AA Technical Memorandum NESDIS 23

A DECISION TREE APPROACH TO CLEAR AIR TURBULENCE ANALYSIS USING SATELLITE AND UPPER AIR DATA

Washington, D.C.
January 1989

UNITED STATES DEPARTMENT OF COMMERCE / **National Oceanic and Atmospheric Administration** / National Environmental Satellite, Data, and Information Service

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NESDIS 7 Surface Soil Moisture Measurements of the White Sands, New Mexico. G.R. Smith, September 1984. (PB85 135754)

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A DECISION TREE APPROACH TO CLEAR AIR TURBULENCE ANALYSIS USING SATELLITE AND UPPER AIR DATA

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UNITED STATES DEPARTMENT OF COMMERCE
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ABSTRACT. A decision tree logic diagram is described which is designed to assist aviation forecasters or flight briefers in the analysis and short range prediction of Clear Air Turbulence (CAT). The decision tree uses satellite imagery and, to a lesser extent, upper air data at standard pressure levels. The levels of confidence are stated for each solution. The primary turbulence signatures as seen in satellite imagery are described and examples of each are shown.

I. INTRODUCTION

A decision tree is a logical series of questions which branch out toward the solution of a problem. It is similar to the flow diagram used in computer programming. The decision tree is useful for problems which involve both subjective and objective criteria. It is superior to a checklist because its branching structure usually requires fewer decisions. In meteorology, the decision tree has been used successfully for such diverse problems as; analyzing the initiation of convection (Bothwell, 1988), estimating convective rainfall amounts from satellite imagery (Scofield and Oliver, 1977; Scofield, 1987) and in forecasting severe downslope windstorms in the Rockies (Brown, 1986).

Another example of a forecast problem which is tailor made for analysis with a decision tree is clear air turbulence (CAT). CAT is a mesoscale aviation hazard which often escapes detection by the current upper air observing network and changes rapidly in character with time. The purpose of this note is to describe a decision tree which has been devised for the analysis and short range prediction of CAT using satellite imagery and upper air data. The decision tree summarizes subjective techniques that have been developed in the past ten years, primarily at the Satellite Applications Laboratory of NESDIS (Anderson, et al., 1982; Ellrod, 1985, 1986, 1987).

II. DESIGN AND USE

The turbulence decision tree was designed for use by weather forecast facilities which do not presently have access to objective computer analyses and forecasts of conditions relevant to turbulence. Examples of these are National Weather Service Central Weather Service Units (CWSUs), FAA Flight Service Stations and remote military airfields. All of these units must provide current advice on weather hazards to aircraft in flight, sometimes without the benefit of pilot reports (PIREPS). Even weather offices which have objective forecast methods must have alternative means of checking current forecasts for accuracy and timeliness.

The flow diagram uses the latest satellite imagery and upper air data. It assumes the availability of hourly infrared images, daytime visible images and a 6.7μ channel water vapor image at least every 3 hours. Water vapor imagery is currently available from GOES and METEOSAT geostationary satellites. Important upper air data consists of the latest rawinsonde winds and temperatures at standard pressure levels or 6 to 12 hour forecasts of the same. For overwater areas, aircraft winds and temperatures may be substituted, although they are more difficult to use because of the variable flight levels at which the data is obtained.

It is assumed that the analyst has a good working knowledge of weather satellite interpretation and can locate important synoptic and subsynoptic features such as jet streams, troughs, ridges and closed lows.

The decision tree begins with an assessment of the upper level synoptic scale flow pattern over the region of interest and then asks questions about features observed in the satellite image. Many of these synoptic flow patterns are described in earlier models of clear air turbulence (e.g., Rammer, 1973). In general, upper flow patterns with longer wavelengths and less curvature are not as conducive to extensive turbulence, except where there are local areas of strong vertical shears generated by jet streaks.

Criteria for the magnitude of the vertical wind shear and the related turbulence intensity are not provided since most forecast units have their own standards. Usually, vertical shears of 6 to 9 knots/1000 feet result in moderate turbulence while 10 knots/1000 feet or more produce moderate to severe CAT. The presence of both speed and directional shear increase the likelihood of CAT. These conditions often result in wave cloud features in satellite imagery which are oriented transverse to the upper flow. For this reason they are often referred to as transverse cloud bands.

Some redundancy is built into the decision tree, so that if a mistake is made in the analysis of the synoptic flow pattern, it is still possible to arrive at the correct solution. Sketches are included to help visualize the image features or flow patterns being described.

Confidence levels are stated when a solution level is reached. These are primarily based on a study completed by the author (Ellrod, 1985), and subsequent research. In most cases, confidence levels range from 50% to 80%. Confidence is usually lowest in mountainous regions where turbulence may occur without any conspicuous image features.

Turbulence intensities range from light (L) to moderate (M) to severe (S). These have been determined from numerous subjective reports, mainly from large commercial and military aircraft. A solution which indicates that MOGR is expected means that moderate turbulence is likely and severe turbulence is possible. A solution of M-S means that moderate to occasional severe turbulence is likely. When possible, an attempt was made to identify features which denote stronger turbulence intensities.

III. DESCRIPTION OF IMAGE FEATURES

1. Deformation Zones

The most common large scale turbulence signature is the deformation zone. This is a hyperbolic flow region commonly found near the comma cloud "head" and also at the base of some troughs (near the "tail" of the comma). Figure 1 shows an example of a deformation zone associated with a steady state storm system moving eastward into the Central Plains. The stretching axis of the deformation flow pattern is usually close to the boundary of the cloud system, as in this example.

Situations where moderate to severe turbulence are most likely are when (1) cyclogenesis is in progress, accompanied by a building or rapidly moving upper ridge to the east of the storm system and/or (2) the cloud system is encountering confluent (opposing) flow caused by a blocking upper level system (a closed low or anticyclone) downstream. In some situations, considerable turbulence may occur when a comma cloud system and its associated low center are dissipating. A precursor to the preceding situation is often a flattening of the cloud border on the upstream side of the comma.

