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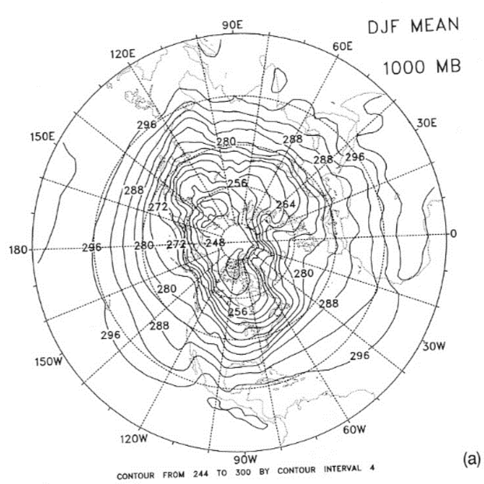
Chapter 6 Introduction to General Circulation of the Atmosphere

- **Major features on sea-level synoptic charts**

The major features include cyclones, fronts, and wave-like large-scale disturbances. The complicated patterns are mainly due to orography and land-sea contrasts.

Northern Hemisphere



(Bluestein 1993)

Southern Hemisphere

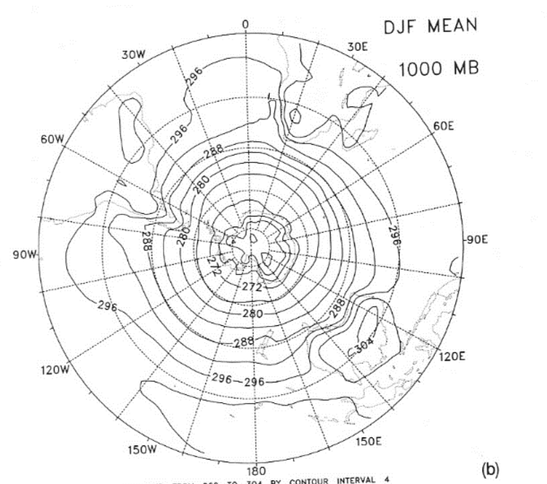


Figure 1.44 Average temperature (K) at 1000 mb in (a) the Northern Hemisph for the winter and (b) the Southern Hemisphere for the summer (Decem January, and February) (from ECMWF data, 1979–1988; courtesy Kevin Trenb and Amy Solomon, NCAR).

- **Major features on 500-mb charts**

  The 500-mb charts are much smoother than sea-level synoptic charts. There are about 5 lows circling around the North Pole, which are associated with baroclinic waves (Fig. 3.1Hess).

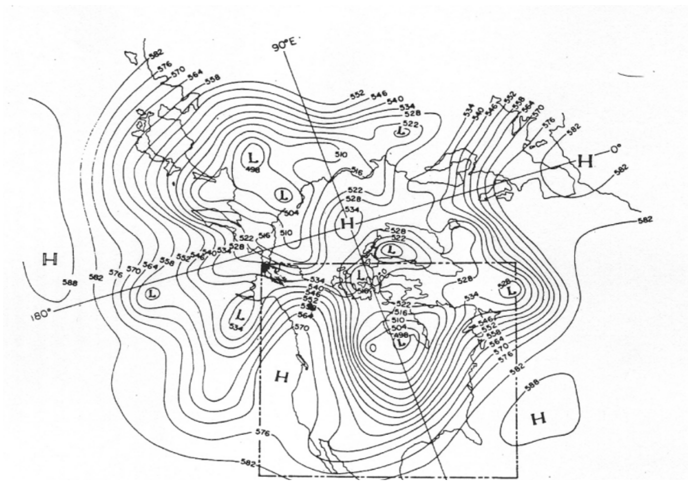
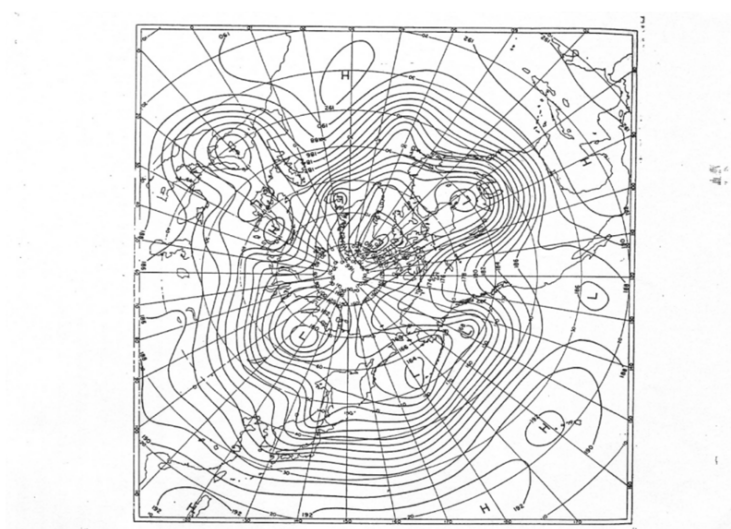


Fig. 3.1(Wallace & Hobbs): Distribution of geopotential height on the 500-mb surface at 00 UTC 20 November 1964. Labels on contours represent geopotential height (in m). The letters H and L denote centers of high and low geopotential height, respectively.

This type of baroclinic waves is often observed in the atmosphere, such as the 500-mb analysis chart shown below.



Meridional cross sections of longitudinally and time averaged zonal wind indicate strong seasonal variation. (Holton)

