ISSUES IN CONVECTIVE MOMENTUM TRANSPORT

Mitchell W. Moncrieff
National Center for Atmospheric Research
Boulder, CO 80307–3000, USA

Abstract

Basic concepts and issues of convective momentum transport are presented, a common theme being the role of organization. We then highlight (i) the treatment of large cloud clusters in the tropical Pacific which are partly resolved in the ECMWF T213 model; (ii) the regional nature of organized convection and the implications for parameterization; and (iii) regime transitions in cold air outbreaks. These issues relate to the role of mesoscale cloud systems in numerical weather prediction models, especially when horizontal resolution approaches the dynamical scale of organized precipitating cloud systems. The ECMWF T213 forecasts and analysis, together with cloud-resolving modeling, are a comprehensive way to address these issues.

1. INTRODUCTION

Satellite images show the ubiquity of convective organization in the Earths atmosphere, yet this process is not included in present-day convective parameterizations. It is timely that it be given attention in view of the increasing resolution of global models and the need to continually improve the physical parameterizations within them. Emphasis herein is on organized convective cloud systems rather than 'ordinary' convection whose parameterization is considered elsewhere in the proceedings.

If any single process can reveal the large-scale role of convective organization it is the transport of momentum because this strongly depends on cloud system dynamics. In turn, the concept of organization involves the ambient wind shear. As far as parameterization in large-scale models is concerned, the key issue is the link between the transports and the resolved-scale variables. Momentum flux is intrinsically more complicated to parameterize than heat and moisture; for example, it is an anisotropic vector field and several distinct regimes can occur. On the other hand, simple representations are required to represent fluxes in convective parameterization schemes and a few have already been attempted.

Key questions arising from a global model perspective are as follows: (i) Are important effects being disregarded in the present treatment of momentum flux? (ii) Are the consequences of uncertainties in heat and moisture parameterizations swamping sensitivity to convective momentum flux (in which case only the most physically advanced models will be useful tools). (iii) Is convective momentum flux intrinsically scale-dependent, in which case impacts will appear only beyond a critical resolution? (iv) How important is momentum flux by *organized* convection when parameterization schemes for ordinary convection already exist? The overriding issue is the profound effect of shear on convective organization which implies that a parameterization should represent both ordinary *and* organized cloud systems. To accomplish this, however, the frequency and global distribution of organized convection is required. It also begs the question: do relatively few vigorous mesoscale convective systems have more impact than numerous small randomly distributed cumulonimbus having the same cloud fraction?

Because uncertainties in parameterizing heat and moisture (a relatively well-studied problem) remain large, little effort has been spent to date on convective momentum parameterization. Other uncertainties are paramount in general circulation (climate) models, such as cloud-radiative interaction not to say horizontal reolution. Global numerical weather prediction (NWP) models are somewhat different. For example, the ECMWF T213 model is beginning to explicitly predict mesoscale convection as later described. This adds a new dimension to the role of the mesoscale and future parameterization techniques. The evaluation of global forecasts against model analysis that includes assimilated data from major field experiments such as TOGA COARE (Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment) is a way to determine to what degree mesoscale organization is an issue in numerical weather prediction.

The ECMWF has developed and tested several convective parameterization schemes. Momentum parameterization is now receiving attention, in part because the operational T213 model shows a sensitivity to this process. Model performance is improved when convective momentum transport is included; for example, the life-cycle and intensity of hurricanes and tropical cyclones are evidently more realistic. The pacing issue is to establish why this is so. This requires basic research into the large-scale effects of momentum flux. A T213 spectral code has a resolution equivalent to about 90 km in physical space (note that considerably higher resolution will soon be implemented), and is useful to investigate the large-scale role of convective momentum transport. Note that momentum flux by disorganized and weakly organized convection is parameterized as described elsewhere by Gregory (workshop proceedings).

Some basic aspects are presented in the next section, followed by a summary of pacing issues. Section 4 summarizes how cloud-resolving models can be used to address the momentum problem. Section 5 sketches future research directions and section 6 summarizes the main conclusions.

2. FUNDAMENTALS

Some basic aspects need to be satisfied in any consideration of convective momentum flux. One of specific relevance to organized convection is the relationship between the vertical tilt of the system and momentum flux (see Moncrieff 1992; Fig. 10). This directly relates to the effect of shear on cloud system organization which, in certain circumstances, can enhance the mean flow through upgradient momentum fluxes. Present parameterizations do not explicitly take account of this process because they are based on mixing principles. This is rooted in eddy diffusion theory, especially the widely used 'entraining plume' model which seems adequate for the parameterization of ordinary convection.

2.1 Momentum parameterization

Momentum transport affects the large scales as an eddy flux divergence. This means that it can be approximated using a mass flux approach. The equation for the convective momentum tendency is

$$\left(\frac{\delta u}{\delta t}\right)_c = -\frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\overline{\rho}(\overline{u'w'}) = -\frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\left[M_c(u_c - \overline{U})\right] \tag{1}$$

where the prime represents a deviation from a spatial mean (represented by the overbar), u_c is the 'in-cloud' momentum, and M_c is the convective mass flux. Since the convective mass flux is derived using thermodynamic considerations, the key question is: what is an accurate approximation of $u_c(z)$?

It is easy to show that in a constant ambient shear, upgradient flux exists if $u_c(z) > \overline{U}(z)$, while $u_c(z) < \overline{U}(z)$ effects a downgradient flux. Various attempts have been made to approximate u_c. For example, Schneider and Lindzen (1976) assumed that convection acts as a 'drag' on the large-scale flow and u_c was assumed to be constant, for example, the value of $\overline{U}$ at cloud base. The horizontal pressure gradient is omitted in Schneider and Lindzen, despite being crucial to a realistic parameterization of momentum flux.

