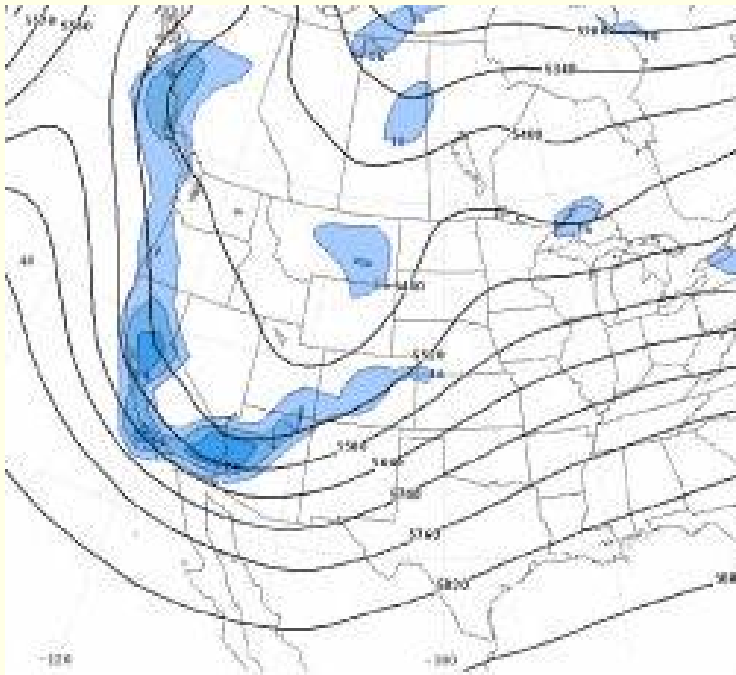


Storm of 10 November, 1998:

The sequence of events

in greater detail.

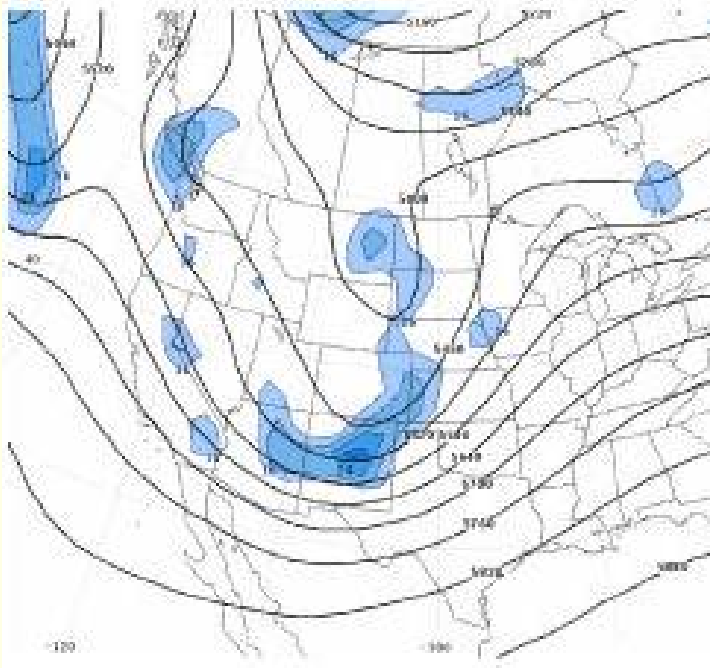


500-hPa height (contours)
and absolute vorticity
(coloured shading),
12 UTC Nov. 9, 1998.

The pronounced long-wave trough over western North America has several smaller scale features embedded in it. These show up clearly in the vorticity field.

The vorticity maxima along the coast of British Columbia (BC) and over Arizona (AZ) correspond to short-wave troughs: the horizontal flow exhibits *both cyclonic curvature and cyclonic shear*.

The **shear** is particularly strong in the case of the latter (AZ) trough.

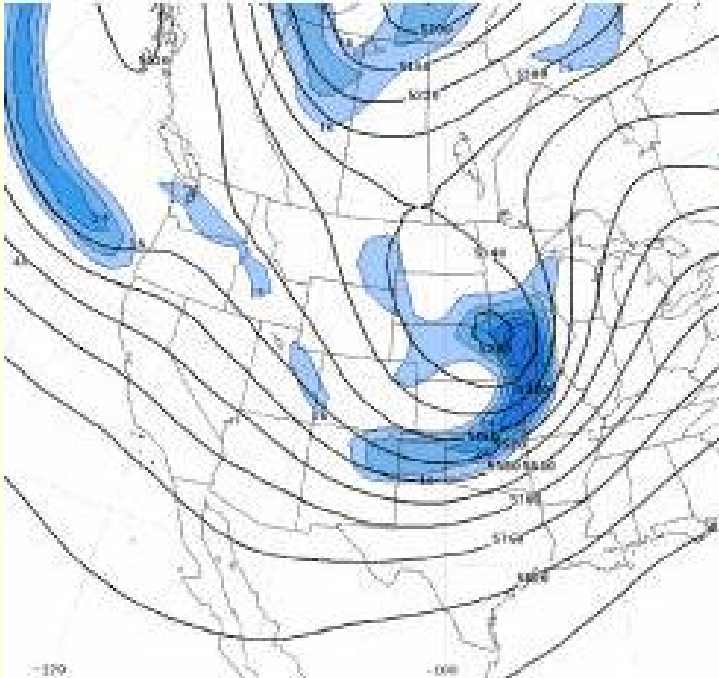


500-hPa height (contours)
and absolute vorticity
(coloured shading),
00 UTC Nov. 10, 1998.

Twelve hours later, these vorticity maxima and their associated troughs appear **downstream** of their previous positions.

The former (BC) is centered over **Vancouver Island** and the latter (AZ) over southern **Colorado**.

This movement is **largely attributable to vorticity advection** by the wind field.



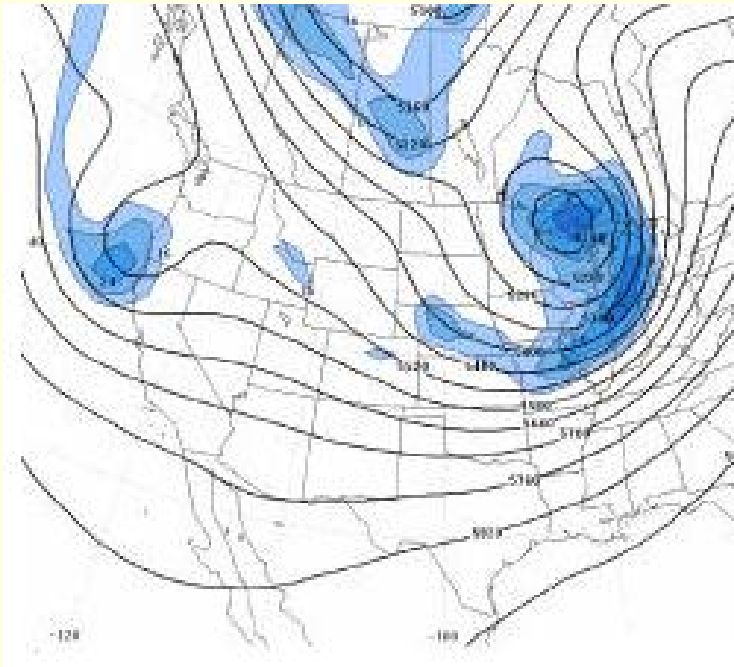
500-hPa height (contours)
and absolute vorticity
(coloured shading),
12 UTC Nov. 10, 1998.

The third chart shows the vorticity maximum that appeared over Arizona now passing over the northwest corner of Iowa.

The short-wave trough associated with this feature has **deepened substantially** and developed a closed contour.

The associated maximum on the vorticity field has **increased substantially** from the previous chart.

Thus, **vorticity is not behaving simply as a passive tracer:** the vorticity perturbations in this system are amplifying.

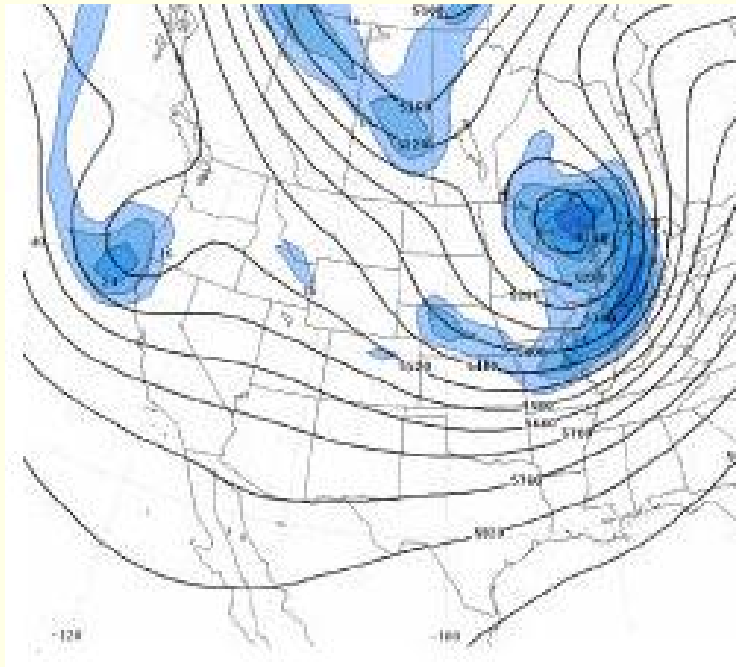


500-hPa height (contours)
and absolute vorticity
(coloured shading),
00 UTC Nov. 11, 1998.

The newly developed cutoff low continues to track towards the north-east and deepen during the last 12 hours of the sequence, passing over Lake Superior.

At this time the 500-hPa height at its center has reached its minimum value of 516 dekameters.

In subsequent 500-hPa charts (not shown) this feature continues to track east-northeastward, while slowly weakening.



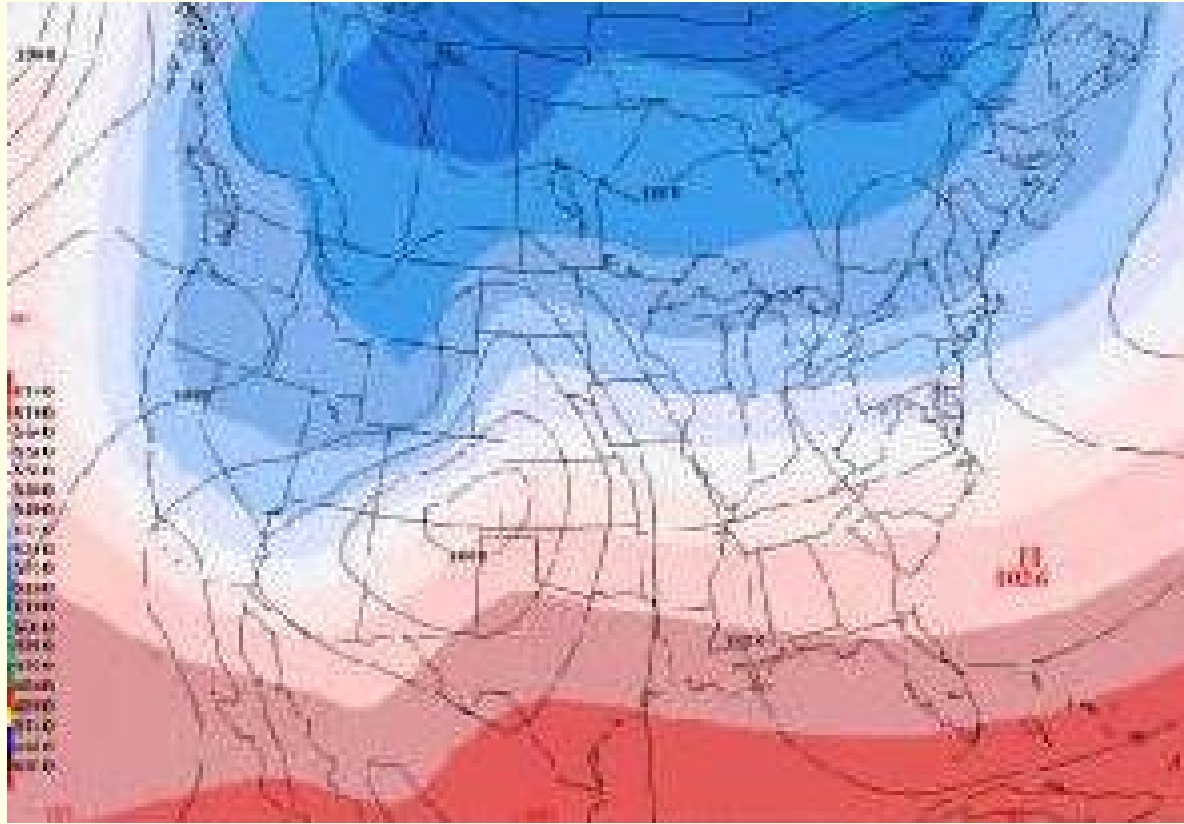
500-hPa height (contours)
and absolute vorticity
(coloured shading),
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The newly developed cutoff low continues to track towards the north-east and **deepen** during the last 12 hours of the sequence, passing over Lake Superior.

At this time the **500-hPa height** at its center has reached its **minimum value** of 516 dekameters.

