

Extratropical Cyclones

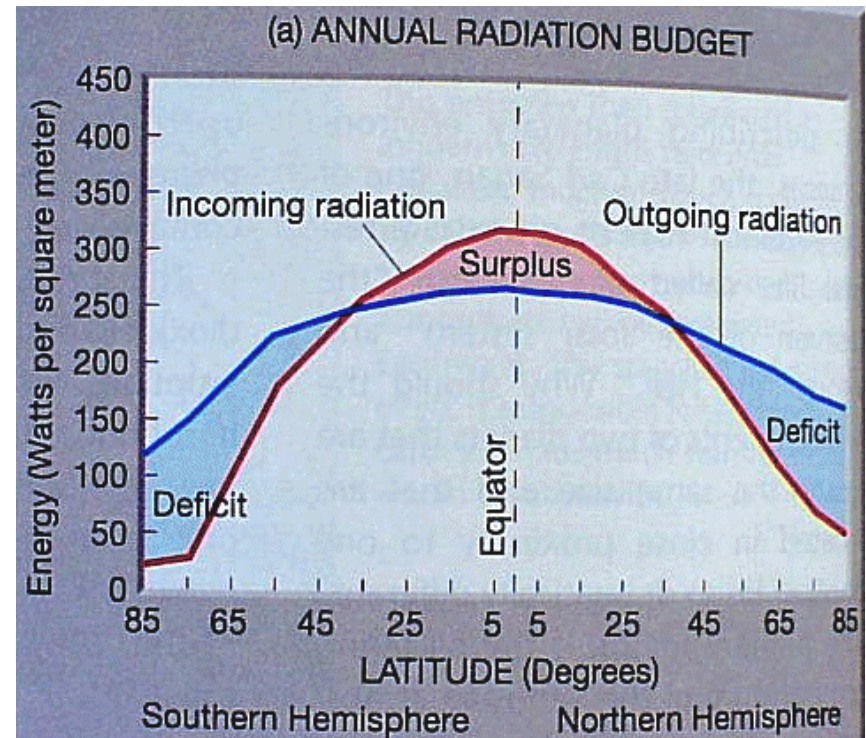
AT 540

What are extratropical cyclones?

- Large low pressure systems
- Synoptic-scale phenomena
 - Horizontal extent on the order of 2000 km
 - Life span on the order of 1 week
- Named by
 - Cyclonic rotation
 - Latitude of formation: extratropics or middle-latitudes

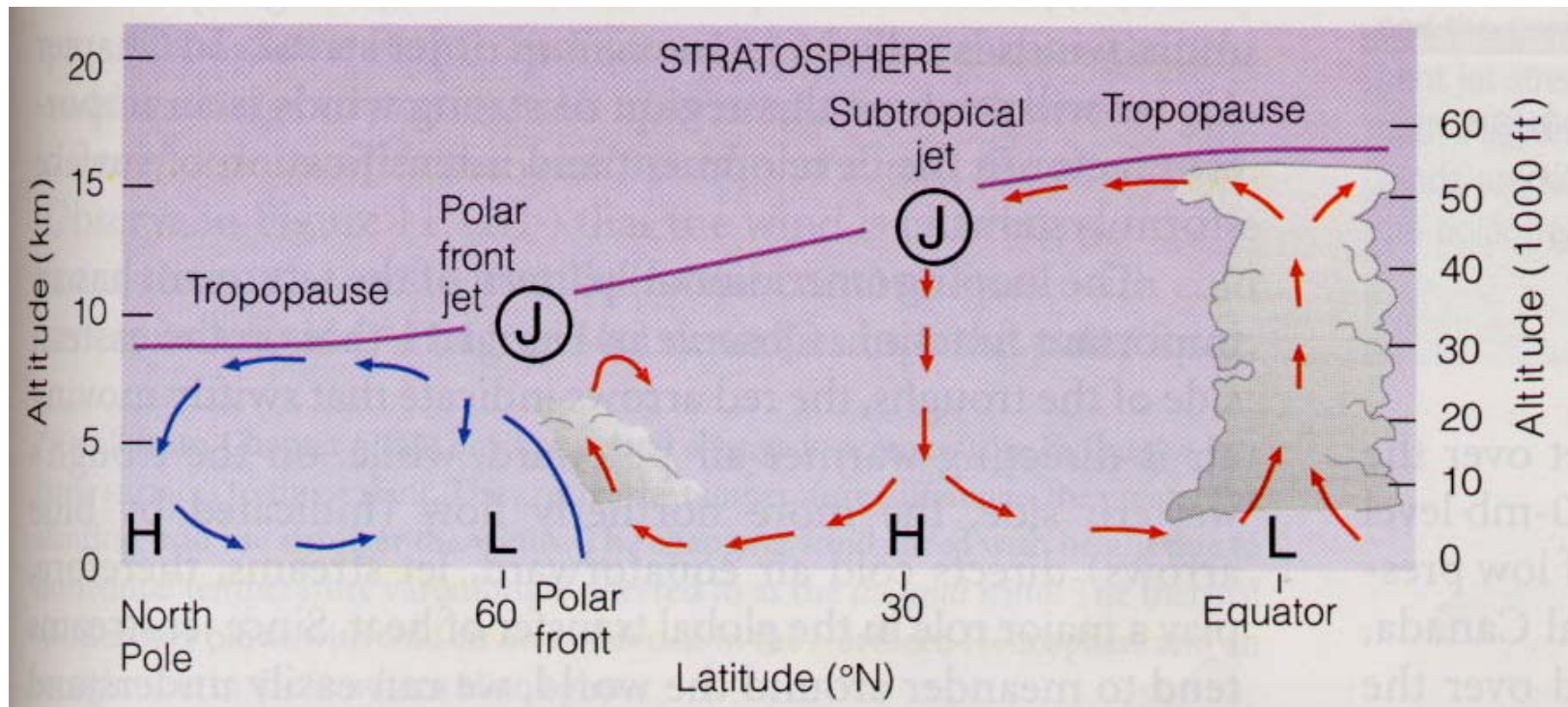
Why do extratropical cyclones exist?

- Energy surplus (deficit) at tropics (poles)
 - Angle of solar incidence
 - Tilt of earth's axis
- Energy transport is required so tropics (poles) don't continually warm (cool)
- Extratropical cyclones are an atmospheric mechanism of transporting warm air poleward and cold air equatorward in the mid-latitudes



Polar Front

- The boundary between cold polar air and warm tropical air is the polar front
- Extratropical cyclones develop on the polar front where large horizontal temperature gradients exist



Polar Front Jet Stream

Large horizontal
temperature gradients



Large thickness gradients

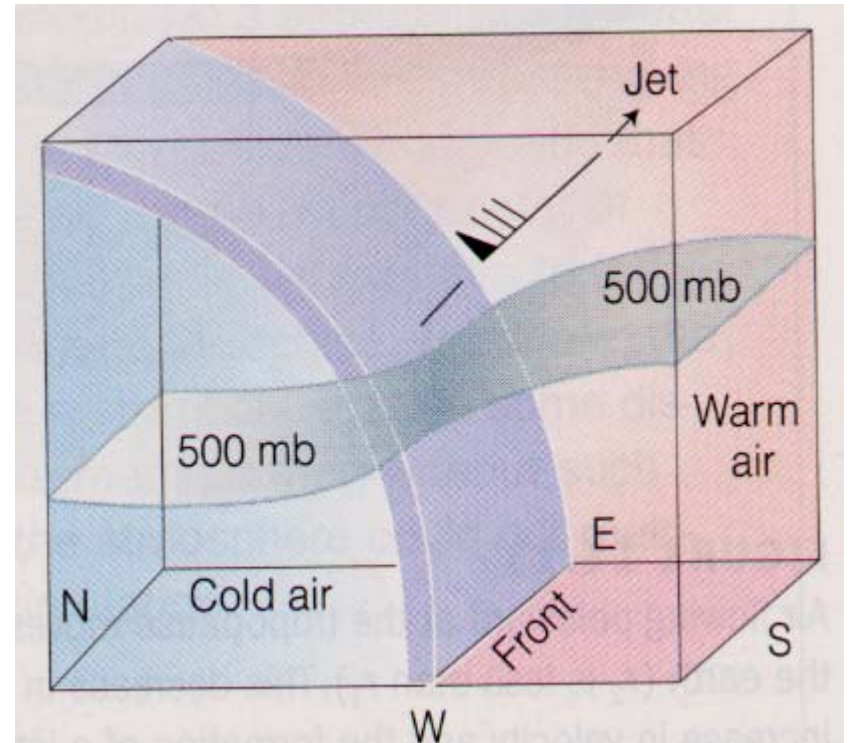


Large horizontal pressure
gradients aloft



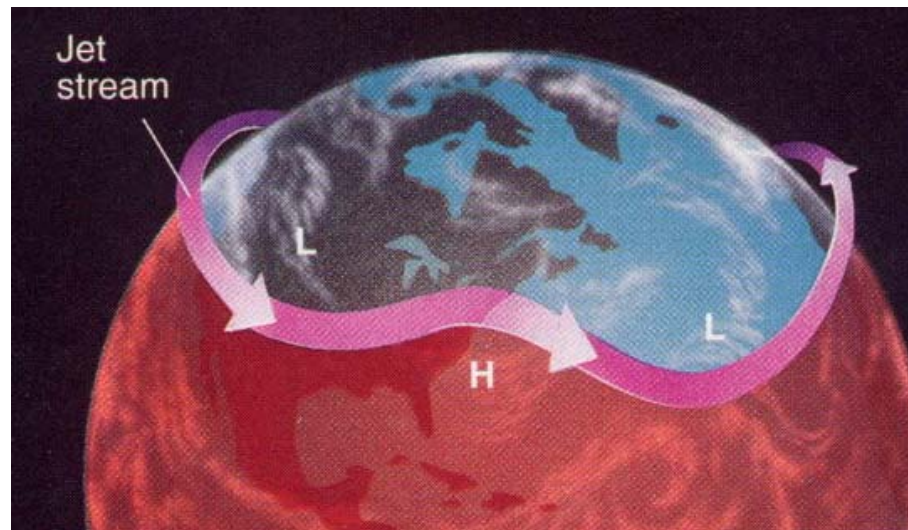
Strong winds

- Warm air to the south results in westerly geostrophic winds – polar jet stream



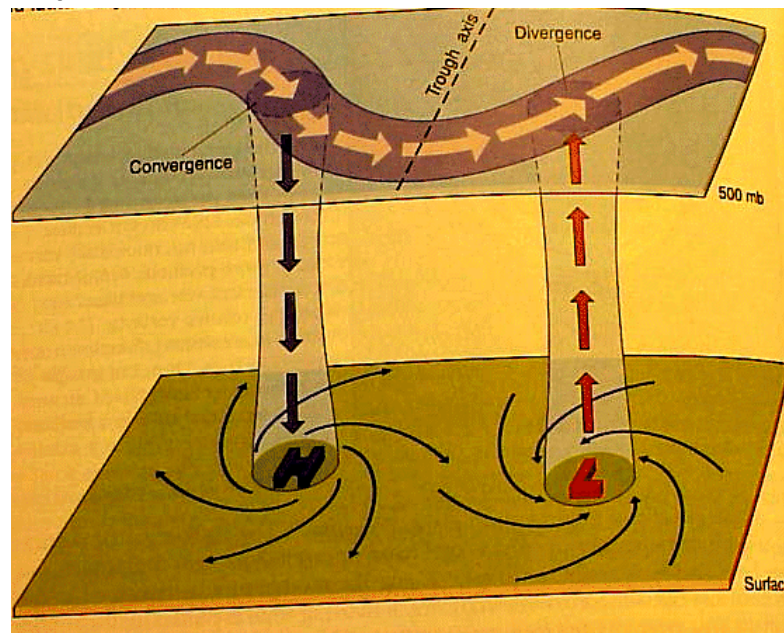
Polar Front Jet Stream

- The polar jet is the narrow band of meandering strong winds (~100 knots) found at the tropopause (why?)
- The polar jet moves meridionally (30° - 60° latitude) and vertically (10-15 km) with the seasons
- At times, the polar jet will split into northern and southern branches and possibly merge with the subtropical jet



Polar Jet and Extratropical Cyclones

- Extratropical cyclones are low pressure centers at the surface; thus, upper-level divergence is needed to maintain the surface lows
- Generally, there is divergence aloft downwind of an upper level trough to the ridge – a prime location for extratropical cyclone development



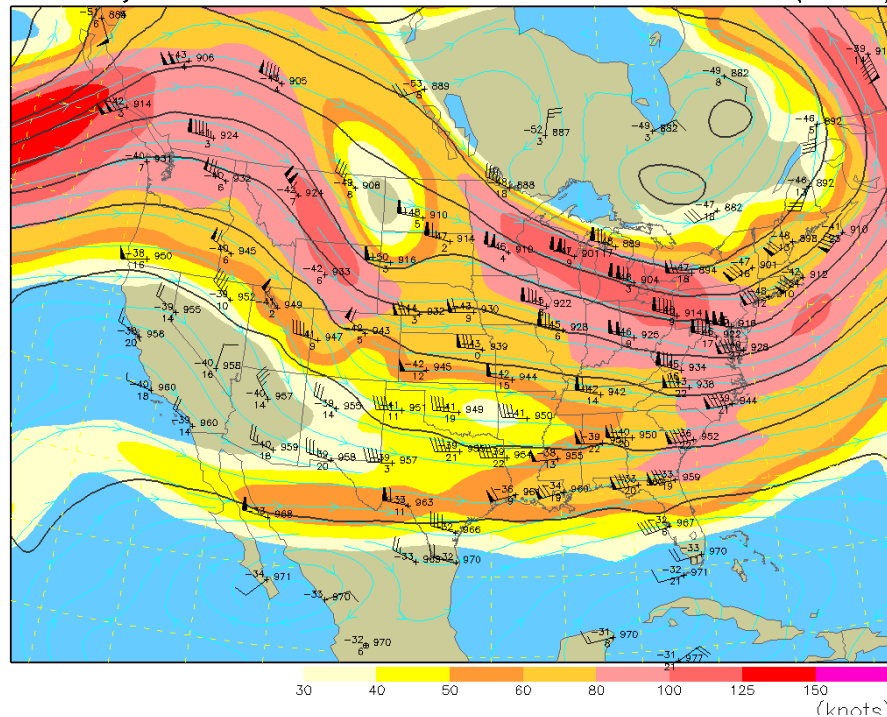
Jet Streaks

- Jet streaks are local maxima of wind speed in the jet stream that also have an influence on upper-level divergence

300 mb Heights (dm) / Isotachs (knots)

0-hour analysis valid 1200 UTC Thu 16 Oct 2003

RUC (12z 16 Oct)



Jet Streaks

Consider u-component of equation of motion with a straight west-east oriented jet streak:

$$\frac{du}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + fv - Fu$$

Neglect friction (upper troposphere) and substitute

$$-\frac{1}{\rho} \frac{\partial p}{\partial x} = -fv_g$$

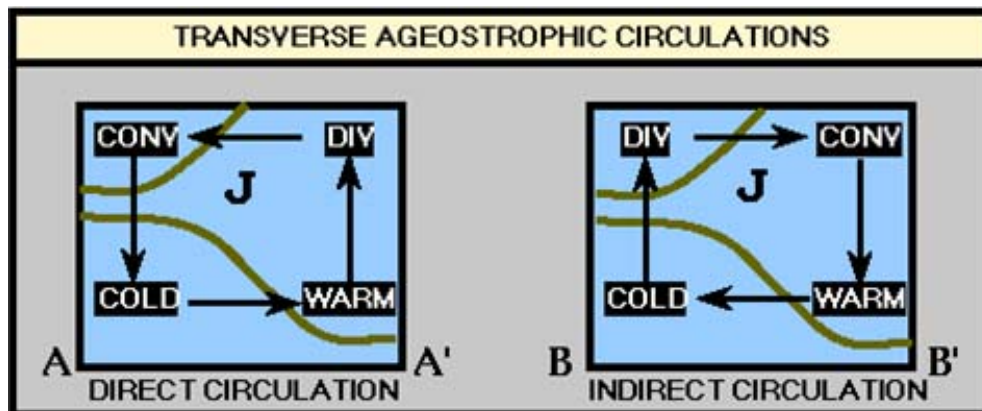
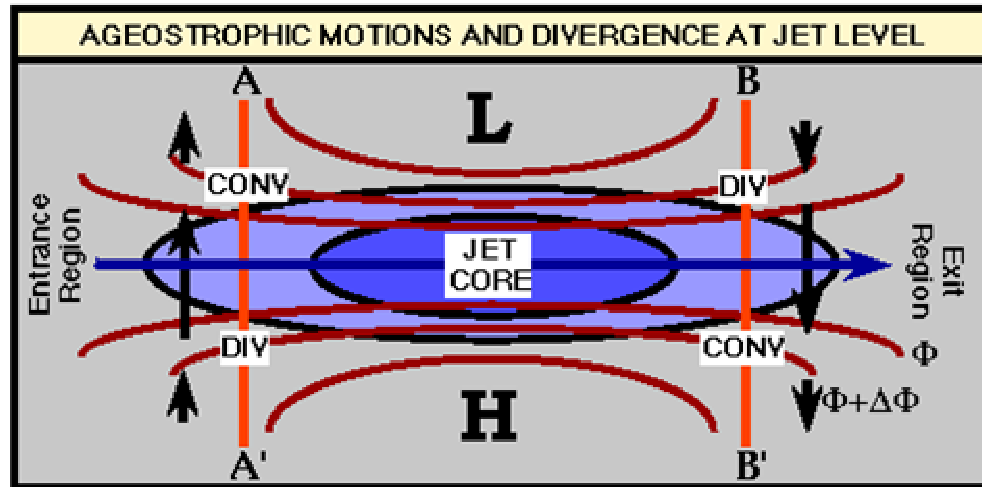
$$\frac{du}{dt} = -fv_g + fv$$

