The Resolution Dependence of Model Physics: Illustrations from Nonhydrostatic Model Experiments

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ABSTRACT

The goal of this paper is to gain insight into the resolution dependence of model physics, the parameterization of moist convection in particular, which is required for accurately predicting large-scale features of the atmosphere. To achieve this goal, experiments using a two-dimensional nonhydrostatic model with different resolutions are conducted under various idealized tropical conditions. For control experiments (CONTROL), the model is run as a cloud-system-resolving model (CSRM). Next, a “large-scale dynamics model” (LSDM) is introduced as a diagnostic tool, which is a coarser-resolution version of the same model but with only partial or no physics. Then, the LSDM is applied to an ensemble of realizations selected from CONTROL and a “required parameterized source” (RPS) is identified for the results of the LSDM to become consistent with CONTROL as far as the resolvable scales are concerned.

The analysis of RPS diagnosed in this way confirms that RPS is highly resolution dependent in the range of typical resolutions of mesoscale models even in ensemble/space averages, while “real source” (RS) is not. The time interval of implementing model physics also matters for RPS. It is emphasized that model physics in future prediction models should automatically produce these resolution dependencies so that the need for retuning parameterizations as resolution changes can be minimized.

1. Introduction

It has been well recognized that cumulus convection in the Tropics plays a central role in the maintenance and evolution of the atmosphere (e.g., Riehl and Malcus 1958) and, therefore, cumulus parameterization has almost always been a core of numerical modeling of the atmosphere. Since the 1960s, a number of cumulus parameterization schemes have been proposed for use in weather prediction and climate simulation models. Early examples of such schemes include Manabe et al. (1965), Kuo (1974), Arakawa and Schubert (1974), and Betts and Miller (1986). In spite of the accumulated experience with these and other schemes over the last decades, however, cumulus parameterization remains a young subject. Besides the very basic question of how to pose the problem, there are a number of uncertainties in modeling cloud and associated processes and in formulating their overall effects on the large-scale environment (e.g., Arakawa 2000).

More generally, as emphasized in a forthcoming paper by Arakawa (2003, submitted to J. Climate), there are the following conceptual problems in conventional model physics used in existing models.

1) Due to the modular structure of models, different physical processes interact only through grid-scale prognostic variables. In the past, our modeling effort has primarily been spent on introducing individual physical processes (radiation, turbulence, large-scale condensation and precipitation, cumulus convection, stratiform cloud formation, chemistry, etc.) more or less separately from each other. Consequently, conventional model physics typically has a modular structure, in which each physical process is formulated as if the others are known. Interactions between these processes then take place only through the time evolution of grid-scale prognostic variables, missing most of their subgrid-scale interactions.

2) Parameterized physics does not converge to real physics as the model’s resolution is refined. Justification of using a discrete model relies on the hope that its solution converges to the solution of the original continuous system as the resolution is refined. When the original equation is specified in a differential form, convergence is a mathematical property of the discrete analog of that equation (e.g., Richtmyer and Morton 1967; Haltiner and Williams 1980). For atmospheric models, however, this concept of convergence cannot be directly applied. Because model physics must include parameterized effects of unresolved scales, the nature of the convergence problem for atmospheric models is quite different.
from that anticipated from the purely mathematical point of view, even when the nonhydrostatic equations are used throughout to eliminate the convergence problem for model dynamics.

The main motivation for the present study comes from the recognition of these problems, the second in particular. Although we are primarily concerned with parameterization of cumulus convection, we can illustrate the convergence problem in a much simpler way for parameterization of diffusion processes. For the atmosphere, molecular processes are effective only for the scales shorter than, say, a centimeter. When the model equation does not resolve such scales, the relevant diffusion process is not the molecular diffusivity but the eddy diffusivity due to turbulence. Formulation of the latter process obviously depends on how we define the mean and, therefore, it is resolution dependent when applied to a discrete model. Convergence of the model physics then requires that the eddy viscosity eventually vanish and the molecular viscosity take over as the resolution is refined. [This convergence problem, however, hardly matters in practice because virtually all atmospheric models, including large eddy simulation (LES) models for turbulence (see Moeng 1998 for a review), are applied to scales for which molecular diffusivity is negligible.]