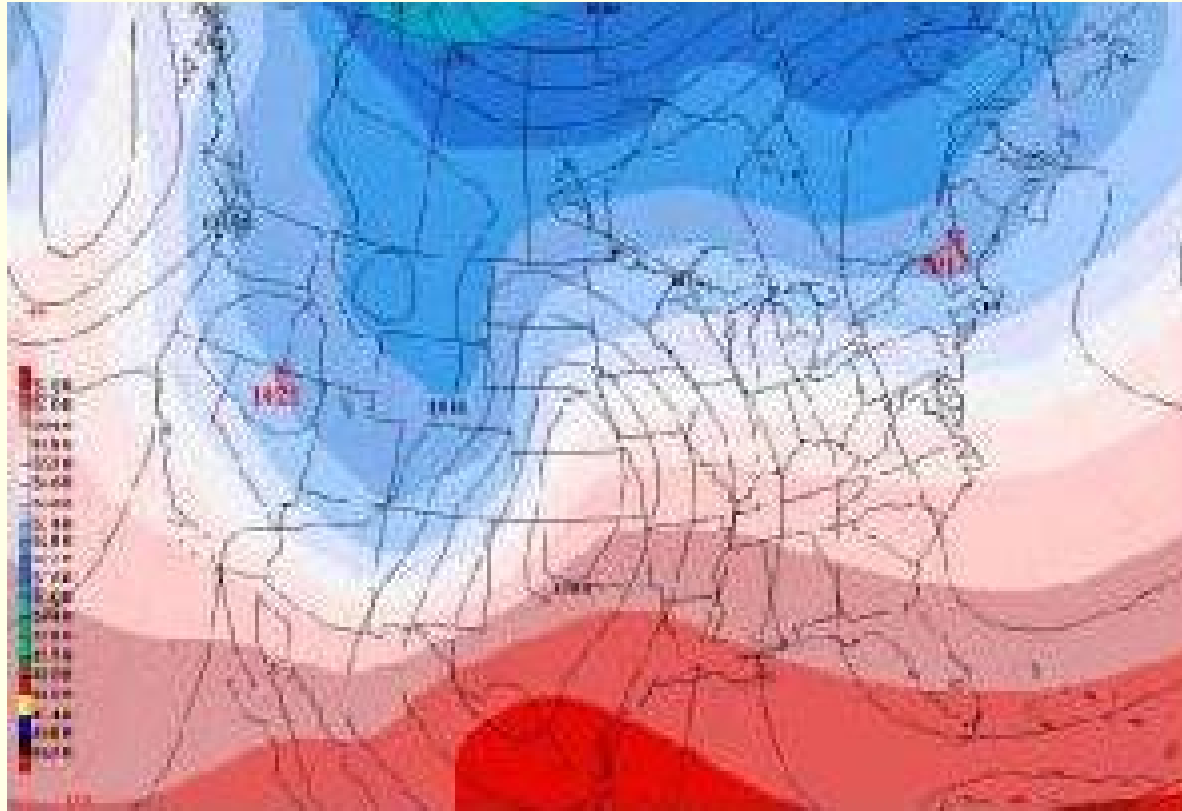
In subsequent 500-hPa charts (not shown) this feature continues to track east-northeastward, while slowly weakening.

[Note the new system forming off the coast of Northern California. The BC system seems to have become entangled in this.]



Sea-level pressure (contours) and 1000–500 hPa thickness (shading)
12 UTC Nov. 9, 1998.

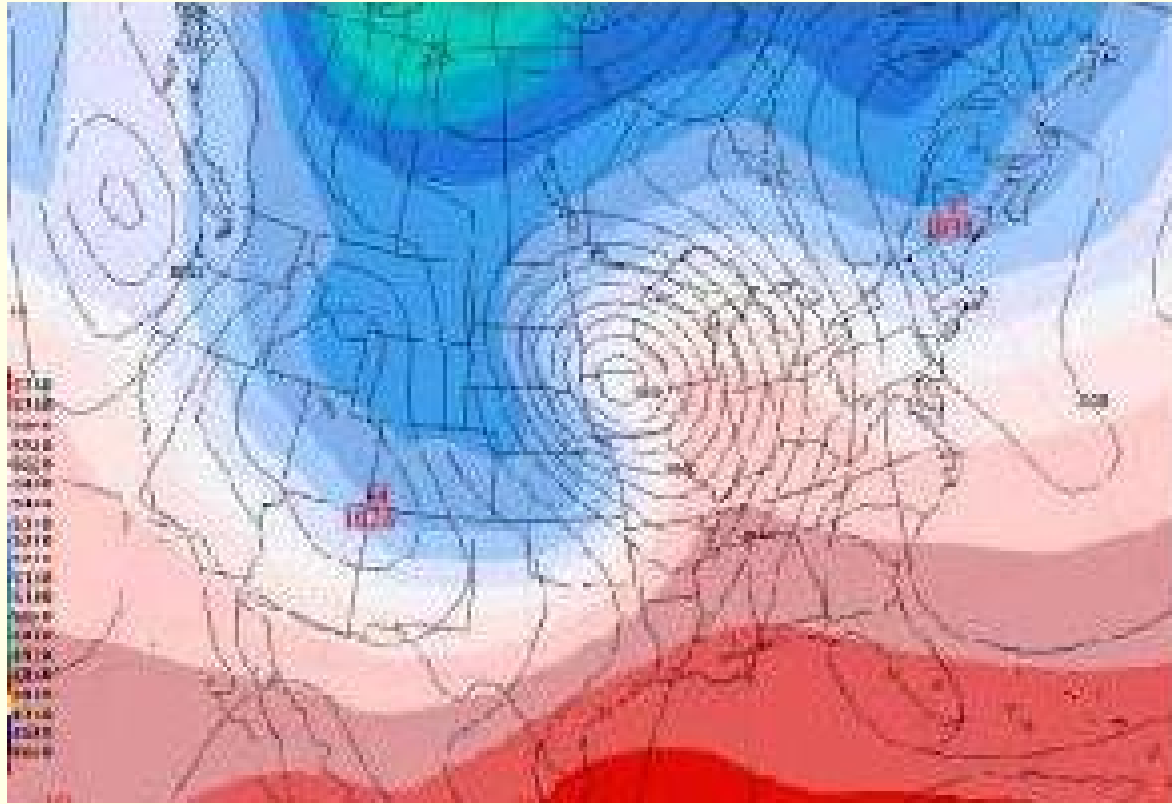
The surface low **deepens** throughout the sequence of charts.
Its central pressure is **996 hPa** at 12 UTC on Nov. 9, 1998.



Sea-level pressure (contours) and 1000–500 hPa thickness (shading)
00 UTC Nov. 10, 1998.

The fastest rate of deepening, observed between the second and third charts of the sequence (**~30 hPa per day**).

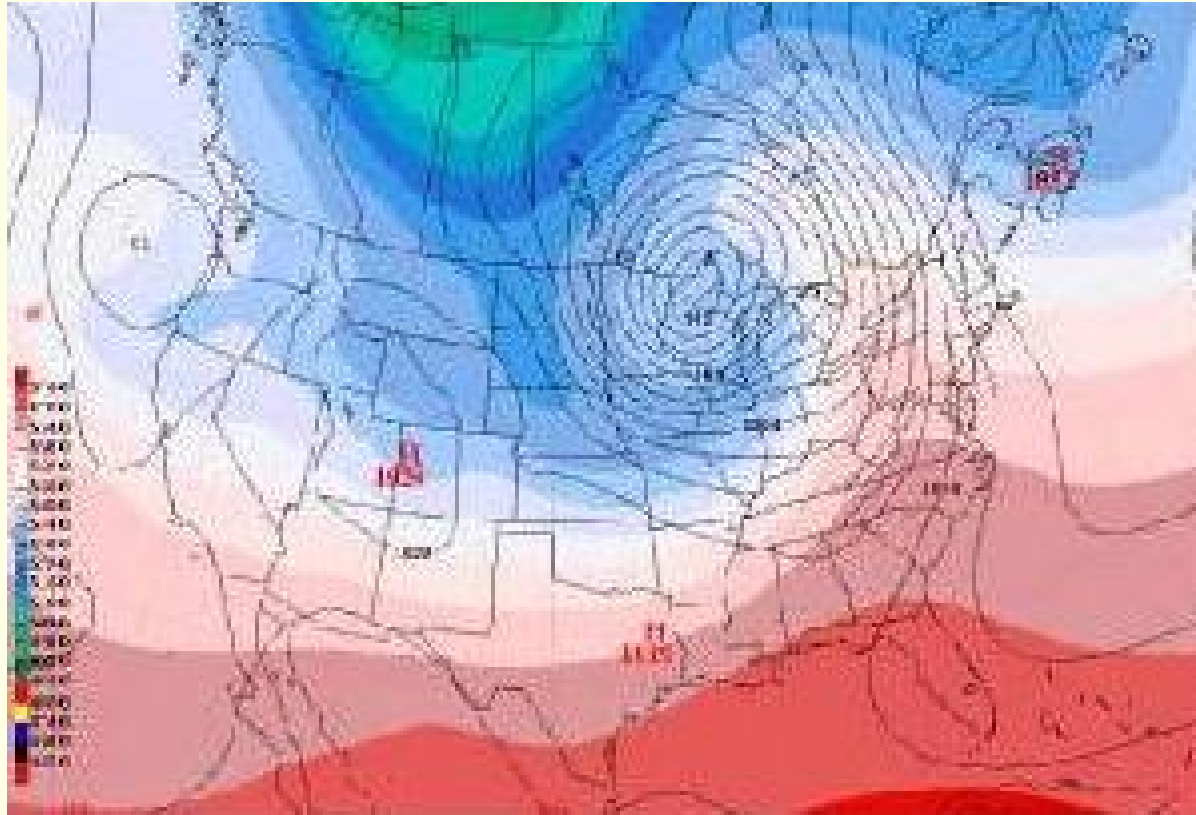
This is about three times as rapid as in a typical extratropical cyclone.



Sea-level pressure (contours) and 1000–500 hPa thickness (shading)
12 UTC Nov. 10, 1998.

The fastest rate of deepening, observed between the second and third charts of the sequence (**~ 30 hPa per day**).

This is about three times as rapid as in a typical extratropical cyclone.



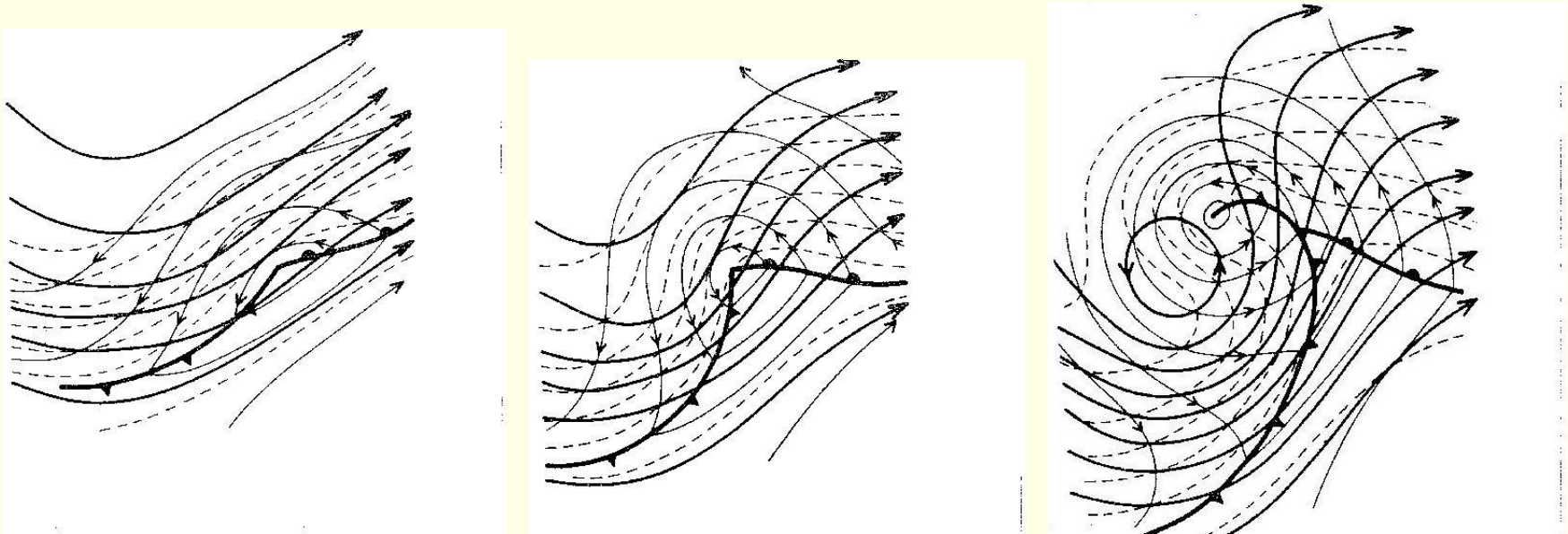
Sea-level pressure (contours) and 1000–500 hPa thickness (shading)
00 UTC Nov. 11, 1998.

The central pressure is 996 hPa at 12 UTC on Nov. 9, 1998.
It is **968 hPa** 36 hours later.

The depression has deepened by **28 hPa in 36 hours**.

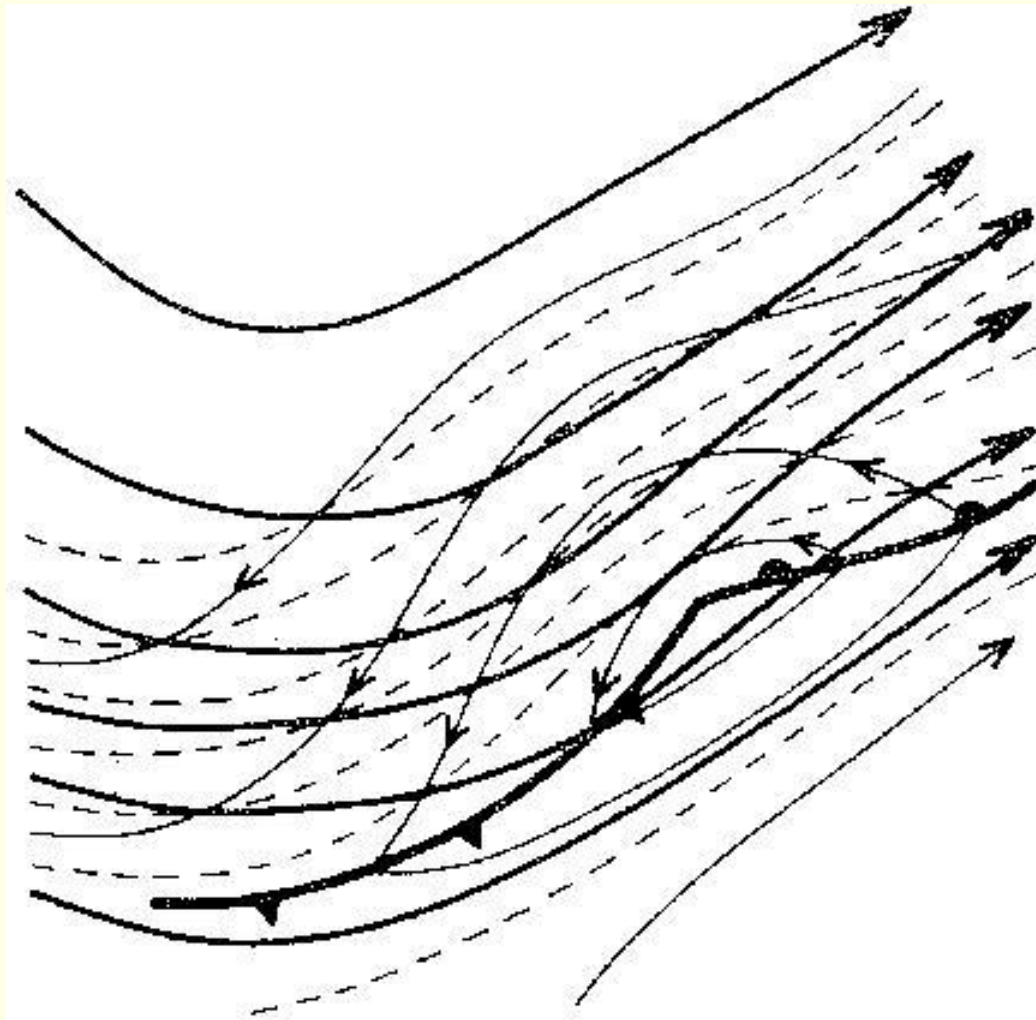
Model of Palmen and Newton

Idealized depictions for a baroclinic wave and its attendant tropical extratropical cyclone.

