Organized convective systems in the tropical western Pacific as a process in general circulation models: A TOGA COARE case-study

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SUMMARY

We examine the large-scale effects of organized convective systems in the tropical western Pacific observed during the Tropical-Ocean Global-Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). In a case-study approach, we examine realizations of a supercluster, associated with the onset of the December 1992 westerly wind burst, in the T213 operational medium-range weather forecasting model of the European Centre for Medium-Range Weather Forecasts (ECMWF). We idealize a supercluster as a hierarchy of three interacting scales, namely organized cumulonimbus $\vec{e}_1$, mesoscale convective systems $\vec{e}_2$, and the supercluster component $\vec{e}_3$. It is shown that the ECMWF model represents this hierarchy as a $\vec{e}_3$-like surrogate whose influence dominates the effect of parametrized convection. This causes over-prediction of the model tendencies which, in the case of zonal momentum, is explained in elementary terms.

The structure of the resolved-scale momentum flux is explained by Moncrieff’s (1992) archetypal theory of organized convection which has been verified against observations and cloud-resolving model data-sets. The parametrization of subgrid-scale convective momentum flux in the ECMWF model, based on a momentum mixing concept, produces subgrid-scale tendencies that are physically different from transports associated with cumulonimbus convection in a shear flow.

We outline a strategy for parametrizing the momentum flux by the $\vec{e}_1$ component based on the archetypal model. The $\vec{e}_2$ component, which is part-resolved and part-parametrized, is at odds with the assumptions of scale separation underpinning parametrization. It is argued that this component should be represented as part of the prognostic treatment of convectively generated circulations.

Finally, we suggest cloud-resolving modelling studies to further quantify the structure and large-scale impact of superclusters in a westerly-wind-burst environment, ranging from idealized models to models having data assimilation capability.

KEYWORDS: Mesoscale convective system Momentum flux Parametrization Supercluster Westerly wind burst

I. INTRODUCTION

The parametrization of organized convection and accompanying mesoscale effects has received little attention in general circulation models (GCMs), despite the frequent occurrence of these processes in the atmosphere. It can be argued that these models do not have adequate resolution, or that the parametrizations of physical processes are not sufficiently sophisticated, to ascertain whether the organization of convection is a legitimate issue. In order to quantify this problem in the best practicable setting, we examine the treatment of large organized cloud-systems in a high-resolution operational medium-range weather forecasting model that contains an advanced parametrization of deep convection.

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The likelihood that organized convection should be taken into account in parametrization was articulated by Yanai et al. (1973). Other evidence includes the derivation of mass fluxes (Houze et al. 1982), the widespread occurrence of mesoscale systems (Miller and Fritsch 1991), and the large-scale effects of mesoscale convective systems (Wu 1994). Considering the many uncertainties relating to the parametrization of physical processes, few of which are understood at a fundamental level, it is not surprising that organized convection has been neglected in global models. This point is put into perspective by realizing that the evaporatively driven downdraught, a process intrinsic to organized convection, has only recently gained attention in the parametrization context. We show that subtle issues regarding the treatment of organized convection are at work in high-resolution operational models. These issues are expected to affect climate models as they gain physical sophistication and their horizontal resolution gradually improves.

Vertical wind-shear is presently not included in convective parametrization, although it has long been known to organize deep convection and affect its transport properties. Latent heating and drying are the main effects represented, but account is not taken of the influence of organization on them, although it has a substantial influence (e.g. Redelsperger and Lafore 1988; Tao et al. 1993). One distinctive aspect of organized convection is its effect on momentum transport, which is not only poorly understood as a process but also in terms of its impact on the large-scale circulation of the atmosphere. We shall outline a dynamical approach to both these issues, subsequent to demonstrating how large organized convective cloud systems are not adequately treated in a state-of-the-art operational global model.

Other aspects are also of a potentially fundamental nature. For example, parametrization methods are based largely on statistical-homogeneity principles and the assumption that the processes being approximated have a dynamical scale much less than the model resolution (scale separability). Homogeneity may be reasonable for ordinary convection, but is at odds with organized convection, which is intermittent rather than homogeneous.

The concept of scale separability in the tropical atmosphere is an assumption rather than a reality. In particular, squall lines and convective systems on the meso-β scale (20–200 km), are highly organized and intermittent. They occur on a scale comparable to the resolution of operational medium-range weather forecasting models (about 90 km in the ECMWF T213 spectral model). The resolution of limited-area operational models used for short-term weather forecasting is about 30 km. In these models, scale separation cannot be well satisfied, yet existing parametrizations are widely used.

We investigate the treatment of mesoscale organized convection in the ECMWF T213 operational model on a timescale of a few days. In order to accomplish this objective, we examine model forecasts of a westerly wind burst and an associated supercluster that occurred during TOGA COARE, when special soundings taken during the field experiment were incorporated into the operational model. Estimates of model errors can be better quantified when these additional data supplement the standard operational analysis in this data-sparse oceanic region. We adopt a case-study approach to examine the effects of organized convection in GCMs, although we recognize that representativity of the results remains to be addressed.

The paper is presented in eight parts. In section 2, we introduce the cloud organization within westerly wind bursts, followed by an idealization of the substructure of a supercluster. In section 3, we describe the predicted supercluster, followed by a quantification of the model tendencies and identification of model errors in section 4. A physical interpretation of these errors is argued in section 5, followed by a formal representation of momentum fluxes by organized convection. Some relevant issues are raised in section 7, followed by conclusions and suggestions for further research in section 8.
2. SUPERCLUSTER IDEALIZATION

We identify three interacting scales of motion pertinent to a supercluster, two of which are associated with the so-called mesoscale convective system that cannot be properly resolved in a GCM. It is the flawed representation of these two scales that is at the root of a distinctive type of model error involving the concept of organized convection.

