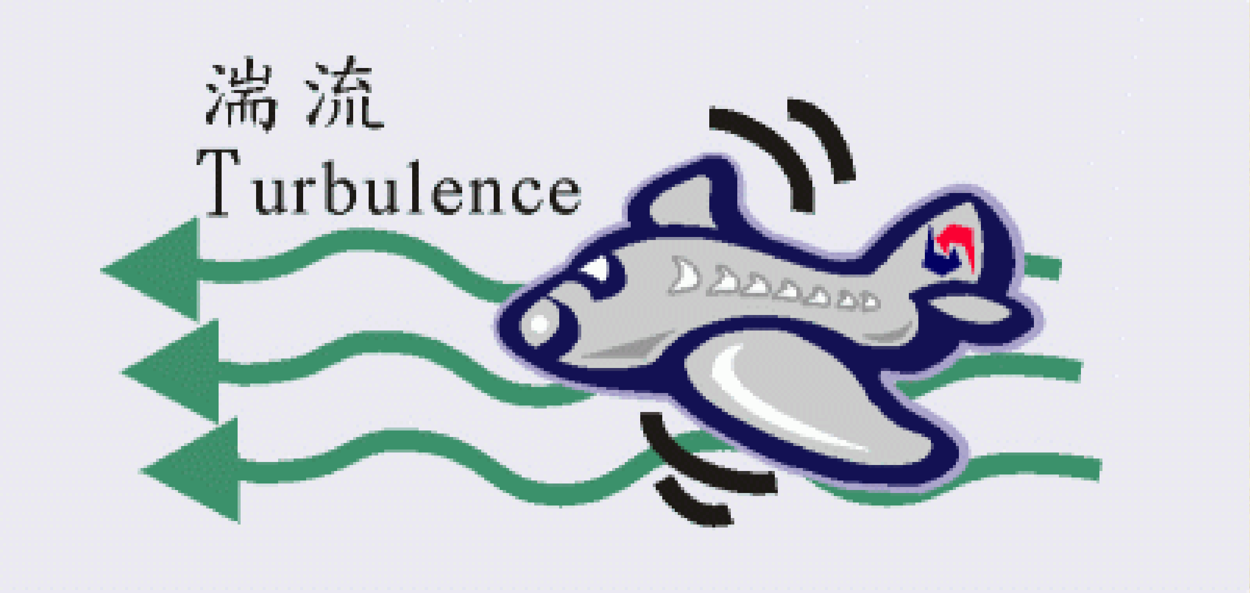
Turbulence



Turbulence

- Turbulence is irregular motion of the atmosphere
- The principal sources of turbulence are thermal, orographic and dynamical, acting separately or in combination.
- Turbulence of significance to the operation of aircraft depends to some extent on the aircraft size, wing span size, weight and speed of motion of the aircraft.

Acceleration

- For an aircraft to experience a 1 g acceleration a wind velocity change of 9.8 m/s (18 kts) would be required.

Change in acceleration vs turbulence

Intensity	Effect on Aircraft	Changes in accelerometer reading	Maximum Derived Equivalent Vertical Gust	EDR index
Light	Effects are less than those for moderate intensity.	less than 0.5 g	2 - 4.5 ms^{-1}	1 – 5 (peak EDR 0.1 – 0.3)
Moderate	Moderate changes in aircraft attitude and/or height. Aircraft remains in control at all times. Air speed variations usually small.	0.5 g to 1.0 g	4.5 - 9 ms^{-1}	6 – 14 (peak EDR 0.3 – 0.5)
Severe	Abrupt changes in aircraft attitude and/or height. The aircraft may be out of control for short periods. Air speed variations usually large.	greater than 1.0 g	> 9 ms^{-1}	15 – 27 (peak EDR >0.5)
Extreme	Effects are more pronounced for severe intensity.			

Turbulence

Thermal turbulence

Occur at the edges of upcurrents and downcurrents in a convective regime, as follows:

- In cloud.
- Outside Cb, particularly in clear air around anvil and just above storm top.
- In dry thermals below cloud base, or in a cloudless atmosphere over any heated land mass. Over deserts, dry convection may reach 5-7 km.
- In downdraughts appearing with the onset of precipitation; these spread out at the surface to produce a line-squall close to the shower area.

Turbulence

Thermal turbulence

- Thermal turbulence can reach heights exceeding 12 km in the temperate latitude and 18 km in some tropical areas.

Magnitude of typical vertical currents in convective cloud

Regime	Verical Velocity	Description of turbulence
Stratocumulus/Altocumulus		light to moderate
dry thermals	1-5	light to moderate
cumulus	1-3	light
cumulus	3-10	moderate
cumulonimbus	10-25	severe
downdraught	3-15	moderate to severe
extreme downdraught	up to 40	extreme

Turbulence

Orographic turbulence

- Include low-level turbulence, mountain wave and rotor-zone turbulence.

Rough guide to the intensities of low-level turbulence on light aircraft.

Surface wind (knots)	Turbulence over Sea	Turbulence over Flat country	Turbulence over Hilly country
15-35	Light-moderate	Moderate	Severe
>35	Moderate-severe	Severe	Extreme

Turbulence

Orographic turbulence

Mountain waves and associated turbulence may be pronounced when the following conditions are all satisfied:

- A wind blowing within 30° of normal to a substantial range of hills.
- A wind speed of 20 knots or more at hill-crest level, with speed increasing with height but with little change of direction (strong waves are often associated with jet streams).
- A stable layer somewhere between hill-crest level and a few thousand feet above.