One way to monitor confluence along the deformation zone is to observe the appearance of the cloud edge in infrared imagery. A well-defined cloud edge with strong gradients of infrared temperature is more likely to have significant

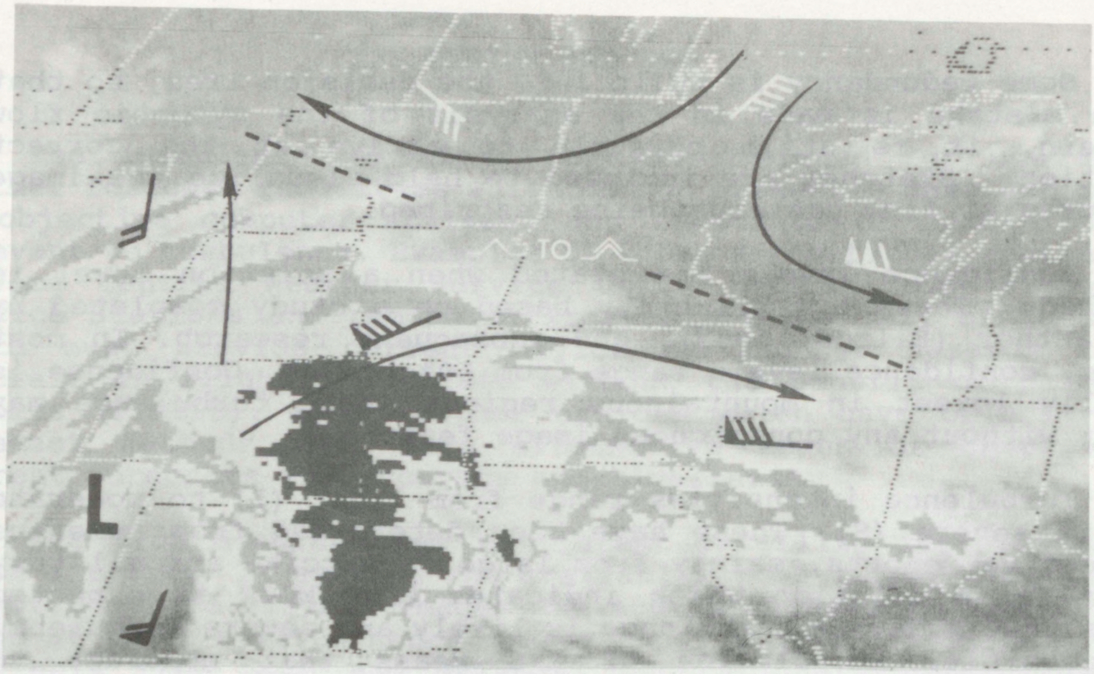


Figure 1. Enhanced infrared GOES image of a deformation zone along the poleward edge of a comma cloud system. Winds and streamlines are for 300 mb. Moderate (⌃) to severe (⩓) turbulence occurred along the stretching axis of the deformation zone (dashed line).

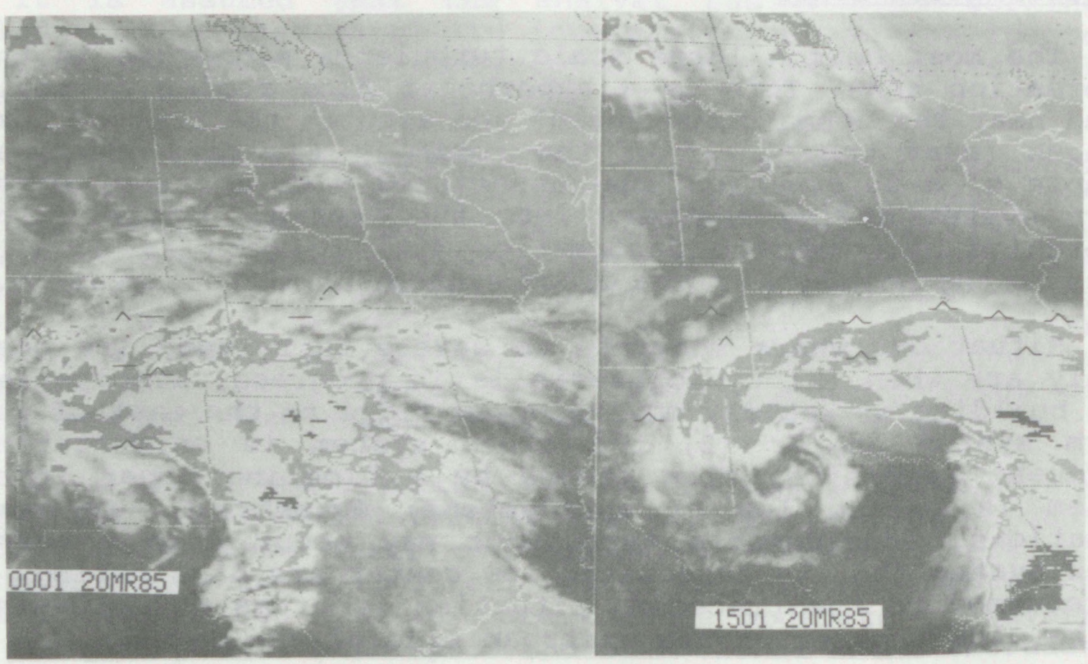


Figure 2. Infrared images of a comma cloud system at an interval of 15 hours. The poleward cloud edge had become considerably better defined in that period and reports of moderate turbulence became more frequent.

turbulence than a poorly defined cloud edge. An example of the evolution of the poleward cloud edge of a comma system to one which has a significant amount of turbulence is shown in Figure 2.

The main upper air data incorporated into the decision tree are standard pressure level wind and temperatures. These are used in situations where well defined upper troughs are present, but satellite image features are not definitive. The data are used to monitor upper level horizontal convergence and thermal gradients. Both of these conditions have been found to be conducive to CAT (Kao and Sizoo, 1966; Bender and Panofsky, 1976; Sorenson and Beckwith, 1975). Deformation is another property important in turbulence generation (Mancuso and Endlich, 1966) but is rather difficult to determine objectively without computer-derived calculations. The table at the bottom of the third page of the decision tree can be used to estimate probable turbulence intensity from upper winds and temperature gradients determined from radiosonde network.

The movement of large scale cloud features is sometimes used, since it easily obtained from satellite imagery. Upper air features which move at a speed of at least 25 kt are more likely to result in significant CAT (Sorenson and Beckwith, 1975).

2. Wave Cloud Signatures

The satellite-observed cloud features which appear most often in the decision tree are the two types of wave formations: transverse bands and billows. Even when large scale satellite signatures are observed, these wave clouds are often present also.

As described in the Glossary (Appendix A), transverse bands are more irregular than billows, and because of their larger spacing and width, are more likely to be observed in lower resolution infrared images such as those from geostationary satellites (e.g., GOES or METEOSAT). They are usually associated with the low latitude subtropical jet stream, and indicate conditions of large vertical and possibly horizontal wind shears. In general, the wider, thicker transverse bands are more likely to contain severe turbulence, possibly due to the added presence of thermal instability. In these situations, the bands often have a carrot-shaped appearance, similar to Cb anvils.

Cloud bands, in general, tend to be aligned with the cloud layer shear vector. For this reason, the presence of cirrus bands which differ in orientation from the prevailing wind direction (transverse to the flow) indicates that directional shear with height is present.

