Simulating suppressed and active convection periods during TOGA COARE

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The two-dimensional Non-hydrostatic σ-coordinate Model (NSM) is used to simulate two twelve day periods and an eight day period observed during the Tropical Oceans Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE). The response of the NSM to the large-scale forcing which occurred over the three periods, and which included both suppressed and active convection, is examined. The NSM is shown to be able to capture the differences in the three experiments and responds correctly to the large-scale forcing (i.e. it is able to distinguish between suppressed and active regimes). However, the model is cooler and drier than the observations.

Key words: Atmospheric modelling, thunderstorms, TOGA COARE, microphysics schemes.

Introduction

Synoptic and mesoscale motions play a major role in the formation, maintenance and structure of thunderstorms. The tropical-temperate trough (TTT), which is associated with the northwest-southeast aligned cloud bands, is a major synoptic rainfall producing weather systems over southern Africa (Hart et al., 2010). Non-hydrostatic models that include the necessary physics to simulate ensembles of clouds explicitly over a large enough domain called Cloud Resolving Models (CRMs) can be used to study the response of thunderstorms to the large-scale circulations. To do this CRMs are driven with large-scale observations similar to the procedure that is followed when testing cumulus parameterisation schemes with a Single Column Model (SCM) (Randall et al., 1996). This method constraints the domain-averaged horizontal velocities to follow the observed values and therefore provides a means in controlling the cloud system dynamics by the large-scale momentum and shear.

Many studies have been conducted in the past two decades over the tropical and midlatitude regions to investigate the response of shallow and deep convective clouds to large-scale processes. The use of observations from the experimental campaigns has contributed to the improvement of models and has also shown that CRMs are useful tools to study cloud systems. In this study, forcing data from the Tropical Oceans Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) (Webster and Lucas, 1992) is used to test the response of a CRM developed in South Africa on the large scale forcing. The CRM uses a σ-coordinate in the vertical, and is called the Non-hydrostatic σ-coordinate Model (NSM) (Engelbrecht et al., 2007). The case study used here was investigated by the Precipitating Cloud Systems Working Group (PCSWG) of the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) (Woolnough et al., 2010). The objective of that case study was to examine the role of the convective process in moistening the atmosphere during the suppressed phase of the Madden-Julian Oscillation (MJO) and assess the impact of moistening on the subsequent evolution of convection in numerical simulations.

The Non-hydrostatic σ-coordinate Model

The basic equation set of the NSM was derived by Engelbrecht et al. (2007), who also used a split semi-Langragian method to solve the set. Two microphysics schemes introduced by Bopape et al. (2013) in the NSM are used in this study. The first scheme is considered as a classic scheme and was developed by Chen and Sun (2002) at the Purdue University, Indiana, USA, and is known as the PURDUE-LIN scheme. It includes six classes of the water substance, namely water vapour, cloud water, cloud ice, rain, snow and graupel. The second scheme was developed at the Stony Brook University (SBU), New York, USA, using the PURDUE-LIN scheme as a starting point (Lin and Colle, 2011). The developers of the scheme called it SBU-YLIN. Snow and graupel share the same category and hence the same processes, which makes the scheme cheaper to run. Dry snow, rimed snow and graupel are included in the precipitation ice category through the introduction of varying riming intensity parameters.

Data and Methods

The simulations are made for three periods, 28 November to December 1992 (A0 experiment), 9 to 21 January 1993 (B0 experiment) and 21 to 29 January (C0 experiment) which were all observed during TOGA COARE. The large-scale advective tendencies of potential temperature and water vapour which are provided six hourly were made by Ciesielski et al (2003). The NSM's simulated horizontal average winds (u) are relaxed towards the observed horizontal wind (u_{obs}) with a timescale (τ) of 2 hours, applied at every time step (Equation 1 and 2). The temperature and water vapour tendencies are interpolated linearly to the NSM's vertical grid and every advection time step and applied directly to the NSM (equation 3 and 4).

$$\frac{Du}{Dt} + \frac{\partial \phi}{\partial x} - \sigma \frac{\partial \phi}{\partial \sigma} \frac{\partial \ln \phi}{\partial x} - \left(\frac{\partial u}{\partial t} \right)_l = 0 \qquad (1)$$

$$\left(\frac{\partial u}{\partial t} \right)_l = -\frac{u - u_{obs}}{\tau} \qquad (2)$$

$$\frac{DT}{Dt} - \frac{RT\omega}{c_p p} = S_h + radhr + \left(\frac{\partial T}{\partial t} \right)_l \qquad (3)$$

$$\frac{Dq_v}{Dt} = S_v + \left(\frac{\partial q_v}{\partial t} \right)_l, \; x=1,\ldots,n \qquad (4)$$

