Numerical Archetypal Parameterization for Mesoscale Convective Systems

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ABSTRACT

Vertical shear commonly organizes atmospheric convection into coherent multiscale structures. The associated countergradient vertical transport of horizontal momentum by organized convection can enhance the wind shear and transport kinetic energy upscale. However, organized convection and its upscale effects are not represented by traditional mass-flux-based parameterizations. The present paper sets the archetypal dynamical models, originally formulated by the second author, into a parameterization context by utilizing a nonhydrostatic anelastic model with segmentally constant approximation (NAM–SCA). Using a two-dimensional framework as a starting point, NAM–SCA spontaneously generates propagating tropical squall lines in a sheared environment. High numerical efficiency is achieved through a novel compression methodology. The numerically generated archetypes produce vertical profiles of convective momentum transport that are consistent with the analytic archetype.

1. Introduction

The mesoscale convective system (MCS; Fig. 1a) is a widely recognized and extensively studied category of organized moist convection associated with vertically sheared environments, but its parameterization in global models is a long-standing unsolved problem (cf. Moncrieff et al. 2012; Yano et al. 2012b). Traditional mass-flux convection parameterizations originally proposed by Ooyama (1971) and Arakawa and Schubert (1974) based on a spectrum of entraining plumes (cf. Yano 2014a) do not consider organized convection and unrealistically assume a scale separation between cumulus and the environment (cf. Yano 2015a).

The Year of Tropical Convection (YOTC)1 (Moncrieff et al. 2012; Waliser et al. 2012) drew attention to, and moved forward with, the parameterization of organized convection in the nascent era of convection-permitting weather prediction models (Yano et al. 2010b) and mesoscale-permitting global climate models (Moncrieff et al. 2007). The concept of a multiscale coherent structure embedded in a field of cumulus is a suitable paradigm for organized convection parameterization (Moncrieff and Waliser 2015) that is consistent with the presence of coherent structures in turbulent flows in general (cf. McWilliams 1984; Zilitinkevich et al. 2006) and atmospheric motion in particular (cf. Yano 1998; Moncrieff 2010).

The parameterization of organized convection seeks to approximate transport properties that are fundamentally distinct from the classical entraining plumes (cf. Yano 2014a). Khouider and Moncrieff (2015) used a multicloud model (Khouider and Majda 2006) to parameterize organized convection in the intertropical convergence zone (ITCZ). They discovered

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selection principles on meso- and synoptic scales that provide a firm basis for the multiscale coherent structure concept.

The objective of our paper is to numerically simulate archetypal models of mesoscale convective systems reported by Moncrieff (1992; cf. Fig. 1b). Particular attention will be given to momentum transport that is known to affect tropical mean wind climatology (P. Bechtold, ECMWF, 2012, personal communication).

**FIG. 1.** (a) Schematic of the observed standard MCS. (b) Schematic of the Moncrieff (1992) analytic archetypal model. Both reproduced from Fig. 1 of Moncrieff (1992).

**FIG. 2.** Phase diagram for the analytic archetypes. The horizontal and vertical axis are the depths of the jump inflow height and the mesoscale downdraft, respectively, both scaled by the depth of the convective system (cf. Fig. 1b). Modified from Fig. 2 of Moncrieff (1992).

**FIG. 3.** The assumed idealized zonal wind profile in the present study (solid) along with the zonal wind profile assumed under the setup by Jung and Arakawa (2005) and Yano and Bouniol (2010), but with the sign flipped for an easier comparison (long dash).
communication) as well as the Hadley circulation and the ITCZ (Wu et al. 2007). Momentum transport has received scant attention in parameterization (cf. Yano 2015b) apart from a few notable exceptions (e.g., Cho 1985; Zhang and Cho 1991; Wu and Yanai 1994; Kershaw and Gregory 1997), but none represent the upgradient transport of momentum, which is a novel property of mesoscale systems and the synoptic-scale tropical superclusters (cf. Moncrieff and Klinker 1997).

