Vertical motions in the jetstream

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Introduction

Much has been written about the jetstream as a potential energy source for sailplanes. While it is well known that mountain waves are highly (and dangerously) developed with a jetstream of proper direction overhead, nobody has so far utilized the jetstream over flat grounds for soaring purposes. There is increasing evidence that this possibility exists indeed. The objective of this paper is to lay some groundwork for the practical approach. Much of the data used here has been collected in "Project Jetstream" of the Airforce Cambridge Research Center, by R. Endlich, R. Rados and G. McLean, whose publications have been essential in today's understanding of the jetstream phenomenon. This article summarizes the following papers read at the 7th OSTIV Congress of 1958 in Osieczna, Poland:

"Unbalance and Vertical Motions in the Jet Stream" by R. Endlich, J. Kuettner, G. McLean and R. Rados, Geophysics Research Directorate, Cambridge, Massachusetts, USA.

"An Occurrence of Severe Clear Air Turbulence and Attendant Vertical Motion in the Jet Stream" by H. Marx, GRD, Cambridge, Massachusetts, USA.

"The Soaring Potential of the Jet Stream" by J. Kuettner, GRD, Cambridge, Massachusetts, USA.

Furthermore, use is made of the time lapse film shown at the meeting:

"Cloud Formations in the Jet Stream" by J. Conover, Harvard Blue Hill Observatory, Boston, Massachusetts, USA.

It may be helpful to first sketch some general characteristics of the jetstream as revealed by the flights of the "Project Jetstream" research aircraft (type B-47 and B-29).

Some characteristics of the jetstream

A typical cross section of an idealized jetstream model is shown in fig. 1 (after Endlich and McLean, 1957). The following features are noteworthy:

First, the bottom of the stratosphere (tropopause) changes height by about 10,000 ft. (3 km) near the jetstream core. It is higher than the core to its right (looking downwind) and lower than the core to its left.

Second, as a consequence of this "tropopause break" the maximumwind-layer falls into the troposphere on the right side, into the stratosphere on the left side. In a westerly jet the right side corresponds to the south, the left side to the north. In other words, south of the jetstream axis one finds a tropospheric jetstream; north of the axis a stratospheric jetstream.

Third, a "jetfront" has been discovered by R. Endlich which seems to emerge from the stratosphere near the jetstream core and slopes down towards the south. This front has no connection with the cold front found frequently near the surface in the neighborhood of the jetstream.

Finally, the triangular area (fig. 1) between the maximum wind level and the jetfront (to the south of the jetcore) has the highest frequency of clouds among all levels and sectors of the jetstream. They consist mostly of cirrus (overcast or broken, McLean, 1957). Towards the core this "cirrus shield" either breaks up into cirrus bands running parallel to the jet axis over distances of many hundred miles (fig. 2) or it has a

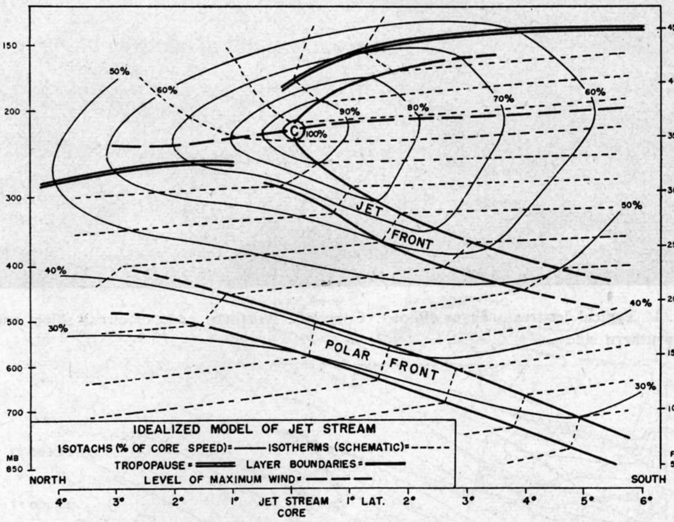

Fig. 1 Cross section of a typical jetstream (after Endlich and McLean)

