Towards Global Large Eddy Simulation: Super-Parameterization Revisited

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Abstract

This paper argues that a global large eddy simulation can be achieved through the application of the superparameterization (SP) methodology on massively parallel computers. SP was proposed over 15 years ago to improve the representation of deep convection and accompanying small-scale processes in large-scale models for the weather and climate. The main idea was to embed in all columns of the large-scale model (featuring horizontal grid lengths of the order of 100 km) a two-dimensional (2D) convection-permitting small-scale model with approximately a 1-km horizontal grid length and periodic lateral boundaries. We propose to expand this methodology by applying a high-spatial-resolution three-dimensional (3D) large-eddy simulation (LES) model as the SP model and by embedding it in all columns of a large-scale model with a horizontal grid length in the range of 10 to 50 km. The outer model can apply hydrostatic equations as typical global numerical weather prediction and climate models today and can simulate atmospheric processes down to the mesoscale, including organized convection. Small-scale processes, such as boundary-layer turbulence and convective drafts, can be simulated by embedded nonhydrostatic (e.g., anelastic) LES models. Although significantly more expensive than the traditional SP, SP LES is ideally suited to take advantage of parallel computation because of the minimal communication between LES models when compared to traditional domain-decomposition methodologies in parallel simulation. Moreover, as illustrated through the idealized 2D mock-Hadley cell simulations, LES models can feature different horizontal and vertical grids in various columns of the large-scale model, and thus target dominant cloud regimes in various geographical regions. Such a system allows an unstructured grid simulation with no additional model development.

Keywords global model; large eddy simulation; superparameterization

1. Introduction

Representation of small-scale and mesoscale processes, such as cloud dynamics and microphysics, precipitation, gravity waves, and boundary-layer processes, in large-scale models of weather and climate remains a formidable challenge, especially in the context of global atmospheric dynamics. Atmospheric moist processes cover an extreme range of spatial and temporal scales, from the formation and growth of cloud droplets and ice crystals at subcentimeter scales, through cloud dynamics (from the inertial range turbulence to organized mesoscale convection, submeter to hundreds of kilometers) and synoptic-scale weather systems in midlatitudes, to planetary-scale circulations, such as the Hadley and Walker cells driven by the release of latent heat in the tropical deep convection. Cloud microphysics involves the formation and growth of cloud and precipitation particles, and it is arguably the most uncertain aspect of the climate and climate change, at least as far as atmospheric processes are concerned. The very fundamental reason likely comes from the disparity of spatial scales involved, cloud microphysics on one side and large-scale circulations on
the role of cloud microphysics in the traditional climate modeling (i.e., involving hydrostatic large-scale dynamics) represents the parametrization squared conundrum, that is, parametrized microphysics in parameterized clouds. The impact of cloud microphysics on large-scale atmospheric dynamics can be studied with more confidence by applying a model that allows direct coupling between cloud dynamics and cloud microphysics, such as the nonhydrostatic convection-permitting large-scale model.

Cloud-scale models have been used in cloud physics research for a long time (e.g., Schlesinger 1975, Tapp and White 1976, Klemp and Wilhelmson 1978, Clark 1979, Lipps and Hemler 1982). Approximately two decades ago, the computational technology advanced sufficiently to allow extended-time (say, a week or two) limited-area convection-permitting model simulations, that is, applying nonhydrostatic equations with a horizontal grid length around 1 km and computational domains covering horizontal areas of 10 to 100 thousand km². Such simulations were driven by either idealized forcings (e.g., convective–radiative quasi-equilibrium as in Tompkins and Craig 1998) or applying observed (i.e., evolving) large-scale conditions obtained from field campaigns, such as GATE (GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment) as in Grabowski et al. (1996, 1998) and Xu and Randall (1996). The doubly periodic horizontal domain was typically of the size of a general circulation model (GCM) gridbox and allowed the simulation of cloud ensembles rather than a single cloud as typically applied in previous cloud-scale simulations. The main motivation of such studies was to improve the representations of processes that cannot be resolved in traditional GCMs, moist convection in particular. These simulations led to some improvements of traditional parametrizations, for instance, the impact of convection on the surface exchange (e.g., Redelsperger et al. 2000) or cloud-radiation interactions (e.g., Xu and Randall 1995). Such studies motivated the development and applications of the Japanese global nonhydrostatic convection-permitting model NICAM (Satoh et al. 2014; see http://nicam.jp/hiki/). A similar more recent development is the German nonhydrostatic global model ICON, an effort supported by the Max Planck Institute for Meteorology and the German Weather Service (Zaengl et al. 2014; see http://www.mpimet.mpg.de/en/science/models/icon.html).

About 15 years ago, Grabowski and Smolarkiewicz (1999) proposed a novel approach, called the Cloud-Resolving Convection Parameterization (CRCP), subsequently, dubbed the superparametrization (SP), to improve the representation of small- and mesoscale processes, moist convection in particular, in large-scale weather and climate models. The main idea behind SP is to apply a two-dimensional (2D) small-scale nonhydrostatic model in all columns of the large-scale model to simulate cloud and convective processes directly, thus removing the need for convective and cloud parametrizations. In the original SP proposal, the large-scale outer model featured a horizontal grid length of the order of 100 km and the embedded horizontally periodic SP models had a horizontal grid length of around 1 km, as illustrated in Fig. 1. The motivation came from cloud-resolving studies of tropical convection documenting that 2D simulations driven by the observed large-scale conditions provide a meaningful representation of tropical deep convection, including regime changes, when compared to a more expensive three-dimensional (3D) case (cf. Grabowski et al. 1998). In the large-scale model equipped with SP (sometimes referred to as the Multiscale Modeling Framework, or MMF, e.g., Arakawa 2004), all traditional parametrizations of small-scale processes, such as dry and moist convection, cloud microphysics, turbulence, cloud overlap, radiative transfer, and boundary-layer parametrizations, can be either removed from the large-scale model as no longer needed or applied inside the small-scale SP model domains (e.g., Randall et al. 2003). Although significantly more expensive (two to three orders of magnitude) than a traditional large-scale model, the SP large-scale model is about three orders of magnitude less expensive than a global convection-permitting model such as NICAM.

The novel idea provided impetus for the creation of the National Science Foundation’s Science and Technology Center (STC) in 2006 as a consortium of United States universities and government laboratories as well as foreign partners to further develop, apply, and advance the main idea behind SP. The STC was named the Center for Multiscale Modeling of Atmospheric Processes (CMMAP), hosted by the Colorado State University. Most of the progress with the SP approach over the last 10 years was accomplished with direct or indirect support from CMMAP. Moreover, the SP concept led to applications beyond the original proposal (e.g., coupling with oceanic and land-surface processes) as well as the development of an improved MMF framework, the quasi-3D MMF (Jung and Arakawa 2010, 2014).

One has to keep in mind that SP methodology
introduces artificial scale separation between scales resolved by the outer large-scale model and scales resolved by the small-scale SP models. For instance, in the high-resolution large-scale model, a convective system can freely propagate across the grid. However, when the high-resolution grid is replaced by a combination of the large-scale low-resolution outer model and embedded SP models (cf. Fig. 1), the convective system cannot coherently propagate from one SP domain to another. It follows that the model applying the SP methodology has to be judiciously designed keeping in mind scale interactions in the natural system. For instance, in the SP climate model (e.g., Khairoutdinov and Randall 2001; Randall et al. 2003), periodic 2D SP domains extend a couple hundred kilometers with the small- and mesoscale dynamics limited to the SP domain. In contrast, one can envision a situation where the large-scale model has a horizontal grid length in the range of 10 to 50 km (i.e., resolving mesoscale dynamics) and the SP models represent only small-scale dynamics (e.g., boundary-layer turbulence and individual convective drafts). Idealized simulations reported in Grabowski (2006a) document that such an approach works well, at least for organized convection. Such a promise provides a starting point to the methodology advocated in this paper.