The presence of billows in cirrus clouds may indicate that strong shear instability (often referred to as Kelvin-Helmholtz instability) exists; a situation conducive to moderate to severe CAT (Ludlam, 1967; Beckman, 1981). In visible satellite images, they are most often seen where a strong jet intersects either a frontal cloud system, or a line of cumulonimbus clouds at a large crossing angle. The anvil debris of convective clouds in these situations extends well downstream from its source. Although individual waves dissipate quickly (usually in less than 30 minutes) new waves can reform nearby when conditions are favorable. The longer the wavelength of the billows, the better the chance of significant turbulence. Based on a small sample of cases, high altitude billows whose wavelengths are 3 nm (5 km) or more, as seen in GOES images, nearly always indicate the presence of severe turbulence. Wave features of similar dimensions were found in a radar study of severe CAT (Reed and Hardy, 1972). If the billows can be observed in 2 km (1 nm) visible images ("B" sectors for GOES-Tap users), then significant turbulence is likely. Figure 3 shows an example where billows and transverse bands were present simultaneously along the east coast of the U. S. The thick, lumpy cirrus patches (scallops) also indicate turbulence.

3. Water Vapor Image Darkening

Another image feature which is often mentioned in the decision tree is darkening with time in 6.7μ water vapor channel images (Ellrod, 1985). This refers to elongated bands or, in some cases, large oval shaped gray regions that becomes darker in successive images. The darkening is usually accompanied by cold advection and convergence in the mid and upper levels of the troposphere (Stewart and Fuelberg, 1986), resulting in compensating sinking through a deep layer. Cross sections through such features reveal sloping baroclinic zones (tropopause leaves or folds), indicating that air of stratospheric origin is descending into the upper troposphere. Moderate or stronger turbulence has been noted to occur a high percentage of the time (80%) when image darkening occurs, especially when the darkening persists for at least 3 hours. An example of a darkening incident over a twelve hour period and the turbulence which occurred within three hours of the image times is shown in Figure 4.

Turbulence has been found to be concurrent with the water vapor image darkening, so the signature cannot be used as a precursor. In some situations, however, darkening with time is preceded by a merger of two smaller dark bands. The location of the turbulence with respect to the dark zone is dependent on altitude. On the downstream side of the darkening region, turbulence is generally found at a lower altitude (say,

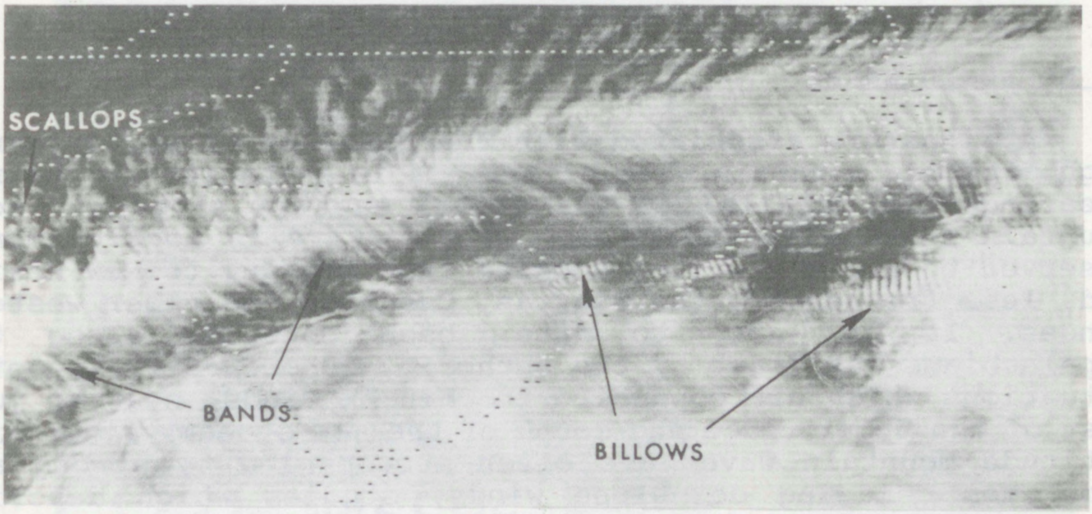


Figure 3. Transverse bands, billows, and scalloped cirrus observed simultaneously in a GOES visible image.

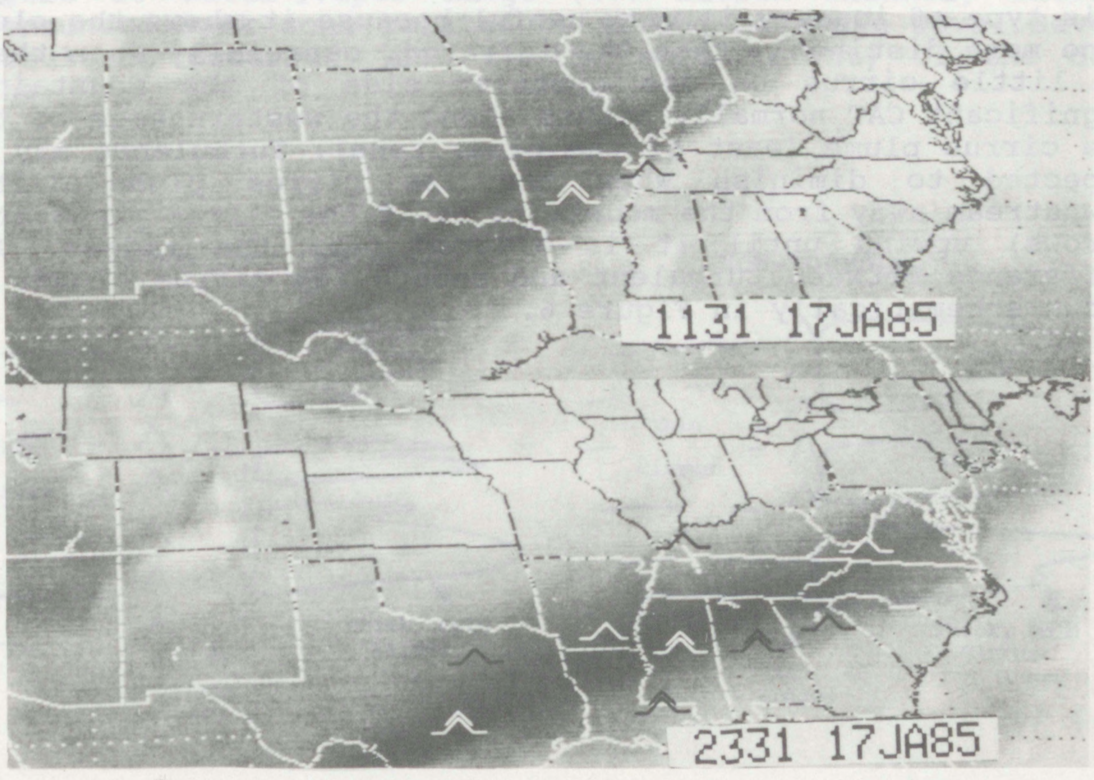


Figure 4. GOES 6.7 micron water vapor images showing an episode of darkening with time over a 12 hour period. Turbulence reports within 3 hours of each image are superimposed.

