Methods for Diagnosing Regions of Conditional Symmetric Instability

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Spectrum of Instabilities Which Can Result in Enhanced Precipitation

- Inertial Instability
- Potential Symmetric Instability
- Conditional Symmetric Instability
- Weak Symmetric Stability
- Elevated Convective Instability

Inertial Instability

Inertial instability is the horizontal analog to gravitational instability; i.e., if a parcel is displaced horizontally from its geostrophically balanced base state, will it return to its original position or will it accelerate further from that position?

Inertially unstable regions are diagnosed where:

$\zeta_g + f < 0$; absolute geostrophic vorticity < 0

OR

if we define $M_g = v_g + fx$ = absolute geostrophic momentum, then inertially unstable regions are diagnosed where:

$\partial M_g / \partial x = \partial v_g / \partial x + f < 0$; since $\zeta_g = \partial v_g / \partial x$

(NOTE: v_g = geostrophic wind normal to the thermal gradient)

x = a fixed point; for wind increasing with height, M_g surfaces become more horizontal (i.e., M_g increases with height)

Inertial Instability (cont.)

Inertial stability is weak or unstable typically in two regions (Blanchard et al. 1998, MWR):

$\zeta_g + f = (V/R_s - \partial V/\partial n) + f$; in natural coordinates
where V/R_s = curvature term and $\partial V/\partial n$ = shear term

- Equatorward of a westerly wind maximum (jet streak) where the anticyclonic relative geostrophic vorticity is large (to offset the Coriolis parameter (which is always > 0 in the NH)

- In sub-synoptic scale ridges where the anticyclonic curvature is large

- Thus, pronounced entrance regions of anticyclonically-curved jet streaks are favorable locations for inertial instability or weak inertial stability

Diagnosing Potential Symmetric Instability (PSI) and Conditional Symmetric Instability (CSI)

- Construct a cross section taken normal to the 850-300 mb thickness isopleths with the x-axis directed towards the warm air

- In the cross-sectional plane, display isentropes of 2_e/ 2_{es} and isopleths of absolute angular momentum (M_g), defined as:

  $M_g = v_g + fx$, where v_g is the geostrophic wind component normal to the cross section, f is the Coriolis parameter, and x is the distance along the x-axis

- Note that $2_e/2_{es}$ tends to increase both upward (in convectively/conditionally stable air) and along the x-axis (towards the warmer air); M_g tends to increases both upward (as the normal wind component increases with height) and along the x-axis (as x increases)

Diagnosing PSI/CSI (cont.)

- It can be shown that:

  $du/dt = f \; (M_{(parcel)} - M_g)$ and

  (M_g = geostrophic momentum of ambient environment)

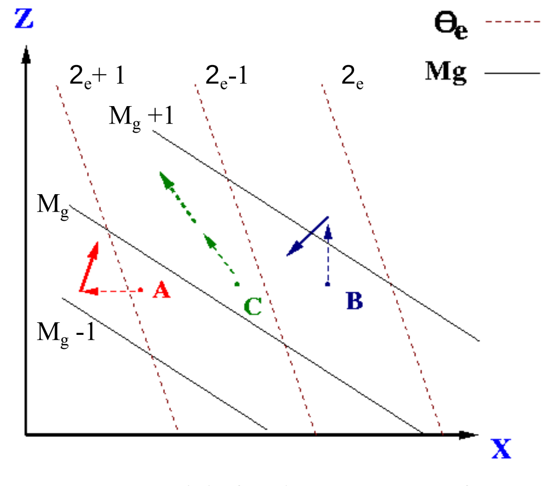
  $dw/dt = g/2_e(2_{e(parcel)} - 2_{e\,(envir)})$

  where the first expression evaluates the inertial (horizontal) stability (i.e., a horizontal acceleration term) and the second expression evaluates the convective (vertical) stability (i.e., a vertical acceleration term) of the parcel

- If $M_{(parcel)} > M_g$, the parcel accelerates to the east (+ x)
- If $M_{(parcel)} < M_g$, the parcel accelerates to the west (- x) (or decelerates if displaced to the east)
- If $2_{e(parcel)} > 2_{e\,(env)}$, the parcel accelerates upward
- If $2_{e(parcel)} < 2_{e\,(env)}$, the parcel accelerates downward (or decelerates if displaced upward)

Understanding Conditional Symmetric Instability

Cross section of 2_e and M_g taken normal to 850-300 mb thickness contours



In this diagram, isentropes of 2_e are sloped more vertical than lines of absolute geostropic momentum, M_g. This implies weak stability (vertical 2_e lines mean neutral stability while more horizontal lines mean increased stability) and decent vertical speed shear (M_g lines that are nearly vertical implies near constant wind speeds with height; the more horizontal the M surfaces, the greater the vertical wind shear and better chance for CSI).

