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USE OF WATER VAPOR IMAGERY TO IDENTIFY CLEAR AIR TURBULENCE

Gary P. Ellrod
Satellite Applications Laboratory (NOAA/NESDIS)
Washington, D.C.

I. INTRODUCTION

Water vapor (WV) imagery in the 6μm wavelength band of the infrared has been produced by the European METEOSAT geostationary satellite since the late 1970's, and in the 6.7μm wavelength by the GOES (Geostationary Operational Environmental Satellites) since 1981. The inclusion of a WV channel on GMS in the mid-1990's should expand the use of this data to a nearly global scale. The imagery represents the net thermal energy reaching the satellite sensor after absorption by moisture in either vapor or condensed form. In regions of high, cold clouds (such as cirrus or cumulonimbus), the imagery appears white because the only energy received at the satellite sensor is from near the cloud tops. Conversely, regions of low humidity aloft appear dark grey or black because thermal energy observed by the satellite is originating from relatively warm lower levels of the troposphere. Intermediate gray shades can represent a wide range of possible moisture stratifications and are thus more ambiguous as to what conditions exist. Usually, WV imagery shows the presence of moisture in a deep layer above 600 mb, with the peak contribution near 400 mb (Weldon and Steinmetz, 1983). The 6.7μm channel is so sensitive that relatively small amounts of mid and upper level moisture can result in large image brightness.

Water vapor imagery has been found to be an excellent tracer of middle and upper tropospheric motion in many cases (Morel, et. al, 1978). Boundaries between moist and dry regions can be used in locating significant features such as the polar jet stream (Ramond, et. al, 1981), upper level lows and troughs, and col regions, also known as deformation zones (Anderson, et. al, 1982). When flow patterns are persistent, as with slow-moving or stationary weather systems, these boundaries eventually become oriented in the direction of the upper flow.

Changes with time in the WV image brightness are also significant. Increasing brightness may be an indication of vertical motion due to an approaching upper trough or jet streak that may initiate convection (Rodgers and Griffith, 1989). Decreasing image brightness has been associated with a net loss of moisture in the atmospheric column caused by upper tropospheric convergence and resulting subsidence (Muller and Fuelberg, 1990; Spayd, 1988). It has also been found that decreasing WV image brightness (darkening) relates to a rather high probability of clear air turbulence (CAT) (Ellrod, 1985). This paper will describe this signature and show a well-documented example.

II. DESCRIPTION OF SIGNATURE

While many of the dark bands observed in WV images contain high altitude turbulence, many do not. It was necessary to look for a characteristic that would increase the confidence of an aviation meteorologist in determining the presence of CAT. It was noticed that when progressive darkening appeared in successive images, the probability of CAT became very high. An example that occurred on January 25, 1984 is shown in Figure 1. In the WV image at 0530 UTC, two narrow dark zones are oriented northeast to southwest across the central United States. In the subsequent image (six hours later) a significant decrease in brightness occurred as the two bands merged (arrows). The 11μm infrared image at 0630 UTC (Figure 2) shows an extensive cirrus shield over the southern United States but does not exhibit the variations in moisture north of the cirrus seen in the WV image at 0530 UTC.

In a study of over 100 cases where such darkening was observed over the United States from 1983 to 1985, about 80% contained moderate or greater intensity CAT along a portion of the dark zone (Ellrod, 1985). One-third (33%) of the cases had at least one report of severe* turbulence. Subsequent study has confirmed these results. Although not all CAT outbreaks are accompanied by WV darkening, a significant percentage of them exhibit this characteristic.

III. CONDITIONS FOR OBSERVATION

A. Image Interpretation

The darkening feature is best observed in animated satellite imagery on video display terminals. Since the changes in brightness are often subtle, it is very important that the imagery be enhanced for proper contrast. A time period of at least 2 or 3 hours (at hourly intervals) is normally needed for the human eye to detect significant changes in image brightness, although in dramatic cases the darkening may be observed in as little as 1 hour. Figure 3 shows the trend in image brightness for several cases in 1984 and 1985. Digital count values represent the minimum brightness observed within a feature as it propagated. (The movement of a dark band is often at a pronounced angle to the upper flow). Decreases in brightness were generally 7% to 12% in six hours, with a maximum change of nearly 20% in six hours. In all of the cases shown, moderate or severe turbulence was reported by aircraft in the vicinity of the dark band.