Turbulence

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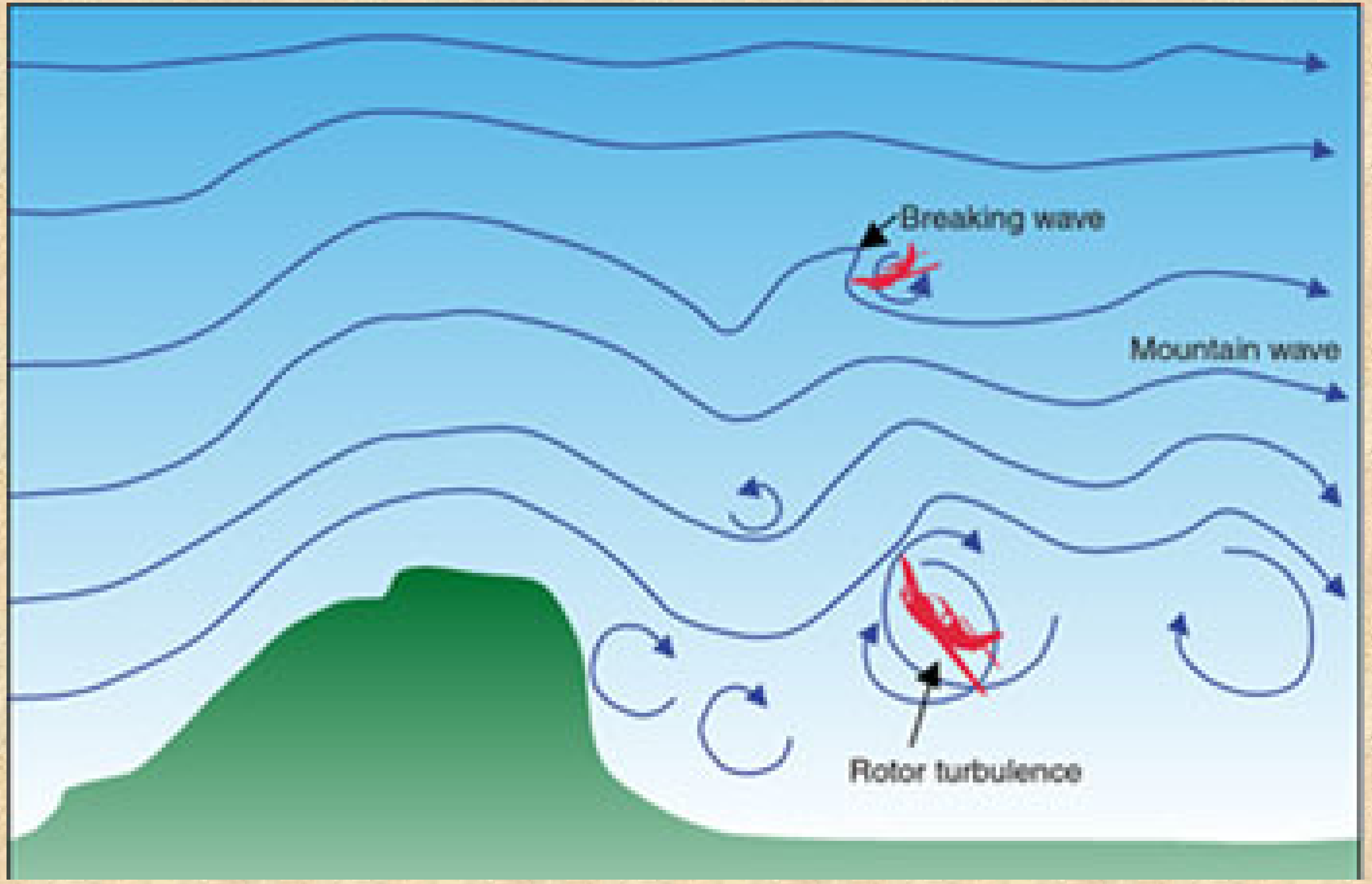
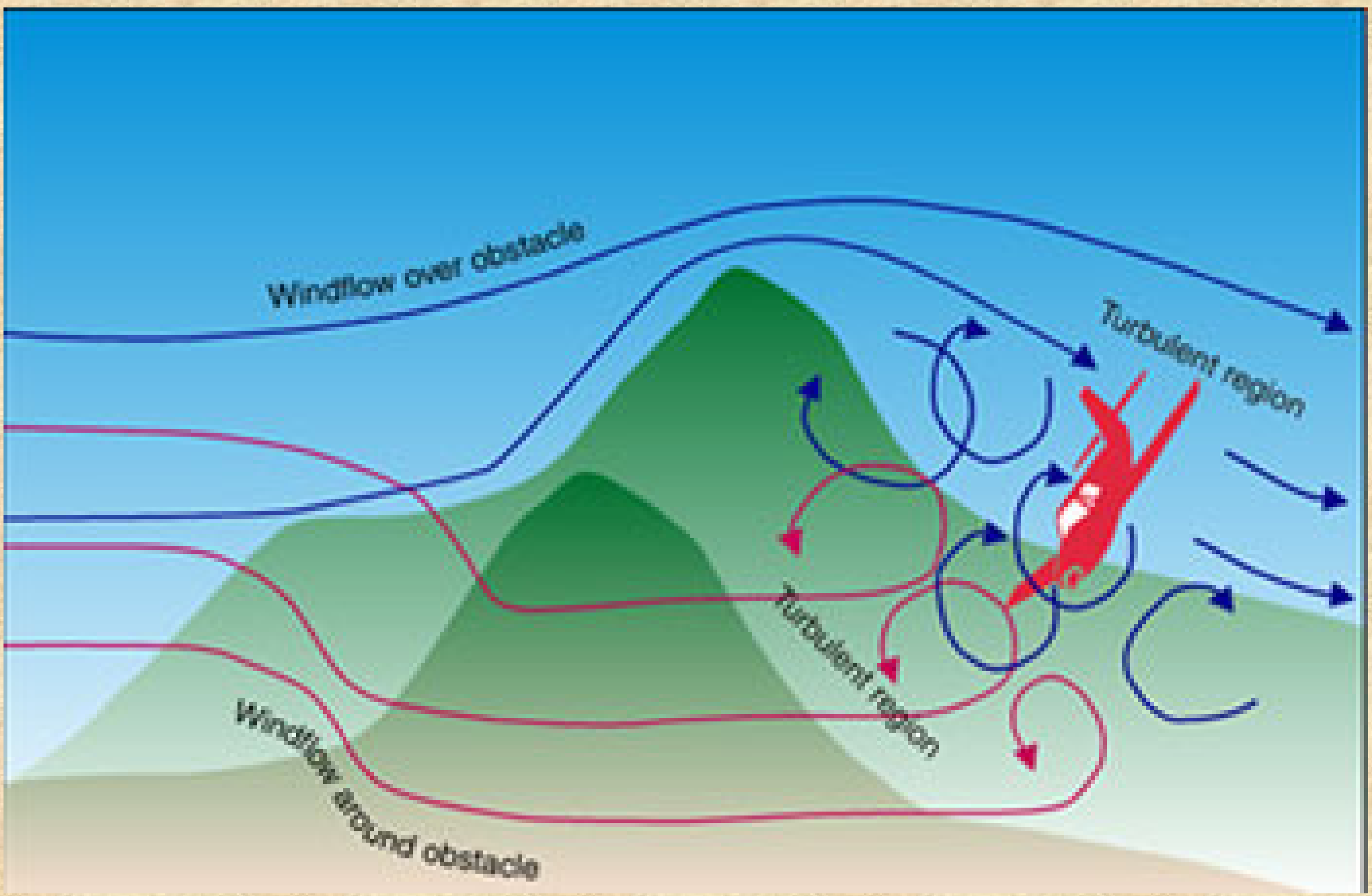
Rotors or eddies can also be found embedded in mountain waves.



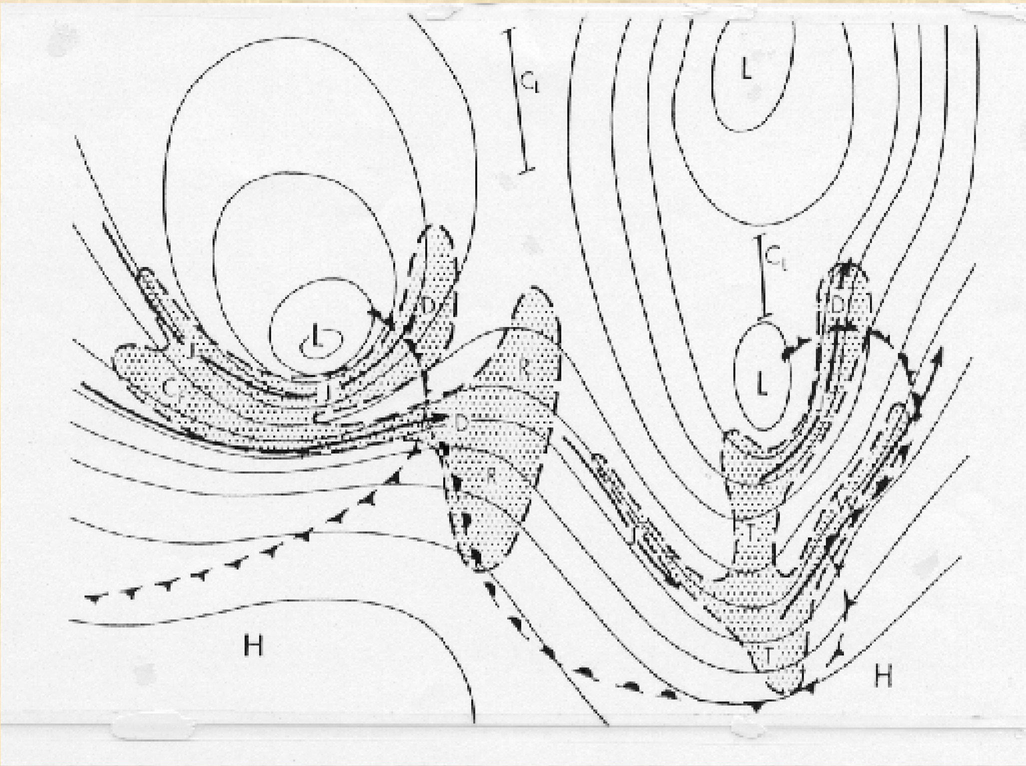
Turbulence induced by windflow around mountains



Turbulence

Dynamical turbulence

- The figure below shows the turbulence-prone areas as related to features of the 300 hPa chart.



Most probable regions of turbulence

- on the cold side, near and below the core
- on the warm side, above the core
- near exits with marked curvature and diffluence
- at the confluence or diffluence of two jet streams
- near sharp upper troughs
- around sharp ridges on the warm side of jets
- where one jet undercuts another
- where the tropopause height fluctuates

Turbulence

- (i) Turbulence within the favourable areas in the figure is most likely to occur near the tropopause or other stable layers.

- (ii) In jet streams, turbulence is generally found in the baroclinic zones above and below the core. There is some tendency for turbulence to be concentrated in the lower zone of cyclonically curved jets and in the upper zone of anticyclonically curved jets.

- (iii) With a minimum wind speed of 60 knots, the following critical values of wind shear may be taken for forecasting CAT.

Turbulence

- (iii) With a minimum wind speed of 60 knots, the following critical values of wind shear may be taken for forecasting CAT.

	Horizontal shear	Vertical shear
Moderate CAT	20 knots/deg lat.	6 knots/300 m
Severe CAT	30 knots/deg lat.	9 knots/300 m

- (iv) In terms of temperature, the criterion for moderate or severe turbulence is 5°C or more per 2 deg latitude.

