Convective Organization in Evolving Large-Scale Forcing Represented by a Highly Truncated Numerical Archetype

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ABSTRACT

Considered as a prognostic generalization of mass-flux-based convection parameterization, the highly truncated nonhydrostatic anelastic model with segmentally constant approximation (NAM–SCA) is tested with time-evolving large-scale forcing. The 20-day GATE Phase III period is taken as a major data source. The main advantage of the NAM–SCA parameterization is consistency with subgrid-scale dynamics as represented by the nonhydrostatic anelastic formulation. The approach explicitly generates important dynamical structures of convection (e.g., mesoscale circulations, cold pools) spontaneously without further tuning or treatment as additional subcomponents. As with other convection parameterizations, the numerical simulation of the precipitation rate, the apparent heat source, and the apparent moisture sink is straightforward and reasonably insensitive to the numerical procedures. However, convective momentum transport by organized convection turns out to be difficult even with NAM–SCA, especially for the inherently three-dimensional shear-parallel systems. Modifications of NAM–SCA regarding the large-scale forcing formulation improves the mesoscale momentum transport. Simulation of the full 120-day TOGA COARE period demonstrates the performance of NAM–SCA in different meteorological conditions and its capacity to operate over a longer time period.

1. Introduction

Mass-flux-based convection parameterization, originally formulated by [Arakawa and Schubert \(1974\)](#), has a firm physical basis. [Plant and Yano \(2015\)](#) systematically review this formulation. However, the original formulation has not been fully implemented in operational models, partly because of technical difficulties. The self-consistency of the formulation and its assumptions, justifiable or not, have not been fully appreciated ([Yano 2014](#)). It has been criticized on the basis that key elements, such as convective downdrafts and the mesoscale

organization, are absent. Indeed, efforts to improve mass-flux-based convection parameterization over about 40 yr may be characterized as ad hoc addition of missing components without due consideration of physical principles (cf. [Yano 2016](#)).

It is crucial that mesoscale organization be included in convective parameterization. It has long been known that the airflow in severe convective storms is governed by the dynamical effects of environmental vertical shear ([Browning and Ludlam 1962](#); [Moncrieff and Green 1972](#)). Ubiquity of mesoscale organization of tropical convection was observed in the 1974 Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) field campaign ([Houze and Betts 1981](#); [Frank 1983](#)). The distinguished transport properties of mesoscale convective organization have been firmly quantified (e.g., [Moncrieff 1981](#); [Donner 1993](#); [Liu et al. 2012](#); [Moncrieff et al. 2012](#)). [Yano and Moncrieff \(1998\)](#) provided a framework for parameterizing organized convection and analyzing its effects on the large-scale tropical circulation. Theoretical studies

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by Khouider and Majda (2006, 2008), Majda and Stechmann (2008, 2009), and Khouider et al. (2012a,b) quantify the role of large-scale convective organization. We refer to Houze (2004), Moncrieff (2010), and Moncrieff and Waliser (2015) and papers cited therein for comprehensive literature reviews.

We address mesoscale convective organization and its feedback to the larger scales by adopting a systematic reformulation of the mass-flux convection parameterization originally introduced by Yano et al. (2010). We use a two-dimensional nonhydrostatic anelastic model with segmentally constant approximation (NAM-SCA) to represent subgrid-scale convection and convective organization in a physically consistent way. Specifically, we adopt the Yano and Moncrieff (2016) procedure as an intermediate approach between a cloud-system-resolving model (CRM) and a mass-flux-based convection parameterization. Their two-dimensional NAM-SCA application is a numerical counterpart of the Moncrieff (1992) analytic archetype of organized convection. Yano and Moncrieff introduced its construction in stepwise manner from a full NAM with numerical demonstrations for each step and tested its performance in conditions of steady large-scale forcing. Here, we apply time-varying large-scale forcing in order to demonstrate the capacity of NAM-SCA to simulate different regimes of organized convection and its performance in longer integrations.

A specific issue concerns the limit of the currently two-dimensional NAM-SCA configuration. The domain-averaged thermodynamic properties of organized mesoscale convection (e.g., rainfall rate, surface sensible and latent heat fluxes, cloud mass flux, cloud fraction, and radiative fluxes) in two-dimensional and three-dimensional simulations of GATE convection are remarkably similar (Grabowski et al. 1998). In contrast, dynamical properties, notably convective momentum transport, are a product of complex interaction between vertical wind shear and the vorticity generated by convection. Here, the spatial dimensionality is significant in defining key structural and transport effects of convective organization (Liu et al. 2012). These dynamical aspects are the focus of the present study.

The GATE field campaign over the tropical eastern Atlantic identified two categories of mesoscale convective organization in terms of structural morphology and eddy transport: shear-perpendicular and shear-parallel systems (LeMone et al. 1998; Moncrieff 1981). The former category is commonly referred to as squall lines (LeMone 1983). Moncrieff (1992, his Fig. 10) illustrated that downshear-moving mesoscale eddies with an upshear (downshear) tilt feature negative-upgradient (positive-downgradient) convective momentum transport. For example, in a westward-moving system, the mean-flow acceleration (i.e., the negative of the vertical

gradient of the momentum flux) is positive (negative) in the upper (lower) levels of the convective layer, respectively. Upshear-tilted eddies are a feature of the classical mesoscale convective system (Moncrieff 1992, his Fig. 1). Shear-parallel mesoscale rainbands, a dominant form of convective organization observed in the intertropical convergence zone (ITCZ) during GATE Phase III, feature shear-downgradient convective momentum transport (Houze and Cheng 1977). These fundamentally three-dimensional rainbands were successfully simulated by Dudhia and Moncrieff (1987) using a three-dimensional CRM and by Khouider and Moncrieff (2015) using an idealized dynamical model and parameterized convection.

It is clear that two-dimensional numerical models cannot properly simulate shear-parallel mesoscale rainbands. However, a key question is, Can the momentum transport tendency be reproduced using the two-dimensional configuration? It should be noted that shear-parallel rainbands may contain embedded cumulonimbi that initiate at the upshear end of the band and move downshear as they mature (Dudhia and Moncrieff 1987). The vertical tilt of these cumulonimbi essentially defines the sign of the momentum transport and the acceleration of the mean flow. The convective inhibition of the planetary boundary layer, for example, affects the tilt (Liu and Moncrieff 2017).

We focus on the GATE Phase III period because both categories of organization occur within the 20-day period in conditions of varying large-scale forcing (Houze and Betts 1981). After introducing the basic model setup in the next section, section 3 presents an overview of the GATE Phase III period, including a full-resolution simulation as a baseline calculation. Issues involved with the extension of the highly truncated NAM-SCA to the case with the time-varying large-scale forcing are stated in section 4. Section 5 describes modifications to the single-column configuration from earlier work (Yano et al. 2012; Yano and Lane 2014) to overcome these difficulties. The results obtained by way of these modifications are presented in section 6. As a supplementary demonstration of the NAM-SCA performance, the longer simulation of the 120-day Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) period is presented in section 7, and the paper concludes in section 8 with further discussion.

