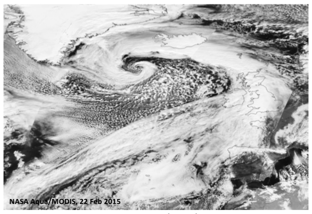
Clouds and Precipitation in Extratropical Cyclones

VU2: Course Number 707813



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Learning Objectives

- After this class you should be able to
  - Recognize key cloud and precipitation features accompanying extratropical cyclones
  - Describe the processes responsible for these cloud and precipitation features

Extratropical Cyclones

Definitions

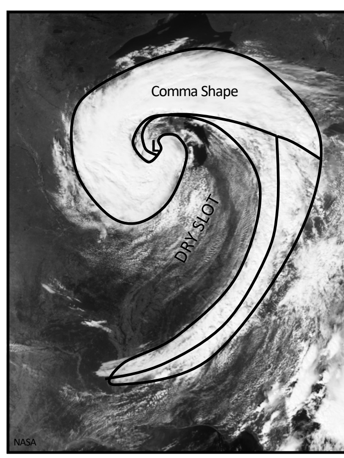
Extratropical Cyclone – a cyclonic storm deriving its energy primarily from the horizontal temperature gradient that exists In the midlatitudes (a.k.a. midlatitude, baroclinic, or frontal cyclone)

Variants – Polar lows and Medicanes, which typically are accompanied by upper-level troughs but develop tropical-cyclone-like characteristics due to air-sea interactions

Extratropical Transition (ET) – Development pathway involving the transition of a tropical cyclone into an extratropical cyclone

Group Activity

Identify the following:
Comma cloud
Dry Slot
Warm, cold, and occluded front
Expected precipitation areas
Possible precipitation bands



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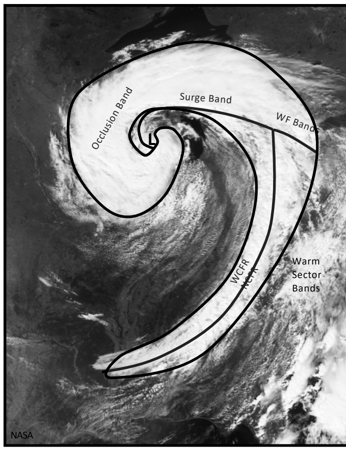
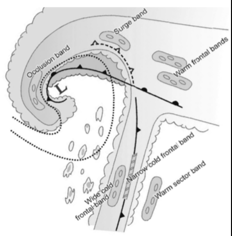
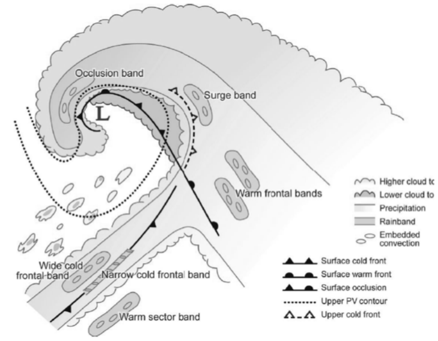




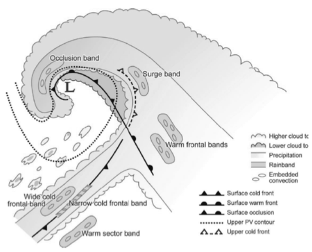
Houze (2014)

Idealized Extratropical Cyclone



Houze (2014)

Group Discussion

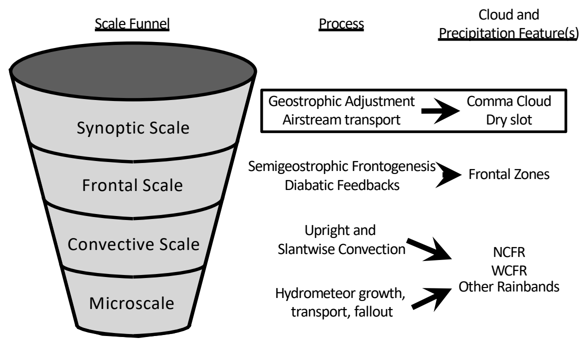


What processes contribute to the development of these precipitation features?