2.2 In-cloud momentum expressed in Lagrangian terms

Since in-cloud momentum is the key quantity in momentum flux parameterization, we formally describe general functional relationships and scalings. The Lagrangian form of the horizontal momentum equation yields an exact expression of the quantities affecting in-cloud momentum because the horizontal gradient of pressure and the eddy diffusion are the *only* processes that can change the momentum along parcel paths. It is easy to show that an integration of the x-momentum equation (on time scales short enough to assume that the effects of the Earths rotation can be neglected) along an arbitrary trajectory (ψ) gives the relationship

$$\frac{(u_c - u_\psi)}{u_\psi} = \int_\psi \left(\frac{K_m}{u_\psi l}\right)\frac{l}{u_c}\frac{\partial^2 u_c}{\partial z^2}\,dx - \int_\psi \left(\frac{u_\psi}{u_c}\right)\frac{1}{\rho u_\psi^2}\left(\frac{\partial p}{\partial x}_z\right)\,dx \tag{2}$$

where K_m is the eddy diffusion of momentum, l an advective length scale, u_ψ the speed of inflow and u_c the 'in-cloud' horizontal speed. All quantities are measured along trajectories. This nondimensional equation reveals the basic scaling: (i) $(u_c - u_\psi)/u_\psi$ is the change in horizontal momentum along ψ; (ii) $K_m/u_\psi l$ is the ratio of small-scale diffusion to advective transport; and (iii) the quantity $p/\rho u_\psi^2$ shows that the effect of pressure depends on the flow regime (u_ψ is regime dependent). This quantity is fundamental to the momentum transport by organized convection in section 3. Equation 2 is not sufficient because mass and thermodynamic equations are required, for example, to determine the vertical displacement of air parcels. Equation 2 could be diagnostically evaluated using cloud-resolving model data, for example to measure the relative importance of the pressure field and small-scale mixing on momentum flux.

We simply highlight two special cases for steady flow (note that Eq. 2 is time dependent). First, if convection is organized in the sense that small-scale mixing is negligible relative to advective transport (i.e., $K_m/u_\psi l$ small), then $p/\rho u_\psi^2$ is the primary quantity. Note that regimes of organization and accompanying momentum flux, obtained analytically by Moncrieff (1981) highlights this quantity. The archetypal model of Moncrieff (1992) is simple enough to be used in a parameterization (see Section 3.2). Second, when the advective effects are small, the entraining plume model used in mass-flux-based schemes must satisfy Eq. 2.

2.3 Eulerian constraints on momentum flux

While providing a formal framework for a distinction between organized and disorganized transport as it affects in-cloud momentum, the Lagrangian formulation is generally intractable, for example, because it requires the entire pressure field. An Eulerian approach reveals powerful constaints on convective momentum flux. Applying the averaging operator $< \; > = \frac{1}{L_x}\int_0^{L_x}(\;)\,dx$ to the Eulerian x-momentum equation, where L_x is the dynamical scale of the convective circulation we obtain

$$\frac{\partial < \rho u >}{\partial t} = -\frac{\partial < \rho u w >}{\partial z} - \Delta\Big[\rho u^2 + p\Big] \tag{3}$$

The difference operator $\Delta[\;]$ refers to the change in the quantity within the square brackets at any level z across $[0, L_x]$. In particular, $< \rho w >$ and $< \rho u w >$ are the *total* mass and momentum fluxes, respectively.

For the meantime, we use a domain with horizontal, rigid and free-slip lower and upper boundaries at $z = 0$ and $z = H$, levels at which $w = 0$. A free-slip condition on the lower boundary precludes turbulent fluxes but these are small compared to the organized fluxes and, in any case, are represented by the boundary layer (turbulence) scheme in a large-scale model. The first term on the right-hand side of Eq. 3 integrates identically to zero over $0 \leq z \leq H$ leaving

$$\frac{\partial}{\partial t}\Big(\int_0^H < \rho u > dz\Big) = -\int_0^H \Delta\Big[\rho u^2 + p\Big]\, dz \tag{4}$$

We call the quantity $\frac{\partial}{\partial t}(\int_0^H < \rho u > dz)$ the *momentum drift.* This occurs only if a gradient of the 'total momentum' $\int_0^H(\rho u^2 + p)dz$ across the domain exists (i.e., a mean current can be generated by the dynamical action of convection).

An integral constraint on momentum drift is revealed by applying the analastic mass continuity equation, $\partial \rho u/\partial x + \partial \rho w/\partial z = 0$. When the mass equation is integrated over $0 \leq z \leq H$ and the boundary conditions on w applied,

$$\int_0^H < \rho u > dz = G(t) \tag{5}$$

With rigid lid conditions, however, unless the mesoscale circulation interacts with the larger scale, $G(t)$ will be determined by the initial conditions at $t = t_0$. For illustration let $G = G(t_0) = 0$ in which case the volume-integrated momentum flux must satisfy

$$\int_0^H \Delta\Big[\rho u^2 + p\Big]\, dz = -\frac{dG}{dt} = 0 \tag{6}$$

A way to examine the effect of momentum drift is to allow evolving two-way interaction between the cloud system and the large-scale circulation, a problem that for the most part remains to be studied.

Special cases of Eq. 3 are as follows. First, if the motion is steady in a frame of reference traveling with the system (i.e., $\partial/\partial t = 0$ in this reference frame), although horizontal momentum can be redistributed by convection, momentum drift cannot occur and

$$-\frac{\partial < \rho u w >}{\partial z} = \Delta\Big[\rho u^2 + p\Big] \tag{7}$$

An important class of organized convection is pertinent; for example, regimes of organization satisfying mass, momentum, thermodynamic equations and the aforementioned integral constraints were produced by Moncrieff (1981).

Second, periodicity in the lateral direction requires that

$$\frac{\partial < \rho u >}{\partial t} = -\frac{\partial < \rho u w >}{\partial z} = g(z,t) \tag{8}$$

for some function $g(z,t)$. The spontaneous generation of mean flow by convection in a periodic domain is an interesting concept. In a study of low-frequency (~60-day) behavior of a cloud-resolving model integrated to radiative-convective-dynamical equilibrium, Held et al. (1993) demonstrated persistent regimes of convection and the generation of a sheared mean flow in a periodic domain. Laboratory experiments by Krishnamurti and Howard (1983) in a rotating annulus also featured shear generation. However, the boundary conditions used in these two examples were not rigid lids which may affect the mean flow response.

2.4 Tropopause tilting and momentum flux

If the upper boundary is a free surface, which is more realistic than the rigid-lid conditions used above, convective perturbations will excite gravity waves which can propagate energy and momentum flux upward. The sign of the momentum flux will depend on the direction of propagation of the system relative to the stratospheric wind direction. Since convectively generated momentum flux is presented by Kershaw (workshop proceedings), we sketch a dynamical mechanism which is distinct from convectively induced gravity wave drag. We examine a local effect of a front-to-rear gradient of convective (tropopause) height caused by the action of traveling mesoscale convection. Gradients of pressure certainly occur across mesoscale convective systems as seen in numerical models (Lafore and Moncrieff 1989; Fig. 8) and observations (LeMone 1983; LeMone and Moncrieff 1994). The dominance of this pressure gradient and its association with flow organization is the essence of the aforementioned mesoscale momentum flux theory.

