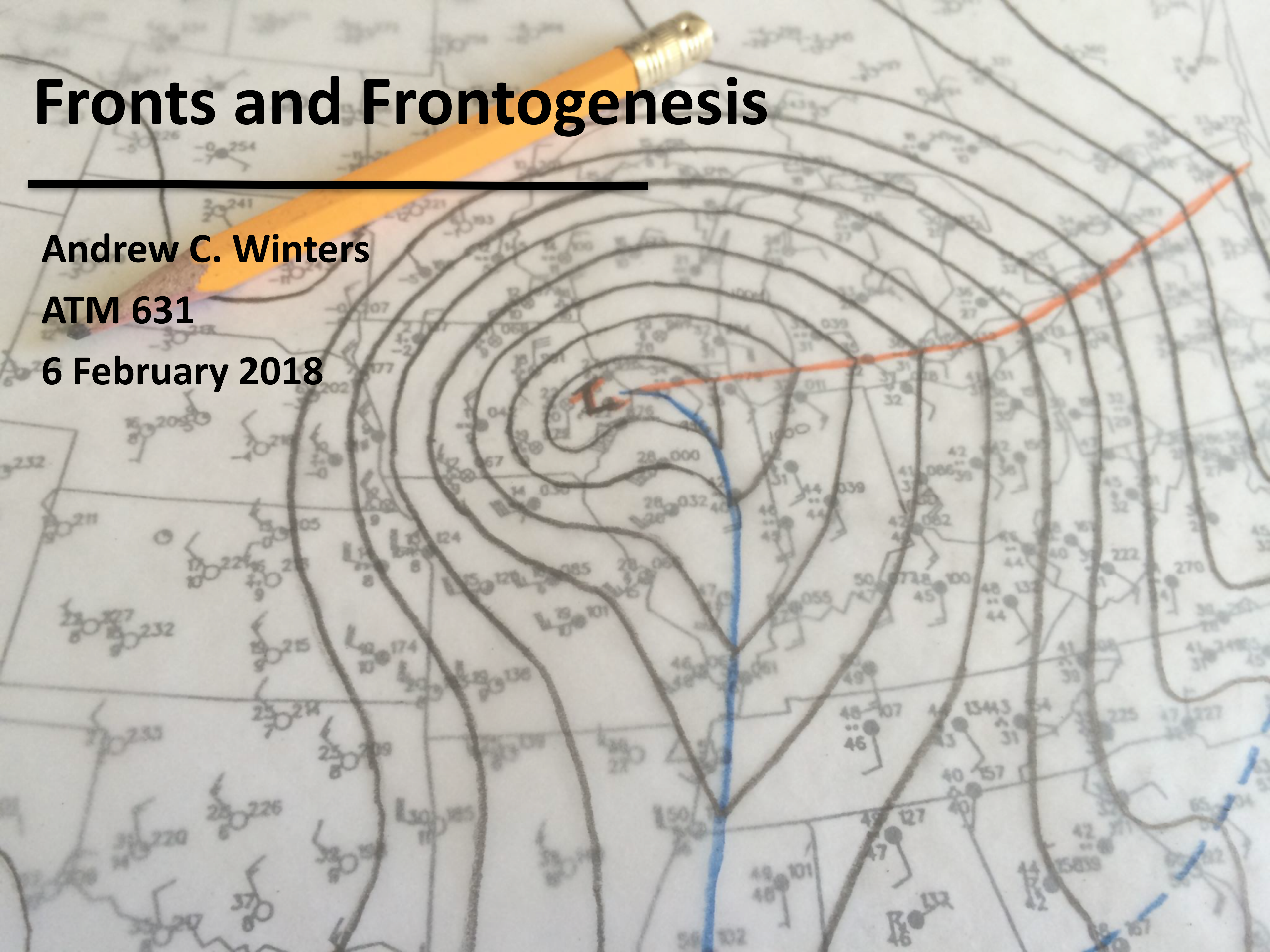

Fronts and Frontogenesis

Andrew C. Winters

ATM 631

6 February 2018

Definitions

Front: "Atmospheric fronts may be defined as sloping zones of pronounced transition in the thermal and wind fields." (Keyser 1986)

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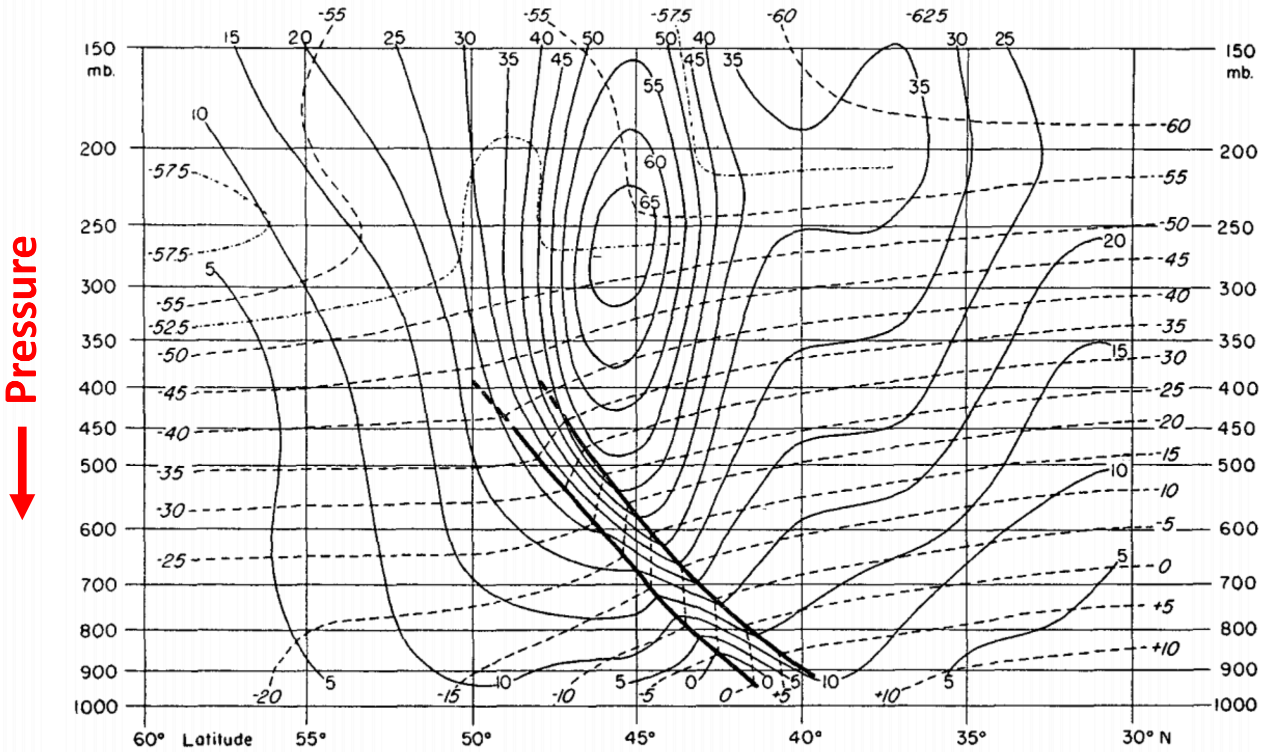

Fig. 1. Mean temperature and zonal component of geostrophic wind, computed from twelve cases in December 1946. The cross section lies along the meridian 80°W. Heavy lines indicate mean positions of frontal boundaries. Thin dashed lines are isotherms (degrees Centigrade, slanting numbers) and solid lines are isolines of westerly component of wind (meters per second, upright numbers). Means were computed with respect to the polar front in this and in the following figures.

Palmén and Newton (1948)

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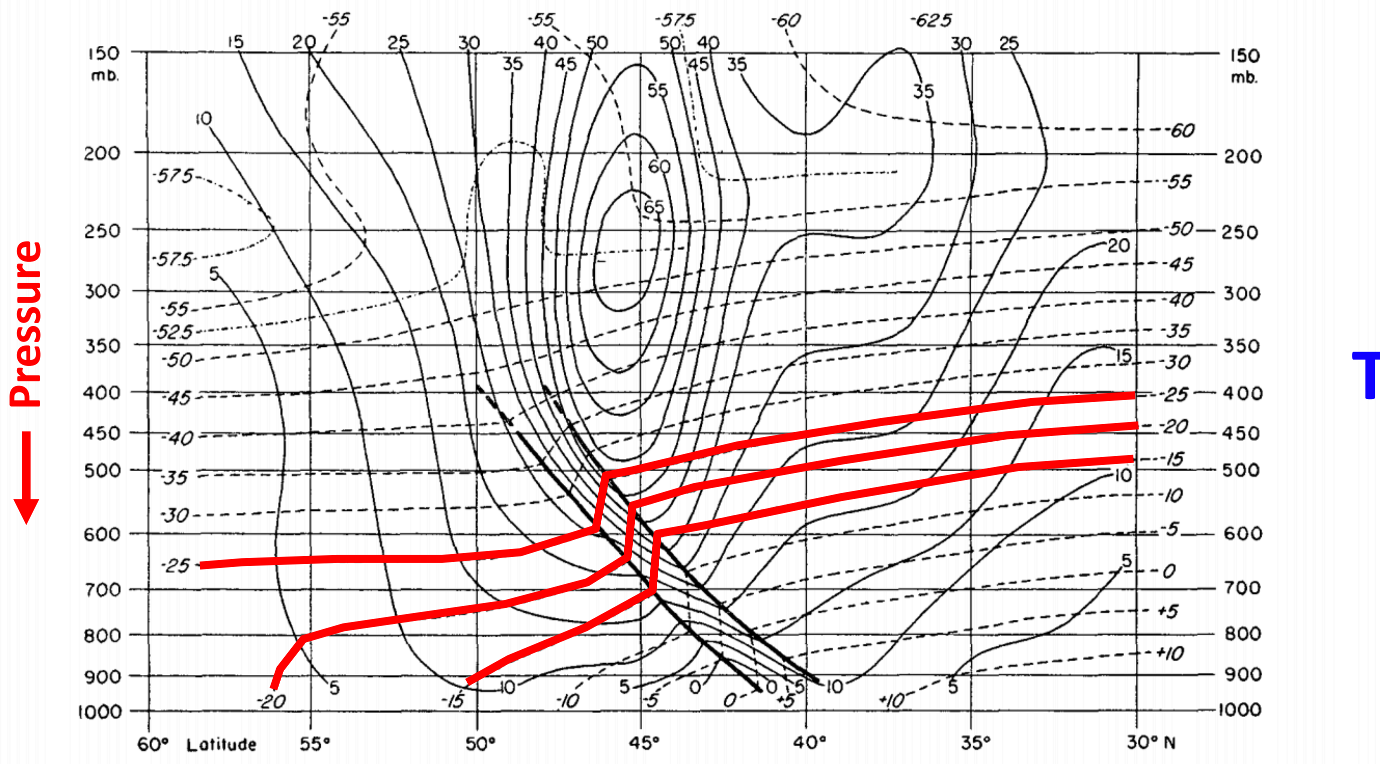

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Strong Horizontal Temperature Gradient

Palmén and Newton (1948)

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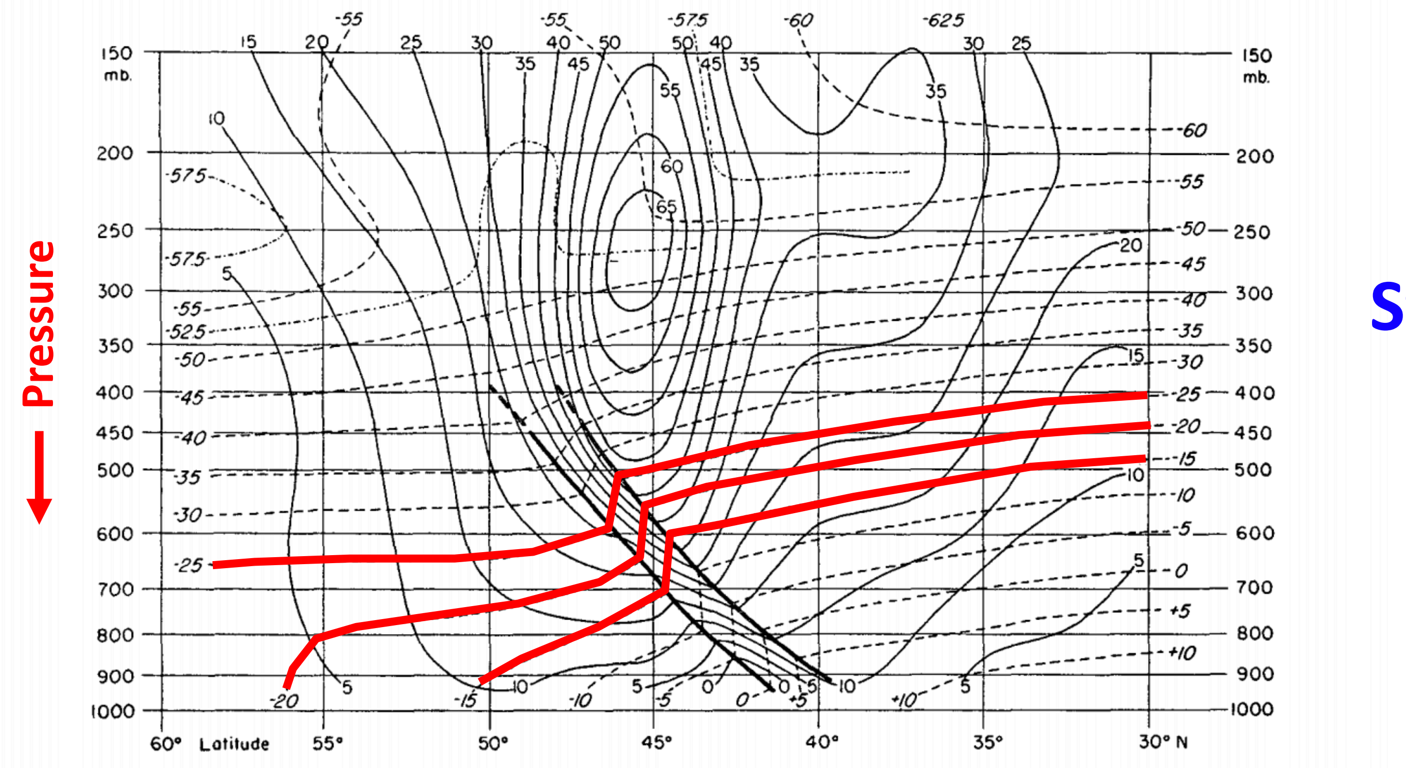

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Strong Static Stability

Palmén and Newton (1948)

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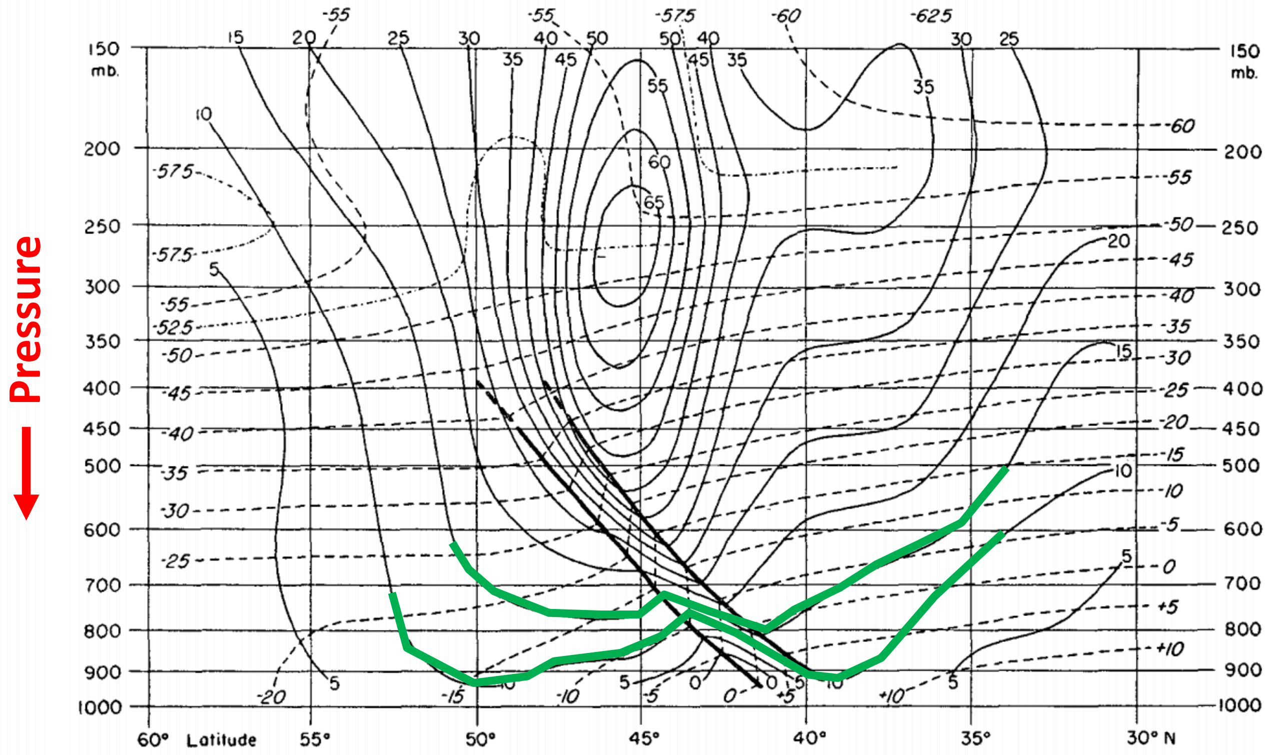

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Large Absolute Vorticity

Palmén and Newton (1948)