Specifically, the comma shape, dry slot, warm-frontal precipitation, NCFR, WCFR, Occluded band, surge band, and warm-frontal bands?

Houze (2014)

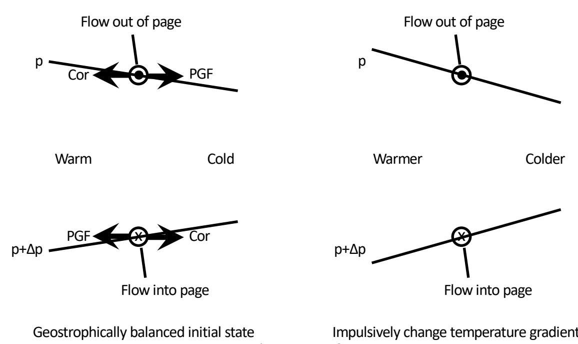
Multiscale Processes



Geostrophic Adjustment

- The mutual adjustment of wind and pressure fields to a geostrophically balanced state
  - i.e., balance between the pressure gradient and Coriolis accelerations
  - Implies thermal wind balance

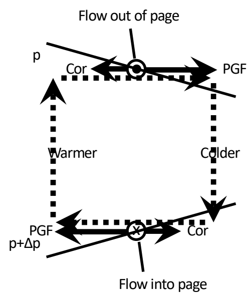
Discussion



What Happens?

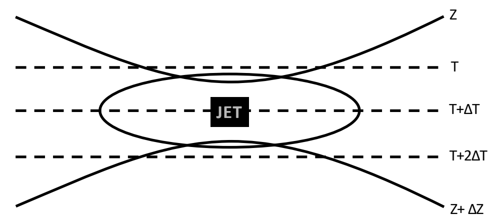
Discussion

- Impulsive change in temperature gradient changes thickness and pressure gradients
- PGF overwhelms Coriolis
  - Oppositely directed ageostrophic winds develop at upper and lower levels
- By continuity warm air ascends and cold air sinks
  - Ageostrophic secondary circulation
- Secondary circulation relaxes atmosphere back toward thermal wind balance
  - Warm air cools, cold air warms
  - Coriolis acting on ageostrphic winds enhances flow aloft and weakens flow near surface, enhancing shear



Ageostrophic Secondary Circulation

Geostrophic Paradox



How does the geostrophic flow affect the thermal wind balance in the entrance and exit regions of this jet streak?

Diagnose the secondary circulations and determine if they relax the atmosphere toward geostrophic balance

Diagnosing Large-Scale Ascent

Assuming quasigeostrophy, the vertical motion needed to maintain thermal wind balance Is given by the Q-vector form of the omega equation

$$\left[\nabla^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right]\omega = -2\nabla\cdot\vec{Q}$$

Q is given by

$$\vec{Q} = \frac{R}{p}\left[\left(\frac{\partial \vec{V}_g}{\partial x}\cdot\nabla T\right)\hat{\imath}, \left(\frac{\partial \vec{V}_g}{\partial y}\cdot\nabla T\right)\hat{\jmath}\right] = \frac{R}{p_0}\left(\frac{p_0}{p}\right)^{c_v/c_p}\frac{D}{Dt_g}\nabla\theta \propto \frac{D}{Dt_g}\nabla\theta$$