See next slide for characterisitics of Parcels A, B, and C.

Conditional Symmetric Instability (CSI): Theory

Parcel Θe and Mg properties are those of parcel at its original location before displacement; after displacement, parcel travels through environment with certain environmental Θe and Mg properties

Parcel A (as it's displaced horizontally to the NW)

2_e (parcel) > 2_e (environ); ˆ dw/dt > 0 (accel. up)

M_g (parcel) > M_g (environ); ˆ du/dt > 0 (accel. to southeast…but eventually returns to near original location)

Parcel B (as it's displaced vertically upward)

2_e (parcel) < 2_e (environ); ˆ dw/dt < 0 (accel. down)

M_g (parcel) < M_g (environ); ˆ du/dt < 0 (accel. to northwest)

Parcel C (as it's displaced slantwise up and from SE to NW)

2_e (parcel) > 2_e (environ); ˆ dw/dt > 0 (accel. up)

M_g (parcel) < M_g (environ); ˆ du/dt < 0 (accel. to northwest)

Thus, Parcel C will accelerate along a slantwise path away from its initial position….it is unstable to slantwise motions even though it is somewhat stable to both horizontal and vertical displacements!

Diagnosing PSI/CSI (cont.)

- For PSI, we use 2_e and M_g surfaces
- For CSI, we use 2_{es} and M_g surfaces (saturated 2_e)
- You should display relative humidity on the cross section since CSI requires near- saturated conditions (i.e., RH > 80%)
- There should also be large scale vertical motion in order to “realize” (release) the CSI
- **Note**: when the 2_e surfaces “fold” underneath themselves, i.e., 2_e decreases with height, there is convective instability, which could result in upright convection and subsequent vertical motions that would overwhelm motions from slantwise convection resulting from the release of CSI

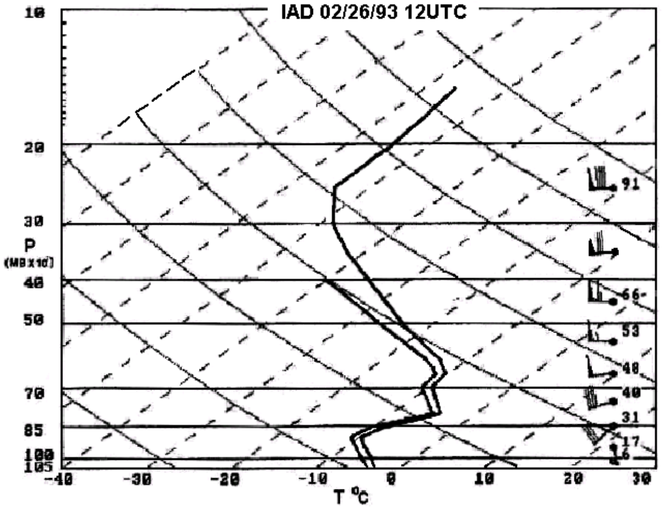
Conditional Symmetric Instability: Synoptic Characteristics

- Typically a cool season phenomenon
- Wind profile: speed increasing with height with weak directional veering with height; indicative of strong baroclinicity
- Thermodynamic profile: nearly saturated and close to the moist-adiabatic lapse rate. Parcel motion will be neutral to moist ascent. Lapse rate is NOT conditionally unstable
- Often found in the vicinity of an extratropical cyclone warm front, ahead of a long-wave trough in a region of strong, moist, mid-tropospheric southwesterly flow
- CSI also is possible near entrance regions of anticyclonically curved jet streaks where inertial and gravitational stability is weak or neutral; however, be aware that gravitational instability is possible in these areas which could lead to upright convection with thunder and lightning (especially south of a CSI area)

Conditional Symmetric Instability: Synoptic Characteristics (cont.)