The Moncrieff (1992) analytic archetypal models and their more complete predecessors, referred to as “slantwise layer overturning” by Moncrieff (2010), represent quasi-laminar MCS circulations that differ fundamentally from entraining–detraining plumes (Yano 2014a). For example, the entire system-scale circulation is approximated instead of perturbations from the mean state, scale separation is not assumed, the grid-scale averages are not necessarily zero, and the momentum transport is distinct from turbulent mixing. These aspects make the archetypal models more amenable to parameterization than the other early theories of organized convection (e.g., Davies-Jones 1984; Rotunno et al. 1988).

The Moncrieff (1992) models are based on the non-dimensional Bernoulli number

$$E = \frac{\Delta p}{\rho U_0^2 c^2},$$

where $\Delta p$ is the pressure change across the system domain from the inflow side to the outflow side, $\rho$ is the air density, $U_0$ is the lower-level inflow wind speed (cf. Moncrieff 1992; Yano 2015b), and $c$ is the system propagation speed. The

![Fig. 4. The four snapshots of the distribution of total water condensate (g kg$^{-1}$) from $t = 5$ days every 8 h showing an eastward propagation of a well-organized squall line. The vertical lines indicate the positions of the finite-volume segment interfaces (boundaries) whose distribution is adapted with time by following the propagation of the squall line.](image-url)
Bernoulli number characterizes the hydraulic properties of slantwise layer overturning and formally identifies a similarity among squall lines, mesoscale convective systems, and density currents (Moncrieff and So 1989). The analytic archetypal models exist for the Bernoulli number in the range $2 < E < 8/9$. Figure 2 shows three distinct regimes of relative flow in the phase space of $(h_0, h)$ defined by the depths of the jump inflow height $h_0$ and the mesoscale downdraft as shown in Fig. 1b: (i) for $(h_0, h) = (1, 2/3)$ the inflow is entirely one-sided, indicating a purely propagating system; (ii) for $(h_0, h) = (1/2, 1/2)$ there is a three-branch structure (jump updraft, overturning updraft, and overturning downdraft); and (iii) for $(h_0, h) = (1/3, 0)$ the downdraft is replaced by a jump updraft.

The above regime dependence raises some technical difficulties for implementation of the analytic archetype as a parameterization. Those difficulties are greatly alleviated by utilizing numerically generated archetypes. The starting point for this numerical archetype is the application of the segmentally constant approximation (SCA) to a full cloud-resolving model (CRM; Yano 2014b). The resulting numerical formulation, called NAM–SCA, is a standard CRM with a nonhydrostatic anelastic model (NAM) dynamical core (Yano et al. 2010a). When a single convective updraft segment is embedded in a homogeneous environment, NAM–SCA reduces to a fully prognostic prototype bulk mass-flux parameterization (Yano and Baizig 2012). This approach is “prototype” in the sense that a standard mass-flux formulation can be derived by introducing further approximations and hypotheses (cf. Yano 2014b). Thus, NAM–SCA, proposed here as a numerical archetype, is also considered a generalization of mass-flux formulation.
The SCA model is the adopted framework for the numerical archetype. As a geometrical constraint, SCA generalizes the mass-flux formulation for the numerical archetype in terms of the subgrid mean of an ensemble of plumes (Yano et al. 2005). The mesoscale circulation of a squall line is partly driven by the horizontal pressure gradient generated by an ensemble of cumulonimbus (Lafore and Moncrieff 1989). Unlike the traditional parameterizations, SCA is consistent with the analytic archetype where the circulation is governed by the Bernoulli number and the pressure gradient is the key quantity. In numerical respects, the SCA is equivalent to the lowest-order finite-volume algorithm (cf. Godunov 1959; LeVeque 2002). Furthermore, its drastic reduction to the two finite-volume elements from a full CRM corresponds to the bulk mass-flux parameterization (Yano and Baizig 2012). Such a drastic reduction of a model is analogous to wavelet-based image compression (cf. Yano et al. 2004).