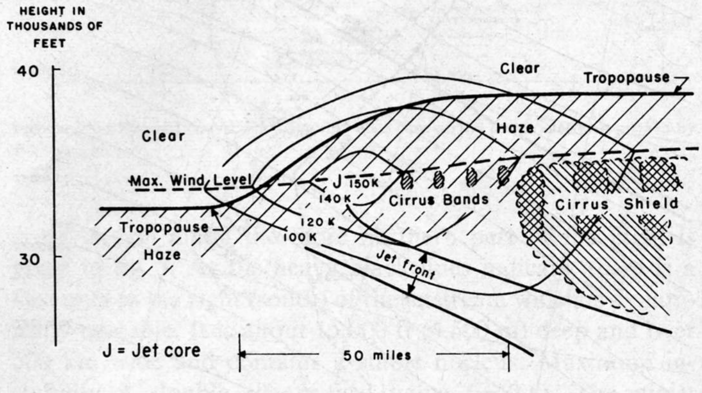

Fig. 2 Tropopause break and cloud pattern near the jet core as observed from high flying aircraft

sharp cutoff just south of the jet axis delineating the jet core along most of its total length (fig. 3, taken from Conover's motion picture). The space between this straight edge and the core itself is about 5 to 50 kilometers wide. In strong jetstreams this structure may exist over distances of several thousand kilometers.

Using airborne Doppler radar wind recorders, it was found that the wind velocity in the jet core is slightly less than should be expected from the pressure gradient. Such "sub gradient winds" are in contradiction to the generally accepted view that winds are "overshooting" in the jetstream core.

