The Multiscale Organization of Moist Convection and the Intersection of Weather and Climate

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Moist convection organizes into cloud systems of various sizes and kinds, a process with a dynamical basis and upscale connotations. Although organized precipitation systems have been extensively observed, numerically simulated, and dynamically modeled, our knowledge of their effects on weather and climate is far from complete. Convective organization is absent de facto from contemporary climate models because the salient dynamics are not represented by parameterizations and the model resolution is insufficient to represent them explicitly. High-resolution weather prediction models, fine-resolution cloud system models, and dynamical models address moist convective organization explicitly. As a key element in the seamless prediction of weather and climate on timescales up to seasonal, organized convection is the focus of the Year of Tropical Convection, an international collaborative project coordinated by the World Meteorological Organisation. This paper reviews the scientific basis of convective organization and progress toward comprehending its large-scale effects and representing them in global models.

1. INTRODUCTION

Numerical weather prediction and climate modeling are on convergent paths with respect to climate variability and change. Weather prediction has historically put extraordinary demands on numerical computation in order to advance forecast skill through improved resolution, data assimilation, and parameterization. Moving forward from their research heritage, climate models must now address the complex problem of "climate prediction," where computer power is ever more necessary. As the primary vertical transport process for thermodynamic quantities (heat and moisture), dynamical quantities (mass, momentum, kinetic energy, and vorticity), and chemical constituents in the Earth's atmosphere, moist convection is a long-standing uncertainty that compromises the fidelity of all numerical prediction systems. The structural complexity of moist convection is compounded by nonlinearities involving microphysics (e.g., phase changes of water) and macrophysics (e.g., latent heating, convective transport, cloud-radiation interaction, and convective organization). Atmospheric convective organization is manifested as coherent structures within fields of clouds. The fact that coherent structures occur in many fields of science (e.g., fluid dynamics, physics, chemistry, biology, and combustion) attests to the fundamental nature of convective organization.

Convective organization implies an upscale cascade of energy and has dynamical connotations involving wind shear, convection-wave interaction, and the maintenance of the atmospheric circulation against dissipation. The organization of certain shallow (nonprecipitating) cloud systems is rooted in the dynamical instability of the base state, e.g., boundary layer "cloud streets" as the Kelvin-Helmholtz instability of shear flow, and cellular convection as gravitational/diffusive Rayleigh instability, structures which may be maintained through to finite amplitude. On the other hand, moist convection is "multiscale" involving systems up to

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hundreds or even thousands of times the size of cumulonimbus and "multistructural" evolving into different morphological structures as time progresses. The evolution involves shear and latent heating, evaporative cooled downdraft outflows, and convectively generated waves among other processes. These systemic properties are inadequately represented by parameterizations, which compromises the interactions between moist convection, the global circulation, and the climate system.

The organization of precipitating convection has been observed for over a century [*Ludlam*, 1980]. While vertical shear had been known much earlier to affect the organization of moist tropical convection [e.g., *Hamilton and Archbold*, 1945], a quantification of the effects of shear on convective precipitation awaited weather radar [e.g., *Newton and Newton*, 1959; *Browning and Ludlam*, 1962]. Dynamical models formalized the effects of shear on convective organization and quantified its upscale properties [*Moncrieff and Green*, 1972; *Moncrieff and Miller*, 1976]. Numerical models simulated the three-dimensional (3-D) effects of shear on cumulonimbus and severe storms [e.g., *Miller and Pearce*, 1974; *Klemp and Wilhelmson*, 1978]. *Lilly* [1983] suggested that even a small amount of kinetic energy transferred upscale by convective outflows could affect synoptic-scale motion. Mesoscale circulations have a downscale effect on cumulus convection [*Cotton et al.*, 1976]. The backscatter procedure by which small-scale kinetic energy gets injected back to large-scale models has been used as a way to parameterize the upscale cascade [*Shutts*, 2005].

The assumption of a scale gap between cumulus convection and synoptic-scale motion used in contemporary cumulus parameterization offers useful simplifications such as the neglect of lateral transport of mass, energy, and momentum. Contrary to observations and dynamical theory, in terms of parameterization, the scale-gap assumption relegates convective organization to a secondary consideration. Observations have long confronted this assumption, e.g., the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) clearly showed that mesoscale cloud clusters populate the scale gap (see the review by *Houze and Betts* [1981]). The existence of a mesoconvective continuum rather than a scale gap has been quantified by observations, simulations, and theory over decades. Lateral fluxes are an important consideration for organized systems, especially those that have a strong vertical tilt.

Ignoring the effects of organized convection undoubtedly retarded the formulation of physically based parameterizations. Until recently, parameterization was the only way by which the effects of precipitating convection in global prediction systems could be estimated. This is no longer the case. Cloud system resolving models (CRMs) simulate multiscale convective organization and its scale interactions. High-resolution global weather prediction models explicitly represent convective organization, albeit as underresolved circulations. The multiscale organization of convection can be addressed with completeness at the intersection of weather and climate (timescales up to seasonal) where high resolution is an affordable option.

This paper focuses on the organization of moist convection, its dynamical approximation and simulation by fine-scale numerical models, and its representation in global weather and climate models. The following section involves global-scale convective organization and propagating precipitation systems. The controls on moist convection are addressed in section 3, followed by fundamentals of mesoscale convective organization in section 4, and the multiscale organization of tropical convection in section 5. Multiscale convective organization in a hierarchy of numerical models is the subject of section 6, followed by its parameterization in section 7. The paper concludes with discussion in section 8 and conclusions in section 9.

2. GLOBAL CONVECTIVE ORGANIZATION

The organization of clouds into coherent systems and their association with the global atmospheric circulation is abundantly clear from satellite observations, e.g., the midlatitude baroclinic systems, the subtropical convective complex, and tropical cloud systems. The correlation between convective organization and the large-scale atmospheric circulation implies that convective organization can, in principle, be represented as functions of the resolved-scale variables, i.e., parameterized.

2.1. Midlatitude Baroclinic Systems

The baroclinic systems within the midlatitude storm tracks have long been understood as a baroclinic instability of the zonal flow, which is a convective process. The kinetic energy of motion derives from a slantwise (almost horizontal) buoyant exchange of mass by two global airstreams: a warm conveyor belt originating in the subtropics and the return cold branch from the polar regions. The meridional convergence of the meridional transport of zonal momentum associated with this mass exchange maintains the jet stream and the westerly vertical shear of midlatitudes.

A hierarchy of moist convective organization is embedded in these airstreams. Rainbands of various descriptions occur within the warm conveyor belt. In the cold branch (category A, Figure 1), flow-parallel shallow bands form near the polar ice sheets and transition downstream into open and closed cellular convection (stratocumulus). Near the cold front,

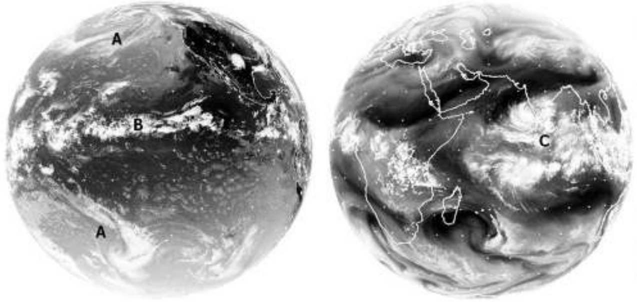

Figure 1. (left) Global image of the large-scale organization of convection, e.g., Intertropical Convergence Zone, subtropical cloud bands, and polar outbreaks. (right) Multiscale organization of deep convection, large mesoscale convective systems (superclusters), and incipient tropical cyclones associated with a Madden-Julian Oscillation (MJO) episode in the Indian Ocean. Image from NERC Satellite Receiving Station, University of Dundee, Scotland, U. K.

convective organization is manifested by clusters of cumulonimbus, rainbands, and squall lines. The largest atmosphere-ocean heat exchange on Earth (~1000 W m^{-2}) near the ice sheets cools the ocean surface and drives deep oceanic convection, forming the thermohaline circulation.

2.2. Subtropical Convective Complex

The subtropical convective complex (category B, Figure 1) is identified with the Intertropical Convergence Zone (ITCZ), fields of trade wind cumulus, and stratocumulus decks. Occurring in conditions of anticyclonic cool advection, the subtropical convective complex has evolutionary properties in common with the polar branch of midlatitude baroclinic systems, e.g., the downstream transition of shallow cumulus into deep convection. Marine stratocumulus has received much attention because of its cooling effect on the climate system. The ITCZ in the Atlantic and Pacific is multi-structural, populated by synoptic-scale easterly waves, tropical cyclones, and mesoscale cloud systems. The ITCZ in the Indian Ocean is modulated by the Asian-Australian monsoon. During boreal summer, the northward migration of the ITCZ into the Bay of Bengal affects the onset of the summer monsoon, the variability of precipitation, agriculture, and livelihood on a continental scale.

2.3. Propagating Convective Systems

Propagating precipitation systems populate sheared environments such as the midlatitude jet streams during the warm season, and subtropical jet streams and tropical wave disturbances throughout the year. Examples are mesoscale convective systems (MCS), the Madden-Julian Oscillation (MJO) [*Madden and Julian*, 1972], and convectively coupled equatorial waves. These systems were reviewed by *Houze* [2004], *Zhang* [2005], and *Kiladis et al.* [2009], respectively. Category C in Figure 1 shows the multiscale and multi-structural nature of the MJO in the Indian Ocean associated with severe weather, heavy precipitation, and floods, e.g., tropical cyclones and superclusters.

Organized propagating precipitation systems are truly a “missing process” in climate models because the pertinent dynamics are not approximated by parameterizations, and the model resolution is insufficient to represent them explicitly. Distinctions between extratropical and tropical convection feed through to parameterization. In weather prediction models, parameterization has a high fidelity in midlatitudes because, being well-resolved, the baroclinic systems provide realistic moisture and vertical shear controls for moist convection (see sections 4.1 and 4.2). Rather than being subject to downscale control, tropical convection is responsive to if not generated by an upscale cascade of energy.

3. CONTROLS ON MOIST CONVECTION

Latent heat released by moist convection is the principal source of energy for the large-scale tropical circulations, whose effects may be transmitted globally by Rossby wave propagation. These circulations are the product of nonlinear interactions among moist processes rather than a dynamical instability of the base state. Latent heating is dispersed by inertial-gravity waves up to the Rossby radius of deformation (~1000 km). The absorption of heat by evaporating liquid precipitation and melting ice drives downdrafts that cool and dry the lower troposphere: Earth’s natural air

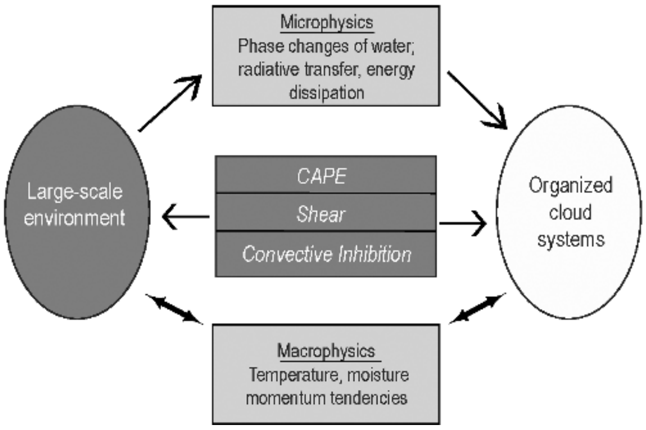

Figure 2. Association of moist convection involving convective available potential energy (CAPE), vertical shear, and convective inhibition.

conditioning system. Propagating for hundreds of kilometers, downdraft outflows (density currents) modulate atmosphere-ocean exchange. Dynamical lifting of planetary boundary layer at density-current fronts triggers new convection. In the tropics, convectively generated gravity waves foster the clustering of cumulonimbus. Vertical shear organizes deep cumulonimbus into long-lasting mesoscale systems. The "top-heavy" profile of heating (tropospheric latent heating and lower-tropospheric evaporative cooling) associated with mesoscale systems affects the tropical circulation through potential vorticity dynamics.

