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THE USE AND ABUSE OF CONDITIONAL SYMMETRIC INSTABILITY (CSI) AS A DIAGNOSTIC TOOL

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1. INTRODUCTION

Single- and multiple-banded clouds and precipitation are commonly observed in association with frontal zones in extratropical cyclones. One proposed explanation for these bands is slantwise convection due to the release of conditional symmetric instability (CSI), a type of moist symmetric instability (MSI). Indeed, some observational studies over extended periods of time show the presence of MSI in association with banded precipitating baroclinic systems to be rather common (e.g., Bennetts and Sharp 1982; Seltzer et al. 1985; Byrd 1989; Reuter and Yau 1990, 1993; Reuter and Aktary 1993, 1995).

Although we do not deny the likely existence of slantwise convection or the possible involvement of MSI in some precipitating systems in the atmosphere, it is our contention that CSI is frequently overused and misused as a diagnostic tool [also noted by Wiesmueller and Zubrick (1998, 86)]. Whereas many of the issues clarified in this presentation are discussed by earlier authors, they are often understated, misinterpreted, or neglected by later researchers and forecasters who rely on CSI as an explanation for banded precipitation.

The purpose of this presentation is (1) to attempt to limit further abuse of the dogma of CSI by researchers and forecasters alike by highlighting common pitfalls, (2) to encourage future *profitable* research explorations by noting the deficiencies in our understanding of MSI and slantwise convection, and (3) to present an approach that can be used in research and operational-forecasting environments to assess MSI.

2. AN INGREDIENTS-BASED METHODOLOGY FOR SLANTWISE CONVECTION

In order to clarify some of the confusion surrounding the concepts of CSI and slantwise convection, we find it useful to demonstrate parallels with the more familiar concepts of moist gravitational instability and convection. An exploration of these parallels begins with an ingredients-based methodology for forecasting deep moist convection (e.g., Johns and Doswell 1992, 589–590). This methodology asserts that three ingredients are required to produce deep moist convection: instability, moisture, and lift. As Doswell (1987, 7) notes, "Remove any one of these and there well may be some important weather phenomena, but the process is no longer deep moist convection."

Our interpretation of the literature is that CSI is treated sometimes as an instability and sometimes as a forcing mechanism for ascent. An example of this confusion is illustrated by those who wish to separate the effect of CSI from that due to frontogenesis, when in fact these two processes cannot be considered independently (see section 4). The ingredients-based methodology firmly labels CSI as the instability, clearly separate from the lifting mechanism.

Applying the ingredients-based methodology to slantwise convection indicates that *the existence of CSI alone is not sufficient to initiate slantwise convection,* in contrast to those who apply CSI as the sole explanation for banded cloud and precipitation patterns, without examination of the existence of adequate moisture and lift. Employing CSI in this manner is tantamount to saying that the occurrence of a severe thunderstorm is due solely to the presence of conditional instability to moist gravitational convection! Since slantwise convection is the process by which the instability is released, it follows that the terms *slantwise convection* and *CSI* do not have the same meaning, contrary to their implied equivalence by some authors (e.g., Moore and Blakely 1988, p. 2167; Howard and Tollerud 1988, 170; Lemaitre and Testud 1988, 261; Bennetts et al. 1988, 368; Reuter and Yau 1993, 375; Wiesmueller and Zubrick 1998, 85). More precisely, CSI can be thought of as a measure of the susceptibility of the atmosphere to moist slantwise convection.

For the purposes of this presentation, we adopt the same triad of ingredients from moist gravitational convection (instability, moisture, and lift) for the production of moist slantwise convection, where the requisite instability becomes MSI, rather than moist gravitational instability. As is shown throughout this presentation and, in particular, our proposed forecast methodology in section 6, the occurrence of slantwise convection depends upon all three ingredients and all must be present in order to justify any suspected claims of slantwise convection.

3. ASSESSING MSI

The derivation of MSI is not presented here, but can be found in the pioneering works of Bennetts and Hoskins (1979) and Emanuel (1983a,b), or the excellent textbook presentations of Bluestein (1993, section 3.5.2), Houze (1993, section 2.9.1), and Emanuel (1994, chapter 12).