Turbulence

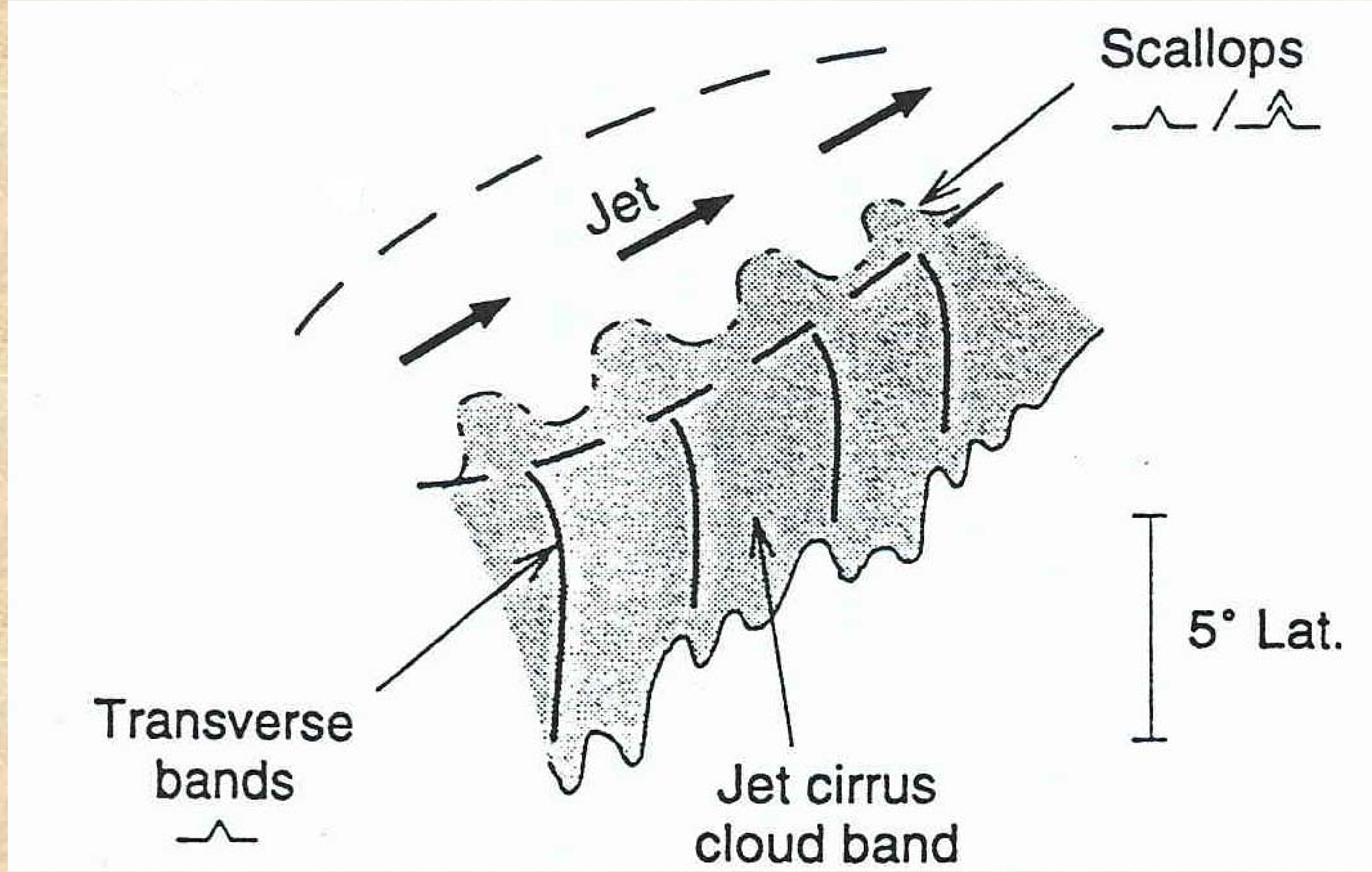
- (v) There is some qualitative evidence that turbulence is more likely to be severe within turbulence-prone areas if rapid change or development in the upper air pattern is occurring locally than if the pattern is relatively static.

- (vi) The incidence of CAT is more frequent over land, particularly over mountains, than over the sea. It is not possible to give precise quantitative values to this difference but it is suggested that a factor of 3 or more over most land areas, increasing perhaps to 10 over very mountainous areas, is reasonable.

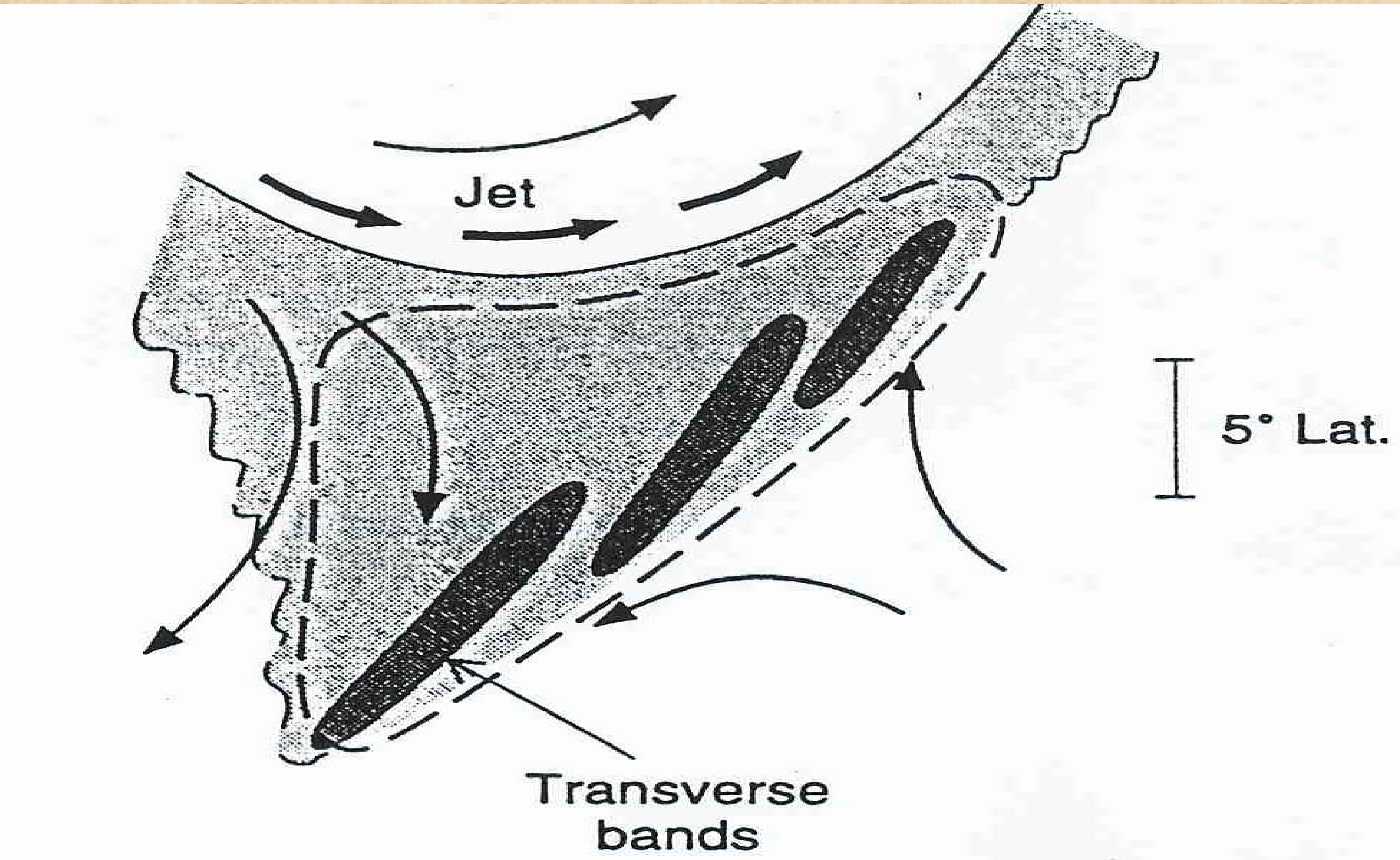
Turbulence

- (vii) CAT appears to affect a relatively small area and occur temporarily although the factors leading to CAT are present all the time. Hence only in a small percentage of CAT forecast will there in fact be turbulence reports by aircraft.