Similar to Woolnough et al. (2003) the large-scale forcing is applied only upto the 150 hPa level. Active and suppressed periods are defined by the nature of the large-scale forcing applied. The suppressed periods are defined by periods when the large-scale forcing is acting to dry and warm the column. The active periods are defined by periods during which there is substantial cooling and moistening of nearly the entire column by the large-scale forcing. The sea-surface temperatures (SSTs) and surface pressure are prescribed at every time step. Surface fluxes are calculated using aero dynamic equations as described in Holtslag and Boville (1993), which allow moisture from the ocean back into the atmosphere. A 2K/day cooling is applied throughout the troposphere. Simulations are made with the PURDUE-LIN and SBU-YLIN schemes. The PURDUE-LIN is run for two cases: One with graupel (PURDUE-LIN1) and one without graupel (PURDUE-LIN2).

Results

The simulations will initially be compared with TOGA COARE observations and then the simulations made with the different microphysics schemes will be compared against one another. Such a comparison will enable us to determine if the NSM simulations are closer to reality, and whether the response to the large scale is dependent on the microphysics schemes. A combination of simulations made with PURDUE-LIN1 and PURDUE-LIN2 will be called PURDUE-LIN simulations. The A0 experiment will be discussed in detail, while the B0 and C0 experiments will only be discussed briefly for comparison with the A0 experiment, and hence only A0 figures are shown.

Comparison with observations

The simulations were compared with the reanalysed full fields generated by Ciesielski et al. (2003) and therefore correspond fully with the initial conditions and forcing fields used to make the simulations. Fig. 1a shows observed temperatures over the twelve day period of the A0 experiment, while Fig. 1b shows how the temperature has changed over the twelve day period with respect to the initial conditions. The troposphere is generally warmer compared to the initial conditions. Almost throughout the twelve day period, there is a cooler region at about the 900 to 700 hPa level. The simulated temperature with all the schemes (Fig. 1c, e, g) decreases significantly in the first few hours of the simulation. The heat seems to be transported from the lower parts of the troposphere to the upper parts. This transport is represented by a much warmer upper troposphere and lower stratosphere compared to the initial conditions in Fig. 1d, f, and h. All the microphysics schemes simulate a much cooler region between the 700 and 900 hPa levels which is simulated as a layer much thicker compared to the observations. This result suggests that the mechanism that leads to a cooler region in the observations is simulated by the NSM even though the simulated layer is much thicker. The cooling in the first few hours of the simulation during the spin-up period is also simulated in the B0 and C0 experiments. The observations show that the atmosphere is generally cooler in the C0 experiment compared to the initial conditions during the 8 day period

The A0 experiment simulated atmosphere becomes much drier than the initial conditions and observations in the first few hours of the simulation, and then it recovers at some point but not to the magnitudes found in the initial conditions or observations (not shown). This feature is also found in the B0 and C0 experiments (not shown). The cooler and drier troposphere correspond because cooler air carries less water vapour than warmer air. Although much drier than the observations, there is a layer close to the 900 hPa level that is less dry in comparison to layers below and above in the A0 experiment. The last two days of the simulation are less dry compared to the rest of the 12 days which suggest that the NSM responds well to the large-scale forcing. The simulated specific humidity values in the C0 experiment are smaller compared to the other two experiments, and are similar to differences seen in observations consistent with temperature differences.

Updrafts simulations

The large-scale forcing applied to the model in the first two days of simulation in all three experiments is done in order to allow deep convection to spin-up the model. In the A0 experiment, convection formed before the end of the first two hours of simulation when using all the three microphysics schemes (Fig. 2 d ,f,h). As soon as the hydrometeors started forming, the simulated maximum updrafts started to appear different. In all three simulations with different microphysics schemes, the updrafts are stronger in the first day of simulation than in the second day of simulation; in the second day the updrafts are stronger in the PURDUE-LIN1 simulation and weaker in the SBU-YLIN simulations.