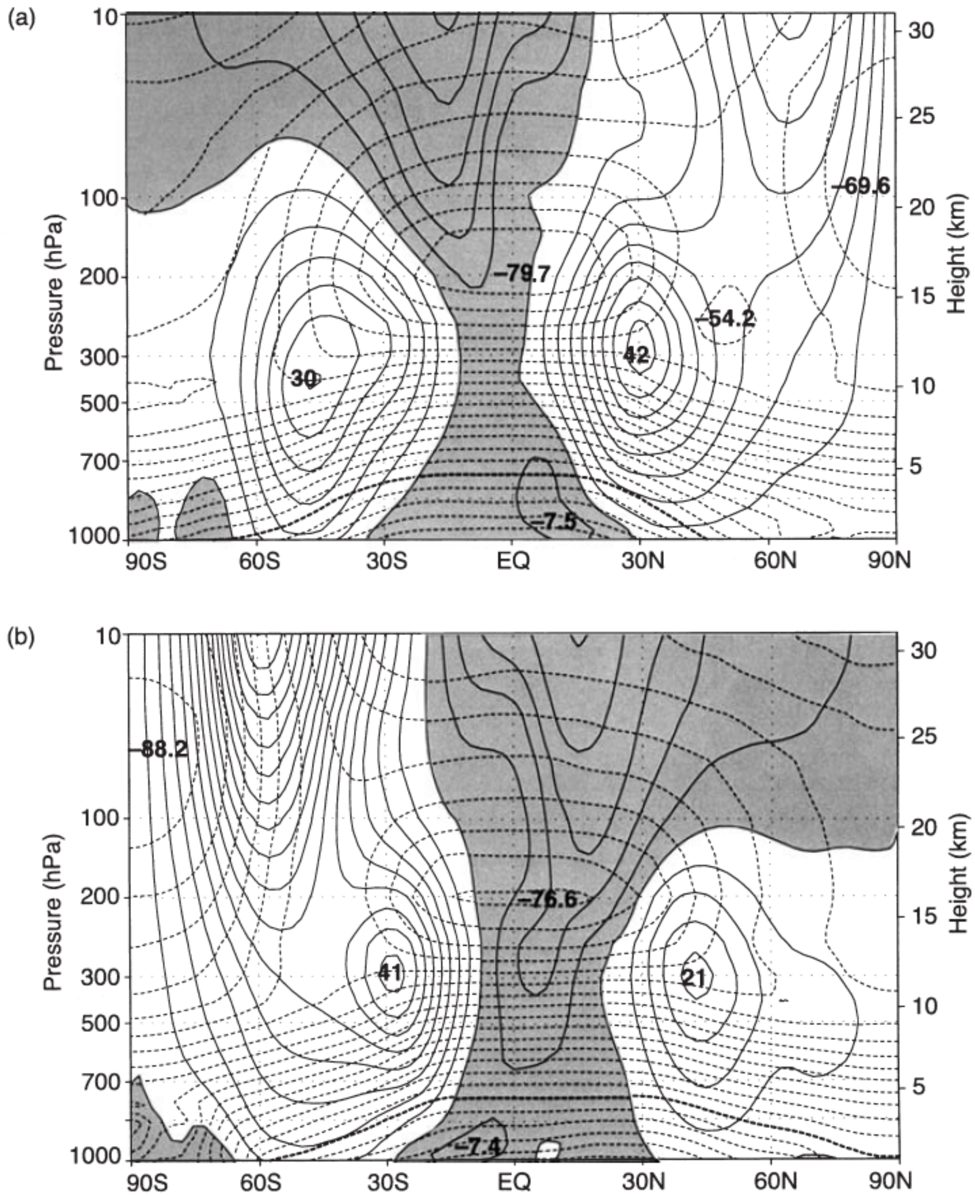


Fig. 6.1 Meridional cross sections of longitudinally and time-averaged zonal wind (solid contours, interval of m s^{-1}) and temperature (dashed contours, interval of 5 K) for December–February (a) and June–August (b). Easterly winds are shaded and 0° C isotherm is darkened. Wind maxima shown in m s^{-1}, temperature minima shown in °C. (Based on NCEP/NCAR reanalyses; after Wallace, 2003.)

- Fig. 6.2 (Holton): Mean zonal wind (heavy contour, 20 m/s) at the 200-mb level for Dec-Feb averaged for 1958-1997 (Wallace 2003). Jet streams in midlatitudes; jet streams are not continuous longitudinally.

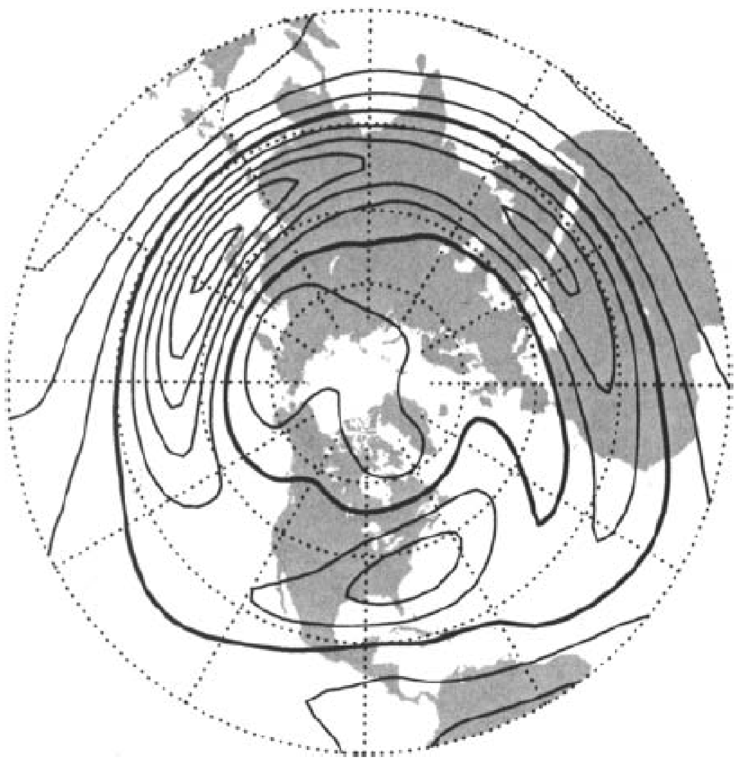
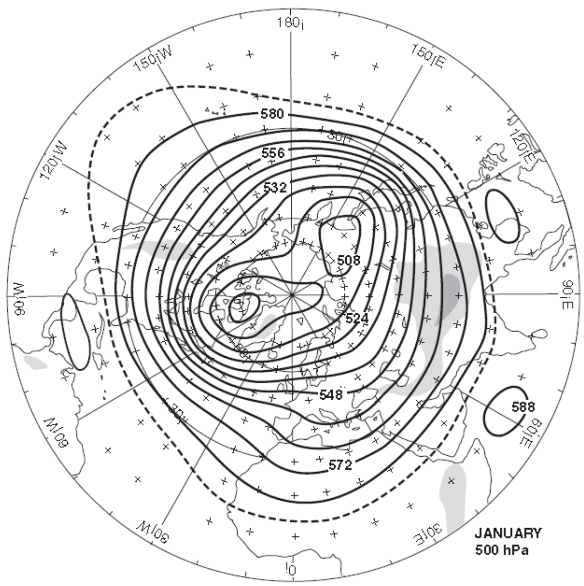
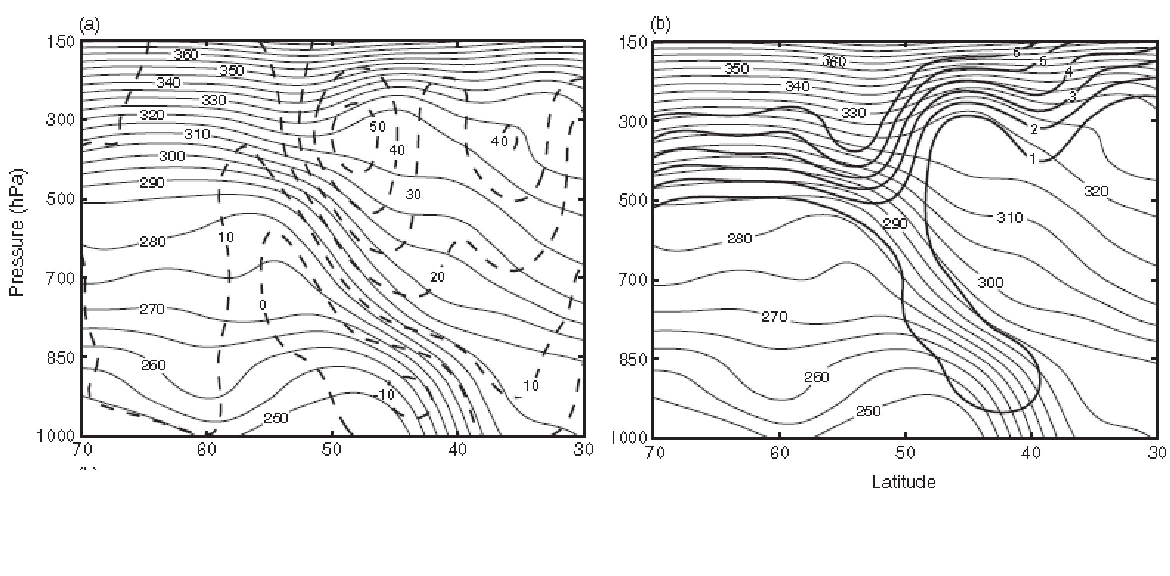