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* Turbulence intensity is determined subjectively. In moderate turbulence, a passenger is forced against the seat belt. In severe turbulence, the aircraft may be temporarily out of control.

B. Synoptic Conditions

There are situations where WV darkening is not observed during significant CAT events. The synoptic weather situation plays an important role in these circumstances. To the north of a developing mid-latitude cyclone, for example, the dark zone (if present) is narrow and is often covered by cirrus clouds that spread poleward ahead of the advancing weather system. The dark zone associated with the subtropical jet stream is often more easily detected because of its smaller slope (Ramond, et. al, 1981).

The synoptic flow patterns most conducive to WV image darkening are shown in Figure 4. Note that the darkening typically occurs on the upstream side of a trough and there is often a wind speed maximum approaching the trough from the west or northwest. For the case shown in Figure 1, the 300 mb plotted wind reports at 1200 UTC featured a northeast to southwest trough (Figure 5) similar to flow type 1a in Figure 4. Southwest winds of up to 140 knots (72 m sec^{-1}) were found east of the trough axis, while a northwesterly flow jet of 110 knots (57 m sec^{-1}) was located over the north central United States. Upper level cold advection is also commonly found with WV darkening episodes, and was quite strong on this day northwest of the trough.

IV. STRUCTURE OF DARK BANDS

The thermal and moisture structure of the dark band at 1200 UTC on January 25, 1984 is shown by an isentropic cross section (Figure 6) along the line A through G in Figure 5. This structure is similar to that observed with many other WV darkening episodes. The solid lines represent potential temperature (Θ), the temperature an air parcel would have if warmed dry adiabatically to a pressure of 1000 mb. For unsaturated conditions, air parcels tend to conserve Θ, and thus flow along the isentropes. The vertical spacing of isentropes is related to stability, the more closely packed they are, the more stable the conditions. For a more detailed discussion of cross sections, see Cahir et al., (1976).

Figure 6 shows that in the region of the dark band (between Topeka, Kansas and Little Rock, Arkansas) there is a deep layer of dry air where temperature-dew point ($T-T_\delta$) was >10°C (unstippled area). In fact, $T-T_\delta$ was >30°C throughout most of the Monett, Missouri sounding. An upper trough was located from 800 mb at Little Rock to about 400 mb at Monett, with a weaker trough to the south associated with an upper level front. From the slope of the isentropes, it can be inferred that subsidence is occurring in the vicinity of the dark zone. The tropopause is observed to lower within the dark (dry) zone, resulting in what is referred to as a tropopause "leaf", a stable layer that descends into the middle levels at Jackson and Bootheville. The dashed isotachs (m s^{-1})

show pronounced deceleration in the flow as a branch of the Polar jet approaches from the north. A dual jet stream structure can be seen to the south of the trough, where the primary component of flow is into the cross section.

V. LOCATION OF TURBULENCE

Figure 7 shows the aircraft turbulence reports on January 25-26, 1984 for the period from 1300 to 0200 UTC (Z), along with the locations of the leading edge of the dark band (or the poleward edge of the cirrus) at 1200 and 0000 UTC.

The turbulence reports were located with respect to the moving dark band/cloud edge and replotted in the plane of the cross section (Figure 8) to show their relationship to significant upper level features. It should be noted that some along-stream variations in the locations of these features may be present. Also, the width of the dark band decreased to 200-300 km by 0000 UTC.

It can be seen that most of the CAT occurred in the leading (southern) portion of the darkening band, just poleward of the cirrus. The majority of the reports occurred in clear air, although two were just above the northern edge of the cirrus. Most were within 250 km of the axis of the primary upper trough. All reports were on the cyclonic side of the lower jet axis (PJ).

The segment of the WV dark band that contains the most frequent and intense turbulence is usually the portion that is darkening most rapidly with time. Therefore, it is not necessarily the darkest area in a WV image that contains the most turbulence. When the dark band begins to lighten as moisture gradually increases, turbulence frequency and intensity usually diminish.

VI. SUMMARY AND CONCLUDING REMARKS

Water vapor imagery from geostationary satellites has become extremely useful in the analysis of upper tropospheric flow features important to aviation meteorologists. Studies of GOES 6.7μm imagery and aircraft pilot reports have found that in areas that darken with time there is the likelihood of significant high altitude clear air turbulence. While some CAT episodes are not accompanied by WV darkening, both occur often in certain types of upper flow patterns. The darkening is associated with pronounced sinking and upper level flow convergence.