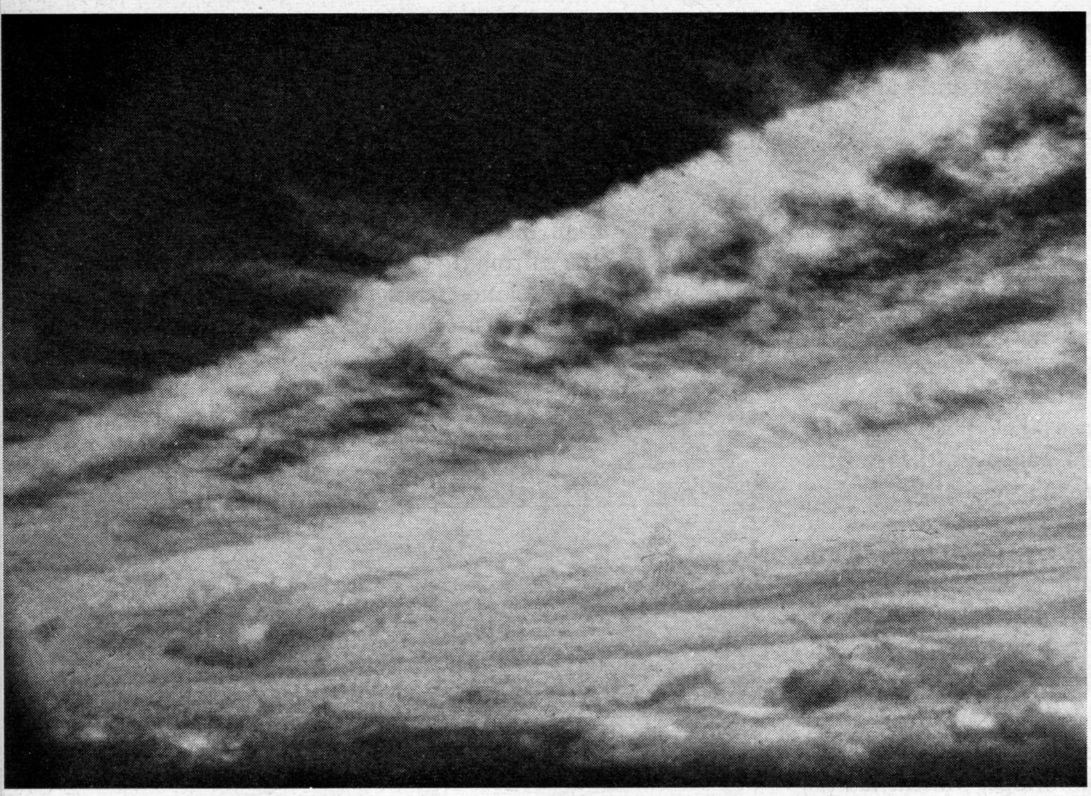

Fig. 3 Typical jetstream cirrus (Photo: Conover). Northern edge of cirrus shield and cirrus bands paralleling jet core on its southern side

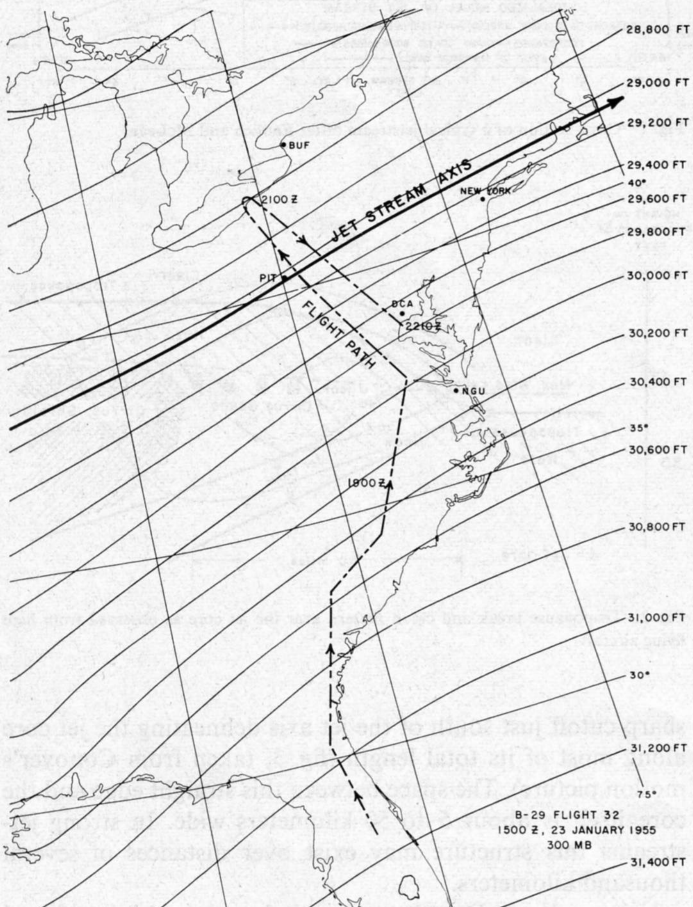

Fig. 4 B-29 flight path at about 9 km height across a straight jetstream of 180 knots

Unbalance and dynamic instability in the jetstream

The inconsistencies between wind, temperature and pressure field near the jetstream core indicate that equilibrium of forces does not exist and that the air parcels are in a state of acceleration. This is not surprising as it takes a considerable portion of a day for a particle to adapt to equilibrium on the rotating earth. During this period the air parcel may have entered the jetstream, traveled 2,000 km and left the jetstream before an equilibrium condition could have been reached.

There is another, less known type of balance in areas of strong horizontal and vertical windshear which, if disturbed, may cause what is called "*dynamic instability*." Existence of this type of instability has so far been considered rare. There is some proof now that strong jetstreams may have a wide area of dynamic instability on the right (southern) side, just about where the cirrus shield and the cirrus bands are observed. We have reason to believe that it is in this area where organized vertical motions exist and where future jetstream soaring may be possible. Before actual cases are discussed, an attempt shall be made to explain shortly the physical nature of "dynamic instability."

