Frontogenesis

Textbooks and web sites references for this lecture:

- Robert McIlveen, Fundamentals of Weather and Climate, Chapman & Hall, 1995, ISBN 0-412-41160-1 (§ 11)
- Joseph M. Moran e Michael D. Morgan, Meteorology, The Atmosphere and the Science of Weather, Mc Millan College Publishing Company, 1994, ISBN 0-02-383341-6 (§ 11)

Fronts and Air masses

- Air mass types and sources
- Frontal types
- Frontal structure in 3-D

Air Mass Properties

- Air masses take on the properties of the underlying surface
- Air masses are classified according to their location of origin
- Geographical Characteristics
  - Tropical, Polar, Arctic
- Surface Properties
  - maritime, continental
- Source region characteristics most prevalent if air mass remains over source region for a long period

Fronts and Air masses (cont.)

- Air mass types
  - Four general categories:
    - » **P** Polar source (also **A** for Arctic source)
    - » **T** Tropical source
    - » **c** continental (land regions)
    - » **m** maritime (ocean regions)

- Source regions
  - Generally flat and uniform composition
  - Light surface winds
  - Places dominated by high pressure
    - » Arctic plains (ice/snow covered)
    - » Subtropical oceans
    - » Desert regions

Air Mass Classifications

- **A or AA** – Arctic or Antarctic
  - Extremely cold and very dry
- **cP** - continental Polar
  - Cold, dry, stable
  - Extremely cold cP air mass may be designated cA (continental Arctic)
- **mP** - maritime Polar
  - Cool, moist, unstable
- **mT** - maritime Tropical
  - Warm, moist, usually unstable
- **cT** - continental Tropical
  - Hot, dry
  - Stable air aloft, unstable surface air

Air Mass Source Regions

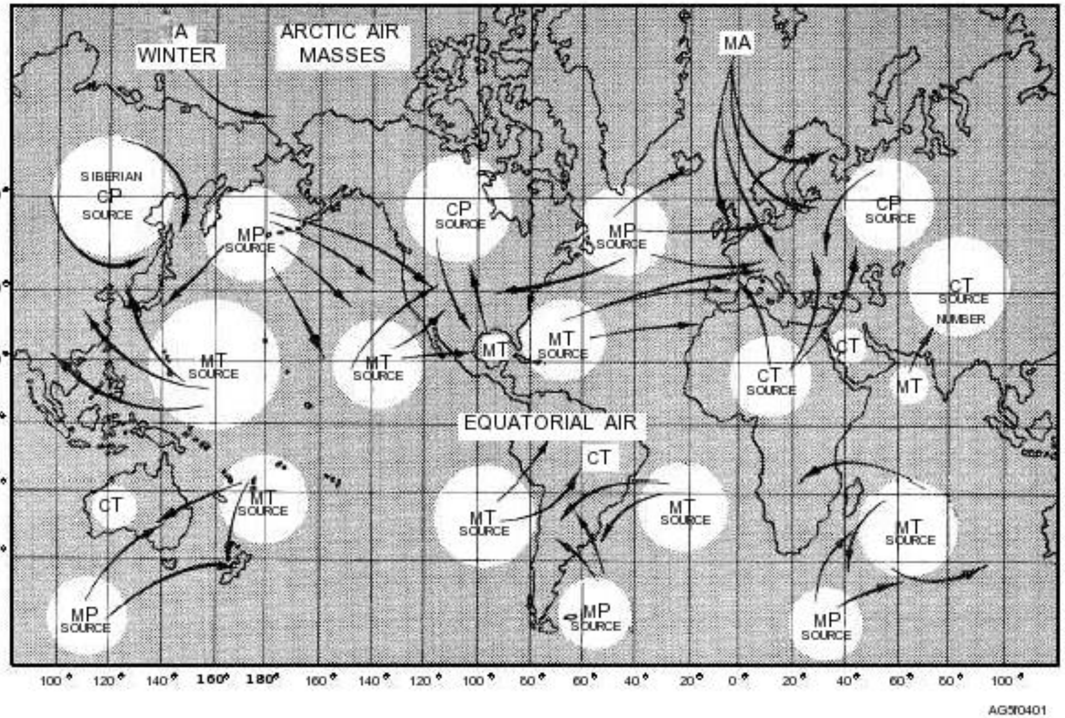
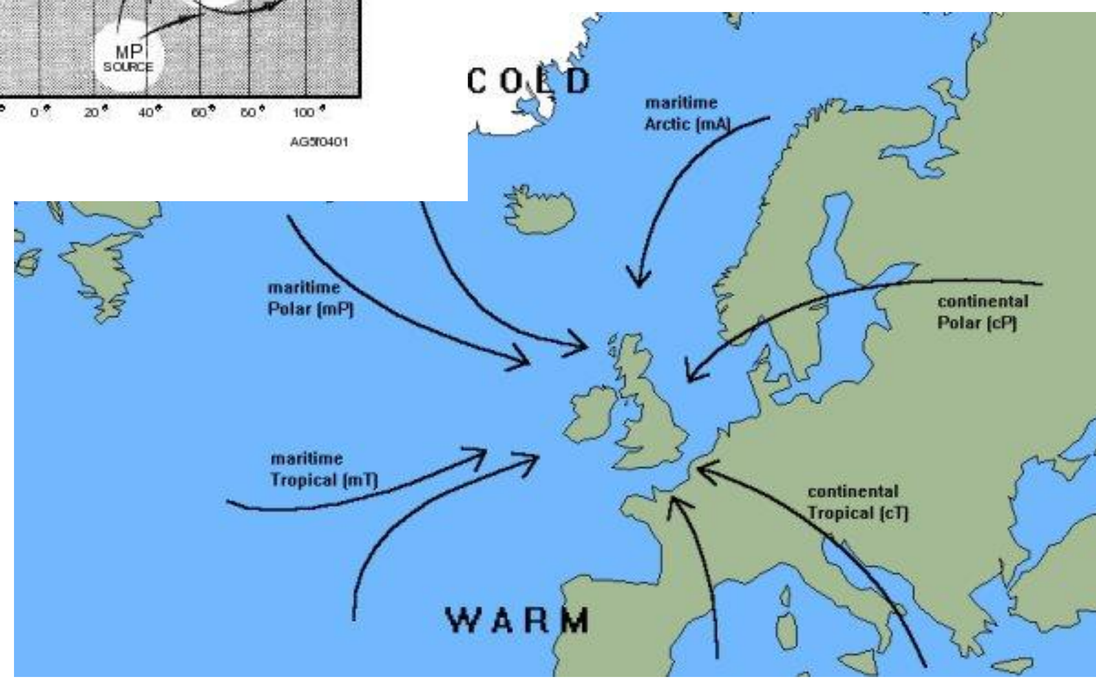
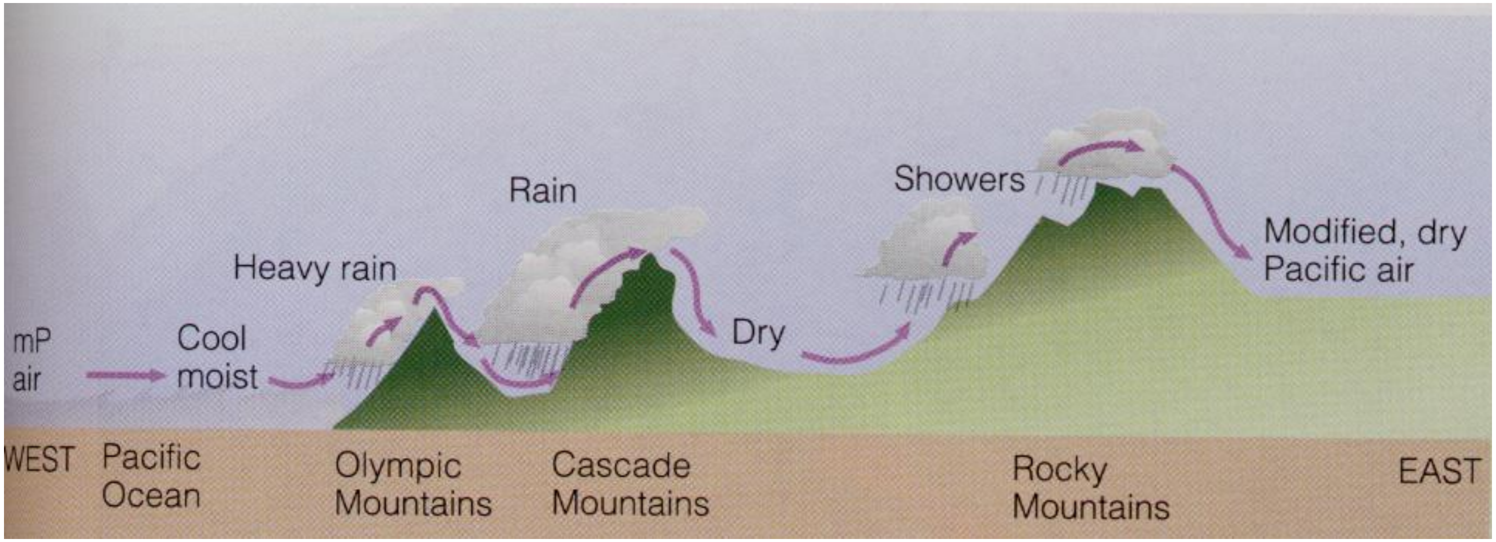


Figure 4-1.—Air mass source regions.



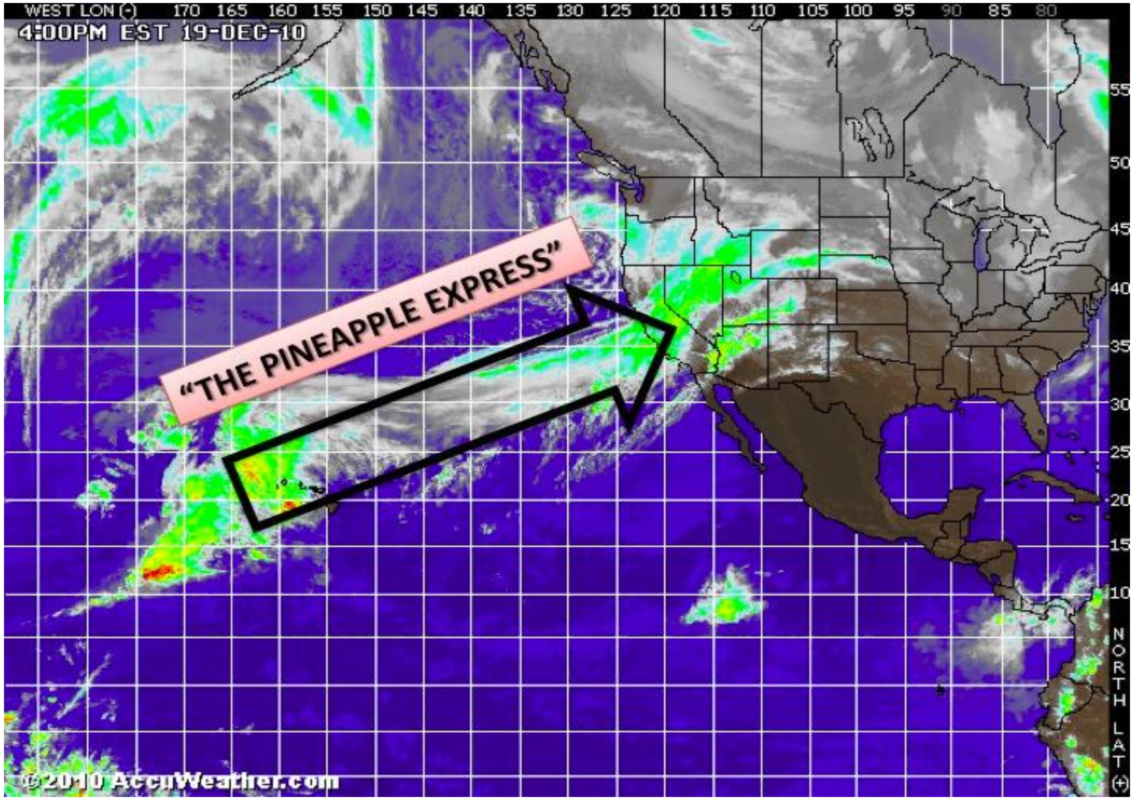
An example of air mass modification

- cP air from Asia and frozen polar regions is carried across the Pacific, circulating around Aleutian low
- Contact with the ocean warms and moistens the air near the surface, transforming it to an unstable mP air mass
- As the mP air moves inland it crosses several mountain ranges, removing moisture as precipitation
- The drier mP air is transformed back to cP air as it travels across the cold, elevated interior of the U.S.

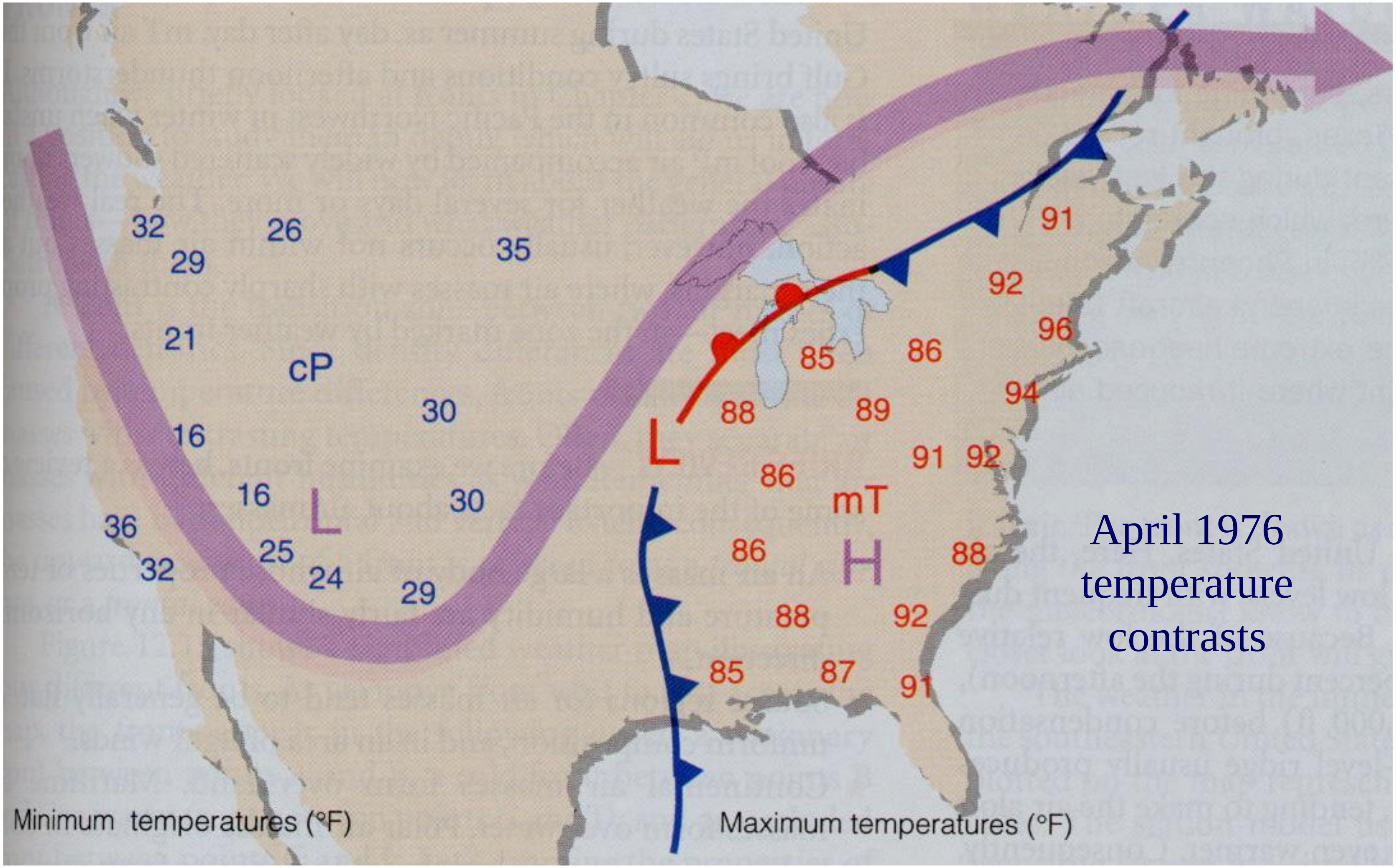


The *Pineapple Express* brings heavy rain

“The Pineapple Express” is a term used in the meteorological world for a strong and persistent flow of atmospheric moisture and associated heavy rainfall from the waters adjacent to the Hawaiian Islands and extending to any location along the Pacific coast of North America.



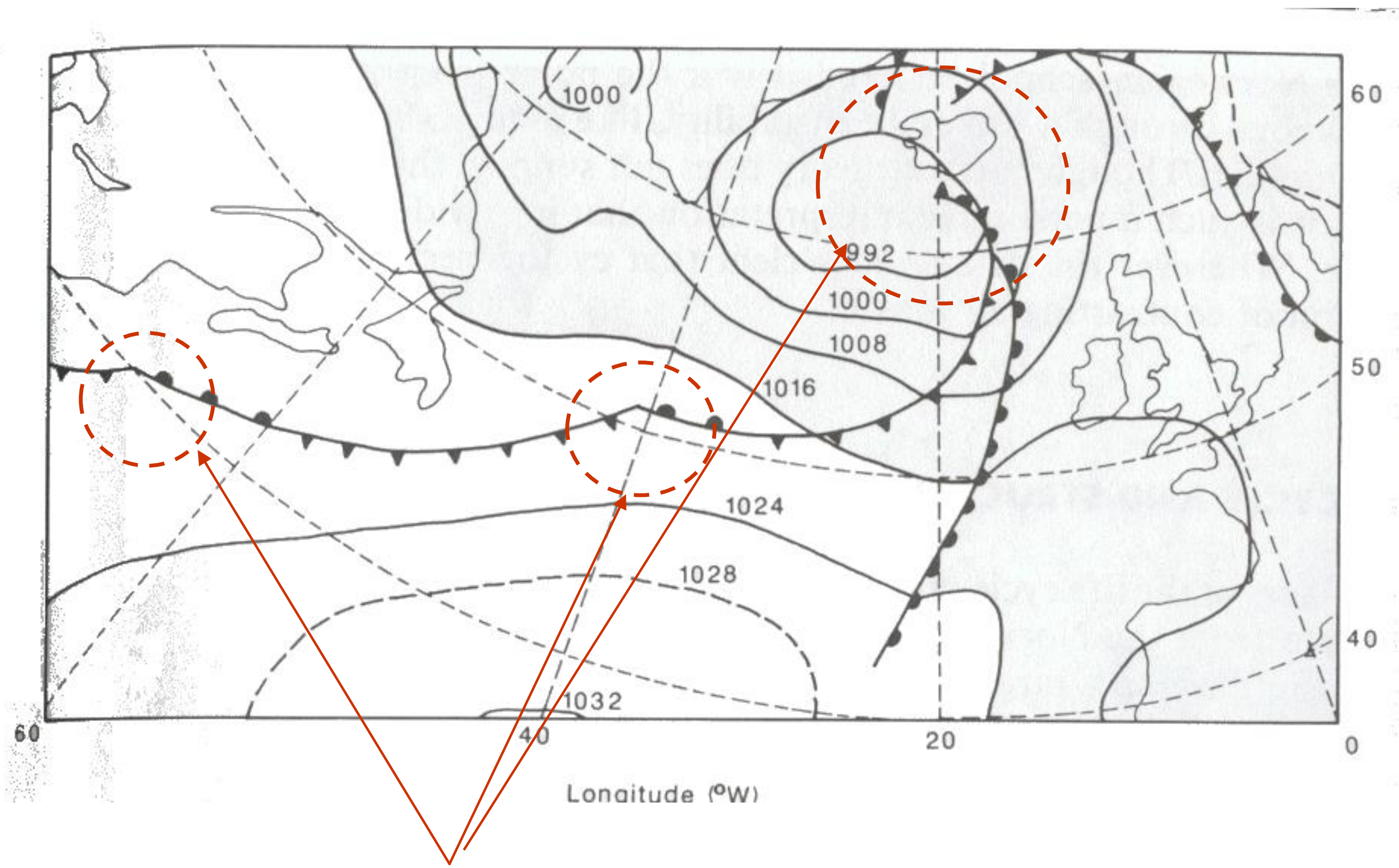
Air mass characteristics can differ tremendously



Fronts and Air masses (cont.)

- A **front** is a transition zone between air masses of different densities.
- Frontal types:
  - Cold front
    - » Zone where colder air is replacing warmer air
  - Warm front
    - » Zone where warmer air is replacing a retreating colder air mass.
  - Stationary front
    - » Zone that has little or no movement.
  - Occlusions
    - » 2 types: Warm and Cold
    - » Occur during mature phase of storm development

La ciclogenesi



• Situazione tipica: famiglie di cicloni extratropicali e fronti in vari stadi di sviluppo estesi per migliaia di Km sull'oceano, di forma ondulata, in moto da O verso E

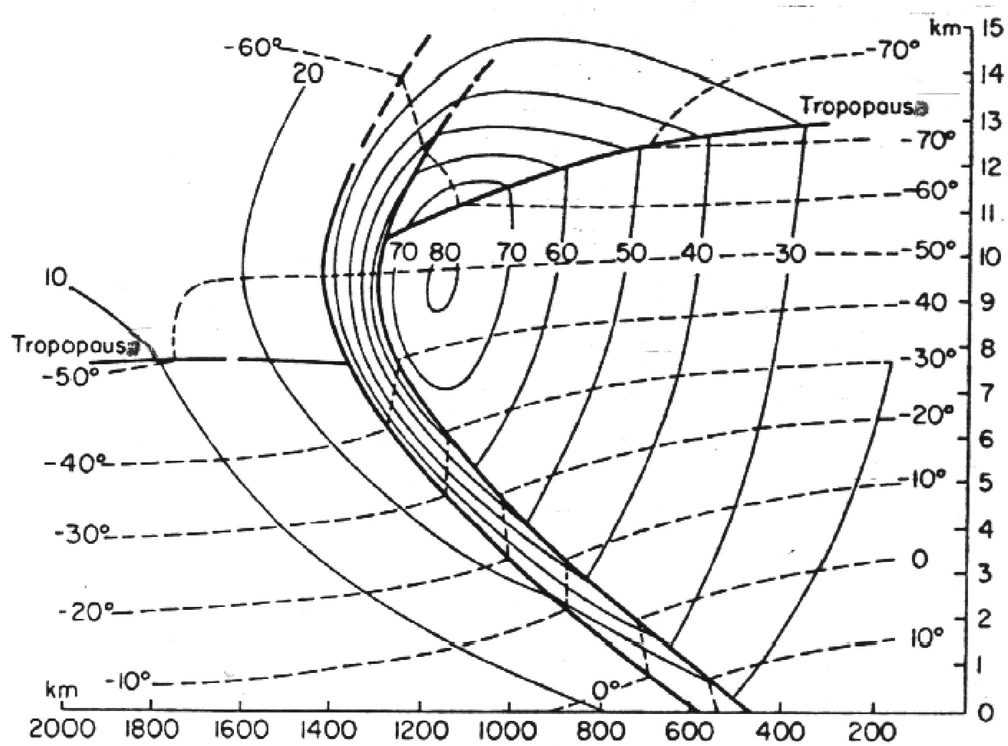
• Ogni ciclone ha un suo ciclo di vita e si trova in un determinato stadio di essa

Fronte

- Il fronte che collega queste depressioni è il fronte polare → zona di rapida transizione termica che separa le masse d'aria (calde) delle basse latitudini da quelle (fredde) delle alte latitudini

- Fronte: sottile zona di transizione tra due masse d'aria, (non è però una superficie netta come quella degli oceani) estesa orizzontalmente per 100-200 Km e verticalmente per 1-3 Km.

- La zona di transizione presenta discontinuità nelle grandezze meteo, è molto sottile rispetto alla sua estensione (100m-1Km) ed è disposta obliquamente



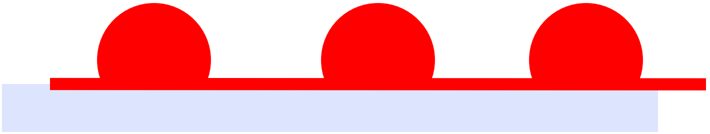
- Nelle mappe i fronti sono sempre disegnati come appaiono in superficie (= al suolo)

- Non è detto che la differenza tra le masse d'aria sia solo termica: possono anche esistere fronti dovuti a differenze di umidità (→ densità)

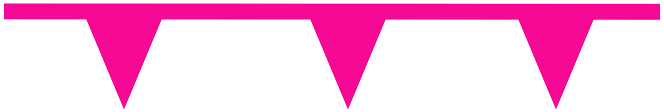
Fronts

A Front - **is the boundary between air masses; normally refers to where this interface intersects the ground (in all cases except stationary fronts, the symbols are placed pointing to the direction of movement of the interface (front)**

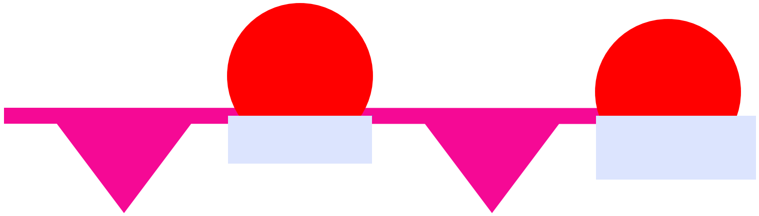
Warm Front



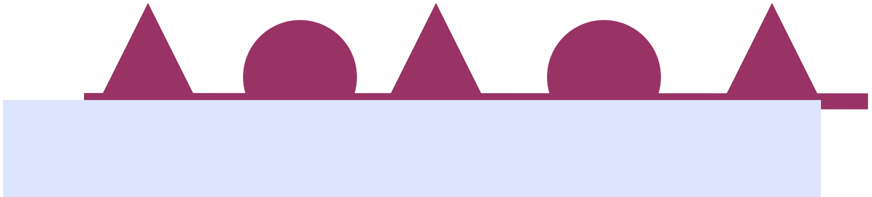
Cold Front



Stationary Front



Occluded Front



Fronts and Frontogenesis

- What is a front
- Temperature, density, and pressure structure?
- Wind variability across the front?
- Frontal slope?
- How do they get stronger (frontogenesis) or weaker (frontolysis)?

What is a front?

- Defined: sloping zones of pronounced transition in the thermal and wind fields
- They are characterized by relatively large:
  - Horizontal temperature gradients
  - Static stability
  - Absolute vorticity
  - Vertical wind shear
- The along frontal scale is typically an order of magnitude larger than the across frontal scale:

- Fronts tend to be shallow phenomena – depths of 1-2 km
- They are observed at the surface and low levels and aloft near the tropopause as well
- Why are they important:
  - Association with cloud and precip patterns
  - Rapid local changes in weather
  - Occur frequently with mid-latitude weather systems

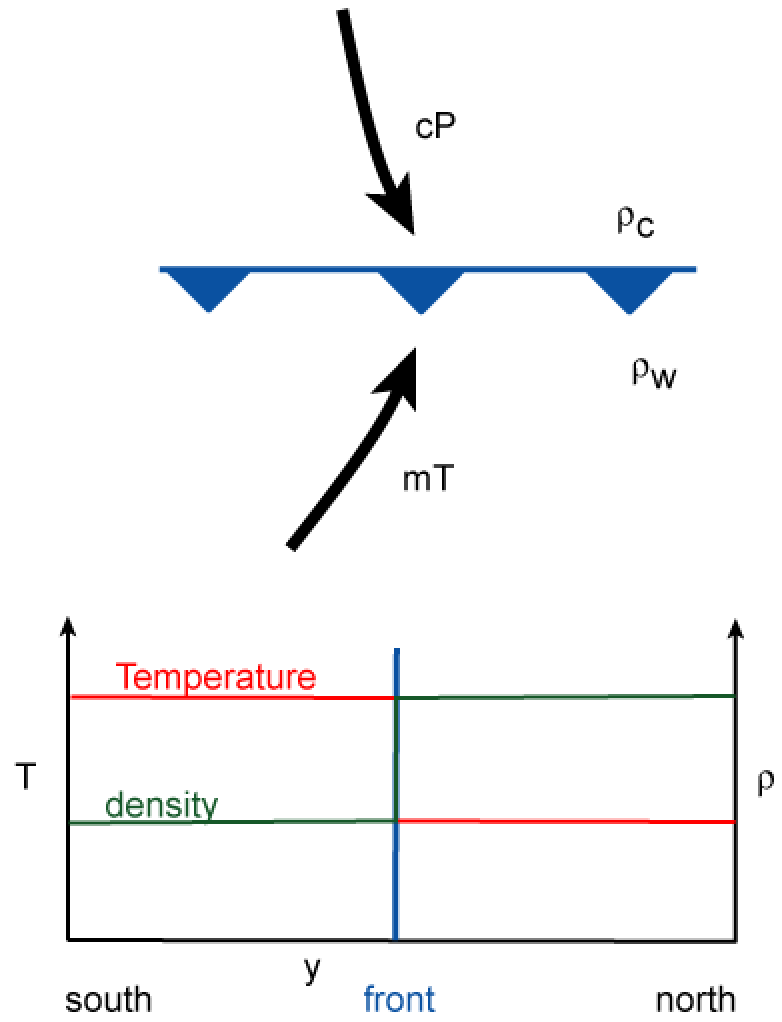
Frontal Structure

•Let’s define a front as a boundary between two different air masses characterized by different densities

•Then ρ is discontinuous across the front.

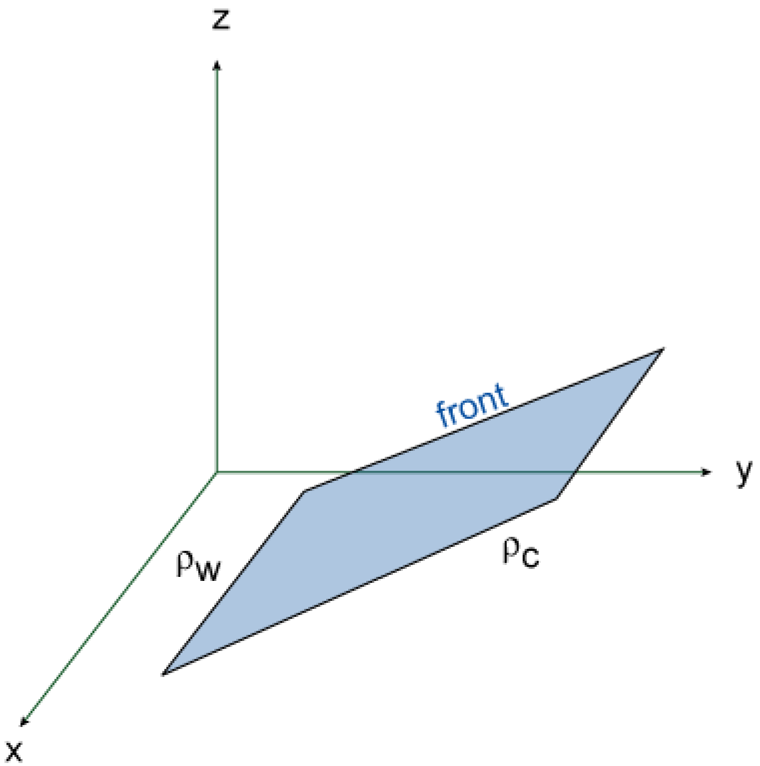
•We know that pressure has to be continuous across the front, otherwise $\Delta P/d$ would be infinite (very strong wind)

•Therefore, from the equation of state: $P=\rho RT$, if density is discontinuous and pressure is continuous across the front, then T must be discontinuous



Frontal Slope

- Let's now ignore any along-frontal variation (in the x direction) and derive an equation for the frontal slope (dz/dy)



Then, the change in pressure can be written as:

$$dP = \frac{\partial P}{\partial y} dy + \frac{\partial P}{\partial z} dz \qquad (1)$$

Dividing by dy gives:

$$\frac{dP}{dy} = \frac{\partial P}{\partial y} + \frac{\partial P}{\partial z} \frac{dz}{dy} \qquad (2)$$

From the hydrostatic equation, we know:

$$\frac{\partial p}{\partial z} = -\rho g$$

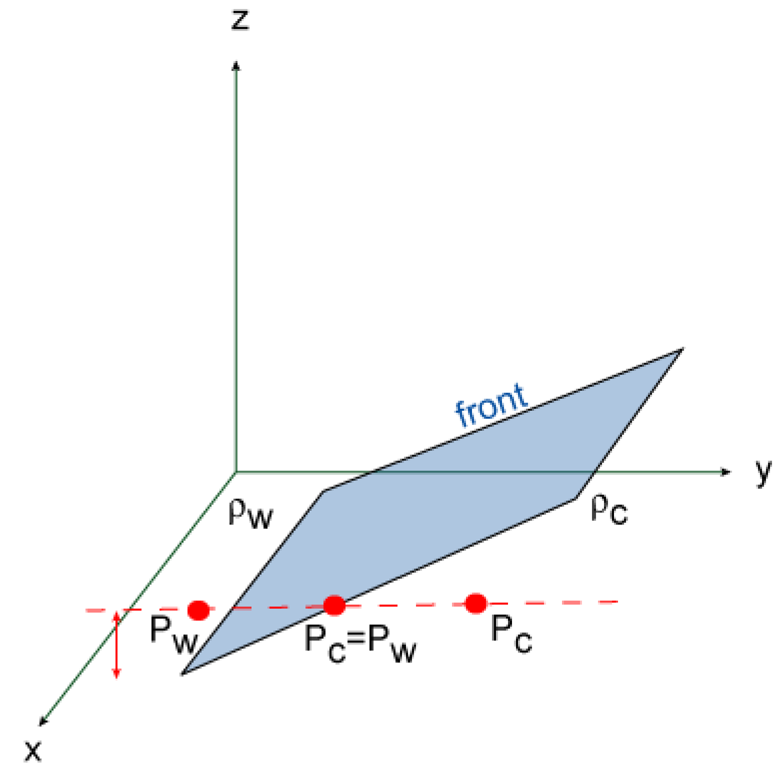
So, substituting the hydrostatic equation into the equation for dP/dy gives:

$$\frac{dP}{dy} = \frac{\partial P}{\partial y} - \rho g \frac{dz}{dy} \qquad (3)$$

Frontal Slope

On the front, since Pressure is continuous, then $P_c = P_w$

Therefore: $$\left(\frac{dp}{dy}\right)_w = \left(\frac{dp}{dy}\right)_c \qquad (4)$$



Substituting (4) into (3) gives:

$$\left(\frac{dP}{dy}\right)_w = \left(\frac{\partial P}{\partial y}\right)_w - \rho_w g\,\frac{dz}{dy} \qquad (5)$$

$$\left(\frac{dP}{dy}\right)_c = \left(\frac{\partial P}{\partial y}\right)_c - \rho_c g\,\frac{dz}{dy} \qquad (6)$$

But, we know from (4) that (5)=(6)

therefore, we can now solve for dz/dy:

$$\left(\frac{\partial P}{\partial y}\right)_w - \rho_w g\,\frac{dz}{dy} = \left(\frac{\partial P}{\partial y}\right)_c - \rho_c g\,\frac{dz}{dy} \qquad (7)$$

$$\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c = \rho_w g\,\frac{dz}{dy} - \rho_c g\,\frac{dz}{dy} \qquad (8)$$

$$\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c = \left(\rho_w g - \rho_c g\right)\frac{dz}{dy} \qquad (9)$$

$$\frac{dz}{dy} = \frac{\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c}{g\left(\rho_w - \rho_c\right)} \qquad (10)$$

Frontal Slope

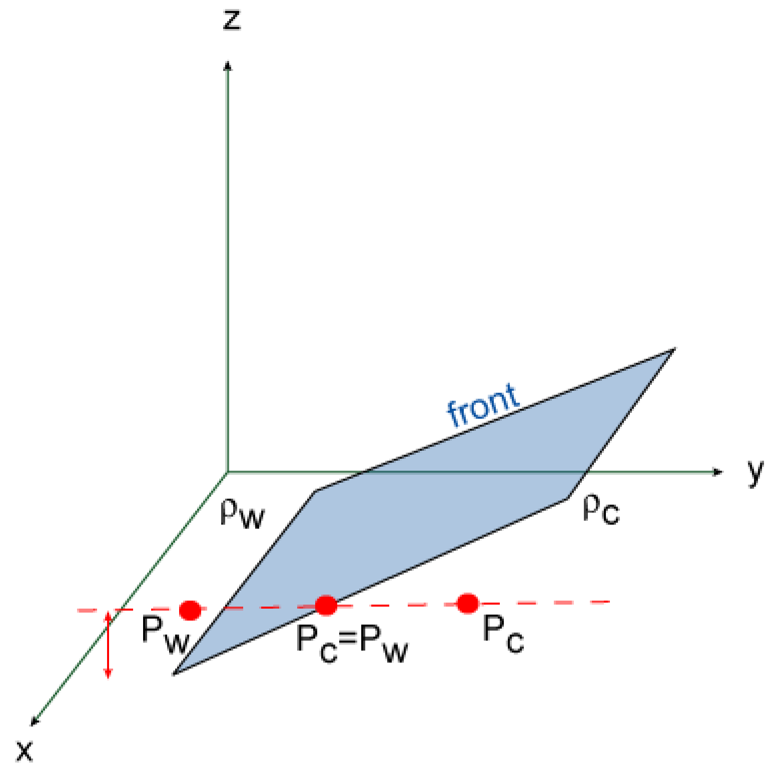
Now, since dz/dy is not equal to zero, and is usually > 0 (front slopes upward and to the north), then from (10):

$$\frac{dz}{dy} = \frac{\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c}{g\left(\rho_w - \rho_c\right)} \qquad (11)$$

$$\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c < 0 \qquad (12)$$

or

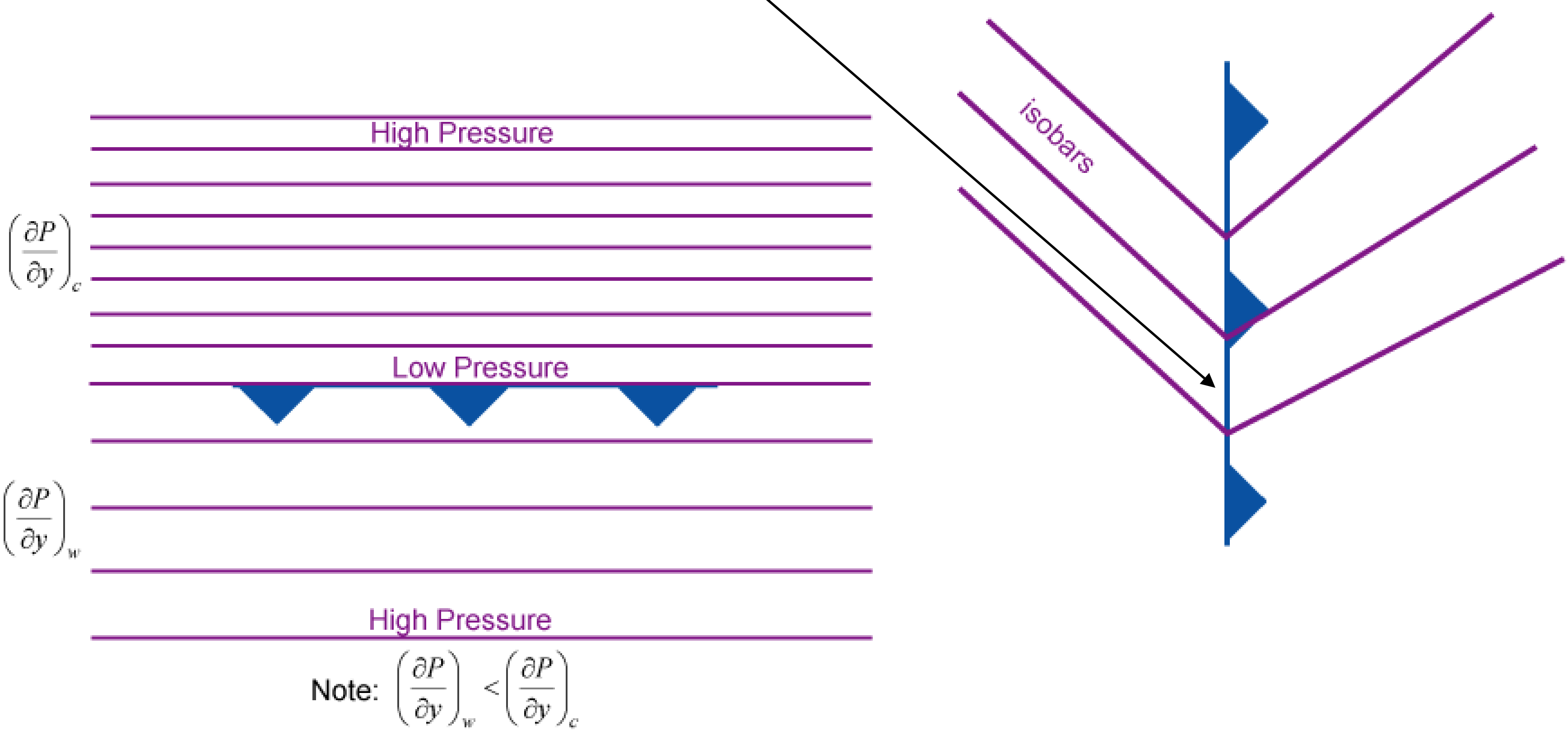
$$\left(\frac{\partial P}{\partial y}\right)_w < \left(\frac{\partial P}{\partial y}\right)_c \qquad (13)$$



Frontal Slope

So, while pressure *is* continuous across the front, the pressure gradient *is not* continuous across the front.

Therefore, the isobars ***must*** **kink** at the front so that the above statement is consistent with the analysis:



Horizontal winds across the front

How do the horizontal winds vary across the front?