The following section summarizes convective available potential energy, convective inhibition, and vertical shear controls on precipitating convection (Figure 2).

3.1. Convective Available Potential Energy

The integrated buoyancy of vertically displaced moist air parcels defines the convective available potential energy (CAPE) [*Moncrieff and Miller*, 1976] for the up and down branches of convective overturning. The concept of CAPE is demonstrated by exchanging two fluid parcels of density ρ_1, ρ_2 initially at the heights z_1, z_2, respectively, where $z_2 > z_1$ and $\rho_2 > \rho_1$, i.e., the fluid is unstably stratified. The initial and final total potential energies per unit volume are $\rho_1 g z_1 + \rho_2 g z_2$ and $\rho_1 g z_2 + \rho_2 g z_1$, respectively. The total change of potential energy is $g(z_2 - z_1)(\rho_2 - \rho_1)$, and the total kinetic energy of convective overturning is $\frac{1}{2}\rho_1 W^2 + \frac{1}{2}\rho_2 W^2 = \bar{\rho} W^2$, where $\bar{\rho} = \frac{1}{2}(\rho_1 + \rho_2)$ is the average density of the exchanged parcels. The symmetry of this simple model requires that the potential energy release be shared equally by the up and down branches. Equating the potential energy to the kinetic energy for the up branch results in $\frac{1}{2}W^2 = \mathrm{g}(\mathrm{z}_2 - \mathrm{z}_1)\ (\rho_2 - \rho_1)/\bar{\rho} =$ CAPE, the parcel theory of convection.

In the above simple example for an unsheared environment, CAPE is the sole source of energy. In a sheared environment, and for precipitating convection in particular, the kinetic energy of shear and propagation and the work done by the horizontal pressure gradient organize convective overturning (see section 4.1). For a moist atmosphere, CAPE is based on similar principles except that moisture affects density, and compressibility introduces potential temperature. For a moist atmosphere, $\mathrm{CAPE} = \int_{z_1}^{z_2} g\left(\frac{\delta\theta_v}{\bar{\theta}_v} - l\right)\mathrm{d}z$ where θ_v the virtual potential temperature represents the effects of water vapor on buoyancy, and l is the water loading. In the tropics, the water loading can deplete CAPE by 30%.

CAPE is generated by the transport of heat and moisture from the surface into the planetary boundary layer, and the large-scale advection of temperature and moisture. Dry adiabatic ascent in cyclonic regions of the midlatitude storm tracks and tropical disturbances cools and destabilizes the troposphere and generates CAPE.

3.2. Convective Inhibition

The planetary boundary layer is usually stably stratified. Therefore, a vertically displaced air parcel will be negatively buoyant unless some finite-amplitude mechanism lifts boundary layer parcels above the level of free convection: the planetary boundary layer is "metastable." The convective inhibition or negative CAPE is the vertical integral of the negative buoyancy below the level of free convection. Two mechanisms (local and nonlocal) can break the metastability barrier. The local mechanism is associated with weakly sheared environments. During daytime, the planetary boundary layer is deepened by the turbulent heat flux from the solar-heated surface. In mountainous terrain, the horizontal gradient of temperature generates upslope flow and initiates deep convection (see section 4.5). The nonlocal mechanism involves boundary layer convergence involving density currents, frontal boundaries, solitary gravity waves on the boundary layer inversion, and nocturnal downslope flow. Density currents have long been used to trigger deep convection in numerical models [*Thorpe et al.*, 1980; *Thorpe and Miller*, 1978].

3.3. Vertical Shear

The controlling effect of deep shear and its association with CAPE was demonstrated by early dynamical models and numerical simulations of squall lines [e.g., *Moncrieff and Green*, 1972; *Moncrieff and Miller*, 1976; *Thorpe et al.*, 1982] and severe convective storms [e.g., *Weisman and Klemp*, 1982]. The interaction between low-level shear and density currents initiates families of cumulonimbus multiscale squall lines and mesoscale convective systems in both midlatitudes [*Rotunno et al.*, 1988] and the tropics [*Lafore and Moncrieff*, 1989]. This dynamical triggering is most effective when the wind and wind-shear vectors point in the opposite direction [*Moncrieff and Liu*, 1999]. Baroclinic systems generate vertical shear.

The following section sets the organization of moist convection onto a rigorous basis with emphasis on propagating mesoscale systems.

4. FUNDAMENTALS OF MESOSCALE CONVECTIVE ORGANIZATION

MCSs have been extensively observed, numerically simulated, and dynamically modeled. Quoting *Houze* [2004,

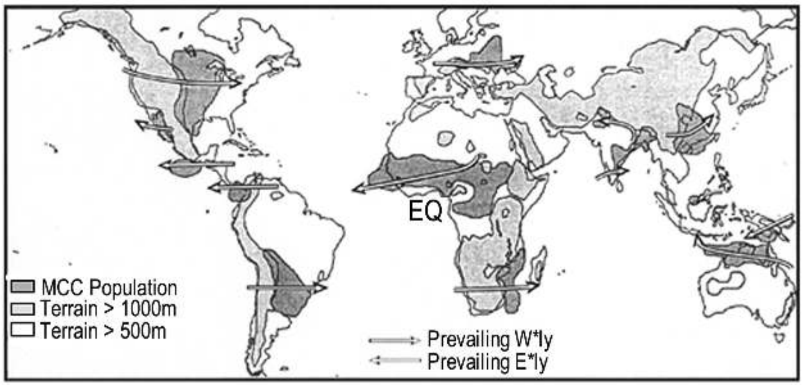

Figure 3. Global distribution of mesoscale convective complexes associated with mountainous terrain and the midlatitude/subtropical jet streams. From *Laing and Fritsch* [1997]. Copyright Royal Meteorological Society, reprinted with permission.

pp. 38–39], "Much of what we know about MCSs . . . has come from field projects and modeling studies carried out in the 1970s and 1980s." Early observations revealed extensive MCSs over the tropical oceans [e.g., *Zipser*, 1969; *Houze*, 1977; *Houze and Betts*, 1981; *LeMone et al.*, 1984]. MCS are embedded within tropical waves [e.g., *Nesbitt et al.*, 2000; *Jakob and Tselioudis*, 2003], synoptic-scale superclusters and the MJO [*Nakazawa*, 1988], and convectively coupled Kelvin waves [*Straub and Kiladis*, 2002; *Haertel and Kiladis*, 2004]. Their propagation and longevity means that MCSs affect the atmosphere and atmosphere-ocean coupling across a range of scales.

Figure 3 shows MCS and mesoscale complexes (MCC) over continents initiated in the neighborhood of mountain ranges, e.g., Rocky Mountains in the United States, the Ethiopian Highlands in Africa, the Andes in South America, the Tibetan Plateau in China, and the eastern Ghats in India. These systems propagate great distances downstream [*Laing and Fritsch*, 1997; *Carbone et al.*, 2002]. The MCC is a special subset of the global MCS population. *Maddox* [1980] defined MCCs in terms of size and longevity: cloud top area with temperature $\leq -32°C$ over a horizontal area of 100,000 km^2 or greater and a cloud top temperature $\leq -52°C$ over an area of 50,000 km^2 or greater, size definitions that must be maintained for at least 6 h.

4.1. Slantwise Layer Overturning in the Vertical Plane

The propagation, dynamical morphology, and longevity of MCS and the accompanying transports of mass, heat, moisture, and momentum is succinctly posed in terms of vorticity. As a class of convective motion, MCS have dynamical properties in common with density currents [*Benjamin*, 1968; *Moncrieff and So*, 1989]. The fact that evaporation-cooled descent occurs rearward of an MCS has basic consequences (see section 4.2), including hydraulic properties that make the MCS a highly efficient, if not the optimally efficient, regime of convective overturning. These aspects were unified in a nonlinear theory of steady convective overturning in shear by Moncrieff and colleagues. Originally applied as a model of squall lines and MCS (this section), this theory has been generalized to model the large-scale organization of tropical convection such as superclusters (section 5).

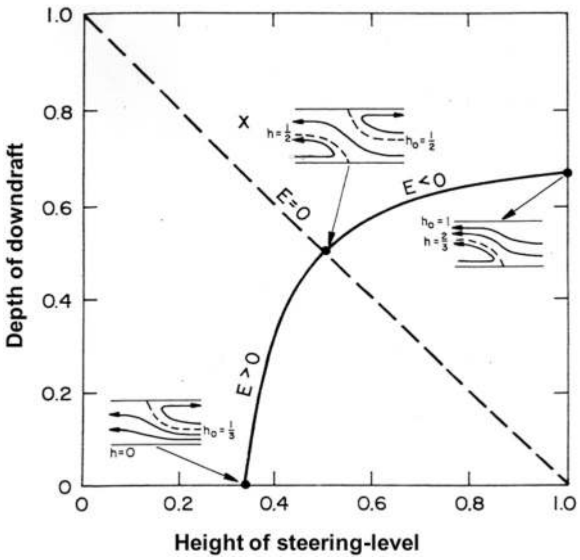

Figure 4. Regimes of archetypal organization each featuring the backward tilt of slantwise layer overturning. Rightmost inset diagram for $E = -8/9$ is purely propagating, i.e., the up branch approaches from the right everywhere. Uppermost inset diagram for $E = 0$ has symmetric up branch and down branches. Leftmost inset diagram for $E = 1$ has a hydraulic jump-like up branch but no down branch, a density current in low-level shear. From *Moncrieff* [1992].

On Figure 4, the uppermost inset diagram displays quasi-laminar branches or "slantwise layer overturning" in the vertical plane that distinguish the Moncrieff models: (1) an upward jump-like branch flows through the system without change of direction resembling a hydraulic jump, (2) an overturning upward branch, (3) an overturning downward branch. Plate 1 casts slantwise layer overturning in terms of the mesoscale circulation associated with the standard observational description of an MCS [*Houze et al.*, 1980]. The organized systems travel eastward/westward in westerly/easterly shear.

As well as the thermodynamic energy (CAPE) normally associated with deep convection, two dynamic forms of energy are fundamental to slantwise layer overturning: the kinetic energy of shear and propagation, AKE $=\frac{1}{2}(U_0-c)^2$ and the work done by the horizontal pressure gradient, WPG $= \Delta p/\rho$. The quantities WPG and AKE are functionally related through the Bernoulli work-energy principle, i.e., the change in the kinetic energy per unit mass along the bottom boundary $\left(\frac{1}{2}U_0^2-\frac{1}{2}U_1^2\right)$ equals the work done by the horizontal pressure gradient ($\Delta p/\rho$).