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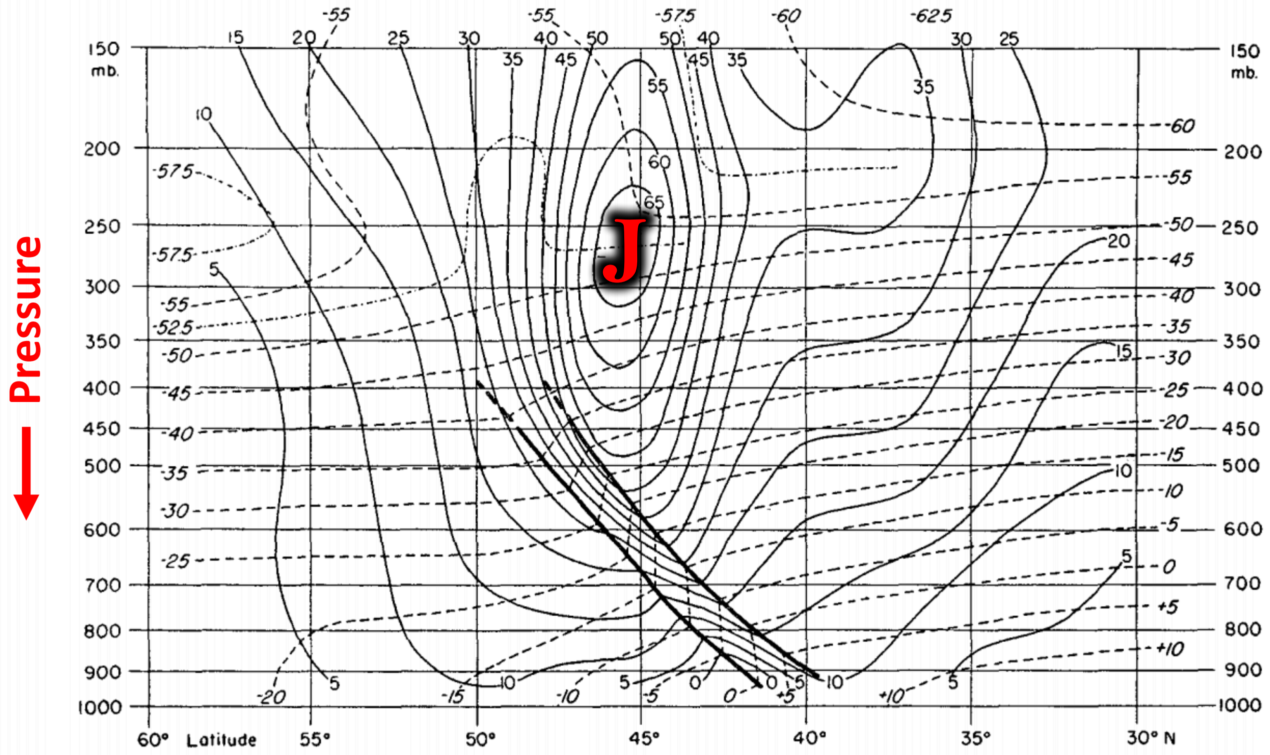

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Large Vertical Shear

Palmén and Newton (1948)

Definitions

Frontogenesis: The formation of a frontal boundary.

Frontolysis: The decay of a frontal boundary.

Definitions

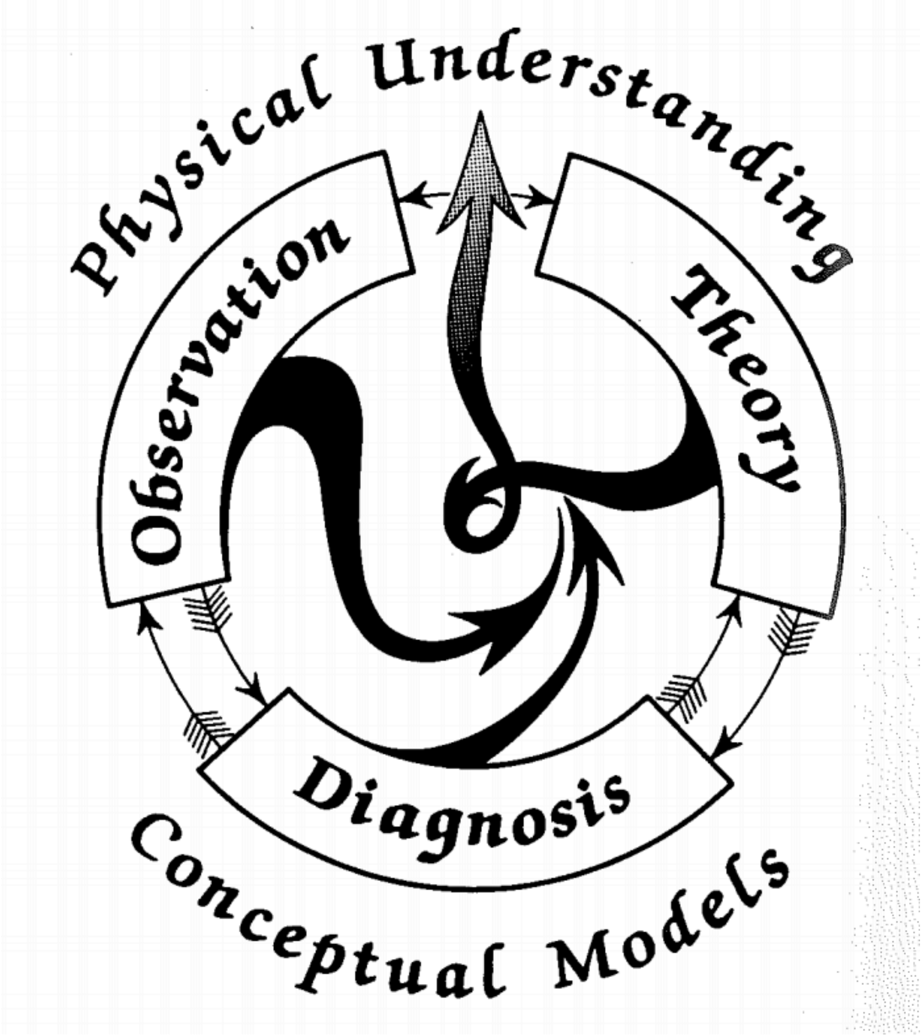
Frontogenesis: The formation of a frontal boundary.

Frontolysis: The decay of a frontal boundary.

Mathematically, it describes the Lagrangian rate of change of the magnitude of the horizontal temperature gradient (Bergeron 1928; Petterssen 1936):

$$\boxed{\mathcal{F} = \frac{d}{dt}|\nabla_h \theta|}$$

Fronts and Frontogenesis

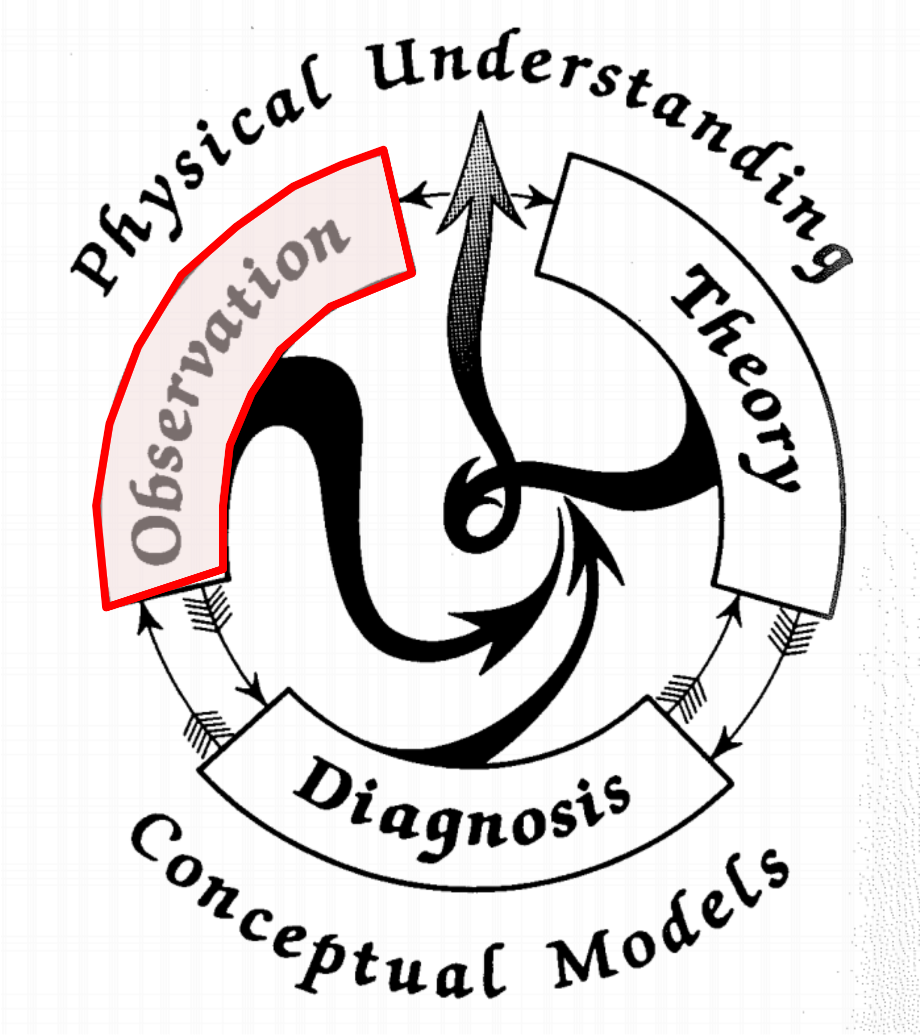


Shapiro et al. (1999)

“The principal task of any meteorological institution of education and research must be to bridge the gap between the mathematician and practical man, that is to make the weather man realize the value of a modest theoretical education and to induce the theoretical man to take an occasional glance at the weather map. The polar front theory, beyond a doubt, represents the most successful effort yet to bridge the gulf that separates meteorological camps”

C.-G. Rossby (1934)

Fronts and Frontogenesis



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Observations of Fronts

Polar Front Theory

Bjerknes (1919); Bjerknes and Solberg (1921, 1922)

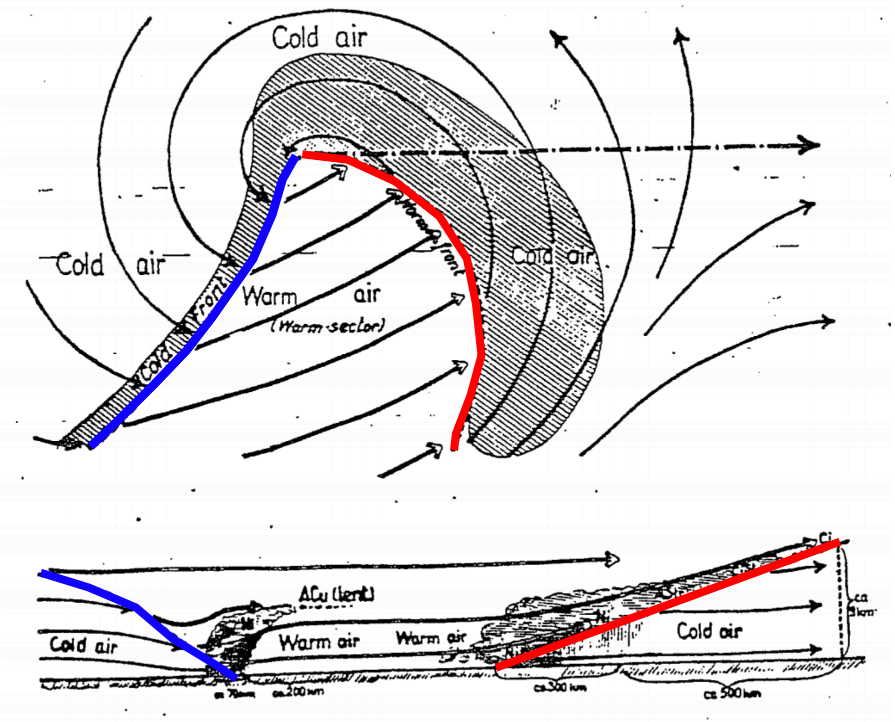
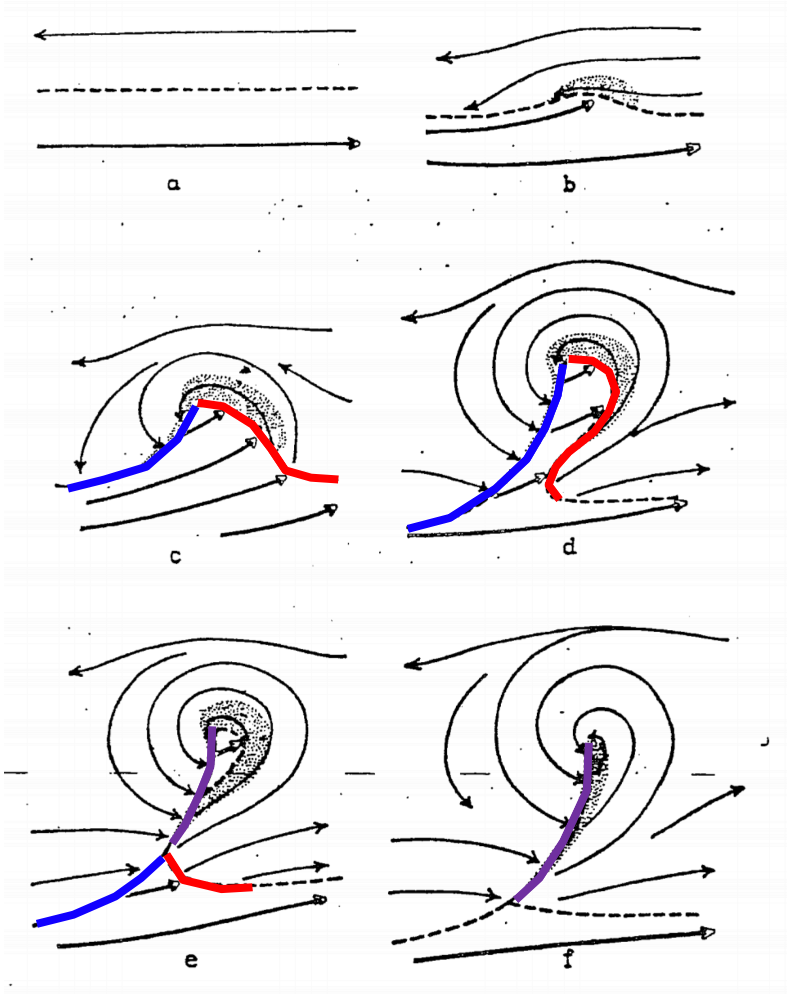


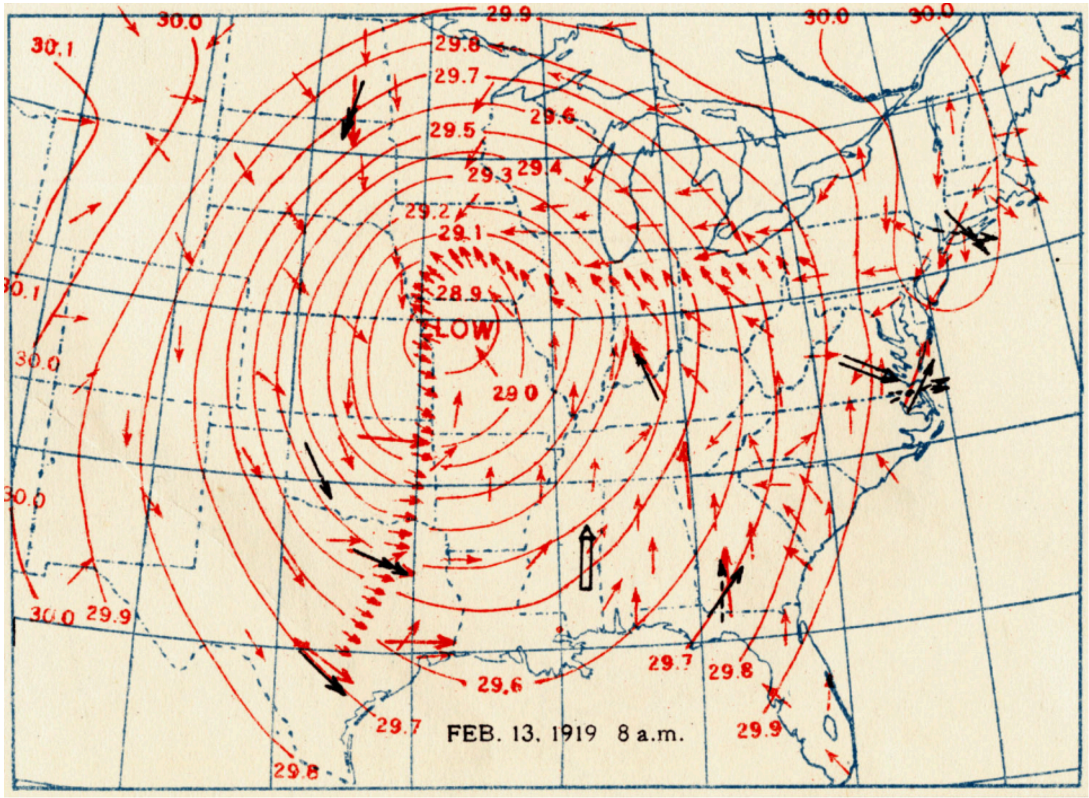
Fig. 1.
Idealized cyclone.



Observations of Fronts

Polar Front Theory in the U.S.

Meisinger (1920): Applied polar front theory concepts to a strong cyclogenesis event in the lee of the Rockies.