- Large scale forcing for upward vertical motion usually is present
- Soundings reveal a deep, moist layer that is convectively stable with a moist-adiabatic lapse rate
- On satellite or radar imagery, CSI is exhibited by multiple bands of clouds/precipitation oriented parallel to the mid-tropospheric thermal wind (or thickness lines); sometimes the bands have a component of motion toward the warm air
- These heavier precipitation bands may be embedded (obscured) by other lighter precipitation
- Warm frontal rain/snow bands are often good candidates for being associated with CSI

Typical CSI Sounding

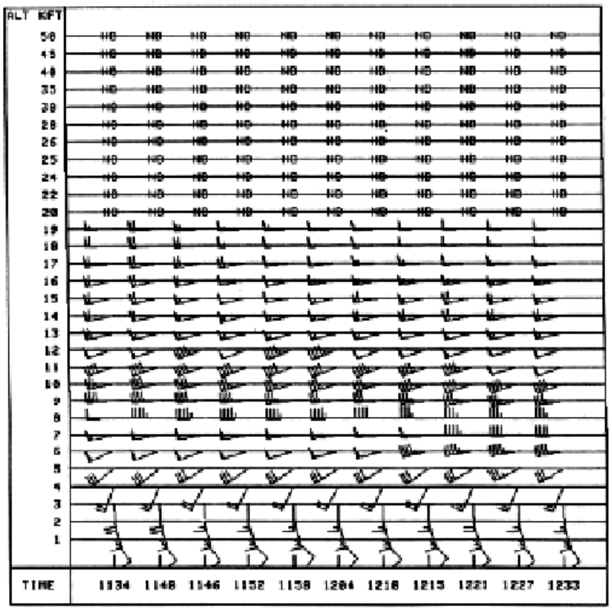


RAOB sounding observations for IAD (Dullus Airport, VA) for 1200 UTC 26 Feb 1993:

Region of CSI is above 600 mb in this case

Wiesmueller and Zubrick, 1998 (WAF)

Vertical Wind Profile from Sterling, VA WSR-88D



VWP from Sterling, VA WSR-88D for 1134-1233 UTC 26 Feb 1993 (matches sounding in previous slide):

Note speed shear dominates above 7000 feet

Wiesmueller and Zubrick, 1998 (WAF)

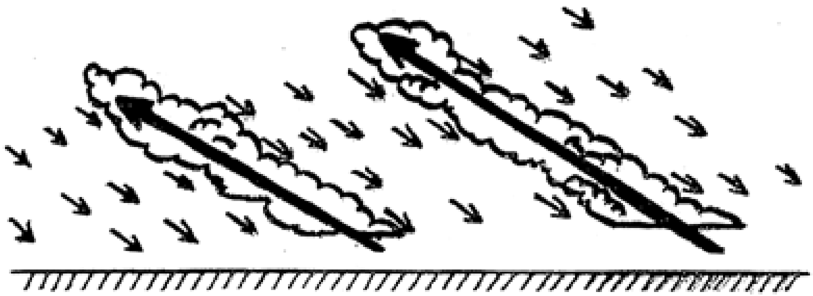
Conditional Symmetric Instability: Physical Characteristics

- Width of the bands is approximately 100 km; length of the bands is approximately 100-400 km; time scale of the bands is approximately 3-4 h
- Typical CSI vertical motions are on the order of tens of cm s^{-1} to a few m s^{-1} and thus, usually DO NOT produce lightning/thunder (need > 5 m s^{-1} to produce lightning)
- However, these mesoscale bands of precipitation can be intense and result in significantly higher rain/snow fall totals than the surrounding area
- CSI is characterized by weak **inertial stability** and **convective stability** but, when realized, results in **slanted or tilted mesoscale circulations** which convert inertial energy into buoyant energy

Conditional Symmetric Instability: Physical Characteristics (cont.)

- Therefore, CSI is favored to occur in regions of:
  - High vertical wind shear (speed shear; baroclinic environment)
  - Weak absolute vorticity (values near zero) (within/near ridges just downstream from trough axis aloft or south side of jets) (see EPV section for more information)
  - Weak convective stability (otherwise upright convection might form)
  - High mean relative humidity
  - Large scale ascent (to release CSI leading to slantwise accelerations)
  - Often these conditions are found in the entrance region of an upper-level jet streak during the cool season but may also occur within a jet streak exit region
- The atmosphere can contain regions of CSI and convective instability (CI), but since CI has a faster growth rate (tens of minutes) relative to CSI (a few hours), CI will dominate.

