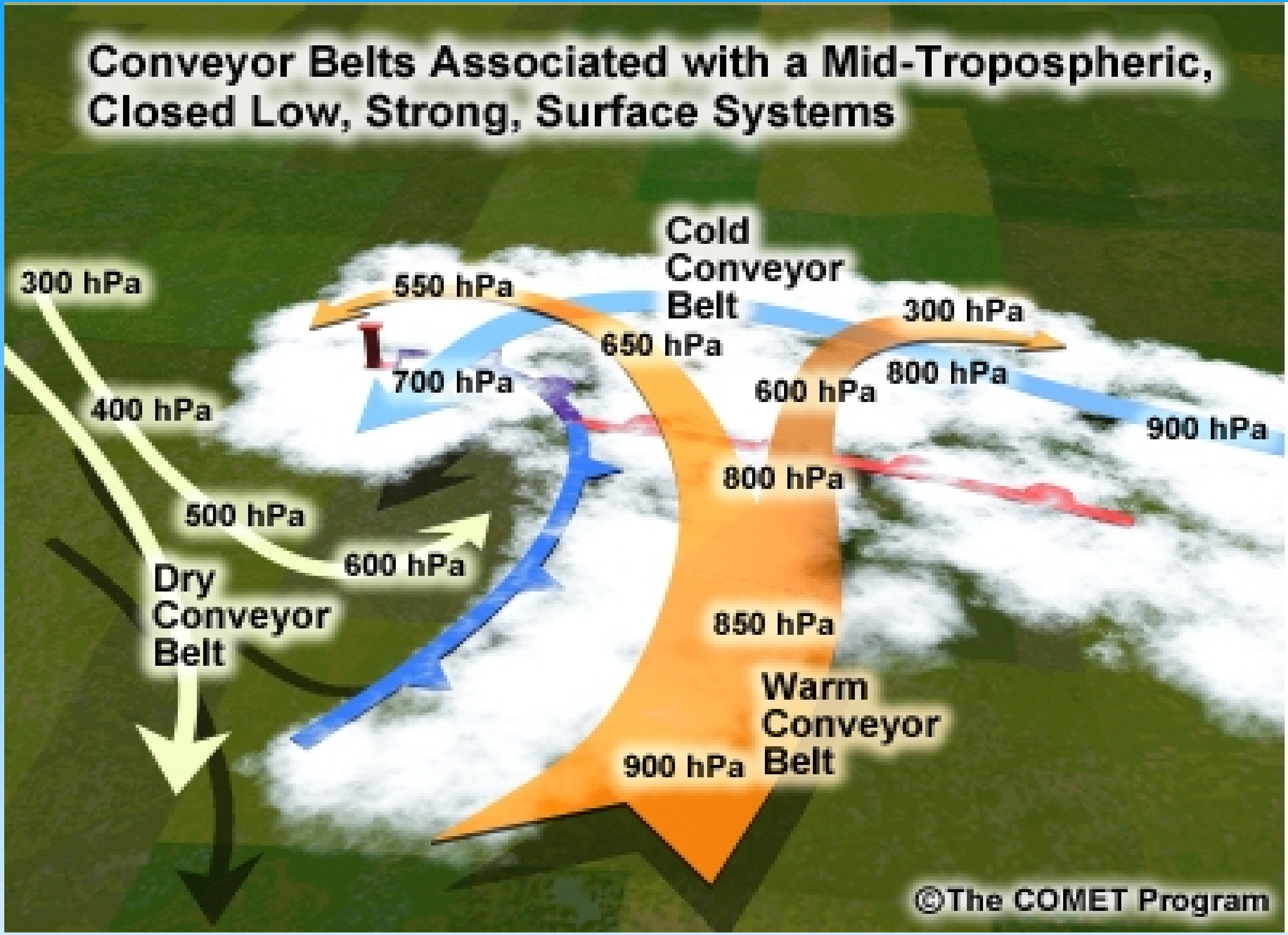
General circulation and meteorology

B. Legras, http://www.lmd.ens.fr/legras

IV Cloud systems associated with fronts

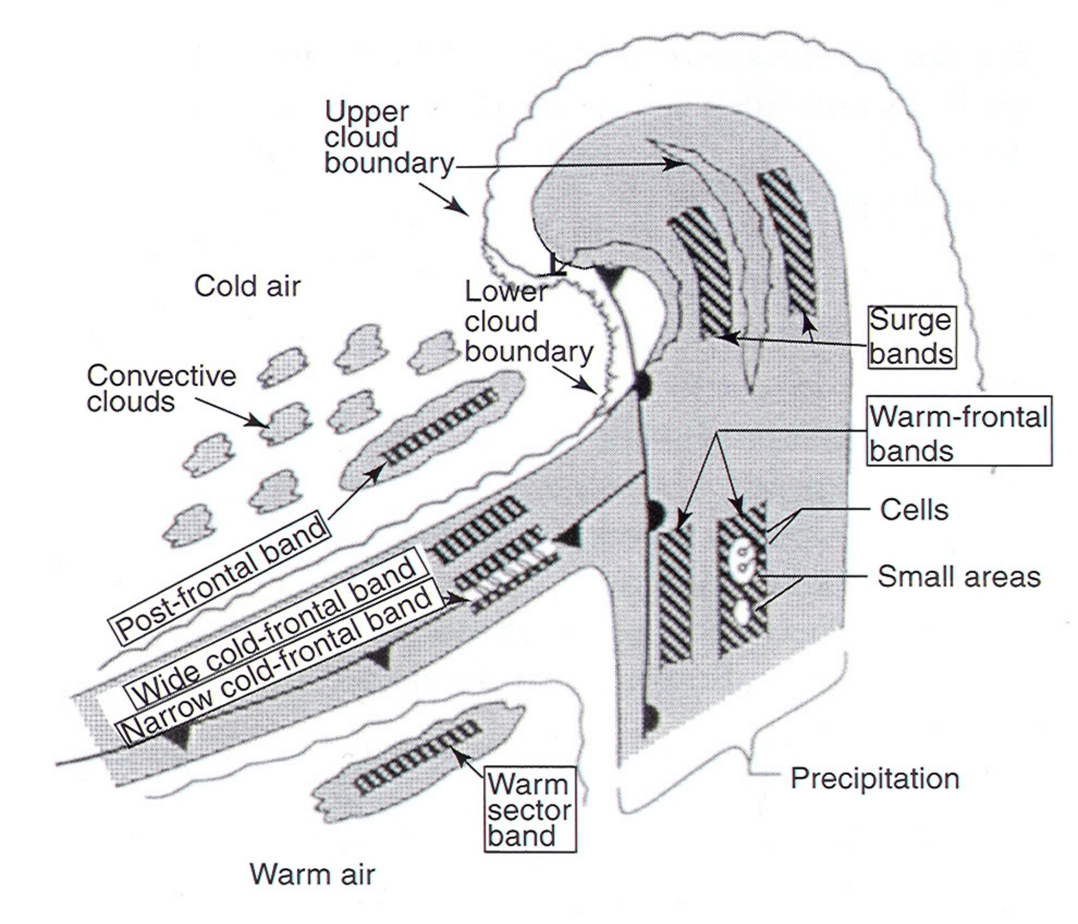
Outline

1. Cloud systems associated with frontogenesis
2. Symmetric instability
3. Complements



Les courants principaux sont ascendants le long des fronts,

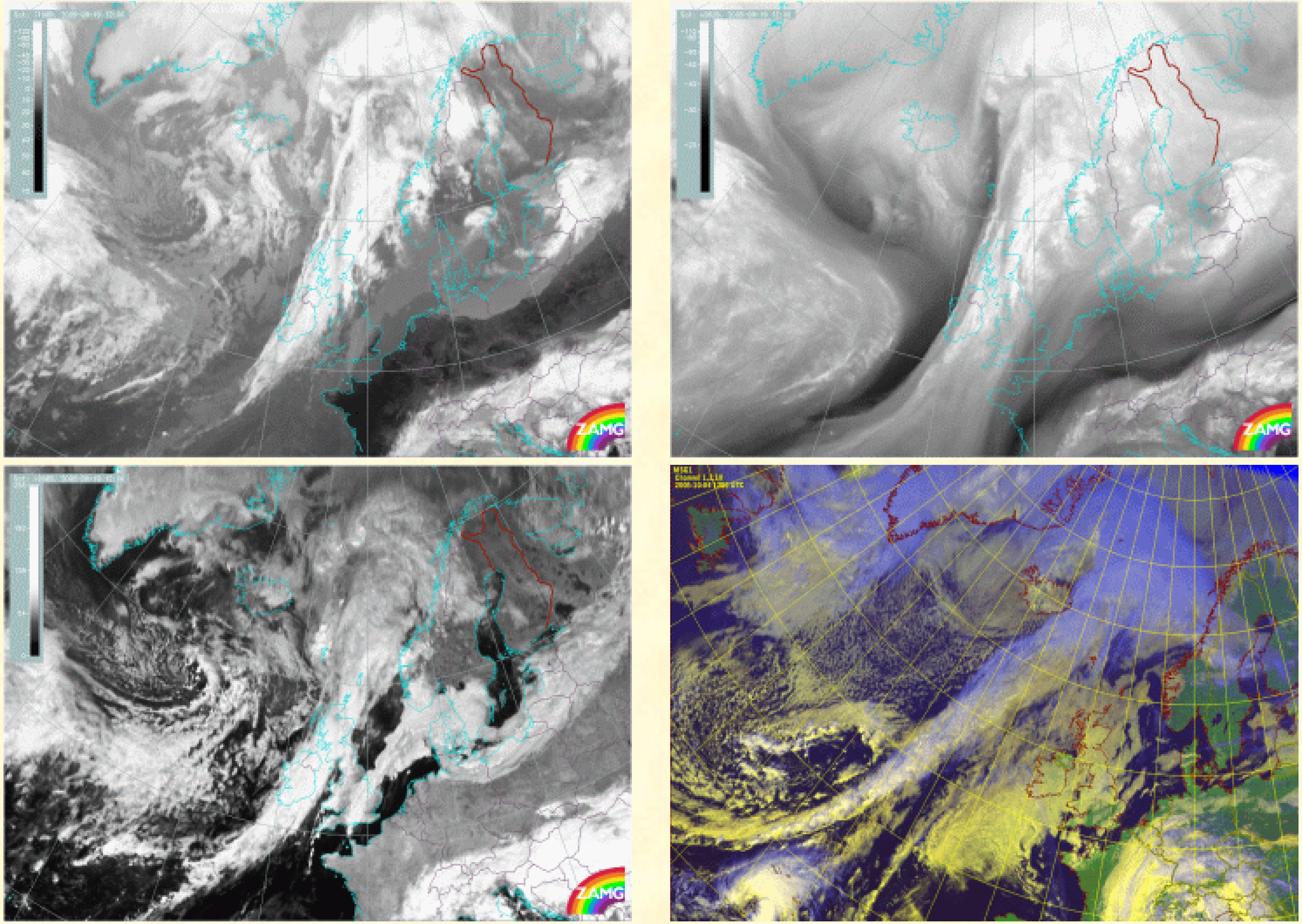
Schematic of the cloud systems associated with warm and cold fronts



Cold front from space observations