$$\frac{du}{dt} = f(v - v_g) = fv_{ag}$$

Jet Streaks

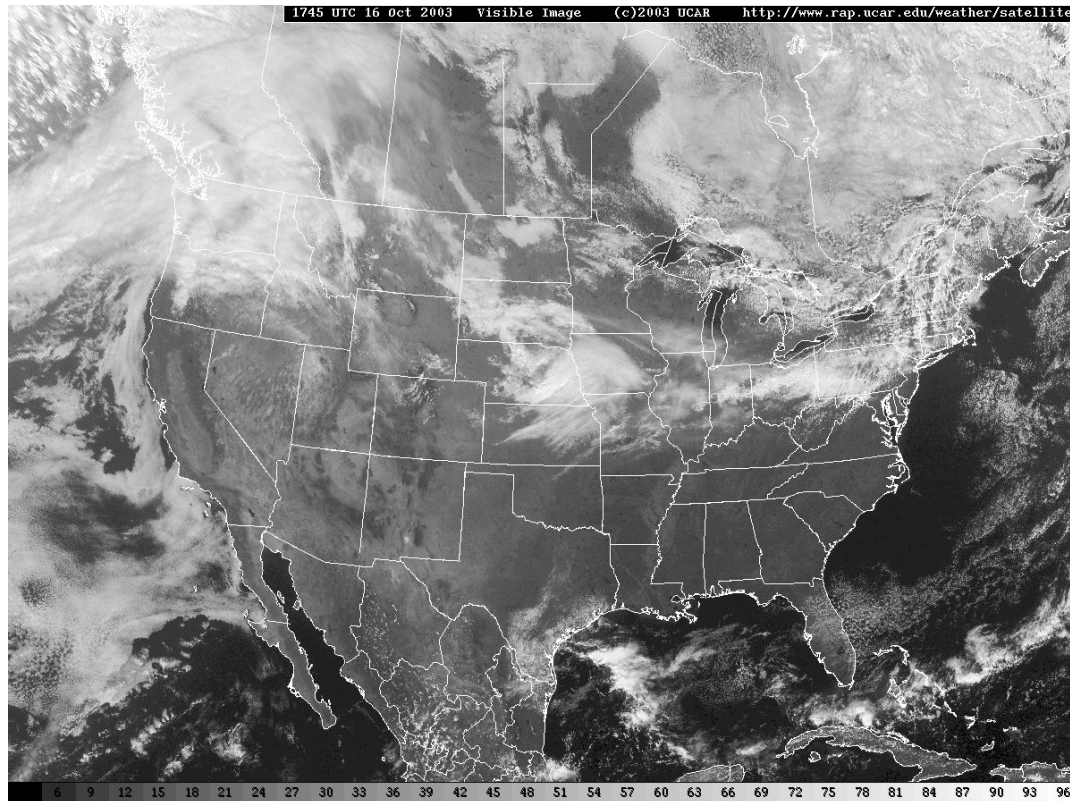
$$\frac{du}{dt} = f(v - v_g) = fv_{ag}$$

THE FOUR QUADRANT STRAIGHT JET MODEL



Jet Streaks

- Right entrance and left exit regions of jet streaks are preferred areas of storm formation and extratropical cyclone development



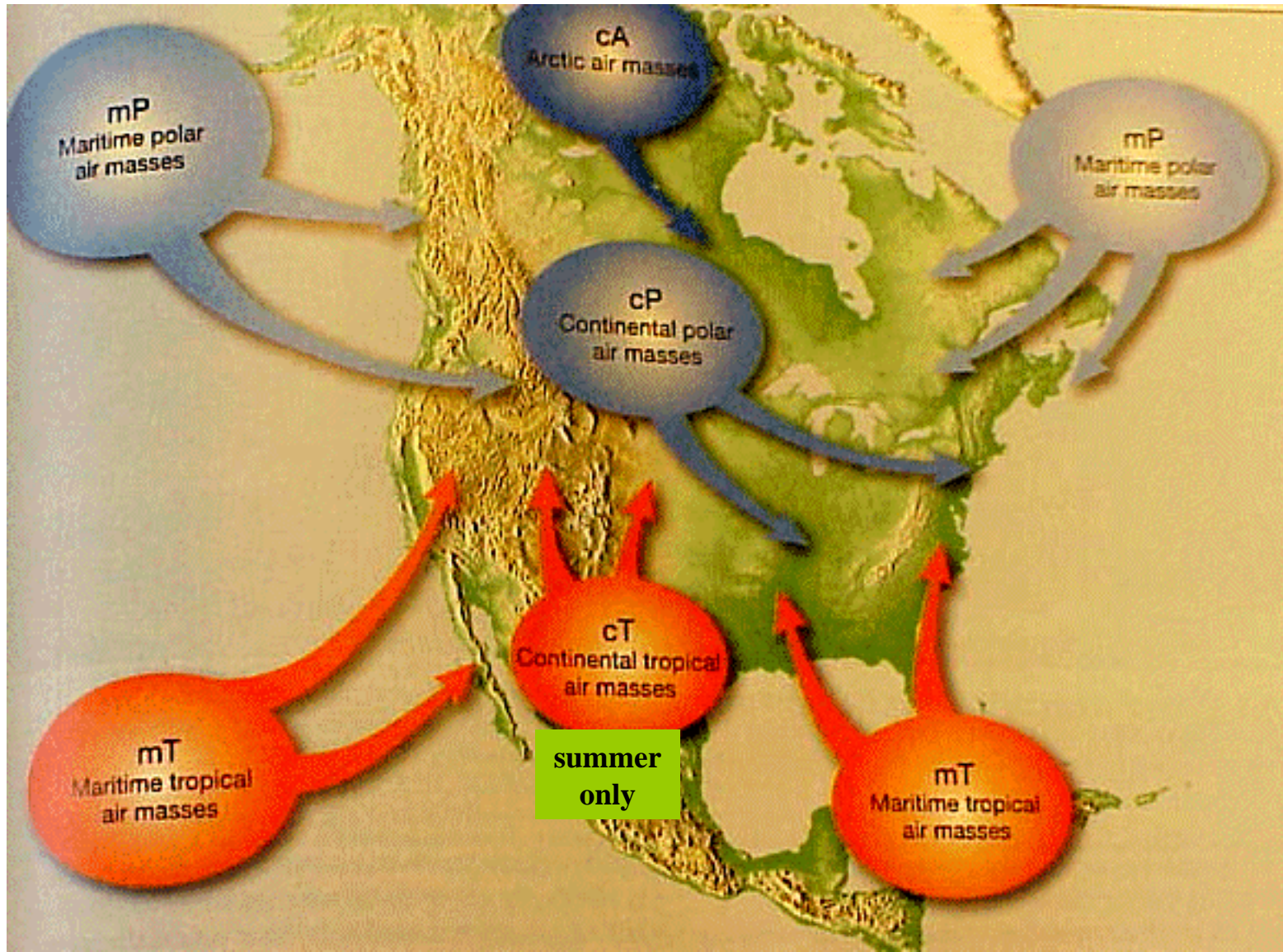
Air Masses

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

Air Mass Classifications

- 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

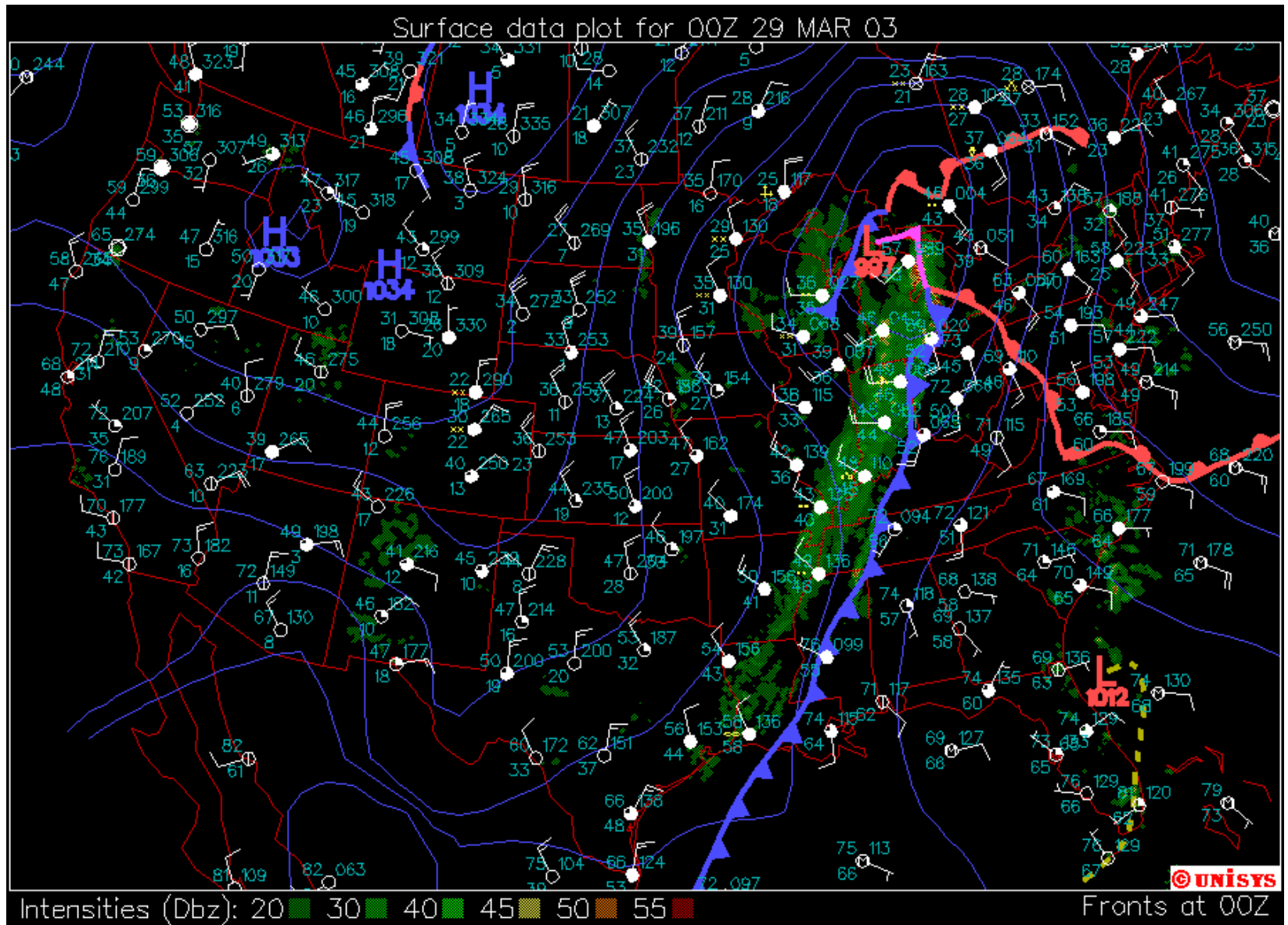


Example of Air Mass Modification

- 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.



Air Masses



Fronts

- Fronts are the boundary or interface between air masses of different density
- A front is located on the warm side of a thickness gradient
- Generally, fronts are identified and plotted where the interface intersects the ground – surface maps

Locating Fronts

- The following indicators can be used to locate a front at the surface:
 - Temperature discontinuity
 - Wind shift line
 - Pressure trough
 - Dew point temperature discontinuity
 - Pressure tendency pattern
 - Horizontal variations in visibility
 - Horizontal variations in precipitation type

What type of front is it?

- Once the existence and location of a surface front have been determined, the type of front can be identified
- The type of front depends on the movement of the colder air mass:
 - If the colder air advances toward the front, it is a **cold front**.
 - If the colder air retreats away from the front, it is a **warm front**.
 - If the colder air moves parallel to the front, it is a **stationary front**.

Characteristics of Fronts

There are 5 basic fronts:

1. Cold front

- shown on surface maps as blue lines with blue triangles which point in the direction of the warmer air
- at a cold front cold air is displacing the warmer air ahead of the front
- SW winds ahead of front, gusty NW winds behind front
- Dry air behind front
- Pressure falls ahead of front, rises behind front
- Excellent visibility behind cold front
- Deep cumulus convection ahead of front

2. Warm front

- Shown on surface maps as red lines with red semicircles which point in the direction of the colder air
- At a warm front, cold air is retreating on the cold side of the front and is being replaced by warmer air
- E winds ahead of front, S/SW winds behind front – not gusty
- Weaker temperature gradients, pressure falls with warm front
- Poor visibility ahead of warm front
- Steady precipitation ahead of front

Characteristics of Fronts

3. Stationary front

- Shown on surface maps as alternating blue triangles and red semicircles (blue triangles point in the direction of the warmer air)
- Stationary fronts move very little or not at all as winds on the colder side of the front tend to blow parallel to the front
- Example is a front that becomes stationary as it reaches mountainous terrain
- Even though cold air is not advancing, often associated with precipitation formation

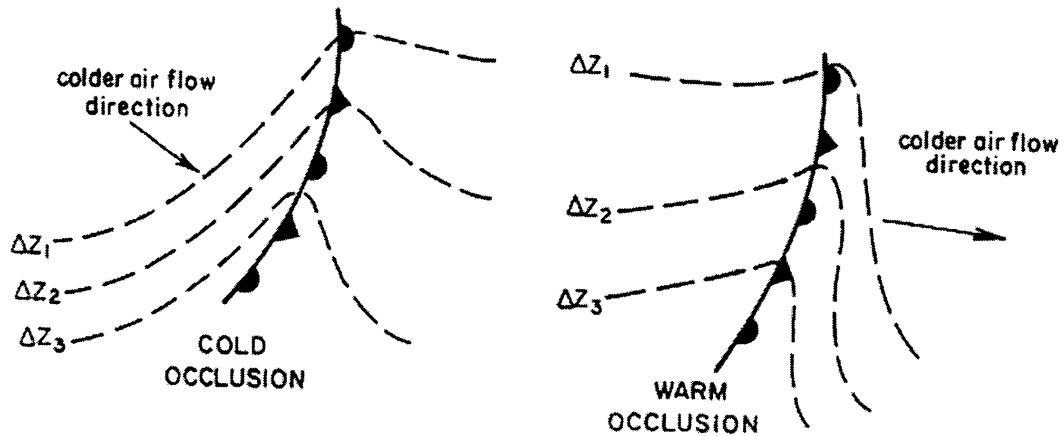
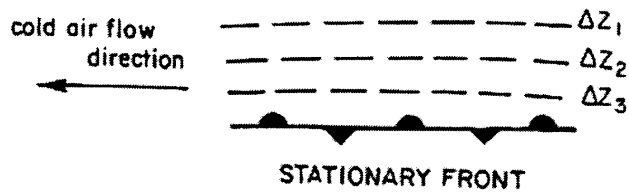
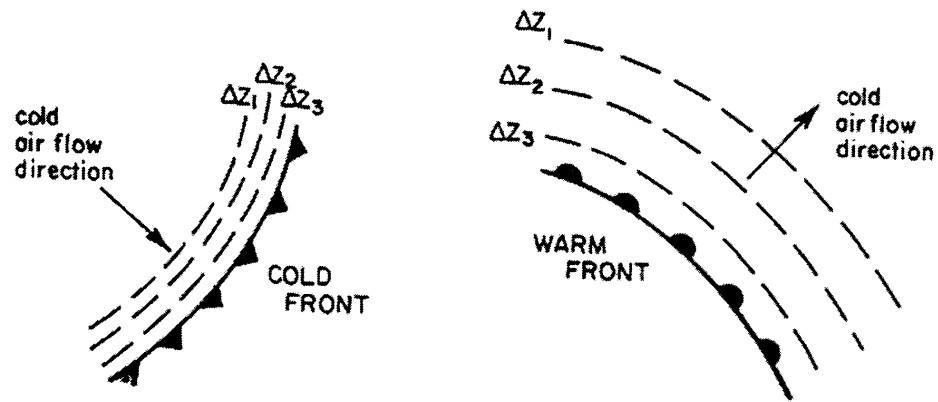
4. Cold Occlusion

- Shown on surface maps as purple with alternating triangles and semicircles on the same side of the line pointing in the direction of movement of the front
- This type of front occurs when the cold front catches up with and overtakes the warm front
- The air behind the cold front is colder than the air ahead of the warm front
- Have general characteristics of a cold front

Characteristics of Fronts

5. Warm Occlusion

- Shown on surface maps as purple with alternating triangles and semicircles on the same side of the line pointing in the direction of movement of the front
 - This type of front occurs when the cold front catches up with and overtakes the warm front
 - The air behind the cold front is warmer than the air ahead of the warm front
 - Have general characteristics of a warm front
- Occluded fronts may also be new fronts that form as the surface low separates itself from the warm/cold front junction and deepens back into the cold air