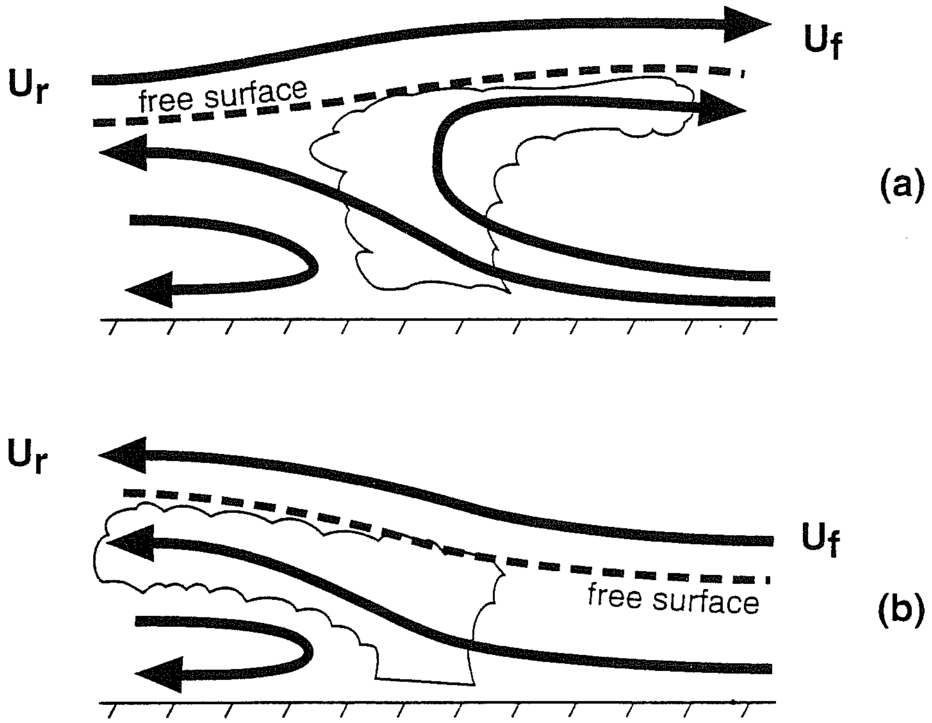

Figure 1: *Idealization of the free-surface models. (a) Case with* $U_f > 0$*, representing a midlatitude convective system in westerly shear and (b) Case with* $U_f < 0$*, representing an tropical squall line in a jet-like (reverse shear) ambient flow.*

The relative heights of the convective and stratiform regions will depend on the convective regime and, therefore, on the ambient wind shear. The tropopause may tilt front-to-rear on a scale of about 100 km and cause a pressure gradient across the topmost levels of the convective system and in the lower stratosphere. (Note this will tend to generate gravity waves of $\sim$ 100 km wavelength).

Figure 1 shows two idealized examples of a free surface along which pressure is constant ($Dp/Dt = 0$). These models could be rigorously examined just as the rigid-lid models of section 2.2 were formulated, but here we simply sketch some basic consequences. Using Eq. (1) with $K_m = 0$, it is readily shown that

$$\frac{\delta u}{U_f} \sim \frac{\delta p}{\rho U_f^2} \tag{9}$$

where, referring to Fig. 1, $\delta u = U_f - U_r$, with an analogous convention for δp. Since $\delta p/\rho U_f^2$ can be of order unity, the velocity change could be as large as U_f.

We use two simple examples for illustration. Assume that the flow above the free surface is unidirectional so all critical level (stagnation) complications are circumvented. First, consider a system having $U_f > 0$. This is relevant to midlatitude systems because the forward-pointing anvil and direction of the flow above the free surface ($U_f > 0$) are consistent with positive (i.e., westerly) shear (Fig. 1a). It follows from Eq. 9 that δu is positive (negative) if δp is positive (negative). Second, consider $U_f < 0$ and the flow shown in Fig. 1b, distinguished by a unidirectional relative inflow at all levels, so the system structure resembles a tropical squall line. This type of organization typically occurs in a jet-like wind profile in which the shear reverses direction with height. In this case the flow response is exactly opposite to the first example; namely, δu is positive (negative) if δp is negative (positive).

3. ISSUES

3.1 Parameterization of organized fluxes

Vertical shear is fundamental to the organization of convection yet it is disregarded in parameterization. While arguably reasonable for heat and moisture, this omission is less clear for momentum, especially considering the shear dependence of convective regimes. There is no basic reason why upgradient momentum transport could not be implemented in a parameterization, provided existing closures are used. We now elaborate on this point. No loss of generality is incurred by considering x-momentum. Following Tiedtke (1989), the mass-flux-based parameterization of momentum flux by *ordinary convection* is

$$\left(\frac{\partial Mu}{\partial z}\right)_c = E\overline{u} - Du - S_u \tag{10a}$$

The overbar denotes the grid-point value and $M_c = \overline{\rho\sigma w}$ is the convective mass flux, σ the cloud fraction, and S_u represents the horizontal pressure gradient. The mass flux is derived from integrating the mass continuity equation:

$$M(z) = M_b + \int_{z_b}^{z} (E - D)\, dz \tag{10b}$$

where E and D, the mass entrainment and detrainment per unit length, are determined from an entraining plume model, assuming a value of $M = M_b$ at cloud base ($z = z_b$).

In view of the structured nature of the momentum flux by organized convection, an entraining plume is not strictly appropriate, although it is widely used. Moncrieff (1992) formalized a method of representing the *total momentum flux due to organized convection.* This is viewed as an essentially mesoscale process (identified by the subscript 'm')

$$\frac{\partial < \rho L_m u_m w_m >}{\partial z} = -\Delta[\rho u_m^2 + p_m] \tag{11a}$$

where L_m is dynamical scale of the organized convection. In this instance,

$$M_m = -\int_0^z \Delta[\rho u_m] dz \tag{11b}$$

where $M_m =< \rho L_m w_m >$ is the total mass flux by the mesoscale system (c.f., Eq. 10b). The right-hand sides of Eqs (11a, b) can be obtained from idealized dynamical models.