2. NAM-SCA formulation

a. Overview

NAM-SCA is a particular implementation of a finite-volume discretization (LeVeque 2002) of NAM. Yano et al. (2010) called this particular version of the finite-volume discretization an SCA. An advantage of

this formulation, currently adopted in two spatial dimensions, is that a number of finite-volume elements introduced in the periodic horizontal domain can be adopted in a flexible manner. The choice of configuration ranges from a dense, homogeneous distribution (as in standard CRMs) down to a sparse distribution, even just two finite-volume elements. These two elements represent the convective updraft (plume) and the environment, respectively (Yano and Baizig 2012). This most severe truncation of two segments can be considered a prototype prognostic bulk mass-flux convection parameterization.

As an intermediate choice, the distribution of the finite-volume elements can be adaptively modified in time by following the evolution of the simulated system so that a dense finite-volume distribution is always placed over a convective region thereby minimizing the finite-volume density over the environmental region (Yano et al. 2010). The full-resolution adaptive NAM-SCA adopted in the next section defines the reference data for the study. We refer to Yano et al. (2010, 2012), Yano and Bouniol (2010), and Yano and Lane (2014) for details of this version and its reliability tests.

Yano and Moncrieff (2016) show that with just four finite-volume elements over a two-dimensional domain, mesoscale convective organization and its characteristic shear-upgradient momentum transfer tendency are adequately simulated. The main part of the paper (sections 4–6) adopts the highly truncated NAM-SCA approach for a further pursuit of its capacity.

b. Basic formulation

In general, NAM-SCA consists of N segments (finite volumes) in the horizontal direction, and the number may change with time as well as with height. The time evolution of any variable, say ϕ_j , of the j th segment for NAM-SCA is described by the sum of the four tendencies on the right-hand side:

$$\frac{\partial \phi_j}{\partial t} = F_{c,j} + Q_R + H_j + F_{L,j}. \quad (2.1)$$

Note that Eq. (2.1) is obtained by a finite-volume discretization of the full nonhydrostatic anelastic model in a straightforward manner, as explicitly derived in Yano et al. (2010). Here, $F_{c,j}$ is the process evaluated within NAM-SCA consisting of advection as well as a source term for a given variable, whereas radiation Q_R and the surface flux H_j (section 5b) are separately defined. The last term, $F_{L,j}$, is the large-scale forcing (advection tendency; see section 5a).

The formulation for the advection process in the term, $F_{c,j}$, is in flux form, which is detailed by Yano et al. (2010).

FIG. 1. The schematic geometry of the highly truncated NAM-SCA over a periodic domain in x .

The only physical source term added to $F_{c,j}$ represents cloud microphysical processes (a simple bulk formulation) as described by Yano and Bouniol (2010). The radiation term Q_R is a domain-average tendency following Kiehl et al. (1994). The large-scale forcing $F_{L,j}$ for the potential temperature and the moisture is provided by observed analysis. In operational implementation, $F_{L,j}$ is provided by the host model (i.e., the coarse-resolution global model), and NAM-SCA, as a subgrid-scale representation, in turn provides the domain-averaged subgrid-scale tendency $\bar{F}_{c,j}$ to the host model.

As a special procedure, the horizontal wind is not predicted by a momentum equation of form Eq. (2.1) but is diagnosed by the mass continuity with a given vertical velocity. The latter is predicted by a momentum equation as usual within NAM-SCA. More precisely, the horizontal wind is diagnosed by integrating the mass-continuity equation horizontally with a given vertical velocity. Under this procedure, the horizontal domain average of the wind remains an arbitrary constant, which is simply set to the observed zonal wind in the present study. As a result, unlike a standard nudging procedure as in Grabowski et al. (1996), the domain-averaged wind remains identical to the observation under the NAM-SCA simulations.

The standard parameters adopted are listed in appendix A based on the test in appendix B.

c. Highly truncated NAM-SCA

In our series of experiments, we use the same geometrical configuration in two spatial dimensions (Fig. 1) as in section 4 of Yano and Moncrieff (2016). The periodic horizontal domain is 512 km long. The three convective segments assume constant values within each segment ($L_1 = 32$ km, $L_2 = 16$ km, and $L_3 = 32$ km in

FIG. 2. Time–height section of the observed zonal wind during GATE Phase III (m s^{-1}).

length) and are placed at the center of the periodic domain. The inner 16-km-wide segment is called *core* and all these three segments are collectively called *convective*, respectively. The remaining large segment is *environment*. The segment sizes (L_1 , L_2 , and L_3) are chosen subjectively but with the intention of representing the mesoscale convective organization in an efficient manner, albeit spatially crude. Sensitivity experiments on the choice are performed in section d of [appendix B](#).

For the preliminary experiments in [section 6a](#), we follow [Yano et al. \(2012\)](#) and [Yano and Lane \(2014\)](#) for the single-column modeling configuration, corresponding to the option $i_L = 0$ defined in [section 5c](#). Following [Yano and Moncrieff \(2016\)](#), the perturbation heat fluxes, δH and $-\delta H/4$, respectively, are added to the center (core) and the two adjoining convective segments in the preliminary tests ([section 6a](#); the option $i_p = 1$ in section c of [appendix A](#)). These perturbation terms are omitted (i.e., $\delta H = 0$) when the modifications are introduced later in [section 6](#) (the option $i_p = 0$). Problems with the original formulation are described in [section 4](#), the modifications are introduced in [section 5](#) and tested in [section 6](#). We provide an overview of the test case in the next section.

3. The GATE case study

a. Overview

GATE was conducted in 1974 over the tropical eastern Atlantic. The Phase III intensive observation period, adopted herein, occurred from 0000 UTC 30 August to 2400 UTC 18 September 1974. The analysis of a sounding network provides the large-scale forcing ([Esbensen et al. 1982](#); [Sui and Yanai 1986](#)), which has been used in numerous CRM studies (e.g., [Grabowski et al. 1996](#); [Xu and Randall 1996](#); [Yano et al. 2012](#)). The time–height section of the zonal wind in [Fig. 2](#) shows this period is characterized by a shallow but dominant lower-level westerly flow and a deep but relatively

FIG. 3. Precipitation-rate (mm h^{-1}) distribution in a longitude–time section for the full-resolution, adaptive NAM–SCA simulation.

weak upper-level easterly flow. The variability of the wind profile over this period is caused by synoptic-scale easterly waves. Typically, the convective systems during this period propagate upwind against the low-level westerly, as in [Fig. 3](#) below.

b. Full-resolution, adaptive NAM–SCA simulation

Convective momentum transfer is difficult to accurately diagnose from observational data, so the available analysis during the GATE period is somewhat fragmental ([Houze and Cheng 1977](#); [LeMone 1983](#)). Convective momentum transfer is more reliably estimated using data generated by numerical models. We use the full-resolution, two-dimensional adaptive NAM–SCA ([Yano et al. 2010, 2012](#); [Yano and Bouniol 2010](#); [Yano and Lane 2014](#)) surrogate of a full CRM to evaluate the performance of highly truncated NAM–SCA. The numerical settings are given in [appendix A](#) except that the maximum possible total segment number is reset to $N = 256$ with the maximum possible resolution $\Delta x = 2$ km.