FEB. 13. 1919 8 a.m.

Observations of Fronts

Polar Front Theory in the U.S.

Meisinger (1920): Applied polar front theory concepts to a strong cyclogenesis event in the lee of the Rockies.

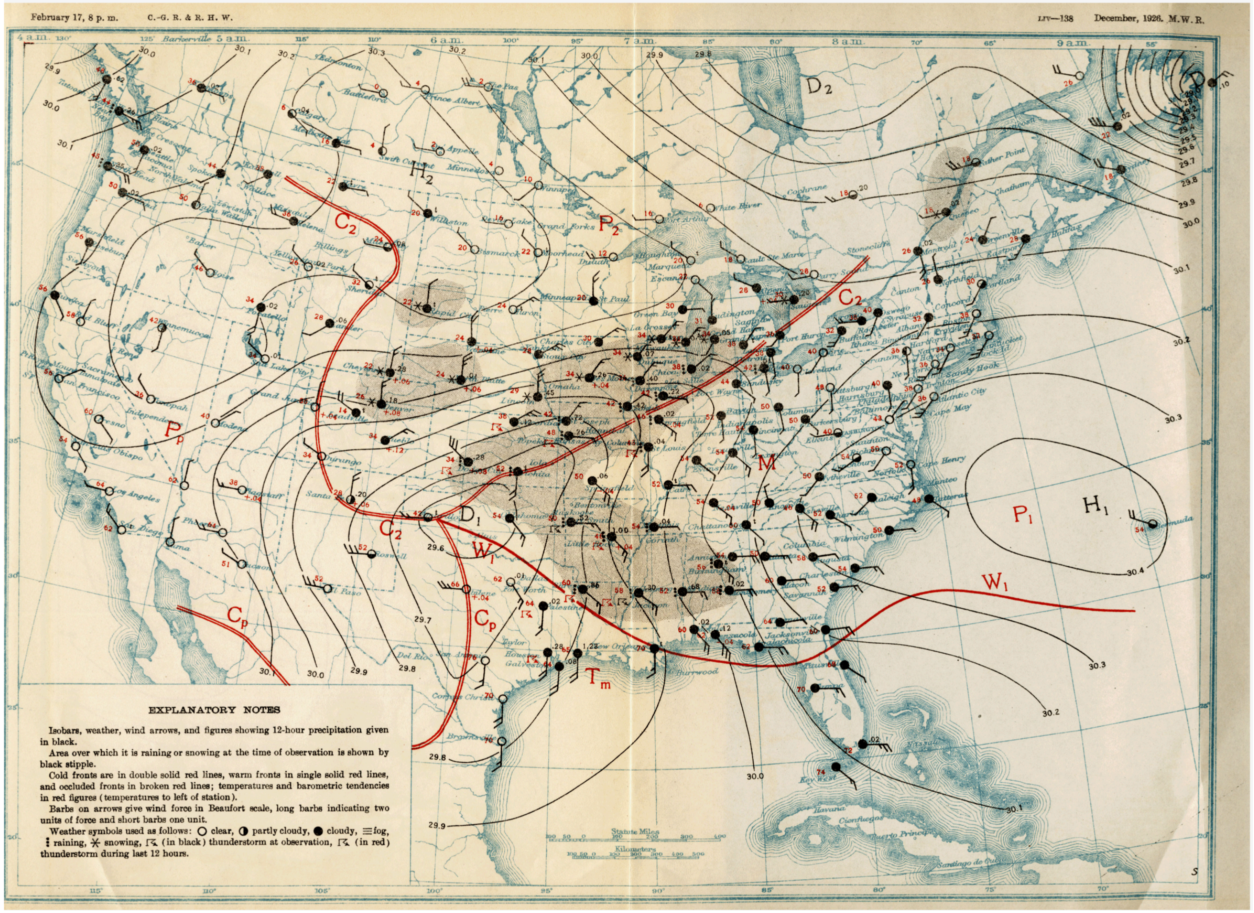
Beck (1922): Appealed the U.S. Weather Bureau to adopt polar front theory concepts and increase observational capabilities.

Observations of Fronts

Polar Front Theory in the U.S.

Rossby and Weightman (1926):

Investigated a case of lee cyclogenesis that featured interactions between four different air masses.



February 17, 8 p. m. C.-G. R. & R. H. W. LIV—138 December, 1926. M. W. R.

EXPLANATORY NOTES

Isobars, weather, wind arrows, and figures showing 12-hour precipitation given in black.

Area over which it is raining or snowing at the time of observation is shown by black stipple.

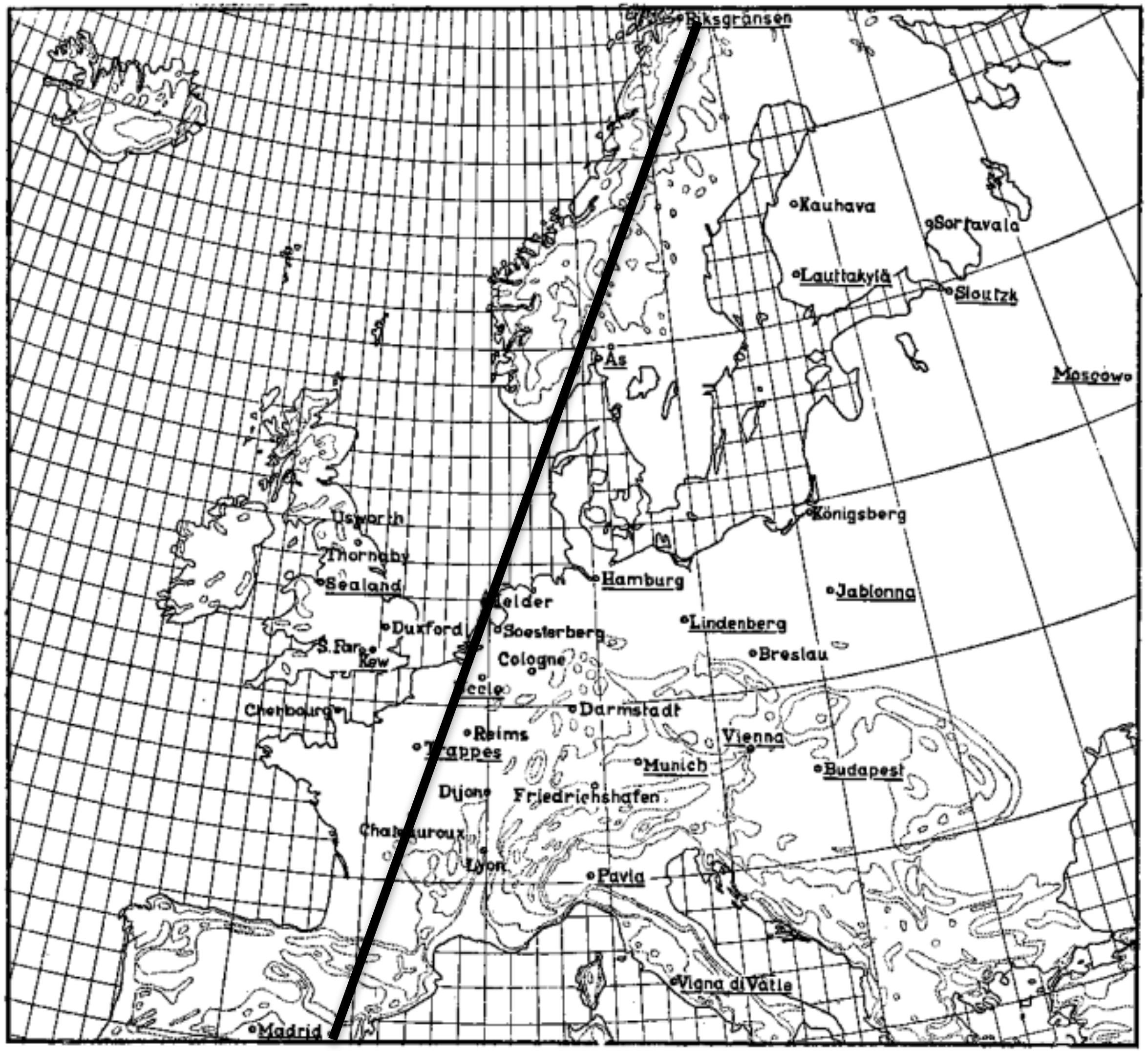
Cold fronts are in double solid red lines, warm fronts in single solid red lines, and occluded fronts in broken red lines; temperatures and barometric tendencies in red figures (temperatures to left of station).

Barbs on arrows give wind force in Beaufort scale, long barbs indicating two units of force and short barbs one unit.

Weather symbols used as follows: ○ clear, ◑ partly cloudy, ● cloudy, ≡ fog, ⁝ raining, ⚹ snowing, ⟎ (in black) thunderstorm at observation, ⟎ (in red) thunderstorm during last 12 hours.

Observations of Fronts

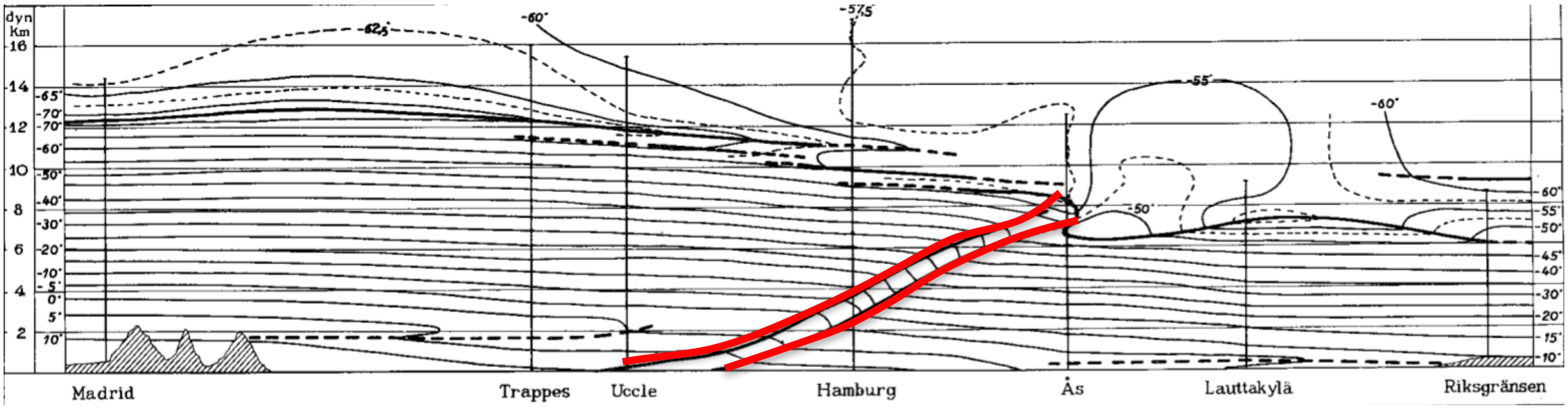
Bjerknes and Palmén (1937)



Coordinated **"swarm ascents"** at 18 different locations across Europe.

Observations of Fronts

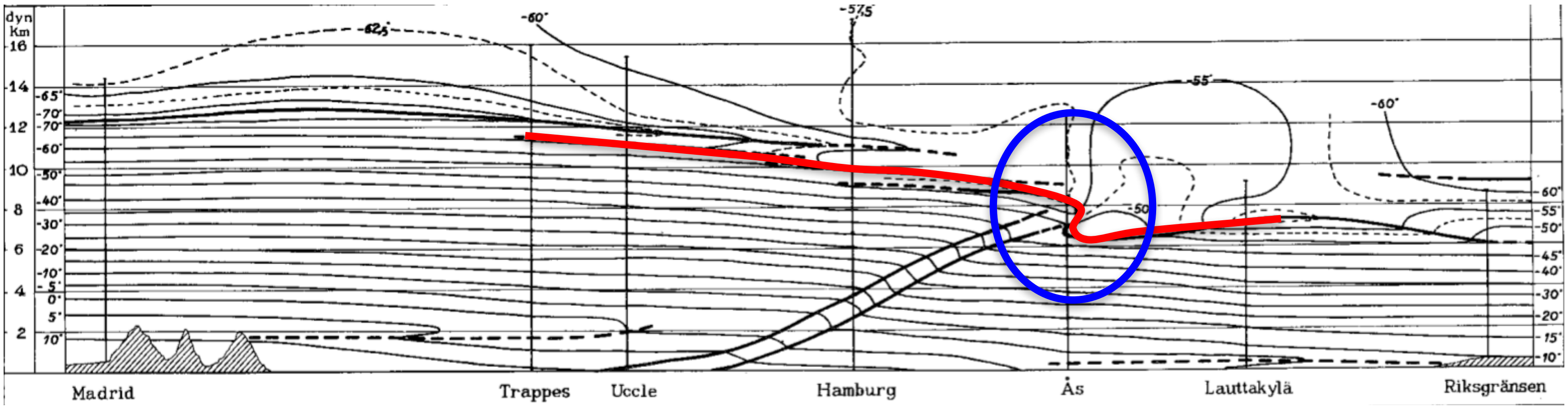
Bjerknes and Palmén (1937)



- The front is a **transition zone** across which the temperature gradient is discontinuous.

Observations of Fronts

Bjerknes and Palmén (1937)

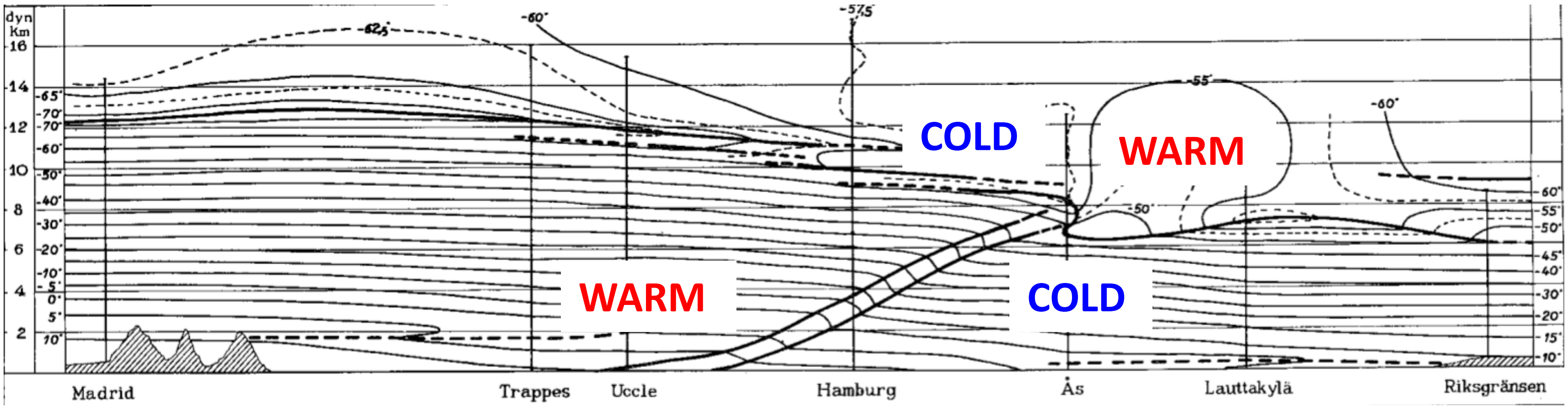


- The front is a **transition zone** across which the temperature gradient is discontinuous.

- The tropopause **abruptly lowers** at the location where the polar front intersects the tropopause.

Observations of Fronts

Bjerknes and Palmén (1937)

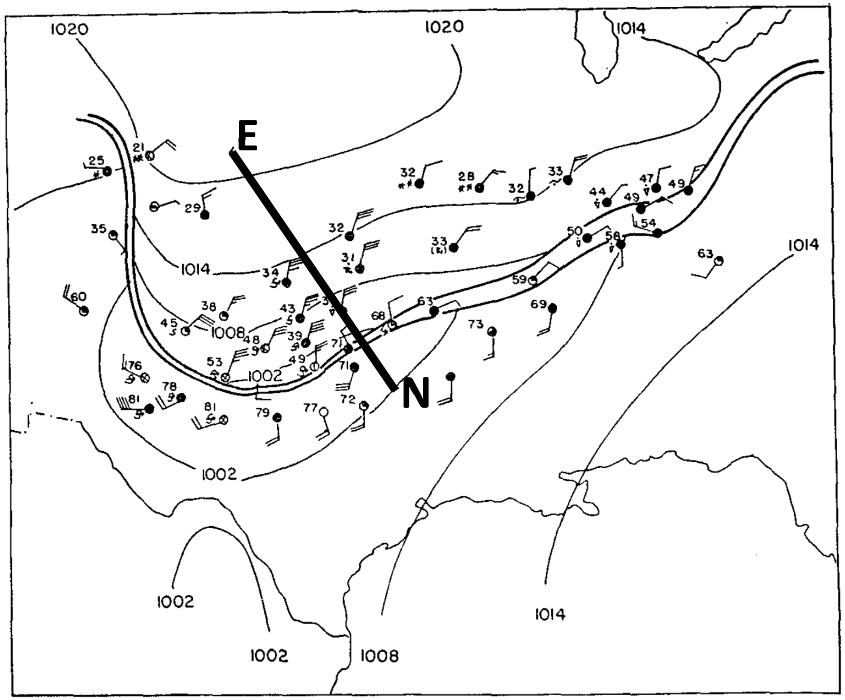


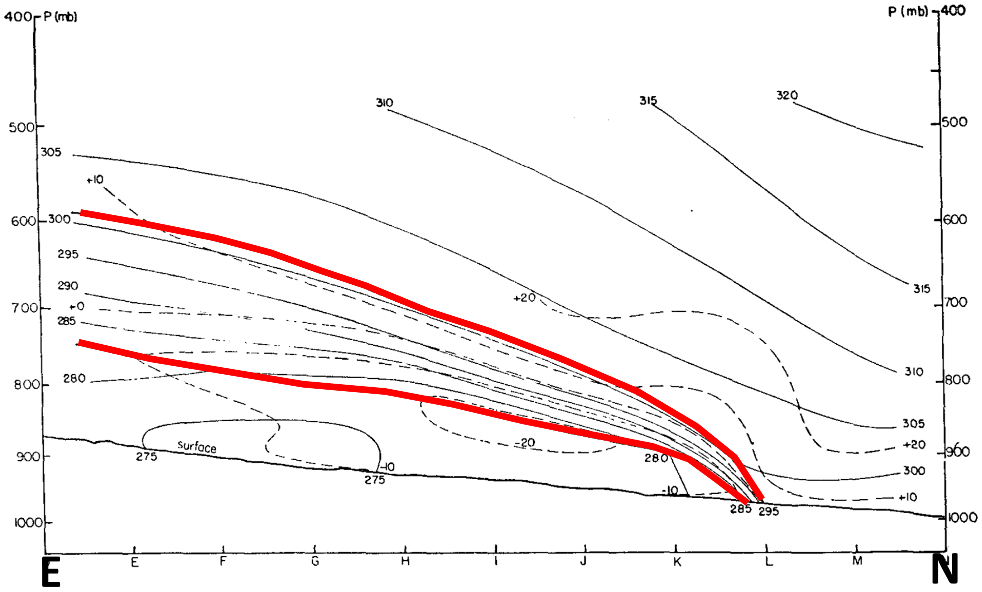
- The front is a **transition zone** across which the temperature gradient is discontinuous.
- The tropopause **abruptly lowers** at the location where the polar front intersects the tropopause.
- The meridional temperature gradient **reverses** directly above the tropopause break.