There is an important *physical* distinction between the cloud systems respectively represented by Eqs. 10 and 11. However, the two sets of formula have a formal one-to-one similarity which should be useful in a parameterization context:

$$< \rho L_m u_m w_m > \quad \equiv \quad Mu \tag{12a}$$

$$\Delta[\rho u_m^2] \quad \equiv \quad E\overline{u} - Du \tag{12b}$$

$$\Delta[p_m] \quad \equiv \quad S_u \tag{12c}$$

In a parameterization application, Eq. 10 would be used for ordinary convection in weakly sheared environments and Eq. 11 (for example) where the shear reverses with height as in jet-like profiles.

Two points are worth mentioning. (i) A shear-dependent selection principle is required; and (ii) to the extent that organized convective momentum flux is anisotropic, the formula for the x- and y-components may be quite different. This is a more substantial point considering a parameterization of momentum depends on the orientation of the convection. However, if orientation can be linked to a resolved-scale variable such (e.g., shear) or to large-scale dynamics (e.g., easterly waves or westerly wind bursts) this issue can be addressed. For example, the y-momentum flux is conserved provided $\partial p/\partial y \approx 0$, where the y-axis is parallel to the line (Moncrieff 1992; section 10a). If the cross-system flux is given by Eq. 11 then *both* components of the momentum flux can be determined. In other words, the dynamical model would replace the plume model *only regarding the deepest cloud element* as illustrated in Fig. 2.

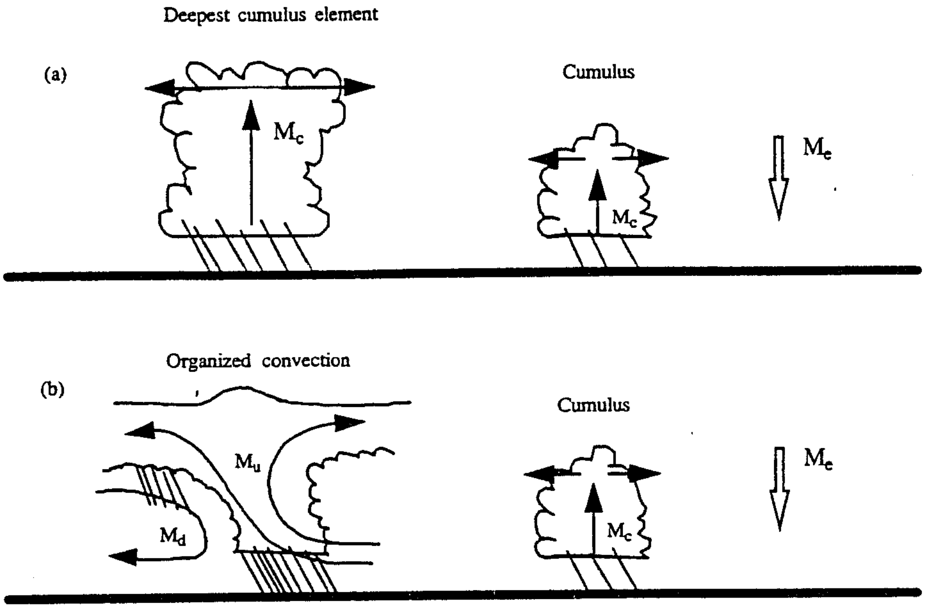

Figure 2: *Conceptualizations of a dynamically based model of organized convection in mass-flux-based parameterization. (a) Traditional method involving entraining plumes that detrain at the topmost level. (b) Dynamical model of organized convection replaces the deepest convective element. M_c, M_e, M_u and M_d are the convective mass flux, subsidence, dynamical model updraft mass flux and dynamical model downdraft mass flux, respectively. [From Wu and Moncrieff (1996)]*

3.2 Partly resolved (surrogate) mesoscale systems

An issue in all numerical models arises when a process being parameterized has a comparable *dynamical* scale to the grid length ('scale separation'). This does not normally arise in global NWP and climate models because scale separation holds even for mesoscale convective systems. An exception is the occurrence of large cloud clusters ('superclusters') in the Indian Ocean and western Pacific which are linked with 'westerly wind bursts' at least in the ECMWF T213