[Figure 3](#) shows the precipitation-rate distribution in a longitude–time section obtained from the adaptive NAM–SCA simulation. Two well-defined periods of westward-propagating squall lines occur on days 3–6 and days 18–20 interspersed by less-organized cloud clusters (shear-parallel bands) on days 14–16 (cf. [Yano et al. 2012](#)). [Khouider and Moncrieff \(2015\)](#) successfully simulate a transition from shear-perpendicular to shear-parallel systems using their idealized model.

FIG. 4. Time–height section of the convective momentum transport–induced zonal-wind tendency [$\text{m s}^{-1} \text{day}^{-1}$, Eq. (3.1)] with the full-resolution, adaptive NAM–SCA simulation.

These distinctively organized convective regimes are characterized by the tendency of the zonal wind due to the convective momentum transport and measured by the vertical gradient of the Reynolds stress, that is,

$$-\frac{1}{\rho} \frac{\partial \overline{\rho u' w'}}{\partial z}, \quad (3.1)$$

based on the simulated zonal and vertical velocities, u and w . Here, ρ is the density, z is the vertical coordinate, and the bar and the prime are the horizontal domain average and the deviation from that average.

The time–height section in Fig. 4 shows that the tendency in Eq. (3.1) due to the convective momentum transport is mainly shear upgradient and therefore enhances the zonal winds in association with the westward-propagating squall lines (LeMone 1983). Days 14–16 are distinctive, because the convective organization was in the form of shear-parallel cloud clusters that transport zonal momentum shear downgradient and decreases the vertical shear (Dudhia and Moncrieff 1987; Houze and Cheng 1977). The dynamical basis of organized convective momentum transport is described by Moncrieff (1997).

Figures 5 and 6 are snapshots of the total condensate water field in the squall line and the shear-parallel cloud regimes, respectively. Both figures demonstrate the adaptive nature of the simulation (i.e., the segment boundaries by vertical bars), whose distribution evolves with time by following the convection evolution. Note that full resolution is retained over the surface layer to maintain enough disturbances to enable continual evolution of the whole system.

The westward-moving squall line (Fig. 5) has a convective core and a stratiform cloud region. The stratiform region extends ahead of the convective core (leading stratiform) instead of behind (trailing stratiform), which is distinct from the standard squall line (e.g., Fig. 25 of Houze 1977). The weakness of this squall

line resembles the two-dimensional GATE cases simulated by Grabowski et al. (1996; Figs. 3b and 3e). The lack of stratiform cloud to the east of the squall line may be partially attributed to the absence of ice in the microphysics formulation (cf. Yano and Buniol 2010), which could otherwise provide enhanced buoyancy associated with ice freezing in the stratiform cloud. Ironically, the condensate morphology in the westward-propagating shear-parallel nonsquall cluster (Fig. 6) resembles the standard trailing stratiform squall line and the nonsquall cluster simulated by Grabowski et al. (1996, their Figs. 3a and 3d). This illustrates the limits of two-dimensional simulation.

Nevertheless, Fig. 4 distinguishes the dynamical characteristics of the two principle regimes of organization in respect to shear-upgradient and shear-downgradient momentum transport, respectively. The two-dimensionality of the model is not a severe restriction in this respect, because mathematically, the key to successful simulation of both shear-upgradient and shear-downgradient convective momentum transfer is the correct tilt of the convective updraft in respect to the shear. This is manifested by the difference between the leading and the trailing stratiform clouds, as remarked above. Parker and Johnson (2000, 2004) emphasized the importance of this distinction.

4. Issues associated with time-varying large-scale forcing

Running the highly truncated NAM–SCA with time-varying large-scale forcing necessitates modification of the standard single-column configuration of Yano et al. (2012) and Yano and Lane (2014). This section summarizes some identified difficulties. The modifications introduced in response to those difficulties are described in section 5. Readers not interested in the background for these modifications should skip to section 5.

a. Delayed convective response

The main problem encountered by the original formulation is the slow spinup of the subgrid-scale system. For instance, with the Yano and Moncrieff (2016) steady forcing, it took more than 12 h for a system to attain equilibrium. Specifically, the convective response trails the large-scale forcing. Convection failed to trigger in the three middle-convective segments of Fig. 1, and the environmental segment responds solely to the large-scale forcing, forming “stratiform” clouds and precipitation therein. Ironically, as Yano et al. (2012) showed, this procedure can produce satisfactory apparent heating and moistening, Q_1 , $-Q_2$, and precipitation. Although the simulation fails to produce the observed convective organization, the eddy momentum transport is nevertheless

FIG. 5. Four snapshots (2 h apart) showing the morphology of the squall-line system for day 6 (4 Sep). The color shades show the total condensate (g kg^{-1}). The vertical lines indicate the positions of the adaptive finite-volume segment boundaries.

shear upgradient. A persistent problem is an exaggerated shear-upgradient momentum transport, even for the shear-parallel regime, where momentum transport should be shear downgradient. We shall concentrate on the latter problem. The preliminary experiments in [section 6a](#) will show that a successful highly truncated NAM-SCA simulation is obtained by modifying the large-scale forcing ([section 5a](#)), which enables convection to respond more spontaneously to the large-scale forcing.

b. Noisy convective response

The noisy nature of the convective response is an additional issue. Basically, the convective response in highly truncated NAM-SCA is not sufficiently spontaneous because the surface flux prescribed from observation (the option $i_f = 0$ in section c of [appendix A](#))

does not actively respond to changes in the planetary boundary layer induced by convection. This issue is removed by implementing interactive surface fluxes ([section 5b](#)).

c. Convective organization

All the experiments without active surface flux (but with observed surface flux) lack convective organization even though the shear-upgradient eddy transport of the horizontal momentum is reasonably simulated. Specifically, the shear-downgradient momentum transport by the shear-parallel cloud-cluster regime is missing. This issue is ameliorated by implementing a coordinate system that travels with the organized system ([section 5c](#)) as introduced by [Yano and Moncrieff \(2016\)](#).

FIG. 6. As in Fig. 5, but for the shear-parallel bands during day 14 and 6 h apart.