3.1 *Conditional Symmetric Instability versus Potential Symmetric Instability*

For moist gravitational convection, conditional instability (CI) is strictly defined locally at each height along a vertical sounding where the environmental lapse rate lies between the moist and dry adiabatic lapse rates, or, equivalently, the saturation equivalent potential temperature θ_e^* (also expressed as θ_{es} in some literature) decreases with height (i.e., $\partial\theta_e^*/\partial z < 0$). Similarly, for slantwise convection, CSI is defined locally at each height where the environmental lapse rate along a geostrophic absolute momentum M_g surface is between the moist and dry adiabatic lapse rates (i.e., is conditionally unstable along an M_g surface), or $\partial\theta_e^*/\partial z|_{M_g} < 0$. The instability is said to be *conditional* because saturation must be present locally in order for the instability (i.e., parcel buoyancy) to be realized.

Contrast these definitions for conditional instabilities to those for potential instabilities. As in moist gravitational convection where the potential instability (PI; also known as convective instability) of a layer along a vertical sounding can be defined ($\partial\theta_e/\partial z < 0$), it is possible to assess layer potential symmetric instability (PSI) along an M_g surface: $\partial\theta_e/\partial z|_{M_g} < 0$. The instability is said to be *potential* because the layer must undergo a finite vertical displacement

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to reach saturation and realize the instability. At saturation, CSI and PSI, like CI and PI, are equivalent. It can be shown that the criterion for PSI is equivalent to the M_g–θ_e relationship (i.e., comparing the slopes of M_g and θ_e contours in cross sections). Therefore, *the commonly employed method of assessment for CSI in the literature, the M_g–θ_e relationship, is really a measure of PSI, not CSI, if we follow the definitions from moist gravitational convection.*

Despite the fact that several authors define and use CSI correctly in their own work (e.g., Emanuel 1983b, 2017; Reuter and Yau 1990, 449; Reuter and Yau 1993, 376–377; Houze 1993, 54–56; Emanuel 1994, 410), this misuse of the term CSI continues and now pervades the literature. *We would like to suggest that, in the future, we, as a meteorological community, use the term CSI only when employing θ_e^* and use the term PSI only when employing θ_e.* We adopt this terminology throughout the rest of the presentation. In addition, we use the term MSI when the method of assessment is unimportant or is not specified.

The question naturally arises as to whether it is more appropriate to calculate CSI or PSI for assessing the possibility of moist slantwise convection in the atmosphere. Drawing an analogy to moist gravitational convection may help provide some insight. The necessary condition for moist gravitational convection is that a rising air parcel be saturated and the lapse rate be greater than the moist adiabatic lapse rate (CI), so that positive buoyancy exists. Consequently, the presence of PI is not necessary for moist gravitational convection to occur in the atmosphere (e.g., Emanuel 1994, 185). Therefore, throughout the rest of this presentation, we use the term CSI, computed with the proper thermodynamic variable θ_e^*, as the appropriate measure of the susceptibility of the atmosphere to slantwise convection. Thus, many previous studies may not determine the true potential for slantwise convection because of their use of θ_e and PSI, rather than θ_e^* and CSI. Further research demonstrating the relative merits of these diagnostics in research and forecasting environments, however, is required.

3.2 *The M_g–θ_e^* Relationship and Moist Geostrophic Potential Vorticity*

Certain assumptions are necessary in order to develop the M_g–θ_e^* relationship for the identification of CSI: (1) the geostrophic wind is constant in the along-front direction, (2) the cross section is perpendicular to the shear of the geostrophic wind (or, equivalently, the thermal wind or isotherms), and (3) the ageostrophic wind (for example, due to flow curvature) is small so that the geostrophic wind is a reasonable approximation to a basic state. Discrepancies in interpreting the existence of CSI in cross sections can result, therefore, because one or more of the above criteria are not strictly met.

