The Norwegian Cyclone Model and Extensions

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Reading: Lackmann Section 5.4; Bjerknes and Solberg (1922), Godske et al. (1957, p. 526-537), Reed (1990)

What is the Norwegian Cyclone Model?

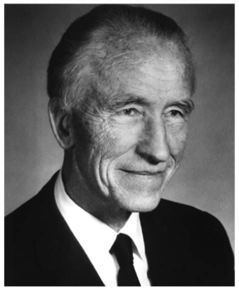
- Conceptual model describing the life cycle *and dynamics* of extratropical cyclones
- Developed by the Bergen School of Meteorology after World War I
- Defined modern meteorological analysis
- Still widely used today

Bergen, Norway

Sources: Google Maps, Wikipedia Commons

Bergen School

Vilhelm Bjerknes and Assistants 1917-1926



Jacob Bjerknes
1897-1975

Halvor Solberg
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Tor Bergeron
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Johan Sandström
Oceanographer
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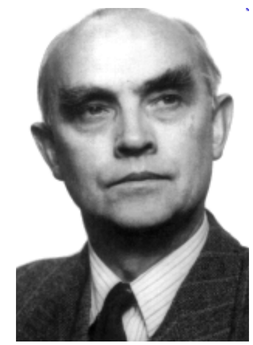


Svien Rossland
Astrophysicist
1894-1985

Also Erik Björkdal

Sources: NOAA, AGU, http://www.snl.no/meteorologi, Time, Wikipedia Commons

Bergen School

Bergen Researchers (ca. 1920). Jacob Bjerknes, Tor Bergeron, unknown, Svein Rosseland, unknown (l.r.).

Source: Shapiro (1994), The Life Cycles of Extratropical Cyclones Commemorative Photo Album

Bergen School

Left to Right: Tor Bergeron, Halvor Solberg, Vilhelm Bjerknes, Harald Sverdrup
Jacob Bjerknes, Sverre Petterssen, Carl Godske

Source: www.snl.no/meteorologi

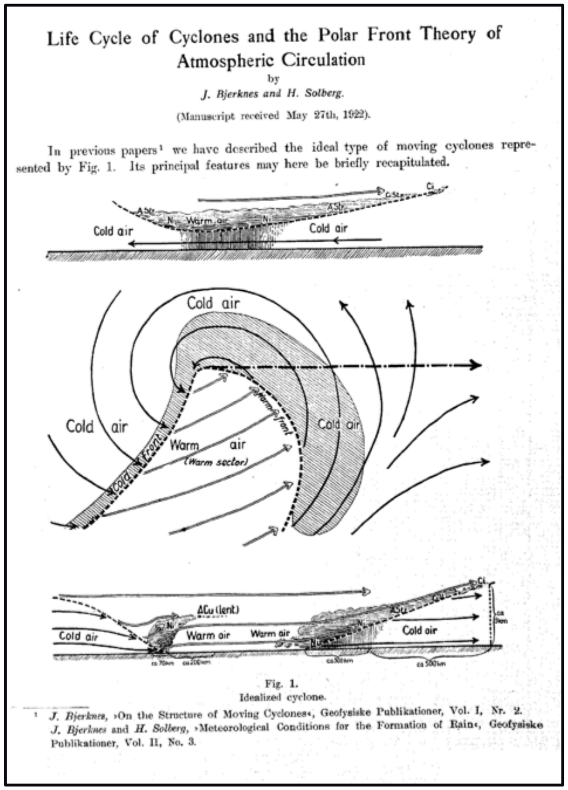
Bergen School

Tor Bergeron and Jacob Bjerknes

Jacob Bjerknes at his weather maps (ca. 1920).

Source: Shapiro (1994), The Life Cycles of Extratropical Cyclones Commemorative Photo Album

Recommended Reading



Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation

by

J. Bjerknes and H. Solberg.

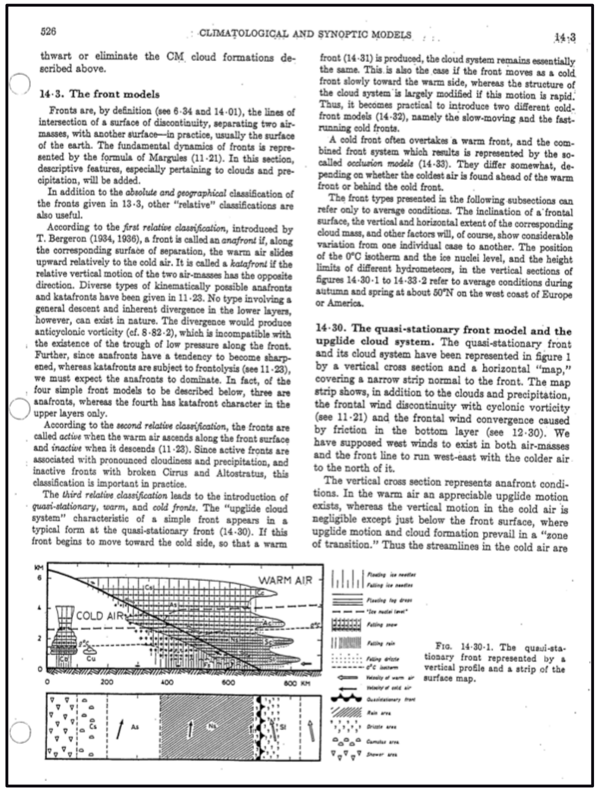
(Manuscript received May 27th, 1922).

In previous papers[1] we have described the ideal type of moving cyclones represented by Fig. 1. Its principal features may here be briefly recapitulated.

Fig. 1.
Idealized cyclone.

[1] *J. Bjerknes*, »On the Structure of Moving Cyclones«, Geofysiske Publikationer, Vol. I, Nr. 2. *J. Bjerknes* and *H. Solberg*, »Meteorological Conditions for the Formation of Rain«, Geofysiske Publikationer, Vol. II, No. 3.

Bjerknes and Solberg (1922)



thwart or eliminate the CM cloud formations described above.

14·3. The front models

Fronts are, by definition (see 6·34 and 14·01), the lines of intersection of a surface of discontinuity, separating two air-masses, with another surface—in practice, usually the surface of the earth. The fundamental dynamics of fronts is represented by the formula of Margules (11·21). In this section, descriptive features, especially pertaining to clouds and precipitation, will be added.

In addition to the *absolute and geographical* classification of the fronts given in 13·3, other "relative" classifications are also useful.

According to the *first relative classification*, introduced by T. Bergeron (1934, 1936), a front is called an *anafront* if, along the corresponding surface of separation, the warm air slides upward relatively to the cold air. It is called a *katafront* if the relative vertical motion of the two air-masses has the opposite direction. Diverse types of kinematically possible anafronts and katafronts have been given in 11·23. No type involving a general descent and inherent divergence in the lower layers, however, can exist in nature. The divergence would produce anticyclonic vorticity (cf. 8·82·2), which is incompatible with the existence of the trough of low pressure along the front. Further, since anafronts have a tendency to become sharpened, whereas katafronts are subject to frontolysis (see 11·23), we must expect the anafronts to dominate. In fact, of the four simple front models to be described below, three are anafronts, whereas the fourth has katafront character in the upper layers only.

According to the *second relative classification*, the fronts are called *active* when the warm air ascends along the front surface and *inactive* when it descends (11·23). Since active fronts are associated with pronounced cloudiness and precipitation, and inactive fronts with broken Cirrus and Altostratus, this classification is important in practice.

The *third relative classification* leads to the introduction of *quasi-stationary*, *warm*, and *cold fronts*. The "upglide cloud system" characteristic of a simple front appears in a typical form at the quasi-stationary front (14·30). If this front begins to move toward the cold side, so that a warm front (14·31) is produced, the cloud system remains essentially the same. This is also the case if the front moves as a cold front slowly toward the warm side, whereas the structure of the cloud system is largely modified if this motion is rapid. Thus, it becomes practical to introduce two different cold-front models (14·32), namely the slow-moving and the fast-running cold fronts.