Assuming that the flow is geostrophic and there is no variation in the y direction, the geostrophic wind can be written as:

$$u_g = -\frac{1}{\rho f}\frac{\partial p}{\partial y} \qquad (14)$$

On the warm and cold sides of the front:

$$u_{gw} = -\frac{1}{\rho_w f}\left(\frac{\partial p}{\partial y}\right)_w \qquad (15)$$

$$u_{gc} = -\frac{1}{\rho_c f}\left(\frac{\partial p}{\partial y}\right)_c \qquad (16)$$

$$\frac{dz}{dy} = \frac{\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c}{g\left(\rho_w - \rho_c\right)} \qquad (17)$$

Substituting (15) and (16) into (17) gives:

Horizontal winds across the front

$$\frac{dz}{dy} = \frac{-\rho_c f U_{gc} + \rho_w f U_{gw}}{g\left(\rho_c - \rho_w\right)} \qquad (18)$$

or

$$\boxed{\frac{dz}{dy} \approx \frac{\bar{\rho} f \left(U_{gw} - U_{gc}\right)}{g\left(\rho_c - \rho_w\right)}} \qquad (19)$$

where

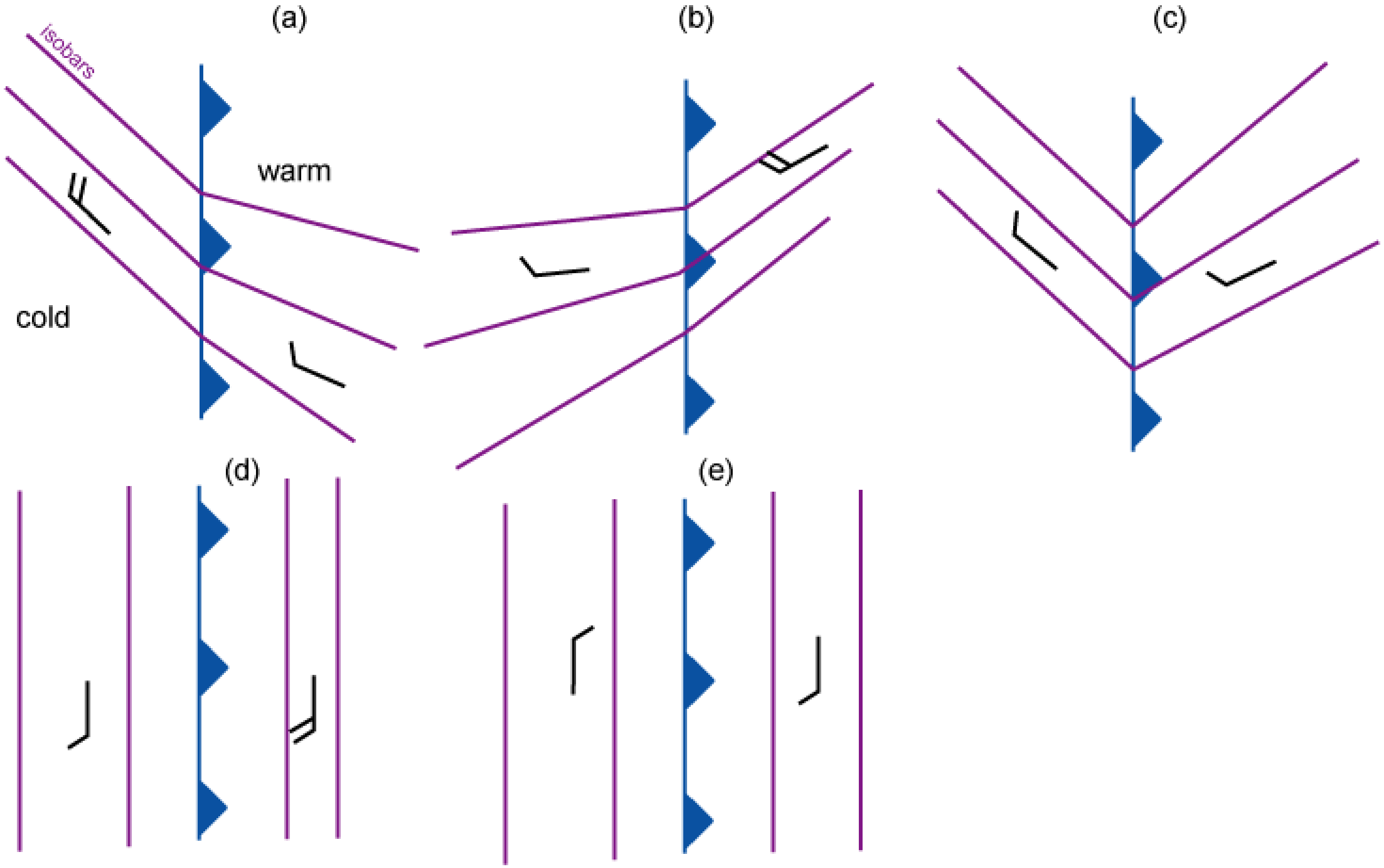
$$\bar{\rho} = \frac{\left(\rho_c + \rho_w\right)}{2}$$

Again, if dz/dy > 0, then $U_{gw} - U_{gc} > 0$ or $U_{gw} > U_{gc}$

Therefore, ***cyclonic shear vorticity must exist across the front***

Here are some possibilities:

Horizontal winds across the front



Margules Equation for frontal slope

Recall the equation for frontal slope:

$$\frac{dz}{dy} \approx \frac{\overline{\rho} f \left(U_{gw} - U_{gc}\right)}{g\left(\rho_c - \rho_w\right)} \qquad (20)$$

Using the equation of state, it can be shown that this equation can be written as:

$$\frac{dz}{dy} \approx \frac{\overline{T} f \left(U_{gw} - U_{gc}\right)}{g\left(T_w - T_c\right)} \qquad (21)$$

(21) is Margules equation for frontal slope

Substituting in typical values:

$$\frac{dz}{dy} \approx \frac{10^{-4} s^{-1} \cdot 300k \cdot 10ms^{-1}}{10ms^{-2} \cdot 10K} \approx 1/300 \qquad (22)$$

This value is similar to what is observed

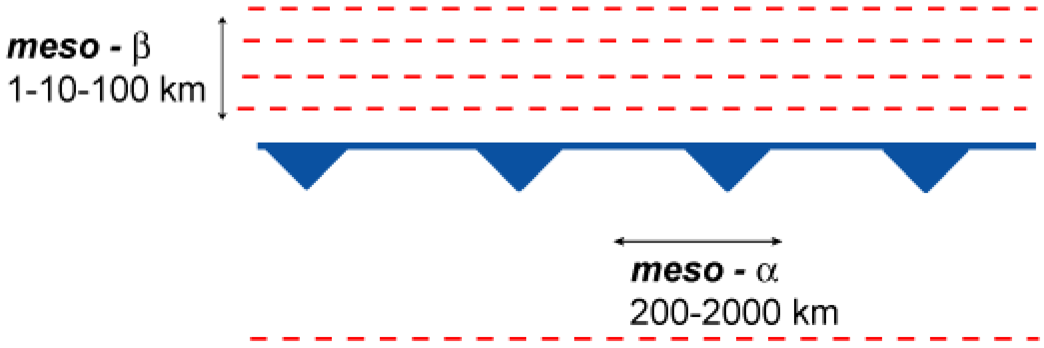
•Recall that our initial assumption was that density and temperature are discontinuous across the front

•This is obviously not very realistic

•In nature, frontal zones exist where:

- •T is continuous
- • $\left(\frac{\partial T}{\partial y}\right)$ is not

•The frontal zone can be 1-10-100 km wide and is generally one order of magnitude small than the along-frontal scale:



What do real fronts look like, anyway?

- Note: sloping frontal zone to about 400 mb
- Front is directly under the polar jet

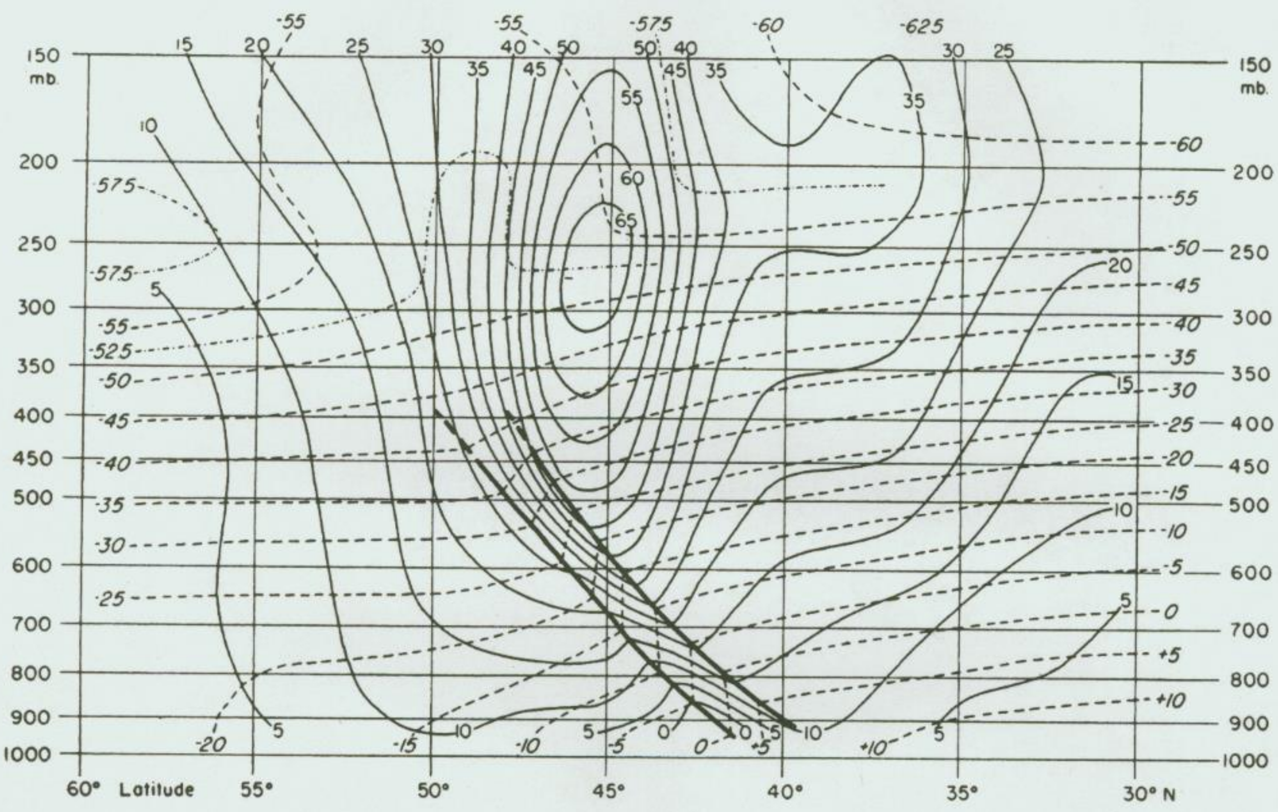


Figure 10.2. Cross section along 80°W of the temperature (°C, dashed) and the zonal component of the geostrophic wind (m s^{-1}, thin solid) averaged over 12 cases in December 1946. Heavy solid lines indicate the boundaries of the polar front. (From Palmén and Newton, 1948.)

Keyser (86)

•Note the sloping fronta
zone

•Strongest near the ground

•This front is shallow

•Cyclonic vorticity acro
front

•Large vertical wind sh
and static stability through the front

•From Keyser (86)

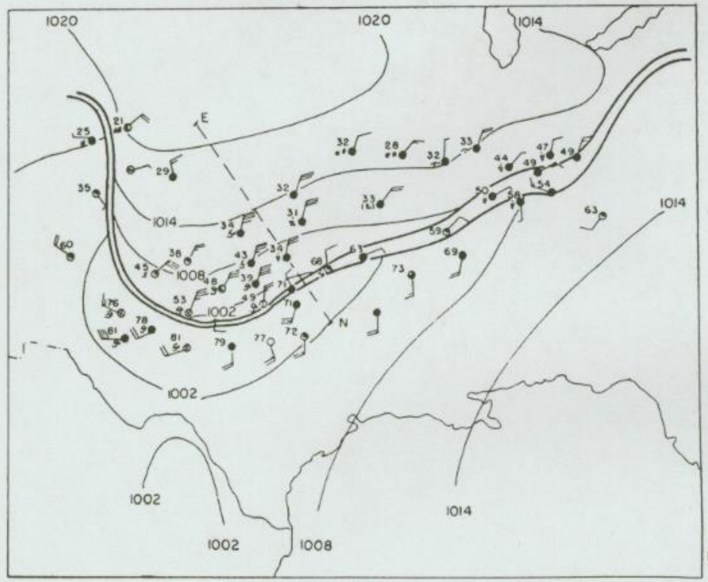


Figure 10.4. Surface analysis for 0330 GMT, 18 April 1953. Dashed line EN indicates position of vertical cross section in Fig. 10.5; heavy solid lines denote boundaries of frontal zone; light solid lines are isobars of sea-level pressure (contour interval, 6 mb). Plotted reports follow conventional station model. (From Sanders, 1955.)

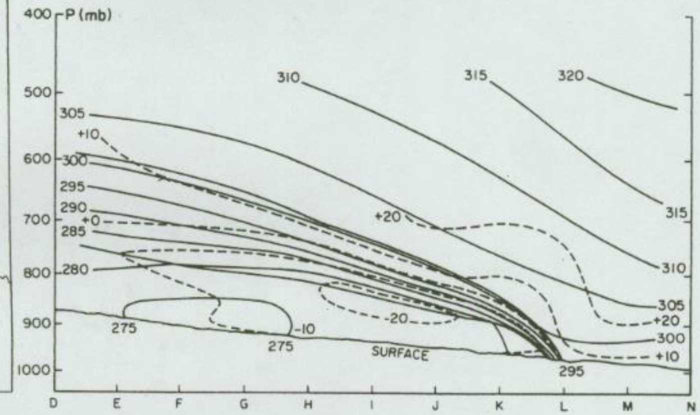


Figure 10.5. Distribution of potential temperature (light solid lines, contour interval 5 K) and wind component (dashed lines, contour interval 10 m s^{-1}) normal to cross section EN in Fig. 10.4 for 0300 GMT, 18 April 1953. Heavy solid lines indicate boundaries of frontal zone. Distance between adjacent letters on horizontal axis is 100 km. (From Sanders, 1955.)

•Notice how the front below strengthens from 12 to 00 UTC.

•Why?

From Keyser (86)

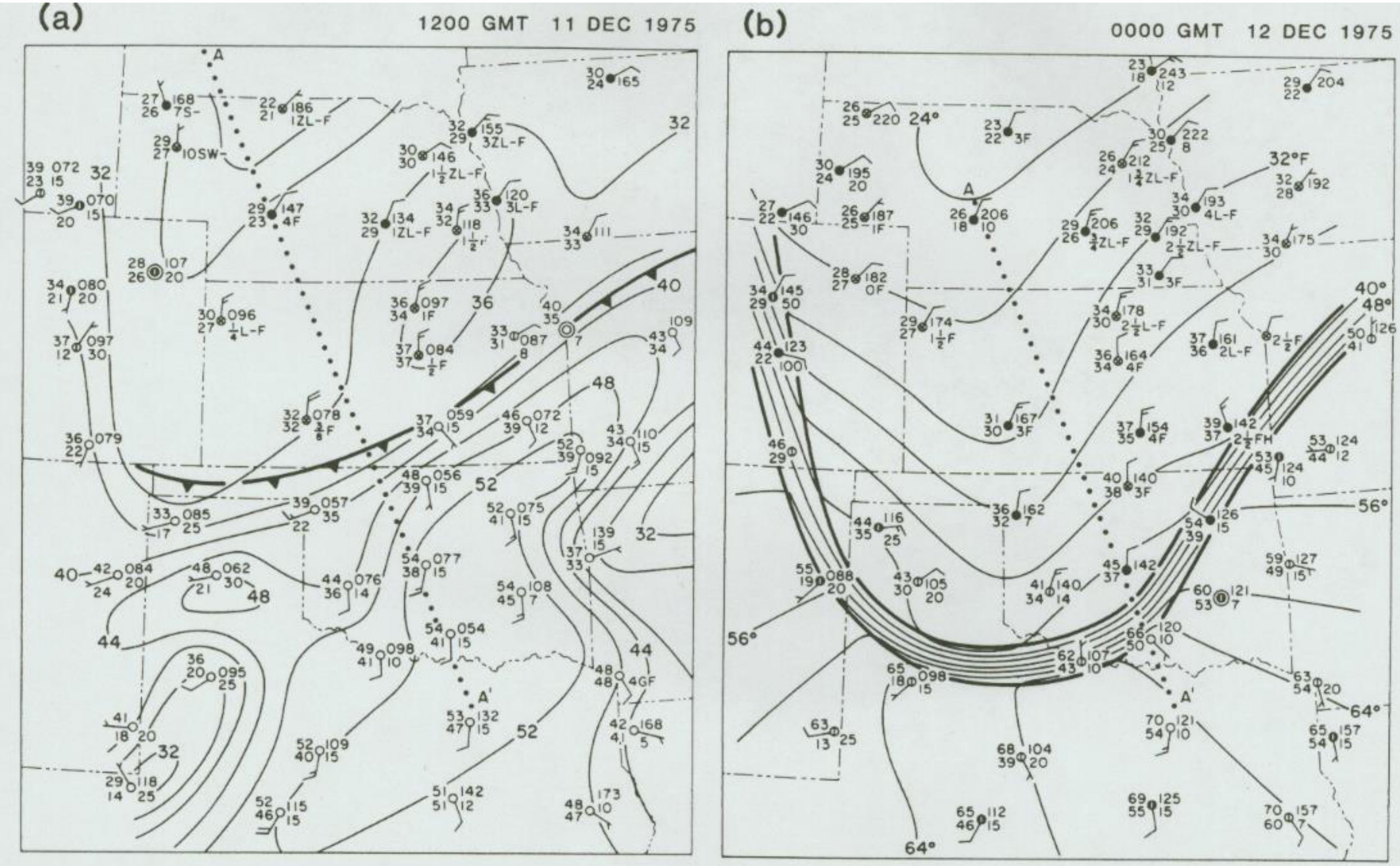


Figure 10.11. Surface analyses of temperature (°F) and frontal position for (a) 1200 GMT, 11 December 1975 and (b) 0000 GMT, 12 December 1975. Plotted reports follow conventional station model. Dotted lines AA′ indicate positions of cross sections in Fig. 10.12 at their respective times. (From Shapiro, 1983.)

•Vertical cross sections at 12 and 00 UTC:

From Keyser (86)

• 12Z:

- •Notice how diffuse the front is, also shallow
- •Weak front at this time due to radiational cooling differences on either side of the front – weakens the front

•00 Z

- •Strong, sharp surface front at this time
- •Due to sensible heat flux difference on either side of the front
- •Note that the boundary layer is well mixed on both sides of the front

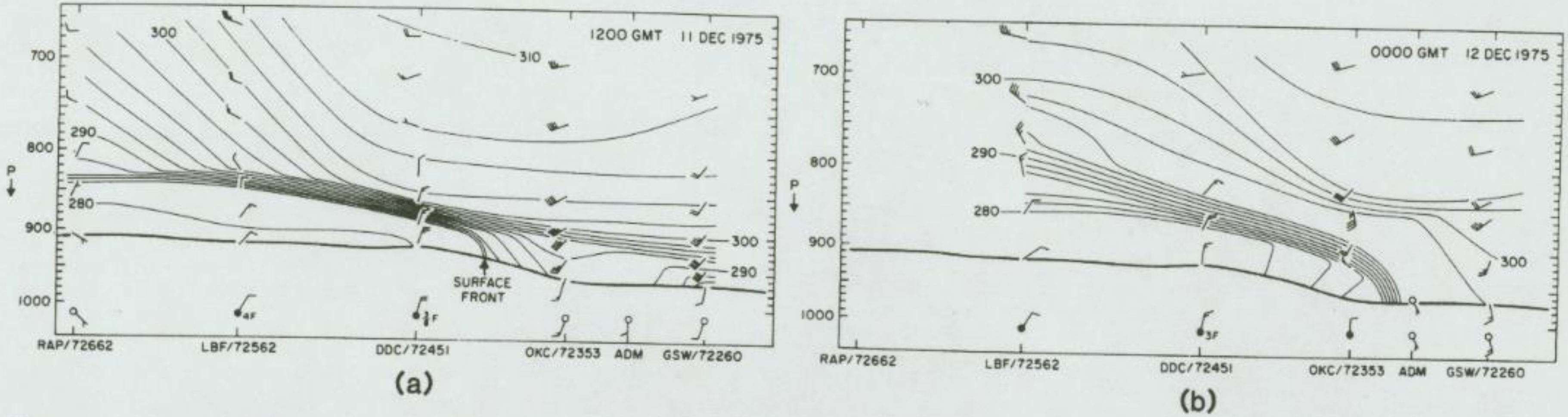


Figure 10.12. Cross sections of potential temperature (K) along paths indicated in Fig. 10.11 for (a) 1200 GMT, 11 December 1975 and (b) 0000 GMT, 12 December 1975. Upper-air wind directions and speeds (kt) are indicated using standard plotting convention; surface observations are entered at the lower portion of the figures. (From Shapiro, 1983.)

How sharp can a cold front get?

Bluestein (92)

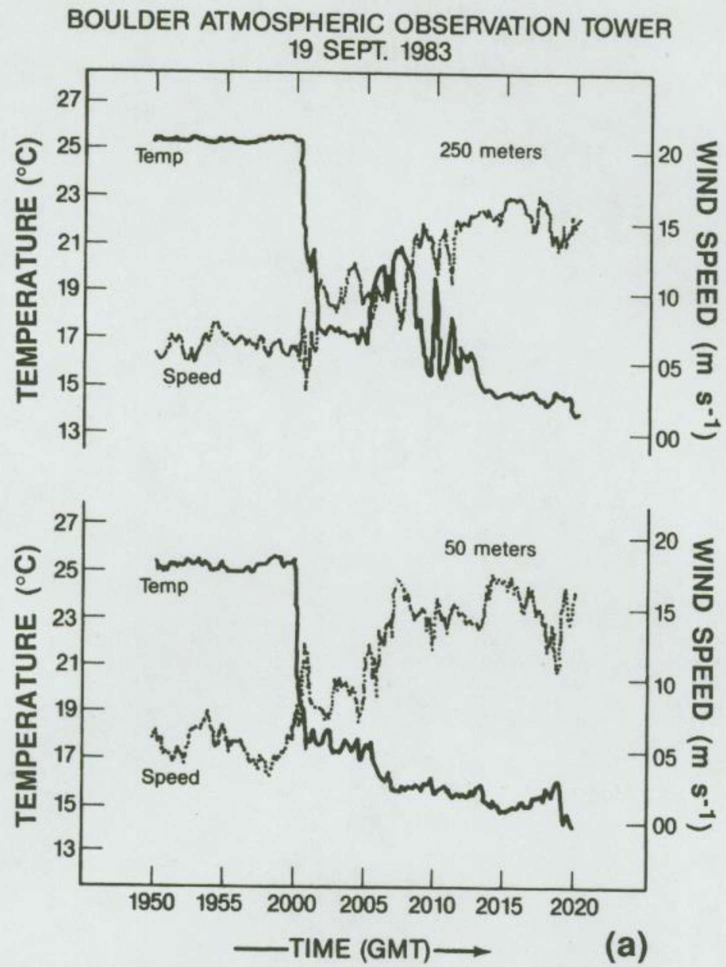


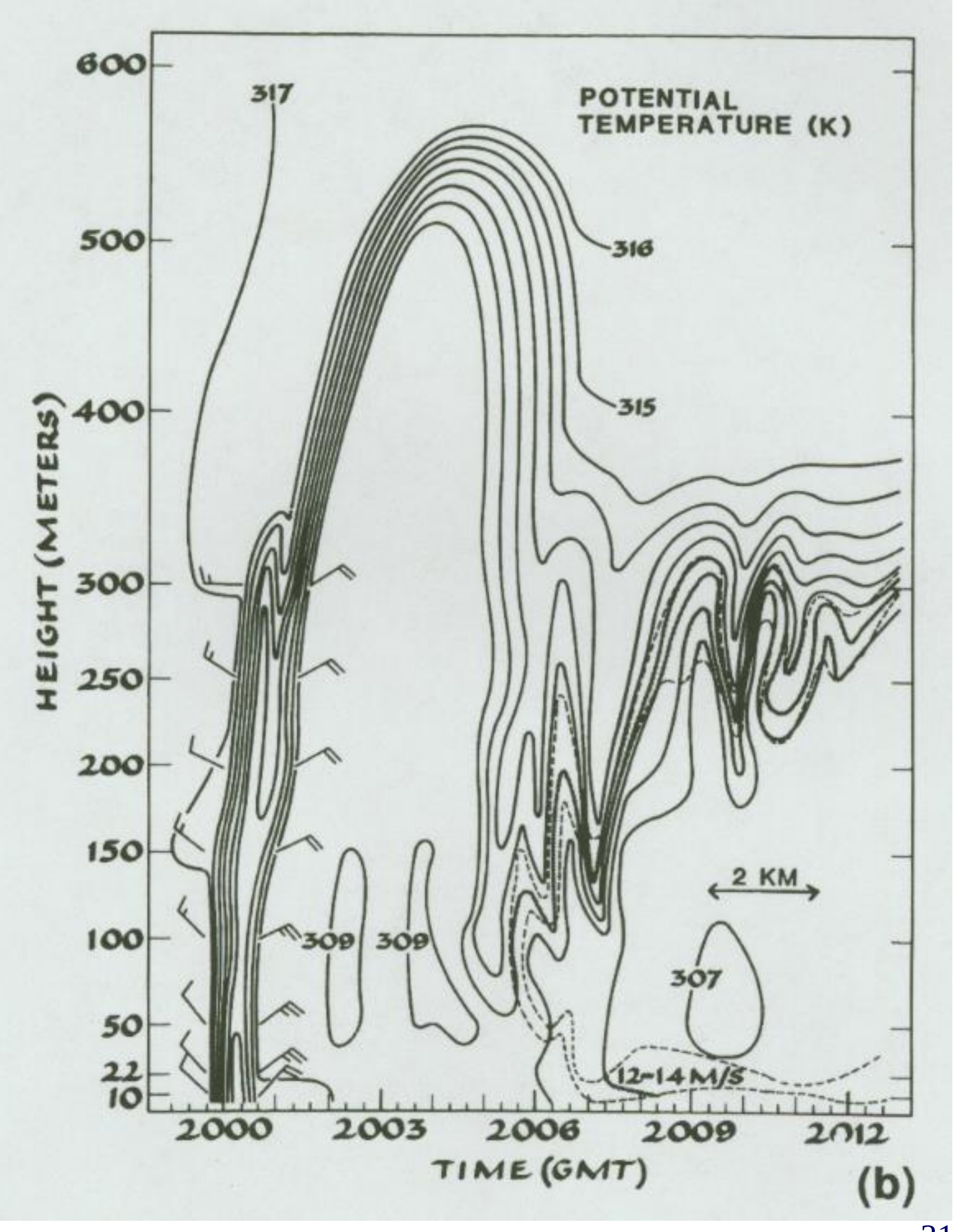
Figure 2.6 Example of the passage of a surface front just east of the Rocky Mountains. (a) Temperature in °C (solid lines) and wind speed in m s^{-1} (dotted lines) for 1950–2020 UTC (GMT), September 19, 1983, measured at the 250-m level (top) and 50-m level (bottom) of the Boulder Atmospheric Observation (BAO) tower in Boulder, Colorado. (b) Analysis of potential temperature in K (solid lines) as a function of height above the ground and time as in (a) up to 600 m AGL. Tower wind vectors preceding and following frontal passage are plotted at the indicated times. The cross-frontal scale is only a few kilometers or less. Such a scale is much less than the spacing between adjacent conventional surface observing stations (from Shapiro et al., 1985). (Courtesy of the American Meteorological Society)

How sharp can a cold front get?

Vertical cross section:

- Note the extremely narrow frontal zone – on order of 1 km!
- The front has “collapsed” to a very small across-frontal scale
- How and why? – don’t know…..

From Bluestein (92)



Frontogenesis

- Defined: the formation or intensification of a front
- It may be described quantitatively through the frontogenesis function:

$$F = {}^{d}\!/_{dt} \left| \nabla_p \theta \right|$$

With a bit of math, F can be written as (assuming no along frontal variation and the front is oriented W-E):

$$F = \left(\frac{\partial v}{\partial y}\right)_p \left(\frac{\partial \theta}{\partial y}\right)_p + \left(\frac{\partial \omega}{\partial y}\right)_p \left(\frac{\partial \theta}{\partial p}\right) - \left(\frac{P_o}{P}\right)^{\kappa} \frac{1}{c_p} \left(\frac{\partial}{\partial y}\right)_p \frac{dQ}{dt}$$

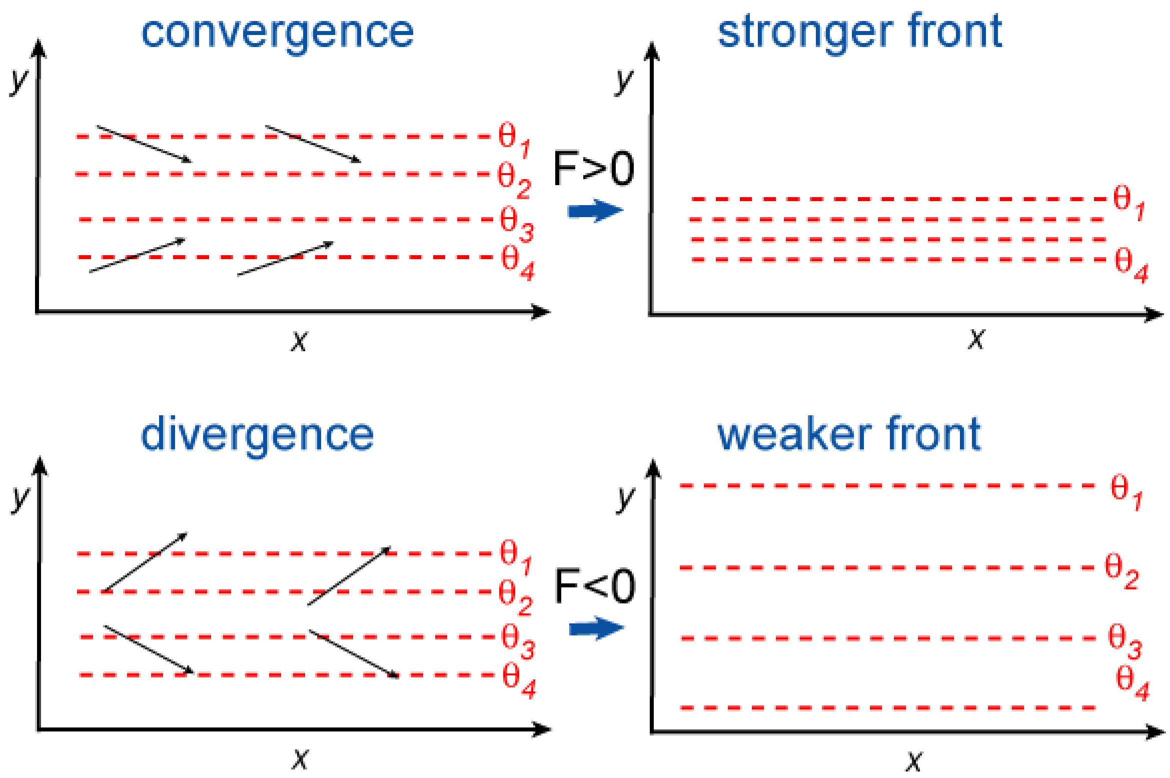
TERM I　　　TERM II　　　TERM III

What is the physical interpretation of these three terms?

Frontogenesis

•Term I = $\left(\frac{\partial v}{\partial y}\right)_p \left(\frac{\partial \theta}{\partial y}\right)_p$

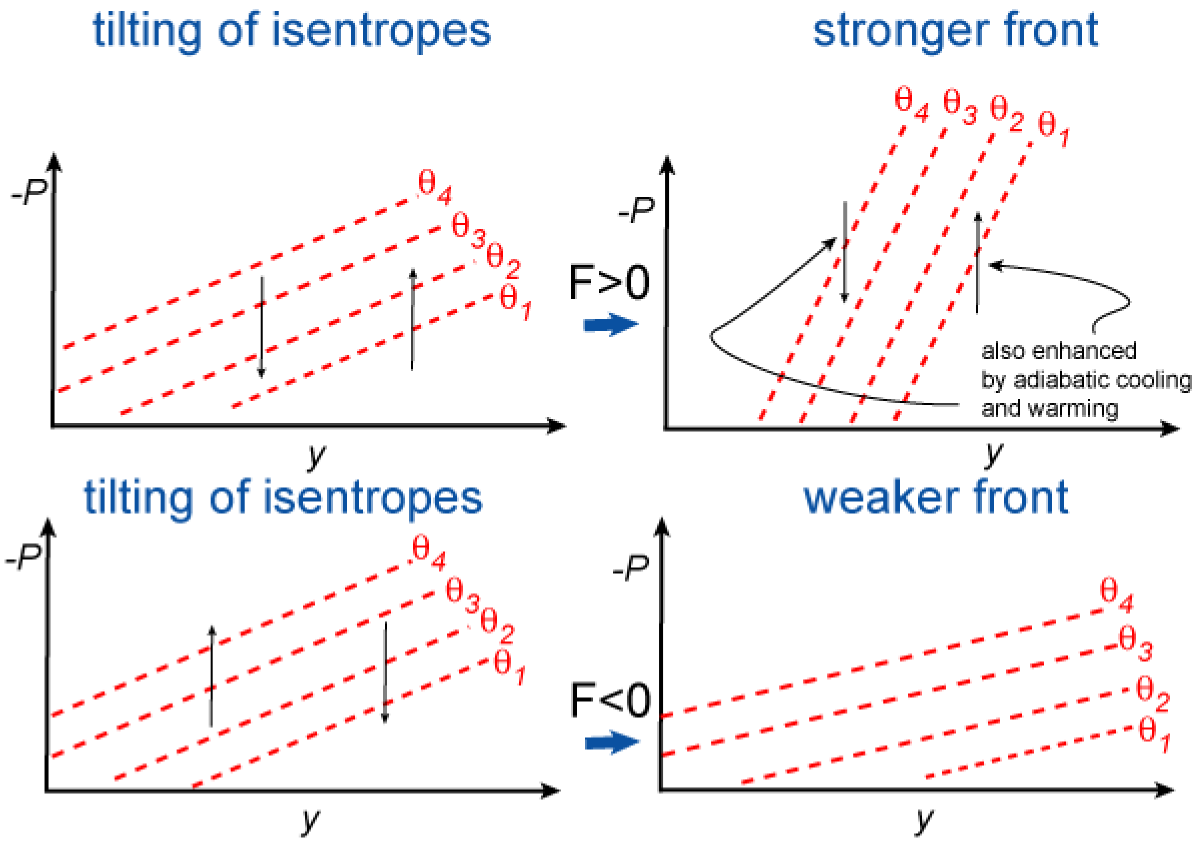
Represents the kinematic effect of convergence on the quasi-horizontal temperature gradient:



Frontogenesis

•Term II = $\left(\frac{\partial \omega}{\partial y}\right)_p \left(\frac{\partial \theta}{\partial p}\right)$

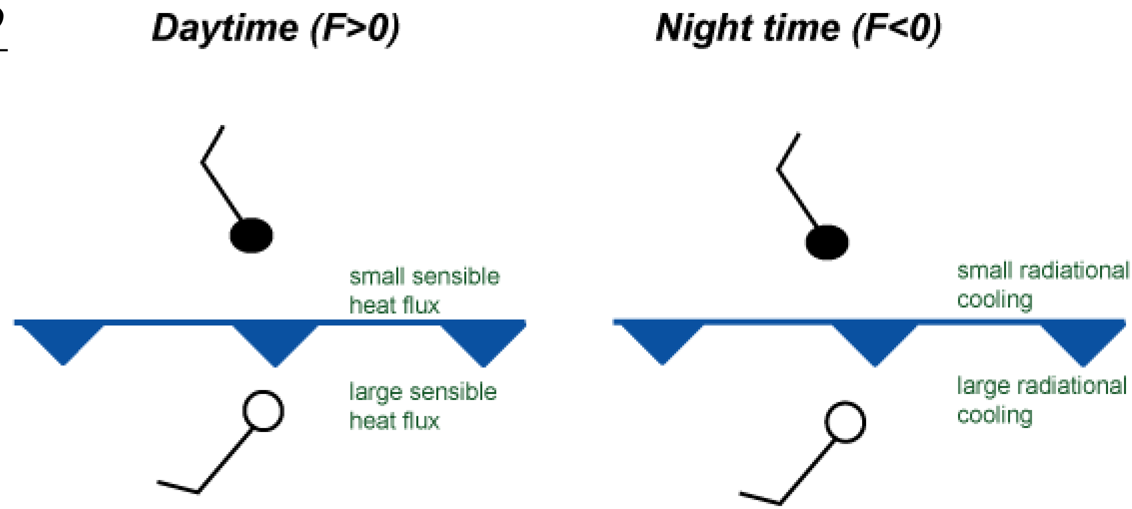
Represents the tilting of isentropes:



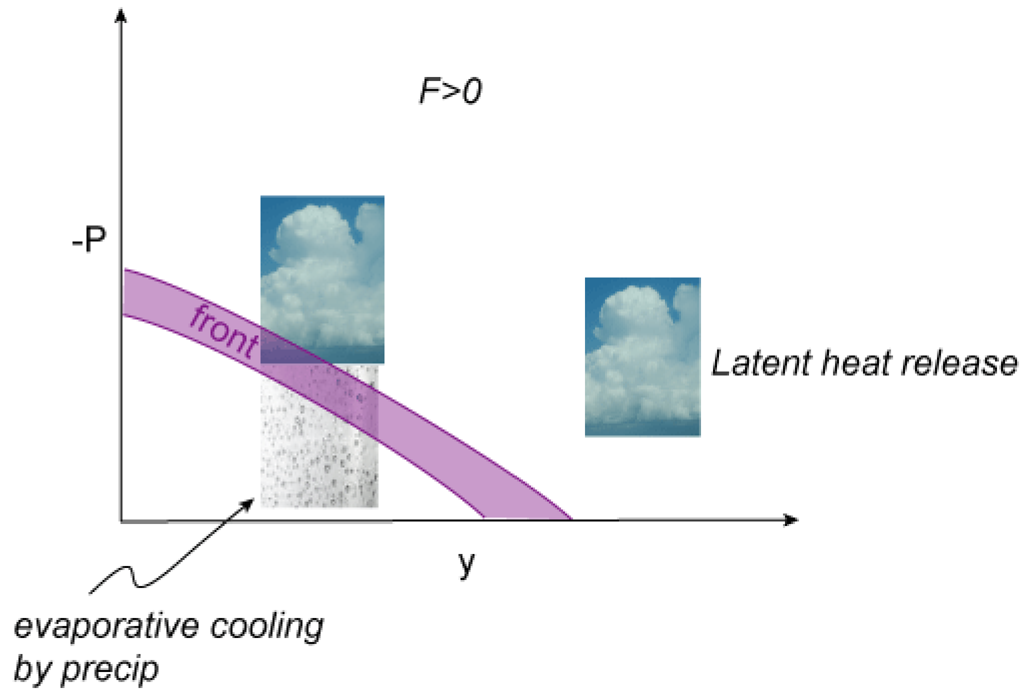
Frontogenesis

•Term III = $\left(\frac{P_o}{P}\right)^{\kappa} \frac{1}{c_p} \left(\frac{\partial}{\partial y}\right)_p \frac{dQ}{dt}$

Represents diabatic heating/cooling:



Or:



•All of our discussion thus far has assumed that there is no variation of wind along the front.

•What happens if we assume that there is along frontal variation by superimposing a stretching deformation field along the front:

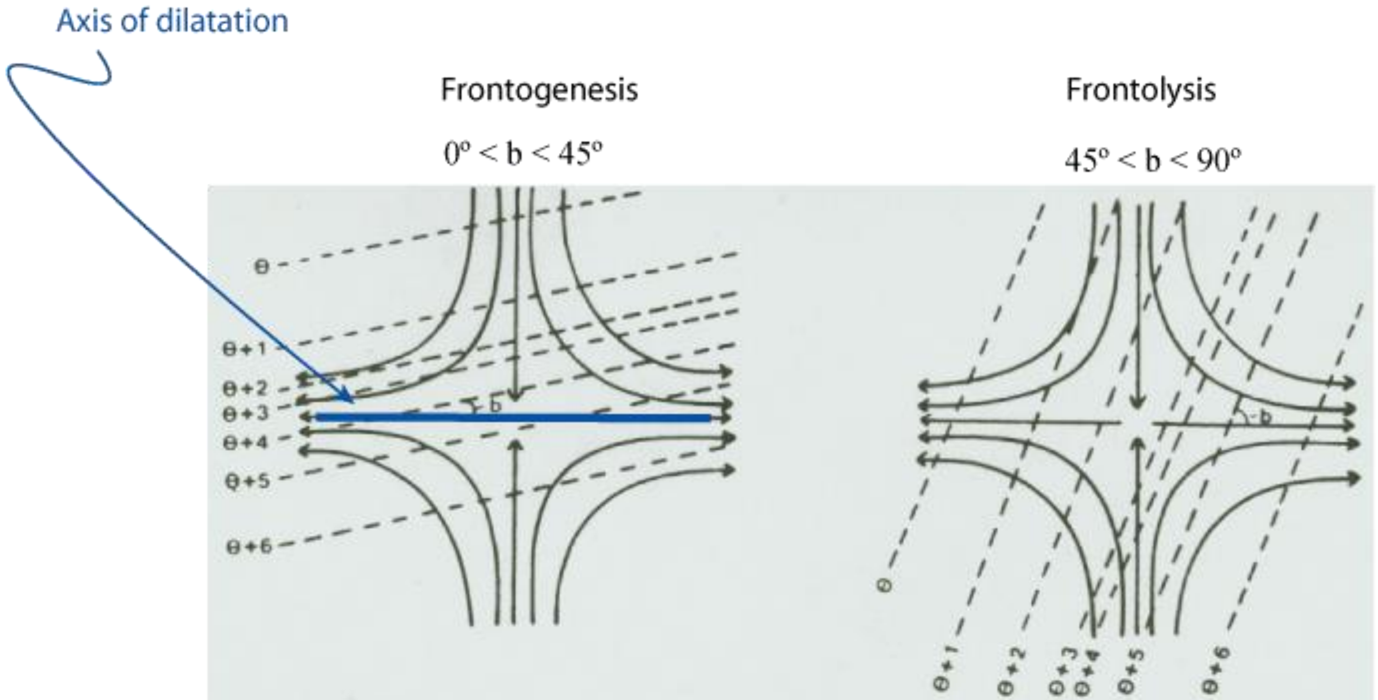


Figure 2.13 The relationship between the relative orientation of the axis of dilatation and the isotherms of potential temperature (dashed lines) as measured by angle b, and frontogenesis. (left) Frontogenesis ($0° < b < 45°$), $F > 0$. (right) Frontolysis ($45° < b < 90°$), $F < 0$ (from Bluestein, 1986; after Petterssen, 1956). (Courtesy of the American Meteorological Society)

From Bluestein (92)

Characteristics of Fronts

- Across the front - look for one or more of the following:
  - Change of Temperature
  - Change of Moisture characteristic
    - RH, T_d
  - Change of Wind Direction
  - Change in direction of Pressure Gradient
  - Characteristic Precipitation Patterns

How do we decide what kind of front it is?