Because of the 2D geometry, an obvious issue is how to align the SP model within each column of the large-scale model. Since initial SP applications focused on the tropical convection and the Madden–Julian Oscillation (MJO), a natural choice was to align SP models along the equator as in 2D cloud-system resolving simulations of Grabowski et al. (1998). One can align SP models according to some additional rules (e.g., along the low-level shear) and allow the models to change their orientation (e.g., Grabowski 2004; Tulich 2015). However, 2D geometry with periodic lateral boundary conditions impose dynamical constraints that may lead to unphysical results because of the differences in convective momentum transport in sheared environments (e.g., Mapes and Wu 2001) or strong wave–mean flow interactions (e.g., Held et al. 1993). Applying a 3D embedded model removes such problems (Khairoutdinov et al. 2005).

The purpose of the paper is twofold. First, the paper provides a brief review of achievements reached by applying the SP methodology over the last 15 years, mostly within CMMAP. Second, the paper argues that there is yet another possibility, suggested in the title of this paper, that can take advantage of the SP methodology. The next section reviews applications of the SP methodology to climate simulation. Section 3 reviews numerical studies that provide rationale for efforts aiming at the development of a global LES modeling system. Section 4 argues why application of the SP methodology may provide a more rapid path to reach global LES. An idealized illustration of the advantages offered by the SP methodology is discussed in Section 5. A short summary in Section 6 concludes the paper.

2. Superparametrization in climate modeling

Grabowski (2001) applied SP to idealized simulation of deep convection organization on a constant sea surface temperature (SST) (“tropics-everywhere”) rotating Earth-size aquaplanet in convective–radiative quasi-equilibrium. These simulations documented development of large-scale convectively coupled features within the equatorial waveguide that propagated slowly eastward and resembled MJO observed in the Earth’s atmosphere. A subsequent study applying this idealized SP setup (Grabowski 2003a) documented that coupling among deep convection, free-tropospheric moisture, and large-scale flow were essential for the coherence of MJO-like structures. This was argued to result from the convection–moisture feedback as discussed in Grabowski and Moncrieff (2004). Grabowski (2006b) extended these simulations by applying a simple SST model to inves-
tigate the impact of interactive SST on the MJO-like coherent structures.

The idealized SP simulations motivated an application of the same methodology to a realistic climate model, the NCAR’s Community Atmosphere Model (CAM) in a T42 configuration (Khairoutdinov and Randall 2001; Randall et al. 2003). Khairoutdinov et al. (2005) showed that the superparametrized CAM (SP-CAM) produced reasonable global distributions of precipitation, precipitable water, top-of-the-atmosphere radiative fluxes, cloud radiative forcing, and high-cloud fraction. Most importantly, SP-CAM showed significant improvement of the intraseasonal (30 to 60 days) variability, including MJO, providing impetus for subsequent studies of the MJO applying SP-CAM and later the SP atmosphere–ocean-coupled climate model as described below. Khairoutdinov et al. (2008) discussed results from the SP-CAM 19-year-long Atmospheric Model Intercomparison Project-style simulation using the 1985–2004 SSTs and sea ice distributions. The annual mean climatology was relatively well simulated, but some significant biases were also noted, such as excessive precipitation associated with the Indian and Asian monsoons and longwave cloud effect biases due to overestimation of high cloud amounts, especially in the tropics. The subseasonal variability of the tropical climate associated with the MJO and equatorially trapped waves were noted as a particular strength of the simulation.

Benedict and Randall (2009) focused on the MJO representation in SP-CAM simulations. They noted that the space–time structures of MJO convective disturbances were well represented in SP-CAM with the progression of the free-tropospheric moistening and heating that agreed with observations. The simulated convective intensity organized on intraseasonal space–time scales was overestimated, particularly in the western Pacific. However, SP-CAM simulations were deficient in the MJO initiation, with the preferred location of the MJO initiation shifted from the Indian Ocean to the Maritime Continent. For the initiation phase, the inferred structure of various model-simulated fields compared poorly with the observational estimates. These biases were argued to come from poor representations of boundary-layer processes (arguably due to low resolution and simple subgrid-scale parametrization of the embedded CRM), lack of weakening of the simulated disturbance over the Maritime Continent (perhaps due to poor representation of the Maritime Continent in the large-scale model and lack of topography in CRM), and mean state differences. On the basis of a variety of statistical measures to evaluate climate model performance, Kim et al. (2009) showed that the SP-CAM simulations had the best skill at representing MJO when compared to several climate models (including NCAR, NCEP, and GFDL models) that featured traditional representation of small-scale processes. However, a recent study of Jiang et al. (2015) showed that superparametrized climate models were near the top but not at the top among approximately two dozen models in the MJO simulation (see their Fig. 5). That said, one needs to keep in mind that traditional climate models achieve improvements in MJO simulation (and climate simulation, in general) through intensive (and arguably never-ending) model tuning and parametrization improvement. In contrast, there is little to tune in the SP simulations, perhaps with the exception of the cloud and precipitation microphysics. Goswami et al. (2011) discussed representation of the Indian summer monsoon and monsoon intraseasonal oscillations in SP-CAM simulations. The study showed some improvements over traditional GCMs but also significant issues argued to come from unrealistic convective heating profiles simulated by the embedded CRMs.

Benedict and Randall (2011) considered the impact of air–sea interactions on intraseasonal convective organization by adding an oceanic mixed layer scheme to the SP-CAM model. Such a coupling allows SSTs to respond to spatial and temporal variability of surface energy and water fluxes. The air–sea interactions in the coupled simulation provided additional improvements of the key aspects of tropical convection on intraseasonal scales, from the relations between precipitation and SST to the space–time structure and propagation of MJO. Fully coupled SP climate model studies that require even more computational resources (because of the requirement of multidecadal simulations) became feasible using the superparametrized NCAR Community Climate System Model (SP-CCSM). Stan et al. (2009) showed that SP-CCSM improved key shortcomings of standard CCSM simulations, such as mean precipitation patterns, equatorial SST cold tongue structure and associated double intertropical convergence zone, Asian monsoon, periodicity of the El Nino–Southern Oscillation, and MJO. They stressed that these improvements had been obtained without the retuning of the coupled model. DeMott et al. (2013) discussed simulated mechanisms of the northward propagation of the boreal summer intraseasonal oscillations and associated Asian summer monsoon. They showed
that the simulations agreed relatively well with the interim European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis. DeMott et al. (2014) used CAM versions 3 and 4 (CAM3 and CAM4) and the superparametrized CAM3 (SP-CAM3), each integrated coupled to an ocean model and as an atmosphere-only model using SSTs from the coupled SP-CAM3. For each model, the intraseasonal variability was best simulated with the SST coupling. Goswami et al. (2013) discussed interactions between Indian summer monsoon and monsoon intraseasonal oscillations applying SP-CCSM. They pointed out significant improvements of the monsoon variability in SP simulations but also issues that needed further improvements. As in the SP-CAM study of Goswami et al. (2011), these issues were argued to result from the deficiencies of the embedded CRM. The most recent results from Indian application of the SP climate model are discussed in Goswami et al. (2015). Finally, recent applications of SP-CCSM to the West African monsoon and South American climate are presented in McCravy et al. (2014a, b) and Krishnamurthy and Stan (2015), respectively. These investigations report significant improvements offered by the SP methodology in modeling of the coupled atmosphere–ocean general circulation and climate.