20-30 kft) than within and upstream from the dark zone. This effect is no doubt due to the normal slope of the upper level frontal zones.

4. Mountain waves

A signature associated with the presence of significant, high altitude mountain wave turbulence is a stationary, narrow clearing zone parallel to the steep, eastern slopes of some mountain ranges. In the U. S., this feature is most commonly observed to the lee of the Rockies from Montana to New Mexico and, less frequently, the Sierras, Cascades and other western ranges. It has not, to date, been observed along the Appalachians (at least by the author). It occurs in synoptic situations which are conducive to chinook winds, near or just east of the upper ridge and south of the jet stream. Since high altitude mountain waves are often accompanied by strong and sometimes damaging downslope winds, studies which describe environmental conditions for these events are also relevant (i.e., Brown, 1986).

Figure 5 is an example of this mountain wave feature over western Montana as seen in a 6.7μ water vapor channel image. This type of imagery is very useful because it shows the clear zone more distinctly than the infrared, especially when there is little cirrus on the upstream side of the mountains. Significant CAT normally occurs along the western edge of the lee cirrus plume (east of the clear zone). Turbulence may be expected to diminish when the lee cirrus plume drifts downstream away from the mountains **or** if the cirrus propagates (grows) upwind until it is aligned over the ridges. The difference between turbulent and smooth lee cirrus clouds is shown schematically in Figure 6.

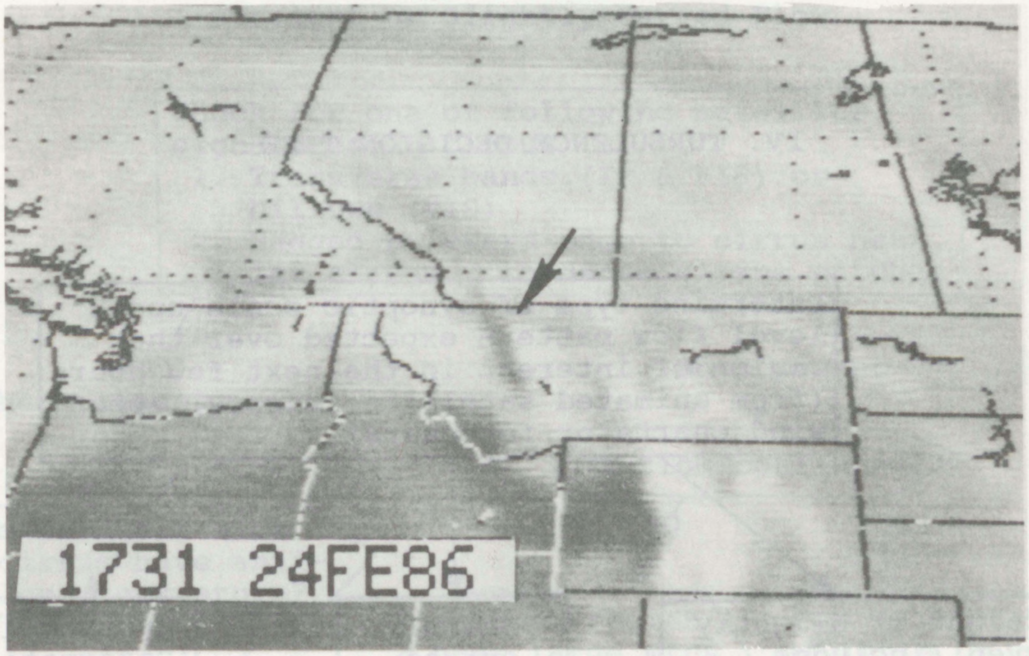


Figure 5. Water vapor image (6.7 micron channel) showing pronounced dark zone related to strong mountain wave. Severe turbulence occurred just to the east (right) of the dark zone.

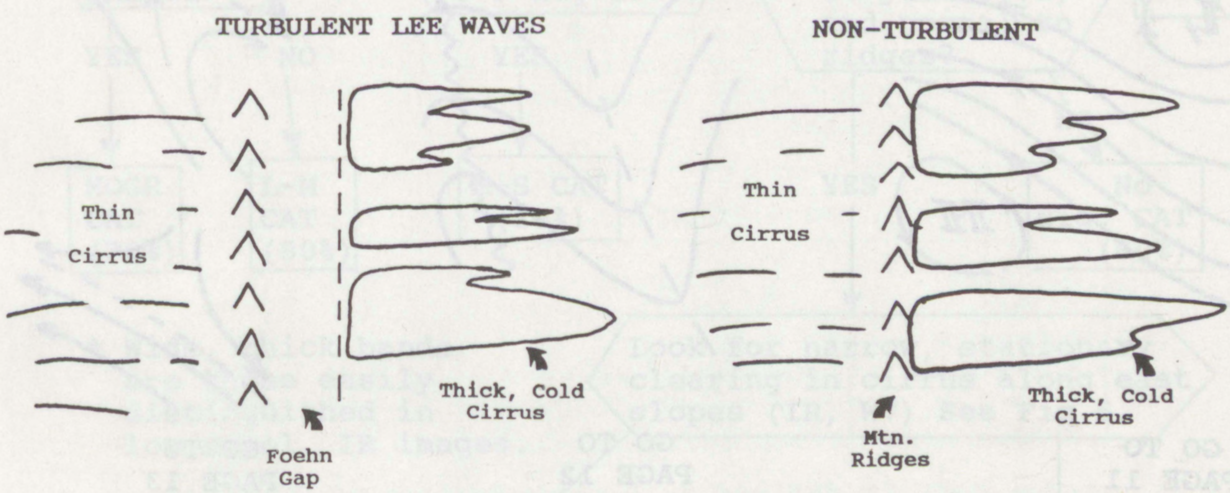
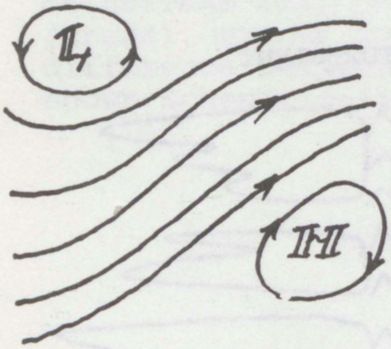


Figure 6. Schematic which shows the difference in cirrus cloud patterns related to turbulent (left) and non-turbulent (right) mountain waves.