- From the vantage point of the ground, if warm air replaces colder air, the front is a warm front

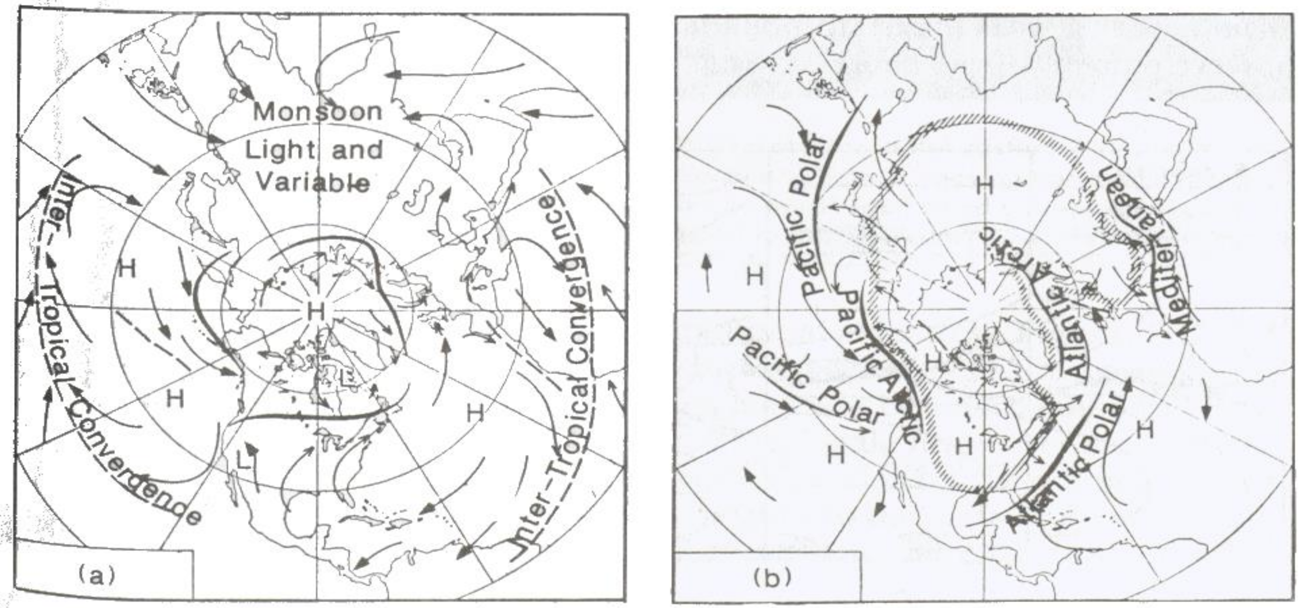
- If cold air replaces warmer air, the front is a cold front

- If the front does not move, it is a stationary front

- Occluded fronts do not intersect the ground; the interface between the air masses is aloft

Morfologia del fronte

- Tale linea di separazione può ondularsi rispetto ad una distribuzione puramente “zonale” (Ovest-Est)



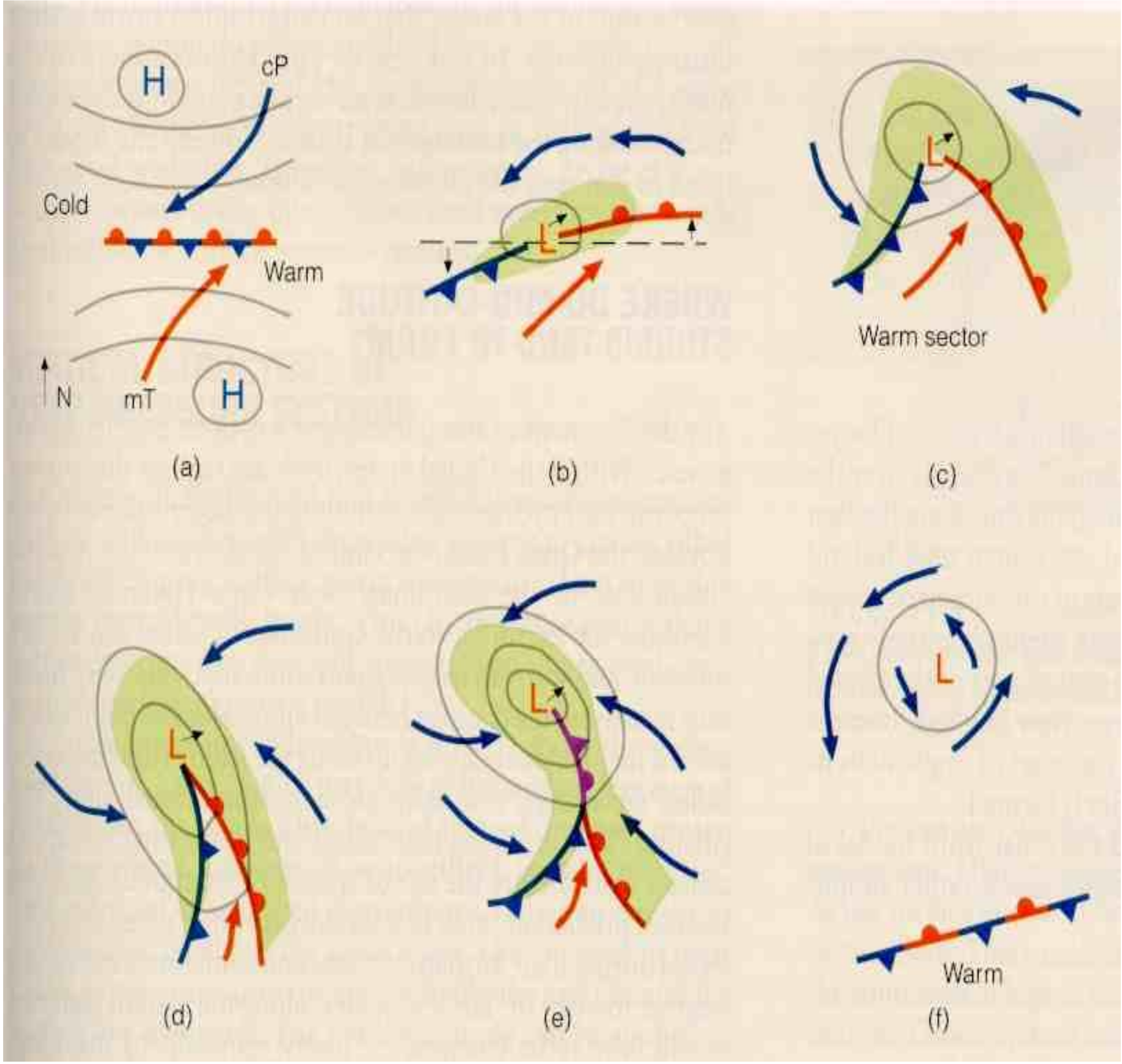
- L’ondulazione avviene per diversi fattori:

  la distribuzione irregolare di terre ed oceani, le diverse caratteristiche termiche delle superfici

- Tali fattori sono attivi prevalentemente nella bassa troposfera, ed è infatti qui che avvengono i principali fenomeni di ciclogenesi
- Sono anche presenti cicli stagionali (monsoni, spostamento ICTZ, ecc.)
- Secondo la teoria norvegese, la ciclogenesi è provocata dal movimento del fronte polare
- Oggi si sa che la causa è il contrasto tra masse d’aria diverse

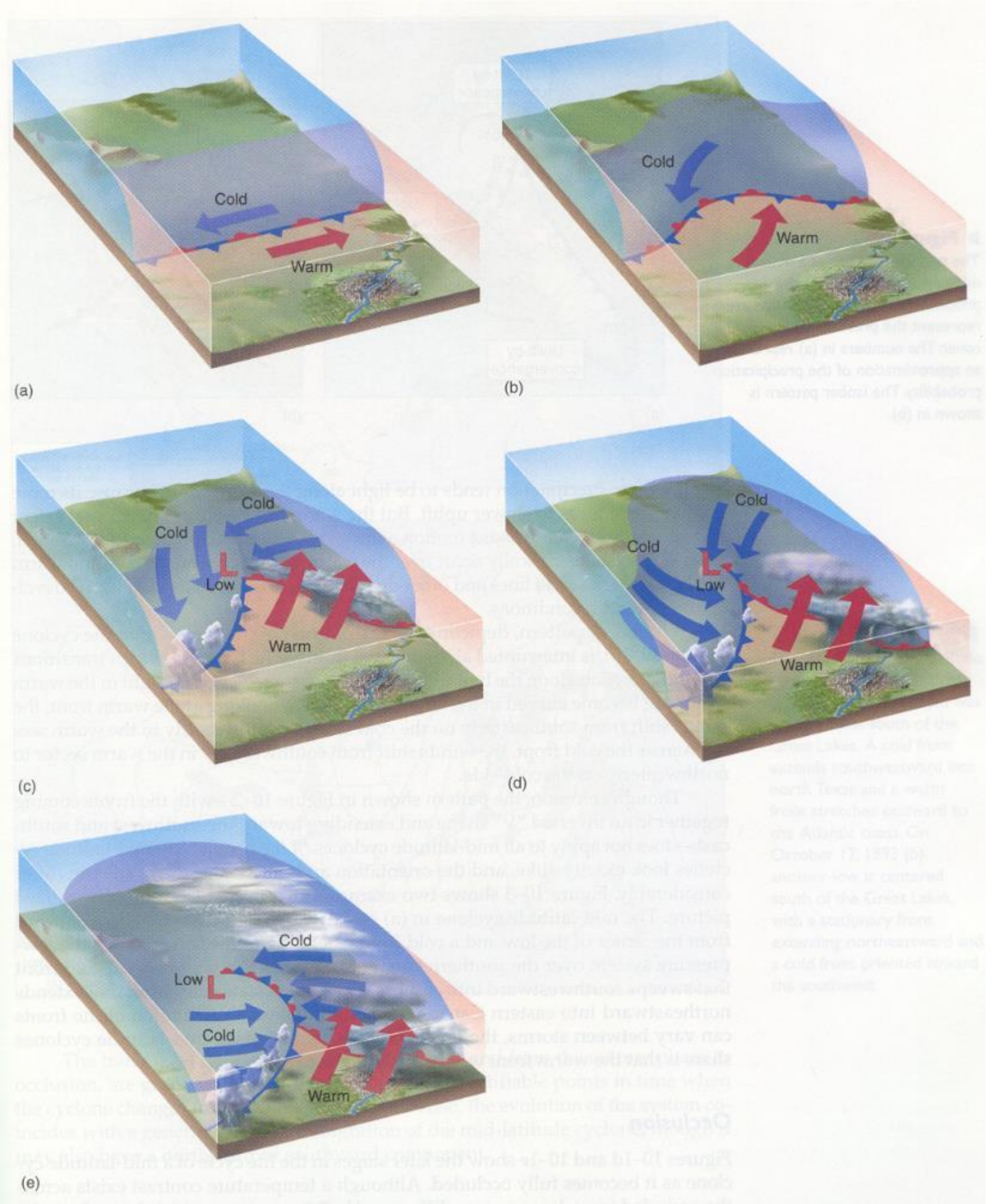
The Wave Cyclone Model
(Norwegian model)

- Stationary Front
- Nascent Stage
- Mature Stage
- Partially Occluded Stage
- Occluded Stage
- Dissipated Stage



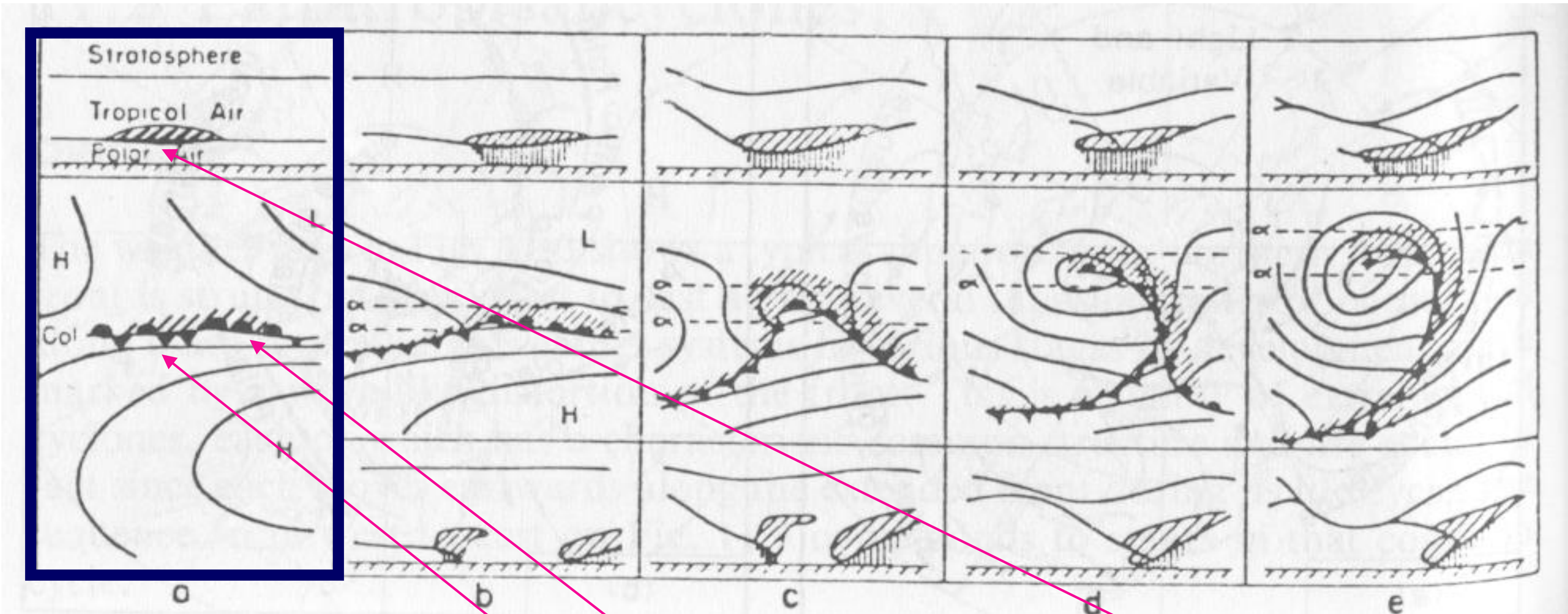
Stages of cyclone development

Lifecycle of a Midlatitude Cyclone



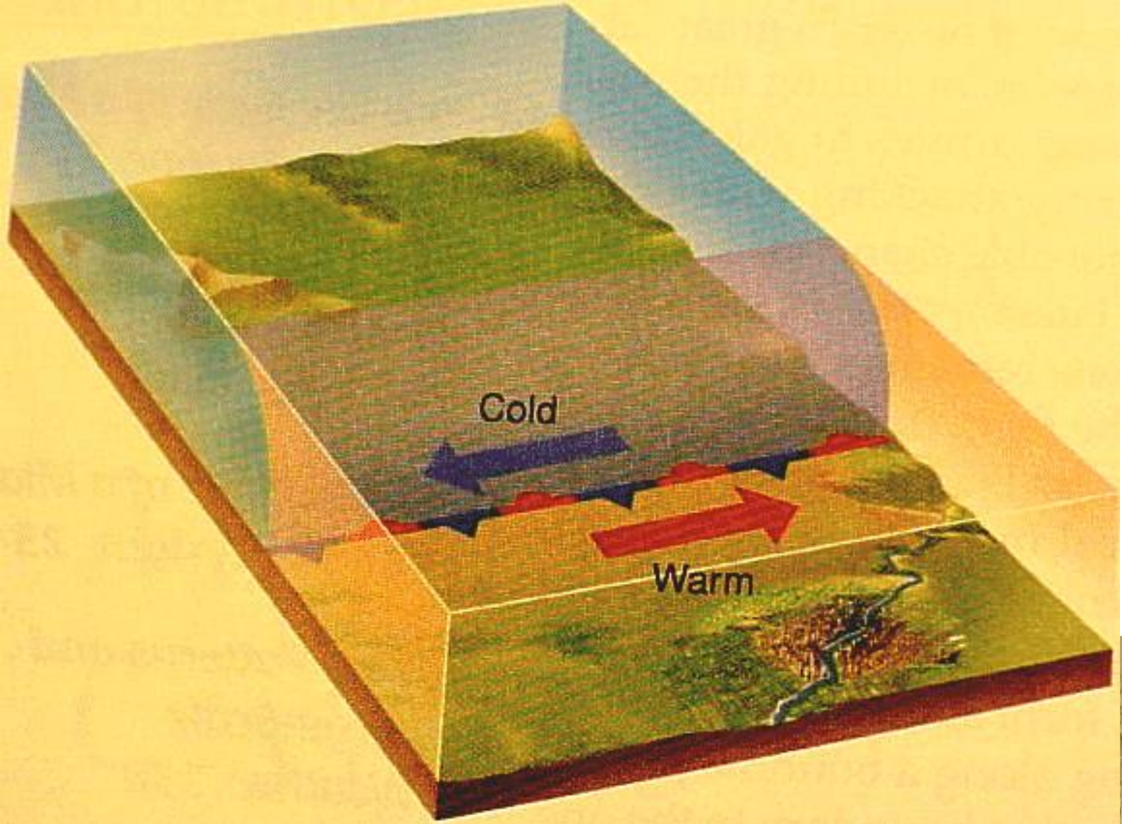
- Pressure surfaces tilt because of N-S temperature contrast
- Passing wave initiates divergence and cyclonic vorticity
- Cold air undercuts warm, and flows south
- Cold air advection undermines upper trough, deepening it
- N-S mixing in cyclone eventually consumes the available potential energy, and cyclone dies

Fasi di evoluzione di una depressione: I

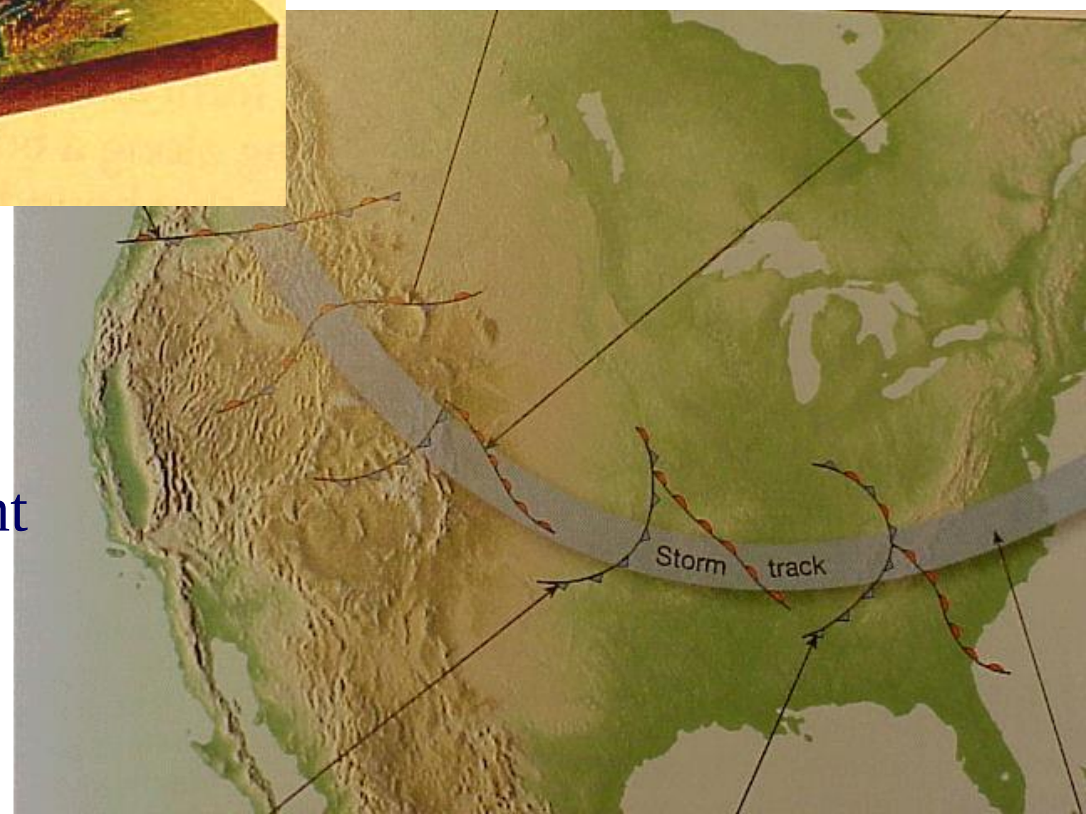


Fase (a)

- Presenza di convergenza ➔ circolazione ciclonica (per conservazione della vorticità) ➔ moti ascendenti verticali ➔ sviluppo di consistente massa di nubi medie stratificate
- Si generano quindi fronti di irruzione di aria fredda e calda

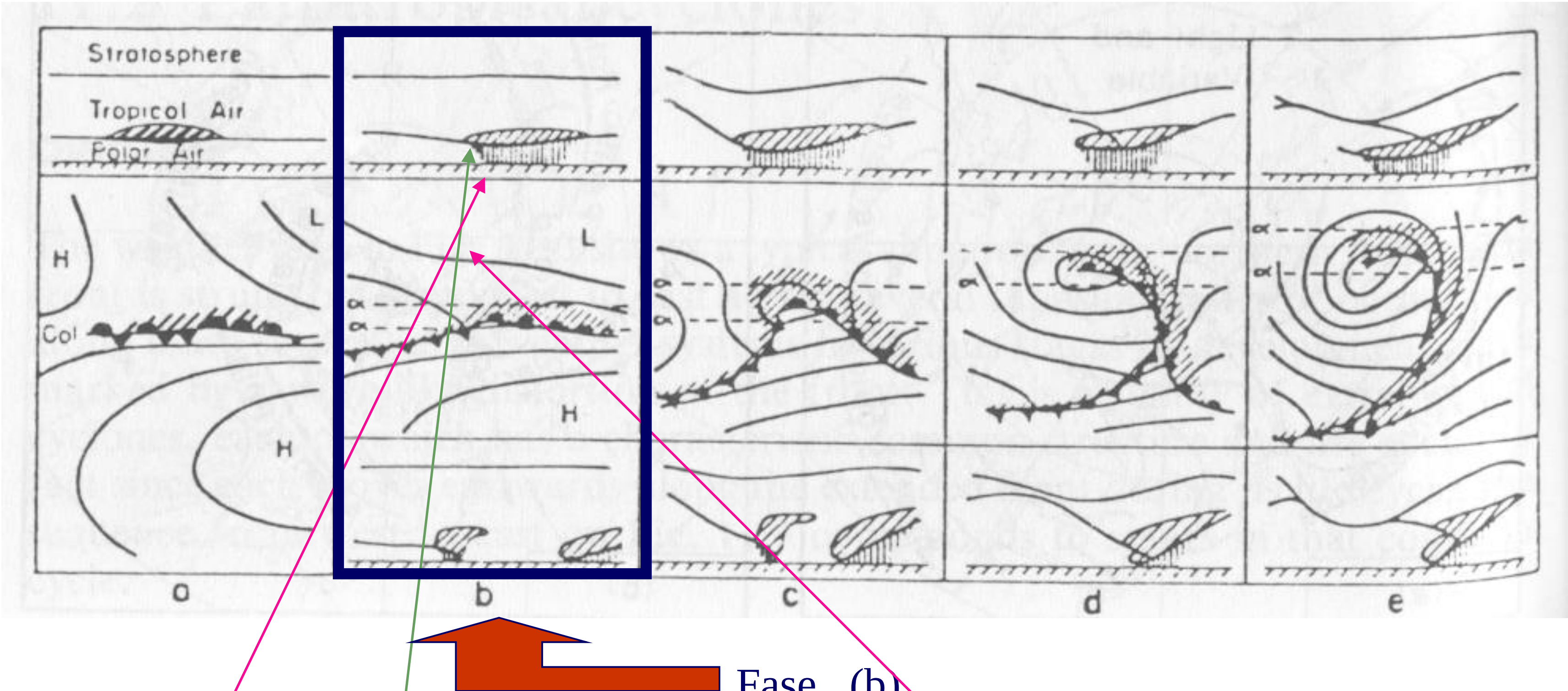


Cyclone Development begins with a **stationary front**



Forecasting where on the Stationary front the development will occur is the tricky part!

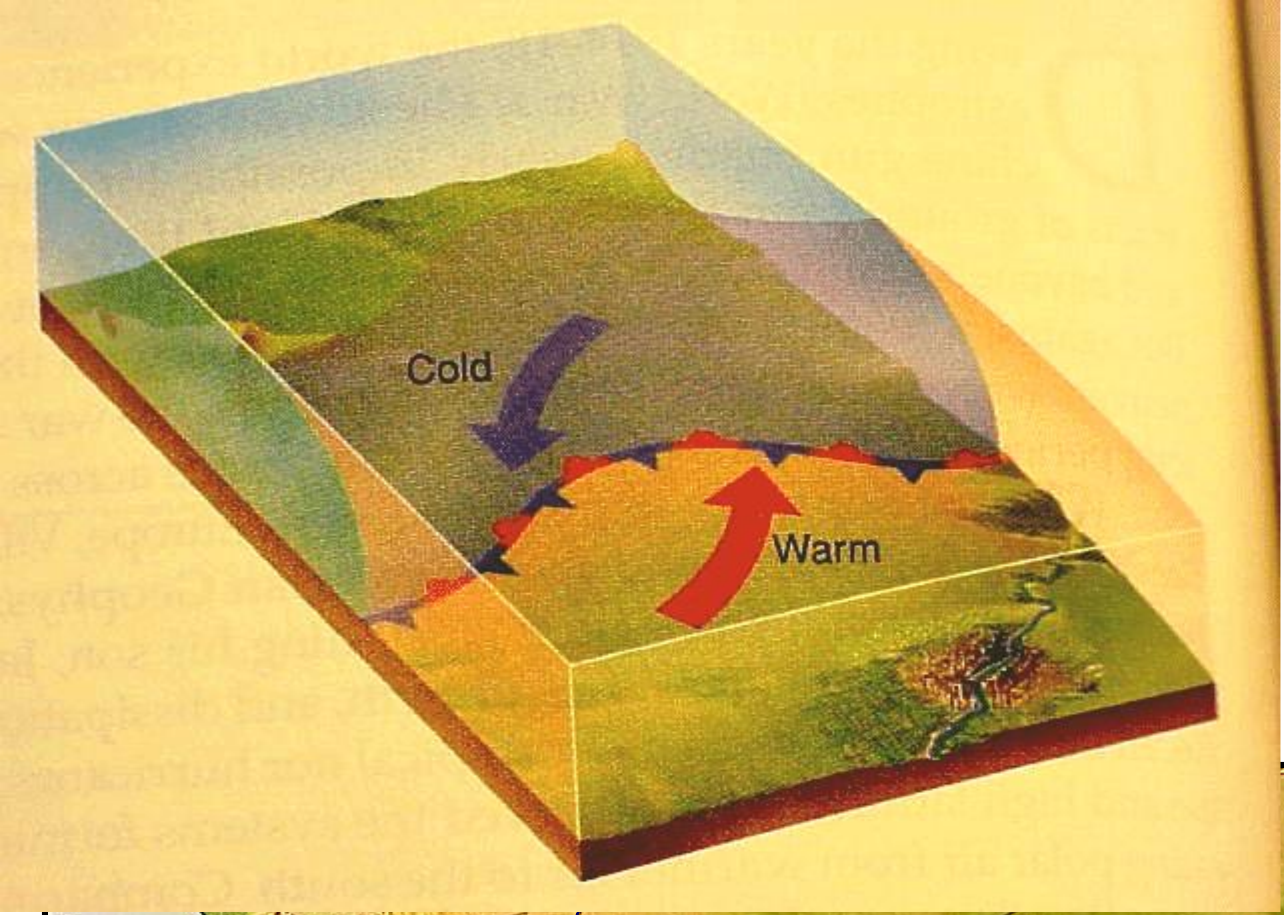
Fasi di evoluzione di una depressione: II

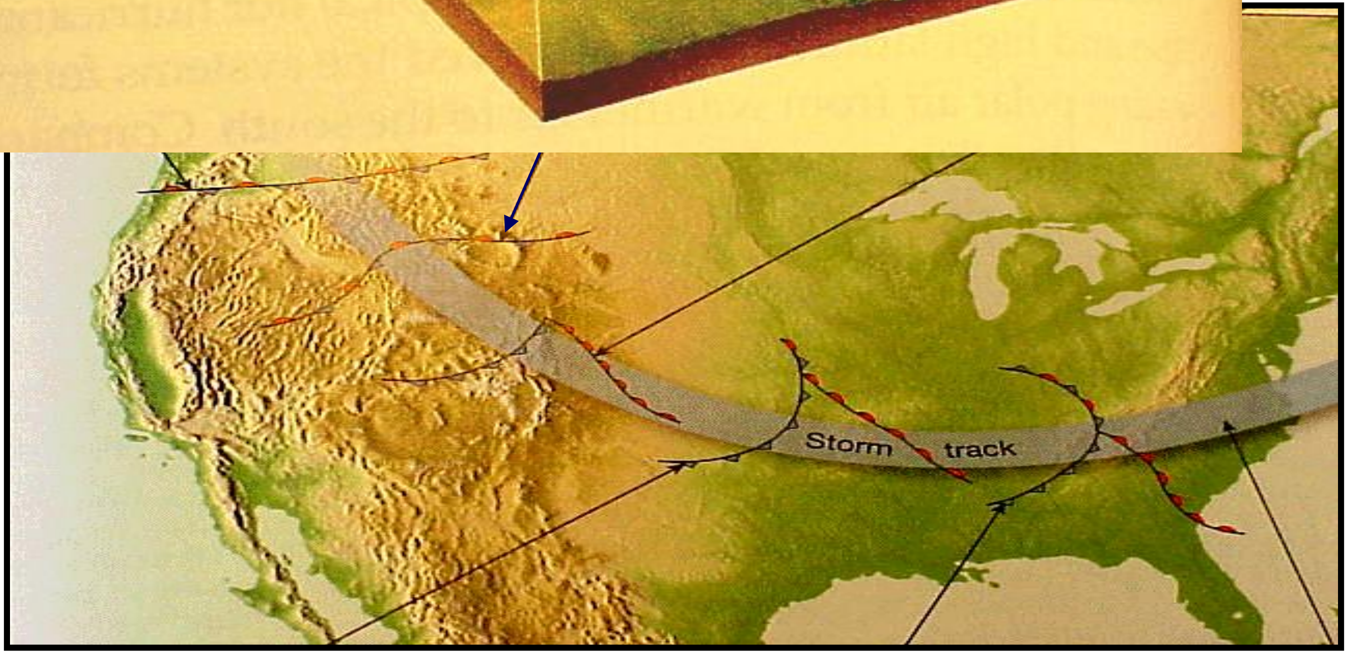


Fase (b)

- formazione nubi alte, ispessimento nubi medie ➔ precipitazioni continue nell'area del fronte caldo;
- Divergenza nell'alta troposfera maggiore della convergenza nella bassa troposfera (attrito) ➔ pressione in diminuzione vicino alla cresta dell'onda
- Fronti molto obliqui rispetto al suolo

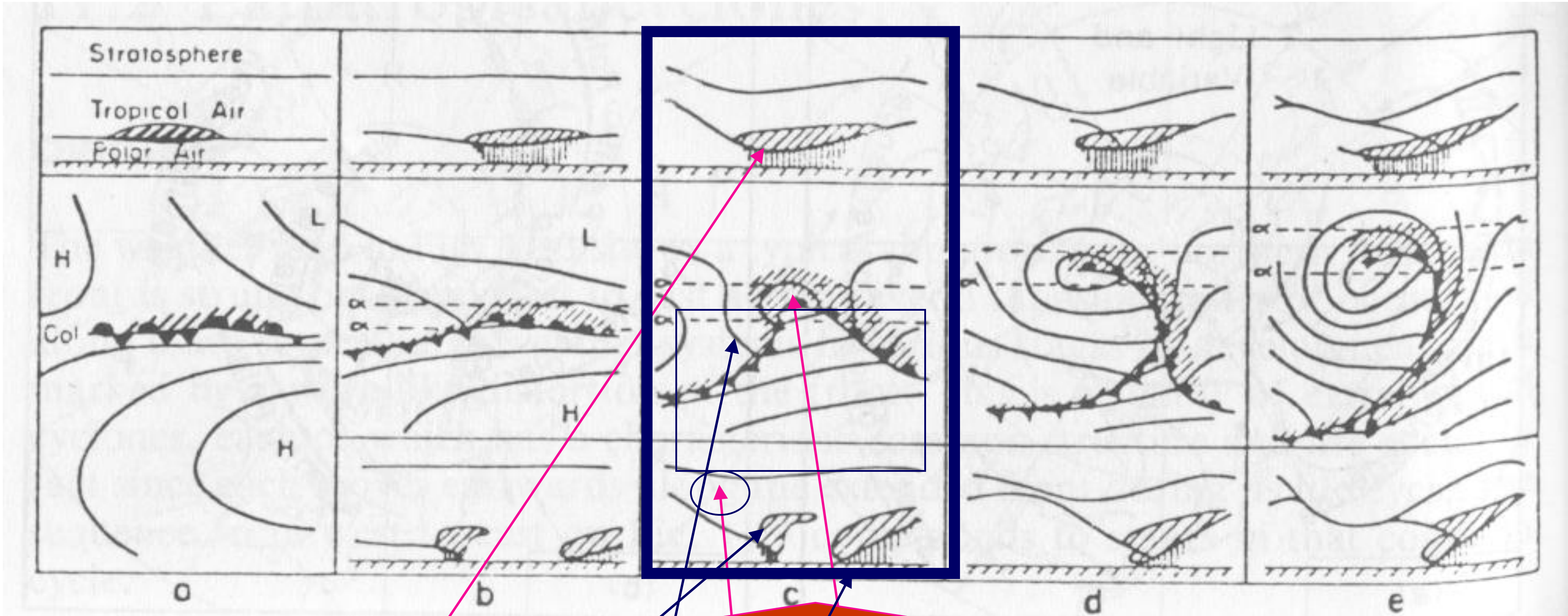
Nascent stage of Cyclone Development





Birth and adolescence

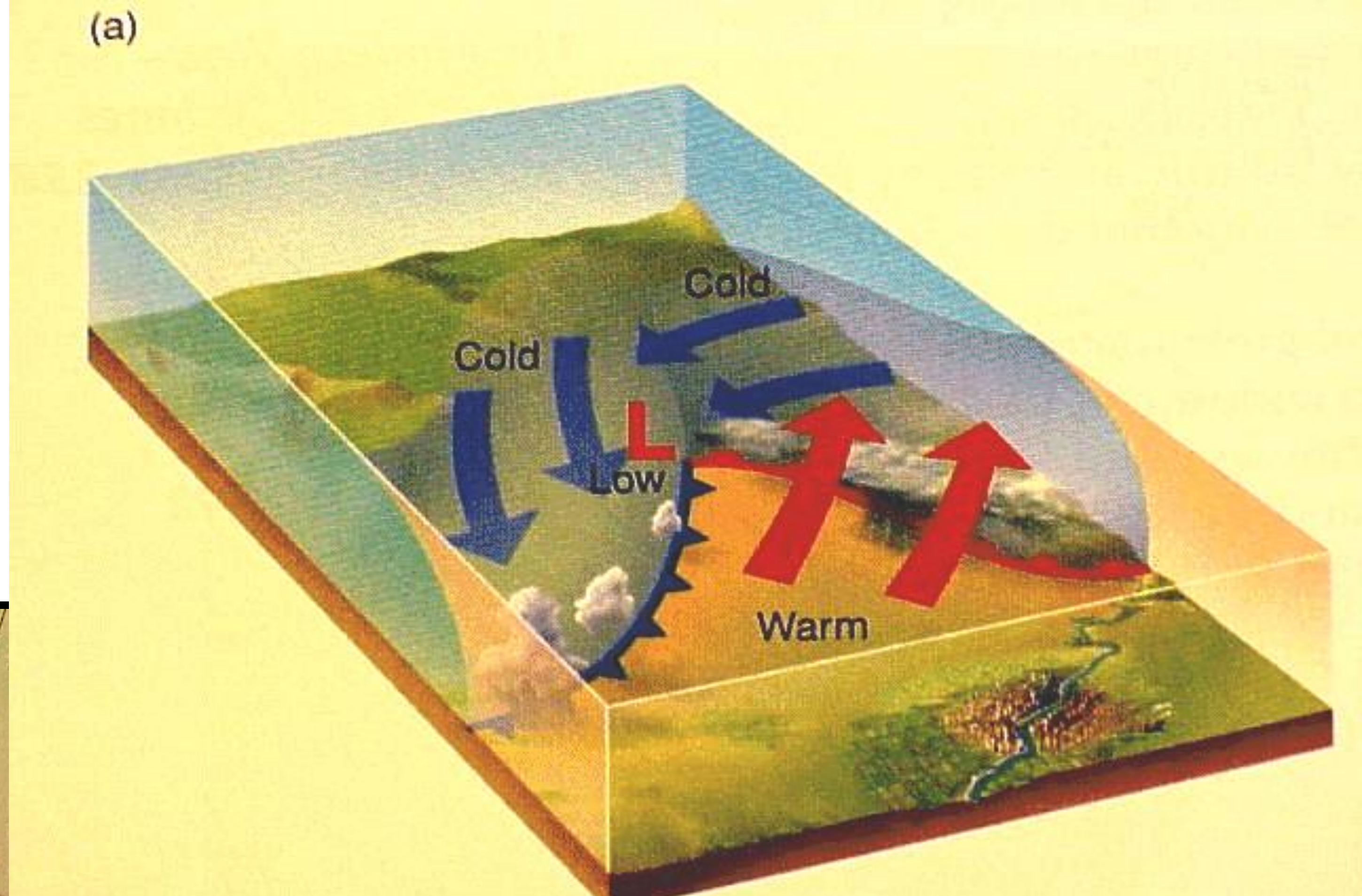
Fasi di evoluzione di una depressione: III

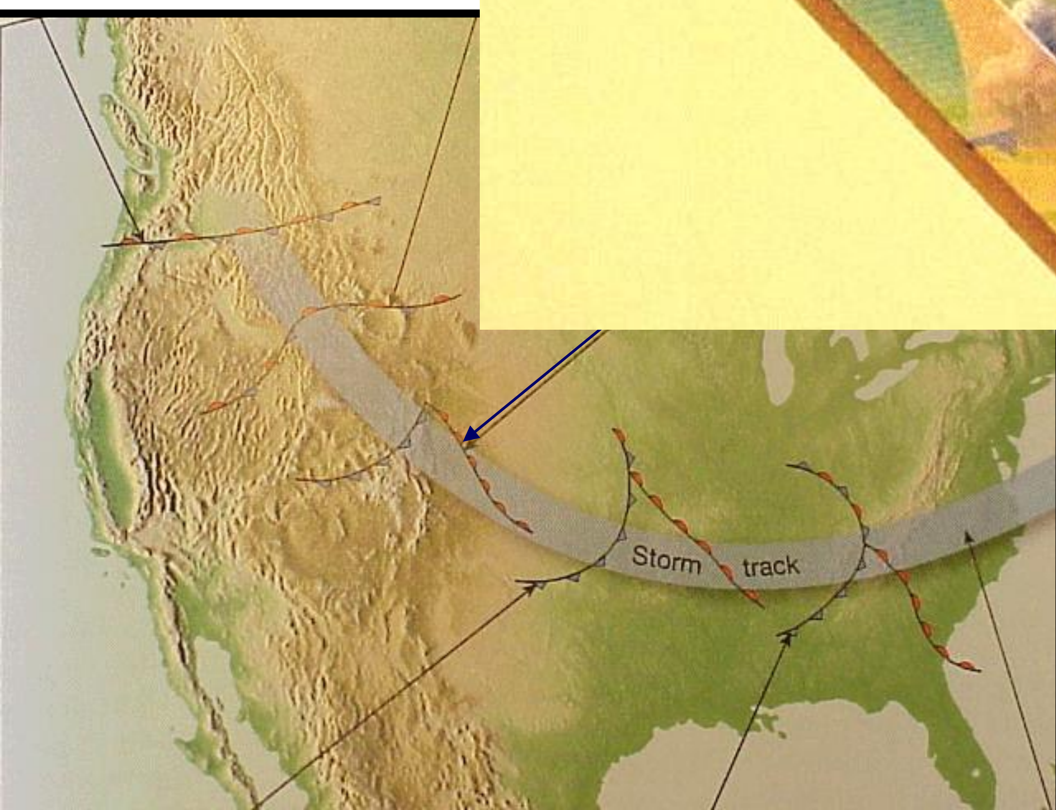


Fase (c)

- Amplificazione dell’onda frontale; diminuzione della pressione nella cresta frontale con formazione di un minimo barico (≥10hPa); venti→intensità di burrasca; nubi: cumulonembi (f.f.) e nembostrati (f.c.) con estesi banchi di As e Cs; precipitazioni consistenti
- Sviluppo di un intenso nucleo di corrente a getto a 200-300 hPa allineato al f.f.