SP provides significantly improved representations of clouds, precipitation, and aerosols in climate system models and allows more confident assessment of the role of cloud processes in climate. Applying the SP methodology, Grabowski (2003b) investigated how cloud microphysics impacts global convective–radiative quasi-equilibrium on a constant-SST aquaplanet. Cloud microphysics impacted quasi-equilibrium temperature and moisture profiles substantially, with small clouds and precipitation particles resulting in a climate that was warmer and moister, with the relative humidity approximately unchanged. The simulations suggested that the main impact of cloud microphysics in the tropics was on the net energy budget at the ocean surface. Ovtchinnikov et al. (2006) contrasted data from two observational sites operated by the U.S. Department of Energy’s Atmospheric Radiation Measurement (ARM) Program (the Southern Great Plains in Oklahoma and at the island of Nauru in the tropical western Pacific) with the results of simulations applying standard CAM and SP CAM. The comparison showed that the clouds simulated in the SP CAM model were more consistent with the observations than the parametrized clouds in the standard CAM, in agreement with results presented in Khairoutdinov et al. (2005). Significant improvements of the surface precipitation statistics in SP-CAM when compared to the standard CAM were reported in DeMott et al. (2007). Zhang et al. (2008) applied the infrared brightness temperature and precipitation radar simulator to the CRM data simulated by SP-CAM and compared the output to the radiances from geostationary satellites and precipitation radar reflectivities from the Tropical Rainfall Measuring Mission (TRMM). The comparison showed significant inconsistencies between simulated and observed diurnal anomalies of the upper-tropospheric cloudiness and relative humidity, as well as too active deep convection over tropical oceans. Marchand et al. (2009) extend the Zhang et al. (2008) study by applying the radar observations from the NASA CloudSat mission. They concluded that SP-CAM reproduced well the broad pattern of tropical convergence zones, subtropical belts, and midlatitude storm tracks as well as their changes in position with the annual solar cycle. The comparison also revealed a number of model deficiencies.

Using TRMM observations, Pritchard and Somerville (2009a, b) applied a variety of statistical methods (e.g., the empirical orthogonal function analysis) to document an improved representation of the diurnal cycle of precipitation over both continents and oceans in SP-CAM when compared to the traditional CAM. Pritchard et al. (2011) focused on the propagating convective systems in the lee of the Rockies over the United States. They linked the improved simulation of the well-documented nighttime eastward propagation of such systems in the SP model to the interaction between SP convective heating and the large-scale model flow that led to apparent eastward “propagation” of convection from one climate model column to the next one. In essence, such a mechanism resembles the one documented in Grabowski (2006a) at the mesoscale. Li et al. (2012) showed that SP-CAM better simulated the distributions of both light and extreme precipitation events over the continental United States when compared to CAM with conventional parametrizations.

Wang et al. (2011a, b) applied the SP methodology to improve the representation of aerosol processes in the atmospheric general circulation. Their novel aerosol–cloud–climate SP model linked aerosol and chemical processes on the large-scale grid with statistics of cloud properties and processes simulated by embedded CRMs. The simple bulk cloud microphysics scheme in CRM was replaced with a two-moment scheme, and a modal aerosol treatment was included in GCM. With these extensions, the
multiscale aerosol–climate model allowed the explicit simulation of aerosol and chemical processes in both stratiform and convective clouds on a global scale. Tao et al. (2009) reported on the development and initial tests of NASA Goddard Space Flight Center SP GCM. It combined the NASA Goddard finite-volume GCM and Goddard Cumulus Ensemble model. Mohr et al. (2013) included a land-surface model (LSM) in the NASA SP GCM, with LSM coupled to the atmosphere on the CRM grid as in nature. Similar effort is also progressing within CMMAP using the Community Land Model (Oleson et al. 2010) coupled to CRMs within SP-CAM (Prof. Scott Denning, personal communication).

Tulich (2015) developed a superparametrized version of the Weather Research and Forecasting model (SP-WRF) by embedding 2D WRF in all columns of 3D WRF. Such a system includes a suite of physics options (e.g., various land-surface, turbulence, radiation, and cloud microphysics schemes) and allows exploration of key model sensitivities, impossible with SP-CAM and SP-CCSM. SP-WRF also includes a convective momentum transport (CMT) scheme that applies the scalar transport and diagnostic pressure gradient force derived from the embedded CRMs. Global simulations document the impact of CMT on the simulated strength of the large-scale circulation (through cumulus friction) and on the convectively coupled tropical wave activity.

Wyant et al. (2006, 2009) and Bretherton et al. (2014) are examples of the application of the SP methodology to the problem of climate sensitivity and change and to the response of shallow clouds to the warming climate. Arnold et al. (2014) applied CCSM and its super-parametrized version, SP-CCSM, and compared simulations assuming preindustrial and quadrupled CO$_2$ concentrations. Simulated effects of the warmer climate were qualitatively similar in the traditional and SP models, but SP produced additional enhancement of the climate change signal (e.g., stronger enhancement of MJO). Arguably, this may come from the fact that traditional climate models are tuned based on the current climate, and such tuning may be invalid in the changed climate. Enhancement of MJO with climate warming was investigated in more detail with SP-CCSM in Arnold et al. (2015). Kooperman et al. (2014) studied changes of the United States summer rainfall to quadrupled CO$_2$ in CAM and SP-CAM. The two models produced very different changes of mean precipitation patterns that developed from differences in large-scale circulation anomalies associated with the planetary-scale response to the warming. Arguably, such studies are needed to advance the SP methodology toward climate change assessment, for instance, through the Intergovernmental Panel on Climate Change (IPCC) process.

The above review shows that SP is now a mature methodology to provide an improved representation of small-scale processes, clouds and precipitation, in particular, in large-scale models of weather and climate. One area that has not been investigated in the past is the representation of the subgrid-scale topography. So far, all applications of the SP methodology include topography only in the outer (large-scale) model. This perhaps explains why SP climate simulations often show problems with MJO propagation over the Maritime Continent that features islands with significant topographic features. Although representation of islands and island topography in 2D SP is unlikely to be realistic, this may change when 3D SP is used.

3. The next challenge: why LES?

Horizontal grid length around 1 km is still quite coarse for a faithful simulation of such small-scale processes as shallow convection or boundary-layer turbulence, not to mention cloud microphysics. Over tropical and summertime subtropical and midlatitude continents, strong surface forcing due to a diurnal cycle of solar insolation leads to a pronounced evolution of convective processes, difficult to capture in traditional GCMs as well as in convection-permitting models (e.g., Grabowski et al. 2006 and references therein). Horizontal grid length around 1 km is also too coarse for deep convection, especially in the context of entrainment and dynamics–microphysics interactions. For the latter, small-scale features of convective updrafts affect such aspects of cloud microphysics as cloud droplet activation and diffusional growth and the initiation and development of an ice field (e.g., as in Bryan et al. 2003; Bryan and Morrison 2012). LES simulations of a tropical cyclone document similar resolution requirements for the realistic cyclone strength simulations (Rotunno et al. 2009).

LES is often considered as an ultimate modeling methodology for turbulent atmospheric flows, providing benchmark solutions to which lower-spatial resolution results should be measured. Bryan et al. (2003) discussed numerical simulations of squall lines conducted with grid lengths decreasing from 1 km to 125 m. The 125-m simulation essentially provides an LES of deep organized convection. Precipitation
amount, system propagation speed, cloud depth, static stability, size of thunderstorm cells, and organizational mode of convective overturning (e.g., upright towers versus sloped plumes) all changed as the grid length increased. Bryan et al. (2012) argued that the ability of higher-resolution runs to become turbulent led directly to different evolutions. There was a sign of convergence of solutions for such key properties as vertical momentum and temperature fluxes as the highest resolution was approached (cf. Figs. 8, 9).