Quotients of CAPE, AKE, and WPG define two dimensionless quantities, the convective Richardson number R = CAPE/AKE and E = WPG/AKE. These quantities control the organization of precipitating deep convection [*Moncrieff*, 1981], rather than CAPE, shear, or pressure-work on their own. The work done by the horizontal pressure gradient expressed by E represents the hydraulic (Bernoulli) character of slantwise layer overturning. The effects of the work done by the horizontal pressure gradient on the generation and maintenance of mesoscale downdrafts were quantified in numerical simulations of tropical squall lines [*Lafore and Moncrieff*, 1989].

The effects of the convective Richardson number were illustrated by a numerical simulation of convective organization in conjunction with the variation of CAPE and shear during the passage of an easterly wave in the eastern Atlantic during GATE [*Grabowski et al.*, 1998]. Plate 2 shows transitions between nonsquall cloud clusters, a squall cluster with a trailing stratiform region, and scattered cumulus over the period of a week. The squall cluster occurred for strong vertical shear and weak CAPE, i.e., small R.

The Moncrieff 2-D models of steady convective overturning in shear are solutions of an elegant general nonlinear integral-differential equation, "the structure equation for the vertical slantwise layer overturning":

$$\nabla^2\psi - G(\psi) - \int_{z_0}^{z}\left(\frac{\partial F}{\partial \psi}\right)_{z'} \mathrm{d}z' = 0 \qquad (1)$$

where $z_0(\psi)$ is the inflow height of the stream function (ψ) defined as ($u = \partial\psi/\partial z$, $w = -\partial\psi/\partial x$). $F(\psi,z)$ is the buoyancy along streamlines or trajectories in steady flow. The first term in equation (1) is the vorticity along trajectories, the second the inflow shear, and the third the vorticity generated by the horizontal gradient of buoyancy. Equation (1) is derived from the vorticity and thermodynamic equations for 2-D flow derived from conserved Lagrangian quantities [*Moncrieff*, 1981].

Equation (1) represents each of the three airflow branches in Plate 1. Far-field solutions give the propagation speed and the lateral boundary conditions for the 2-D near-field problem. The three branches must fit together, defining a "free-boundary problem" where the shape and orientation of interfaces between the branches must be calculated as part of the solution. (Continuity of pressure is the dynamic boundary condition at free boundaries.) As shown in section 4.2, backward tilted free boundaries are vitally important for slantwise layer overturning. Special cases of equation (1) are the Helmholtz equation (neutral overturning) and Laplace's equation (unsheared inflow and neutral overturning). More mathematically tractable than equation (1), which has no known analytic solution, these simplified equations model 2-D convective overturning.

The archetypal model is the canonical regime of overturning [*Moncrieff*, 1992]. A solution of equation (1) for the hydrodynamic limit for CAPE = 0 ($R = 0$), the archetypal model is defined by constant inflow for the jump branch and constant inflow shear for the up and down overturning branches. Solutions exist only in the range $-8/9 \le E \le 1$. For illustration, three regimes are sketched on Figure 4: (1) the purely propagating density-current-like regime ($E = 1$) generalizes the *Benjamin* [1968] model to include circulation in the density current, (2) regime for $E = 0$ is symmetric slantwise layer overturning, and (3) the jump-like regime ($E = -8/9$) identifies the hydraulic nature of the slantwise overturning.

Generalizations of the archetypal model include 2-D buoyant overturning for $R \neq 0$ [*Thorpe et al.*, 1982] and density-current-like phenomena such as cold-frontal rainbands [*Carbone*, 1982; *Moncrieff*, 1989; *Moncrieff and So*, 1989; *Moncrieff and Liu*, 1999]. In the *Moncrieff and Miller* [1976] tropical squall-line model, 3-D overturning occurs in the plane transverse to the direction of propagation modeling the "crossover zone" observed in tropical squall lines [*Zipser*, 1969].

Slantwise layer overturning was originally developed to explain MCS-type convective organization on the ~100-km scale. *Moncrieff and Klinker* [1997] showed that this concept also explains the ~1000-km scale superclusters observed during the Tropical Ocean Global Atmosphere

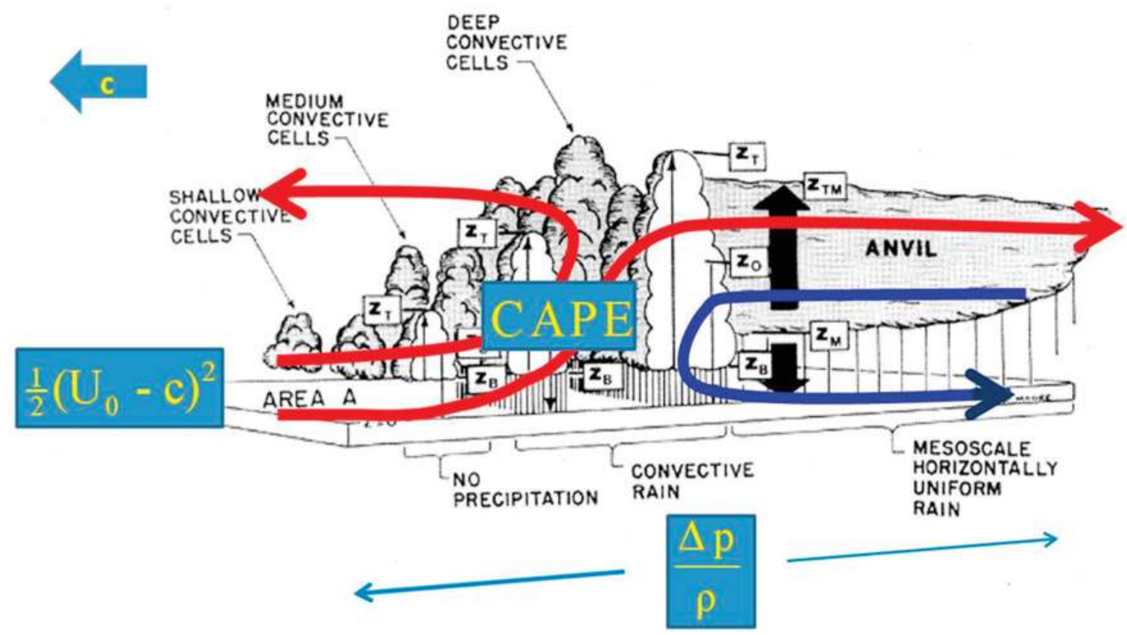

Plate 1. Underlying diagram is the standard observational description of a mesoscale convective system (MCS) propagating leftward [*Houze et al.*, 1980] consisting of shallow cumulus, medium convective cells and deep convection ahead, and a stratiform anvil region and downdraft to the rear. Overlying this diagram is the slantwise layer overturning circulation consisting of a jump up branch, an overturning up branch, and an overturning down branch and the associated three forms of energy, per unit mass: (1) CAPE, (2) the kinetic energy of relative inflow, $\frac{1}{2}(U_0 - c)^2$, and (3) the work done by the horizontal pressure gradient, $\Delta p/\rho$. Adapted from *Tao and Moncrieff* [2009].

Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) simulated by the European Centre for Medium-Range Weather Forecasts (ECMWF) model. This scale invariance between MCS and synoptic-scale superclusters remains to be fully exploited.

4.2. An Existence Principle for Slantwise Layer Overturning

The Lagrangian basis of the Moncrieff models means that the far-field solutions are obtainable, along with the corresponding transports of mass, energy, momentum, and vorticity, without requiring near-field solutions. However, the far- and near-field solutions must be thermodynamically and dynamically consistent. Thermodynamic consistency of 2-D steady overturning requires that the up branches tilt backward (overlie) the down branch enabling precipitation to fall into, evaporate, and sustain the cool down branch. Dynamical consistency requires that the vertical tilt and hence the near-field momentum transport be consistent with the far-field inflow/outflow.

The upward jump is vital. Without it, the system tilts forward, contradicting the thermodynamic consistency [*Moncrieff*, 1978]. The archetypal model demonstrates this point. The upward jump produces the required backward tilt by its effects on the pressure distribution. That the upward jump is crucial for slantwise layer overturning is consistent with the trailing stratiform region being basic to MCS-type organization. The next section affirmatively answers the question: Is the existence principle upheld by numerical models and observations?

4.3. Representativeness of the Slantwise Layer Overturning

The Moncrieff dynamical models were developed side-by-side with numerical simulations [e.g., *Moncrieff and Miller*, 1976; *Thorpe et al.*, 1980, 1982; *Dudhia et al.*, 1987; *Lafore and Moncrieff*, 1989; *Liu and Moncrieff*, 2001], so these dynamical models are, by design, representative of numerical simulations. The intriguing possibility that the slantwise layer overturning model has a general application is based on the following statement made from the observational perspective. *Houze* [2004] states

> An MCS does not always take the form of a crisply defined leading convective line with a trailing-stratiform region; however, it tends to always have a stratiform region with a middle level inflow guided into the system by the environmental relative wind. The rear inflow behind squall lines appears to be a particularly clear example of the more general phenomenon of middle level inflow into and mesoscale descent within the lower reaches of a stratiform region of an MCS.

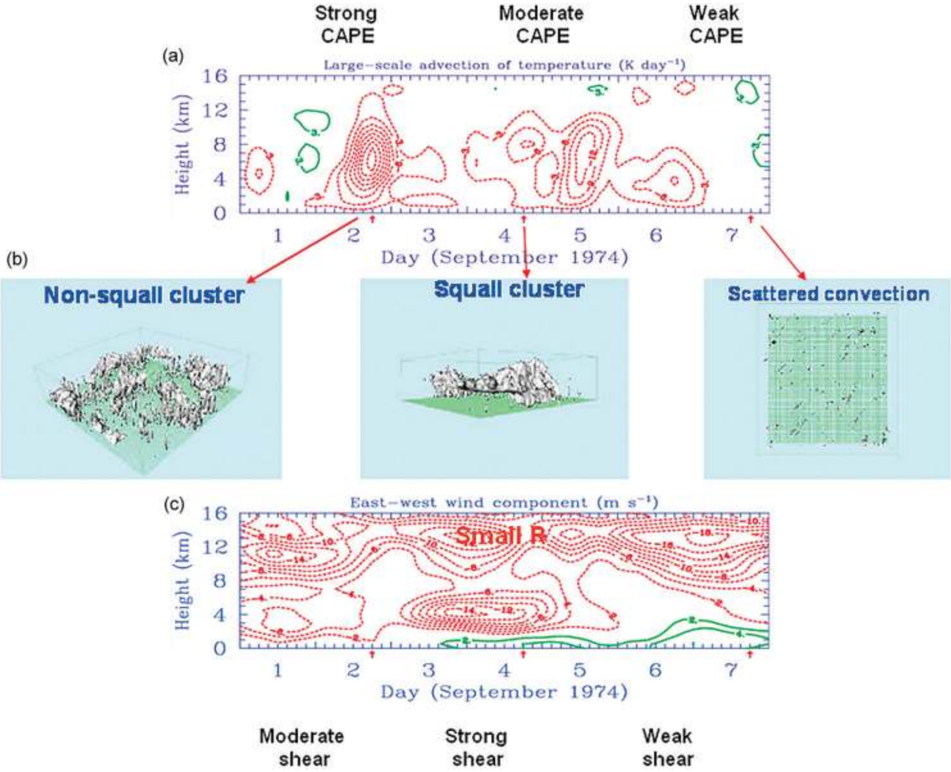

Plate 2. Effects of shear and CAPE (convective Richardson number, R) on the organization of tropical convection in a cloud system resolving model (CRM) simulation showing three regimes of convection: (a) nonsquall cluster for large CAPE and moderate shear, (b) squall cluster for weak CAPE and large shear, and (c) scattered convection for weak CAPE and weak shear. The squall cluster has the backward tilt of MCS-type convective organization. *Tao and Moncrieff* [2009]. Copyright American Meteorological Society.