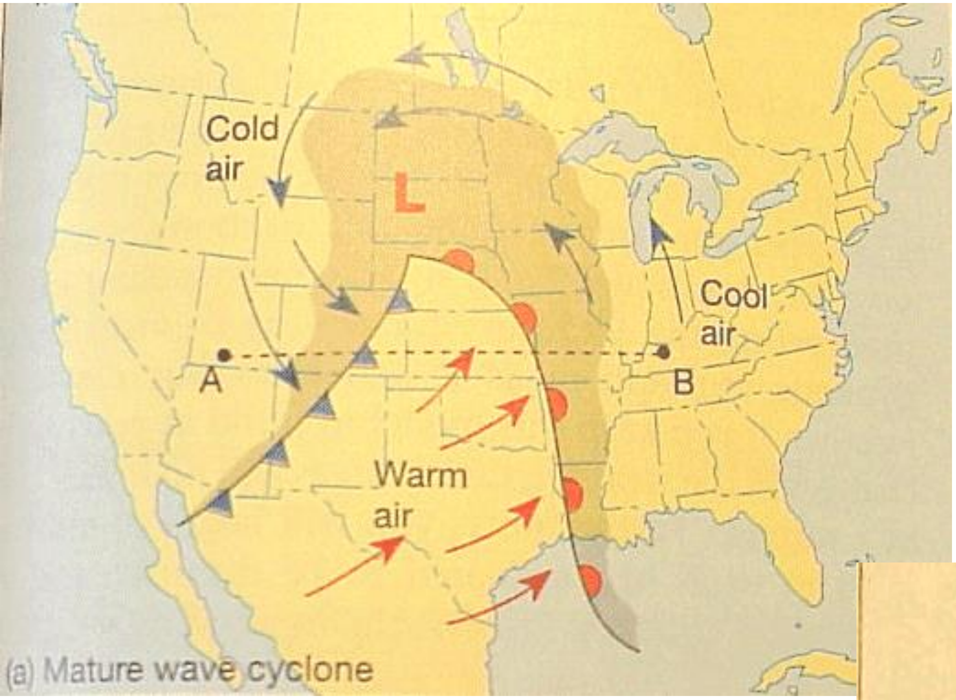
Mature stage of Cyclone Development



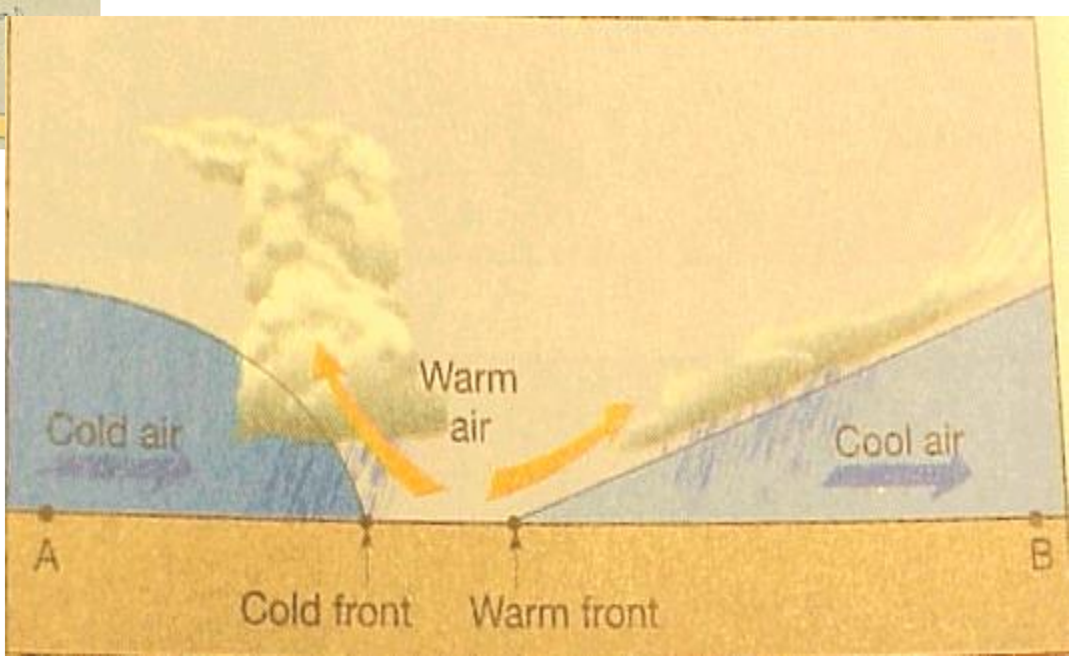


Adulthood

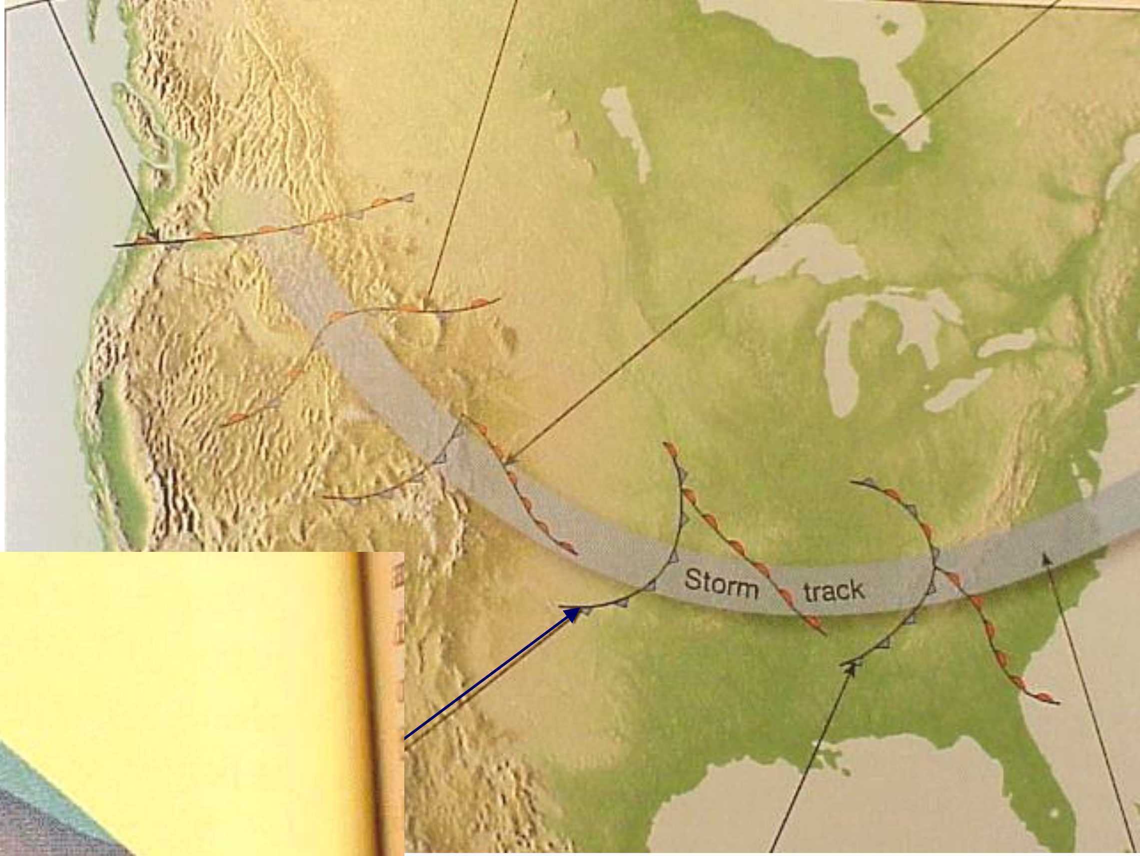
Mature Wave Cyclone

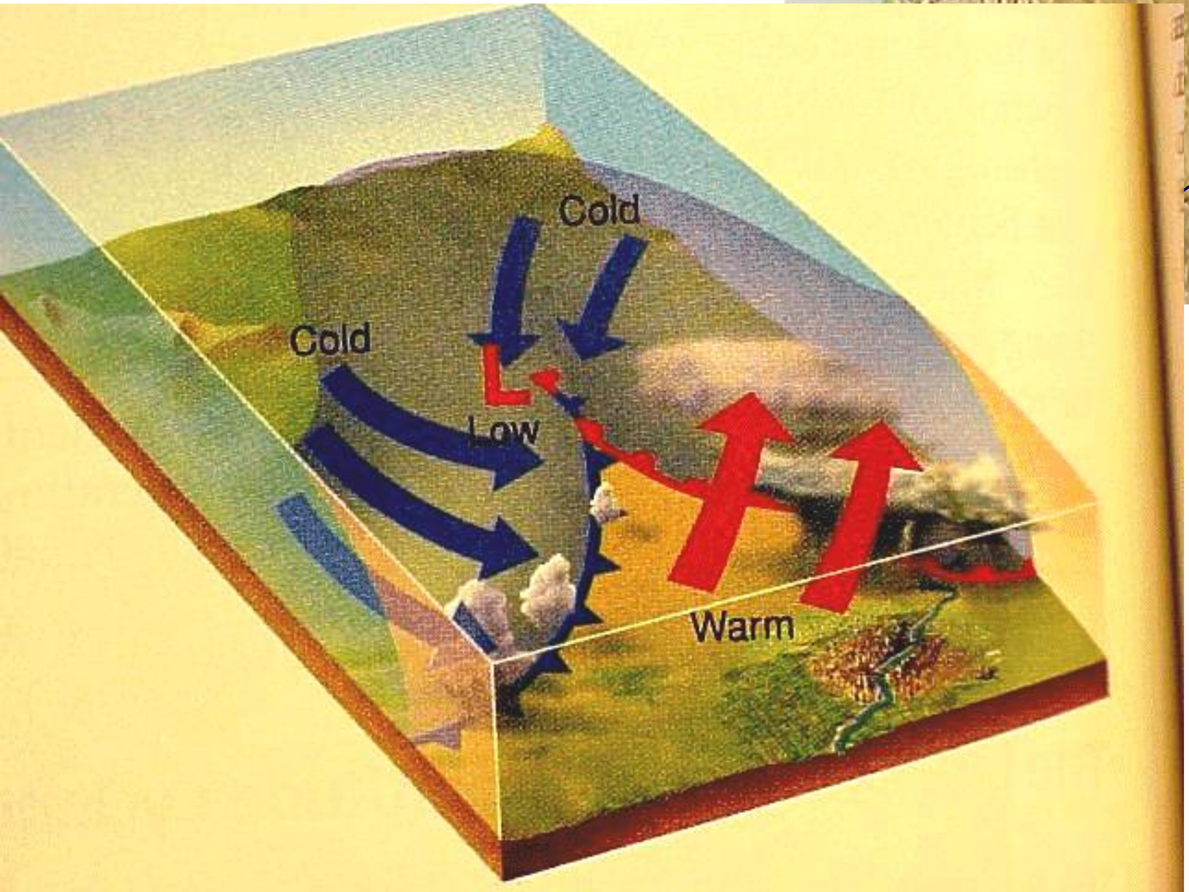


(a) Mature wave cyclone



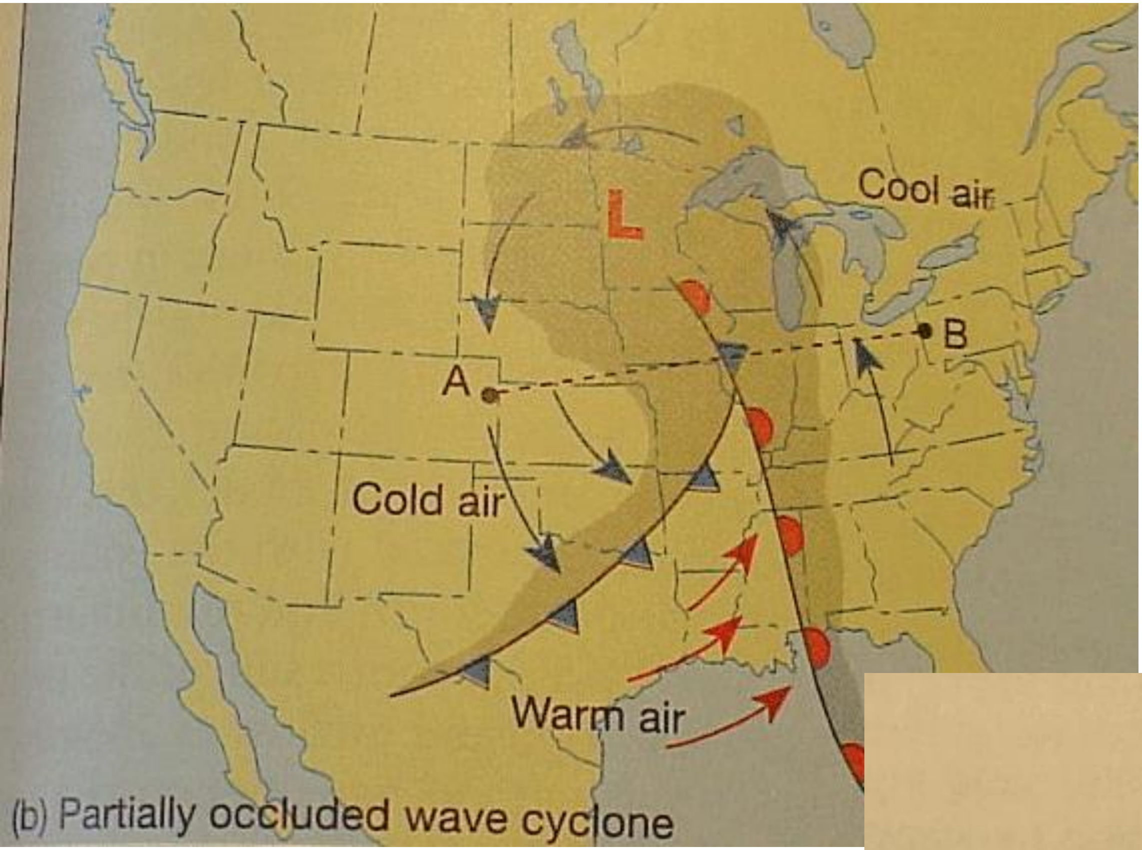
The **Partially Occluded Stage** begins
when the cold front
starts to overrun the
warm front



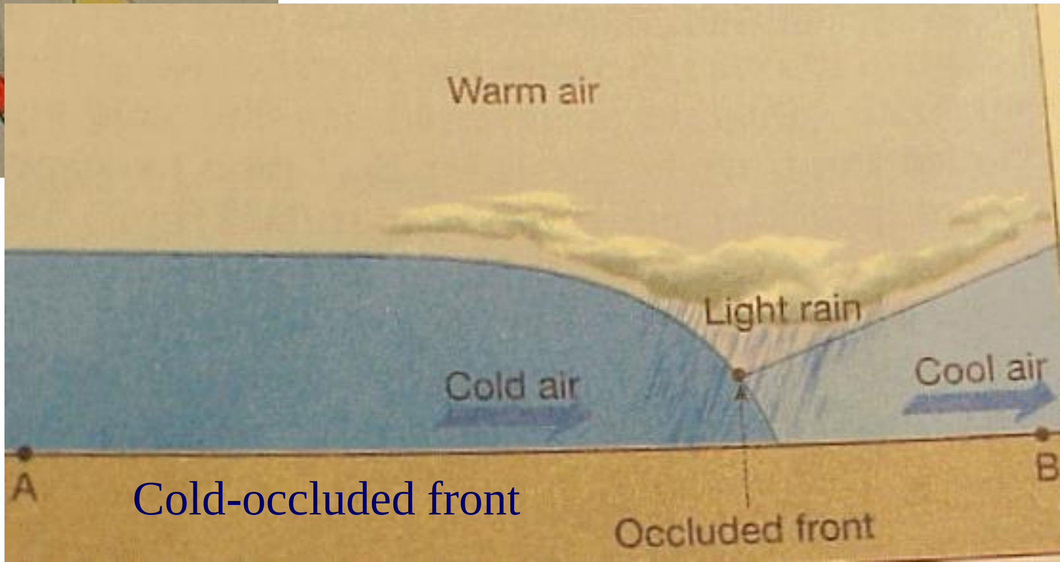


Middle age

Partially occluded wave cyclone



- Cold-occluded front
  - Approach brings weather sequence like a warm front
  - Frontal passage brings weather more like a cold front



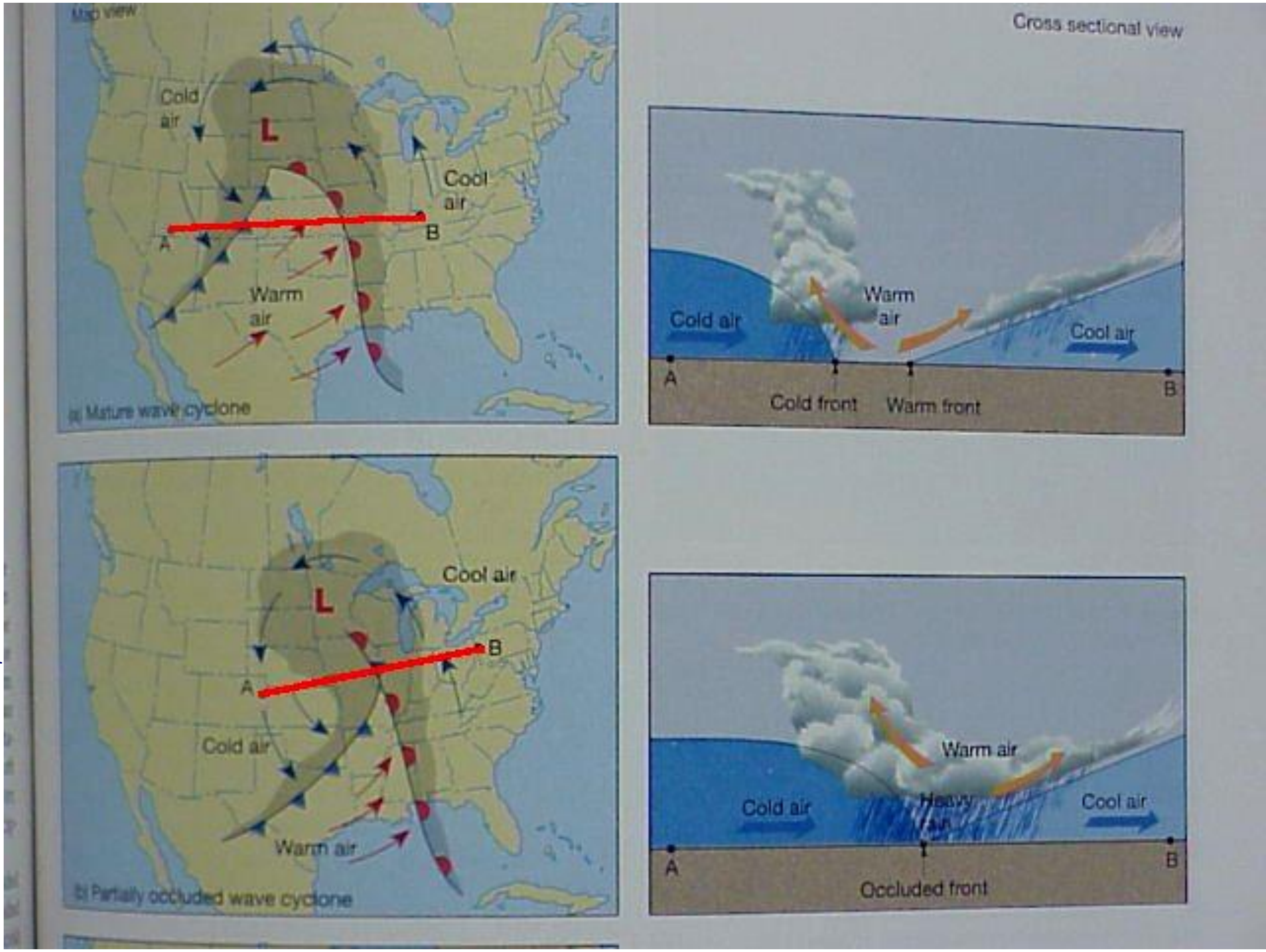
Cold-occluded front

- Warm-occluded fronts also possible

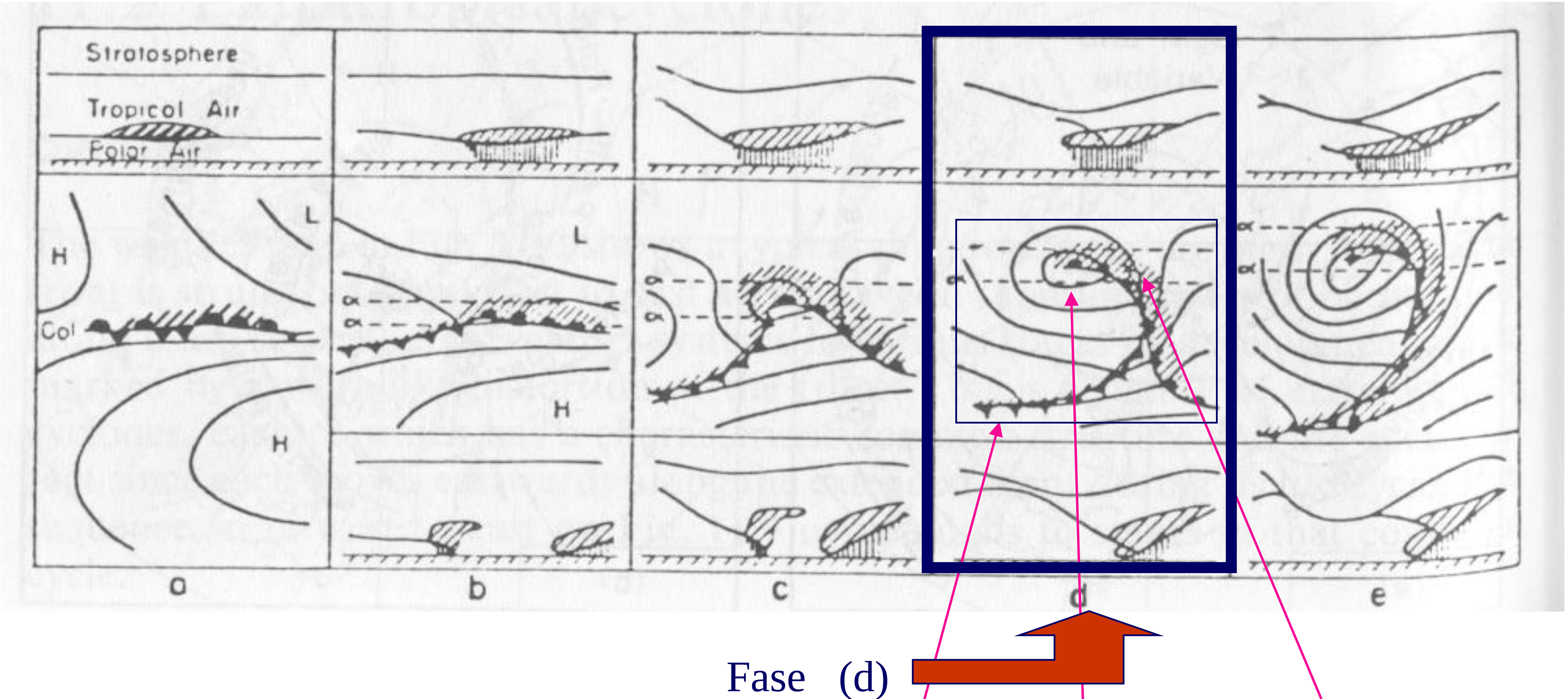
Relationship between occluded fronts and Midlatitude cyclone development

Mature wave cyclone

Partially occluded wave cyclone



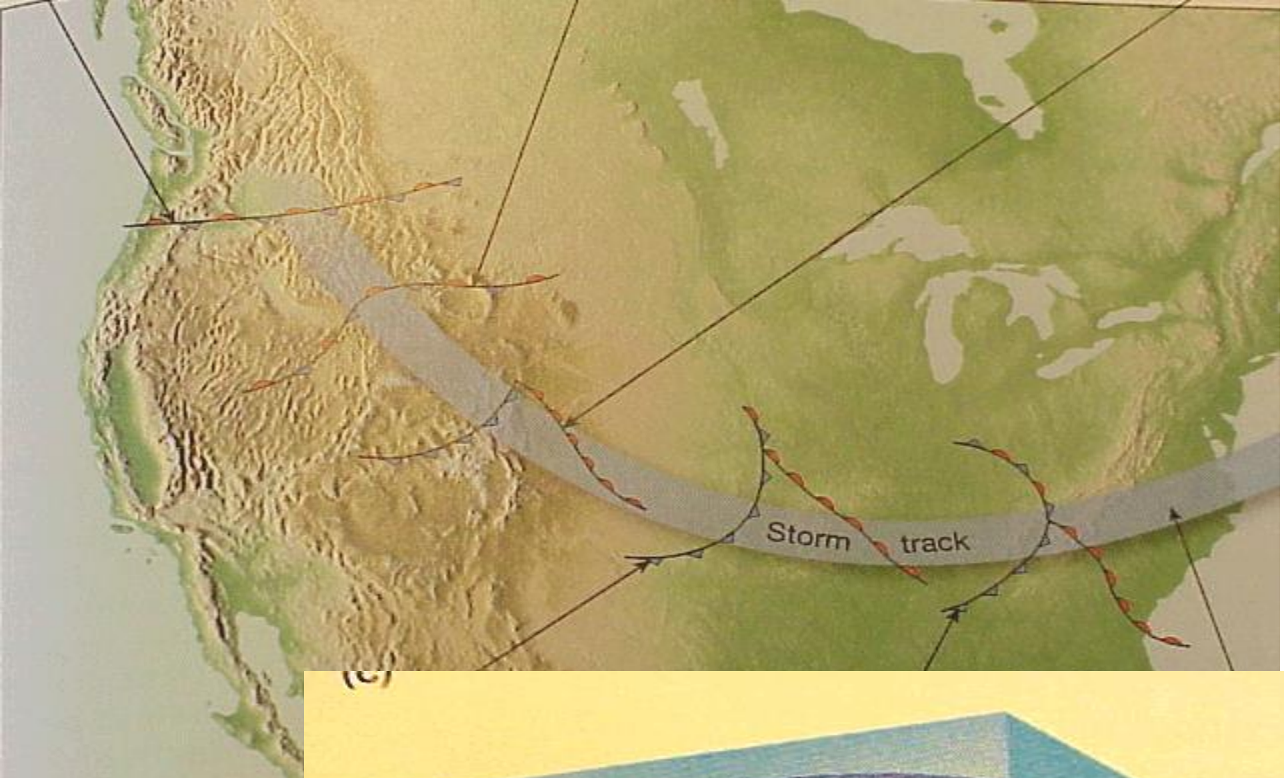
Fasi di evoluzione di una depressione: IV



•Nella depressione ampiezza logitudinale ≈ ampiezza trasversale; riduzione dell'area del fronte caldo → occlusione (l'aria fredda scaraventa in alto l'aria calda)

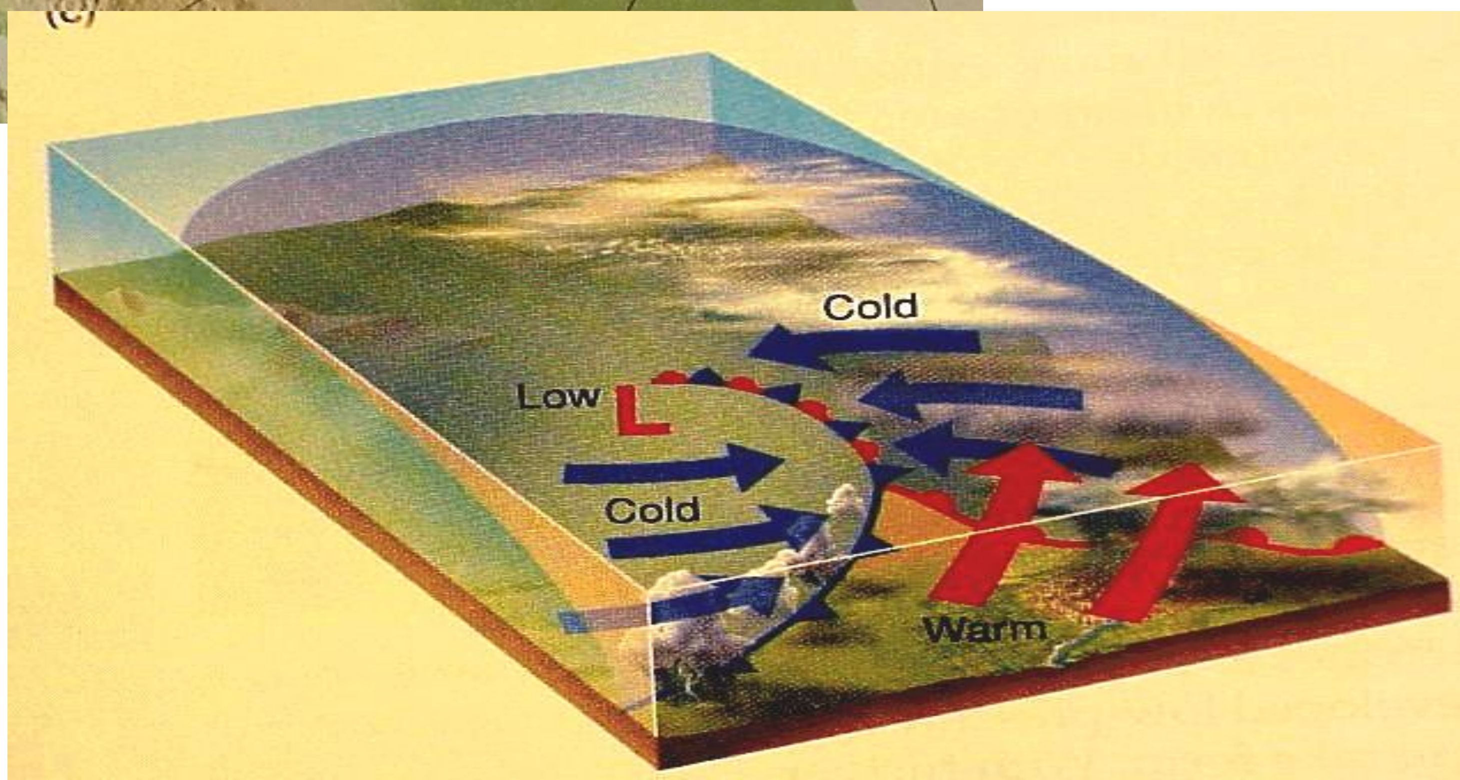
•Spostamento verso N (e verso O) del minimo depressionario e del fronte occluso; allineamento della corrente a getto col f.f. (e non col f.o.)

•Contrasto termico nel f.o. < che nel f.f.



The **Occluded Stage** is characterized by more warm air being pushed aloft and the size of the warm air wedge at the surface decreases significantly

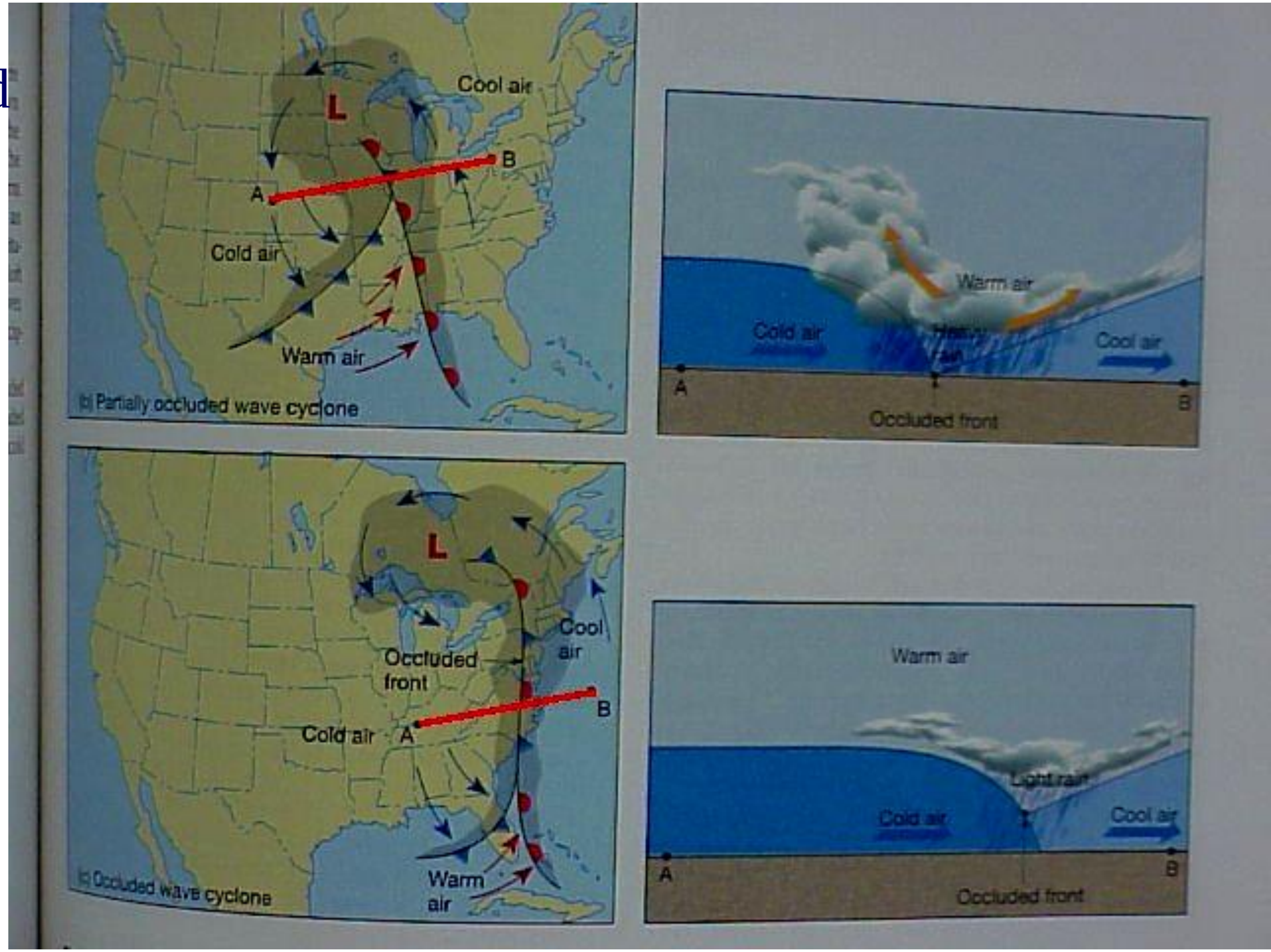
Over the Hill



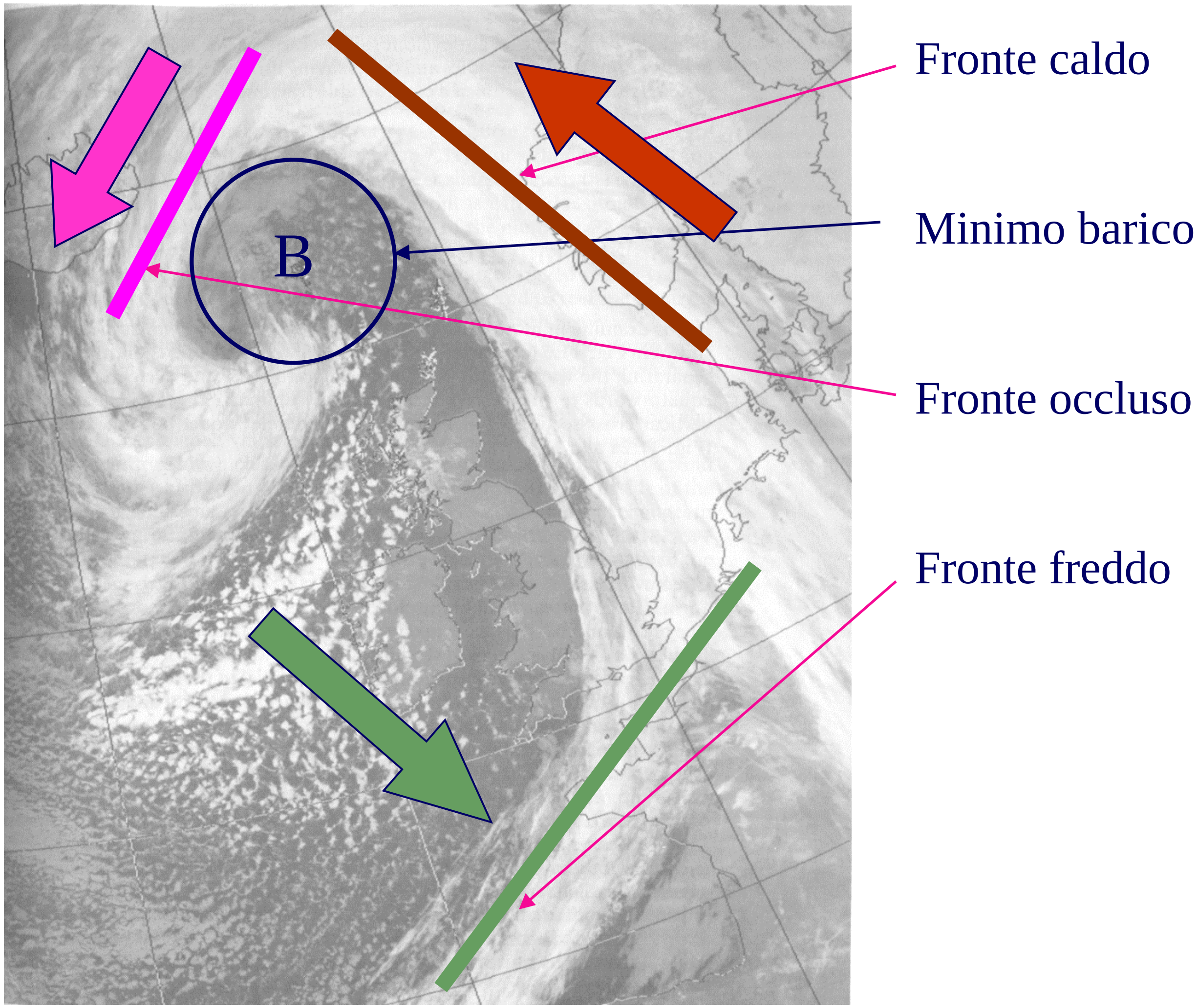
Relationship between occluded fronts and a Midlatitude cyclone

Partially occluded wave cyclone

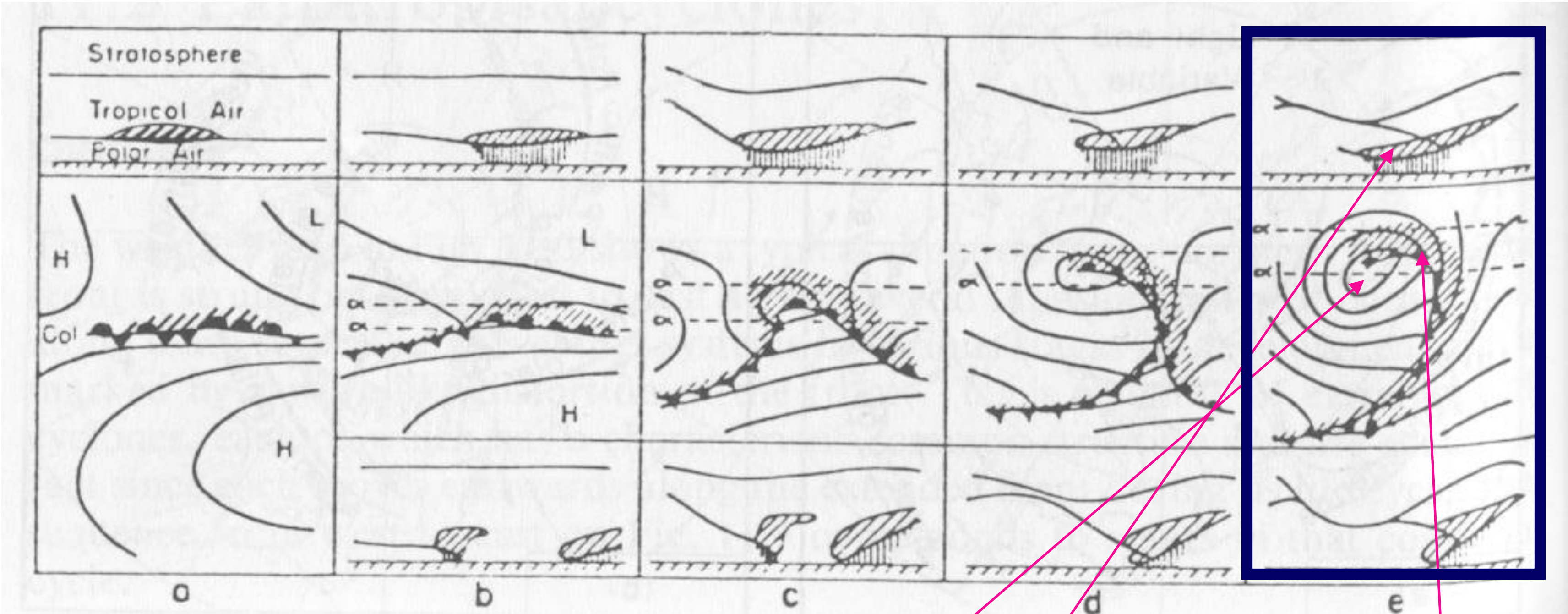
Occluded wave cyclone



Fronti in una depressione “matura”



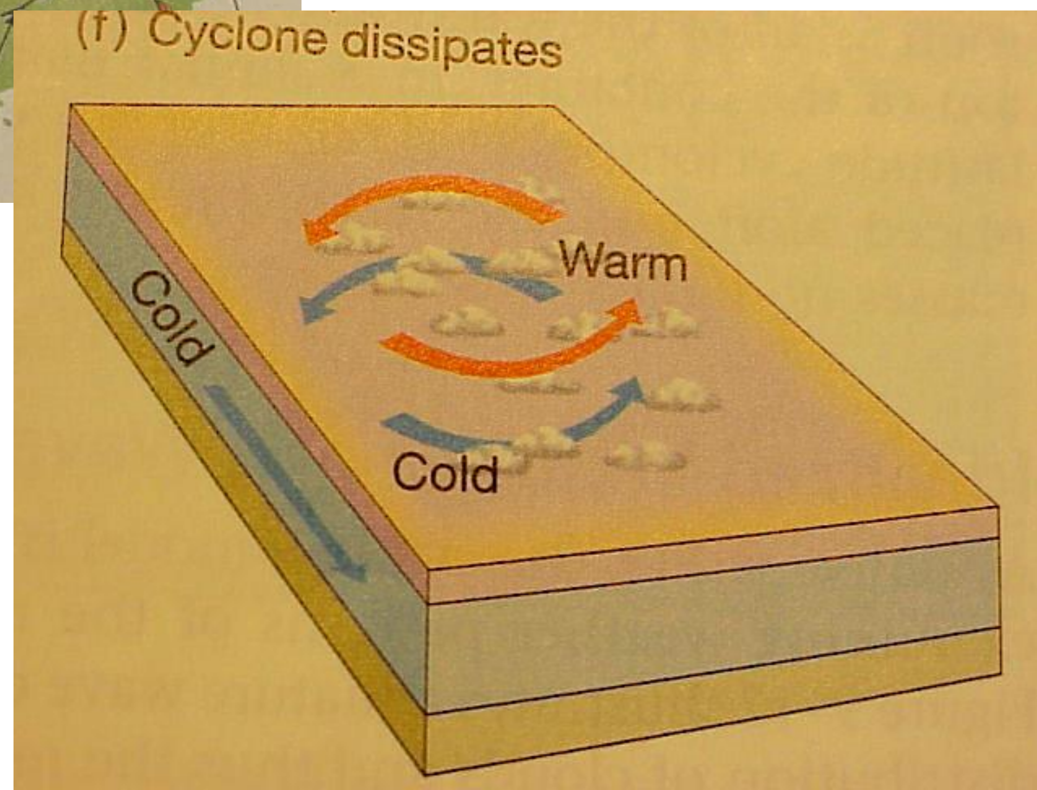
Fasi di evoluzione di una depressione: V



Fase (e)

- Ulteriore diminuzione dei contrasti termici → il centro della depressione rimane freddo (nucleo freddo, o goccia fredda)
- Si mantengono nubi e piogge per diversi giorni ➔ il f.o. spiralizza attorno al minimo con venti forti
- Dopo alcuni giorni la depressione "si colma" (per attrito)

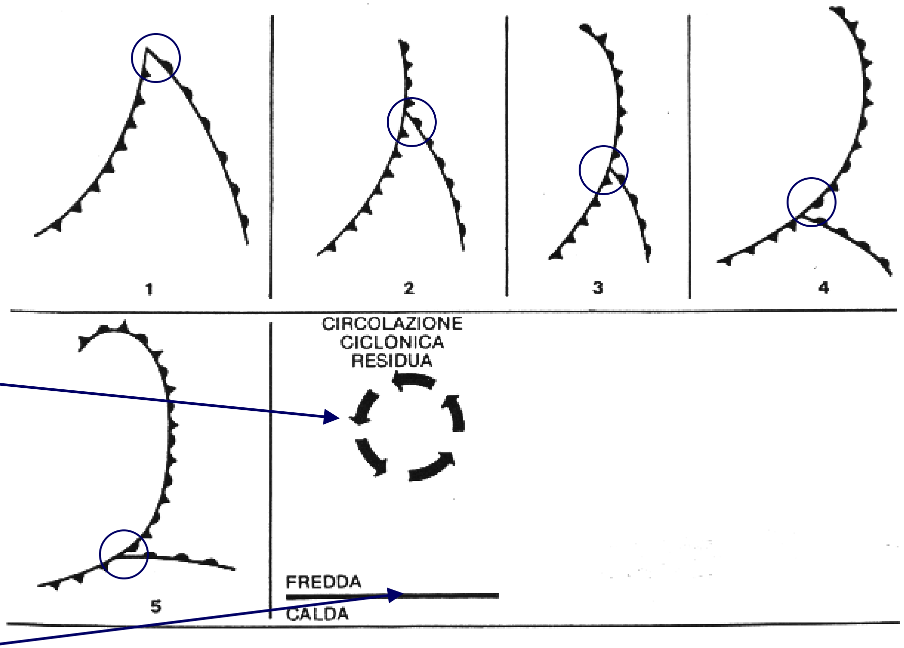
The final decay stage of the cyclone. The warm air is isolated aloft with cold air beneath.



