Part 5. Extratropical Cyclones

Extratropical Synoptic Scale Disturbances

Cyclone – rotates in the same sense as the earth's rotation (counterclockwise in Northern Hemisphere, clockwise in Southern Hemisphere).

Extratropical Cyclones are poleward of 25° (Tropics).

Air Masses and Fronts

In the classical Norwegian concept, cyclones are born along a *front* between warm and cold *air masses*. Normally, the temperature and humidity of the air near the surface change only slowly over great distances of 1,000 miles (1,600 km) or more, leading to the concept of broad, relatively uniform *air masses.* Temperature and moisture are their main distinguishing features. Basically, we differentiate between warm (topical) and cold (polar) air masses and between humid (maritime) and dry (continental) air masses. Combining these, the four principal air masses according to geographic origin are:

Continental polar
Maritime polar
Continental tropical
Maritime tropical

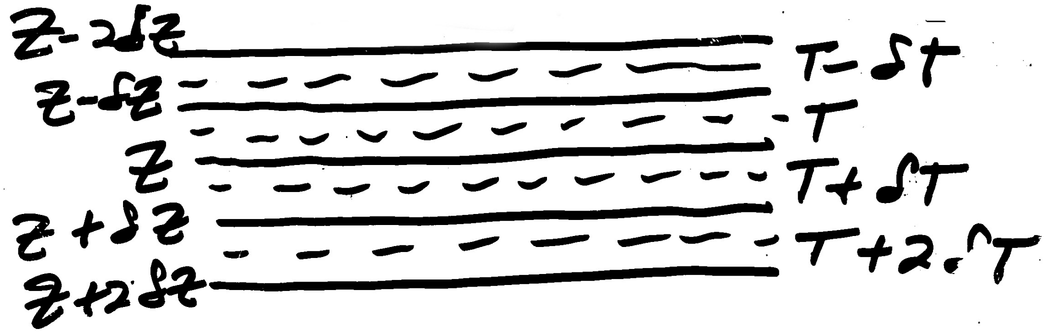
Classification of air masses has been carried much farther than presented in this simple scheme, but with little advantage in most circumstances.

Frequently two air masses, especially tropical and polar, develop a sharp *boundary* or *interface,* where the temperature difference between them becomes concentrated. Such boundaries were named *fronts* by the Norwegians.

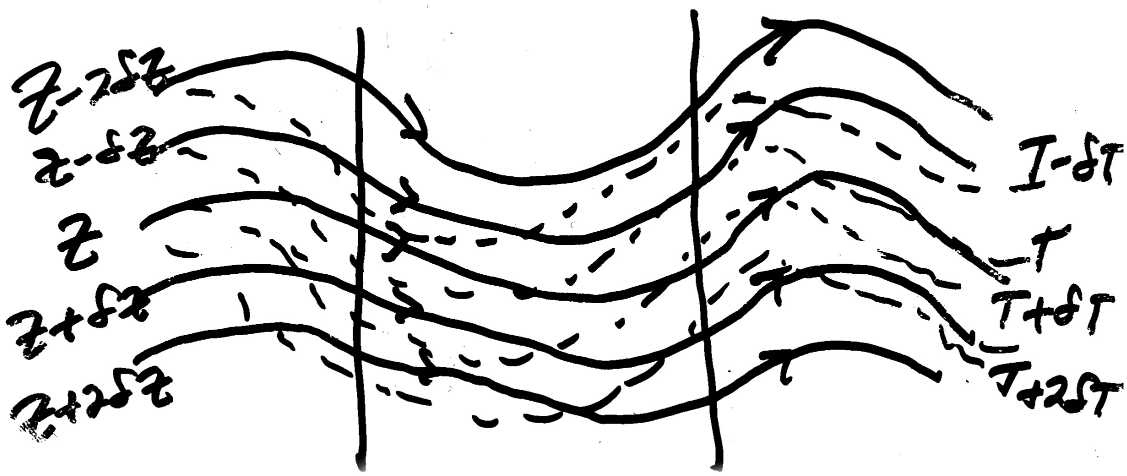
Extratropical cyclones form by baroclinic instability – where north/south temperature gradient becomes so strong that an infintitely small perturbation amplifies into a synoptic-scale wave disturbance.

- Assume that this perturbation exists in a uniform zonal flow u.
- Assume wavelike perturbation moves at speed $c=u$.
- Assume N/S velocity associated with perturbations will distort T patterns.

Initial



After



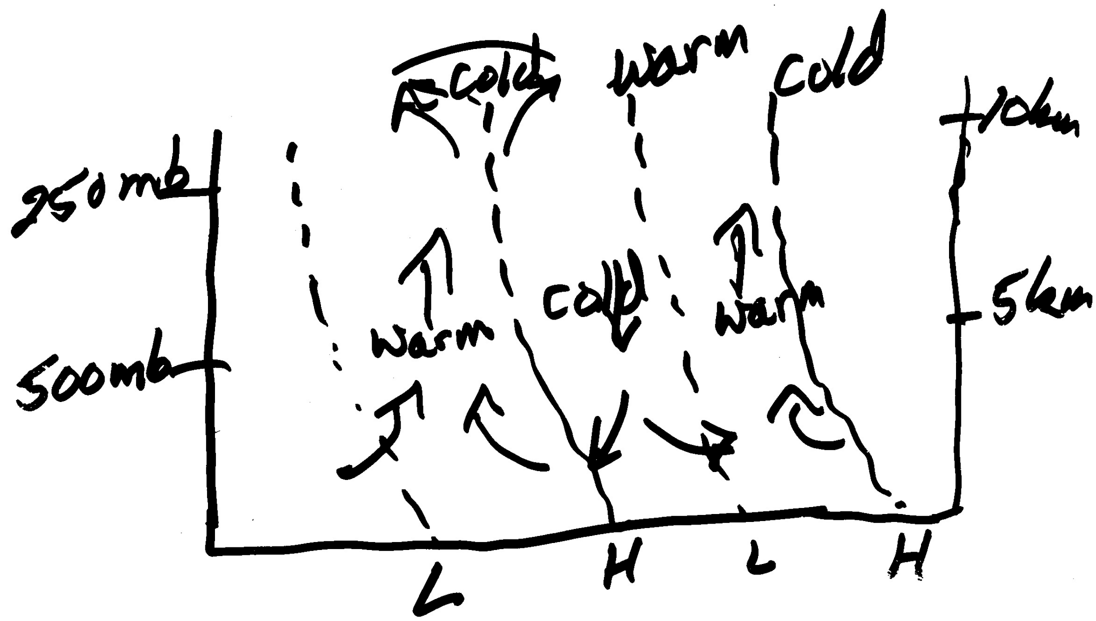
Cold Axis Warm Axis

Northerly flow advects colder air southward.	Southerly flow advects warmer air northward.

Structure of baroclinic waves

- If $\bar{u} > c$, the wave in the isotherm pattern will be advected toward the east.
- If $\bar{u} < c$, the wave in the isotherm pattern will lie to the west of its position for $\bar{u} \approx c$. In lower troposphere $\bar{u} < c$ (usually).
- In the upper troposphere $\bar{u} > c$ (usually).
- In the middle troposphere $\bar{u} \approx c$ (usually).

Vertical structure of developing baroclinic wave is:

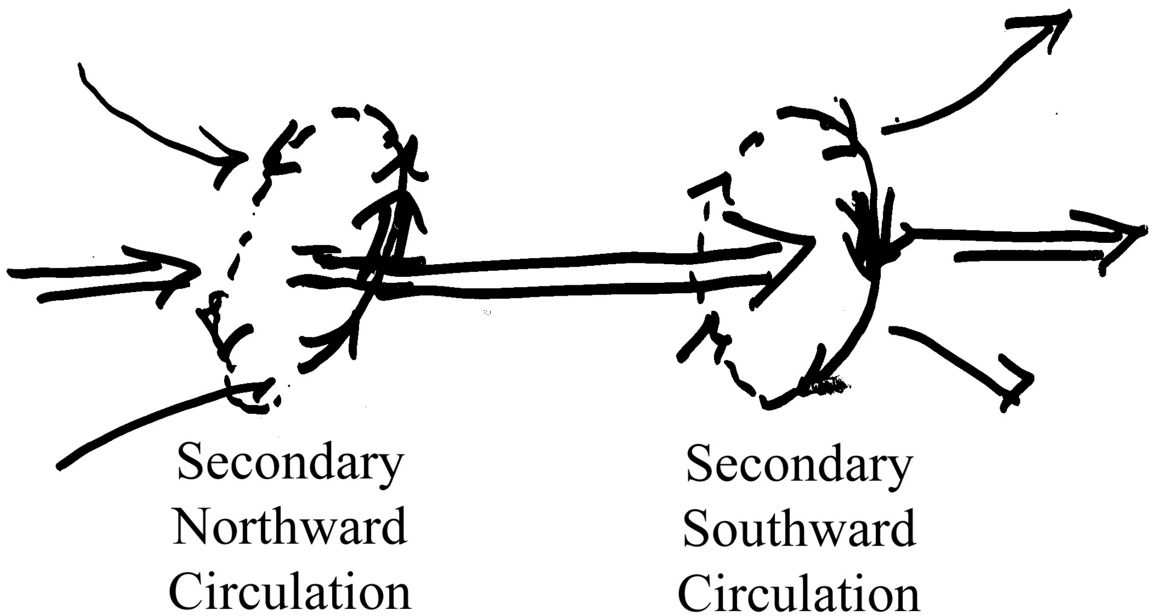


Jet Streams and Jet Streaks

Where do extratropical cyclones form?

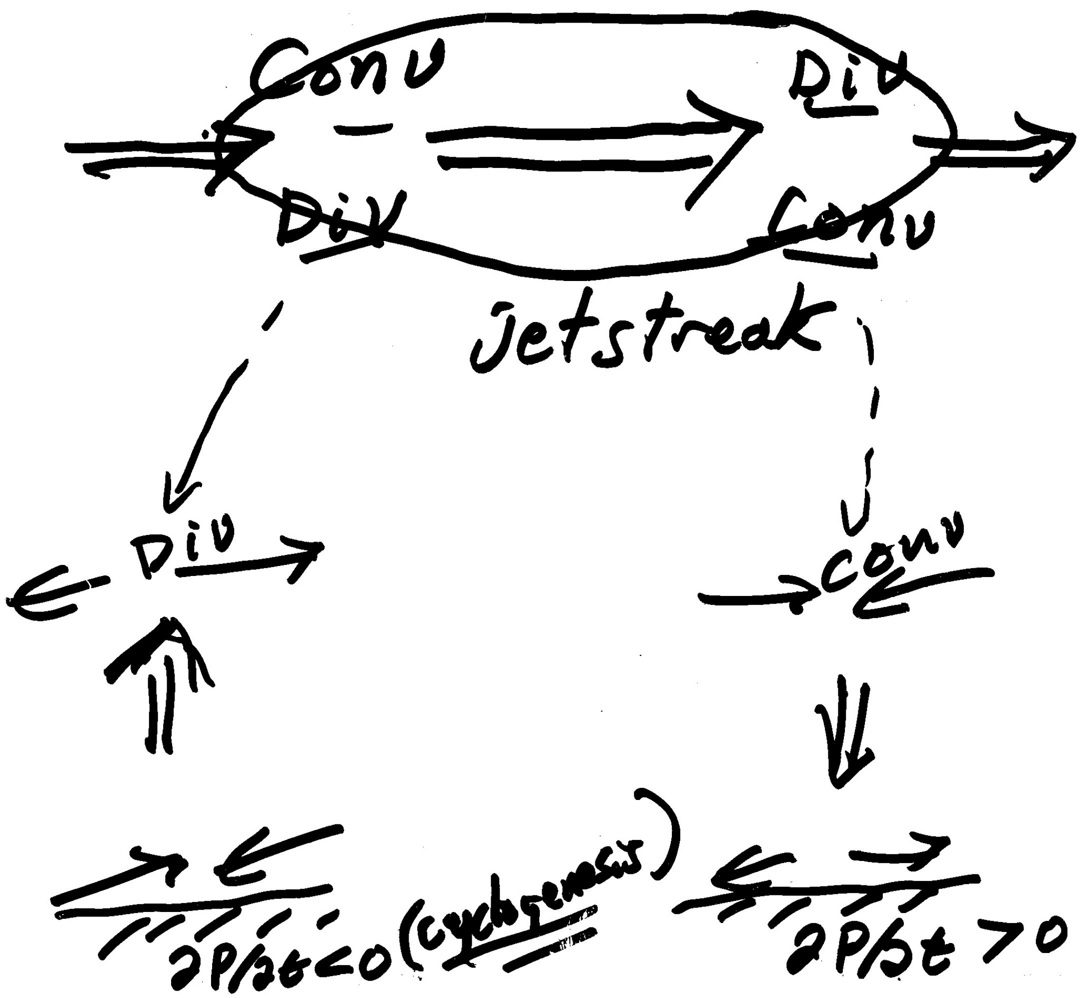
- Near jet streams.
- Particularly near jet streaks.