The existence principle (section 4.2) is consistent with this quotation.

While observations do not give a precise estimate of the global representativeness of the slantwise layer overturning model, evidence on regional scales and for different climate states does support its validity. *Fritsch et al.* [1986] estimated the contribution of precipitation from mesoscale convective weather systems (74 MCCs and 32 MCSs) over the continental United States during the warm season (April–September). Examining two climatic scenarios, a “normal” year (1982) and a drought year (1983), Fritsch et al. found that mesoscale convective weather systems account for 30–70% of the warm season precipitation in the region from the Rocky Mountains to the Mississippi. The contribution is even larger in midsummer. The implication is that propagating convective weather events are “very likely the most prolific precipitation producers in the United States” and “may be a crucial precipitation-producing deterrent to drought.”

In a study of stratiform rain in the tropics estimated from the precipitation radar on Tropical Rainfall Measuring Mission (TRMM) over a 3-year period, *Schumacher and Houze* [2003] estimated that stratiform precipitation associated with slantwise overturning accounts for 73% of the rainy area and 40% of the total rain.

Kingsmill and Houze [1999] examined the momentum fields in all the MCSs observed by airborne Doppler radar in TOGA COARE. These systems contained the fundamentals of the Moncrieff 2-D model (see Plate 1). They also showed 3-D aspects of the MCSs and how the overturning and jump components of the 2-D model fit into the more complex 3-D context of natural MCSs. The Kingsmill and Houze study shows that even though MCSs in nature are 3-D, the fundamental properties of the Moncrieff model remain.

4.4. Downgradient and Upgradient Convective Momentum Transport

The convective momentum transport (CMT) per unit volume and unit length in the transverse (y) direction is $\langle \rho u'w' \rangle = \frac{1}{L}\int_0^L \rho u'w' \mathrm{d}x$, where L is the dynamical scale. The

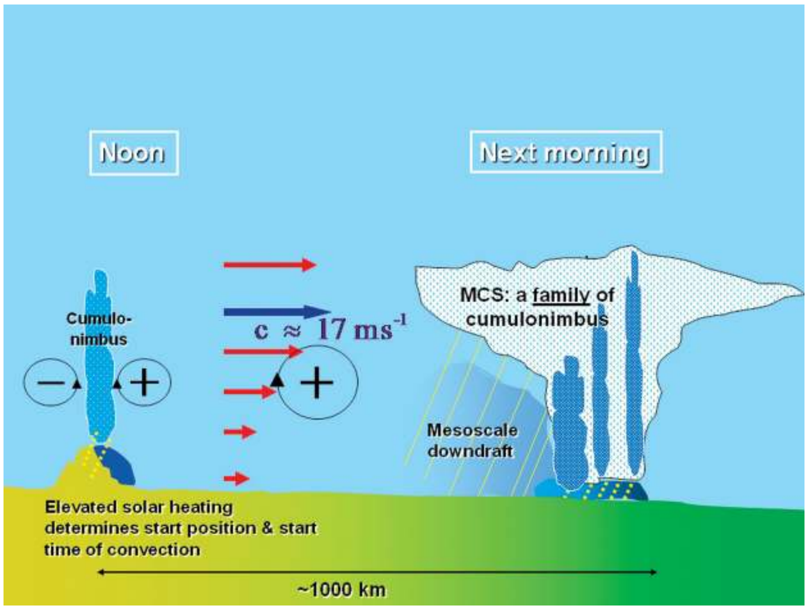

Plate 3. Conceptual model of an MCS originating over the Continental Divide. Cumulonimbus initiated by the elevated heating (baroclinic generation of horizontal vorticity) evolve in a sheared environment into multiscale systems over the Great Plains sustained by the large-scale advection of moisture in the low-level jet originating over the Gulf of Mexico.

momentum transport by cumulus convection, called cumulus friction by *Schneider and Lindzen* [1976], is parameterized by $\langle \rho u'w' \rangle = M_c(u_c - \bar{U})$, where $M_c = \sigma_c \rho \bar{w}_c$ is the updraft mass flux, σ_c the fractional area of cloud in the grid box, $\bar{w}_c(z)$ the horizontally averaged updraft speed, $u_c(z)$ the in-cloud momentum, and $\bar{U}$ the mean-flow momentum per

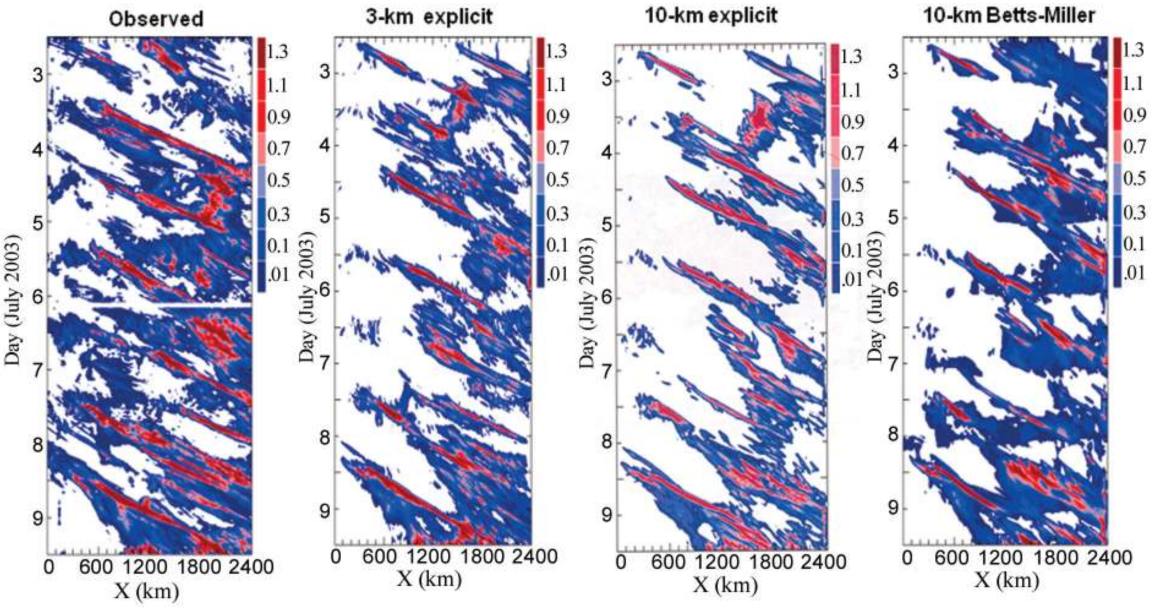

Plate 4. Precipitation rate in mm h^{-1} (left to right): Next Generation Weather Radar analysis [*Carbone et al.*, 2002], 3-km grid simulation, 10-km grid simulation, and 10-km grid simulation including the *Betts* [1986] convective parameterization. From *Moncrieff and Liu* [2006]. Copyright American Meteorological Society.

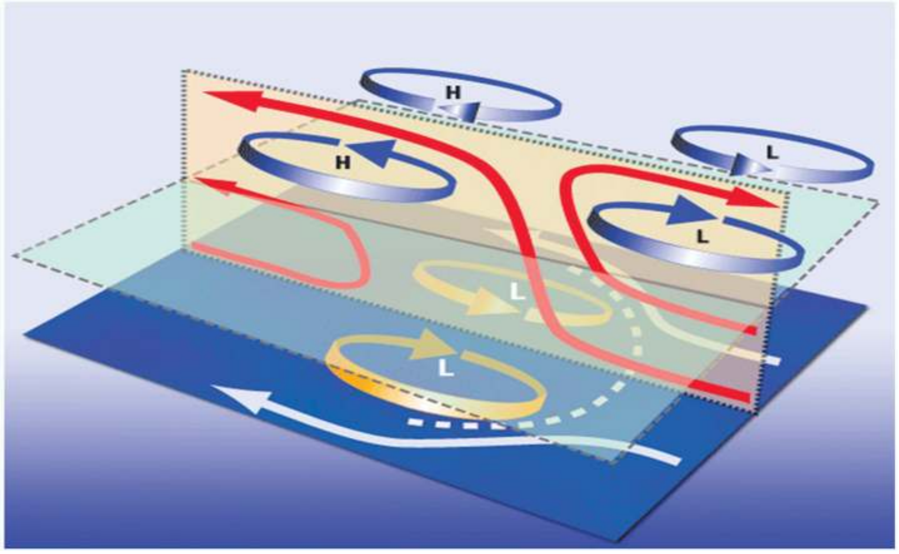

Plate 5. Dynamical models of the 3-D MJO-like system in the *Grabowski* [2001] superparameterized simulation showing vertically tilted MCS-like superclusters interlocked with a Rossby-gyre circulation approximated by a two-level model of slantwise layer overturning in the horizontal plane. These two circulations satisfy simplified forms of equations (1) and (2), respectively. From *Moncrieff* [2004a]. Copyright American Meteorological Society.

unit mass. The mean-flow acceleration is the negative of the vertical gradient of the momentum transport. Schneider and Lindzen assumed that in-cloud updraft momentum is conserved and equal to the cloud-base value. However, momentum is not normally conserved in convective updrafts due to the horizontal pressure gradient. Based on CRM simulations, *Kershaw and Gregory* [1997] approximated the pressure gradient effects on the in-cloud momentum. By

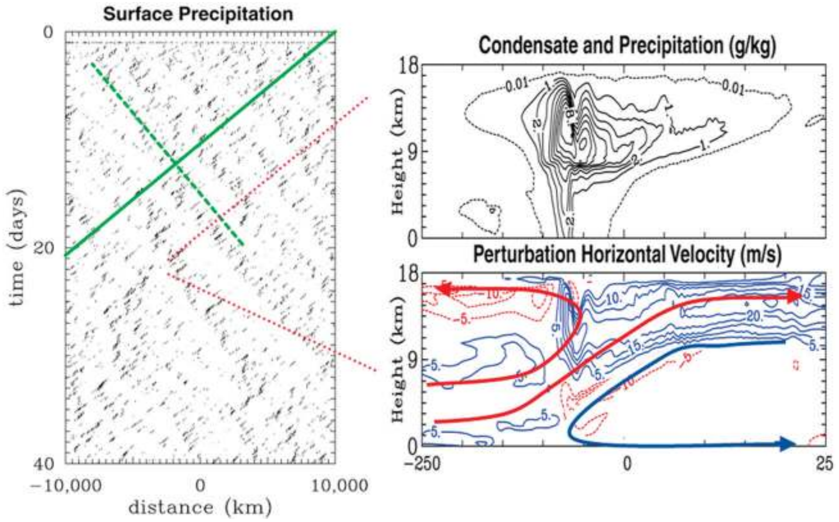

Plate 6. Multiscale convective organization simulated in a 2-D global CRM. (left) Hovmöller diagram of westward propagating precipitation systems embedded in eastward propagating cloud envelopes. (top right) Vertical section of the condensate and precipitation. (bottom right) Westward propagating MCS-like systems approximated by slantwise layer overturning. Adapted from *Grabowski and Moncrieff* [2001]. Copyright Royal Meteorological Society, reprinted with permission.

reducing the difference between in-cloud and mean-flow momentum, the pressure gradient brought the parameterized momentum transport into closer agreement with the CRM simulations. The convective momentum transport represented in the above way is not necessarily downgradient. When $u_c > \bar{U}$, upgradient transport occurs because the mean flow is accelerated.