Khairoutdinov et al. (2009) and Moeng et al. (2009) reported results of deep tropical convection simulations in a low-shear environment applying a domain of around 200 by 200 km$^2$, horizontal grid lengths as small as 100 m, and high vertical resolution (50 m near the surface and 100 m in the free troposphere). They referred to the highest-resolution simulation as the Giga LES because it contained around $10^9$ grid points. The high-resolution LES simulations highlighted the role of convective cold pools. The majority of shallow and intermediately deep convective clouds were present at the cold pool leading edges. Some properties of simulated cloud fields, such as environmental temperature and moisture profiles as well as vertical precipitation and momentum fluxes, were weakly sensitive to the horizontal resolution. Some, like updraft core velocity, converged only close to the highest resolution applied, an aspect essential for cloud microphysics and microphysics–dynamics interactions. Moeng et al. (2009) analyzed boundary-layer statistics in the Giga LES focusing on the vertical velocity and water vapor mixing ratio. The variance of the vertical velocity resided at the boundary-layer turbulence scales, and the water vapor variance peaked at the cold pool scales. Moeng et al. also compared turbulent vertical fluxes with parameterized fluxes from the eddy viscosity model applied to smoothed LES fields. The comparison was rather poor, especially within the boundary layer. Arguably, these results provide strong support for the use of high resolution, down to LES, in simulations of tropical maritime convection, in agreement with results discussed in Bryan et al. (2003) and Bryan and Morrison (2012).

Schalkwijk et al. (2015) argued that the application of multicore processors led to the increase in computational resources to the point where turbulence-resolving numerical weather forecasts over a region the size of The Netherlands at a 100-m grid length is feasible. The LES model they used was coupled to a low-resolution large-scale weather model that provided boundary conditions and forcings for the high-resolution simulations. A similar effort is also progressing at the Max Planck Institute for Meteorology with a goal to complete a long (multimonths) LES simulation over Germany using the ICON model (Prof. B. Stevens, personal communication). Arguably, such methodologies can be viewed as a stepping stone for the global LES approach in weather and climate studies.

### 4. Superparametrization revisited

Three-dimensional finite-difference large-scale models typically apply horizontal domain decomposition for parallel processing. With the global LES as a target, one can imagine the entire Earth covered with tiles of a few hundred km$^2$ (say, 20 km by 20 km), each tile having a grid length (horizontal and vertical) to be considered LES (say, of the order of 100 m). LES over such a tile would have around 200 points in the vertical (applying a stretched grid with high resolution in the lower troposphere reaching the height of, say, 25 km) and between $10^4$ and $10^5$ points in the horizontal. To cover the entire Earth, one would need of the order of 1 million such tiles. It follows that a parallel supercomputer with up to a million cores can be used in a global LES simulation, that is, each core computing LES solutions over a single tile. However, exchanging the data at the tile edges every time step, required for parallel computation, creates a bottleneck that is arguably extremely difficult to overcome.

From the computational point of view, SP meth-
odology is advantageous because periodic SP models run independently and communicate only through the large-scale outer model. Each SP model obtains large-scale model profiles every large-scale model time step and sends back profiles that include effects of processes considered in the small-scale model. It follows that the SP methodology is “embarrassingly parallel” because each core of a parallel computer can run a single SP model and communicate infrequently with the large-scale model (i.e., receiving and sending appropriate profiles). These profiles are used to define large-scale forcing (i.e., profiles received by the SP model are applied to calculate evolution of small-scale fields) and to derive the small-scale model response (i.e., profiles sent back to the large-scale model), see Section 2 in Grabowski (2004). For each SP model, the profiles are only exchanged every large-scale model time step. Moreover, SP models do not need to cover the entire extent of the outer model gridbox (as in simulations discussed in Grabowski 2003a, 2006b, and in Section 5 of this paper) and can apply additional techniques to accelerate calculations (e.g., Slawinska et al. 2015; Jones et al. 2015).

The SP methodology is well suited for a large-scale model with horizontal grid lengths of a few tens of kilometers. This is because such a model can realistically simulate mesoscale circulations (including organized convection, e.g., Liu et al. 2001 and references therein), and only small-scale processes (e.g., convective drafts) are left for the embedded SP models. Grabowski (2006a) showed that such a methodology works well in idealized simulations of organized convection. The SP methodology can be used with a 3D small-scale model and thus eliminate issues associated with the SP model orientation and 2D dynamics of the original SP proposal. MMF featuring 3D SP models requires significantly larger computational effort, but problems with the two-dimensional dynamics and model orientation mentioned above are removed. Because small-scale dynamics (e.g., boundary-layer turbulence) is inherently three-dimensional, the 2D SP model has to be aligned in a particular way to mimic fully 3D dynamics (e.g., Moeng et al. 2004). Moreover, it is unclear if a single alignment strategy can be suitable for all meteorological situations. All these problems go away with 3D SP.

Yet another issue concerns the mathematical formulation of an efficient high-resolution nonhydrostatic global model. A model based on compressible equations is appropriate for the all-scale atmospheric dynamics, but its numerical implementation is cumbersome due to fast-propagating acoustic modes that have limited relevance to weather and climate (see discussion in Smolarkiewicz et. al. 2014). Soundproof models (i.e., anelastic or pseudo-incompressible) are a perfect choice for small-scale atmospheric dynamics (even for severe convection, Kurowski et al. 2014) but face significant problems at global scales (e.g., Smolarkiewicz et. al. 2014; Kurowski et al. 2015). These arguably come from simplified vorticity dynamics in the anelastic system. In contrast, the hydrostatic system of equations appears perfectly suited for large-scale atmospheric dynamics. On the basis of such arguments, Arakawa and Konor (2009) proposed a unified system of equations that combine the hydrostatic dynamics at large-scales and anelastic dynamics at small scales. Such a system of equations is valid across the entire range of horizontal scales. In agreement with such an argument, one can design the SP system that applies hydrostatic dynamics for the large-scale model and anelastic dynamics for the 3D small-scale model embedded in each column of the large-scale model. The anelastic models embedded within the global model can be based on environmental profiles that change from one large-scale model column to another and provide accurate small-scale solutions.

Finally, SP allows application of different grids depending on the geographical location, an aspect so far not considered in the SP applications. For deep tropics and summertime continents, grids appropriate for deep convection can be used. For instance, the 3D SP model can apply a horizontal grid length several hundred meters and a stretched vertical grid featuring a vertical grid length around 100 m near the surface and lower vertical resolution in the upper troposphere (as, for instance, used in simulations of daytime convective development over Amazonia in Grabowski 2015). In contrast, the 3D SP model over subtropi-
ical oceans can apply a higher vertical resolution in the lower troposphere in regions of shallow convection and stratocumulus, and can apply much lower vertical resolution in the middle and upper troposphere. Below, we present a computational example to illustrate such a capability. Note that a standard 3D high-resolution model would require an unstructured mesh to allow this. One can even envision the 3D SP model grid evolving locally as the simulation progresses (i.e., on the fly) as the weather patterns evolve.