The convergence problem is far more serious and complicated for parameterization of cumulus convection. A usual assumption implicit in cumulus parameterization schemes is that turbulence processes are already parameterized in terms of cloud-scale variables so that cumulus parameterization can concentrate on the link between cloud and larger scales, including the mean transports induced by cloud processes. The distinction between cloud and larger scales is, however, usually made through a nonphysical scale introduced for computational purpose—grid size—which is not necessarily sufficiently larger than the typical size of individual deep cumulus clouds. This generates difficulties in high-resolution models in which grid-scale and subgrid-scale moist processes are not well separated as is typical in mesoscale models (Molinari and Dudek 1992; see also Molinari 1993 and Frank 1993).

Under such situations, it is not obvious even what the input from model physics to model dynamics should be for different resolutions. Conventional model physics is designed and turned for a fixed model resolution, not to formulate physics as a function of resolution in such a way that it automatically converges to the physics of individual cloud systems as the model’s resolution is refined. As a consequence, model results can become worse with a higher resolution unless the model physics is reformulated. At present, this kind of reformulation is commonly done through retuning the parameterizations. There are two standard methods that directly use observations for testing parameterization schemes. The first method, which was initiated by Lord (1982), compares sources calculated with a parameterization scheme for an observed state with the apparent sources diagnosed from the residuals in the observed large-scale budgets (a semiprognostic test). The second method, which was initiated by Betts and Miller (1986), is through integrating a single-column version of the model forced by observed large-scale processes (a single-column prediction test). Both of these methods, however, can hardly verify the scale dependence of parameterized effects because of the strong constraint on the methods by the network size and frequency of observations.

The approach followed in this study involves a systematic use of nonhydrostatic models. Nonhydrostatic cloud models have been used by many authors to study the dependence of model response on model resolution. For example, Weisman et al. (1997) investigated the effect of resolution on the evolution of midlatitude squall lines in the range of 1 and 12 km horizontal grid sizes. They showed that the model response is degraded as the resolution is decreased and suggested that the 4-km resolution is the minimum resolution necessary to explicitly simulate a squall-line-type systems. In a similar way, Nasuno and Saito (2002) investigated capabilities and limitations of using explicit physics for simulating a tropical squall line. Also, Liu et al. (2001) conducted numerical experiments using a 2D cloud-resolving model and 2D and 3D coarse-grid models with or without convective parameterization in the range from 10 to 25 km horizontal grid sizes. They suggested that a moist-convective parameterization is essential for a realistic simulation of the 3D squall system in the mesoscale range, whereas nonsquall clusters can be simulated without it. Commonly, these studies pointed out the need of a moist-convective parameterization even in mesoscale models.

A part of this paper is devoted to confirm the need of cumulus parameterization for resolutions in the mesoscale range using our own model (section 3). This further motivates us to look into this range of resolution more deeply, with the objective to gain insight into the resolution dependence of model physics, including its convergence to the physics of the original system. Specifically, we analyze simulated “real source” (RS) and “required parameterized source” (RPS) in the thermodynamic and moisture budget equations. Here RS stands for the source produced by a model that explicitly and accurately resolves all relevant processes. Since we have the cumulus parameterization problem in mind, we temporarily assume that a cloud-system-resolving model (CSRM) is sufficient to identify RS. Then RPS becomes the source required by a coarser-resolution version of the model for its solution to be consistent with the solution of the CSRM as far as resolvable scales are concerned.

The paper is organized as follows. Section 2 describes the model that we use and presents the results of the CONTROL experiments. To confirm the need of a cu-
imum parameterization for typical resolutions of meso-scale models, section 3 presents simulations using the same formulation of model physics as in CONTROL but with coarser resolutions. Section 4 discusses the conceptual difference of RPS from simple averages of RS and describes the approach we use to diagnostically identify RPS from model results. Sections 5 and 6 present the main results of this paper: analysis of the dependence of RPS on time intervals for implementing physics and horizontal resolution. These results suggest what the model physics in future prediction models is supposed to produce for different resolutions. Finally, section 7 presents summary and conclusions.

2. CONTROL experiments

a. The model

A 2D nonhydrostatic CSR MM is used throughout this study. Although the two-dimensionality is an artificial constraint, 2D models have been applied to actual situations rather successfully as far as the bulk thermodynamic effects of cumulus convection are concerned (see, e.g., Xu et al. 2002; Xie et al. 2002). This is probably because cumulus convection is dominantly penetrative and, unlike the problem of turbulence generated by local shears, the 1D parcel method is still a useful starting point. A 2D model at least introduces an important step beyond the parcel method by allowing the cloud–environment interactions to be explicit.