The simulated maximum updrafts in the suppressed period are much smaller compared to those in the spin-up period in both the A0 and C0 experiments when using all three microphysics schemes. Woolnough et al. (2010) found the suppressed period to be dominated by shallow convection with some updrafts penetrating above the melting level. The updrafts strength during the suppressed period in the B0 experiment are stronger than in the A0 and C0 experiment with more ice and liquid water simulated here (not shown). The suppressed period in the B0 experiment forms part of the period where the large-scale forcing was suspected to have errors. Temperatures in the SBU-YLIN scheme are generally higher than the PURDUE-LIN temperatures in the troposphere suggesting that the cooler and drier biases that are found in the simulations are stronger in the PURDUE-LIN simulations.

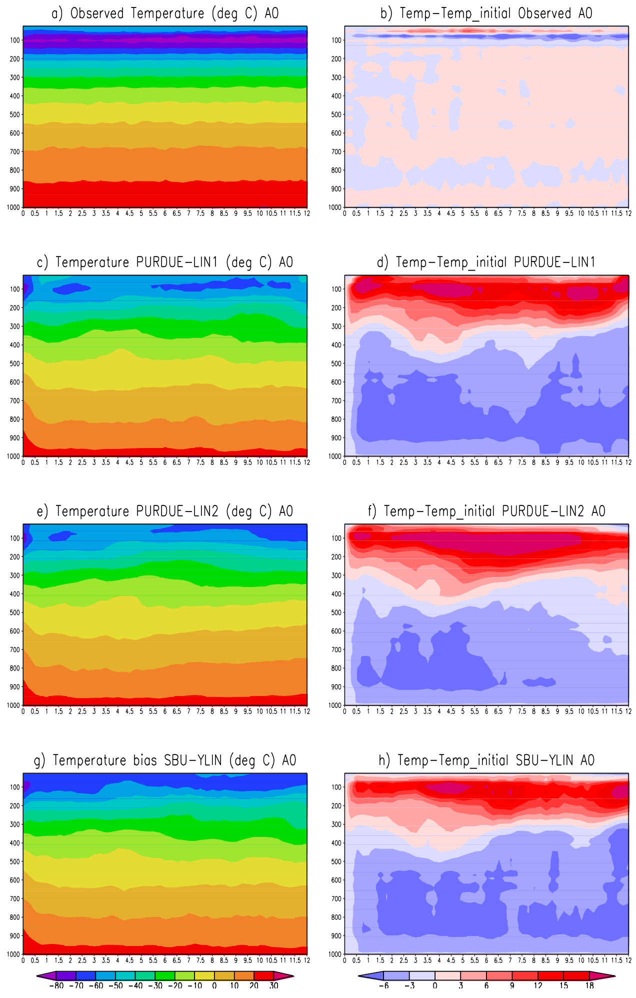

Fig. 1. The a) observed temperature and b) change over time relative to the initial conditions. The simulated temperature by the different microphysics schemes (c,e,g) and change in temperature over time (d,f,h) for the A0 experimentFigure 1

The simulated maximum updrafts are stronger in the transition period compared to the suppressed period in both the PURDUE-LIN1 and SBU-YLIN simulations and in the A0 and C0 experiments. No recovery is simulated in the PURDUE-LIN2 simulations in the A0 experiment, which illustrates the need for graupel in the simulations. The temperature differences show that the PURDUE-LIN2 is generally much warmer compared to the PURDUE-LIN1 and SBU-YLIN during the transition period. Maximum updrafts in the B0 experiment during the transition period are smaller than during the suppressed period. Woolnough et al. (2010) found a steady increase in precipitation in the simulations and observations during the transition between the suppressed period and the active period. There is a general recovery in the amount of simulated specific humidity in all the simulations during the transition period.