A cold front often overtakes a warm front, and the combined front system which results is represented by the so-called *occlusion models* (14·33). They differ somewhat, depending on whether the coldest air is found ahead of the warm front or behind the cold front.

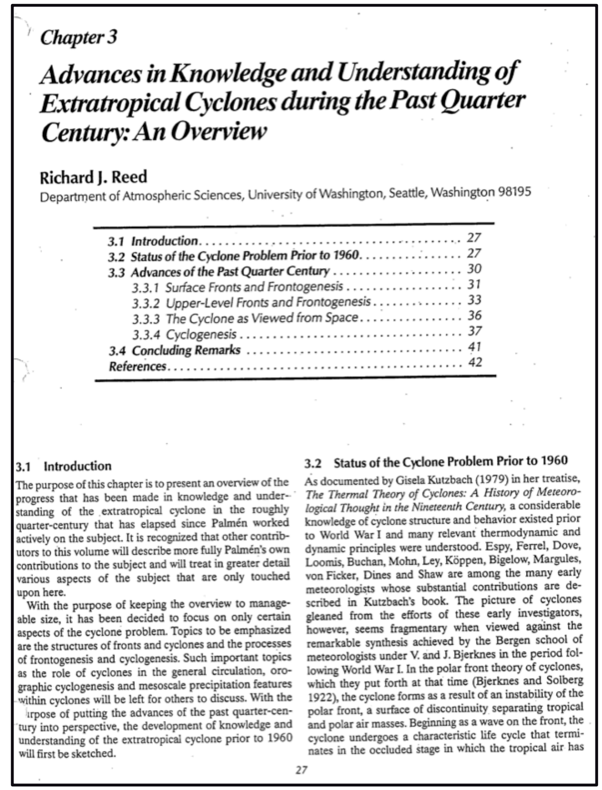
The front types presented in the following subsections can refer only to average conditions. The inclination of a frontal surface, the vertical and horizontal extent of the corresponding cloud mass, and other factors will, of course, show considerable variation from one individual case to another. The position of the 0°C isotherm and the ice nuclei level, and the height limits of different hydrometeors, in the vertical sections of figures 14·30·1 to 14·33·2 refer to average conditions during autumn and spring at about 50°N on the west coast of Europe or America.

14·30. The quasi-stationary front model and the upglide cloud system. The quasi-stationary front and its cloud system have been represented in figure 1 by a vertical cross section and a horizontal "map," covering a narrow strip normal to the front. The map strip shows, in addition to the clouds and precipitation, the frontal wind discontinuity with cyclonic vorticity (see 11·21) and the frontal wind convergence caused by friction in the bottom layer (see 12·30). We have supposed west winds to exist in both air-masses and the front line to run west-east with the colder air to the north of it.

The vertical cross section represents anafront conditions. In the warm air an appreciable upglide motion exists, whereas the vertical motion in the cold air is negligible except just below the front surface, where upglide motion and cloud formation prevail in a "zone of transition." Thus the streamlines in the cold air are

FIG. 14·30·1. The quasi-stationary front represented by a vertical profile and a strip of the surface map.

Godske et al. (1957)



Chapter 3

Advances in Knowledge and Understanding of Extratropical Cyclones during the Past Quarter Century: An Overview

Richard J. Reed
Department of Atmospheric Sciences, University of Washington, Seattle, Washington 98195

3.1 Introduction

The purpose of this chapter is to present an overview of the progress that has been made in knowledge and understanding of the extratropical cyclone in the roughly quarter-century that has elapsed since Palmén worked actively on the subject. It is recognized that other contributors to this volume will describe more fully Palmén's own contributions to the subject and will treat in greater detail various aspects of the subject that are only touched upon here.

With the purpose of keeping the overview to manageable size, it has been decided to focus on only certain aspects of the cyclone problem. Topics to be emphasized are the structures of fronts and cyclones and the processes of frontogenesis and cyclogenesis. Such important topics as the role of cyclones in the general circulation, orographic cyclogenesis and mesoscale precipitation features within cyclones will be left for others to discuss. With the purpose of putting the advances of the past quarter-century into perspective, the development of knowledge and understanding of the extratropical cyclone prior to 1960 will first be sketched.

3.2 Status of the Cyclone Problem Prior to 1960

As documented by Gisela Kutzbach (1979) in her treatise, *The Thermal Theory of Cyclones: A History of Meteorological Thought in the Nineteenth Century*, a considerable knowledge of cyclone structure and behavior existed prior to World War I and many relevant thermodynamic and dynamic principles were understood. Espy, Ferrel, Dove, Loomis, Buchan, Mohn, Ley, Köppen, Bigelow, Margules, von Ficker, Dines and Shaw are among the many early meteorologists whose substantial contributions are described in Kutzbach's book. The picture of cyclones gleaned from the efforts of these early investigators, however, seems fragmentary when viewed against the remarkable synthesis achieved by the Bergen school of meteorologists under V. and J. Bjerknes in the period following World War I. In the polar front theory of cyclones, which they put forth at that time (Bjerknes and Solberg 1922), the cyclone forms as a result of an instability of the polar front, a surface of discontinuity separating tropical and polar air masses. Beginning as a wave on the front, the cyclone undergoes a characteristic life cycle that terminates in the occluded stage in which the tropical air has

Reed (1990)

Initial Description: Ideal Cyclone

- Two airmasses (warm and cold) separated by a fairly distinct boundary surface that runs through the center of the system
- The boundary surface is imagined to continue through a greater part of the troposphere at a small angle to the horizon

Zonal section through cold sector north of low center

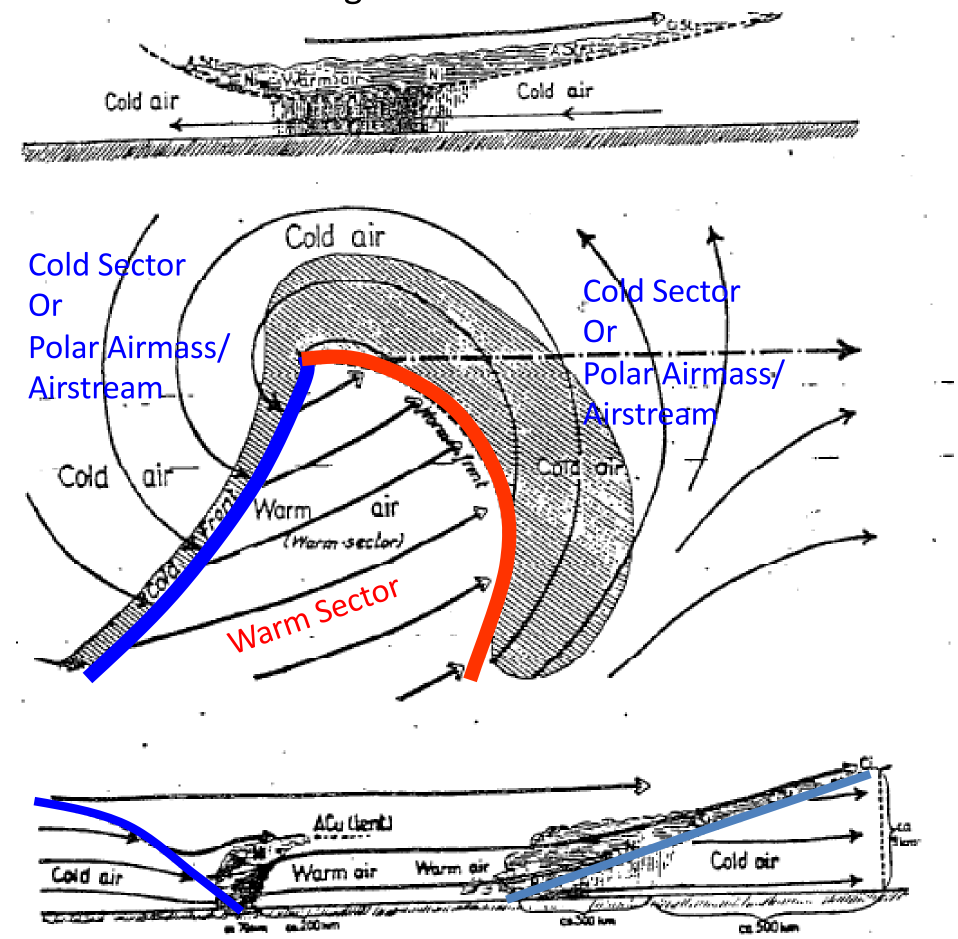


Fig. 1.