(a) Mesoscale convective system

A mesoscale convective system (MCS), or cloud cluster as it is often called in tropical meteorology, is the manifestation of a distinctive and ubiquitous process on the meso-β scale of motion (20–200 km). It is a special case of the larger mesoscale convective complex (MCC) described by Maddox (1983). There are several reviews of this type of convection, for example Cotton and Anthes (1989) and Houze (1993), to which the reader is referred for details. As far as our work is concerned, a key point is that mesoscale convective systems have two primary interacting scales, namely a heavily precipitating convective region of characteristic scale about 10 km and a lightly precipitating stratiform region of scale about 100 km. This dual-scale aspect is particularly relevant because the convective region is treated by a convective-parametrization scheme, while the stratiform precipitation is treated as part of the diagnostic treatment of large-scale precipitation.

The expression ‘supercluster’ was introduced by Nakazawa (1988) to describe extensive cirrostratus, and the deep convection embedded within it, commonly seen in satellite images (e.g. Fig. 1). Upper-tropospheric cirrus produced by outflow from organized convective cloud systems has gained attention because of its effect on radiative fluxes in climate models. A supercluster is similar to a mid-latitude MCC, but has more extensive cirrostratus when measured in terms of satellite-derived brightness-temperatures. Little is known of the internal structure of superclusters, but it is expected that the dynamically active regions (e.g. as measured by radar) occur on a meso-β scale. This is one-to-two
orders of magnitude smaller than space-based observations imply and, moreover, is not resolvable in present-day GCMs. The UHF wind profilers deployed in the tropical western Pacific are capable of quantifying the internal structure. For example, Gage et al. (1994—Fig. 2) shows the sub-structure of large precipitating cloud systems moving over the ship Kexue (2°S, 156°E) 20–22 December 1992.

It has been shown that superclusters occur in the Indian Ocean, the tropical western Pacific and Indonesian regions (e.g. Nakazawa 1988; Lau et al. 1991; Mapes and Houze 1993). They are associated with the convectively disturbed ascending branch of the Madden–Julian oscillation (MJO) (Madden and Julian 1971), and often originate in the Indian Ocean, travel eastward over the Indonesian ‘maritime continent’ and into the western-Pacific warm-pool. During an El Niño episode they can reach the central Pacific. Unlike a tropical cyclone, which has a clear scale and is under strong rotational control, we view a supercluster as a hierarchy of weakly coupled, multi-scale convective systems rather than a system having a single dominant scale of motion. For example, the extensive convectively generated cirrus outflow is indicative of horizontal advection rather than definitive of a large dynamical scale. Superclusters are modulated by the influence of Australia and the maritime continent. Spatial continuity is more evident in satellite-based, meridionally averaged, time–space representations of convectively generated cirrostratus (e.g. Nakazawa 1988).

An example of an eastward-moving supercluster that occurred during the December 1992 westerly wind burst is shown in Fig. 1. It contains several MCS-like components as shown by the brightest areas. (Convectively generated cirrostratus spanned this entire region within 24 hours.) Assuming an analogy to MCCs, the deepest and most intense convection will be on the cumulonimbus scale which is not resolvable by the GMS-4 satellite.

Considering the above points, we view a supercluster as the three-component hierarchy shown in Fig. 2. This conceptualization consists of $C_1$, which is cumulonimbus convection on a meso-$\gamma$ scale (2–20 km); $C_2$, meso-$\beta$-scale convective systems (cloud clusters) which are usually organized ensembles of cumulonimbus; and $C_3$, a meso-$\alpha$-scale (200–2000 km) component or ‘envelope’. It has long been known that cumulonimbus convection is organized by wind shear (see Ludlam (1980) for an historical perspective), but this triple-scale hierarchy is arguably unique to the Indian Ocean and the western Pacific. It is an aspect of convective organization that should be of concern in large-scale models.
(b) Westerly wind burst

A westerly wind burst is a large-scale episode of strong low-tropospheric westerly winds occurring from time to time in the light easterly-wind regimes of the western Pacific. Studies of the relationship between organized convection and westerly wind bursts were part of the primary objectives of TOGA COARE. The field experiment took place between November 1992 and February 1993 and has been summarized by Webster and Lukas (1992). Westerly bursts take various forms and we refer to a paper by Harrison and Giese (1991) for a dynamical classification.

Three westerly-burst episodes occurred during TOGA COARE, namely in early November, late December until early January, and early February. These have been detailed by Lin and Johnson (1996) and are illustrated in Fig. 3. The prominent, albeit not unusually strong, December 1992 westerly wind burst all but reversed the tropospheric zonal flow in the Intensive Flux Array (IFA). The wind burst was accompanied by strong vertical shear and strong large-scale ascent which helped maintain deep convection by generating convective available potential energy (CAPE). The treatment in the T213 model of a supercluster that occurred during the December westerly wind burst is our focal point.

The three TOGA COARE observing domains span an area which is vast in comparison with that normally associated with convective processes. A GCM is therefore a practicable way to examine the large-scale effects of a supercluster associated with westerly wind bursts. The sounding-array remained operational during the mature phase of the December westerly wind burst but aircraft and shipborne intensive observations were temporarily discontinued during the Christmas period. This is not a limiting factor in our approach.

