ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 26, NO. 6, 2009, 1108–1114

Dependence of the Accuracy of Precipitation and Cloud Simulation on Temporal and Spatial Scales

GAO Shouting*[1] (高守亭) and Xiaofan LI[2]

[1] *Laboratory of Cloud-Precipitation Physics and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2] *Joint Center for Satellite Data Assimilation and NOAA/NESDIS/Center for Satellite Application and Research, Camp Springs, Maryland, USA*

(Received 3 November 2008; revised 12 February 2009)

ABSTRACT

Precipitation and associated cloud hydrometeors have large temporal and spatial variability, which makes accurate quantitative precipitation forecasting difficult. Thus, dependence of accurate precipitation and associated cloud simulation on temporal and spatial scales becomes an important issue. We report a cloud-resolving modeling analysis on this issue by comparing the control experiment with experiments perturbed by initial temperature, water vapor, and cloud conditions. The simulation is considered to be accurate only if the root-mean-squared difference between the perturbation experiments and the control experiment is smaller than the standard deviation. The analysis may suggest that accurate precipitation and cloud simulations cannot be obtained on both fine temporal and spatial scales simultaneously, which limits quantitative precipitation forecasting. The accurate simulation of water vapor convergence could lead to accurate precipitation and cloud simulations on daily time scales, but it may not be beneficial to precipitation and cloud simulations on hourly time scales due to the dominance of cloud processes.

Key words: temporal and spatial scales, cloud and rainfall simulations, cloud-resolving model, initial conditions

Citation: Gao, S., and X. F. Li, 2009: Dependence of the accuracy of precipitation and cloud simulation on temporal and spatial scales. *Adv. Atmos. Sci.*, **26**(6), 1108–1114, doi: 10.1007/s00376-009-8143-2.

1. Introduction

Intercomparison studies of atmospheric general circulation models have shown that the uncertainties of climate simulations and predictions stem mainly from the treatments of clouds in the models (e.g., Cess et al., 1990, 1991). The improvement of the representation of clouds in general circulation models relies on the reduction of uncertainties of the diagnostic cumulus parameterization schemes that are constructed from observational data and supplemental output from cloud resolving models. Recently, cloud resolving models have been embedded within general circulation models (Grabowski, 2001, 2003; Khairoutdinov and Randall, 2001) and cloud resolving models have been applied to the global domain (Satoh et al., 2005; Tomita et al., 2005). The sensitivity of cloud resolving model to their framework has been intensively tested in recent decades in terms of the horizontal resolution (Petch and Gray, 2001; Petch et al., 2002), domain (Petch, 2004, 2006), dimensionality (Grabowski et al., 1998; Donner et al., 1999; Xu et al., 2002; Phillips and Donner, 2006; Petch et al., 2008), cloud microphysical parameterization (Khairoutdinov and Randall, 2003), turbulence closure (Cheng and Xu, 2006), and large-scale forcing (Guichard et al., 2000; Petch, 2004). Khairoutdinov and Randall (2003) found that uncertainties of initial conditions could lead to much greater uncertainties in precipitation simulations than undertainties stemming from cloud microphysical pa-

*Corresponding author: GAO Shouting, gst@lasg.iap.ac.cn

rameterization schemes. Petch (2004) showed that the uncertainties of initial thermal conditions are responsible for the uncertainties of diurnal rainfall in both phase and amplitude. Li et al. (2006) and Gao and Li (2008b) revealed that small uncertainties of initial temperature and water vapor conditions could lead to the significant uncertainties in cloud and rainfall simulations.

In this study, we further address the dependence of accurate cloud and precipitation simulations on temporal and spatial scales by analyzing two-dimensional cloud-resolving model simulation output from Gao and Li (2008b) and studying the sensitivities of precipitation and cloud simulations to perturbed initial thermodynamic soundings and cloud conditions with ranges of observational errors (e.g., Khairoutdinov and Randall, 2003; Li et al., 2006). The model, experiments, and methodology are briefly discussed in the next section. Results are presented in section 3. A summary is given in section 4.