Fig. 6.2 Mean zonal wind at the 200-hPa level for December–February averaged for years 1958–1997. Contour interval 10 m s^{-1} (heavy contour, 20 m s^{-1}). (Based on NCEP/NCAR reanalyses; after Wallace, 2003.)

- Fig. 6.3 (Holton): Mean 500-mb height contours (in 10m) in January in the Northern Atmosphere (Palmen and Newton 1969).



- Fig. 6.4 (Holton): Latitude-height cross sections through a cold front: (1) strong baroclinicity near the front, (2) jet stream is collocated with the cold front due to thermal wind effect.



- <u>General Circulation</u> – The Hadley Cell Model (1735)

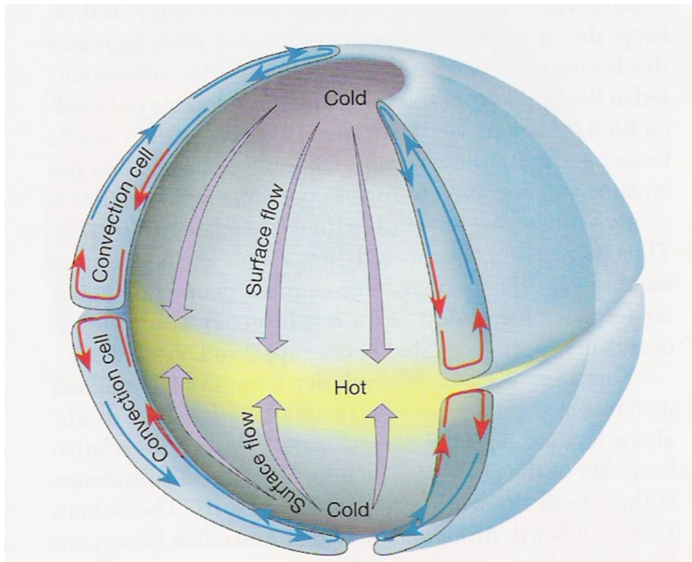


FIGURE 7-6 Global circulation on a nonrotating Earth. A simple convection system is produced by unequal heating of the atmosphere on a nonrotating Earth.

(Lutgens and Tarbuck 2004)

The major problem with the Hadley Model!!!

There is net radiative loss of heat by the atmosphere associated with the upper-level flow toward poles. This cold air must subside and spread poleward and equatorward.

Thus the radiative consideration forces a breakdown of the single Hadley cell!

- Three-Cell Circulation Model (Ferrel 1859)