5. Modifications to the highly truncated NAM-SCA formulation

The following modifications are introduced to address the above difficulties with the original highly truncated NAM-SCA.

a. Weighted large-scale forcing

The “weighted” large-scale moisture forcing, aimed at overcoming the convective response problem (section 4a), made it possible to turn off the perturbation surface heat flux used in Yano and Moncrieff (2016). The standard procedure for driving the time evolution of subgrid-scale processes in a CRM (Grabowski et al. 1996) is to apply the large-scale forcing (i.e., advective tendency) homogeneously over the model domain. Thus,

$$F_{L,j} = -\left(\nabla \cdot \bar{\mathbf{u}} \bar{\varphi} + \frac{1}{\rho} \frac{\partial}{\partial z} \rho \bar{w} \bar{\varphi}\right) \equiv \bar{F}_L \quad (5.1)$$

is independent of the segment index j , where the right-hand side is an explicit large-scale advection tendency with all the domain-averaged quantities identified by the overbar and $\mathbf{u}$ is the horizontal velocity vector. As pointed out in section 4a, this standard formulation fails to produce a spontaneous convective response over the middle-convective segments that faithfully follows the evolution of the large-scale forcing. Therefore, we generalize the large-scale forcing formulation by enabling its nonuniform application over the model domain subject to a weight $\bar{w}_j$:

$$F_{L,j} = \bar{w}_j \bar{F}_L. \quad (5.2)$$

An important constraint is that the original large-scale forcing rate is maintained in the model domain average; thus,

$$\sum_{j=1}^N \sigma_j F_{L,j} = \bar{F}_L$$

or

$$\sum_{j=1}^N \sigma_j \bar{\omega}_j = 1, \quad (5.3)$$

where σ_j is the fractional area occupied by the j th segment and N is the total number of the segments considered with $N = 4$ in the present study.

Four options for the weight $\bar{\omega}_j$ are considered with choices indicated by the flag i_L . Different choices can be applied to the potential temperature θ and the moisture q_v separately. In that case, the choice is identified by an argument, for example, $i_L[\theta] = 0$ and $i_L[q_v] = 3$ for the final default choice in section 6. Recall that large-scale forcing is applied only to potential temperature and moisture.

- (i) $i_L = 0$: homogeneous application (standard single-column formulation), $\bar{\omega}_j = 1$
- (ii) $i_L = 1$: large-scale forcing applied only to the environment, $\bar{\omega}_e = 1/\sigma_e$, $\bar{\omega}_j = 0$ ($j = 1, 2, 3$), where the subscript e identifies the environment segment; $j = 1, 2, 3$ correspond to the three convective segments, with the middlemost core identified by $j = 2$ (cf. Fig. 1)
- (iii) $i_L = 2$: large-scale forcing applied only to the three convective segments, $\bar{\omega}_e = 0$, $\bar{\omega}_j = 1/\sum_{j=1}^3 \sigma_j$ ($j = 1, 2, 3$)
- (iv) $i_L = 3$: large-scale forcing applied only to the core convective segment, $\bar{\omega}_2 = 1/\sigma_2$, $\bar{\omega}_j = 0$ ($j = e, 1, 3$)

As noted in section 4a, the standard single-column setup results in the model responding to the large-scale forcing in the environmental segment, whereas a physically consistent convective response should avoid that situation. For instance, the environmental segment should preferably be a region of descent rather than ascent, which would result in large-scale condensation and latent heating.

$$u_{0,j}^* = \begin{cases} u_{0,j-1/2} & \text{when } u_{0,j-1/2} > 0 \text{ and } u_{0,j+1/2} > 0 \\ u_{0,j+1/2} & \text{when } u_{0,j-1/2} < 0 \text{ and } u_{0,j+1/2} < 0 \\ (u_{0,j-1/2} + u_{0,j+1/2})/2 & \text{when } u_{0,j-1/2} > 0 \text{ and } u_{0,j+1/2} < 0 \\ 0 & \text{when } u_{0,j-1/2} < 0 \text{ and } u_{0,j+1/2} > 0 \end{cases} \quad (5.5)$$

The evaluated surface flux is distributed homogeneously (but weighted by air density) over the predefined boundary layer depth of $h_b = 500$ m as described in Yano et al. (2012).

c. Moving coordinate

To overcome the problem with the eddy momentum transport discussed in section 4c, we apply a procedure introduced in Yano and Moncrieff (2016); namely, move the system horizontally at an estimated convective organization phase speed c_p . Thus, the mean zonal wind $\bar{u}$ in

b. Active surface flux

In the original formulation, as described in Yano et al. (2012), the surface flux is prescribed for the potential temperature and the moisture as domain-averaged values based on observational estimates. However, this formulation lacks a spontaneous response of the boundary layer to changes induced by convection (section 4b). To overcome this problem, the bulk surface flux is introduced over the j th segment by

$$H_j = C_s |u_{0,j}^*| (\varphi_{j,s} - \varphi_{j,0}). \quad (5.4)$$

Here, $C_s = 10^{-4}$ is the bulk coefficient, $|u_{0,j}^*|$ is the magnitude of the horizontal velocity (i.e., wind speed) at the lowest model level, $\varphi_{j,0}$ is the value of a physical variable that is controlled by the surface flux (potential temperature or moisture) at the lowest model level, and $\varphi_{j,s}$ is its “surface” value. The surface potential temperature is simply set to 300 K as in GATE, and the moisture is the saturated mixing ratio at this temperature.

The treatment of the surface wind $|u_{0,j}^*|$ is less straightforward. The obvious choice is to set it at the segment-averaged value; that is, $u_{0,j}^* = (u_{0,j-1/2} + u_{0,j+1/2})/2$, where $u_{0,j-1/2}$ and $u_{0,j+1/2}$ are the values of the horizontal velocity at the left and the right edges of the j th segment (finite volume), where the horizontal velocity is defined according to the SCA formulation (Yano et al. 2010). Unfortunately, this choice results in numerical instability. So we opted for the following “upstream” approximation. When the wind blows in from the left (right) edge and out to the right (left) edge, the left (right) edge value is adopted; when it blows in from both sides, the average value is taken; and when it blows out from both sides, the surface wind is set to zero. Thus,

simulations is replaced by $\bar{u} - c_p$, where the phase speed c_p is estimated by the density-weighted vertical average of the mean zonal wind $\bar{u}$. Note that, under the present setting, both the latter and former evolve with time.

6. Results

The results are presented in a stepwise manner, beginning with the preliminary experiments, where the main problems summarized in section 4 are identified

FIG. 7. Time series of the precipitation rate (mm h^{-1}) under the standard single-column configuration (black) to be compared with the observation (dark green). Here, the example is with $z_{\text{max}} = 30 \text{ km}$ and $z_{1,R} = 30 \text{ km}$, $N_p = 50$, and $\tau = 500 \text{ s}$ and $\Delta t = 2 \text{ s}$.

and the modifications in section 5 are introduced independently. For this reason, the results in the beginning of the section are somewhat unsatisfactory, but they improve as the modifications are introduced one by one.

a. Preliminary experiments

Figure 7 is a typical example of the results from the preliminary experiments that highlight a problem with the standard single-column configuration; namely, the convective response is never spontaneous and always has a substantial delay. Once convection is triggered, it causes extreme precipitation and dies out quickly, as in the first 4 days of simulation. After 4 days, the simulated convection almost completely dies out, and the response to the large-scale forcing causes stratiform rain over the environmental segment. The performance of the model under the stratiform rain after 4 days, though maybe not problem free, is definitely an improvement compared to the first 4 days because of the presence of convection. This is ironic because, effectively, the observed convective rain is predicted reasonably without convection. A rather good prediction of precipitation and apparent source, Q_1 and Q_2 , by environmental segments only is described by Yano et al. (2012). Preliminary attempts for addressing these problems are discussed in section a of appendix B. In the next subsection, we first test the sensitivity of the highly truncated NAM-SCA to the choice of the large-scale option introduced in section 5a with all the other original formulations retained.