19 September 2005/12.00 UTC - Meteosat 8 IR 10.8 image

19 September 2005/12.00 UTC - Meteosat 8 WV 6.2 image



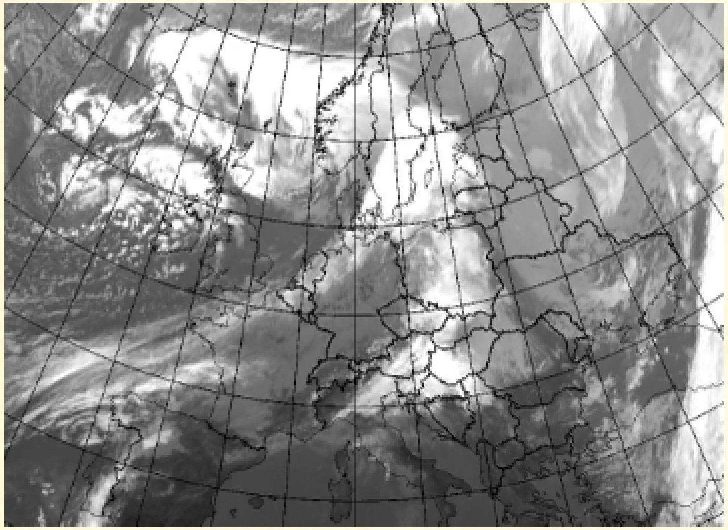
19 September 2005/12.00 UTC - Meteosat 8 VIS 0.8 image

19 September 2005/12.00 UTC - Meteosat 8 RGB image (0.6, 0.8 and 12.0)

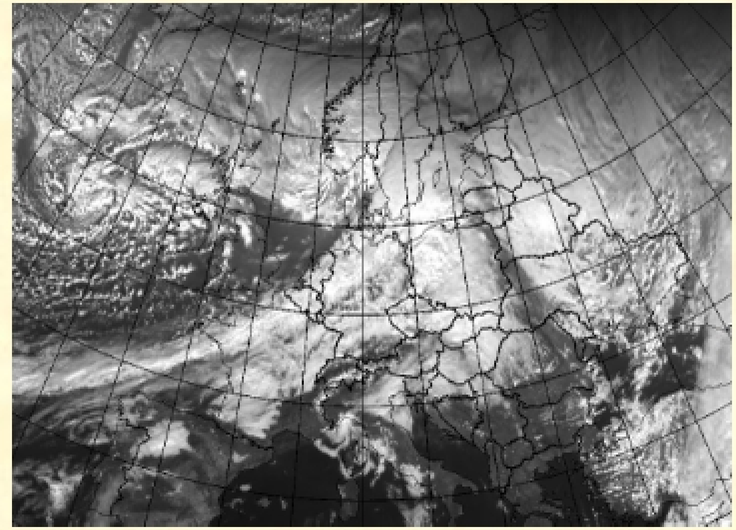
From the satellite meteorology course of ZAMG
http://www.zamg.ac.at/docu/Manual

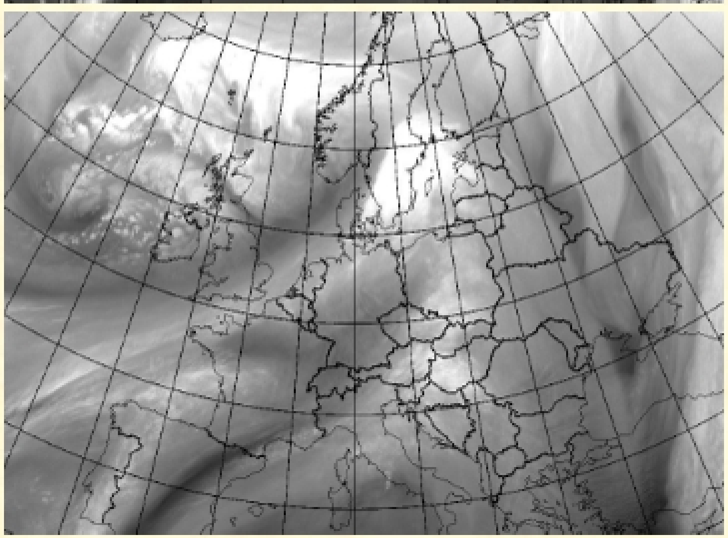
Cold and warm fronts from satellite observations