Zonal section through warm sector north of low center

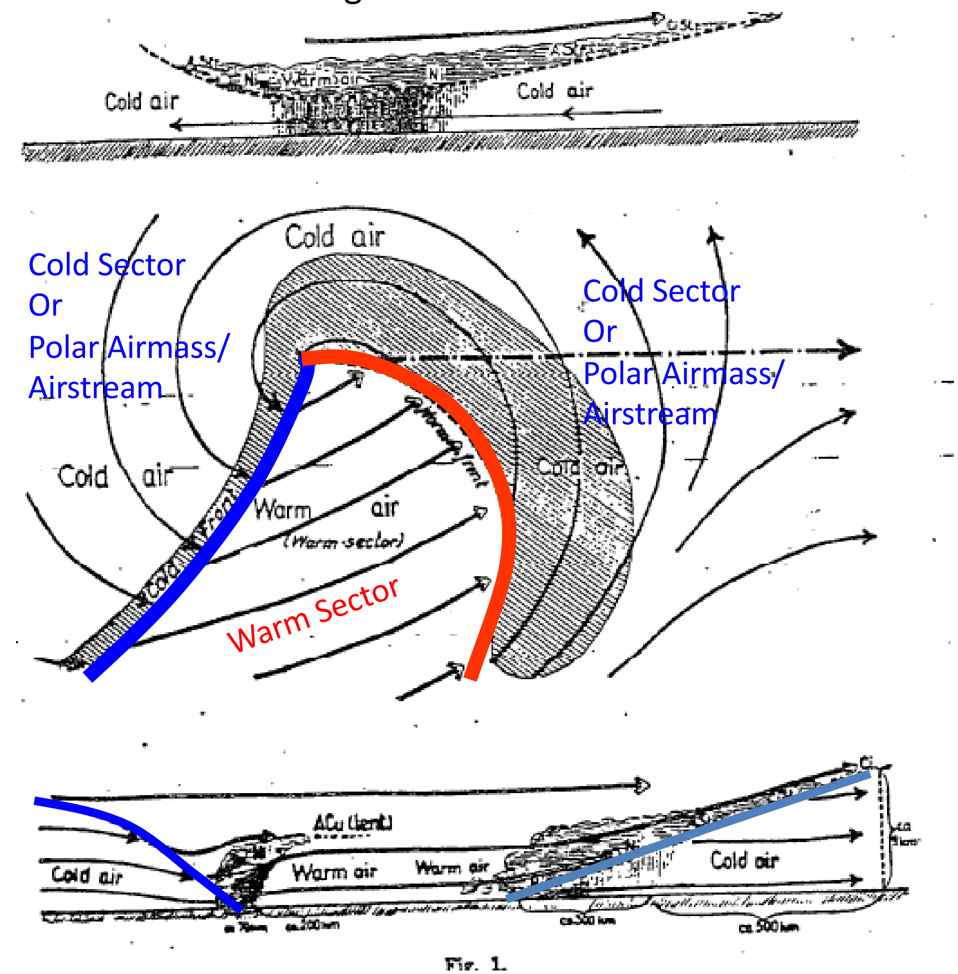
Source: Bjerknes (1919), Bjerknes and Solberg (1922)

Initial Description: Ideal Cyclone

- Warm air in the warm sector is conveyed by a SW or W current & ascends the wedge of cold air ahead of the warm front, producing warm-frontal precipitation

- The intrusion of cold air from behind the system into the warm sector lifts the warm airmass, producing cold-frontal precipitation

Zonal section through cold sector north of low center



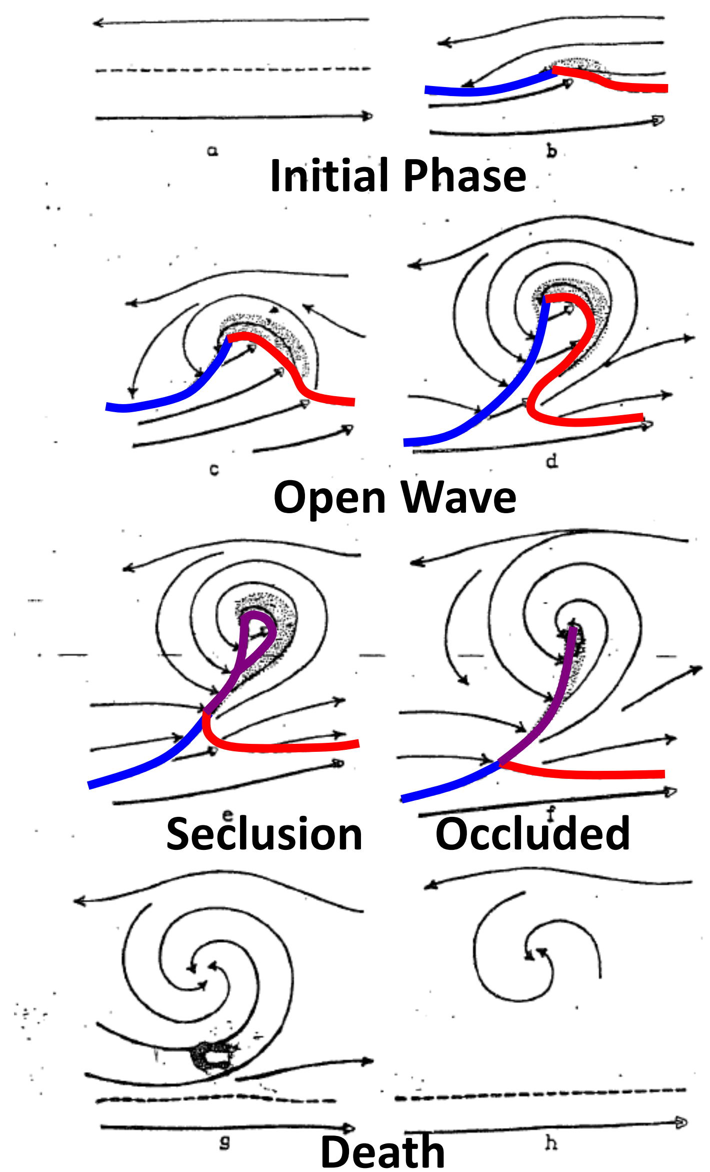
Zonal section through warm sector north of low center

Source: Bjerknes (1919), Bjerknes and Solberg (1922)

Idealized Cyclone Life Cycle

- Initial Phase
  - Two oppositely directed currents of different temperature are separated by a nearly straight boundary
  - The boundary begins to bulge toward the cold air at the place where the cyclone will form