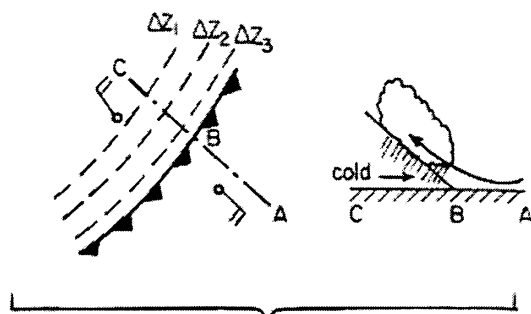


$$\Delta Z_1 < \Delta Z_3$$

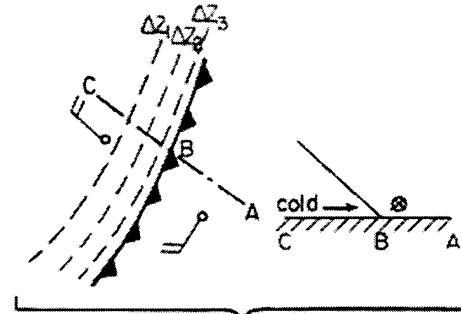
Characteristics of Fronts

There are two types of each front:

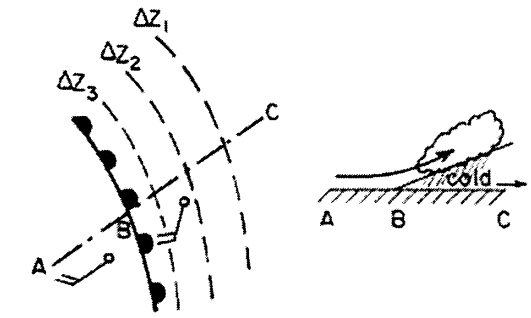
1. Active fronts: occurs when the warmer air mass is overrunning the cold air mass
2. Inactive fronts: occurs when the warmer air mass is not overrunning the cold air mass



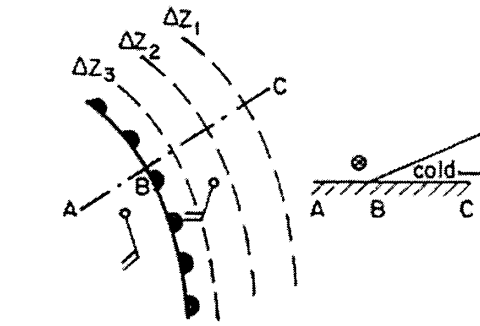
Active Cold Front



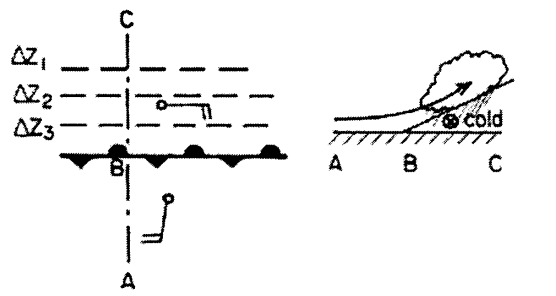
Inactive Cold Front



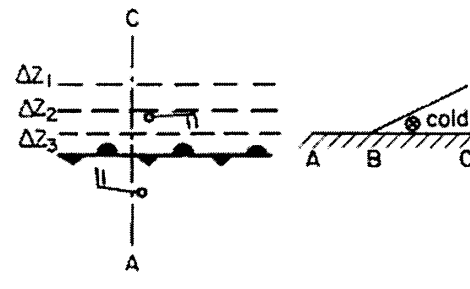
Active Warm Front



Inactive Warm Front

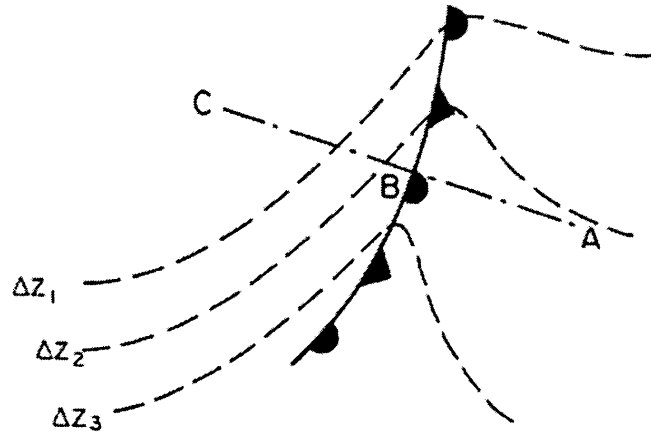


Active Stationary Front

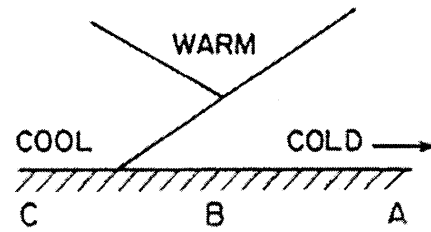
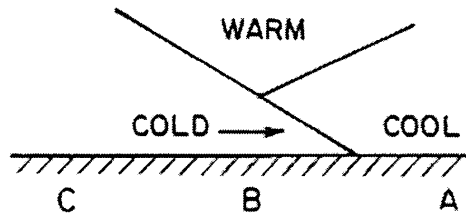
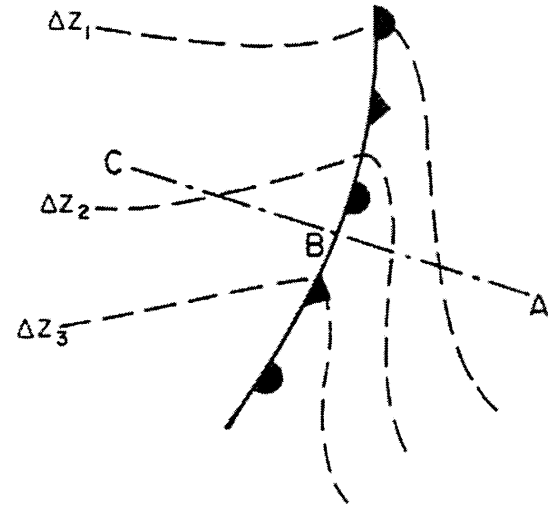


Inactive Stationary Front

Cold Occlusion

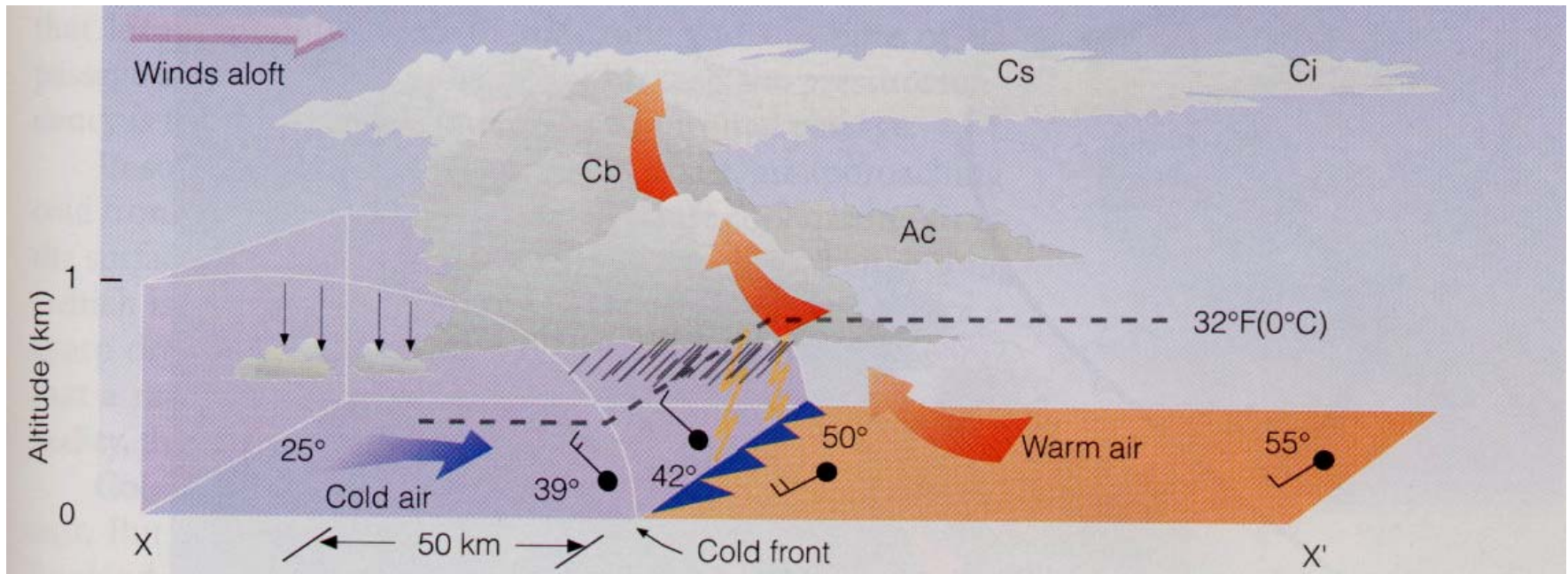


Warm Occlusion



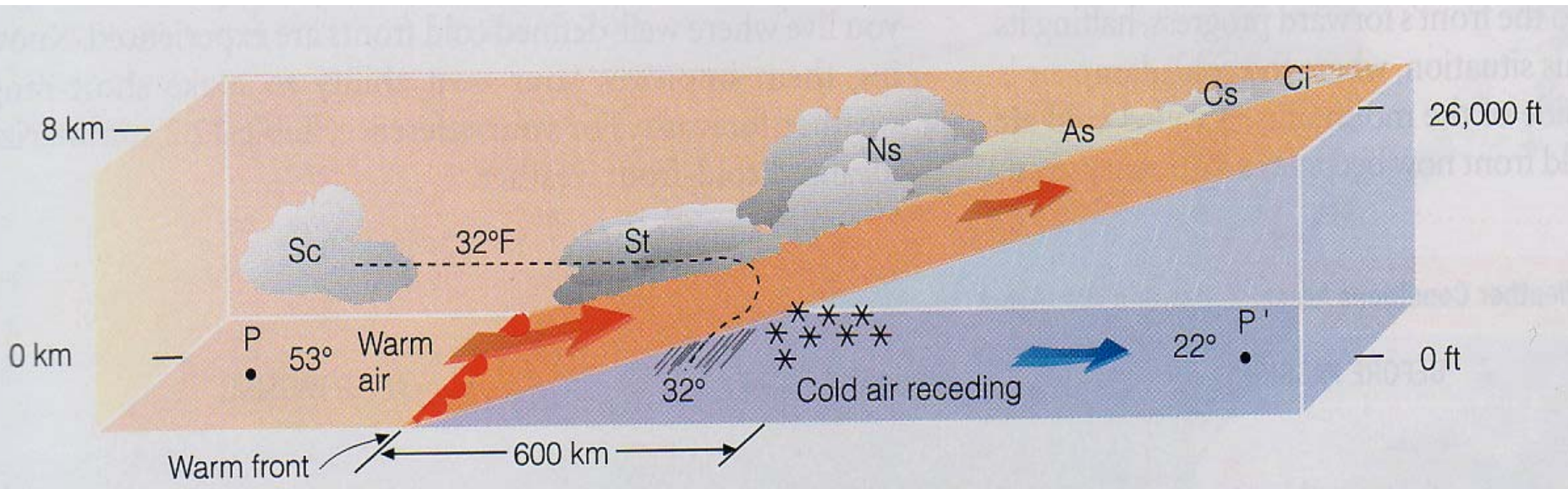
Typical Cold Front Structure

- 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





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



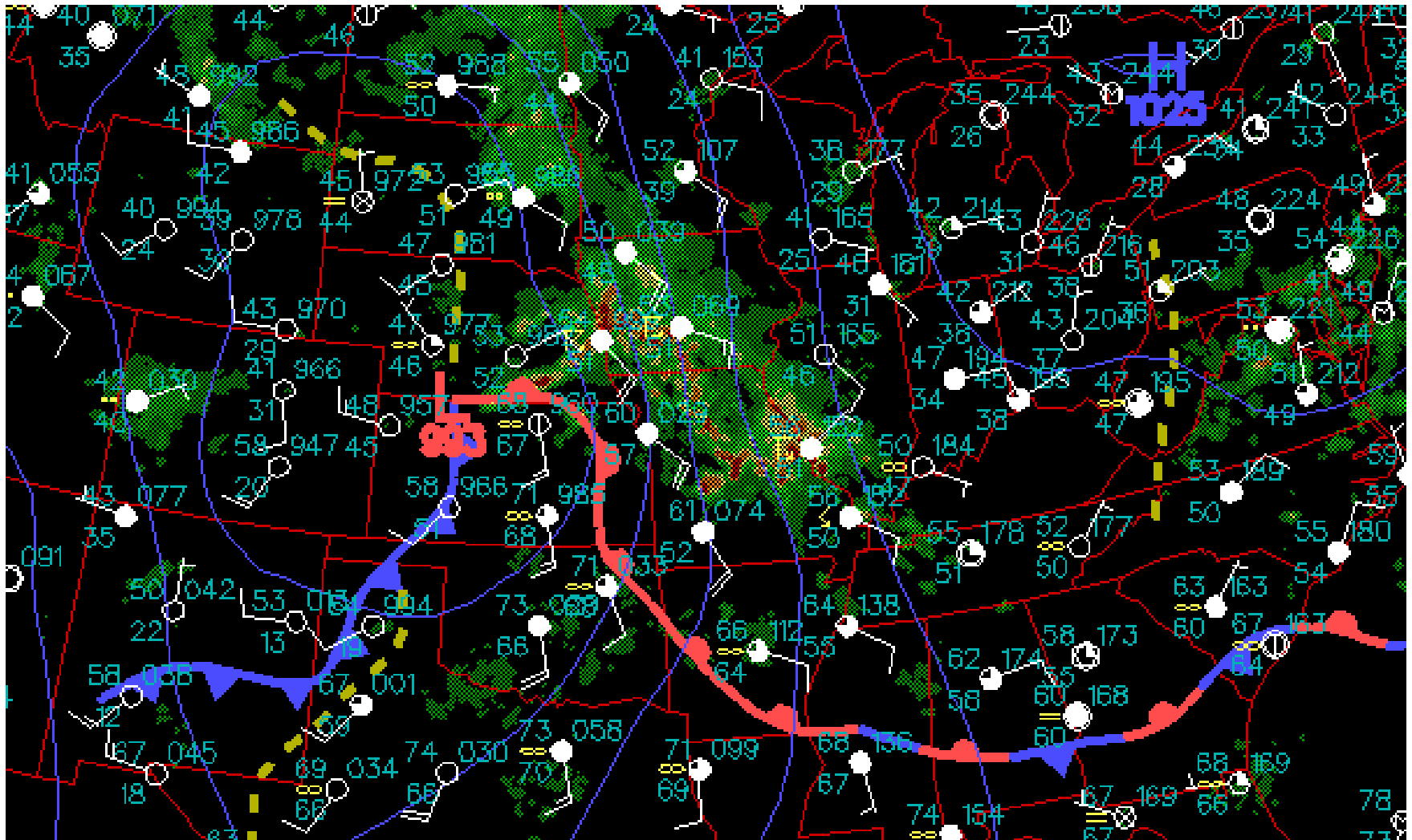
FRONTAL CHARACTERISTICS

	WARM FRONT	COLD FRONT
SEQUENCE	Warm air replaces cold air	Cold air replaces warm air
SLOPE	$\approx 1/300$ 	$\approx 1/50$ 
WIND SHIFT	Yes, cyclonic	Yes, cyclonic
TEMPERATURE CHANGE	Cool to warm	warm or cool to cold
MOISTURE CHANGE	Yes, air mass dependent	Yes, air mass dependent
PRECIPITATION	Steady, large area	Convective, locally heavy
SPEED OF MOVEMENT	5-10 mph (slow)	10-50 mph (fast)