b. Weighted large-scale forcing

In the tropical atmosphere, the adiabatic heating due to the subgrid-scale environmental descent defined as a deviation from the domain average is in overall balance with the large-scale forcing. This implies that the

FIG. 8. Time series of the precipitation rate (mm h^{-1}): (a) when the whole large-scale forcing is exclusively applied to the environmental segment ($i_L = 1$; black), and (b) when only the large-scale thermal forcing is exclusively applied to the environmental segment ($i_L[\theta] = 1$, $i_L[q_v] = 0$; black), to be compared with the observation (dark green).

large-scale forcing should be applied only to the environmental segment in Fig. 1 (having been divided by a fractional area occupied by the environmental segment) to enable compensating environmental descent. Therefore, we first apply both thermal and moist large-scale forcing only to the environmental segment, corresponding to the option $i_L = 1$ in section 5a.

Figure 8a illustrates the effects of the above modification: the convective response is totally suppressed and replaced by the large-scale environmental response. Animation reveals that the convective segments are dominated by descent rather than ascent despite the large-scale thermal forcing being limited to the environmental segment. Downdrafts in the convective segments dry the boundary layer therein, which further suppresses the convection. Moistening by the large-scale forcing, applied exclusively to the environmental segment, has the dominant effect of weak ascent in the environmental segment and a tendency over the convective segments as described.

To address this unfavorable tendency, the large-scale moisture tendency is applied homogeneously to the entire domain (i.e., $i_L[q_v] = 0$), as in the original formulation. Only the large-scale thermal forcing is restricted to

the environmental segment (i.e., $i_L[\theta] = 1$). This procedure did not change the model behavior, because the cooling tendency by large-scale forcing can readily be locally compensated by the condensation heating subject to the availability of moisture. The precipitation time series under this modification ($i_L[q_v] = 0$, $i_L[\theta] = 1$) in Fig. 8b begins with a prolonged 7.5-day active convective response, which is longer than Fig. 7 under the standard single-column configuration ($i_L = 0$). However, at later times, the response to the large-scale forcing is exclusively in the environmental segment as evidenced by the smooth time evolution of the precipitation rate. Unfortunately, the noisy convective response is not reduced by this modification.

Further analysis of these two cases in Fig. 9 shows the time–height section of the eddy-induced zonal-wind tendency defined by Eq. (3.1). Only a weak eddy-induced zonal-wind tendency occurs in the case corresponding to Fig. 8a with $i_L = 1$ because of downdrafts generated over the convective area (Fig. 9a). In the case corresponding to Fig. 8b with $i_L[\theta] = 1$ and $i_L[q_v] = 0$ (Fig. 9b), a substantial eddy-induced zonal-wind tendency occurs only in the first 7.5 days during the convective response.

It follows that the key procedure is to focus the large-scale moisture forcing on the convective segments and thus enable condensation of water to occur within those segments. There are two application options (cf. Fig. 1): (i) homogeneous over the three convective segments ($i_L[q_v] = 2$; convective segments case) and (ii) only to the innermost convective core segment ($i_L[q_v] = 3$; convective core case). Experiments were first performed with a finite surface-flux perturbation, that is, $\delta H \neq 0$ ($\delta H = 10^{-9} \text{ K s}^{-1}$ by default). However, a follow-up experiment presented in section *a* of appendix B showed that the surface-flux perturbation can be turned off postmodification, so cases with $\delta H = 0$ are presented below.

Confining the large-scale moistening exclusively to the middle-convective “core” locates the condensation heating and hence the convective updraft almost exclusively at core. On the other hand, a homogeneous distribution over the three convective segments leads to a variable location of the convective updrafts, which can adversely affect the organization of convection.

The results with these two choices are in Fig. 10, showing that the precipitation time series is much smoother, and it also occurs over the convective region, as confirmed by an animation. This result is further verified by the convection-induced zonal-wind tendency as a time–height section in Fig. 11, where the tendency is the vertical gradient of the Reynolds stress, as in Eq. (3.1). These results confirm that it is sufficient to focus the large-scale moisture forcing to the convective area

FIG. 9. Time–height section of the convectively induced zonal-wind tendency [Eq. (3.1)] for the cases shown in Fig. 8 with (a) $i_L = 1$ and (b) with $i_L[\theta] = 1$, $i_L[q_v] = 0$.

and inessential to limit the large-scale thermal forcing to the environment segment. As follows, the experiments are repeated by turning off the latter (i.e., $i_L[\theta] = 0$) and applying the large-scale thermal forcing homogeneously over the entire domain.

c. Convective organization experiments

The experiments in the last subsection significantly narrowed the choice of large-scale forcing to $i_L[\theta] = 0$ and $i_L[q_v] = 2$ or 3. In this subsection, we turn on the active surface-flux formulation ($i_f = 1$) in section 5b and examine the effects of the moving coordinate (section 5c). Figure 12 shows the convectively induced zonal-wind tendency. The left-hand diagram (Figs. 12a and 12c) shows the result of the large-scale moisture forcing applied to all three convective segments ($i_L[q_v] = 2$). The NAM-SCA generates predominantly shear-upgradient convective momentum transport with a fixed coordinate ($i_c = 0$; Fig. 12a). When the system moves with the estimated phase speed ($i_c = 1$), the shear-upgradient transport tendency is merely weakened and does not reverse (Fig. 12c). The right-hand diagram (Figs. 12b and 12d) shows the result when the large-scale moisture forcing is applied only to the central convective core segment ($i_L[q_v] = 3$). The convectively induced zonal-wind tendency is stronger and features a predominantly shear-upgradient momentum transport with a fixed coordinate (Fig. 12b). Finally, when the experiment is repeated with the

FIG. 10. As in Fig. 8b ($i_L[\theta] = 1$), but when the large-scale moisture forcing is further limited to (a) the three convective segments ($i_L[q_v] = 2$) and (b) the convective core ($i_L[q_v] = 3$).

moving frame ($i_c = 1$; Fig. 12d), occasional reversal of the zonal-wind tendency to shear downgradient corresponds to shear-parallel cloud-cluster events.

Figure 13 shows the precipitation time series as for the same four cases as in Fig. 12: all the time series are much smoother than in the previous cases (cf. Fig. 10), arguably apart from the case with (Fig. 13a, $i_L[q_v] = 2$ without coordinate transformation). The snapshots for the squall line and the shear-parallel bands for the last case in Figs. 12 and 13 ($i_L[q_v] = 3$ with moving coordinates) are shown in Figs. 14 and 15, respectively. Although spatially crude, the basic features in the full-resolution adaptive NAM-SCA simulations (cf. Figs. 5 and 6) are reproduced by the highly truncated NAM-SCA.