5. Two-dimensional mock-Hadley circulation

In this section, we present results of idealized simulations that illustrate some of the points discussed above. We consider two-dimensional mock-Hadley simulations that follow the mock-Walker simulations of Grabowski et al. (2000; GYM2000 hereinafter). The key difference is the temperature contrast between the warm and cold sea surface temperature (SST): 12 °C here versus 4 °C in GYM2000. The two-dimensional horizontally periodic computational domain is 6000 by 24 km$^2$, with a high SST of 28 °C and a low SST of 16 °C, varying horizontally as a cosine function. Radiative cooling is prescribed as 1.5 K day$^{-1}$ between the surface and a height of 12 km and decreasing linearly to zero at 15 km. A gravity wave absorber is applied in the upper part of the domain, with the inverse time scale of 1/600 s$^{-1}$ at the upper rigid lid boundary and decreasing to zero at 17 km. No rotational effects are considered, and surface friction is excluded as well. Latent and sensible surface heat fluxes balancing the radiative cooling are calculated assuming a simple bulk formulation (see Eqs. 19–21 in Grabowski 1998). The fluxes are uniformly distributed over the lowest 600 m of the atmosphere, that is, assuming the fluxes vary linearly between the surface flux at $z = 0$ and zero at 600 m. Divergence of these fluxes provides boundary-layer heating and moistening. Simulations start from a typical tropical sounding and are run for 40 days, reaching conditions close to quasi-equilibrium. As in the natural Hadley circulation, one expects deep convection over the high-SST part of the domain and a well-mixed stratocumulus-topped boundary layer under a strong inversion over the low SSTs.

In the first simulation (referred to as the CRM simulation), a uniform grid is used throughout the domain with a horizontal grid length of 2 km and a stretched grid in the vertical with 81 levels (see Fig. 4). A time step of 3 s is used. Figure 5 shows Hovmueller diagrams of the liquid (cloud water plus rain) and ice (cloud ice and snow) water paths, LWP and IWP, respectively, for the CRM simulation. The figure shows that deep convection is limited to the warmest SSTs, as expected. Individual convective systems are typically initiated near the center of the domain (i.e., over the warmest SSTs), and they propagate toward lower SSTs. As discussed in GYM2000, the propagation reflects the coupling between convection and gravity waves. These wave–convection interactions lead to pronounced fluctuations of convective activity and surface rainfall as discussed in GYM2000 (see Figs. 1, 3 there), see also Slawinska et al. (2014). The period of these oscillations, about 3 days in current simulations, is consistent with GYM2000 (i.e., 2 and 1 day for domain sizes of 4000 and 2000 km, respectively) and with Slawinska et al. (2014) where the period was about 40 days for the domain size of 40,000 km. Shallow water clouds over cold SSTs are only present during the initial few days of the simulation.

Closer inspection of model results reveals an unrealistic structure of the lower troposphere over cold SSTs. This is illustrated in Fig. 6 that shows temperature and relative humidity (RH) profiles over warm and cold SSTs and compares them to the initial profiles. As expected, free-tropospheric temperature profiles over warm and cold SSTs differ little because
of the homogenizing effect of convectively generated gravity waves. In contrast, RH profiles show an extreme difference between warm and cold SSTs, in agreement with results discussed in GYM2000 (cf. Fig. 5 there). The warm SST RH profile is relatively humid, whereas the cold SST RH profile is extremely dry across most of the troposphere. This is due to the subsidence drying as discussed in GYM2000. However, the boundary layer over cold SST is stable and does not show the expected structure of a well-mixed stratocumulus-topped boundary layer overlaid by a strong inversion as in natural subtropical cold-SST boundary layers (e.g., Stevens 2005). Arguably, this is because of the inability of the SP model to develop and maintain the mixed-layer structure due to relatively coarse vertical and horizontal resolutions and lack of cloud-top radiative cooling, the dominant driver of the stratocumulus-topped boundary layer overturning. One might expect that the stratocumulus-topped well-mixed boundary layer can also be simulated applying a suitable subgrid-scale turbulent mixing scheme in the CRM, an option that is beyond the scope of the simple illustrative example presented here.

The second simulation applies the SP methodology with the outer model featuring a horizontal grid length of 60 km (i.e., 100 columns) and the same SP models embedded in each outer model column. The SP models feature a horizontal domain extent of 60 km, 2 km horizontal grid length, and the same vertical grid as in the CRM model. It will be referred to as the homogeneous SP simulation. This is essentially the same design as CRM except for the partitioning of the 6000-km simulation domain into independent 60-km wide subdomains with SP models inside. In general, the homogeneous SP simulation results resemble those for the CRM simulation (not shown). This should not be surprising because the homogeneous
SP model framework adds nothing to the model capabilities. In fact, one may expect some deterioration of the CRM results because of the way neighboring SP models communicate.

In an attempt to improve the cold-SST boundary layer, a heterogeneous SP simulation is introduced, with the grid of the SP models changing depending on their location within the outer model domain. SP models over the warmest SST (i.e., in the center of the computational domain) are the same as in the homogeneous SP (i.e., 60 km horizontal domain, 2 km horizontal grid length, the same stretched vertical grid as in CRM). In contrast, a truly “eddy-resolving” grid is applied over the coldest SST, with the same number of grid points in the horizontal and vertical as over the warmest SST (i.e., 30 by 81). The horizontal extent of the high-resolution SP model is just 3 km, and the horizontal grid length is 100 m. The vertical grid features even higher resolution near the surface (the vertical grid length is 30 m below 1200 m) and rapidly stretches above. The grid layout changes between the warmest and the coldest SST as the cosine function, that is, in the same way as does the SST (see Fig. 7). The same SP model time step of 3 s is used in all SP models. An important addition of

![Fig. 6. Initial (short-dashed) and quasi-equilibrium profiles of the (left) potential temperature and (right) relative humidity over (long-dashed) high SST and (solid) low SST. Note the unrealistic boundary-layer structure over cold SST.](image)

![Fig. 7. Configuration of the heterogeneous SP simulation domain for a mock-Hadley cell. Bottom panel shows the distribution of SST. Middle panel shows the horizontal grid of SST. Upper panel shows heights of the model levels within SP domains with only every second level shown. The outer model levels are as in Fig. 4.](image)
the heterogeneous SP system is the need to interpolate profiles passed from the outer model to the SP models, and vice versa, between the vertical grids used in both models. This is done through a simple linear interpolation in the simulation described here. Arguably, a more elaborate approach would be desirable, for instance, applying interpolations that maintain water and dry/moist static energy conservation between the two profiles.

Figure 8 (in the same format as Fig. 5) shows Hovmueller diagrams of LWP and IWP for the heterogeneous SP simulations. As far as deep convection is concerned, the results resemble those from CRM, with deep ice-bearing clouds over warm SSTs and convection propagating toward colder SSTs. An important new element is the presence of warm ice-free stratocumulus-type clouds over cold SSTs.

Figure 9 shows snapshots of model data at day 40 to further illustrate the two cloud types present in the simulation, deep convection over warm SSTs and drizzling stratocumulus over cold SSTs. The data are shown on the outer model grid, that is, after averaging of the SP data and interpolating them onto the large-scale model vertical grid. The figure shows a relatively uniform potential temperature field above the boundary layer across the entire domain, large contrast between relative humidity over warm and cold SSTs, precipitating deep clouds over warm SSTs, strong temperature and moisture inversion above well-mixed stratocumulus-topped boundary layer, and drizzling stratocumulus over cold SSTs. The realistic simulation of the boundary layer over cold SSTs is arguably because of the eddy-resolving grid used there, even with no cloud-top radiative cooling.

Finally, Figure 10 shows the spatial distribution of time-averaged surface latent and sensible heat fluxes in CRM, homogeneous SP, and heterogeneous SP simulations. The figure shows that distributions are relatively similar in all cases, as one might expect. Most interestingly, CRM and homogeneous SP simu-
lations show unrealistic surface sensible heat fluxes over cold SSTs, with the ocean being heated by the atmosphere. The fluxes over cold SST in the heterogeneous SP simulation are positive, although arguably unrealistically small. One might expect that inclusion of the interactive radiation leading to strong cloud-top cooling and thus more energetic boundary-layer circulations might improve this aspect of the 2D mock-Hadley cell simulation.