3. Supercluster structure in the GCM

(a) Supercluster

We analyse results from the ECMWF T213 spectral model. (T106 forecast experiments were also undertaken to derive a physical interpretation and will be mentioned accordingly.) The ECMWF model uses the Tiedtke (1989) mass-flux-based convective parametrization that was developed using data sets from large field experiments such as
the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE). It is a physically based and comprehensive convection scheme; for example, it contains a parametrization of ice processes and a detrainment of ice and cloud water. In this respect, it partly accounts for convectively generated anvils, although it cannot adequately represent the effects of mesoscale circulations intrinsic to the stratiform region. The Tiedtke scheme includes a cumulus momentum exchange parametrization based on the same mixing concept as was used in the thermodynamic parametrizations. Cloud-scale downdraughts are also represented in this scheme.

Compared to cloud-resolving models (CRMs) that contain fully prognostic equations for all three phases of water, the water cycle is treated in a simple way, as in all global models. Stratiform precipitation is treated in a diagnostic manner as large-scale condensation which occurs when the relative humidity exceeds a specified threshold (100%). Note that there is widespread effort, and the ECMWF model is no exception, to develop prognostic cloud-schemes for GCMs that have time-dependent microphysical terms in the thermodynamic equations (see WCRP-90). A study relevant to prognostic methods, specifically relating to organized convection, was performed by Zhang et al. (1988), who compared the effects of an explicit prognostic scheme and of parametrized convection. This was a regional-scale prediction of severe summertime weather caused by strong MCSs and MCCs.

Global data, transmitted over the Global Transmission System (GTS), is assimilated four times per day into the ECMWF operational model. As far as our study is concerned, a unique feature is that data from the research-oriented soundings from the TOGA COARE field experiment were assimilated into the T213 operational analyses, including, for example, data from the Integrated Sounding System (ISS) deployed at six sites (Parsons et al. 1994). These supplement the typically sparse standard soundings over this oceanic region. Because of technical difficulties, not all the additional soundings were included. In particular, the 0000 GMT and 1200 GMT data enjoyed high success (about 90%), but a much lower success (about 10%) was achieved with the 0600 GMT and 1800 GMT data. Note that global data from various sources, including the TOGA COARE special soundings, are being reanalysed, using the T106 version of the ECMWF model, as a contribution to the World Climate Research Programme (WCRP) TOGA Level IIIA Atmospheric Archive. Selected periods are to be analysed at higher resolution and have much potential for extending the scope of our type of study.

Figure 4(a) shows a marked westerly wind burst that is distinct from the light surface winds otherwise typical over the western-Pacific warm-pool. The diverging wind-vectors in the neighbourhood of (1°N, 163°E) is due to a resolved mesoscale down-draught. The wind speed maximum is located a few degrees south of the equator and east of the ISS site on the island of Nauru (0.3°S, 166.6°E), whose location is shown by the circle on Fig. 4(a). We show that this wind burst is maintained partly by a $e_3$-like 'surrogate' supercluster, which is spanned by more than 100 grid points. Essentially, a GCM cannot resolve the multi-scale structure that is intrinsic to a real supercluster. (For convenience, but without implying a true physical similarity, we shall sometimes refer to the predicted system as a supercluster).

The low-tropospheric north-westerly wind is strongly accelerated behind the supercluster and the resolved-scale mesoscale ascent/descent is prominent. The arrows in Fig. 4(b) show distinct mesoscale downdraughts behind the large arc-like mesoscale updraught. The predicted supercluster travels eastwards at a few metres per second. It slowly evolves over a period of a day or two, but maintains an overall integrity. The relative inflow is from the north-east, showing that the supercluster propagates relative to the tropospheric winds (i.e. the synoptic flow in the 1000–200 hPa layer has an easterly component). Mass in the
anvil, which probably originates from the lower troposphere, is detrained westwards. This process is similar to that occurring in a propagating tropical squall-line except it has a much larger scale. The south-westerly flow from the rear in the 700–800 hPa layer is dry, which helps maintain an evaporatively driven mesoscale resolved downdraught.

When included in the assimilation procedure, the few special observations from the TOGA COARE soundings are unlikely to affect the predictability of mesoscale convection at a $\mathcal{C}_2$ scale significantly and certainly not the predictability of the $\mathcal{C}_1$ scale. In this respect, the supercluster, or rather the $\mathcal{C}_3$ surrogate, is spontaneously generated in the GCM.

A conceptual model of the system-relative flow organization in the surrogate supercluster, consisting of two tilted branches, is shown in Fig. 5. The mesoscale downdraught is maintained by the evaporation of water and melting ice falling from the ascending branch. This process is analogous to mesoscale downdraughts in CRMs, albeit with an important distinction. In CRMs, the cloud and mesoscale circulations are well resolved and prognostically coupled to the parametrized microphysics in the thermodynamic equations, whereas, in GCMs, precipitation and cloud dynamics (e.g. mass fluxes) are parametrized.
In summary, although the ECMWF model predicts a surrogate supercluster, it obviously cannot resolve the triple-scale organization identified in Fig. 2. The key point is whether the fluxes, sources and sinks are flawed and if so, what is the physical explanation. The remainder of the paper is devoted to these issues.

4. THERMODYNAMIC AND MOMENTUM TENDENCIES

Referring to Fig. 2, the $C_3$ scale will obviously be resolved in preference to $C_2$ in a global model. We shall show that, although the vertical profile of the diabatic tendencies is consistent with that expected of an MCC/MCS, the amplitudes are exaggerated (i.e. the supercluster is over-predicted), especially the momentum tendency. We then show that the momentum error is consistent with a dynamical model of organized convection albeit on an exaggerated scale. In assessing the model error, we normally use 12-hour forecasts from 0000 GMT and 1200 GMT analyses because, at these times, about 90% of the TOGA COARE soundings were accepted by the ECMWF data-assimilation procedure.