The organization of moist convection is associated with distinctive mesoscale momentum transport (MMT). The vertical integral of momentum flux divergence is zero for steady flow bounded above and below by horizontal boundaries. In other words, although horizontal momentum can be redistributed, should shear increase in a particular layer, it must decrease in another, i.e., both upgradient and downgradient transport of momentum will occur. The sign of the MMT is opposite to that of the propagation vector, i.e., an eastward propagating system is associated with westward momentum transport. Its magnitude peaks near the middle of the convective layer, consistent with field-experiment analysis [*LeMone et al.*, 1984; *Wu and Yanai*, 1994]. The archetypal MMT agrees with numerical simulations [*Wu and Moncrieff*, 1996] and observations [*LeMone and Moncrieff*, 1993]. The kinetic energy generation is comparable to the rate of change of CAPE [*Wu and Moncrieff*, 1996]. More information can be found in the work of *Moncrieff* [1997].

Houze et al. [2000] gave empirical evidence for how the mesoscale circulations associated with MCSs can feedback either positively or negatively to the large-scale circulation of the MJO. In the strong westerly wind zone of the MJO, the MMT reinforces the larger-scale structure. *Mechem et al.* [2006] present model results that support the empirical evidence that MMT feeds back to the larger-scale wave. These downdraft-related transports of momentum present complications that may need to be considered in a complete representation of momentum transport by MCS. The Kelvin-Rossby wave structure of the MJO also organizes convection as seen in the analysis of TOGA COARE observations [*Houze et al.*, 2000].

Tung and Yanai [2002a, 2002b] studied convective momentum transport associated with the MJO, tropical waves, squall, and nonsquall MCSs. They examined the momentum budget deduced from the objectively analyzed observations during TOGA COARE in the intensive flux array (IFA) at 2.5° × 2.5° areal resolution. The IFA-mean kinetic energy transfer is downscale for about 60–65% of time in the lower troposphere, but in the upper troposphere, upscale and downscale kinetic energy transfers occur with similar frequency. In other words, different kinetic energy transfers are associated with different regimes of convective organization (recall the role of R and E). Upscale kinetic energy transfer occurs in the line-normal direction of squall lines. During the westerly wind phase (burst) of the MJO, the convective momentum transport is upgradient, and the upscale kinetic energy transfer assists the westerly wind burst. In the subsequent strong low-to-midlevel westerlies, the momentum transport is mostly downgradient reducing the shear in midtroposphere.

4.5. Orogenic Mesoscale Convective Systems

Using brightness temperature obtained from satellite-based observations as a proxy for deep convection, *Laing and Fritsch* [1997] showed a relationship between MCCs, orography, and the midlatitude/subtropical jet streams (Figure 3). Using data from the surface-based network over the continental United States, *Carbone et al.* [2002] showed that during the warm season (May–October), episodes of MCS originate over the Continental Divide, propagate eastward for ~1000 km over the continental United States in the westerly shear flow characteristic of that region. The episodic nature of these MCSs is indicative of upper tropospheric eastward traveling short waves, which episodically generate CAPE and shear. The MCSs may evolve nocturnally into MCCs over the Great Plains (Plate 3) when the low-level jet of moisture from the Gulf of Mexico penetrates deep into the Midwest. The nocturnal maximum of precipitation is partly due to CAPE generated by the advection of moisture by the low-level jet originating over the Gulf of Mexico. The diurnal cycle of energy is affected on a continental scale [*Knievel et al.*, 2004]. The large nocturnal systems tend to be more 3-D than MCS and during the later stages of evolution may develop synoptic-scale vortices that further prolong their life.

Tripoli and Cotton [1989] simulated diurnal convection in the lee of the Rocky mountains and proposed a conceptual model of the life cycle of orogenic propagating convection. The *Moncrieff and Liu* [2006] 3-D simulations were initialized and forced by global analysis provided by the National Centers for Environmental Prediction (NCEP). The simulated squall lines resemble those of *Davis et al.* [2003] for other observed episodes. The precipitation patterns produced by explicit convection at 3-km grid spacing, explicit convection at 10-km grid spacing, and hybrid (explicit plus parameterized) convection at 10-km grid spacing were compared with radar measurements (Plate 4). The MCS propagation and the distribution of precipitation are similar. The precipitation is mostly from the explicit (grid-scale) circulation, not the parameterized convection. The grid-scale circulations do not approximate MCS unless the grid spacing is at least 10 km.

The simulated MCS over the U.S. continent displays the backward tilt characteristic of slantwise layer overturning.

The MMT at 3- and 10-km grid spacings have a similar structure. At 10-km grid spacing, a systematic warming occurs in the lower troposphere, a consequence of a weak mesoscale downdraft. At 30-km grid spacing, the MCS propagate too slowly, the unrealistic lower-tropospheric warming gets more pronounced, and the mesoscale momentum transport is unrealistic.

5. MULTISCALE ORGANIZATION OF TROPICAL CONVECTION

The leading mode of tropical intraseasonal variability, the MJO, poses a major challenge for prediction models. This is hardly surprising considering that at least four decades of scale are involved: cumulonimbus (~1–10 km, hour), MCS (~100–500 km, day), superclusters (~1000–3000 km, week), and the MJO envelope (~10000 km, months). The organization of convection in convectively coupled equatorial waves (e.g., Kelvin waves) and propagating systems associated with the Indian summer monsoon feature broadly similar large-scale organization [*Liu and Moncrieff*, 2008]. The reader is referred to an extensive bibliography on the MJO, convectively coupled waves, and associated issues: *Houze* [1982]; *Nakazawa* [1988]; *Houze* [1989]; *Mapes and Houze* [1995]; *Chen et al.* [1996]; *Chen and Houze* [1997]; *Houze et al.* [2000]; *Moncrieff* [2004b]; *Zhang* [2005]; *Haertel and Kiladis* [2004]; *Lau and Waliser* [2005]; *Waliser et al.* [2005]; *Lin et al.* [2006]; *Kiladis et al.* [2005]; *Liu et al.* [2008]; *Woolnough et al.* [2007]; *Kiladis et al.* [2009].

The mechanisms for onset of the MJO are poorly understood. For the most part, current knowledge centers on three not necessarily independent hypotheses: (1) the recharge mechanism for the large-scale environment involving ocean-atmosphere heat fluxes, upper ocean heat content, large-scale moisture advection [*Blade and Hartmann*, 1993]; (2) the upscale cascade involving multiscale organization, e.g., cumulonimbus, MCS, and superclusters (this paper); (3) external excitation involving disturbances traveling into the tropics from the extratropics, e.g., Rossby waves and wintertime cold surges from the Asian continent. In the latter context, *Matthews* [2007] classified observed MJOs either as primary (no preceding event) or successive (following a preceding event). He found that 40% of MJOs are primary events to which precursor features cannot be attributed. For example, a suppressed convective anomaly grows and decays in situ over the Indian Ocean prior to the onset of most primary events. The most frequent initiation of the primary events is the Indian Ocean, but more than half the events start in the Maritime Continent and propagate to at least the western Pacific.

5.1. Inertial-Gravity Waves

Inertial-gravity waves with long horizontal and vertical wavelengths, the transient response to deep convective heating [*Nicholls et al.*, 1991], affect interactions between MCS and the large-scale circulation and organization of convection. In accordance with the dispersive properties of linear gravity waves, the phase speed of the bore-like first baroclinic mode is about 50 m s^{-1} and second baroclinic mode about 25 m s^{-1}. *Mapes* [1993] explained the "gregarious" behavior of tropical convection in terms of such waves. *Liu and Moncrieff* [2004] showed that planetary rotation reduces the spacing between cloud clusters; therefore, the largest cloud clusters (e.g., superclusters) should be associated with equatorial regions as is the case.

Ascent in the lower troposphere involving the second baroclinic mode triggers convection in the near environment. *Mapes* [1998] showed that bore-like gravity waves propagating from a convectively active region in the tropics lead to a planetary wave structure of the type described by *Matsuno* [1966], *Gill* [1980] and others. *Mapes et al.* [2006] describes the upscale evolution of MCS in terms of three cloud types (shallow convective, deep convective, and stratiform). The existence of such a cloud spectrum has long been acknowledged. For example, the work of *Yanai et al.* [1973] is based on a cloud spectrum represented by a 1-D cloud model in which the entrainment rate is determined by cloud size. *Houze et al.* [1980] envisioned a cloud spectrum consisting of small cumulus, moderate cumulus, cumulonimbus, and MCS. *Johnson et al.* [1999] argued that the midsized clouds (cumulus congestus) may be significant, although the radar-echo signature does not have a distinct peak at this scale.

Wave forcing associated with simulated organized convection was examined by *Crook and Moncrieff* [1988] in terms of the effect of convergence on scales larger than the convective scale of MCSs. Imposed as a momentum forcing at the lowest levels of the computational domain, convergence has important effects before and after the onset of convection. Before onset, the large-scale convergence lifts the troposphere over a wide region to saturation or near saturation. As the environment ahead of the MCS at a distance from the cold pool is brought close to saturation, even small perturbations may trigger convection, leading to discrete propagation as observed [*Houze*, 1977; *Fortune*, 1980]. After onset, the MCS can self maintain because the inflow requires minimal lifting. Crook and Moncrieff showed that large-scale convergence affects mature MCS since the total vertical displacement affects convective intensity for timescales comparable to or longer than the time that inflow spends in the convergence zone. The average rainfall rate was increased by up to 40%.

The effects of long gravity waves on large-scale convective organization in the tropics has been addressed by idealized models constructed of (1) a dynamically passive boundary layer, a reservoir of heat and moisture; (2) simplified parameterizations of convection, surface heat exchange, and radiative cooling; and (3) a dynamically active troposphere involving the first- and/or second baroclinic vertical wave modes. While large-scale convective organization does occur with the first baroclinic mode [*Yano et al.*, 1996], a highly truncated vertical discretization, the second baroclinic mode provides a more realistic vertical structure and propagation [*Khouider and Majda*, 2007].