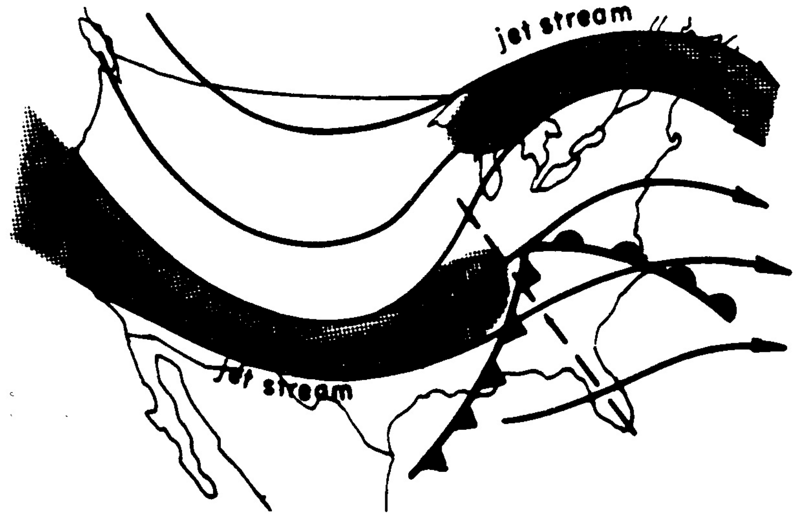
Jet Streak – a region within jet stream where the wind speeds are a local maximum.

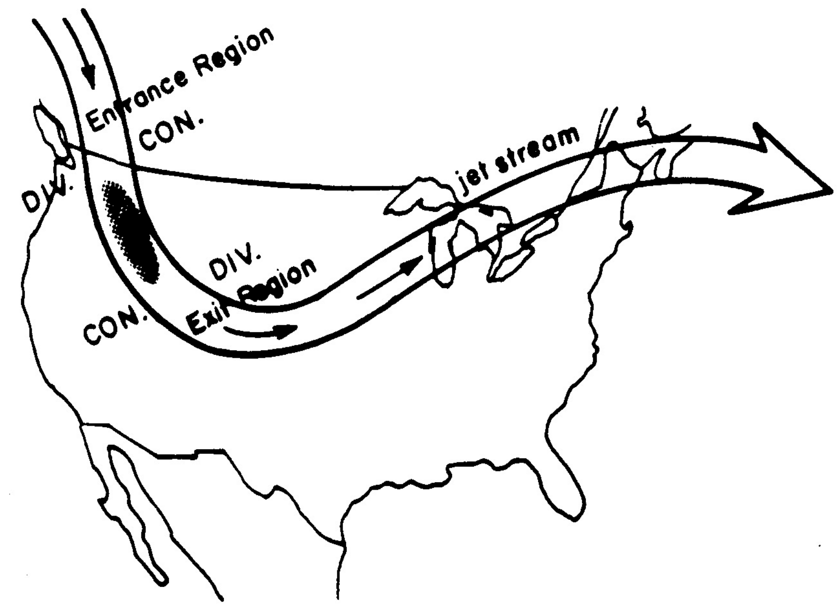


Jet streaks are a focusing mechanism for cyclogenesis.

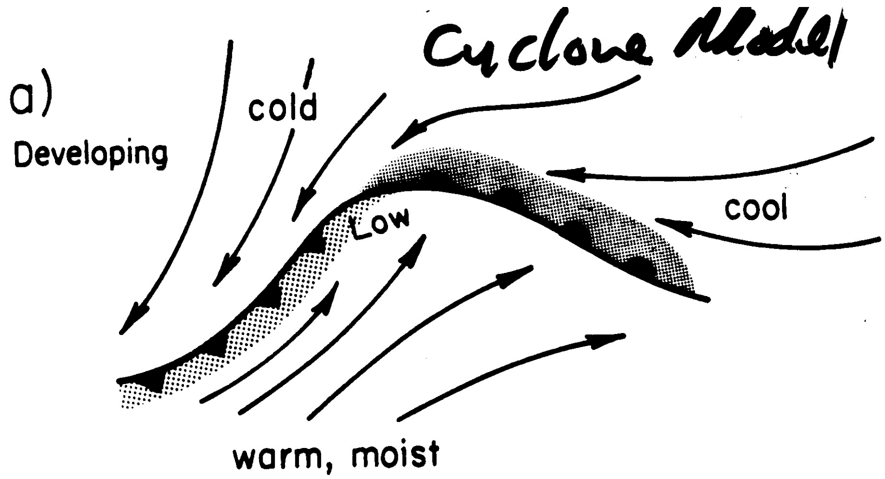
~200 mb

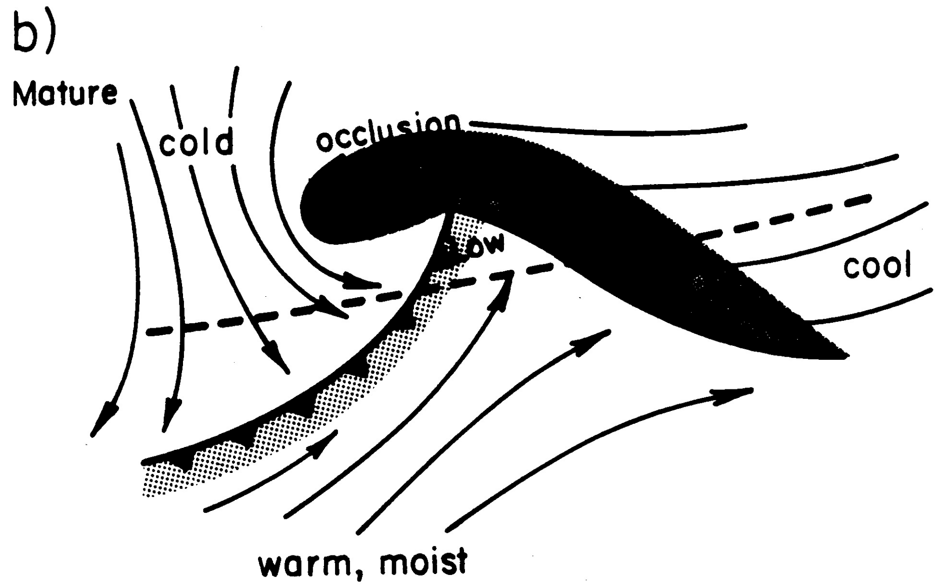



jet stream
jet stream


Entrance Region
CON.
DIV.
jet stream
DIV.
Exit Region
CON.

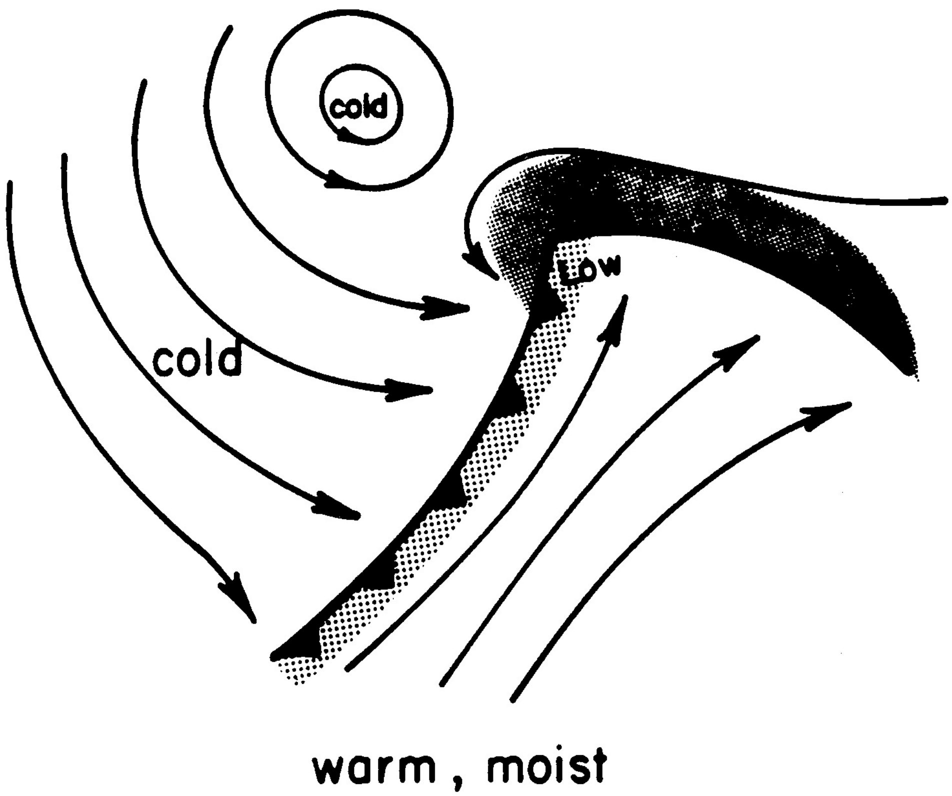
Lifecycle – Norwegian Cyclone Model

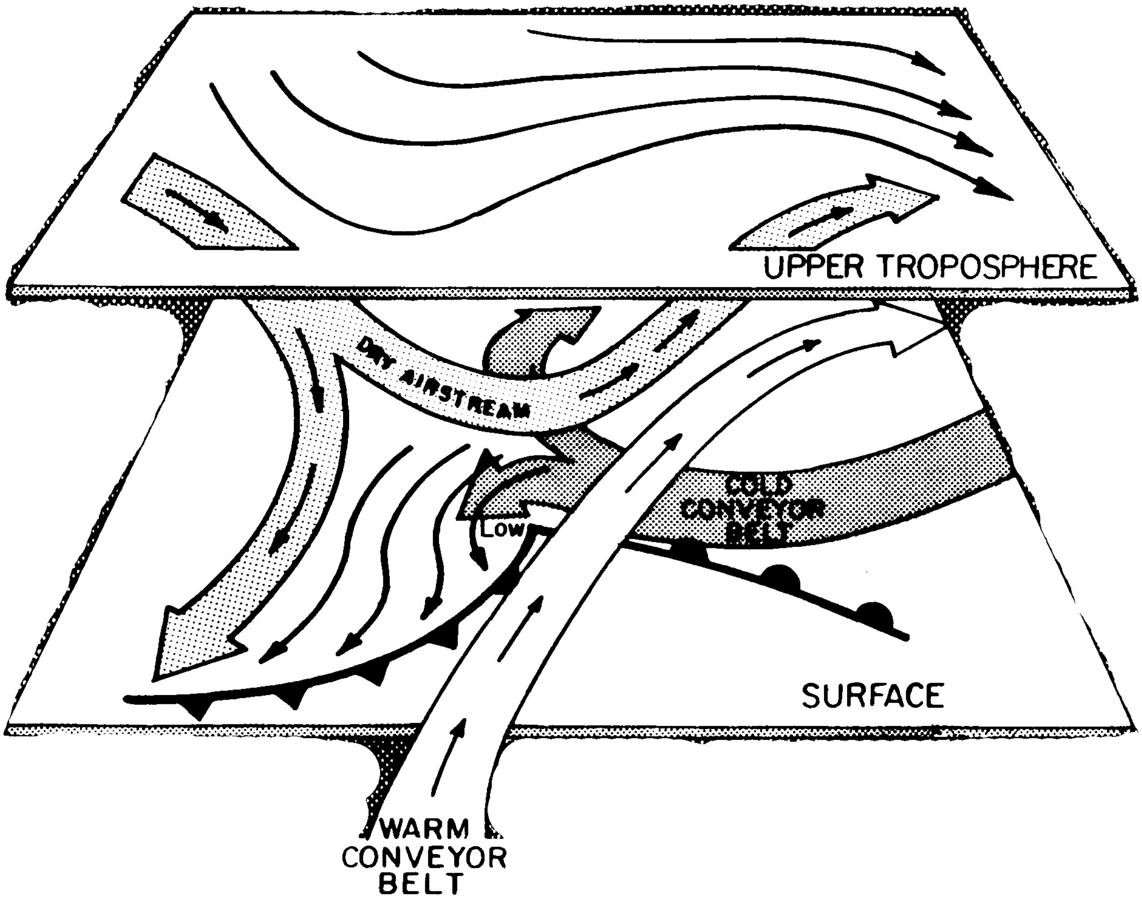




c)