Death

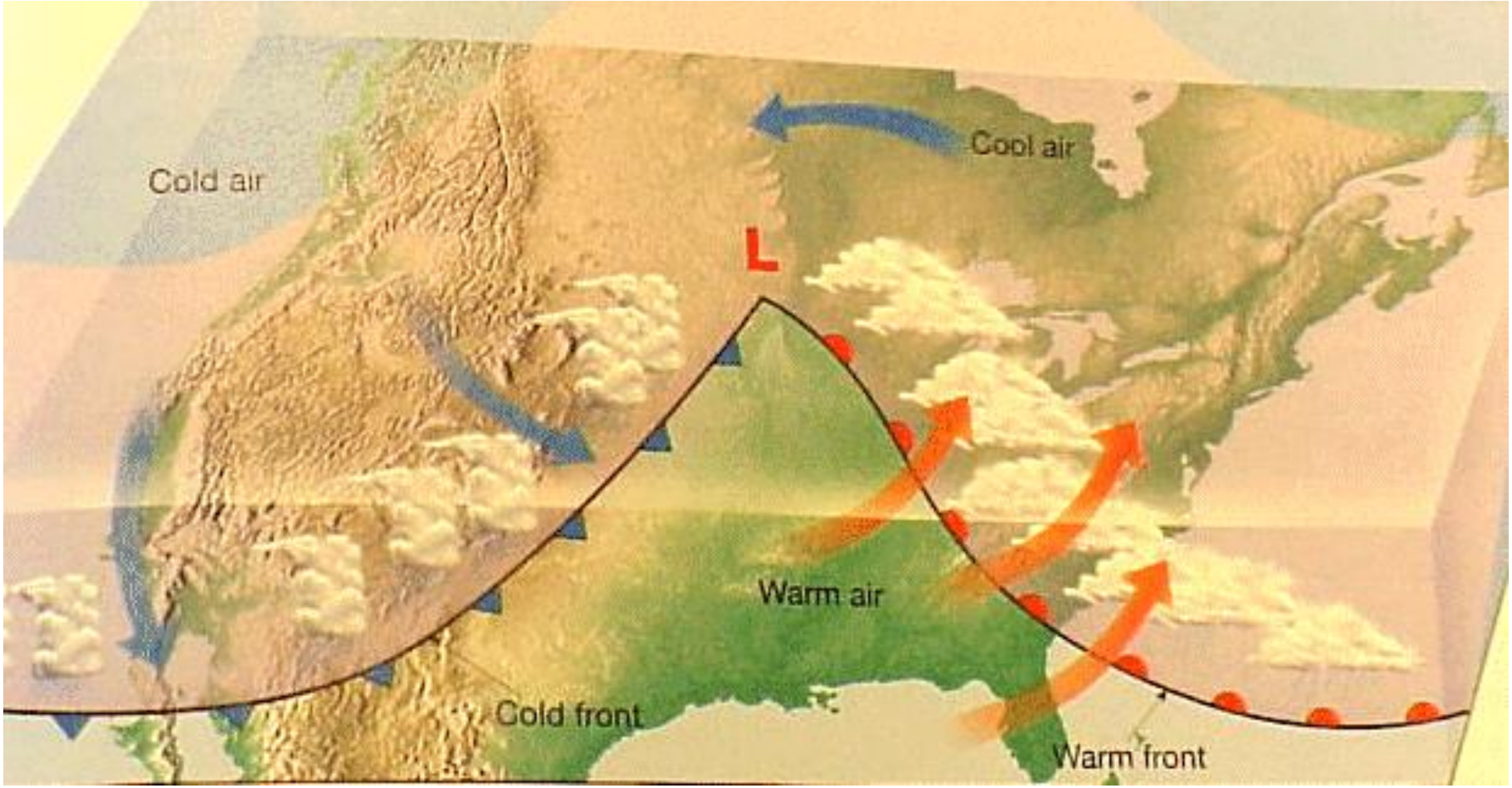
Le famiglie di depressioni

- Le depressioni tendono a muoversi verso E fino alla comparsa dell'occlusione
- Poi tendono a rimanere quasi stazionarie, ruotando attorno ad un centro fisso (il minimo)
- Il residuo del f.f. possiede ancora un notevole contrasto termico; esso tende a svincolarsi dalla depressione ed a procedere verso SE acuendo il proprio contrasto termico

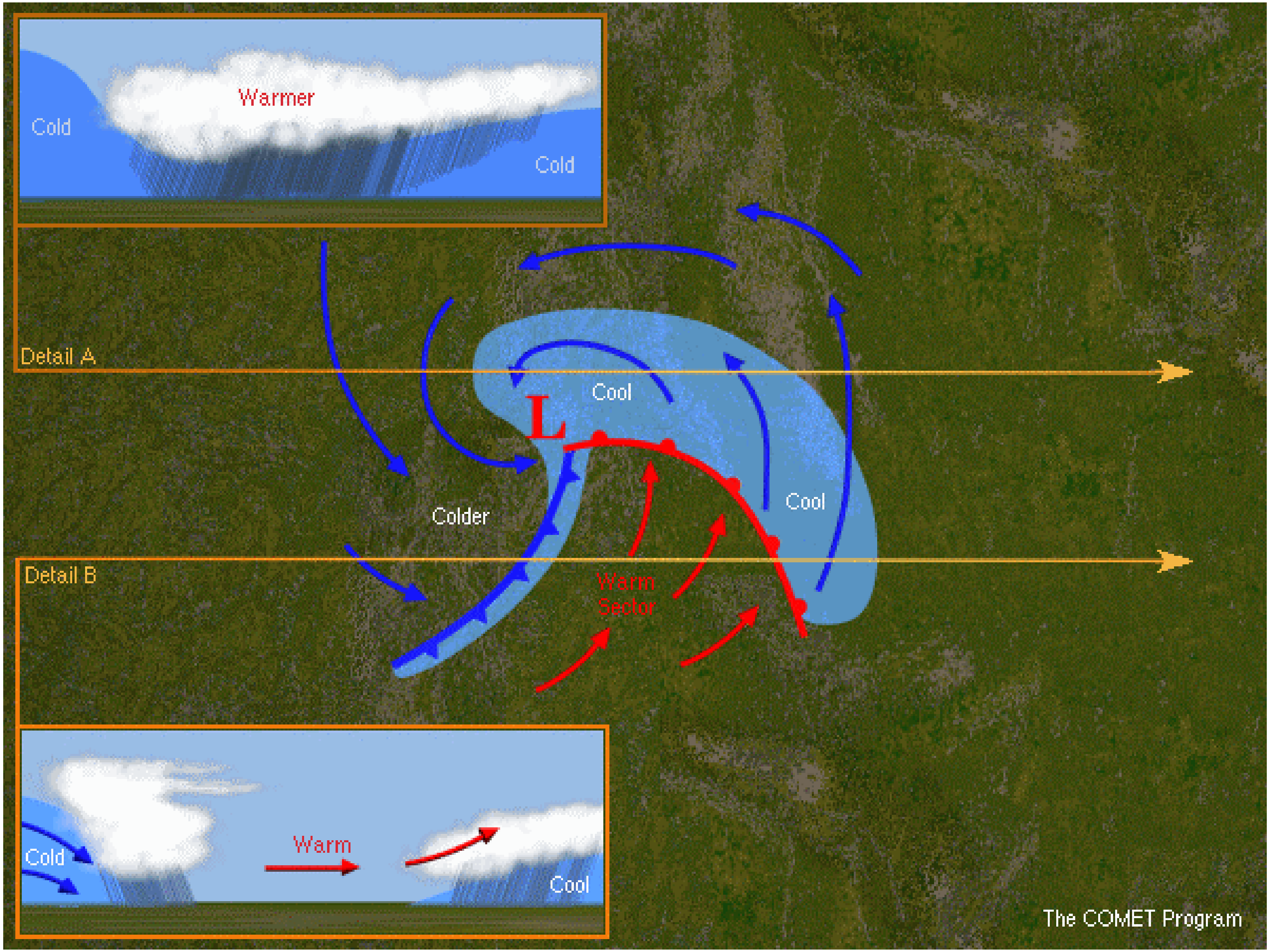


- Tale contrasto può provocare ulteriori eventi ciclogenetici simili al primo, e così via ➔ si generano "famiglie" di depressioni (anche 6 o più), ognuna "figlia" delle altre, distese in obliquo dalle latitudini subpolari a quelle subtropicali
- Alla fine il "vecchio" vortice si smorza e "muore", lasciando dietro di sé una scia di sistemi che hanno ricoperto una regione estesa per oltre due settimane

Midlatitude Cyclone Frontal Structure

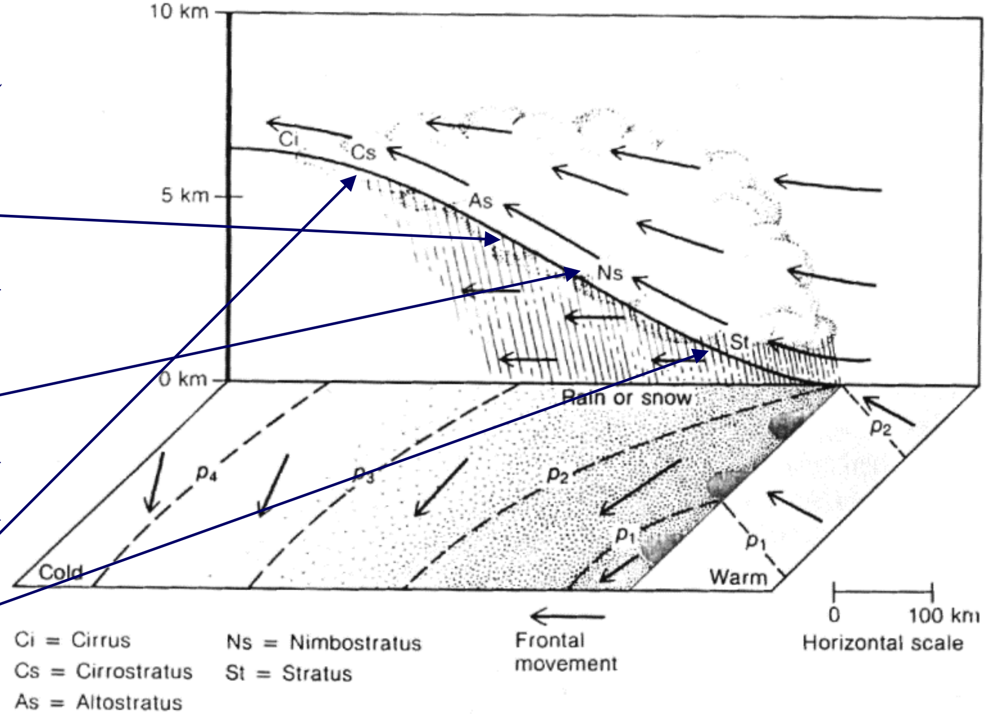


3-D Frontal Structure



Fronte caldo

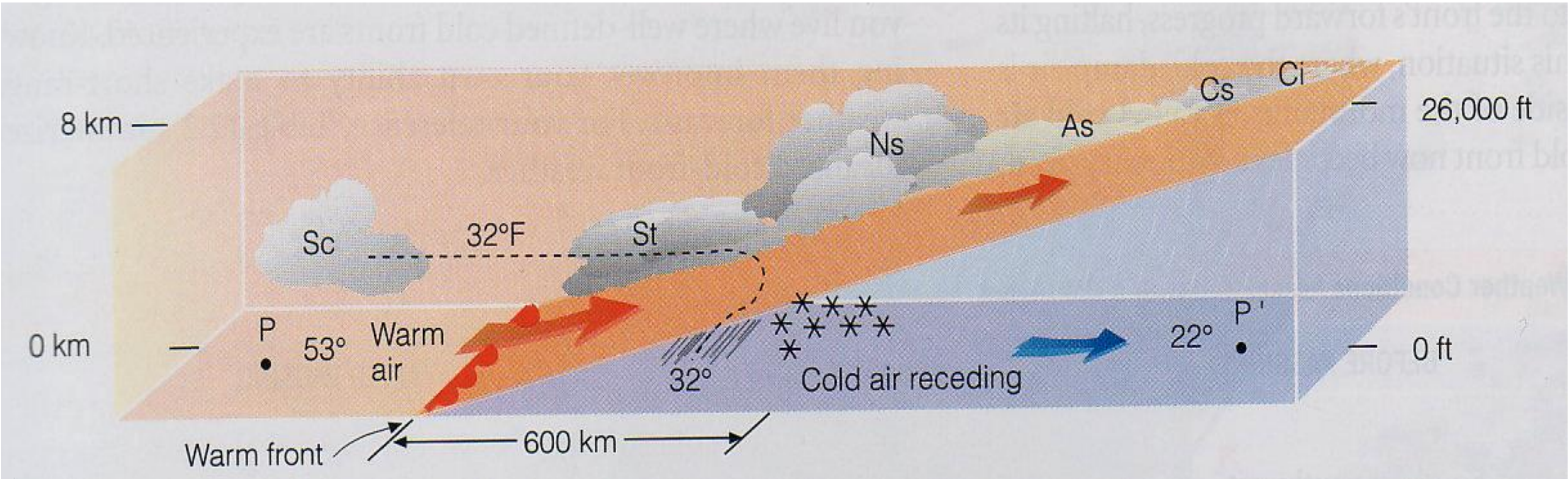
- Prodotto dallo scorrimento dell'aria calda sull'aria fredda (come piano inclinato)
- L'aria calda si solleva e si raffredda sino al punto di rugiada, → condensazione del vapore acqueo → nubi a carattere stratificato più spesse (Ns → precipitazioni), poi nubi via via più sottili (As, Ci, Cs)
- Evaporazione della pioggia → aumento dell'umidità → nubi basse (St, nebbie)



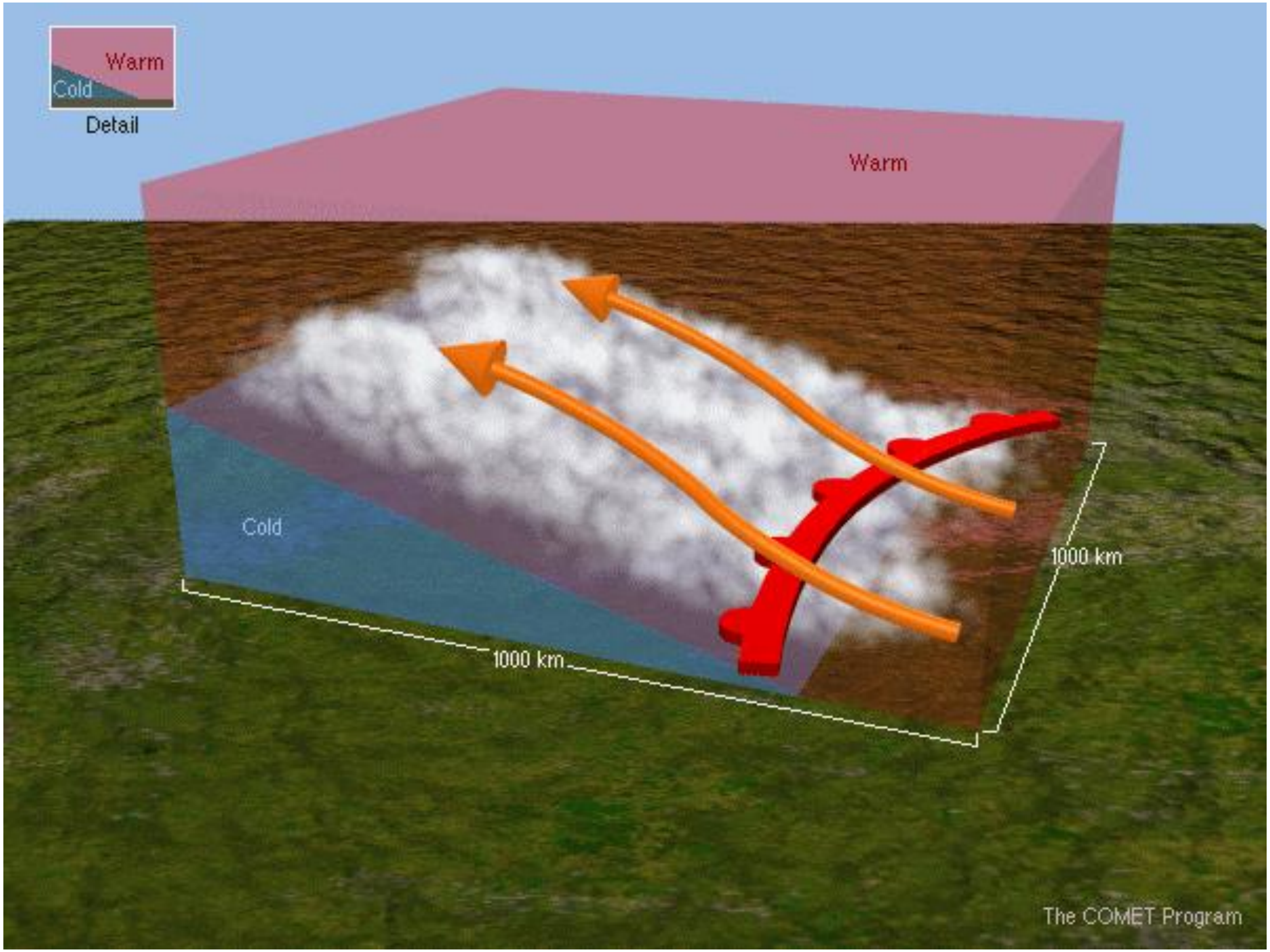
- Tipologie di fronte caldo: quelli a gradiente termodinamico stabile (nubi: strati continui e compatti, con limiti superiori appiattiti e precipitazioni a carattere continuo) e quelli a gradiente termodinamico instabile (saturo), nei quali la parte superiore delle nubi basse forma rigonfiamenti che possono dare origine a Cb.

Typical Warm Front Structure

- In an advancing warm front, warm air rides up over colder air at the surface; slope is not usually very steep
- Lifting of the warm air produces clouds and precipitation well in advance of boundary
- At different points along the warm/cold air interface, the precipitation will experience different temperature histories as it falls to the ground

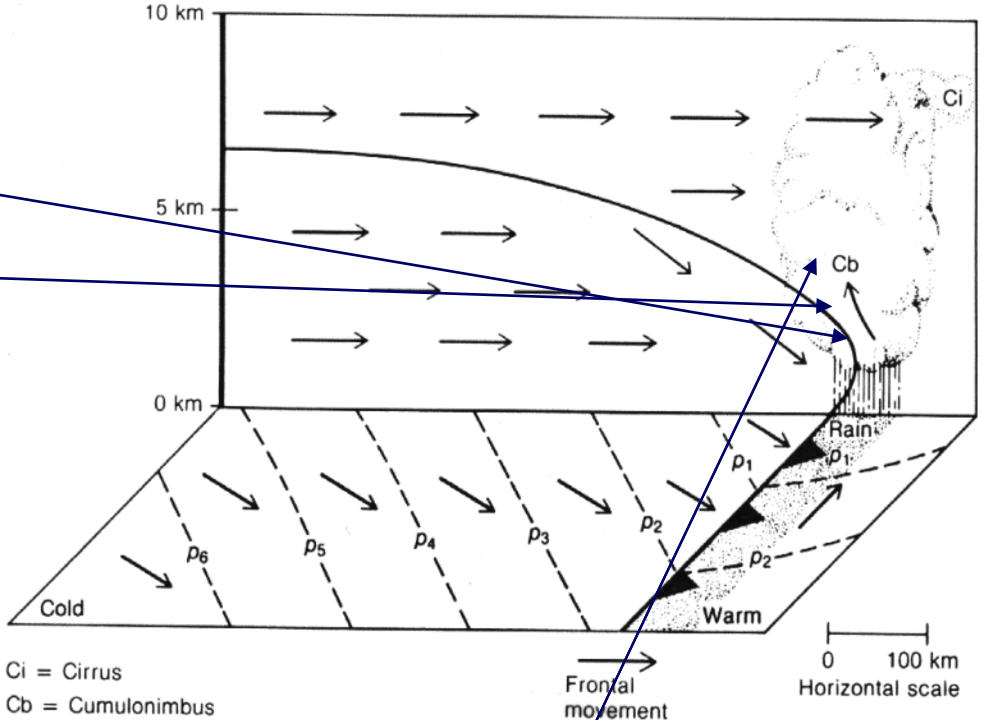


Warm front structure



Fronte freddo

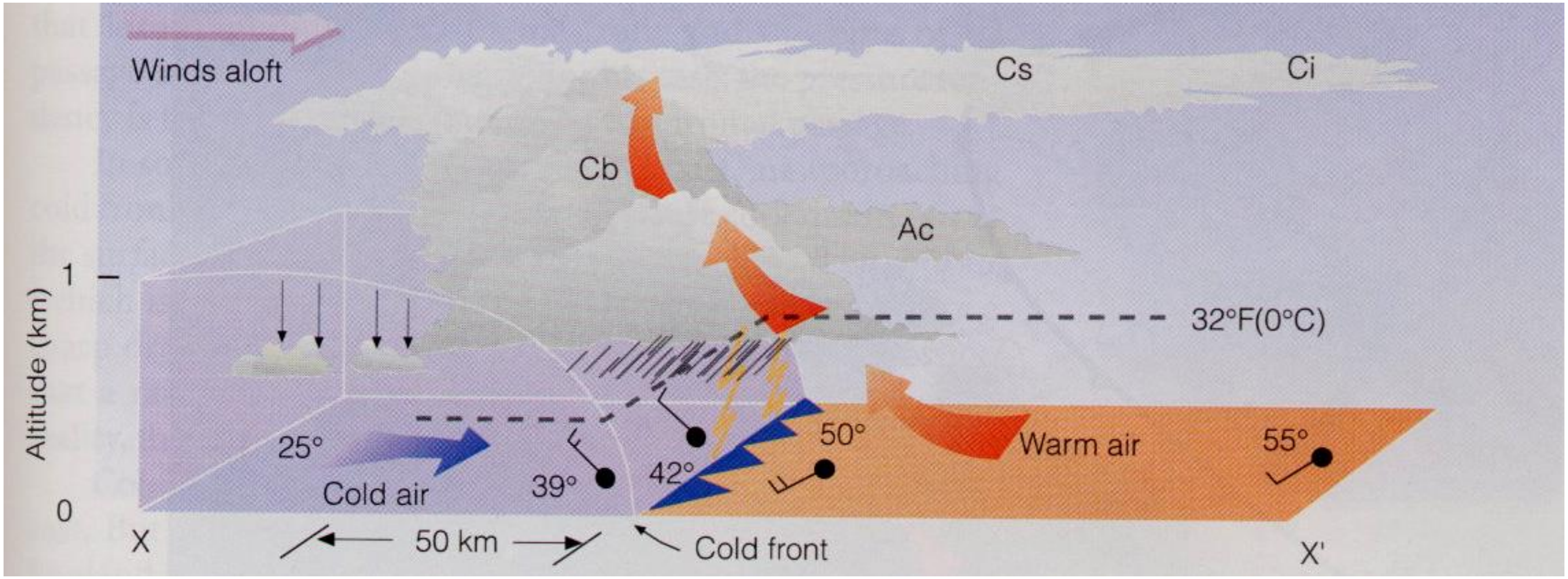
- L'aria fredda essendo più pesante si propaga a contatto con il suolo (per attrito si forma il "naso") e scalza l'aria calda preesistente che è costretta forzatamente a salire
- Salendo l'aria calda si raffredda sino al punto di rugiada, → condensazione del vapore acqueo → nubi a carattere convettivo (sviluppo verticale): Cu, Tc, Cb
- L'estensione verticale dello strato freddo è modesta (max 2-3 Km)



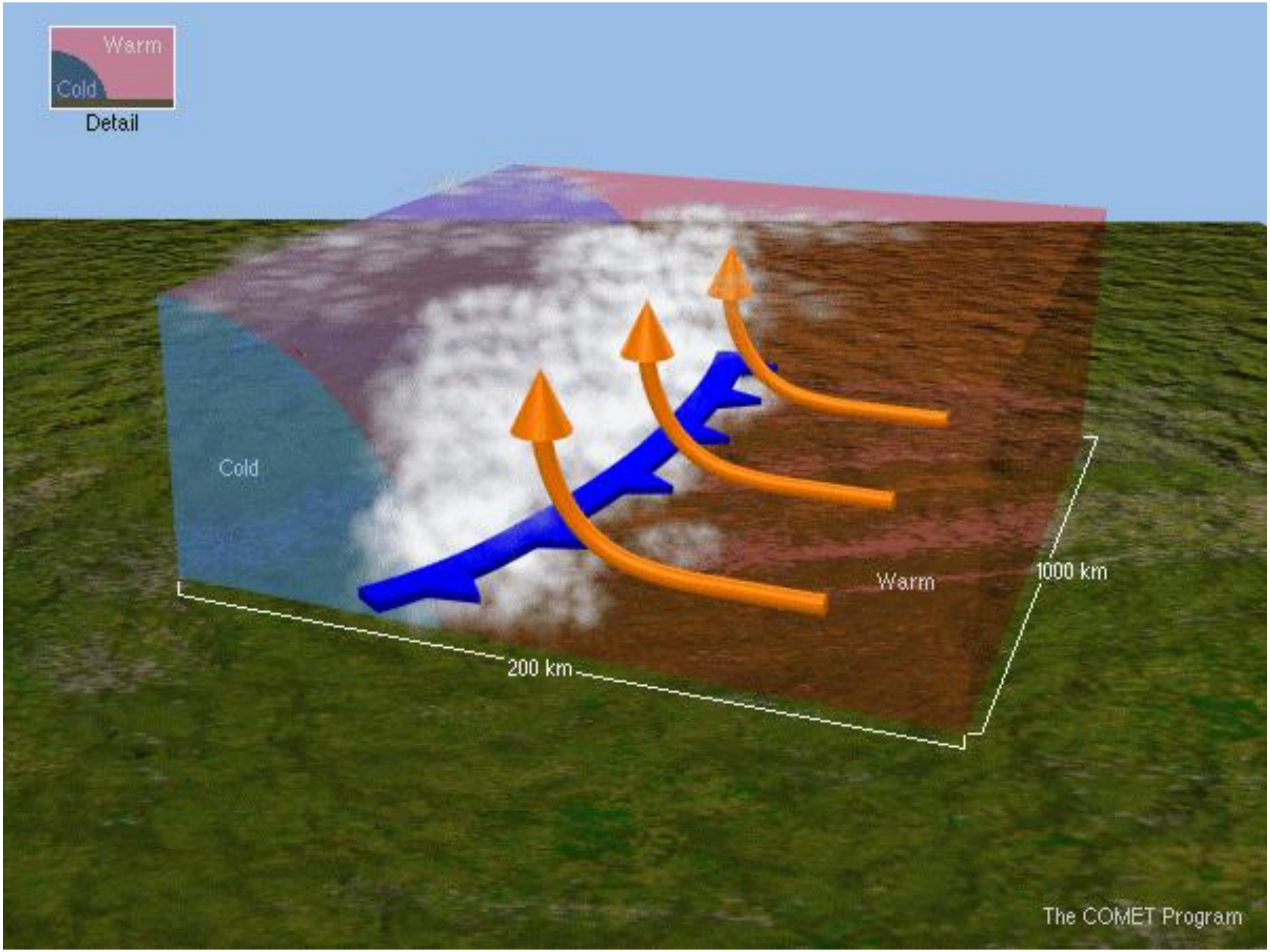
- Tipologie di fronte freddo: se l'aria calda che precede l'aria fredda è convettivamente stabile → nubi = Ns con forti precipitazioni e possibile presenza di nubi basse (Sc);
- Se invece l'aria calda è convettivamente instabile → nubi = Cb con forti rovesci e/o a temporali, precipitazioni più intense ma in zone ristrette; dietro il fronte, Ac

Typical Cold Front Structure

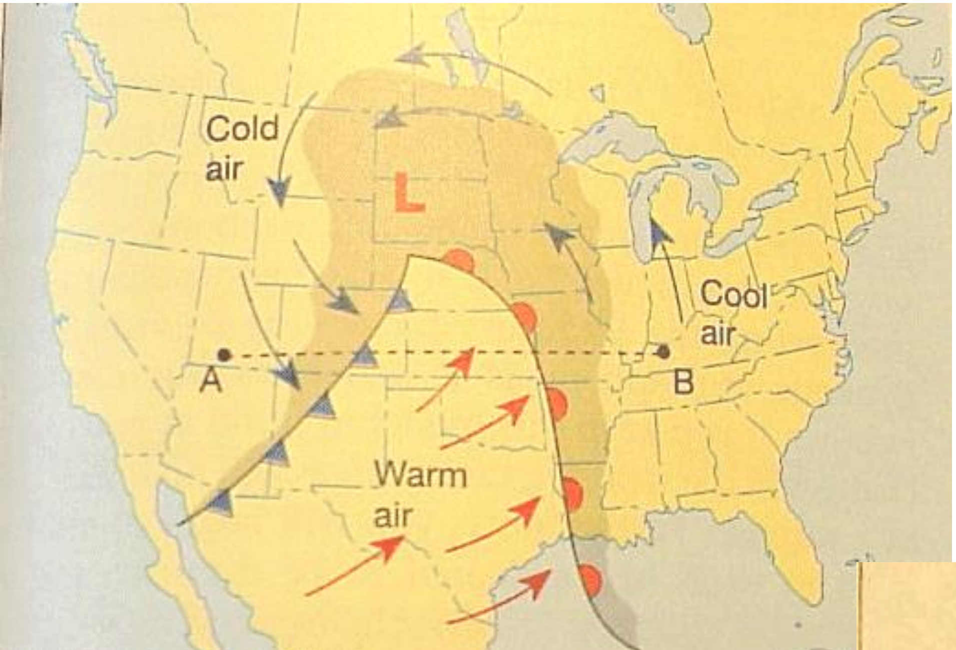
- Cold air replaces warm; leading edge is steep in fast-moving front shown below due to friction at the ground
  - Strong vertical motion and unstable air forms cumuliform clouds
  - Upper level winds blow ice crystals downwind creating cirrus and cirrostratus
- Slower moving fronts have less steep boundaries and less vertically developed clouds may form if warm air is stable



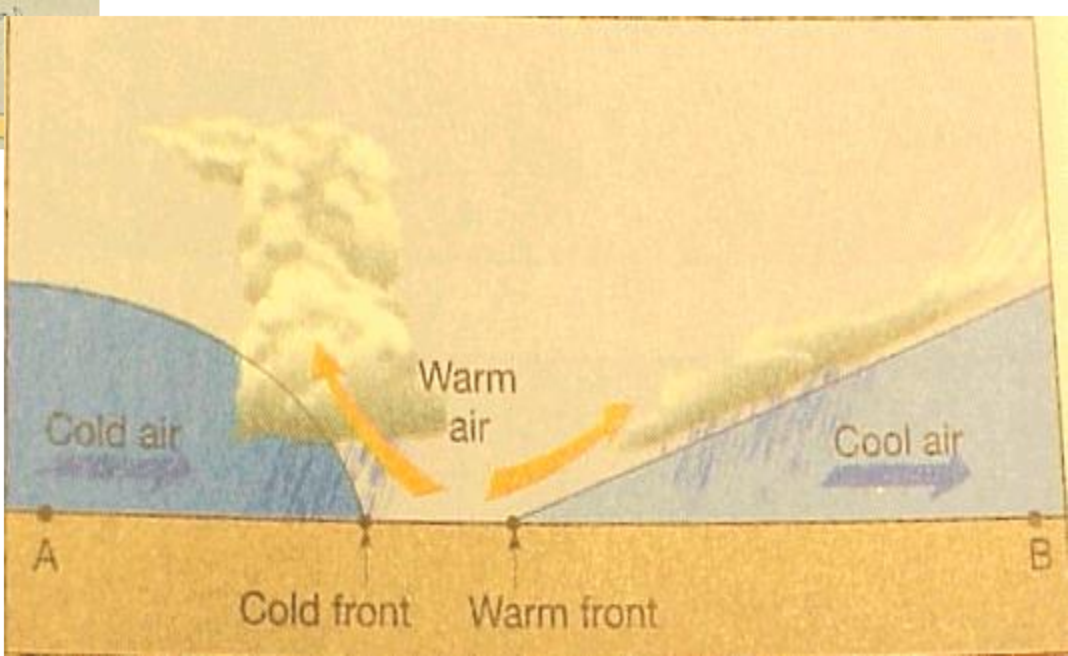
Cold front structure



Mature Wave Cyclone



(a) Mature wave cyclone



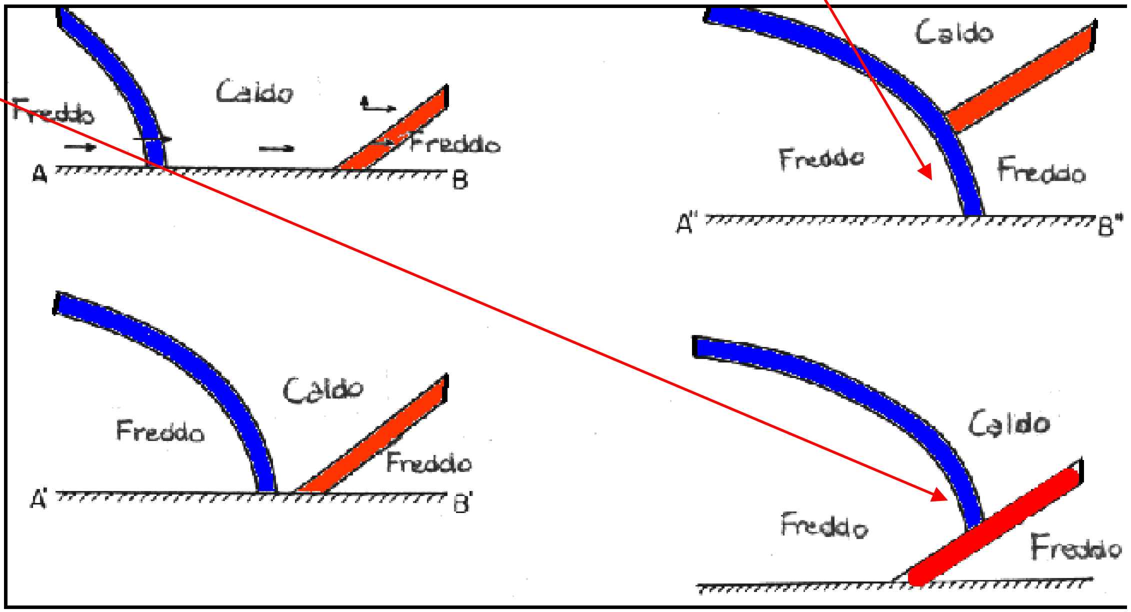
Fronte occluso

- A mano a mano che il settore caldo si chiude fino quasi a scomparire dalla superficie del suolo ed a rimanere solamente in quota, si forma il fronte occluso
- Si distinguono due tipi di occlusioni:

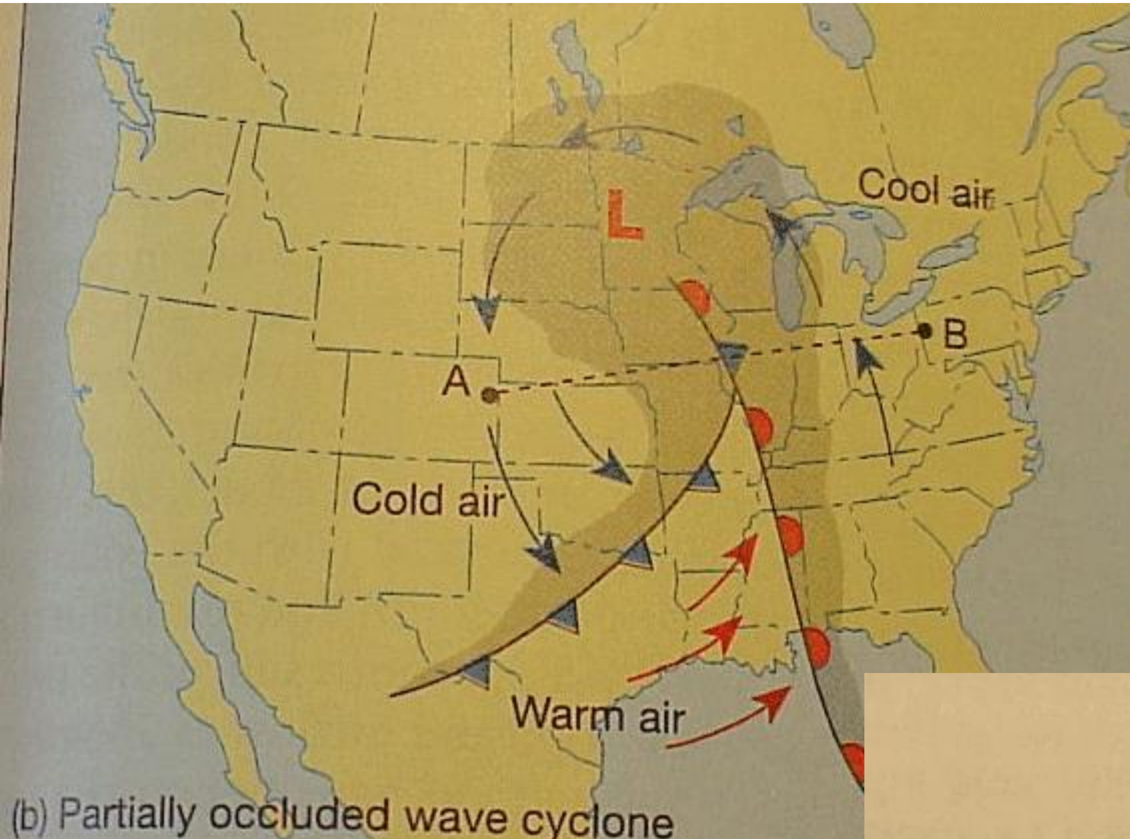
fredda (l'aria dietro al fronte freddo è più fredda di quella davanti al fronte caldo → agisce come un cuneo → il fronte al suolo ha carattere freddo)

calda (l'aria dietro al fronte freddo è più calda di quella davanti al fronte caldo → sale sopra → il fronte al suolo ha carattere caldo) .

In ogni caso, l'aria calda è sempre sollevata dalla superficie.



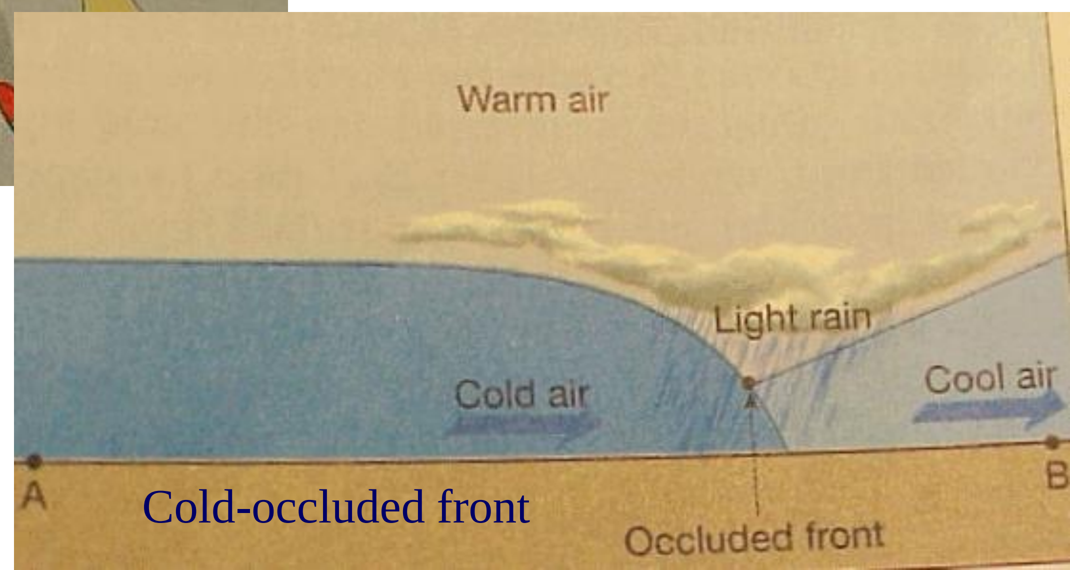
Partially occluded wave cyclone



(b) Partially occluded wave cyclone

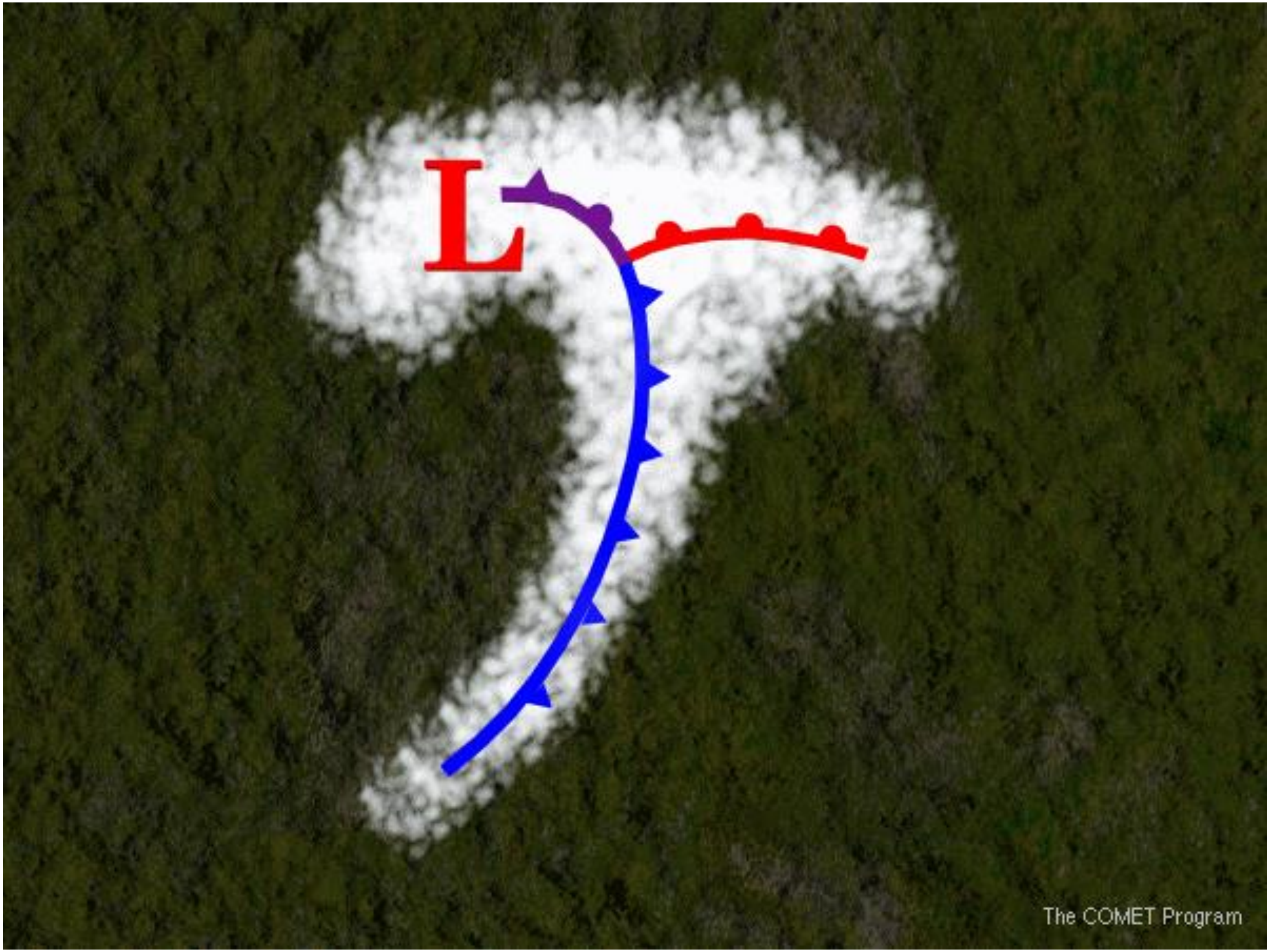
- Cold-occluded front
  - Approach brings weather sequence like a warm front
  - Frontal passage brings weather more like a cold front