It was shown in section 4.1 that slantwise layer overturning in the vertical plane approximates MCS-like organization (scale ~100 km). *Moncrieff and Klinker* [1997] showed that supercluster organization was approximated by the same dynamical principles applied on the synoptic scale (~1000 km). In the following section, this scale invariance is shown to model MJO-like large-scale airflow in the horizontal plane.

5.2. Horizontal Slantwise Layer Overturning

Based on the similarity of the airflow morphologies, *Moncrieff* [2004a] formalized the scale invariance between MCS-type organization and the MJO on (1) the mathematical equivalence of the convective Richardson number for convective overturning (R) and a Rossby number for the MJO and (2) the scale interlocking involving work done by the horizontal pressure gradient expressed in terms of E (section 4.1). Just as the horizontal vorticity equation for vertical convective overturning and the thermodynamic buoyancy led to equation (1), so the vertical vorticity for horizontal large-scale overturning and the difference between planetary and parcel vorticity results in the structure equation for "horizontal slantwise layer overturning":

$$\nabla^2\phi - H(\phi) - \int_{y_0}^{y} \left(\frac{\partial C}{\partial \phi}\right)_{y'} \mathrm{d}y' = 0, \qquad (2)$$

where the stream function ϕ is defined by $u = -\partial\phi/\partial y$, $v = \partial\phi/\partial x$, C is the difference between the vertical vorticity of MJO circulation and the planetary vorticity measured along trajectories, and H the far-field vertical vorticity. The scale invariance of the MCS-type convective organization in the vertical plane and large-scale organization in the horizontal plane is readily indicated by the one-to-one mathematical correspondence between equations (1) and (2). *Moncrieff* [2004a] used equation (2) as the basis of a two-layer supercluster model illustrated in Plate 5.

The *Biello et al.* [2007] multiscale model, which is based on the systematic asymptotic perturbation technique of *Majda and Klein* [2003], showed that MJO-like systems are maintained by upscale momentum and heat fluxes approximated by an analytic balanced model. That the upscale effects of meridional momentum transport are important is in agreement with *Moncrieff* [2004a] and is described further in section 6.4.

Other dynamical studies quantify MJO-type organization. *Majda and Stechmann* [2009] approximate the dispersion properties, the slow phase speed, and the horizontal quadropole vortex of the MJO. Modulations of synoptic wave activity induced by low-level moisture preconditioning are assumed to occur mainly through the heating. The model is neutrally stable on interaseasonal/planetary scales. Instabilities are anticipated to occur on the synoptic scale and/or the mesoscale.

Wedi and Smolarkiewicz [2010] showed that MJO-like systems can be generated by dry Rossby-wave dynamics. Solitary-wave structures are excited and maintained via zonally propagating wave oscillations on the meridional boundaries, approximating the effects of extratropical disturbances on tropical disturbances.

The following section shows that the dynamical analogs of scale-invariant vertical and horizontal slantwise layer overturning described in previous sections explained the multiscale organization simulated by full-physics cloud system resolving models, tropical channel models, high-resolution weather prediction systems, and superparameterized climate models.

6. MULTISCALE CONVECTIVE ORGANIZATION IN NUMERICAL MODELS

Previous sections of this paper addressed the formal dynamics of organized convection with emphasis on slantwise layer overturning of the MCS type. It is now shown that MCS-type organization occurs spontaneously in prediction models across a range of scales indicating scale invariance. This proves that organized convection should no longer be ignored in climate models.

6.1. Cloud System Resolving Models

In the *Grabowski and Moncrieff* [2001] 2-D global-scale CRM simulation, multiscale convective organization evolved spontaneously starting from motionless, horizontally uniform initial conditions (Plate 6). Two regimes of large-scale convective organization were simulated. First, backward tilted westward traveling MCS-like overturning occurred within the eastward propagating MJO-like large-scale envelope, broadly consistent with satellite analysis [e.g., *Nakazawa*, 1988]. The redistribution of horizontal momentum by the MCS systems generated vertical shear that, in turn, controlled MCS-like organization (section 4.1). This is an example of positive feedback between organized convection and the large-scale circulation. Second, the MJO-like system in regard to propagation speed (about 7 m s^{-1}) compared to natural MJOs (about 5 m s^{-1}). The momentum transport properties of this system are commented upon in section 6.4.

A 3-D global CRM configured with an icosahedral grid (Nonhydrostatic ICosahedral Atmospheric Model (NICAM)) has been developed [*Satoh et al.*, 2008]. An aquaplanet model with grid spacing of 7 and 3.5 km simulates large-scale convective organization [*Tomita et al.*, 2005; *Miura et al.*, 2005; *Nasuno et al.*, 2007]. The NICAM simulations show eastward propagating cloud envelopes in the tropics. Embedded in these envelopes are westward-propagating clusters that resemble the multiscale convective organization in natural MJOs. However, the fast propagation (about 17 m s^{-1}) of the 3-D large-scale organization resembles Kelvin-like rather than MJO-like dynamical coherence. *Nasuno et al.* [2007] found that the mesoscale properties of the westward-propagating MCS-like systems are similar to observed systems in the sense that cold pools triggered new convective activity in the form of MCS in regions of strong vertical shear.

6.2. Tropical Channel Models

A tropical channel model (TCM) is global in the zonal direction and bounded in the meridional direction. The elimination of the zonal boundary conditions enables explicit large-scale organization such as the MJO, convectively coupled Kelvin waves, and superclusters to be simulated more realistically than with a standard regional model requiring zonal boundary conditions. Computationally more efficient and controllable than global cloud system resolving models, TCMs permit higher resolution and more advanced parameterizations of microphysics and turbulence than global circulation models. Moreover, the meridional boundary conditions represent excitation by disturbances propagating into the tropics from midlatitudes. Interactively nested TCMs simulate interaction between the mesoscale convective organization and the large-scale circulation, providing information on the upscale cascade of energy.

Ray et al. [2008] used a TCM based on the Mesoscale Model Version 5 (MM5) to examine the effects of extratropical forcing on MJO onset. *Ray et al.* [2010] used the interactively nested NCAR TCM based on the Weather Research and Forecasting forced at the meridional boundaries by NCEP global analysis with specified sea surface temperature (SST). Nested within the parent outer domain are subdomains at 12- and 4-km grid spacing (run for shorter periods) simulating convective organization. The precipitable water (not shown) illustrates meteorological events such as the large-scale tropical organization, synoptic-scale organization associated with tropical cyclones, superclusters, and atmospheric rivers of moisture flowing from the tropics to the western United States.

6.3. MJO in High-Resolution Global Weather Prediction Models

Plate 7 shows that over a few years, the strength of the MJO in the ECMWF model has progressively improved from a barely detectable disturbance to a robust organized system [*Bechtold et al.*, 2008]. The reasons for the improvement are unclear because the improvements included the parameterization of moist and shallow convection and the boundary layer; the resolution increased (now about 15 km grid spacing), and there were advancements in data assimilation, especially satellite data.

Models with 15- to 25-km meshes simulate meso-to-synoptic convective organization in terms of coarsely resolved grid-scale circulations (section 4.5). Supercluster organization complete with the characteristic backward tilt are simulated even with a coarse 80 km mesh (Plate 8). *Houze* [2004] noted that the structure of the supercluster system in Plate 8 is consistent with observations of the largest MCSs observed during TOGA COARE. Mesoscale-to-synoptic-scale convective organization associated with African easterly waves occurs in the ECMWF model at 15- and 25-km grid spacing (P. Bechtold, private communication, 2009).

The implication is that a 10-km mesh should be capable of simulating convective organization is encouraging for future high-resolution climate models. In the following section, it is shown that the simulation of mesoconvective dynamics promotes convective organization in climate models.

6.4. Superparameterized Climate Models

In cloud-resolving convection parameterization, also known as superparameterization, CRMs are applied in place of conventional parameterizations of convection [*Grabowski and Smolarkiewicz*, 1999; *Grabowski*, 2001; *Khairoutdinov et al.*, 2005]. With a mesh size of a few kilometers, the CRMs simulate the mesoscale dynamics associated with organized convection. Superparameterization explicitly represents moist convective organization on scales upward from the mesoscale as well as interaction between organized systems and the large-scale circulation. The CRMs are normally 2-D. While 3-D CRMs have been tested, the computational overhead restricts the CRM domain to just a

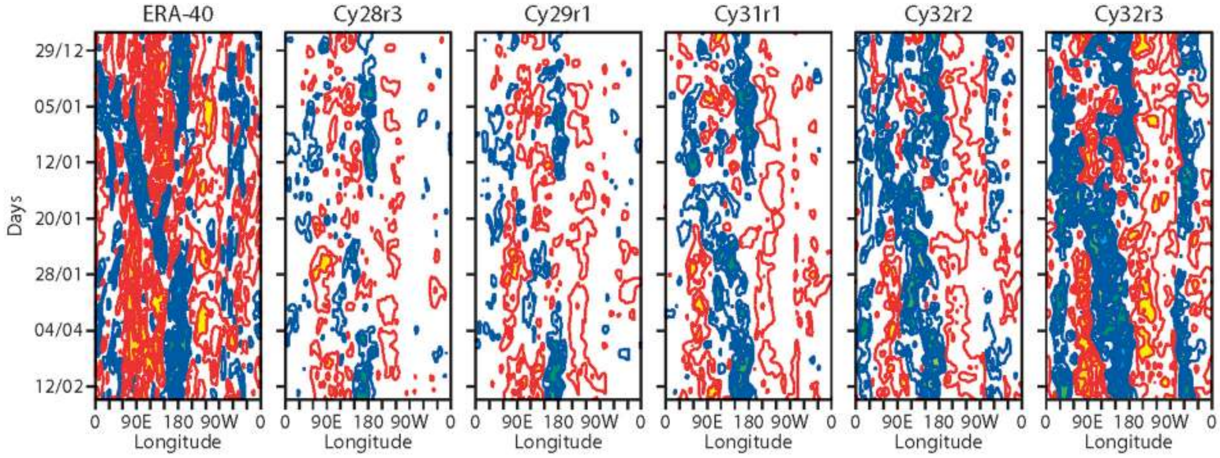

Plate 7. Hovmöller diagrams of the progressively improved MJO in the ECMWF global weather prediction model. The leftmost diagram is the analysis. The other diagrams show the improvement in the MJO in accordance with improved convective parameterization, horizontal resolution and data assimilation over a 5-year period. From *Bechtold et al.* [2008]. Copyright Royal Meteorological Society, reprinted with permission.

few points in the horizontal direction, precluding mesoscale convective organization.