2. Model, experiments, and methodology

The data analyzed in this study are from six model simulations conduced by Gao and Li (2008b), who used large-scale vertical velocity, zonal wind, and sea surface temperature averaged over 150°–160°E, EQ from 1100 LST 18 to 1700 LST 26 April 2003 (their Fig.1 is shown in Fig.1 here) as the model forcing. The large-scale vertical velocity and zonal wind are from the 6-hourly National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) data, whereas the daily-mean sea surface temperature is retrieved from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) radiometer with a 10.7 GHz channel (Wentz et al., 2000). The control experiment is integrated with the above large-scale forcing. The five perturbation experiments are identical to the control experiment, but with different initial conditions. Two of the perturbation experiments are perturbed by ±0.5°C of mass-weighted mean temperature, whereas two other perturbation experiments are perturbed by ±1 mm of precipitable water (PW). The last perturbation experiment is conducted by setting the cloud mixing ratios to zero after a 6-hour spin-up. The detailed descriptions of these experiments can be found in Gao and Li (2008b).

The cloud-resolving model (Soong and Ogura, 1980; Soong and Tao, 1980; Tao and Simpson, 1993; Li et al., 1999) in Gao and Li (2008b) uses cyclic lateral boundary conditions and includes prognostic cloud microphysical parameterization schemes (Rutledge and Hobbs, 1983, 1984; Lin et al., 1983; Tao et al., 1989; and Krueger et al., 1995) and interactive radiative parameterization schemes (Chou et al., 1991; Chou and Suarez, 1994; Chou et al., 1998). The model uses a horizontal domain of 768 km, a horizontal grid resolution of 1.5 km., 33 vertical layers, and a time step of 12 s. The model has been used to successfully simulate convection and to study physical processes associated with convective development (e.g., Gao and Li, 2008a).

The simulation data are first averaged over different spatial and temporal scales and are used to calculate the root-mean-squared (RMS) difference and standard deviation (SD). The ratio (RS ratio) of the RMS difference to SD is then calculated to measure the sensitivity of cloud and precipitation simulations to the

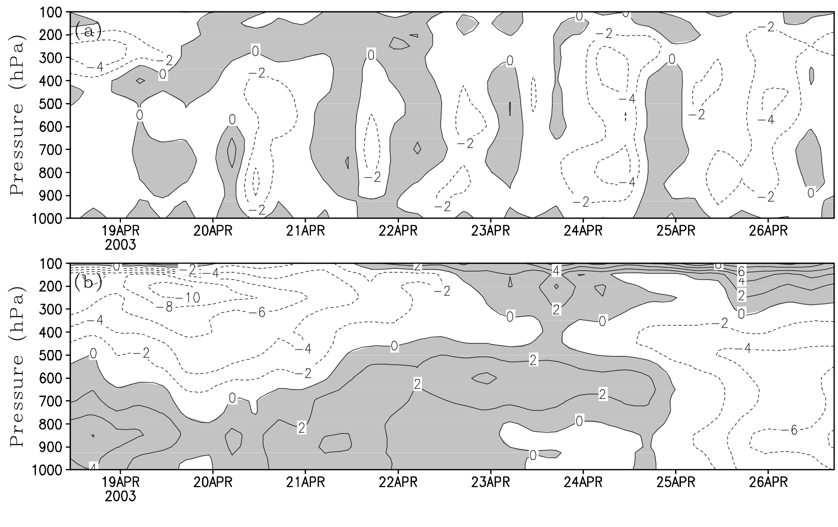

Fig. 1. Temporal and vertical distributions of (a) vertical velocity (hPa h^{-1}) and (b) zonal wind (m s^{-1}) obtained from GDAS for a selected 8-day period. Downward motion in (a) and westerly wind in (b) are shaded (From Gao and Li, 2008b).