- Warm-occluded fronts also possible

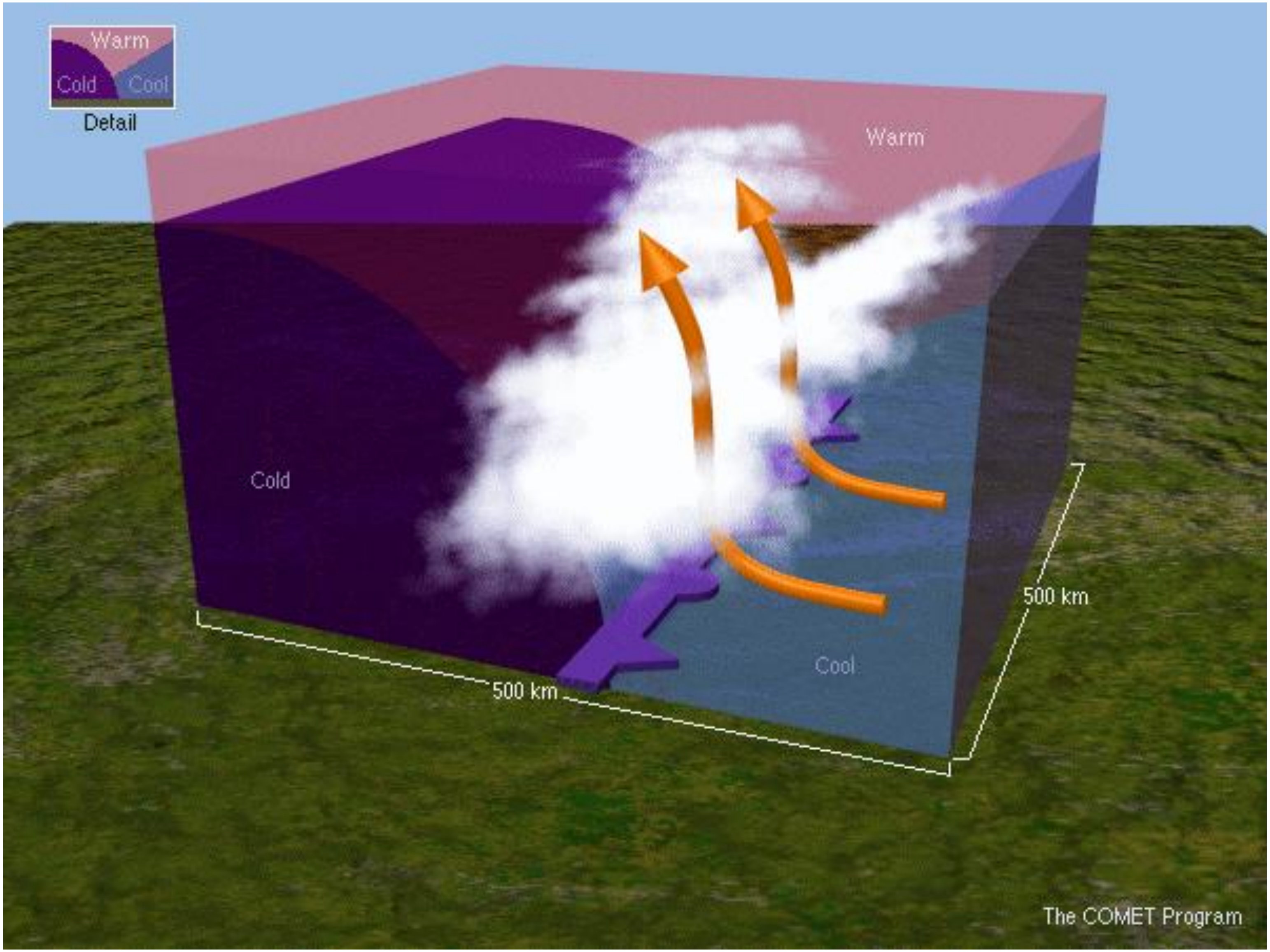


Cold-occluded front

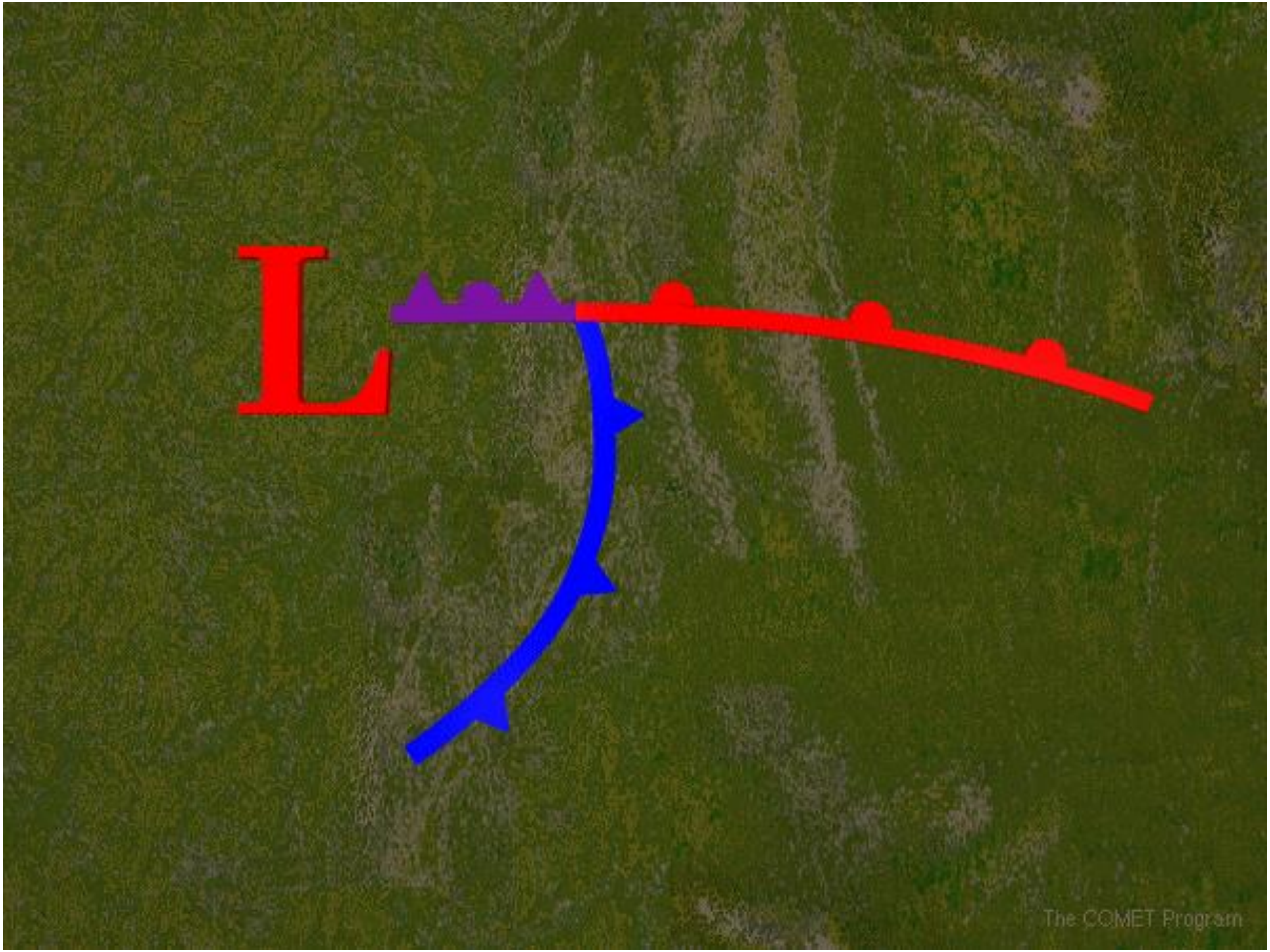
Cold occlusion



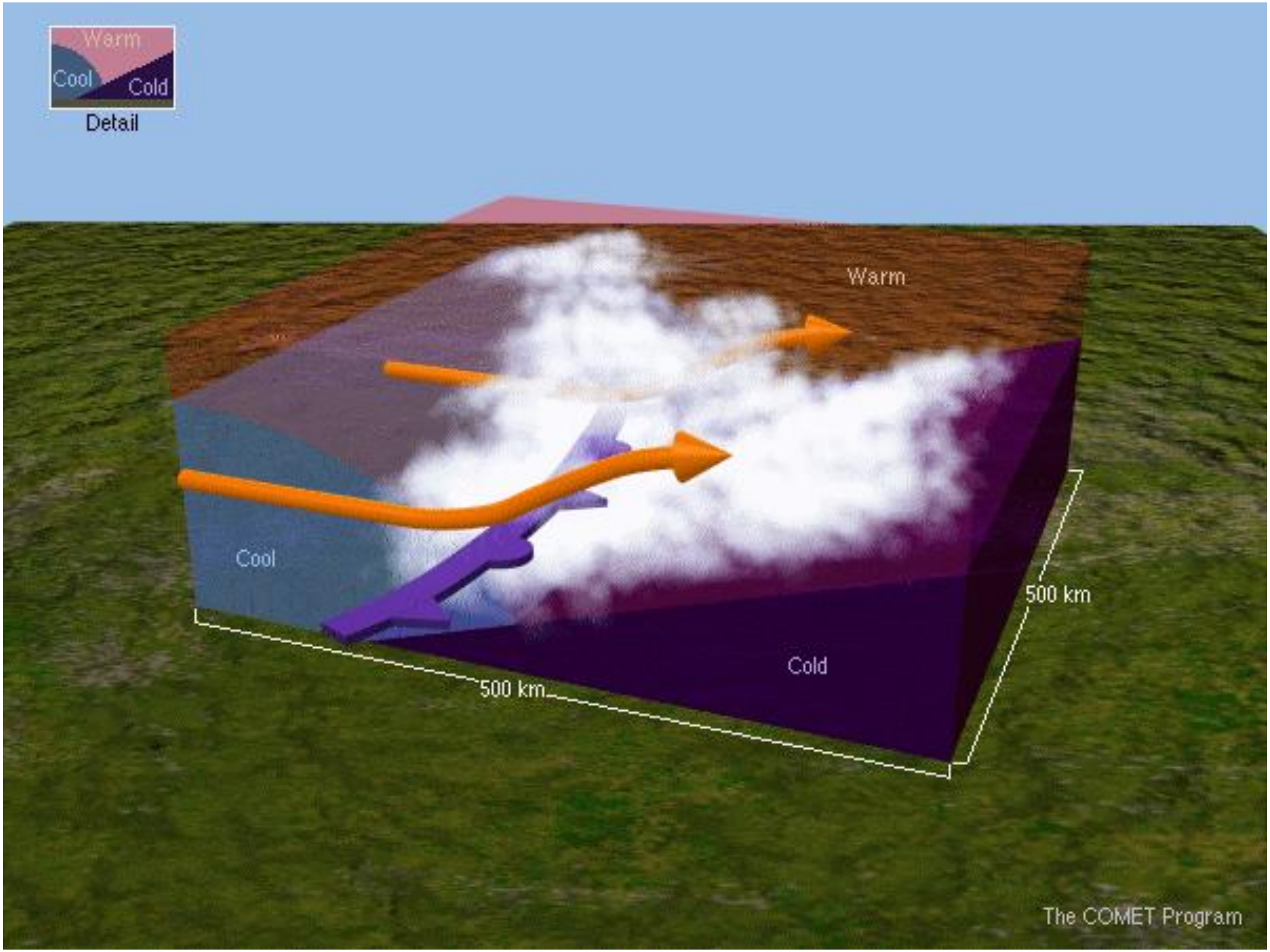
Cold occlusion structure



Warm occlusion



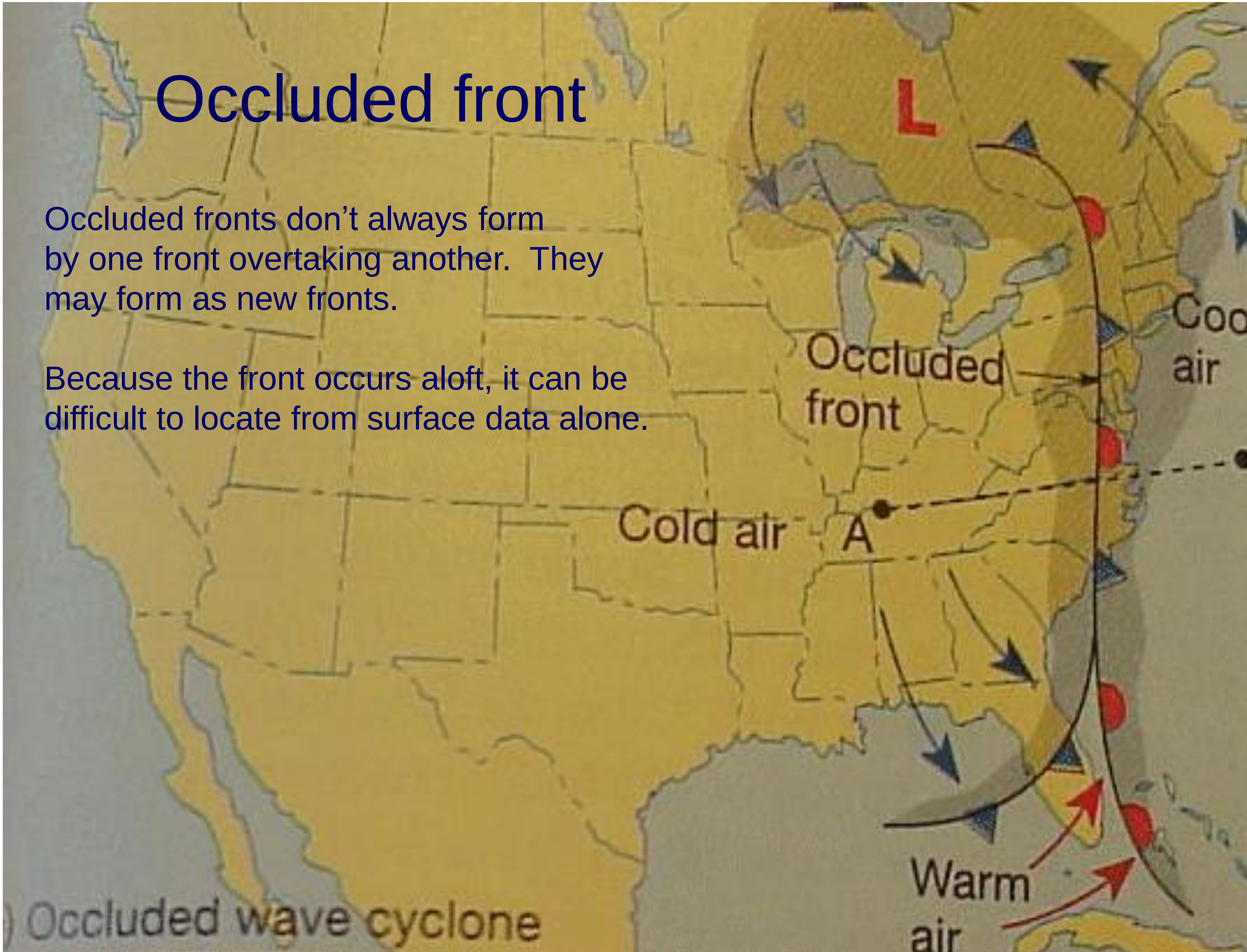
Warm occlusion structure



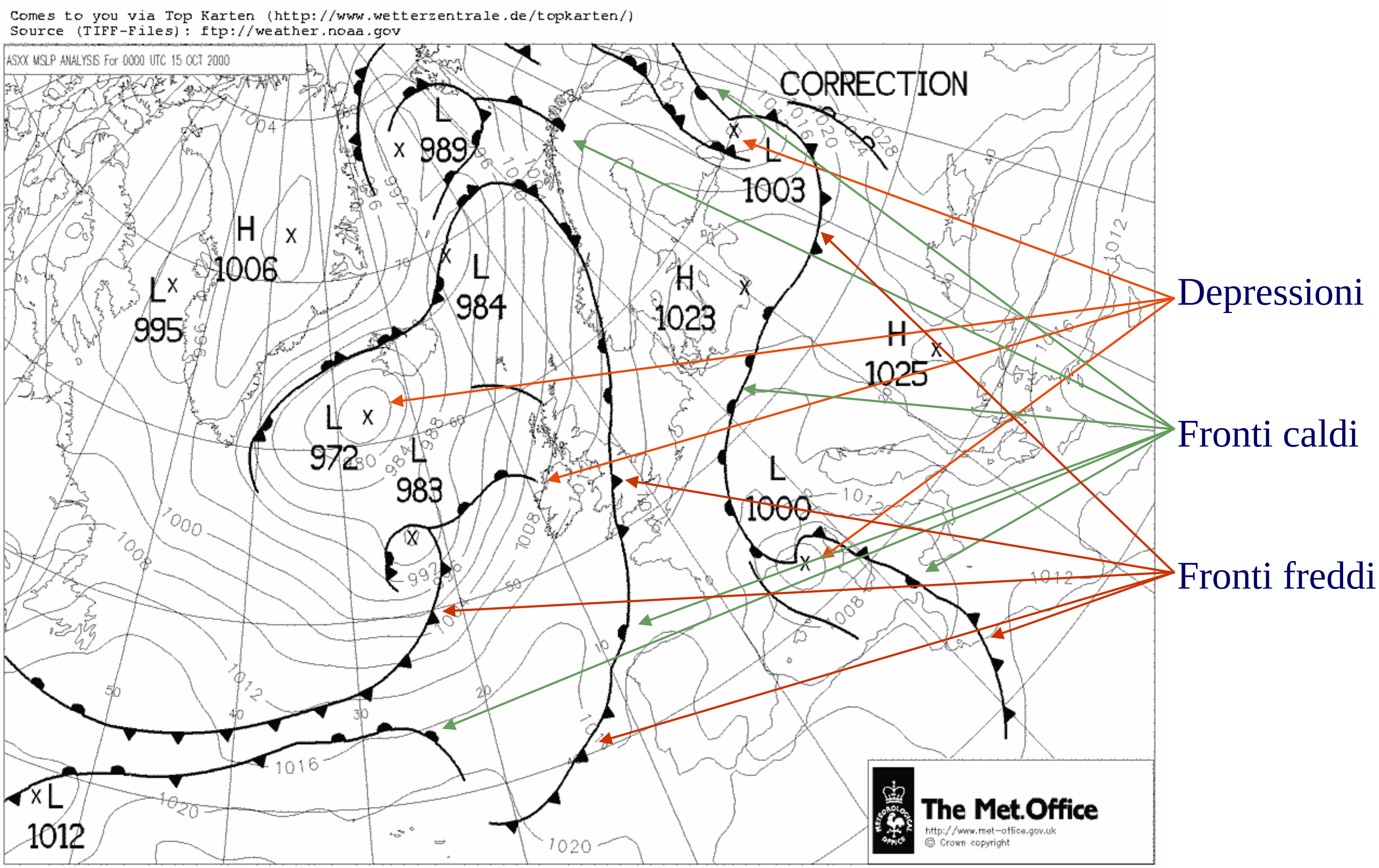
Occluded front

Occluded fronts don’t always form by one front overtaking another. They may form as new fronts.

Because the front occurs aloft, it can be difficult to locate from surface data alone.



Esempio di mappa: alluvione Piemonte 2000

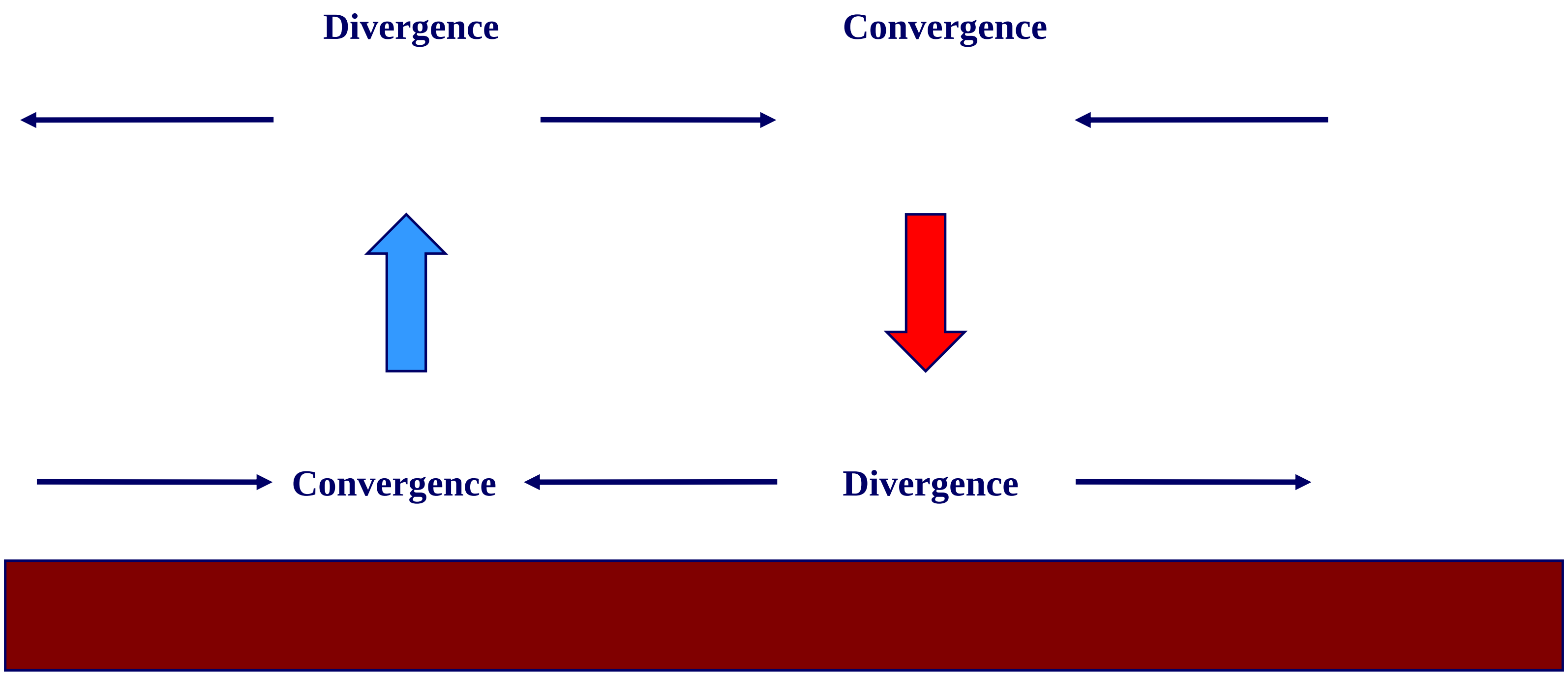


Dynamics, Jets, and Surface Development

- Divergence/Diffluence and Convergence/Confluence
- Vorticity
- Jets and jet-induced circulations
- Connecting upper-level features with surface development and precipitation

Dynamics, Jets, and Surface Development

- Divergence and Convergence



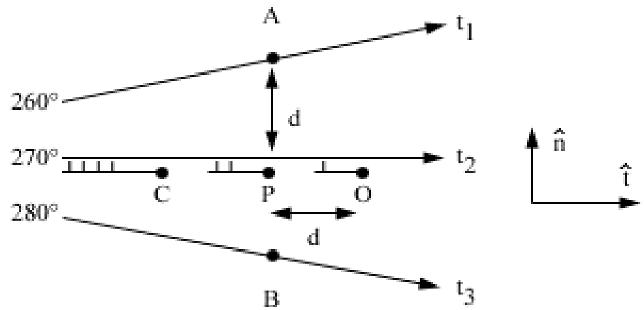
$$\nabla \cdot V\hat{t} = \underbrace{\frac{\partial V}{\partial s}}_{A} - \underbrace{\frac{V\pi}{180} \frac{\partial a}{\partial n}}_{B}$$

A = Speed Divergence

B = Directional Divergence / Diffluence

Divergence

A kinematic property of the atmosphere that measures whether the fluid is "*spreading out*" or "*contracting*".



Winds are in knots

$V_c = 40$ kts $= 20$ ms^{-1}

$V_p = 20$ kts $= 10$ ms^{-1}

$V_o = 10$ kts $= 5$ ms^{-1}

$d = 100$ km

Term A: $\frac{\partial V}{\partial s} = \frac{V_0 - V_C}{2d} = \frac{(5 - 20)\text{ms}^{-1}}{2 \text{ x } 10^5\text{m}} = -7.5 \text{ x } 10^{-5}\text{s}^{-1}$

Term B: $-\frac{V\pi}{180} \frac{\partial \alpha}{\partial n} = -Vp \frac{\pi}{180} \cdot \frac{\alpha_A - \alpha_B}{2d}$

$= -(10 \text{ ms}^{-1}) \cdot \frac{\pi}{180} \cdot \frac{(260^o - 280^o)}{2 \text{ x } 10^5\text{m}}$

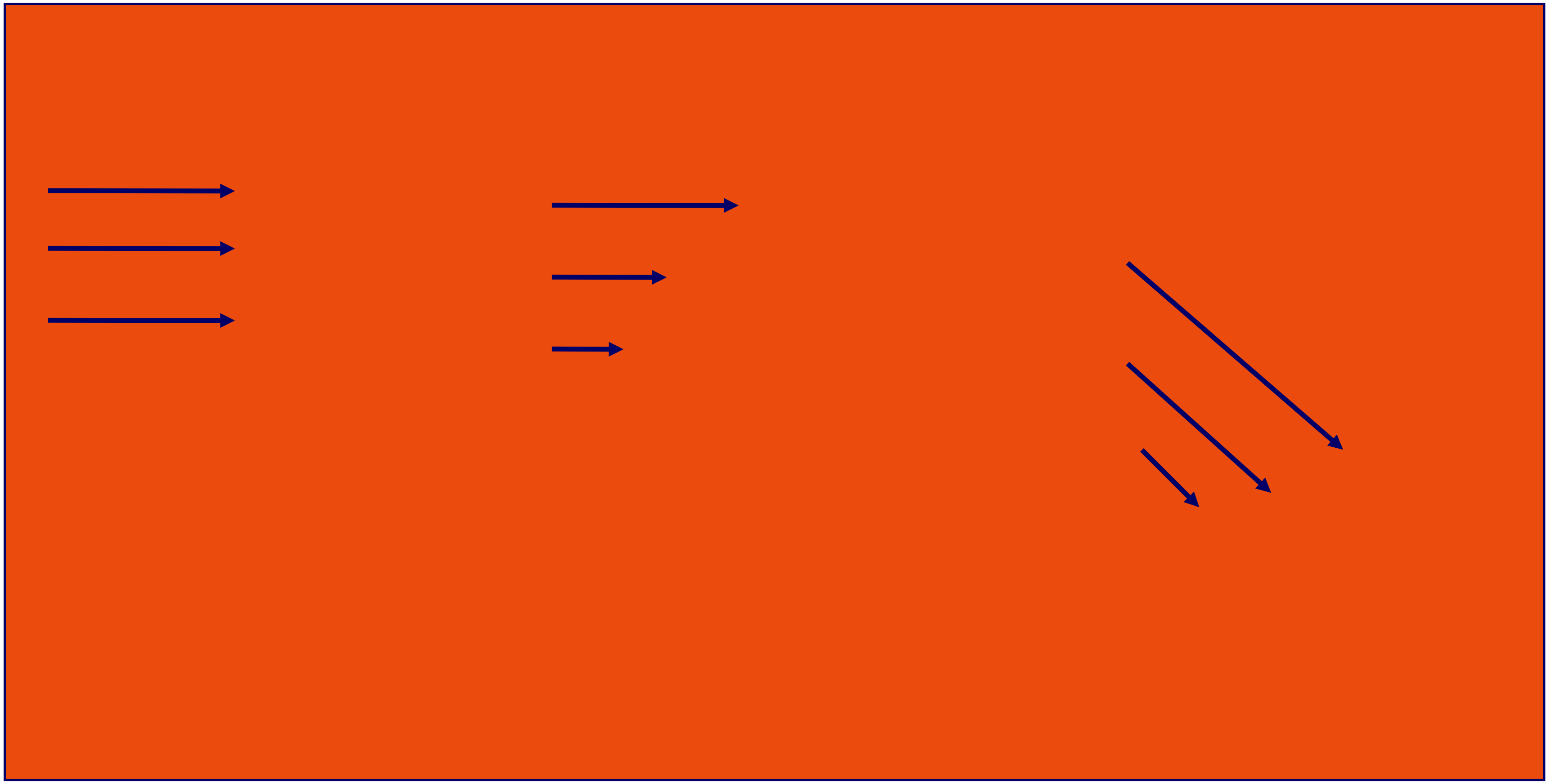
$= +1.7 \text{ x } 10^{-5}\text{s}^{-1}$

Total $= -7.5 \text{ x } 10^{-5}\text{s}^{-1} + 1.7 \text{ x } 10^{-5}\text{s}^{-1} = -5.8 \text{ x } 10^{-5}\text{s}^{-1}$

(Convergence) (Divergence) (Convergence)

Dynamics, Jets, and Surface Development (cont.)

- Vorticity



Vorticity

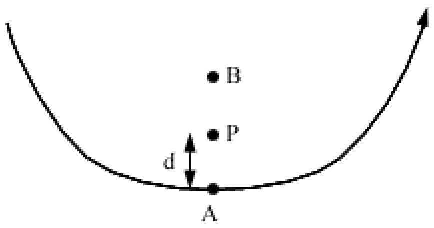
A kinematic property of the atmosphere that measures the "*spin*" of the fluid (i.e., the curl of the velocity).

$$\zeta = \frac{V}{R} - \frac{\partial V}{\partial n}$$

F G

F = Curvature

G = Speed Shear



$R = +600$ km

$V_p = 100$ kts $= 50$ ms^{-1}

$V_A = 120$ kts $= 60$ ms^{-1}

$V_B = 80$ kts $= 40$ ms_{-1}

$d = 100$ km

$$\text{Term F: } \frac{V}{R} = \frac{V_p}{R} = \frac{50\ ms^{-1}}{6 \times 10^5\ m} = +\ 8.3 \times 10^{-5} s^{-1}$$

$$\text{Term G: } -\frac{\partial V}{\partial n} = -\frac{(V_B - V_A)}{2d} = -\frac{(40 - 60)\ ms^{-1}}{2 \times 10^5\ m}$$

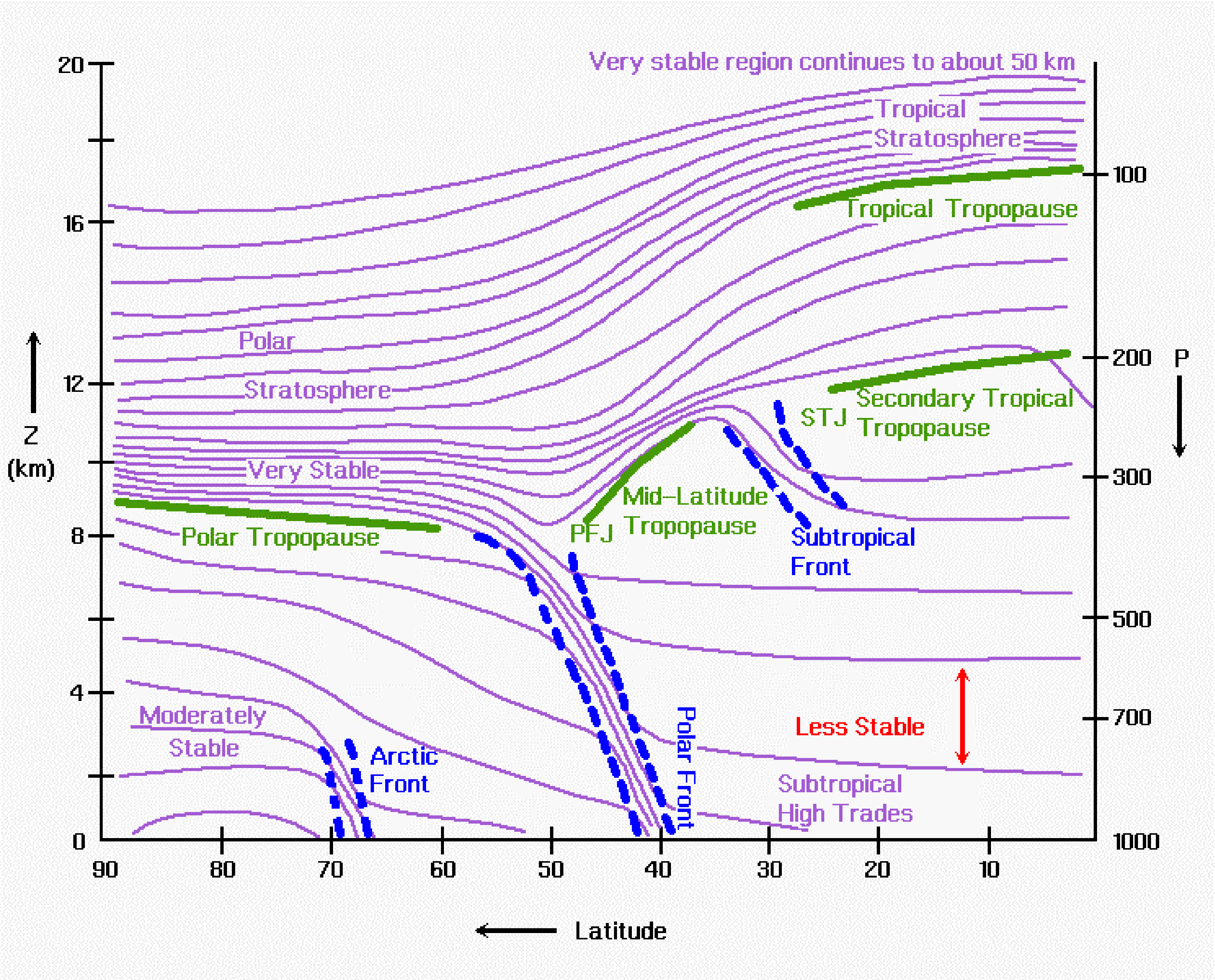
$$-\frac{\partial V}{\partial n} = -\frac{(40 - 60)\ ms^{-1}}{2 \times 10^5 m} = 10 \times 10^{-5} s^{-1}$$

$$\zeta = +\ 8.3 \times 10^{-5} s^{-1} + 10 \times 10^{-5} s^{-1}$$

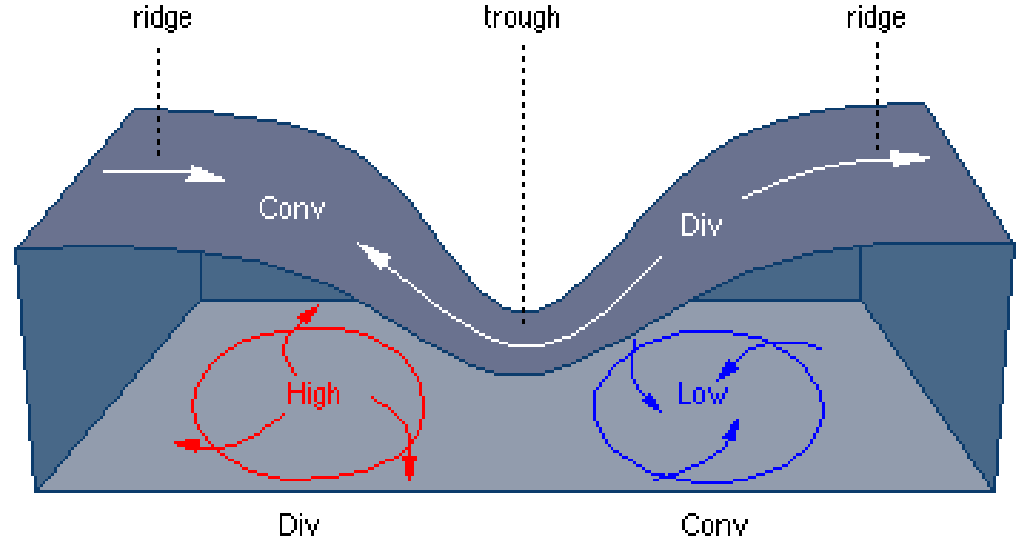
Therefore $\zeta = 18.3 \times 10^{-5} s^{-1}$

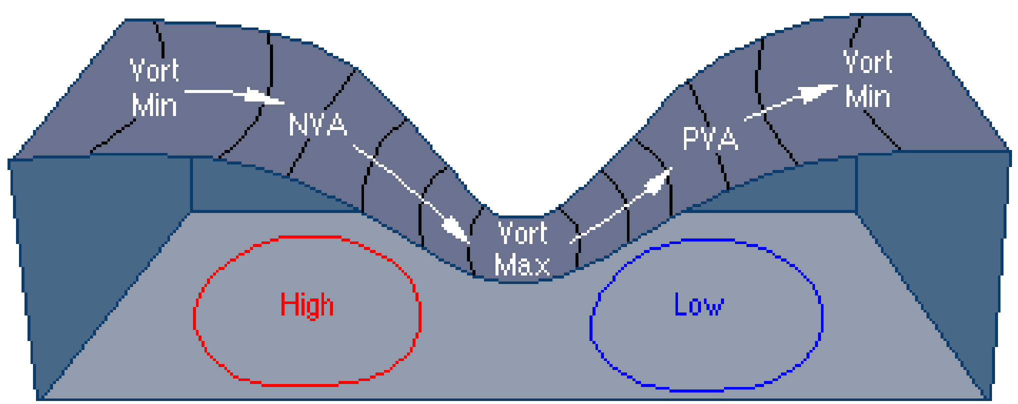
The COMET Program

Fronts and Jets



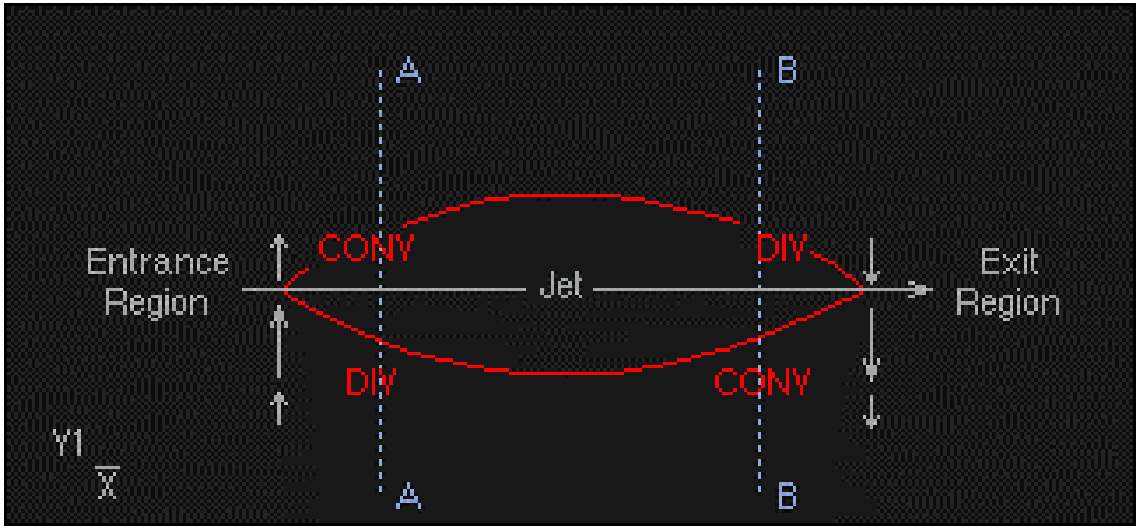
Divergence and Vorticity patterns in an upper-level wave and associated surface system.

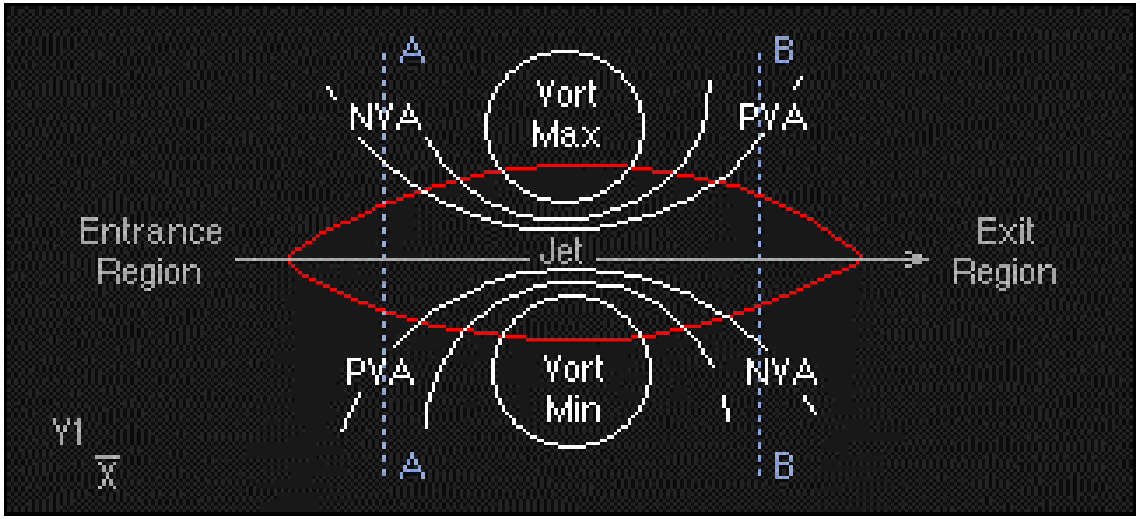




The COMET Program

Divergence and Vorticity patterns in an idealized jet streak.