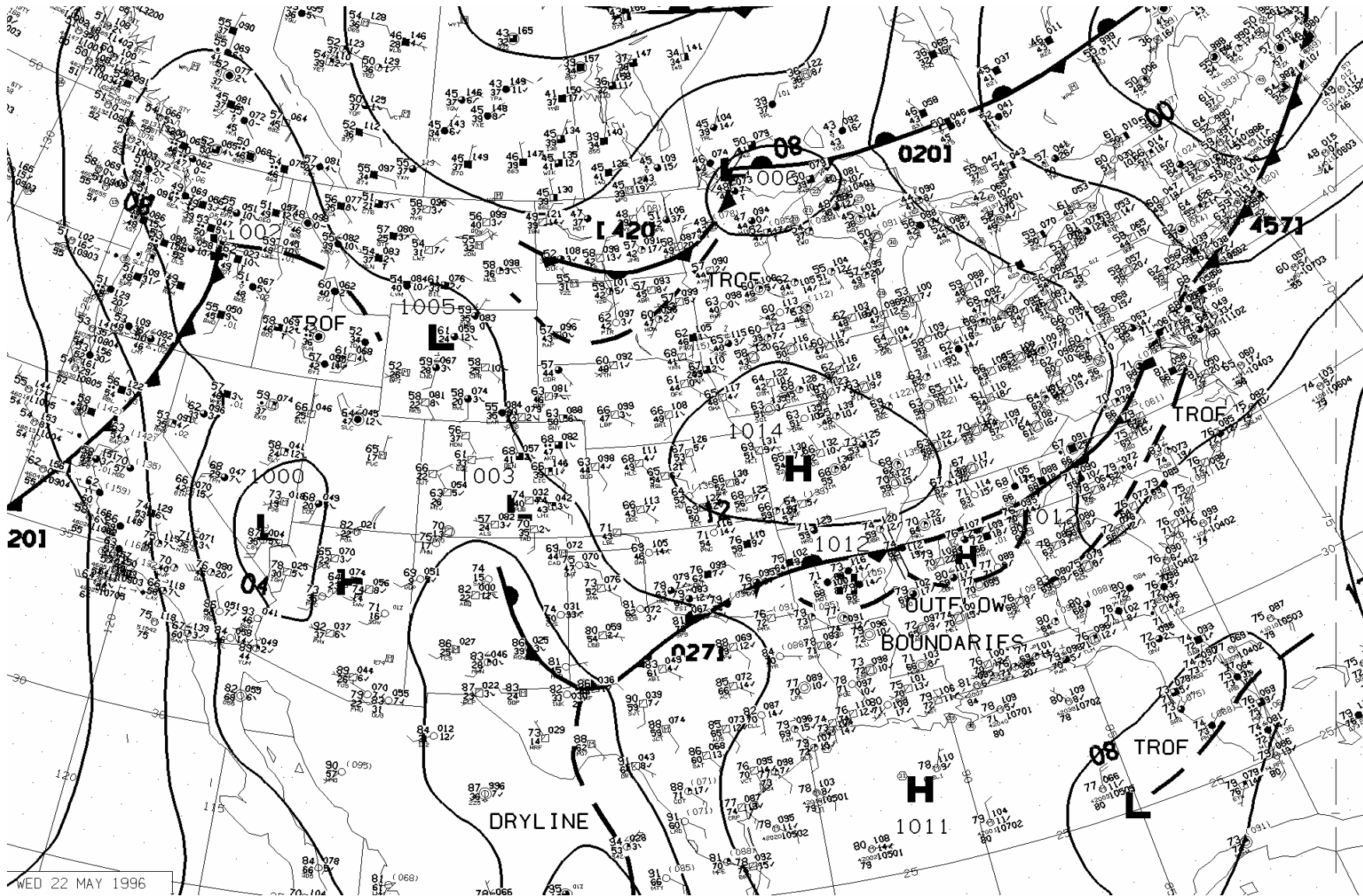
Other Boundaries

- Dryline
 - Sharp horizontal discontinuity in moisture
 - Often found during the warm season of the southern U.S. High Plains
 - Warm, dry cT air to the west and warm, moist mT air to the east
 - Typically, horizontal discontinuities only about 1500 m deep
 - Does not display typical frontal circulation characteristics
 - Nearly stationary with a diurnal oscillation
 - Often serve as a focal point for convective initiation
- Outflow boundary
 - Cool, moist air that exits and spreads horizontally from a thunderstorm – a mesoscale cold front
 - Dry, mid-level air is brought down to the surface in the downdraft of a thunderstorm
 - Precipitation evaporates into this air cooling it down
 - Can act as a focusing mechanism for new thunderstorms
 - Difficult to detect with current surface network, unless the outflow boundary is from a large convective system

Example



Example



Frontal Vertical Cross Section

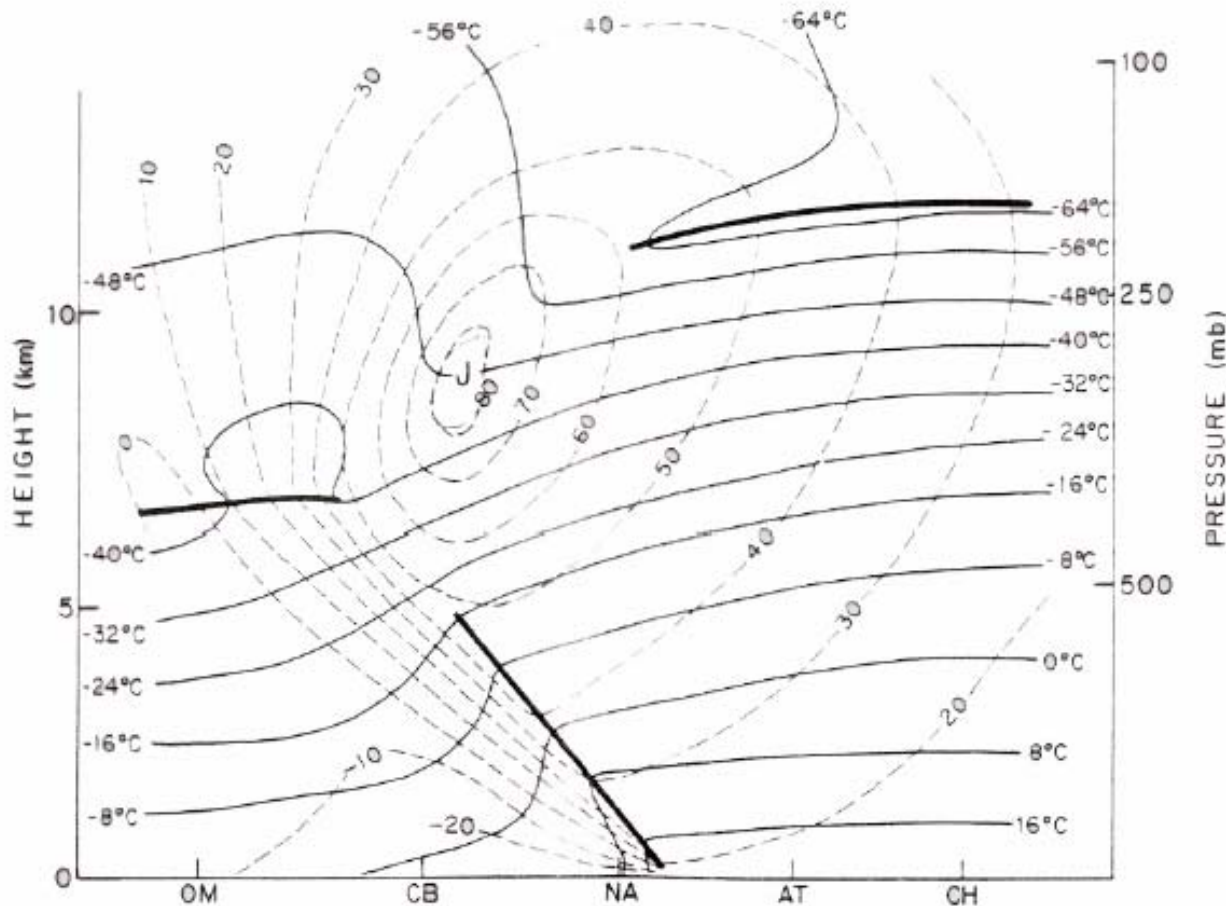


Fig. 3.19 Distribution of isotherms in degrees Celsius (—) and isotachs in meters per second (---) in a vertical cross section through the cold front at 00 GCT 20 November 1964. Station locations are indicated in Fig. 3.9. Isotachs refer to the geostrophic wind component normal to the section. Positive 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.

Frontal Vertical Cross Section

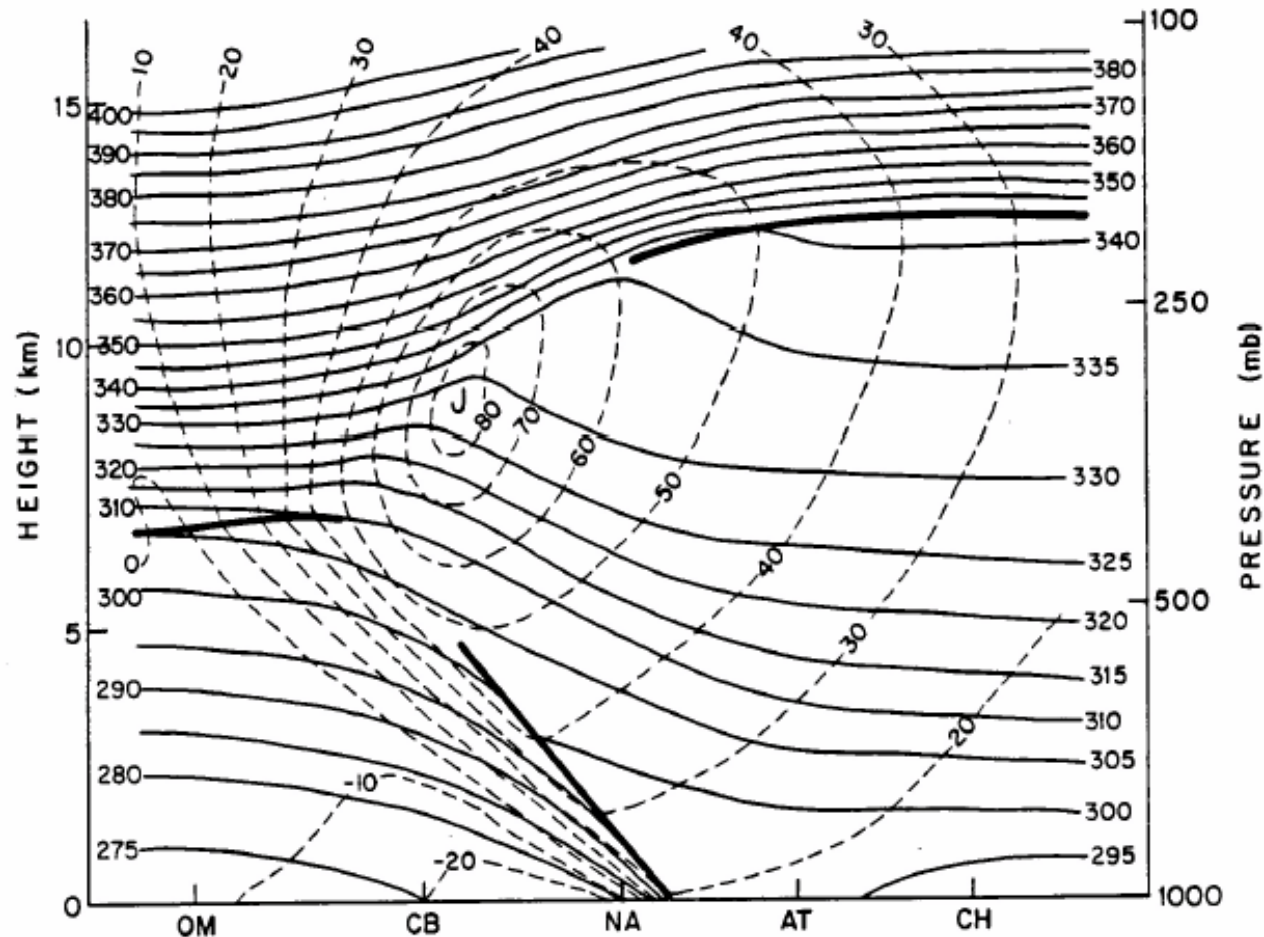


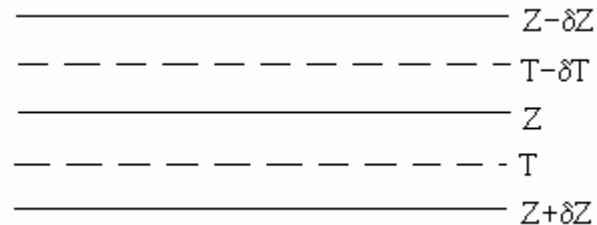
Fig. 3.20 Vertical cross section through frontal zone as shown in the previous figure except that solid lines represent isentropes (lines of constant potential temperature), labeled in degrees Kelvin.

Cyclogenesis

- Cyclogenesis is the development or strengthening of an extratropical cyclone
- Cyclogenesis occurs in baroclinic environments - an environment where a thickness gradient exists
- The potential energy associated with the strong horizontal temperature gradients is the source of energy for developing extratropical cyclones
- Baroclinic instability is the primary mechanism for cyclogenesis

Baroclinic Instability

- Baroclinic instability occurs when a north/south temperature gradient becomes so strong in a uniform zonal flow that an infinitesimal perturbation amplifies into a synoptic-scale wave disturbance
- Northerly flow advects colder air southward and southerly flow advects warmer air northward, which increases amplitude of trough/ridge pattern

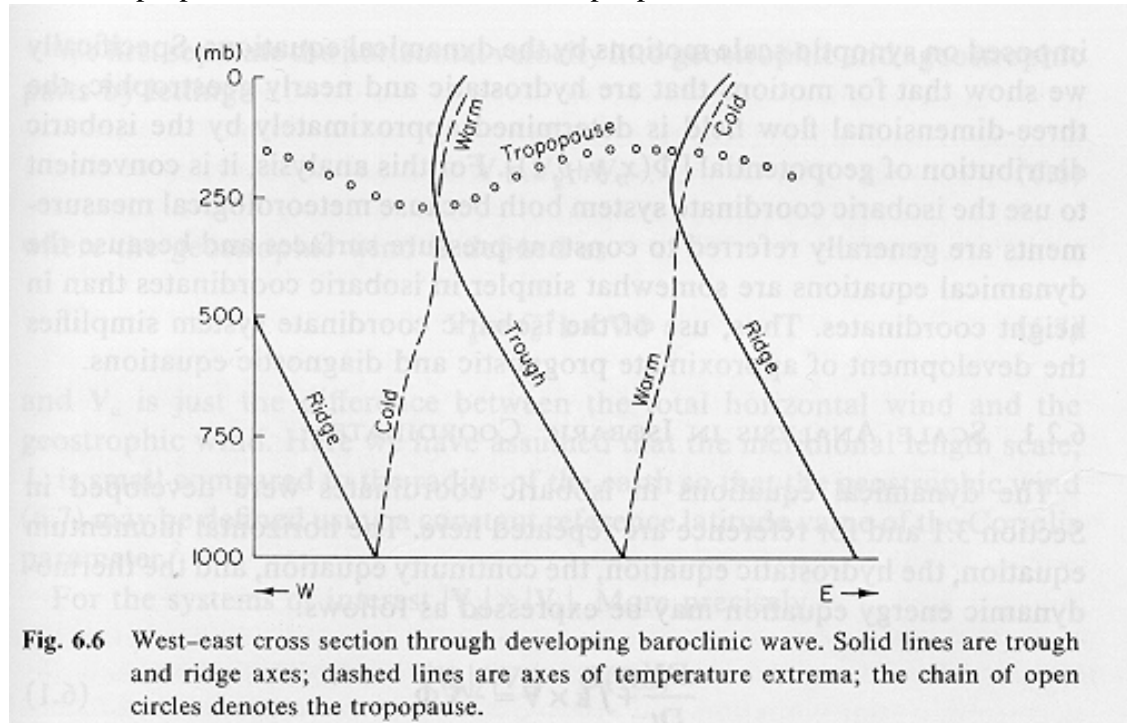


Developing Baroclinic Wave Structure

Baroclinic instability is associated with the vertical shear of the mean flow. For the idealized developing baroclinic wave below,

$$\overline{u}_{\text{upper troposphere}} > \overline{u}_{\text{mid-troposphere}} \approx c > \overline{u}_{\text{lower troposphere}}$$

- Stronger westerly winds aloft result in the isotherm pattern being advected farther east. \Rightarrow eastward tilt with height of warm/cold axes
- Consequently, trough and ridge axes tilt westward with height – thickness relationship
- Tilt determines the degree of development. WAA, PVA, and upper-level divergence coincident with surface low are best for development.



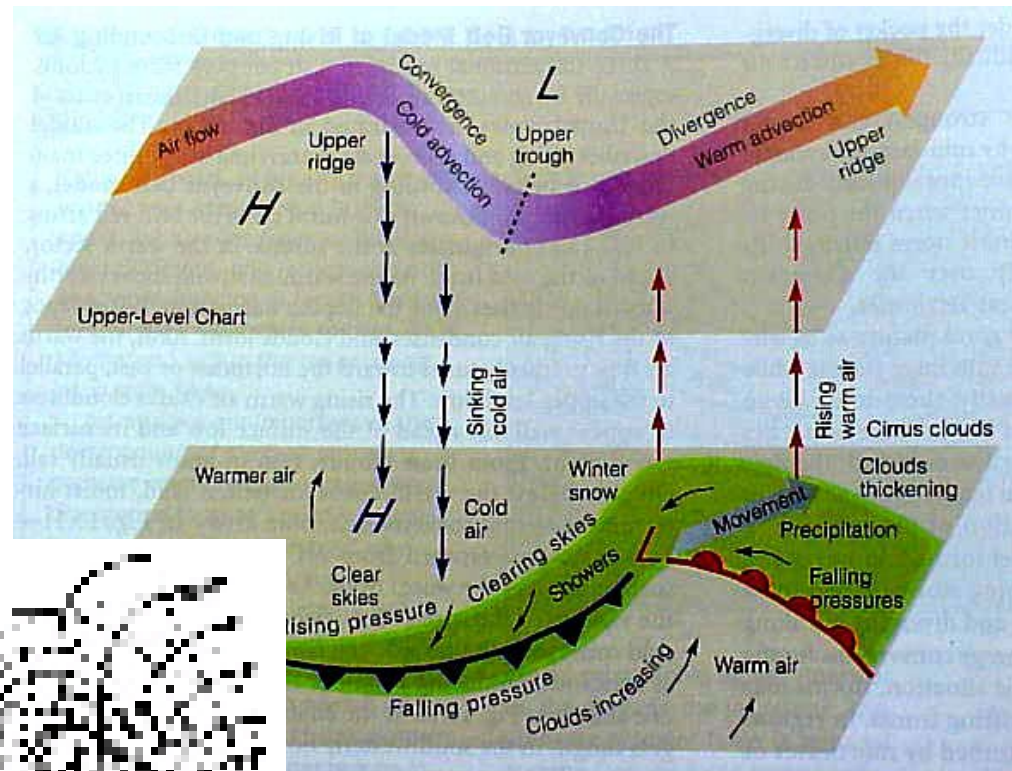
$$\frac{\partial u_g}{\partial \ln p} = \frac{R_d}{f} \frac{\partial T}{\partial y}$$

[From Holton (1992)]

Characteristics of Cyclogenesis

- Upper-level divergent geostrophic winds, which generates anticyclonic relative vorticity building the upper-level ridge downstream
- Surface pressure falls in response to upper-level divergent forcing
- Ageostrophic wind convergence acceleration at the surface
- Convergence generates cyclonic vorticity at low levels
- Midlevel ascent and associated cloudiness as a result of the convergence

Surface/Upper Air Relationship



The diagram illustrates the relationship between surface and upper air conditions. It shows how surface features like high and low pressure systems, fronts, and air masses are related to upper-level features like ridges, troughs, and air flow patterns. The diagram also shows how these relationships affect weather conditions like temperature, pressure, and cloud formation.