Compression of the finite-volume formulation is further facilitated by adopting time-dependent adaptive mesh refinement (Yano et al. 2010a). Yano and Bouniol (2010) show that NAM–SCA simulates a tropical squall-line system using a mere 10% of the total number of meshes in a full-resolution CRM. Here, NAM–SCA runs with an initial inhomogeneous distribution of meshes, with higher resolution in the convective regions and lower resolution elsewhere, and with time-dependent mesh adaptation. The total mesh number can be further reduced if the objective is
simply to generate an archetypal circulation, as is the case herein.

Consistent with the theoretical framework that accompanied a series of two-dimensional numerical simulations (e.g., Moncrieff and Green 1972; Moncrieff 1978, 1981, 1992; Thorpe et al. 1982), we use the two-dimensional configuration as a test bed. This is consistent with our chief intent to reduce the mesoscale organization to the simplest possible (archetypal) form and is consistent with the configuration of the current NAM–SCA (Yano et al. 2010a). This does not exclude a future approximation of three-dimensional organization to quasi-two-dimensional forms (e.g., Moncrieff and Miller 1976; Lane and Moncrieff 2015; Moncrieff and Lane 2015). The following NAM–SCA experiments should be interpreted in this manner.

The organization of this paper is as follows. Section 2 introduces the approach and technical setup and illustrates the results of the standard simulation. Section 3 presents the NAM–SCA archetype in a Lagrangian frame of reference that makes mesh adaptation unnecessary. Section 4 shows that the total mesh number in the horizontal direction can be drastically reduced. The paper concludes in section 5 with a discussion and description of the next steps.

2. Overview, setup, and results of the standard NAM–SCA simulation

a. Overview

NAM–SCA is constructed from a standard CRM (NAM) but designed to work as a parameterization. Its current configuration in two spatial dimensions has vertical velocity $w$, potential temperature $\theta$, and the three components of water (vapor, cloud, and precipitation) as the prognostic variables. The zonal wind $u$, a deviation from the domain mean, is diagnosed by mass continuity from the vertical velocity. The domain-mean zonal wind profile $\bar{u}$ is prescribed. The domain-averaged vertical velocity is zero by virtue of the periodic lateral boundary condition, but the CAPE generation is included as large-scale forcing.

The NAM–SCA formulation for a dry atmosphere is described in Yano et al. (2010a) and the bulk cloud microphysics parameterization in Yano and Bouniol (2010, 2011), with minor modification [e.g., cloud water evaporates in undersaturated environments as in Yano et al. (2012b) and Yano and Lane (2014)]. From a purely numerical perspective, SCA has a finite-volume dynamical core (Yano et al. 2010a). Yano and Bouniol (2010) describe the time evolution of convection as a process that adaptively adds and removes finite-volume elements: a generalized mass-flux formulation representing the growth and decay of individual convective elements (cf. Yano et al. 2010a). Note that NAM–SCA is implemented in some single-column models: European Centre for Medium-Range Weather Forecasts (ECMWF) Hamburg version Atmospheric Model (ECHAM), Australian Community Climate and Earth-System Simulator (ACCESS) (Yano et al. 2012a), and more recently in NCAR Community Atmosphere Model (CAM).

b. Model setup

A similar setup to Yano and Bouniol (2010) is adopted. The NAM–SCA is driven by the total large-scale advection tendencies for potential temperature and water vapor mixing ratio in the stand-alone manner described in Yano et al. (2012a), under a single-column configuration. Specifically, the time-independent large-scale forcing is from Jung and Arakawa (2005, their Fig. 2), which is based on Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) phase III mean observation. No surface flux is applied under the present setup.