(a) Thermodynamic tendency

Figure 6 is a profile through the supercluster in a T106 forecast experiment at the point shown on Fig. 4(a), as well as the profiles of the individual temperature-tendency
terms. (A T106 forecast was used because the physical tendencies from the operational T213 model are not archived.)

A series of experiments showed good agreement between the T213 and T106 forecasts, so the results in Fig. 6 can be considered as reasonably accurate measures of the T213 tendencies. Indeed, we found a remarkably close agreement between the supercluster structure, diabatic effects and transports at these two resolutions. The treatment of large, organized convective systems is therefore an issue at T106 resolution but (to our knowledge) not so in lower-resolution models. This implies that the explicit treatment of superclusters in global models, and the new issues this raises, occurs at about T106 resolution.

The environmental effects of the surrogate supercluster are evident in Fig. 6. The upper part of the green curve shows latent heating by condensation in the resolved-scale updraught, and the lower part, cooling due to evaporating precipitation in the mesoscale downdraught. The blue curve shows the corresponding adiabatic response—cooling (warming) as the result of ascent (descent). The mesoscale downdraught corresponds to westerly inflow from behind the supercluster, as shown in the inset at the right-hand side of Fig. 6. For the most part, this thermodynamic signature is typical of tropical squall-lines (e.g., Zipser 1977). It follows that the supercluster not only resembles a squall line structurally but also has a similar environmental impact.

The temperature tendency resulting from the convective parametrization scheme is shown by the thick yellow curve but, at this time, the downdraught was not activated in the scheme. Figure 6 shows that the total thermodynamic effect (i.e., including large-scale forcing and convective response) involved the difference between large compensatory terms. This is the classic impediment to attaining an accurate parametrization of precipitating convection. The yellow curve in the right-hand inset is the $\omega$ profile. As expected, this is similar to that of the adiabatic tendency. The model sounding is saturated, apart from the low troposphere where the mesoscale downdraught is active.

Figure 7 shows the thermodynamic tendencies averaged over a meridional section (0.5°N–1°N) in the 12-hour forecast from 0000 GMT on 21 December. This vertical cross-section was chosen because it transects the region of strong mesoscale descent. Averages taken over a wider latitudinal band (e.g., 0–2°N) differ in detail but not in kind. Figure 7(a,b) shows that the parametrized convective heating is much smaller than resolved-scale heating caused by the surrogate supercluster. Figure 7(c) shows the total (resolved + parametrized) heating. The prominent tilt of the heating is indicative of a robust organized circulation. This type of dynamical structure is unusual in a GCM, and on a much larger scale than that occurring in cloud-resolving simulations of squall lines (e.g., Redelsperger and Laffont 1988; Tao et al. 1993), which it otherwise resembles.

We suggest two explanations for the organized heating, both of which derive from the way the GCM treats the water cycle. Firstly, it treats the water cycle as an indirect mechanism involving the detrainment of water substance in the convective-parametrization scheme. Since the convective-parametrization scheme detains cloud water and cloud ice, it will moisten the upper troposphere (i.e., it crudely represents a stratiform region). Environmental ascent will subsequently cause the resolved-scale (stratiform) precipitation to be activated when the relative humidity reaches the threshold value. As we have shown, the parametrized heating is dominated by the resolved-scale heating, so subgrid-scale detrainment of water is unlikely to be the primary mechanism. Secondly, there is the direct mechanism by which resolved-scale ascent transports water vapour, saturates the middle and upper troposphere and activates the large-scale precipitation scheme, again when the relative humidity reaches the threshold value. The direct mechanism is mainly responsible for maintaining the surrogate supercluster, although the indirect mechanism also contributes (see Fig. 6).
In summary, the supercluster circulation is resolved, but only in the sense that a "ɛ₃-like surrogate is predicted in place of the hierarchy in Fig. 2. It is tempting to refer to this behaviour as numerical aliasing, but this is not the case for momentum: the aliasing of subgrid-scale processes in physical space (which can occur) does not feed back to the dynamics because it is truncated in the spectral transform. Hence, 'surrogate' is an apt term for this resolved, albeit unphysical, behaviour of a supercluster in a GCM.

(b) Momentum tendency

In the ECMWF model, cumulus momentum exchange is parametrized using a mixing concept. The magnitude of the momentum tendency is proportional to the vertical gradient of $M(u_c - U)$ where $M(z)$ is the convective mass-flux, and $u_c - U$ the difference between
the 'in-cloud momentum' \( u_c \), and the zonal wind component \( U(z) \). Cumulus momentum exchange is operative only in a sheared flow and where subgrid-scale cumulus mass-flux exists (i.e. where criteria for activating the thermodynamic subgrid-scale parametrization are satisfied).

The parametrized tendency is shown in Fig. 8(a). The total dynamical tendencies in Fig. 8(b) are dominated by the resolved-scale momentum contribution which is highly structured. Structure is most evident in the positive region in the lower troposphere and the negative region in mid- to upper-troposphere. Turbulent diffusion is negligible, except near the surface and the tropopause. Cumulus momentum exchange is, for the most part, of opposite sign from the resolved-scale tendency (cf. Fig. 8). This demonstrates the fundamental distinction between cumulus momentum exchange and the transport of momentum by organized convection. The (surrogate) momentum flux shown in Fig. 9 has a profile consistent with theoretical expectation, but it is over-predicted. These results are for an
Figure 8. Zonal-momentum tendency in m s\(^{-1}\) d\(^{-1}\) calculated from the 12-hour forecast from 0000 GMT 12 December 1992 averaged over 0.5°N–1°N: (a) cumulus momentum exchange; (b) dynamical tendencies, for the most part arising from the transport of resolved-scale momentum.