IV. TURBULENCE DECISION TREE

Determine type of synoptic scale upper level flow pattern expected over the region of interest in the next few hours (from animated satellite imagery, upper wind charts or forecasts).

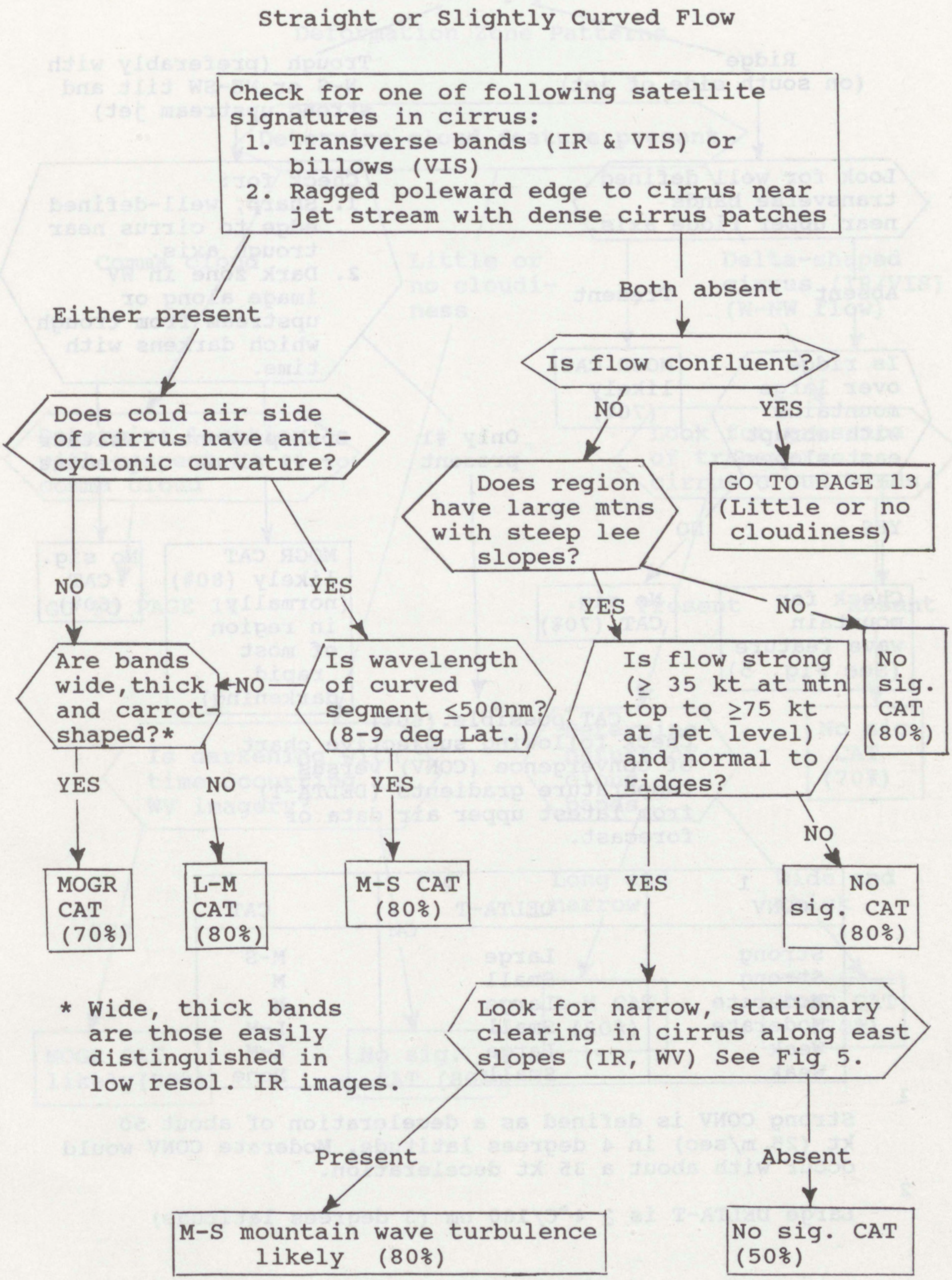
Straight or slightly curved (includes broad, smooth upper lows, ridges or troughs and confluent jets)	Sharply curved (ridge or trough)	Hyperbolic (Deformation zones)