A significant difference from Yano and Bouniol (2010) is the idealized westerly wind profile with a
10 m s\(^{-1}\) maximum at the surface decreasing linearly to zero at a height of 5 km. Figure 3 shows the assumed zonal wind profile (solid) and the zonal wind profile from Jung and Arakawa (2005) (long dash) with the sign flipped to facilitate comparison of the simulation with the archetypal model configuration in Fig. 1. As in Yano and Boulin (2010), the horizontal domain size is 512 km with the maximum horizontal resolution \(\Delta x = 2\) km and a minimum horizontal resolution \(\Delta X = 256\) km. The model top is at 30 km with the vertical grid size (full layer depth) gradually stretched from \(\Delta z = 50\) m at the surface to \(\Delta z = 1000\) m at the 20-km level above which the vertical grid is homogeneous. Another significant difference is the addition of a Rayleigh-damping layer similar to Yano et al. (2012a). The damping rate linearly increases from zero at 18 km to \(\tau^{-1}\) with \(\tau = 600\) s above 24 km. Otherwise, the parameters are as in Yano and Boulin (2010), except for some modifications noted in the following sections. Importantly, the pressure field is always solved over the mesh with the maximum resolution, \(\Delta x = 2\) km, regardless of the truncation levels in the following, as described in Yano et al. (2010a).

c. Standard simulation

Snapshots from the standard model described above are shown in Fig. 4. A well-organized squall line evolves over a period of about 1.5 days, similar to Yano and Boulin (2010). The squall line travels steadily eastward at about 4 m s\(^{-1}\) relative to the earth, as shown by the four snapshots of the total condensed water in Fig. 4. For reference, Fig. 5 shows the same result under a full resolution (i.e., assuming finite-volume size \(\Delta x = 2\) km everywhere): clearly, the compression with adaptive mesh refinement reproduces the full-resolution result.
The streamlines in Fig. 6, plotted in the frame of reference traveling with the squall line and zoomed to the centers of the jump updraft in Fig. 4, show a westward-tilting ascending branch (jump updraft). A descending branch (overturning mesoscale downdraft) underlies the ascending branch. The relative airflow in the simulated system corresponds to the Moncrieff (1992) purely propagating regime having no overturning updraft, corresponding to \((h_0, h) = (1, 1/3)\) in the Fig. 2 phase diagram.

Figure 7 shows the vertical transport of horizontal momentum (momentum flux) in terms of the domain-averaged Reynolds stress \(\tau\) recalling that the zonal wind (i.e., \(u\)) is defined as a deviation from the domain mean. There is no domain-averaged vertical velocity owing to the periodic lateral boundary condition. The momentum transport is negative from the surface up to the 14-km level (see more discussion in section 3b). Figure 10 of Moncrieff (1992) shows that this is a direct consequence of the rearward-tilted circulation. The acceleration of the mean flow (the negative of the vertical gradient of the momentum flux) is positive below and negative above about the 4-km level. Therefore, the low-level vertical shear is increased by the upgradient momentum transport, in contrast to the downgradient turbulent mixing by unorganized cumulus convection.

The compression ratios, defined as the ratio of the total active volume segments to that for a full-resolution simulation, for these four frames are 0.173, 0.170, 0.169, and 0.173. This simulation, as well as Yano and Bouniol (2010), show that NAM–SCA can represent squall-line systems even for a compression ratio on the order of 10%.

3. NAM–SCA archetype in a Lagrangian framework

a. Further compression

The results of the last section are promising in that the computational cost of a squall-line simulation is on...
the order of 10% of a full CRM simulation. Nevertheless, the snapshots in Fig. 4 suggest an excessive distribution of volume elements around the convection center.

A large number of volume elements enables the model to follow the propagation of the squall line in Eulerian space–time by virtue of mesh adaptation. Volume elements may be eliminated by repeating the simulation in a Lagrangian frame of reference propagating at the squall-line speed to make mesh adaptation unnecessary. Thus, we replace the background zonal wind speed ($u_e$) by $u_2$, where $c$ is the squall-line propagation speed ($4\text{ m s}^{-1}$).