Jet streams and instability



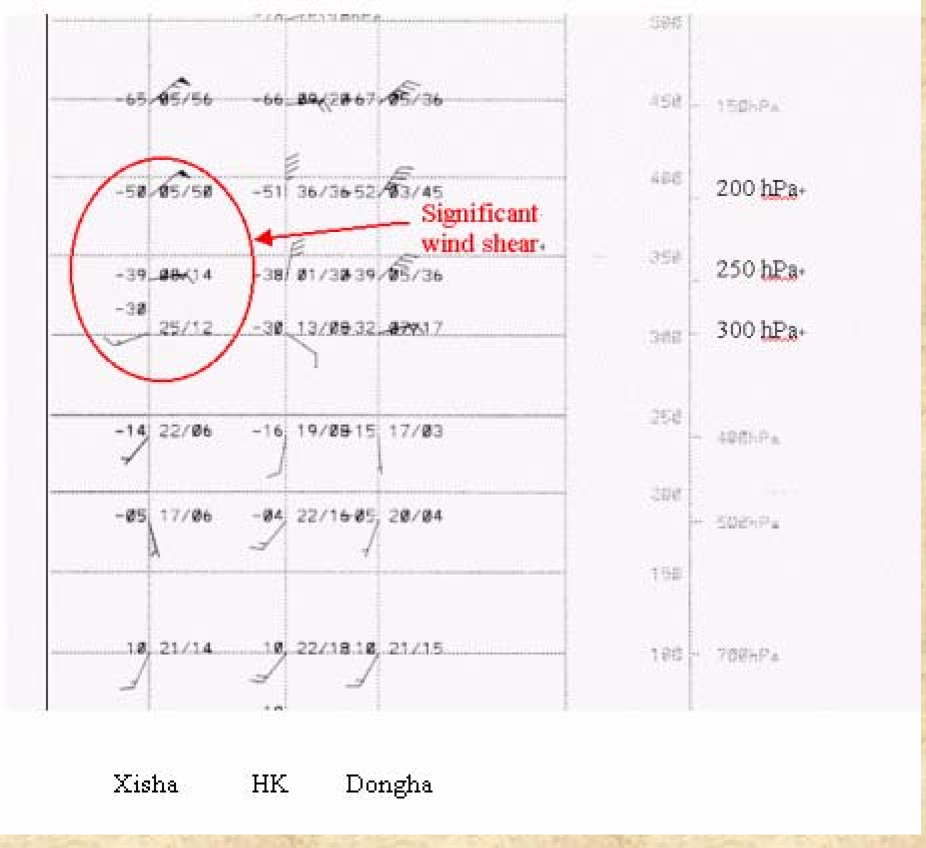
Turbulence in deformation zones



Turbulence

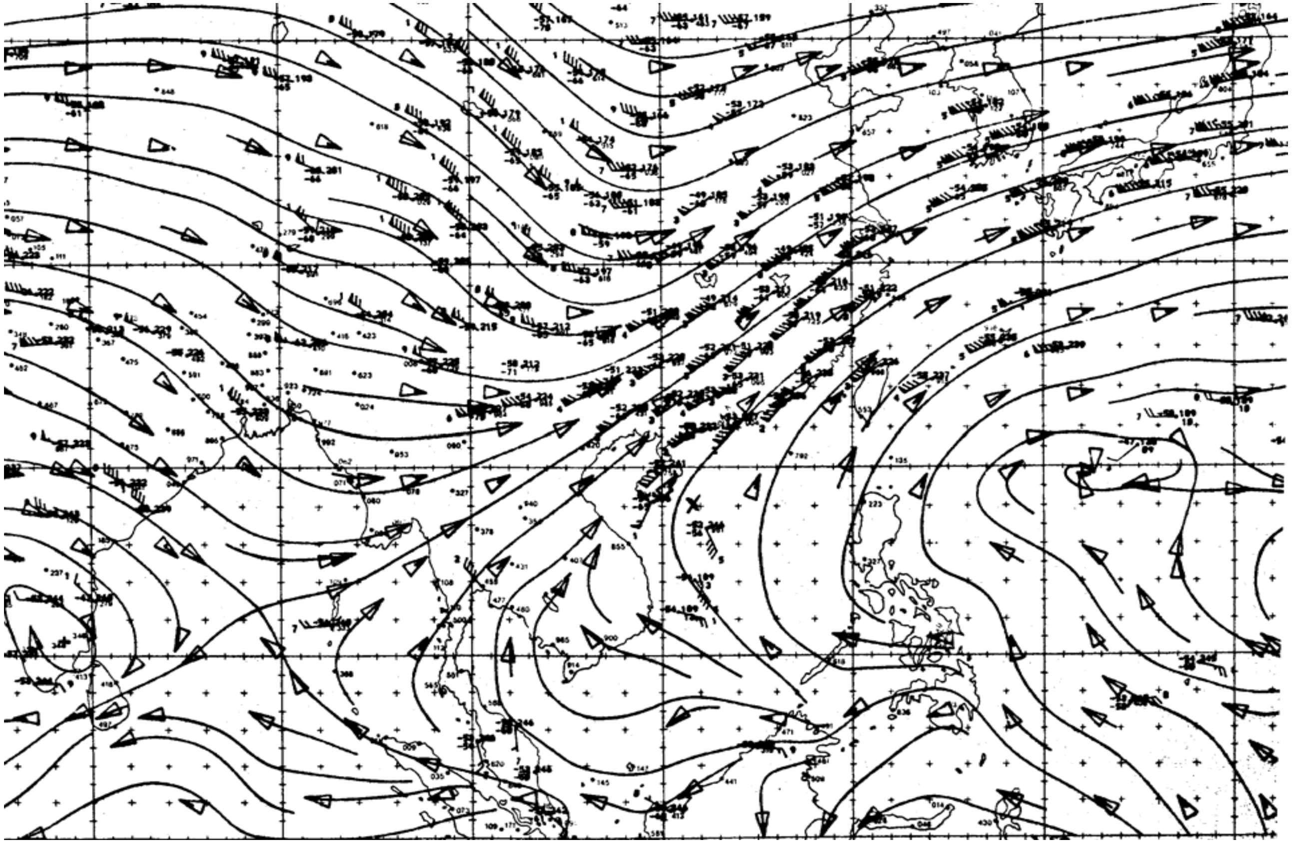
Analysis of upper-air data

- A key initial step in the turbulence assesment process. The presence of large vertical shear can be identified in space cross-section chart.



