7.2 THE USE AND MISUSE OF CONDITIONAL SYMMETRIC INSTABILITY

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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, we contend 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 CSI concept by researchers and forecasters by highlighting common pitfalls and (2) to encourage future research explorations by noting the deficiencies in our understanding of MSI and slantwise convection.

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. 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, 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 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

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CSI correctly in their own work (e.g., Reuter and Yau 1990, 449; 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 this article. 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 needed.

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 for evaluating the M_g–θ_e^* relationship is perpendicular to the vertical 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 is 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. 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. Doswell (1987, 7) has argued that synoptic-scale ascent probably is not responsible for initiation of deep, moist gravitational convection. On the other hand, slantwise convection occurs on slightly larger scales than gravitational convection. Therefore, resolving the processes responsible for lift on the meso-α and synoptic scales (greater than 200 km) is likely in most cases of suspected MSI. The relative roles of synoptic and mesoscale processes in the initiation of gravitational and slantwise convection is poorly known, compounding the difficulty in understanding convective initiation (Ziegler and Rasmussen 1998).

In comparing observations to idealized models, it is useful to distinguish between the release of MSI occurring due to the growth of infinitesimal perturbations (i.e., normal-mode theory) and the release of MSI occurring in the presence of some larger-scale forcing (i.e., frontogenesis, orographical circulations, etc.). Fischer and Lalaurette (1995a,b) compare these scenarios, finding that idealized normal-mode simulations produce growth rates that are too slow [$\sim$(11 h)$^{-1}$] to account for observed features. Strong forcing (say, in the form of frontogenesis) is required to overcome two factors that inhibit the release of MSI: turbulent diffusion in the narrow, moist ascent and the resistance of the positive buoyancy in the broader, dry, compensating subsidence. Therefore, finite-amplitude forcing is usually considered to be present for the release of MSI in the real atmosphere [see also Innocentini and dos Santos Caetano Neto (1992)]. These studies support the observation that few examples of MSI in the absence of frontogenesis exist [a possible exception is Wood and Nielsen-Gammon (1994)].

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 ($MPV_g^* < 0$ and the M_g–θ_e^* relationship) will identify regions of CI and blindly applying the tests for PSI ($MPV_g < 0$ and the M_g–θ_e relationship) will identify regions of PI.* Whereas there have been some attempts to discriminate between situations characterized by CI/PI from those characterized by CSI/PSI (Bennetts and Sharp 1982, 598–599; Moore and Lambert 1993; Wiesmueller and Zubrick 1998, 86), this distinction is not always made (e.g., Gyakum 1987, p. 2339; Lemaître and Scialom 1992, Fig. 12; Lagouvardos and Kotroni 1995, Fig. 10; Chen et al. 1998, Fig. 21) or is made, but not applied properly (e.g., Moore and Blakley 1988, p. 2170, Fig. 19; Wang et al. 1990, Figs. 1 and 8; Shields et al. 1991, 956–959; Davidson et al. 1998, p. 1623). In order to be precise, we strongly recommend assessing CI/PI and inertial instability prior to assessing CSI/PSI, in any given case.

Ultimately, a deeper understanding of how convection (gravitational, slantwise, or both) organizes in the presence of both CI/PI and CSI/PSI is sought. Xu and Clark (1985) argue for a continuum between gravitational and slantwise convection, so, in a sense, the distinction that is drawn between gravitational and slantwise convection can be considered arbitrary. As further noted by Jones and Thorpe (1992, 242), "the strong distinction which is often made between flows with positive and negative potential vorticity is an artifact of the use of balanced equations, rather than a physical property of atmospheric flow."

Nevertheless, as an initially gravitationally and symmetrically stable baroclinic atmosphere is destabilized by, for example, surface heating or increasing the vertical shear of the geostrophic wind, CSI/PSI will arise before CI/PI (Emanuel 1994, 410), but owing to the larger growth rate and energy release of moist gravitational convection compared to slantwise convection, gravitational convection, if initiated, is likely to dominate in time. Following Emanuel (1980, 220, 245–250), 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 (1986a, 331) proposes two mechanisms for rainband development, mechanisms we now recognize as forms of convective-symmetric instability. 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 (1986a) 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 band formation. Xu's (1986a) downscale development is similar to the three-stage process of frontal-precipitation-band development hypothesized by Bennetts and Hoskins (1979, 961–962).

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.

An alternate scenario for the release of upscale convective–symmetric instability is modeled by Zhang and Cho (1992), Seman (1994), and Bélair et al. (1995). Zhang and Cho (1992) and Bélair et al. (1995) use mesoscale numerical-model simulations of real squall lines to demonstrate how the typical structure of a squall line [a schematic of which is presented in Houze et al. (1989, Fig. 1)] acts to release both PI and PSI simultaneously. The convective line reduces the moist gravitational instability, whereas remnant negative MPV$_g$ is transported back toward 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 (dry and/or moist) isentropes. Comparison to a barotropic simulation (PI present only) indicates that the baroclinicity enhances the mesoscale circulation leading to more intense, longer-lived updrafts and more precipitation, consistent with the results of Xu (1986a). Case studies of upscale development in the presence of convective–symmetric instability and inertial instability are also presented by Blanchard et al. (1998).

