ASME 434 Atmospheric Dynamics II Dr. Yuh-Lang Lin

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Chapter 11 Baroclinic Instability and Cyclogenesis

11.1 Concept of Baroclinic Instability

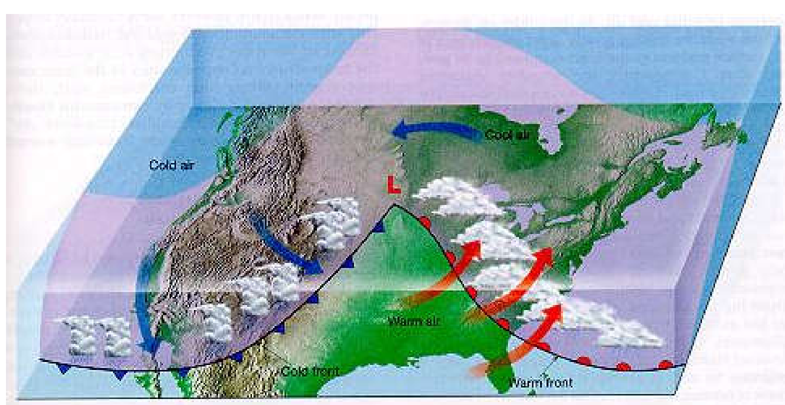
Two major problems in extratropical large-scale dynamics are : (A) frontogenesis, (B) cyclogenesis.

(A) Frontogenesis

- *Bjerknes polar front model* (http://apollo.lsc.vsc.edu/classes/met130/notes/chapter12/polar_front_schema.html)

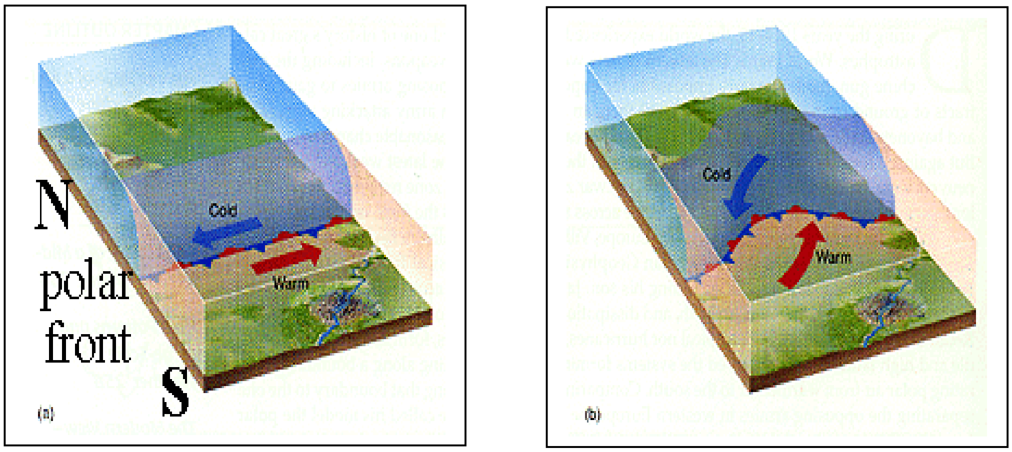
  Fronts are boundaries between contrasting air masses.

  - If an air mass is warmer than the other, it is more buoyant.
  - When two air masses meet the warmer, the more buoyant (warmer) air mass with be uplifted relative to the colder, denser air mass.
  - If the cold (warm) air mass is advancing against warm (cold) air mass, it is called cold (warm) front.



Polar Front Theory - **Development and Evolution of a Wave Cyclone**

(a) A frontal wave develops along a polar front. When a large temperature gradient exists across the polar front - the atmosphere contains a large amount of Available Potential Energy.



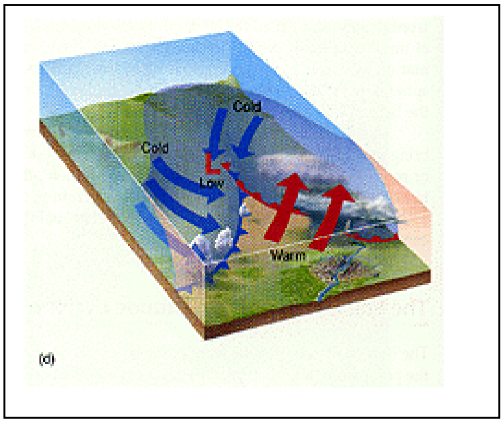
(From Aguado and Burt, 1999, Understanding Weather and Climate, Prentice-Hall, Inc)