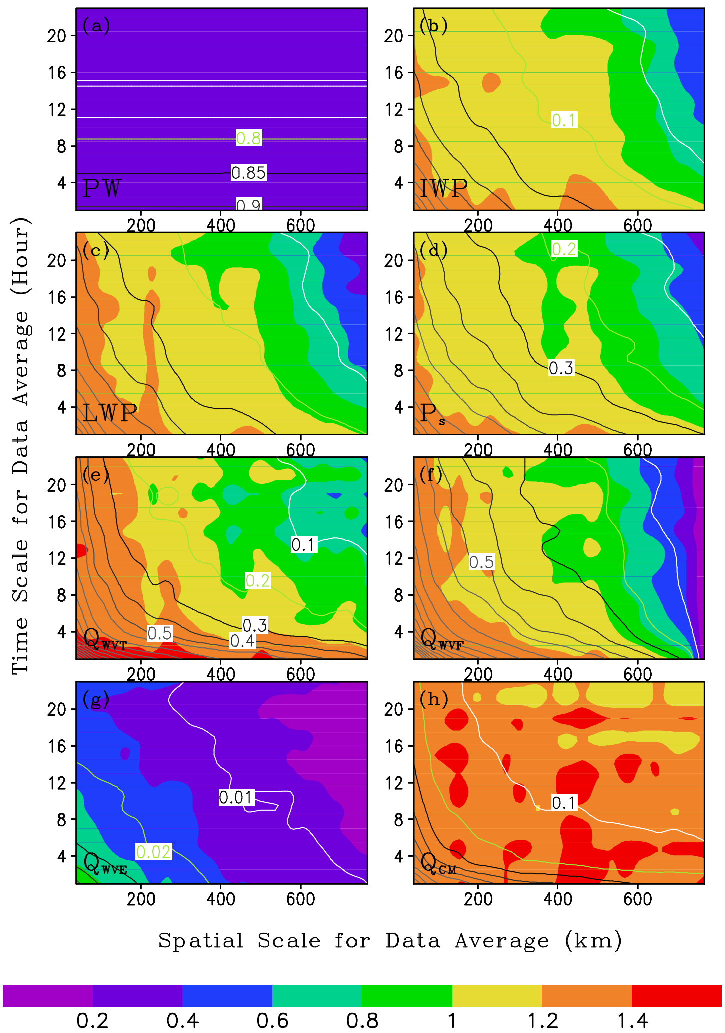

Fig. 2. RMS differences between perturbation experiments and control experiment (contours) and the ratios of RMS difference to standard deviation (background) of (a) PW, (b) IWP, (c) LWP, (d) P_{s}, (e) Q_{WVT}, (f) Q_{WVF}, (g) Q_{WVE}, and (h) Q_{CM} as functions of time and spatial scales for the average of data. The contour intervals of RMS differences are 0.05 mm for PW, IWP, and LWP, 0.1 mm h^{-1} for P_{s}, Q_{WVT}, Q_{WVF}, and Q_{CM}, and 0.01 mm h^{-1} for Q_{WVE}.

initial conditions. When the RS ratio is smaller than 1, model sensitivity to the uncertainty of the initial condition is weak and the simulation is considered accurate. When the RS ratio is larger than 1, the model simulation is strongly sensitive to the uncertainty of the initial condition.

3. Results

The RMS difference in PW between the perturbation experiments and control experiment varies with the time scale for the average of data, whereas it is insensitive to the spatial scale for the average of data (Fig. 2a). The RS ratio of PW is nearly a constant (~ 0.23). This indicates that the initial conditions do not have significant impacts on PW changes in the perturbation experiments. The RMS differences in ice water path (IWP), liquid water path (LWP), and surface rain rate (P_{s}) increase as time and spatial scales decrease (Figs. 2b, 2c, and 2d). Accurate cloud and rainfall simulations, in which the RS ratios of IWP, LWP, and P_{s} are smaller than 1, require a small spatial scale (~ 300 km) for daily averaged data and a much larger spatial scale (> 750 km) for hourly averaged data.