Observations of Fronts

Sanders (1955)

*"Fred **[Sanders]** and I were kindred spirits who fed each other's discontent with what we regarded as the nearly blind acceptance by many meteorologists of the **[Norwegian Cyclone Model]**" – Reed (2003)*



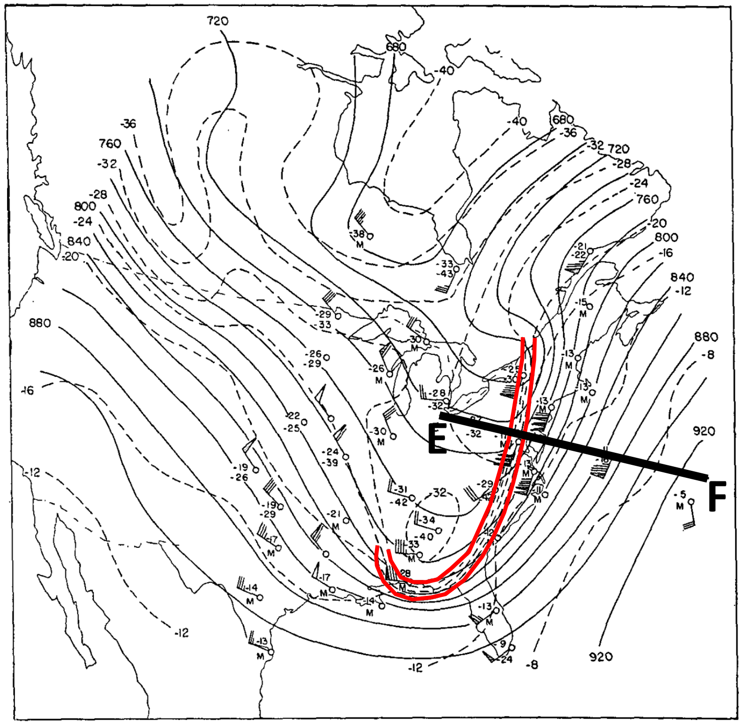


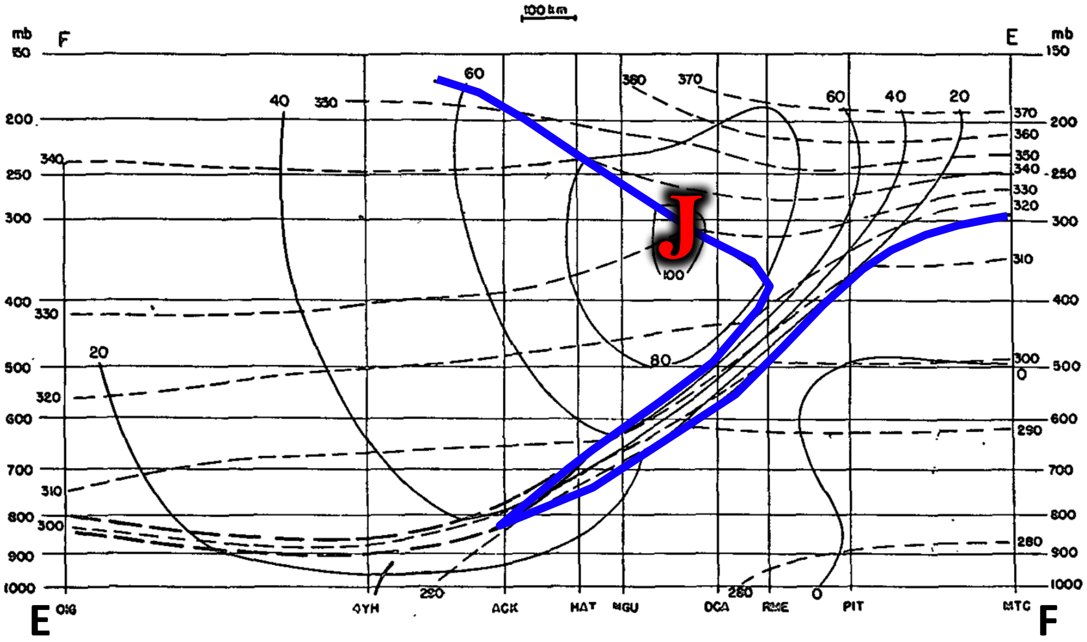
Sanders (1955)

Observations of Fronts

Revisions to Polar Front Theory

Upper-level fronts are distinct from surface fronts



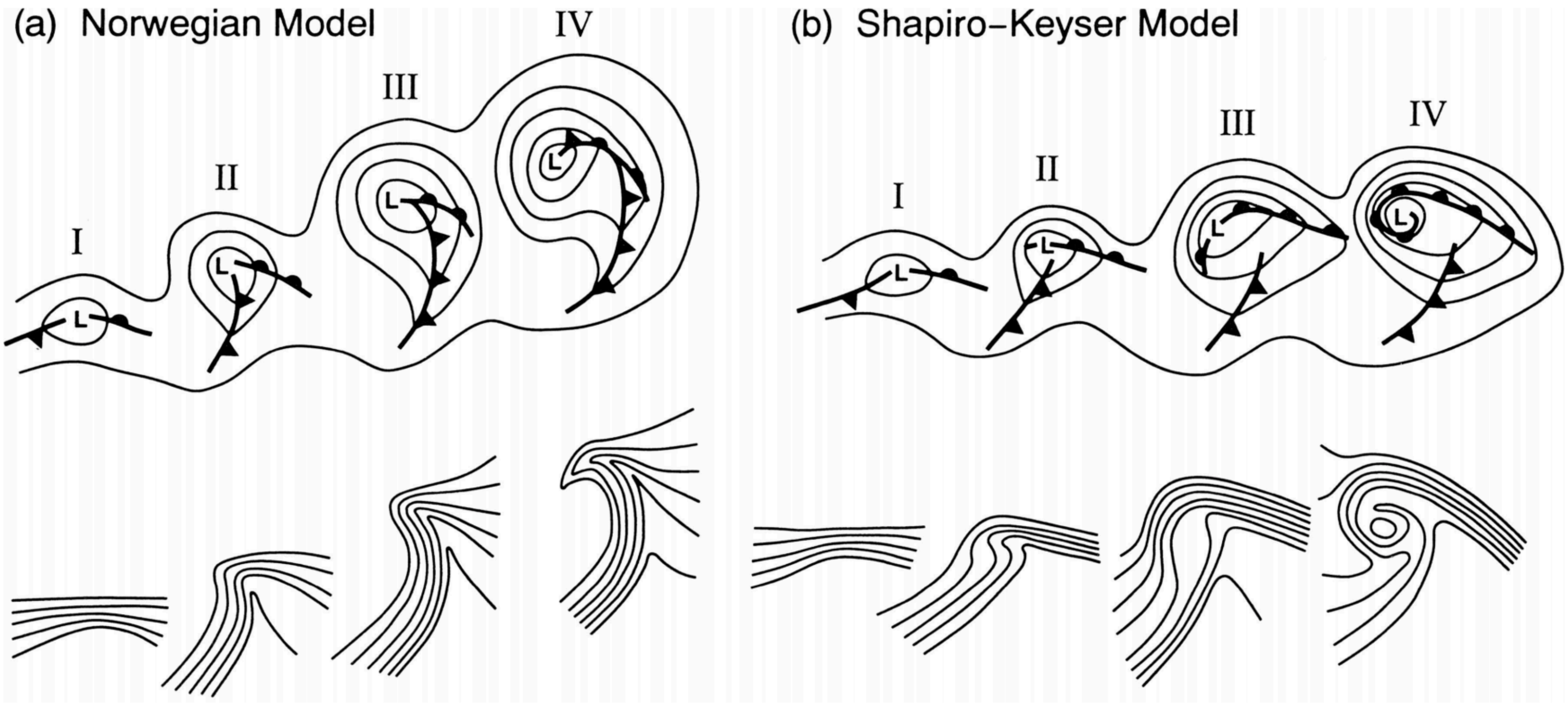


Reed (1955)

Observations of Fronts

Revisions to Polar Front Theory

The Shapiro–Keyser Cyclone Model (1990)

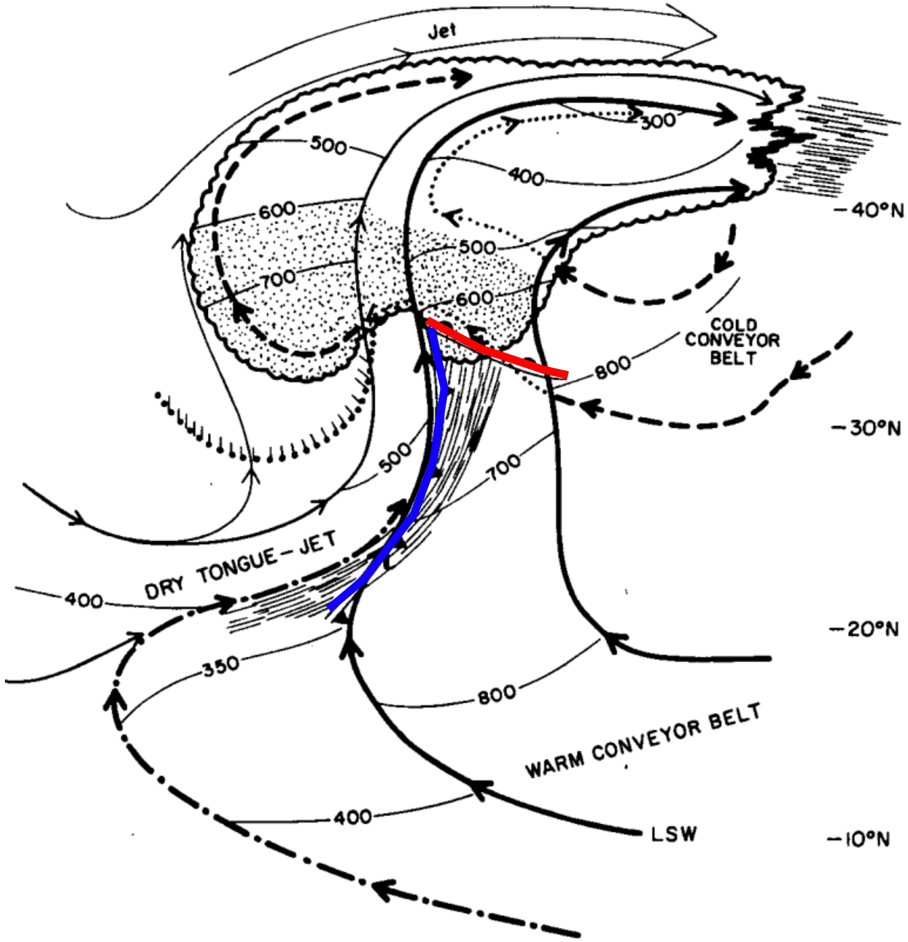


Schultz et al. (1998)

Observations of Fronts

Revisions to Polar Front Theory

Airstream models of midlatitude cyclones



AIRFLOW THROUGH MID-LATITUDE WAVE CYCLONE

Increased observations from multiple platforms, including satellites, resulted in further revisions to polar front theory.

The position of fronts are identified at the boundaries of the different airstreams.

Carlson (1980)

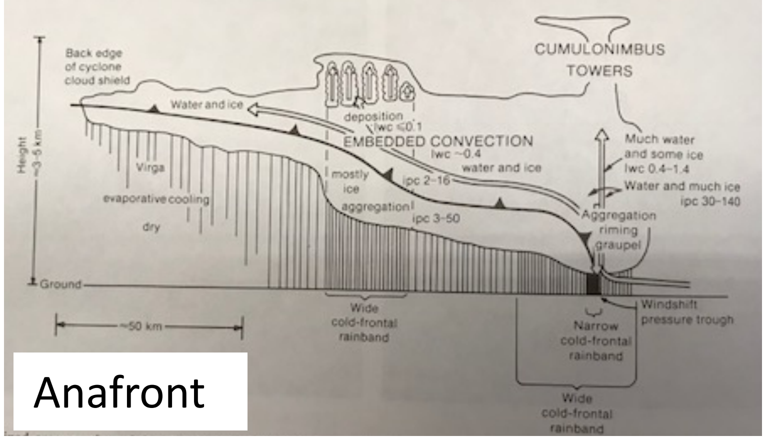
Observations of Fronts

Revisions to Polar Front Theory

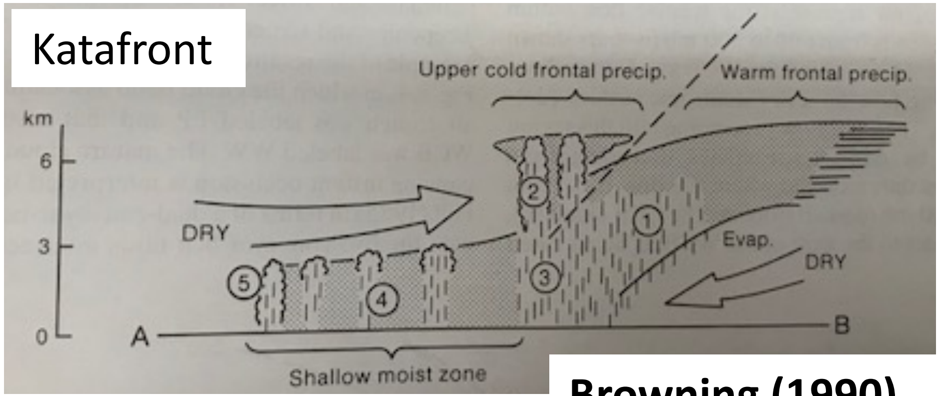
Additional structures that did not conform to Polar Front Theory

Katafronts/Anafronts: Katafronts (Anafronts) feature a forward (backward) sloping frontal boundary and pre- (post-)frontal cloud bands (Bergeron 1937; Sansom 1951).

Split Fronts/Cold Fronts Aloft: Conforms well with the concept of a katafront, with a dry airstream overrunning the warm conveyor belt near a cold front (Browning and Monk 1982; Browning 1990; Hobbs et al. 1990; Mass and Schultz 1993).



Anafront



Katafront

Browning (1990)

Observations of Fronts

Revisions to Polar Front Theory

Additional structures that did not conform to Polar Front Theory

Warm/Cold Occlusions: Occurs as a result of the "wrap-up" and lengthening of the warm-air tongue within a cyclone as it experiences deformation and rotation around the cyclone center (Bjerknes and Solberg 1922; Schultz and Vaughan 2011; Schultz et al. 2014).

Cold Occlusion **Warm Occlusion**

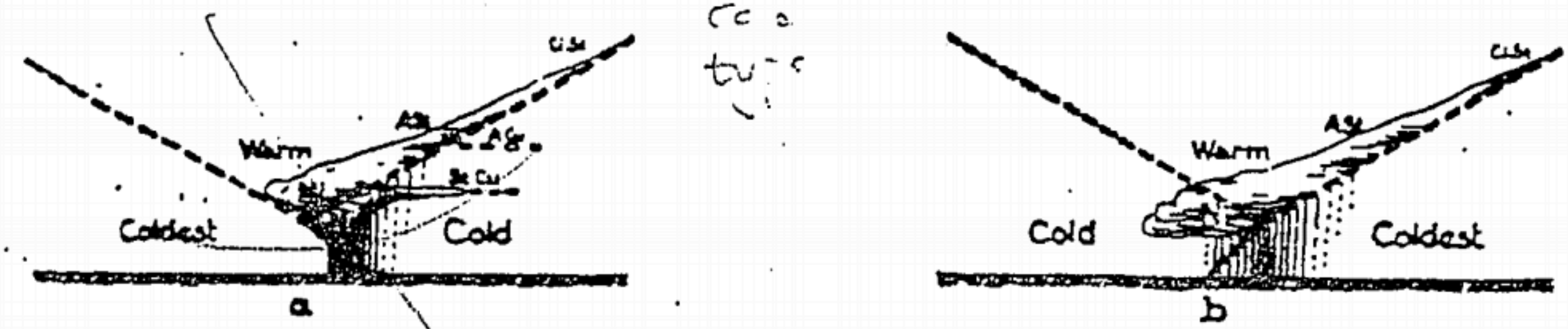


Fig. 4. The two kinds of occlusions seen in vertical section.