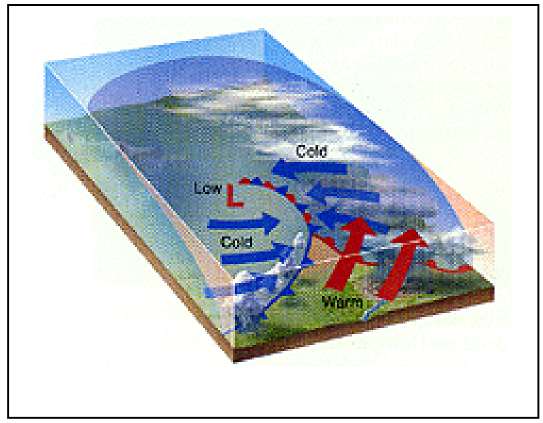
(b) The polar front develops when an instability occurs, which converts available potential energy to kinetic energy. This polar front is an incipient cyclone.

(c) A fully-developed "wave cyclone" is seen 12-24 hours from its inception. It consists of:

- a warm front moving to the northeast
- a cold front moving to the southeast
- region between warm and cold fronts is the "warm sector"
- the central low pressure (low, which is deepening with time)
- overrunning of warm air over the warm front
- cold air surging southward behind the cold front
- wide-spread precipitation ahead of the warm front
- narrow band of precipitation along the cold front
- Wind speeds continue to get stronger as the low deepens - the Available Potential Energy (APE) is being converted to Kinetic Energy (KE) (i.e., baroclinic instability occurs)

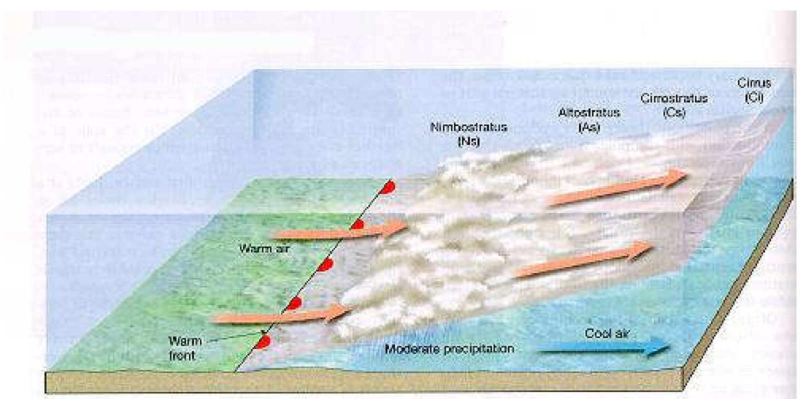
- The production of clouds and precipitation also generates energy for the storm as Latent Heat is released





(d) As the cold front moves swiftly eastward, the systems starts to occlude.

- Storm is most intense at this stage
- have an occluded front trailing out from the surface low
- triple point/occlusion - is where the cold, warm and occluded fronts all intersect

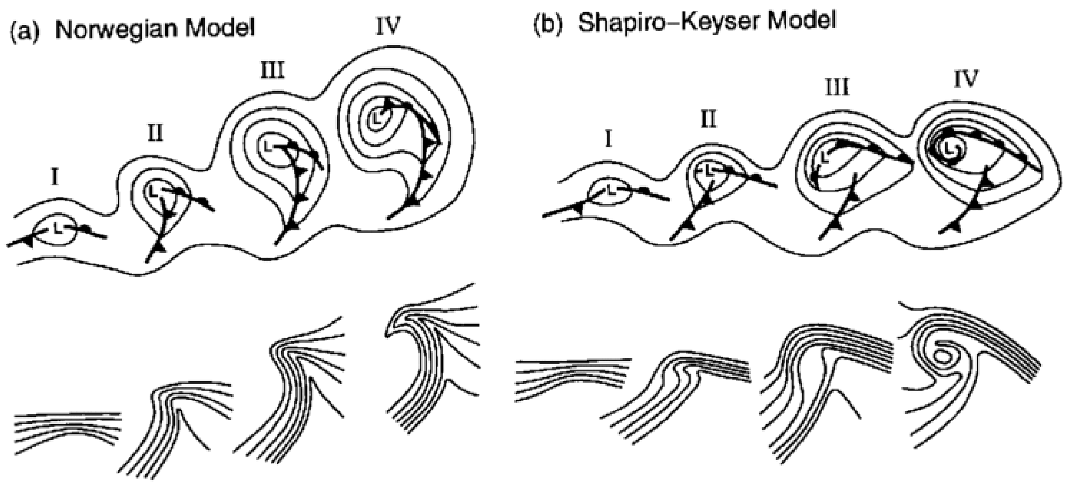


Warm front produced as warm air glides up over a cold air mass.