Dissipating





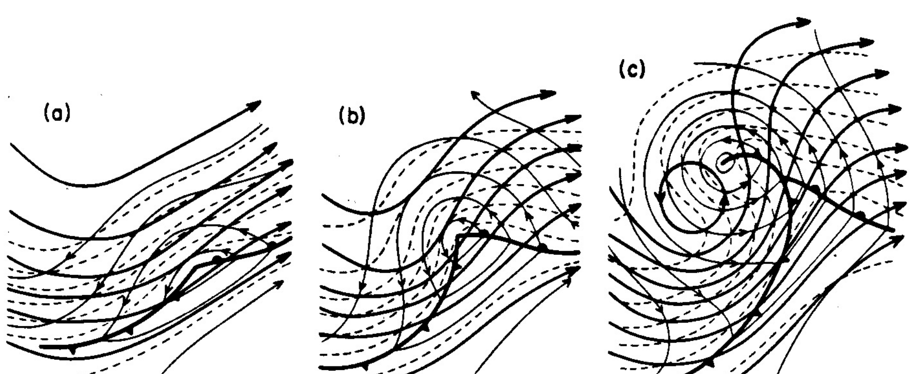
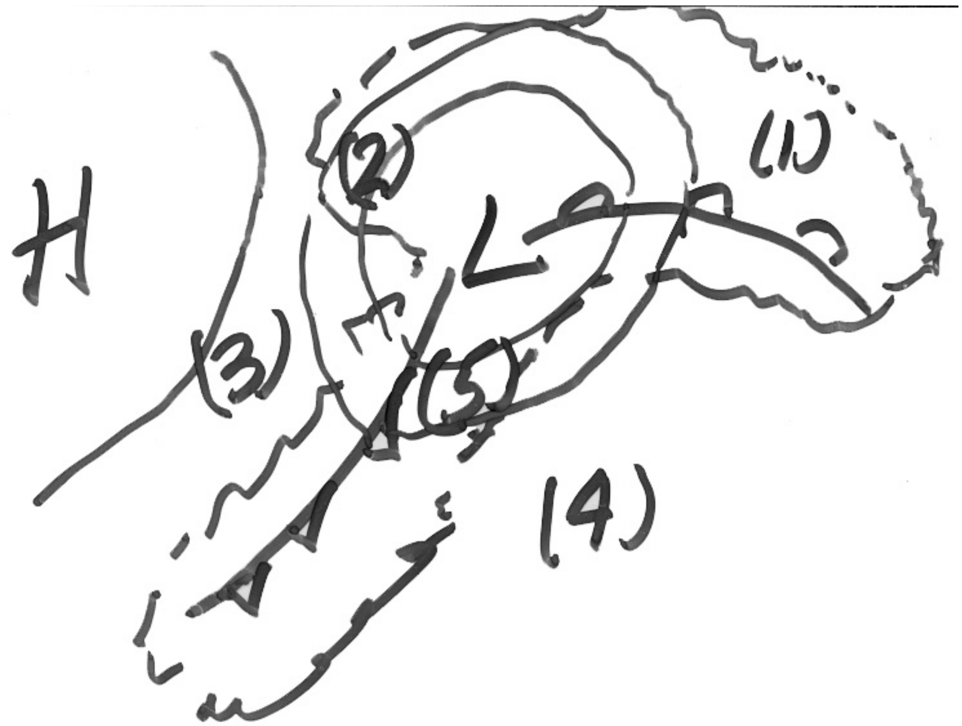
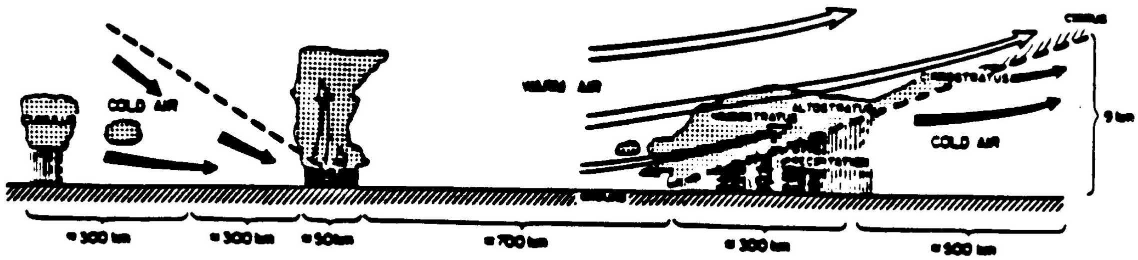


Fig. 3.22 Idealized Model of a middle-latitude storm in three stages of development: (a) initial stage, (b) developing stage, and (c) occluded stage. (____) isobars of sea level pressure, (____) contours of 500-mb height, (----) contours of 1000-500-mb thickness. (From F. Palmer and C.W. Newson, "Atmospheric Circulation Systems." Academic Press, New York, 1969, p. 326.)

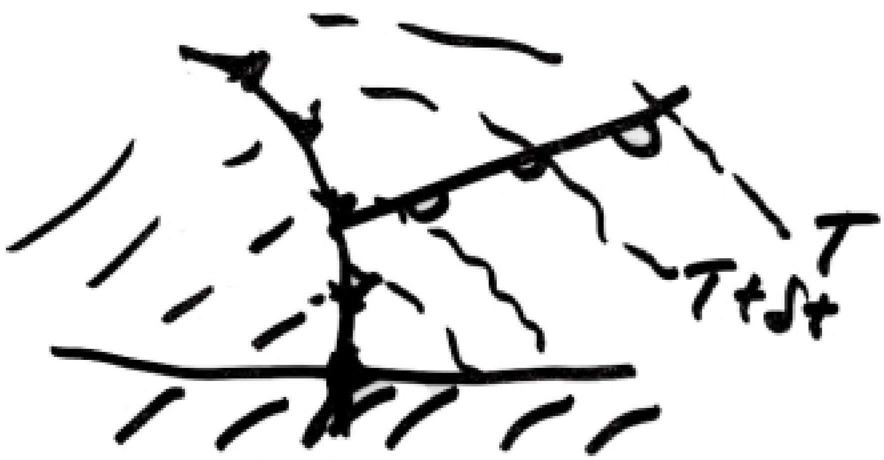


Precip.	Clouds	Temp.
(1) Continuous	Low stratus overcast, fog	Cool highs
(2) Very light showers	Broken shallow cu, intermittent blue skies	Cool highs
(3) None	Fair wx. Cu. > 75% sunshine	Warm highs, cold lows
(4) Spotty conv. showers, pre-frontal squall lines	Hazy sunshine, thin overcast	Hot
(5) Cbs. in summer and winter	Cb's dark sky	Hot turning cool after Fropa



Occluded Fronts

Occluded Fronts



Cold occlusion

Warm occlusion

- The common notion is that such fronts form when the cold front catches up with part of the warm front during cyclogenesis.

- However there are few examples of cold fronts overtaking warm fronts to form occlusions.

- It appears most occluded fronts are new fronts which form as surface lows separate from the junctions of their respective warm and cold fronts and deepen further back into cold air.

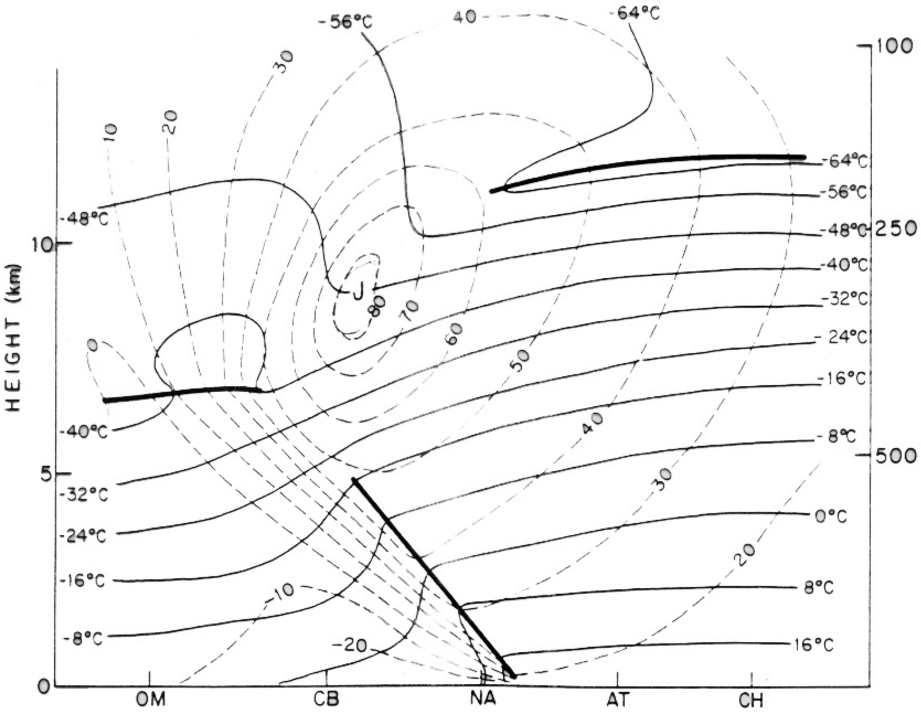


Fig. 3.19 Distribution of isotherms in degrees Celsius (——) and isotachs in meters per second (– – –) in a vertical cross section through the cold front at 00 GCT 20 November 1964. Station locations are indicated in Fig. 3.9. Isotachs refer to the geostrophic wind component normal to the section. Positive values indicate winds directed into the section. The heavy lines indicate the cold front and the tropopause. J refers to the axis of the jet stream.

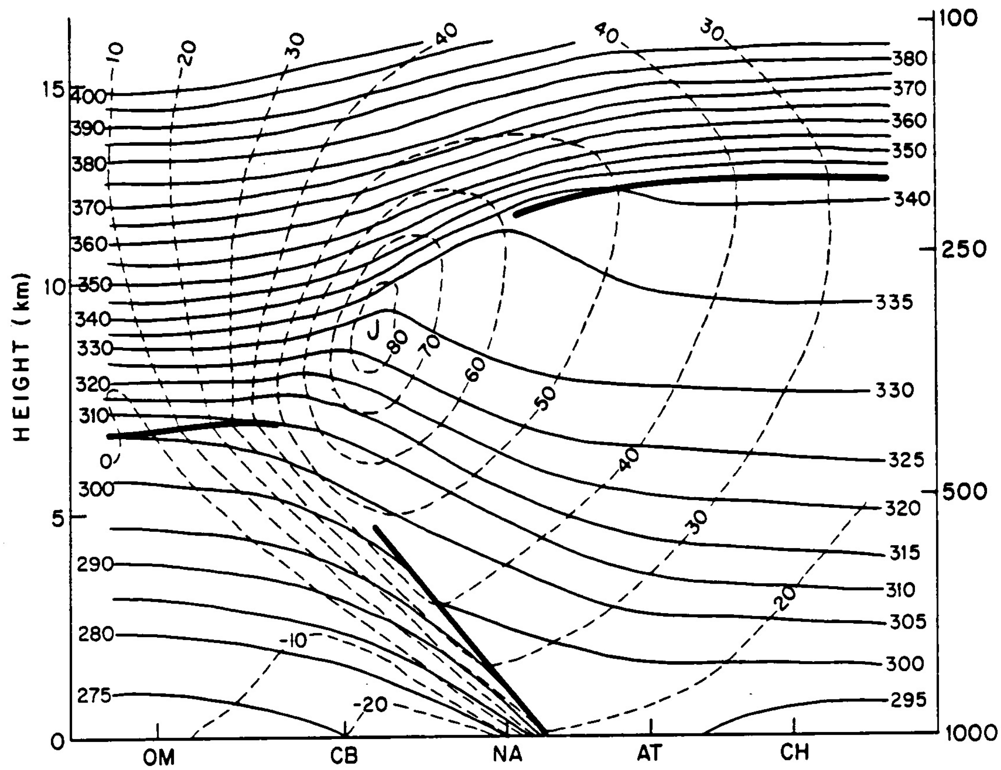


Fig. 3.20 Vertical cross section through frontal zone as shown in the previous figure except that solid lines represent isentropes (lines of constant potential temperature), labeled in degrees Kelvin.