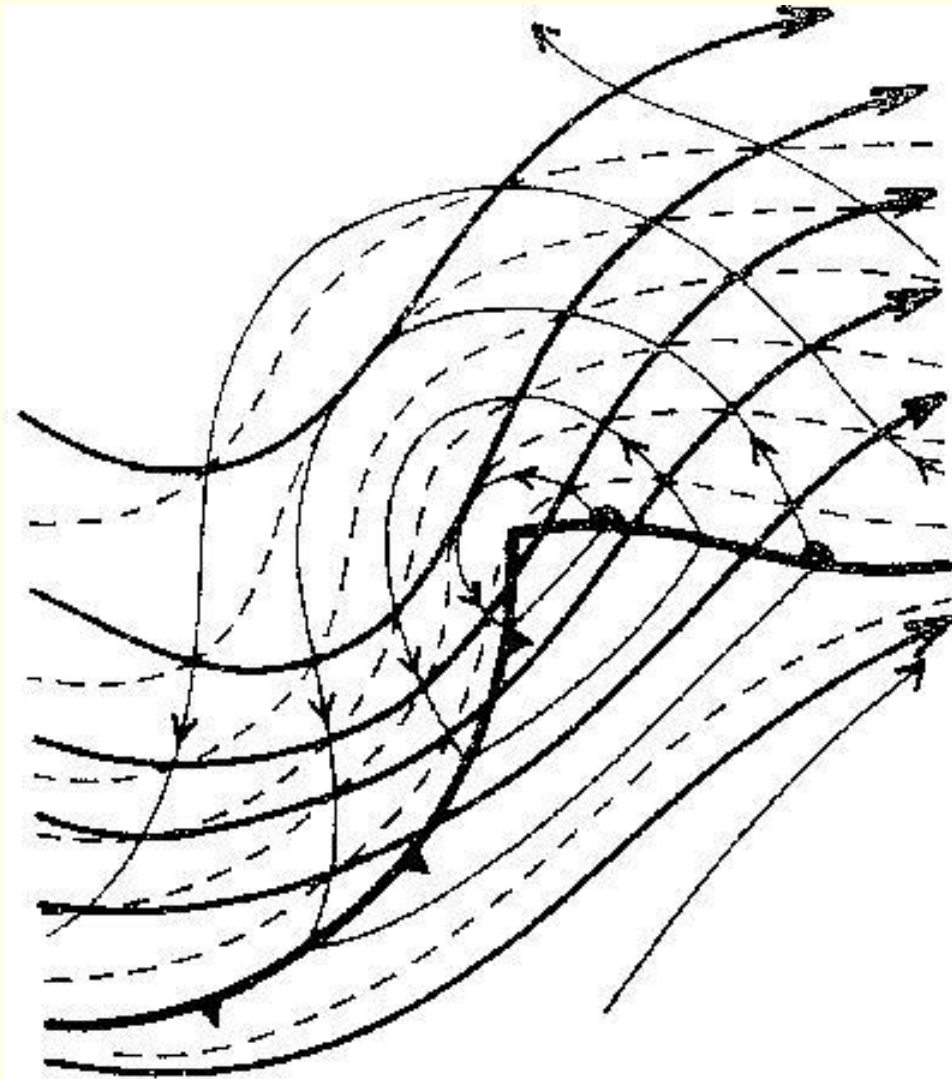


From E. Palmen and C.W. Newton, 1969:

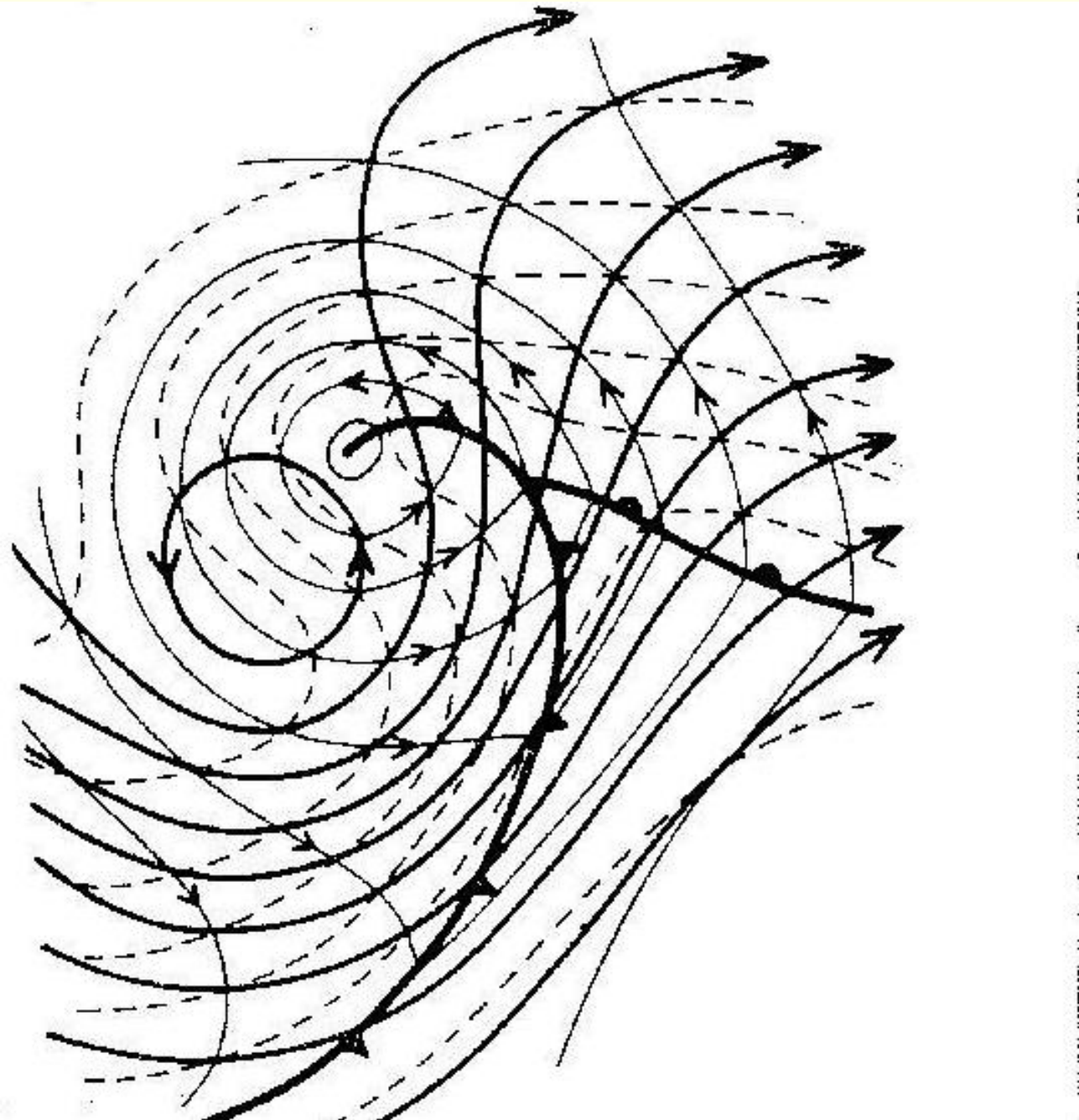
Atmospheric Circulation Systems, Academic Press, New York, p. 326.



Early stage of
development of
extratropical
storm.



**Middle stage of
development of
extratropical
storm.**



**Late stage of
development of
extratropical
storm.**

Atmosphere *versus* Model

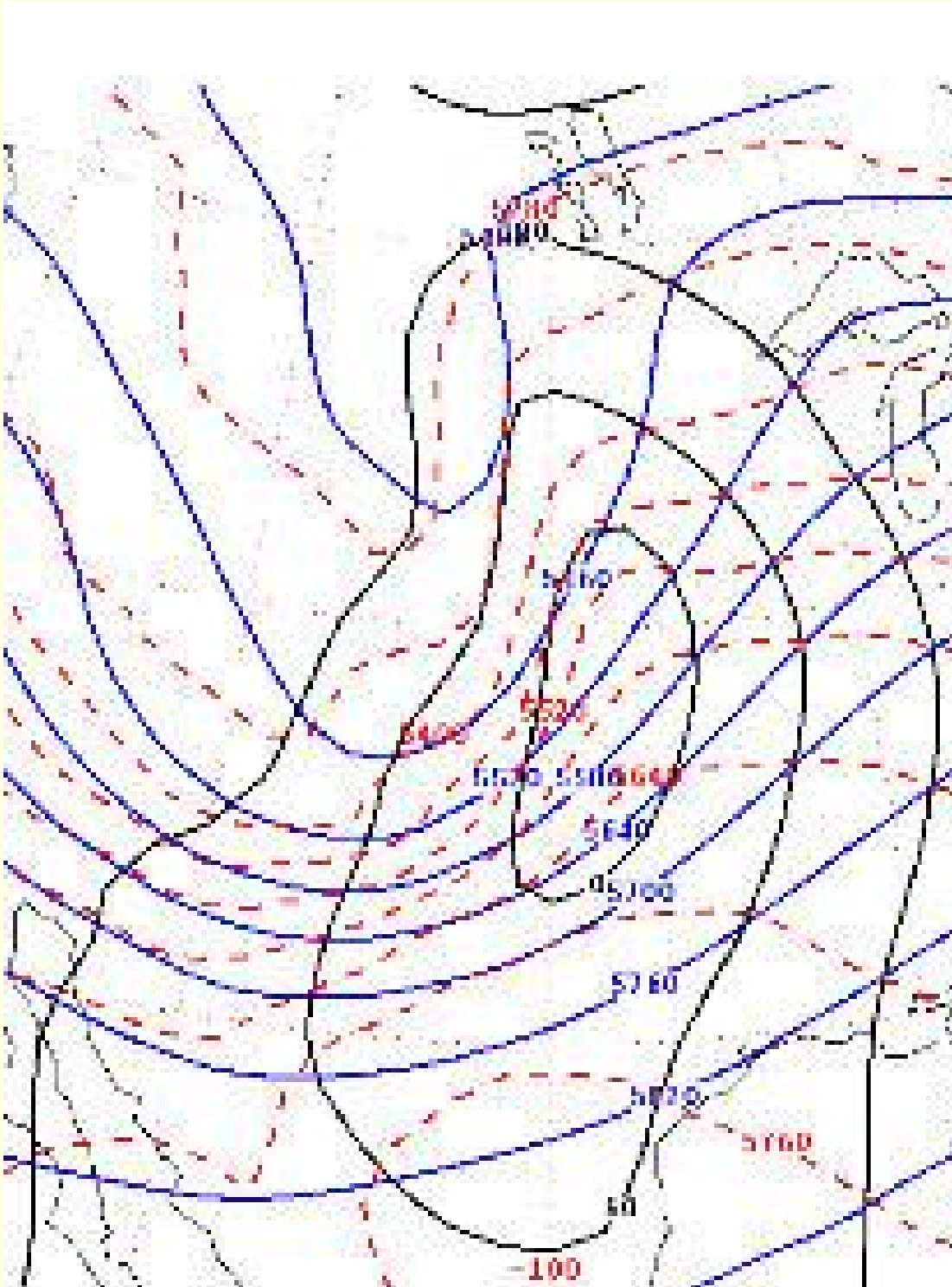
We will plot the fields of

- 500-hPa height (blue)
- Sea-level pressure (black)
- 1000–500-hPa thickness (dashed red)