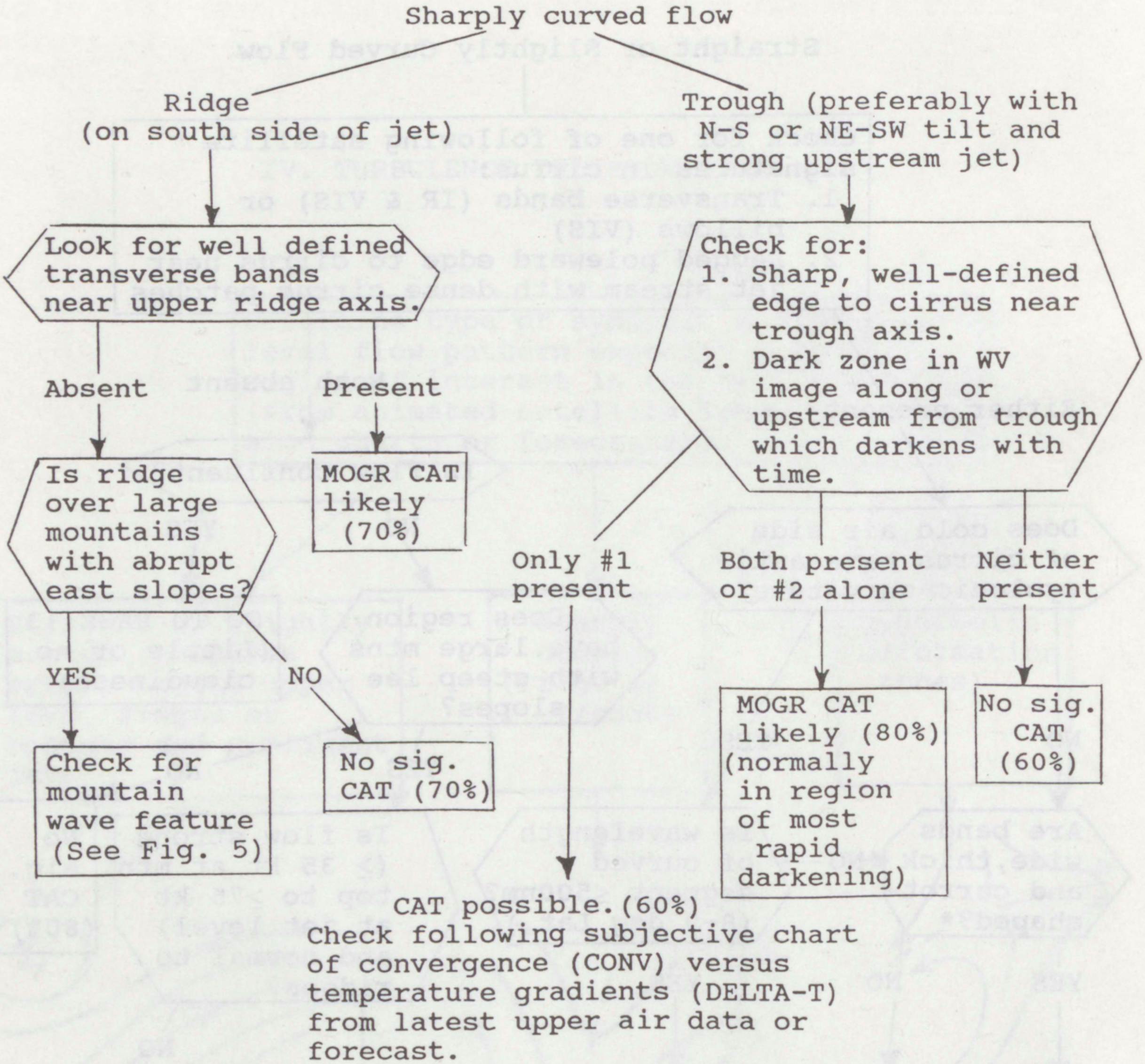


GO TO PAGE 11

GO TO PAGE 12

GO TO PAGE 13


Straight or Slightly Curved Flow
Check for one of following satellite signatures in cirrus:
1. Transverse bands (IR & VIS) or billows (VIS)
2. Ragged poleward edge to cirrus near jet stream with dense cirrus patches
Either present
Both absent
Does cold air side of cirrus have anti-cyclonic curvature?
NO
YES
Are bands wide, thick and carrot-shaped?*
YES
NO
Is wavelength of curved segment ≤500nm? (8-9 deg Lat.)
NO
YES
MOGR CAT (70%)
L-M CAT (80%)
M-S CAT (80%)
Is flow confluent?
NO
YES
GO TO PAGE 13 (Little or no cloudiness)
Does region have large mtns with steep lee slopes?
YES
NO
No sig. CAT (80%)
Is flow strong (≥ 35 kt at mtn top to ≥75 kt at jet level) and normal to ridges?
YES
NO
No sig. CAT (80%)
Look for narrow, stationary clearing in cirrus along east slopes (IR, WV) See Fig 5.
Present
Absent
M-S mountain wave turbulence likely (80%)
No sig. CAT (50%)
* Wide, thick bands are those easily distinguished in low resol. IR images.