It can be shown that the M_g–θ_e^* relationship for CSI is equivalent to saturated geostrophic potential vorticity MPV_g^* (also known as the saturated equivalent geostrophic potential vorticity) being negative (Bennetts and Hoskins 1979; Shutts and Cullen 1987; Martin et al. 1992; Moore and Lambert 1993; McCann 1995). From the three-dimensional form of MPV_g [moist geostrophic potential vorticity; $\mathrm{MPV}_g = -g\eta_g \cdot \nabla\theta_e$; their equation (1)], Moore and Lambert (1993) derive a two-dimensional form of MPV_g [their equation (2)]. Unfortunately, they use the two-dimensional form of MPV_g to assess PSI in their cross sections. Therefore, their results depend upon the orientation of the cross section as in the M_g–θ_e relationship (i.e., the full potential of MPV_g as a three-dimensional parameter for diagnosis is not being utilized). Thus, even in cross sections, application of the full three-dimensional form of MPV_g is essential for an accurate assessment of PSI. Unfortunately, employing the two-dimensional form of MPV_g has been increasing in popularity (e.g., Weisman 1996; Wiesmueller and Zubrick 1998).

To summarize, assessing CSI using the three-dimensional form of MPV_g^* does not require strict adherence to the same assumptions as using the M_g–θ_e^* relationship. *Due to the potential confounds with assessing M_g–θ_e^* relationships in vertical cross sections, a more reliable assessment of CSI is obtained by employing MPV_g^*.* On the other hand, use of $\mathrm{MPV}_g/\mathrm{MPV}_g^*$ as a diagnostic tool does not differentiate between regions of PI/CI and PSI/CSI, as noted by Wiesmueller and Zubrick (1998, 87, 94–95). Therefore, MSI diagnostics should be employed in conjunction with a test for moist gravitational instability.

4. FRONTOGENESIS AND MSI

As with moist gravitational instability, the eventual release of MSI is predicated upon slantwise parcel lifting beyond the lifting condensation level to the level of free slantwise convection (LFSC). Therefore, sufficient moisture, and eventual saturation, must be present in the region of slantwise ascent in order for the instability to be released. Typically, previous authors examine the relative humidity and if it is greater than some threshold (say, 80%), then saturation is considered to have occurred or is imminent.

The ascent required to lift a parcel forcibly to its LFSC can arise from frontogenetical circulations, traveling meso- or synoptic-scale systems, orography, or any other mechanism of sufficient magnitude. Since slantwise ascent occurs on the mesoscale (20–200 km), resolving the larger-scale processes responsible for lift seems likely in most cases of suspected MSI.

Because both frontogenesis and slantwise convection due to the release of MSI produce banded precipitation, some authors try to distinguish between situations characterized by banded precipitation due to frontogenetical forcing from those characterized by the release of MSI (e.g., Seltzer et al. 1985; Snook 1992). As discussed previously, MSI is an instability and frontogenesis is a forcing mechanism for vertical motion, a fact implicit in the Sawyer–Eliassen equation for secondary frontal circulations. In the Sawyer–Eliassen equation, the symmetric stability (through the geostrophic potential vorticity) modulates the atmospheric response to the forcing (i.e., the same forcing produces narrower, stronger ascent in an environment of weaker symmetric stability than in an environment of stronger symmetric stability). As such, *the atmospheric response in an environment characterized by MSI is closely related to the frontogenetic forcing,* as previously noted by Thorpe and Emanuel (1985, 1821–1822) and Emanuel (1994, 412).