20 January 2007/12.00 UTC - Meteosat 8 IR10.8 image

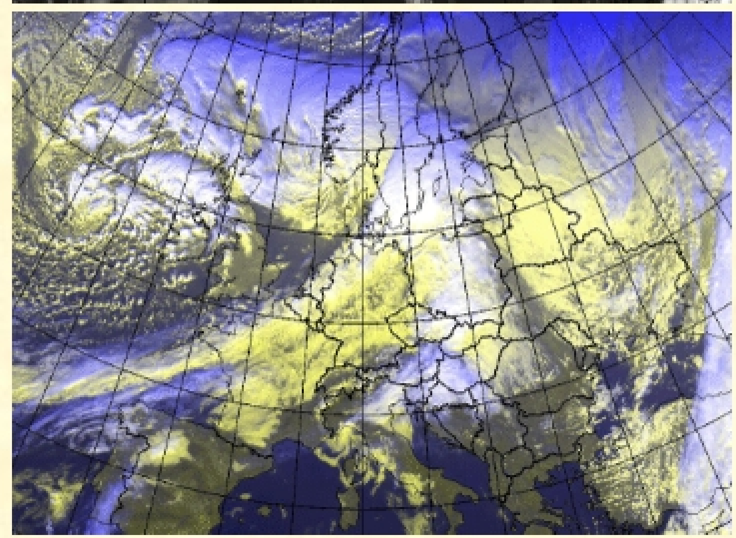


20 January 2007/12.00 UTC - Meteosat 8 VIS0.6 image



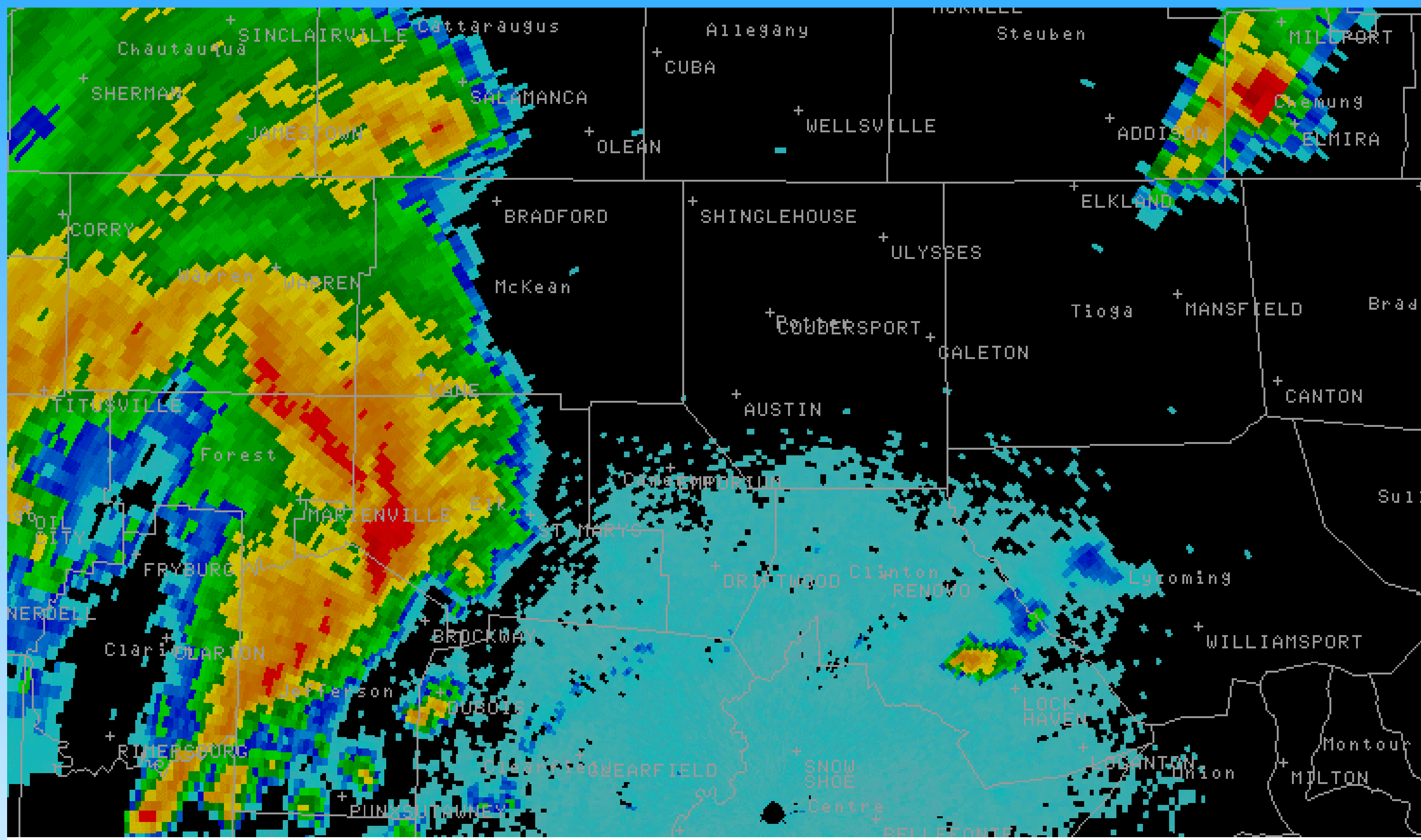


20 January 2007/12.00 UTC - Meteosat 8 WV6.2 image

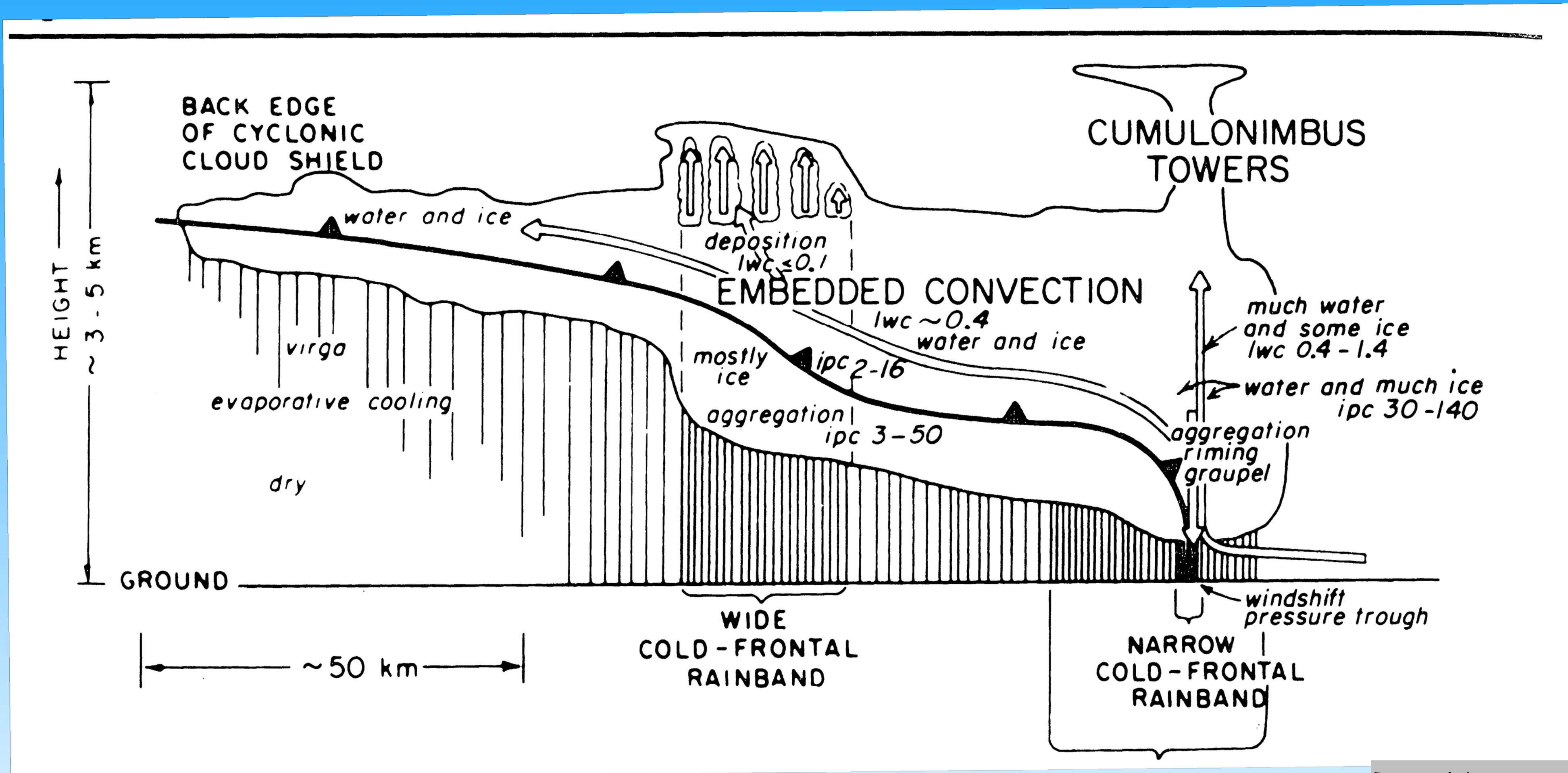


20 January 2007/12.00 UTC - Meteosat 8 (hrvis hrvis IR10.8i) image

Radar images of the development of a cold front (radars waves are reflected by precipitating droplets)