Warm Fronts have broader, less steep slopes

(B) Cyclogenesis

- *Norwegian Cyclone Model (Bjerknes 1951)*
  (http://en.wikipedia.org/wiki/Norwegian_cyclone_model)

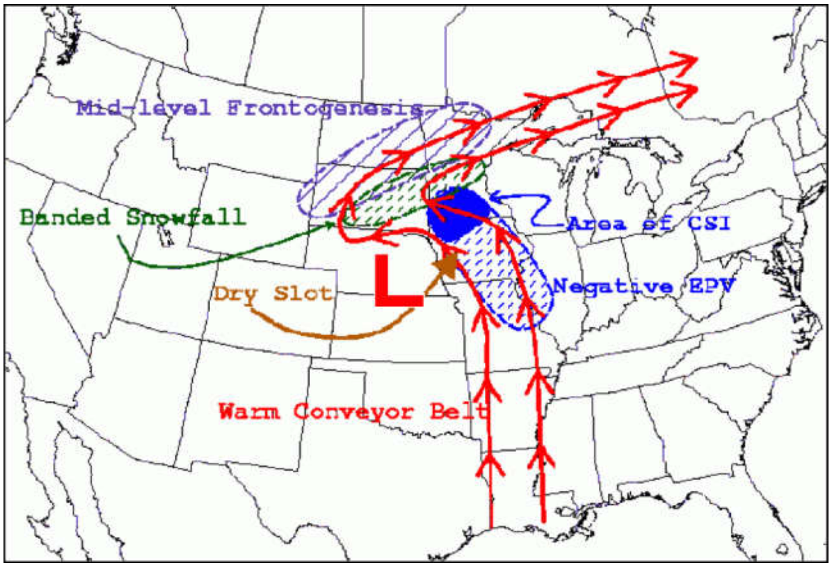


The older of the models of extratropical cyclone development is known as the Norwegian Cyclone Model, developed during and shortly after World War I within the Bergen School of Meteorology.

In this theory, cyclones develop as they move up and along a frontal boundary, eventually occluding and reaching a barotropically cold environment.[1]

It was developed completely from surface-based weather observations, including descriptions of clouds found near frontal boundaries.

Developed from this (Norwegian) model was the concept of the warm conveyor belt, which transports warm and moist air just ahead of the cold front above the surface warm front.



- Progresses in the development of cyclogenesis theories

  - Development of the Pettersen-Sutcliffe development theory (Q. J. 1947)

    Describe development in terms of vertical distribution of divergence.

    Start with the Q-G omega equation,

$$\left(\nabla^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\omega = -\frac{f_0}{\sigma}\frac{\partial}{\partial p}\left[-V_g \cdot \nabla \left(\zeta_g + f\right)\right] - \frac{R}{\sigma p}\nabla^2\left(-V_g \cdot \nabla_p T\right) - \frac{R}{pc_p}\nabla^2\left(\frac{DQ}{Dt}\right)$$

    Ignoring the b effect and integrating the above equation from surface to the level of non-divergence (LND) leads to (see Lackman – Midlatitude Synoptic Meteorology for details)

$$-f_0^2 \frac{\partial \omega}{\partial p}\bigg|_{p_{sfc}} = -f_0\left(-\vec{\mathbf{v}}_g \cdot \nabla \zeta_g\right)\Big|_{p_{LND}} - \nabla^2 \int_{p_{sfc}}^{p_{LND}} \left(-\vec{\mathbf{v}}_g \cdot \nabla\left(-\frac{\partial \Phi}{\partial p}\right)\right) dp - \int_{p_{sfc}}^{p_{LND}} \left[\sigma \nabla^2 \omega + \frac{R}{pc_p} \nabla^2 \left(\frac{dQ}{dt}\right)\right] dp$$

Equation (6) is what we call the *Pettersen-Sutcliffe Development Equation* and relates the time rate of change of the surface geostrophic vorticity – as manifest through its tie to $\partial\omega/\partial p$ in the quasi-geostrophic vorticity equation – to a set of three forcing terms. We now wish to consider the contributions from each of these terms to surface cyclone development in isolation.

(Lackmann, Midlatitude Synoptic Meteorology)

Cyclogenesis has to be accompanied by low-level convergence and upper-level divergence (see Carlson, p. 182). This also has established the foundation of NWP.