Most glider pilots are familiar with the meaning of dry and moist adiabates. These are lines along which air particles may move up and down without using up energy. According to definition they do not change their "potential temperature" along these lines (although they change their absolute temperature). How are the adiabatic surfaces oriented in the "frontal zone" under the jetstream where the temperature drops toward the north? That depends on the thermal stability of the air mass. If the stratification is very stable the adiabatic surfaces are almost horizontal. If it is less stable they are tilted upwards toward the north and if there is no stability at all they are practically vertical. Since air parcels will move up and down along such surfaces they will do so due to turbulent impulses that are always in existence. In areas of vertical adiabatics, they may form thermals. In a typical frontal zone with cloud formations the surfaces may rise toward the north by about 1 km for every 20 km horizontal distance.

Having reached understanding on this point, we may ask ourselves what happens to a rising air parcel on such a surface. Due to the earth's rotation the parcel moving upwards toward the north will curve toward the right (east) and gain "zonal speed," that is velocity in the direction of the jetstream. Dynamic equilibrium exists if the parcel gains precisely the same speed which the environmental air has already at the new level. Since the earth rotation is constant, the speed increment of the parcel rising along the tilted adiabatic surface is also a fixed constant for each latitude φ given by the Coriolis parameter $f = 2\omega \sin \varphi$. It corresponds to a velocity increase of about 1 m/sec (2 knots) for every 10 km of travel. If the actual wind of the jetstream increases faster than this value, the sliding air parcel will arrive too slow at the new level and will travel further towards the low pressure side (farther north). This happens because it is actually the horizontal pressure gradient which determines the wind speed prevailing at a given location, therefore, a particle traveling too slow will be sucked toward the lower pressure until it has accelerated to the proper velocity. In this way, an air parcel starting its travel on the slanted adiabatic surface towards the North will be continually accelerated in the same direction and will rise to ever higher levels.

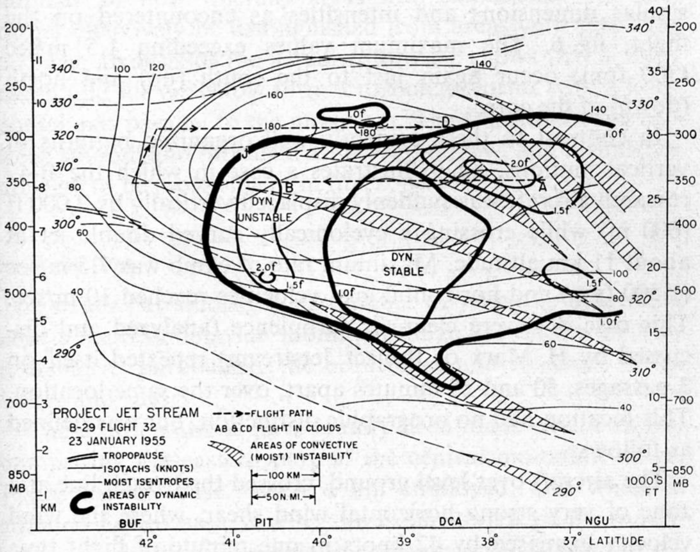

Fig. 5 Vertical cross section through jetstream (fig. 4) showing areas of dynamic and convective instability

In the same way an air parcel gliding down this surface will be continually accelerated towards the south and towards lower levels. This situation, called dynamic instability, resembles thermal instability and may create a special type of convection along slanted surfaces.