Rate of change of $\nabla\theta$ following geostrophic motion

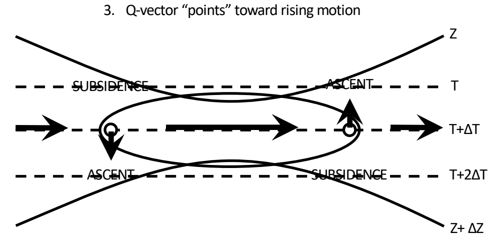
With vertical velocity (w) proportional to the divergence of the Q vector

$$w \propto -\omega \propto \nabla\cdot\vec{Q}$$

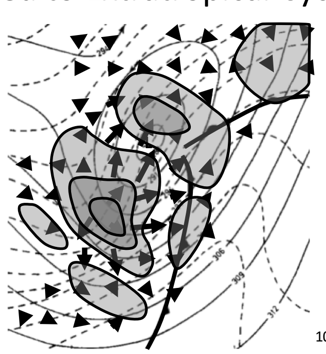
Diagnosing Q and w

Diagnosing orientation of Q

1. Determine the vector change of the geostrophic wind along an isotherm
2. Rotate 90˚
3. Q-vector "points" toward rising motion



Applied to Extratropical Cyclone



Approximate Comma Shape Ascent Zone

Subsidence Behind Low Center

700 mb
10 November 1975

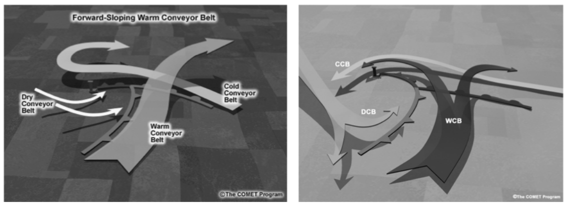
Hoskins and Pedder (1980)

Airstream Perspective: Conveyor Belts

- Simple depictions of the airflow associated with midlatitude frontal cyclones
- Warm Conveyor Belt – A coherent airstream originating in the warm sector that moves poleward, rises vigorously over the warm-frontal zone, and turns anticyclonically or fans out at upper levels
- Cold Conveyor Belt – A coherent airstream that moves toward the low center poleward of the occluded and warm fronts and splits into two branches, one that turns anticyclonically, ascends, and forms the comma cloud head, the other that wraps cyclonically around the low center, contributing to strong winds along the bent-back front
  - Anticyclonic branch may be thought of as a transition airstream between the cyclonic cold conveyor belt branch and the warm conveyor belt
- Dry Airstream – A coherent mid-level airstream of descended origin that forms the dry slot

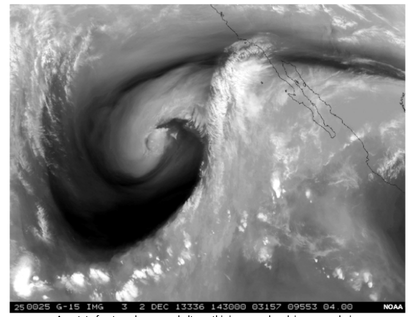
Carlson (1980); Schultz (2001); Schemm and Wernli (2014)

Conveyor Belts



COMET

Class Activity



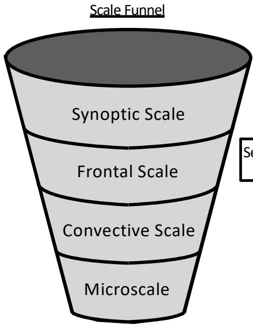
Annotate fronts and conveyor belts on this image and explain your analysis

Image Source: NOAA, COMET

Nice, but…

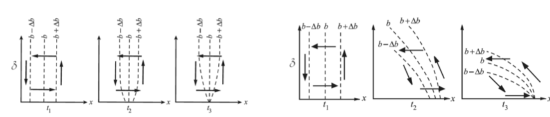
- Only explains general comma shape
- Does not account for details, especially fine-scale frontal structure and circulation
- Fine-scale details better captured if ageostrophic advection is included in the cross-front direction

Multiscale Processes



Process		Cloud and Precipitation Feature(s)
Geostrophic Adjustment Airstream transport	→	Comma Cloud Dry slot
Semigeostrophic Frontogenesis Diabatic Feedbacks	→	Frontal Zones
Upright and Slantwise Convection	→	NCFR WCFR Other Rainbands
Hydrometeor growth, transport, fallout	→	