We introduce a further model compression based on the standard deviation $[(\bar{\phi} - \phi_j)^2]^{1/2}$ of a given variable $\phi$ as a measure of variability, where square brackets designate the spatial average over the entire model domain. The decision to remove a given finite-volume interface depends on the size of the jump across the interface between the $j$th and the $(j + 1)$th volume elements measured by

$$(\Delta \phi)_{j+1/2} = \text{Max}(l_j, l_{j+1})^a |\phi_{j+1} - \phi_j|,$$

where

$$l_j = \frac{x_{j+1/2} - x_{j-1/2}}{\Delta x}$$

is an integer length of the $j$th volume element in the unit of model minimum resolution $\Delta x$ and $a$ is an adjustable parameter.

Note that otherwise there is no change in numerical setup of NAM–SCA apart from turning off the adaptive mesh refinement for now.
When the jump across an interface satisfies the condition
\[(\Delta \varphi)_{i+1/2} < \gamma ([\varphi - [\varphi]]^2)^{1/2}\]
for all prognostic variables (vertical velocity, potential temperature, and the three water types), the given finite-volume interface is removed, where \(\gamma\) is a selected compression threshold. A large \(\alpha\) favors the retention of larger-scale structures [e.g., Yano et al. (2010a) with \(\alpha = 1\)]. When \(\alpha = 0\), there is no discrimination of the volume element length. The compression procedure requires no additional conditions to enable higher compression [e.g., neighboring interfaces required for the adaptive mesh refinement in Yano et al. (2010a)].

The four snapshots in Fig. 4 are used as initial conditions for the Lagrangian-frame experiments. For each initial condition, the 15 compressed reinitializations are prepared with the parameters \(\alpha = 1, 0.5, 0\) and \(\gamma = 1, 1.5, 2, 3, 5\), along with a simple continuation of the runs from the last section. Thus, there are 16 cases in total for each of the 4 initial conditions, giving a total of 64 cases. They are run in a Lagrangian framework and without time-dependent mesh refinement.

b. Simulation results

As the Reynolds’ stress profiles in Fig. 7 suggest, the simulated squall line in the last section in the Eulerian framework is not perfectly steady. The profile at \(t = 5\) days, 8 h (long dash) is especially weaker than those at the other profiles for this reason. Fluctuations imply that...
the Lagrangian simulations may not be successful without mesh adaptation. In the extreme situation, the squall line will disappear if it escapes from the fine-mesh region. Fine tuning of the propagation speed by \( \pm 0.1 \text{ m s}^{-1} \) did not prevent such escapes.

In contrast to the Eulerian case with adaptive mesh refinement, only about half of the simulations show coherent or persistent propagating systems. Even when persistence is maintained, the amplitude of the convective systems tends to be weak. Occasionally, without time-dependent mesh refinement, numerical instability can occur (e.g., a middle-segment convective updraft goes astray without adaptive upward extension of a segment). Examination of all 64 runs failed to identify clear rules, so success or failure seems a matter of chance.

For demonstration of the runs in the Lagrangian framework, we focus on the two extreme cases shown in Figs. 8 and 9. These are continuations of the simulations reported in the last section from \( t = 5 \) days, 8 h and \( t = 5 \) days, 16 h, respectively, with the adaptive mesh refinement turned off. Figure 8 shows a smooth continuation of the squall line, whereas Fig. 9 shows less continuity with noticeable fluctuations. The squall line is maintained for 10 days in the first case, whereas in the second case it dissipates in about 2 days.

Figure 10 shows snapshots of Lagrangian runs after 48 h from the continuation from \( t = 5 \) days, 8 h for \( \gamma = 2, \alpha = 1 \) (Fig. 10a); \( \gamma = 2, \alpha = 0.5 \) (Fig. 10b); \( \gamma = 2, \alpha = 0 \) (Fig. 10c); and \( \gamma = 3, \alpha = 1 \) (Fig. 10d). These values correspond, respectively, to compression ratios of \( 2.19 \times 10^{-2}, 1.99 \times 10^{-2}, 1.90 \times 10^{-2} \), and \( 1.28 \times 10^{-2} \).