The CSRM, originally developed by Krueger (1988), is based on the anelastic set of equations with the Coriolis force. The physical parameterizations in the model include a third-moment turbulence closure (Krueger 1988), a diagnostically determined turbulence length scale (Xu and Krueger 1991), a scheme for turbulent-scale condensation (Chen 1991), a three-phase microphysical parameterization (Krueger et al. 1995a; Lord et al. 1984), and an advanced radiative transfer parameterization (Fu et al. 1995; Krueger et al. 1995b). The model has been extensively applied to study a variety of cloud regimes including stratocumulus, alto-cumulus, cumulonimbus, and cirrus clouds (see, e.g., Krueger 2000).

b. Experiments

In this study, we apply the CSRM with 2-km horizontal grid size to an idealized 512-km horizontal domain. In the vertical, the model has 34 levels based on a stretched grid with a top at 19 km. The vertical grid size ranges from about 100 m near the lower boundary to about 1000 m near the model top. The upper and lower boundaries are rigid and the lateral boundaries are cyclic.

Two types of idealized surface conditions are used: ocean and land. There is no diurnal variation over ocean with a prescribed temperature of 299.7 K. In this case, the cosine of the solar zenith angle is set to 0.5, representing a typical daytime condition. Over land, diurnal cycles are included with the ground wetness set to 75%.

The initial thermodynamic state is based on the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) Phase III mean sounding. The initial horizontal wind field is set to $-2$ m s$^{-1}$ everywhere. The Coriolis parameter for 15°N is used.

Large-scale advective cooling and moistening are prescribed as forcing, which is either zero or strong, as shown in Fig. 1a. In this figure, the moistening is multiplied by $L/c_p$, where $L$ and $c_p$ are the latent heat of condensation and the specific heat of dry air, respectively. The strong forcing is obtained by enhancing the mean vertical distributions of advective cooling and moistening for the GATE Phase III. The prescribed large-scale forcing varies in the horizontal according to a full cosine function with a maximum at the center of the model domain (Fig. 1b).

As CONTROL experiments, we perform integrations of the CSRM for each of the four combinations of the land/ocean surface conditions without/with prescribed large-scale forcing. Each integration is 13 days long with a 10-s time step. The radiative fields are calculated every 150 s.

We first examine the simulated budgets of moist static
energy $h$ and total water (water vapor + cloud liquid water) mixing ratio $Q$. Recall that condensation does not influence these quantities. The budget equation for the moist static energy $h$ can be written as

$$\frac{\partial h}{\partial t} = -\frac{1}{\rho_0} \nabla \cdot (\rho_0 \mathbf{V} h) + \left( \frac{\partial h}{\partial t} \right)_{\text{LS}} + \left( \frac{\partial h}{\partial t} \right)_{\text{SA}} + R + M$$

$$- \frac{1}{\rho_o} \nabla \cdot \mathbf{F}_h,$$  \hspace{1cm} (1)

where $\rho_0$ is the density of the reference state and $\mathbf{V}$ is the velocity. The first term in the right-hand side represents the transport process explicitly treated in the model and the remaining terms represent the sources of $h$ due to various processes. The term with the subscript LS stands for the prescribed large-scale effect to force the model. The term with the subscript SA stands for the effects of freezing (melting) and sublimation associated with the grid-scale saturation adjustment included in the model; $R$ is the radiative heating (cooling), $M$ is the source (sink) of moist static energy due to the parameterized subgrid-scale cloud-microphysical processes involving ice phase, and $\mathbf{F}_h$ is the turbulent flux of $h$. Similarly, the budget equation for the total water mixing ratio $Q$ can be written as

$$\frac{\partial Q}{\partial t} = -\frac{1}{\rho_0} \nabla \cdot (\rho_0 \mathbf{V} Q) + \left( \frac{\partial Q}{\partial t} \right)_{\text{LS}} + \left( \frac{\partial Q}{\partial t} \right)_{\text{SA}} + P$$

$$- \frac{1}{\rho_o} \nabla \cdot \mathbf{F}_Q,$$  \hspace{1cm} (2)

where $P$ is the net source (sink) of total water due to the parameterized subgrid-scale cloud-microphysical processes involving either ice phase or precipitation (e.g., formation of rain, snow and graupel, rain evaporation, sublimation/deposition of snow and graupel, and formation of cloud ice via the Bergeron process); $\mathbf{F}_Q$ is the turbulent flux of $Q$.