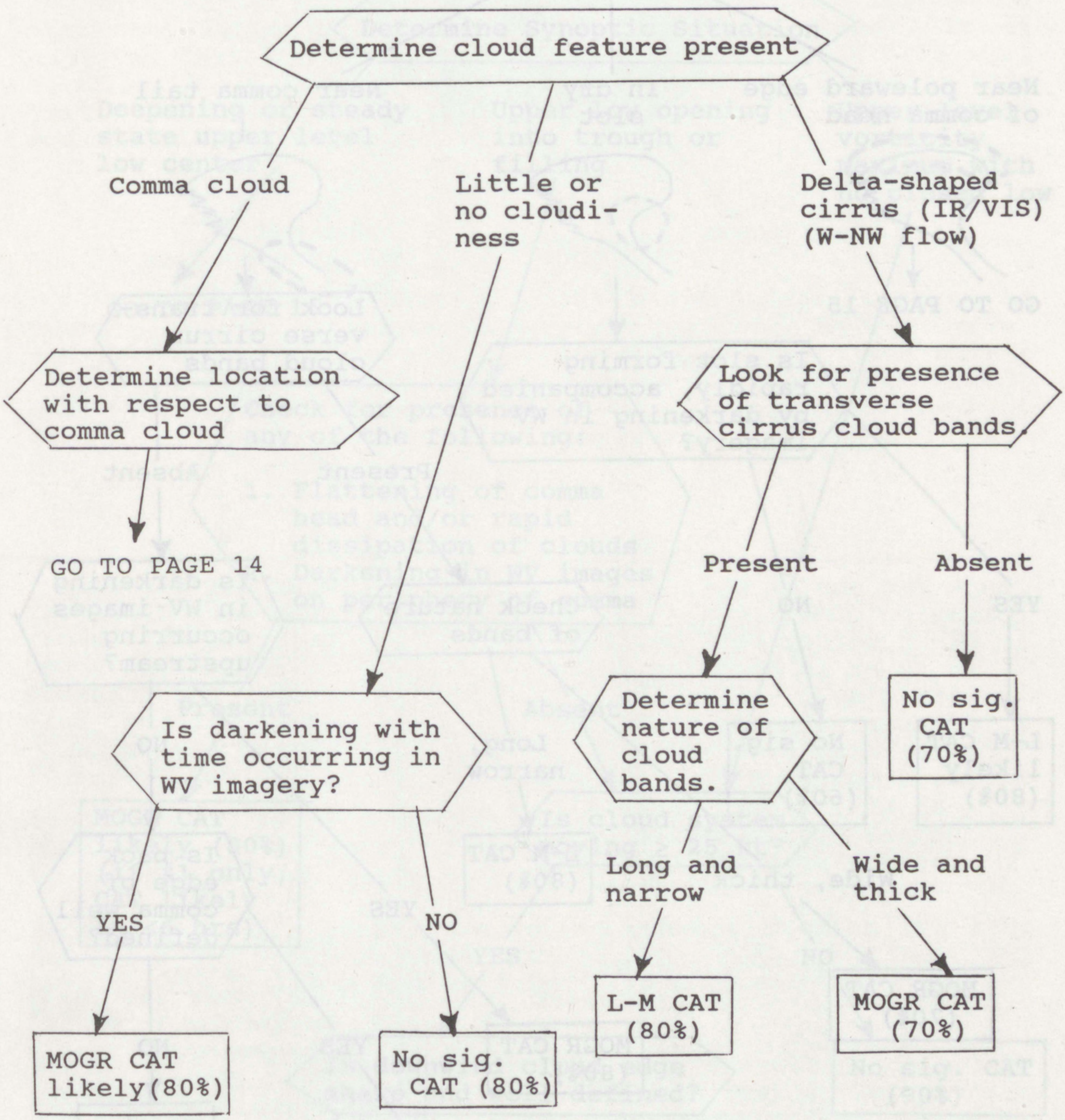


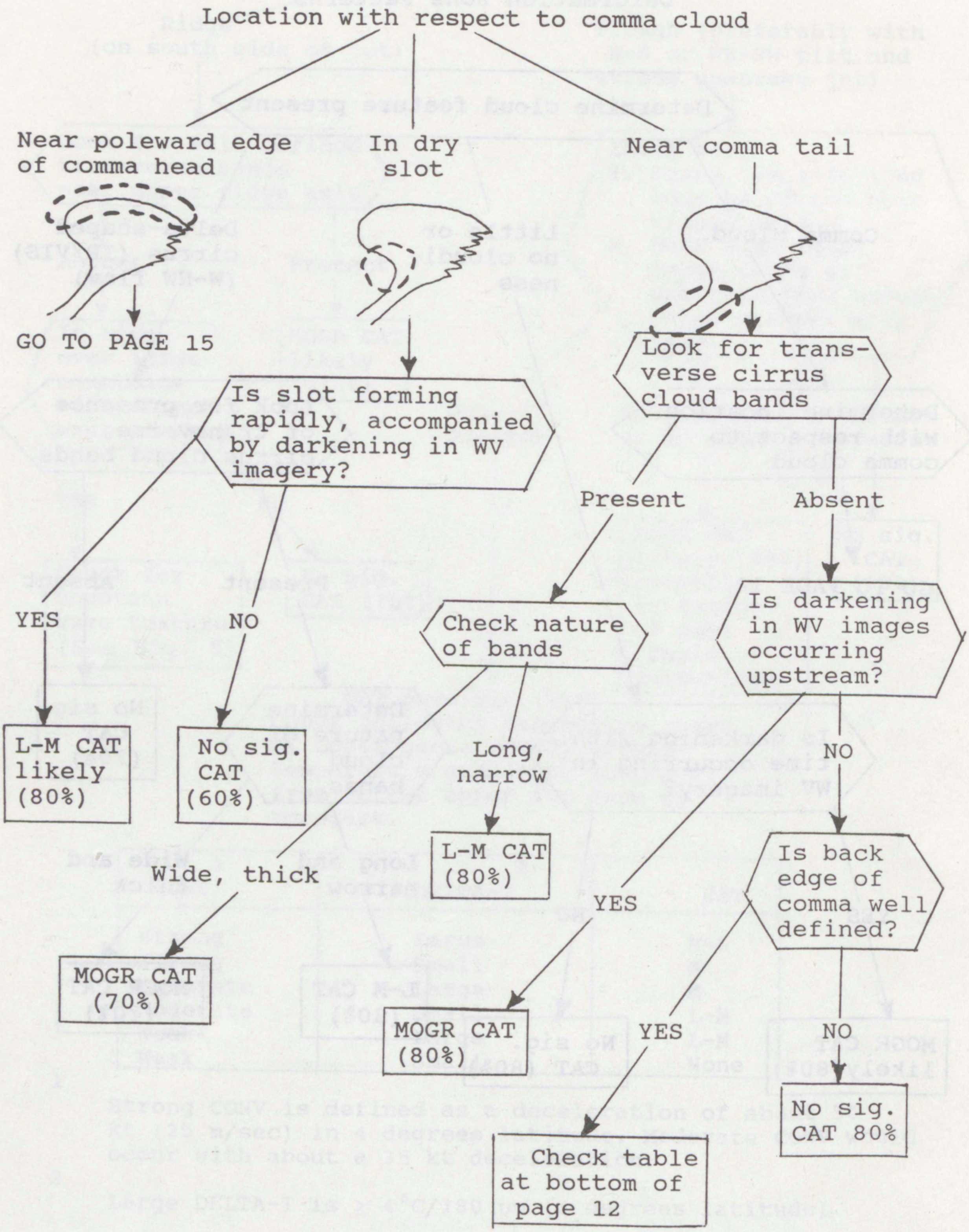
CONV[1]	DELTA-T[2]	CAT
Strong	Large	M-S
Strong	Small	M
Moderate	Large	M
Moderate	Small	L-M
Weak	Large	L-M
Weak	Small	None

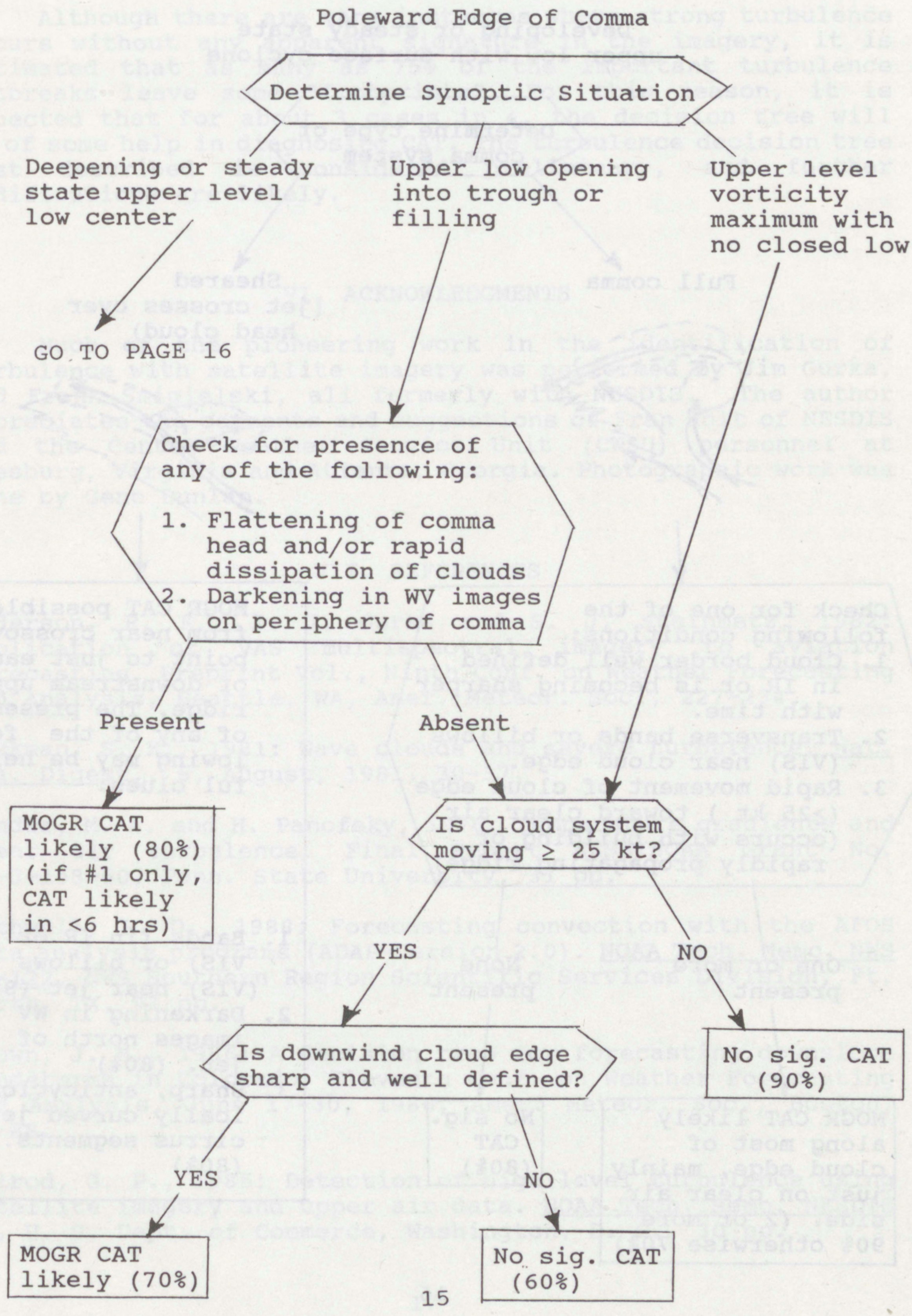
1 Strong CONV is defined as a deceleration of about 50 kt (25 m/sec) in 4 degrees latitude. Moderate CONV would occur with about a 35 kt deceleration.