In summary, application of the heterogeneous SP system allows a more realistic simulation of the mock-Hadley circulation, with deep convection over warm SSTs and drizzling stratocumulus topping the well-mixed boundary layer over cold SSTs.

6. Conclusions

This paper makes the case for applying the SP methodology to reach the global large-eddy simulation. The review in Section 2 documents that SP is already a well-established climate simulation approach, and it provides significant improvements for the representation of clouds and precipitation and their interactions with radiative and surface processes. A brief discussion in Section 3 shows that convection-permitting horizontal resolution applied in the original SP is still relatively coarse from the point of view of the scale range of relevant physical processes involved in deep convection and numerical model convergence. Large eddy simulation allows representing a wide range of atmospheric small-scale processes such as boundary-layer turbulence, shallow convection, convective drafts in deep convection, cloud turbulence, interactions between cloud microphysics, and dynamics, etc. Arguably, global large eddy simulation is the ultimate all-scale research tool for weather and climate studies.

The 2D geometry in the original SP methodology raises important issues, like the selection of the orientation of the 2D SP mode and the coupling of horizontal flows between large-scale and small-scale models. These issues are resolved once a 3D model is used as SP. The 3D SP model can also include
small-scale topography, an aspect so far not considered in the SP applications and deserving a separate investigation. Moreover, separation between large-scale and small-scale dynamics, the key feature of SP, mitigates significant issues related to the selection of the suitable mathematical formulation of the model equations. Compressible equations are valid across the entire range of spatial scales, from small-scale turbulence to global-scale circulations. However, their numerical implementation is cumbersome because of the presence of fast acoustic modes that are typically irrelevant to weather and climate phenomena. With the global SP LES, the outer model can feature a horizontal grid length of a few tens of kilometers, similarly to NWP models a few decades ago, and can be based on hydrostatic primitive equations. The embedded SP LES models can be anelastic and predict small-scale perturbations around base state and environmental profiles that vary between warm regions near the equator and cold regions near the poles. Moreover, as illustrated by idealized mock-Hadley circulation simulations, the SP grid structure can vary between different SP models and thus offers an unstructured grid environment with practically no additional code development. Finally, global SP LES offers embarrassingly parallel environment because each SP LES model is to be run on a separate core of a parallel computer and communicate with the outer model infrequently by sending/receiving only mean profiles during the simulation. Overall, the global SP LES can provide a stepping stone for the ultimate global LES. We hope to see such a development in the near future.

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References

Arakawa, A., 2004: The cumulus parameterization problem: Past, present, and future. *J. Climate*, 17, 2493–2525.
Arakawa, A., and C. S. Konor, 2009: Unification of the anelastic and quasi-hydrostatic systems of equations. *Mon. Wea. Rev.*, 137, 710–726.
Arnold, N. P., M. Branson, M. A. Burt, D. S. Abbot, Z. Kuang, D. A. Randall, and E. Tziperman, 2014: Effects of explicit atmospheric convection at high CO₂. *Proc. Nat. Acad. Sci.*, 111, 10943–10948.
Arnold, N. P., M. Branson, Z. Kuang, D. A. Randall, and E.
Tziperman, 2015: MJO intensification with warming in the superparameterized CESM. *J. Climate*, 28, 2706–2724.

Benedict, J. J., and D. A. Randall, 2009: Structure of the Madden-Julian oscillation in the superparameterized CAM. *J. Atmos. Sci.*, 66, 3277–3296.

Benedict, J. J., and D. A. Randall, 2011: Impacts of idealized air–sea coupling on Madden–Julian oscillation structure in the superparameterized CAM. *J. Atmos. Sci.*, 68, 1990–2008.

Bretherton, C. S., P. N. Blossey, and C. Stan, 2014: Cloud feedbacks on greenhouse warming in the superparameterized climate model SP-CCSM4. *J. Adv. Model. Earth Syst.*, 6, 1185–1204.

Bryan, G. H., and H. Morrison, 2012: Sensitivity of a simulated squall line to horizontal resolution and parameterization of microphysics. *Mon. Wea. Rev.*, 140, 202–225.

Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution requirements for the simulation of deep moist convection. *Mon. Wea. Rev.*, 131, 2394–2416.

Clark, T. L., 1979: Numerical simulations with a three dimensional cloud model: Lateral boundary condition experiments and multicellular severe storm simulations. *J. Atmos. Sci.*, 36, 2191–2215.

DeMott, C. A., D. A. Randall, and M. Khairoutdinov, 2007: Convective precipitation variability as a tool for general circulation model analysis. *J. Climate*, 20, 91–112.

DeMott, C. A., C. Stan, and D. A. Randall, 2013: Northward propagation mechanisms of the boreal summer intraseasonal oscillation in the ERA-Interim Reanalysis and SP-CCSM. *J. Climate*, 26, 1973–1992.

DeMott, C. A., C. Stan, D. A. Randall, and M. D. Branson, 2014: Intraseasonal variability in coupled GCMs: The roles of ocean feedbacks and model physics. *J. Climate*, 27, 4970–4995.

Goswami, B. B., N. J. Mani, P. Mukhopadhyay, D. E. Waliser, J. J. Benedict, E. D. Maloney, M. Khairoutdinov, and B. N. Goswami, 2011: Monsoon intraseasonal oscillations as simulated by the superparameterized Community Atmosphere Model. *J. Geophys. Res.*, 116, D22104, doi:10.1029/2011JD015948.

Goswami, B. B., P. Mukhopadhyay, M. Khairoutdinov, and B. N. Goswami, 2013: Simulation of Indian summer monsoon intraseasonal oscillations in a superparameterized coupled climate model: Need to improve the embedded cloud resolving model. *Climate Dyn.*, 41, 1497–1507.

Goswami, B. B., R. P. M. Krishna, P. Mukhopadhyay, M. Khairoutdinov, and B. N. Goswami, 2015: Simulation of the Indian summer monsoon in the superparameterized Climate Forecast System version 2: Preliminary results. *J. Climate*, 8988–9012.

Grabowski, W. W., 1998: Toward cloud resolving modeling of large-scale tropical circulations: A simple cloud microphysics parameterization. *J. Atmos. Sci.*, 55, 3283–3298.

Grabowski, W. W., 2001: Coupling cloud processes with the large-scale dynamics using the Cloud-Resolving Convection Parameterization (CRCP). *J. Atmos. Sci.*, 58, 978–997.

Grabowski, W. W., 2003a: MJO-like coherent structures: Sensitivity simulations using the Cloud-Resolving Convection Parameterization (CRCP). *J. Atmos. Sci.*, 60, 847–864.

Grabowski, W. W., 2003b: Impact of cloud microphysics on convective-radiative quasi-equilibrium revealed by Cloud-Resolving Convection Parameterization. *J. Climate*, 16, 3463–3475.

Grabowski, W. W., 2004: An improved framework for superparameterization. *J. Atmos. Sci.*, 61, 1940–1952.

Grabowski, W. W., 2006a: Comments on “Preliminary tests of multiscale modeling with a two-dimensional framework: Sensitivity to coupling methods” by Jung and Arakawa. *Mon. Wea. Rev.*, 134, 2021–2026.

Grabowski, W. W., 2006b: Impact of explicit atmosphere-ocean coupling on MJO-like coherent structures in idealized aquaplanet simulations. *J. Atmos. Sci.*, 63, 2289–2306.

Grabowski, W. W., and P. K. Smolarkiewicz, 1999: CRCP: A cloud resolving convection parameterization for modeling the tropical convecting atmosphere. *Physica D*, 133, 171–178.

Grabowski, W. W., and M. W. Moncrieff, 2004: Moisture-convection feedback in the Tropics. *Quart. J. Roy. Meteor. Soc.*, 130, 3081–3104.