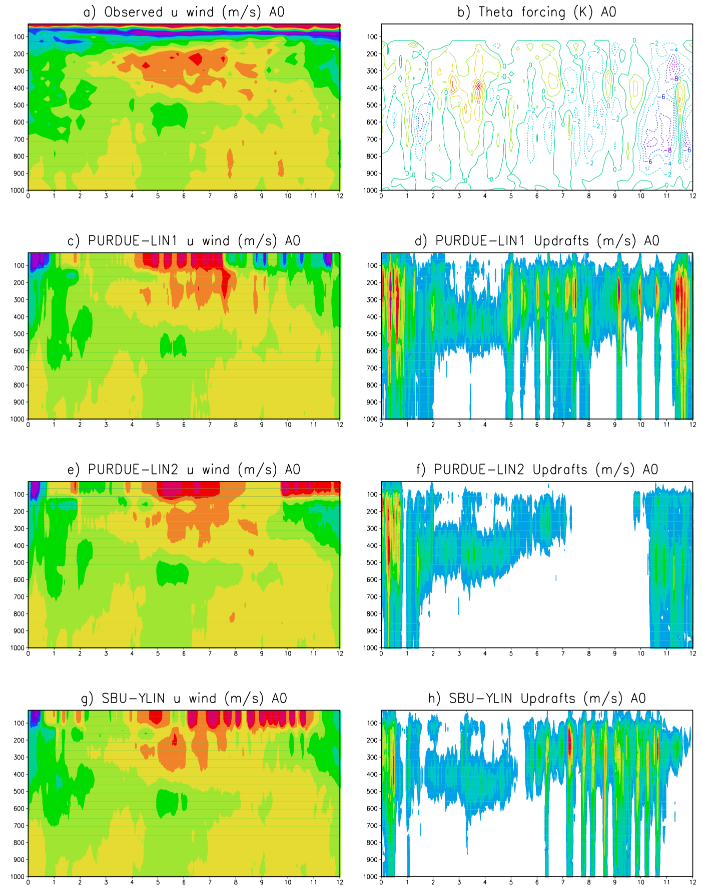

Fig. 2. The a) observed and (c,e,g) simulated average horizontal wind by the different schemes. b) The large scale warming or cooling applied to the NSM. (d,f,h) The simulated maximum updrafts across the domain by the different schemes over a 12-day period for the A0 experiment.

The maximum updrafts are generally bigger in the convective period towards the end compared to the suppressed and transition periods in all three experiments. In the A0 experiment, SBU-YLIN simulates the highest updrafts during the first day, and much smaller updrafts in the second day of simulation. PURDUE-LIN1 simulates the highest values during the second day of the active period. PURDUE-LIN2 simulates the smallest values of maximum updrafts and it is also found to be warmer than simulations with two other microphysics schemes. All three schemes simulate the atmosphere reasonably well, and can all potentially be used for operational forecasting.

Summary, Conclusions and Recommendations

The non-hydrostatic σ-coordinate model (NSM) is used with two microphysics schemes to simulate periods of suppressed and active convection during TOGA COARE. The model is found to be colder and drier compared to the observations and initial conditions, however, it is able to respond correctly to the large scale forcing. Further development of the NSM is continuing, with the implementation of sophisticated radiation scheme being almost completed. Preliminary results show a slightly warmer lower troposphere, which is an improvement over the simulations without a radiation scheme.

References

1. Bopape MM, FA Engelbrecht, DA Randall and WA Landman, 2013: Simulations of an isolated two-dimensional thunderstorm: sensitivity to cloud droplet size and the presence of graupel. *Asia Pacific Journal of Atmopsheric Science*.In press
2. Engelbrecht F.A., McGregor J.L. and Rautenbach C.J.de.W. (2007). On the development of a new non-hydrostatic atmospheric model in South Africa. *South African Journal of Science*, **103**, 127-134.
3. Randall D.A., Xu K., Sommerville R.J.C. and Iacobellis S. (1996). Single-Column Models and Cloud Ensemble Models as Links between Observations and Climate Models. *Journal of Climate*, **9**, 1683-1697.
4. Hart N.C.G., Reason C.J.C., and Fauchereau N. (2010). Tropical-Extratropical Interactions over Southern Africa: Three Cases of Heavy Summer Season Rainfall. *Monthly Weather Review*, **128**, 2608-2623.
5. Chen S. and Sun W. (2002). A One-dimensional Time Dependent Cloud Model. *Journal of Meteorological Society Japan*, **80**, 99-118.
6. Holtslag AM and BA Boville, 1993: Local Versus Nonlocal Boundary-Layer Diffusion in a Global Climate Model. *Journal of Climate*, **6**, 1825-1842
7. Lin Y. and Colle B.A. (2011). A New Bulk Microphysical Scheme That Includes Riming Intensity and Temperature-Dependent Ice Characteristics. *Monthly. Weather Review*, **139**, 1013-1035.
8. Ciesielski P.E., Johnson R.H., Haertel P.T., Wang J. (2003). Corrected TOGA COARE Sounding Humidity Data: Impact on Diagnosed Properties of Convection and Climate over the Warm Pool. *Journal of Climate*, **16**, 2370-2384.
9. Woolnough SJ and PN Blossey, K-M Xu, P Bechtold, J-P Chaboureau, J Hosom, Sf Iacobellis, Y Luo, JC Petch, RY Wong and S Xie, 2008: Modelling Convective processes during the suppressed phase of the single-column models with cloud-resolving models. *Quarterly Journal of the Royal Meteorological Society*, **136**, 333-353.