5. THE COEXISTENCE OF MOIST GRAVITATIONAL INSTABILITY AND MSI

It is often observed in the atmosphere that regions of moist gravitational instability (CI or PI) may be associated with regions of MSI (CSI or PSI). CI is a special case of CSI in which θ_e^* surfaces not only tilt more steeply than M_g surfaces, but are overturned, such that $\partial\theta_e^*/\partial z < 0$. Likewise, PI is a special case of PSI in which θ_e surfaces not only tilt more steeply than M_g surfaces, but are overturned, such that $\partial\theta_e/\partial z < 0$. As such, *blindly employing the tests for CSI ($\mathrm{MPV}_g^* < 0$ and the M_g–θ_e^* relationship) will identify regions of CI and blindly applying the tests for PSI ($\mathrm{MPV}_g < 0$ and the M_g–θ_e relationship) will identify regions of PI.* Whereas there has been some research attempting to discriminate between situations characterized by CI/PI from those characterized by CSI/PSI (Bennetts and Sharp 1982, 596, 598–599; Moore and Lambert 1993; McCann 1995; Wiesmueller and Zubrick 1998, 86), this distinction is not always made (e.g., Gyakum 1987) or is made, but not applied (e.g., Moore and Blakley 1988, Fig. 19; Shields et al. 1991, 956–959). That MPV$_g$ can be used to identify PI and PSI led McCann (1995) to refer to MPV$_g$ as an "all-purpose convection diagnostic tool" to locate regions where the atmosphere is susceptible to moist gravitational or symmetric instability, seemingly without regard to the nature of any resulting convection. Furthermore, his statement that "the effects of equal CAPE [convective available potential energy] and SCAPE [slantwise convective available potential energy] are probably about the same, since parcel accelerations are the same" implies that vertical and horizontal accelerations of similar magnitudes produce similar dynamics in the atmosphere, a misinterpretation of the differing dynamics of moist gravitational and symmetric instabilities.

5.1 *Convective–Symmetric Instability*

Ultimately, a deeper understanding of how convection (gravitational, slantwise, or both) organizes in the presence of both CI/PI and CSI/PSI is sought. We begin by noting that as an initially gravitationally and symmetrically stable atmosphere is destabilized, CSI/PSI will arise before CI/PI (Emanuel 1994, 410), but due to the larger growth rate and energy release of moist gravitational convection compared to slantwise convection, gravitational convection is likely to dominate in time (Bennetts and Sharp 1982, 598–599). Jascourt et al. (1988, 188–189) term the situation where CI/PI and CSI/PSI coexist *convective–symmetric instability*. Therefore, the question arises as to the mesoscale circulations in the atmosphere to organize any resulting convection in such an environment.

Xu (1986, 331) proposes two types of convective-symmetric instabilities. The first he refers to as "upscale development", where small-scale moist gravitational convection develops first, followed by mesoscale banded organization of clouds due to the release of symmetric instability as the environment becomes gravitationally stabilized. It seems that this type of development would be most likely to occur outside of frontal regions where small-scale moist gravitational convection organizes in the absence of synoptic-scale airmass boundaries. In contrast, Xu (1986) refers to "downscale development," where bands generated during frontal ascent in a moist symmetrically unstable environment lead to latent-heat release, effectively destabilizing the midtroposphere to gravitational convection. Eventually, the release of moist gravitational instability leads to rainband formation. Xu's (1986) downscale development is similar to the three-stage process of frontal-rainband development hypothesized by Bennetts and Hoskins (1979, 961–962) and illustrated schematically by Locatelli et al. (1994, Fig. 13).

A likely observational example of upscale development in a region of convective–symmetric instability is documented by Jascourt et al. (1988). From a region of scattered cumulus over northern Louisiana, five parallel cloud bands simultaneously grew to become lines of thunderstorms. The bands were aligned along the 700–500-mb shear, a layer in which the moist symmetric stability was especially weak. The vertical stratification in the lower troposphere, however, was conditionally unstable to gravitational convection with CAPE of more than 1000 J kg^{-1}. Jascourt et al. (1988) hypothesize that the initial latent-heat release by the scattered cumulus in the layer of weak symmetric stability favored the development of convective–symmetric instability and organized the convection into the five bands. This research suggests that the nature and organization of convection can be modulated by the symmetric stability.

Upscale convective–symmetric instability also is modeled by Zhang and Cho (1992) and Seman (1994). Zhang and Cho (1992) demonstrate how the typical structure of a squall line (Houze et al. 1989, Fig. 1) acts to release both PI and PSI. The convection along the leading edge reduces the moist gravitational instability, whereas remnant negative MPV$_g$ is transported back towards the trailing precipitation region, where the release of PSI in the ascending front-to-rear flow helps to enhance precipitation. These results are consistent with those of Seman (1994), who shows that convection in an idealized environment similar to that of Jascourt et al. (1988) results in nearly upright updrafts. Slantwise ascent then occurs, releasing symmetric instability, followed by downdrafts that descend following sloping isentropes.