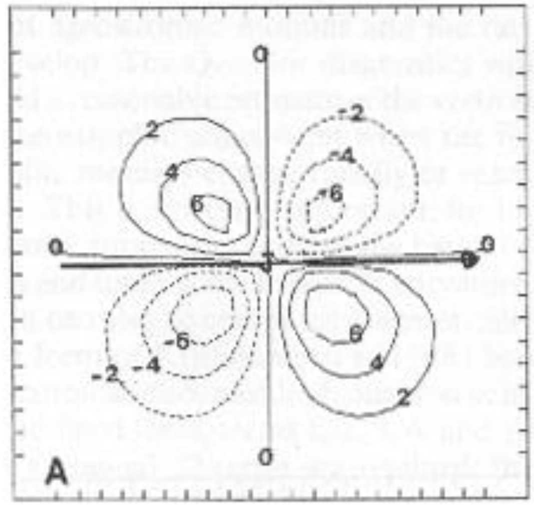




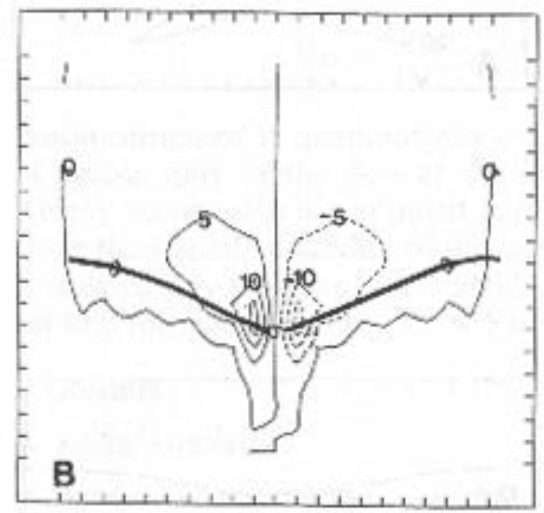
The COMET Program

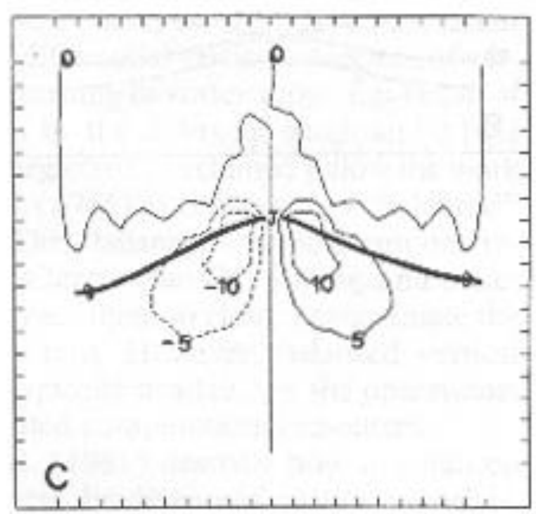
Vertical motions in a jet streak and the effect of curvature

Straight Jet



Cyclonically-curved Jet



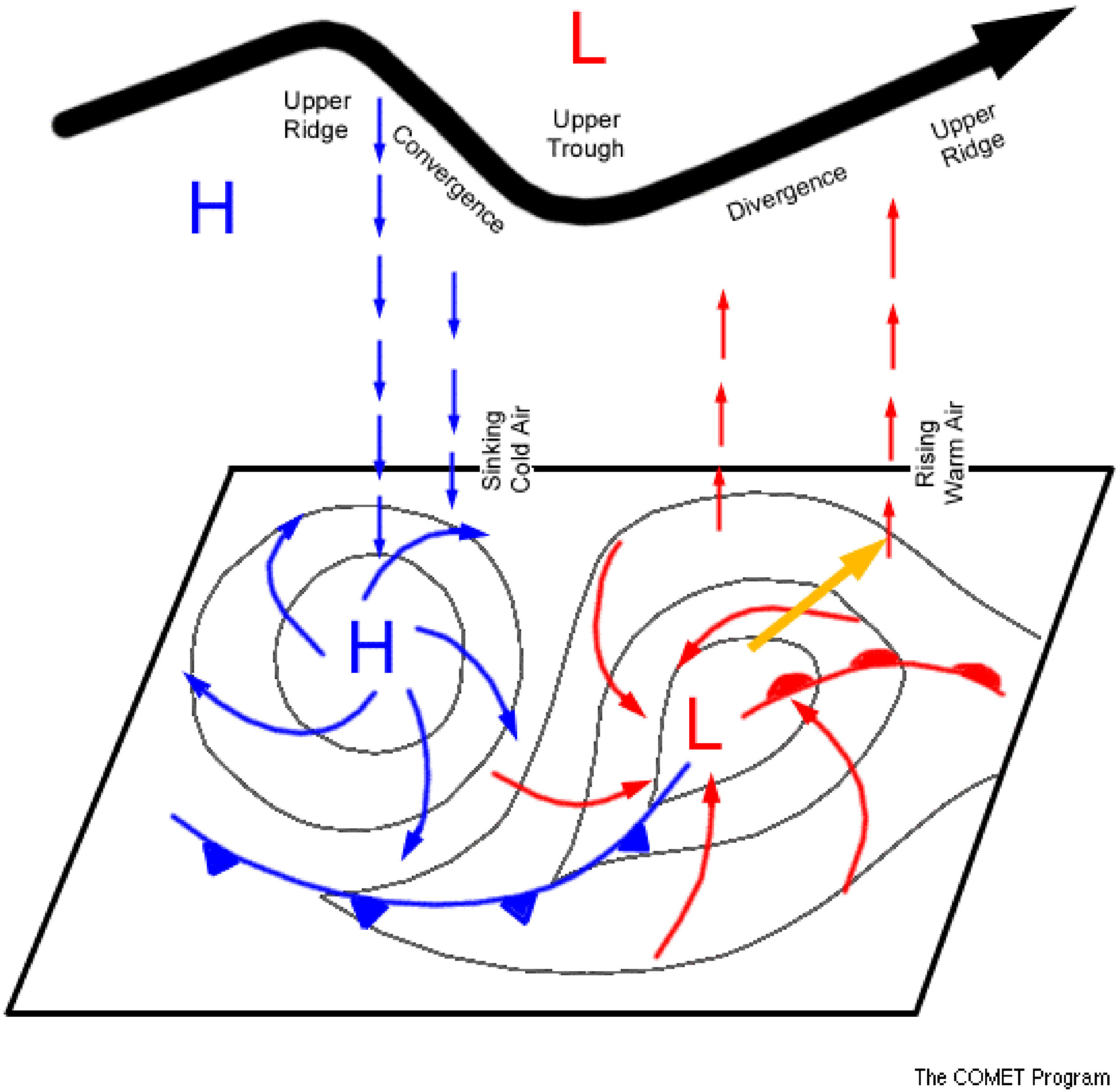


Anticyclonically-curved Jet

The 3-D Atmosphere

Bringing it all together

- Relationship between upper-level and surface processes
- Cyclogenesis
- Conveyor belt processes
- Fancier stuff


L
Upper
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Convergence
Upper
Trough
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Sinking
Cold Air
Rising
Warm Air
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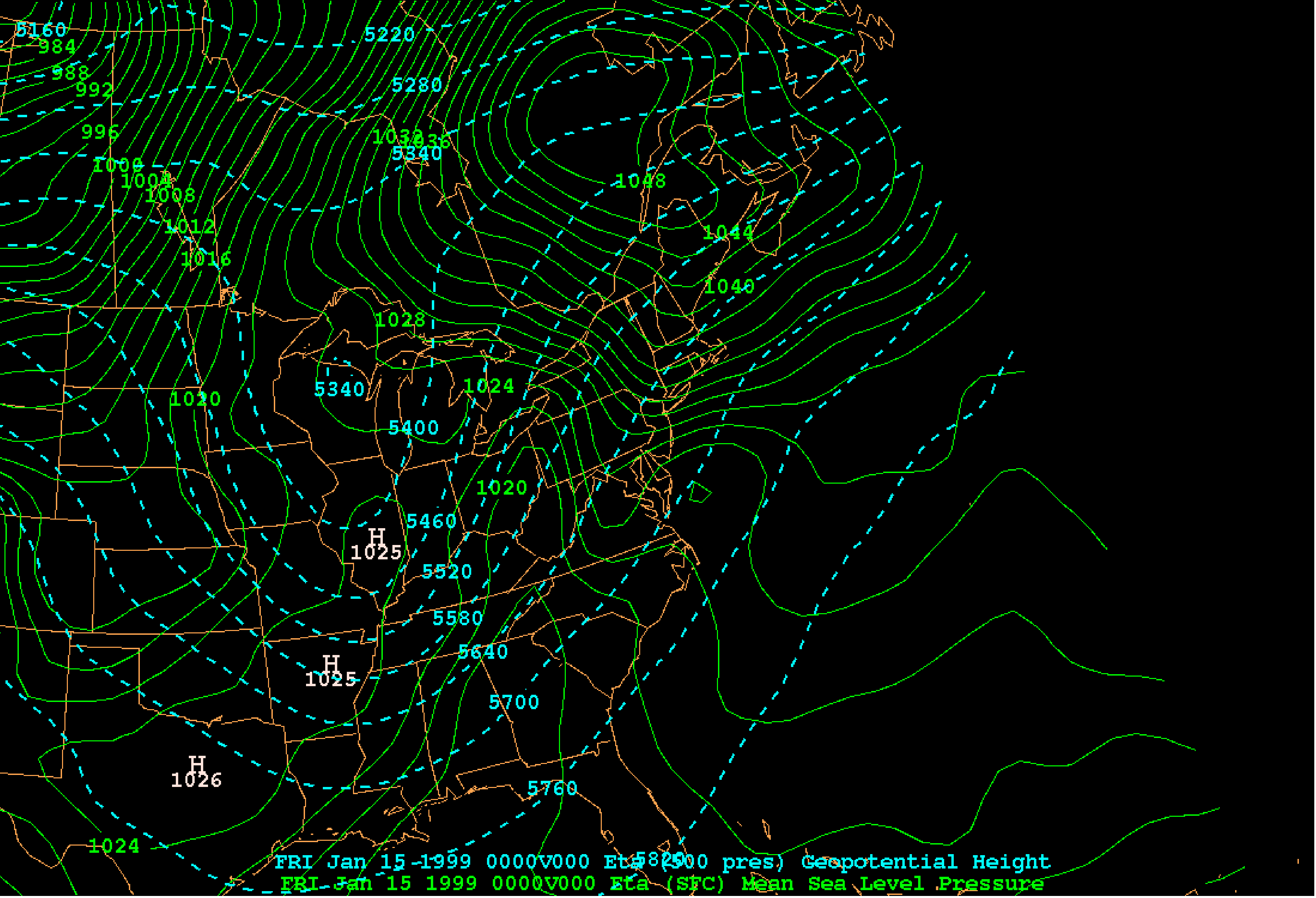
L
The COMET Program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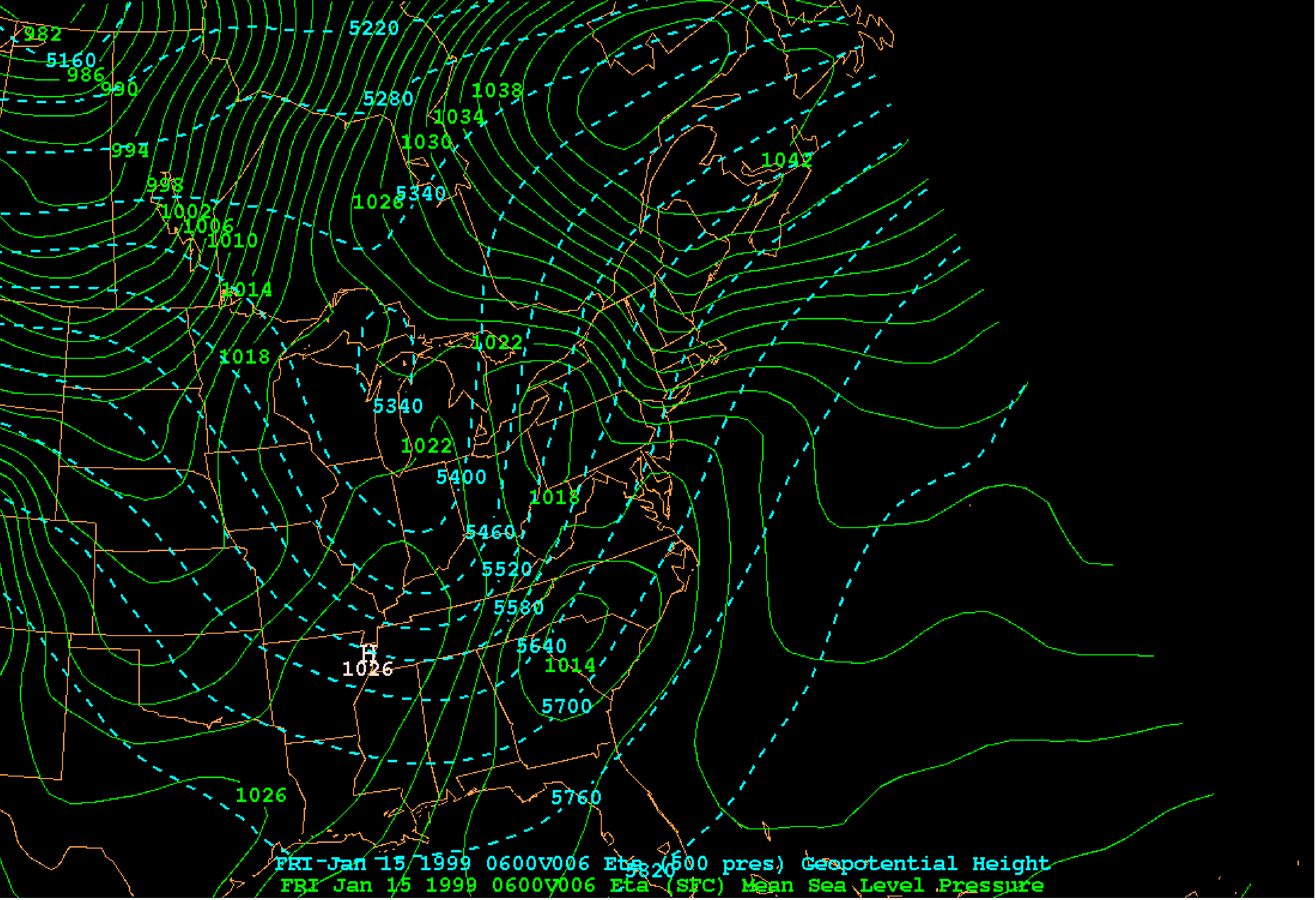
FRI Jan 15 1999 0000V000 Eta (500 pres) Geopotential Height
FRI Jan 15 1999 0000V000 Eta (SFC) Mean Sea Level Pressure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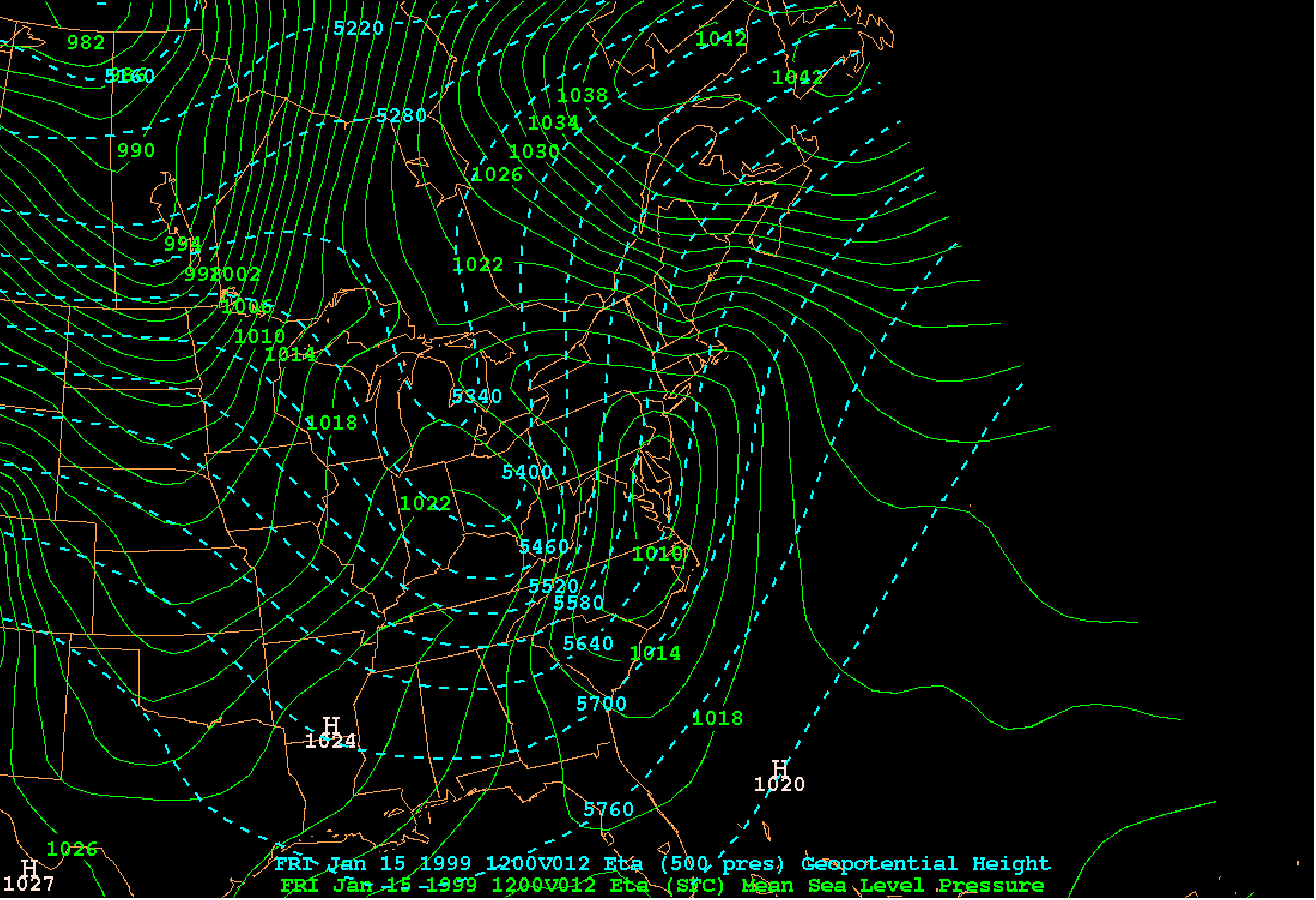
FRI Jan 15 1999 0600V006 Eta (SFC) Mean Sea Level Pressure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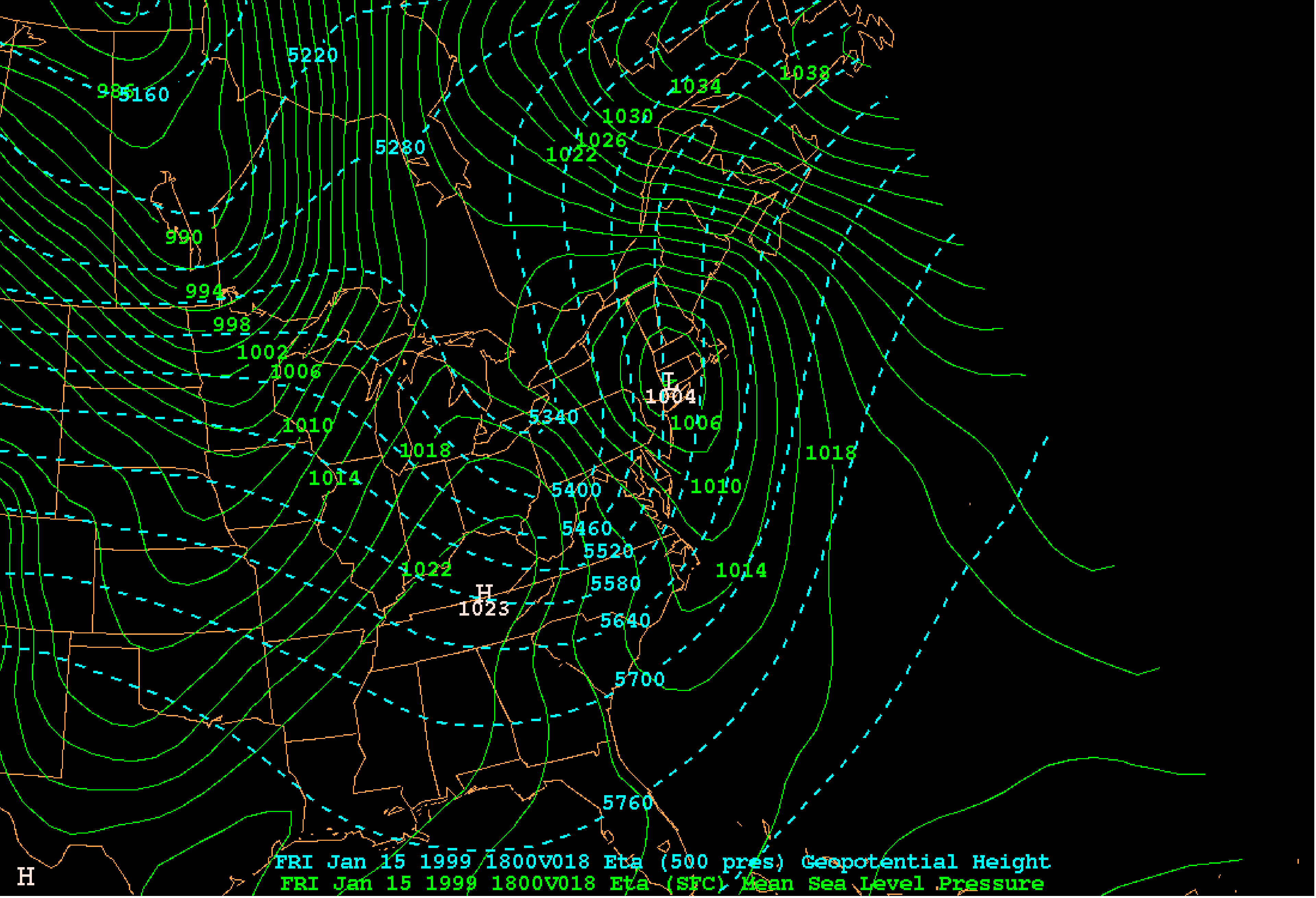
FRI Jan 15 1999 1200V012 Eta (SFC) Mean Sea Level Pressure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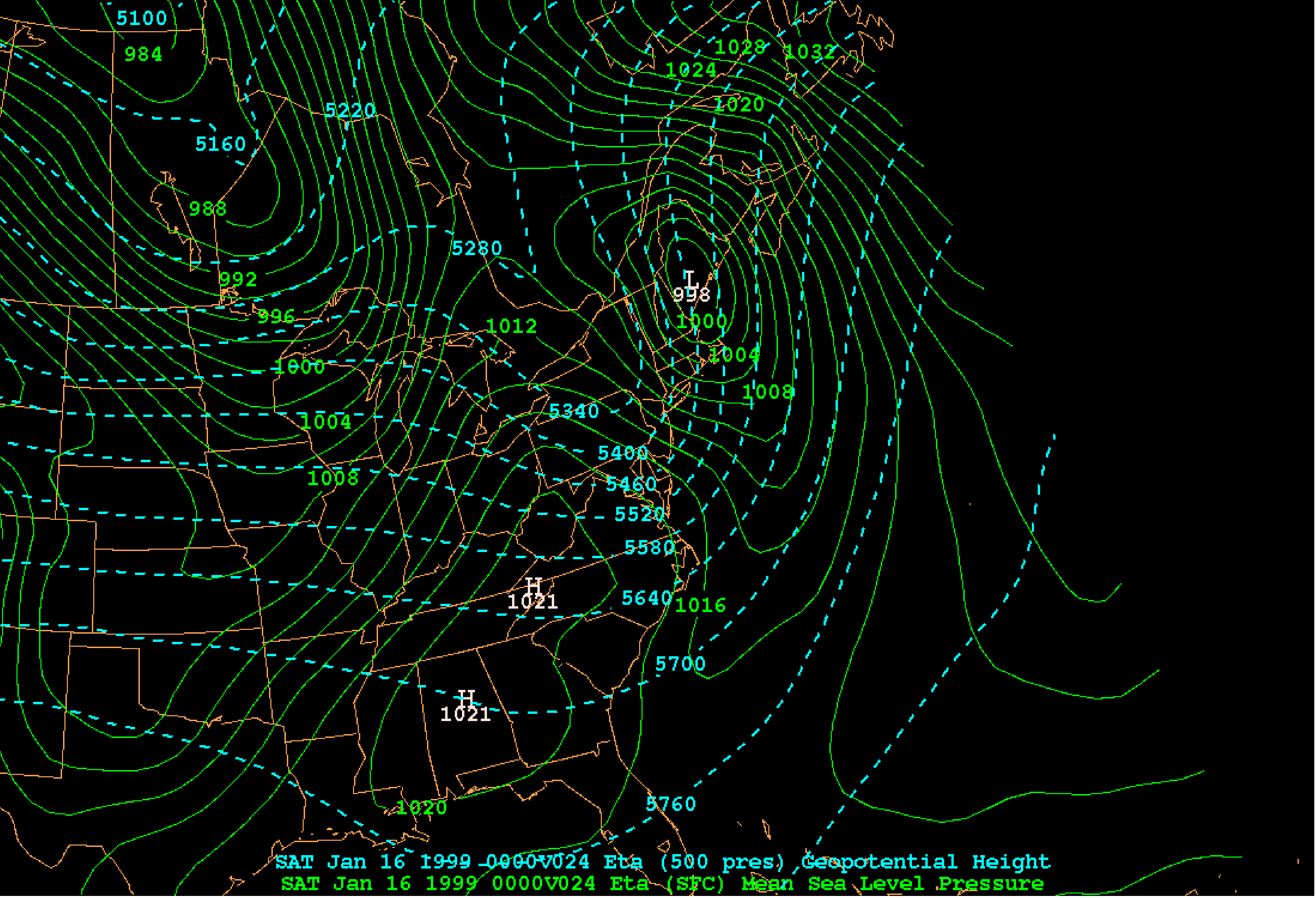
FRI Jan 15 1999 1800V018 Eta (500 pres) Geopotential Height
FRI Jan 15 1999 1800V018 Eta (SFC) Mean Sea Level Pressure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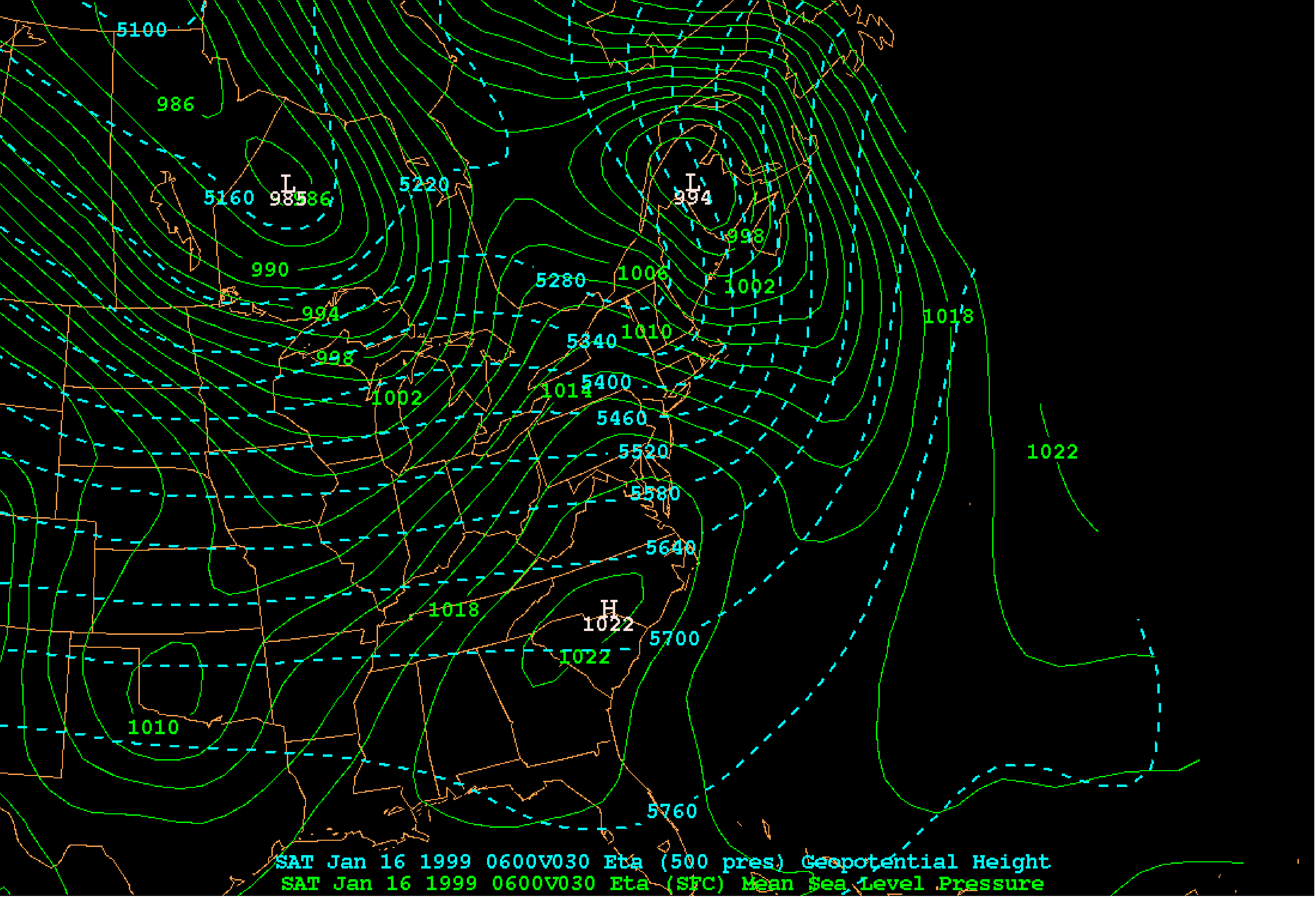
SAT Jan 16 1999 0000V024 Eta (500 pres) Geopotential Height
SAT Jan 16 1999 0000V024 Eta (SFC) Mean Sea Level Pressure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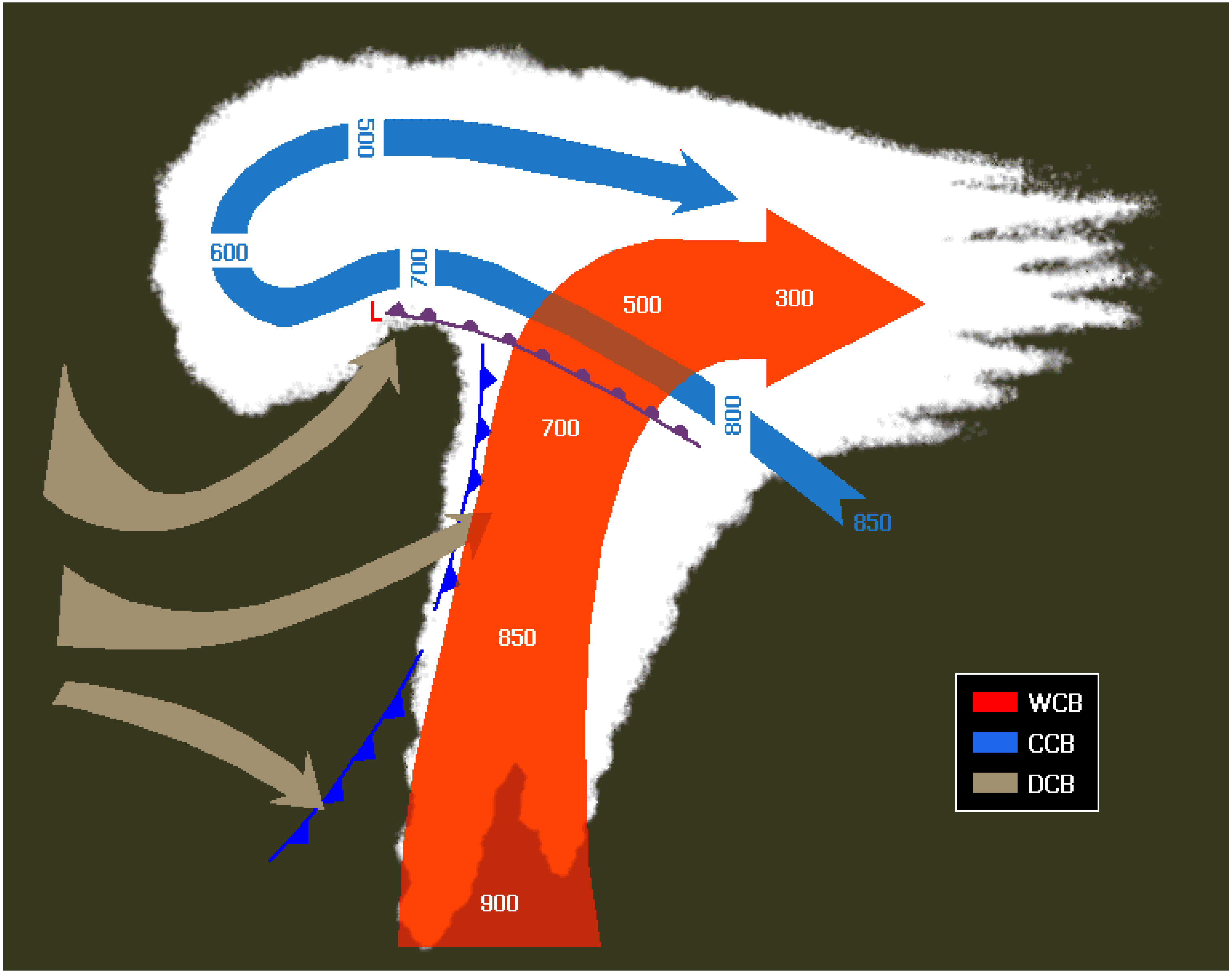
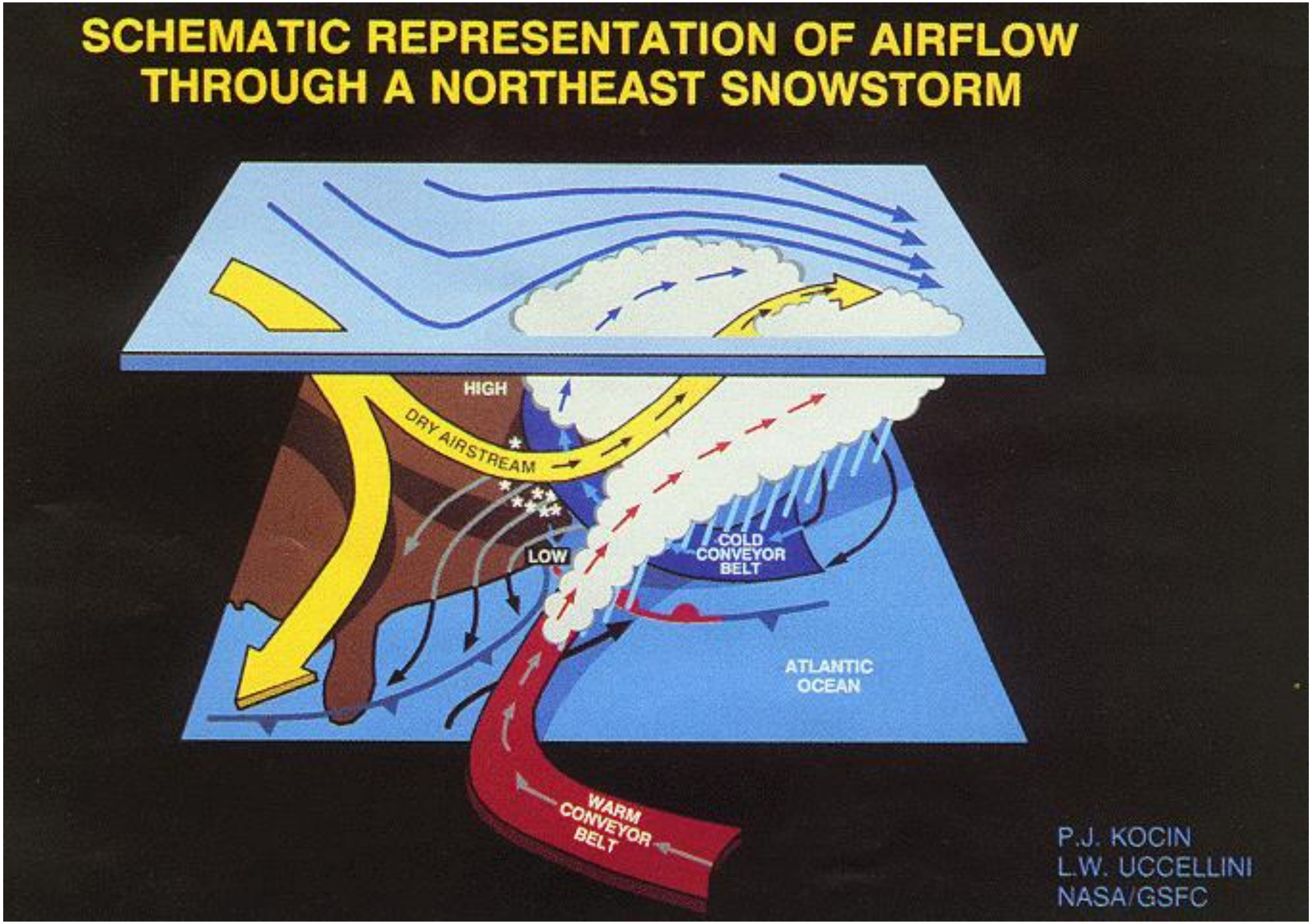
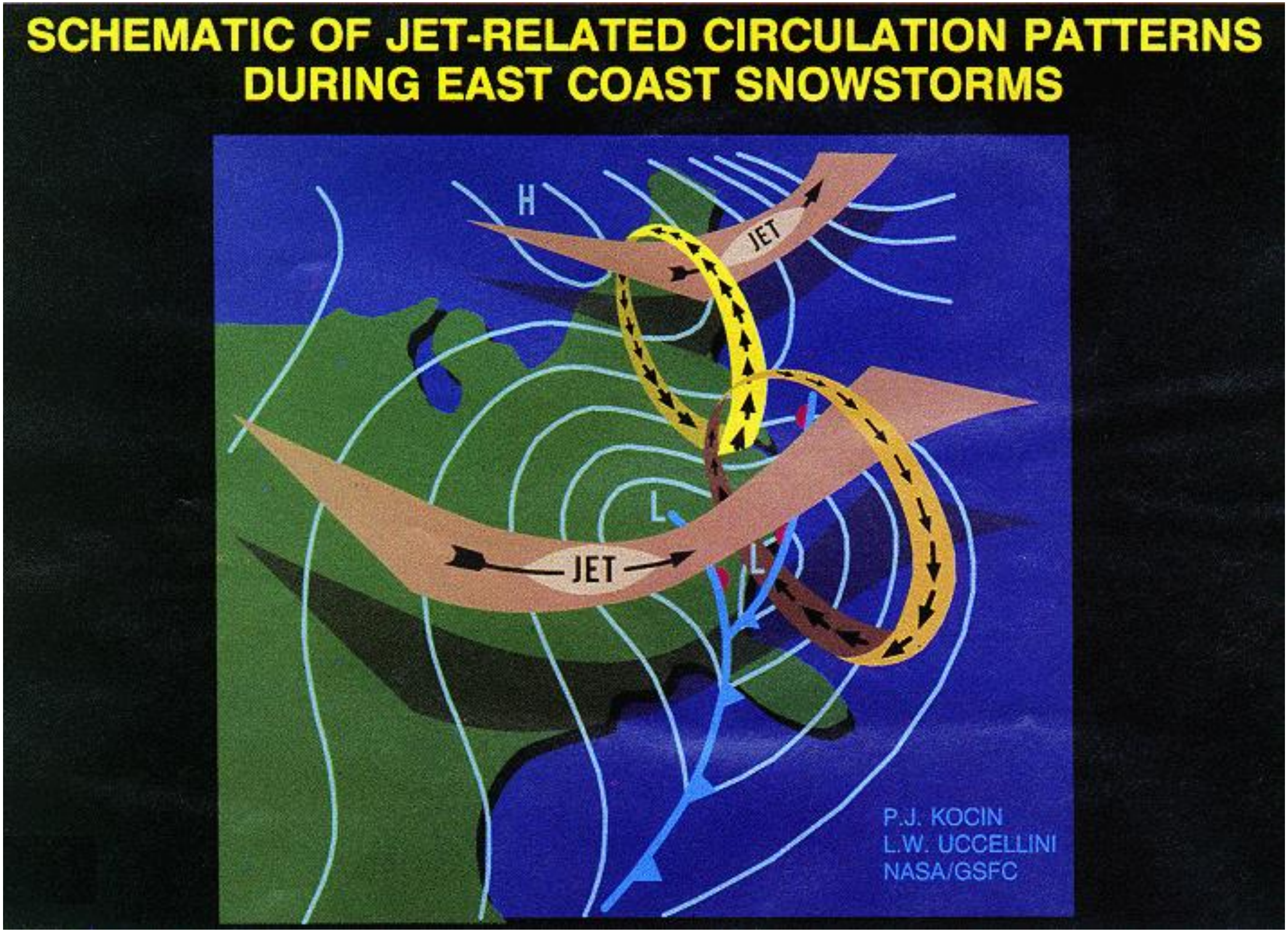
SAT Jan 16 1999 0600V030 Eta (500 pres) Geopotential Height
SAT Jan 16 1999 0600V030 Eta (SFC) Mean Sea Level Pressure

Idealized Conveyer belt flow in a mature cyclone




SCHEMATIC REPRESENTATION OF AIRFLOW THROUGH A NORTHEAST SNOWSTORM
HIGH
DRY AIRSTREAM
LOW
COLD CONVEYOR BELT
ATLANTIC OCEAN
WARM CONVEYOR BELT
P.J. KOCIN
L.W. UCCELLINI
NASA/GSFC


SCHEMATIC OF JET-RELATED CIRCULATION PATTERNS
DURING EAST COAST SNOWSTORMS
H
JET
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JET
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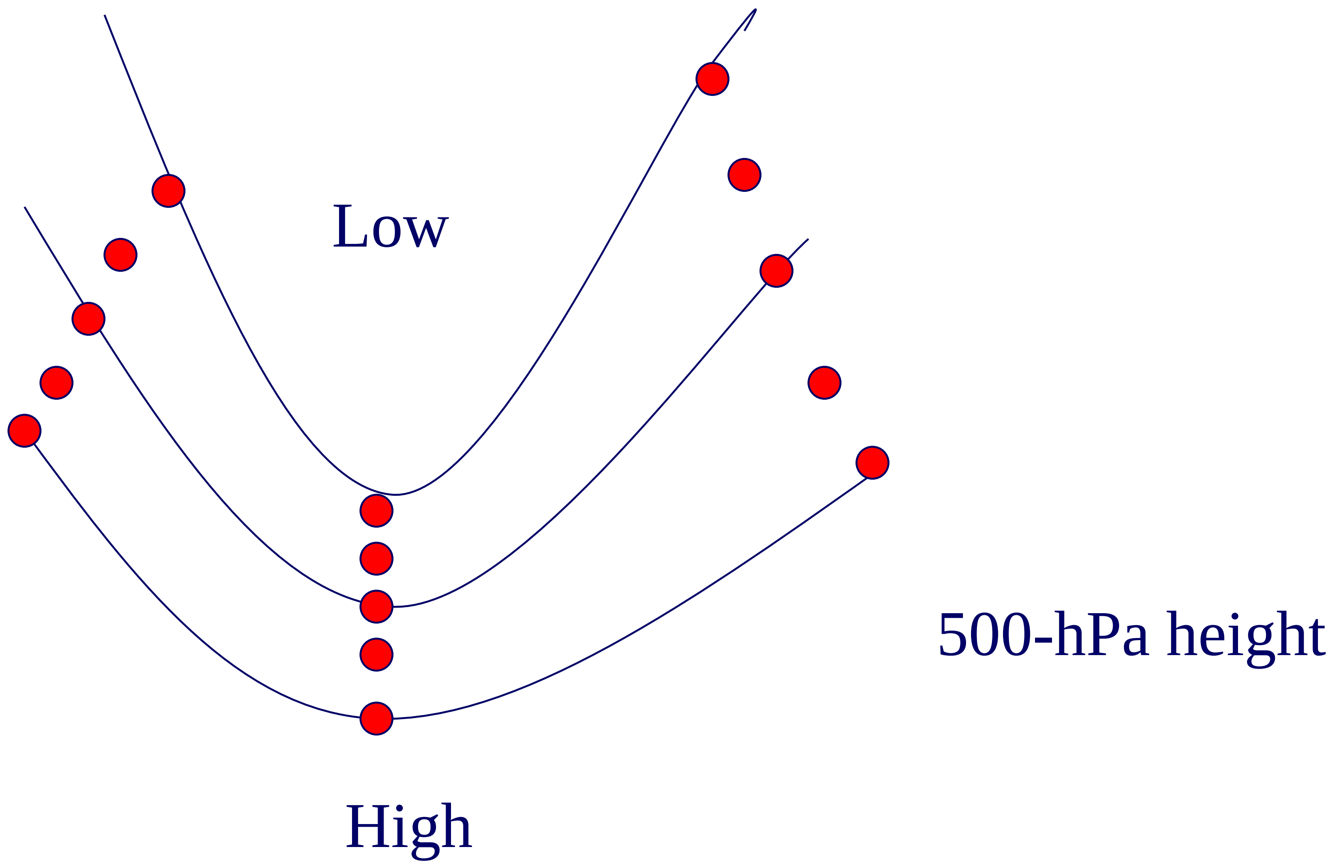
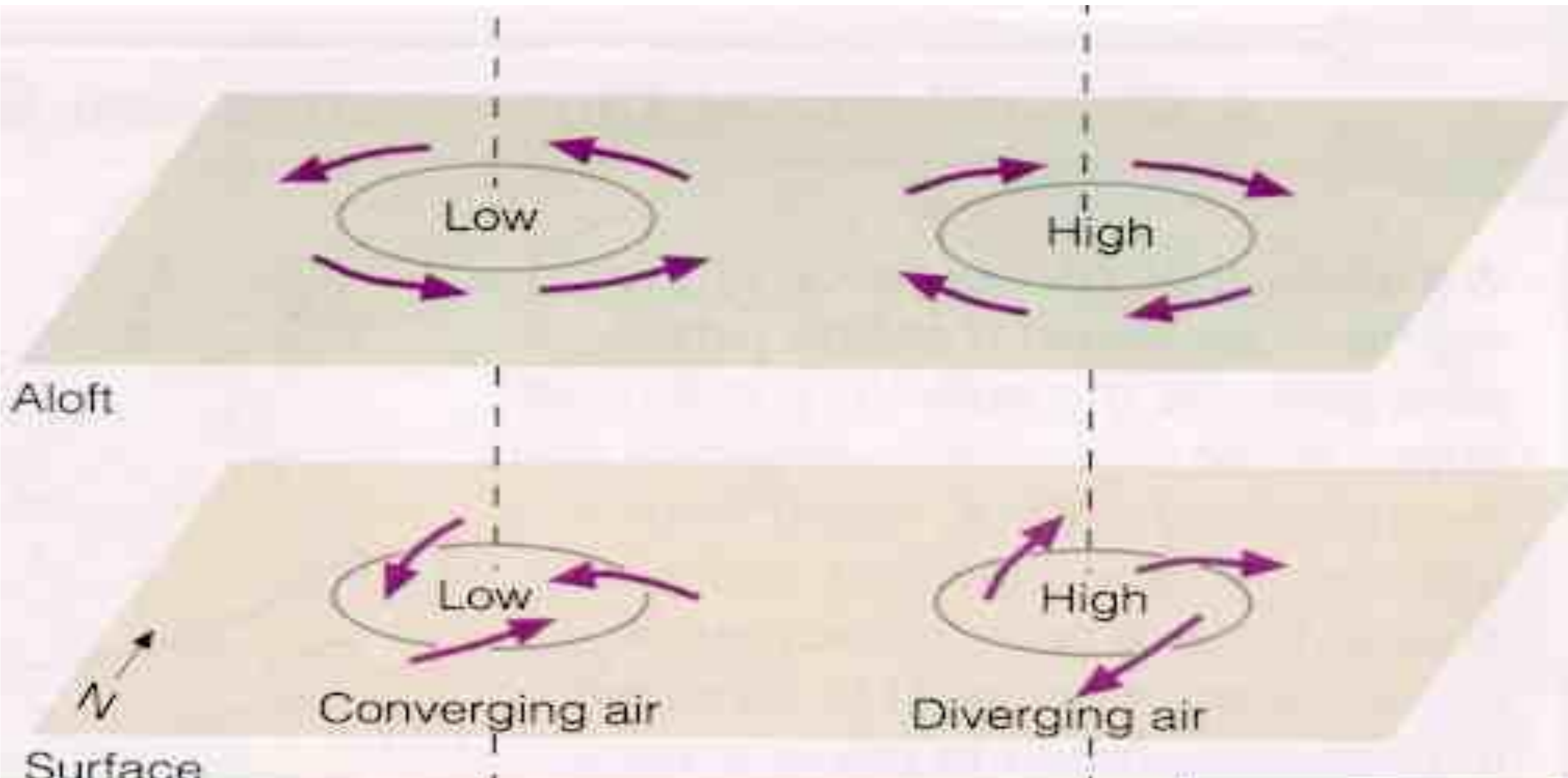
P.J. KOCIN
L.W. UCCELLINI
NASA/GSFC

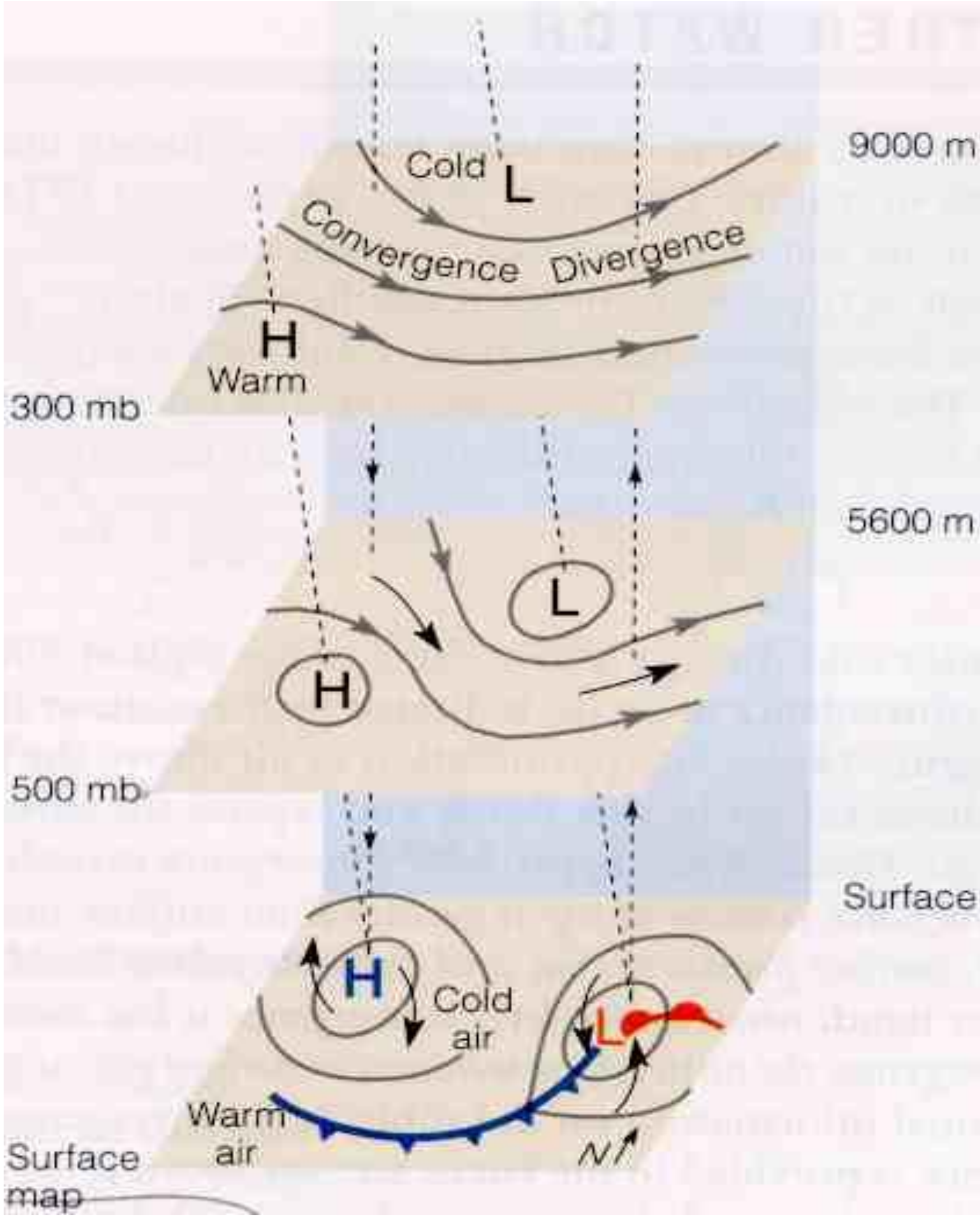
What initiates cyclogenesis?