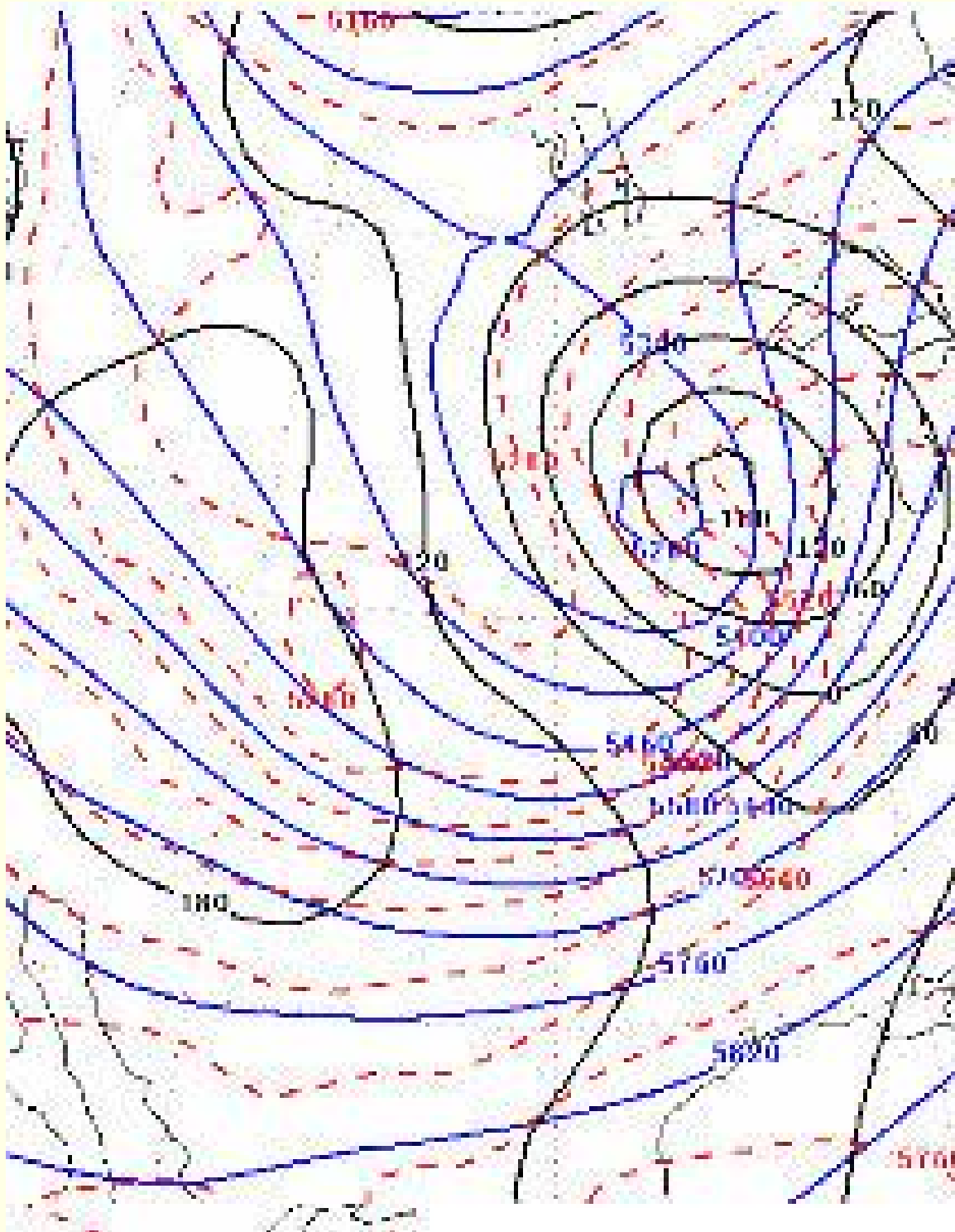
in the early, middle and late stages of development of the baroclinic wave.

We will examine the position of the center of the surface low relative to the corresponding feature on the 500-hPa chart.

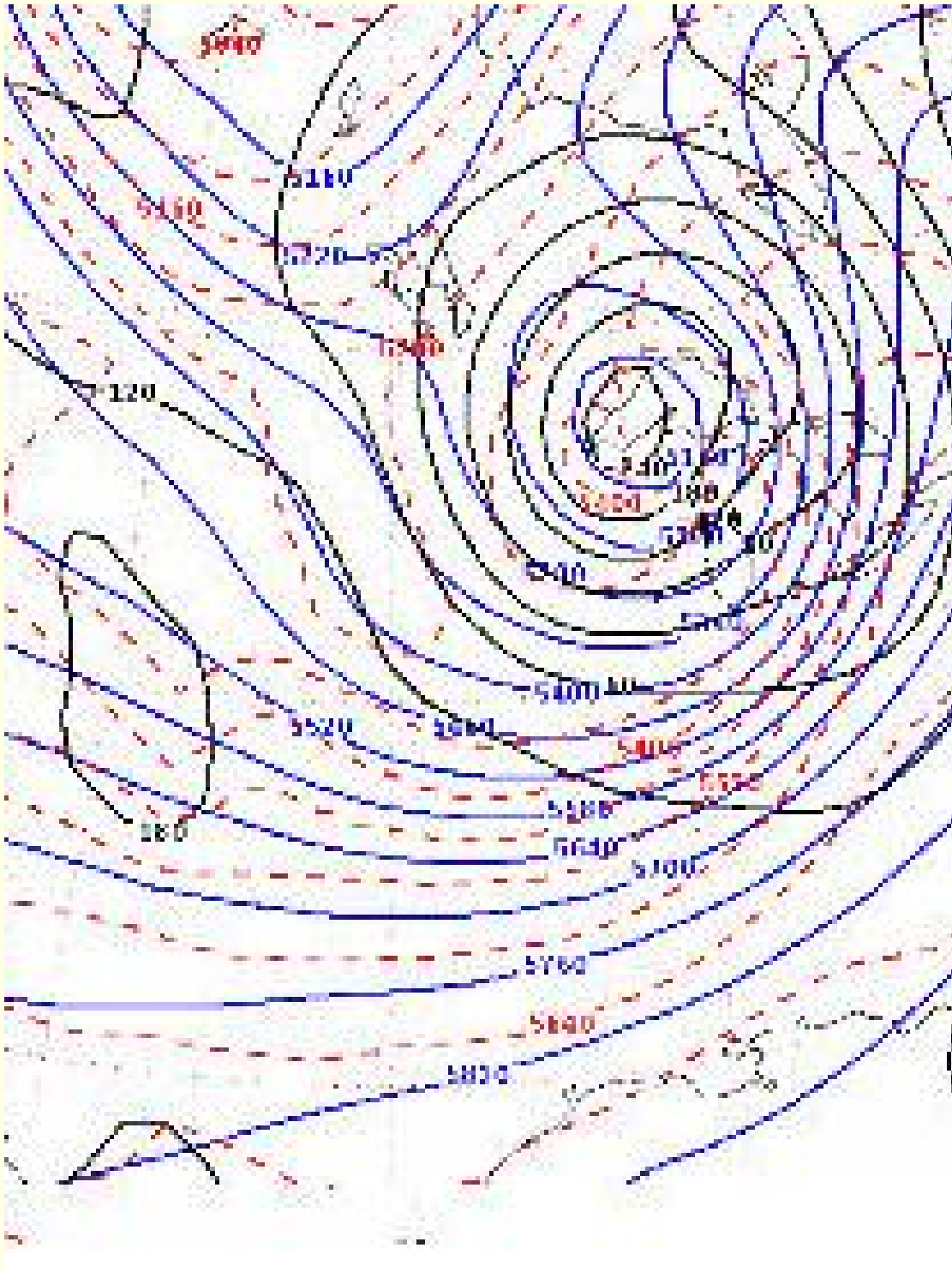
We will **compare the results** to the **mechanistic model** of Palmen and Newton.



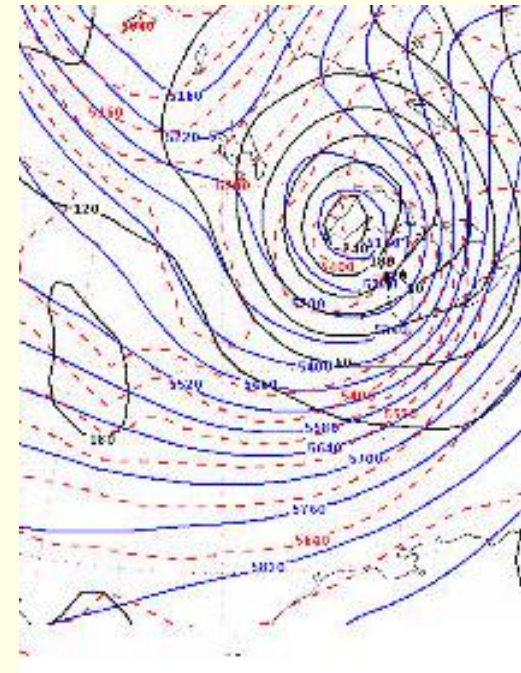
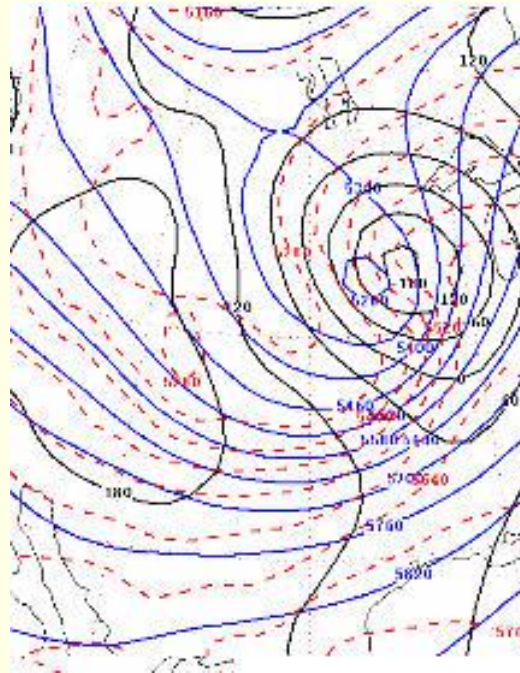
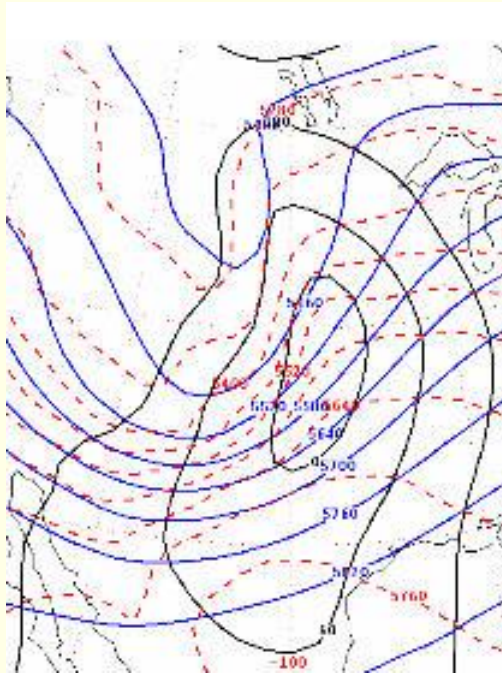
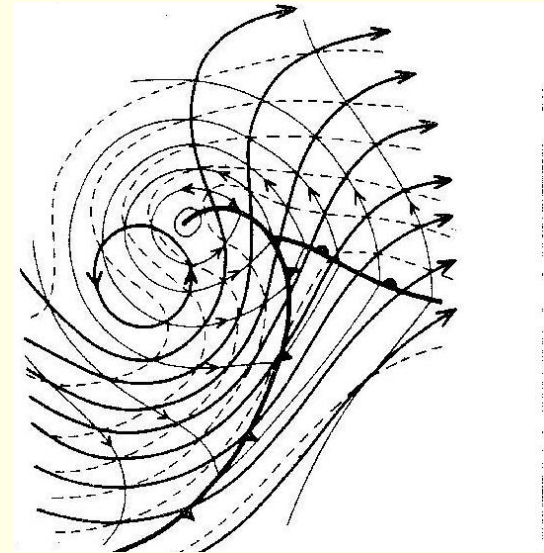
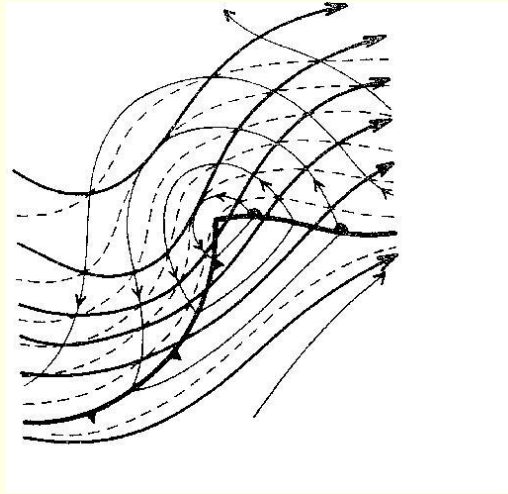
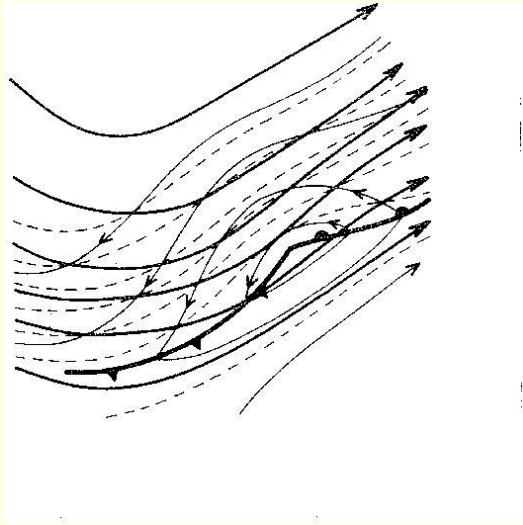
At 12 UTC
November 9 the
center of the
extratropical cyclone
(as defined by the
sea-level pressure
field) is located well
downstream of the
500-hPa trough and
just about directly
underneath the
position of the jet
stream.



By 12 UTC
November 10th, the
upper trough is
gaining on the
surface feature.



By 00 UTC Nov. 11, 1998, the surface low lies almost directly beneath the cutoff low in the 500-hPa height field, and on the poleward (cyclonic) side of the jet stream.



Top: idealized baroclinic wave and its attendant tropical extratropical cyclone. Bottom: observed conditions in case study.

The comparison relates the **case study** to the evolving structure of a **typical baroclinic wave** as depicted in a synoptic meteorology textbook written over a generation ago, before numerical models were widely used by weather analysts and forecasters.

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The amplification of the wave in the thickness field is due to **horizontal temperature advection** by the cyclonic circulation around the deepening surface low; i.e., the southerly wind component to the east of the low advects the thickness contours northward while the northerly component to the west of the low advects them southward.

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The strengthening of the the east-west temperature contrasts in the lower tropospheric temperature field is **at the expense of the equator-to-pole temperature gradient**.

As the surface low intensifies during the **early stages** of development, the **winds around it strengthen**, the angle between the geopotential height contours and the thickness contours increases, and the **horizontal temperature advection increases dramatically**.

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However, in the **final stages** of development in which the surface low comes into alignment with the 500-hPa trough, the sea-level pressure 500-hPa height and 1000–500-hPa thickness contours tend to come into alignment, and the **horizontal temperature advection weakens**.

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The **geostrophic wind** field evolves from a **highly baroclinic pattern**, with strong turning of the wind with height in amplifying baroclinic waves, to a more **equivalent barotropic pattern**, with much less directional shear of the lower tropospheric geostrophic wind field in fully developed baroclinic waves.

Zoom on 00–18 Z, 10th Nov., 1998

We have studied the evolution of the storm over the 36-hour period from 12 Z on 9th November to 00 Z on 11th November.

