Cloud-resolving simulation of TOGA-COARE using parameterized large-scale dynamics

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Abstract

Variations in deep convective activity during the 4-month TOGA-COARE field campaign are simulated using a cloud-resolving model (CRM). The model is driven by large scale vertical velocities that are parameterized using one of two different methods: the damped gravity wave method and the weak temperature gradient (WTG) method. Sea surface temperature, radiative fluxes, and relaxation of the horizontal mean horizontal wind field are also imposed. Simulations with large-scale vertical velocity imposed from the observations are performed for reference. The primary finding is that the CRM with parameterized large-scale vertical motion can capture the intraseasonal variations in rainfall to some degree. Surface evaporation from the CRM with parameterized large-scale dynamics compares particularly well with that derived from TOGA sounding array. The parameterized large scale vertical velocity has a vertical profile that is too bottom-heavy compared to observations when the wave coupling method is used with vertically uniform Rayleigh damping on horizontal wind, but too top-heavy when the WTG method is used.
1. Introduction

Cloud-resolving models (CRMs) on small doubly periodic domains have been widely used to study many aspects of deep convection and its response to the large scale environment. One important application of CRMs is to simulate specific sequences of weather events which have been observed in field campaigns [e.g., Soong and Ogura, 1980, Grabowski et al., 1996, Johnson et al., 2002, Tao et al., 2004; Khairoutdinov and Randall, 2003; Blossey et al., 2007; Fridlind et al., 2012]. In this context, it is standard to specify large scale forcings derived from sounding arrays. These forcings – particularly the large-scale vertical motion or vertical advection terms – control the occurrence and intensity of convection, and keep it close to that observed. The simulated precipitation, in particular, is tightly constrained by the forcings. Model biases may appear in the simulated temperature, moisture, clouds, and radiative and surface fluxes.

While much has been learned from such simulations, it may be argued that they misrepresent the causality of many tropical circulations. Large-scale vertical motion is arguably as much a consequence of deep convection as a cause [e.g., Mapes, 1997; Sobel and Bretherton, 2000]. When large-scale vertical motion is specified, one cannot use the simulation to understand the factors which control the occurrence or intensity of deep convection.

In the past decade, methods have been developed to allow interaction between CRM-resolved convective dynamics and parameterized large scale dynamics. One group of methods uses the weak temperature gradient (WTG) approximation [e.g., Sobel and Bretherton, 2000; Raymond and Zeng, 2005]. Another set of methods involves coupling to a large-scale gravity wave of specified horizontal wavelength [Kuang 2008, 2011;
Blossey et al., 2009; Romps, 2012 a and b]. We explore both of these in this study. Still others have been introduced, but are not considered here [e.g., Bergman and Sardeshmukh, 2004; Mapes, 2004].

Thus far, these parameterizations of large scale dynamics have been used almost exclusively in idealized settings. They have been used to study, for example, the response of deep convection to relative sea surface temperature [Sobel and Bretherton, 2000; Wang and Sobel, 2011; Kuang, 2012] or imposed surface wind speed [Raymond and Zeng, 2005; Sessions et al., 2010] or the interaction of convection with a pure plane gravity wave [Kuang, 2008] or idealized tropical depression [Raymond and Sessions, 2007].

In this study, we use these methods to simulate specific time-varying field observations. We expect that these methods will not be able to simulate the variations of deep convection as accurately as the standard method with specified forcing can, because the large-scale vertical motion is no longer directly constrained by observations. On the other hand, the degree to which these variations are simulated represents genuine success or failure of the simulation, and the model can provide nontrivial information about what factors control the convection.

We use a CRM with parameterized large scale dynamics to simulate a four-month sequence of weather observed in the western Pacific Ocean during the TOGA-COARE (Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment, Webster and Lukas, 1992) field program. The atmospheric state was sampled by a sounding array during the 4-month intensive observing period (IOP), from November 1, 1992 to Feb 28, 1993. During this time two active phases of the Madden-Julian
oscillation (MJO) traversed the sounding array [Chen et al., 1999]. Several previous studies have reported CRM simulations of convective phases of the MJO during TOGA-COARE, using standard methods with imposed large-scale vertical motion or vertical advection [e.g., Johnson et al., 2002; Wu et al., 1998]. Here, our focus will be on capturing the evolution of convection over intraseasonal time scales during the entire TOGA-COARE period using parameterized dynamics. To the extent that we are able to simulate the time variations of precipitation, the implication is that the processes which are specified from observations as time-varying forcings – which no longer include large-scale vertical motion – control the variations in deep convection.