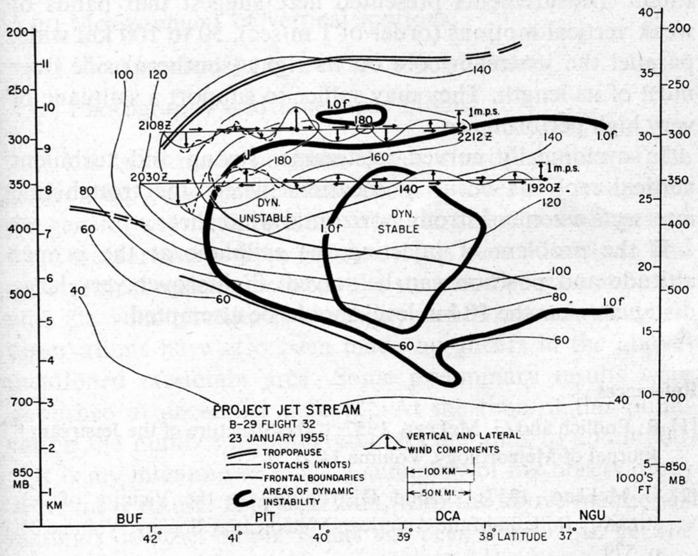

Fig. 6 Vertical motions measured by B-29 aircraft during traverse of jetstream (same case as fig. 4 and 5)

The stronger the vertical wind shear in the jetstream and the steeper the slope of the adiabatic surfaces, the greater the chance that dynamic instability occurs. Since moist adiabates have less temperature drop per unit height than dry adiabates, they have a steeper slope and offer a better chance for this type of instability than dry air. Once condensation has started, a small dynamic instability tends to increase the cloud mass, thereby extending the area of dynamic instability on the moist adiabatic surfaces. The measurements of strong jetstreams show that the cirrus shield to the south of the jetstream and the zone of dynamic instability coincide. It is here that organized vertical motions are encountered.

Vertical motions in the jetstream

Fig. 4 shows the flight path of Project Jetstream's B-29 at about 9 km height across an almost straight west-south-westerly jetstream of 180 knots (over 300 km/h). The vertical

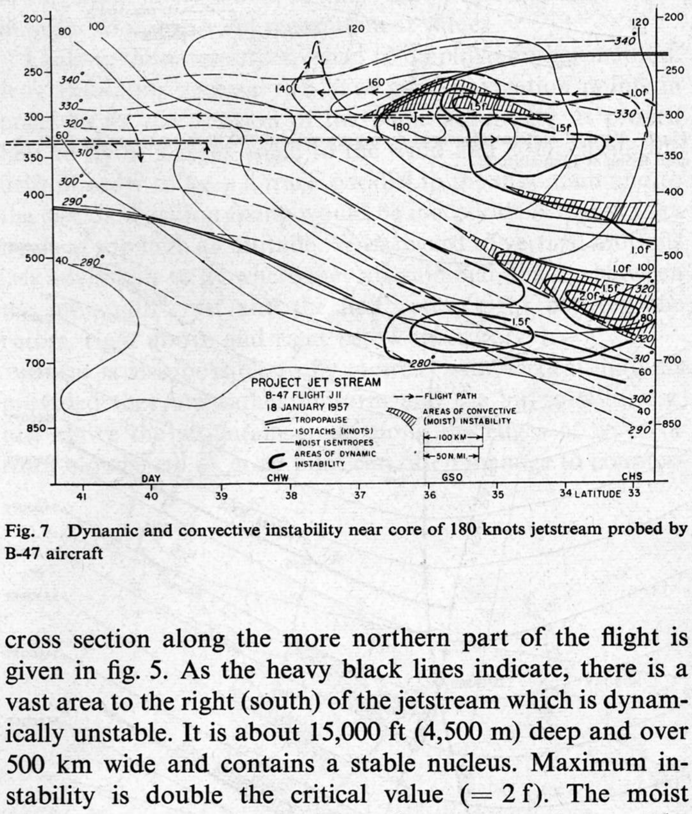

Fig. 7 Dynamic and convective instability near core of 180 knots jetstream probed by B-47 aircraft

cross section along the more northern part of the flight is given in fig. 5. As the heavy black lines indicate, there is a vast area to the right (south) of the jetstream which is dynamically unstable. It is about 15,000 ft (4,500 m) deep and over 500 km wide and contains a stable nucleus. Maximum instability is double the critical value (= 2 f). The moist adiabates (= "Moist Isentropes") are also shown. The hatched areas are thermally unstable. As the flight path indicates, the aircraft was continually in clouds to the right of the jet core (from *A* to *B* and from *C* to *D*).