Bjerknes and Solberg (1922)

Observations of Fronts

Revisions to Polar Front Theory

Additional structures that did not conform to Polar Front Theory

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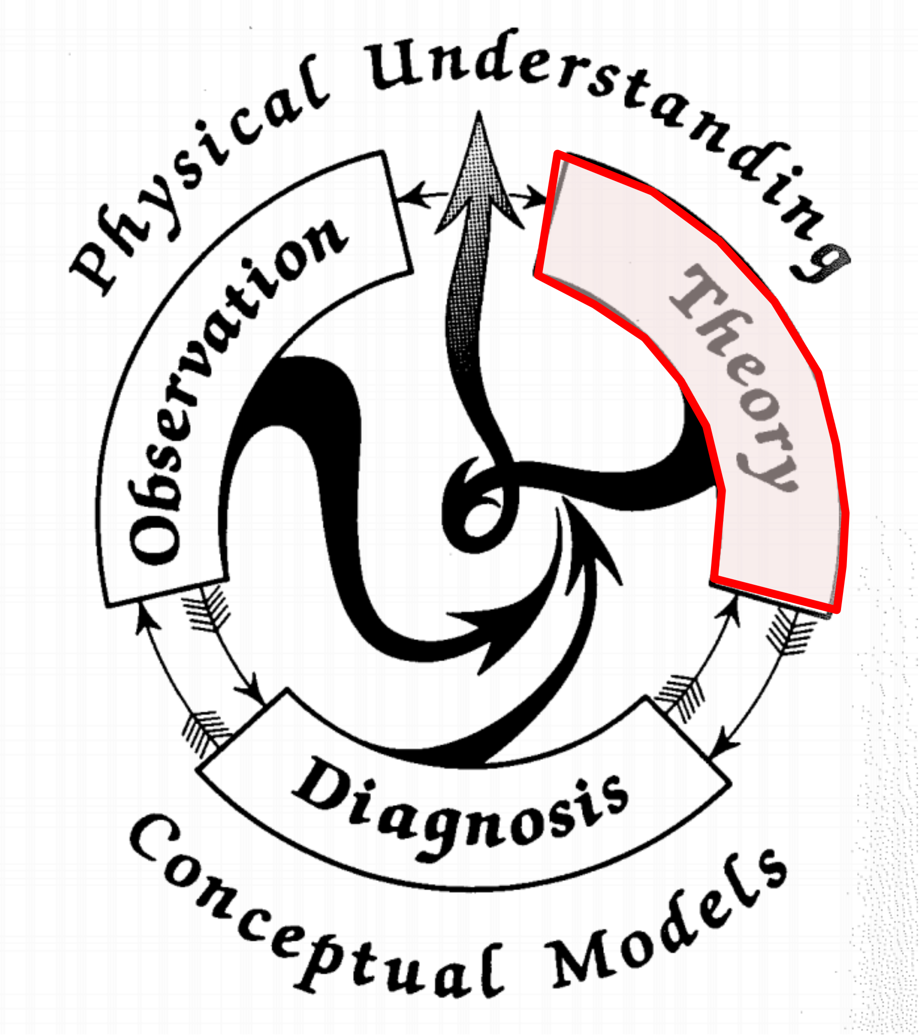
Backdoor Fronts: Cold-air damming along the eastern slopes of topography can aid in the formation of backdoor cold fronts (Carr 1951).

Coastal Fronts: Most favorable in areas of topography that lock in cold air over the continent. Surface latent and sensible heat fluxes can also result in warming over the ocean and a strong land/sea temperature contrast (Bosart et al. 1972; Bosart 1975, 1981).

Fronts and Frontogenesis



Shapiro et al. (1999)

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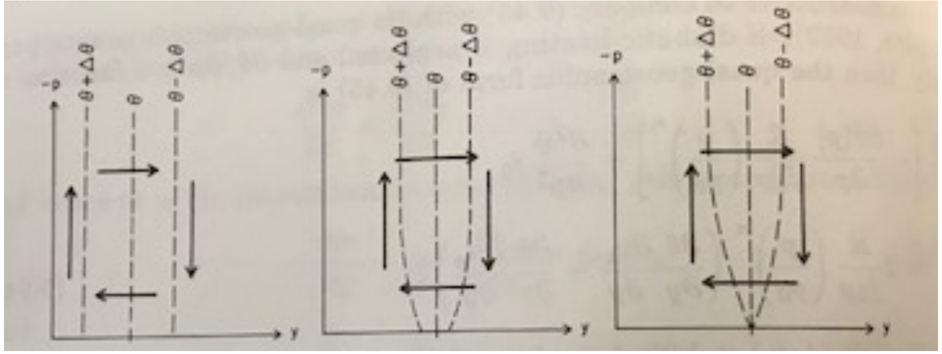
C.-G. Rossby (1934)

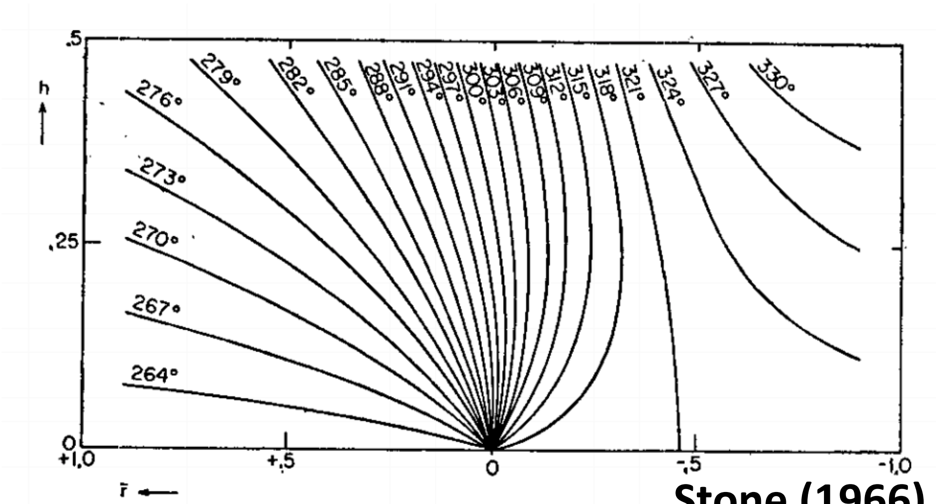
Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)



Bluestein (1986)



Stone (1966)

Quasi-geostrophic theory

(Stone 1966; Williams and Plotkin 1968; Williams 1968,1972; Mudrick 1974)

1) Frontogenesis is slow near the ground.
2) The frontal zone does not tilt with height.
3) The relative vorticity field contains large areas of anticyclonic vorticity too.
4) Regions of static instability are produced.

Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

Arnt Eliassen

Norwegian Encyclopedia

Semi-geostrophic theory

(Sawyer 1956; Eliassen 1962; Hoskins 1971; Hoskins and Bretherton 1972; Hoskins 1972)

1) Retains across-front advections of temperature and momentum by the ageostrophic wind.

2) The Sawyer (1956)–Eliassen (1962) Circulation Equation.

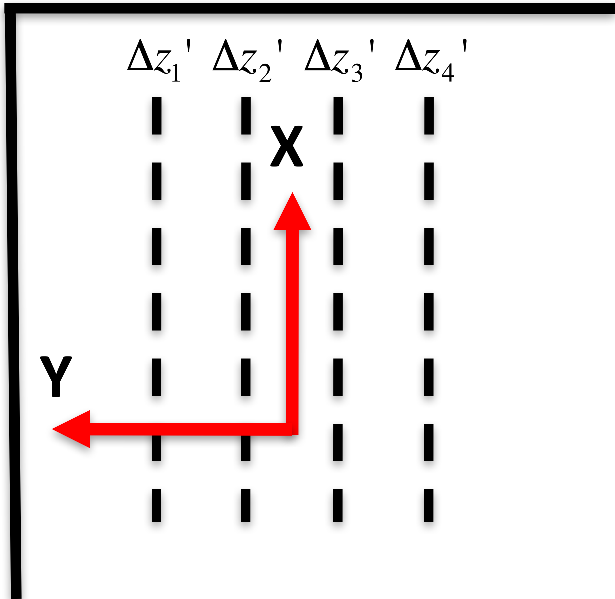
Theory of Fronts

$$\left(-\gamma\frac{\partial\theta}{\partial p}\right)\frac{\partial^2\psi}{\partial y^2}+\left(2\gamma\frac{\partial\theta}{\partial y}\right)\frac{\partial^2\psi}{\partial p\partial y}+\left(-\frac{\partial u_g}{\partial y}+f\right)\frac{\partial^2\psi}{\partial p^2}=Q_g-\gamma\frac{\partial}{\partial y}\left(\frac{d\theta}{dt}\right)$$

Where:

$$\omega=\frac{\partial\psi}{\partial y}$$

$$v_{age}=-\frac{\partial\psi}{\partial p}$$



Theory of Fronts

$$(-\gamma\frac{\partial\theta}{\partial p})\frac{\partial^2\psi}{\partial y^2}+(2\gamma\frac{\partial\theta}{\partial y})\frac{\partial^2\psi}{\partial p\partial y}+(-\frac{\partial u_g}{\partial y}+f)\frac{\partial^2\psi}{\partial p^2}=Q_g-\gamma\frac{\partial}{\partial y}(\frac{d\theta}{dt})$$

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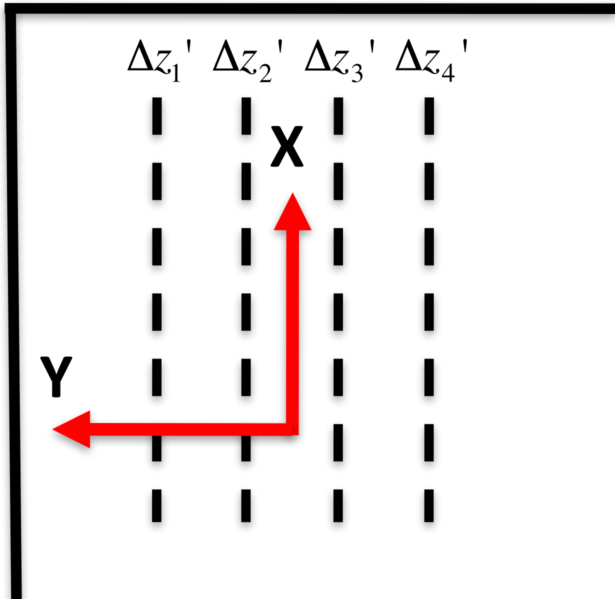


Theory of Fronts

$$\boxed{(-\gamma\frac{\partial\theta}{\partial p})}\frac{\partial^2\psi}{\partial y^2}+\boxed{(2\gamma\frac{\partial\theta}{\partial y})}\frac{\partial^2\psi}{\partial p\partial y}+\boxed{(-\frac{\partial u_g}{\partial y}+f)}\frac{\partial^2\psi}{\partial p^2}=Q_g-\gamma\frac{\partial}{\partial y}(\frac{d\theta}{dt})$$

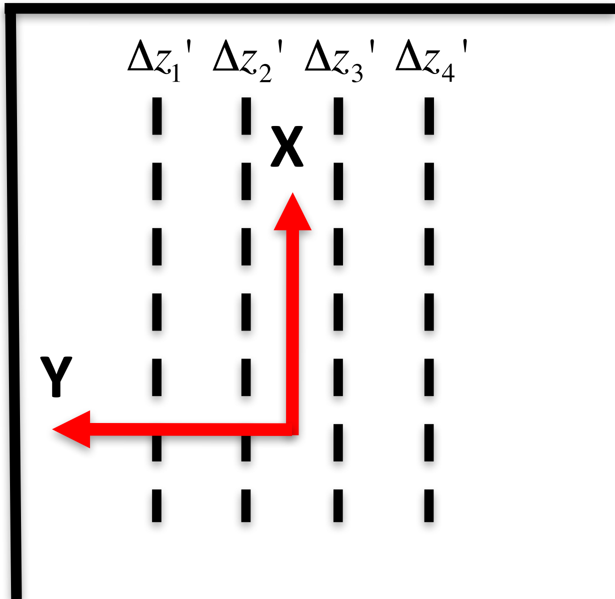
Static Stability
Across-Front Baroclinicity
Horizontal Absolute Vorticity

Frontal Characteristics

Where:

$$\omega=\frac{\partial\psi}{\partial y}$$

$$v_{age}=-\frac{\partial\psi}{\partial p}$$



Theory of Fronts

$$\boxed{(-\gamma\frac{\partial\theta}{\partial p})}\frac{\partial^2\psi}{\partial y^2}+\boxed{(2\gamma\frac{\partial\theta}{\partial y})}\frac{\partial^2\psi}{\partial p\partial y}+\boxed{(-\frac{\partial u_g}{\partial y}+f)}\frac{\partial^2\psi}{\partial p^2}=\boxed{Q_g-\gamma\frac{\partial}{\partial y}(\frac{d\theta}{dt})}$$

Static Stability

Across-Front Baroclinicity

Horizontal Absolute Vorticity

Frontal Characteristics

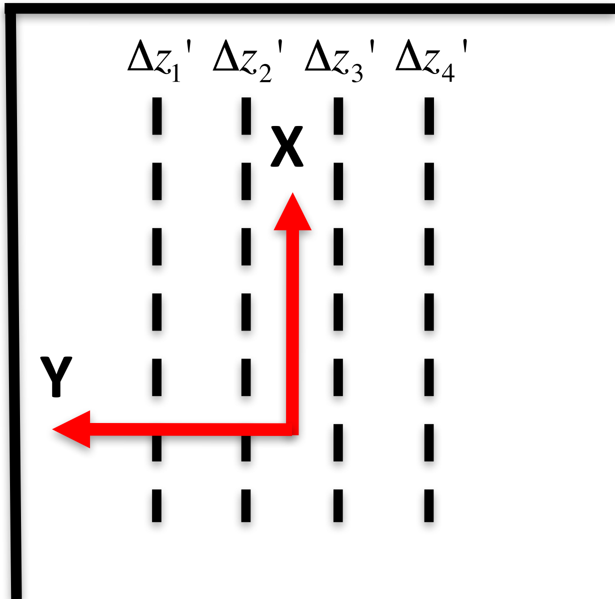
Geostrophic and Diabatic Forcing

Where:

$$\omega=\frac{\partial\psi}{\partial y}$$

$$v_{age}=-\frac{\partial\psi}{\partial p}$$

$$Q_g=2\gamma(\underbrace{\frac{\partial U_g}{\partial y}\frac{\partial\theta}{\partial x}}_{\text{Shearing}}+\underbrace{\frac{\partial V_g}{\partial y}\frac{\partial\theta}{\partial y}}_{\text{Confluence}})$$



Theory of Fronts

$$\boxed{(-\gamma\frac{\partial\theta}{\partial p})\frac{\partial^2\psi}{\partial y^2}+(2\gamma\frac{\partial\theta}{\partial y})\frac{\partial^2\psi}{\partial p\partial y}+(-\frac{\partial u_g}{\partial y}+f)\frac{\partial^2\psi}{\partial p^2}=Q_g-\gamma\frac{\partial}{\partial y}(\frac{d\theta}{dt})}$$

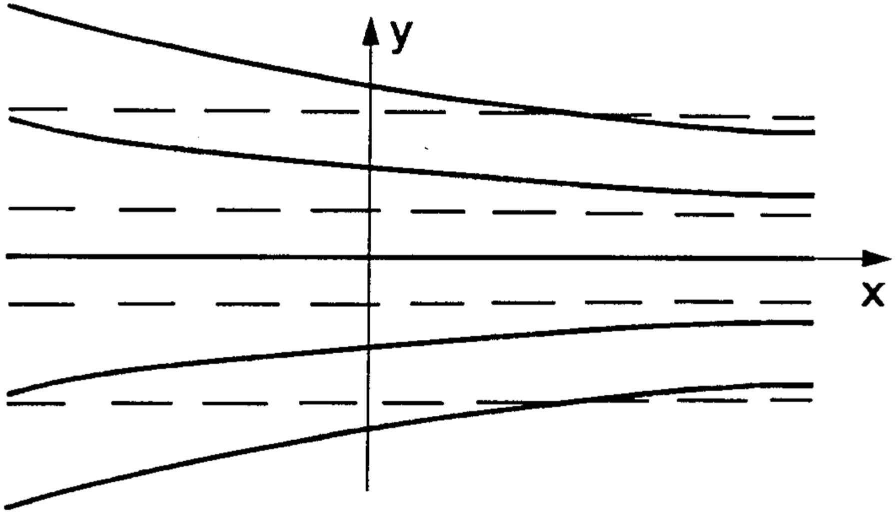
$$Q_g=2\gamma(\underbrace{\frac{\partial U_g}{\partial y}\frac{\partial\theta}{\partial x}}_{\text{Shearing}}+\underbrace{\frac{\partial V_g}{\partial y}\frac{\partial\theta}{\partial y}}_{\text{Confluence}})$$