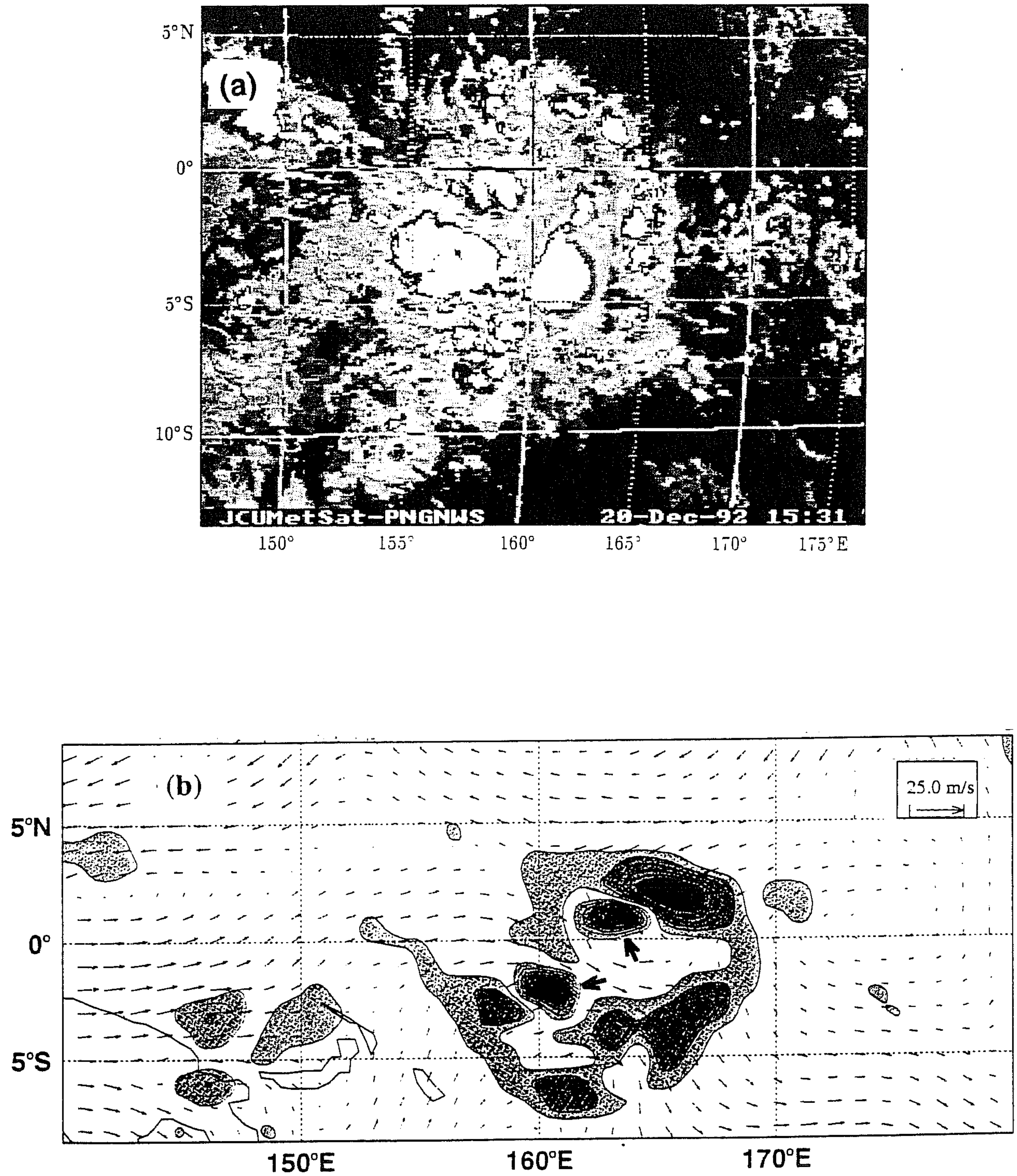

Figure 3: *(a) GMS-4 infrared image of a supercluster at 1531 GMT 20 December 1992. (b) The surrogate supercluster in the ECMWF T213 model.*

model. These episodes of lower-tropospheric westerly winds can last for weeks. Both westerly bursts and superclusters are associated with the ascending (convectively disturbed) phase of the Madden-Julian Oscillation (MJO; Madden and Julian 1971).

Three wind burst episodes occurred during TOGA COARE. Moncrieff and Klinker (1997) examined the treatment of a supercluster in the ECMWF T213 medium-range operational weather prediction model during the early stage of the December 1992–January 1993 westerly wind burst. (Note that similar structures were identified at T106 resolution). Superclusters consist of cloud clusters and deep convection which, according to satellite images, can extend 1000's km (Fig. 3a). A supercluster can be idealized as a hierarchy of three scales of convection: 10 km (cumulonimbus), 100 km (cloud clusters) and 1000 km (stratiform region). The 1000-km scale is more a convectively driven response than a 'free' dynamical mode.

A T213 model obviously cannot resolve the 10–100 km scales of motion, but attempts to explicitly treat the 'free' response as a *surrogate supercluster* (Fig. 3b), so-called because the hierarchy is, for the most part, treated as a 1000-km scale system. Although parameterized convection occurred it was suppressed (and even shut down) during the mature phase of the supercluster (which lasted for days). More significantly, the surrogate system developed a strong vertical tilt. This caused a *highly organized, explicitly resolved* form of momentum transport. This led to an error in the zonal wind field. Unfortunately, this error could not be unambiguously quantified because only about half the TOGA COARE research soundings were accepted by the operational data assimilation procedure. The ongoing global reanalysis at T213 (or preferably higher resolution) is essential to quantify the error.

The basic issues raised by Moncrieff and Klinker (1997) are: (i) Since it is difficult to either control or correct the spontaneous surrogate behavior, will improved resolution alleviate this problem at a certain critical resolution? (ii) Is it necessary to parameterize cloud cluster transport (e.g., mesoscale mass and momentum flux) in high-resolution NWP models? (iii) Can a T213 global model, having a resolution of about 90 km, forecast a supercluster with predictive skill? However, a 2-km horizontal resolution was found necessary to properly model convection of this type, as shown by Grabowski et al. (1997) for GARP Atlantic Tropical Experiment (GATE) cloud systems, and by (Wu et al. 1997; workshop proceedings) for TOGA COARE systems. This implies that even at high resolution a global model may not accurately predict the transport in the explicit sense. Unfortunately, we cannot be more definitive about this issue at present.

3.3 Regional nature of organization

The global frequency and distribution of mesoscale convective complexes was described by

Laing and Fritsch (1996). They showed that, rather than being uniformly distributed, organized cloud systems tend to occur in specific regions; for the most part, these regions are correlated with moderate to strong vertical shear. This implies that convective momentum flux will be *regionally dependent*: a new concept because present-day parameterizations are universally applied. That is, no consideration is given to geographic region or (more fundamentally) shear. This point has important implications to how momentum flux is parameterized in global models. For example, just as gravity wave drag is linked to orography, so transport of momentum by organized convection may be regional and even linked to orography (Laing and Fritsch 1996).

In particular, Laing and Fritsch (1993; Fig. 1) shows the distribution of mesoscale convective complexes over Africa, which is an example of the regional nature of organized convective cloud systems. Note that the conditional sampling used to identify mesoscale convective complexes is a more general selection than would be applied to squall lines *per se*. However, radar measurements usually show that many complexes contain linear structures, to the distinction is of degree rather than kind.

West African squall lines were comprehensively studied in the Convection Profonde Tropicale (COPT) field experiment in the Ivory Coast. They have also been extensively modeled in two and three spatial dimensions. These systems are very long lasting, even for squall lines. Such longevity is almost certainly a function of shear generation due to easterly waves. For the most part, W. African squall lines are two dimensional and shear perpendicular (Redelsperger and Lafore 1988). We cannot say with certainty that momentum flux by three-dimensional lines consisting of a series of aligned convective elements can be approximated by a two-dimensional model. This point relates to the large-scale role of upgradient momentum transport.

The large-scale impact of organized momentum flux could be investigated using global NWP diagnostics. However, it is difficult to identify the mechanisms at work from global model diagnostics. Yano and Moncrieff (1997) therefore took an idealized approach. They used the Moncrieff (1992) momentum flux (with a novel dynamical closure) and an idealized large-scale model of the tropical atmosphere. Only organized fluxes were represented, so this work should be interpreted as a regional impact study rather than a global investigation; for example, the effect of momentum fluxes associated with (say) African easterly waves or westerly wind bursts in the tropical western Pacific and Indian Ocean. Examining the linear stability of the system, Yano and Moncrieff demonstrated three main points: (i) Organized momentum transport suppresses wind-induced surface heat exchange (WISHE; Yano and Emanuel 1991), a specific type of air-sea interaction. (ii) A new kind of instability called momentum transport induced (MTI) instability occurred purely through the momentum flux effect. (iii) A realistic phase speed of the MJO occurred which otherwise propagates unrealistically fast in linear models). It is too early to say if these results will hold in a fully nonlinear model of the tropical atmosphere.