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To observe the development in finer detail, we will now zoom in on the **18-hour period** from 00 Z to 18 Z on 10th November, 1998.

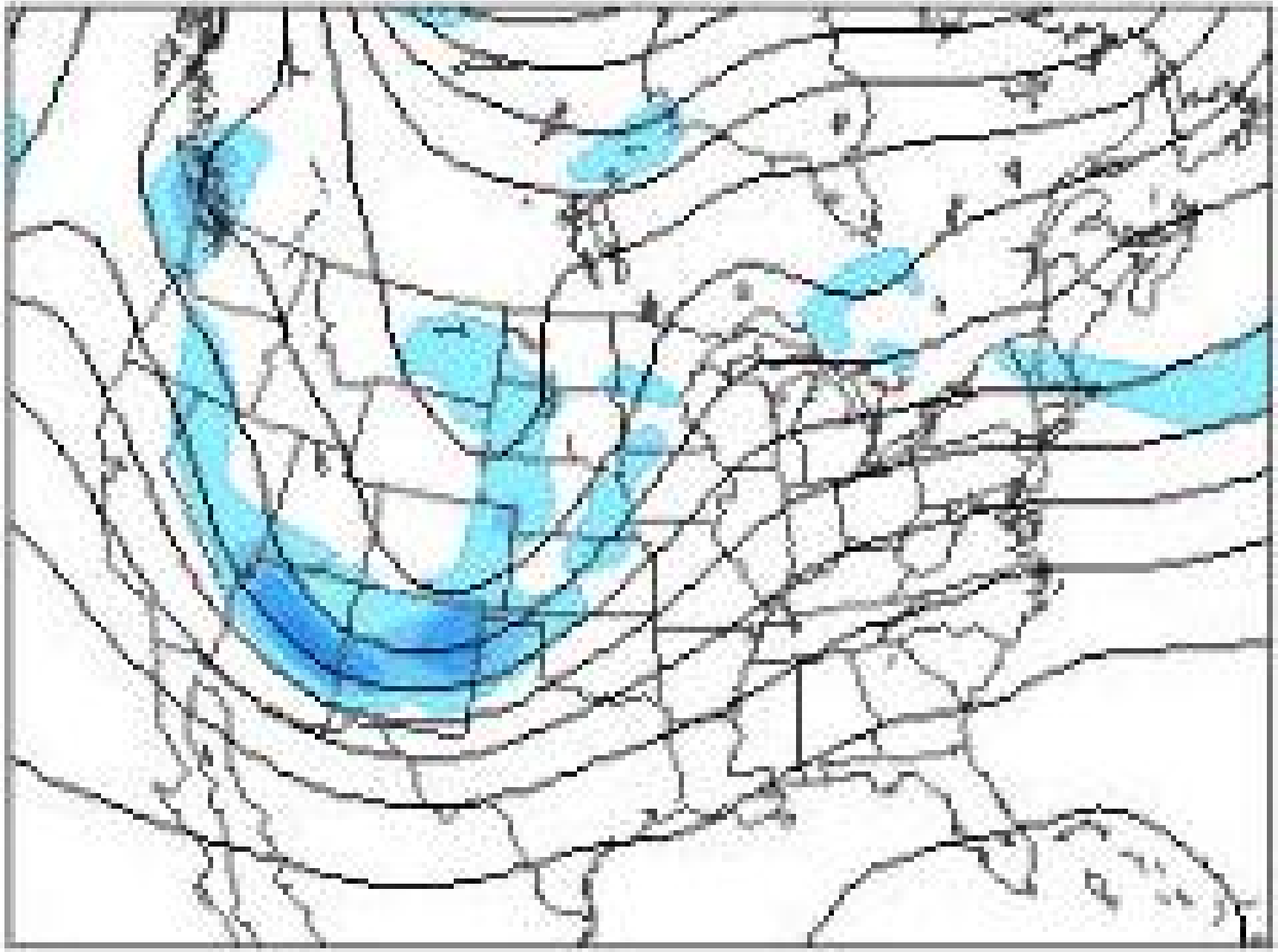
Zoom on 00–18 Z, 10th Nov., 1998

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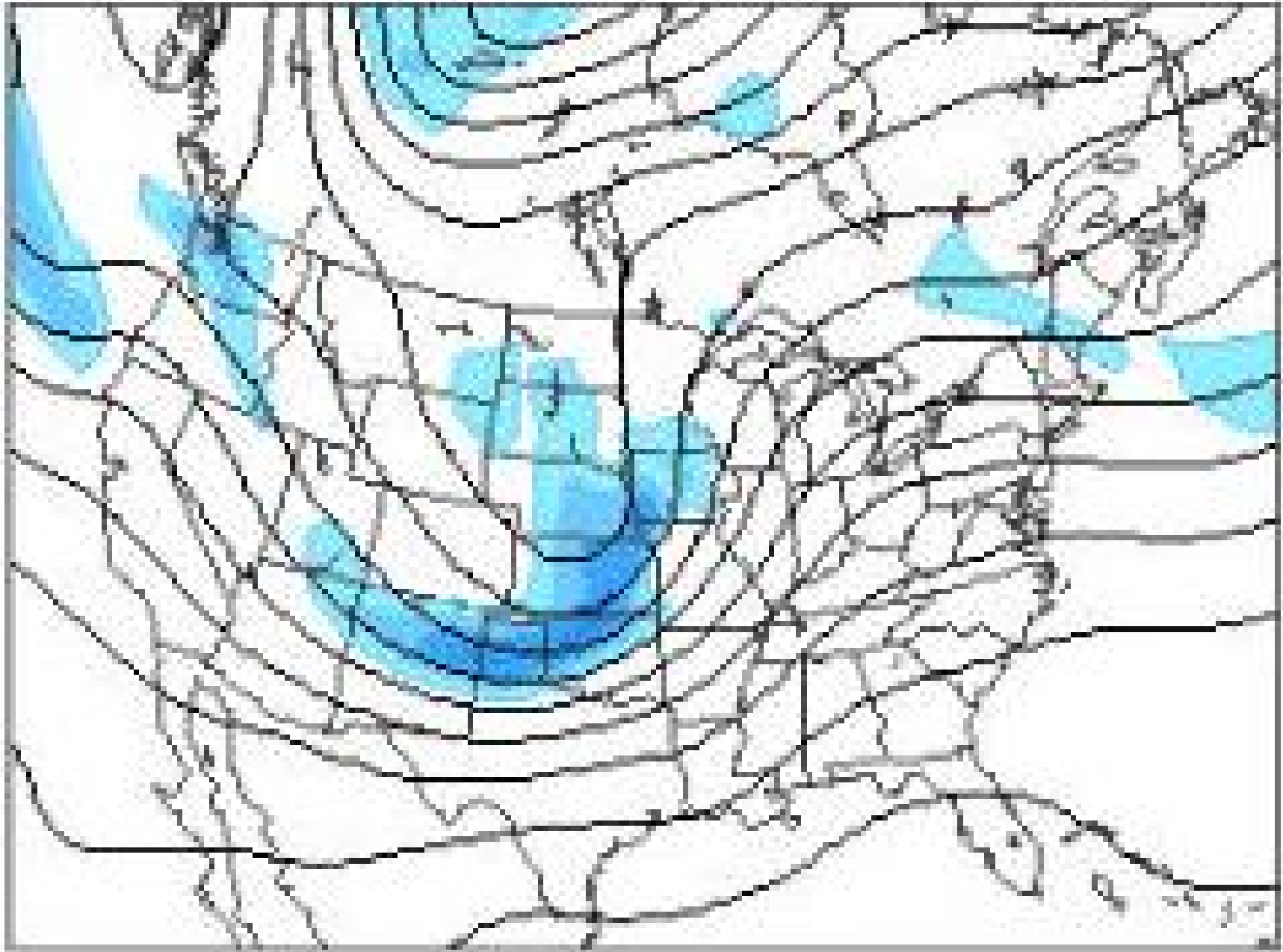
To observe the development in finer detail, we will now zoom in on the **18-hour period** from 00 Z to 18 Z on 10th November, 1998.

Repeated study of the charts is valuable in consolidating our understanding of the development of the system.

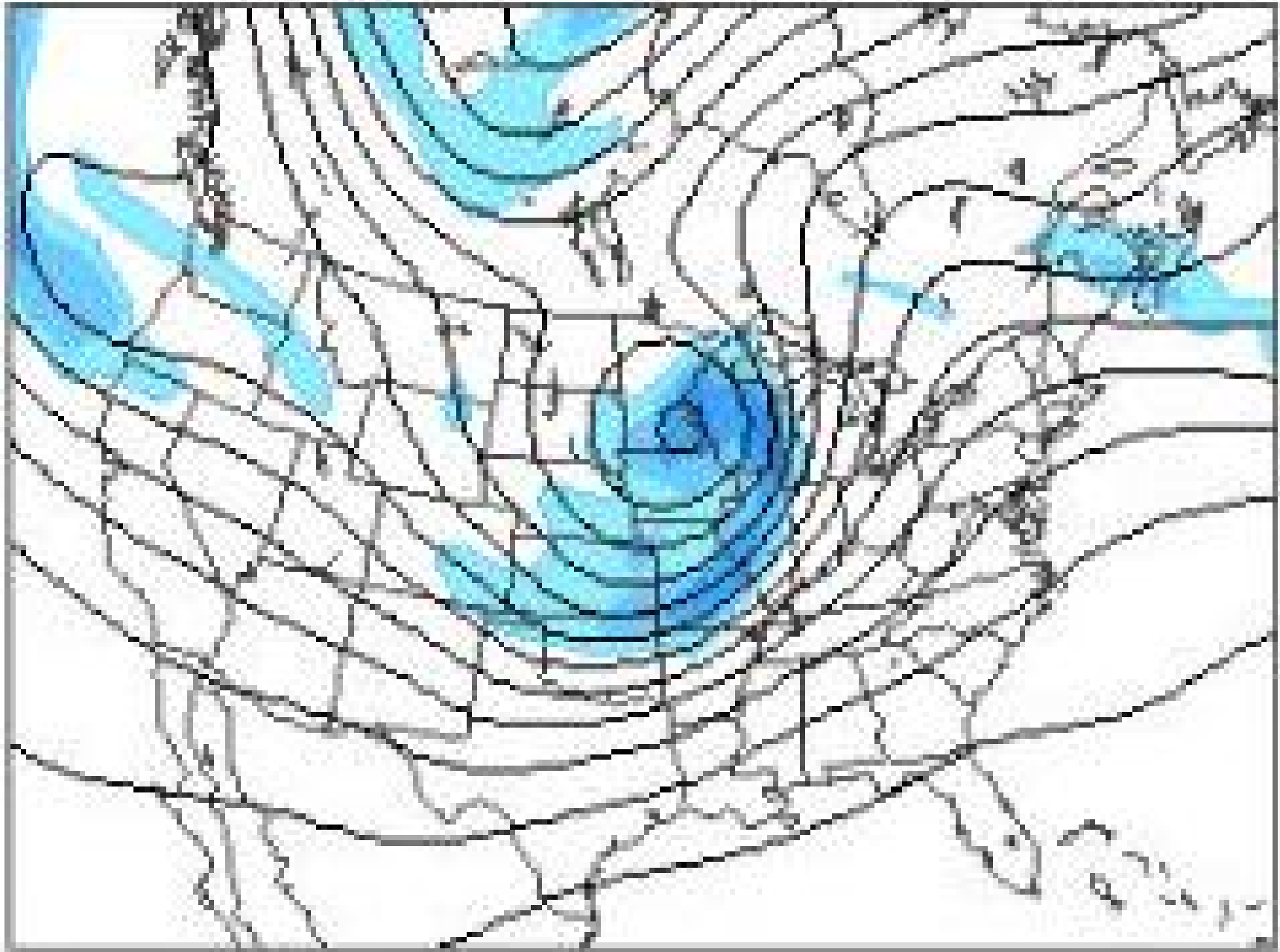
A synoptic meteorologist / forecaster may spend considerable time examining charts of this sort in an effort to predict the weather.



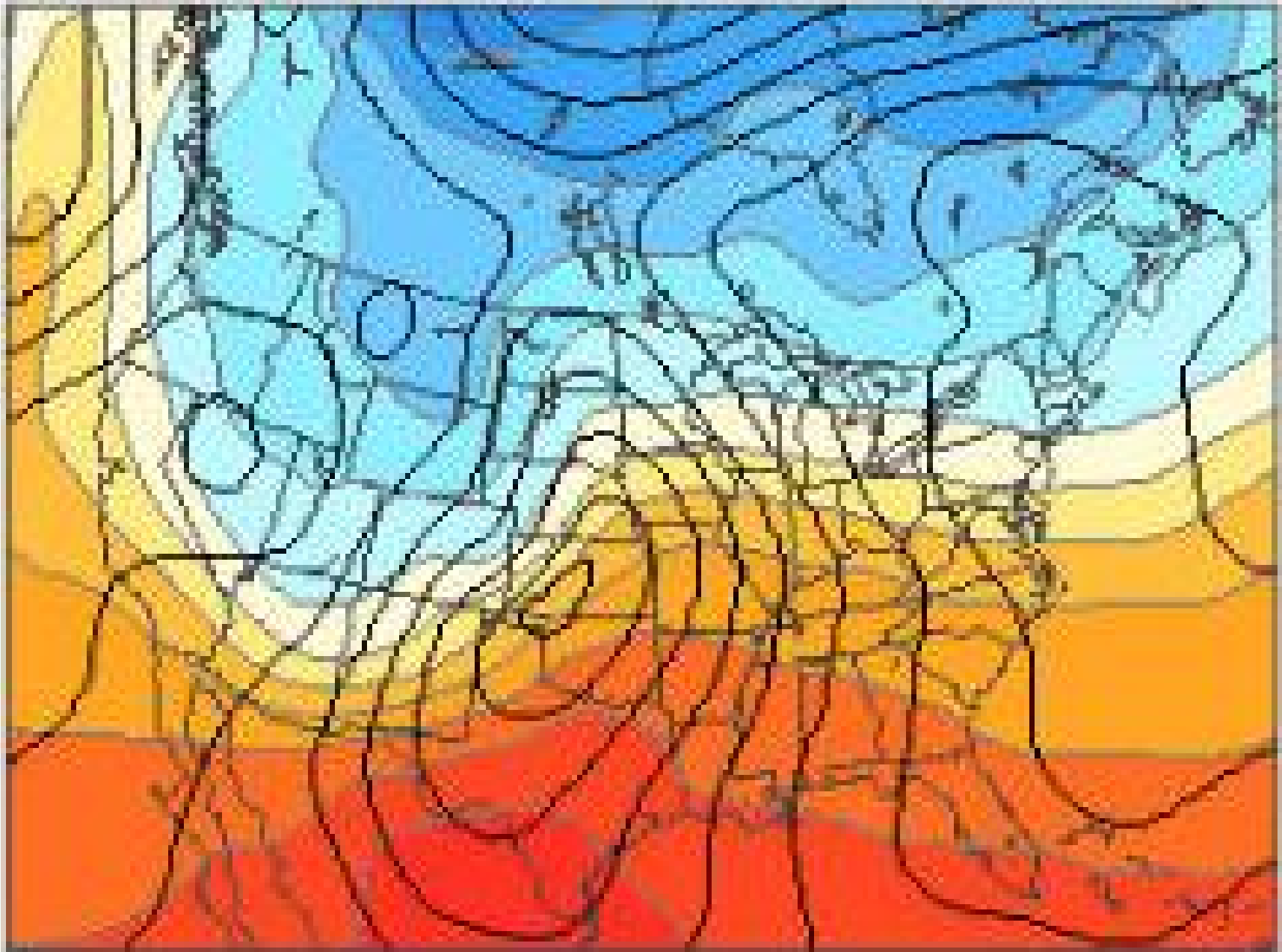
500 hPa geopotential and vorticity
00 UTC November 10th, 1998