E–W section, but, considering the south-westerly tilt of the system with height, the effect will be even more prominent in a NE–SW section. Figure 10 further quantifies this aspect in terms of a horizontal average over (0.5°N–1°N; 160°E–170°E).

Zonal-wind errors in Fig. 11(a) show that the easterlies are too strong in the 800–300 hPa layer, while the westerlies are accelerated in the low troposphere. The positive error centred on 150 hPa is partly the result of model diffusion—probably caused by resolved-scale momentum-fluxes changing the vertical shear locally. As we will show later, throughout most of the troposphere the momentum error has the characteristic signature of resolved-scale momentum-flux.

An attempt was made to measure the error statistically, that is as a bias estimate using the 0000 GMT and 1200 GMT analyses in the small region that we examined in detail. An easterly bias was found in the 450 hPa–150 hPa layer, as measured by the difference
Figure 9. Longitudinal structure of the vertical flux of zonal momentum (Pa m s$^{-2}$) averaged over 0.5°N–1°N. Derivations are from the 12-hour forecast starting 0000 GMT 21 December 1992, averaged between 0600 GMT and 1200 GMT.

Figure 10. Average of $-u\omega \approx \beta spw$ in the domain (160°E, 170°E) and (0.5°N, 1.0°N), for the same periods as in Fig. 9 (Pa m s$^{-2}$).

between the analysis and forecast data. Although supportive of the case-study results, these data are not sufficiently plentiful to be statistically meaningful. A re-analysis of the TOGA COARE data, to include all the special soundings obtained during the field experiment, should provide a better estimate of the momentum bias.

5. PHYSICAL INTERPRETATION

Errors attributable to the treatment of convective processes in GCMs are manifested in several ways. For instance, most climate models have difficulty in predicting and maintaining entire cloud-systems (e.g. marine stratocumulus to the west of continents, or regions
of enhanced deep convection in the tropics) for reasons that are not always quantifiable and usually of non-local origin. In contrast, the errors we have identified have a precise dynamical explanation springing from the flawed treatment of organized convection and, in particular, the convective transport of momentum. The case-study approach facilitates a mechanistic interpretation.

We begin by examining the momentum-flux problem in an Eulerian setting. Figure 12(a) shows the relationship between eddies and momentum transport: an eddy tilted westward with height causes a negative momentum-flux because negative values of $u$ are correlated with positive values of $w$ and vice versa. However, a more concise dynamical interpretation is in terms of the total momentum-flux derived from Lagrangian principles. The relationship between these approaches is depicted in Fig. 12(b), where sloping trajectories evince the eddy tilt and Eulerian momentum-flux.

The supercluster lies nearly on the equator, so planetary rotation can be ignored to a first approximation; formally, $f v$ is neglected in the momentum equation, following a large-Rossby-number approximation. Together with the relatively small value of the vertical diffusion (e.g. Fig. 6), the horizontal gradient of pressure is dominant, so the Lagrangian form of the momentum equation is, approximately,

$$\frac{Du}{Dt} + \frac{\partial}{\partial x} \left( \frac{p_m}{\rho} \right) = 0,$$

where $p_m$ is the (mesoscale) pressure-perturbation within the supercluster. Referring to a coordinate system moving with the translation speed of the system, and on integrating along an arbitrary relative trajectory ($\psi$), it is easily shown that

$$u_{\text{outflow}} = u_{\text{inflow}} - \int_{\psi} \left( \frac{\partial}{\partial x} \right) \frac{p_m}{\rho} \, dt,$$

where $dt$ is a time increment along this trajectory.

While Eq. (2) succinctly demonstrates that the Lagrangian integral of the horizontal pressure gradient is the sole contributor to the total momentum-flux, a disadvantage is that the internal pressure field is required. This can neither be measured accurately from observations nor expressed in mathematical terms. For this reason, Moncrieff (1992) formulated
the total-momentum-flux divergence based on the Eulerian $x$-momentum equation. Making a steady-state assumption, but without further approximation, this gives

$$\frac{\partial (\rho \Delta_m u_m w_m)}{\partial z} = -\Delta \left[ \rho u_m^2 + p_m \right]_{L_m}^{L_m},$$

(3)

where the averaging operator $\langle \cdot \rangle = \frac{1}{L_m} \int_0^{L_m} (\cdot) \, dx$. The difference operator $\Delta \left[ \cdot \right]_{0}^{L_m}$ represents an asymptotic change across the domain $x \in [0, L_m], z \in [0, H]$ spanned by the system. The total momentum-tendency by organized convection is approximated by the negative of the momentum-flux divergence: this is a standard simplification in convective parametrization.

The following integral constraint on the redistribution of horizontal momentum by organized convection is obtained by integrating Eq. (3) over the domain, assuming that $w = 0$ at $z = 0$ and $z = H$, (essentially the tropospheric depth), and by employing Gauss's theorem

$$\int_0^H \Delta \left[ \rho u_m^2 + p_m \right]_{0}^{L_m} \, dz = 0.$$

(4)

In other words, the change of $\int_0^H (\rho u_m^2 + p_m) \, dz$ across the system must be zero, which means that any positive contribution to the momentum-flux divergence is exactly balanced (in an integral sense) by a negative contribution. Such compensation is evident in Fig. 8(b).
Once the divergence is obtained from Eq. (3), the momentum flux is obtained by vertical integration, again assuming that \( w = 0 \) at \( z = 0 \). Equation (4) ensures that \( \langle \rho u_m w_m \rangle = 0 \) at \( z = H \). The utility of this approach is that only remote or asymptotic quantities appear on the right-hand side of Eqs. (3) and (4). Therefore, having defined the integral constraint based on an Eulerian principle, the quantities within the square brackets are obtained using Lagrangian-based models—for example, the Moncrieff (1992) archetypal model—to provide the asymptotic quantities. In particular, the horizontal pressure gradient, which is the key quantity, is automatically built into this formulation. An important point is that the momentum-flux formula satisfies the conservation properties of the nonlinear equations of motion and is exactly consistent with the mass flux (see section 6(b)).