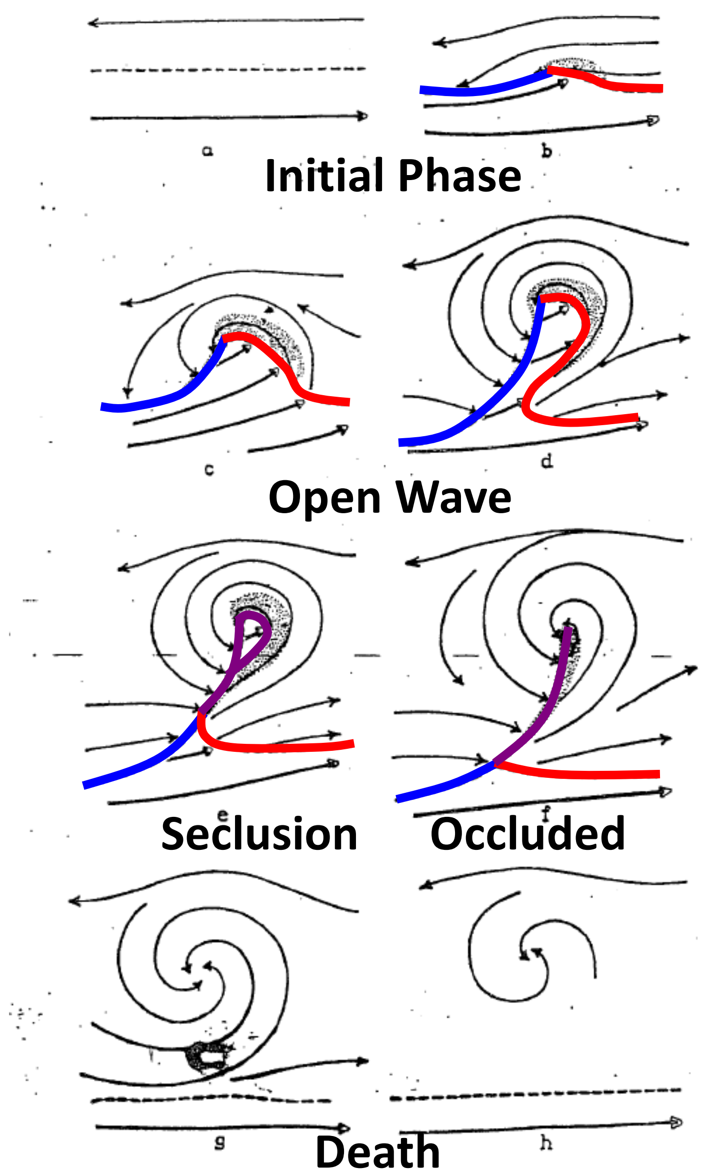
- Open Wave
  - The amplitude of the warm wave increases
  - Cold air moves cyclonically around the low center
  - Warm sector narrows



Source: Bjerknes and Solberg (1922)

Idealized Cyclone Life Cycle

- Secluded Phase
  - Cold front overtakes warm front south of low center
  - Piece of warm sector air is cut off
- Occluded Phase
  - Remaining part of warm sector is removed from surface
- Maturity/Death
  - Occluded front dissipates
  - Cyclone becomes symmetric vortex of cold air



Source: Bjerknes and Solberg (1922)

Vertical Evolution

- Open Wave Phase
  - Two wedges of cold air approach each other
  - Intermediate warm sector air is lifted
  - Transforms potential to kinetic energy
    - Simplistic view

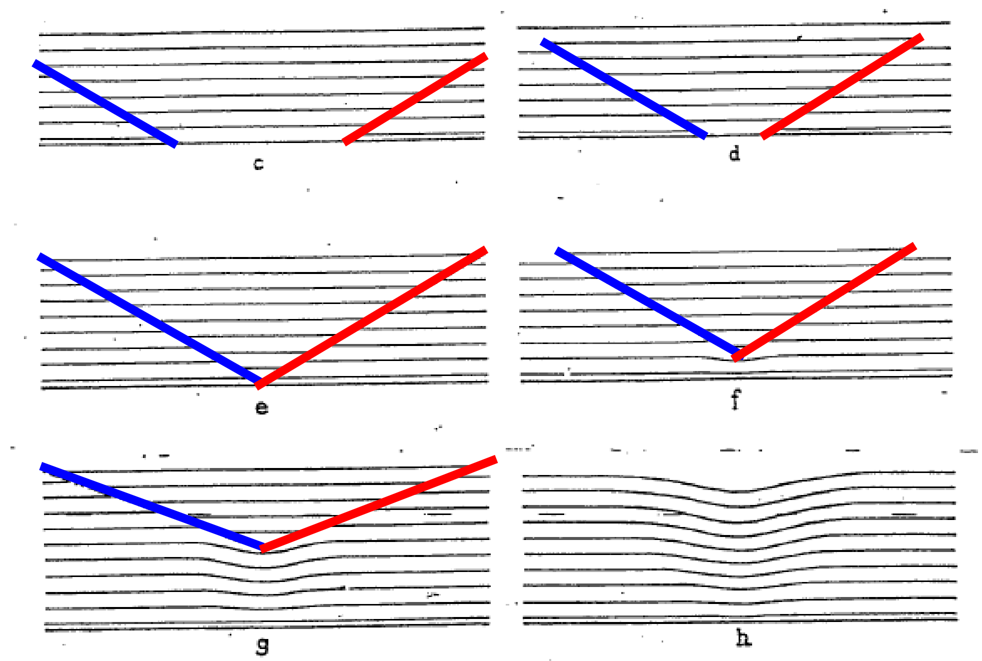


Fig. 3. Vertical sections through cyclones in different stages of development.
——— isothermal lines.
.... — .... lines of discontinuity.

Source: Bjerknes and Solberg (1922)

Vertical Evolution

- Occluded Phase
  - Once two wedges have met on the ground, the upper warm sector is lifted until warm sector has cooled adiabatically to the temperature of its surroundings
  - Throughout this phase, cyclone gains kinetic energy

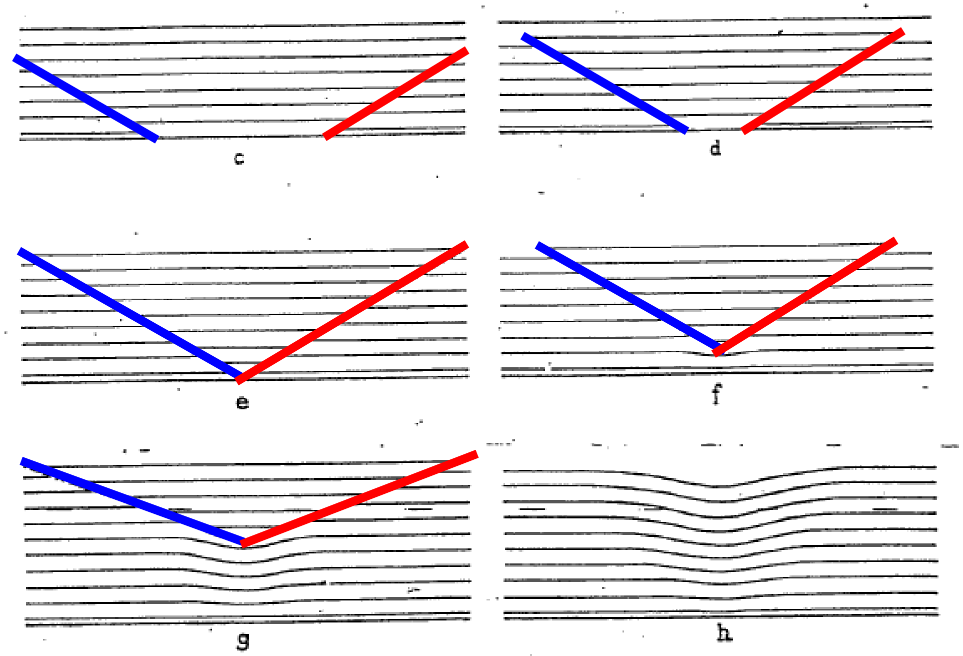


Fig. 3. Vertical sections through cyclones in different stages of development.
——— isothermal lines.
..... —— .... lines of discontinuity.