Explicit convection in superparameterization has advantages over the implicit traditional parameterization: (1) moist convection simulated by CRMs has a realistic life cycle, convective "memory" is passed to the global model, (2) cloud microphysics interacts with explicit cloud dynamics more realistically than possible with the oversimplified plume models applied in convective parameterization, (3) cloud-scale and mesoscale downdrafts generate density currents that trigger new generations of moist convection, (4) organized mesoscale momentum transport differs in important ways from the mixing associated with disorganized cumulus convection; and (5) the absorption of gravity waves in the

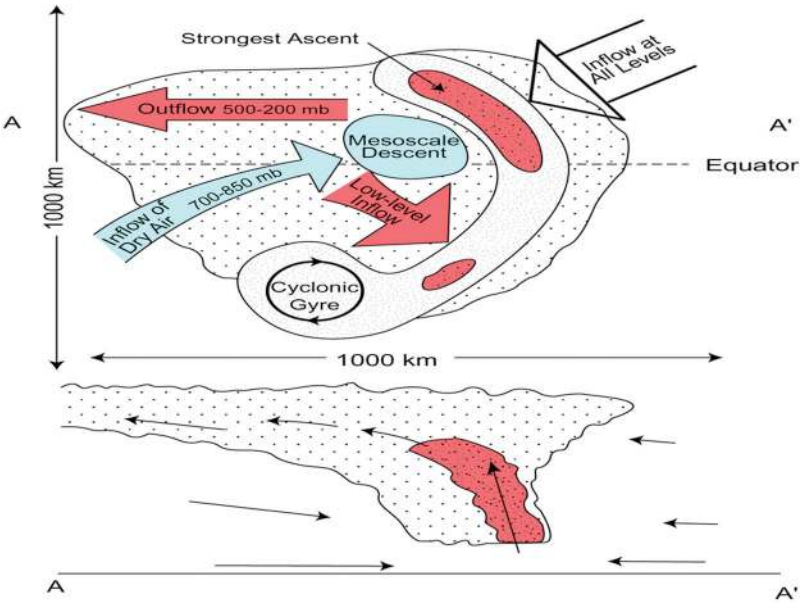

Plate 8. Schematic diagram of the horizontal airflow and precipitation; backward tilted MCS-type airflow organization in the vertical direction of a supercluster in the ECMWF T213 operational model. From *Moncrieff and Klinker* [1997]. Copyright Royal Meteorological Society, reprinted with permission.

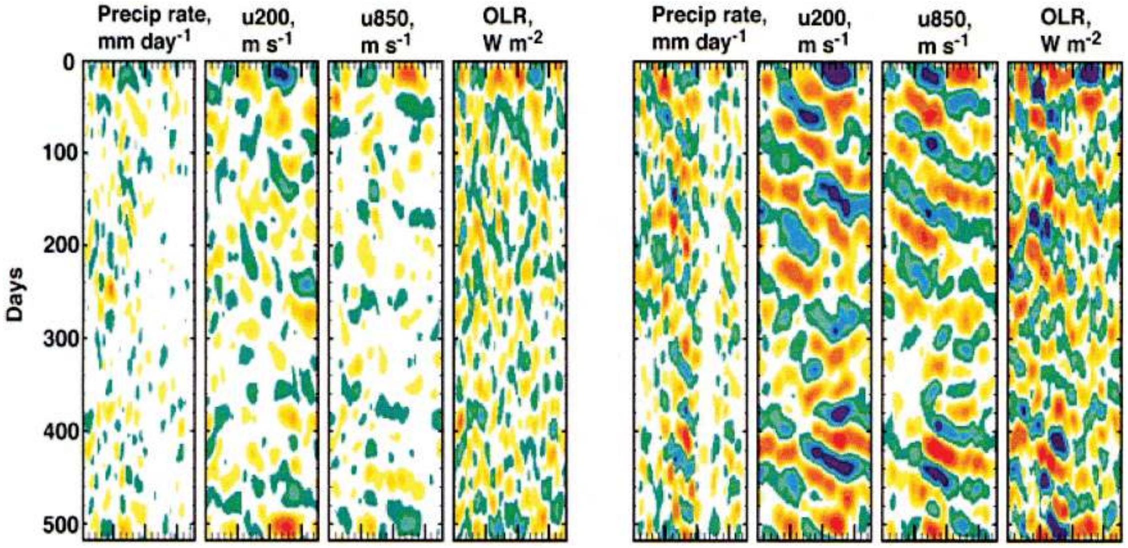

Plate 9. (left) Precipitation rate, 200 hPa zonal wind, 800 hPa zonal wind, and OLR in standard CAM. (right) Same except for superparameterized CAM (SP-CAM). Images courtesy of M. Khairoutdinov, State University of New York at Stony Brook.

stratosphere generated by organized convection in the troposphere [e.g., *Lane and Moncrieff*, 2008].

Two-dimensional models provide just one of the two horizontal components of momentum transport. Interestingly, 2-D models can approximate convective momentum transport by MCS as shown by comparing models to observations [e.g., *LeMone and Moncrieff*, 1984; *Kingsmill and Houze*, 1999; *Houze*, 2004; *Schumacher and Houze*, 2003]. Nevertheless, the choice may be made not to pass the momentum increments generated by the CRMs in superparameterization onto the large-scale grid. This is inconsistent because the thermodynamic increments are communicated.

Momentum transport is important. An MJO-like wave number 1 eastward propagating cloud envelope evolved after about 50 days [*Grabowski*, 2001]. Prior to this MJO episode, the large-scale organization took the form of eastward propagating wave number 4 disturbances. *Moncrieff* [2004a] analyzed these large-scale organizations in terms of slantwise layer overturning. The acceleration of the zonal flow by the wave number 4 disturbances was explained in terms of the MMT by slantwise layer overturning in the vertical plane (section 4.4). For the MJO-like system, equatorial superrotation and momentum transport were explained in terms of the momentum transport by horizontal slantwise layer overturning (see section 5.2 and Plate 5).

Khairoutdinov et al. [2005] conducted a 500-day superparameterization experiments with the Community Atmosphere Model (CAM) at T42 spectral resolution (2.8° × 2.8° grid), in an approach called the Multiscale Modeling Framework. Called SP-CAM, these experiments apply either a 2-D CRM (2-D SP) or a 3-D CRM (3-D SP). The double ITCZ in standard CAM disappears in the simulation with convective momentum transport. The uppermost diagram in Plate 9 shows that the MJO in SP-CAM was improved compared to standard CAM. The 2-D CRMs in SP-CAM generated backward tilted MCS-like systems with heavily precipitating convective regions and a moderately precipitating stratiform region described in section 4. The density current outflows trigger new convection. Convective moistening has a positive effect on the MJO [*Thayer-Calder and Randall*, 2009], consistent with other MJO results [e.g., *Grabowski and Moncrieff*, 2004]. It remains to be explained why SP-CAM generates MJOs that are too robust compared to weak MJOs in standard CAM.

Khairoutdinov et al. [2005] showed that superparameterization applied in CAM in place of convection, clouds, and the planetary boundary layer improves the diurnal cycle of precipitation, and subseasonal and interannual variability compared to the standard convective parameterization in CAM.

Earlier in this paper, the MCS was deemed a missing process in climate models because its effects are not represented by traditional convective parameterizations, and the resolution of climate models is too coarse for explicit MCSs. The following section is a step toward parameterizing MCS-like organization, which is necessary for climate models run for millennia, probabilistic ensemble models, and future Earth-system models.

7. PARAMETERIZATION OF MCS

The 1-D entraining plume is the transport module regularly used for the parameterization of thermodynamic quantities [e.g., *Arakawa and Schubert*, 1974] and convective momentum transport [*Kershaw and Gregory*, 1997] associated with cumulus convection. It was implied earlier that MCS have properties that require a transport module distinct from an entraining plume in order to approximate propagating systems. One option is hybrid parameterization where convective parameterization, cumulus parameterization, and explicit grid-scale circulations occur side-by-side. That a numerical model should spontaneously simulate, albeit crudely, a process already parameterized in the model implies that convective organization is indeed a "missing" process. The dual existence of cumulus convection and mesoscale circulations in MCS (e.g., lowermost diagram on Plate 1) requires that both these scales need to be parameterized in climate models. Although grid-scale circulations underresolve mesoscale systems, they are a vast improvement over contemporary parameterizations which do not represent the salient dynamics. Section 4.5 showed that MCSs are explicitly represented by 10-km-mesh models.

There has been little attention to hybrid convective parameterization. *Kuell et al.* [2007] proposed a hybrid cumulus parameterization scheme for cumulonimbus convection for use in nonhydrostatic weather prediction models. *Moncrieff and Liu* [2006] proposed a conceptual parameterization for MCS-type organization intended for global models. Heating in the stratiform region overlying the evaporatively cooled mesoscale downdraft (i.e., top-heavy heating) was approximated as a second baroclinic or dipole mode. The total convective heating is $\dot{H}(p,t) = \dot{H}_c(p,t) + \dot{H}_m(p,t)$ where $\dot{H}_c$ and $\dot{H}_m$ are the heating rates by cumulus and mesoscale circulations, respectively. The following formulation is a simplification of the one suggested by *Moncrieff and Liu* [2006] in which the mesoscale tendencies were assumed to be proportional to the convective tendencies:

$$\dot{H}_m(p,t) = \alpha_1 \sin 2\pi \frac{p-p_s}{p_s-p_t}, \quad p* \le p \le p_s$$

$$\dot{H}_m(p,t) = \alpha_2 \sin 2\pi \frac{p_s-p}{p_s-p_t}, \quad p_t \le p \le p*$$

A second baroclinic formulation for momentum transport also represents the total momentum tendency as the sum of cumulus friction [*Kershaw and Gregory*, 1997] and organized mesoscale momentum transport, i.e., $\dot{M}(p,t) = \dot{M}_c(p,t) + \dot{M}_m(p,t)$. For a system propagating in the positive x-direction, the mesoscale tendency for momentum is

$$\dot{M}_m(p,t) = \alpha_3 cos 2\pi \frac{p-p_s}{p_s-p_t}, \quad p* \le p \le p_s$$

$$\dot{M}_m(p,t) = \alpha_4 cos 2\pi \frac{p_s-p}{p_s-p_t}, \quad p_t \le p \le p*$$

In the above equations, the heating rates and momentum tendencies are zero at the center of mass of the convective layer, $p* = \frac{1}{2}(p_s - p_t)$. The parameters α_1, α_2, α_3, α_4 can be estimated from CRM simulations. Summarizing, a second baroclinic vertical mode is a simple approximation of stratiform heating and evaporative cooling associated with MCS.

8. DISCUSSION

8.1. Atmosphere-Ocean Interaction and the MJO

An important question is how the ocean responds to the atmosphere upon moving from short-range weather forecasting to extended-range prediction, seasonal variability prediction, and ultimately climate prediction. While robust MJO-like systems do occur for constant SST aquaplanet models [e.g., *Grabowski and Moncrieff*, 2001; *Grabowski*, 2001], this does not imply that atmosphere-ocean interaction is unimportant especially at long timescales. The MJO is usually most active, and atmosphere-ocean interaction most significant in the Indian Ocean and tropical western Pacific, where the SST is a maximum, e.g., westerly wind bursts and their possible effects on El Niño onset.