Figure X.20 provides another illustration of extratopical cyclone development including regions of thickness advection and vorticity advection.

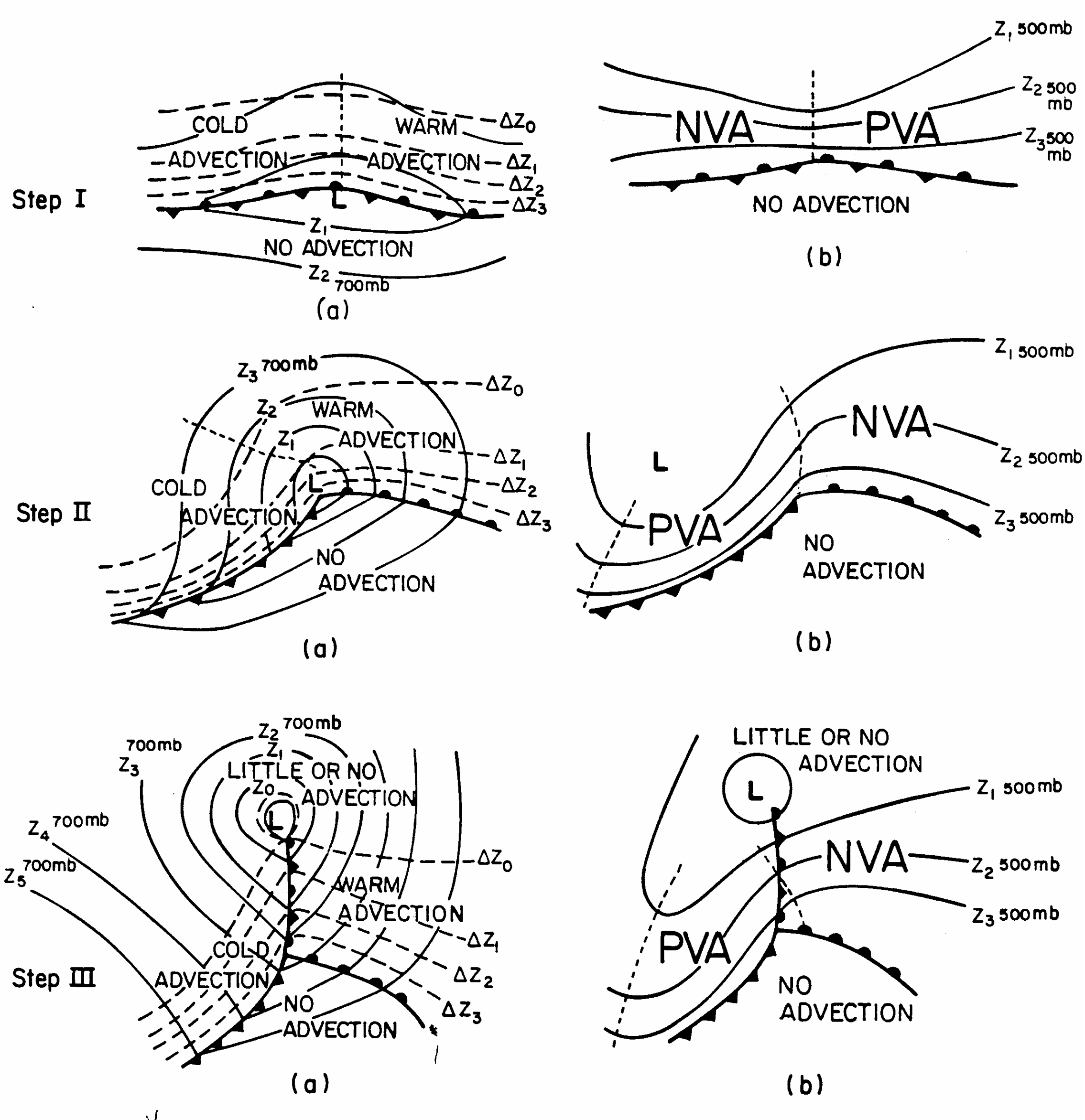


Figure 3.20: Schematic illustration of thickness advection and vorticity advection associated with extratropical cyclone development. The 700 mb height contours (solid lines), 1000-500 mb thickness contours (dashed lines), and surface frontal location are given in (a). The 500 mb height contours (solid lines) and surface frontal location are shown in (b).

The conditions associated with the development of extratropical storms is as follows:

- Favorable conditions:
    - The existence of a thickness gradient in the lower troposphere (i.e, a front); particulary when it is anticyclonically curved;
    - The presence of an upper-level trough with cold advection to its rear and warm advection ahead; and
    - Release of latent heat near the center of the surface low by deep cumulonimbus and stratiform precipitation.
- Unfavorable conditions:
    - A weakening thickness gradient as a result of low-level divergent flow; and
    - The absence of an upper-level trough or a trough with cold advection ahead ot it, and warm advection behind resulting in a trough which will decrease in intensity with time.

Extratropical cyclones are different from hurricanes and tropical storms because their energy is primarily from the juxtaposition of cold and warm air masses (i.e., a horizontal thickness gradient). Tropical cyclones, in contrast, derive their energy though heating around the central core as a result of deep cumulonimbus. In addition, the wind field of extratropical cyclones, although spread over a large area, has weaker maximum speeds since the pressure gradient is not as strong as found in mature, well-developed hurricanes. Oceanic extratropical cyclones are less of a danger to shipping than hurricanes because the seas are not as chaotic since the wind direction does not vary through 360° around a small center as it does for the tropical storm.

Symmetric and Conditional Symmetric Instability (CSI)

Consider the more complicated problem of a parcel of air in the region of a cold front or what we called a baroclinic zone. We noted previously that wherever there is a strong, horizontal, temperature gradient, the winds increase in speed with height. Thus, a parcel in geostrophic equilibrium will experience an equilibrium angular momentum that also increases with height. Figure 5.1 illustrates a west-to-east cross section through a

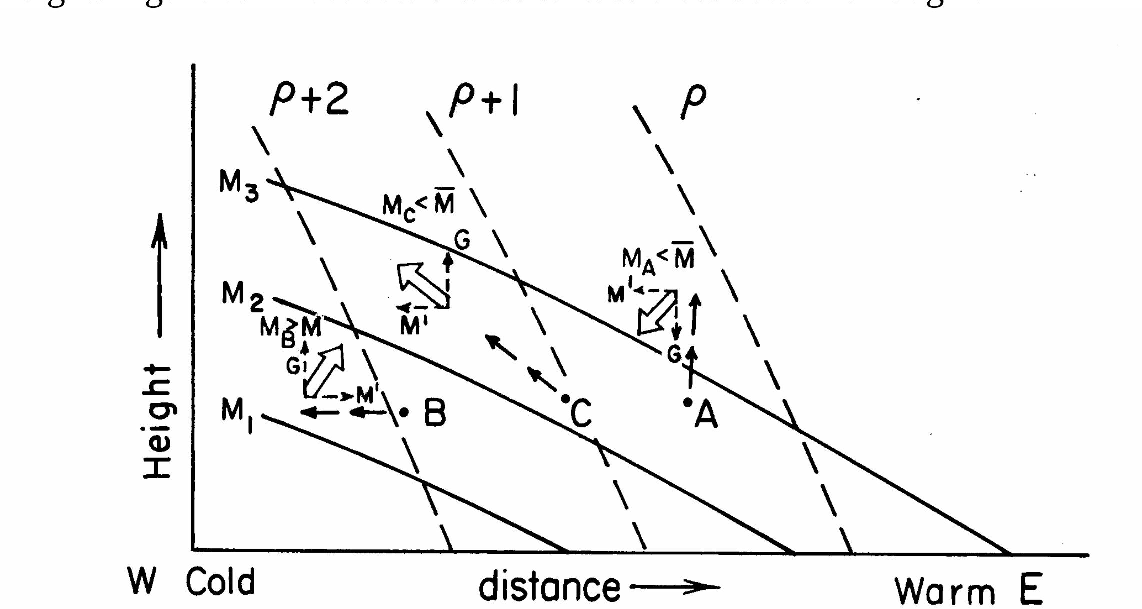


Figure 5.1. Schematic of a west-east, vertical cross-section illustrating symmetric instability. Solid lines represent absolute angular momentum, *M*, of the undisturbed flow. Dashed lines represent the air density of the undisturbed flow. Movement of parcels from positions A, B, and C are indicated by the small arrows, while the accelerations of the parcels are indicated by the double arrows. The acceleration is decomposed into a vertical component due to gravity (G) and a horizontal component due to imbalances of absolute angular momentum (*M'*). (Adapted from Sanders, F. and L.F. Bosart, 1985: Mesoscale structure in the megalopolitan snowstorm of 11-12 February 1983. Part I: Frontogenetical forcing and symmetric instability. *J. Atmos. Sci.*, **42**, 1050-1061.)

baroclinic zone. The solid lines M1, M2, M3 represent surfaces of constant angular momentum for parcels in geostrophic equilibrium. As is typical across frontal zones, these surfaces are not horizontal but exhibit a weak tilt from the horizontal. As noted previously, this is due to angular momentum decreasing with latitude and increasing with height. Quite evident in the figure is the tendency for the equilibrium absolute angular momentum to increase with height. Also shown are surfaces of constant air density which are not horizontal across a frontal zone. Colder, more dense air lies to the west. Nonetheless, the tendency for air density to decrease with height is also evident in the figure. The vertical variation in density in the figure corresponds to a stable, environmental temperature-lapse rate.

Let us consider the vertical, horizontal, and slantwise displacements of parcels A, B, and C, respectively. Displacing A upward in a stably stratified environment results in the density of A being greater than its environment, causing a downward acceleration. The upward-displaced parcel, A, will also carry its angular momentum, M_A, to higher levels and find itself in a region where the environmental geostrophically balanced angular momentum $\bar{M}$ is greater. This imbalance will create an acceleration of A toward lower absolute angular momentum in the environment or to the west (left). Because $\bar{M}$ decreases in magnitude toward the west, the westward acceleration rapidly decreases as the parcel moves in that direction. The dominant acceleration is, therefore, downward due to the stable stratification. Parcel A, thus, experiences a net restoring force bringing it back to its original position.

Let us now consider the westward displacement of parcel B. Because parcel B conserves its absolute angular momentum as it is displaced westward, it will find itself with excess angular momentum relative to its environment. This will create a horizontal acceleration toward larger environmental angular momentum, or to the right. Parcel B will also become less dense than its environment, resulting in a net acceleration that is upward and to the right. Because the environmental stratification is stable, the upward acceleration will not continue and parcel B will experience a net restoring force to its initial position. Thus, in the environment depicted in Figure 5.1 a parcel displaced either vertically or horizontally will experience a restoring force that will return the parcel to its original position. The environment is stable to either vertical or horizontal displacements.

Consider now the slantwise displacement of parcel C along the path shown in Figure 5.1, which has a slope that is between the slopes of the environmental angular momentum and density surfaces. In this case, while carrying its lesser angular momentum to higher levels, it will experience a deficit in angular momentum relative to its environment and therefore accelerate toward lower environmental angular momentum or to the left. Likewise, as parcel C ascends, it will become less dense than its environment and therefore experience an acceleration that is upward. The parcel undergoing slantwise displacement will therefore experience a net acceleration in the direction of its displacement. An environment in which the slope of the environmental angular momentum surfaces is shallower than that of the surfaces of environmental density is said to be unstable to slantwise motion or symmetrically unstable.

Just as the latent heat of condensation can result in conditional instability during vertical displacements, the latent heat of condensation released during slantwise displacements can also lead to conditional instability called *conditional symmetricinstability* (CSI), or *wet slantwise instability*.