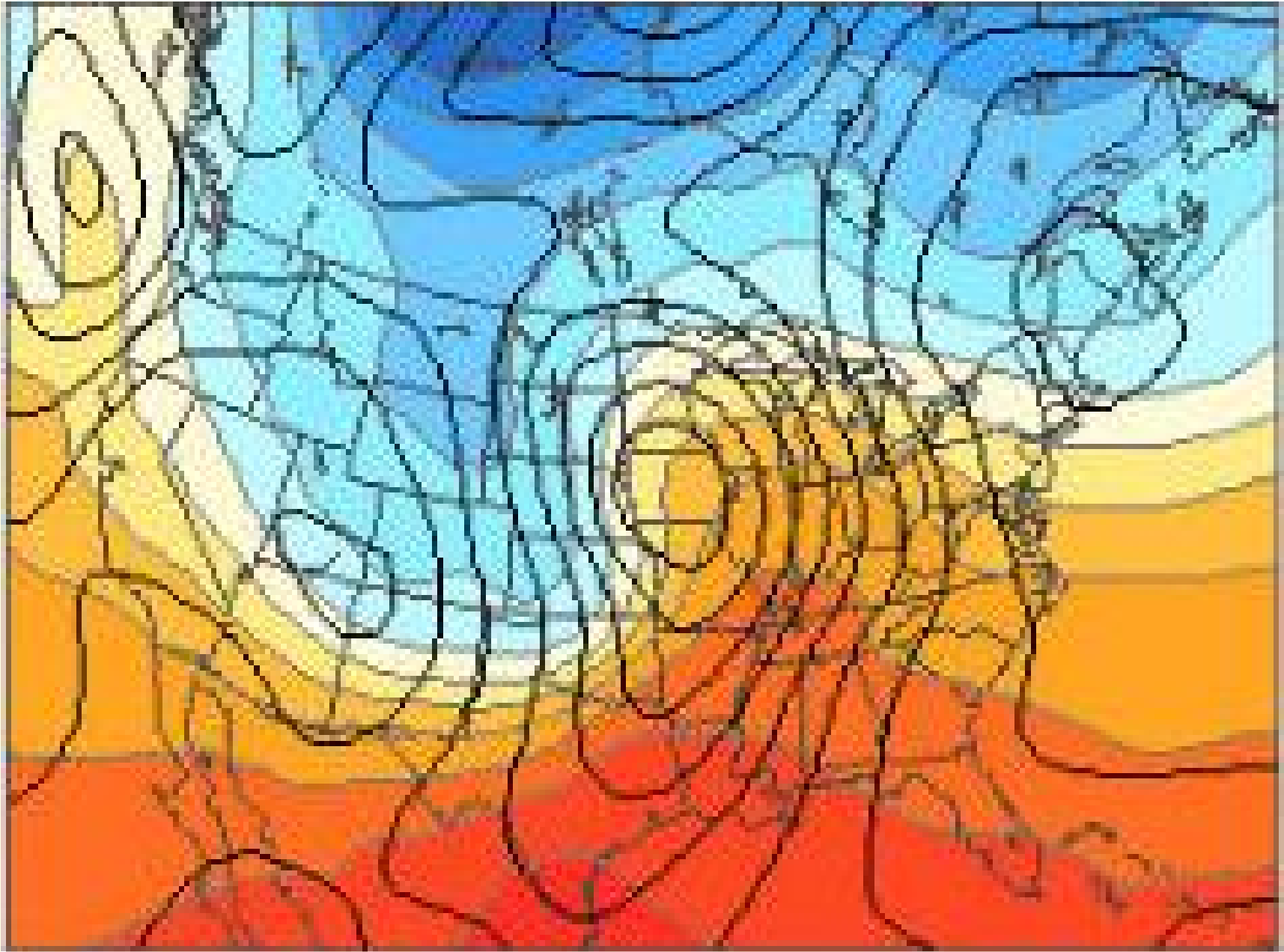
500 hPa geopotential and vorticity
09 UTC November 10th, 1998



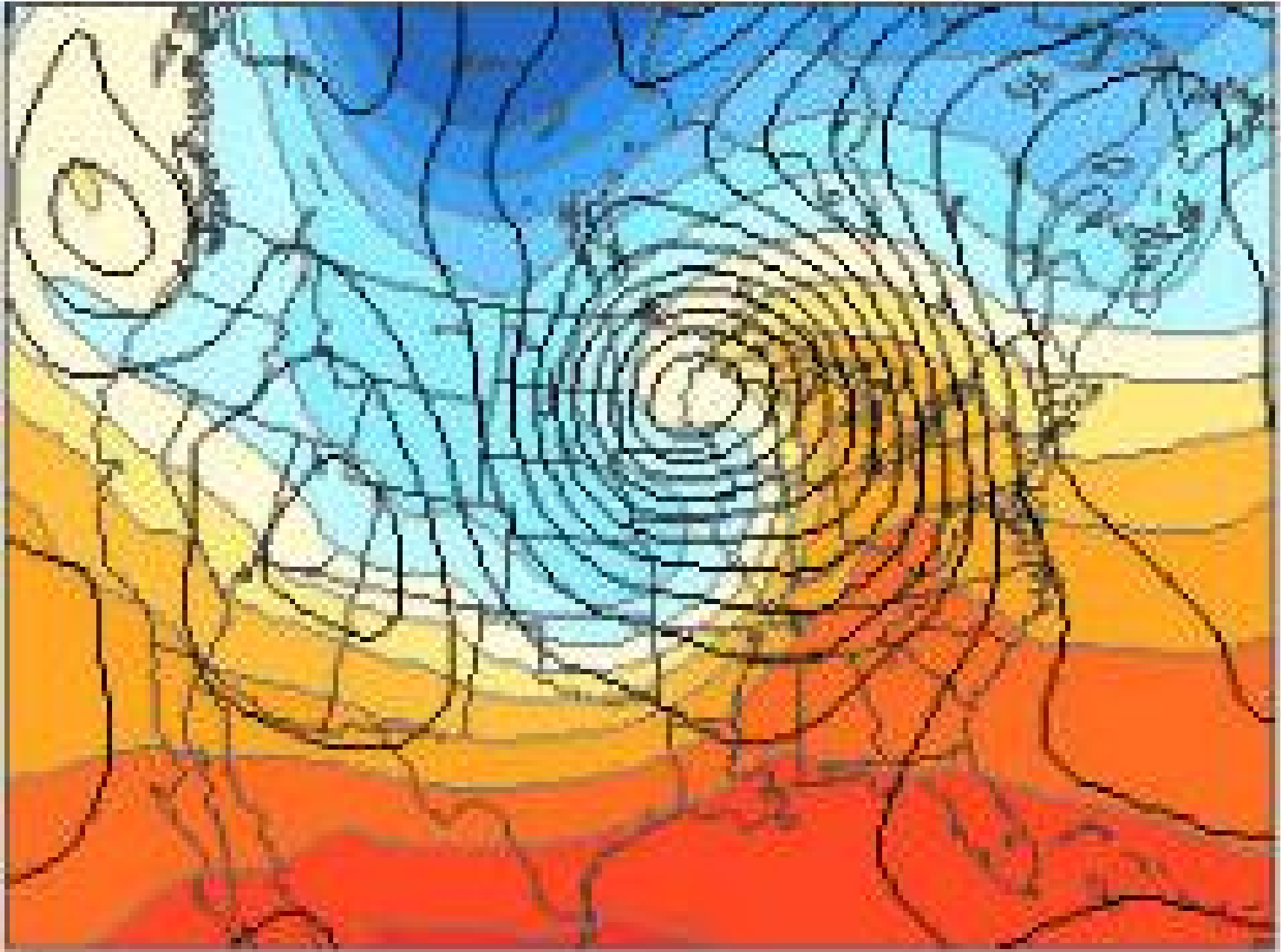
500 hPa geopotential and vorticity
18 UTC November 10th, 1998



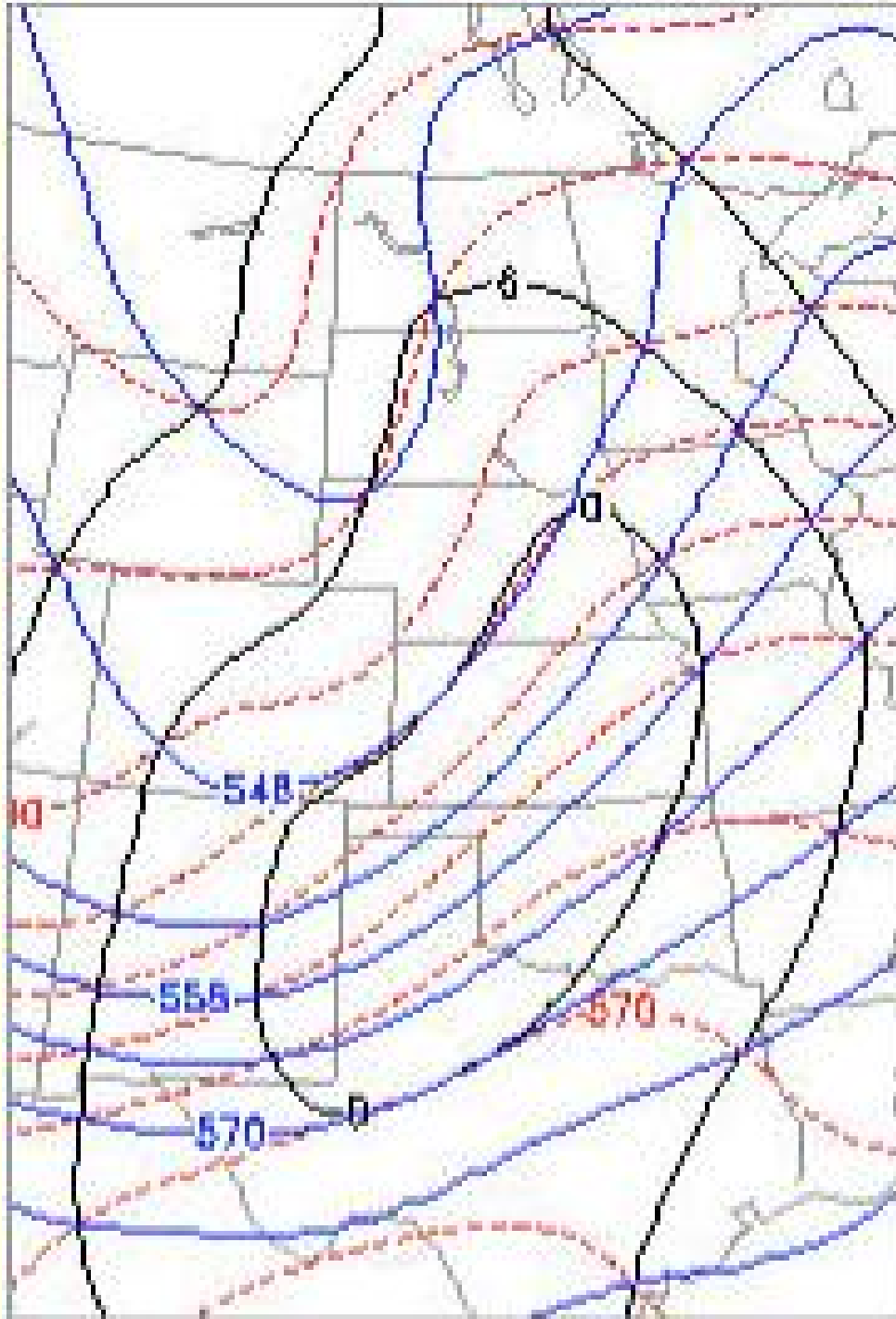
Sea level pressure and 1000-500 hPA thickness
00 UTC November 10th, 1998