- Baroclinic instability theories
  - Eady model (1949): on f-plane, vertically confined by surface and a rigid tropaupose
  - Charney model (JAS 1947): on β-plane, semi-infinite atmosphere.

- Hoskins and Bretherton’s semi-geostrophic model (1975 JAS)

- Development of a Baroclinic Cyclone

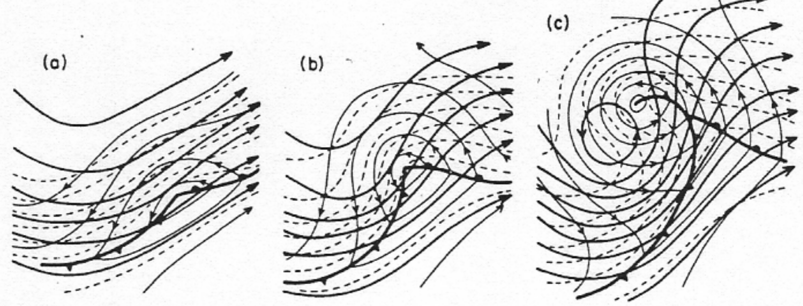
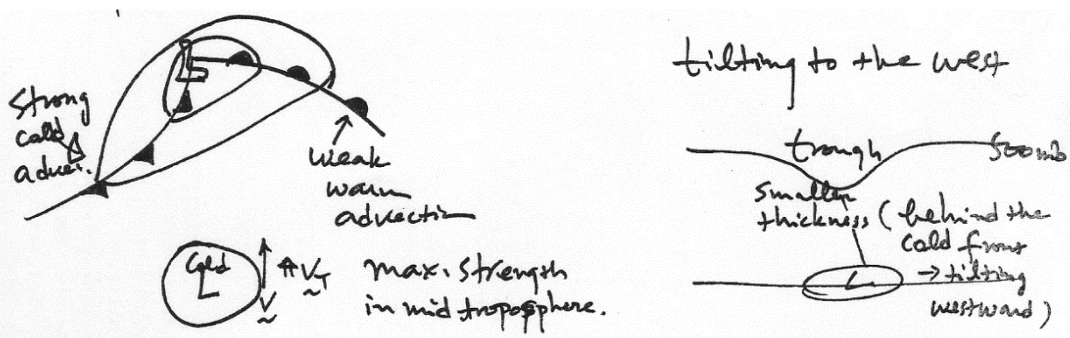
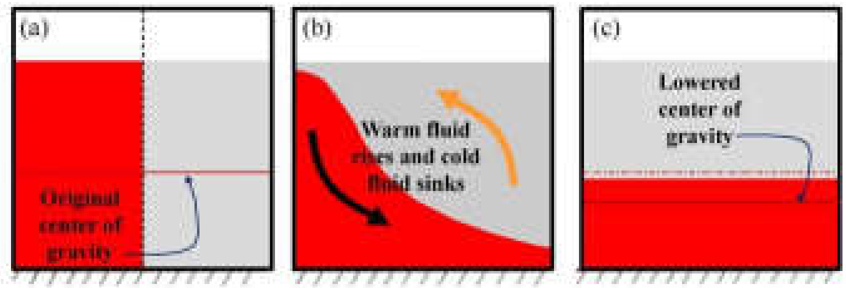


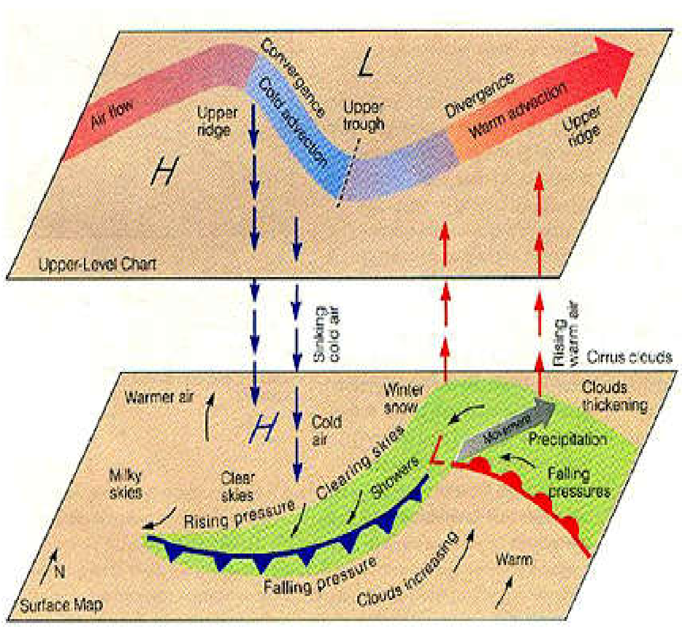
Fig. 6.5 Schematic 500-mb contours (heavy solid lines), 1000-mb contours (thin lines), and 1000–500-mb thickness (dashed) for a developing baroclinic wave at three stages of development. (After Palmén and Newton, 1969.)