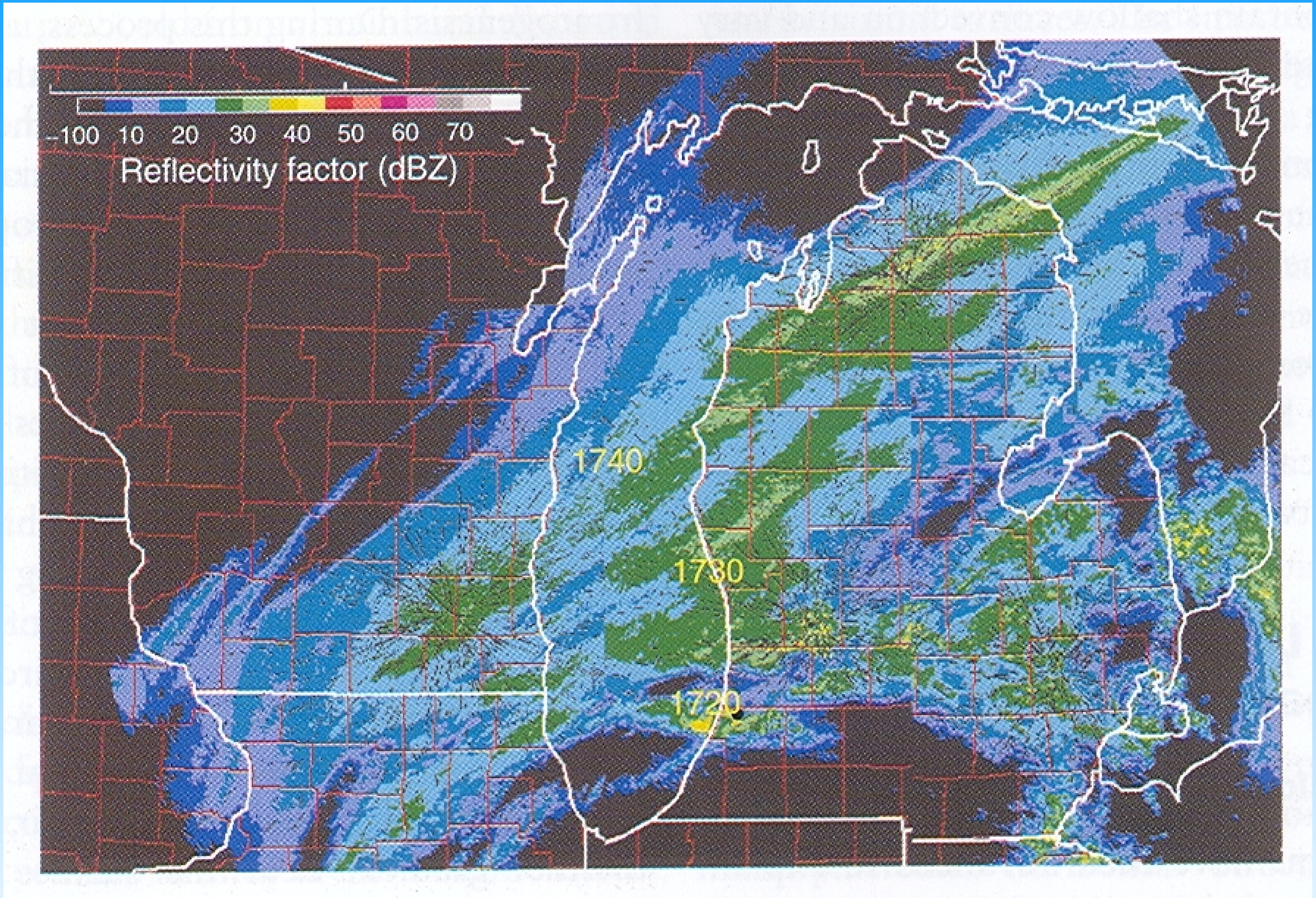


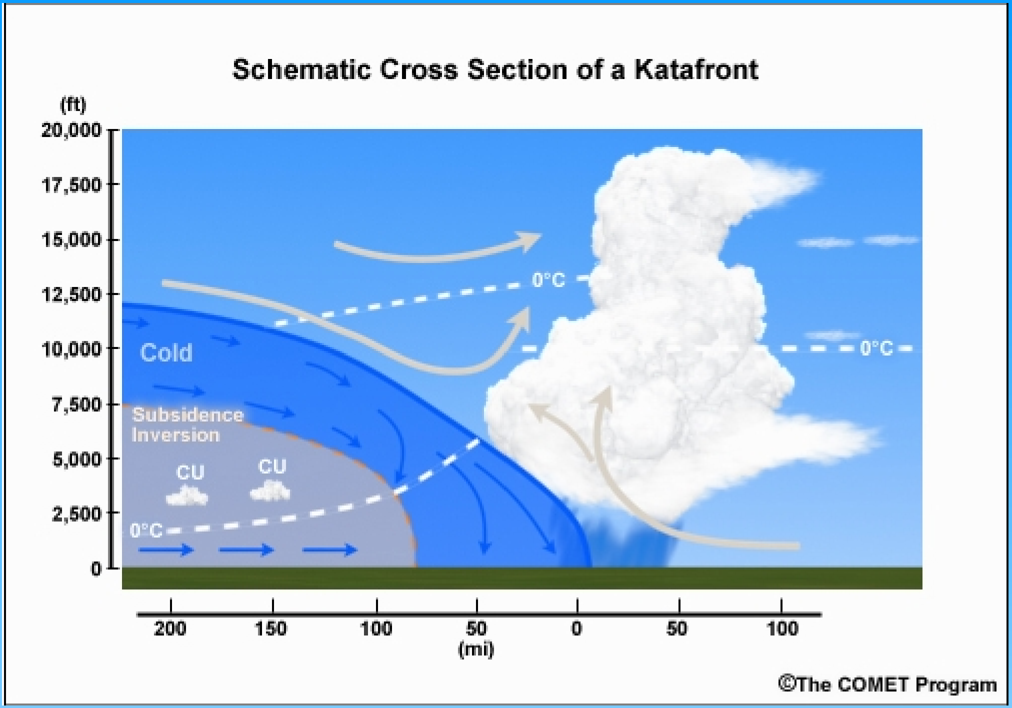
Transverse section of the cloud structure associated with a cold front



R.A. Houze

Band structure of the precipitations (radar)



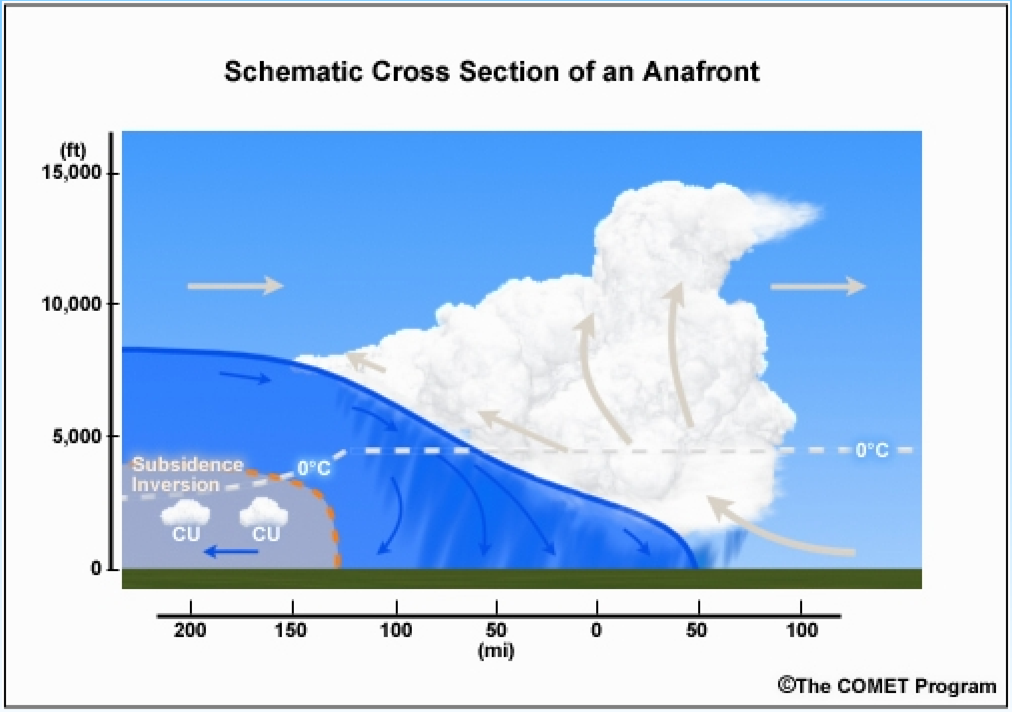


Vertical motion over a narrow band

Rapid drop of the temperature

Initial stage of a cold front

Two types of cold fronts



The front moves forward faster than the flow.

Less steep and vigourous than the kata front.

Extended bands of precipitations.

Mature stage of a cold front.

Outline

1. Cloud systems associated with frontogenesis
2. Symmetric instability
3. Complements

Inertial instability (prerequisite)

Assumptions:

(1) The basic flow is constant and geostrophic, such as $\bar{u}=\bar{w}=0$ and $\bar{v}=v_g(x)$,

(2) The perturbed flow does not depend of y or z

The absolute momentum is defined by $M \equiv v + fx$

The equations of motion in x et y are therefore

$$\frac{Du}{Dt}=f\left(M-M_g\right)$$

$$\frac{DM}{Dt}=0$$

where $M_g=v_g+f\,x$ is the moment of the basic low which is constant

By combining these two equations, we have

$$\boxed{\frac{D^2 u}{D t^2}+u\,f\,\frac{\partial M_g}{\partial x}=0}$$

which appears as an harmonic oscillator equation for u.