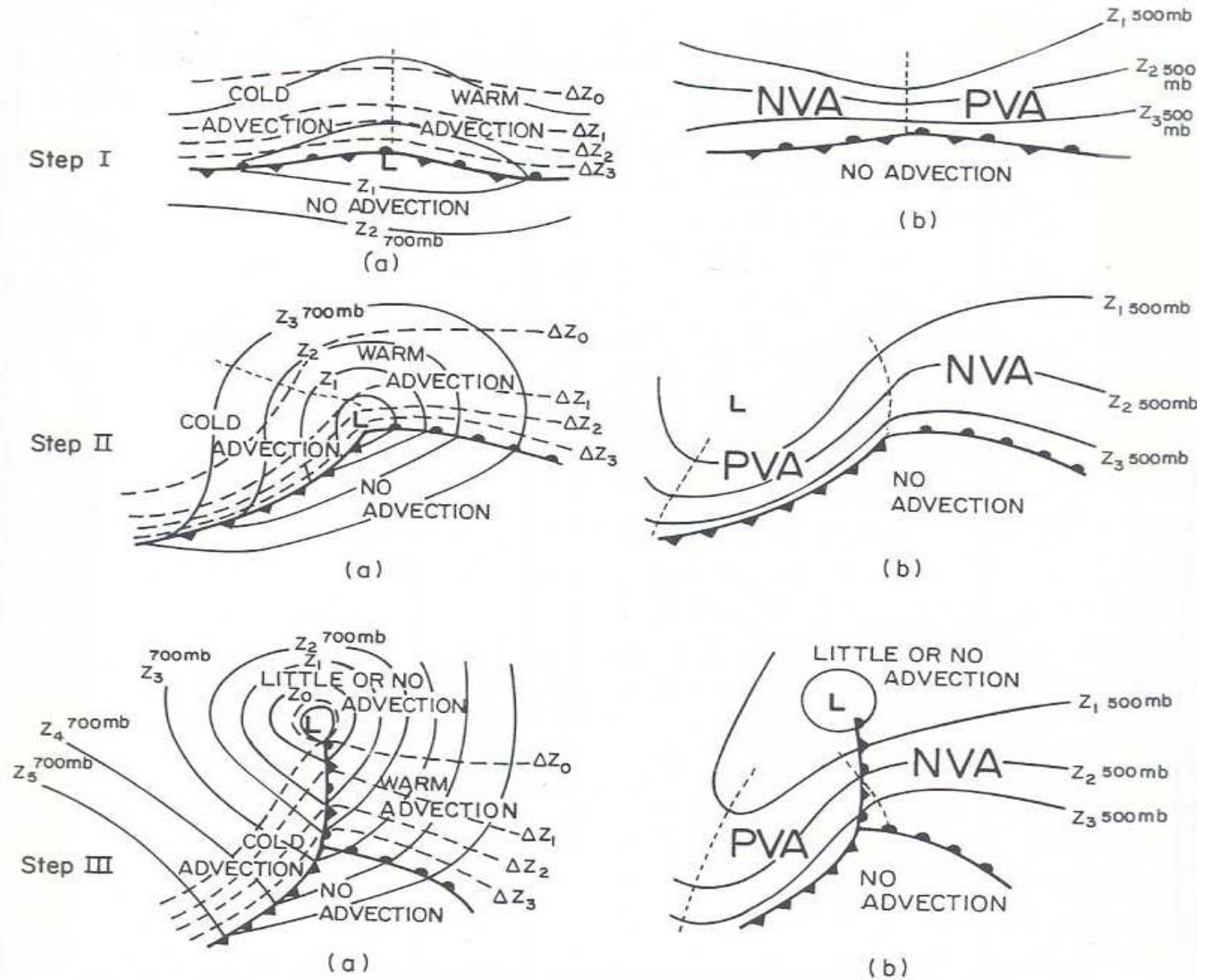
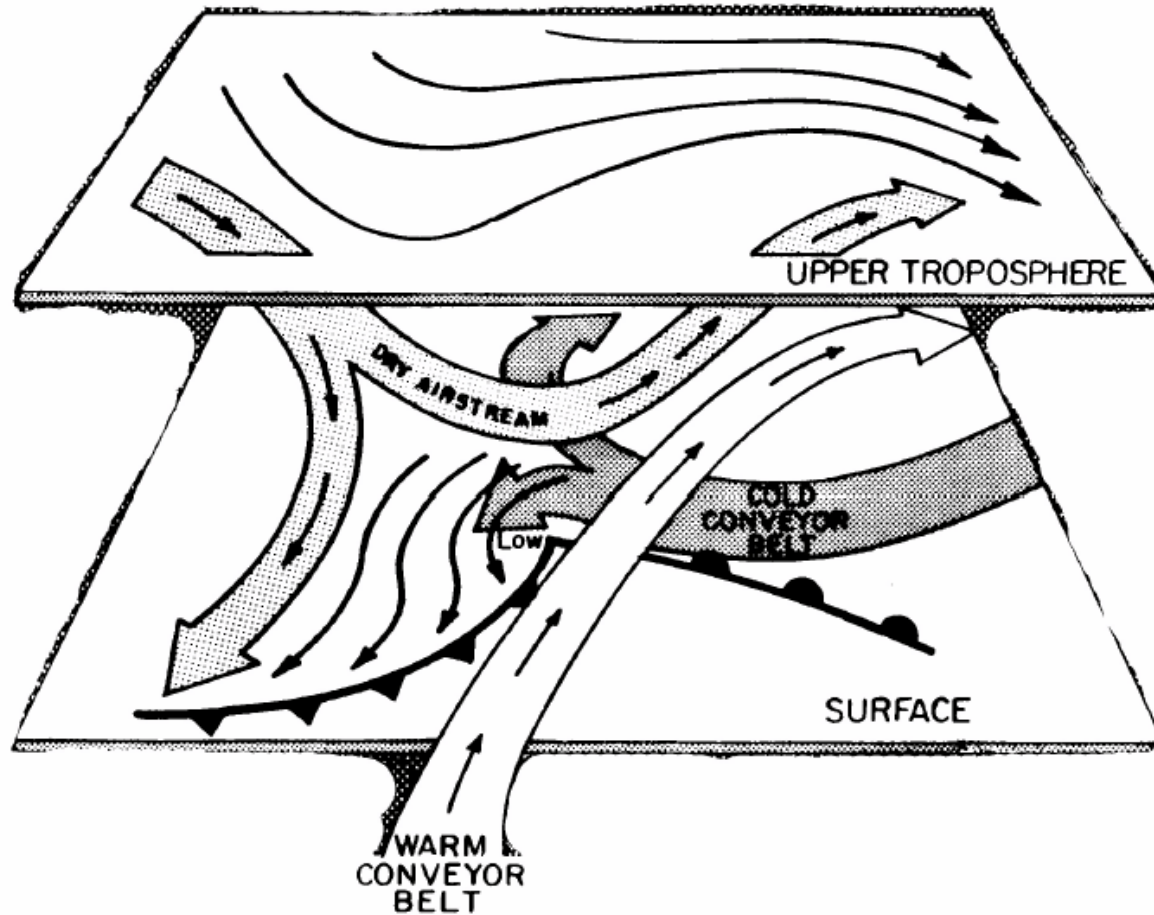


Figure 3.20: Schematic illustration of thickness advection and vorticity advection associated with extratropical cyclone development. The 700 mb height contours (solid lines), 1000-500 mb thickness contours (dashed lines), and surface frontal location are given in (a). The 500 mb height contours (solid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

3-D Structure of Developing Extratropical Cyclone

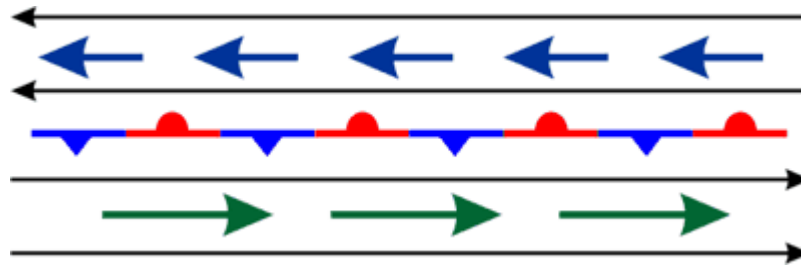


Conditions for Cyclogenesis

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

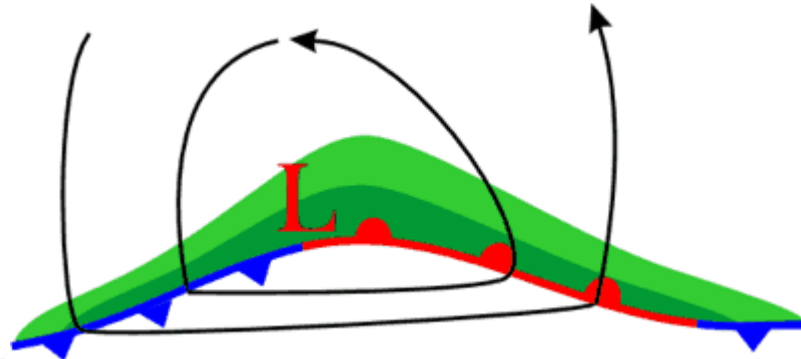
Norwegian Cyclone Model

- The Norwegian Cyclone Model is named in honor of the Norwegian meteorologists who first conceptualized the life cycle stages of an extratropical cyclone shortly after World War I.

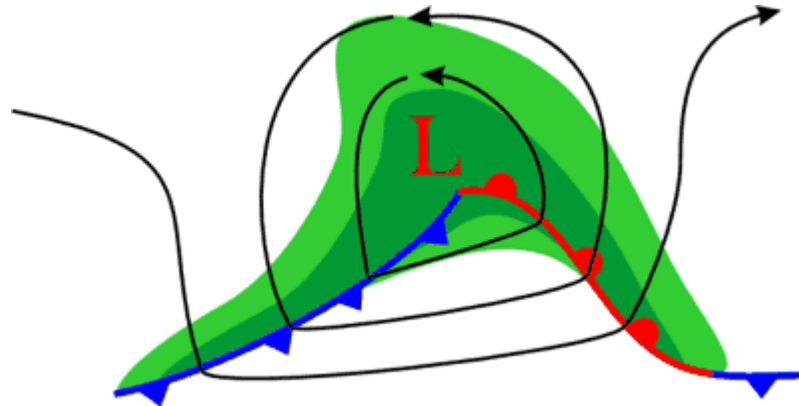


There needs to be an initial thickness gradient (i.e., front) for cyclogenesis to begin. This is often a stationary front.

Norwegian Cyclone Model

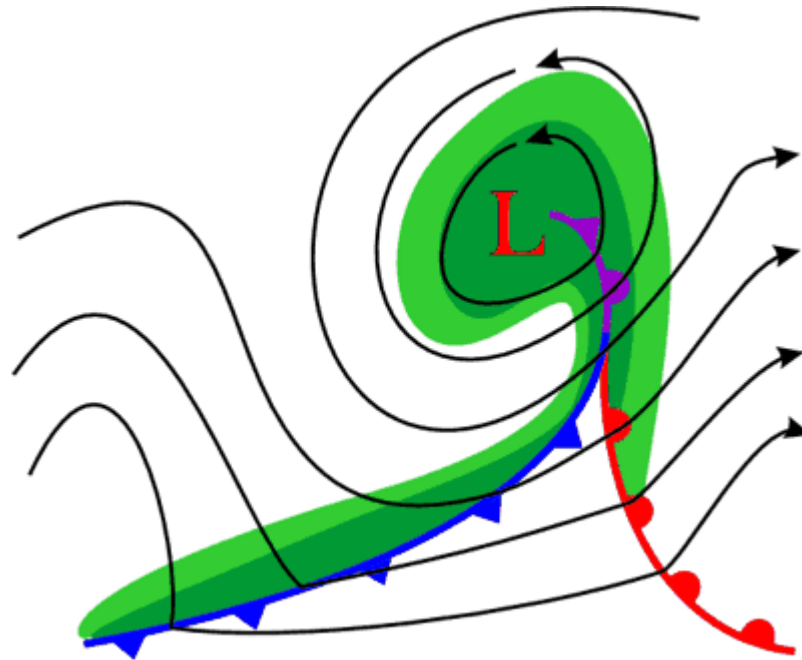


The initial (or incipient) stage of development is often called a wave cyclone. The front becomes anticyclonically curved.



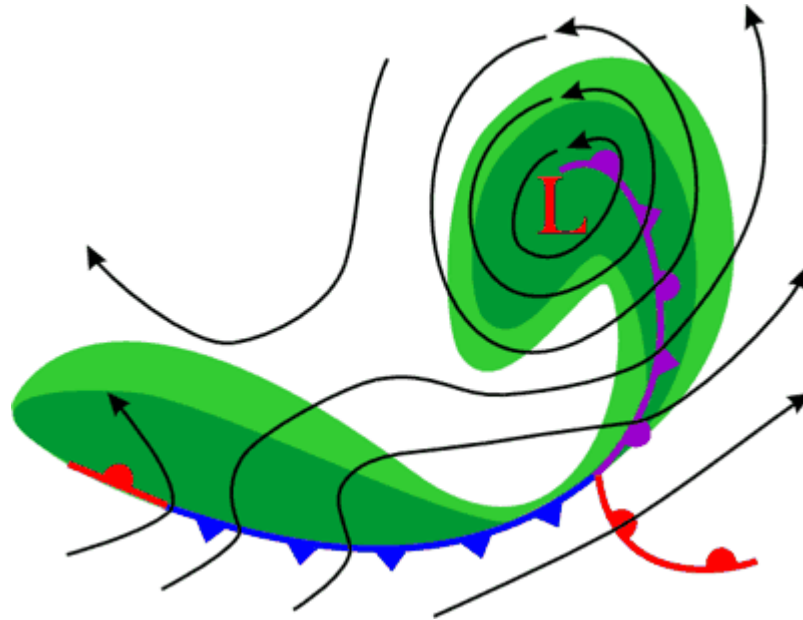
The system continues to strengthen into a more organized system in the development stage.

Norwegian Cyclone Model



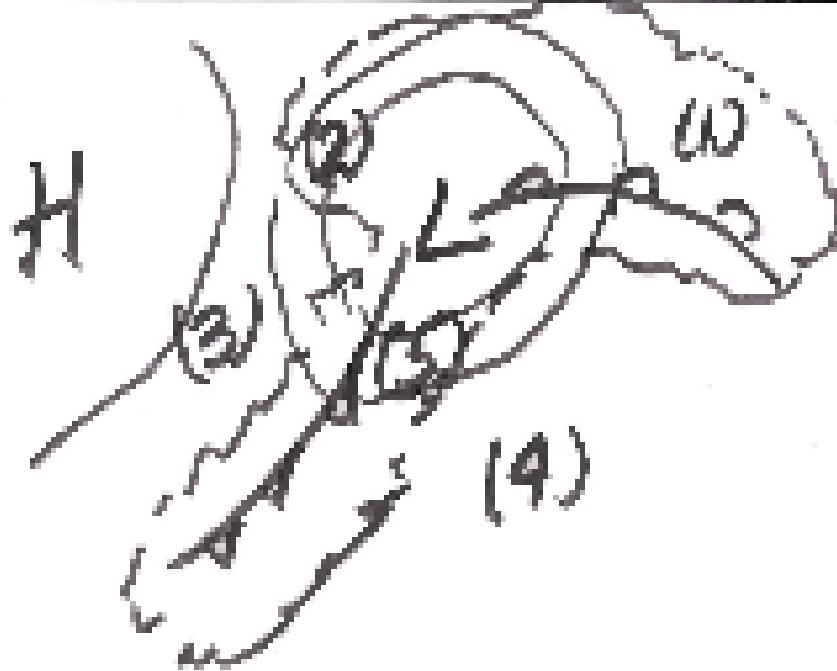
The mature stage is characterized by the formation of an occluded front near the surface low. Notice the comma shaped cloud and precipitation structure at this stage.

Norwegian Cyclone Model



The occluded stage is characterized by an increase in the occlusion, which cuts off the supply of warm, moist air and leads to dissipation.