The relationship between WV darkening and the production of CAT is not well understood. It is apparent, however, that the processes that result in the darkening also play an important role in CAT generation. Those processes are believed to be: (1) upper level convergence, (2) cold advection, (3) deformation and (4) differential vertical motion in the vicinity of upper fronts. All of these factors have been implicated in prior research as important in the production and maintenance of strong vertical wind shears that lead to CAT.

VII. REFERENCES

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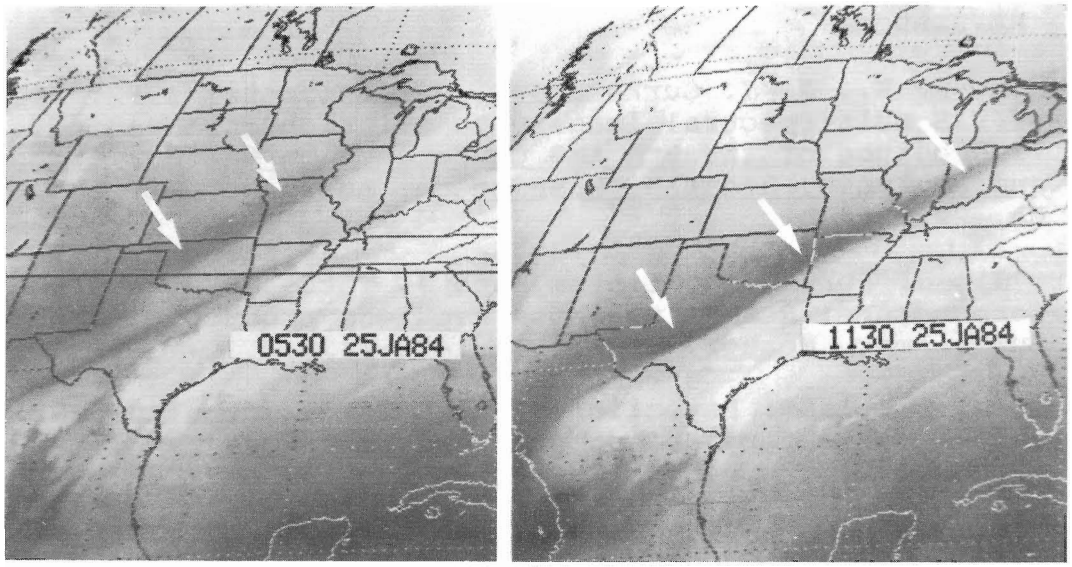

Figure 1. GOES 6.7μm water vapor images at 0530 UTC (left) and 1130 UTC (right), January 25, 1984. Arrows refer to dark band that has undergone substantial darkening in the six hour period.