Illustration of Slantwise Updrafts Due to Released CSI



Schematic illustration of moist slantwise convective updrafts and downdrafts resulting from the release of CSI; slanted updrafts are narrow, saturated, and intense, while downdrafts are diffuse, unsaturated, and weak.

From Emanuel (1984) Dynamics of Mesoscale Weather Systems, NCAR Summer Colloquium Lecture Notes, 11 June – 6 July 1984, p. 159.

Equivalent Potential Vorticity (EPV)

- Equivalent Potential Vorticity (EPV) is a parameter that can be used to diagnose areas of CSI
- You want to find areas of negative or small positive EPV
- Consider the EPV equation and the terms that contribute it on the next slide

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Three-Dimensional Form of
Equivalent Potential Vorticity (EPV) Equation

McCann (1995 WAF) derived a 3-D form of the EPV equation which can be computed from gridded data:

$$EPV = g\left[\frac{\partial\theta_e}{\partial x}\frac{\partial v_g}{\partial p} - \frac{\partial\theta_e}{\partial y}\frac{\partial u_g}{\partial p} - \left(\frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} + f\right)\frac{\partial\theta_e}{\partial p}\right]$$

A B C D

Note that in this form, EPV is a function of:

Terms A and B: Horizontal gradient of 2_e and vertical shear of the geostrophic wind (i.e., the thermal wind)

Term C: Absolute geostrophic vorticity

Term D: Convective stability

Three-Dimensional Form of EPV Equation (cont.)

How can EPV become small positive or even negative?

Terms A and B: To simplify, consider westerly flow increasing with height and 2_e decreasing to the north, i.e., $Mu_g/Mp < 0$ and $M2_e/My < 0$, therefore – $(Mu_g/Mp)(M2_e/My) < 0$

Thus, the stronger the 2_e gradient from south to north and the greater the vertical wind speed shear, the smaller (less positive or more negative) EPV will be.

Term C: $Mv_g/Mx - Mu_g/My + f$ = absolute geostrophic vorticity is usually > 0, thus we want to make this term small, i.e., create an area of weak inertial stability

This term (and thus EPV) is small within ridge axes and south of jet streaks.

Term D: $M2_e/Mp$: in a convective stable atmosphere this term is < 0, therefore we want this term to be a small negative number.

Thus {– (Term C x Term D)} will yield a small positive number, i.e., {- (+) (-)} = small (+) number, which must be minimized to keep EPV a small (+) or (-) number.

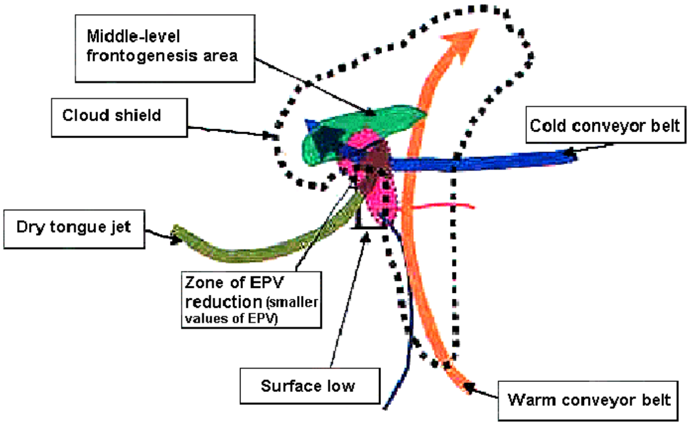
If Term D is > 0, then 2e decreases with height, i.e., convective instability is present which would lead to a negative EPV but also upright convection which would overwhelm any CSI-induced motions.

So Terms A and B tend to contribute to negative EPV while terms C and D normally contribute to positive EPV

Equivalent Potential Vorticity (EPV)

- When EPV < 0, potential symmetric instability (PSI) is present.
- However, EPV also is < 0 when there is convective instability; thus, you must see if the lines of 2_e (on a cross-section) are "folded," i.e., where 2_e decreases with height to separate areas of CI from areas of CSI. IF so, CI will dominate.
- Schultz and Schumacher (1999 MWR) suggest using 2_{es} (saturated 2_e instead of regular 2_e) to assess CSI. However, it is perfectly acceptable to use 2_e and check to be sure that the relative humidity is greater than 80 percent.