Fig. 6 showing the same case illustrates the vertical motions encountered during this flight. There are alternating bands of updrafts and downdrafts, about 50 to 100 km wide in which the vertical velocity is of the order of 1 m/sec (= 200 fpm). The maximum upcurrents occur just south of the core, the maximum downdrafts just north of it. Horizontal wind components across the jetstream are also shown indicating confluence just below the core. It is interesting that Conover's synoptic cloud analysis gave major cirrus bands of about the same width. If one can identify these bands with the vertical

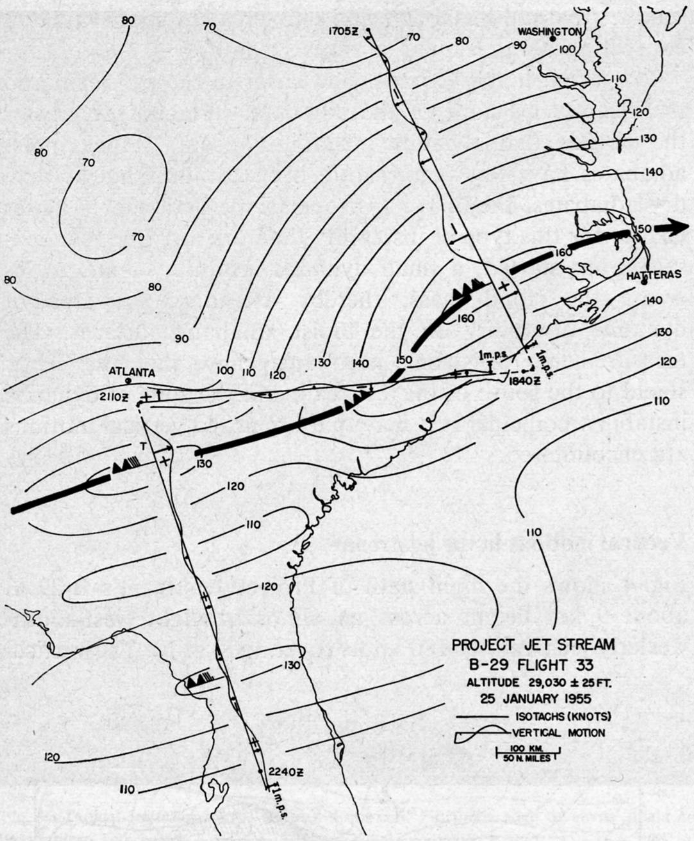

Fig. 8 Vertical motions measured during traverse of 160 knot jetstream by B-29 aircraft flying at 9 km altitude