2. Data, method, numerical method

2.1. Large scale forcing data

We use version 2.1 of the large-scale forcings derived from the Intensive Flux Array (IFA) sounding network [Ciesielski et al., 2003] from November 1, 1992 to Feb 28, 1993 during the TOGA-COARE. After a long suppressed phase of the MJO, the first active period of convection began around day 40 and ended around day 55 from Nov 1, as shown in black Figure 1a. The 2nd active MJO phase passed the COARE region from day 80 to the end of the period.

2.2 Numerical Model

We use the WRF model Version 3.3 [Skamarock et al., 2008]. Boundary layer turbulence and vertical subgrid eddies are parameterized using the Yonsei University (YSU) scheme [Hong et al., 2006]; horizontal subgrid eddies are treated using
Smagorinsky first order closure; the surface moisture and heat fluxes are parameterized following Monin-Obukhov similarity theory; the radiative transfer scheme is from CAM [Collins et al., 2004]; and the Purdue-Lin scheme is used for cloud microphysics [Lin et al., 1983]. The horizontal and vertical advection schemes are 5th order and 3rd order accurate, respectively. Moisture and condensate are advected using a positive definite scheme. We use the implicit damping scheme to suppress unphysical reflection of vertically propagating gravity waves in the top 5 km of the numerical grid [Klemp et al., 2008]. We use a doubly periodic domain with zero Coriolis parameter. 60 vertical levels are used with stretched vertical level spacing. The horizontal grid spacing is 1 km within a grid of 64x64x22 km³. An adaptive time step is used for all simulations in this study.

2.3 Methodology

As a point of reference, we first impose the following forcings to our CRM at 6-hourly resolution, as in many previous studies: (1) large-scale vertical motion to advect domain-averaged potential temperature and moisture, (2) time-varying uniform SST as the lower boundary condition, and (3) relaxation of the horizontal domain mean horizontal winds are relaxed to the observed IFA mean profiles with a relaxation time scale of 1 hour.

Of these forcings, large scale vertical velocity is by far the most important for controlling surface rainfall. Horizontal advection terms are not included in this study. Preliminary investigation suggests that their impact is small for surface rainfall, and their proper inclusion is a subtle matter. Including them as fixed forcings neglects their actual dependence on the local state and in principle allows bad behavior if the model is biased
(for example, if the advective forcing on humidity is negative and the humidity becomes zero, there is nothing to prevent it from becoming negative). We have represented horizontal moisture advection as a relaxation to an upstream value in idealized studies [e.g., Sobel and Bellon, 2009; Wang and Sobel, 2012], but determining the appropriate upstream value and relaxation time are more complex in the present observation-based case studies. We defer inclusion of these terms to future work.

We have used both the WTG and damped gravity wave methods to parameterize large-scale dynamics. In both methods, large scale vertical motion is dynamically derived as part of the model solution, and used for advecting temperature and moisture in the vertical. In the WTG method, large scale vertical velocity \( W \) in the free troposphere is derived as:

\[
W \frac{\partial \theta}{\partial z} = \frac{\theta - \theta_T}{\tau},
\]

where \( \theta \) is potential temperature horizontally averaged over the CRM domain, and \( \theta_T \) is the target potential temperature. Within the boundary layer, \( W \) is linearly interpolated between its value at top of boundary layer obtained from equation (1) and its surface value \( W=0 \). Here, we simply take the boundary layer height to be 1.5 km and apply equation (1) from 1.5 km to 17 km (~100 hPa). \( \theta_T \) is the observed values to which potential temperature is relaxed at a time scale of \( \tau = 4 \) hours. In the damped gravity wave method [Kuang, 2008 and 2011, Blossey et al., 2009, Romps, 2012 a and b], large scale vertical velocity is obtained using an equation that relates it to virtual temperature anomalies [see derivations in Blossey et al., 2009 or Kuang, 2011]:
\[
\frac{\partial}{\partial p} \left( \frac{\partial \omega}{\partial p} \right) = -\frac{k^2 R_d}{p} (T_v - T_v^b), \tag{2}
\]