Since the surface rainfall could result from water vapor processes including water vapor convergence and cloud microphysical processes, the water vapor budget and cloud budget are combined to form a diagnostic surface rainfall equation (Gao, et al 2005; Cui and Li, 2006), which can be expressed as

$$P_{\mathrm{s}} = Q_{\mathrm{WVT}} + Q_{\mathrm{WVF}} + Q_{\mathrm{WVE}} + Q_{\mathrm{CM}} \ , \tag{1}$$

$$Q_{\mathrm{WVT}} = -\frac{\partial [q_{\mathrm{v}}]}{\partial t} \ , \tag{1a}$$

$$\begin{aligned} Q_{\mathrm{WVF}} = & -\left[\bar{u}^{\mathrm{o}}\frac{\partial \bar{q}_v^{\mathrm{o}}}{\partial x}\right] - \left[\overline{w}^{\mathrm{o}}\frac{\partial \bar{q}_v}{\partial z}\right] - \left[\frac{\partial (u' q_v')}{\partial x}\right] \\ & -\left[\bar{u}^{\mathrm{o}}\frac{\partial q_v'}{\partial x}\right] - \left[\overline{w}^{\mathrm{o}}\frac{\partial q_v'}{\partial z}\right] - \left[w'\frac{\partial \bar{q}_v}{\partial z}\right] \ , \end{aligned} \tag{1b}$$

$$Q_{\mathrm{WVE}} = E_{\mathrm{s}} \ , \tag{1c}$$

$$Q_{\mathrm{CM}} = -\frac{\partial [q_5]}{\partial t} - \left[u\frac{\partial q_5}{\partial x}\right] - \left[w\frac{\partial q_5}{\partial z}\right] \ , \tag{1d}$$

where Q_{WVT} is the local watervapor storage, Q_{WVF} is water vapor convergence, Q_{WVE} is the surface evaporation (E_{s}), Q_{CM} is hydrometeor convergence minus storage, u and w are zonal and vertical air wind components, respectively, $q_5 = q_{\mathrm{c}} + q_{\mathrm{r}} + q_{\mathrm{i}} + q_{\mathrm{s}} + q_{\mathrm{g}}$, $q_{\mathrm{c}}, q_{\mathrm{r}}, q_{\mathrm{i}}, q_{\mathrm{s}}, q_{\mathrm{g}}$ are the mixing ratios of cloud water, raindrops, cloud ice, snow, and graupel, respectively; a prime denotes a perturbation from the model domain mean; the symbol $^{\mathrm{o}}$ is for an imposed forcing. This diagnostic rainfall equation shows that the surface rain rate (P_{s}) is determined by large-scale water vapor processes represented by the local water vapor change (Q_{WVT}), water vapor convergence (Q_{WVF}), surface evaporation flux (Q_{WVE}), and small-scale cloud processes denoted by the local hydrometeor change/hydrometeor convergence (Q_{CM}).

The RMS differences in P_{s}, $Q_{\mathrm{WVT}}, Q_{\mathrm{WVF}}$, and Q_{CM} have similar magnitudes, which are much larger than those of Q_{WVE} (Figs. 2d–2h). The RS ratio of Q_{CM} is always larger than 1 in the temporal and spatial scales, indicating a large sensitivity of the cloud simulation to the uncertainty of the initial conditions. The RS ratio of P_{s} is smaller than 1 when the spatial scale is larger than 350 km and the time scale is larger than 8 hours or when the spatial scale is larger than 750 km and the time scale is smaller than 4 hours. Accurate precipitation simulation, in which the RS ratio of surface rain rate is smaller than 1, requires a small spatial scale with a large time scale or a large spatial scale with a small time scale. This indicates that accurate precipitation simulation in which the RMS difference is smaller than the SD cannot be obtained on both fine temporal and spatial scales simultaneously, which limits quantitative precipitation forecasting. The large RS ratio for Q_{CM} and small RS ratio for P_{s} implies that a larger uncertainty exists in cloud simulations than in precipitation simulations. This does not contradict the result from Khairoutdinov and Randall (2003) because different aspects of model simulations such as Q_{CM} and P_{s} are analyzed in this study based on the same simulation dataset, whereas differences in the same variables (e.g., precipitation rate) between the two sets of ensemble experiments with randomly perturbed initial thermodynamic soundings and the same microphysics scheme and with changed microphysics parameters and the same initial conditions are examined by Khairoutdinov and Randall (2003).