Among the components in (1) and (2), here we present the simulated sources due to radiative, turbulent, and cloud-microphysical processes. Figure 2 shows the domain- and time-averaged profiles of these sources for moist static energy divided by $c_p$ for each CONTROL. Clearly, which sources/sinks are dominant depends on the height. Near the tropopause level, the sink of moist static energy due to radiation is dominant for all cases. This can be attributed to the radiative cooling near the top of upper-tropospheric stratiform clouds. The sources/sinks of moist static energy due to microphysical processes are prominent especially with the strong large-scale forcing. The microphysical sources due to the la-
tent heat release through the depositional growth of cloud ice and the formation of snow and graupel are located in the broad range of height between 5 and 10 km (Figs. 2b,d). Allowing the coexistence of cloud liquid water and ice above $-40^\circ$C in the model explains the existence of such a broad range. The microphysical sinks due to the latent heat absorption through the melting of snow and graupel are located in the narrow region around the 5-km level. The convergence of turbulent flux is the main source of moist static energy near the surface for all cases. Besides, we see a secondary maximum in the turbulent source around the 2-km level in each of the simulations with the land condition (Figs. 2a,b).

Figure 3 is the same as Fig. 2 but for the total water multiplied by $L/c_p$. With the strong large-scale forcing, pronounced microphysical sinks exist in the middle troposphere, mainly due to the conversion of cloud liquid water to rain, snow and graupel, and to cloud ice via Bergeron process (Figs. 3b,d). Without large-scale forcing, on the contrary, only weak microphysical sources exist in the middle troposphere due to the evaporation of rain and the sublimation of snow and graupel in cloud-free regions. Near the surface, both the convergence of turbulent flux and the evaporation of rain become the main sources of total water. The secondary maxima in the turbulent sources are also found near the 2-km level (Figs. 3a,b).

In order to see why the secondary maxima appear in the turbulent sources, we analyze the composite domain-averaged turbulent sources of moist static energy and total water as functions of local time for the case of land without large-scale forcing (Fig. 4). We see that the boundary layer deepens during the daytime, extending the turbulent flux to about the 1-km level. In the afternoon, the turbulence activity tends to decrease with time, but the secondary maximum still appears above the 1-km level due to shallow clouds often formed during afternoon. In the case of strong large-scale forcing (not shown), the secondary maximum is less distinct due to weaker diurnal changes.

3. Coarser-resolution experiments with identical formulations of model physics

We present in this section experiments with coarser resolutions to confirm that a cumulus parameterization is required even in models with resolutions in the mesoscale range. In these experiments, we repeat the integrations described in section 2 using identical formulations of model physics but with 8-, 16-, 32-, and 64-km horizontal resolutions. Here we only show the results of the land simulations with 8- and 32-km horizontal resolutions. The results of ocean simulations are similar to those of land simulations especially with strong forcing, and the results with 16- and 64-km resolutions can be qualitatively inferred from those with the resolutions shown.
To visualize the impact of different resolutions on the simulation, we first present snapshots of cloudiness (light gray), precipitation (dark gray), and wind (arrows) with the strong large-scale forcing over land conditions for each resolution (Fig. 5). In the figure the zonal average of the zonal wind component is removed from the wind field. In CONTROL, organized cloud systems and local small-scale circulations are coexisting. As the resolution decreases, however, the small-scale circulations are not resolved. Instead, we see that spurious mesoscale circulations develop as substitutes to the unresolved cumulus convection, especially with the 32-km grid size. These characteristic features appear throughout the entire integration period.

Figure 6 shows the composite domain-averaged (heavy line) surface precipitation and its standard deviation (gray) as functions of local time for no forcing and land conditions. Contour interval is 0.2. The sink areas are shaded gray.