The stable or unstable nature of the oscillations depends of the sign of

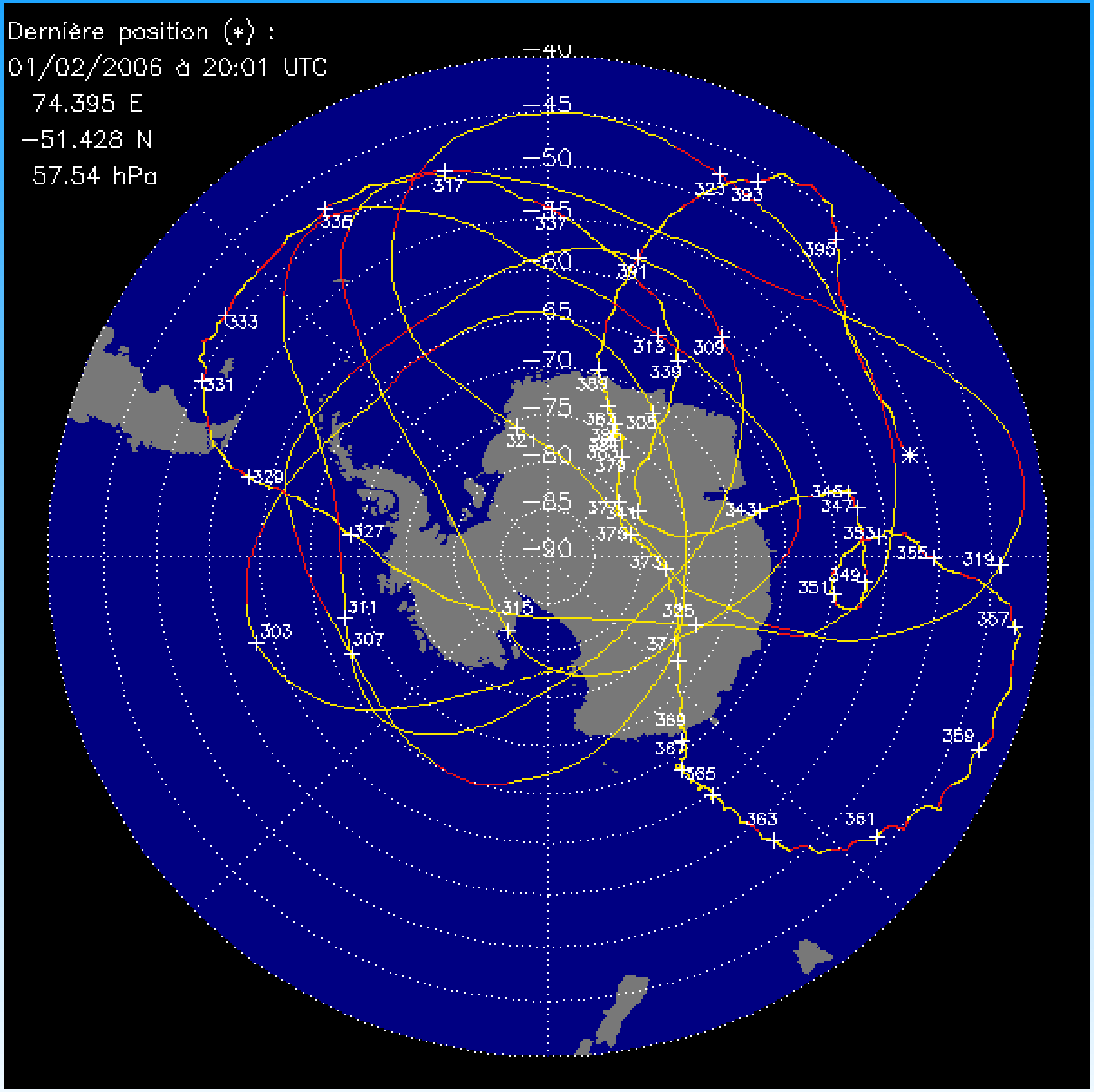
$$\frac{\partial M_g}{\partial x}=\frac{\partial v_g}{\partial x}+f$$

In general, $\partial v_g/\partial x$ is dominated by f and the oscillations exhibit a frequency $\mu=\pm\sqrt{f\left(\partial v_g/\partial x+f\right)}$ close to f.

However, for $\partial v_g/\partial x+f<0$ in the northen hemisphere, that is when the absolute vorticity is negative, an instability occurs.

The rule is inverted in the southern hemisphere.

If the absolute vorticity remains negative, inertial oscillations ensue (balloon trajectories)



Symmetric instability (slantwise convection)

A flow which is stable regarding both the inertial instability (in the horizoantl) and the convective instability (in the vertical) may be unstable with respect to slanted motion.

The basic flow $v_g(x,z)$ is quasi -geostrophic and independent of y. It satisfies the thermal wind balance

$$f\,\partial_z v_g = \partial_x \bar{b}$$

with $f\,v_g = \partial_x \bar{\phi}$

The non-hydrostatic Boussinesq equations are linearized with respect to this basic flow by separating each field as a mean component $(\bar{b}, \bar{\phi})$ plus a pertubation (u', v', w', b', ϕ'). We assume the perturbation is independent of y. The equations are

$$\partial_t u' - f\,v' + \partial_x \phi' = 0$$

$$\partial_t v' + u'\partial_x v_g + w'\partial_z v_g + f\,u' = 0$$

$$\partial_t w' - b' + \partial_z \phi' = 0$$

$$\partial_t b' + u'\partial_x \bar{b} + w'\partial_z \bar{b} = 0$$

$$\partial_x u' + \partial_z w' = 0$$

By denoting $\bar{M} = f\,x + v_g$, the equation in v' is

$$\partial_t v' + u'\partial_x \bar{M} + w'\partial_z \bar{M} = 0$$

Thus, the generation of v' depends on the angle of the trajectories of air parcels d'air moving with (u', w') with the surface $\bar{M}$ sloping as $\partial_x \bar{M} / \partial_z \bar{M} \equiv F^2 / S^2$.

The generation of b' depends on the angle with the surface $\bar{b}$ sloping as $\partial_x \bar{b} / \partial_z \bar{b} \equiv S^2 / N_s^2$.

We have used $F, S\, N_s$ defined earlier and we have

$$\partial_t b' = -u' S^2 - w' N_s^2,$$

$$\partial_t (f\,v') = -u' F^2 - w' S^2,$$

hence

$$\partial_{t^2}^2 (\partial_z u' - \partial_x w') = f\,\partial_z \partial_t v' - \partial_x \partial_t b'$$

$$= -F^2 \partial_z u' + S^2 (\partial_x u' - \partial_z w') + N_s^2 \partial_x w'$$

using $\partial_x S^2 = \partial_z F^2$ and $\partial_x N_s^2 = \partial_z S^2$.

By introducing agian the vertical streamfunction ψ, such that $u' = \partial_z \psi$ et $w' = -\partial_x \psi$, we obtain

$$\partial_{t^2}^2 (\partial_{x^2}^2 \psi + \partial_{z^2}^2 \psi) = -F^2 \partial_{z^2}^2 \psi + 2\,S^2 \partial_{xz}^2 \psi - N_s^2 \partial_{x^2}^2 \psi$$

Symmetric instability (continued)

$$\partial^2_{t^2}(\partial^2_{x^2}\psi+\partial^2_{z^2}\psi)=-F^2\partial^2_{z^2}\psi+2S^2\partial^2_{xz}\psi-N_s^2\partial^2_{x^2}\psi$$

Within a finite domain, we look for a solution under the form $\psi=\psi_0 e^{i\sigma t}e^{iK(x\sin\varphi+z\cos\varphi)}$, yielding the dispersion equation $\sigma^2=N_s^2\sin^2\varphi-S^2\sin 2\varphi+F^2\cos^2\varphi$

Notice that there is no dependency in K!

1) Inertial oscillations : $\varphi=0$ et $\sigma=F$

2) Brünt-Vaissala oscillations: $\varphi=\frac{\pi}{2}$ et $\sigma=N_s$

3) General case, we write

$$2\sigma^2=N_s^2+F^2-A\cos 2(\varphi-\phi_1)$$

where $A=\sqrt{(N_s^2-F^2)^2+4S^4}$ and the angle ϕ_1 is defined by $\sin(2\phi_1)=2\frac{S^2}{A}$ and $\cos(2\phi_1)=\frac{N_s^2-F^2}{A}$.

Hence: $\sigma^2_{min}\sigma^2_{max}=\frac{1}{4}[(N_s^2+F^2)^2-A^2]=N_s^2F^2-S^4$

Since the potential vorticity of the basis flow is

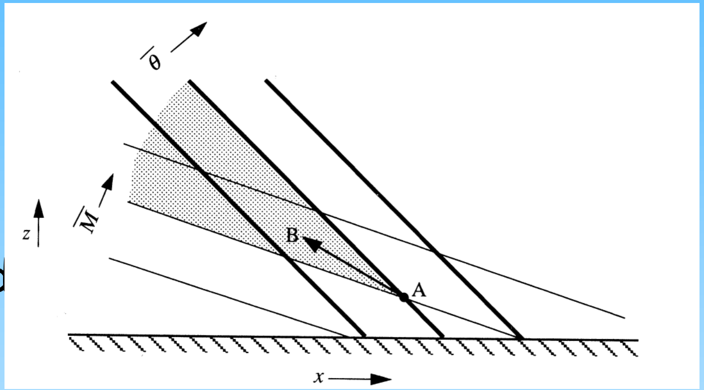
$$q=-\partial_z v_g\partial_x b+(f+\partial_x v_g)\partial_z b=\frac{1}{f}(-S^4+N_s^2F^2)$$

we have $\sigma^2_{min}\sigma^2_{max}=f\,q$.