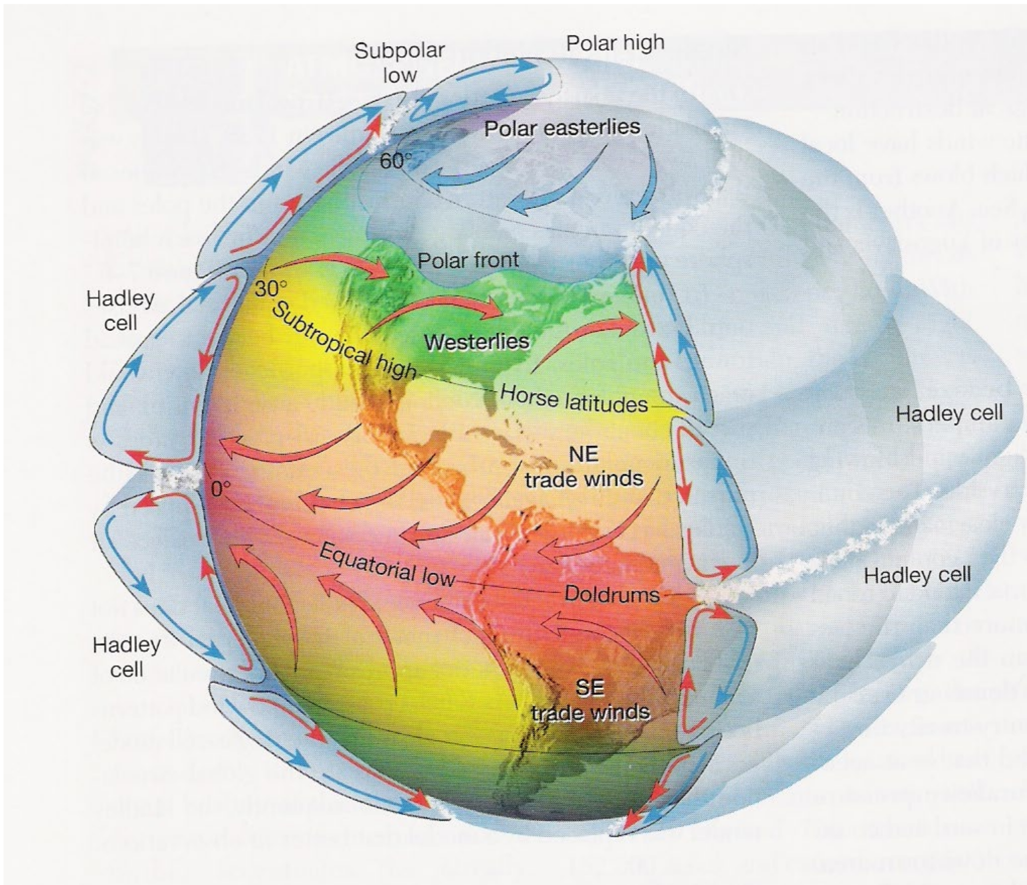


Figure 7.7 (Lutgens and Tarbuck 2004): Idealized global circulation proposed for the three-cell (Ferrel cell) circulation model of a rotating Earth.

- The 3-cell circulation was mainly driven by Earth's rotation and radiation on the upper branch of the Hadley cell.

- The problem with the three-cell model is that the theory fails to account for the fact that the westerlies of middle latitudes increase with height!

- Rossby suggested that *large-scale turbulence* might link the upper westerlies of the Hadley cell and the polar cells to the upper troposphere of middle latitudes.

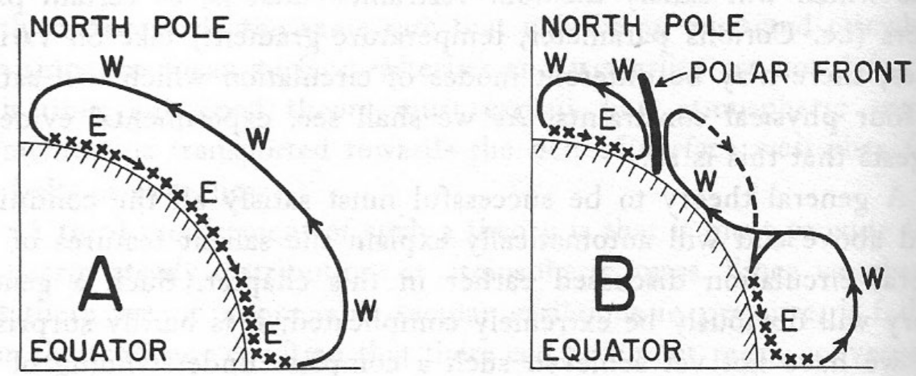
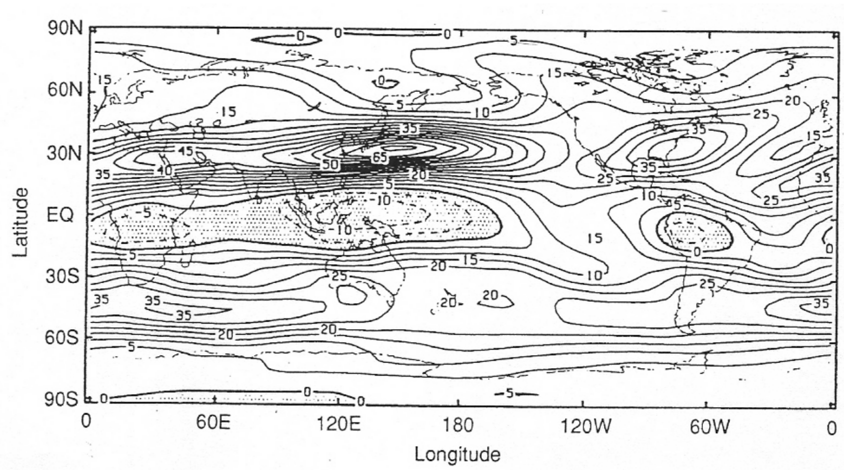


FIG. 21.4. Evolution of three cells in the general circulation according to a Hadley-meridional circulation theory

- The fact is that there exists a longitudinal variation of the flow, thus the jet stream is not continuous around the globe.



Latitude-longitude cross section of time-averaged zonal wind speed at 200 mb for DJF averaged for years 1980–1987. (After Schubert *et al.*, 1990.)

- Observed General Circulation of the Atmosphere

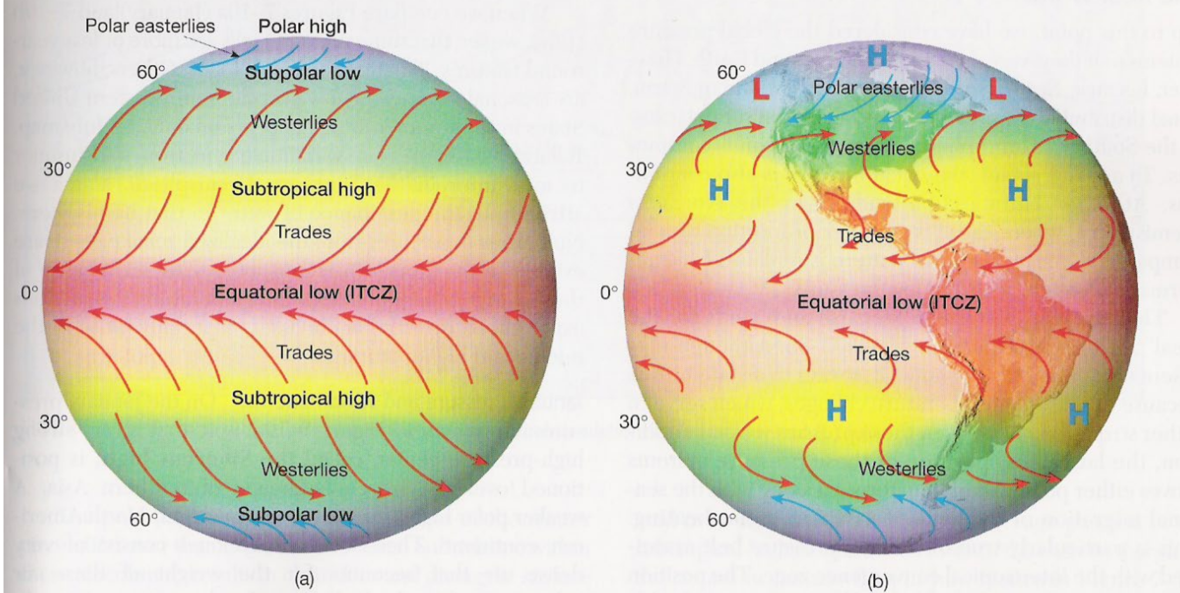
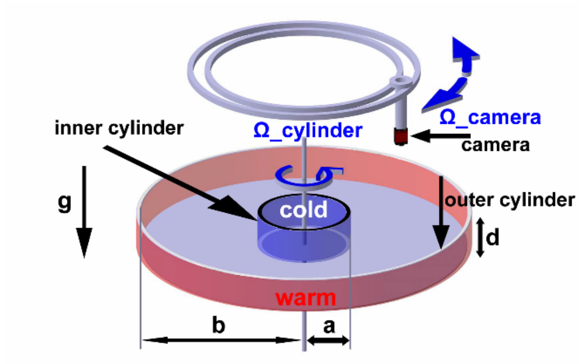