We also see that the fluctuation of precipitation becomes large as the grid size increases. It can be attributed to the spurious mesoscale circulations that have longer lifetime than cloud-scale circulations. Such a feature can be seen more clearly in Fig. 7, which shows the composite domain-averaged kinetic energy (heavy line) and its standard deviation (gray) as functions of local time, for vertical (left) and horizontal (right) components. Here, only the results from the simulations with no forcing are presented because the strong forcing case shows similar features. The kinetic energy for vertical component decreases as the grid size increases, while the kinetic energy for horizontal component increases. This is consistent with the fact that the spurious circulations in the coarser-resolution simulations have a large horizontal dimension. We also see in Fig. 7 that distinct diurnal cycles exist in CONTROL, but not in the simulations with coarse resolutions.

Figure 8 displays the deviations of the domain- and time-averaged moist static energy divided by $c_p$ (upper) and total water multiplied by $L/c_p$ (lower) from those of CONTROL. (Here the time average is taken over the last 10 days of the 13-day integration.) These deviations represent the errors due to the use of the coarse resolutions. As anticipated, the errors are larger with the 32-km resolution than with the 8-km resolution. In the no-forcing case, the error is mainly in the lower-level water-vapor field, presumably due to poor simulations of the diurnal cycle of the planetary boundary layer and shallow clouds. In the strong-forcing case, the error is mainly in the upper-level water-vapor field, presumably due to poor simulations of deep convection and associated upper-tropospheric stratiform clouds. In the runs with the coarse resolutions, the spurious mesoscale circulations are almost entirely responsible for the vertical transports in the free atmosphere.

Consequently, errors appear even in the domain- and time-averaged vertical profiles of the simulated thermodynamic variables.

Then, let us take a look at the sensitivity of simulated sources due to cloud microphysics, radiation, and turbulence to horizontal resolution. Figure 9 shows the domain- and time-averaged net sources for moist static energy divided by $c_p$ (upper) and total water multiplied by $L/c_p$ (lower) for different resolutions. We find in this figure that the domain- and time-averaged sources hardly change with horizontal resolution, except near the tropopause and the surface where either radiation or turbulence plays a dominant role. This suggests that the great sensitivity of the simulated results, shown in Figs. 5 and 8, cannot be explained by the sensitivity of the simulated source.

The results above confirm the limitation of using explicit physics and the need of cumulus parameterization in models with resolutions in the mesoscale range. In the rest of this paper, we investigate what the model physics of prediction models is supposed to produce for different resolutions.
Fig. 5. Snapshots of cloudiness, precipitation, and wind at hour 184 obtained from the simulations with (a) 2-, (b) 8-, and (c) 32-km horizontal resolutions under the strong forcing and land condition. The areas of higher cloudiness than 0.5 are shaded light gray, and the mixing ratios of rain, snow, and graupel larger than 0.1 g kg\(^{-1}\) are indicated with dark gray. Winds are shown with arrows.

4. Approach for identifying required parameterized source

In the next two sections, we analyze simulated RS and RPS in the thermodynamic and moisture budget equations. Here RS stands for the source produced by a perfect model that explicitly and accurately resolves all relevant processes. When a model does not resolve all relevant processes, RS must be replaced by “parameterized source” (PS). RPS referred to above stands for PS with which the model prediction is consistent with that of the perfect model as far as the resolvable scales are concerned. In addition to the direct effect of the unresolved process(es), RPS must include all of its (their) indirect effects, such as the net effect of transports induced by the unresolved process(es).

To elucidate the conceptual difference between RS, PS, and RPS let us first consider the parameterization problem in which the original governing equation and the governing equation for averaged fields are given by

\[
\frac{\partial \Psi}{\partial t} = -\mathbf{V} \cdot \nabla \Psi + RS \quad \text{and} \quad (3)
\]

\[
\frac{\partial \bar{\Psi}}{\partial t} = -\bar{\mathbf{V}} \cdot \nabla \bar{\Psi} + PS, \quad (4)
\]

respectively, where \(\Psi\) is an arbitrary prognostic variable, \(\mathbf{V}\) is the velocity, and the overbar denotes a space/time running average, which is still a function of space and time. When \(\Psi\) is a thermodynamic variable conserved with respect to individual material elements under an adiabatic process, RS in (3) represents nonadiabatic effects acting on the material elements. In the diagnostic studies of observed cumulus activities, PS can be found as a residual in the application of (4) to
an observed time sequence of large-scale budgets. For the sensible and latent heat budgets, the diagnosed PS is often called “apparent heat source,” $Q_1$, and “apparent moisture sink,” $Q_2$, respectively (Yanai et al. 1973). In the prognostic problem, on the other hand, it is required that (4) be consistent with (3) for an accurate prediction of the averaged field. Then, PS in (4) must be equal to RPS given by

$$RPS = \bar{RS} - (\nabla \cdot \nabla \Psi) - \nabla \cdot (\rho \nabla \Psi). \quad (5)$$