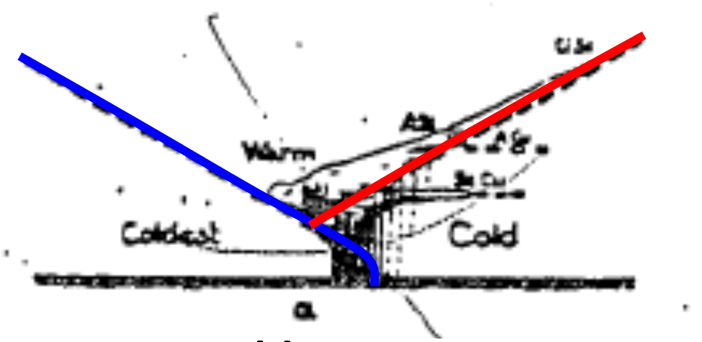
Source: Bjerknes and Solberg (1922)

Energy Transformations

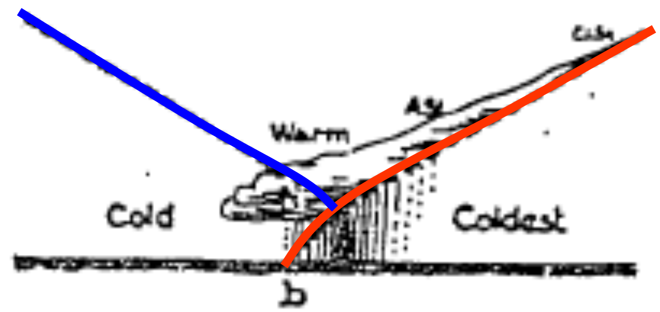
- Essential condition for cyclone formation is coexistence of warm & cold air adjacent to each other
- All cyclones which are not yet occluded have increasing kinetic energy
- Soon after occlusion, the cyclone begins to fill
- In later stages, cyclone becomes a homogenous vortex of cold air that consumes the previously generated kinetic energy

Source: Bjerknes and Solberg (1922)

Occlusion Types



Cold Type



Warm Type

- Cold Type
  - Forms if air behind cold front is colder than air ahead of warm front
  - Has character of cold front with narrow precipitation zone

- Warm Type
  - Forms if air behind cold front is warmer than air ahead of warm front
  - Has character of warm front with broad precipitation zone

- Claim cold type is most common

Source: Bjerknes and Solberg (1922)

Secondary Cold Fronts

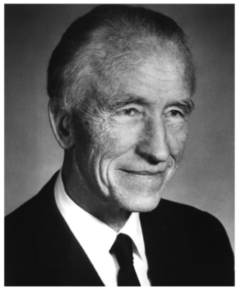
- The cold air may contain a series of secondary cold fronts accompanied by only small contrasts in temperature and wind

- The appearance of a strong secondary cold front that is stronger than the primary cold front indicates a reinforcement of the cyclone

Source: Bjerknes and Solberg (1922)

Subsequent Refinements

Bergen School meteorologists did not stop working in 1922!



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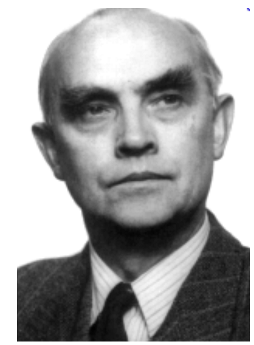

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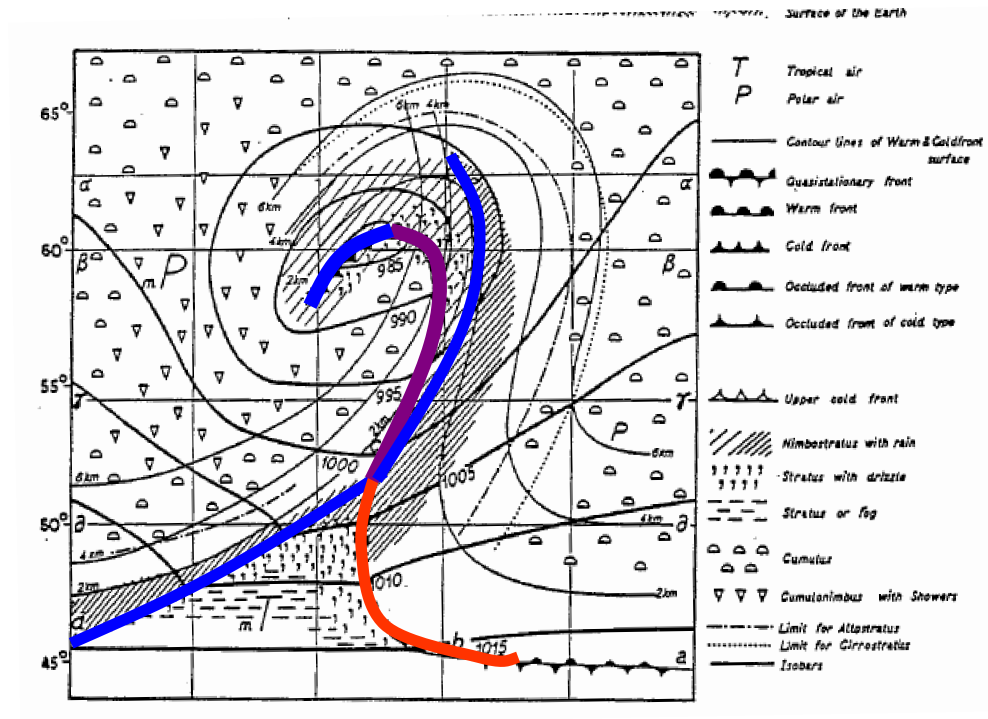
Sources: NOAA, AGU, http://www.snl.no/meteorologi, Time, Wikipedia Commons

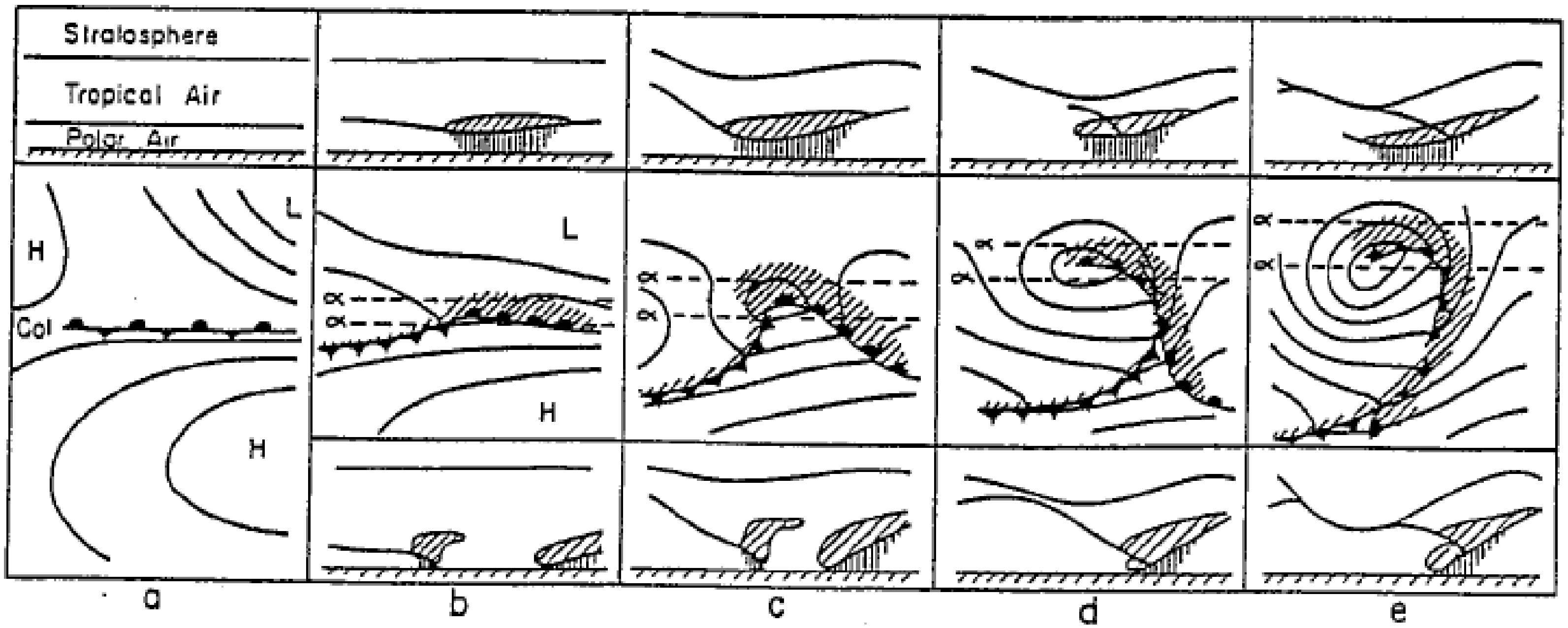
Occluded Cyclone Refinements

- Identify new features
  - Upper-cold front
    - Accompanies warm-type occlusions
  - Bent-back occlusion
    - Extends into polar airstream behind low
  - False warm sector
    - Between bent-back occlusion and primary cold front