Nicosia and Grumm Model for EPV Reduction Near Extratropical Cyclones



Zone of EPV reduction occurs where the mid-level dry tongue jet overlays the low-level easterly jet (or cold conveyor belt), north of the surface low. In this area, dry air at mid-levels overruns moisture-laden low-level easterly flow, thereby steepening the slope of the 2_e surfaces.

Figure from Nicosia and Grumm (1999,WAF)

Conceptual Model for CSI

(Nicosia and Grumm 1999, WAF)

- Differential moisture advection northeast of the surface low (in the previous slide) leads to a steepening of the $2_e/2_{es}$ surfaces
- Mid-level frontogenesis (associated with a deformation zone aloft to the north of the upper low) increases the north-south thermal gradient, thereby increasing the vertical wind shear. In this case, the low-level easterlies increase below while the westerlies increase above – which increases the differential moisture advection, increasing the 2_e/ 2_{es} surfaces' slope
- Also, since the vertical wind shear is increasing with time, the M_g surfaces become more horizontal (become flatter). Thus, a region of PSI/CSI develops where the $2_e/2_{es}$ surfaces are more vertical than the M_g surfaces
- In this way, frontogenesis and the development of PSI/CSI are linked

Problems in Diagnosing CSI Operationally

- Temporal Resolution: CSI occurs over time scales of about 3-6 hours while current upper air data collection is every 12 hours
- Spatial Resolution: Precipitation bands are meso-$ scale with lengths of 100-200 km and widths of 50-100 km
- Geostrophic assumption is not always valid (e.g., in regions of cyclonic curvature or within ULJ exit/entrance regions).
- When the shear vector turns with height, the inertial stability criteria is no longer valid for some portions of the cross section; M_g is not strictly conserved
- Nevertheless, a forecaster can **anticipate** when/where CSI might occur from looking at model and observed data (situational awareness). Then in the short term, when banded precipitation is noted, physical processes responsible can be understood, and the forecast adjusted as needed to refine precipitation amounts

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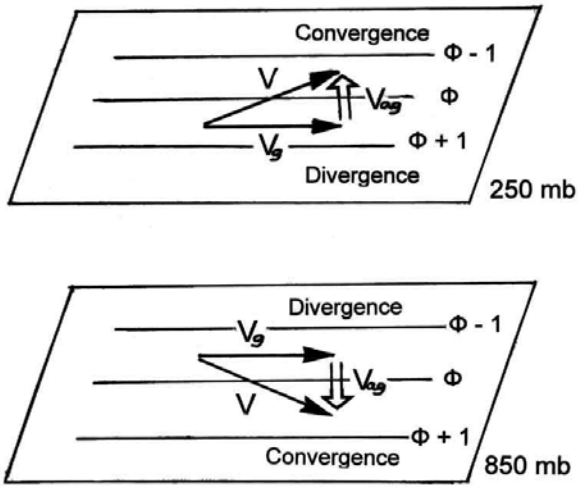
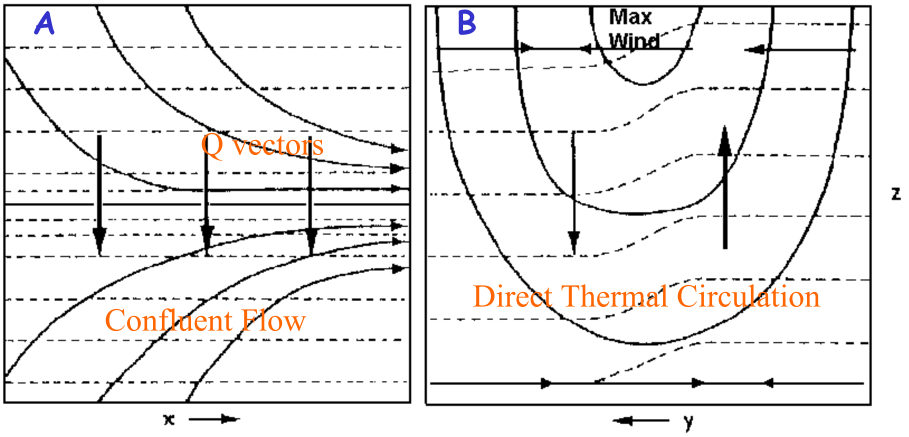
Frontogenetical Circulation