FIGURE 7-8 (a) An imaginary uniform Earth with idealized zonal (continuous) pressure belts. (b) The real Earth with disruptions of the zonal pattern caused by large landmasses. These disruptions break up pressure zones into semipermanent high- and low-pressure cells.

Annulus Experiments



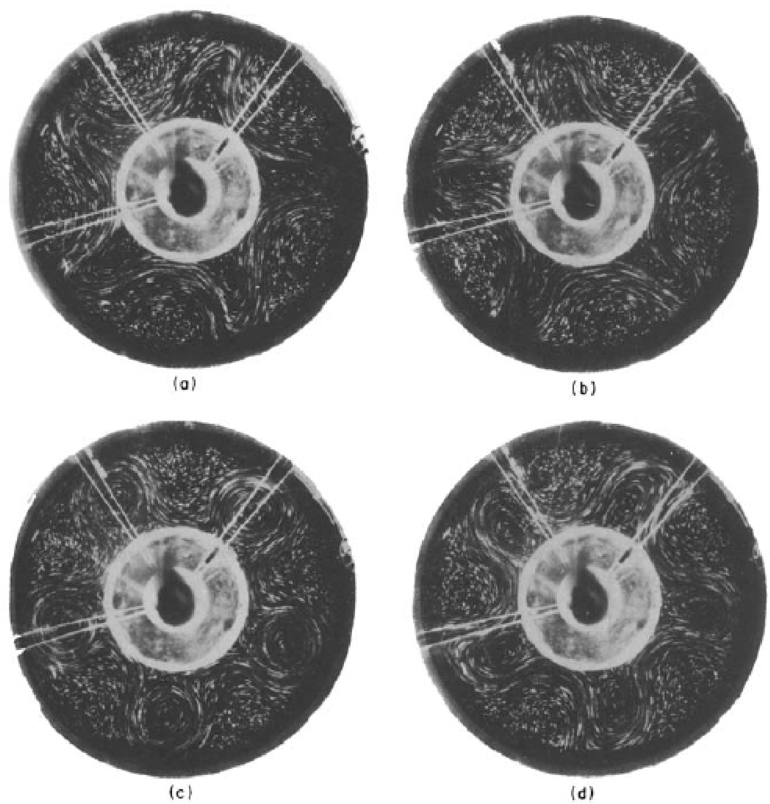


Fig. 10.20 (Holton): Time exposures showing the motion of surface tracer particles in a rotating annulus with heating at the rim and cooling at the core.

Flow regimes found from annulus experiment:

(1) Large Rossby number (low rotation rate) -- Hadley Regime

- Hadley cell circulation develops.
- The circulation is steady and symmetric.

(2) Moderately large Rossby number (medium rotation rate)

- Meridional flow breaks down.
- Jet streams can be found near the upper surface.
- Very steady pattern of Rossby waves exists in westerlies.
- Number of waves evolves from 3, 4, to 5 as rotation rate increases.
- Motions are quasi-geostrophic.

(3) Moderately small Rossby number (large rotation rate) -- Rossby Regime

- Flow is similar to regime 2
- Jets are shorter in length, not continuous
- Flow is markedly unsteady
- Five to six Rossby waves form
- Low-level cyclones and fronts appear
- Observed atmosphere features, such as cold anticyclones, are reproduced
- Troughs in the wave patterns tilted from NE to SW instead of lying along a meridian.

(4) Small Rossby number (very high rotation rate)

- Physical circulation entities become smaller, which mimic convective Elements or Bernard cells.
- Cells are quite unsteady and short-lived.
- Narrow jets are winding in and out among the cells.

Evolution of Frontogenesis and Cyclogenesis Theories

- Two major problems in extratropical large-scale dynamics

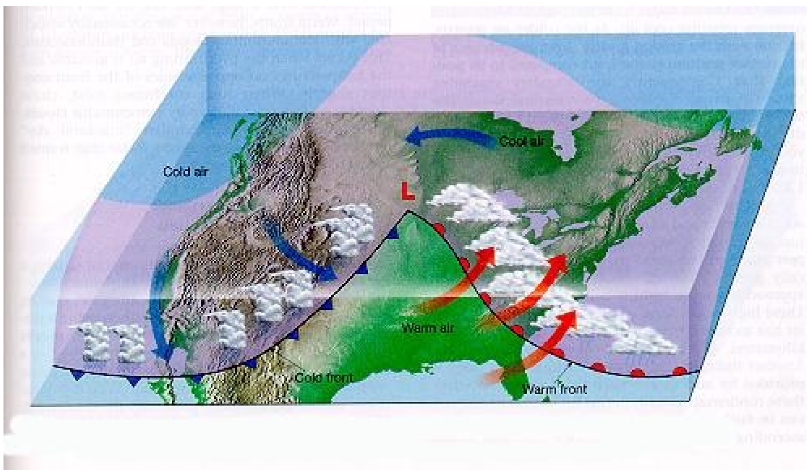
➤ Frontogenesis

- Bjerknes polar front model

(http://apollo.lsc.vsc.edu/classes/met130/notes/chapter12/polar_front_schema.html)