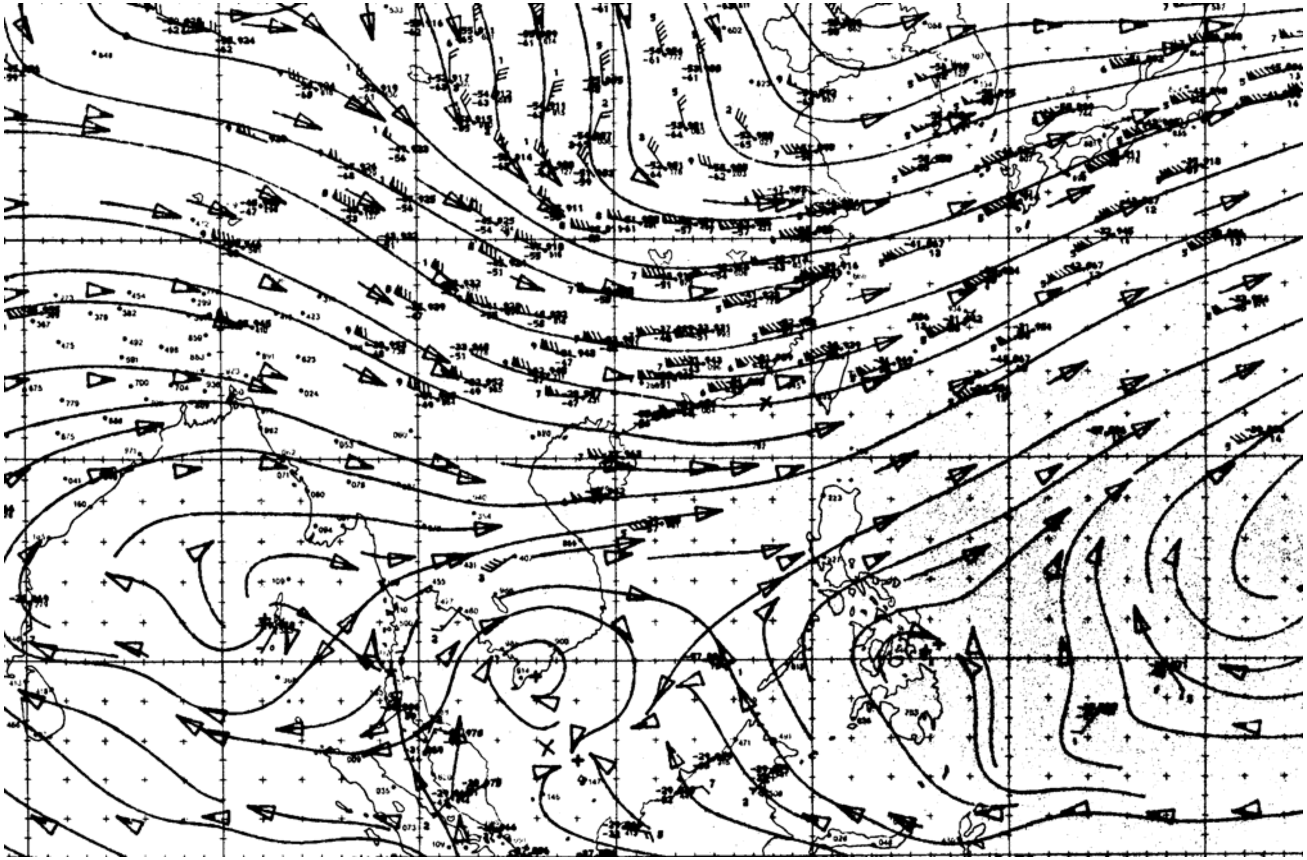
Analysis of upper-air data

Sharply curved ridge < 200 hPa 99113012

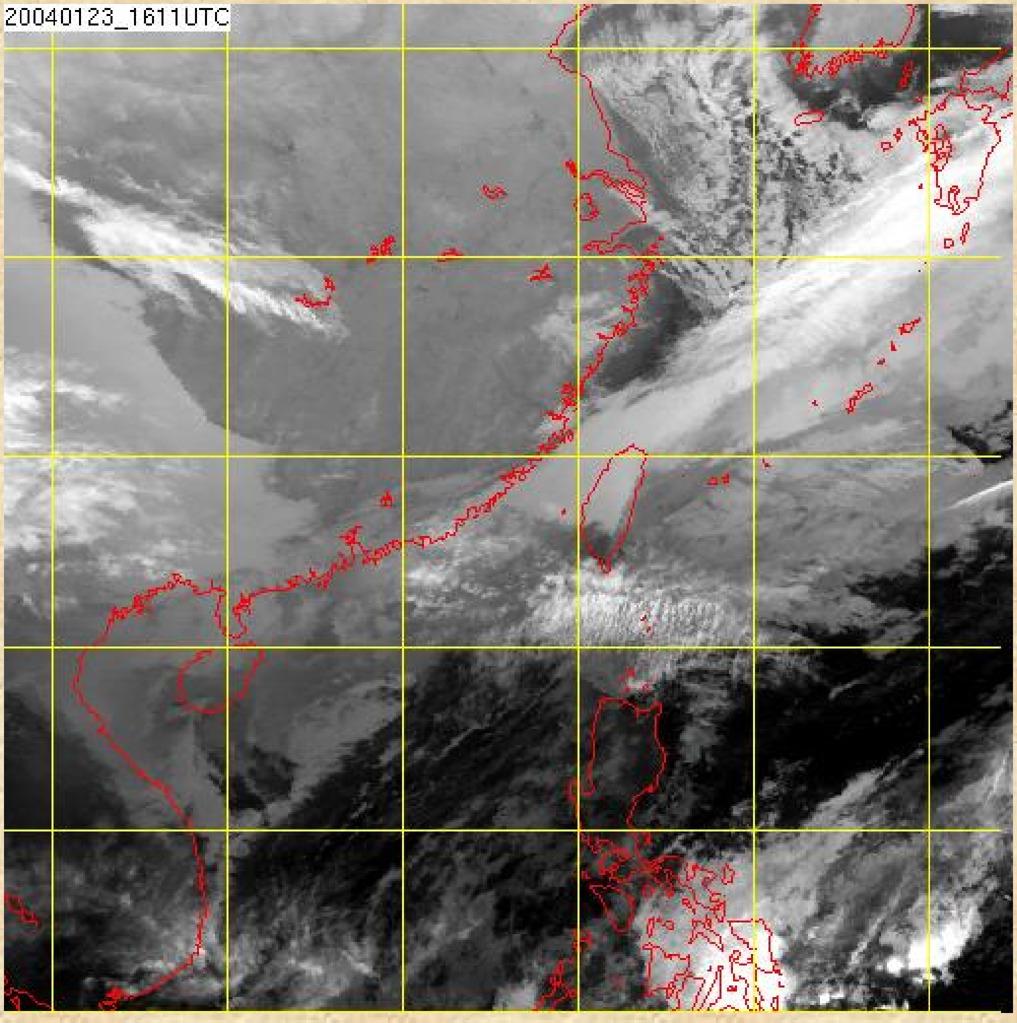


Analysis of upper-air data

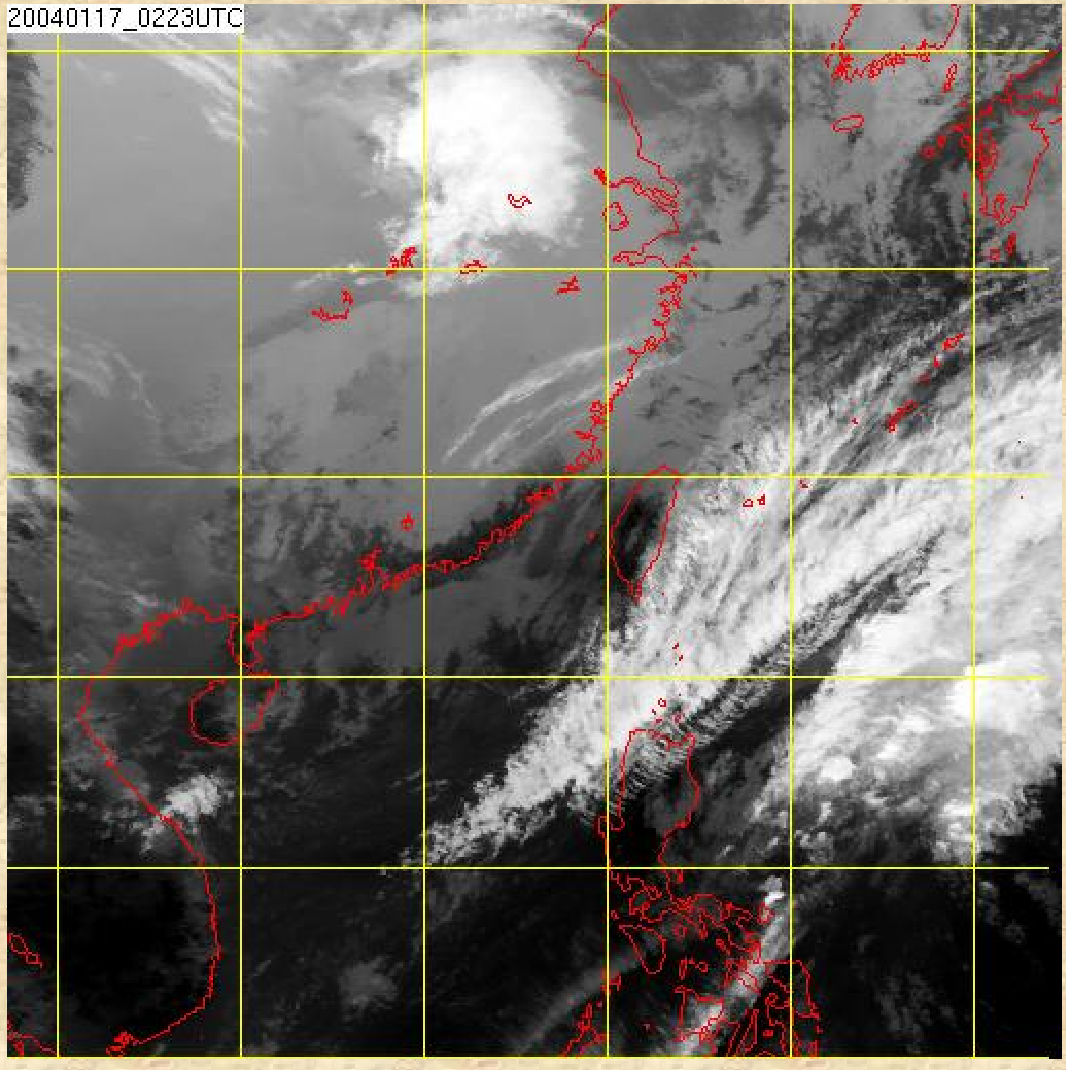
Base of upper trough < 300 hPa 99122312



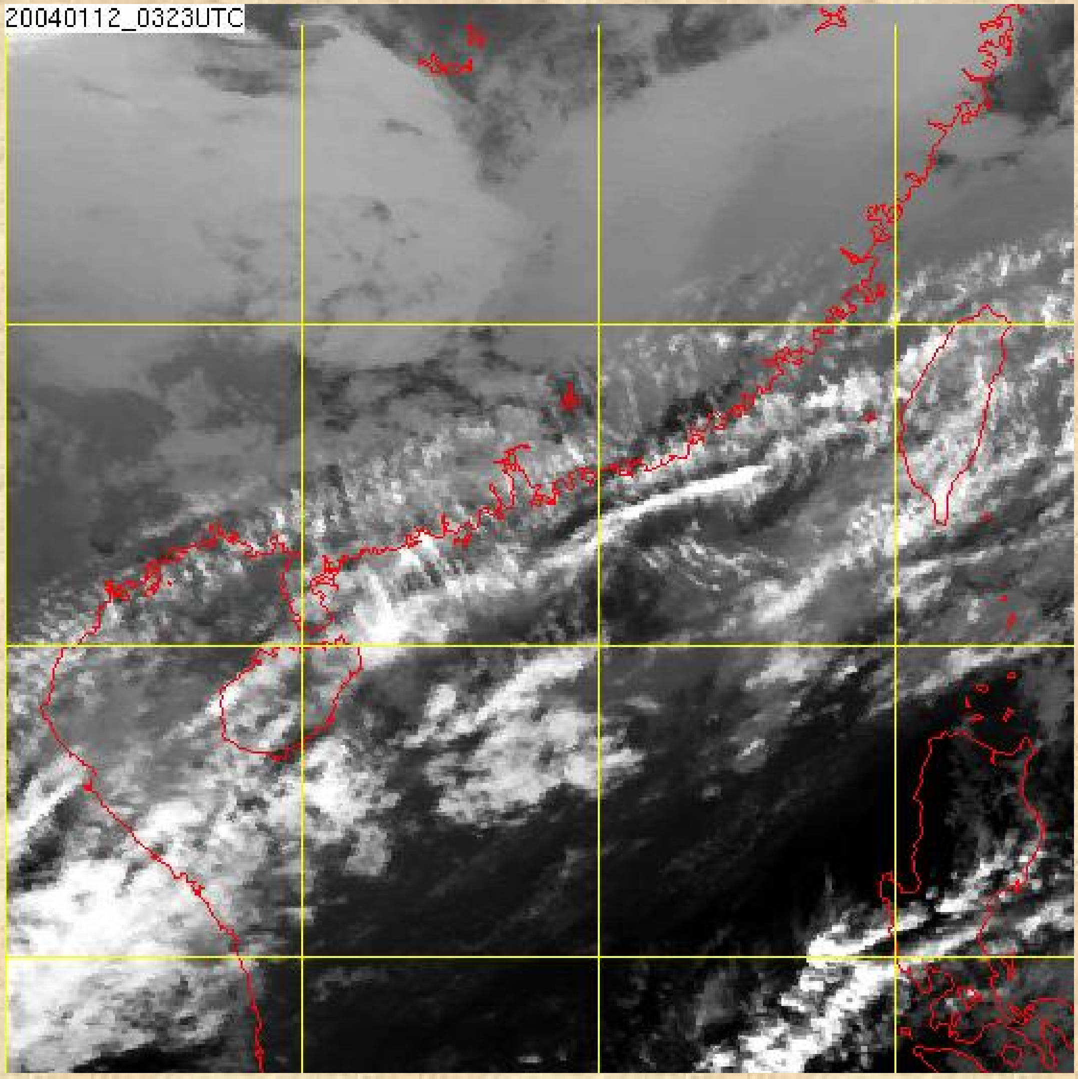
Transverse cloud band



Transverse cloud band



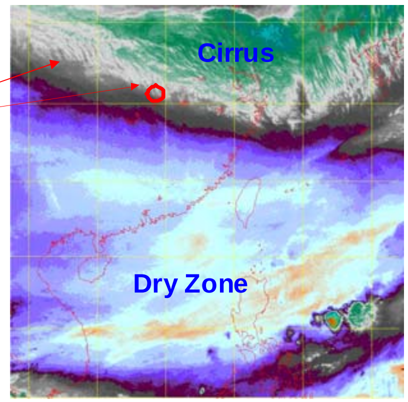
Transverse cloud band



Turbulence

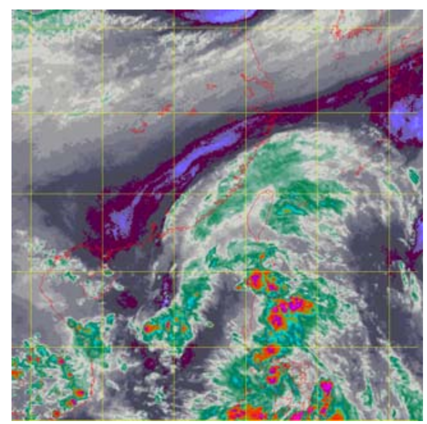
Satellite Imagery

Transverse Cloud Bands

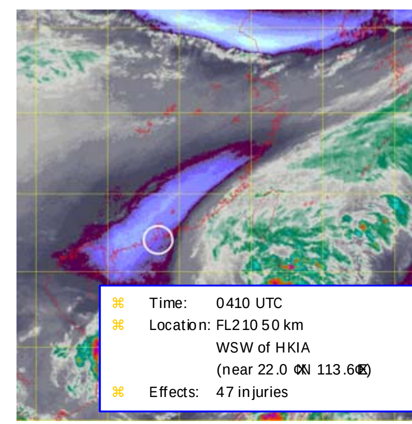


GMS WV Imagery at 0332 UTC