When the spatial scale is the length of the model domain (768 km), the RS ratio of Q_{WVF} is nearly zero since all experiments have the same imposed vertical velocity that largely determines Q_{WVF}. The RS ratios of P_{s}, Q_{WVT}, and Q_{WVE} are smaller than 1, while for Q_{CM} the ratio is larger than 1. The water vapor processes are dominated by water vapor convergence, which has stronger impacts on surface precipitation than the cloud processes do when the time scale is larger than 3 hours, whereas the cloud processes have dominant effects when the time scales are shorter than 3 hours. This may be due to the fact that the time scale of water vapor processes (dominated by water vapor convergence) is mainly determined by the imposed large-scale vertical velocity ($\sim$ a day), and is much longer than that of Q_{CM} ($\sim$ an hour). The time scales of fluctuations of Q_{CM} are hourly (Fig.8 in Gao and Li, 2008b). The maximum and minimum of Q_{CM} do not reveal any time preference for occurrence. Thus, Q_{CM} is dominated by cloud activity only.

To further understand the sources of uncertainties of cloud and precipitation simulations, the surface rainfall budgets can be separated into a water vapor equation

$$Q_{\mathrm{WVT}} + Q_{\mathrm{WVF}} + Q_{\mathrm{WVE}} = S_{q_v} \tag{2a}$$

and a cloud equation

$$P_{\mathrm{s}} - Q_{\mathrm{CM}} = S_{q_v} \ . \tag{2b}$$

Here,

$$\begin{aligned} S_{q_v} = & [P_{\mathrm{CND}}] + [P_{\mathrm{DEP}}] + [P_{\mathrm{SDEP}}] + [P_{\mathrm{GDEP}}] \\ & - ([P_{\mathrm{REVP}}] + [P_{\mathrm{MLTG}}] + [P_{\mathrm{MLTS}}]) \ . \end{aligned}$$

($[P_{\mathrm{CND}}] + [P_{\mathrm{DEP}}] + [P_{\mathrm{SDEP}}] + [P_{\mathrm{GDEP}}]$) represents the sink term in the water vapor budget and the source term in the cloud budget that consist of the vapor condensation rate ($[P_{\mathrm{CND}}]$) and vapor deposition rates for the growth of cloud ice ($[P_{\mathrm{DEP}}]$), snow ($[P_{\mathrm{SDEP}}]$), and graupel ($[P_{\mathrm{GDEP}}]$); $-([P_{\mathrm{REVP}}] + [P_{\mathrm{MLTG}}] + [P_{\mathrm{MLTS}}])$ denotes the source term in the water vapor budget and the sink term in the cloud budget that includes growth