QG vs. SG Fronts

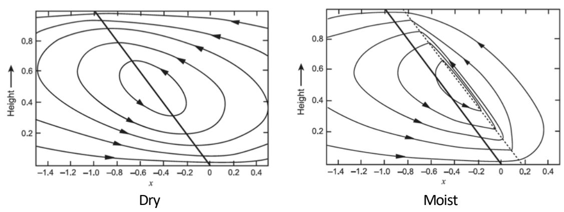


QG
Unrealistic vertical orientation
(and slow development)

SG
More realistic frontal tilt
(and more rapid development)

Houze (2014)

SG Dry vs. Wet

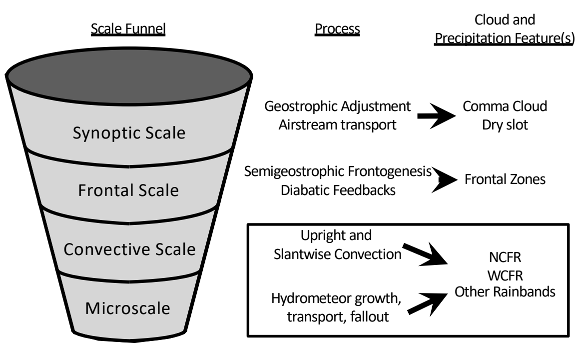


Latent heating concentrates lifting into a narrow zone
More consistent with observations

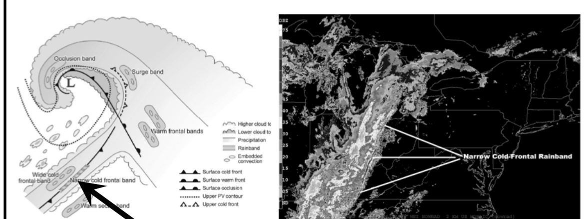
Emanuel (1985); Houze (2014)

Precipitation Bands

Multiscale Processes



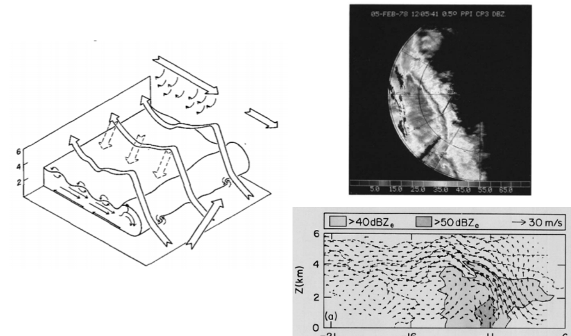
Narrow Cold-Frontal Rainband (NCFR)



NCFR – band of intense forced or free convection associated with the density-current-like structure at the leading edge of a cold front

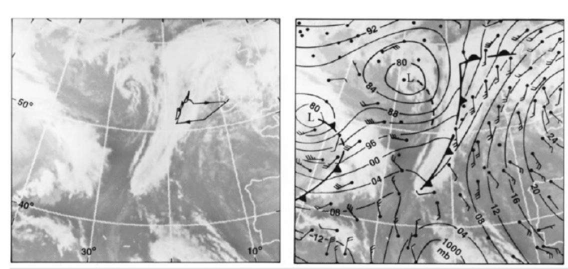
Houze (2014); https://www.wunderground.com/blog/24hourprof/narrow-coldfrontal-rainbands.html

Narrow Cold-Frontal Rainband (NCFR)



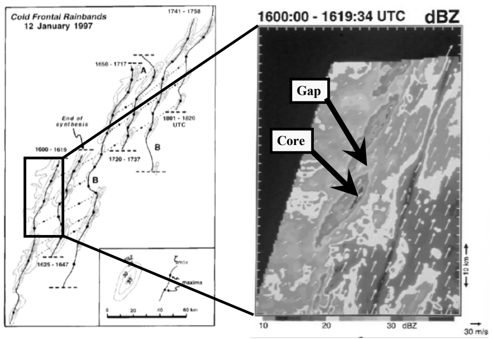
Carbone (1982)