Suspected CAT Near Macau on 17 Oct 1999



GMS WV Animation
160632 – 171232 UTC

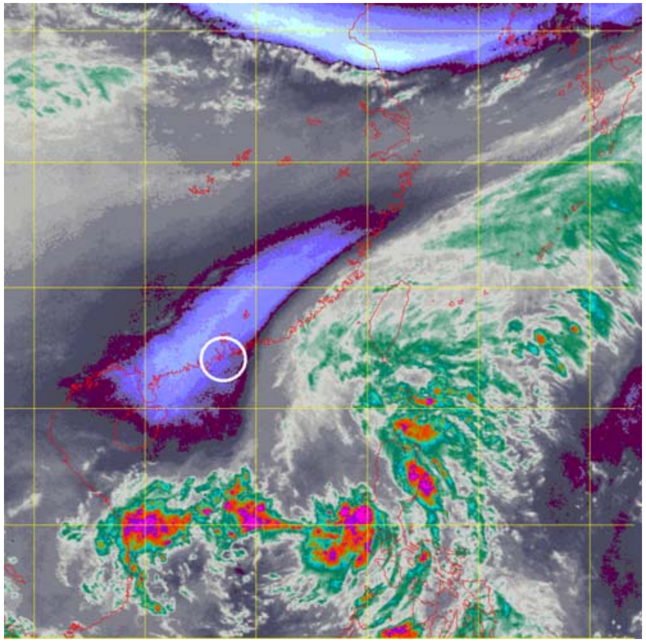


GMS WV Imagery at 0425 UTC

Turbulence

Darkening in WV Images

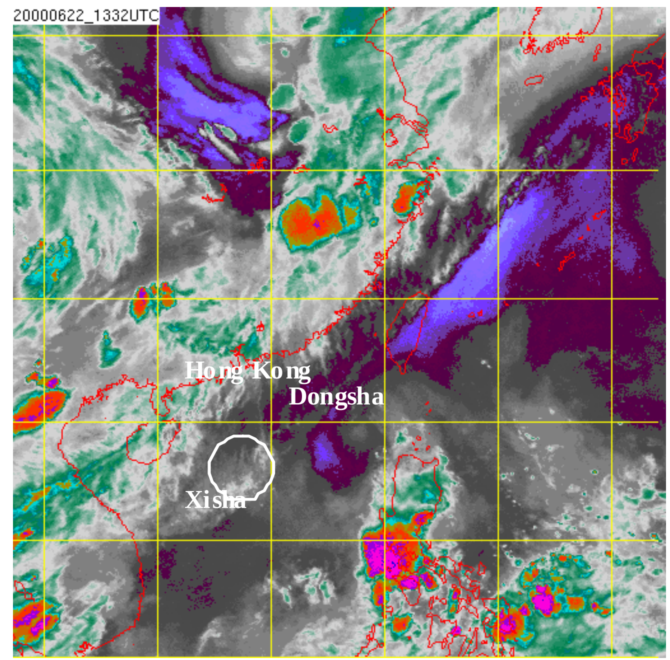
- LUT to view 6.7 micron WV images
- Dry slot that becomes darker (i.e. drier) in successive images
- Accompanied by cold advection & convergence in the mid- and upper-levels, resulting in compensating sinking motion (Result of dynamical process)
- Mod or Sev CAT occur about 80% of the time when WV image darkening occurs
- Most CAT occurs along the leading edge of the darkening band