The squall-line structure is maintained at even higher compression, although the stratiform cloud gradually erodes.
Figure 11 shows additional physical fields and total condensate for the Lagrangian run with $\gamma = 2, \alpha = 1$ for comparison with further compressions reported in the next section. Note that the downdraft is weak and narrow and no evaporative cooling occurs beneath the stratiform cloud. Figure 12 shows the streamlines of the compressed results, shown in Fig. 10, zoomed over the range of 128–256 km. Despite the drastic compression, the jump updraft and the associated downdraft circulation are both well represented. Figure 13 shows the vertical profiles of the Reynolds stress (i.e., $\pi \overline{w}$) for these four cases. At that compression, along with the weak downdraft and absence of the evaporative cooling, the mesoscale transport of momentum is confined to the lowest 3 km. Above that level, the convective momentum transport decreases the westerly mean flow and generates an easterly mean wind. This is due to the major change of the airflow structure because the downdraft is replaced by a weak widespread environmental descent (cf. Fig. 11a).

It follows that subtle aspects of compression (e.g., reduced spatial resolution) can critically influence the airflow structure and hence the momentum transport profile. In simulations of mesoscale convective systems, Moncrieff and Liu (2006) showed that differences between 3-, 10-, and 30-km computational grids significantly affect the airflow structure, especially the mesoscale downdrafts. The 3- and 10-km cases had similar mesoscale downdrafts and momentum transport profiles but the 30-km case featured no mesoscale downdraft and, instead of being vertically tilted, the system was upright. Therefore, the momentum transport profile was very different.

4. Highly truncated archetype

The analysis of the previous section shows that the compression rate can be dramatically enhanced for the Lagrangian framework, although the compression is not necessarily optimal in terms of the squall-line structure and momentum transport. As the compression rate increases, the stratiform cloud and the underlying mesoscale downdraft erode rapidly but an excessive distribution of finite-volume elements remains around the convective updraft. Therefore, we speculate that further compression may be possible by a judicious choice of finite-volume elements.

This optimization is accomplished by using just four finite-volume segments, a configuration that gives a compression rate of $4/256 = 1.56 \times 10^{-2}$. More precisely, a segment of 16-km size is placed in the middle of the domain adjacent to two 32-km-size segments. The convective circulation is sustained by adding to the lowest model layer a constant sensible heating of $10^{-7}$ K s$^{-1}$ for the middle segment and cooling of $-\nu/4 \times 10^{-7}$ K s$^{-1}$ for the two adjacent segments. As a result, the perturbation surface flux does not contribute to the domain average. Unlike the original run in section 2, no initial perturbation is added.

A technical problem occurs at high truncation: suppression of the horizontal propagation of gravity waves from the three central finite-volume elements to the environment segment. To partially alleviate this problem, these three segments are extended to the top of the model. As a result, the compression rate becomes larger than some of the smallest compression rates achieved in the last section, in which the uppermost part of the domain is often truncated down to the minimum two segments.

Even with this procedure, especially during the convection spinup phase, the model can generate a strong artificial standing oscillation which may still cause numerical instability. We have further introduced artificial lateral diffusion whenever the absolute value of the vertical velocity exceeded a prescribed threshold for a given finite-volume segment, as detailed in the appendix. The threshold value is set, arbitrarily, to $10$ m s$^{-1}$ for the middle finite-volume segment (16-km length).
and 5 m s$^{-1}$ to the two contiguous segments (32-km length). Whenever the absolute vertical velocity exceeds the threshold at the end of a given time step, the excessive momentum is numerically diffused horizontally so that the absolute value is maintained at the threshold value. All the prognostic physical variables diffuse horizontally at the same rate. The diffusion criterion is first applied to the middle finite-volume element and proceeds to the two other elements. This artificial horizontal diffusion is activated only if the vertical velocity exceeds the threshold at a given vertical level. Such a highly selective diffusion procedure minimizes the artificial dissipation of energy in the spirit of Margolin et al. (1999). Although a squall line is generated (not shown), this extreme truncation suppresses the Reynolds’ stress for the standard time step of $\Delta t = 5$ s owing to numerically generated standing oscillations that remain. It was therefore necessary to reduce the time step to $\Delta t = 2$ s for a similar reason as discussed in Yano and Lane (2014).