Source: Godske et al. (1957)

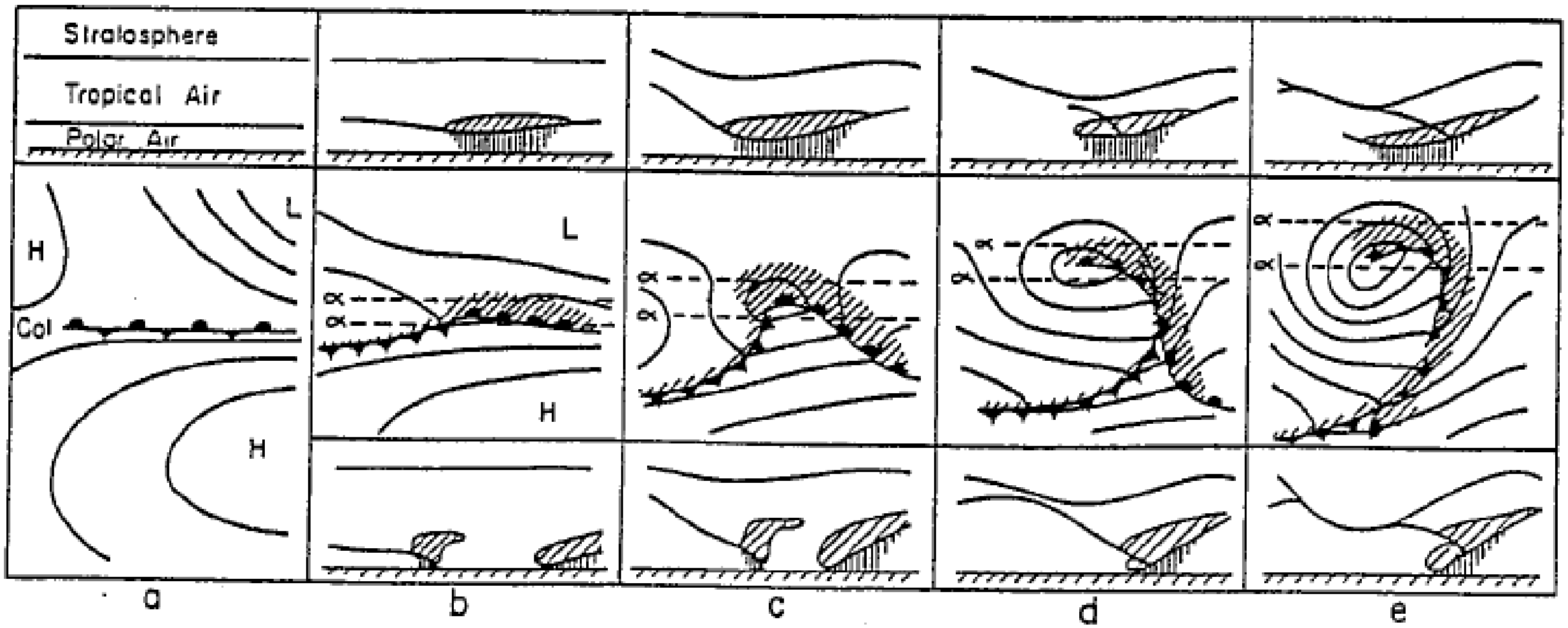
Life Cycle Refinements



- Antecedent Stage
  - Similar to Bjerknes and Solberg (1922)
- Nascent Stage
  - Newly formed wave with velocity nearly equal to that of warm-sector air near ground

Source: Godske et al. (1957)

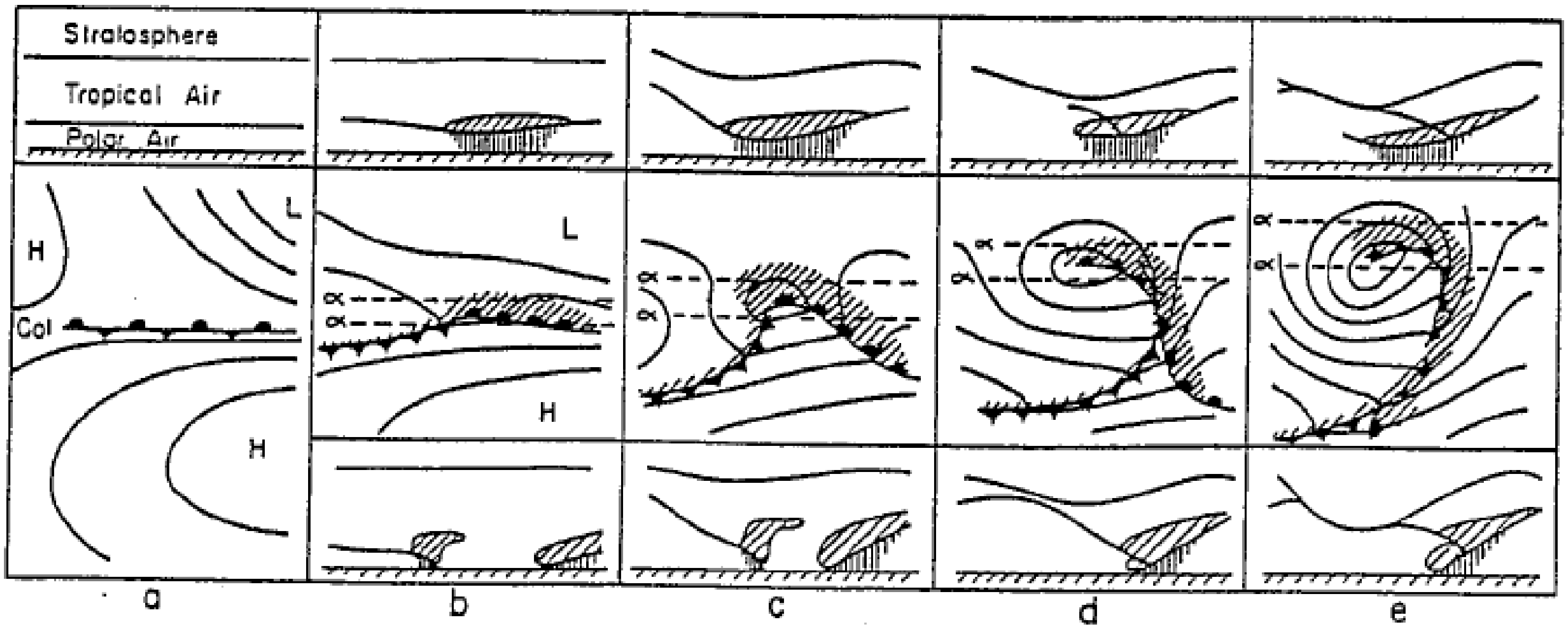
Life Cycle Refinements



- Wave Cyclone
  - Further development of cyclone and frontal wave
  - Frontolysis occurs along cold front near low center
  - Phase lag of upper-level wave relative to surface wave

Source: Godske et al. (1957)