The flow is unstable iff

$\sigma^2_{min}<0$ or $q<0$

that is $\frac{\partial(\bar{M},\bar{b})}{\partial(x,z)}<0$



Introducing the Richardson number

$R_i=\frac{\partial_z b}{(\partial_z v_g)^2}=\frac{f^2N^2}{S^4,}$ which characterizes the ratio between thermal stratification and shear, the instability criterion is

$R_i<\frac{f^2}{F^2,}$ that is $R_i<1$ si $f\gg\partial_x v_g$

Again, the criterion on q is reversed is the southern hemisphere

Generalisation of the symetric instability to the moist case and comparison with the convective and inertial instabilities

Conditional	Convective	Inertial	Symmetric
Dry θ	Absolute convective instability $d\theta/dz < 0$	Inertial instability $f+\zeta < 0$ (1,2)	Absolute symmetric instability $PV < 0$ (2)
Potential θ_e	Potential convective instability $d\theta_e/dz < 0$	N/A	Potential symmetric instability $Pv_e < 0$ (2)
Condition-nal θ_e*	Conditional convective instability $d\theta_e^*/dz < 0$	N/A	Conditional symmetric instability $Pv_e^* < 0$ (2)

(1) : $\zeta = \frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y}$

(2) : **Revert the sign of the inequality in the southern hemisphere**

R.A. Houze

Symmetric instability for the generation of precipitation bands

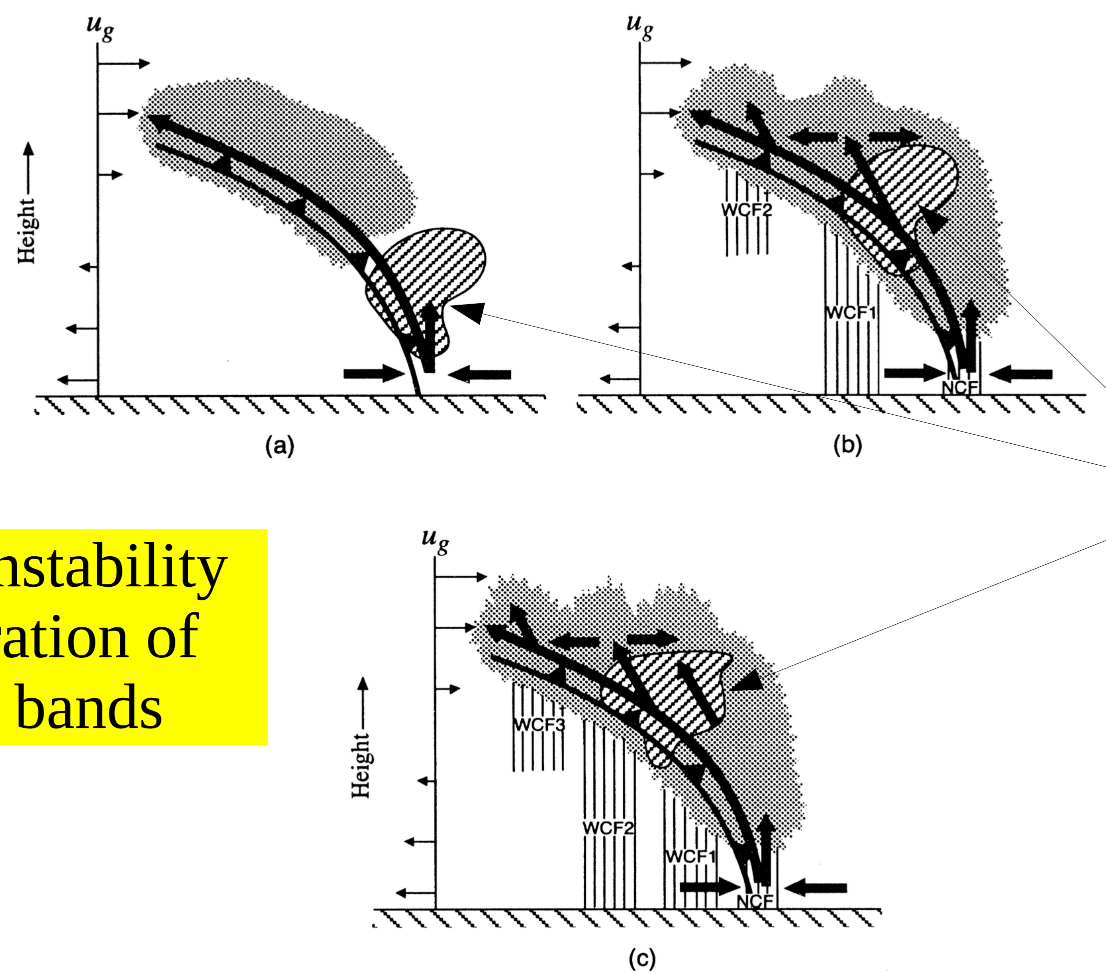


Figure 11.33 Schematic of the processes leading to the formation of cold-frontal rainbands in a mesoscale numerical model. The crosshatching shows the region of negative equivalent potential vorticity. Shading shows the region containing cloud water. Vertical hatching below cloud base represents precipitation. The geostrophic wind in the plane of the cross section (u_g) is indicated on the left-hand side of the figure. Broad arrows show ageostrophic air motions. All winds shown are relative to the motion of the baroclinic wave within which the frontal system developed. (a) A region of negative equivalent potential vorticity, which forms in the warm air, is advected up along the frontal surface by the ageostrophic motions. (b) When the region of conditional symmetric instability becomes saturated the instability is realized, resulting in a wide cold-frontal rainband (WCF1). A second rainband (WCF2) is forced by convergence behind WCF1. Convergence in the planetary boundary layer produces a narrow cold-frontal rainband (NCF). (c) WCF1 moves toward the warm air; WCF2 moves into the region of conditional symmetric instability and intensifies. A third band (WCF3) is forced by convergence behind WCF2. (Adapted from Knight and Hobbs, 1988. Reproduced with permission from the American Meteorological Society.)

Region with negative PV

We have here the moist moist potential vorticity where θ is replaced by θ_e.
In the same way as the convective instability, the symmetric instability is potential, being realized only after saturaion is reached in the layer.

Surface P and thickness

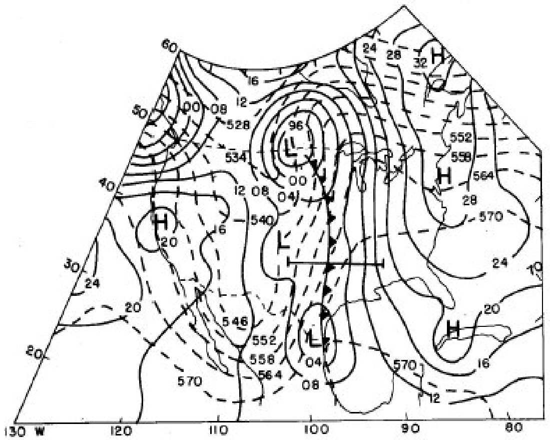


FIG. 3. (a) Surface pressure (solid lines, in millibars with hundreds and thousands digits missing) and 1000–500 mb thickness (dashed lines, in decameters) for North America at 0000 GMT 3 December 1982. Major frontal positions and pressure centers are indicated. Solid bar denotes location of cross sections shown in Fig. 6.