What maintains the surface low?

Imagine a surface low forming below an upper level low.





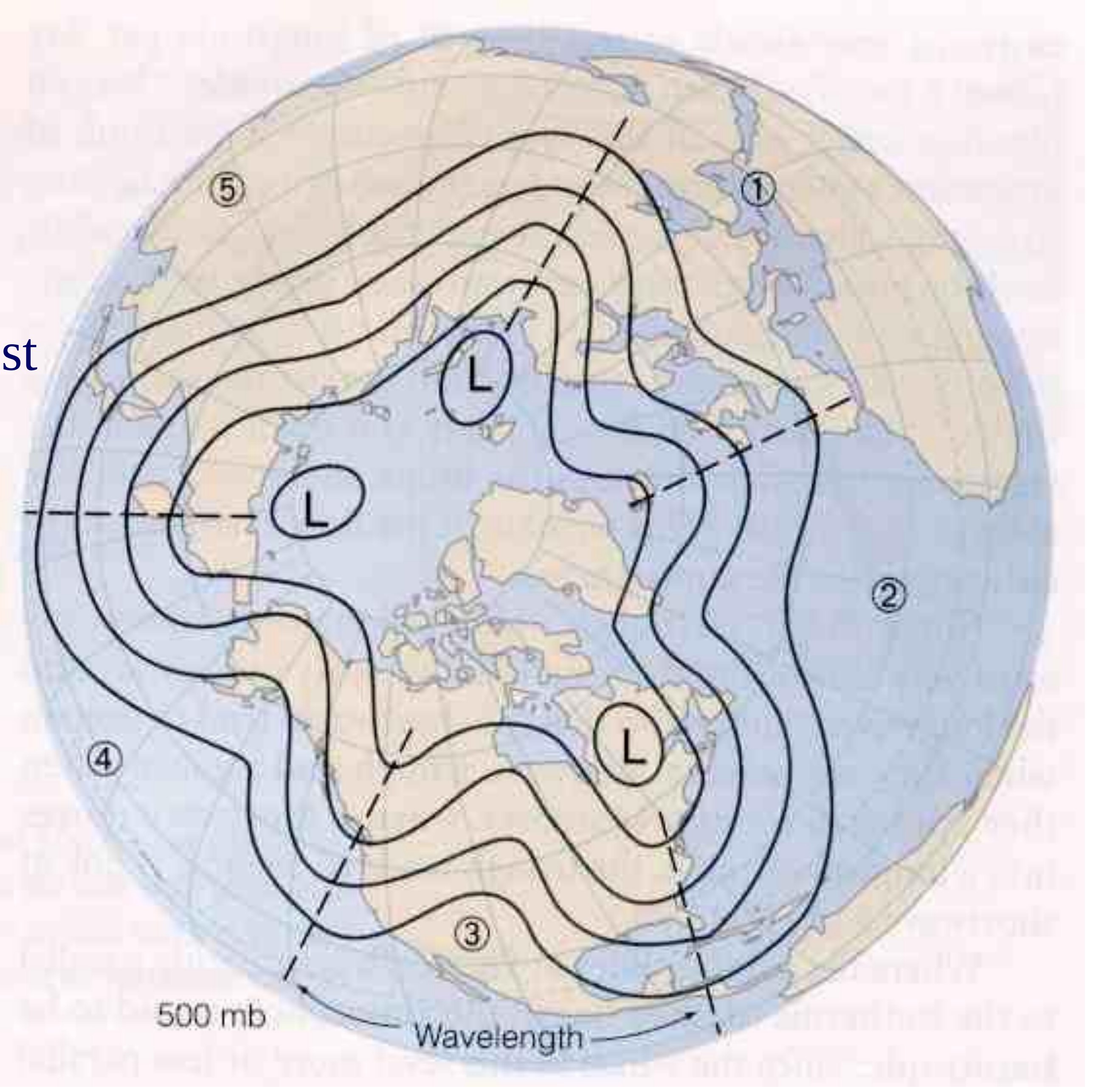
Actual vertical structure:

Upper level low is tilted westward with height with respect to the surface.

UPPER LEVEL DIVERGENCE INITIATES AND MAINTAINS A SURFACE LOW.

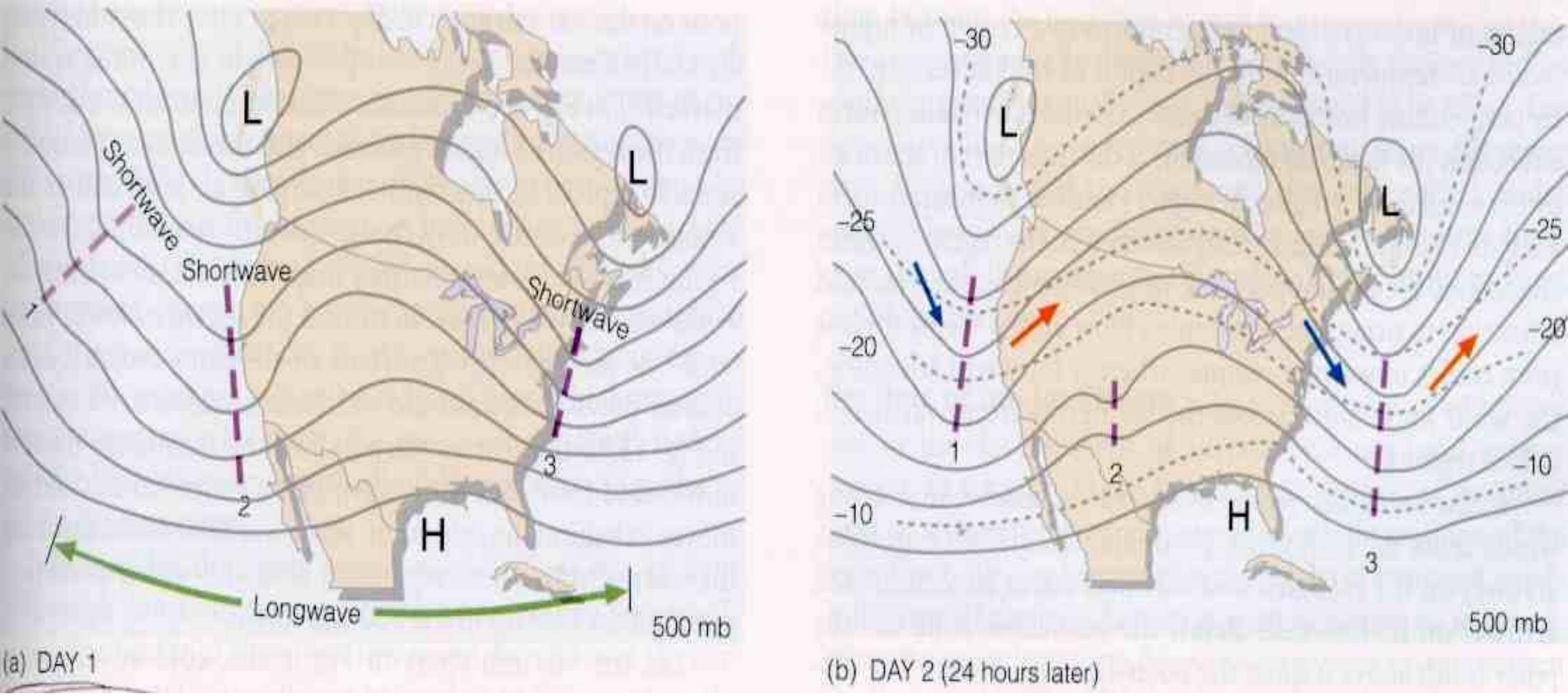
A look at the large scale.

Where is upper level divergence most likely to occur?



Cyclone initiation:

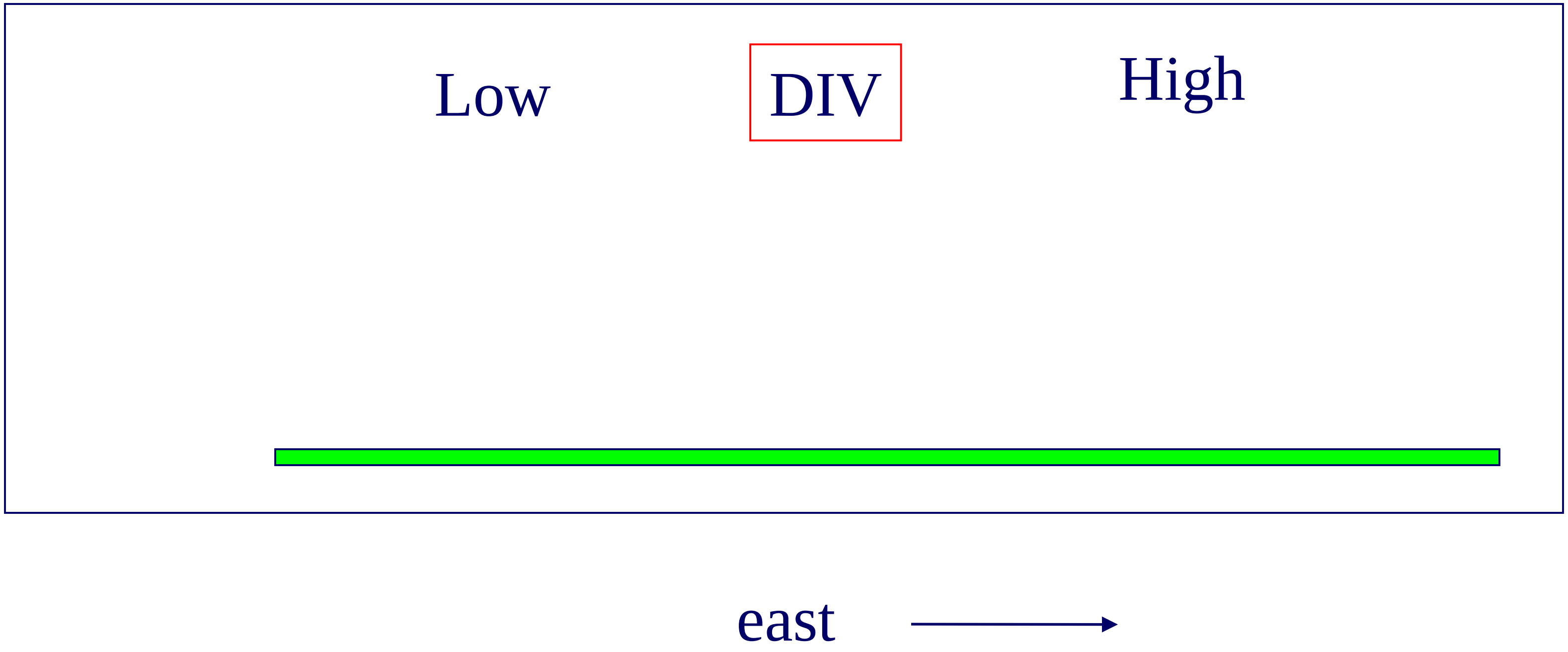
Passage of a shortwave often initiates the formation of a surface low.



Cyclone development:

- baroclinic instability (baroclinic means temperature varies on an isobaric surface) causes initial ‘perturbation’ to grow.
- occurs in the presence of strong temperature gradients.

Imagine a short wave trough passes overhead (*looking North*):
Where will surface low develop?



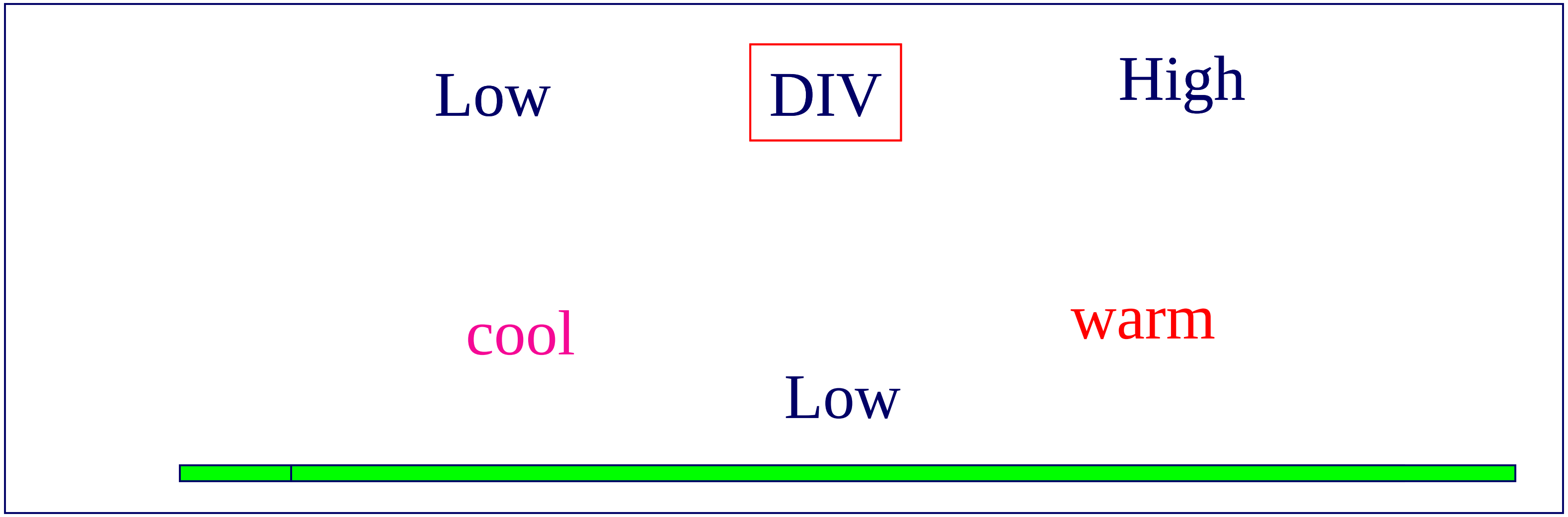
(*looking North*):

Near the surface, where will we have cold and warm advection?

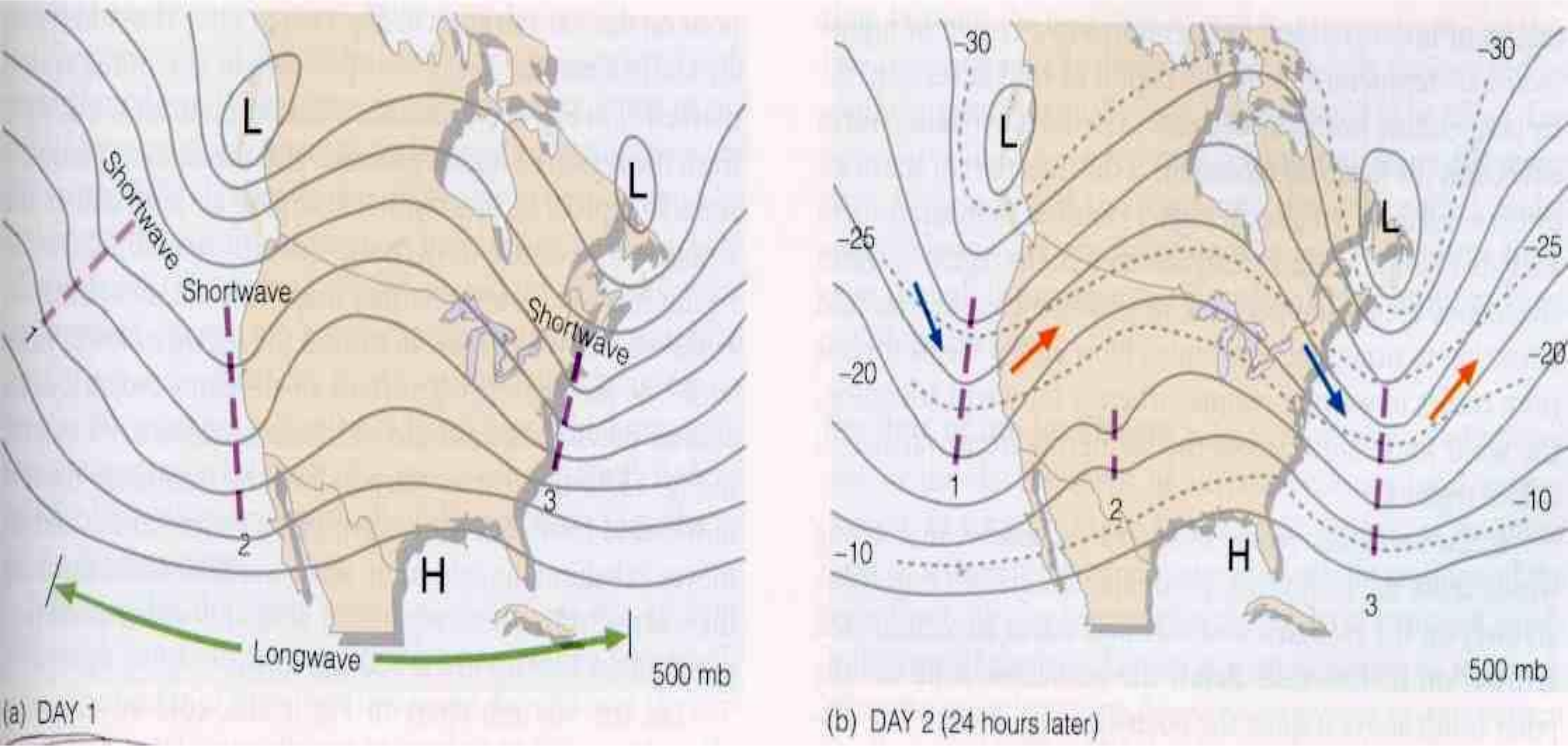
Will this amplify or weaken the upper level low?

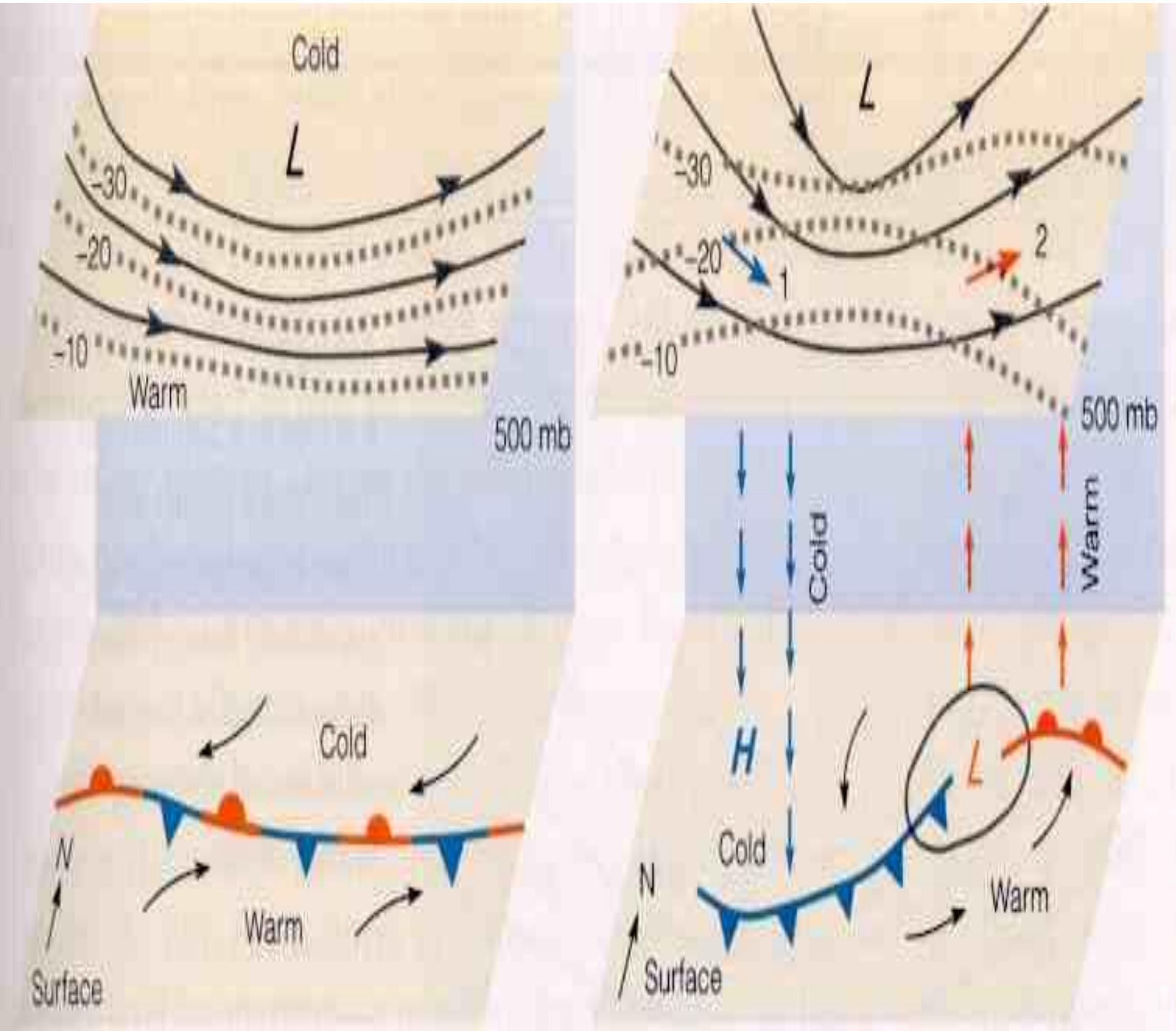
How about the upper level divergence?

Will a more intense upper level low strengthen or weaken the surface low?



Cyclone development:
Strong north south gradient+passage of a shortwave trough
Can lead to rapid cyclogenisis via baroclinic instability
(baroclinic means temperature varies on an isobaric surface)

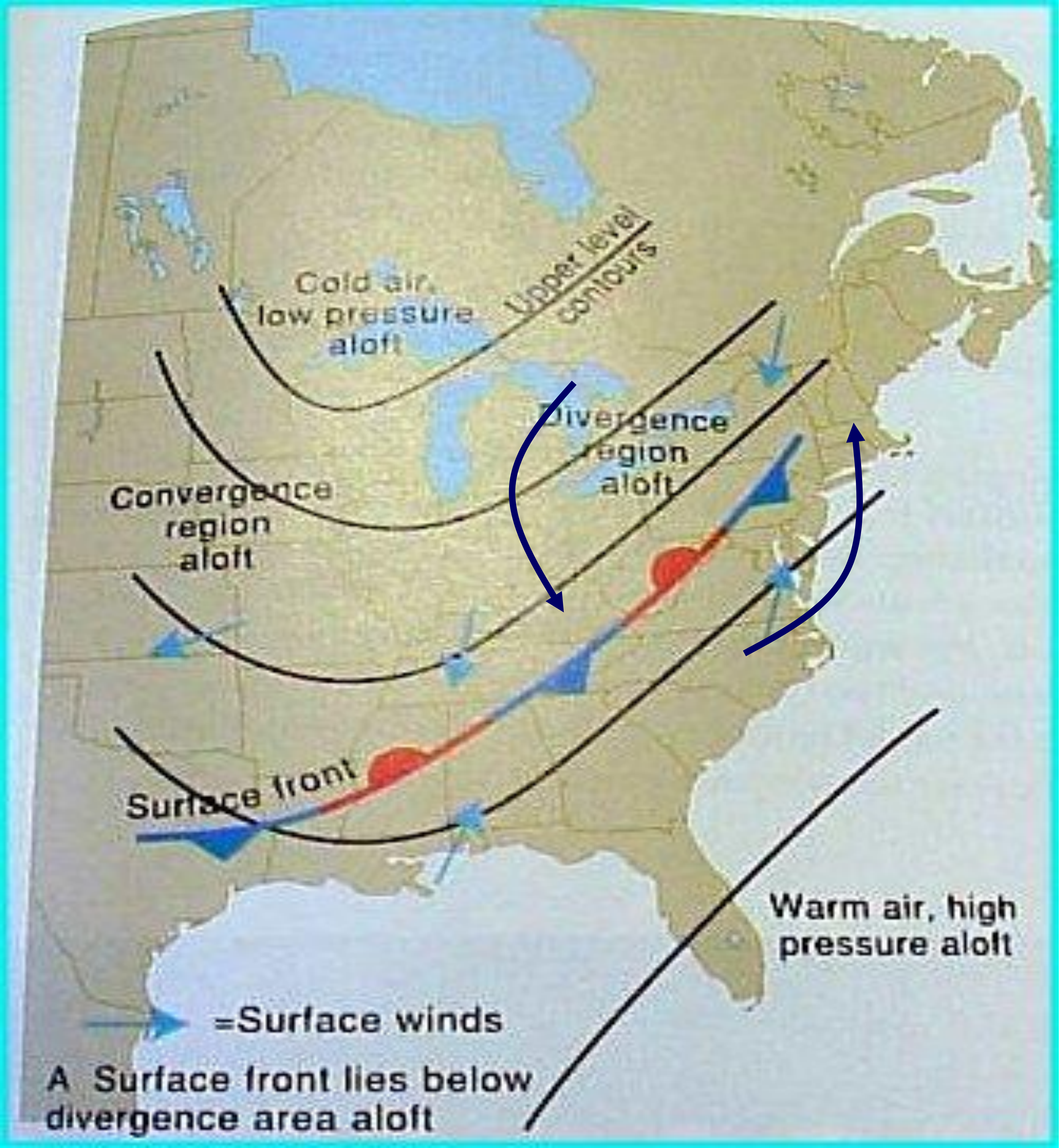




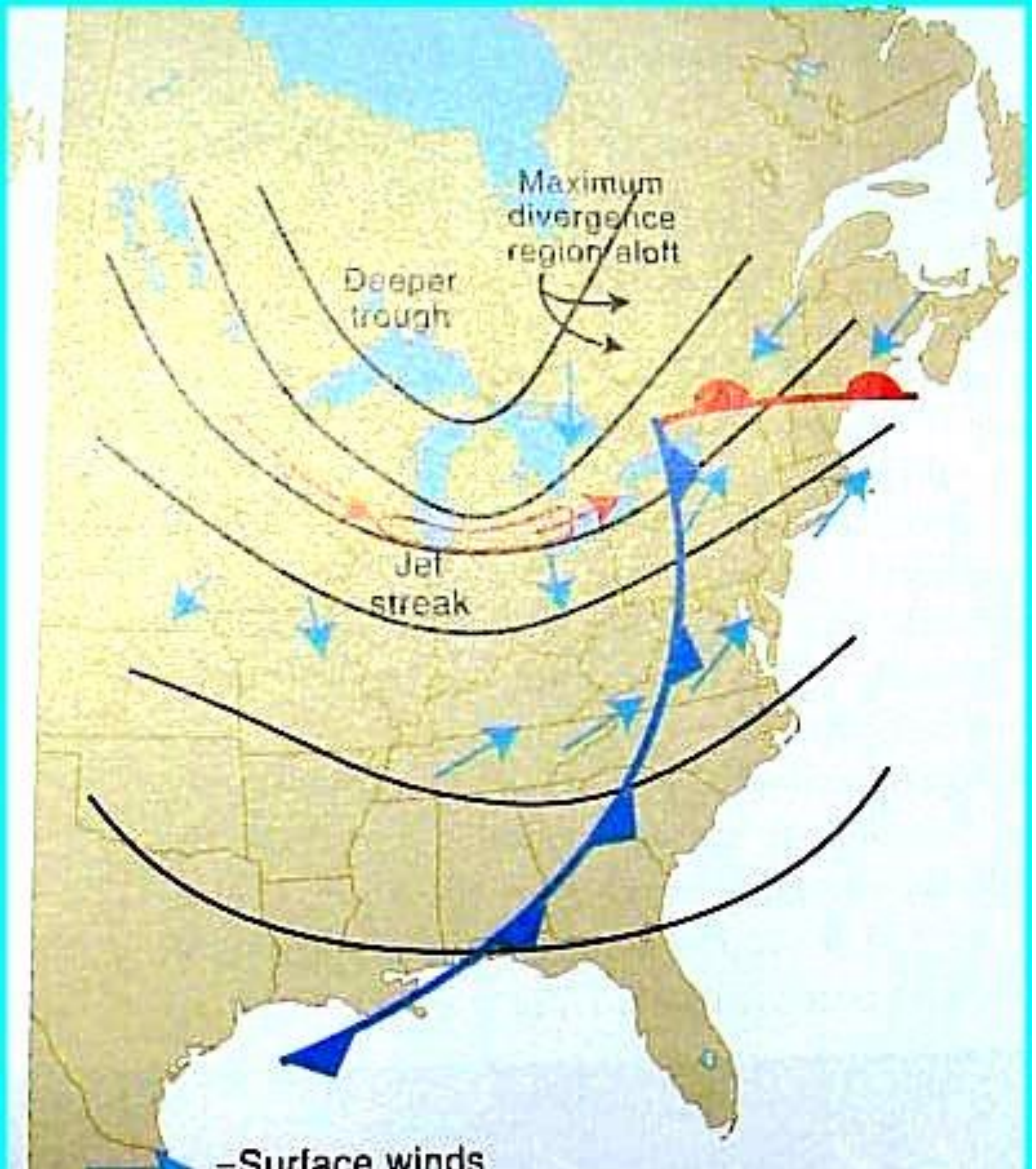
Baroclinic instability

- Upper level shortwave passes.
- Upper level divergence -> sfc low.
- Cold advection throughout lower troposphere.
- Cold advection intensifies upper low.
- Leads to more upper level divergence.
- Intensifies sfc low.

ADVECTION IS KEY.

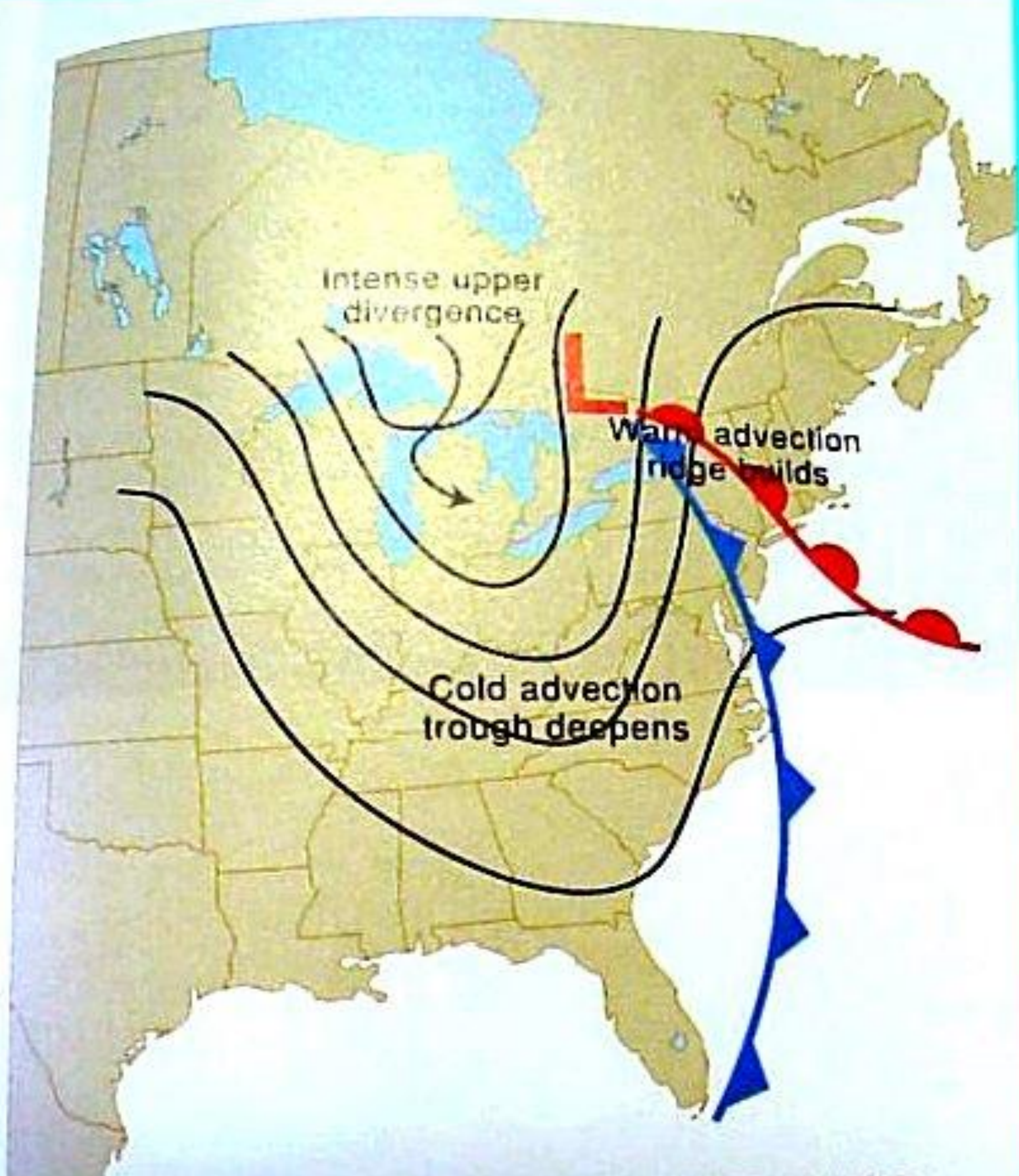


1. Divergence aloft
2. Leads to lower SLP underneath divergence
3. Flow associated with low SLP leads to cold/warm advection on lower troposphere.
4. Temp advection increases upper level trough, and hence leads to more divergence.

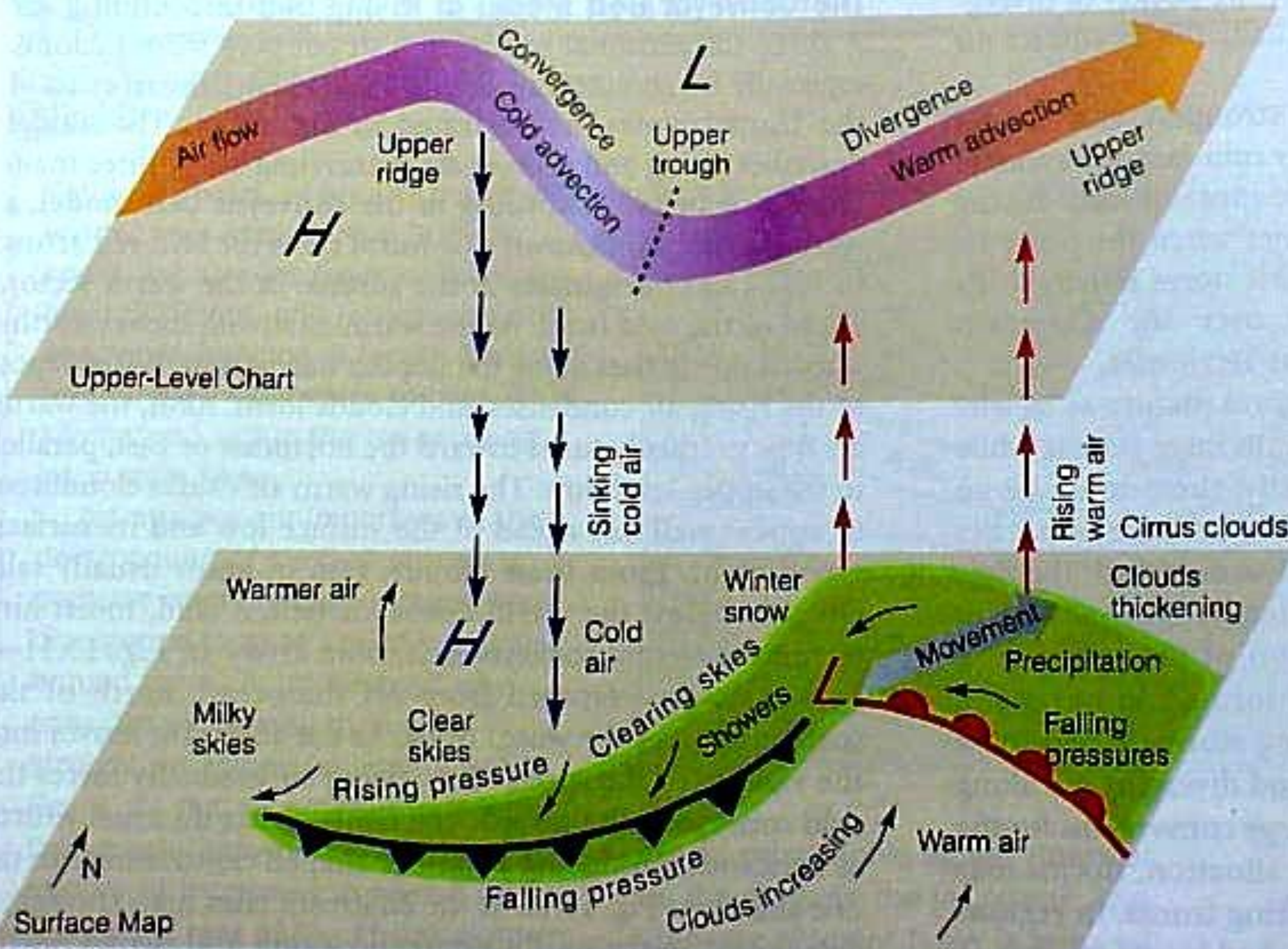


B Upper level trough deepens due to short wave. Jet Streak occurs, focusing divergence aloft. Surface convergence, circulation intensify.

Intensification occurs typically just ahead of upper air trough axis.



C Baroclinic flow intensifies upper level trough/ ridge pattern, causing stronger upper divergence over surface cyclone.



FIGUR
Summar
motions
wave cy