7. The TOGA COARE case study

To test the robustness of the highly truncated NAM-SCA with all the modifications introduced in the last two sections, the experiment is repeated for the whole 120 days of the TOGA COARE intensive observing period (IOP; 1 November 1992–28 February 1993). The large-scale moisture forcing option is set to $i_L[q_v] = 3$. The adopted large-scale forcing is based on an analysis over the intensive flux array (IFA) during this period processed at Colorado State University

FIG. 11. Time-height section of the convectively induced zonal-wind tendency [Eq. (3.1)] for the two cases shown in Fig. 10.

(http://tornado.atmos.colostate.edu/togadata/ifa_data.html; Ciesielski et al. 2003). As a modification from the GATE case, the observed SST value is used for computing the surface fluxes as described in section 5b [see Lin and Johnson (1996) for an observational overview of this period].

Only basic results are shown herein; namely, the time-height sections for the apparent heat source Q_1 and the apparent moisture sink Q_2 in Fig. 16 and the precipitation time series in Fig. 17. The prediction of Q_1 and Q_2 for this case may be compared with those for the GATE case presented by Fig. 17a in Yano and Moncrieff (2016). These two figures, which are pertinent to observation and the simulation, demonstrate that the highly truncated NAM-SCA runs successfully for the full 120-day period. A possible reason why the precipitation tends to overshoot the observations is that the rain observations are not well constrained. Alternatively, this may be a remaining problem with the highly truncated NAM-SCA, still to be solved.

8. Summary and closing remarks

a. Summary

The highly truncated NAM-SCA approach was introduced by Yano and Moncrieff (2016) to represent mesoscale convective organization as a subgrid-scale process. This approach is a numerical counterpart of the Moncrieff (1992) archetypal analytic model, which is the

FIG. 12. With the active surface flux ($i_f = 1$) added under the standard large-scale thermal forcing ($i_L[\theta] = 0$), but the large-scale moisture forcing applied (a),(c) to all the three convective segment ($i_L[q_v] = 2$) and (b),(d) only to the central convective core segment ($i_L[q_v] = 3$). In (a) and (b), the observed mean zonal wind $\bar{u}$ is prescribed. In (c) and (d), the mean zonal wind $\bar{u} - c_p$ subtracted from the phase velocity c_p , defined as the density-weighted vertical average of the mean zonal wind, is used instead.

minimalist analog of his previous more complete nonlinear dynamical models (e.g., Moncrieff and Green 1972; Moncrieff and Miller 1976; Moncrieff 1978, 1981). Therefore, the drastic truncation that permits NAM-SCA to be utilized as a subgrid-scale parameterization has a robust physical and dynamical basis. From the numerical standpoint, the highly truncated NAM-SCA

is a nonhydrostatic anelastic system discretized into four finite-volume segments in a periodic domain. Yano and Moncrieff (2016) considered the simple case of steady large-scale forcing. The present paper shows the capacity of highly truncated NAM-SCA to represent mesoscale systems in time-varying large-scale forcing conditions. The GATE Phase III period is selected

FIG. 13. As in Fig. 12, but precipitation time series are plotted.

FIG. 14. Four snapshots 2 h apart of a squall-line system for the day 6 (4 Sep) simulated by the highly truncated NAM-SCA for 8 h. The color shades show the total condensate (g kg^{-1}).

mainly because two distinct categories of convective organization, shear-perpendicular and shear-parallel rainbands, were observed during the intensive observation period. The application of NAM-SCA in these conditions was not straightforward, and critical modifications of the original formulation were necessary.

A general problem with the original NAM-SCA formulation is the delay of the convective response in time-evolving large-scale forcing conditions. When deep convection eventually forms, it is noisier than observations, and the planetary boundary layer dries rapidly. After a few days, the convective subcolumns are dry, and in turn, the environment segment responds to the large-scale forcing as stratiform precipitation. Our preliminary experiments examined various possibilities. For instance, an increased perturbation in surface heating δH aims to maintain the convection and shorten the convective response time. While this has positive

effects, it unfortunately exacerbates the noisiness and adversely affects the numerical stability.

To overcome the above problem, three modifications are applied to the single-column configuration. First, the large-scale forcing formulation is generalized (section 4a), and the following options are considered. When the large-scale forcing is applied only to the environment segment, one might expect that negative buoyancy generated by the adiabatic cooling due to the large-scale ascent would induce the environmental descent. However, the large-scale moisture supply to the environmental segment causes condensation in that segment, which dominates the descent-based drying associated with the large-scale thermal forcing. The preferred configuration concentrates the large-scale moisture tendency on the single convective core segment and retains the large-scale heating tendency as in the standard formulation. Second, introduction of an active surface flux

FIG. 15. As in Fig. 14, but for the shear-parallel bands during day 14.

based on a bulk formulation (section 4b) is crucial for the maintenance of a spontaneous convective response. Third, the introduction of a system-relative coordinate system is computationally important. The estimated propagation speed of the coordinate system is a density-weighted vertical average of environmental wind. A side benefit of the latter two modifications is the removal in the original formulation of an artificial surface-flux perturbation.

b. Weighted large-scale moisture forcing: Physical rationale

The introduced weighted large-scale forcing formulation, at first sight, may appear unphysical but can nevertheless be justified in terms of the following two closely related considerations.

First, in real situations, convection is triggered independently at different locations of the horizontal domain in response to large-scale moistening. More

specifically, propagating mesoscale convective organization (e.g., a squall line) would sweep through the domain and efficiently consume the available moisture provided by a large-scale advection. However, under the highly truncated NAM-SCA configuration, convection is permitted only within three central narrow segments (cf. Fig. 1), and the large-scale moisture supply outside of these three segments (i.e., the environmental region) would be unrealistically consumed by stratiform clouds if not efficiently transported into the convective segments—the recursive problem identified at an early stage of testing (cf. discussions associated with Figs. 7 and 8). This tendency can be avoided by “focusing” the large-scale moistening on the convective segments, because under the truncated NAM-SCA formulation, convection itself does not propagate.