Theory of Fronts

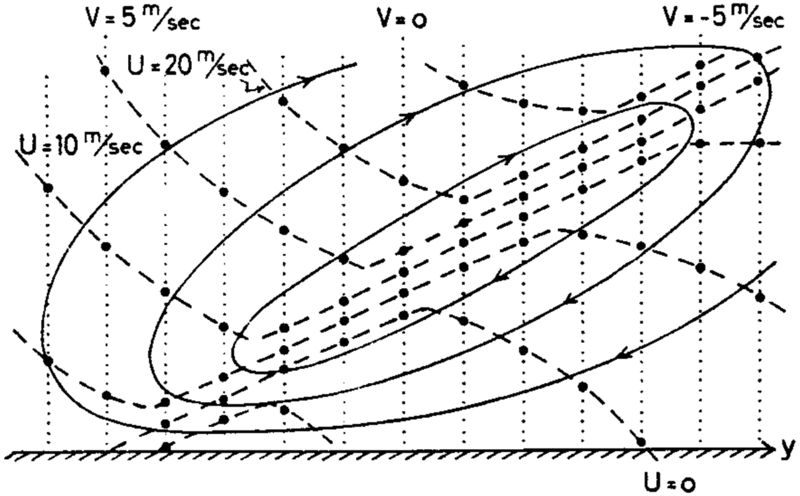
$$(-\gamma\frac{\partial\theta}{\partial p})\frac{\partial^2\psi}{\partial y^2}+(2\gamma\frac{\partial\theta}{\partial y})\frac{\partial^2\psi}{\partial p\partial y}+(-\frac{\partial u_g}{\partial y}+f)\frac{\partial^2\psi}{\partial p^2}=Q_g$$

Ageostrophic Circulation Generated by Geostrophic Confluence Deformation

$$Q_g = 2\gamma(\underbrace{\frac{\partial U_g}{\partial y}\frac{\partial\theta}{\partial x}}_{\text{Shearing}}+\underbrace{\frac{\partial V_g}{\partial y}\frac{\partial\theta}{\partial y}}_{\text{Confluence}})$$



Eliassen (1990)



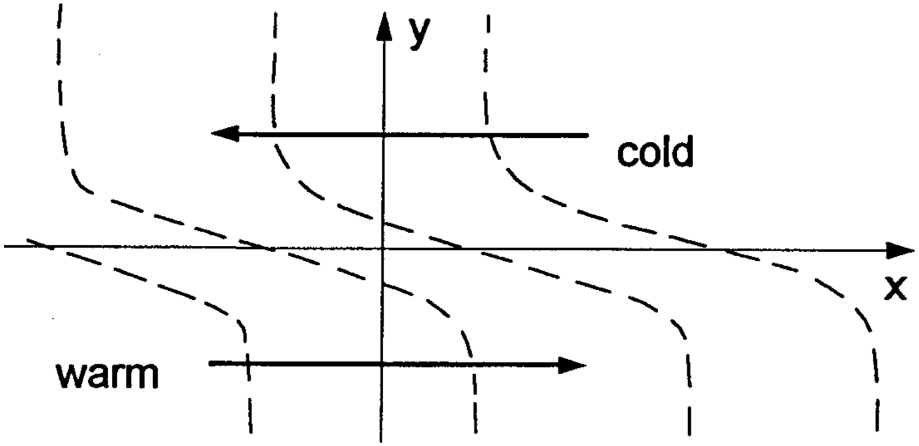
Eliassen (1962)

Theory of Fronts

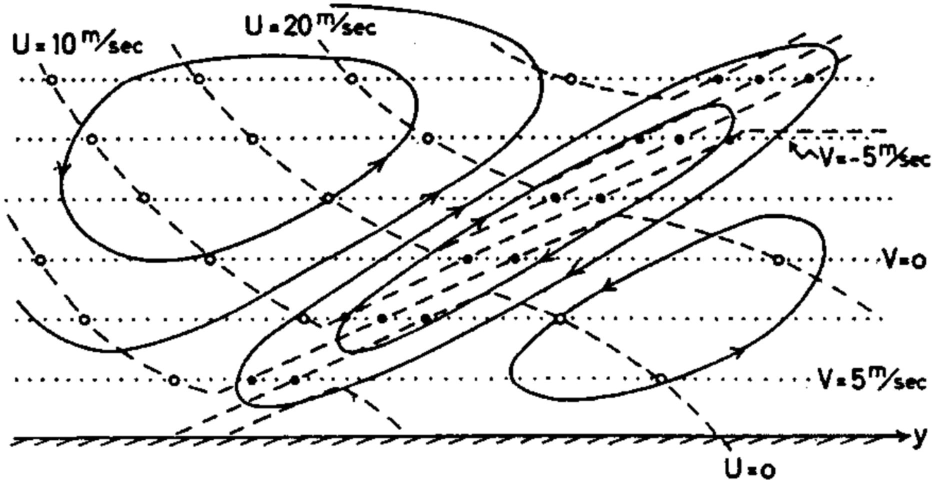
$$\left(-\gamma\frac{\partial\theta}{\partial p}\right)\frac{\partial^2\psi}{\partial y^2}+\left(2\gamma\frac{\partial\theta}{\partial y}\right)\frac{\partial^2\psi}{\partial p\partial y}+\left(-\frac{\partial u_g}{\partial y}+f\right)\frac{\partial^2\psi}{\partial p^2}=Q_g$$

Ageostrophic Circulation Generated by Geostrophic Shearing Deformation

$$Q_g = 2\gamma\left(\underbrace{\frac{\partial U_g}{\partial y}\frac{\partial\theta}{\partial x}}_{\text{Shearing}}+\underbrace{\frac{\partial V_g}{\partial y}\frac{\partial\theta}{\partial y}}_{\text{Confluence}}\right)$$



Eliassen (1990)



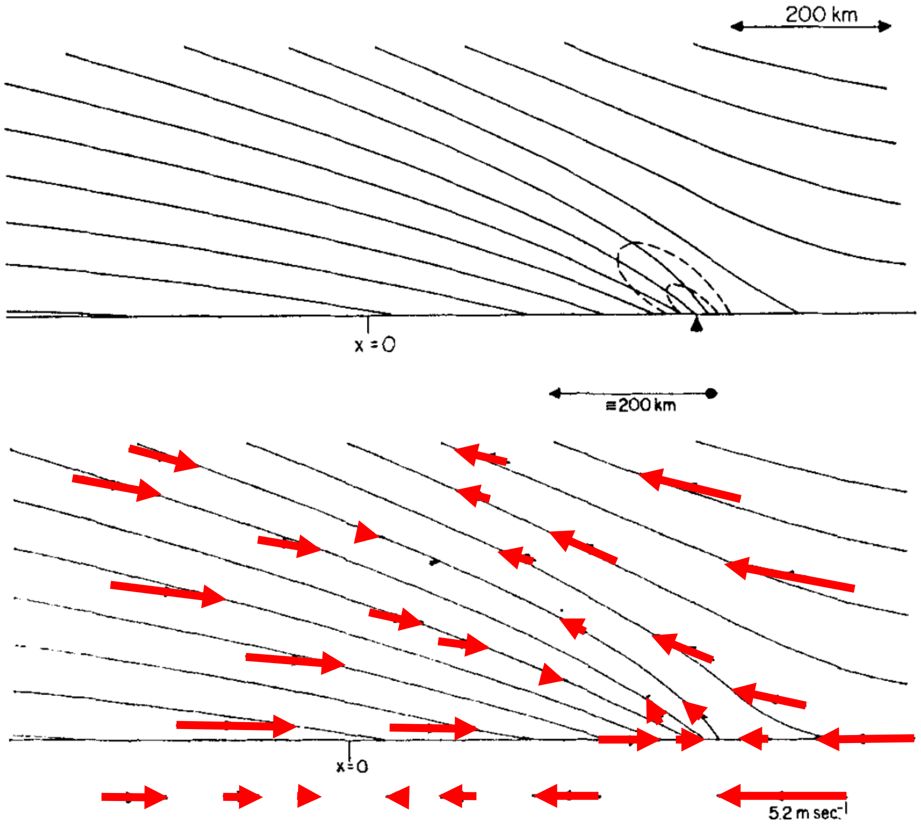
Eliassen (1962)

Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

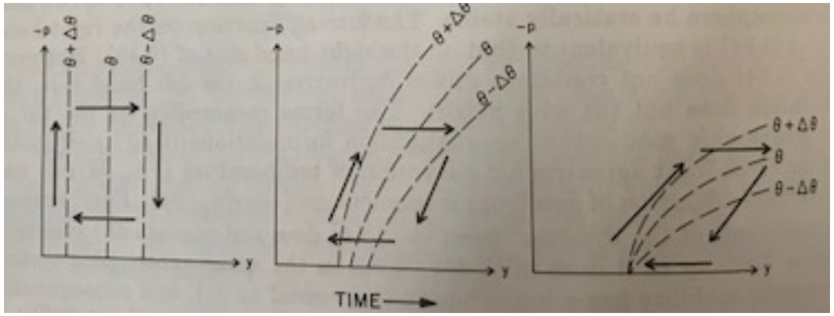
Hoskins (1971)



Semi-geostrophic theory

(Sawyer 1956; Eliassen 1962; Hoskins 1971; Hoskins and Bretherton 1972; Hoskins 1972)

3) Simulates surface and upper-level fronts that are similar to those observed by Sanders (1955) and Reed (1955).



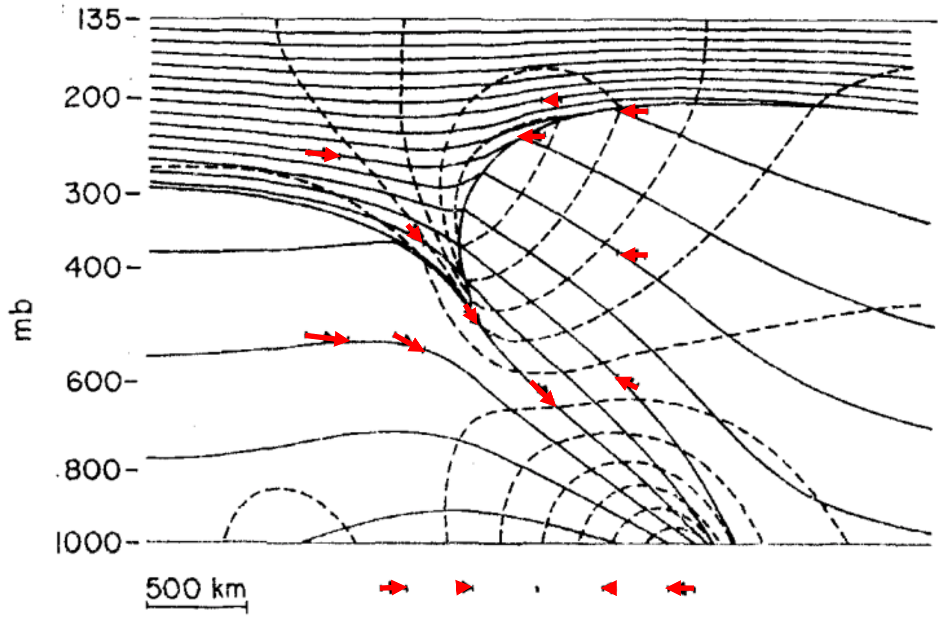
Bluestein (1986) →

Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

Hoskins (1972)



Semi-geostrophic theory

(Sawyer 1956; Eliassen 1962; Hoskins 1971; Hoskins and Bretherton 1972; Hoskins 1972)

3) Simulates surface and upper-level fronts that are similar to those observed by Sanders (1955) and Reed (1955).

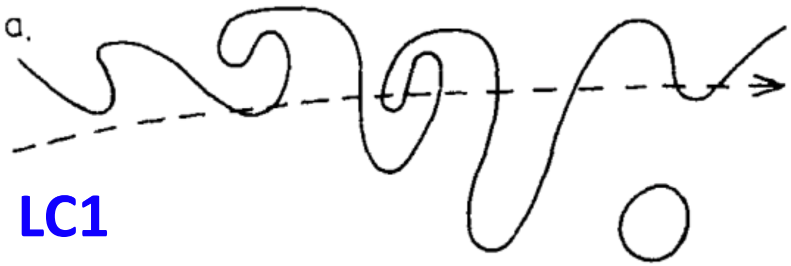
4) Inclusion of frictional (e.g., Keyser and Anthes 1982) and diabatic effects (e.g., Thorpe and Emanuel 1985) further reconciled modelled versus observed frontal structures.

Theory of Fronts

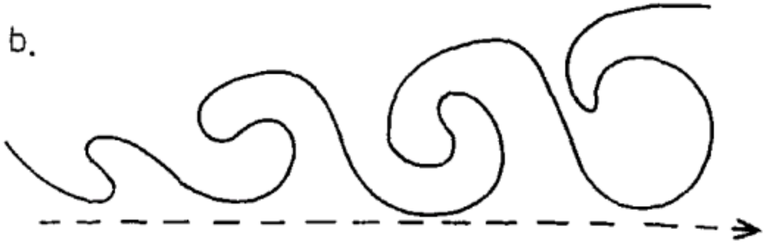
Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

Thorncroft et al. (1993)



LC1



LC2

Primitive Equation Models

(Snyder et al. 1991; Thorncroft et al. 1993; Rotunno et al. 1994; Muraki et al. 1999; Rotunno et al. 2000)

1) Cyclone lifecycles differ considerably based on the background barotropic shear.

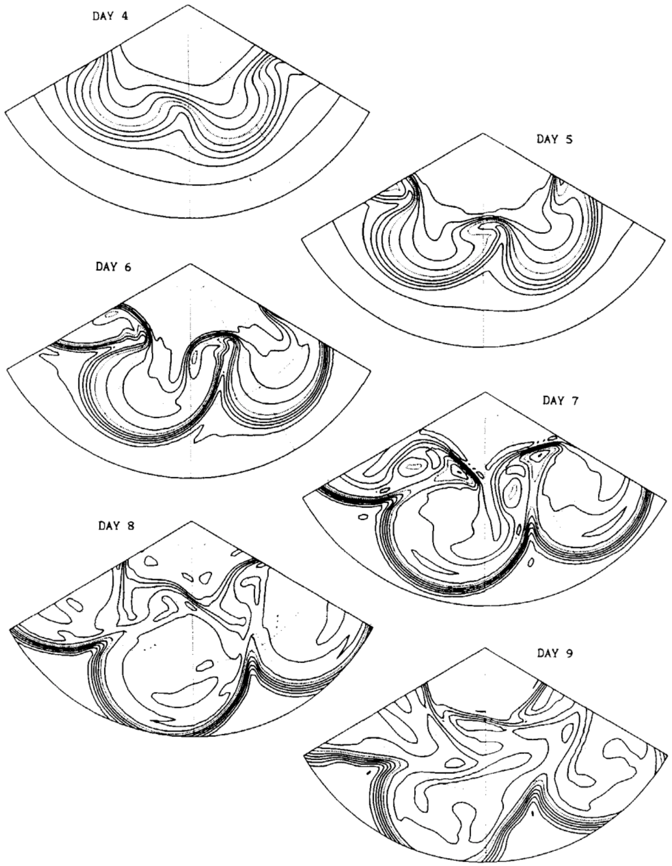
Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

Thorncroft et al. (1993)

LC1



Primitive Equation Models

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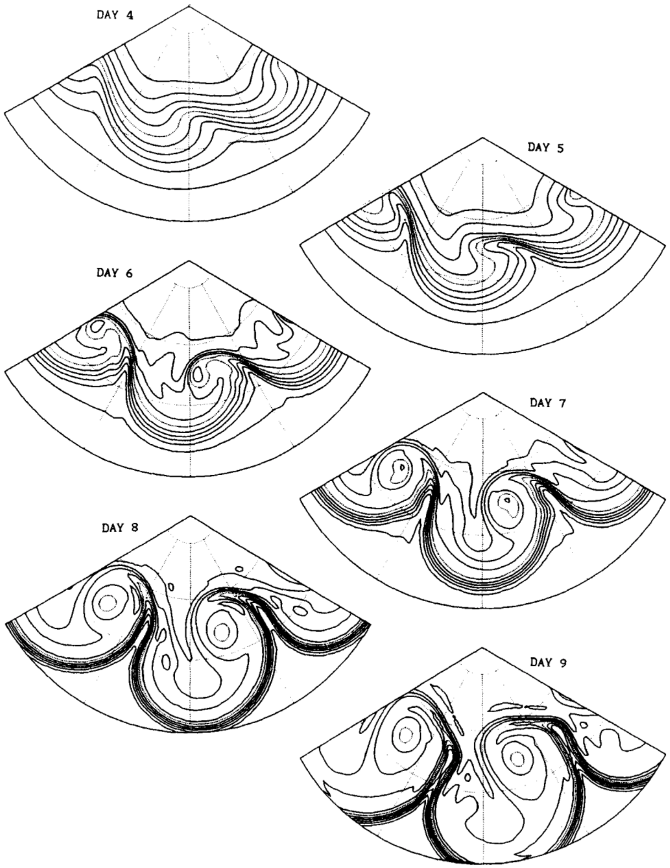

Primitive Equation Models

(Snyder et al. 1991; Thorncroft et al. 1993; Rotunno et al. 1994; Muraki et al. 1999; Rotunno et al. 2000)