Latent heating and evaporative cooling will modify the horizontal gradient of pressure and impart a momentum tendency directed rear-to-front across the organized propagating system (Lafore and Moncrieff 1989—Fig. 9). However, Eq. (4) is such a powerful integral constraint that diabatic heat sources and sinks cannot substantially affect the momentum-flux profile (although they do alter the detailed structure). However, these details are unimportant compared to the large difference (even in sign) between the organized transport of momentum and diffusive-like mixing in cumulus momentum exchange. This point is substantiated by verification against observations (LeMone and Moncrieff 1994) and cloud-resolving model data-sets (Wu and Moncrieff 1996) even though the archetypal model does not contain heat sources and sinks. This simplicity facilitates the application of dynamical models in convective parametrization.

Figure 13 illustrates the organized flows represented by the archetypal model. The general relationship between the regimes and the tropospheric shear is also indicated. Regime A is distinguished by the deep downdraught and inflow originating ahead of the...
Figure 14. (a) Total momentum-flux \( \langle \rho u w_m \rangle \) due to the idealized regimes A (full), B (broken) and C (dotted) normalized by \( \rho U_0^2 \), the inflow momentum-flux per unit volume \( \Lambda \). (b) Momentum tendency, \(-\frac{\partial}{\partial z} \langle \rho u w_m \rangle\), normalized by \( \rho U_0^2 / H \), where \( H \) is the depth of the convection \( T \). The vertical coordinate \( \mu(p) = (p_s - p)/(p_s - p_i) \), where \( p_s = 1000 \) hPa and \( p_i = 100 \) hPa, allows for the variation of density with height.

This is essentially a two-dimensional realization of the surrogate supercluster (cf. Fig. 5), which has a westward-directed anvil and a deep mesoscale downdraught. The other limit case travels at the speed of the ambient flow at a mid-tropospheric (steering) level. It has no downdraught but does have a prominent eastward-directed anvil (C). Regime \( B \) has symmetric airflow organization intermediate between these two limits.

Figure 14(a) shows the momentum flux corresponding to each regime. A common factor is that the momentum flux is opposite to the direction of propagation of the cloud system, a feature observed in tropical squall-lines (LeMone 1983). In other words, an eastward-moving cloud-system will produce a westward-directed (negative) momentum-
flux. The archetypal momentum-transport is consistent with the resolved-scale momentum-flux deduced for the supercluster (Fig. 10).

A simple explanation follows from consideration of the Lagrangian representation in Eq. (2); too large a pressure perturbation, arising from diabatic heating on too large a scale, will exaggerate the vertical transport of horizontal momentum. This type of over-prediction may be a general feature of the momentum transport by highly organized, but interrelated, convective systems. This aspect needs to be examined in detail, for example, by using cloud-resolving modelling outlined in section 8.

6. Formal parametrization of momentum flux

(a) Physical nature of the problem

The inability of the GCM to resolve the hierarchy in Fig. 2 causes three sources of uncertainty. Firstly, the organized cumulonimbus-convection (\( \mathcal{C}_1 \)) is not correctly represented by parametrized momentum exchange, a point that springs indirectly from not considering the role of vertical shear in convective parametrization. Secondly, the mesoscale convective system (\( \mathcal{C}_2 \)) is neither adequately resolved nor parametrized. Lastly, the GCM represents the entire hierarchy as a surrogate \( \mathcal{C}_3 \)-like system that leads to over-prediction.

As for the representation of organized cumulonimbus (\( \mathcal{C}_1 \)), we can be definitive—parametrized cumulus momentum exchange does not properly represent the coherent nature of the momentum fluxes. Figure 8 shows that cumulus momentum exchange and surrogate momentum-flux divergence are of opposite sign. The latter occurs in this type of organized convection. This statement was substantiated further by Wu and Moncrieff (1996—Fig. 16), who showed in a numerical simulation of a squall line developing in idealized westerly wind burst conditions, that the archetypal momentum-flux is similar to that shown in Fig. 14(a). The vertical profiles of the surrogate fluxes, albeit of a form consistent with the above dynamical principles, are over-predicted.

Having identified deficiencies in the parametrization of momentum flux resulting from organized convection, we now outline a strategy for addressing them.

(b) \( \mathcal{C}_1 \) component

Considering a physical situation in which the scale-separability condition is satisfied (e.g. in a climate model), we formally show how the \( \mathcal{C}_1 \) component could be represented within the framework of existing parametrization methods. Specifically, the new approach uses the archetypal model of organized convection in place of the entraining plume widely used in mass-flux-based convective-parametrization schemes.

(i) Plume model: traditional approach

Tiedtke (1989) presented a formulation for the mass-flux approach which can be expressed in a general way as

\[
\frac{\partial (\mathcal{M} \phi)}{\partial z} = \mathcal{C}_1 \phi - \mathcal{D} \phi + \mathcal{S}_\phi.
\]  

(5)

Here \( \phi = u \), the convectively-generated \( x \)-momentum, but the expression also represents other quantities (e.g. static energy and specific humidity). The overbar denotes the grid-point value and \( \mathcal{M} = \rho \sigma \mathcal{U} \) is the convective mass-flux, \( \sigma \) the cloud fraction, and \( \mathcal{S}_\phi \) represents the source of \( \phi \), which for momentum is the horizontal pressure gradient. This formulation was used by Kershaw and Gregory (1997) to represent momentum transport in a GCM.
The equation for the mass flux is derived from averaging the mass-continuity equation
\[ \frac{\partial M}{\partial z} = \mathcal{E} - \mathcal{D}, \] (6)
where \( \mathcal{E} \) and \( \mathcal{D} \) are the mass entrainment and detrainment per unit length respectively. In existing methods, \( \mathcal{E}, \mathcal{D} \) and \( M \) are determined from an entraining-plume model, assuming a cloud-base value of \( M \).