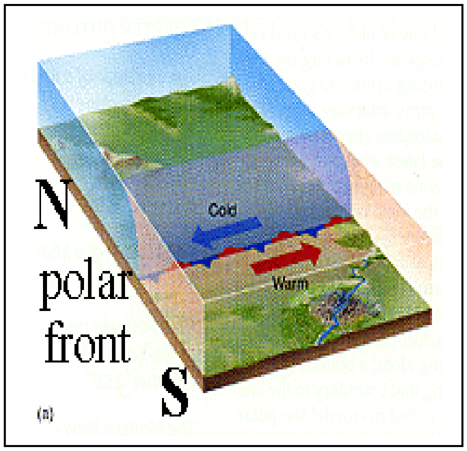
Fronts are boundaries between contrasting air masses

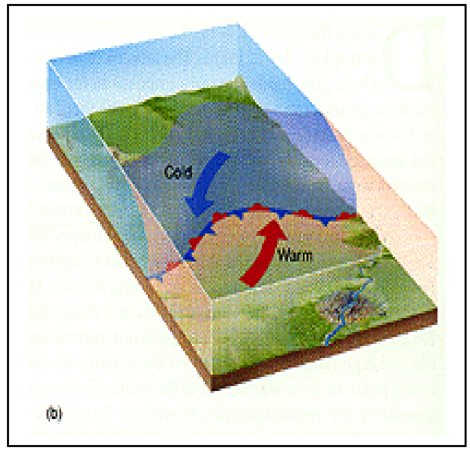
Once air masses are warmer than the other and therefore more buoyant. Where the two air masses meet the warmer, more buoyant air masses uplifted relative to the colder, more dense air mass. Depending on which of the air masses are advanced there will be either an advancing **Warm Front** or an advancing **Cold Front.**



<u>Polar Front Theory</u> - Development and Evolution of a Wave Cyclone

(a) The wave cyclone (often called a frontal wave) develops along the polar front. When a large temperature gradient exists across the polar front - the atmosphere contains a large amount of **Available Potential Energy.** *(image adopted from Understanding Weather and Climate by Aguado and Burt, © 1999 by Prentice-Hall, Inc)*



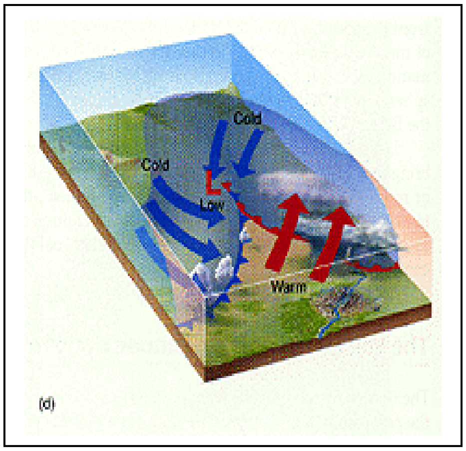


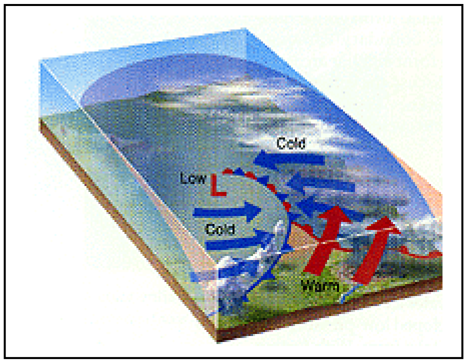
(b) An instability (kink) forms in the polar front. This instability is the incipient cyclone.

(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 precip ahead of the warm front
- narrow band of precip 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)

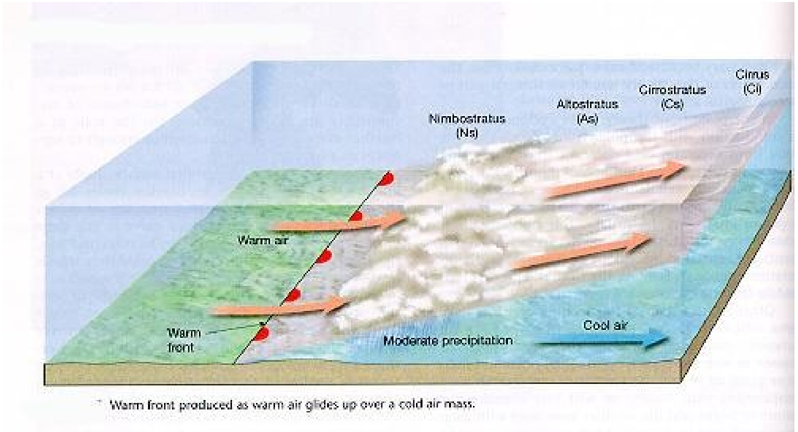
- The production of clouds and precipitation also generates energy for the storm as Latent Heat is released





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

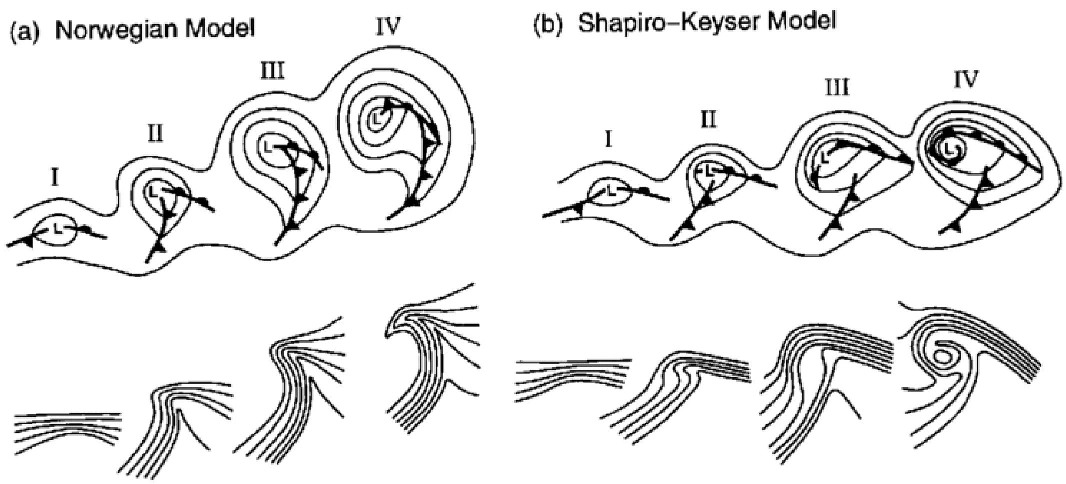
- Storm is most intense at this stage
- have an occluded front trailing out from the surface low
- triple point/occlusion - is where the cold, warm and occluded fronts all intersect