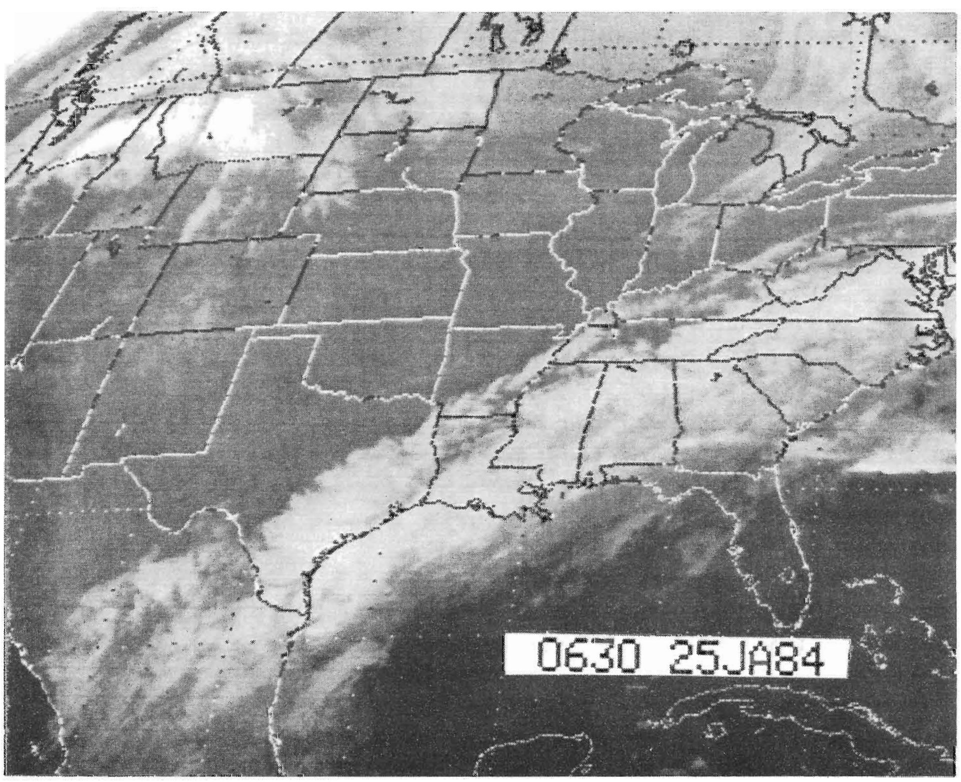

Figure 2. GOES 11μm infrared image at 0630 UTC, January 25, 1984.

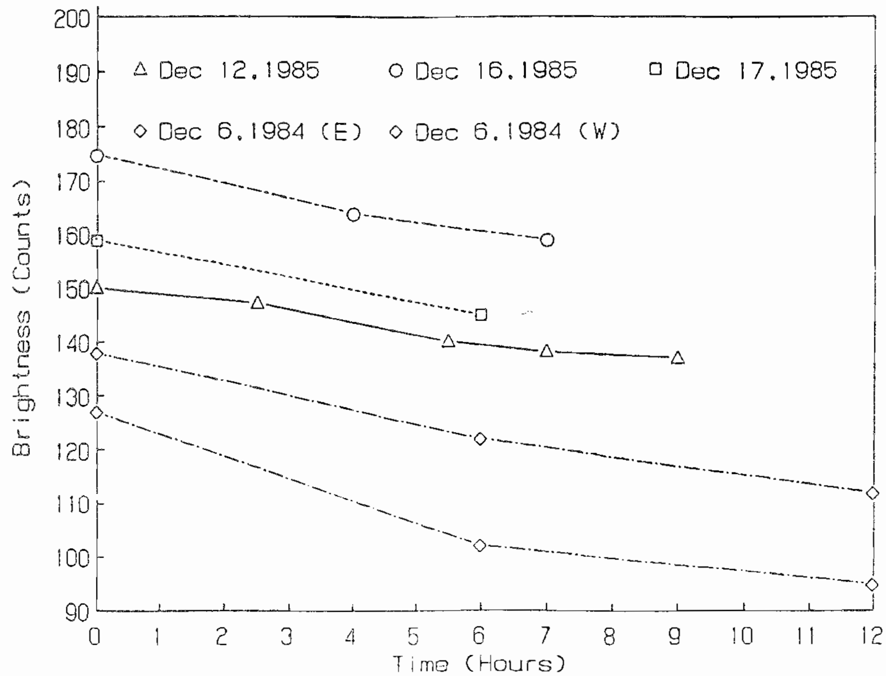

Figure 3. Change in GOES water vapor image brightness with time for several cases in 1984-85. Two rates were determined for the December 6, 1984 event in the eastern (E) and western (W) portions of the dark band. Data were obtained from digital data on an interactive display system.