3.4 Regime transitions in cold air outbreaks

A distinguishing aspect of momentum transport is its dependence on the regime of organization which, as aforementioned, is a function of the ambient vertical shear. Outstanding examples of the distinct regimes of organization are the diverse range of cloud system regimes occurring in cold air outbreaks air behind mid-latitude cold fronts. The area covered by these systems can be very large ($\sim 10^6$ km^2). Examples are (i) polar outbreaks from the Arctic ice sheet over the N. Atlantic and N. Pacific; (ii) polar outbreaks from Antarctica over the S. Atlantic, S. Pacific and S Indian Oceans; and (iii) outflow from the wintertime Siberian anticyclone over the Sea of Japan and the E. China Sea. The largest ocean-atmosphere heat fluxes of anywhere on Earth, in excess of 1000 Wm^{-2}, occur in these regions. They are climatically important because of the accompanying strong air-sea fluxes over large areas. They affect not only the atmosphere but also the ocean, noting that strong surface cooling near the ice sheets can drive deep oceanic convection (Jones and Marshall, 1993). Cold outbreaks are also identified with strong cloud radiative forcing. Their importance in weather forecasting is also notable, for example, the copious snowfall over west coast of Japan associated with the outbreaks. Note that the organization of convection over the Canadian/U.S. Great Lakes in wintertime north-westerly flow is dynamically akin to the upstream part of oceanic cold air outbreaks (e.g., boundary layer rolls) not to say the lake-effect snowfall.

The richness of organized cloud system regimes (Fig. 4a) and accompanying regime transitions (Fig. 4b) are unique to cold air outbreaks. Numerical simulation of the entire range of transitions have not yet been attempted and is computationally challenging. The transport of momentum by individual convection regimes will be very different because of the distinct dynamical structure. Note that systematic errors in an earlier T106 version of the ECMWF model occurred in cold air outbreak regions (Hollingsworth, private communication). This error was manifested by the directional wind shear being too small in the boundary layer. It is not known if this error occurs in the T213 model; moreover, its physical basis is obscure to say the least.

As far as parameterization is concerned, the accurate prediction of the convective regimes and transitions among regimes is a strict test not only for parameterization schemes (momentum fluxes in particular) but also for cloud-resolving models, because both must accurately model individual regime *and* regime transitions.

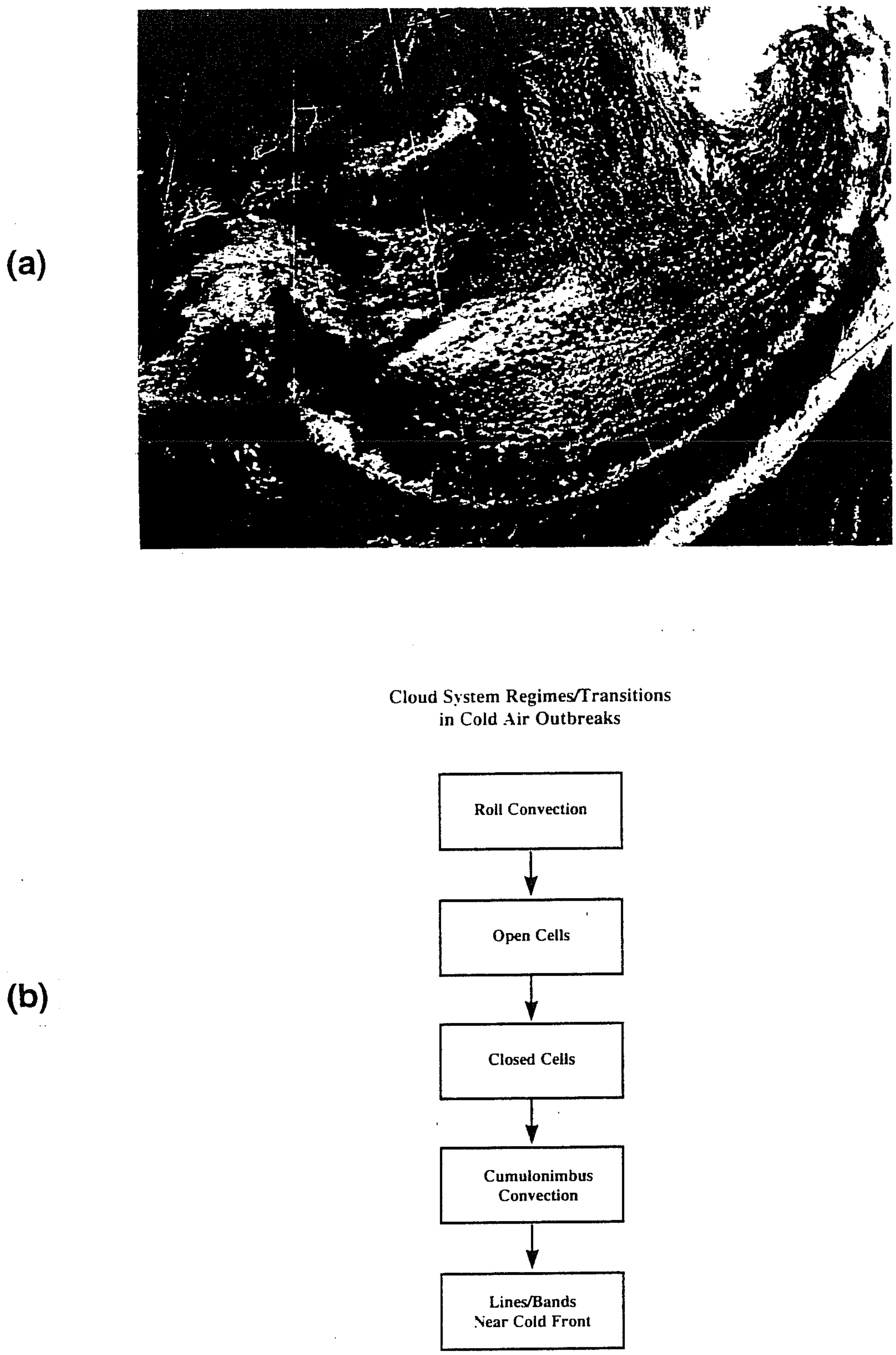

Figure 4: *a) Cloud system regimes over the N. Pacific during a cold air outbreak seen in visible wavelength from GMS-1 satellite on Jan 28 1980. b) Cloud system regime transitions that occur in a typical cold air outbreak.*

3.5 Broader considerations

Issues involving convective organization will remain even if the parameterization of momentum transport was perfect! For example, convective momentum flux is not a stand-alone process because organized cloud systems (i) contain strong convective *and* mesoscale downdrafts, the latter not being included in present parameterizations; (ii) cause a 'convectively disturbed' boundary layer which is physically distinct from boundary layer parameterizations based on homogeneous turbulence and similarity principles; (iii) directly affect the surface fluxes through convectively generated 'gustiness'; (iv) produce extensive cirrostratus anvils that interact strongly with radiation; and (v) cause precipitation in the stratiform region to be coupled to convective precipitation. These considerations may call for a different physically based approach to parameterization, an issue beyond the scope of this paper.