Warm Fronts have broader, less steep slopes

➢ Cyclogenesis

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

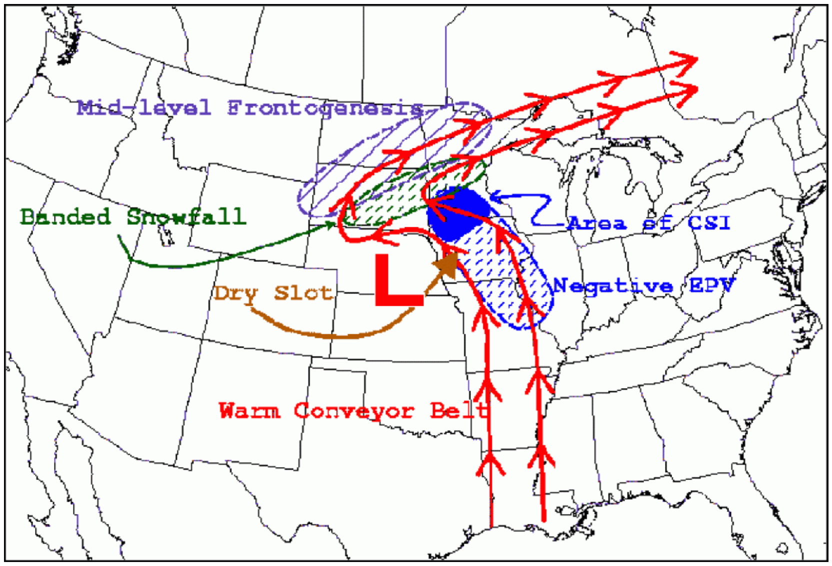


The older of the models of extratropical cyclone development is known as the **Norwegian Cyclone Model**, developed during and shortly after World War I within the Bergen School of Meteorology.

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.



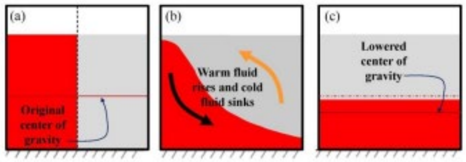
- Progresses in the development of theories

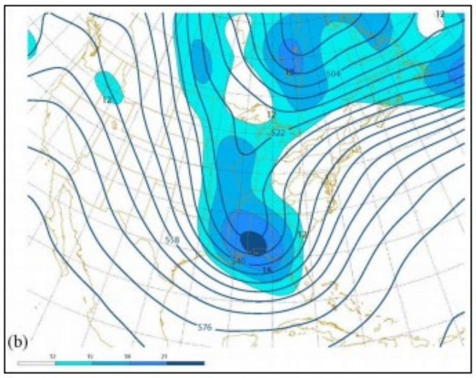
  - Sutcliffe development theory (Q. J. 1947)
    Describe development in terms of vertical distribution of divergence.

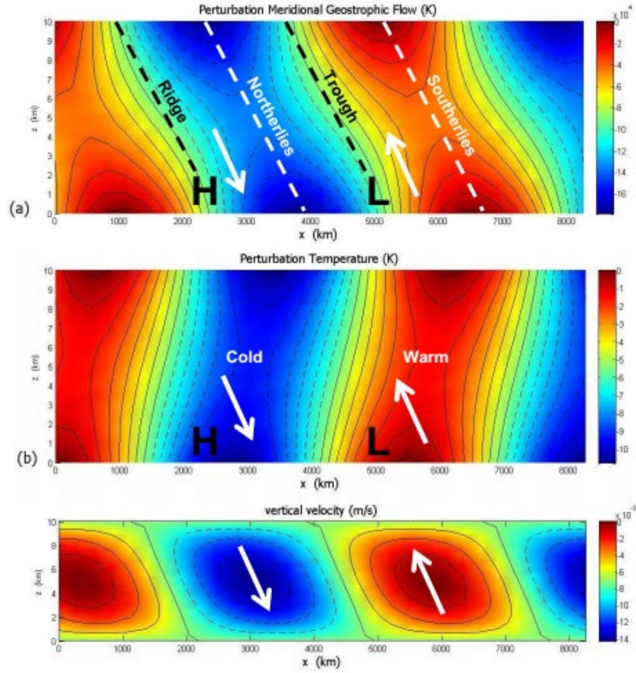
    Cyclogenesis has to be accompanied by low-level convergence and upper-level divergence (see Carlson, p. 182). This also has established the foundation of NWP.