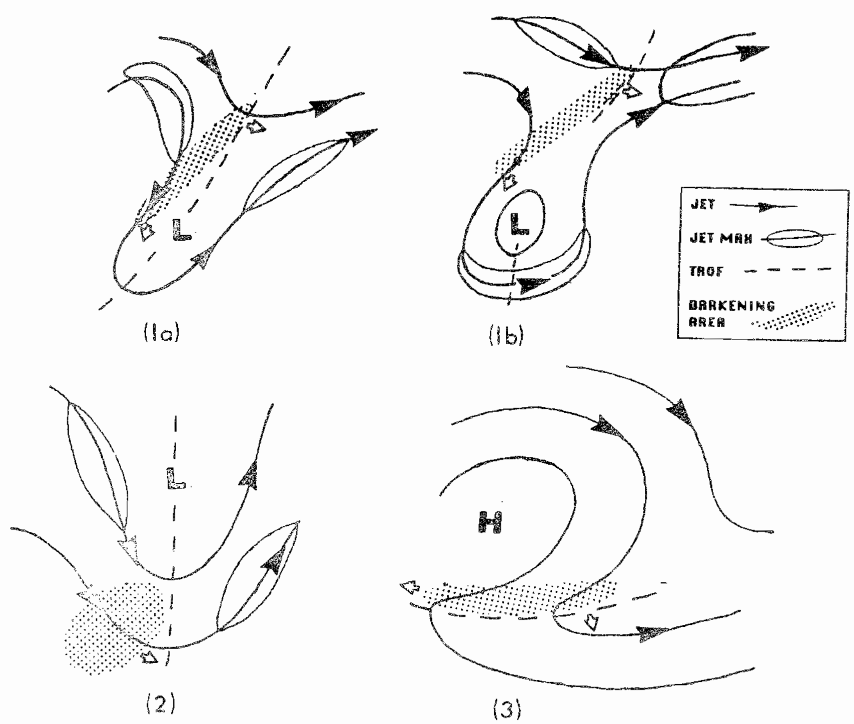

Figure 4. Upper tropospheric flow patterns most conducive to water vapor channel image darkening (stippled areas).

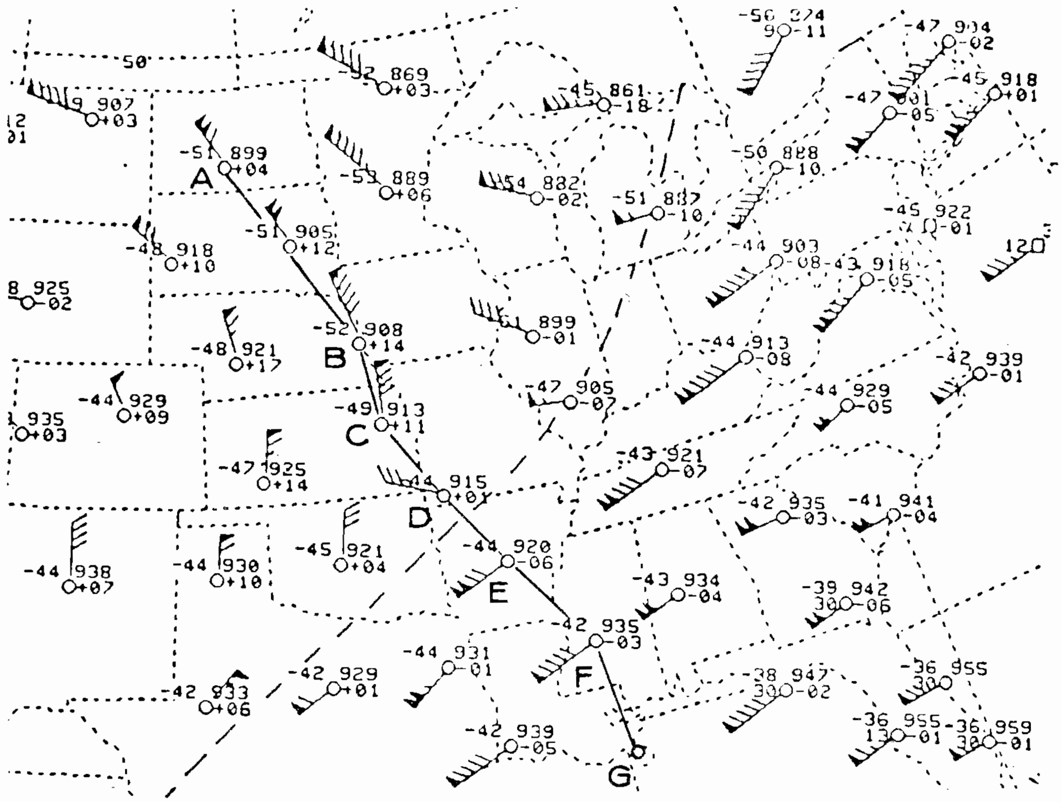

Figure 5. Plotted upper air data at 300mb for 1200 UTC, January 25, 1984. Dashed line shows location of upper trough and shear line.

