knots).	80	142	75
% of core speed	56	100	53
2. Speed (knots).	92	140	55
% of core speed	66	100	39
3. Speed (knots).	94	143	84
% of core speed	66	100	59

It appears that significant differences exist between the average shears of the two subtropical jets on their polar sides. In fact, as regards this shear, the Southern Hemisphere subtropical jet stream resembles more closely the Northern Hemisphere polar front jet. This probably reflects frequent equatorward penetration of the polar front in the Australian region during winter.

The vertical shear of the wind is characteristically two orders of magnitude larger than the horizontal shear, and therefore of greater relevance to the selection of optimum flight paths. Temperature and density variations are also most pronounced in the vertical, and for flight planning must be considered in conjunction with the vertical wind shear. No jet core co-ordinate data describing the vertical variations in the Australian jet stream, corresponding to

Muffatti's material for the jet core level, have yet been published; but some idea can be gained from the results of the clear-air turbulence investigation mentioned earlier.

3. PROJECT 'TOPCAT' AND THE MEAN STRUCTURE OF THE AUSTRALIAN JET STREAM

Between 21 July and 3 October, 1963, a specially instrumented Canberra aircraft of the Royal Aircraft Establishment, Farnborough, England, made 41 high-level flights over southern Australia. These flights formed Project TOPCAT (1964), a clear-air turbulence (CAT) research project. It was co-ordinated by Dr. U. Radok of the University of Melbourne, and supported by the Weapons Research Establishment, the Aeronautical Research Laboratories of the Australian Department of Supply, the Divisions of Meteorological Physics and Radio Physics of CSIRO, and the Australian Bureau of Meteorology. This writer organised on behalf of the Bureau the meteorological support for the flights, a large number of which had the advice and guidance of Dr. E.R. Reiter of the Colorado State University.

The research aircraft was instrumented to measure gust velocities both continuously in the form of acceleration counts, and on occasions of significant CAT, as time-base records of the three dimensional air velocity. Doppler navigation equipment provided in-flight winds during both 'routine' traverses of subtropical jet streams and 'special' searches for regions of significant turbulence.

Eleven routine flights were made across the jet core parallel to, and in the region of, 140°E. Six of the flights occurred when no polar front jet was near the subtropical jet. These provided the mean picture of zonal wind and temperature relative to the jet core shown in Fig. 3. Vertical and horizontal wind speed profiles constructed from this diagram are shown in Fig. 4. To this the mean wind profile corresponding to Fig. 2, and the corresponding profiles for the Northern Hemisphere polar front and subtropical jets, have also been added for comparison.

From Fig. 4(a), it is seen that the mean vertical shear below the cores of the subtropical jet streams traversed by the routine flights of Project TOPCAT was significantly greater than that of the polar front jet. Above the cores these profiles resemble each other closely. In contrast to these vertical profiles, those for a space-fixed co-ordinate system of Krishnamurti's Northern Hemisphere subtropical jet, and for the space-fixed co-ordinate system of Fig. 2, show close agreement with one another.

The horizontal velocity profiles of all jets are very similar on the equatorial side at distances of more than 1° latitude from the jet core. This confirms the result obtained for longer-term averages in Table 1. On this side of the jets there exists a dynamic constraint on the magnitude of the horizontal shear in steady flow. It follows from the vorticity equation for isobaric flow that the flux of the vertical absolute vorticity is non-divergent; Riehl and Fultz (1957) showed in connection with rotating tank ('dishpan') model experiments (which achieve a degree of dynamic similitude with the atmosphere) that the shear of the flow component V_s, parallel to the jet axis, when averaged in space and time for steady flow, can be put into the form

$$\frac{\delta V_s}{\delta n} = f - \frac{z_o}{m}$$

where n is the distance normal to the jet axis, z_o is a constant for a particular state of flow, m the space and time average of the flow component normal to the jet axis from its equatorial side, and f is the Coriolis parameter.