The results with the coordinate transformation turned off ($c = 0$ m s$^{-1}$) are shown in Fig. 14 as a snapshot after 2 days of simulation in the same format as in Fig. 11. A squall line occurs even at very strong truncation and produces a reasonable vertical profile of Reynolds stress (Fig. 15), albeit with about half the amplitude in the original lower-truncation simulation (cf. Fig. 7). A more realistic Reynolds stress is obtained for the Lagrangian framework, although from an operational perspective this is somewhat impractical because the propagation speed is not known a priori. A simple way to estimate the propagation speed is to

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**Fig. 14.** Snapshot after 48 h of an NAM–SCA system consisting only of the four SCA segments under an idealized tropical situation. Shown are (a) vertical velocity (m s$^{-1}$), (b) potential temperature anomaly (K; deviation from a horizontal average), (c) water vapor mixing ratio (g kg$^{-1}$), and (d) total water condensate (g kg$^{-1}$).
assume the density-weighted vertical average of the environmental zonal wind (i.e., 2.6 m s\(^{-1}\))—a minor underestimate of the actual speed of 4 m s\(^{-1}\). Figure 16 shows a reasonably realistic Reynolds stress under this configuration.

5. Discussion

It has long been known that atmospheric convection in sheared environments organizes into squall lines, mesoscale convective systems, and other categories of organized convection. However, organized convection is not reliably represented by traditional convection parameterizations, mostly because of deficiencies associated with the mass-flux parameterization regarding the realistic representation of organized dynamics (Moncrieff 2010; Moncrieff et al. 2012; Yano 2014b). Dynamical consistency is particularly important for squall lines and mesoscale convective systems owing to the strong control environmental shear exerts on the mesoscale circulation structure and the associated transports. Moreover, by interacting with downdraft outflows (density currents) and latent heating, vertical shear enables systems to propagate into CAPE-rich regions, often traveling great distances and thus displaying a longevity that greatly exceeds unorganized convection.

The Moncrieff (1992) analytic archetypal model and NAM–SCA as an efficient numerical archetypal simulator provide a novel framework for the explicit parameterization of mesoscale convective systems. The successful comparison of the analytic and numerical convective momentum transports is a significant advance over the common custom of prescribing additional components for convection parameterization—for example, inclusion of a cold pool (e.g., Grandpeix and Lafore 2010; Park 2014).

The NAM–SCA numerical archetype was systematically constructed as a prototype prognostic mass-flux formulation; in essence, a CRM with finite-volume dynamical core. A key feature is the numerical efficiency achieved through compression techniques. First, high compression is due to adaptive mesh refinement. Second, further compression in a Lagrangian frame of reference alleviates the need for adaptive mesh refinement. Finally, a prescribed segment distribution realizes squall lines with compression on the order of 1% without drastic deterioration of momentum transport. Note that we chose not to present the heat and moisture profiles (\(Q_1\) and \(Q_2\); Yanai et al. 1973) that are fundamentally constrained by the large-scale forcing (cf. Fraedrich and McBride 1989; Yano 2001; Yano et al. 2012a).

The periodic lateral boundary conditions on NAM–SCA (as well as the CRMs used in superparameterization;
Pritchard et al. (2011) confine the simulated mesoscale systems to their domains of birth. Interaction between vertical shear on the global domain and latent heating on the CRM/NAM–SCA domain can generate mesoscale systems on the global grid. However, these systems are underresolved on that grid so their mesoscale downdrafts and momentum transports are biased (Moncrieff and Liu 2006).