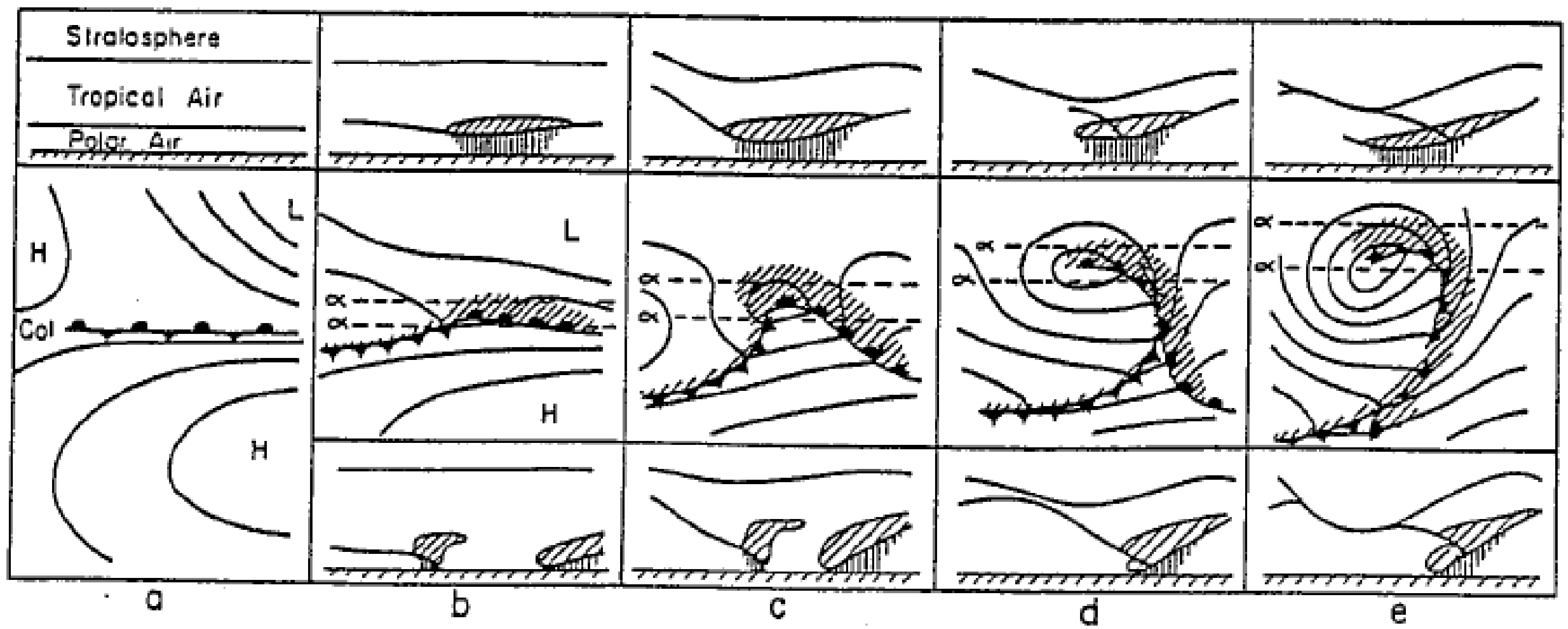
Life Cycle Refinements



- Occluded cyclone
  - Cold front climbs warm front and forms upper-cold front
  - Pressure trough forms to rear of cyclone and rotates cyclonically around low center
  - Near low-center, a bent-back occlusion may coincide with trough

Source: Godske et al. (1957)

Life Cycle Refinements

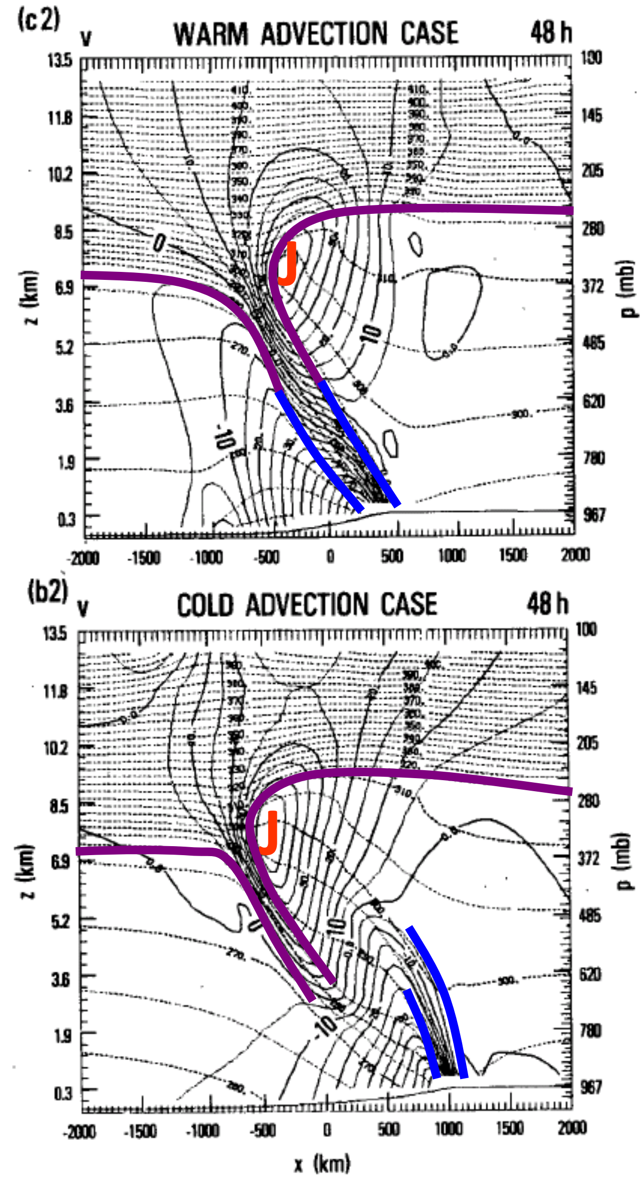


- Occluded cyclone
  - More removed from low center, it may be a non-frontal trough
  - Cyclone regeneration can occur if bent-back front is longer and stronger than normal and separates polar airmasses of differing temperature

Source: Godske et al. (1957)

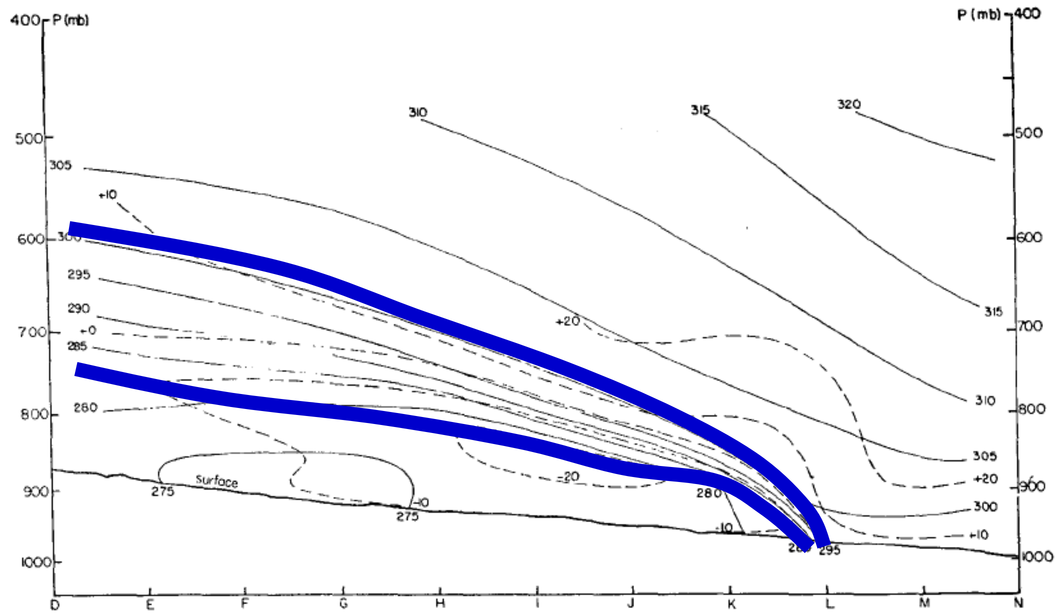
More Modifications and Extensions

- Frontal Structure/Dynamics
  - Depiction of the polar front as a discontinuity separating tropical and polar airmasses is an overidealization
  - Upper-level and surface-based fronts may be discontinuous and have differing dynamics