- As the thermal gradient strengthens, the geostrophic wind aloft and below must respond to maintain balance with the thermal wind
- Winds aloft increase and “cut” to the north while winds below decrease and “cut” to the south, thereby creating regions of divergence/convergence (note diagram on next slide)
- By mass continuity, upward motion develops to the south and downward motion to the north – a direct thermal circulation
- This direct thermal circulation acts to weaken the frontal zone with time and works against the original geostrophic frontogenesis (i.e., it acts to restore thermal wind balance)

Ageostrophic Adjustments in Response to Frontogenetical Forcing

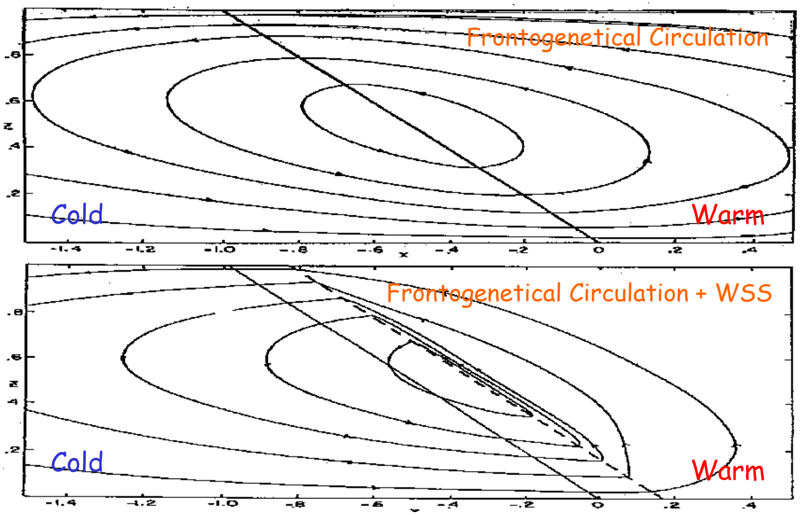


Frontogenetical Circulation



(A) Horizontal streamlines, Q vectors (thick arrows), and isotherms (dashed) in a pattern of frontogenetical confluence. **(B)** Vertical cross-section across the confluence showing isotachs (solid), isotherms (dashed), and vertical and transverse motions (arrows). In this example, ascent within the frontogenetically-induced direct thermal circulation occurs within/near a ridge axis of warmer air in the right entrance region of the jet.

Frontogenetical Circulation



In the presence of weak symmetric stability (WSS) or CSI (i.e., the co-existence of frontogenesis and small values of EPV), the updrafts of the frontogenetical circulation become stronger and more concentrated than in a stable environment. Thus, you MUST assess stability when considering forcing and subsequent lift.

Frontogenetical Circulation

- Frontogenetical circulations typically result in one major band of significant precipitation which is parallel to the frontal zone (may be embedded within lighter precipitation)

- The strength of this circulation is modulated by the ambient static stability (the less stable the air, the stronger the lift)

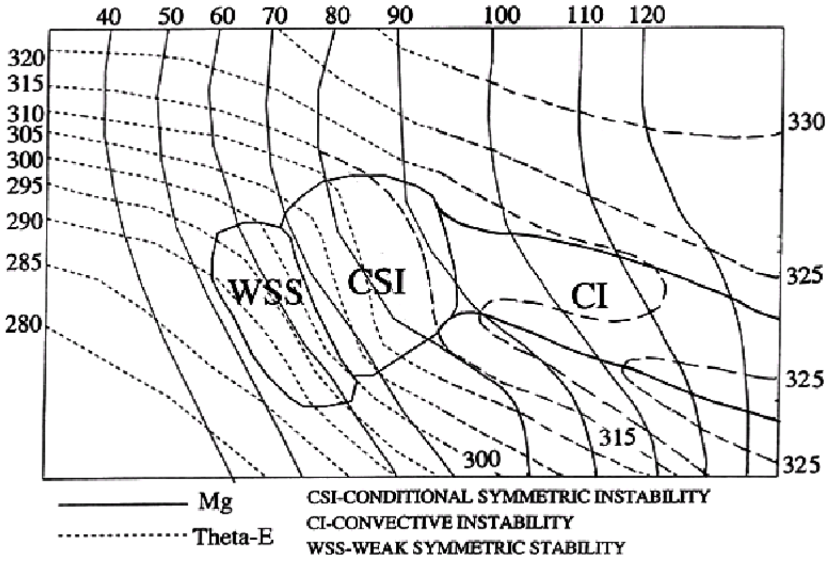
- Grumm and Nicosia (1997, NWD) found in their studies that a weakly stable environment in the presence of frontogenesis led to one transient band of heavy precipitation