(ii) Organized convection model: new approach

A representation of momentum flux using a dynamically based method is the Moncrieff (1992) dynamical theory for the total momentum-flux by organized convection,
\[ \frac{\partial \langle \rho \mathcal{L}_m u_m w_m \rangle}{\partial z} = -\Delta \left[ \rho u_m^2 + p_m \right]_0 \mathcal{L}_m, \] (7)
where \( \mathcal{L}_m \) is the fraction of the grid occupied by organized convection. In this situation,
\[ \frac{\partial M_m}{\partial z} = -\Delta \left[ \rho u_m \right]_0 \mathcal{L}_m \] (8)
where \( M_m = \langle \rho \mathcal{L}_m w_m \rangle \) is now the total mass-flux. Equation (8) can obviously be integrated to give \( M_m(z) \), assuming \( w_m = 0 \) at \( z = 0 \). The right-hand sides of these two equations are obtained from the archetypal-model solutions.

Although there is an important physical difference between the dynamics of the cloud systems represented by these respective formulae, inspection of Eqs. (5), (6), (7) and (8) shows a formal resemblance between the traditional momentum-parametrization (Eqs. (5) and (6)), and the new method based on the archetypal model (Eqs. (7) and (8)). Equations (7) and (8) would be used in certain tropospheric-shear conditions, for example, when the shear reverses with height as in jet-like flow or when the low-level shear is significantly larger than the upper-level value. Equations (5) and (6) would be used for quasi-random cumulus momentum exchange typical of weakly-sheared environments.

The momentum flux by organized convection is usually anisotropic. For line convection, the flux of \( y \)-momentum is easily obtained if it is assumed that \( \partial p/\partial y = 0 \), where the \( y \)-axis is directed parallel to the line. It follows that \( v \) is conserved along trajectories (Moncrieff 1992—section 10(a)). Both components of the momentum flux can be determined if the orientation of the line is specified. This specification could be based on statistical principles, noting that a deterministic theory for line orientation is not at our disposal. It follows that, because the \( \mathcal{C}_1 \) component normally satisfies the scale-separation criterion in a GCM, existing methods could be modified to examine the large-scale impact of organized momentum-flux. Existing closure methods could be adapted to incorporate the total momentum-fluxes into a GCM; in other words, the dynamical model would replace the plume model.

(c) \( \mathcal{C}_2 \) component

The representation of momentum flux by the \( \mathcal{C}_2 \) mesoscale component is more problematic. Although the transport could also be represented by the archetypal model in low-resolution GCMs (e.g. climate models), unlike the \( \mathcal{C}_1 \) cumulonimbus component, \( \mathcal{C}_2 \) does not always satisfy the scale-separation criterion. For instance, it is obvious that \( \mathcal{L}_m \sim 1 \) in regional mesoscale models and, as we have shown, in global NWP models. It follows that the existing parametrization framework is not strictly appropriate, so new closures may need to be devised. In view of the scales of motion involved, the parametrization of \( \mathcal{C}_2 \)
should arguably be in concert with the prognostic treatment of cirrus-producing convection. Note that since the archetypal model explicitly represents lateral mass-detrainment, it could be used in prognostic methods for representing convectively generated cirrostratus in GCMs. This has been discussed further by Moncrieff et al. (1995).

7. Discussion

The regime of organization in the archetypal model is expressed in terms of either the depth of the mesoscale downdraught or the scaled pressure-change across the cloud system (Fig. 13). In all three regimes, negative momentum-flux is caused by eastward-moving cloud systems as shown in Fig. 14(a), an aspect also seen in observations (LeMone 1983). It should be borne in mind, however, that other regimes of organization have different momentum-transport (Moncrieff 1981), a property which depends on the tropospheric shear.

While the momentum flux has a universal form, the effect on the surface wind is dependent on the momentum tendency which is proportional to the negative of the vertical gradient of the momentum flux. Also, the westerlies/easterlies will be enhanced in the low-to-middle/upper troposphere. We illustrate the surface effect by considering an eastward-moving cloud system. (Momentum tendencies resulting from westward-moving organized systems are identical apart from a change of sign.) In Fig. 13, the propagating system (A) has a deep downdraught and a westward-extending upper-tropospheric outflow (i.e. cirrostratus anvils). Since the zonal-momentum tendency is negatively proportional to the momentum-flux divergence, it is clear that the surface westerlies and the upper-tropospheric easterlies will be enhanced. Consequently, the surface-momentum tendencies oppose the westerly-wind burst, causing a negative dynamical feedback. In contrast, the idealized systems having shallow downdraughts (C) accelerate the surface westerlies and the upper-tropospheric easterlies—a positive dynamical feedback. In particular, the impact of organized convection on wind-generated ocean-currents will depend on the convective regime and, in turn, on the vertical wind-shear. This dependence of near-surface momentum-flux upon convective regime is consistent with the surface westerlies being strong to the south of the equator where mesoscale downdraught is indiscernible, and weakest to the north where it is prominent (Fig. 4).