An important feature of symmetric instability is that it is fundamentally mesoscale in character, developing a series of roll circulations (see Figure 5.2), with axes along the mean geostrophic shear and with slopes in the vertical plane comparable to those of the environmental density surfaces. The horizontal scale of the bands ranges from 50 to 500 km.

We thus see that in an otherwise uniform airstream, the airflow Can break down into bands of upward motion which can lead to cloud and precipitation formation. If the airstream at the top of the roll circulation is unstable-to-wet convection then the upward motion in the bands can trigger deep convective clouds, perhaps to the strength of squall lines. We have seen however, that conditional instability is not essential to the formation of vertical circulations leading to bands of clouds and precipitation. With the appropriate alignment of environmental angular momentum surfaces and density surfaces, the environment can become unstable to either dry or wet slantwise ascent, leading to the formation of bands of upward motion and precipitation concentrated into narrow corridors rather than being widespread, as one would be led to believe from the conceptual model of an extratropical cyclone shown earlier.

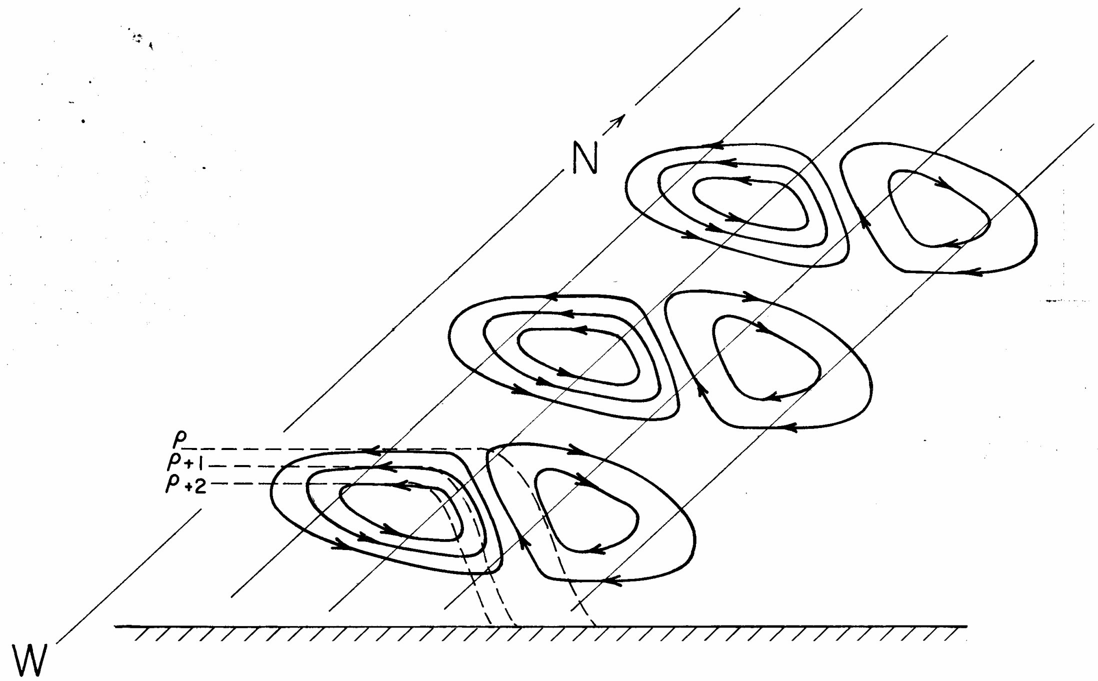


Figure 5.2. Schematic of the circulation resulting from conditional symmetric instability. The dashed lines show positions of environmental density surfaces. The roll circulation exhibits a long axis in the north-south direction in the case illustrated.

Rapidly Deepening Coastal Cyclones

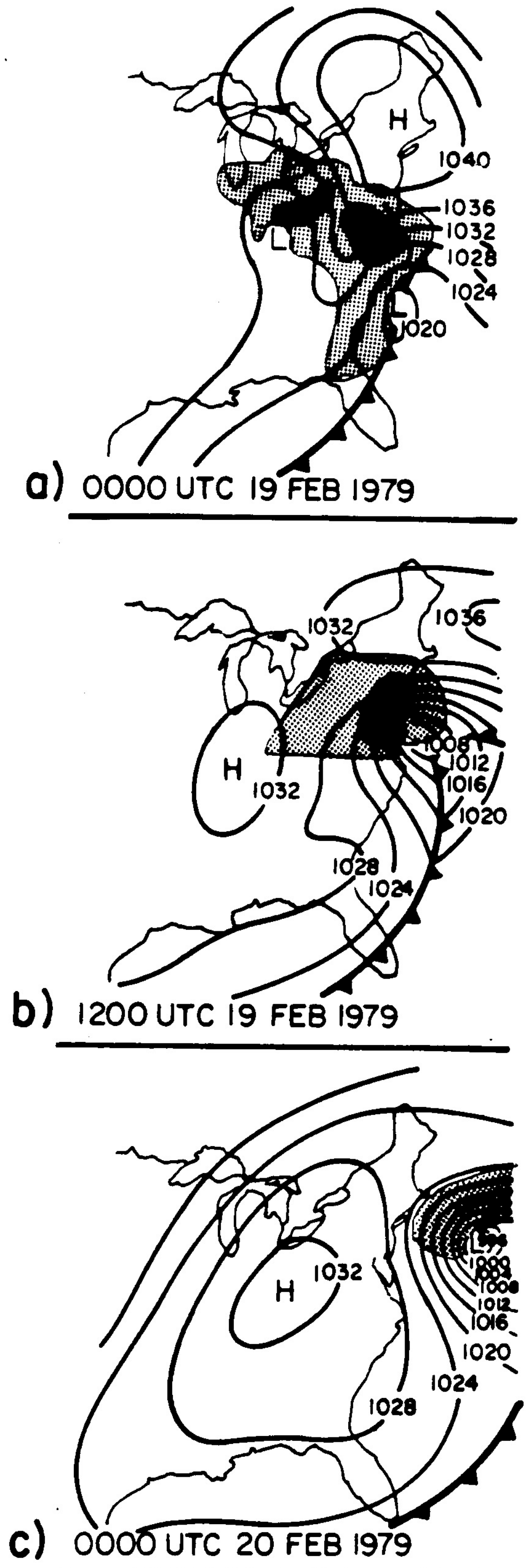
Or “bombs”

Characterized by (surface) pressure falls of ~24 mb in 24 hr or more.

Associated severe weather hurricane force winds, high seas, intense cb’s, heavy precip. – (snow)

(Noreaster)

President's Day Storm



President’s Day Storm:

P-deepened from 1020 mb to 996 mb in 24 hr.

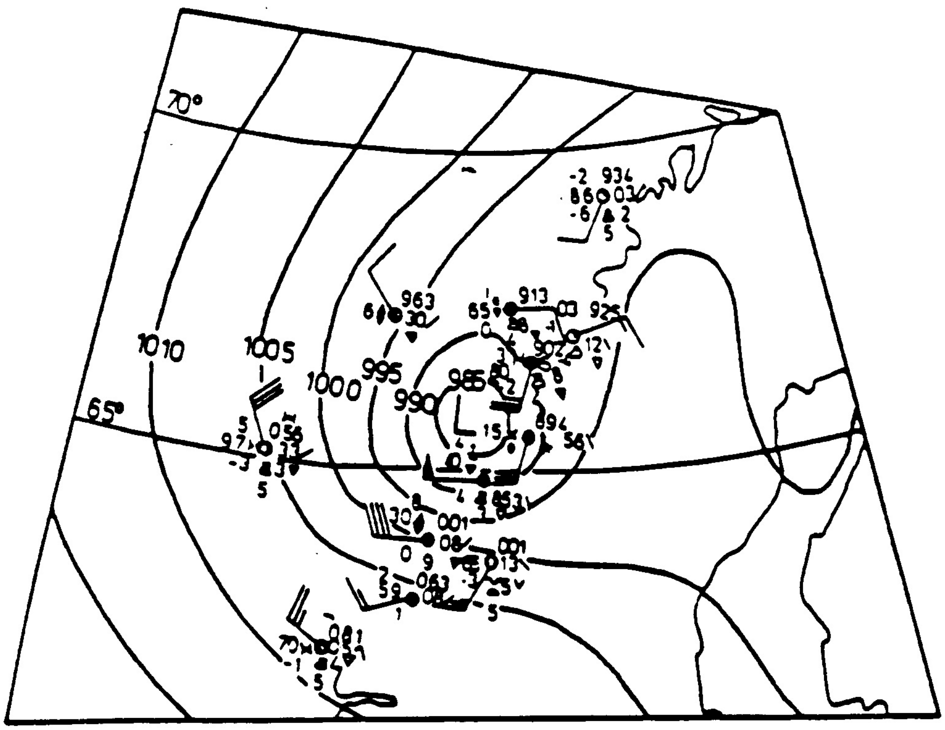
From DC to NY snow amounts in excess of 60 cm (~2 ft.).

Such a storm can receive as much as half its energy from the fluxes of sensible and latent heat from the ocean (Gulf stream). The other half from baroclinicity.

Polar Lows

- Resemble tropical cyclones in scale and structure.
- Produce high winds, sometimes of hurricane force.
- Form in polar airstream behind cold fronts where cold air (off ice pack) flows over warm water.

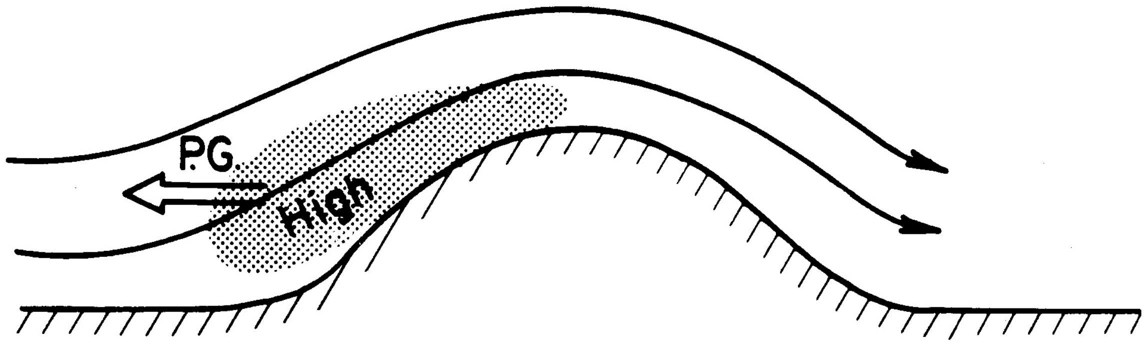
Figure 7.12: *NOAA-5 VHRR infrared satellite image for 1932 UTC 24 November, 1978, showing a polar low just south of Iceland. Faroe Isles are located just south of cyclone, which shows a cloud-free center. (From Rasmussen, E., 1981: An investigation of a polar low with a spiral cloud structure. J. Atmos. Sci., 38, 1785-1792.)*