The ocean has an effect even on short convective timescales. Downdrafts from precipitating convection rapidly affect atmosphere-ocean interaction. Because CRMs explicitly represent convective downdrafts and surface atmospheric momentum, surface fluxes are more realistic than those supplied by a parameterization. If the ocean is not allowed to respond to the convective downdrafts, the imbalance in surface energy may result in spurious atmospheric convection. In contrast, coupled atmosphere-ocean models absorb the cooling and momentum fluxes associated with downdraft outflows. While these outflows propagate large distances from active convection, this long-range effect is not in parameterizations because they do not represent propagating density currents. The importance of high-frequency SST variability on the intraseasonal variability of Indian summer monsoon rainfall have been shown in coupled simulations with a fine-resolution mixed-layer ocean model [*Klingaman et al.*, 2008]. The relevance of CRMs is set into context by the quotation "atmosphere-to-ocean feedbacks are of little value if the atmospheric models cannot diagnose fluxes of the magnitude required to substantially modify the SSTs" [*Klingaman et al.*, 2009].

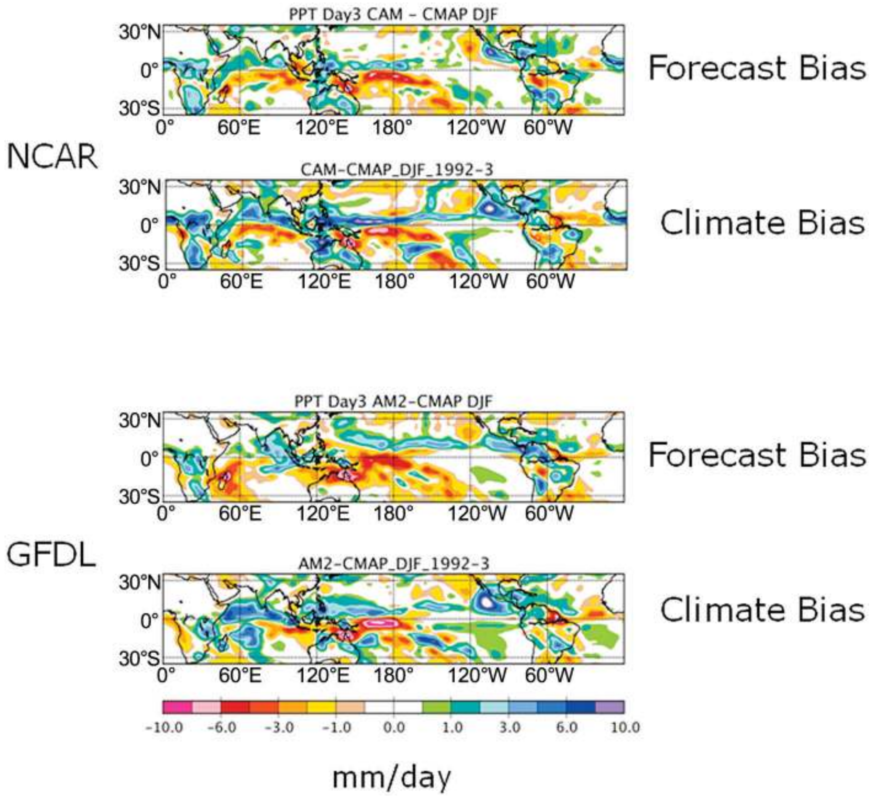

Plate 10. Comparison of weather-climate bias measured as the precipitation rate (mm d^{-1}) for GFDL and NCAR models. Weather bias is the difference between predicted and observed precipitation rate for composited 3-day forecasts for December, January, and February (DJF), 1992–1993. Climate bias is from a single integration of the modeling systems with prescribed SSTs (AMIP mode) for DJF 1992–1993. From *Boyle et al.* [2008]. Copyright American Meteorological Society.

Using a CRM, *Liu and Moncrieff* [2008] examined the interaction between organized convection and SST over tropical warm pools. The most active convection occurred near the edge of the warm pools, with a local minimum around the warm center, consistent with observations that convection commonly does not peak where SST is a maximum. The rainfall maxima may be displaced hundreds of kilometers from the warmest SST. When the wind-induced surface exchange is excluded, convective activity is confined to a much smaller area of high SSTs. Surface friction affects the interaction between convection and the large-scale flow, the dual-maximum precipitation, and the large-scale circulation. Consequently, as well as the temperature/pressure gradients resulting from nonuniform SSTs, other processes must be taken into consideration in regard to the effects of precipitating convection on the atmospheric large-scale tropical circulation.

Physically based parameterizations in climate models that include convective momentum transport improve large-scale convective organization, e.g., the MJO and El Niño–Southern Oscillation. *Wu et al.* [2007] showed an improved life cycle for the 1997/98 El Niño. Moist convection occurs less frequently, is better organized, and is closer to TRMM observations. Improvements are greatest for coupled GCMs where deep convection acts as a less frequent but stronger stochastic forcing on the ocean. By improving the westerly wind anomalies that affect El Niño, the large-scale organization of convection provides a coherent stochastic forcing for the ocean circulation.

The Research Moored Array in the Indian Ocean [*McPhaden et al.*, 2009] will provide new measurements of atmospheric-ocean exchange, e.g., onset of the MJO in the Indian Ocean. Considering the effects of land, the Indonesian Maritime Continent decreases the amplitude of the MJO. There are several possible reasons, e.g., the disruptive effect of an enhanced diurnal cycle over land on the dynamics of deep convection, the effect of mountainous terrain and/or the indirect effect orographically induced gravity waves, coastal effects involving land and sea breezes and their influence on the onset and organization of deep convection.

8.2. International Coordination

International coordination has historically played an important role in the atmosphere-ocean science, e.g., the GARP and the TOGA program, and subprograms such as the First GARP Global Experiment (1979), the GATE (1974), the Winter and Summer Monsoon Experiments (1978–1979), and the TOGA COARE (1992–1993). The reader is referred to reviews by *Betts* [1974], *Greenfield and Krishnamurti* [1979], *Johnson and Houze* [1987], *Webster and Lukas* [1992], *Godfrey et al.* [1998], respectively. These regional field campaigns and the accompanying numerical prediction experiments set the stage for subsequent advances in global weather prediction.

Observationally verified CRMs provide a physical basis for improving convective parameterizations for global models and cloud microphysical parameterizations for CRMs. The successful simulation of cumulonimbus, squall lines, and MCS over the previous decades encouraged the World Climate Research Program (WCRP) Global Energy and Water Cycle Experiment (GEWEX) to form the GEWEX Cloud System Study (GCSS) in the early 1990s [*GCSS Science Plan*, 1993]. Intercomparison of models and their evaluation against observations showed that explicit precipitating convection by CRMs is superior to single-column models used in convective parameterization [*Moncrieff et al.*, 1996; *Randall et al.*, 2004]. *Tao and Moncrieff* [2009] describe the extensive use of CRMs for research, prediction, and the development of retrieval algorithms for satellite applications.

The large dynamic range of modern CRMs, tropical channel models, and superparameterized models present new challenges for validation. Dating to 1983, the International Satellite Cloud Climatology Project provides global cloud characterization at 3-h intervals [e.g., *Rossow and Duenas*, 2004; *Rossow and Schiffer*, 1999; *Rossow et al.*, 2005]. The Data Integration for Model evaluation activity provides "test kits" for model evaluation based on the GCSS model intercomparison projects and including detailed results from the participating CRMs.

The World Meteorological Organization's WCRP and the World Weather Research Programme-The Observing-System Research and Predictability Experiment (WWRP-THORPEX) are jointly coordinating an observing, modeling, and forecasting project, the Year of Tropical Convection (YOTC). The research emphasis of YOTC is moist convection, its multiscale organization, and its large-scale interaction on timescales up to seasonal seamless prediction or the intersection of weather and climate. The YOTC project consists of three major components: (1) analysis, forecasts, and special diagnostics from high-resolution deterministic prediction systems, e.g., the ECMWF T799 (25 km) analysis, forecasts, and special diagnostic fields; (2) integrated observation including multisensor satellite data; (3) a research agenda focused on major issues in global models: MJO and convectively coupled equatorial waves, monsoons, easterly waves and tropical cyclones; tropical-extratropical interaction, and the diurnal cycle. The ECMWF is archiving its comprehensive database for the period May 2008 to April 2010 for use by the community. The research phase of the YOTC will last many years. The YOTC project was recommended by an international workshop convened at the International Centre for Theoretical Physics (ICTP), Trieste, Italy in March 2006 supported by ICTP, WCRP, and WWRP-THORPEX [*Moncrieff et al.*, 2007]. The YOTC Science Plan has been published [*Waliser and Moncrieff*, 2008]. The YOTC Implementation Plan and progress to date is available at http://www.ucar.edu/yotc.

The YOTC project is aligned with the seamless prediction of weather and climate, a WCRP and WWRP-THORPEX priority. In climate models, the effects of the initial conditions are assumed to be minimal compared to the boundary forcing (e.g., SST and top-of-atmosphere energy balance), whereas the initial conditions are vital in numerical weather prediction. Convection is a "fast" process in both weather and climate where within days convective processes can affect the distribution of clouds and precipitation. This justifies the use of similar parameterizations of convection (suitably tuned) in weather and climate models. Plate 10 [*Boyle et al.*, 2008] shows that precipitation errors in weather prediction are similar to those in climate modeling, notably in regions associated with organized convection. Climate models run in initial-value mode and are being used more extensively to improve convective parameterizations.

9. CONCLUSIONS

The dynamical basis of moist convective organization and progress toward quantifying its large-scale effects and its representation in global model are addressed in this paper. The attention to MCS was motivated by advances in observation, modeling, and prediction of these systems over a period of decades and, above all, the need to understand how MCSs affect weather and climate. Important in their own right and as building blocks of larger-scale convective organization, MCSs are not only an optimally efficient organization (section 4.1) but also the preferential regime simulated by explicit models (section 6).

Since the early 1990s, the priority has been to bring to climate models the major Earth-system components (e.g., ocean, land, cryosphere, chemistry, biogeochemistry). These components are in place. Convective organization now needs attention to enable climate models to represent the behavior and effect of water in the atmosphere with completeness.

Parameterization was once the only way by which the large-scale effects of moist convection in global models could be estimated. This is no longer the case. Superclusters (families of MCS) observed in TOGA COARE were explicitly represented by global weather models a decade ago. Nowadays, the superclusters and MCS are explicit CRMs used in superparameterization. This is encouraging for the advent of high-resolution climate modeling. However, note that the climate community will require improved contemporary parameterizations for the foreseeable future.

While the problem of weak MJOs in global models is not solved, advances have been made. For example, the amplitude of the MJO in the ECMWF operational medium-range weather prediction model is more realistic through improved resolution, data assimilation, and parameterization. Explicit convective organization is the reason for robust MJOs both in superparameterized models and global CRMs. That MJOs in superparameterized models tend to be too strong likely results from overactive MCSs.

Many important questions remain to be addressed, for example: (1) Is the improved MJOs due to the upscale cascade of energy involving convective organization or a downscale conditioning due extratropical excitation of the tropics? (2) What controls the onset of the MJO, are the onset mechanisms different in winter compared to summer, and the Indian Ocean compared to the tropical Western Pacific? The intersection of weather and climate (timescales up to seasonal) is where such issues can be addressed most effectively. This is where the YOTC databases (high-resolution global analyses/forecasts and multisensor satellite measurements) are unique resources. A comprehensive set of question and steps toward addressing them can be seen in the YOTC Science Plan and the YOTC Implementation Plan (http://www.ucar.edu/yotc).

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