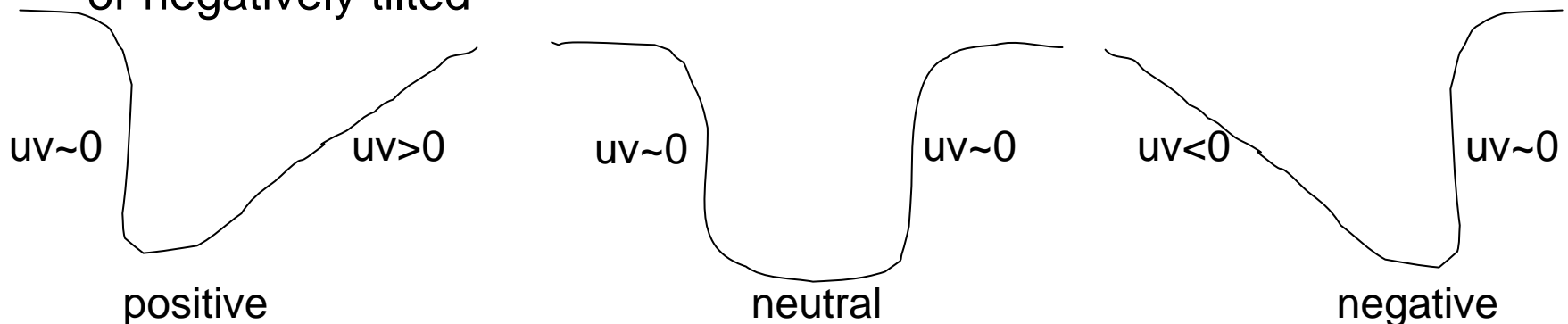
Expected Weather Conditions



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

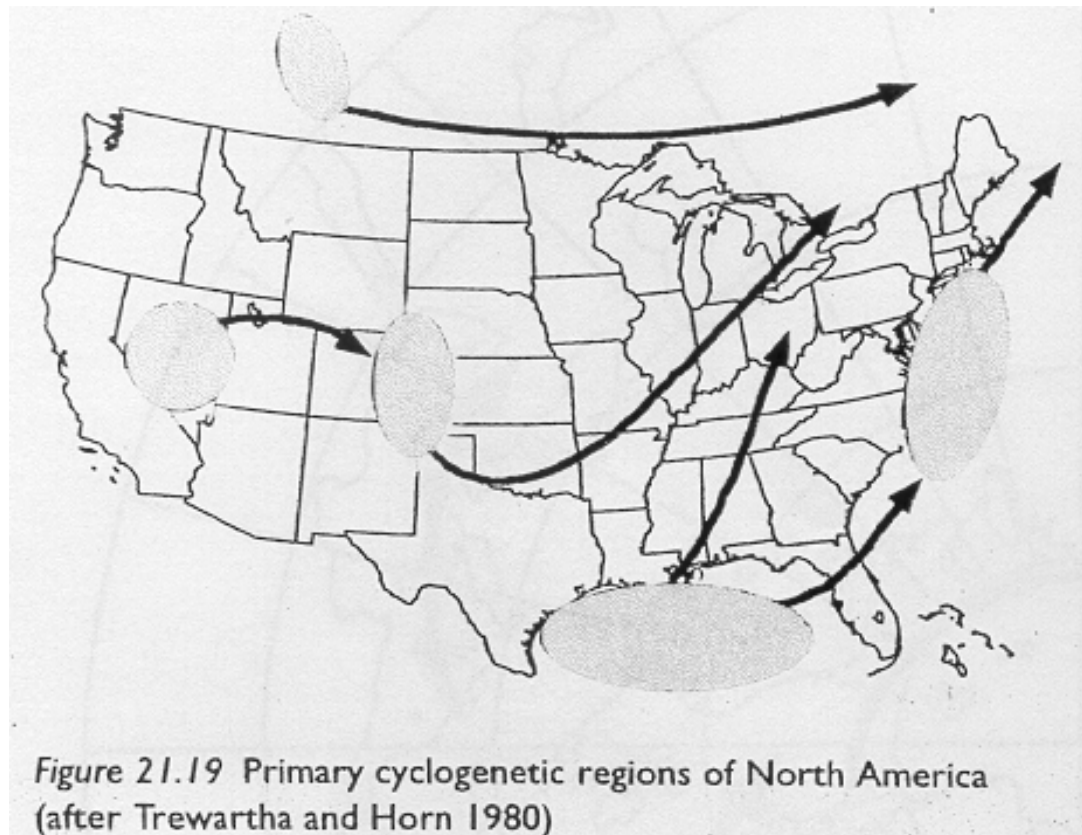
Trough Patterns

- Troughs can be defined by their tilt: positive, neutral (zero), & negative
- In a positively tilted trough, zonal momentum is transported northward, so cold air advection (CAA) is needed into the trough to prevent it from weakening
- The negatively tilted trough will tend to deepen as zonal momentum and cold air is transported into the trough.
- The atmosphere tends to be more unstable with negatively tilted troughs as there is a rapid change from sub- to super-geostrophic winds. In addition, if this tilt occurs east of the Rockies in the U.S., there will be CAA aloft and warm, moist air at the surface
- With the development of extratropical cyclones, it is most common for upper-level troughs to be positively tilted initially and end up neutrally or negatively tilted



Preferred Areas of Cyclogenesis

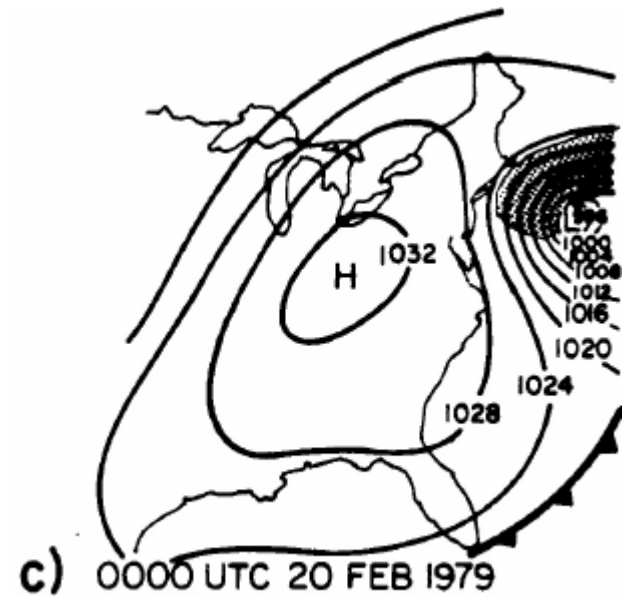
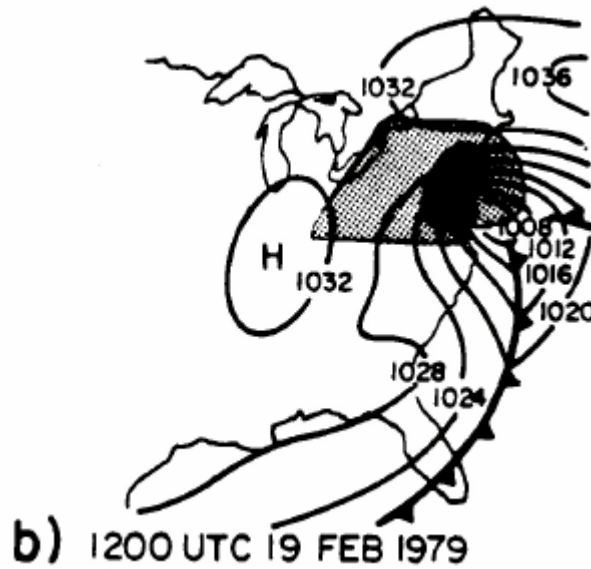
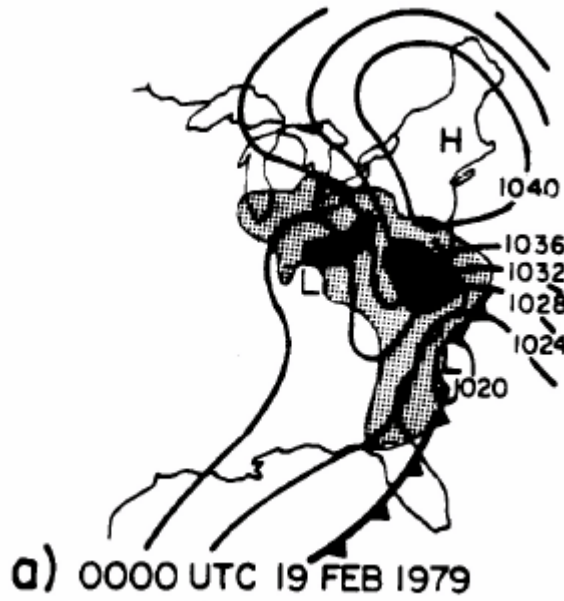
- Cyclogenesis occurs farthest south ($\sim 37^\circ$ latitude) in the winter and is reduced and farthest north ($\sim 47^\circ$ latitude) in the summer.
- Cyclogenesis preferentially occurs in strong baroclinic zones and on the lee side of mountain ranges.



Explosive Cyclogenesis

- Explosive (or “bomb”) cyclogenesis occurs when extratropical cyclones deepen rapidly – the surface pressure falls ~24 mb in 24 hours
- These are often associated with severe weather, strong winds, and heavy precipitation
- Two examples:
 - President’s Day Storm: 19-20 February 1979
 - System dumped ~2 feet of snow from Washington, D.C., to New York
 - A nor’easter – an extratropical cyclone that develops and intensifies as it moves northeast along the Atlantic coast of the U.S. bringing heavy precipitation and strong northeast winds along the coast
 - Does receive some energy from sensible and latent heat fluxes from the ocean (hurricane characteristic) along with baroclinicity (mid-latitude cyclone characteristic)
 - 9-11 November 1998 over the continental U.S.

President's Day Storm



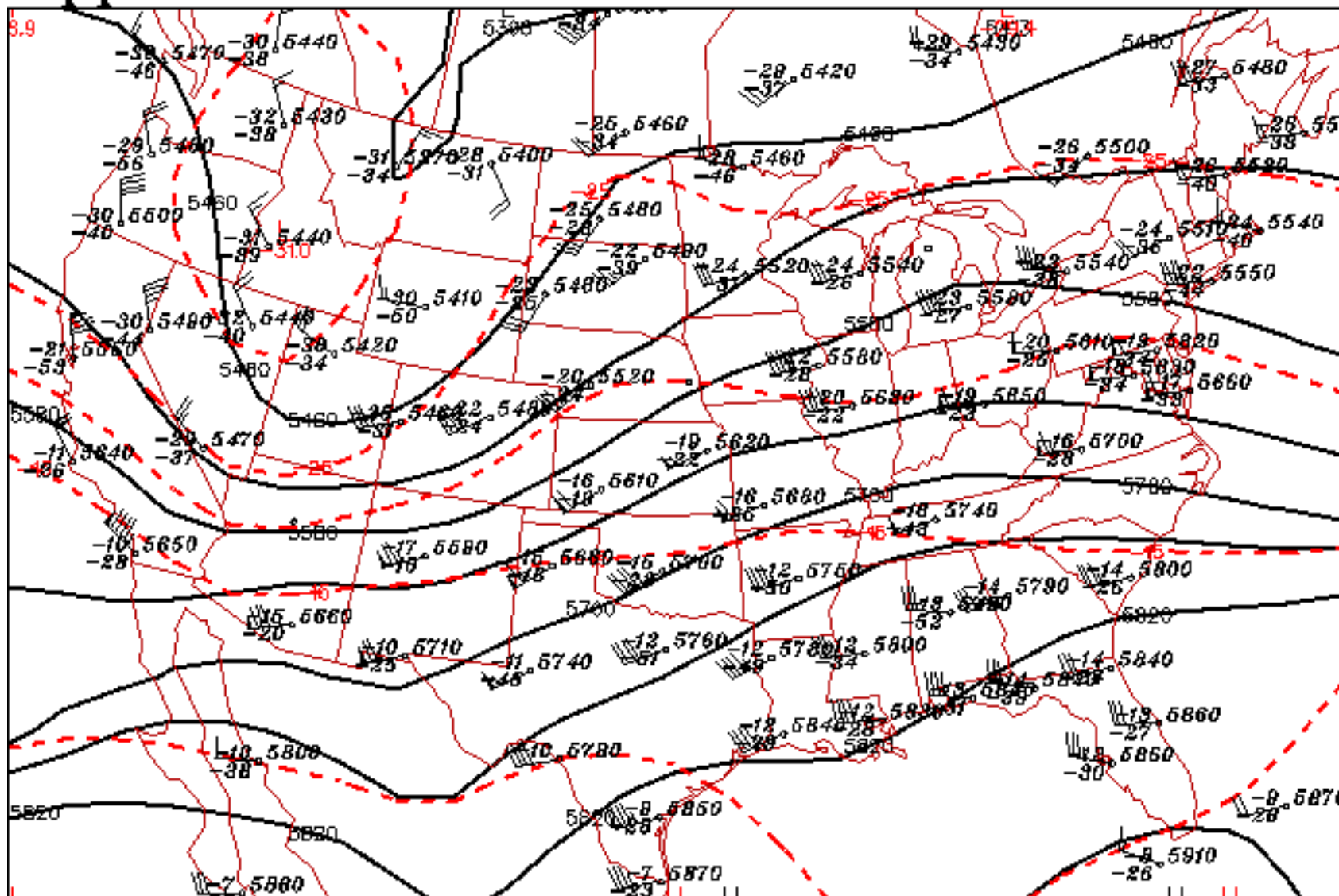
Rapid Cyclone Intensification

An Example from November 9, 10
and 11, 1998

Upper Air Obs.

500 mb

12Z 9 NOV 1998

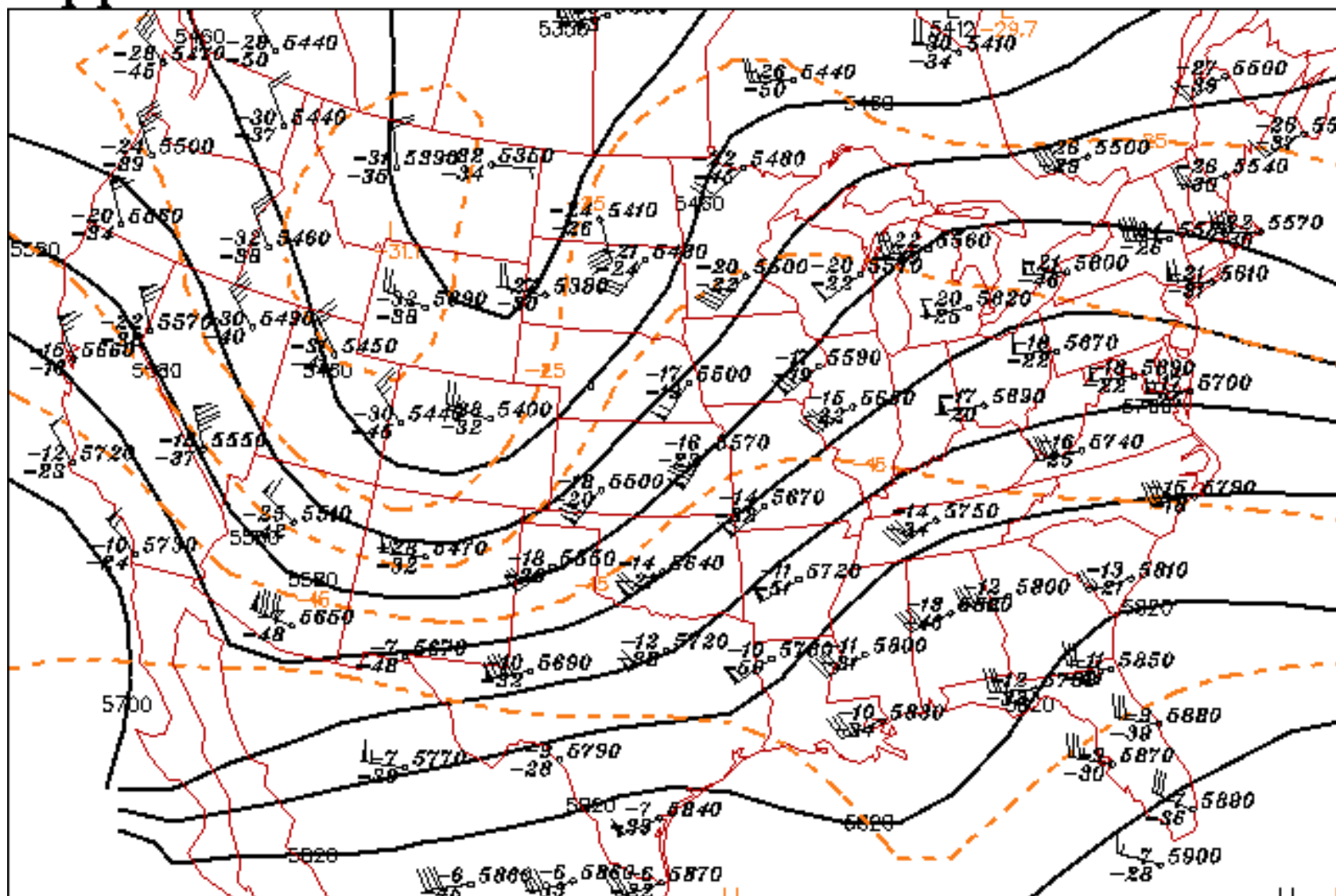


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Upper Air Obs.