4. ROLE OF CLOUD-RESOLVING MODELS

A cloud-resolving model (CRM) resolves cloud-scale dynamics in either two or three spatial dimensions. For example, in simulating a precipitating convective cloud system, a CRM can resolve individual convective cells while its domain encompasses the entire cloud system.

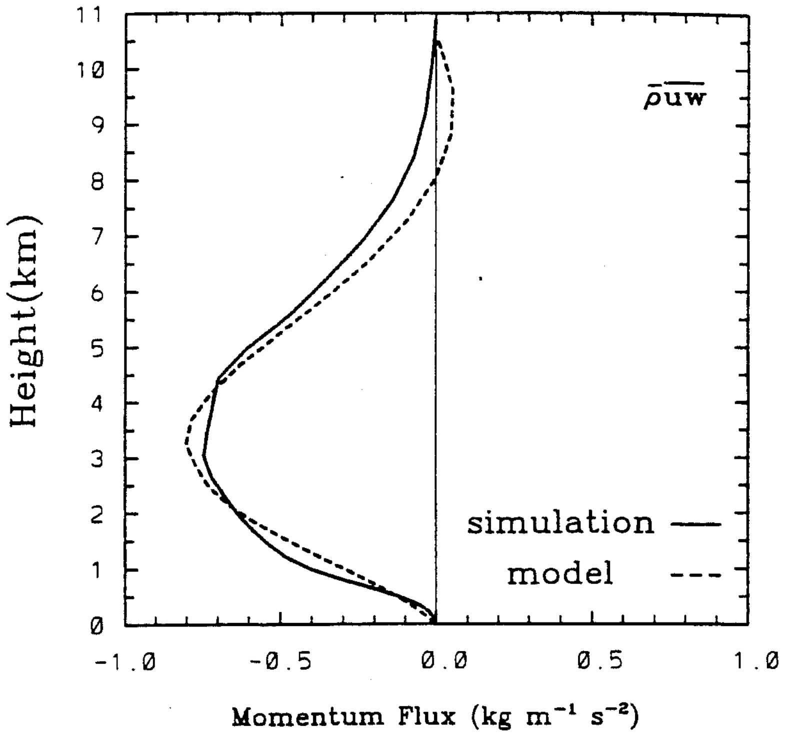

Figure 5: *Momentum flux by a tropical squall line from the Moncrieff (1992) archetypal dynamical model (dashed) and cloud-resolving model diagnostics (full). [From Wu and Moncrieff 1996].*

In contrast, even the highest resolution NWP models, with a grid size of less than 100 km, cannot resolve the individual convective cells. Even the accompanying mesoscale circulations are subgrid scale and their effects on the large-scale fields should arguably be parameterized. A CRM is able to determine these collective effects directly, to the extent that the parameterizations of its own subgrid processes are accurate: an effective tool for cloud system studies and their large-scale effects. An example of cloud system evolution in a three-dimensional simulation is shown in Wu and Moncrieff (workshop proceedings; Fig. 12). Different regimes occur in response to the evolution of the large-scale forcing and the shear during passage of an easterly wave.

Bulk properties, such as mass and momentum fluxes, which are impossible to accurately obtain from observations, are readily obtained from CRM diagnostics. For example, Wu and Moncrieff (workshop proceedings; Figs. 6, 14 and 15) show the convective mass flux derived from 7-day, two and three dimensional cloud system simulations in GATE as well as a 39-day two-dimensional TOGA COARE simulation. The decomposition of mass flux into updraft and downdraft components can be used to evaluate and improve mass-flux-based parameterization schemes. Momentum fluxes can be derived from these data to evaluate models of organized momentum fluxes. In particular, the squall line momentum transport represented by the Moncrieff (1992) archetypal model was evaluated against CRM results by Wu and Moncrieff (1996), as shown in Fig. 5. Kershaw and Gregory (1997) used a cloud-resolving model to empirically estimate the pressure gradient term in a momentum flux parameterization by ordinary convection which was tested in the UKMO unified model (Gregory et al. 1997).

A comprehensive description of the use of cloud-resolving models in the context NWP and climate model parameterizations can be found in Moncrieff et al. (1997).

5. FURTHER RESEARCH

We have made the case that is timely to comprehensively investigate the process of convective momentum transport in global models and build on the parameterization of ordinary convection. Investigations should involve high-resolution global numerical weather prediction models (T213 or preferably higher resolution). Not only do these models have a resolution that should be able to reveal weaknesses in present methods of parameterizing momentum transport, they have arguably attained a level of sophistication that will enable the complex process of convective momentum transport to be comprehensively assessed. Such studies should ideally be in combination with the use of state-of-the-art cloud-resolving models, including those with interactive grid nesting capability. We identify on three particular studies.

5.1 **Tropical oceanic convection:**

A three-pronged approach to studying the large-scale role of superclusters in TOGA COARE is envisaged: (i) cloud-resolving models of regimes and regime transitions; (ii) high-resolution ($\sim$ T1000) global model forecasts to assess how well global models explicitly treat superclusters; and (iii) the reanalysis (at least T213 resolution) of the TOGA COARE period to quantify the systematic errors relating to superclusters and their predictability.

5.2 **Midlatitude oceanic convection:**

Cloud systems within cold air outbreaks have been little studied. While field experiments have been conducted, none has examined the large-scale aspect of the problem relating to air-sea interaction and, in particular, to convective momentum transport. It would be illuminating to use (i) global models to evaluate issues like thermodynamic transports, surface fluxes, cloud fraction, momentum transport, role of radiation, among others; and (ii) cloud-resolving models to explicitly determine the aforementioned quantities. Note that an entire cold air outbreak (i.e., convection over much of the N. Atlantic could be explicitly modeled using modern computers).