Grabowski, W. W., X. Wu, and M. W. Moncrieff, 1996: Cloud resolving modeling of tropical cloud systems during Phase III of GATE. Part I: Two-dimensional experiments. *J. Atmos. Sci.*, 53, 3684–3709.

Grabowski, W. W., X. Wu, M. W. Moncrieff, and W. D. Hall, 1998: Cloud resolving modeling of tropical cloud systems during Phase III of GATE. Part II: Effects of resolution and the third spatial dimension. *J. Atmos. Sci.*, 55, 3264–3282.

Grabowski, W. W., J. Yano, and M. W. Moncrieff, 2000: Cloud resolving modeling of tropical circulations driven by large-scale SST gradients. *J. Atmos. Sci.*, 57, 2022–2039.

Grabowski, W. W., P. Bechtold, A. Cheng, R. Forbes, C. Halliwell, M. Khairoutdinov, S. Lang, T. Nasuno, J. Petch, W.-K. Tao, R. Wong, X. Wu, and K.-M. Xu, 2006: Daytime convective development over land: A model intercomparison based on LBA observations. *Quart. J. Roy. Meteor. Soc.*, 132, 317–344.

Held, I. M., R. S. Hemler, and V. Ramaswamy, 1993: Radiative-convective equilibrium with explicit two-dimensional moist convection. *J. Atmos. Sci.*, 50, 3909–3927.

Jiang, X., D. E. Waliser, P. K. Xavier, J. Petch, N. P. Klingaman, S. J. Woolnough, B. Guan, G. Bellon, T. Waliser, J. J. Benedict, E. D. Maloney, M. Khairoutdinov, S. Lang, T. Nasuno, J. Petch, W.-K. Tao, R. Wong, X. Wu, and K.-M. Xu, 2006: Daytime convective development over land: A model intercomparison based on LBA observations. *Quart. J. Roy. Meteor. Soc.*, 132, 317–344.
Khairoutdinov, M. F., C. DeMott, C. Hannay, H. Lin, W. Hu, D. Kim, C.-L. Lappen, M.-M. Lu, H.-Y. Ma, T. Miyakawa, J. A. Ridout, S. D. Schubert, J. Scinocca, K.-H. Seo, E. Shindo, X. Song, C. Stan, W.-L. Tseng, W. Wang, T. Wu, X. Wu, K. Wyser, G. J. Zhang, and H. Zhu, 2015: Vertical structure and physical processes of the Madden-Julian oscillation: Exploring key model physics in climate simulations. J. Geophys. Res., 120, 4718–4748.

Jones, C. R., C. S. Bretherton, and M. S. Pritchard, 2015: Mean-state acceleration of cloud-resolving models and large eddy simulations. J. Adv. Model. Earth Syst., 7, 1643–1660.

Jung, J.-H., and A. Arakawa, 2010: Development of a Quasi-3D Multiscale Modeling Framework: Motivation, basic algorithm and preliminary results. J. Adv. Model. Earth Syst., 2, 11, doi:10.3894/JAMES.2010.2.11.

Jung, J.-H., and A. Arakawa, 2014: Modeling the moist-convective atmosphere with a Quasi-3-D Multiscale Modeling Framework (Q3D MMF). J. Adv. Model. Earth Syst., 6, 185–205.

Khairoutdinov, M. F., and D. A. Randall, 2001: A cloud resolving model as a cloud parameterization in the NCAR Community Climate System Model: Preliminary results. Geophys. Res. Lett., 28, 3617–3620.

Khairoutdinov, M. F., D. A. Randall, and C. DeMott, 2005: Simulations of the atmospheric general circulation using a cloud-resolving model as a superparameterization of physical processes. J. Atmos. Sci., 62, 2136–2154.

Khairoutdinov, M. F., C. DeMott, and D. A. Randall, 2008: Evaluation of the simulated interannual and subseasonal variability in an AMIP-style simulation using the CSU Multiscale Modeling Framework. J. Climate, 21, 413–431.

Khairoutdinov, M. F., S. K. Krueger, C.-H. Moeng, P. A. Bogenschutz, and D. A. Randall, 2009: Large-eddy simulation of Maritime deep tropical convection. J. Adv. Model. Earth Syst., 1, 15, doi:10.3894/JAMES.2009.1.15.

Kim, D., K. Sperber, W. Stern, D. Waliser, I.-S. Kang, E. Maloney, W. Wang, K. Weickmann, J. Benedict, M. Khairoutdinov, M.-I. Lee, R. Neale, M. Suarez, K. Thayer-Calder, and G. Zhang, 2009: Application of MJO simulation diagnostics to climate models. J. Climate, 22, 6413–6436.

Klemp, J. B., and R. B. Wilhelmson, 1978: The simulation of three-dimensional convective storm dynamics. J. Atmos. Sci., 35, 1070–1096.

Kooperman, G. J., M. S. Pritchard, and R. C. J. Somerville, 2014: The response of US summer rainfall to quadrupled CO2 climate change in conventional and superparameterized versions of the NCAR Community atmosphere model. J. Adv. Model. Earth Syst., 6, 859–882.

Krishnamurthy, V., and C. Stan, 2015: Simulation of the South American climate by a coupled model with super-parameterized convection. Climate Dyn., 44, 2369–2382.

Kurowski, M. J., W. W. Grabowski, and P. K. Smolarkiewicz, 2014: Anelastic and compressible simulation of moist deep convection. J. Atmos. Sci., 71, 3767–3787.

Kurowski, M. J., W. W. Grabowski, and P. K. Smolarkiewicz, 2015: Anelastic and compressible simulation of moist dynamics at planetary scales. J. Atmos. Sci., 72, 3975–3995.

Li, F., D. Rosa, W. D. Collins, and M. F. Wehner, 2012: “Super-parameterization”: A better way to simulate regional extreme precipitation? J. Adv. Model. Earth Syst., 4, M04002, doi:10.1029/2011MS000106.

Lipps, F. B., and R. S. Hemler, 1982: A scale analysis of deep moist convection and some related numerical calculations. J. Atmos. Sci., 39, 2192–2210.

Liu, C., M. W. Moncrieff, and W. W. Grabowski, 2001: Hierarchical modeling of tropical convective systems using resolved and parameterized approaches. Quart. J. Roy. Meteor. Soc., 127, 493–515.

Mapes, B. E., and X. Wu, 2001: Convective eddy momentum tendencies in long cloud-resolving model simulations. J. Atmos. Sci., 58, 517–526.

Marchand, R., J. Haynes, G. G. Mace, T. Ackerman, and G. Stephens, 2009: A comparison of simulated cloud radar output from the multiscale modeling framework global climate model with CloudSat cloud radar observations. J. Geophys. Res., 114, D00A20, doi:10.1029/2008JD009790.

McCrary, R. R., D. A. Randall, and C. Stan, 2014a: Simulations of the West African monsoon with a superparameterized climate model. Part 1: The seasonal cycle. J. Climate, 27, 8303–8322.

McCrary, R. R., D. A. Randall, and C. Stan, 2014b: Simulations of the West African monsoon with a superparameterized climate model. Part 2: African easterly waves. J. Climate, 27, 8323–8341.

Moeng, C.-H., J. C. McWilliams, R. Rotunno, P. P. Sullivan, and J. Weil, 2004: Investigating 2D modeling of atmospheric convection in the PBL. J. Atmos. Sci., 61, 889–903.

Moeng, C.-H., M. A. LeMone, M. F. Khairoutdinov, S. K. Krueger, P. A. Bogenschutz, and D. A. Randall, 2009: The ‘tropical marine boundary layer under a deep convection system: A large-eddy simulation study. J. Adv. Model. Earth Syst., 1, 16, doi:10.3894/JAMES.2009.1.16.