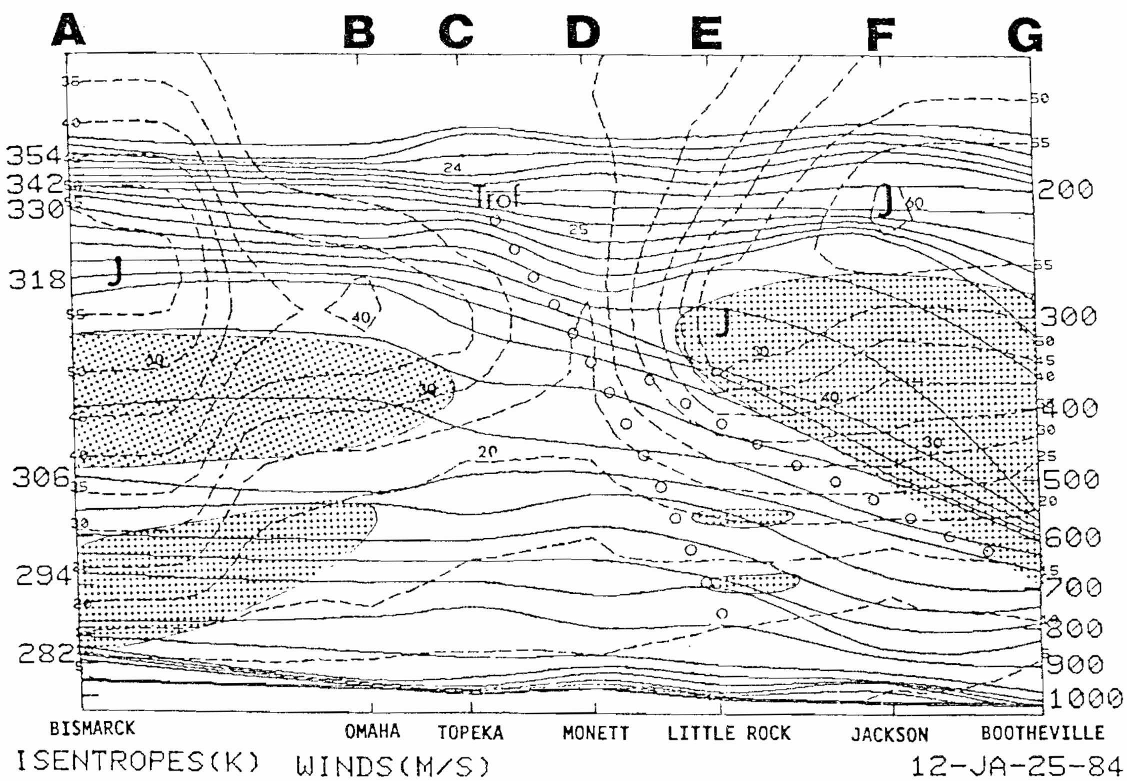

Figure 6. Isentropic cross section along line A-G in Figure 5. Solid lines are potential temperature (Θ, °K), dashed lines are isotachs (m s^{-1}). Stippled area approximates where $T\text{-}T_d < 10°C$. Open dotted lines are positions of upper troughs from radiosonde winds. Jet stream cores are labeled (J).