Second, the basic idea of NAM-SCA may be considered as subdividing the gridbox domain into subdomains

FIG. 16. Time–height section of (left) Q_1 and (right) Q_2 (K day^{-1}) during the TOGA COARE IOP: (top) observation, (middle) simulation result, and (bottom) the difference (experiment – observation).

and let them individually represent subgrid-scale processes. However, simply subdividing the gridbox domain is insufficient [essentially a mesh-refinement procedure, as pointed out in section 7.1 of Yano (2016)], but each subdomain must somehow be “prescribed” to perform an expected function (convective updrafts, downdrafts, etc.). This last problem is called “subcomponent prescription” in section 4.5 of Yano (2012). In this respect, a heavy weighting of the large-scale moisture forcing to convective segments is considered a particular form of subcomponent prescription. Note that the surface-flux perturbation δH added in the original formulation (which may also equally be considered artificial) is an alternative prescription of the convective segments. As our numerical experiments show, the weighted large-scale forcing obviates this prescription procedure.

c. Weighted large-scale moisture forcing and the free-ride principle

The weighted large-scale moisture forcing is designed to accomplish the following balance observed in the tropical atmosphere:

$$w \frac{d\bar{q}}{dz} \simeq -\frac{C_p}{L} Q_2, \quad (8.1)$$

where C_p and L are the heat capacity at constant pressure and the latent heat, respectively. Following

Fraedrich and McBride (1989), Yano and Plant (2015) called this balance the “free-ride principle.” Legitimacy of Eq. (8.1) is ensured by focusing the large-scale moisture forcing (left-hand side) on the convective region where condensation, represented by Q_2 (right-hand side), occurs because of the vertical transport of moisture.

The equivalent thermodynamic free-ride principle,

$$w \frac{d\bar{\theta}}{dz} \simeq Q_1 + Q_R, \quad (8.2)$$

is less straightforward. The vertical heat transport that leads to adiabatic cooling is not compensated by the

FIG. 17. Precipitation time series during the TOGA COARE IOP: observation (dark green) and the experiment (black).

condensation heating Q_1 in a direct manner. Moisture supply is required rather than adiabatic cooling. It is not legitimate to focus on the large-scale thermal forcing on the convective region. It could be appropriate to focus on the environmental segment of compensating environmental descent, but that does not work in practice.

Geleyn et al. (1982) and Lindzen (1981, 1988) proposed an analogous approach salient to Eq. (8.1) in the form of a convective parameterization closure condition. Although somewhat at odds with the physics of convection, which is driven by buoyancy rather than moisture per se, their configuration recalls the key point that the moisture condensation is the principal source of convective buoyancy. On this basis, Yano and Plant (2016) proposed the convective-scale moisture budget as a possible basis for convection parameterization closure.

d. Limits of the two-dimensional configuration

The two-dimensional configuration of NAM-SCA is legitimate for shear-perpendicular systems, such as squall lines, which are observed to be approximately two-dimensional. There are comprehensive literature reviews on this particular aspect and its role in global weather and climate (e.g., Houze 2004; Moncrieff 2010; Moncrieff and Waliser 2015). Shear-parallel cloud clusters are more problematic because they are inherently three-dimensional (Houze and Betts 1981; Dudhia and Moncrieff 1987; Khouider and Moncrieff 2015). While the highly truncated NAM-SCA can represent the momentum transfer tendencies for both

TABLE A1. Choice of the model-top height-dependent parameters.

$z_{\max}$ (km)	N_v	$z_{1,R}$ (km)	$z_{2,R}$ (km)
25	20	15	20
30	20	15	25
40	40	15	35
50	40	15	35
60	45	20	50
70	45	20	50

regimes, the morphology of the shear-parallel systems is severely compromised, so three-dimensional computation is a necessity for these systems. The next crucial goal and significant challenge in NAM-SCA development is the generalization to a fully three-dimensional configuration.

APPENDIX A

List of Parameters

a. Parameters independent of the model-top height

$L = 512$ km: horizontal domain size

$N = 4$: total number of segmentally constant segments

$$\Delta t = \begin{cases} 5 \text{ s} & \text{: default in preliminary experiments} \\ 15 \text{ s} & \text{: final default} \end{cases}$$

$\tau_R = 60$ s: the maximum Rayleigh damping time scale in the sponge layer

$$\delta H = \begin{cases} 10^{-9} \text{ K s}^{-1} & \text{: default in preliminary experiments } (i_p = 1) \\ 0 \text{ K s}^{-1} & \text{: final default } (i_p = 0). \end{cases}$$

Constant perturbation sensible heat flux applies to the core convective segment ($j = 2$). The perturbation heat flux of $-\delta H/4$ is added to the two adjacent convective segments ($j = 1, 3$).

b. Model-top height and dependent parameters (with default values)

$z_{\max} = 70$ km: model-top height

$N_z = 45$: total number of full vertical levels

$z_{1,R} = 20$ km: the bottom of the sponge layer

$z_{2,R} = 50$ km: the level above which the maximum Rayleigh damping rate is imposed

See Table A1 when the model-top height different from $z_{\max} = 70$ km is used.

c. Flags for the model configuration

i_p : the choice of the perturbation heat flux, δH ($i_p = 1$ when $\delta H \neq 0$; $i_p = 0$ when $\delta H = 0$; appendix A, section a)

i_f : choice of the surface flux [$i_f = 0$: prescribed by observation; $i_f = 1$: computed by bulk formula (section 4b)]

i_L : large-scale forcing formulation choice (cf. section 4a; default: $i_L[\theta] = 0$, $i_L[q_v] = 3$)

FIG. B1. The RMS errors as functions of the time step Δt with $z_{\max} = 30$ (solid), 50 (long dash), and 70 km (short dash): (a) precipitation rate (mm h^{-1}), (b) apparent heat source (K day^{-1}), and (c) apparent moisture sink (K day^{-1}).

i_c : choice of the horizontal coordinate [$i_c = 0$: in fixed coordinate ($c_p = 0$); $i_c \neq 0$: in moving coordinate ($c_p \neq 0$)]

APPENDIX B

Further Model Sensitivities

This appendix summarizes further tests of the sensitivities of the highly truncated NAM-SCA. The first section describes details of preliminary experiments, and the remainder describes the sensitivity test under the weighted large-scale moisture forcing formulation with $i_L[\theta] = 0$ and $i_L[q_v] = 3$ introduced in section 4a.

a. Further details of the preliminary experiments

Under the preliminary setting (with $i_p = 1$, $i_f = 0$, and $i_c = 0$), a series of experiments examine the sensitivity on the strength of the imposed surface heat-flux perturbation δH for the range of 0 – 10^{-5} K s^{-1} with both $i_L[q_v] = 2$ and 3. Here, $i_L[\theta] = 0$. In both cases, the simulations are insensitive to the surface heat-flux perturbation, although

FIG. B2. Time–height section of the convectively induced zonal-wind tendency [Eq. (3.1)] with $z_{\max} = 50 \text{ km}$ for examining the time step dependence: (a) $\Delta t = 15$ and (b) $\Delta t = 30 \text{ s}$. Both in moving frames.

the runs with $\delta H = 10^{-5}$ and $\delta H = 0 \text{ K s}^{-1}$ with $i_L[q_v] = 3$ become numerically unstable at 12.5 days and 15 days, respectively. This implies that the highly truncated NAM-SCA may be unstable beyond the certain range of the surface heat-flux perturbation values, when other parts of the setup are less well defined.