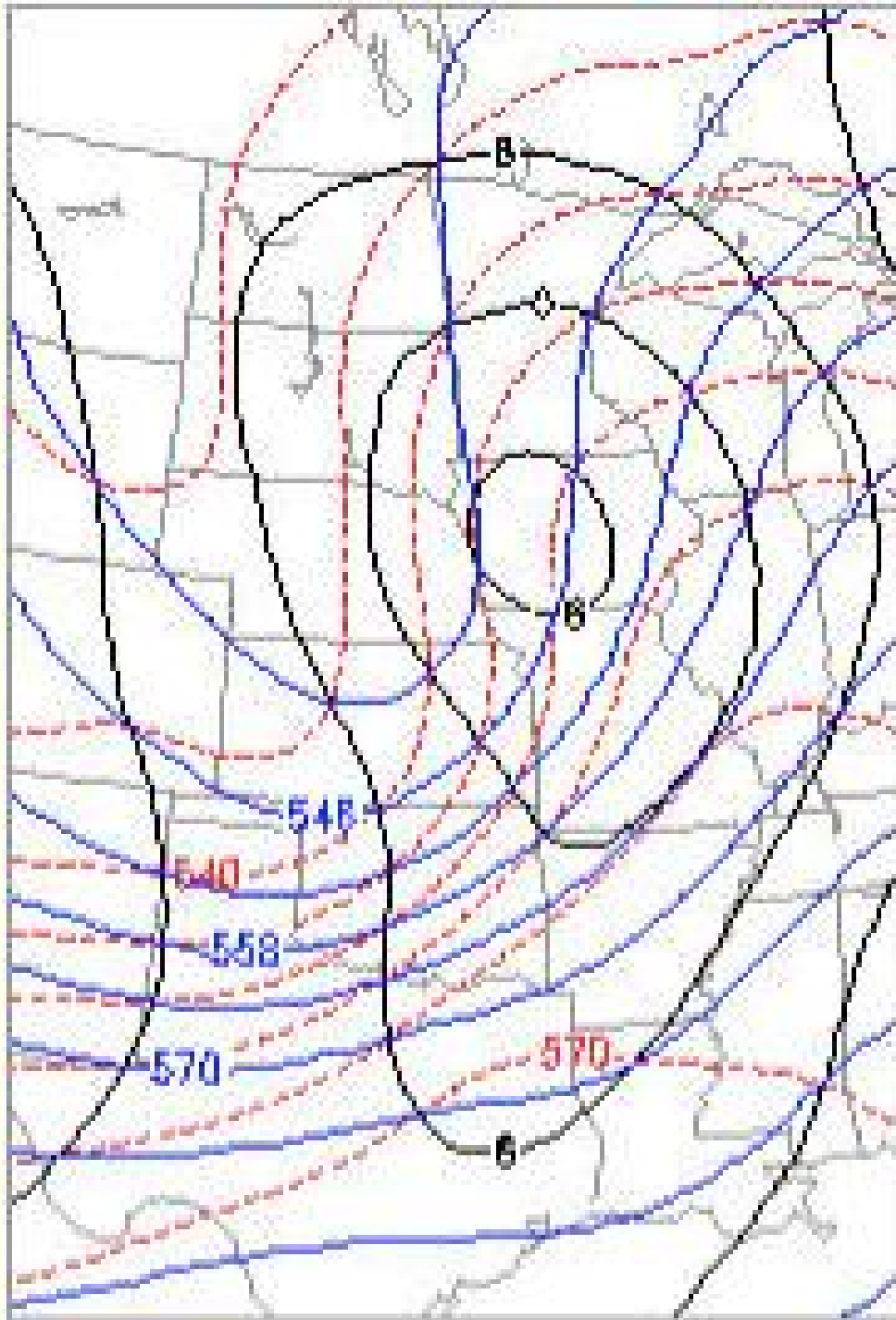
Sea level pressure and 1000-500 hPA thickness
09 UTC November 10th, 1998



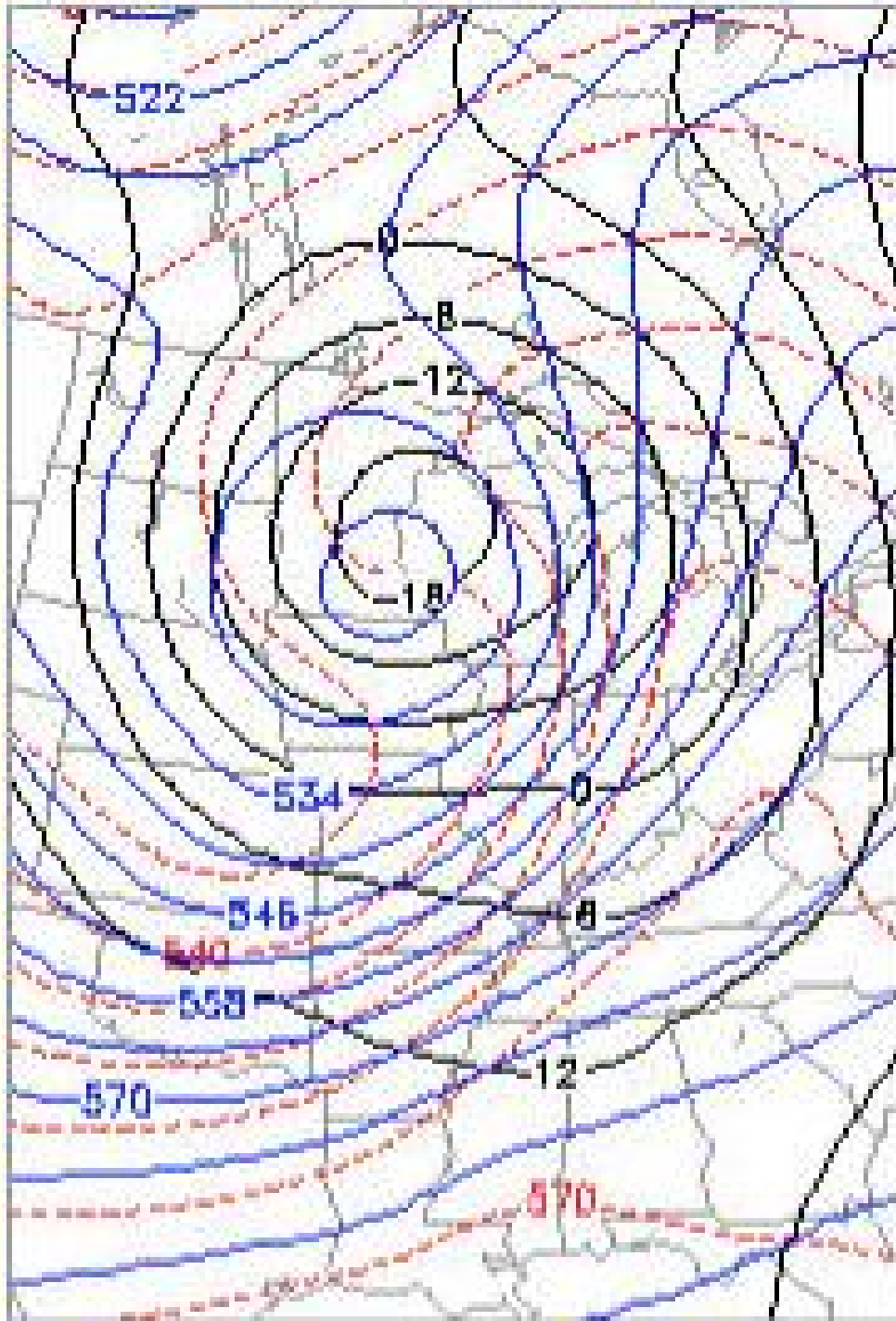
Sea level pressure and 1000-500 hPA thickness
18 UTC November 10th, 1998



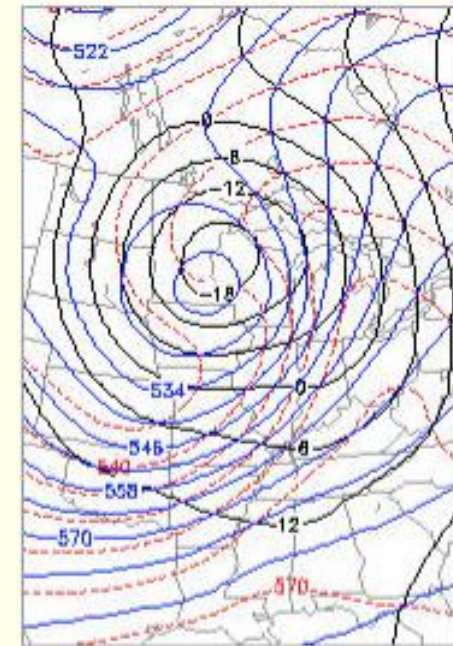
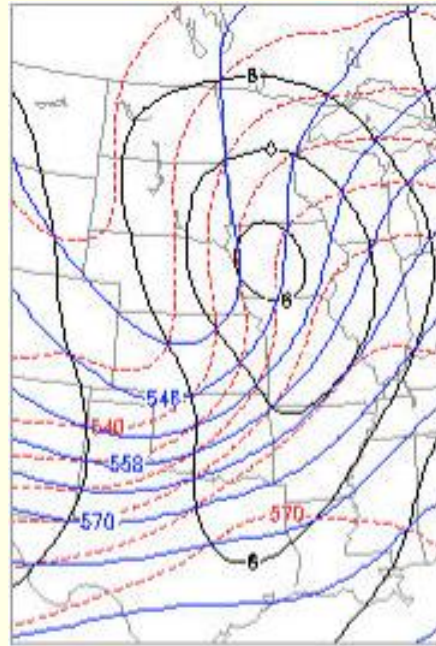
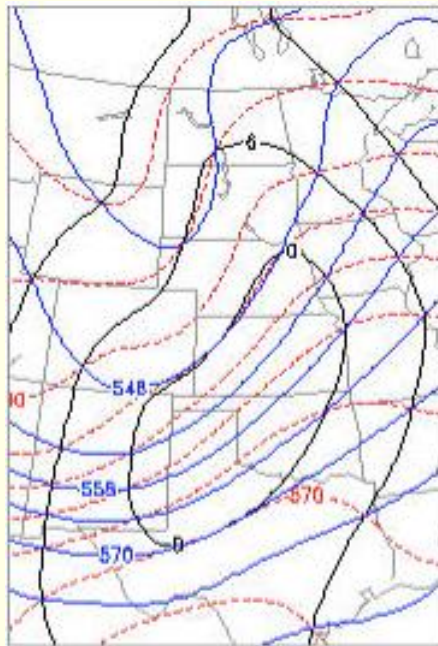
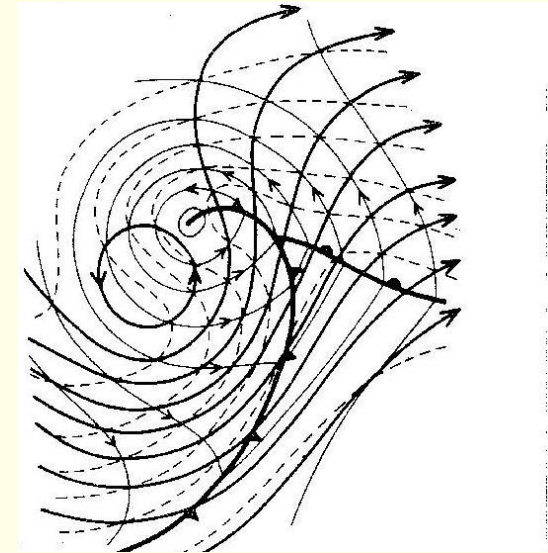
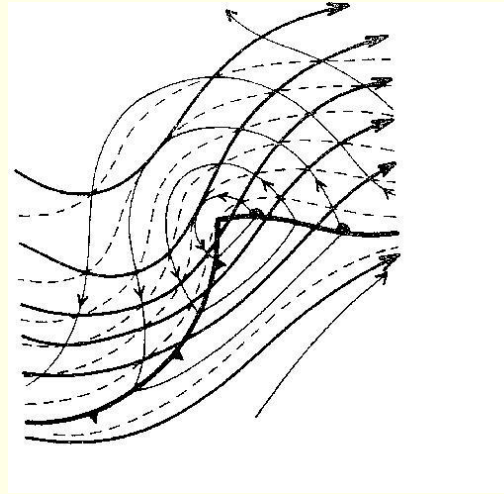
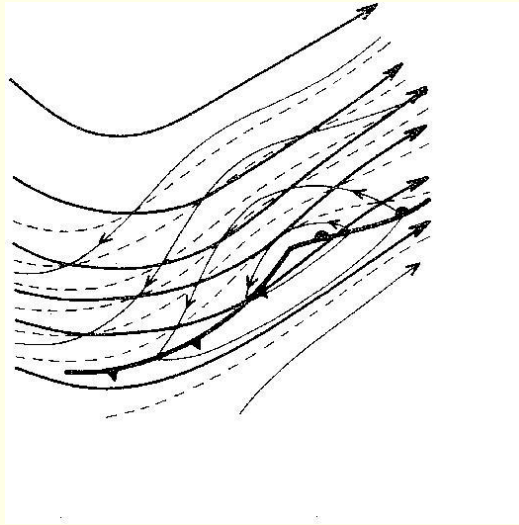
At 00 UTC
November 10 the
center of the
extratropical cyclone
is located
downstream of the
500-hPa trough.



By 09 UTC
November 10 the
500-hPa trough is
gaining ground on
the surface feature.