When the anelastic continuity equation $\nabla \cdot (\rho_0 \nabla) = 0$ is used, (5) may be rewritten as
FIG. 8. Deviations of domain/time averaged profiles of moist static energy divided by $c_p$ (top) and total water multiplied by $L/c_p$ (bottom) of the simulations with 8- and 32-km horizontal resolutions from those of CONTROL under (a), (c) no forcing and land and (b), (d) strong forcing and land conditions.

\[ \text{RPS} = \overline{\text{RS}} - \frac{1}{\rho_0} \nabla \cdot [\rho_0(\nabla \Psi - \nabla \Psi)]. \]  

(6)

Here the density $\rho_0$ is treated as a constant during the averaging. Note that prediction of the averaged field is not accurate unless (5) or (6) is satisfied.

It is extremely important to recognize that RPS is generally not equal to even the space/time average of RS, as these equations show. The terms in the brackets in (5) or (6) represent the mean (vertical and horizontal) transports due to the deviation from the mean. Obviously, these transports depend on how we define the mean through the averaging operator \((\overline{\cdot})\). In discrete models, the average is usually over each grid box instead of a continuous running average as used above. The expression for the mean transport is then more complicated than those shown in (5) and (6), depending on how the model discretizes the advection term \(V \cdot \nabla \Psi\).

The concept of RPS can be used not only for total physics but also for a particular component of physics, cloud-microphysical process for example. While many physical processes interact with each other on cloud scale, there is little doubt that the most fundamental process for cumulus convection is cloud-microphysical process. This is because cumulus convection is primarily driven by the buoyancy force generated by the heat of condensation released within clouds. The downward buoyancy force due to the evaporation of rain outside of clouds also matters. Nevertheless, it is the indirect effects of cloud-microphysical process that are primarily responsible for the difference between RS and RPS. The difference can be most easily recognized for the source of moist static energy. When phase changes involving ice are ignored, the cloud-microphysical process is relevant only through condensation and evaporation, under which the value of moist static energy is conserved. This means that in this case RS for moist static energy is identically zero. On the other hand, RPS is nonzero due to the convergence and divergence of the cloud-scale (horizontal and vertical) transports induced by the cloud-microphysical process, as well as due to induced modifications of turbulence and radiation processes.

While we do recognize the important conceptual difference between RS and RPS, we have little understanding of how the difference between them quantitatively depends on resolution. To gain an insight into this matter, we analyze RPS diagnosed from model-simulated
results in the next two sections. In the rest of this section, we describe the procedure we use to identify RPS, taking the case of RPS due to cloud microphysics as an example. In the procedure, we first need to define what the “perfect model” is. A well-tested LES model, in which only small eddies in the inertial subrange of turbulence are parameterized, is close to such a model. However, since we have mainly the parameterization of deep cumulus convection in mind, we temporarily assume that a CSRM is sufficient for our purpose. For this reason, the simulated sources in CONTROL are used as RS. We then introduce a new version of the nonhydrostatic model, which we call a “large-scale dynamics model” (LSDM). (This name is only for convenience because the LSDM may have certain components of physics.) The LSDM is basically the same as the CSRM used for CONTROL but different in the following ways:

1) the cloud-microphysical process is turned off while turbulence and radiation processes are retained;
2) a coarser horizontal resolution is used while the same discrete formulations are used for dynamics and advection terms;
3) it is applied to selected realizations in CONTROL as a diagnostic tool so that it is integrated only over a short period comparable to the time intervals for implementing physics commonly used in weather and climate models.

We then take the following steps:

1) perform an LSDM integration for a particular realization in CONTROL;
2) find the difference between the LSDM results and the corresponding results of CONTROL averaged over the LSDM grid size;
3) from this difference, infer the RPS for that situation as a function of space;
4) repeat these steps for many realizations under fixed external conditions, including a fixed narrow range of local time;
5) an ensemble average is taken over the entire realizations;
6) for a compact presentation of the results, the results

**Fig. 9.** Domain/time-averaged profiles of the sources for moist static energy divided by \( c_p \) (top) and total water multiplied by \( L/c_p \) (bottom), obtained from the simulations with 2-, 8-, and 32-km horizontal resolutions under (a), (c) no forcing and land and (b), (d) strong forcing and land conditions.
are further averaged over the model’s entire horizontal domain.