500 mb

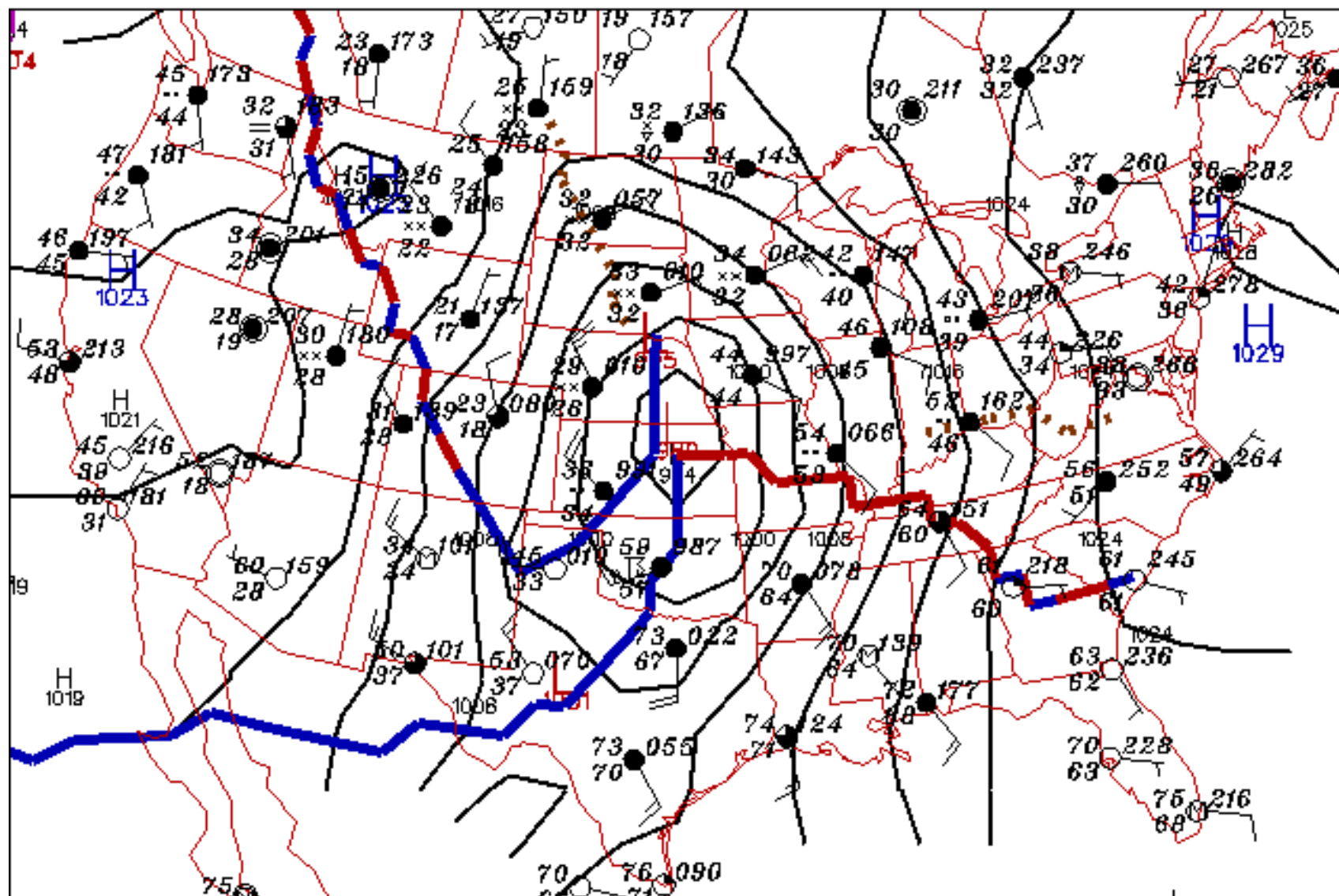
0Z 10 NOV 1998



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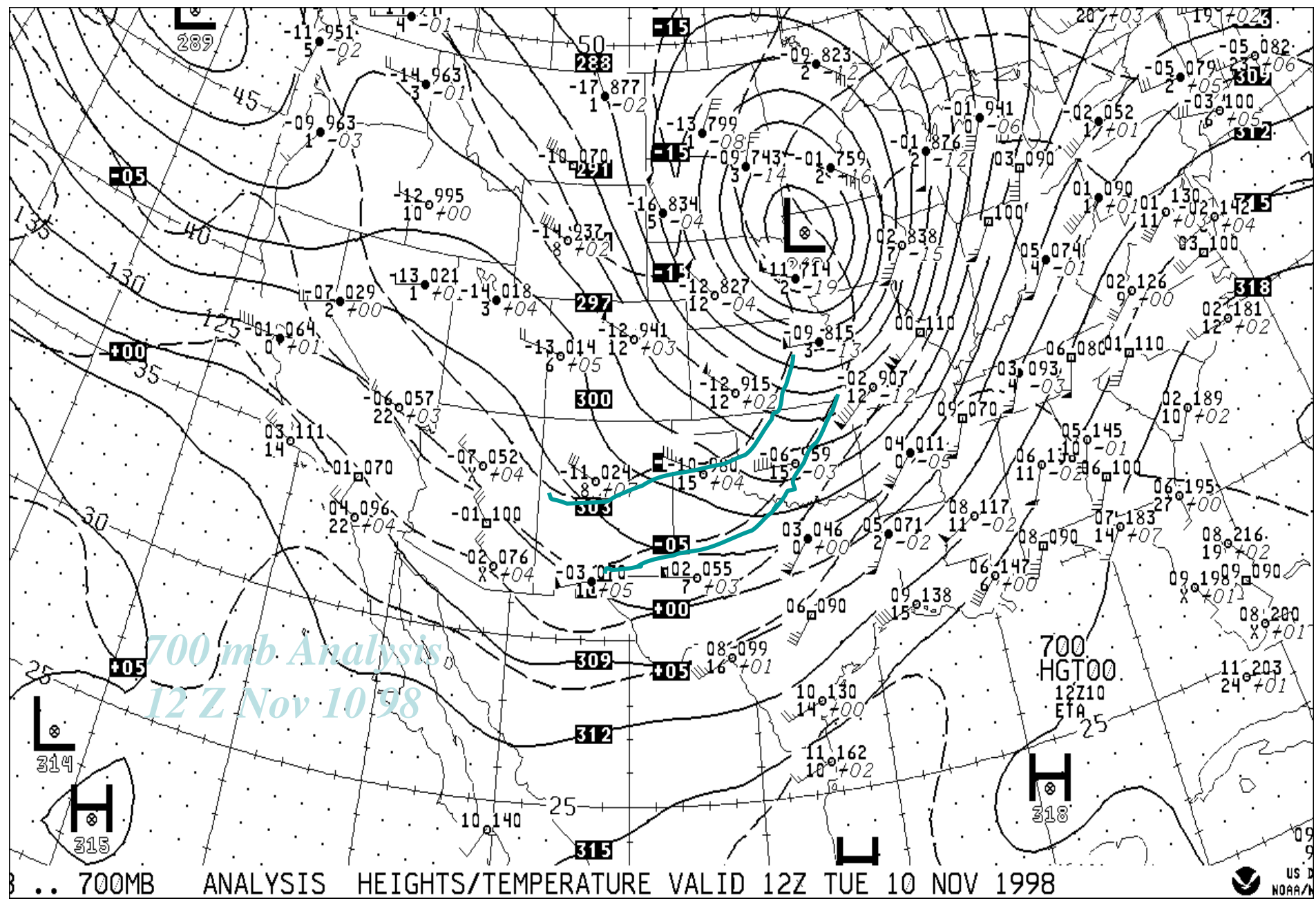
Surface Observations

0Z 10 APR 1996



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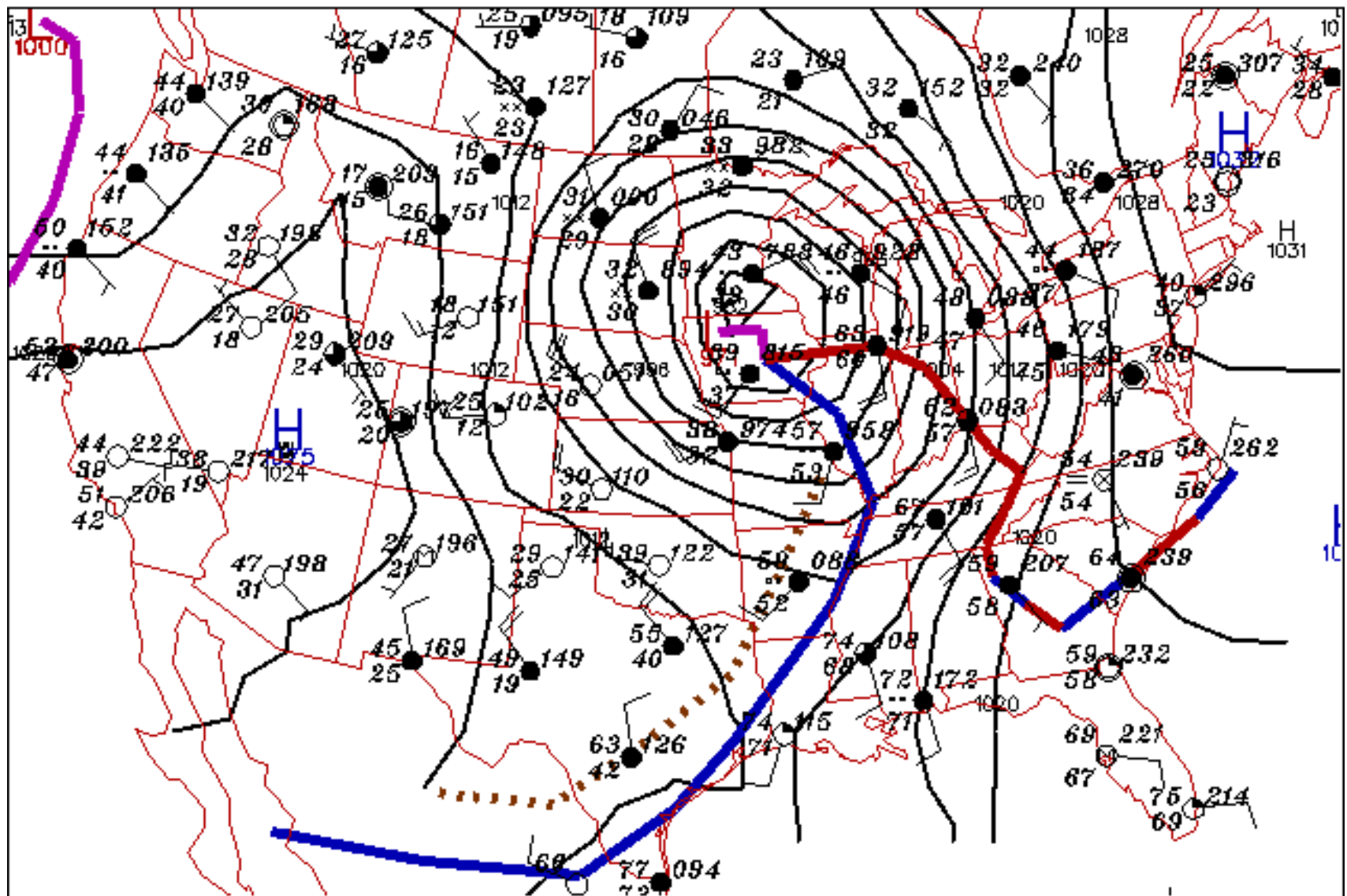
700MB ANALYSIS HEIGHTS/TEMPERATURE VALID 12Z TUE 10 NOV 1998



US D
NOAA/N

Surface Observations

12Z 10 NOV 1998

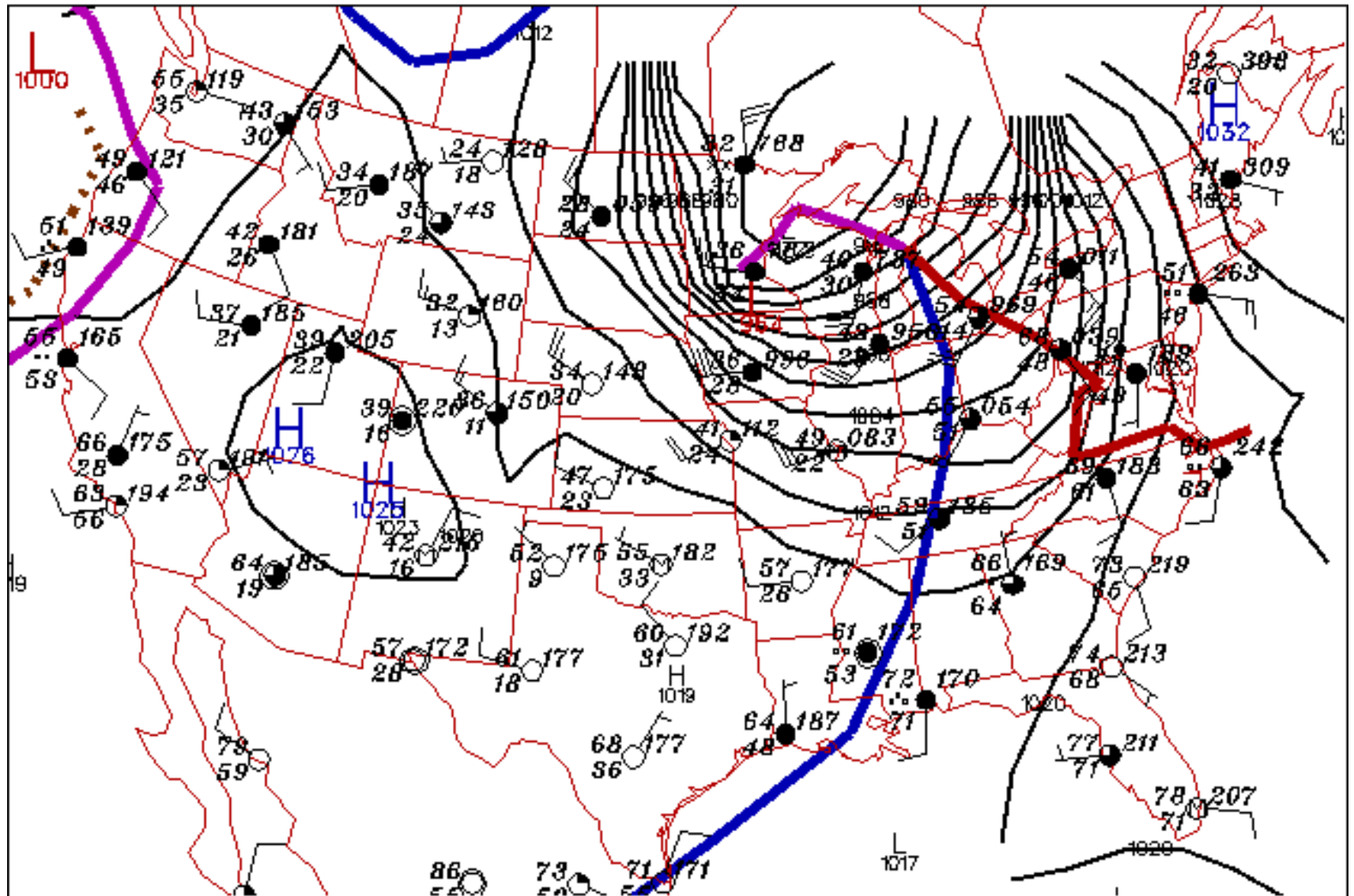


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- | | | | |
|----------------------|--------------|--------------------|---|
| — Isobars | — Cold Front | — Occluded Front | Radar Echo Intensities |
| - - - Isotherms | — Warm Front | — Stationary Front | Light ■ ■ ■ ■ ■ Heavy |
| - - - Isodrosotherms | | | |