On the other hand, with the modified large-scale moisture forcing, the function of surface heat-flux perturbation designed to maintain a convective-scale circulation is, in principle, no longer necessary. The success with $i_L[q_v] = 3$ and $i_f = 1$ suggests that it is actually meaningful to turn it off. This reasoning leads us to set $\delta H = 0$ ($i_p = 0$) in the default experiments.

b. Time stepping

The following experiments examine sensitivities in terms of the root-mean-square (RMS) errors of the precipitation, the apparent heat source Q_1 and the apparent moisture sink Q_2 against the observational diagnosis as in Yano et al. (2012). Although the convective momentum transfer is, arguably, more important for the effects of convective organization, the error estimate was not possible with a lack of an observational reference.

In performing the preliminary results in sections 6a and 6b, the default choice is set to $\Delta t = 5 \text{ s}$. The possibility of lengthening the time step is examined under this preliminary setup: the case with $z_{\max} = 70 \text{ km}$ and the original default setup ($i_p = 0$, $i_f = 0$, and $i_c = 0$) is

FIG. B3. The RMS errors as functions of the top model height, $z_{\max}$: (a) precipitation rate (mm h^{-1}), (b) apparent heat source (K day^{-1}), and (c) apparent moisture sink (K day^{-1}).

extendable to the time step, $\Delta t = 10$ s. When the active surface flux as well as the moving coordinate are further introduced to the above ($i_p = 1$, $i_f = 1$, and $i_c = 1$), it is possible to extend it to $\Delta t = 15$ s. Thus, in the main part of the analysis in section 6b, the default time step is increased to $\Delta t = 15$ s.

Figure B1 shows the RMS errors of the highly truncated NAM-SCA, with the default setting ($i_p = 0$, $i_f = 1$, and $i_c = 1$), as functions of the time step with $z_{\max} = 30$ (solid), 50 (long dash), and 70 km (short dash). Note that the scheme does not run with $\Delta t > 30$ s for $z_{\max} = 30$ and 50 km and with $\Delta t > 15$ s for $z_{\max} = 70$ km. This is implied by a general tendency for the errors to increase with increasing time step. However, as the case for the top height dependence shown later (in Fig. B3), the sensitivities of the scheme on the choice of the time step are, as a whole, relatively weak. The sensitivities are the largest with $z_{\max} = 50$ km, and the errors increase by 20% by increasing the time step from 5 to 30 s.

A relatively weak increase of the errors with increasing time step is tempting to choose the largest possible time step ($\Delta t = 30$ s). However, the increase of the errors with the convective momentum transfer is much larger with increasing time step, as seen in Fig. B2. A clear

FIG. B4. Time-height section of the convectively induced zonal-wind tendency [Eq. (3.1)] with $z_{\max} = 30$ km but under (a) the fixed coordinate and (b) the moving frame.

deterioration of the convective momentum transfer with $\Delta t = 30$ s, with strongly noisy behavior in time, makes this choice simply unpractical. A need for a relatively short time step in NAM-SCA simulations is discussed in section 3.3 of Yano and Lane (2014), especially for properly describing the convective momentum transport.

c. The model-top height $z_{\max}$

The sensitivity of the result on the model-top height $z_{\max}$ is also examined with the default setting ($i_p = 0$, $i_f = 1$, $i_c = 1$, and $i_L[\theta] = 0$, and $i_L[q_v] = 3$): the results are shown in Fig. B3 in terms of the RMS errors. The other parameters are as in Table A1. In general, the number of vertical levels are chosen such that the lowest-layer depth of about 200 m gradually stretches to about 2 km at the model-top level logarithmically. The lowest level, z_1 , for imposing the Rayleigh damping is chosen high enough not to affect the performance of the scheme in the troposphere but low enough so that a sufficiently deep sponge layer is in place. According to the experience with Yano and Lane (2014), a deep sponge layer is required in order to properly absorb the upward-propagating gravity waves. Henceforth, we expect that the model performance improves with the increasing model-top height. However, this tendency is only true with the errors for the apparent heat source (Fig. B3b). The minimum of the errors is found with $z_{\max} = 30$ km both for the precipitation and the apparent moisture sink. Overall, the performance of the scheme is insensitive to

FIG. B5. Time–height section of the convectively induced zonal-wind tendency [Eq. (3.1)] with (a) $L_1 = L_3 = 64$ km, $L_2 = 16$ km, and (b) $L_1 = L_2 = L_3 = 16$ km.

the choice of $z_{\max}$, and the errors do not fluctuate more than 10% over the whole range considered.

The performance with a low model-top height with $z_{\max} = 30$ km is promising, because it suggests that the highly truncated NAM–SCA can run relatively efficiently with a relatively small number of vertical levels. However, the main drawback with the low ceiling is that it hinders proper convective organization, and as a result, insufficient eddy momentum transfer occurs, as seen in Fig. B4.

d. Choice of segment sizes

Finally, the sensitivities on the choice of the segment sizes are examined (cf. Fig. 1). Here, the three types of sensitivity test are performed. The first is when the convective core segment size L_2 is further reduced; the second is when the size $L_2 = L_3$ of the side convective segments is further increased; and the third is a set of cases setting all the convective segment sizes equal, $L_1 = L_2 = L_3$.

A further decrease of the convective core size L_2 simply destabilizes the model. All the choices attempted ($L_2 = 8, 4$, and 2 km) exploded in less than one day. An increase of the side convective segment size $L_1 = L_2$ turns out to be less unstable. However, the case with $L_1 = L_3 = 128$ km runs for less than one day. The case with $L_1 = L_3 = 64$ km is stable, and the resulting convective momentum transport–induced zonal-wind tendency [Eq. (3.1)] is shown in Fig. B5a, a snapshot at $t = 6$ days (squall-line regime) in Fig. B6a and the precipitation time series in Fig. B7a. The

FIG. B6. Snapshots (at $t = 6$ days) of the squall-line regime simulated by three different segment size distributions: (a) $L_1 = L_3 = 64$ km, $L_2 = 16$ km, and (b) $L_1 = L_2 = L_3 = 16$ km and (c) $L_1 = L_2 = L_3 = 32$ km.

FIG. B7. Precipitation time series with three different segment size distributions: (a) $L_1 = L_3 = 64$ km, $L_2 = 16$ km, (b) $L_1 = L_2 = L_3 = 16$ km, and (c) $L_1 = L_2 = L_3 = 32$ km.

performance for this case is overall comparable with the standard configuration.

Three equal-sized narrow convective segments with $L_1 = L_2 = L_3 = 8$ km turns out to be numerically unstable, and it runs only for 13 days. The cases with $L_1 = L_2 = L_3 = 16$ and 32 km run successfully. With $L_1 = L_2 = L_3 = 16$ km, the tendency for the convective momentum transport-induced zonal wind is much reduced (Fig. B5b), and the tendency with $L_1 = L_2 = L_3 = 32$ km is even weaker (not shown). The reason is understood in terms of less efficient generation of downdrafts in both cases as indicated by the snapshots in Figs. B6b and B6c. On the other hand, the precipitation time series (Figs. B7b and B7c) tends to be noisier under this configuration, which is reminiscent of the preliminary run results (cf., Figs. 7 and 8), and it is exacerbated with the increasing segment sizes.

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