Whether the trailing precipitation region behind a mesoscale convective system, oftentimes referred to as the stratiform region, is characterized by stratiform or convective precipitation is being debated. The results of Zhang and Cho (1992) and Bélair et al. (1995), if general to mesoscale convective systems, would indicate that this region is characterized by slantwise convection due to the release of MSI. Indeed, further observational and modeling studies continue to suggest regions of MSI in the trailing precipitation region of squall lines (e.g., Jiang and Raymond 1995; Braun and Houze 1996). Therefore, referring to this region as "stratiform" (i.e., occurring in a stable environment) may have to be reconsidered.

Observed inhomogeneities in vertical motion and precipitation rate along frontal zones in the form of embedded bands or cells may suggest manifestations of downscale convective–symmetric instability. As the amount of moisture available to the circulation increases, the likelihood of generating embedded moist gravitational convection increases (Saitoh and Tanaka 1988). A possible example of downscale convective–symmetric instability is Neiman et al.'s (1993) elevator/escalator concept for warm-frontal ascent in which isolated regions of strong sloping ascent (45° to the horizontal) 10 km wide (the "elevator") contrast with weaker regions of gentler slantwise ascent (10° to the horizontal) roughly 15 km wide (the "escalator"). Reuter and Yau (1993, 378) 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" slantwise regions. Parsons and Hobbs (1983, p. 2385), Bennetts and Ryder (1984, Fig. 16), Byrd (1989, p. 1127), and Colman (1990a,b) also observe similar convective structures embedded in slantwise ascent in an environment characterized by both PI and PSI. Rainband studies before the advent of MSI theory in the early 1980s (e.g., Browning et al. 1973) and the idealized modeling work of Xu (1989b, Figs. 16 and 18) also may indicate such a process. These precipitation structures may represent a form of downscale convective–symmetric instability, where both moist gravitational and moist slantwise convection occur in an environment characterized by both moist gravitational and moist symmetric instabilities. That these precipitation structures commonly are observed may suggest that convective–symmetric instability is not atypical.

6. MSI IN MESOSCALE MODELS

Molinari and Dudek (1992, section 5) discuss the implications for slantwise convection in numerical weather prediction models. Whereas grid-resolvable precipitation is calculated by the large-scale explicit precipitation schemes, convective precipitation due to the release of moist gravitational instability is calculated by cumulus parameterization schemes. Precipitation generated by the release of MSI during slantwise convection, however, is neither grid-resolvable nor convectively parameterized at resolutions greater than about 10 km. The inclusion of this missing effect may substantially improve the numerical prediction of quantitative precipitation, as suggested by Emanuel (1983a, p. 2375) and Persson and Warner (1993, p. 1832). For a simulation of a central United States cyclone, Lindstrom and Nordeng (1992) apply Nordeng's (1987, 1993) parameterization of slantwise convection patterned after the Kuo scheme for moist gravitational convection, which produces neutrality to slantwise convection along a M surface. Their results show that the parameterization improves the simulation of the quantity and areal extent of precipitation associated with a midwest United States cyclone, indicating the potential usefulness of this approach. Also, the addition of the slantwise-convective parameterization helps the model generate divergent circulations more quickly (improving the so-called model-spinup problem). Consequently, future research in this area might result in improvements in quantitative precipitation forecasting.

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 or inertial instability.

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. Implementation of slantwise convective parameterization has the potential to improve numerical weather prediction.

Drawing parallels to the familiar conceptualizations of gravitational convection allows a reconsideration of the extent to which slantwise convection is understood and used in research and forecasting environments. Indeed, the argument could be made that the near-omnipresence of baroclinicity in midlatitudes, even during the warm season, requires an evaluation of the potential for slantwise convection. An example where such diagnosis might be useful is during the early and late stages of deep, moist convection, when gravitational instability is likely to be small. The dichotomy between gravitational and slantwise convection is also apparent in numerical modeling where parameterizations for slantwise convection presently are not included in the majority of research-mesoscale and operational-forecast models. Consideration of convective–symmetric instability appears to be a prudent step toward a more general consideration of atmospheric convection. It is tempting to speculate that combining the intellectual resources of those studying meso- and synoptic-scale processes with those studying convective-scale phenomena, from both the research and operational communities, has the potential to lead to further improvements in our understanding of convective phenomena.

EPILOGUE

This review is based on a manuscript accepted for publication in *Monthly Weather Review*. A copy of our manuscript and various diagnostic approaches for assessing slantwise convection are shared at our web site: `http://www.nssl.noaa.gov/~schultz/csi.shtml`.

REFERENCES

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