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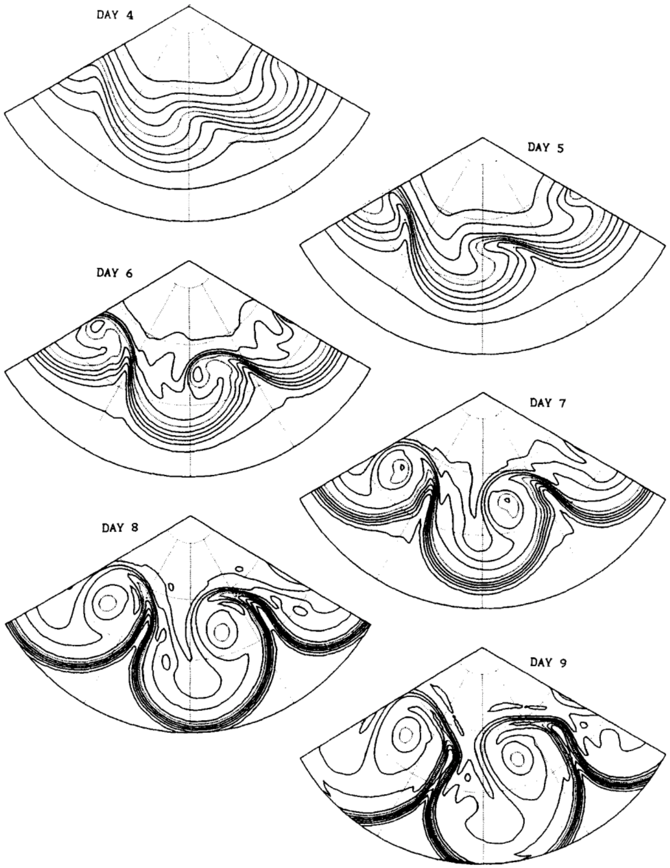
Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

Thorncroft et al. (1993)

LC2



Primitive Equation Models

(Snyder et al. 1991; Thorncroft et al. 1993; Rotunno et al. 1994; Muraki et al. 1999; Rotunno et al. 2000)

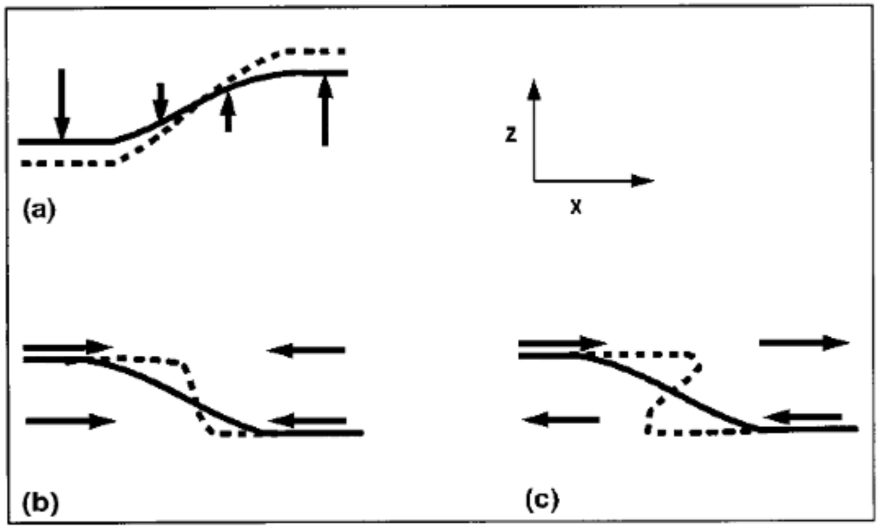
1) Cyclone lifecycles differ considerably based on the background barotropic shear.
2) Numerically-simulated cyclones can be affected significantly by the semi-geostrophic approximation.

Theory of Fronts

Theory as a Bridge to Observations

Replicating Sanders (1955) and Reed (1955)

Wandishin et al. (2000)



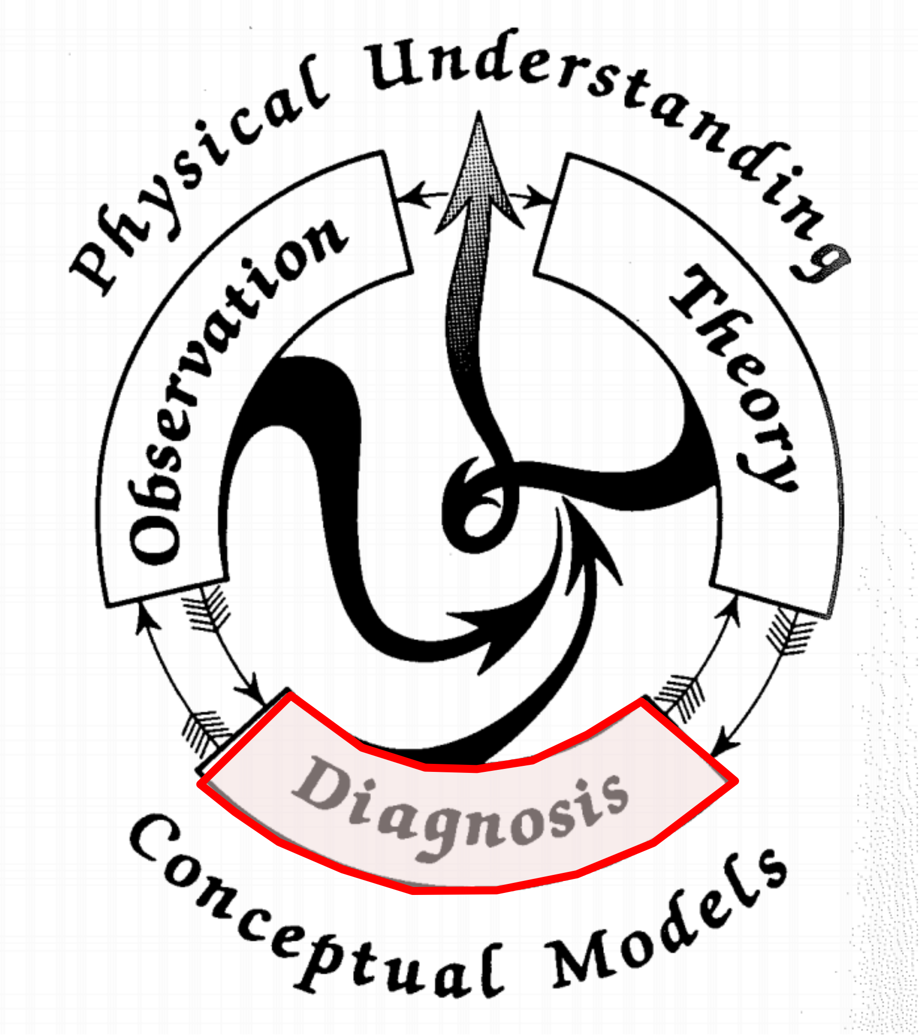
1) **Differential vertical motions** can <u>vertically steepen</u> the tropopause.
2) **Convergence** or a **vertical shear** can produce a <u>differential horizontal advection</u> of the tropopause surface.

PV Frontogenesis

(Davies and Rossa 1998; Wandishin et al. 2000; Pyle et al. 2004)

1) Processes that contribute to an increase in the magnitude of the temperature gradient on the tropopause can be used to diagnose tropopause folding.

Fronts and Frontogenesis



Shapiro et al. (1999)

"The principal task of any meteorological institution of education and research must be to bridge the gap between the mathematician and practical man, that is to make the weather man realize the value of a modest theoretical education and to induce the theoretical man to take an occasional glance at the weather map. The polar front theory, beyond a doubt, represents the most successful effort yet to bridge the gulf that separates meteorological camps"

C.-G. Rossby (1934)

Diagnosis of Fronts

Frontogenesis: The formation of a frontal boundary.

Frontolysis: The decay of a frontal boundary.

Diagnosis of Fronts

Frontogenesis: The formation of a frontal boundary.

Frontolysis: The decay of a frontal boundary.

Mathematically, it describes the Lagrangian rate of change of the magnitude of the horizontal temperature gradient (Bergeron 1928; Petterssen 1936):

$$\boxed{\mathcal{F} = \frac{d}{dt}|\nabla_h \theta|}$$

Diagnosis of Fronts

Frontogenesis: The formation of a frontal boundary.

Frontolysis: The decay of a frontal boundary.

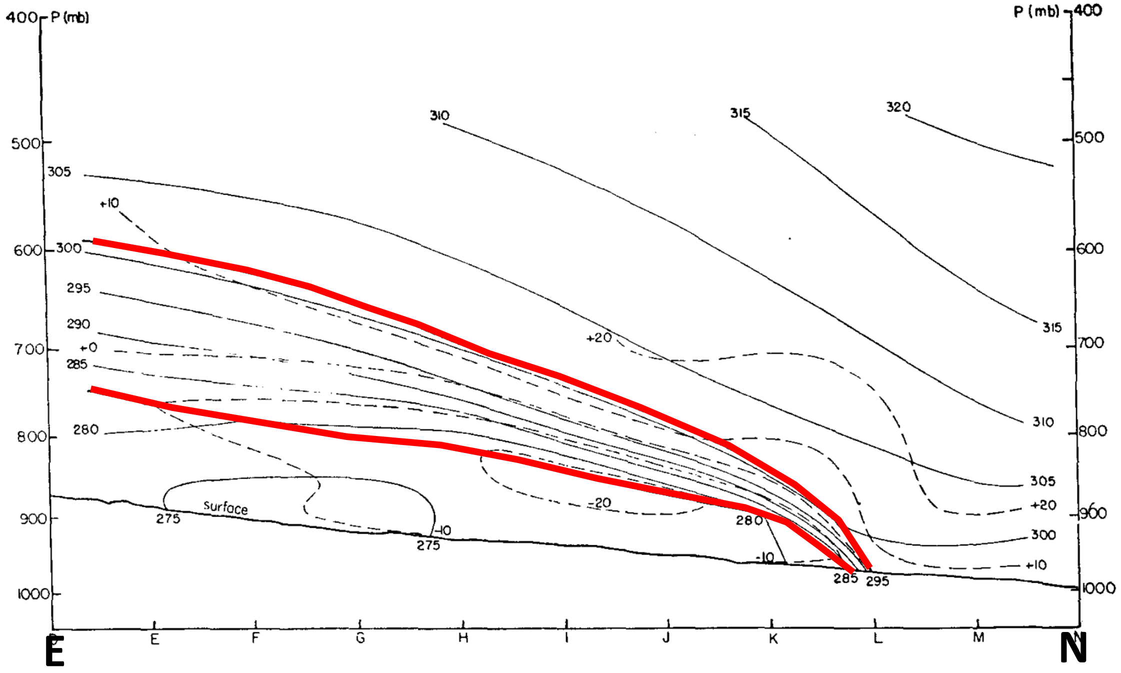
Mathematically, it describes the Lagrangian rate of change of the magnitude of the horizontal temperature gradient (Bergeron 1928; Petterssen 1936):

$$\boxed{\mathcal{F} = \frac{1}{2}|\nabla_h \theta|(\delta - E cos 2\beta)}$$

Diagnosis of Fronts

Kinematics of Frontogenesis

(Miller 1948; Sanders 1955)



$$-\frac{d}{dt}\left(\frac{\partial\theta}{\partial y}\right) = -\frac{\partial}{\partial y}\left(\frac{d\theta}{dt}\right) + \frac{\partial v}{\partial y}\frac{\partial\theta}{\partial y} + \frac{\partial w}{\partial y}\frac{\partial\theta}{\partial z},$$

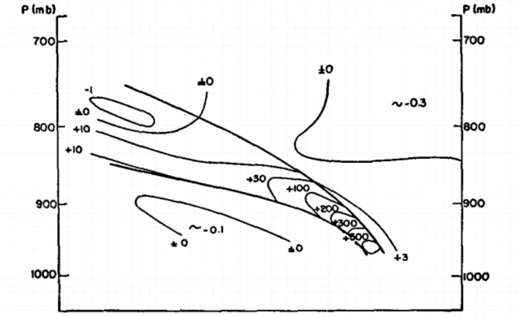


FIG. 11. Frontogenetical effect $(\partial v/\partial y)(\partial\theta/\partial y)$ for part of cross section E–N. Units expressed as 3-hr changes in horizontal temperature gradient in (deg C) (100 km)$^{-1}$. Positive values indicate frontogenesis in temperature field.

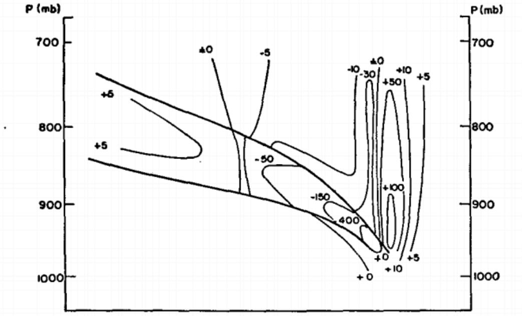


FIG. 12. Frontogenetical effect $(\partial w/\partial y)(\partial\theta/\partial z)$ for part of cross section E–N. Units as in fig. 11.

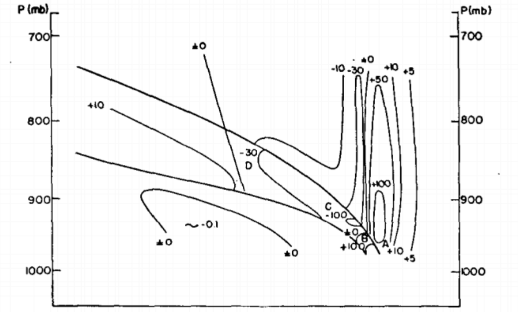
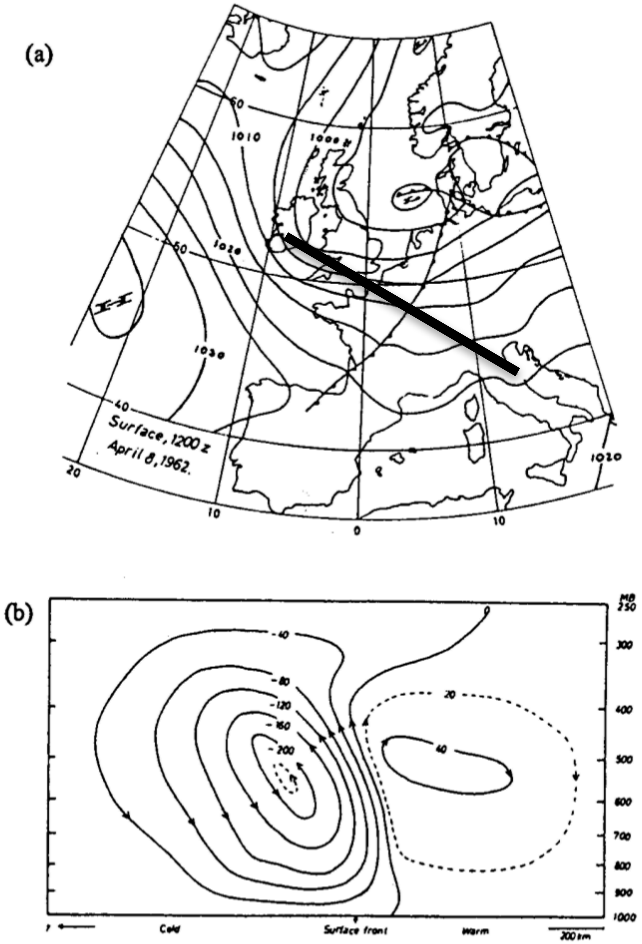


FIG. 13. Net frontogenetical effect, $(\partial w/\partial y)(\partial\theta/\partial z) + (\partial v/\partial y)(\partial\theta/\partial y)$, for part of cross section E–N. Units as in fig. 12.

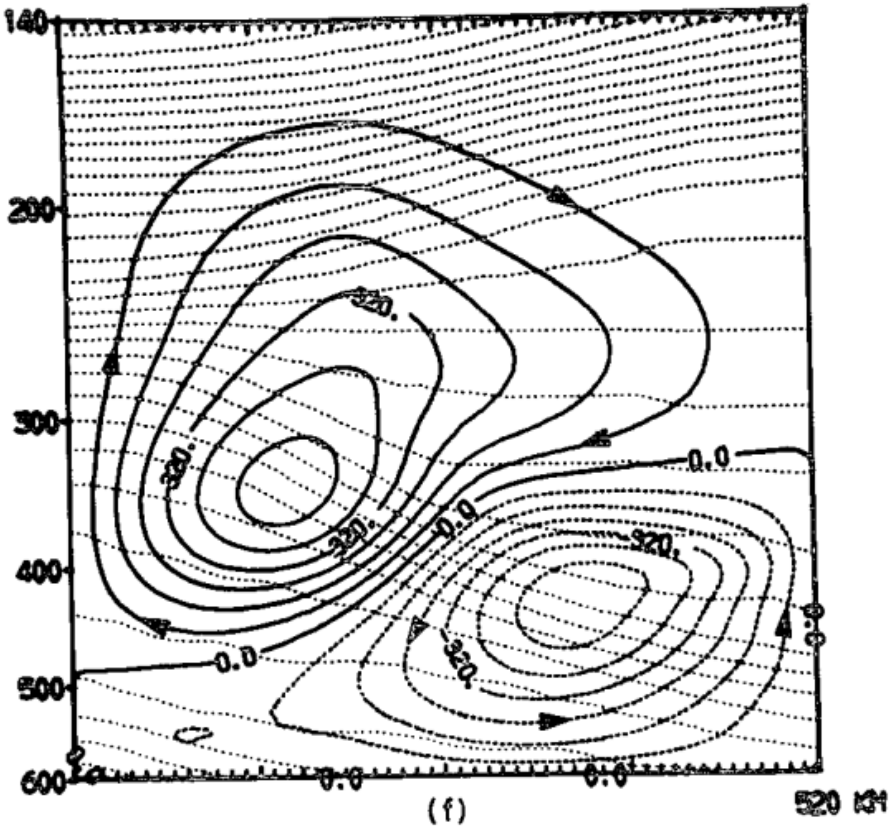
Diagnosis of Fronts

Application of the Sawyer–Eliassen Circulation Equation

Diagnosis of Ageostrophic Transverse Circulations



Todsen (1964)