where \( p \) is pressure, \( \omega \) is pressure velocity, \( \varepsilon \) is the time scale of momentum damping, \( k \) is the wavenumber, \( R_d \) is the dry gas constant, \( T_v \) is the domain averaged virtual temperature, and \( T_v^b \) is the target virtual temperature against which linearized wave perturbations are defined. In idealized simulations it is taken constant in time, while here it is set to the observed time-varying virtual temperature profile. For the experiment below, \( \varepsilon = 1 \) day\(^{-1} \) and \( k = 10^{-6} \) m\(^{-1} \). The elliptic equation (2) is solved with boundary conditions \( \omega = 0 \) at surface and 100 hPa. Both equation (1) and (2) are solved at every time step of the model integrations.

The model is initialized with the sounding on 00Z Nov 1, 1992. Uniformly distributed random noise of magnitude 1 K is added to the initial potential temperature field. We discuss three experiments, using the above-mentioned two methods. The first one, with imposed large-scale vertical velocity, will be referred to as “Imposed-W”. The experiments using the WTG and damped gravity wave methods will be referred to as “WTG” and “Damped-wave”, respectively. For the WTG simulations, we find that it is necessary to boost initial conditional instability in order to avoid a persistent dry state, where there is no rainfall, and troposphere is completely dry and dominated by large-scale descent. This behavior is presumably directly related to the existence of multiple equilibria under steady forcings [Sobel et al., 2007; Sessions et al., 2010]. We prevent the occurrence of this dry solution by setting the initial relative humidity to 85% over the whole troposphere.
In both the WTG and Damped-wave experiments, we do not compute radiative fluxes interactively, but instead impose time-dependent radiative heating obtained from the Imposed-W experiment. We do this to avoid complications resulting from radiative feedbacks, which are much more important with parameterized dynamics than in the standard approach. These feedbacks will be studied in greater detail in future work. In all experiments, we specify the SST and relax the horizontal mean profile of horizontal wind towards that observed.

3. Results

Figure 1a shows the domain-averaged rainfall from the Imposed-W experiment. COARE budget-derived rainfall is also shown in black. Rainfall from the Imposed-W simulation shows good agreement with the COARE budget-derived rainfall, as expected. The domain-averaged rainfall time series from the WTG and Damped-wave experiments are shown in Figure 1b and c. They do not agree with the observations as well as that from the Imposed-W experiment does. This is also as expected. The large-scale vertical velocity – which controls the dominant terms in the heat and moisture equations as shown in Figure 1a - is no longer taken from observations. It is now a nontrivial part of the solution, depending on the validity of the large-scale parameterization using equation (1) or (2), as well as on model physics and other choices (numerics, resolution, domain size etc.), and is free to deviate from that observed. It is not obvious, a priori, that the simulation need capture the observed variability of precipitation at all. There is, however, some agreement, particularly on the intraseasonal time scale. These experiments capture the convectively suppressed period during day 15
– 40, the convectively active phase of the first MJO event during day 30-55, and, to a lesser (but still significant) extent, the second MJO event for the last 20 days. Significant deviations from observations are also evident. Both simulations produce too little rainfall during days 65-80 and overestimates rainfall during days 90-100. The WTG experiment has an extended strong rainy phase that was not observed during days 50-70. Damped-wave shows good agreement with observations during this period, but Damp-wave simulates too little rainfall during the first 15 days.

To the extent that the simulation with parameterized dynamics is able to capture some of the observed variability, the implication is that that variability is controlled by those factors which are externally imposed from observations. This includes the domain-averaged target tropospheric temperature profile and horizontal wind profile, including the surface winds. We have performed experiments in which each of these factors is set to its time-mean value to determine its importance relative to the other factors (not shown). These experiments reveal that the surface wind speed, through its control on the surface latent heat flux, is the most important factor controlling the simulated intraseasonal variability.