Turbulence

CAT over South China Sea on 22 Jun 2000

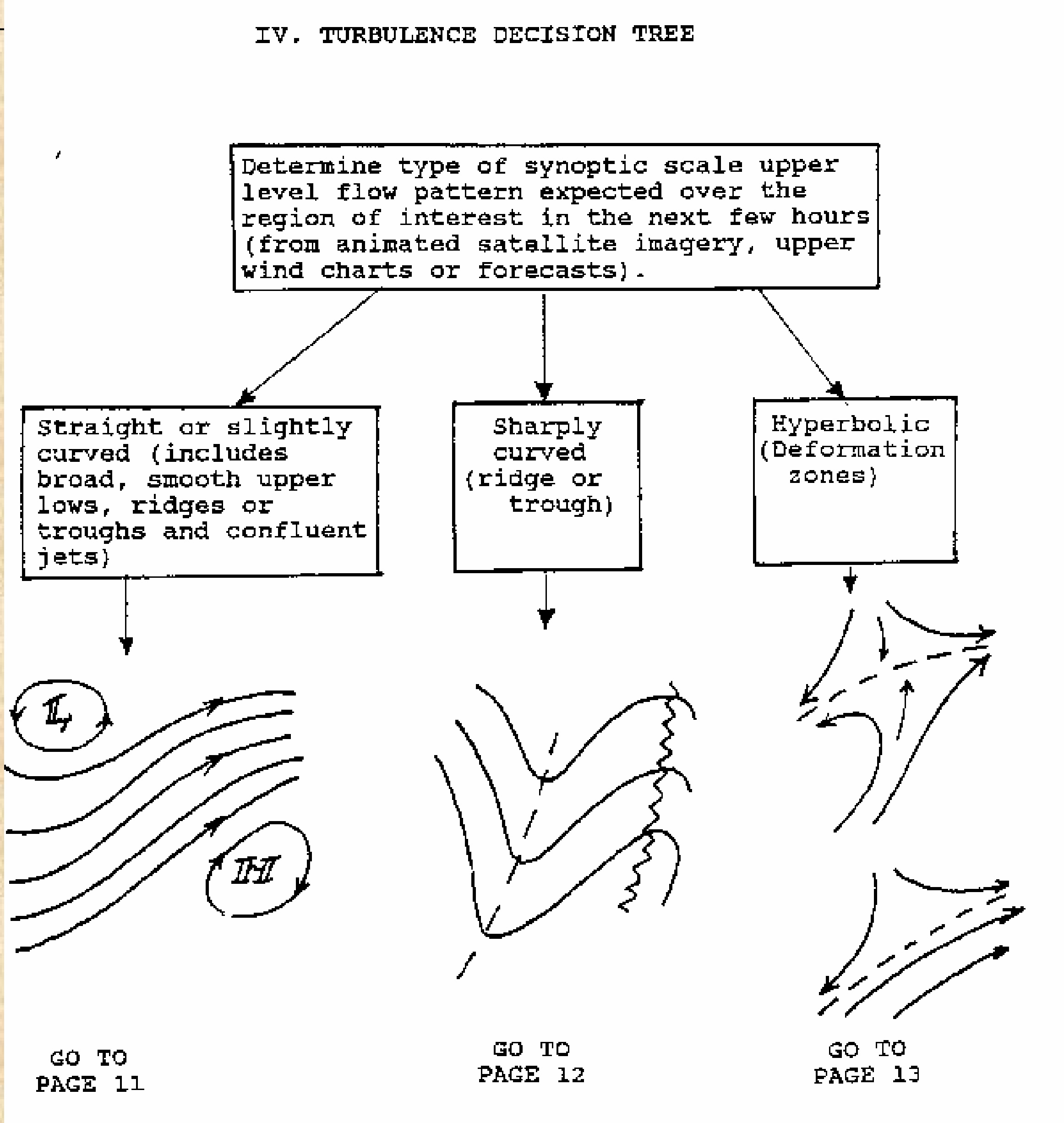
- Time: 1343 UTC
- Location: FL370 530 km S of Hong Kong (near 17.5°N 113.8°E)
- Effects: Moderate to severe CAT reported



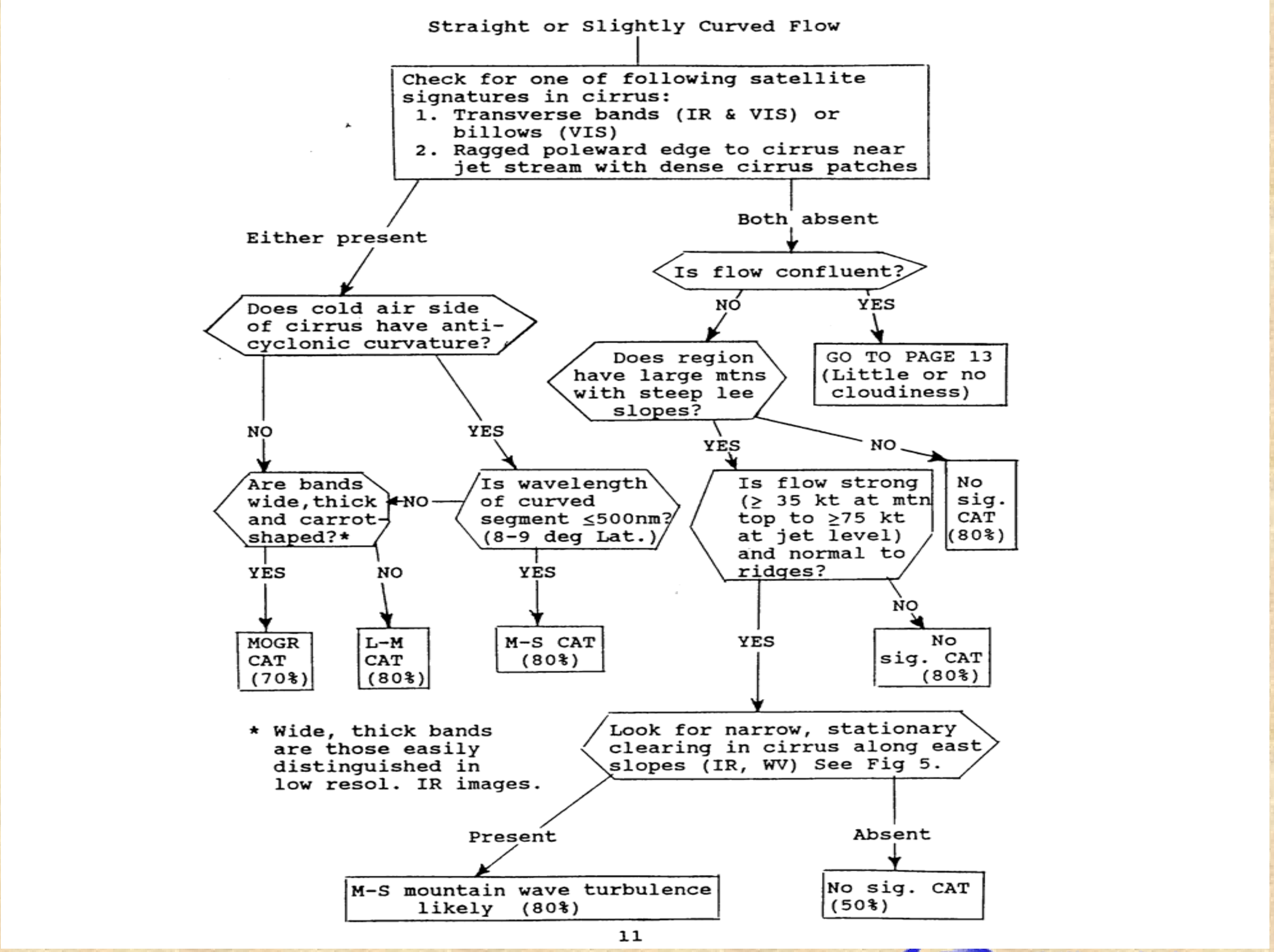
Turbulence

Turbulence Decision Tree

The decision tree is a logical series of questions which branch out toward the solution.



Turbulence Decision Tree



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Turbulence

Turbulence Decision Tree

- The decision tree for short range prediction of CAT 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.

- The levels of confidence are provided for each solution in most cases, which range from 50% to 80%. Turbulence intensities range from light (L) to moderate (M) to severe (S). A solution of MOGR (moderate or greater) indicates that moderate turbulence is likely and severe turbulence is possible.

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Turbulence

Turbulence Decision Tree

- In general, upper flow patterns with longer wavelengths and less curvature are not as conducive to extensive turbulence, except there are local areas of strong vertical shears generated by jet streaks.

Turbulence

Turbulence indices

- Turbulence indices were also developed using output of NWP. From quantities like wind speed and direction, temperature, etc.

- Vertical wind shear (VWS) and horizontal wind shear (HWS) are defined as:

$$VWS = \text{SQRT} (\text{SQUARE}(\partial u/\partial z) + \text{SQUARE}(\partial v/\partial z))$$

$$HWS = (u/s)\partial s/\partial y - (v/s)\partial s/\partial x,$$

where s = is wind speed.