Mohr, K. I., W.-K. Tao, J.-D. Chern, S. V. Kumar, and C. D. Peters-Lidard, 2013: The NASA-Goddard Multi-scale Modeling Framework-Land Information System: Global land/atmosphere interaction with resolved convection. Environ. Model. Software, 39, 103–115.

Oleson, K. W., D. M. Lawrence, B. Gordon, M. G. Flanner,
E. Kluzek, J. Peter, S. Levis, S. C. Swenson, E. Thornton, J. Feddema, C. L. Heald, J.-F. Lamarque, G.-Y. Niu, T. Qian, S. Running, K. Sagakuchi, L. Yang, X. Zeng, and X. Zeng, 2010: Technical description of version 4.0 of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-478+STR, National Center for Atmospheric Research, CO, USA, 257 pp.

Ovtchinnikov, M., T. P. Ackerman, R. T. Marchand, and M. F. Khairoutdinov, 2006: Evaluation of the multi-scale modeling framework using data from the Atmospheric Radiation Measurement program. J. Climate, 19, 1716–1729.

Pritchard, M. S., and R. C. J. Somerville, 2009a: Empirical orthogonal function analysis of the diurnal cycle of precipitation in a multi-scale climate model. Geophys. Res. Lett., 36, L05812, doi:10.1029/2008GL036964.

Pritchard, M. S., and R. C. J. Somerville, 2009b: Assessing the diurnal cycle of precipitation in a multi-scale climate model. J. Adv. Model. Earth Syst., 1, 12, doi:10.3894/JAMES.2009.1.12.

Pritchard, M. S., M. W. Moncrieff, and R. C. J. Somerville, 2011: Orogenic propagating precipitation systems over the United States in a global climate model with embedded explicit convection. J. Atmos. Sci., 68, 1821–1840.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003: Breaking the cloud-parameterization deadlock. Bull. Amer. Meteor. Soc., 84, 1547–1564.

Redelsperger, J.-L., F. Guichard, and S. Mondon, 2000: A parameterization of mesoscale enhancement of surface fluxes for large-scale models. J. Climate, 13, 402–421.

Rotunno, R., Y. Chen, W. Wang, C. Davis, J. Dudhia, and G. J. Holland, 2009: Large-eddy simulation of an idealized tropical cyclone. Bull. Amer. Meteor. Soc., 90, 1783–1788.

Satoh, M., H. Tomita, H. Yashiro, H. Miura, C. Kodama, T. Seiki, A. T. Noda, Y. Yamada, D. Goto, M. Sawada, T. Miyoshi, Y. Niwa, M. Hara, T. Ohno, S. Iga, T. Arakawa, T. Inoue, and H. Kubokawa, 2014: The non-hydrostatic icosahedral atmospheric model: Description and development. Prog. Earth. Planet. Sci., 1, 18, doi:10.1186/s40645-014-0018-1.

Schalkwijk, J., H. J. J. Jonker, A. P. Siebesma, and E. van Meijgaard, 2015: Weather forecasting using GPU-based large-eddy simulations. Bull. Amer. Meteor. Soc., 96, 715–723.

Schlesinger, R. E., 1975: A three-dimensional numerical model of an isolated deep convective cloud: Preliminary results. J. Atmos. Sci., 32, 934–957.

Slawinska, J., O. Pauluis, A. J. Majda, and W. W. Grabowski, 2014: Multiscale interactions in an idealized Walker circulation: Mean circulation and intraseasonal variability. J. Atmos. Sci., 71, 953–971.

Slawinska, J., O. Pauluis, A. J. Majda, and W. W. Grabowski, 2015: Multiscale interactions in an idealized Walker cell: Simulations with sparse space–time superparameterization. Mon. Wea. Rev., 143, 563–580.

Smolarkiewicz, P. K., C. Kühnlein, and N. P. Wedi, 2014: A consistent framework for discrete integrations of soundproof and compressible PDEs of atmospheric dynamics. J. Comput. Phys., 263, 185–205.

Stan, C., M. Khairoutdinov, C. A. DeMott, V. Krishnamurthy, D. M. Straus, D. A. Randall, J. L. Kinter III, and J. Shukla, 2009: An ocean-atmosphere climate simulation with an embedded cloud resolving model. Geophys. Res. Lett., 37, L01702, doi:10.1029/2009GL040822.

Stevens, B., 2005: Atmospheric moist convection. Ann. Rev. Earth Planet. Sci., 33, 605–643.

Tao, W.-K., J.-D. Chern, R. Atlas, D. Randall, M. Khairoutdinov, J.-L. Li, D. E. Waliser, A. Hou, X. Lin, C. Peters-Lidard, W. Lau, J. Jiang, and J. Simpson, 2009: Multi-scale modeling system: Development, applications and critical issues. Bull. Amer. Meteor. Soc., 90, 515–534.

Tapp, M. C., and P. W. White, 1976: A non-hydrostatic mesoscale model. Quart. J. Roy. Meteor. Soc., 102, 277–296.

Tompkins, A. M., and G. C. Craig, 1998: Radiative–convective equilibrium in a three-dimensional cloud-ensemble model. Quart. J. Roy. Meteor. Soc., 124, 2073–2097.

Tulich, S. N., 2015: A strategy for representing the effects of convective momentum transport in multiscale models: Evaluation using a new superparameterized version of the Weather Research and Forecast model (SP-WRF). J. Adv. Model. Earth Syst., 7, 938–962.

Wang, M., S. Ghan, M. Ovchinnikov, X. Liu, R. Easter, E. Kassianov, Y. Qian, and H. Morrison, 2011a: Aerosol indirect effects in a multi-scale aerosol-climate model PNNL-MMF. Atmos. Chem. Phys., 11, 5431–5455.

Wang, M., S. Ghan, R. Easter, M. Ovchinnikov, X. Liu, E. Kassianov, Y. Qian, and M. Khairoutdinov, 2011b: The multi-scale aerosol-climate model PNNL-MMF: Model description and evaluation. Geosci. Model Dev., 4, 137–168.

Wyant, M. C., M. Khairoutdinov, and C. S. Bretherton, 2006: Climate sensitivity and cloud response of a GCM with a superparameterization. Geophys. Res. Lett., 33, L06714, doi:10.1029/2005GL025464.

Wyant, M. C., C. S. Bretherton, and P. N. Blossey, 2009: Subtropical low cloud response to a warmer climate in a superparameterized climate model. Part I: Regime sorting and physical mechanisms. J. Adv. Model. Earth Syst., 1, 7, doi:10.3894/ JAMES.2009.1.7.

Xu, K.-M., and D. A. Randall, 1995: Impact of interactive radiative transfer on the macroscopic behavior
of cumulus ensembles. Part II: Mechanisms for cloud-radiation interactions. *J. Atmos. Sci.*, 52, 800–817.

Xu, K.-M., and D. A. Randall, 1996: Explicit simulation of cumulus ensembles with the GATE Phase III data: Comparison with observations. *J. Atmos. Sci.*, 53, 3710–3736.

Zängl, G., D. Reinert, P. Ripodas, and M. Baldauf, 2014: The ICON (ICOsahedral Non-hydrostatic) modeling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. *Quart. J. Roy. Meteor. Soc.*, 141, 563–579.

Zhang, Y., S. A. Klein, C. Liu, B. Tian, R. T. Marchand, J. M. Haynes, R. B. McCoy, Y. Zhang, and T. P. Ackerman, 2008: On the diurnal cycle of deep convection, high-level cloud, and upper troposphere water vapor in the Multiscale Modeling Framework. *J. Geophys. Res.*, 113, D16105, doi:10.1029/2008JD00990.