- However, they also found that frontogenesis in the presence of greater stability resulted in classic CSI (multiple) bands of precipitation

Spectrum of Mesoscale Instabilities

- Many heavy precipitation events display different types of mesoscale instabilities including:
  - **Convective Instability** (CI; 2_e decreasing with height)
  - **Conditional Symmetric Instability** (CSI; lines of 2_e are more vertical than lines of constant absolute geostrophic momentum or M_g)
  - **Weak Symmetric Stability** (WSS; lines of 2_e are nearly parallel to lines of constant absolute geostrophic momentum or M_g) (but still can result in banded precipitation in the presence of frontogenetical forcing)

Conceptual Model for CI-CSI-WSS



Spectrum of Mesoscale Instabilities

- These mesoscale instabilities tend to develop from north to south in the presence of strong uni-directional wind shear (typically from the SW)
- CI tends to be in the warmer air to the south of the cyclone while CSI and WSS tend to develop further north in the presence of a cold, stable boundary layer
- It is not unusual to see CI move north and become elevated, producing thundersnow
- CSI may be a precursor to elevated CI, as the vertical circulation associated with CSI may overturn 2_e surfaces with time creating convectively unstable zones aloft

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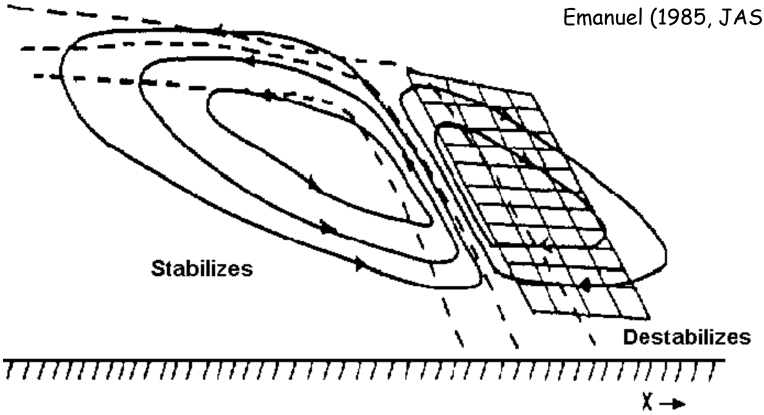
Spectrum of Mesoscale Instabilities

- We believe that most thundersnow events are associated with elevated convective instability (as opposed to CSI)
- CSI can generate vertical motions on the order of 1-3 m s^{-1} while elevated CI can generate vertical motions on the order of 10 m s^{-1} which are more likely to create charge separation and lightning
- NOTE: Given model resolution, it may be difficult at times to fully and accurately resolve small-scale zones of elevated CI, CSI, or WSS in vertical cross-sections; keep this in mind when assessing instability

Emanuel's Conceptual Model of CSI-Associated Vertical Circulation

Emanuel (1985, *JAS*)



Estimated mass circulation resulting from moist symmetric instability (CSI). The dashed lines show the position of original theta-e surfaces, while the hatched area denotes the region where the theta-e surfaces may become overturned, resulting in convective instability, due to the CSI-associated vertical circulation. Thus, precipitation could become more convectively-based with time.

Final Thoughts on Banded Precipitation

- Numerical experiments suggest that weak positive symmetric stability (WSS) in the warm air in the presence of frontogenesis leads to a single band of ascent that narrows as the symmetric stability approaches neutrality
- Also, if the forcing becomes horizontally widespread and EPV < 0, multiple bands become embedded within the large scale circulation; as the EPV decreases, the multiple bands become more intense and more widely spaced
- However, more research needs to be done to better understand how bands form in the presence of frontogenesis and CSI