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Turbulence

Turbulence indices

- The **TI2 index** (Ellrod and Knapp) is used in the US WAFC. It is based on product of horizontal deformation and vertical wind shear:

$TI2 = VWS \times (DEF - \Delta H)$,

where $DEF = SQRT(\ SQUARE(DST) + SQUARE(DSH)\ )$

$DST = \partial u/\partial x - \partial v/\partial y$ is stretching deformation,

$DSH = \partial v/\partial x + \partial u/\partial y$ is shearing deformation,

$\Delta H = \partial u/\partial x + \partial v/\partial y$ is horizontal divergence.

Turbulence

Turbulence indices

- The **Dutton index** is used in UK WAFC. It is based on linear regression analyses of a pilot survey of turbulence reports over the North Atlantic and NW Europe during 1976 and various synoptic scale turbulence indices produced from the then-operational UK Met Office forecast model (Dutton). The result of the analyses was the "best fit" of the turbulence reports to meteorological **outputs** for a combination of horizontal and vertical wind shears:

$$\text{Dutton} = 1.25\text{HWS} + 0.25\text{VWS} + 10.5.$$

Turbulence

Turbulence indices

- Theory and observations have shown that at least in some situations patches of CAT are produced by KH instabilities. The **Richardson number** (RI) is a measure of such instability from the windshear:

RI = SQAUARE (N) / SQUARE (VWS)

where $N = (g/\theta \, \partial\theta/\partial z)$ is stability, θ is potential temperature.

Laminar flow becomes turbulent when RI < 0.25 and

Turbulent flow becomes laminar when RI > 1.0.

Turbulence

Turbulence indices

- The **Inverse Richardson number** (INRI) is defined as:

$$INRI = 1/RI$$

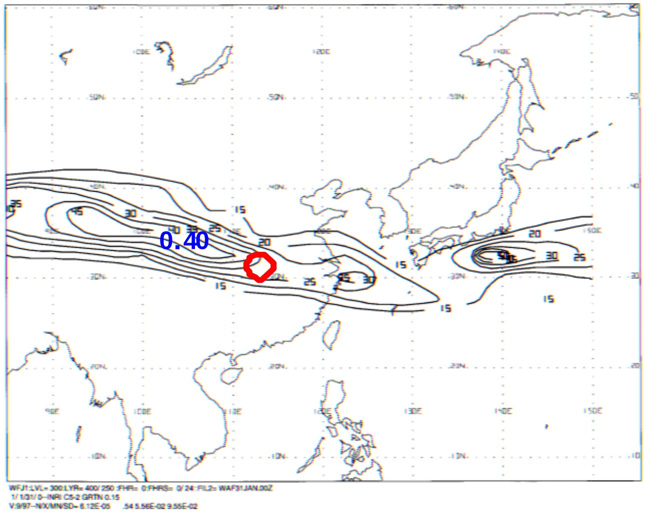
Turbulence

Turbulence indices

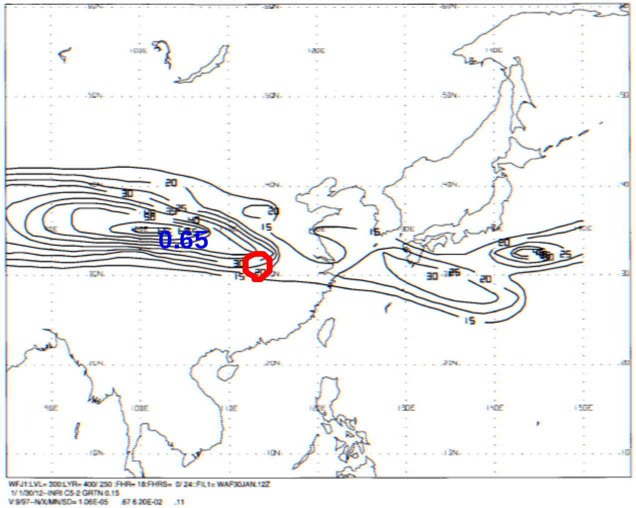
- A Personal Computer based Gridded Interactive Display and Diagnostic System (PCGRIDDS) is developed by NOAA in support of WAFS.
- It is intended as a forecaster's tool for providing interactive access high resolution meteorological information The product provides plan view, cross-section and time-section of a number of basic and derived meteorological fields.

Turbulence indices

Use of INRI in CAT forecasting



Actual INRI at 00 UTC, for 300 hPa



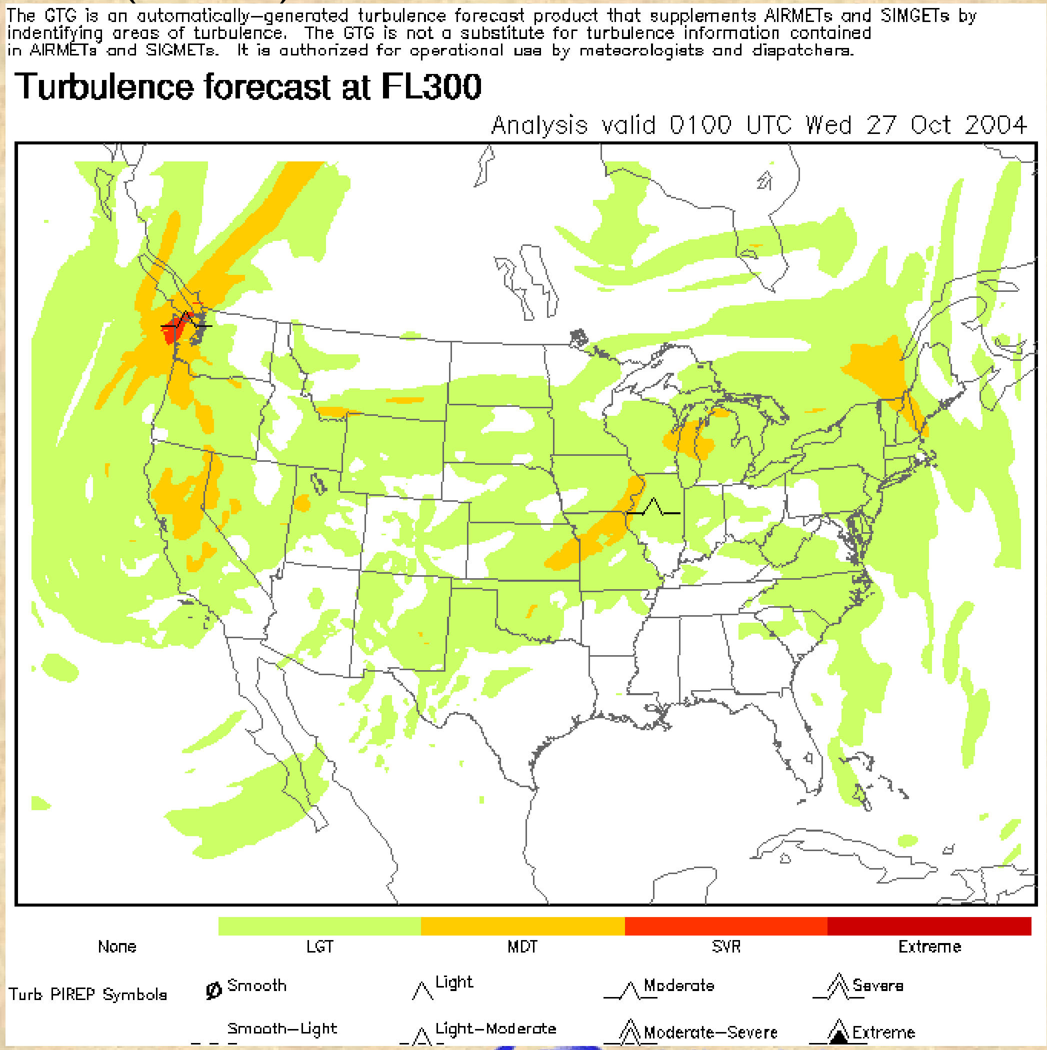
18 hr INRI Prognostic Valid at 06 UTC For 300 hPa

Turbulence

The Graphical Turbulence Guide (GTG)

- An operational version of this Integrated Turbulence Forecasting Algorithm (ITFA).

http://adds.aviationweather.gov/turbulence/



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Limitation

- for synoptic pattern analysis, due to the time and spatial resolution of the synoptic data, shear, curvature and deformation might not be fully captured by the available data
- transverse cloud bands might not be observed in areas where the moisture at the level concerned is not sufficient to form clouds
- darkening of water vapour imageries would not work if there is no strong subsidence accompanying the occurrence of CAT

Turbulence

- [redacted] tree approach to clear air turbulence analysis [redacted] and upper air data, NOAA Technical [redacted] NESDIS 23
- [redacted] MET Office developments in aircraft icing [redacted] forecasting
  - [redacted].ch/web/aom/amprog/Documents/TORONTO%20Seminar/Presentation [redacted]%20TURB%20pres.ppt

Thanks You