Figure 2 compares the domain-averaged surface evaporation with observations. Interestingly, the simulated surface evaporation agrees significantly better in the Damped-wave experiment than in the imposed-W experiment. We do not have a good explanation for this at present, but simply note that we expect surface flux errors in the imposed-W case to be less consequential than they would be in the parameterized-W cases. Moisture convergence provides most of the moisture for precipitation, and it is
specified in the imposed-$W$ experiment while it is (apparently) controlled by the surface fluxes in the cases with parameterized $W$.

Figure 3 shows the large-scale vertical motion as a function of time and height from OBS and from the WTG and damped-wave simulations. For both, the degree of agreement in the time variability is similar to that in precipitation. However, we see extended strong ascent during active phases in WTG, some additional high-frequency variability in the damped-wave experiment, and stronger concentration of descent in the upper troposphere during suppressed periods in that simulation. Figure 4 compares the time-averaged vertical profiles of large-scale vertical velocity. While there is good agreement in the lower troposphere between model and OBS, the shapes of the parameterized large scale $W$ profiles deviate from OBS significantly. The profile from WTG is too top-heavy, with a peak value more than 30 cm/s around 11 km, as opposed to ~ 15 cm/s in observations, while the damped-wave simulation is insufficiently top-heavy, with a peak around 7 km, as opposed to ~ 12 km in observations.

We can understand this difference between the two methods qualitatively. Due to the structure of moist adiabats, convectively produced temperature anomalies tend to be greatest at upper levels. WTG relates $W$ to heating locally, and so will produce the largest vertical velocity near the largest temperature anomalies, by (1). The damped-wave method incorporates a momentum budget and hydrostatic balance, and so upper-level temperature anomalies can influence the circulation at lower levels. Mathematically, (2) is an elliptic problem in which the response of $W$ to $T_v$ is nonlocal in the vertical. Arguments as to why this nonlocality should result in more bottom-heavy profiles in particular are given in [Kuang, 2011, 2012]. In the damped-wave method, we expect the
shape of the vertical motion profile to be influenced by the value and vertical structure of
the Rayleigh drag coefficient, $\varepsilon$, (here taken constant) in equation (1). Sensitivity to this
quantity, and to the form of the damping (which need not formulated as a Rayleigh drag)
will be explored in future work.

4. Discussion and Conclusions

In this study, the variability of deep convection during the 4-month TOGA-
COARE is simulated using a cloud-resolving model with large-scale dynamics
parameterized using two different methods: the weak temperature gradient and the
damped gravity wave method. The results are compared to observations and to results
from a simulation in which the large-scale vertical motion is prescribed, as is more
standard.

The simulations with parameterized large-scale dynamics, though far from perfect,
are able to simulate the intraseasonal variability of surface rainfall with some success.
The surface latent heat flux, which seems to be an important control on the simulated
convection with parameterized dynamics, is actually simulated better in that simulation
than in the one with imposed large-scale vertical motion. The vertical profile of
parameterized large-scale vertical motion is too top-heavy using the WTG method, and
insufficiently top-heavy using damped gravity wave method, as compared to observations,
though we expect this to be sensitive to the treatment of momentum damping in the latter.

These results encourage us to think that simulations with interactive large-scale
dynamics may provide a new and useful modality for comparing CRMs and single-
column models to observations from field campaigns. A number of issues need to be
explored in more depth first, however, in order for us to understand the strengths and
limitations of the methods. Important issues include the roles of interactive radiation,
horizontal advection of moisture, initial conditions and free parameters such as the
horizontal wavelength of the assumed gravity wave. Study of these issues is underway
and will be reported in due time.

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Figure 1. Budget-derived daily rainfall (black) and model simulated rainfall (blue) for (a) the Imposed-W experiment, (b) the WTG experiment, and (c) the Damped-wave experiment.
Figure 2. Daily mean surface evaporation from COARE (black curves) and model simulations (blue) for (a) the Imposed-W experiment, (b) the WTG experiment, and (c) the Damped-wave experiment.
Figure 3. Large-scale vertical motion as a function of time and height for (a) the observations (and Imposed-W experiment), (b) the WTG experiment, and (c) the Damped-wave experiment.
Figure 4. Time averaged vertical velocity profiles from COARE (red), the WTG experiment (black), and the Damped-wave experiment (blue).