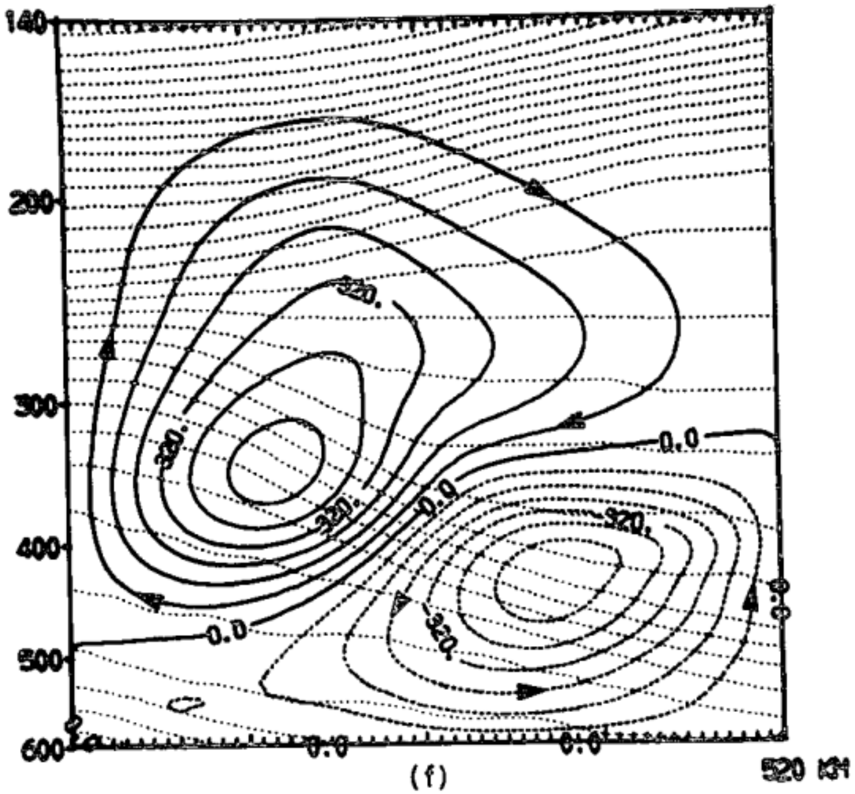


Shapiro (1981)

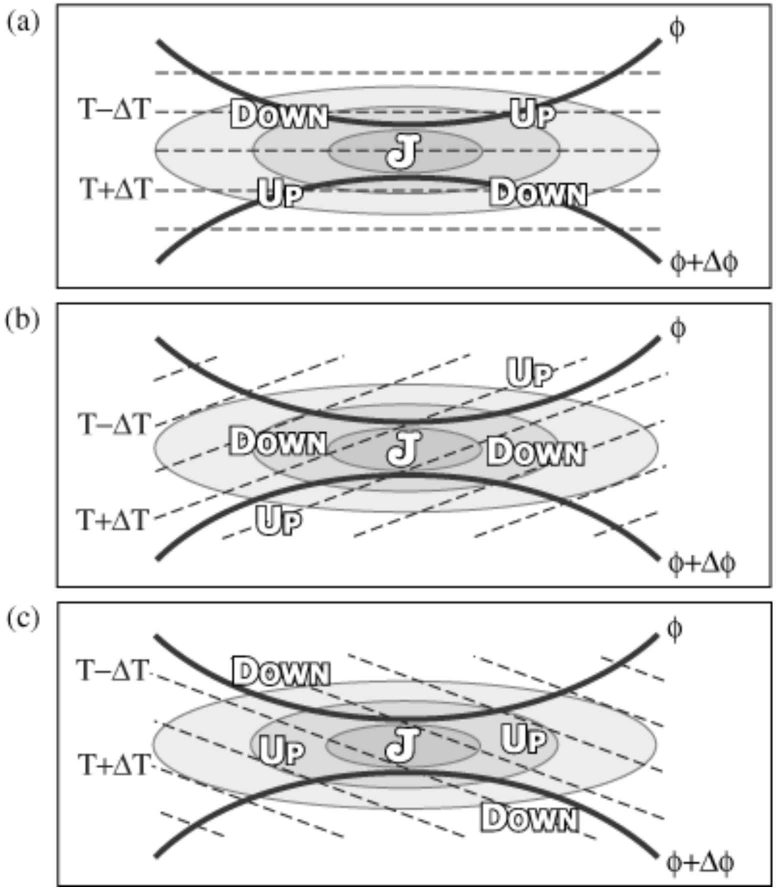
Diagnosis of Fronts

Application of the Sawyer–Eliassen Circulation Equation

Diagnosis of Ageostrophic Transverse Circulations



Shapiro (1981)

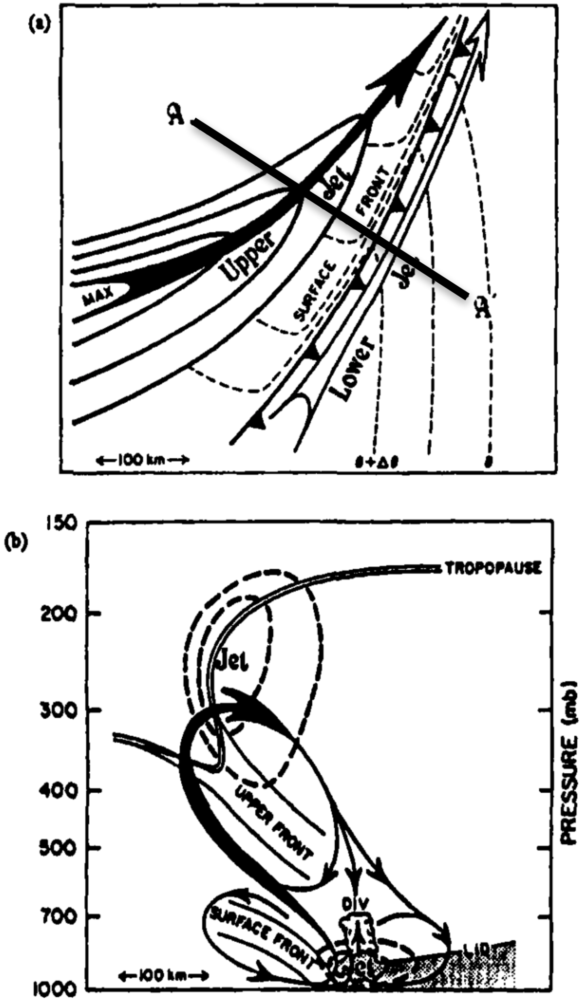

Upper Troposphere

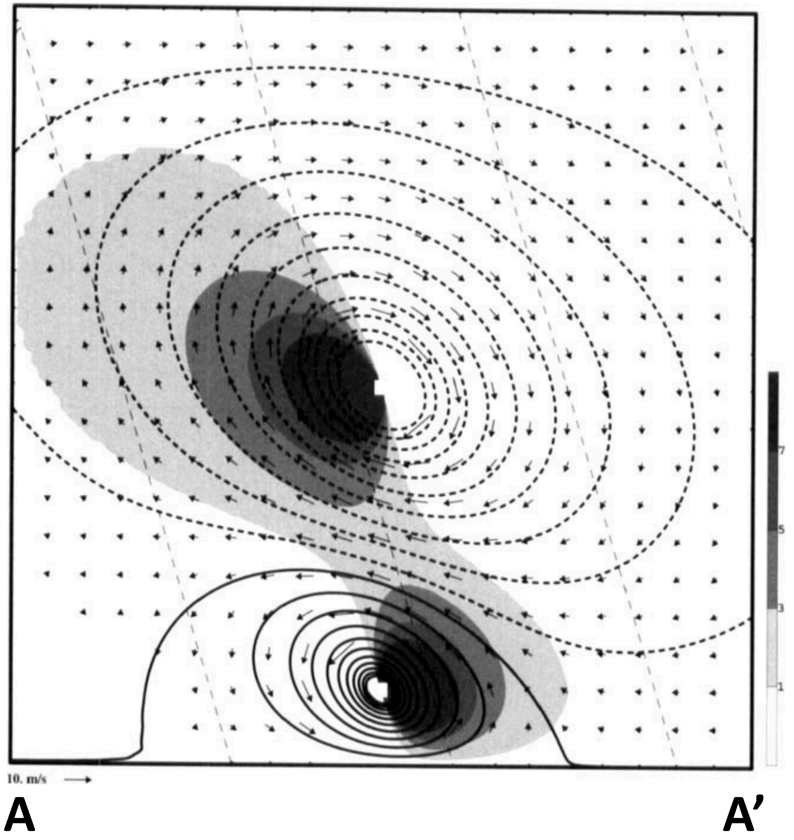
Lang and Martin (2012)

Diagnosis of Fronts

Application of the Sawyer–Eliassen Circulation Equation

Diagnosis of Ageostrophic Transverse Circulations



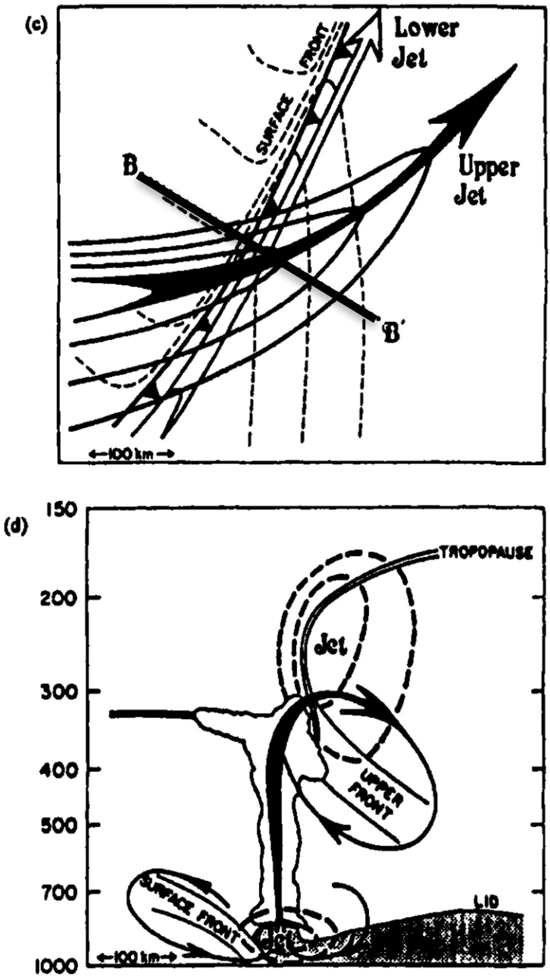


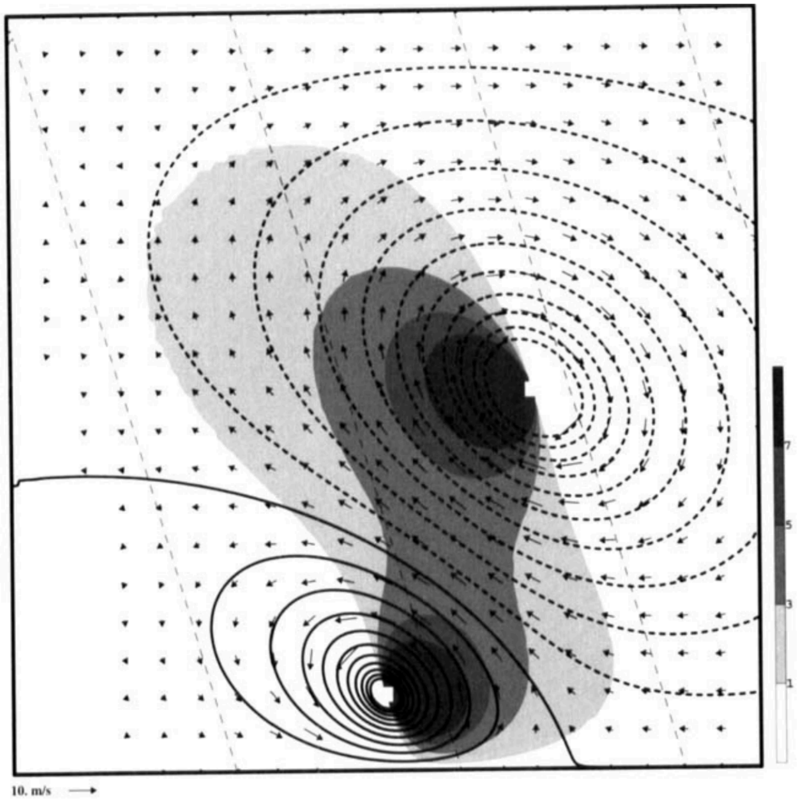
Hakim and Keyser (2001)

Diagnosis of Fronts

Application of the Sawyer–Eliassen Circulation Equation

Diagnosis of Ageostrophic Transverse Circulations





B **B’**

Hakim and Keyser (2001)

Diagnosis of Fronts

Frontal Circulations in Three-Dimensions

The Sawyer–Eliassen Circulation Equation has been generalized to three-dimensions, but its application has been limited (Hoskins and Draghici 1977; Bosart and Lin 1984; Xu 1990).

Diagnosis of Fronts

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The Q-vector can be used to diagnose frontogenesis (Hoskins et al. 1978; Hoskins and Pedder 1980; Keyser et al. 1992; Morgan 1999; Martin 2006).

$$\boxed{\mathcal{F} = \frac{d}{dt}|\nabla_h \theta|}$$

Diagnosis of Fronts

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$$\boxed{\vec{Q} = f\gamma \frac{d}{dt} \nabla_h \theta}$$

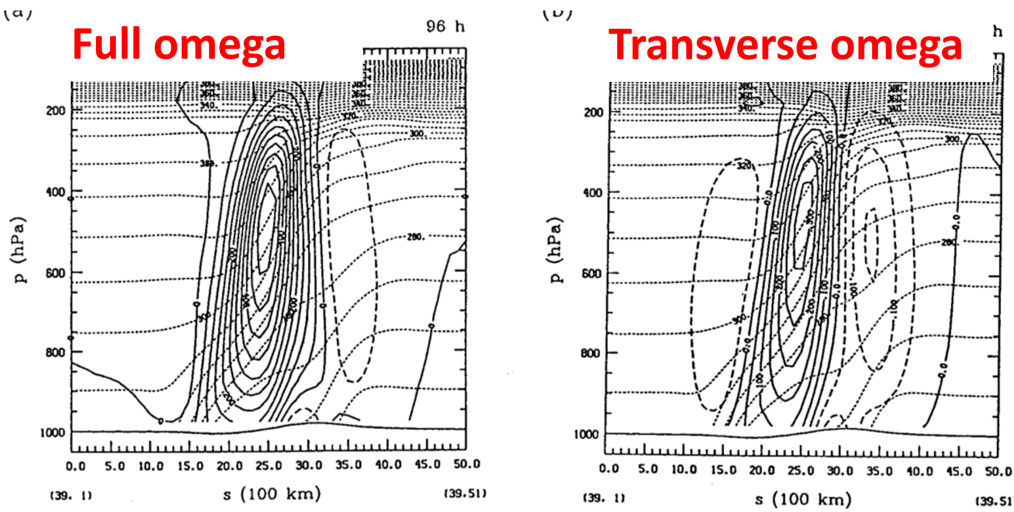
Diagnosis of Fronts

Frontal Circulations in Three-Dimensions – The Psi Vector

The Sawyer–Eliassen Circulation Equation neglects the along-flow component of the ageostrophic wind.

A majority of the vertical motion is of the transverse variety.

There are non-negligible contributions to the vertical motion field in the along-flow direction.



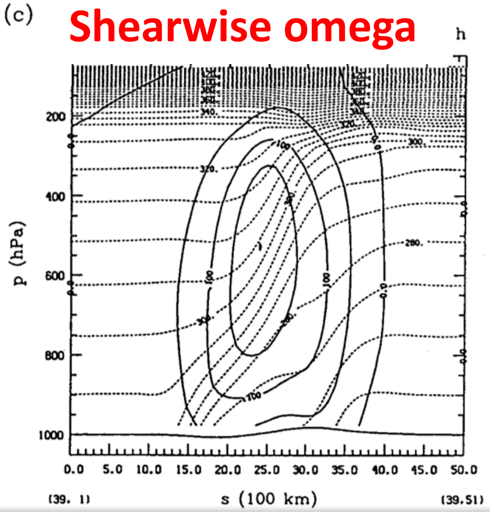


FIG. 16. Cross sections showing total vertical velocity partitioned int cross- and along-front components for the simulated upper-level jet front system depicted in Fig. 14: (a) total pressure-coordinate vertica velocity, ω; (b) vertical velocity associated with divergent circulatio in cross-front direction, ω_s; (c) vertical velocity associated with divergen circulation in along-front direction, ω_n. Contour interval for vertica velocity fields is 0.05 Pa s^{-1}; negative values are long dashed; zero an positive values are solid. Background field is potential temperatur (contour interval 5 K, short dashed). Cross sections extend from gri point (39, 1) ($x = 3800$ km, $y = 0$ km) to grid point (39, 51) ($x = 3800$ km $y = 5000$ km), as indicated on the lower abscissa; distance s along th cross section is in units of 100 km. The nearly horizontal line immediatel above the lower abscissa indicates surface pressure. The sam conventions are used in Figs. 17–19. Cross- and along-front coordinate (vertical velocity components) transform to those in this chapter a follows: $s \rightarrow x$ ($\omega_s \rightarrow \omega_x$) and $n \rightarrow y$ ($\omega_n \rightarrow \omega_y$), where the first entr refers to the coordinate (component) in the figure and the second to it counterpart in the chapter (Keyser et al. 1989).

Keyser et al. (1989)

Future of Frontal Research

1. New observational and modelling capabilities permit reexaminations of frontal characteristics.

2. Research is required to better understand the interaction between diabatic, frictional, and frontal dynamics.

3. An influx of reanalysis and reforecast datasets permits novel evaluations of frontal-cyclone structure and the variability inherent in those structures.

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