Observed inhomogeneities in vertical motion and precipitation rate along frontal zones may suggest manifestations of downscale convective–symmetric instability. In a frontal environment initially characterized by PSI, Bennetts et al. (1988, 368) and Locatelli et al. (1994, Fig. 13) argue that the circulation of a PSI band will overturn contours of θ_e, thereby leading to PI. A possible example of this type of instability is the elevator/escalator concept for warm-frontal ascent (Neiman et al. 1993, Fig. 8). They describe isolated regions of strong sloping ascent (45° to the horizontal) 10 km wide (the "elevator") that contrast with weaker regions of gentler slantwise ascent (10° to the horizontal) roughly 15 km wide (the "escalator"). Reuter and Yau (1993) determine that the warm-frontal environment that Neiman et al. (1993) analyze is characterized by both PI and PSI, suggesting that the release of PI may be occurring in the "elevator" convective elements, while the release of PSI may be occurring in the "escalator" regions. Parsons and Hobbs (1983, p. 2385), Bennetts and Ryder (1984, Fig. 16), Byrd (1989, 1123, 1127), and Colman (1990a,b) also observe similar convective structures embedded in slantwise ascent in an environment characterized by both PI and PSI. These circulations may represent a form of convective–symmetric instability, where both moist gravitational and moist slantwise convection occur in an environment characterized by both moist gravitational and moist symmetric instabilities. Whereas a few examples of upscale and downscale convective–symmetric instability have been discussed in the literature, diagnosis of situations in which both moist gravitational and moist symmetric instabilities are present may lead to different perspectives on the general nature (e.g., structure, evolution, dynamics) of atmospheric convection.

5.2 *Lightning*

Some authors state that the existence of lightning (i.e., thunderstorms) must imply moist gravitational, rather than moist slantwise, convection (e.g., Bennetts and Sharp 1982, 598–599; Moore and Lambert 1993, 305). Williams (1991, p. 2512) notes that the mechanisms that lead to charge separation are, in principle, independent of the existence of moist gravitational instability, indicating the possibility that lightning could be associated with slantwise convection. Indeed, the occurrence of lightning in environments characterized by MSI is discussed by Engholm et al. (1990), Williams (1991), Colman (1990b, 1991), Lindstrom and Nordeng (1992), and Holle and Watson (1996). In fact, many of these environments characterized by MSI are also associated with the occurrence of higher-than-normal percentages of positive cloud-to-ground lightning. Positive cloud-to-ground lightning tends to occur during the cool season in situations of strong vertical wind shear (Orville et al. 1988) and during the warm season in the trailing precipitation region of mesoscale convective systems (MacGorman and Rust 1998, 275–277), both regions where slantwise convection is likely occurring. These observations support our contention that the slantwise ascent occurring in regions releasing MSI shears out the charge distribution in the vertical, thereby exposing positive charge aloft to the ground (MacGorman and Rust 1998, 275, 290). Coupled with our incomplete understanding of the conditions under which cloud electrification occurs (Vonnegut 1994), we do not know enough at this time to state conclusively that the existence of lightning precludes the existence of slantwise convection.

6. PROPOSED METHODOLOGY

We now propose a methodology for assessing slantwise convection, based on the ingredients-based forecasting methodology discussed in section 2 and the discussion throughout the rest of this presentation. The methodology involves finding regions of the atmosphere that (1) exhibit CSI, (2) have adequate moisture for air parcels to reach saturation in the region of CSI, and (3) possess forcing mechanism(s) that lift parcels to the LFSC, thereby allowing the instability to be released. We propose seven steps that can be employed to assess CSI in a research or operational-forecasting environment. Our methodology is illustrated by a suite of products that can be automated and made available to forecasters in real-time. (For further information, including a copy of the version of this presentation submitted for publication and GEMPAK scripts for assessing slantwise convection, please see `http://www.nssl.noaa.gov/~schultz/csi.shtml`.)