Since the latitudinal locations in either hemisphere of the mean subtropical jet cores now under discussion are symmetrical about the equator, similar horizontal shear values imply that the mean meridional flow components on the equatorial side of the jets are similar, at any rate over distances of 300 n. miles from the jet axis.

Fig. 4(b) shows that on the poleward side, the Australian subtropical jet of July 1963 has a profile intermediate to those of the subtropical and polar front jets of the Northern Hemisphere. Fig. 4(b) also shows the weaker horizontal shears in the space-fixed mean profile of Fig. 2 compared with the jet co-ordinate profiles.

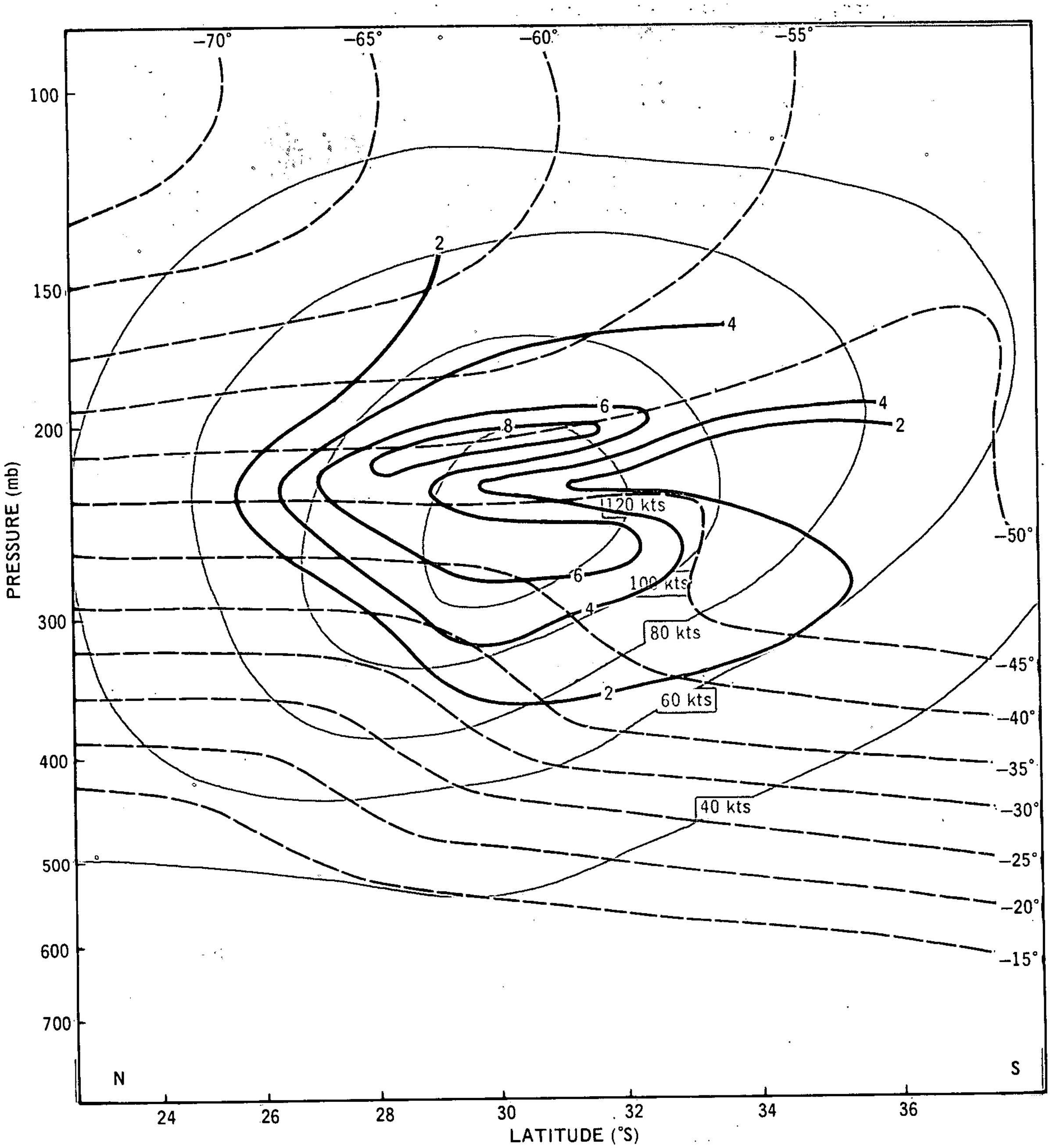

Fig. 3 PROJECT TOPCAT. Mean vertical cross section of winter subtropical jet stream (July 1963).

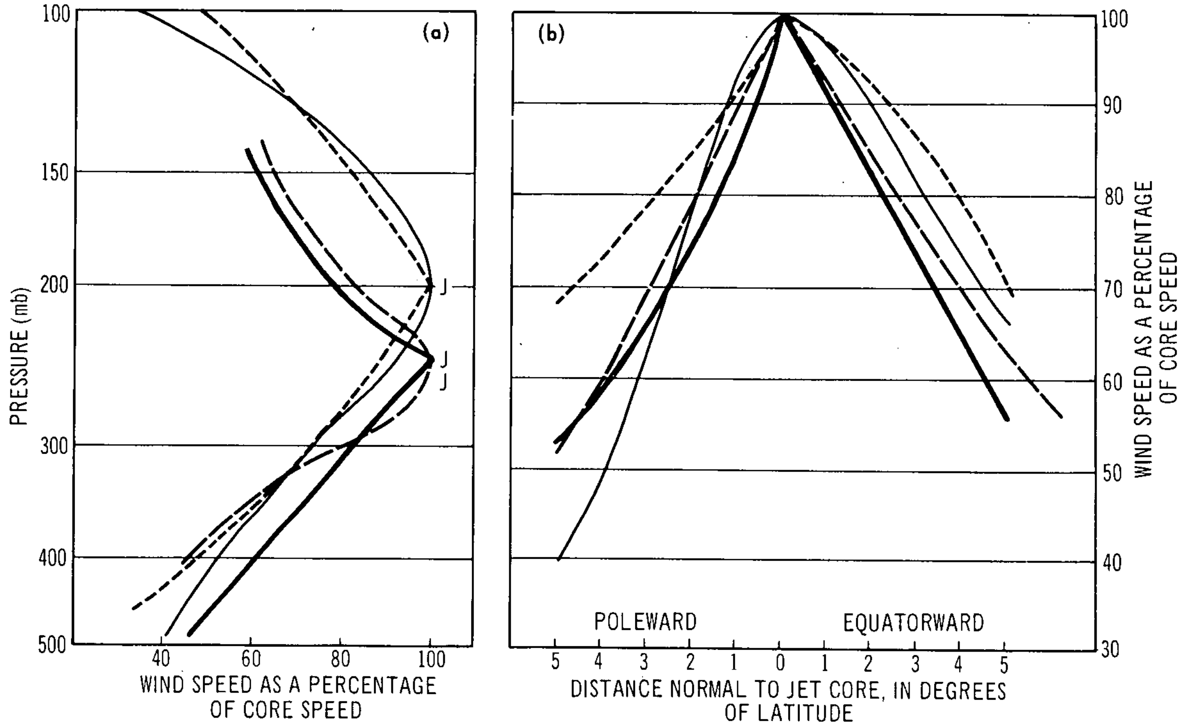

Fig. 4 Average verticle (a) and average horizontal (b) profiles of wind speed through various jet stream cores.