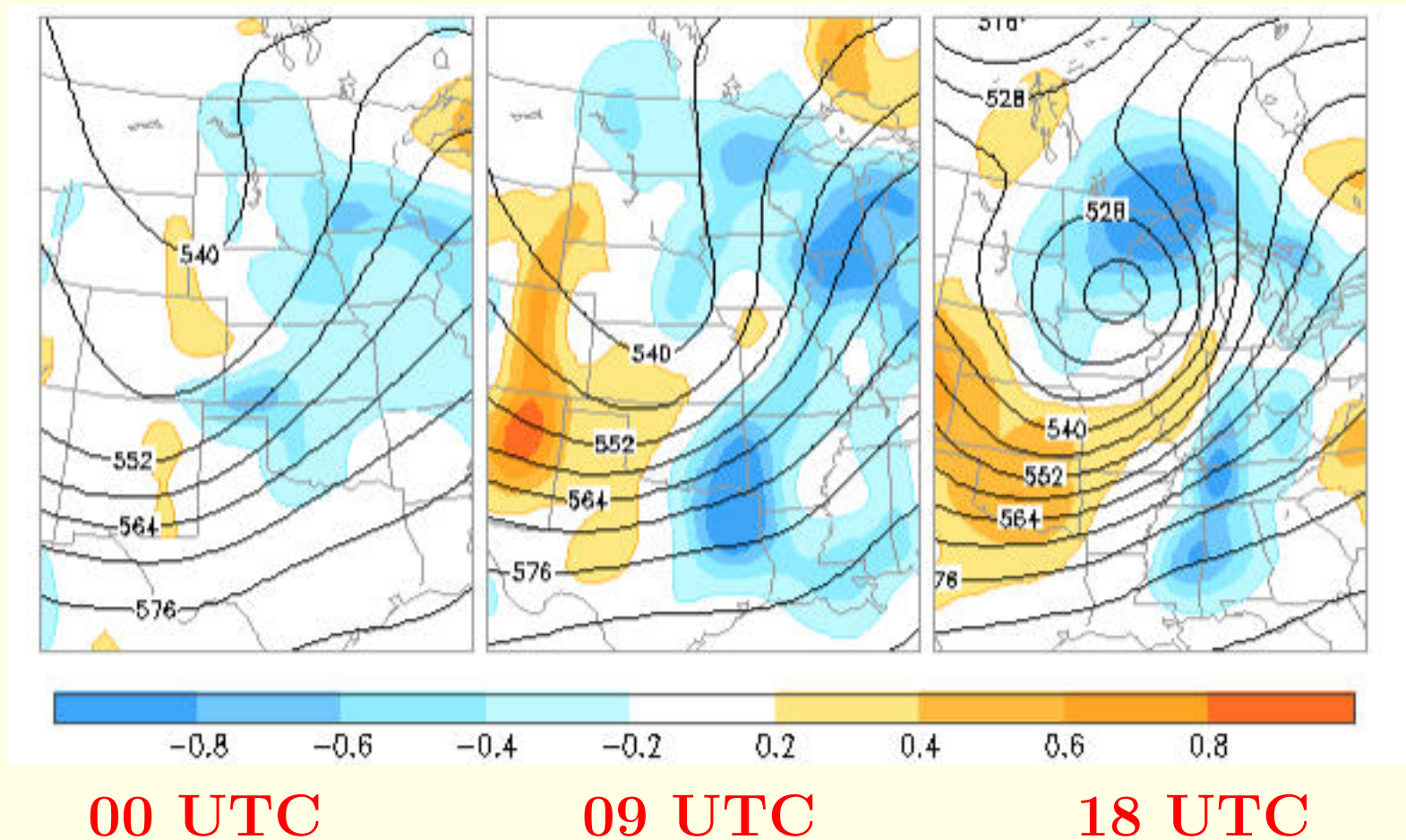
By 18 UTC
November 10 the
centers of circulation
at the surface and
500 hPa are almost
in a vertical line.



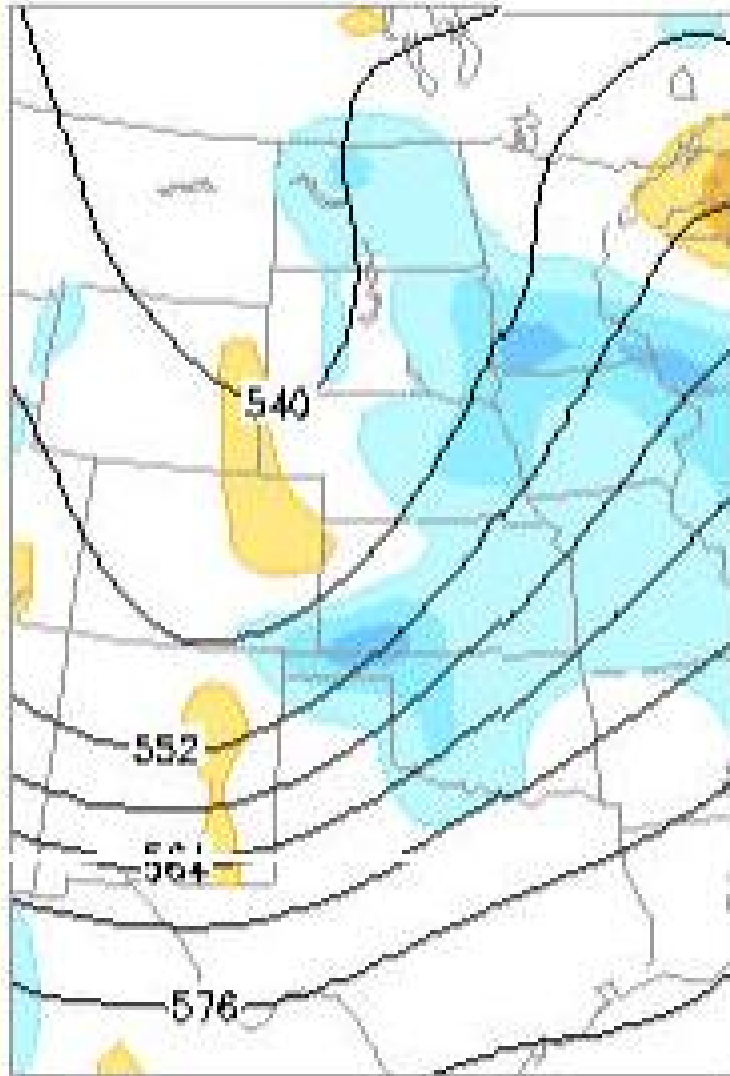
Top: idealized baroclinic wave and its attendant tropical extratropical cyclone. Bottom: observed conditions in case study.

Vertical Velocity (10 Nov. 1998)

The **vertical velocity field** also plays an important role in the development of baroclinic waves.



Vertical velocity field in units of hPa per day, represented by shading.

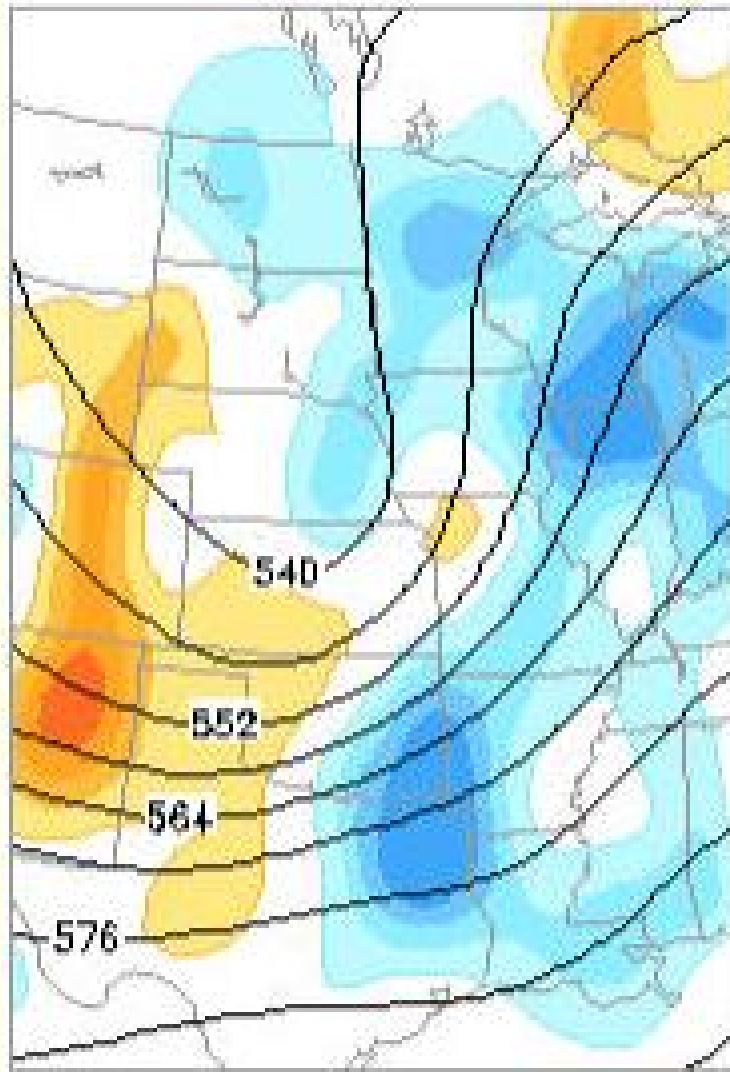


00 Z, 10 Nov. 1998

At the earlier stage of development, there is large-scale rising motion to the east of the upper-level trough.

(Blue is upward motion, reddish is downward motion).

There is weak downward motion in the vicinity of the 500 hPa trough, but it is not very pronounced.

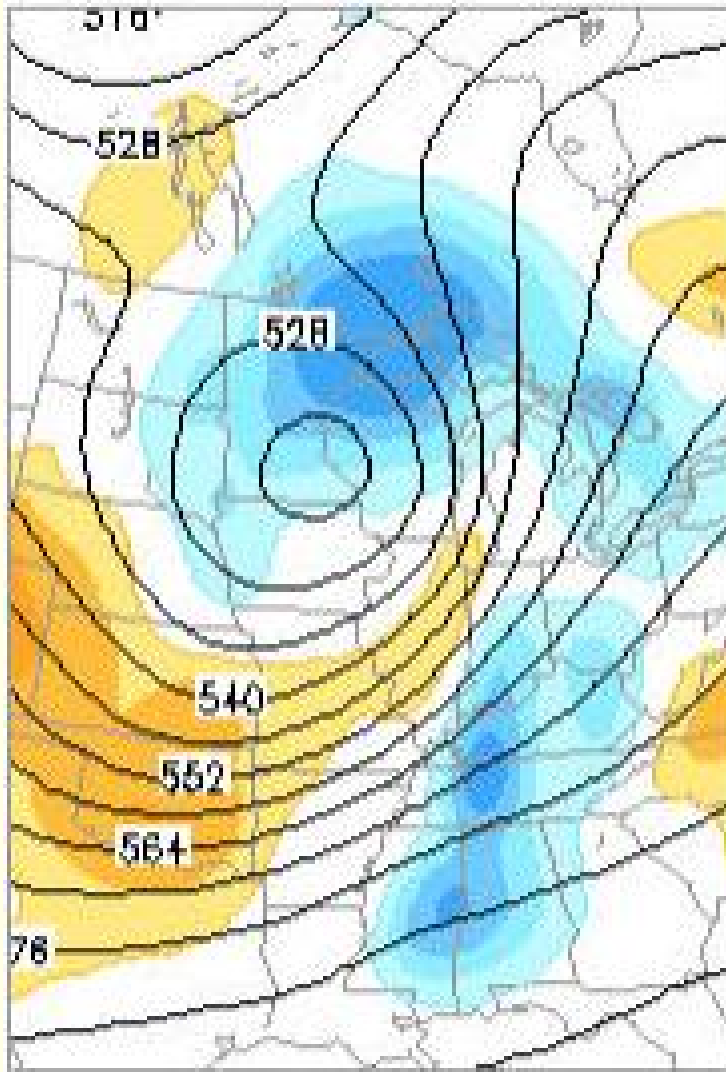


09 Z, 10 Nov. 1998

At the time when the most **rapid development** is occurring, the northward moving air in the region of **warm advection** in advance of the developing surface low is **rising**, while the southward moving air in the region of **cold advection** to rear of the cyclone is **sinking**.

The **rising air** to the east of the surface low **is warmer** than the sinking air to the west of it.

Recall that the rising of warm air and sinking of cold air means **conversion of potential energy into kinetic energy**.



18 Z, 10 Nov. 1998

At the **later stage**, the major features in the vertical velocity field relate not so much to the baroclinic wave, which is no longer amplifying, as to the extratropical cyclone.

Warmer air to the east of the cyclone is still rising, but the region of ascent wraps around the northern side of the surface low. In a similar manner, the region of subsidence to the west of the cyclone wraps around its southern flank.

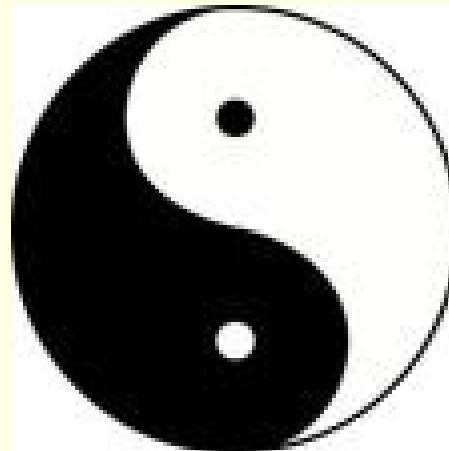
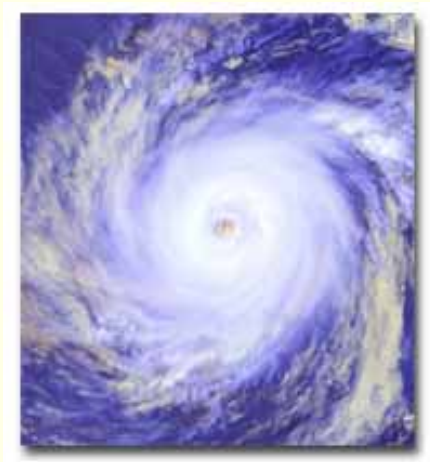
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The juxtaposition of these spiraling rising and sinking air currents, somewhat reminiscent of the yin-yang pattern is influential in shaping the cloud and precipitation patterns associated with extratropical cyclones.

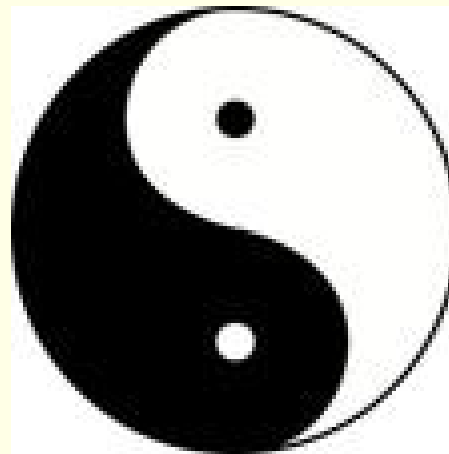
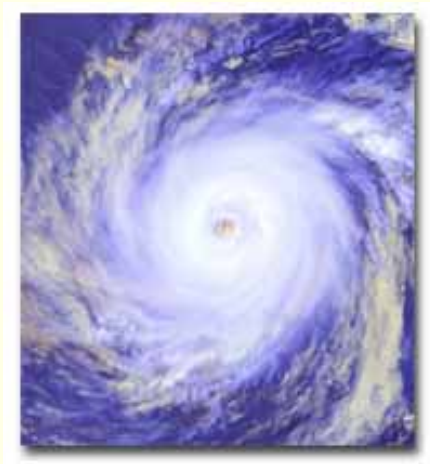
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The juxtaposition of these spiraling rising and sinking air currents, somewhat reminiscent of the **yin-yang pattern** is influential in shaping the **cloud and precipitation patterns** associated with extratropical cyclones.



The dominance of ascent in the vicinity of the cyclone itself is a consequence of **frictionally induced low level convergence**.