The success of the compressed NAM–SCA stems from the numerically efficient time-dependent mesh refinement that is missing from conventional CRMs used in superparameterization. We consider that the addition of lateral interaction with the neighboring grid boxes in NAM–SCA should be relatively straightforward, for instance, by replacing a standard gridbox value with an environmental value.

The NAM–SCA was developed utilizing a single analytic archetype as a test bed. Further development—for instance, simulation of different archetypal regimes in varying wind and large-scale forcing—will be investigated. Three-dimensional numerical archetypes in early simulations (e.g., Moncrieff and Miller 1976) and recent simulations (Lane and Moncrieff 2015; Moncrieff and Lane 2015) encourage the development of the three-dimensional version of NAM–SCA.

Currently, testing is underway to examine a wider applicability of the highly truncated archetype NAM–SCA using time-dependent large-scale forcing obtained from field campaigns. We refer to Yano et al. (2012a) for the details. Preliminary results for the cases from GATE and Tropical Warm Pool–International Cloud Experiment (TWP-ICE) are shown in Fig. 17 as the time–height sections of the simulated apparent heat sources, which compare favorably with observations. The complete results will be reported in a separate paper.

Finally, the numerical algorithms must be further improved [e.g., efficient pressure solvers (cf. Yano et al. 2010a) and a lengthened time step achieved by controlling the deep gravity waves (cf. Yano and Lane 2014)]. The implementation of the highly truncated and compressed NAM–SCA into global models, such as ECHAM, ACCESS, and NCAR CAM, will be a significant step toward an operational capability.

Fig. 17. A preliminary test with a highly truncated archetype NAM–SCA under time-evolving large-scale forcing. Time–height sections of the apparent heat source for the (a) GATE and (b) TWP cases. (top)–(bottom) Observation, the archetype result, and the difference of the latter to the former. See Yano et al. (2012a) for the case details.
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APPENDIX

Artificial Horizontal Diffusion for Stabilization

An artificial horizontal diffusion is applied at a given vertical level within three middle-volume elements when the absolute value of the vertical velocity exceeds a threshold \( w_{j}^* \) prescribed at each volume element \( j \). When required, the vertical velocity is reset to the threshold value with a sign consistent with the original value; thus,

\[
    w_j' = w_j - \Delta w,
\]

(A.1)

where \( \Delta w \) is a required horizontal diffusion in order to maintain this state:

\[
    w_j' = w_j - \text{sgn}(w_j)w_j^*.
\]

(A.2)

Here, the prime represents a value after the adjustment.

The momentum excess \( \Delta w \) is diffused to both sides, by default, with the rates \( \lambda_j(w_{j-1} - w_j) \) and \( \lambda_j(w_{j+1} - w_j) \) to the left and to the right, respectively, where the consistent diffusion coefficient \( \lambda_j \) is estimated by

\[
    \lambda_j = \frac{\text{sgn}(w_j)w_j^* - w_j}{w_{j-1} + w_{j+1} - 2w_j}.
\]

(A.3)

All the other prognostic variables \( \phi_j \) are also diffused to the neighboring volume elements at the same rates given by \( \lambda_j(\phi_{j-1} - \phi_j) \) and \( \lambda_j(\phi_{j+1} - \phi_j) \) to the left and to the right, respectively.

The test is performed starting from the middlemost volume element and proceeds sideward to the environment. When a diffusive transport is performed from one of the neighboring volume elements, the diffusive transport from the given volume element is performed only for the other remaining neighbor volume element. Therefore, diffusion is not repeated...
for a single-volume-element interface twice. The consistent diffusion coefficient in this case is

$$\lambda_j = \frac{\text{sgn}(w_j) - w_j}{w_{j+1} - w_j} \quad (A.4)$$

with the plus/minus sign depending on the direction of the diffusion. This adjustment is performed at the end of all the updates for a given numerical time step.

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