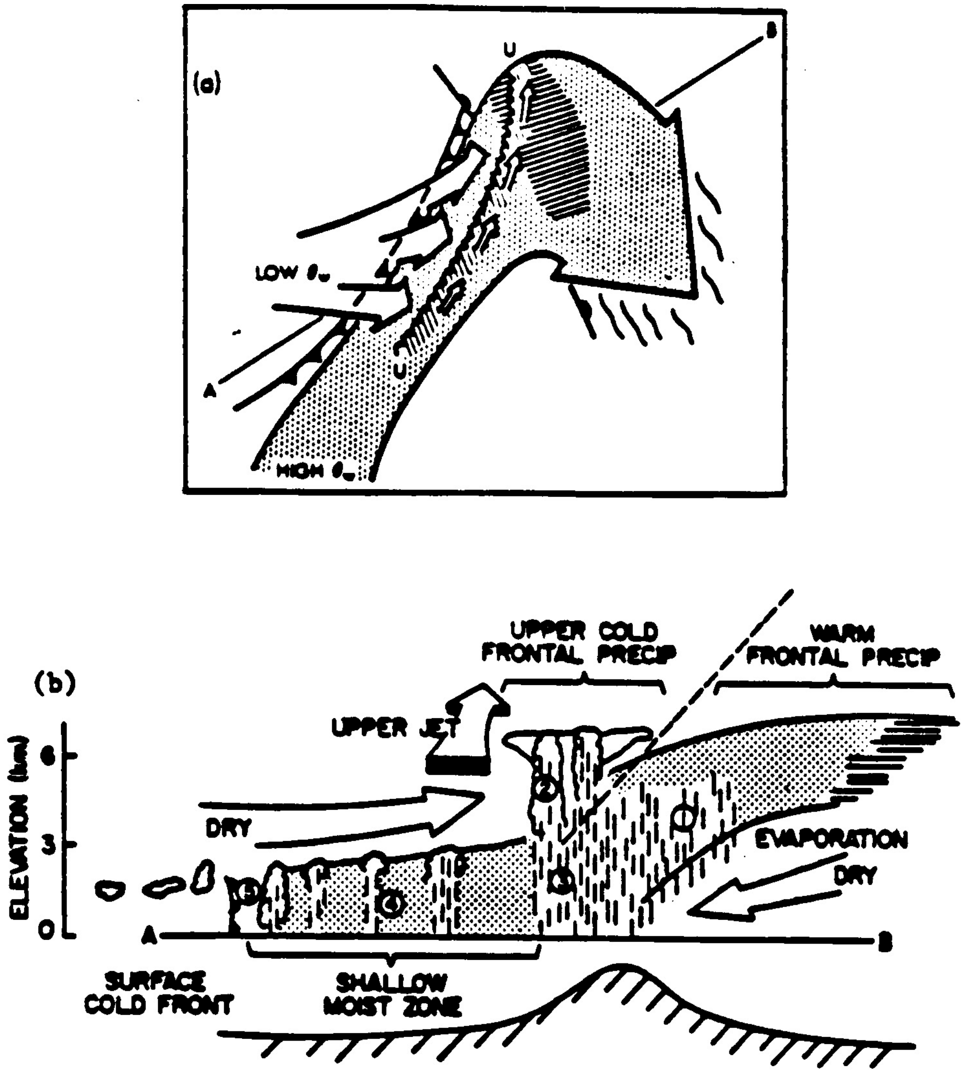
7.13

Fig. ~~11.14~~. A well-developed polar low off Norwegian coast at 00 GMT 13 October 1971. Surface data are plotted according to normal convection. Each full wind barb represents 10 kts. Maximum wind south of center is 50 kts. Temperature and dewpoint are in °C. Isobars are labeled in mb. [From Rasmussen, 1979.]

Topographic Block of Cold Air

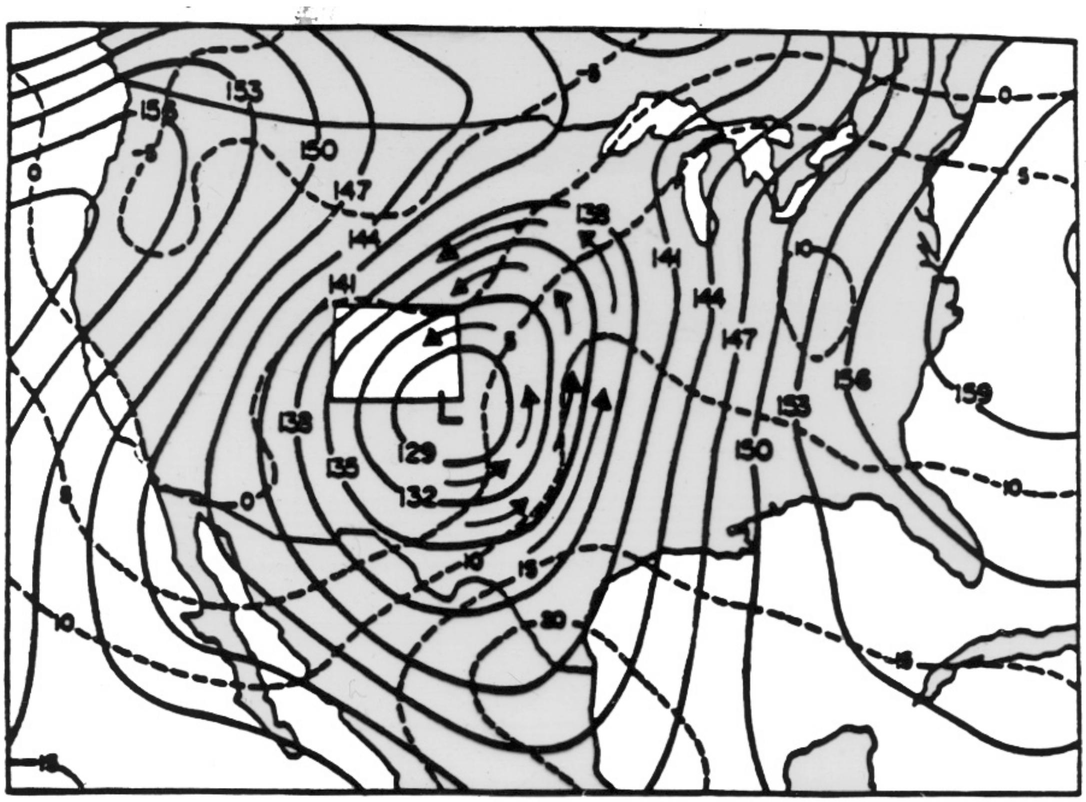


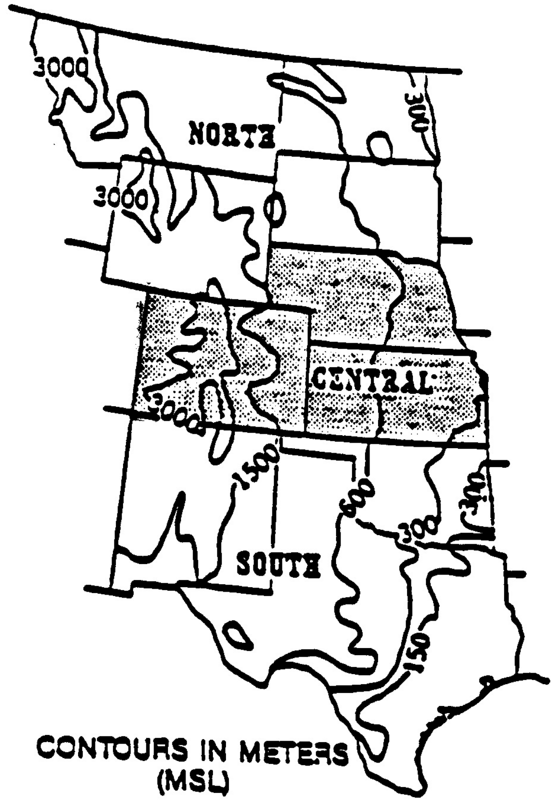
Split Front



(a)
U
B
LOW θw
A
U
HIGH θw
(b)
UPPER COLD FRONTAL PRECIP
WARM FRONTAL PRECIP
UPPER JET
ELEVATION (km)
6
3
0
DRY
EVAPORATION
DRY
A
B
SURFACE COLD FRONT
SHALLOW MOIST ZONE

Cyclonic Upslope Storms in Colorado





HIGH PLAINS TOPOGRAPHY

Fig. ~~12.29~~ 7.21. Elevation high-plains topography doubles with each contour. [From Reinking and Boatman, 1986 after Whiteman, 1973.]

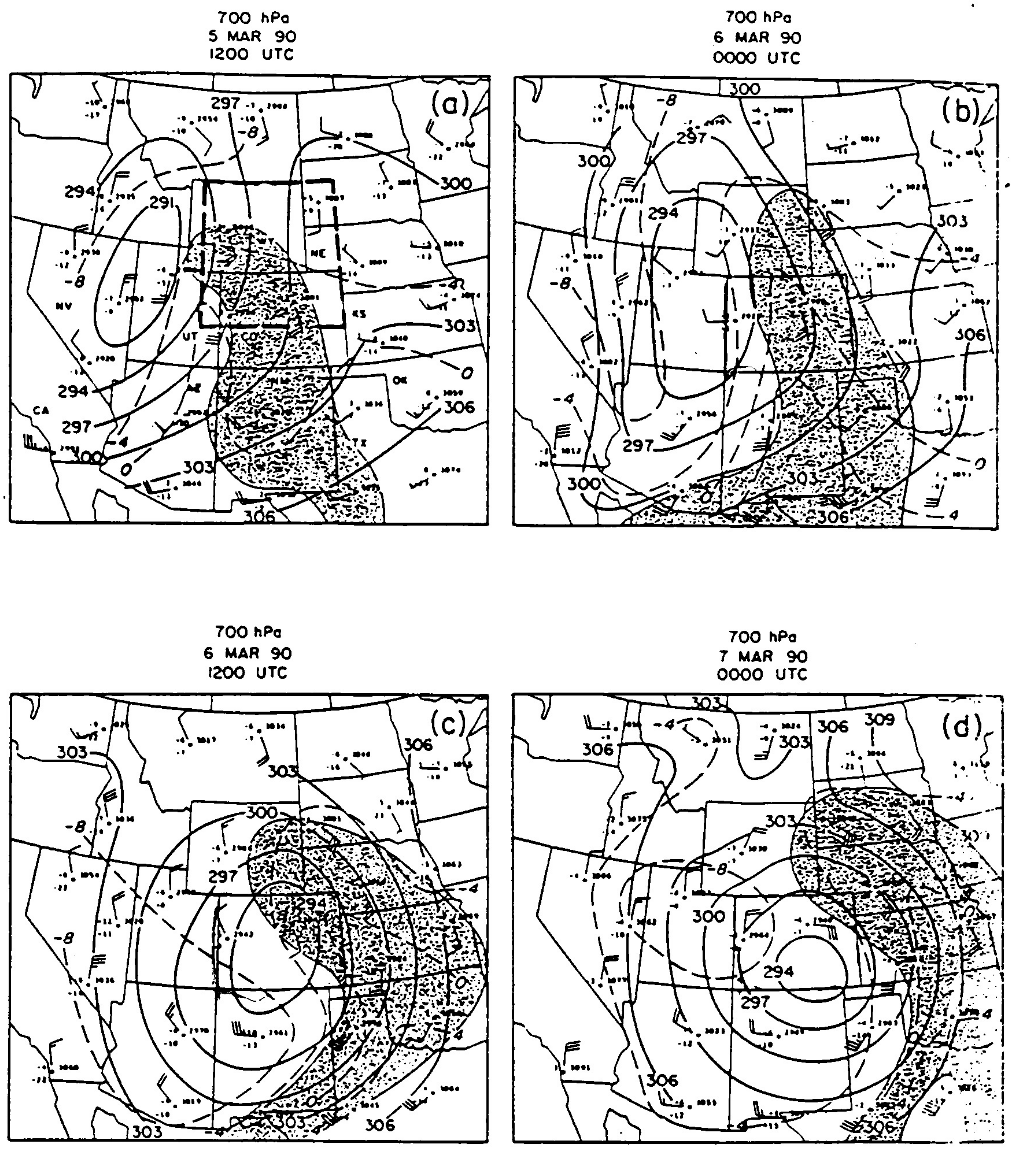


Fig. 2. Analysis of 700 hPa data for the times indicated. Full barb = 5 m s^{-1} wind speed. Solid lines are height contours with 30 m interval. Dashed lines are isotherms with 4 °C interval. Shading indicates dewpoint ≥ –5 °C. Two–letter state identifiers are included in (a). The broken box in (a) is the area shown in the surface analyses of Fig. 5.