2 Large DELTA-T is $\geq 4^{\circ}C/180$ nm (3 degrees latitude)

Deformation Zone Patterns



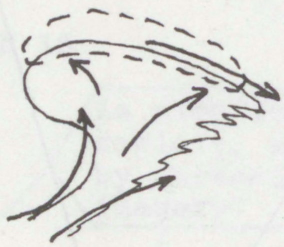

Location with respect to comma cloud
Near poleward edge of comma head
In dry slot
Near comma tail
GO TO PAGE 15
Is slot forming rapidly, accompanied by darkening in WV imagery?
YES
NO
L-M CAT likely (80%)
No sig. CAT (60%)
Look for transverse cirrus cloud bands
Present
Absent
Check nature of bands
Long, narrow
Wide, thick
L-M CAT (80%)
MOGR CAT (70%)
Is darkening in WV images occurring upstream?
YES
NO
MOGR CAT (80%)
Is back edge of comma well defined?
YES
NO
No sig. CAT 80%
Check table at bottom of page 12


Poleward Edge of Comma
Determine Synoptic Situation
Deepening or steady state upper level low center
Upper low opening into trough or filling
Upper level vorticity maximum with no closed low
GO TO PAGE 16
Check for presence of any of the following:
1. Flattening of comma head and/or rapid dissipation of clouds
2. Darkening in WV images on periphery of comma
Present
Absent
MOGR CAT likely (80%) (if #1 only, CAT likely in <6 hrs)
Is cloud system moving ≥ 25 kt?
YES
NO
Is downwind cloud edge sharp and well defined?
No sig. CAT (90%)
YES
NO
MOGR CAT likely (70%)
No sig. CAT (60%)

Developing or steady state
upper low with surface cyclone

Determine type of
comma system

Full comma



Check for one of the following conditions:

1. Cloud border well defined in IR or is becoming sharper with time.
2. Transverse bands or billows (VIS) near cloud edge.
3. Rapid movement of cloud edge ($\geq$25 kt) toward clear air (occurs with building or rapidly propagating ridge)

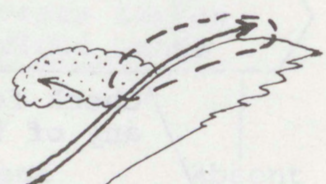
One or more present

MOGR CAT likely along most of cloud edge, mainly just on clear air side. (2 or more 90% otherwise 70%)

None present

No sig. CAT (80%)

Sheared
(jet crosses over head cloud)



MOGR CAT possible from near crossover point to just east of downstream upper ridge. The presence of any of the following may be helpful clues:

1. Bands (in IR or VIS) or billows (VIS) near jet (80%)
2. Darkening in WV images north of jet. (80%)
3. Sharp, anticyclonically curved jet cirrus segments. (80%)

V. CONCLUDING REMARKS

Although there are many instances where strong turbulence occurs without any apparent signature in the imagery, it is estimated that as many as 75% of the important turbulence outbreaks leave some "footprints". For this reason, it is expected that for about 3 cases in 4, the decision tree will be of some help in diagnosing CAT. The turbulence decision tree just described is considered preliminary, and further modifications are likely.

VI. ACKNOWLEDGMENTS

Much of the pioneering work in the identification of turbulence with satellite imagery was performed by Jim Gurka, and Frank Smigielski, all formerly with NESDIS. The author appreciates the comments and suggestions of Fran Holt of NESDIS and the Center Weather Service Unit (CWSU) personnel at Leesburg, Virginia and Atlanta, Georgia. Photographic work was done by Gene Dunlap.

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APPENDIX A

GLOSSARY OF TERMS AND ABBREVIATIONS

billows - Wave cloud patterns in cirrus or middle level clouds which are regularly spaced, narrow and oriented perpendicular to the upper flow.

CAT - Clear air turbulence. Refers to non-convective turbulence at altitudes above 18,000 feet MSL (Mean sea level). May occur within or near cirrus clouds.

Cb - cumulonimbus cloud

confluence - flow patterns in which adjacent streamlines approach each other, normally resulting in acceleration.

CONV - Convergence in the upper wind flow pattern.

deformation zone - A region where the atmosphere is undergoing contraction in one direction and elongation or stretching in the perpendicular direction, relative to the motion of the air stream. A cloud border is often located near and parallel to the stretching axis.

DELTA-T - Gradient of temperature on a constant pressure surface.

diffluence - the spreading apart of adjacent streamlines, normally accompanied by deceleration.

GOES - Geostationary Operational Environmental Satellite

GOES-Tap - Telephone line transmission system which provides standard sector GOES imagery to users in the United States.

IR - Infrared satellite imagery.

L - Light intensity

M - Moderate intensity

METEOSAT - European geostationary meteorological satellite

MOGR - Moderate or greater intensity.

S - Severe intensity

scallops - thick patches of cirrus whose shape is circular or oval.

transverse bands - Irregular, wave-like cirrus cloud patterns which form nearly perpendicular to the upper flow. They are most commonly found on the equatorward side of the subtropical jet stream and indicate the presence of strong vertical and possibly, horizontal wind shears.

VIS - Visible satellite imagery

WV - 6.7 micron water vapor imagery

(Continued from inside front cover)

NESDIS 8 A Technique that Uses Satellite, Radar, and Conventional Data for Analyzing and Short-Range Forecasting of Precipitation from Extratropical Cyclones. Roderick A. Scofield and Leroy E. Spayd Jr., November 1984. (PB85 164994/AS)

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