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

Baroclinic Instability







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

- Development of a Baroclinic Cyclone

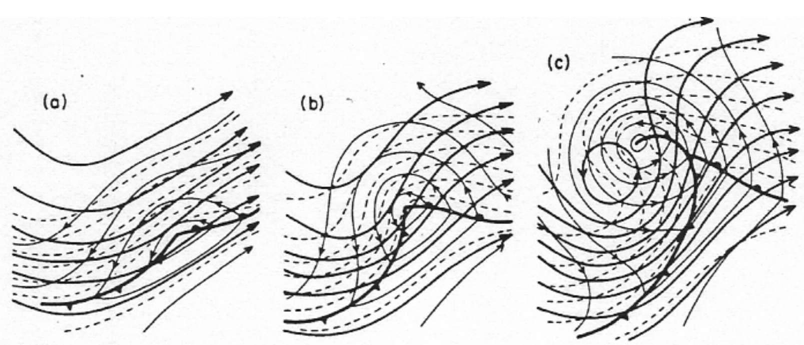
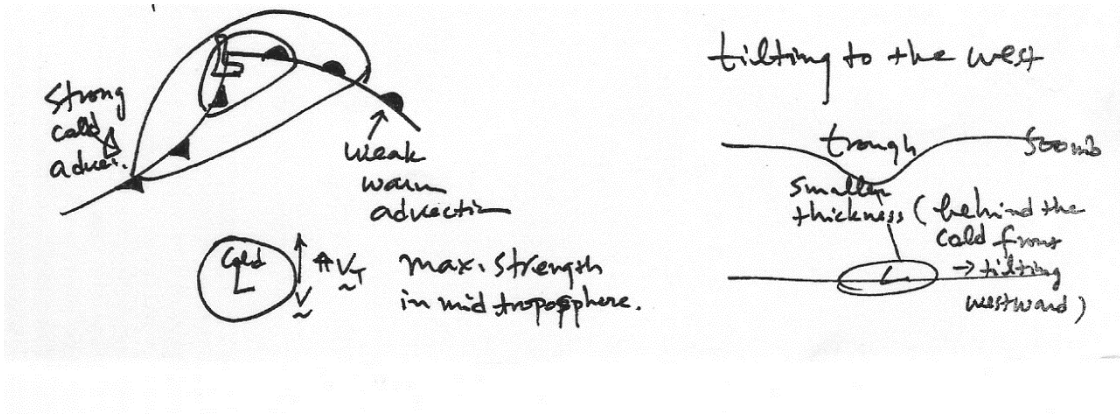
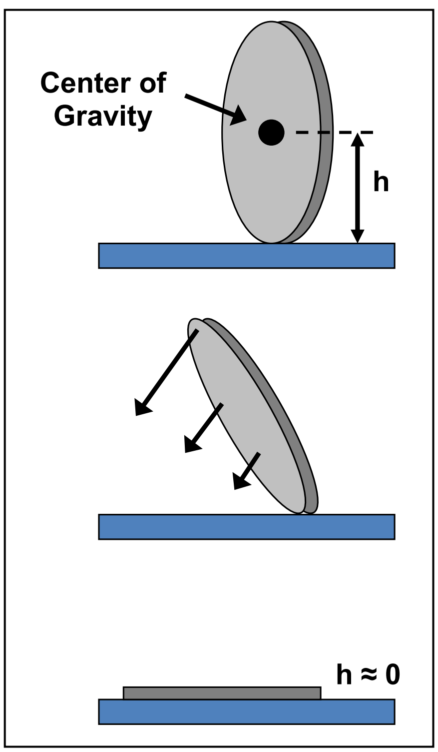


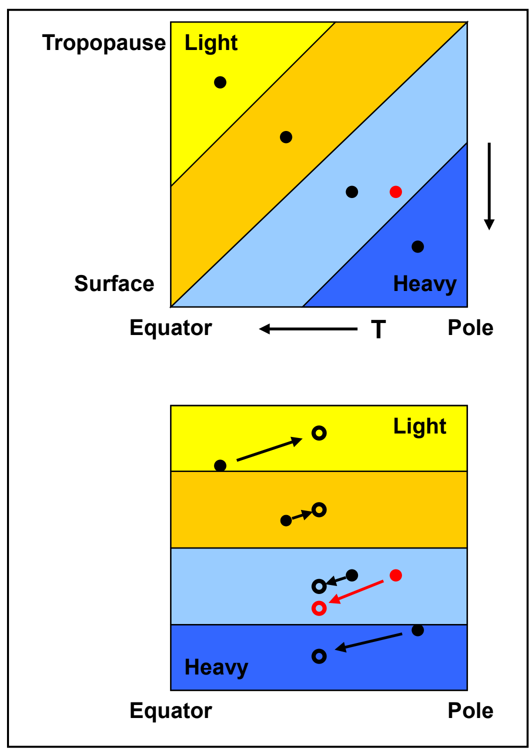
Fig. 6.5 Schematic 500-mb contours (heavy solid lines), 1000-mb contours (thin lines), and 1000–500-mb thickness (dashed) for a developing baroclinic wave at three stages of development. (After Palmén and Newton, 1969.)

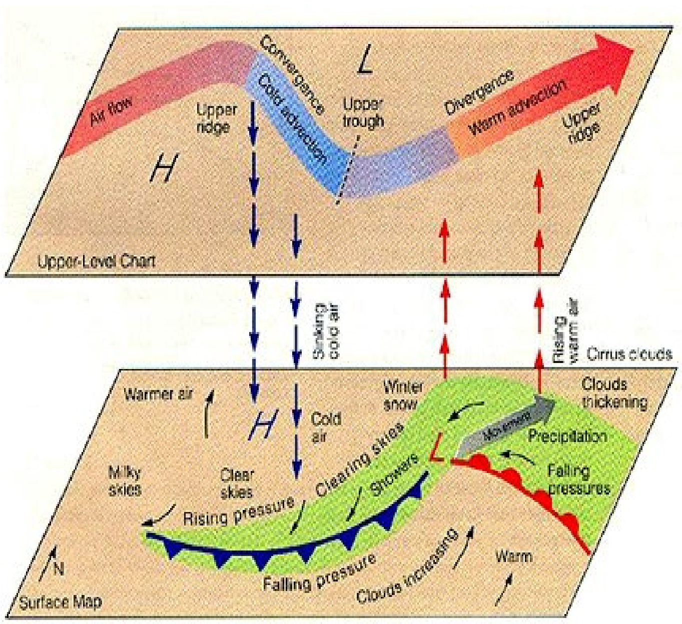


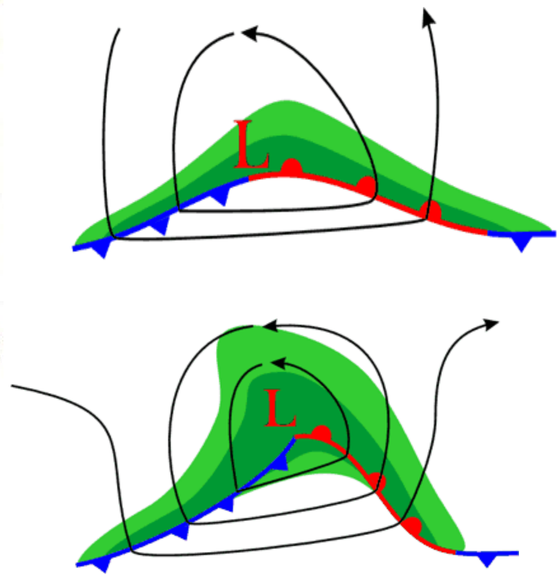
- Baroclinic Instability and Cyclogenesis

Available Potential Energy (APE)
⇨ Kinetic Energy (KE)






Air flow
Upper ridge
Convergence
Cold advection
L
Upper trough
Divergence
Warm advection
Upper ridge
H
Upper-Level Chart
Sinking cold air
Rising warm air
Cirrus clouds
Warmer air
H
Cold air
Winter snow
Clouds thickening
Movement
Precipitation
L
Falling pressures
Milky skies
Clear skies
Clearing skies
Showers
Rising pressure
Falling pressure
Clouds increasing
Warm
N
Surface Map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