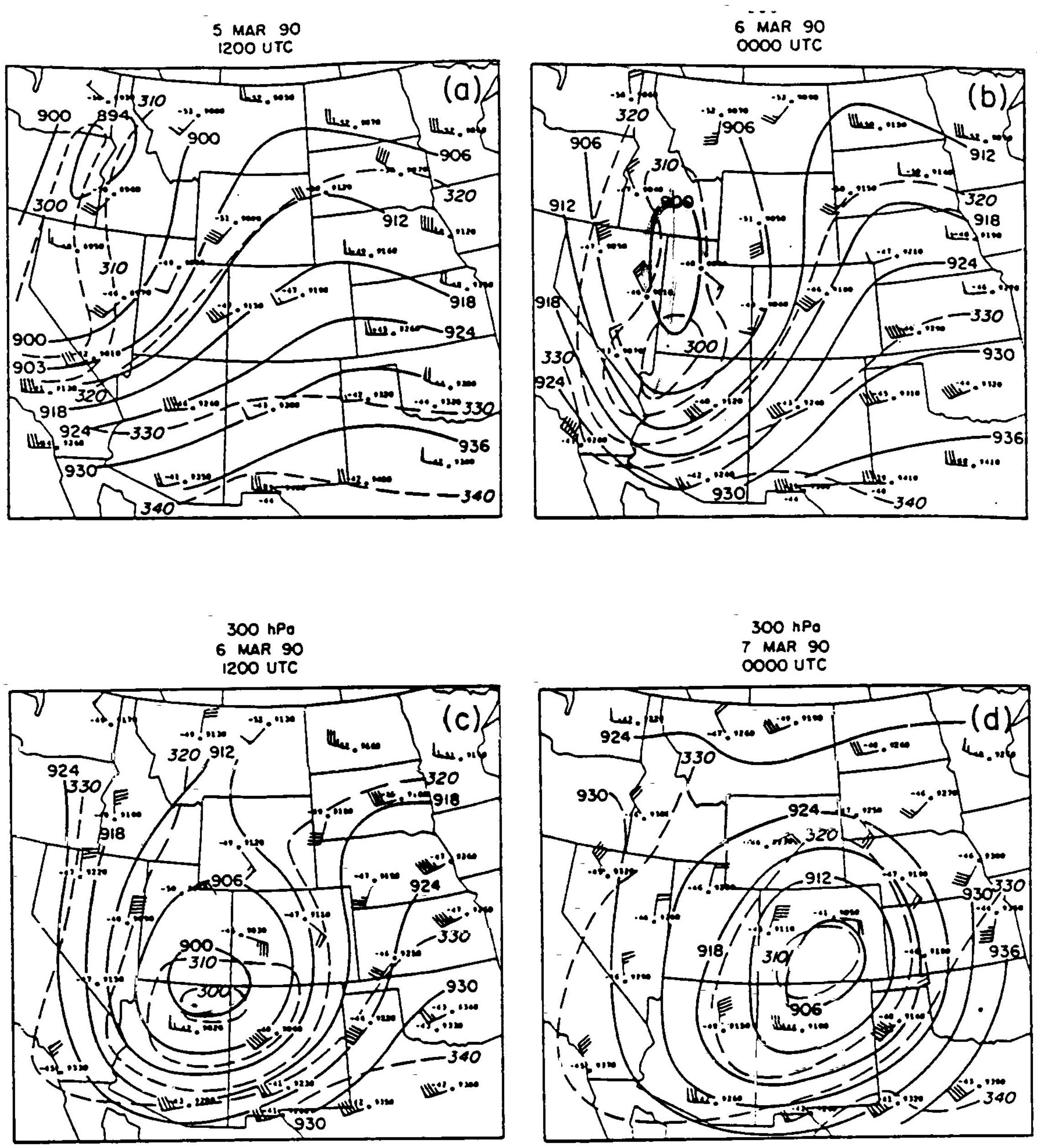


Fig. 3. Analysis of 300 hPa and tropopause data for the same times as in Fig. 2. Solid lines are height contours with 60 m interval. Dashed lines are tropopause isentropes with 10 K interval.

Surface Analysis

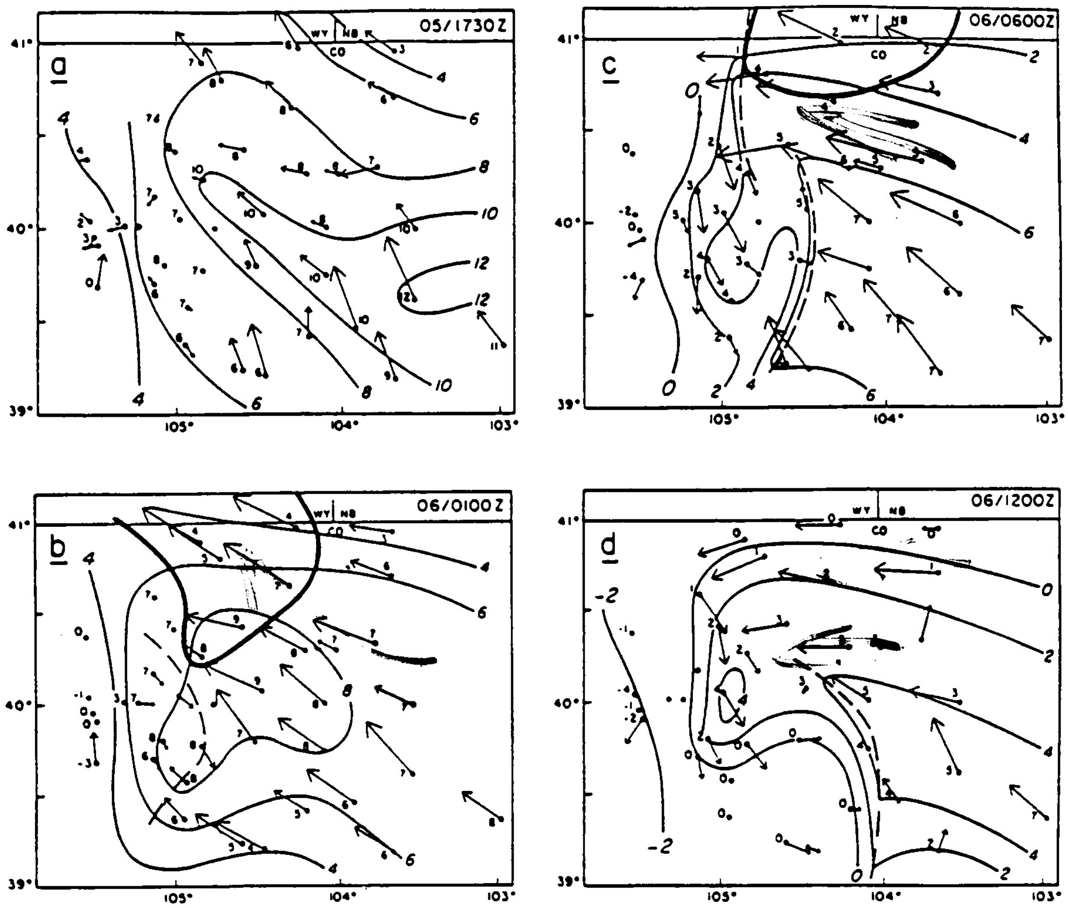
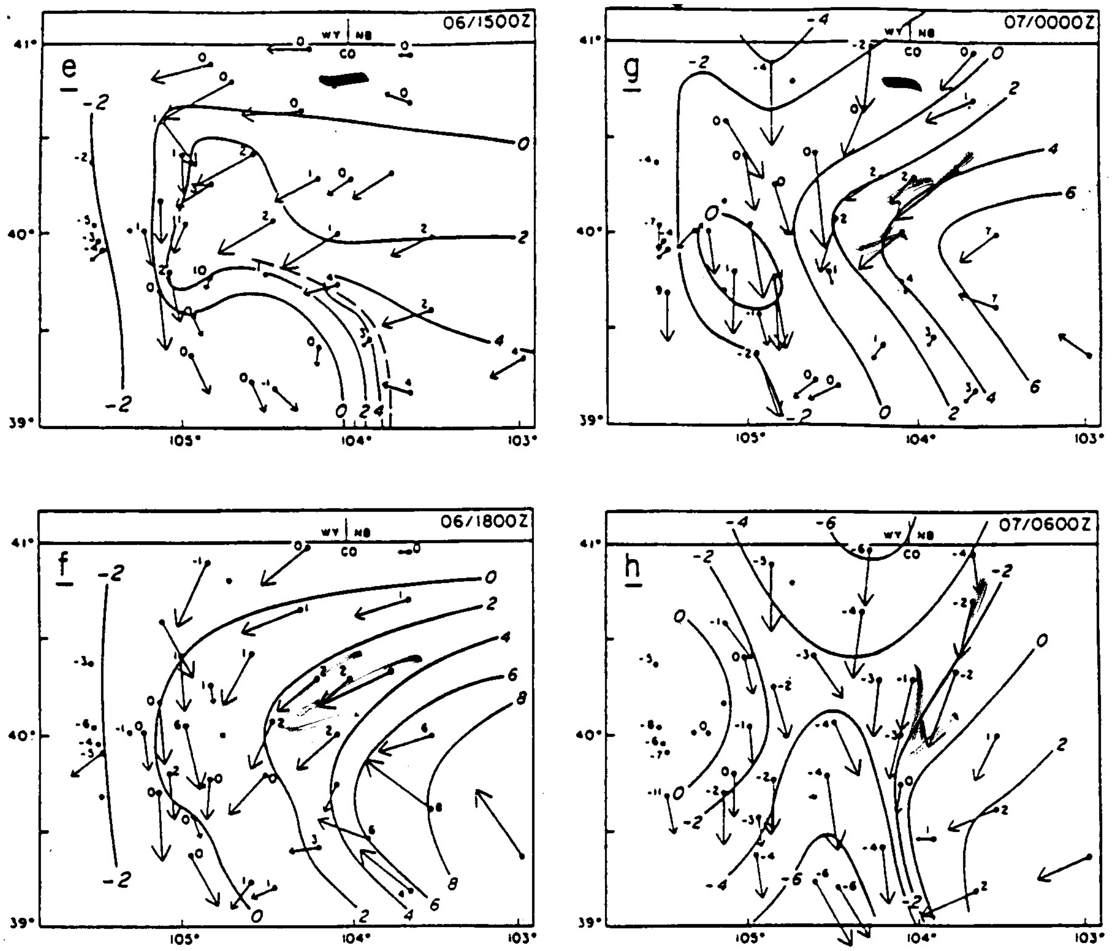
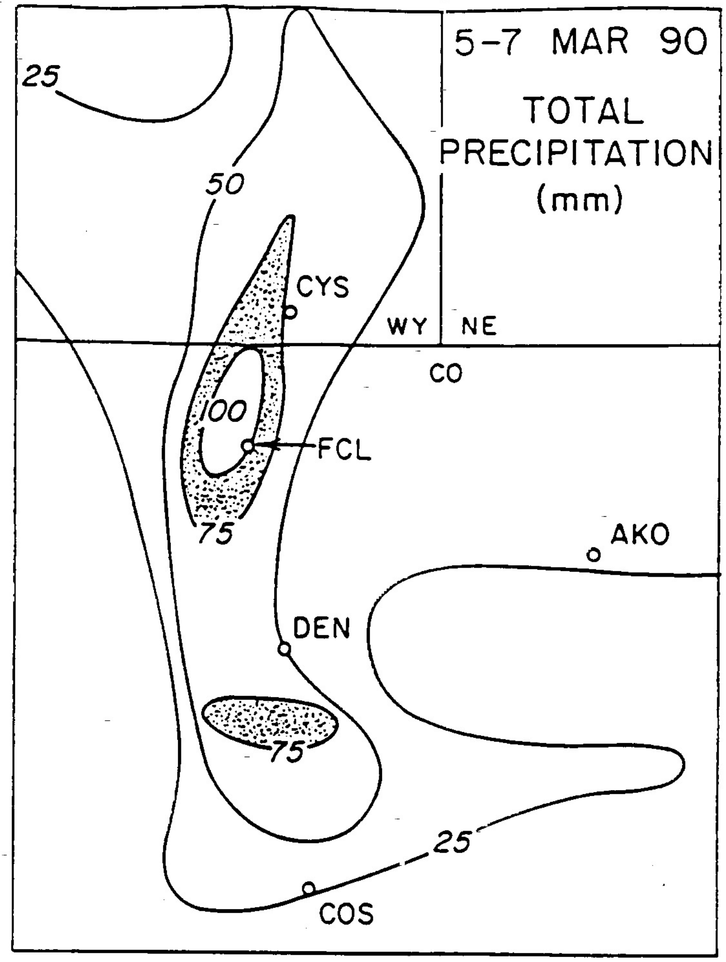


Fig. 6. PAM II and PROFS surface data for the times indicated. The wind vector is scaled to 20 m s^{-1} = 1° of longitude and the number beside each site is T °C (NOTE: the wet snow caused some erroneous temperature data). Within the broad line is WAA > 1 C h^{-1}, solid thin lines are isotherms, and dashed lines are mesoscale fronts.