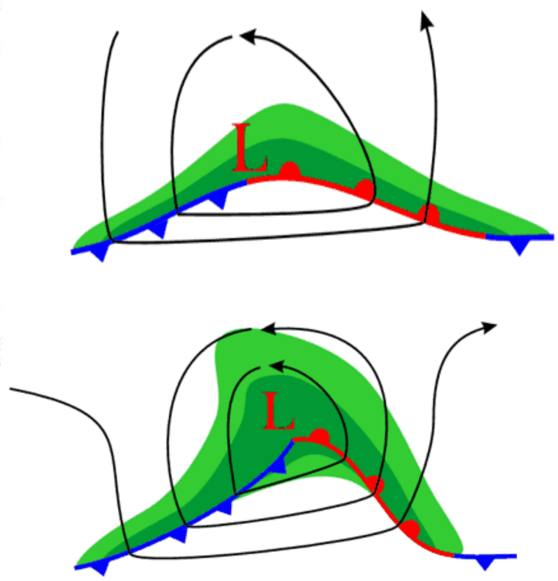


- Baroclinic Instability and Cyclogenesis

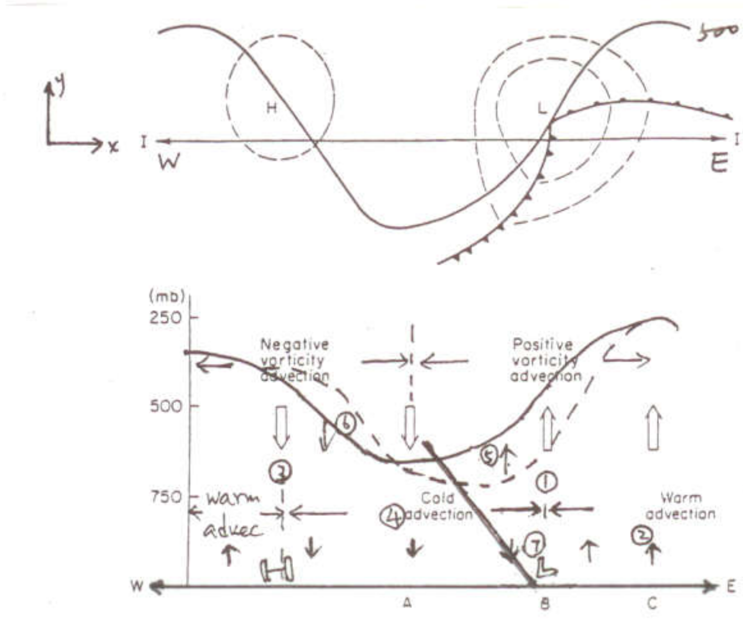
  Available Potential Energy (APE) => Kinetic Energy (KE)







11.2 Idealized Model of Cyclogenesis



Holton's Fig. 6.16

A. Based on ω equation [simple form: $w \propto \frac{\partial}{\partial z}(-V_g \cdot \nabla \zeta_g) - V_g \cdot \nabla T$]

(1) & (5): PVA at 500mb -> Positive differential VA -> w>0.
(2): Warm advection -> w>0.
(3) & (6): NVA at 500mb -> Negative differential VA -> w<0.
(4): Cold advection -> w<0.

B. Based on χ equation [simple form: $-\chi \propto -V_g \cdot \nabla \zeta_g + \frac{\partial}{\partial z}\left(-V_g \cdot \nabla T\right)$]

(5): Ahead of 500 mb trough -> PVA -> $\phi \downarrow$ and
cold advection near surface -> $\frac{\partial}{\partial z}\left(-V_g \cdot \nabla T\right) > 0$ -> $\phi \downarrow$.

(6): Ahead of 500mb ridge -> NVA -> $\phi \uparrow$ and
cold advection near surface -> $\frac{\partial}{\partial z}\left(-V_g \cdot \nabla T\right) > 0$ -> $\phi \downarrow$. ϕ?

C. Development of the surface low

(7): (i) Overall w>0 creates surface convergence -> spin up surface positive vorticity -> low deepens.
(ii) 500 mb vorticity strengthens due to PVA -> coupled with surface low.