Surface Observations

23Z 10 NOV 1998



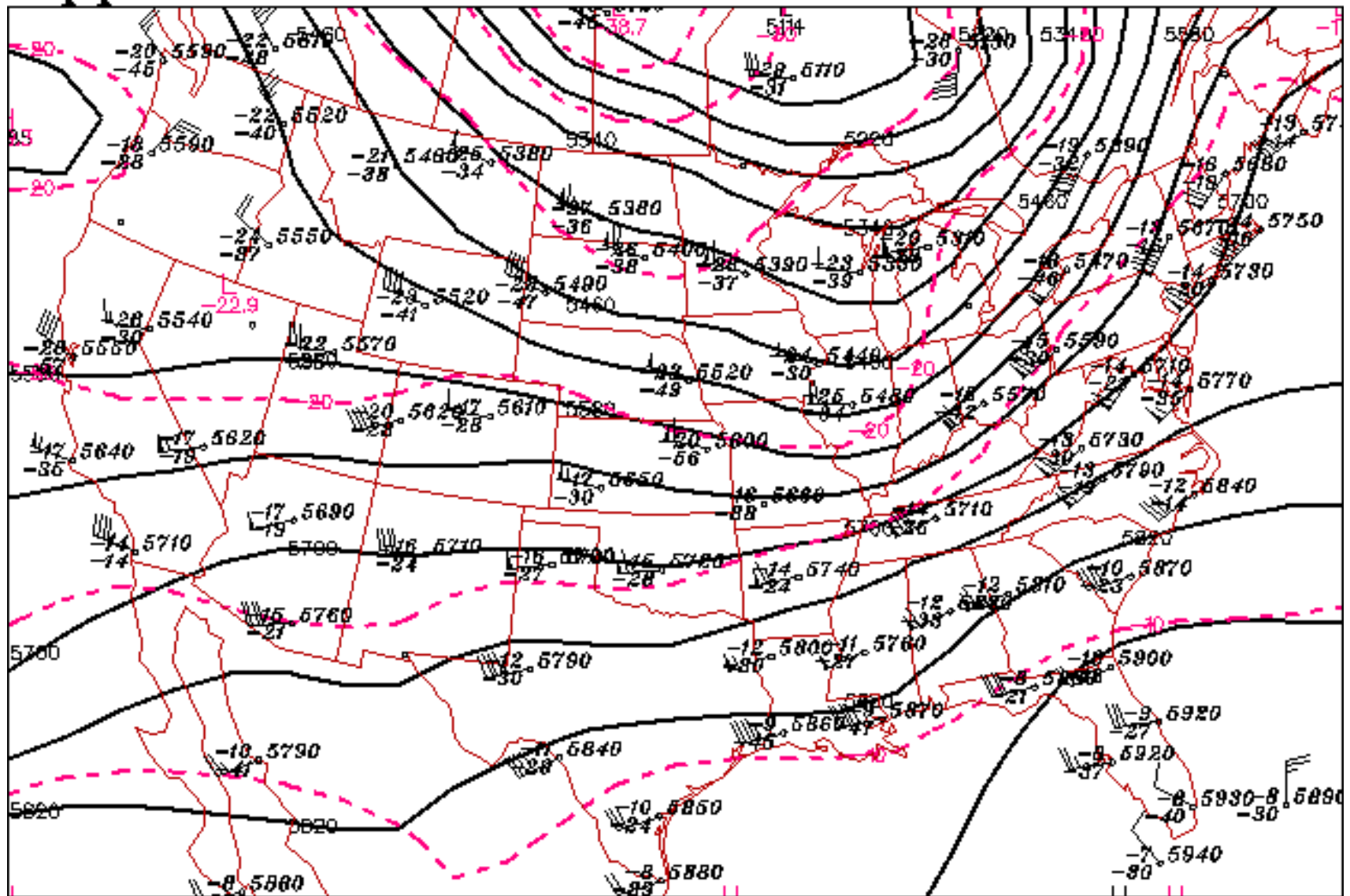
DEPARTMENT OF ATMOSPHERIC SCIENCES/UNIVERSITY OF ILLINOIS



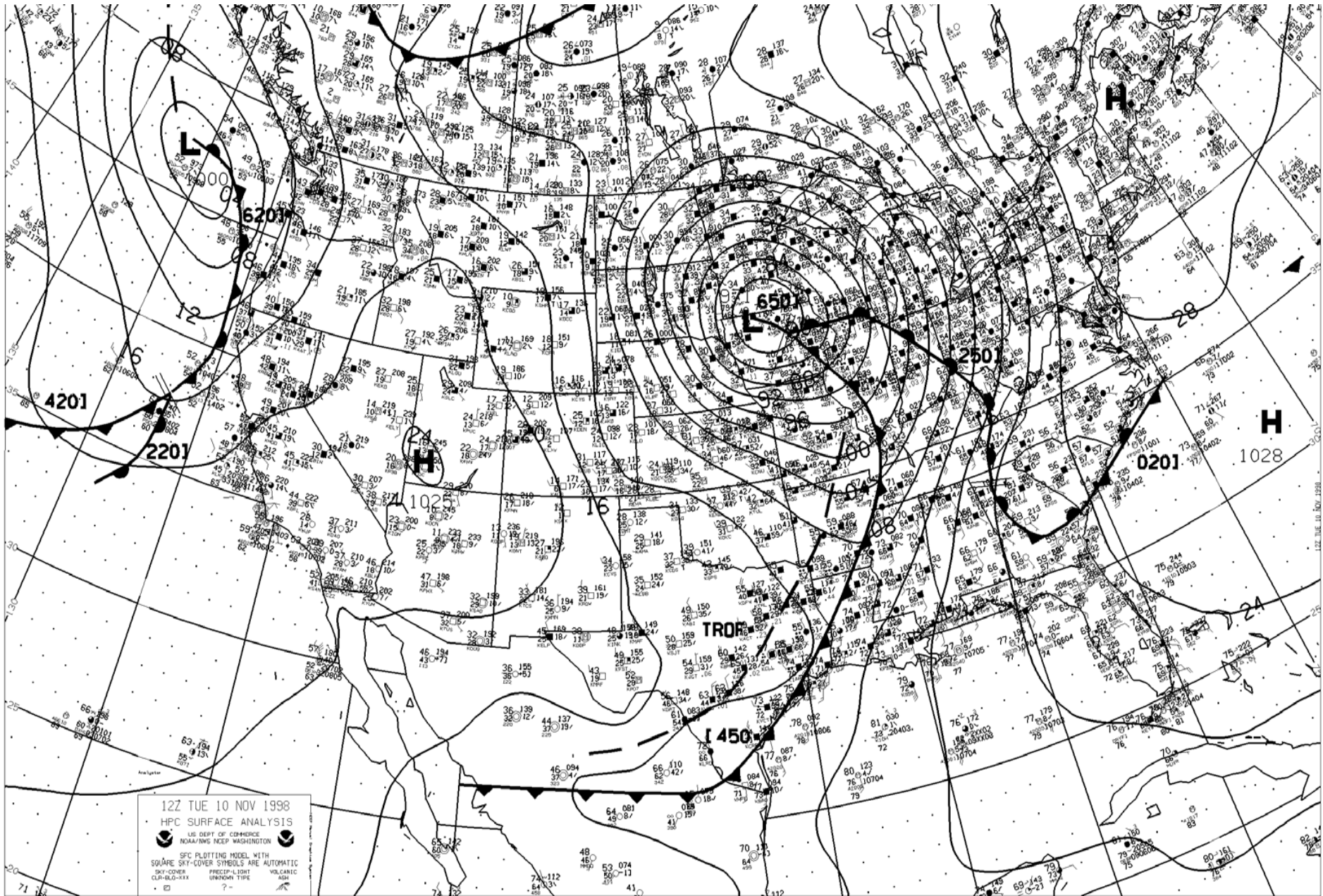
Upper Air Obs.

500 mb

12Z 11 NOV 1998



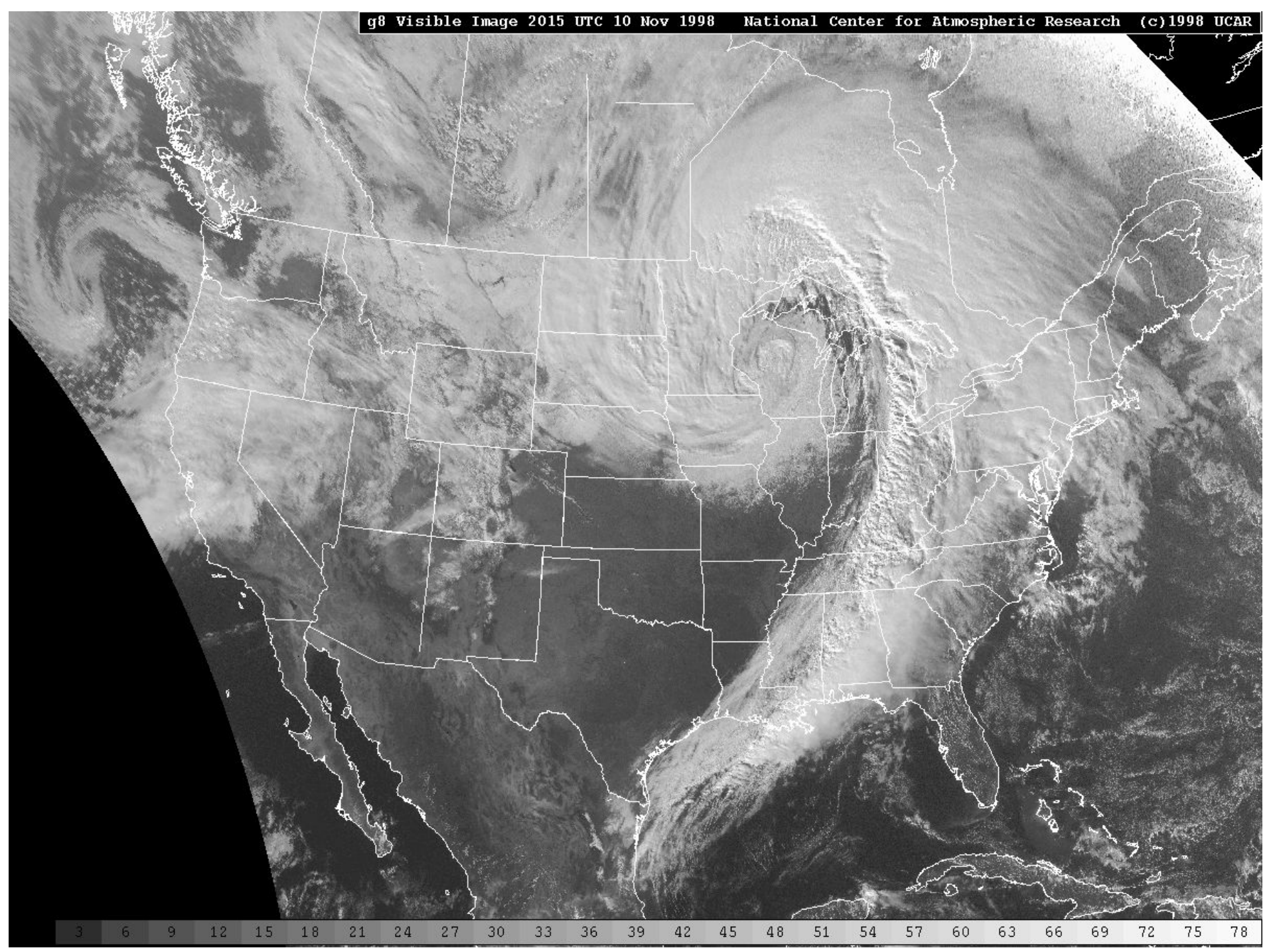
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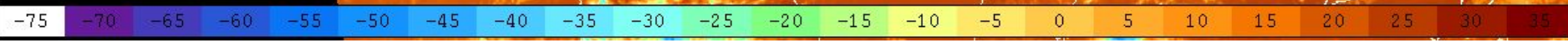
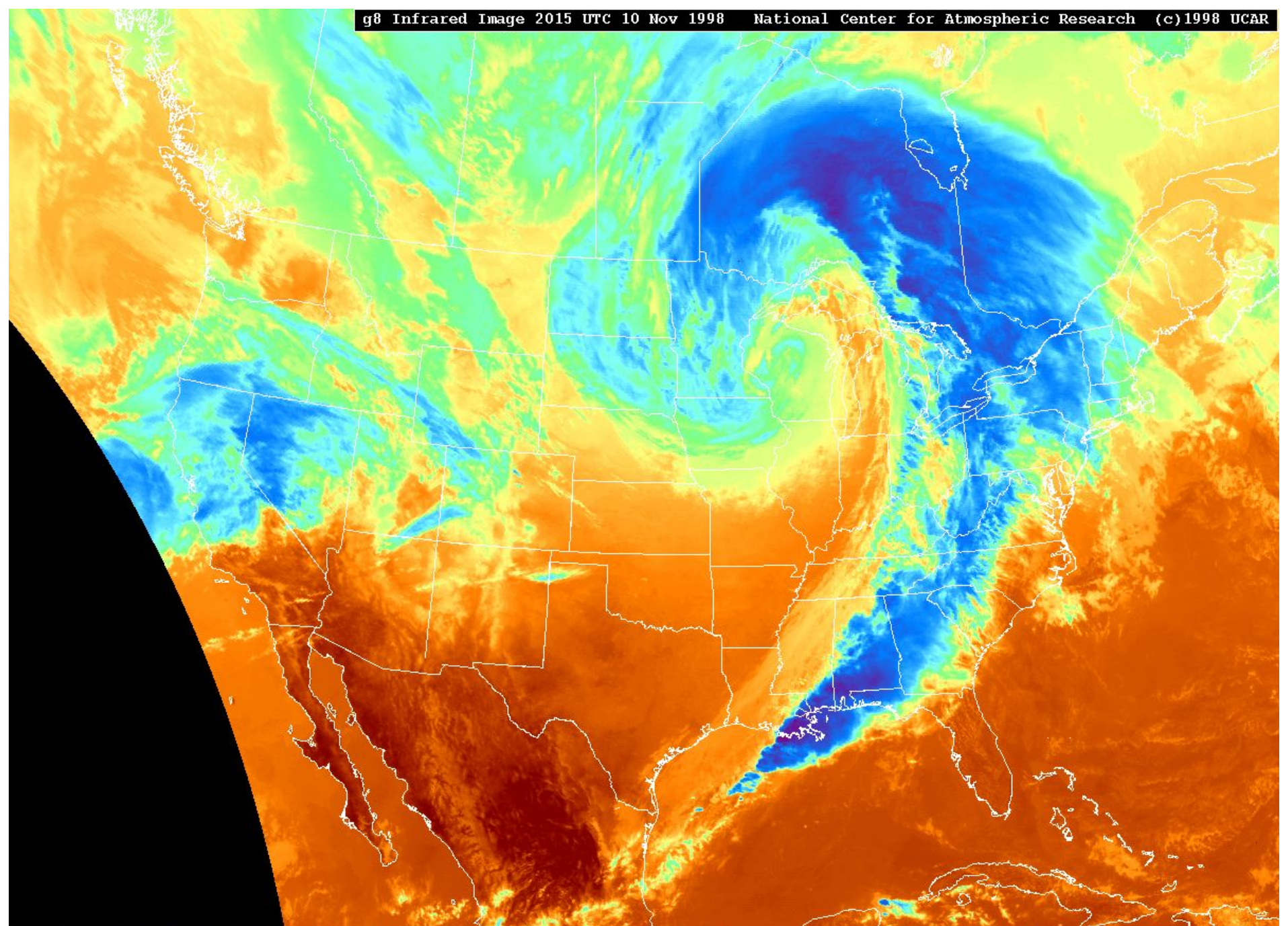


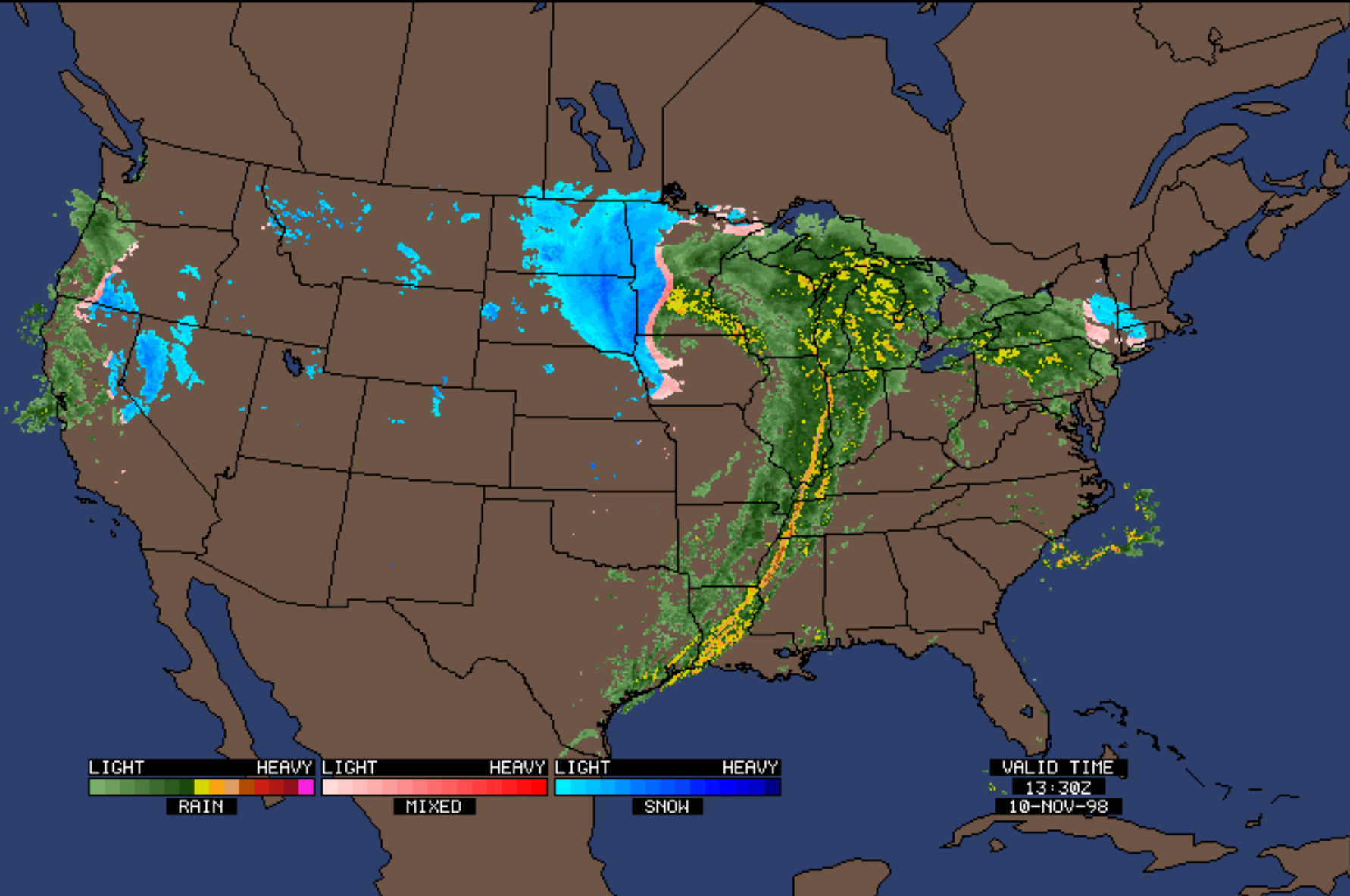
12Z TUE 10 NOV 1998
 HPC SURFACE ANALYSIS
 US DEPT OF COMMERCE
 NOAA/NWS NCEP WASHINGTON

SFC PLOTTING MODEL WITH
 SQUARE SKY-COVER SYMBOLS ARE AUTOMATIC
 SKY COVER PRECIP-LIGHT VOLCANIC
 CLR-SG-XXX UNKNOWN-TYPE ASH

? -







VALID TIME
13:30Z
10-NOV-98