Source: Keyser and Pecnick (1985), Reed (1990)

More Modifications and Extensions

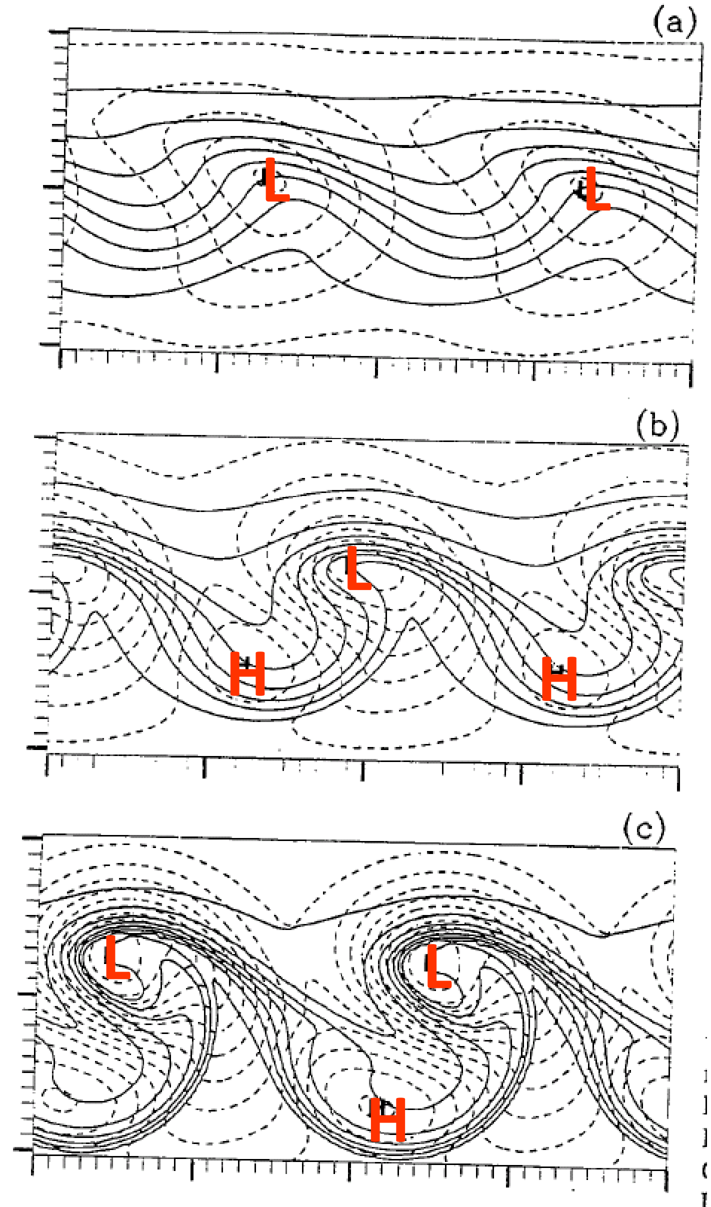


- Frontal Structure/Dynamics
  - Surface-based fronts may have extreme intensity at the ground, but weaken with height

Source: Sanders (1955), Reed (1990)

More Modifications and Extensions

- Frontal Structure/Dynamics
  - Frontal zones are better regarded as regions of active frontogenesis rather than semi-permanent phenomenon
  - Fronts are often a consequence of cyclogenesis rather than the cause



Source: Schar (1989), Reed (1990)

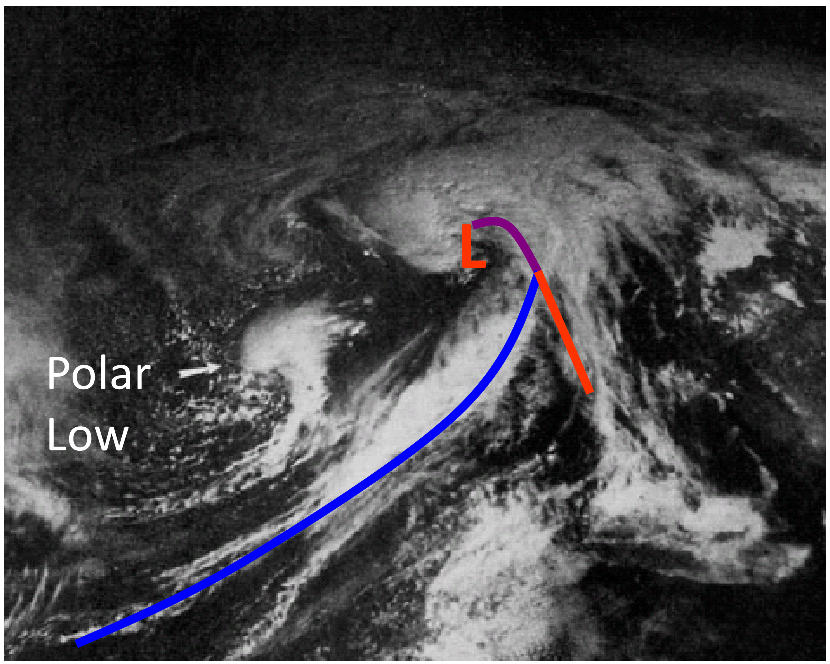
More Modifications and Extensions

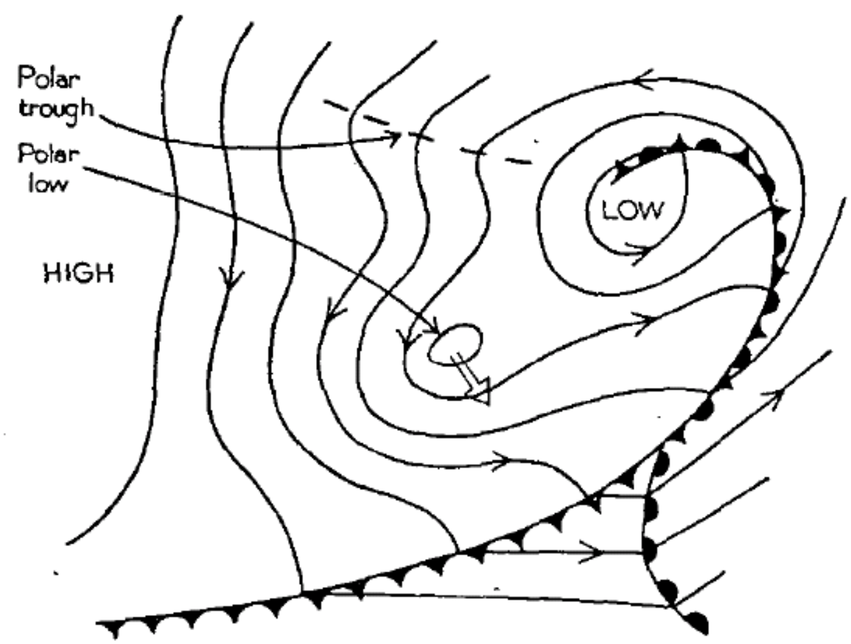
- Cyclone Dynamics
  - Cyclone development may be viewed as a consequence of baroclinic instability rather than frontal instabilities
  - There are three major building blocks for observed cyclogenesis (thanks to discovery of jet stream and development of PV thinking)
    - Upper-level trough/cyclonic PV anomaly
    - Surface front (surrogate cyclonic PV anomaly)
    - Diabatic heating

Source: Reed (1990)

More Modifications and Extensions

- Cyclone Dynamics
  - There are patterns of cyclone development not envisioned by the Bergen School
    - e.g, cyclogenesis in polar airstreams (a.k.a the polar





Source: Reed (1990)

Class Activity

- Divide into groups of 3-4 students
- Each group analyzes the life cycle of selected (and independent) frontal cyclones identified with the IDV "Global-10day" bundle
- Base frontal analyses on the 925-mb temperature analysis and use IDVs drawing control options to analyze the fronts every 12 hours
- Drawing control may be accessed by clicking on the pencil at the top of the IDV window
- Use a different drawing control (by clicking on the pencil again) for each analysis time