Fine-Scale Structure: FASTEX IOP2



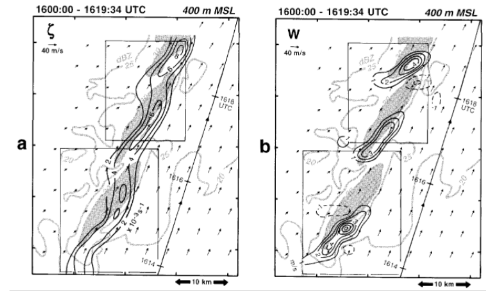
Wakimoto and Bosart (2000)

Core and Gap Structure



Wakimoto and Bosart (2000)

Vorticity and Vertical Velocity



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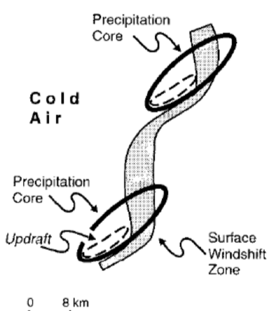
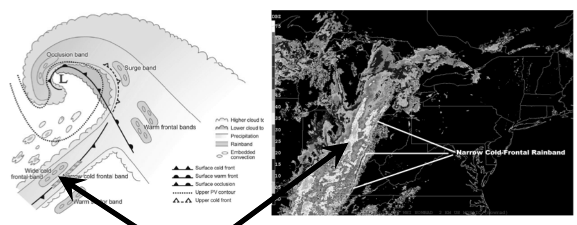
Wakimoto and Bosart (2000)

Conceptual Model



Wakimoto and Bosart (2000)

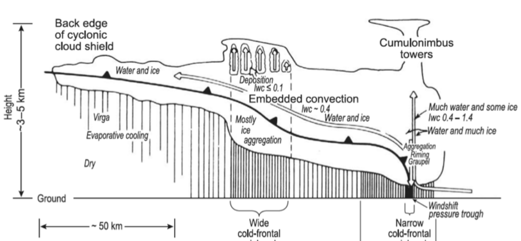
Wide Cold-Frontal Rainband (WCFR)



WCFR – region of enhanced stratiform precipitation associated with ascent aloft; sometimes trails the NCFR

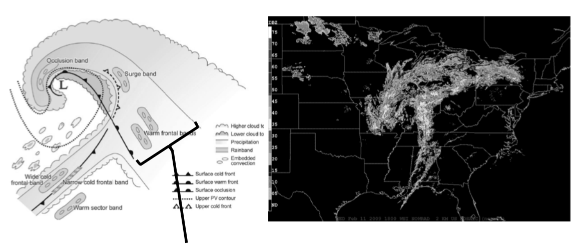
Houze (2014); https://www.wunderground.com/blog/24hourprof/narrow-coldfrontal-rainbands.html

Wide Cold-Frontal Rainband



Houze (2014), adapted from Matejka et al. (1980)

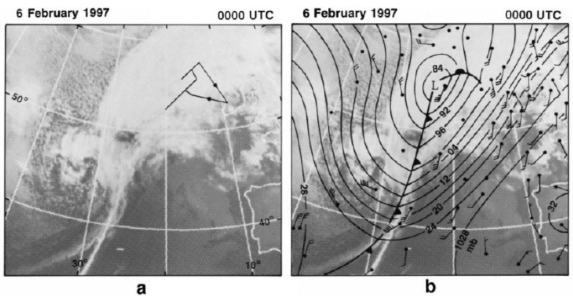
Warm-Frontal Precipitation



Region of precipitation associated with broad ascent accompanying warm front that may contain embedded bands or convective elements

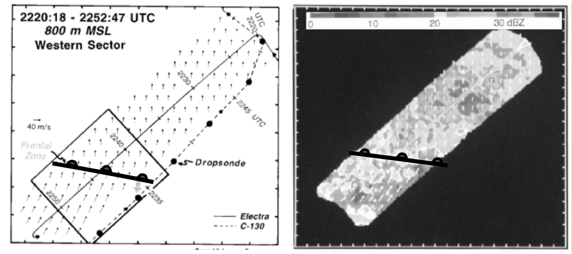
Houze (2014); https://www.e-education.psu.edu/worldofweather/book/export/html/2026