5.3 **Continental convection:**

Consideration needs to be given to cloud systems in (i) tropical continental regions such as Africa and Amazonia, considering these regions are primary heat sources for the atmosphere; (ii) organized convection over midlatitude continents during the warm season. The latter has the advantage of having dense standard observations. Cloud systems over the central U.S. are of special interest because the standard observations are augmented by special intensive observations from the GEWEX Continental-scale International Project (GCIP) and the Atmospheric Radiation Measurement (ARM) program.

6. CONCLUSIONS

Issues have been raised that are relevant even if the existing methods for treating ordinary convection in global models were completely accurate. These center on the broad role of convective organization. The effect of shear on convection has long been known and recently dynamically quantified. However, as far as the large-scale impact is concerned, this aspect remains a fundamental enigma. If the effect of organized transport is basically at regional scales (i.e., in association with specific shear profiles), a new element is thus added to the parameterization problem—one that demands a strong physical basis.

It is argued that future resolution enhancement, particularly in global NWP models, will require a full understanding of the large-scale role of precipitating convection. We stress that the collective effects of cloud systems are the pacing issue, not individual clouds *per se*, in keeping with the GEWEX Cloud System Study (GCSS) approach (Moncrieff et al. 1997).

Finally, a comprehensive study of the large-scale impact of organized convection necessarily involves issues in addition to momentum transport. For example, organized convection is associated with mesoscale downdrafts, stratiform rainfall and extensive radiatively active cirrus. The mesoscale downdraft is a particular example of a well-known process absent from present-day parameterizations, for example, in the mass flux estimate. Improvements in present convective parameterization methods are obviously necessary. In the longer term, however, a physically complete approach to the parameterization of organized convection may have to be more cognizant of the interactions among processes; that is, *cloud systems rather than individual cloud processes* may prove to be the pacing issue in parameterization. While this is presently only a speculative closing remark, note that the thermodynamic interaction between convective and stratiform clouds is now represented in a few convective parameterization schemes (e.g., Tiedtke 1989) and, to a certain degree, in the prognostic treatment of clouds in NWP and climate models.

Acknowledgements

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

Grabowski, W.W., X. Wu, and M.W. Moncrieff, 1996: Cloud resolving modeling of tropical cloud systems during Phase III of the GATE. *J. Atmos. Sci.*, **53**, in press.

Gregory, D., R. Kershaw, P.M. and Inness, 1997: A numerical study of the parameterization of momentum transport by convection. II: Tests in single-column and general circulation models. *Quart. J. Roy. Met. Soc*, **113**, in press.

Held, I.M., Hemler, R.S., and Ramaswamy, V., 1993: Radiative-convective-dynamical equilibrium with explicit two-dimensional moist convection. *J. Atmos. Sci.*, **50**, 3039-3927.

Jones, H., and J, Marshall, 1993: Convection with rotation in a neutral ocean: A study of deep ocean convection. *J. Phys. Oceanogr.*, **22**, 583-595.

Kershaw, R., and D. Gregory, 1997: Parameterization of momentum transport by convection. I: Theory and cloud modelling results. *Quart. J. Roy. Met. Soc.*, **113**, in press.

Krishnamurti, R., and L.N. Howard, 1983: Large scale flow in turbulent convection: Laboratory experiments and a mathematical model. *Papers in Meteorological Research*, *Met. Soc. Republic of China*, **6**, No. 2.

Lafore, J.-P., and M. W. Moncrieff, 1989: A numerical investigation of the organization and interaction of the convective and stratiform regions of a tropical squall line. *J. Atmos. Sci.*, **46**, 521-544.

Laing, A., and J. M. Fritsch, 1993: Mesoscale convective complexes in Africa. *Mon. Wea. Rev.*, **121**, 2254-2263.

Laing, A., and J. M. Fritsch, 1996: The global properties and environment of mesoscale convective complexes. *Preprints.* 12th International Conference on Clouds and Precipitation, 19-23 August, 1996, Zurich, Switzerland.

LeMone, M. A., 1983: Momentum flux by a line of cumulonimbus. *J. Atmos. Sci.*, **40**, 1815-1834.

LeMone, M.E., and M. W. Moncrieff, 1994: Momentum and mass transport by convective bands: comparisons of highly idealized dynamical models to observations. *J. Atmos. Sci.*, **51**, 281-305.

Madden, R.A., and P. R. Julian, 1971: Detection of a 40-50 day oscillation of the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702-708.

Moncrieff, M.W., 1981: A theory of organized steady convection and its transport properties. *Quart. J. Roy. Met. Soc.*, **107**, 29-50.

Moncrieff, M.W., 1992: Organized convective systems: Archetypal dynamical models, mass and momentum flux theory, and parameterization. *Quart. J. Roy. Met. Soc.*, **118**, 819-850.

Moncrieff, M.W., and E. Klinker, 1997: Large mesoscale cloud systems in the tropical western Pacific as a process in General Circulation Models. *Quart. J. Roy. Met. Soc.*, **123**, April edition.

Moncrieff, M.W., S.K. Krueger, D. Gregory, J.-L. Redelsperger, and W.-K. Tao, 1997: GEWEX Cloud System Study Working Group 4: Precipitating Convective Cloud Systems. *Bull. Amer. Met. Soc.*, **78**, in press (May issue).

Redelsperger, J.-L., and J.-P. Lafore, 1988: A three-dimensional simulation of a tropical squall line: convective organization and thermodynamic vertical transport. *J. Atmos. Sci.*, **45**, 1334-1356.

Schneider, E.K., and R.S. Lindzen, 1976: A discussion of the parameterization of momentum exchange by cumulus convection. *J. Geophys. Res.*, **81**, 3158-3160.

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Wea. Rev.*, **117**, 1799-1800.

Wu, X., and M.W.Moncrieff, 1996: Collective effects of organized convection and their approximation in general circulation models. *J. Atmos. Sci.*, **53**, 1477-1495.

Wu, X., W.W. Grabowski, and M.W. Moncrieff, 1996: Long-term behavior of cloud systems observed during TOGA COARE. Part I: Two-dimensional cloud-resolving models. *J. Atmos. Sci.*, **54**, submitted.

Yano, J.-I., and K.A. Emanuel, 1991: An improved model of the equatorial troposphere and its coupling with the stratosphere. *J. Atmos. Sci.*, **48**, 377-389.

Yano, J.-I., and M. W. Moncrieff, 1997: Impact of mesoscale momentum transport on the large-scale tropical circulation: A linear analysis. *J. Atmos. Sci.*, submitted.