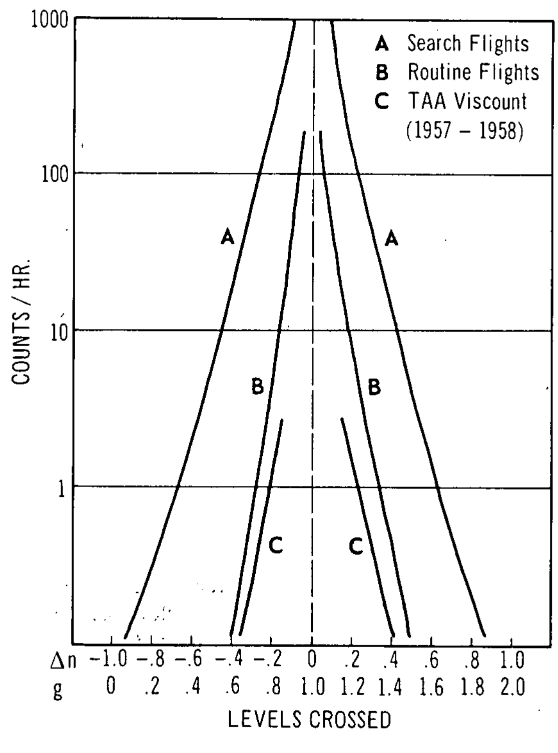

FIG. 4 LEGEND

- - - - Southern hemisphere (region 120° E to 160° E) mean wind profiles from Fig. 2.

▬▬ Northern hemisphere polar front jet, after Endlich and Mc Lean 1965.

— — Subtropical jet of July 1963 as samples in project TOPCAT over Central Australia.

—— Northern hemisphere winter subtropical jet, after Krishnamurti 1959.

Fig. 5 Frequency distribution in counts / hour of vertical accelerations experienced by a Canberra aircraft (430 kts) during project TOPCAT, and by a Viscount (approx 300 kts) in routine flight operations between 17,500 and 22,500 ft (after C. K. Rider).

4. CLEAR AIR TURBULENCE NEAR THE JET CORE

Frequency counts per hour of various acceleration levels obtained from project TOPCAT and from Trans Australia Airlines, have been made available to the writer by Mr. C.K. Rider of the Aeronautical Research Laboratories. These are shown in Fig. 5.

The distribution shown for A. SEARCH FLIGHTS relates to the turbulent sections of TOPCAT flights ranging from 24,000 to 42,000 ft and flown at 430 kt. On these flights about 4 hours 37 minutes were spent in clearly defined regions of CAT, the maximum vertical acceleration increment experienced being - 0.8 g.

The distribution for B. ROUTINE FLIGHTS relates to the total time, about 17 hours, of TOPCAT flights at 430 kt within 5,000 ft vertically and 300 n. miles horizontally of the subtropical jet cores; while the distribution for C. TAA VISCOUNT FLIGHTS relates to routine Viscount operations between 17,500 and 22,500 ft around Australia at an airspeed of about 300 kt. The Viscount data include turbulence encountered both in cloud and in clear air. Notwithstanding differences in aircraft speed and type, distributions B and C in Fig. 5 suggest that the region of the subtropical jet core is roughly five times more turbulent than the 20,000 ft level over Australia.

The distribution of acceleration changes (Δn) equal to or larger than ± 0.2 g has been indicated in Fig. 3 as frequency isopleths per 100 n. miles of flight. A clear minimum of gust incidence is found about 2,000 ft above the jet core and extending poleward, while a belt of high turbulence frequency is wrapped around the equatorial side of the subtropical jet core. This is the complete reverse of the distribution of turbulence around the polar front jet core, where Endlich and McLean found the band of maximum frequency to be on the polar side of the jet. However, with evidence from only six flights, this contrast cannot yet be regarded as conclusive and further studies along the lines of Project TOPCAT are needed to confirm it.

Implications of Fig. 5 can also be summarised by stating that at the jet core level, an average of one mile of flight in every 20 would be in a patch of clear air turbulence. From Fig. 3, however, we see that if a flight could be planned to follow the jet stream 2,000 ft above the core and about 100 n. miles on its polar side, the average turbulence would only be comparable with that experienced during the cruise at 20,000 ft. This illustrates the advantages to be gained for aviation from the detailed study of the Australian jet stream and its turbulence.

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