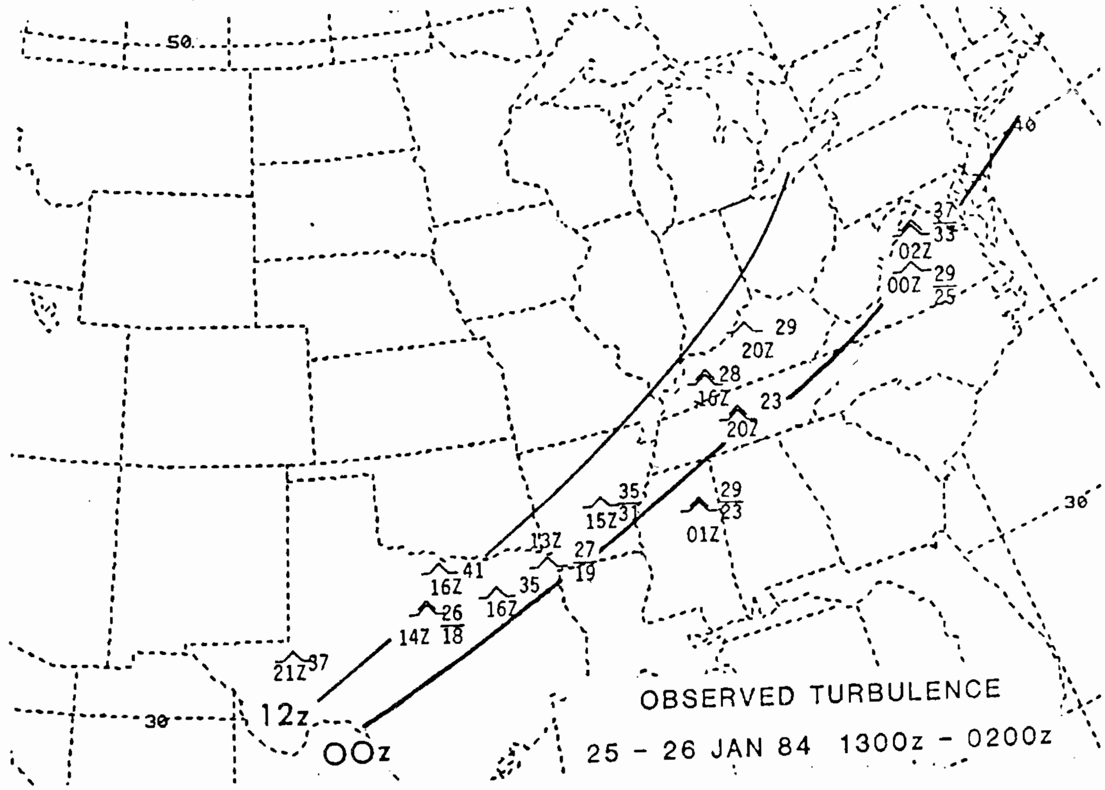

Figure 7. Locations of turbulence reports from 1300 UTC January 25, 1984 to 0200 UTC, January 26, 1984. Severe intensity = ⋀, moderate = ⋀. Altitudes are in thousands of feet. The location of the Equatorward edge of the dark band is shown for 1200 UTC (12Z) and 0000 UTC (00Z), January 26.

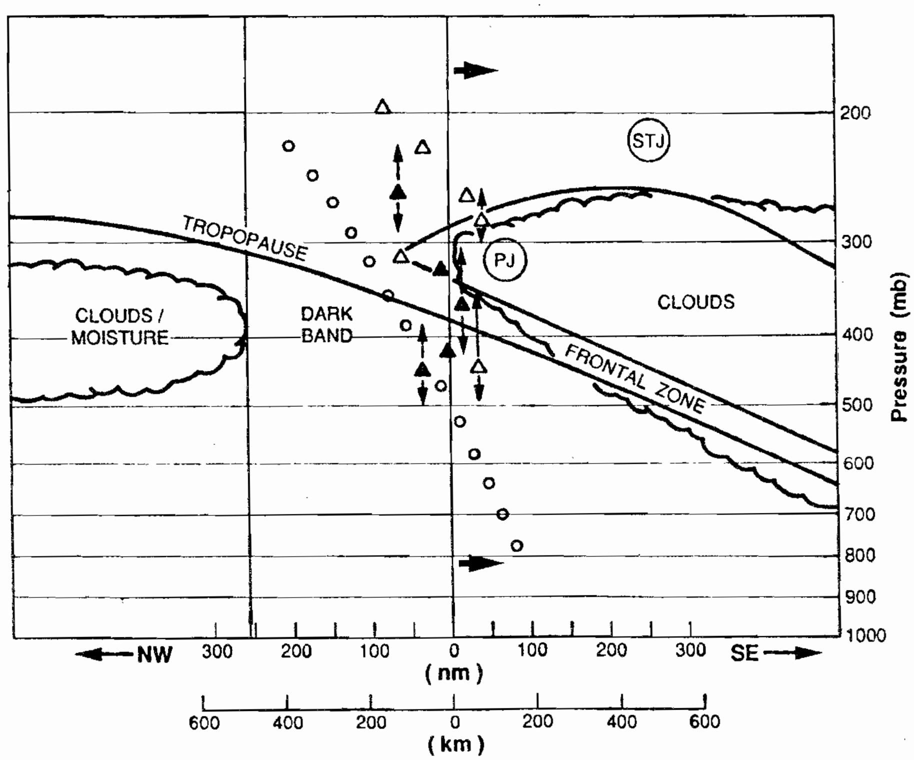

Figure 8. Turbulence reports in Figure 7 located in the x-z plane with respect to the moving dark zone/cloud edge. Upper level features were determined from Figure 6. STJ = subtropical jet core, PJ = Polar jet, moderate turbulence =△, severe turbulence =▲. Large solid arrows show movement of dark band.