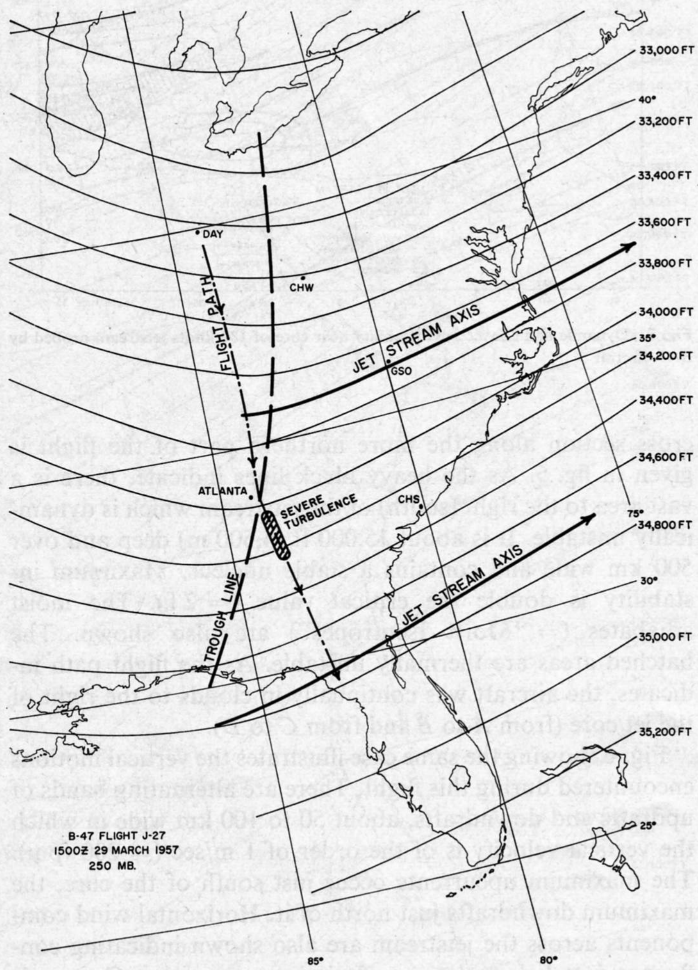

Fig. 9 Severe clear air turbulence encountered by B-47 aircraft near intersection of trough line and strong horizontal shear zone during traverses of double jet at 10 to 12 km height (after H. Marx)

currents measured, it may be concluded that the vertical motions are oriented in long bands paralleling the jetstream core. As the special flight technique used to measure these vertical currents does not allow to determine smaller scale motions, it must be left open whether or not stronger vertical drafts occur within these bands. A possible interpretation is that of large scale convection due to dynamic instability.

Another case measured by a B-47 aircraft is shown in fig. 7. Again a strong jetstream of 180 k contains an area of dynamic instability to the south of the core. The area is about 10,000 ft. (3 km) thick and several hundred kilometers wide. Layers of thermal instability are imbedded in the dynamically unstable part.

Fig. 8 pictures the measured vertical motion pattern along an extended Z type flight path of the B-29 crossing a jetstream of 165 knots at 9 km height. Up and downdraft areas are of similar dimensions and intensities as encountered on the flight, fig. 6. The maximum values exceeding 1.5 m/sec (300 fpm) occur again just to the south (up) and north (down) of the core.

In contrast to these evidently well organized patterns of vertical motions, fig. 9 illustrates a case in which the B-47 research aircraft was suddenly displaced vertically by 2,000 ft (600 m) while crossing a cyclonically curved double jet at about 11 km altitude. Maximum rate of climb was 7.5 m/sec (1,500 fpm) and horizontal gust velocities reached 10 m/sec. This case of severe clear air turbulence (analyzed and discussed by H. Marx of Project Jetstream) repeated itself on 3 passages, 50 and 25 minutes apart, over the same location. This location had no orographic distinction, but was defined as follows:

The aircraft over level ground, crossed the trough line at a zone of very strong horizontal wind shear, where the wind velocity increased by 42 knots in one minute of flight time (corresponding to a shear of almost 2 m/sec per km of flight). The horizontal dimensions of the major turbulent elements ranged from 0.5 to about 3 km.

Other flights bear out the same experience. The intersection of a trough line and a strong horizontal shear zone favors development of severe clear air turbulence.

Conclusion

Flight measurements presented here suggest that bands of weak vertical motions (order of 1 m/sec), 50 to 100 km wide, parallel the jetstream core on its right (southern) side over most of its length. They may suffice to support a sailplane of very high performance.

In cyclonically curved jetstreams, strong and turbulent vertical motions occur at locations where the trough line intersects a zone of strong horizontal wind shear.

If the problem of injecting the sailplane at the proper altitude and position can be solved, flights over very large distances near the 10 km level should be attempted.

References

[1] R. Endlich and G. McLean, 1957: "The Structure of the Jetstream," Journal of Meteorology, Volume 14, p. 543.

[2] G. McLean, 1957: "Cloud Distribution in the Vicinity of Jetstream," Bulletin of the American Meteorology Society, Volume 38, p. 579.

[3] See also the four OSTIV papers mentioned in the introduction.

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