1. Construct a cross section of MPV_g^* and θ_e^*.

2. Choose a level(s) where MPV_g^* is negative and create a horizontal map of MPV_g^* and $\partial\theta_e^*/\partial p$ on the same level(s).

3. Generate cross sections and horizontal maps overlaying MPV_g^* and relative humidity.

4. Construct a cross section of frontogenesis.

5. Generate a horizontal map of frontogenesis at the level determined from step 4 and MPV_g^* from the level found in steps 1 and 2.

6. Construct a horizontal map of frontogenesis and an upper-level forcing mechanism for vertical motion.

7. Compare the characteristics associated with the band(s) with those predicted by CSI theory. [See Seltzer et al. (1985) for further elaboration on this point.]

This methodology has been applied to several cases with some success at the National Weather Service Office for eastern North Dakota. Based on this methodology, heavier precipitation was forecast, but the location and duration was not always correctly predicted due to errors in the numerical models examined.

7. SUMMARY

The following points represent our basic tenets regarding MSI.

1. Like deep moist gravitational convection, moist slantwise convection requires the simultaneous presence of instability, moisture, and lift. The absence of any one of these three is sufficient to prevent moist slantwise convection from occurring.

2. Slantwise convection and CSI do not have interchangeable meanings.

3. Strictly speaking, hydrostatically and geostrophically balanced basic states for θ_e^* and M_g, respectively, are required for determination of CSI. In practice, the restriction on θ_e^*, but not on M_g, can be relaxed.

4. Analogies to CI and PI indicate that the definitions commonly employed for CSI are really for PSI. Ideally, when assessing CSI, θ_e^* should be used; when assessing PSI, θ_e should be used.

5. CSI, when correctly diagnosed using θ_e^*, is the appropriate measure of the susceptibility of the atmosphere to slantwise convection.

6. Owing to the potential confounds with assessing the M_g–θ_e^* relationship, we recommend that MPV_g^*, along with a measure of CI, be employed to assess CSI.

7. By definition, an environment characterized by CSI possesses a horizontal gradient in θ_e^* and vertical wind shear, likely indicating a frontal zone. In an environment in which CSI and frontogenesis coexist, it is improper to attempt to separate the circulations due to CSI from the frontal circulation.

8. Blindly applying tests for CSI/PSI may result in the identification of regions of CI/PI.

9. The coexistence of CSI/PSI and CI/PI, as well as adequate moisture and lift, may result in a mixture of moist gravitational and moist slantwise convection associated with the release of convective–symmetric instability.

10. The existence of lightning is not an adequate discriminator between the existence of moist gravitational and moist slantwise convections.

8. IS CSI *REALLY* USEFUL AS A DIAGNOSTIC TOOL?

We have not addressed whether our ability to assess MSI makes a noticeable improvement in our ability to forecast the weather. Although MSI is apparently present in many precipitation events, other similar events may exhibit forced slantwise ascent in the absence of any instability. Therefore, we may rephrase our question: Given advance knowledge that the atmosphere releases MSI over a forecast area, how does it affect the operational forecast decision-making process? Dunn (1988) and Wiesmueller and Zubrick (1998, 86) note that even given advance knowledge of the presence of MSI and the other ingredients for slantwise convection, determination of the locations affected by banded precipitation would be difficult to predict and include in a typical National Weather Service forecast.

The use of MSI as an operational forecasting tool is being addressed by operational meteorologists at least for short-range forecasting (e.g., Wiesmueller and Zubrick 1998), but further discussion and implementation of useful forecasting techniques would benefit all. Research meteorologists must also step up and address some of the issues raised in this presentation. As a meteorological community, we must move beyond the era of presenting case studies from our pet heavy-precipitation events and forecast busts that illustrate the existence of MSI and show its utility towards our understanding of how convection works and how its use can improve forecasts. We feel that these issues need to be addressed before progress can occur. We invite comments and encourage further research on this final point.

REFERENCES

A complete list of references can be found at `http://www.nssl.noaa.gov/~schultz/csi.shtml` or by contacting the authors.