Warm Front Example: FASTEX IOP11



Wakimoto and Bosart (2001)

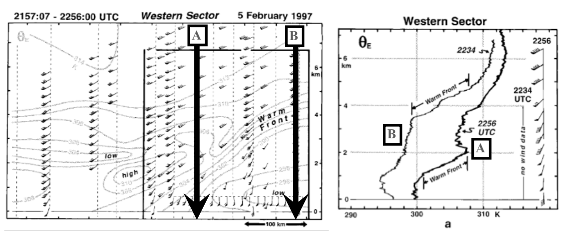
Mesoscale Structure



- Weak wind shift across front at low levels (800 m AGL)
- Precipitation (infered from dBZ) strongest ahead (poleward) of warm front

Wakimoto and Bosart (2001)

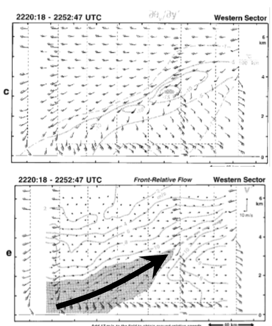
Vertical Structure



- Sloping region of enhanced horizontal and vertical θ_e gradient
- Veering winds with height
- No distinct frontal discontinuity at surface (front best defined aloft)

Wakimoto and Bosart (2001)

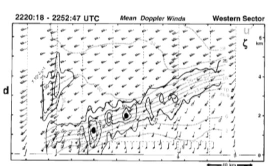
Vertical Structure



- Front-relative winds show strong veering with height
- Cross-front θ_v gradient delineates frontal zone
  - Weak near surface
- Strong sloping region of front-relative cross-frontal flow
  - Warm sector air ascending underlying cold air

Wakimoto and Bosart (2001)

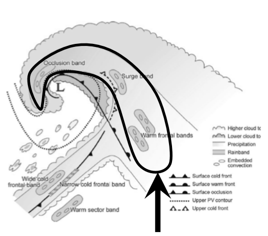
Vertical Structure



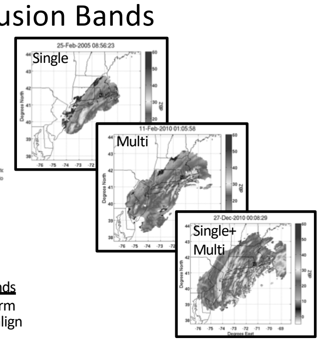
- Strip of high vertical vorticity with localized maxima in frontal zone
- Highest vorticity also found aloft, not at the surface

Wakimoto and Bosart (2001)

Warm-Frontal, Surge, & Occlusion Bands

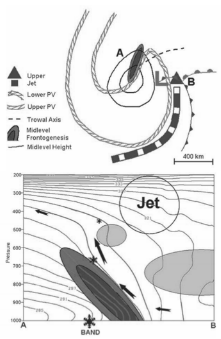


Warm-frontal, surge, and occlusion bands
Single and multi bands that form in warm frontal zone or comma head. Typically align parallel to isotherms



Houze (2014); http://cstar.cestm.albany.edu/nrow/NROWXV/Ganetis_NROW_2014.pptx; Ganetis (2017)

Warm-Frontal, Surge, & Occlusion Bands



- Key mechanisms:
  - Lower-to mid-level frontogenesis (red)
    - Often associated with horizontal deformation
  - Associated secondary circulation with slantwise ascent
  - Surmounting layer of conditional instability (blue), weak conditional stability, or conditional symmetric instability
- Strong frontogenesis increases likelihood of single band forming
- Single bands often form at edge of upper-level PV "hook"

Novak et al. (2010) ; Ganetis (2017, 2018)

Real-Time Examples (Hopefully!)

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