500 hPa

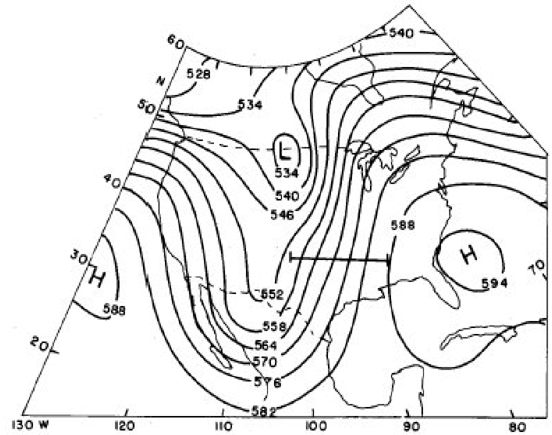
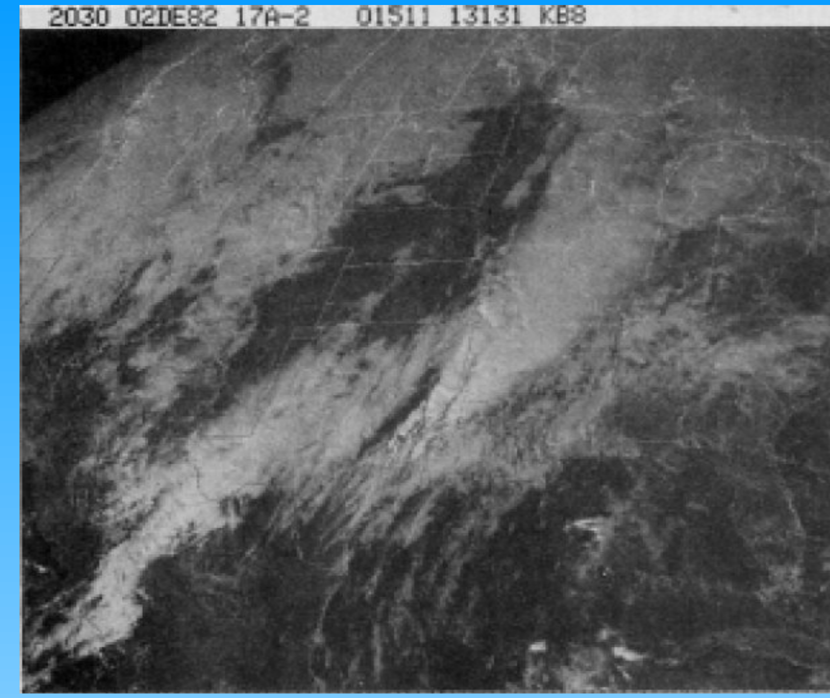


FIG. 4. (a) 500 mb geopotential height (decameters) over North America at 0000 GMT on 3 December 1982.



Indications that slantwise convection mixes cloudy air in the frontal region to make parallel the surfaces of moment M et of equivalent potential temperature.

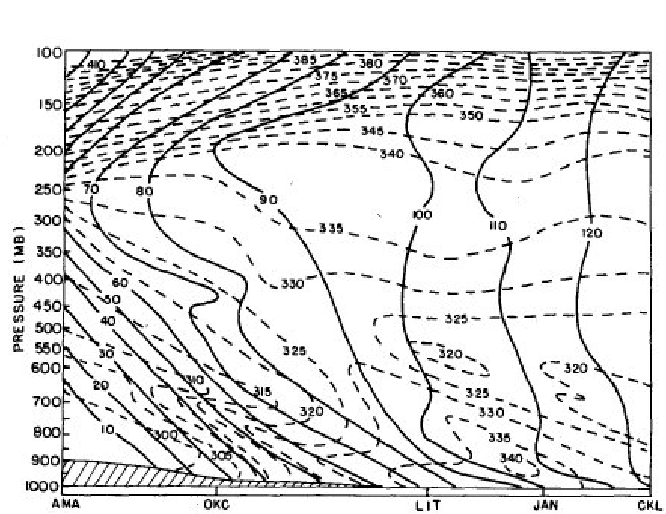


FIG. 6. (a) Cross section from Amarillo, Texas to Centreville, Alabama at 0000 GMT 3 December 1982. Solid lines denote M (m s^{-1}), dashed are θ_e (K).

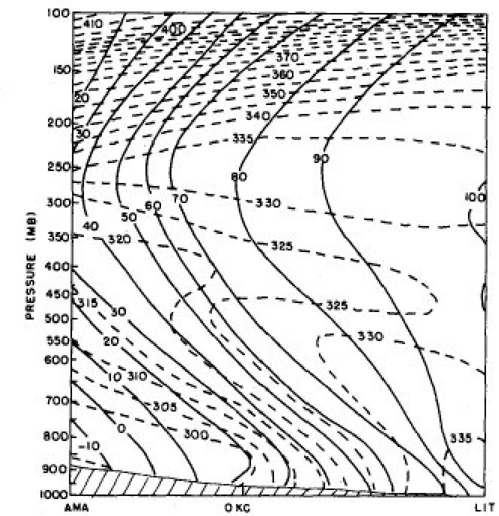
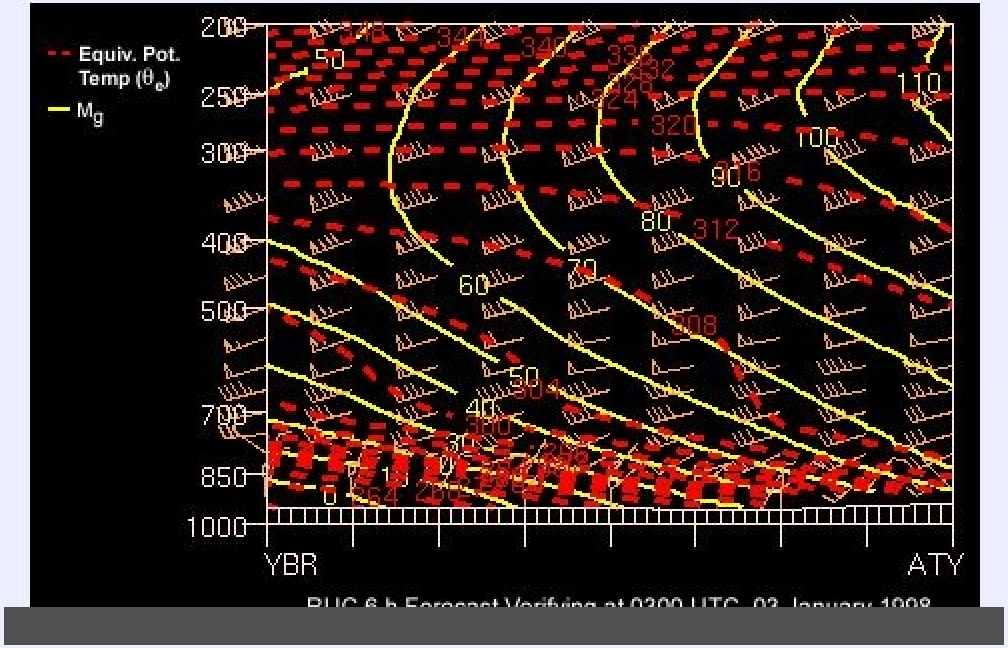


FIG. 6. (b) As in Fig. 6(a) but from Amarillo to Little Rock, Arkansas at 1200 GMT 3 December 1982.