Even if the LSDM had the same horizontal resolution as that of CSRM, the difference obtained in step 2 would consist of not only the direct effect of cloud microphysics but also its indirect effects induced during the period of the LSDM integration. In this paper, we call the length of this integration period “physics time interval” (not to be confused with the computational time step used for the LSDM integration). If the physics time interval is not sufficiently shorter than the typical time scale for cloud evolution, as is usually the case, a formulation of these indirect effects must be included in the parameterization. Furthermore, since the LSDM has a coarser horizontal resolution than the CSRM in practice, the difference obtained in step 2 is also due to the horizontally unresolved components of both direct and indirect processes. Formulation of this difference for general use in prediction models represents another aspect of the parameterization problem, commonly referred to as “subgrid-scale parameterization.” In this paper, we address these two aspects assuming that the vertical resolution is sufficiently high.

5. Resolution dependence of RPS due to cloud microphysics

In this section, we present RPS due to cloud microphysics diagnosed from the model-simulated results. Figure 10 shows the domain- and ensemble-averaged profiles of RPS for moist static energy divided by $c_p$ and total water multiplied by $L$/$c_p$, obtained using different physics time intervals but with the same 2-km horizontal grid size under the strong large-scale forcing and land condition. Here, the heavy dotted lines represent RS due to cloud microphysics averaged over an ensemble of late afternoon hours. We first note that, as the physics time interval becomes small, RPS converges to RS for both moist static energy and total water. As the time interval increases, the profiles of RPS for moist static energy are dispersed both upward and downward from the localized peaks, while those of RS remain approximately the same. Such dispersion also appears in the profiles of RPS for total water, but with a less extent. The difference between RS and RPS clearly shows the existence of the indirect effects of cloud microphysics induced during the physics time interval. These results...
suggest that RPS depends on how frequently physics is calculated in the model.

Figure 11 displays the horizontal resolution dependence of domain- and ensemble-averaged profiles of RPS due to cloud microphysics for moist static energy divided by $c_p$ (top) and total water multiplied by $(L/c_p)$ (bottom) under (a), (c) no forcing and land and (b), (d) strong forcing and land conditions. A fixed physics time interval ($\Delta t = 1$ h) is used for all cases. We see, especially from the case of strong forcing, that the heights of RPS peaks considerably shift as the resolution decreases. For example, see the pronounced sink near the surface and the source in the middle and upper troposphere for moist static energy and the sink near the surface for total water. These features commonly appear both with no forcing and strong forcing. It implies that the coarser-resolution LSDM, which has no cloud microphysics, misses not only the direct thermodynamic effect of microphysics but also its indirect effect, mainly the upward transport of moist static energy and total water by cloud-scale circulations from the lower troposphere. In CONTROL, these transports are carried out by deep convolutions that are directly resolved in the model. These results thus suggest that it is not RS but such a resolution-dependent RPS that the model physics in future prediction models should produce.

6. Resolution dependence of RPS due to total physics

We now repeat the procedure described in section 4 but using the LSDM with no physics to identify RPS due to total physics. As mentioned in the introduction, conventional model physics typically has a modular structure and thus interactions between individual processes take place only through the time evolution of grid-scale prognostic variables, missing most of their subgrid-scale interactions. To improve such a situation, Arakawa (2000) suggests development of a unified parameterization of all physics as a possible future direction. Having this possibility in mind, we now investigate RPS due to total physics.

Figures 12 and 13 are the same as Figs. 10 and 11, respectively, except for RPS due to total physics, which consists of radiation and turbulence as well as cloud microphysics. In Fig. 12 the net RS due to total physics, shown by the heavy dotted lines, slightly changes with the physics time interval. On the other hand, for both moist static energy and total water, RPS due to total physics...
physics significantly depends on how frequently physics is implemented, while it converges to RS as the physics time interval becomes small. The way in which RPS due to total physics deviates from the corresponding RS is similar to that of the RPS due to cloud microphysics. Figure 13 shows that in the case of strong forcing the resolution dependencies of RPS due to total physics also have features similar to those of RPS due to cloud microphysics, such as the sink near the surface and the source in the middle and upper troposphere for moist static energy. This is because the main source of heat and moisture in this case is the large-scale forcing rather than the fluxes from the underlying surface. In the case of no forcing, on the other hand, the only significant source of heat and moisture is the fluxes from the underlying surface. Therefore, RPS due to total physics is very different from that of RPS due to microphysics alone. In this case, the effect of turbulent transport from the surface is one of the main components of RPS along with the transport effect induced by cloud microphysics. (In the left panels of Fig. 13, lines for the 2-km cases are omitted because the solutions of the LSDM with no physics are not well behaved due to the lack of turbulent fluxes.)