Surface Analysis

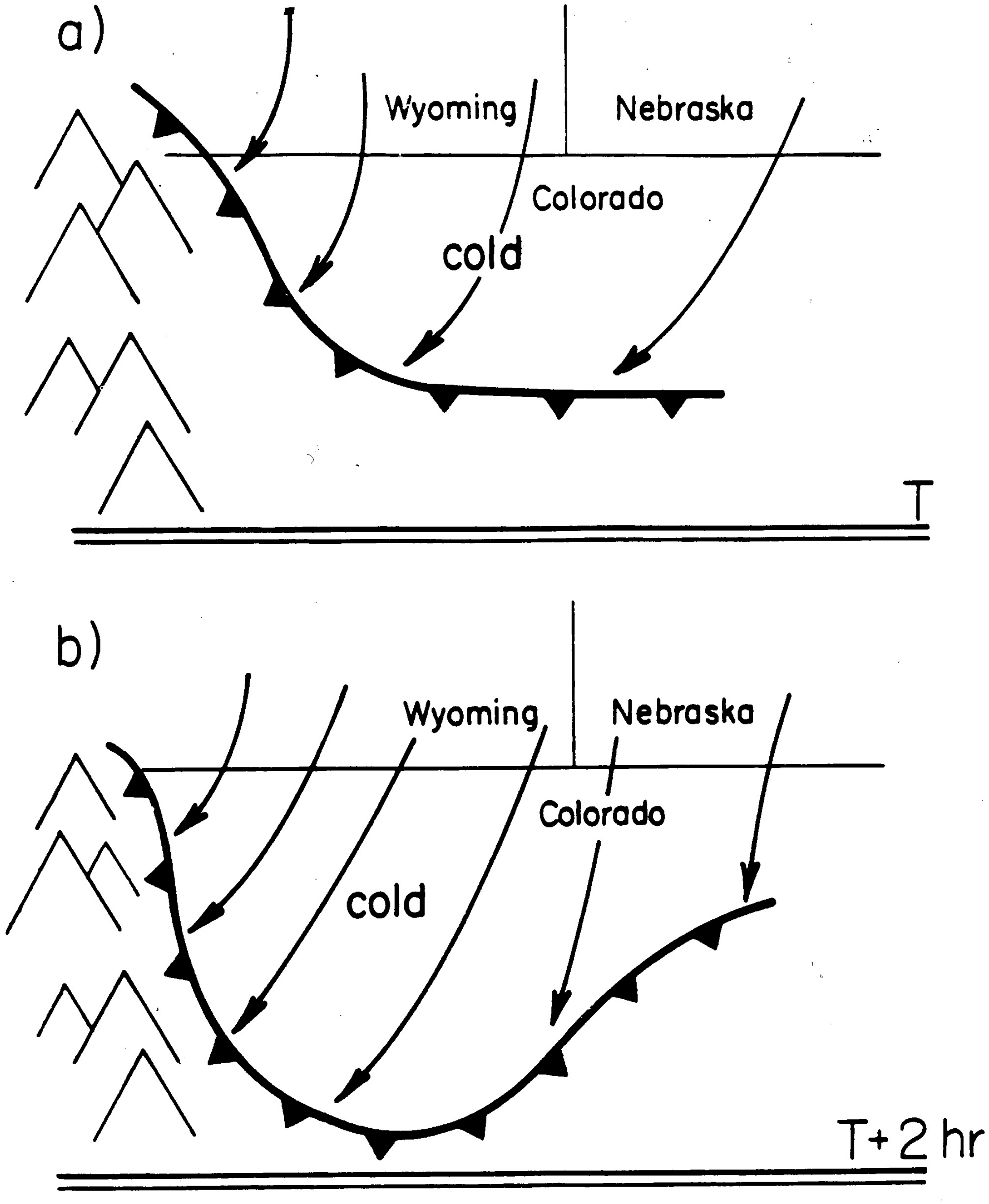


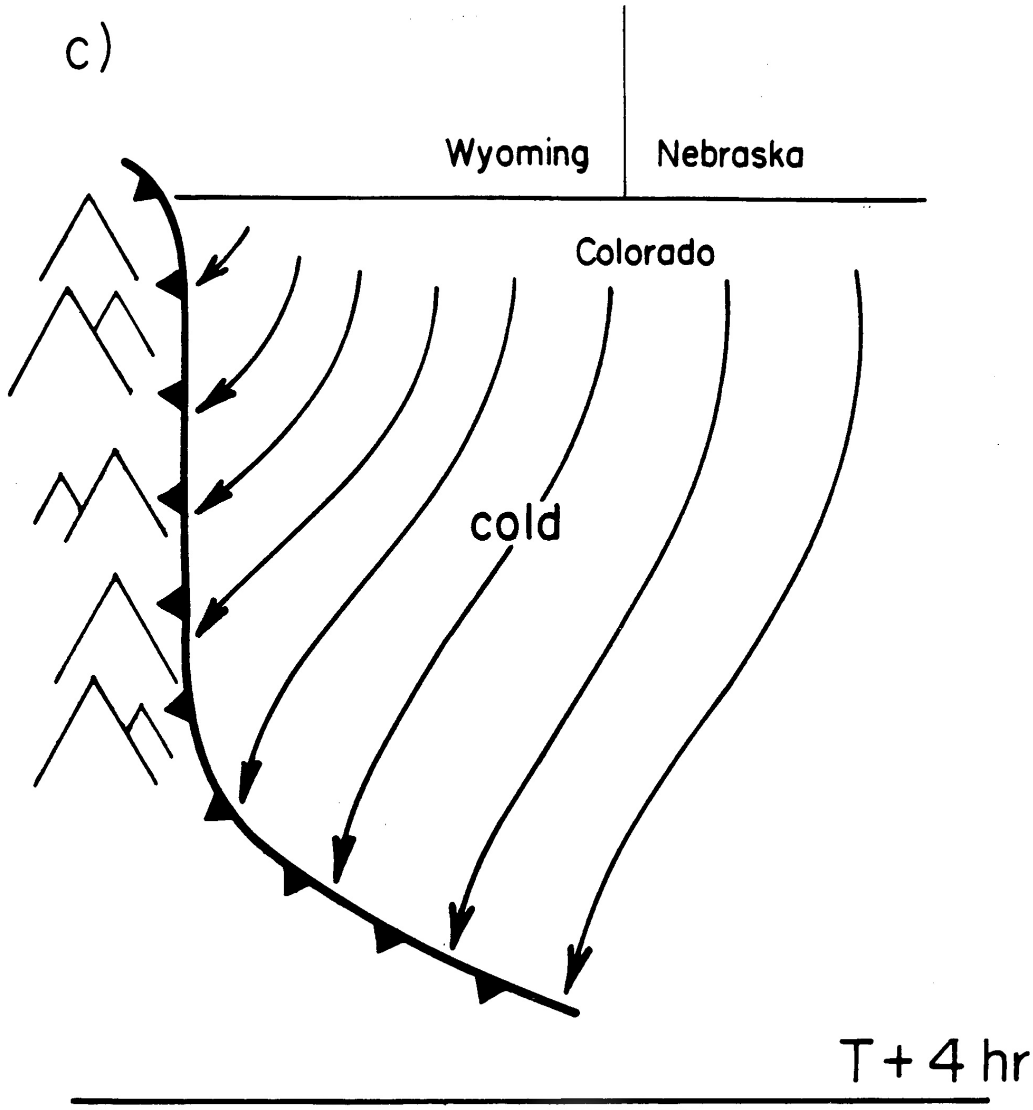

5-7 MAR 90
TOTAL
PRECIPITATION
(mm)
25
50
CYS
WY
NE
CO
100
FCL
75
AKO
DEN
75
25
COS

7-8 March 1990 Storm

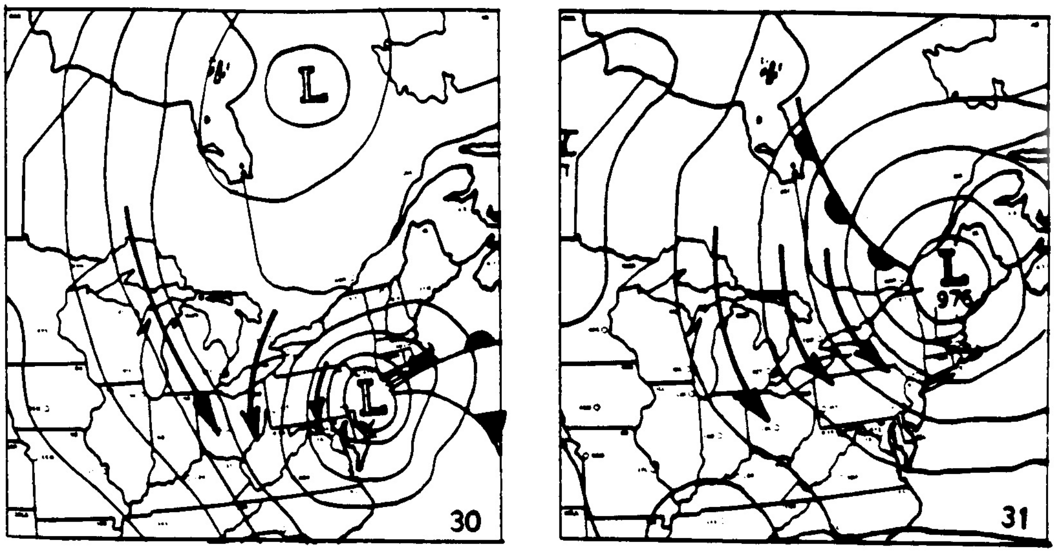
Accumulation at Cotton's at 7300' (my house) was 54" snow (137 cm) and 6.74" precip. (161 mm).

Shallow Upslope Storms

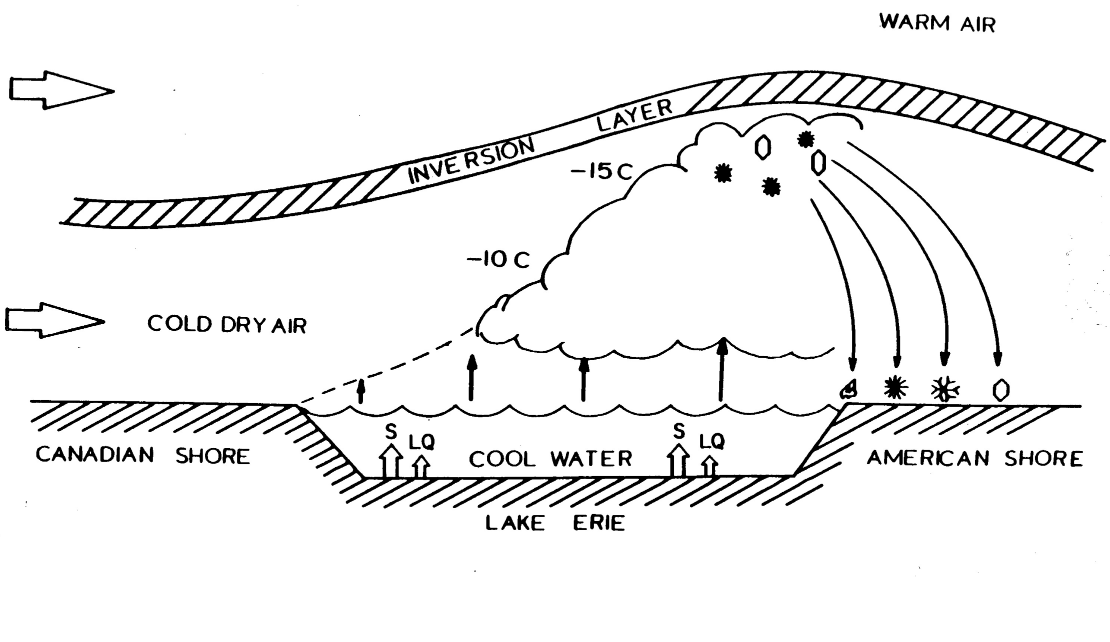



c)
Wyoming
Nebraska
Colorado
cold
T + 4 hr

Lake Effect Storms



Surface charts—0700 EST, 30 and 31 January 1966.



Lake effect storm example:

Oswego, NY – south of Lake Ontario

January 1966

5-day total snowfall of 101 inches.