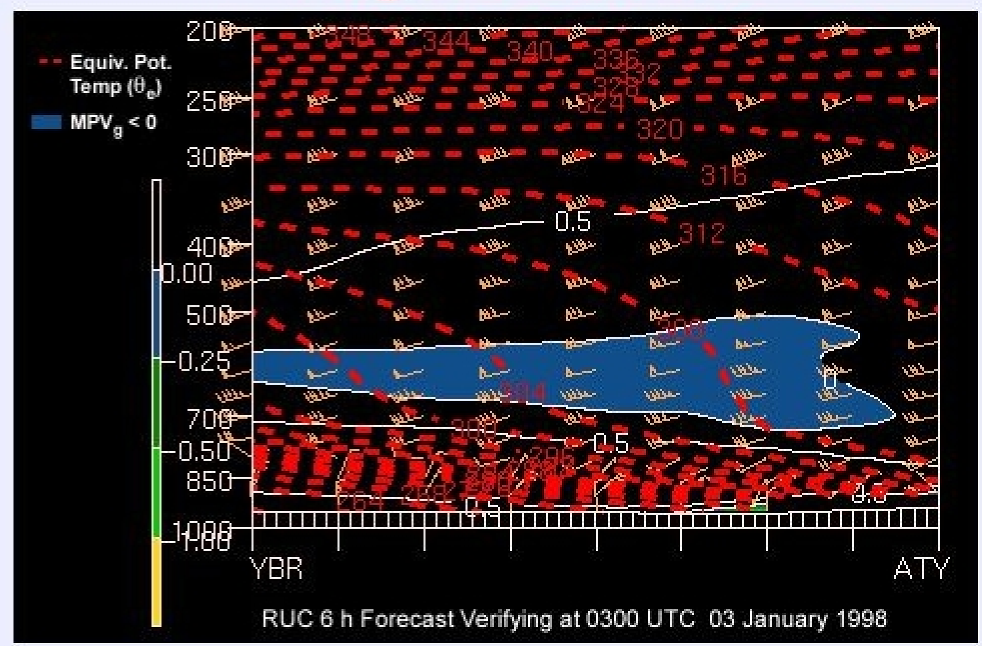
Cross-section of M and θ_e

K. Emanuel

M_g - θ_e Cross Section



MPV$_g$ Cross Section

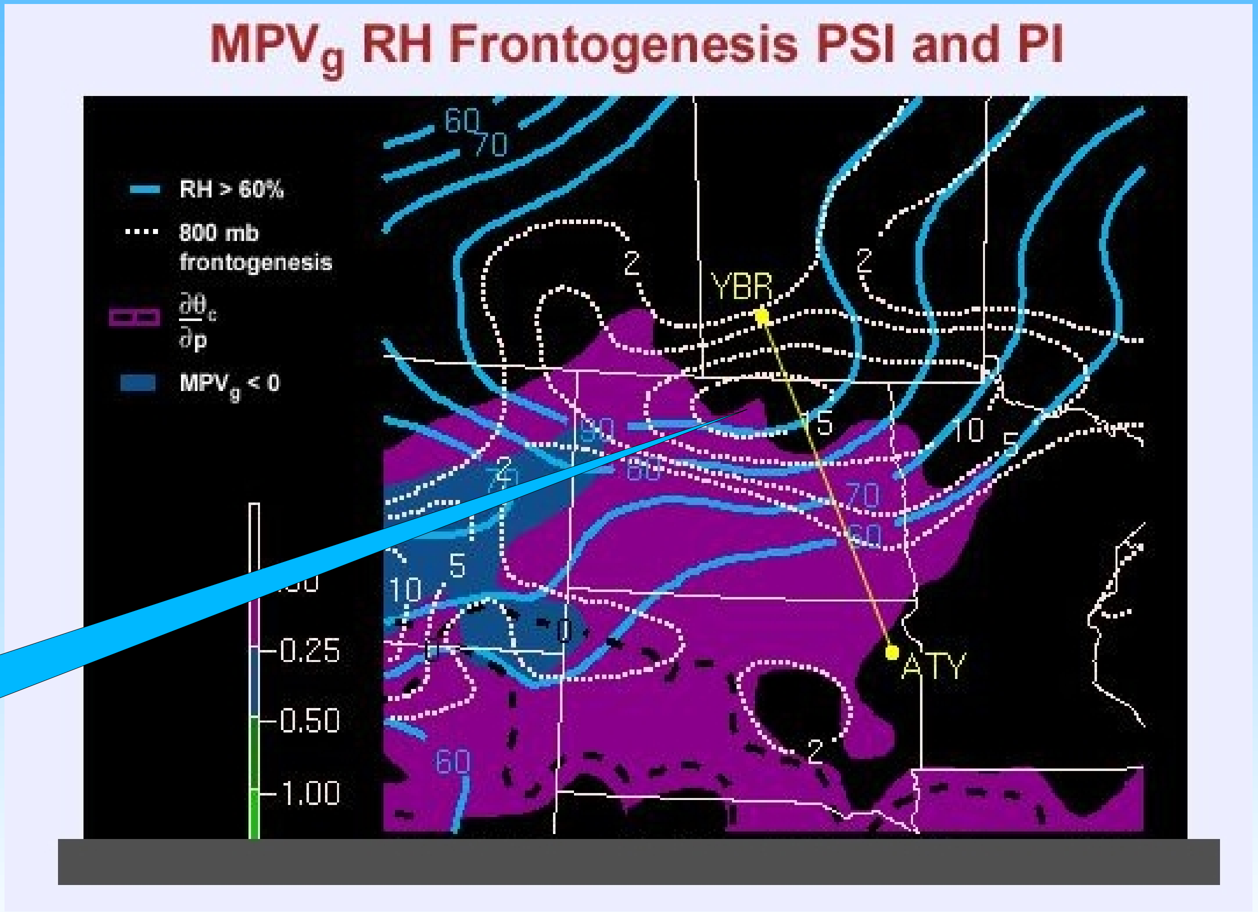


It is easier to foresee the preence of a region of potential instability from the moist potential vorticity than from the diagramme of moment / potential temperature.

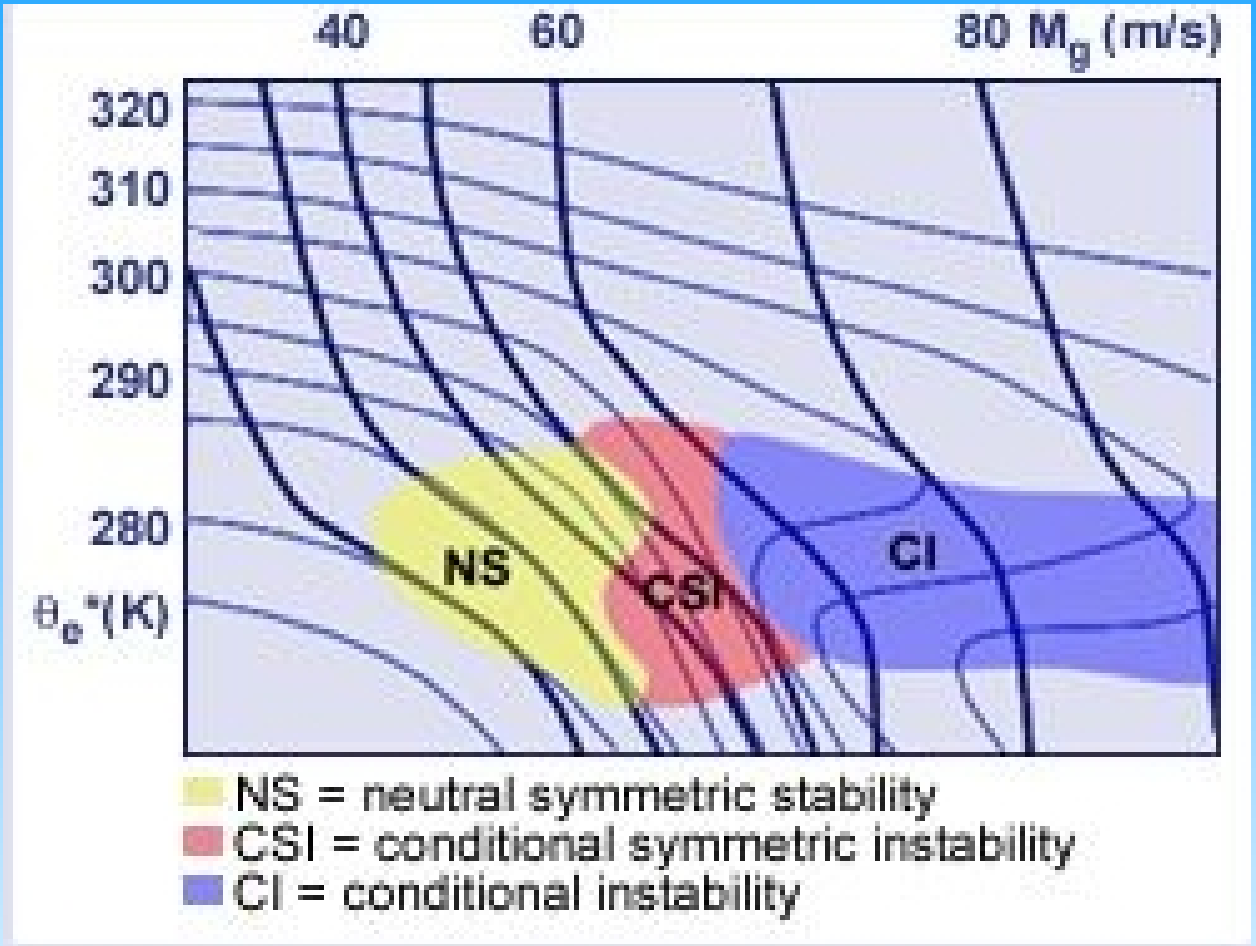
Attention:

The conditional or potential symmetric instability is not enough to forecast the formation of precipitation bands. An ascending motion and air close to saturation are also requiredWhen these three conditions are met together in synoptic maps, the occurrence of precipitation bands can be forecasted.

$$\text{frontogenesis} = \frac{d}{dt}|\nabla\theta|$$



The 3 conditions are satisfied


40
60
80 M_g (m/s)
320
310
300
290
280
θ_e*(K)
NS
CSI
CI
NS = neutral symmetric stability
CSI = conditional symmetric instability
CI = conditional instability

To go further

book de R. Houze, Clouds dynamics, Academic Press

book de Cotton, Bryan et van den Heever, Storm and cloud dynamics, Academic Press

Course on the concept of symetric instability and its application
http://www.nssl.noaa.gov/~schultz/csi.shtml

Interactive course of satellite meteorology
http://www.zamg.ac.at/docu/Manual/

Ensemble of courses of meteorology intended for previsionists
http://www.comet.ucar.edu

Review article by R. Houze on the meso-scale convective systems
http://www.atmos.washington.edu/MG/PDFs/ROG04_houze_MCS.pdf