7. Summary and conclusions

Conventional model physics is designed and tuned for a fixed model resolution, not as a function of resolution. As a consequence, model results can become worse with a higher resolution unless model physics is reformulated. At present, this kind of reformulation is commonly done through retuning parameterizations. In our point of view, the future formulation of model physics should automatically produce the resolution dependence of model physics, which is mainly due to that of unresolved transport effects.

The goal of this study is to gain an insight into the resolution dependence of model physics, having parameterization of moist convection mainly in mind. To achieve this goal, we conduct a variety of experiments using a two-dimensional nonhydrostatic model with different horizontal resolutions under various idealized tropical conditions. For control experiments (CONTROL), we run the model as a cloud-system-resolving model (CSRM) with a 2-km horizontal resolution. The results of CONTROL show that the simulated sources of moist static energy and total water in the thermodynamic and moisture equations are mainly due to cloud microphysics associated with the formation of precip-
eration in the middle and upper troposphere and due to turbulence near the surface. Without large-scale forcing, the role of turbulence becomes more crucial and affects even higher levels in the troposphere.

In order to see the impact of resolution changes on the simulations, we repeat the integrations using identical formulations of model physics but with 8-, 16-, 32-, and 64-km horizontal resolutions. In these coarse-resolution simulations, spurious mesoscale circulations develop as substitutes to unresolved moist convections. Consequently, systematic errors appear even in the domain- and time-averaged vertical profiles of simulated thermodynamic variables, although the domain- and time-averaged vertical profiles of the simulated sources remain very similar to those of CONTROL. These results confirm the need of moist-convective parameterization in the range of typical resolutions of mesoscale models, giving further motivation to investigate what the model physics or parameterization is supposed to produce for different resolutions.

We then analyze “real source” (RS) and “required parameterized source” (RPS) in thermodynamic and moisture equations for the idealized situations. Here, RS stands for the source simulated by a model that explicitly and accurately resolves all relevant processes. A well-tested large-eddy simulation (LES) model, in which only small eddies in the inertial subrange of turbulence are parameterized, is close to such a model. However, since we have mainly parameterization of deep cumulus convection in mind, we assume that a CSRM is sufficient to produce RS. Then RPS becomes the source required by a coarser-resolution version of the model for its solution to be consistent with the solution of the CSRM as far as resolvable scales are concerned. By definition, RPS is not equal to the space and time average of RS, and their difference depends on the model’s resolution. Yet, we have little understanding of how the difference quantitatively depends on resolution.

In this study, we diagnose RPS from the difference between the results of the CSRM and those of a “large-scale dynamics model” (LSDM), which is a coarser-resolution version of the CSRM but with only partial or no physics. We integrate the LSDM starting from a selected realization in CONTROL over a short period (1 h or less) and compare the result with that of CONTROL to identify RPS for that realization. We repeat this procedure over a number of realizations in each CONTROL run and take an ensemble average over the entire realizations. RPS identified in this way is considerably deviated from RS, even when averaged over the entire domain and over many realizations, while it converges to RS as the physics time interval becomes small and the horizontal resolution becomes close to that of CONTROL. Unlike RS, RPS highly depends on the horizontal resolution as well as on the time interval for implementing physics.
Even though the results reported in this paper are obtained only for selected idealized conditions, they clearly illustrate that RPS is not simply the domain and time averages of RS and highly depends on the resolution and the physics time interval. The future formulation of model physics should produce these dependencies at least in the range of typical resolutions of mesoscale models. This is a difficult task, however. Since observations with fixed network size and frequency do not tell the scale dependency of the transport effect, experiments such as those reported in this paper should be performed more extensively, perhaps with a three-dimensional model, to gain further insights into the problems involved. Such results can also be used to verify the scale dependency of model physics while it is being developed.

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