Problems relating to an under-resolution of organized convection are seen on other scales of motion. For example, over-prediction occurred in a hydrostatic prediction of an MCC by Zhang et al. (1988), who used a regional mesoscale model. The explicit (grid-scale) representation of convection caused excessive precipitation and a mesoscale depression which was too intense. A similar result was noted by Tripoli et al. (1986) in a non-hydrostatic mesoscale model with a 14-km resolution, so the issue is not intrinsically of hydrostatic origin. (This is hardly surprising because resolution needs to be finer than 10 km for the hydrostatic approximation to be seriously violated). Weisman (personal communication) has examined the effect of resolution on convective systems in a certain shear-profile and showed that retarded evolution because of under-resolution of a cold pool affected the momentum transports. While mid-latitude MCCs were the focus of these studies, in view of the previous remarks regarding similarity between MCCs and tropical superclusters, the issues quantified herein may have broader implications. This point is given added relevance by the ubiquity of these organized convective systems (Miller and Fritsch 1991).

We believe that the results we have demonstrated will eventually occur in climate models, once a resolution of about T106 and sufficiently advanced parametrizations of physical processes are used.
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8. CONCLUSIONS

The T213 data identified specific issues relating to the treatment of the triple-scale hierarchy of organized convection, mesoscale systems and the supercluster component. Although intrinsic to western-Pacific meteorology, the precise role of this hierarchy is poorly understood, especially as regards its environmental effects. We took a step toward quantifying this problem by showing how the ECMWF operational model treats this hierarchy as a surrogate. We explained errors attributable to the surrogate treatment of a supercluster in elementary dynamical terms using the Moncrieff (1992) dynamical theory.

It was shown how the archetypal model can be used in a mass-flux-based parametrization of the $\zeta_1$ component. At present this is neither adequately resolved nor parametrized in GCMs, because the effects of organized convection are omitted. More fundamental issues arise, however, in regard to the treatment of the $\zeta_2$ component.

The T213 data sets contained data assimilated in real time from the TOGA COARE field-experiment. Since a significant fraction of these special soundings (e.g. those for 0600 GMT and 1800 GMT) was not assimilated in real time, the estimates of systematic error, as well as the predictability of the supercluster, will be adversely affected. A more complete evaluation of the statistical significance of the impact of organized convection awaits the re-analysis of the TOGA COARE data sets at T213 or, preferably, at higher resolution.

A mechanistic evaluation of the momentum fluxes in a case-study approach led to a plausible physical explanation of the model errors. (A preliminary examination of T213 realizations of other TOGA COARE cases showed similar behaviour.) It was found that the resolved-scale precipitation and diabatic heating interacts with the wind shear and over-predicts the vertical transport of horizontal momentum. This stems from inadequate resolution of the $\zeta_2$ component, as well as the absence of organized transport in the cumulus momentum exchange parametrization on the $\zeta_1$ scale. In summary, the surrogate momentum-flux is largely of the correct form, because it is the response of a shear flow to diabatic heating. However, it is over-predicted because at T213 resolution, the key $\zeta_1$ and $\zeta_2$ components cannot be properly treated. We note that this type of problem has also been identified in regional models. The most noticeable large-scale effect of the surrogate momentum flux is an easterly wind error. This will exacerbate easterly bias in GCMs prone to this error, but will otherwise (albeit serendipitously) alleviate low-tropospheric easterly and middle- and upper-tropospheric westerly bias.

In addition to the GCM impact study using the new idea suggested in subsection 6(b), the relationship between mesoscale and large-scale processes, implicit in the hierarchy shown in Fig. 2, needs to be quantified by explicitly resolving the hierarchy using CRM. The following studies, ranging from idealized models to ones including full data-assimilation capability, would be insightful.

(i) The Wu and Moncrieff (1996) two-dimensional, two-way nested simulation had a 4500 km outer domain and a 1500 km inner domain, and idealized wind- and thermodynamic-profiles typical of a westerly-burst environment. A squall line was successfully simulated and caused a strong $\zeta_1$-scale momentum-transport and a weaker $\zeta_2$-scale transport. However, the $\zeta_3$ component was absent, perhaps because of the lack of time-dependent large-scale forcing that is characteristic of a westerly-wind-burst environment. This type of study therefore needs to be extended.

(ii) A more complete approach is to include all the physical processes, which are explicitly coupled by the cloud-scale dynamics, in the supercluster hierarchy. Although this approach is computationally formidable, its feasibility has been demonstrated by Grabowski et al. (1996) in a study of convection in GATE. This week-long two-dimensional
simulation had comprehensive, but not particularly sophisticated, parametrizations of microphysics, radiation, surface-fluxes and boundary-layer turbulence. The bulk effects of organized convection were well represented even with a 2 km resolution, a 900 km model domain, and even with periodic lateral boundary conditions. Similarly encouraging conclusions are also seen in a recently completed three-dimensional GATE simulation as well as a 39-day, two-dimensional simulation of convection during the TOGA COARE December 1992/January 1993 westerly-wind-burst episode.

(iii) An investigation that would build on the work herein would be to use a three-dimensional CRM in which re-analysed TOGA COARE data were assimilated. In order to have realistic large-scale ascent, it would be preferable to assimilate 3-hour or 6-hour forecast fields from the T213 (or higher resolution) global model into the CRM. This would enable a more precise evaluation of the fluxes and diabatic tendencies than would be possible with the T213/T106 data-sets alone.

Generalizations are premature since we studied only one case. Nevertheless, we believe that large-scale effects of organized convection should no longer be ignored in state-of-the-art GCMs, even at T106 resolution, because, by attempting to resolve superclusters, specific problems relating to organized convection are manifested.

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