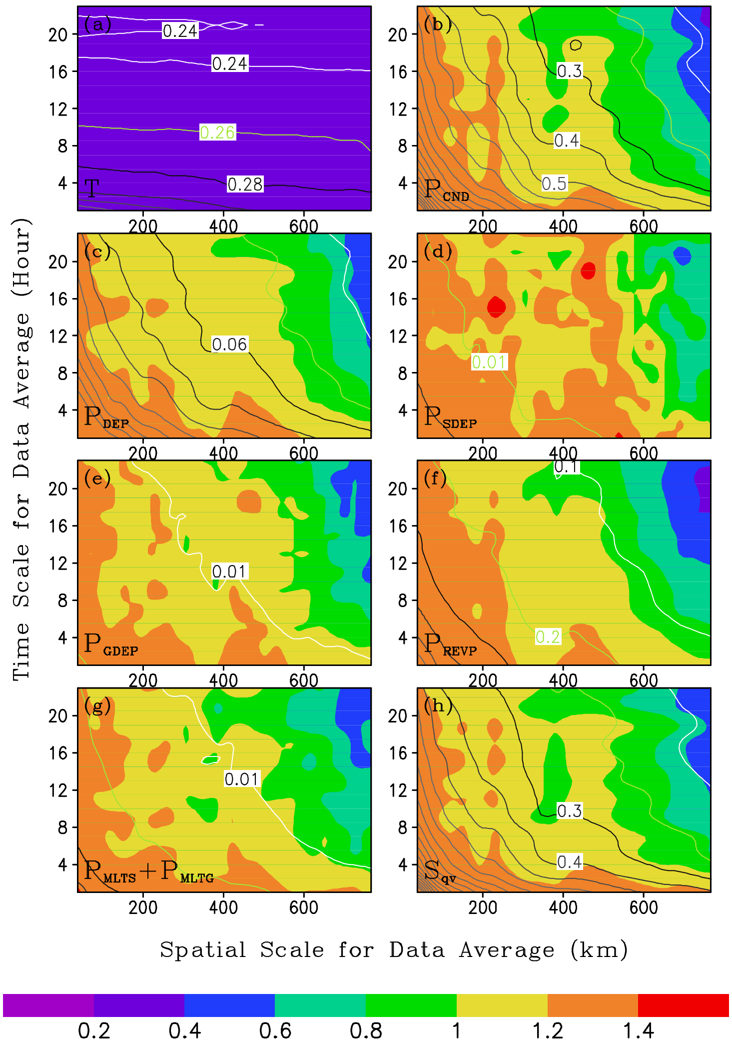

Fig. 3. RMS differences between perturbation experiments and control experiment (contours) and the ratios of RMS difference to standard deviation (background) of (a) mass-weighted mean temperature, (b) P_{CND}, (c) P_{DEP}, (d) P_{SDEP}, (e) P_{GDEP}, (f) P_{REVP}, (g) $P_{\mathrm{MLTS}} + P_{\mathrm{MLTG}}$, and (h) S_{q_v} as functions of time and spatial scales for the average of data. The contour intervals of RMS differences are 0.04°C for mass-weighted mean temperature, 0.1 mm h^{-1} for P_{CND}, P_{REVP}, and S_{q_v}, and 0.02 mm h^{-1} for P_{DEP}, and 0.01 mm h^{-1} for P_{SDEP}, P_{GDEP}, and $P_{\mathrm{MLTS}} + P_{\mathrm{MLTG}}$.

of vapor by evaporation of raindrops ([P_{REVP}]), evaporation of liquid from graupel surfaces ([P_{MLTG}]), and evaporation of melting snow ([P_{MLTS}]).

The distributions for temporal and spatial scales of averaged data for the RS ratio of S_{q_v} (Fig. 3h) are those of P_s, IWP, and LWP. The RMS differences in vapor condensation between the control experiment and perturbation experiments are significantly larger than the RMS differences in the other terms in S_{q_v} (Fig. 3). Thus, the RS ratio of S_{q_v} is mainly determined by that of vapor condensation. The vapor condensation is largely determined by the difference between specific humidity and saturation specific humidity, which is a nonlinear function of temperature. The RS ratio of mass-weighted mean temperature is 0.25–0.37. Both RS ratios of mass-weighted mean temperature (Fig. 3a) and PW (Fig. 2a) are smaller than 1, but the RS ratio of vapor condensation could be larger than 1 when the spatial scale is larger than 350 km and the time scale is larger than 8 hours, or when the spatial scale is larger than 750 km and the time scale is smaller than 4 hours. This is because the vapor condensation is a small residual between the two large terms of specific humidity and saturation specific humidity Li et al. (2006). This means smaller uncertainties of temperature and water vapor could lead to large uncertainties of vapor condensation, which significantly reduce the predictability of clouds and rainfall.

4. Summary

The temporal and spatial dependence of sensitivity of cloud and precipitation simulations to uncertainties in initial conditions are examined by comparing experiments with perturbed initial conditions with the control experiment, which were conducted by Gao and Li (2008b). Our cloud-resolving modeling analysis demonstrates that accurate precipitation and cloud simulations cannot be obtained when the spatial scale is smaller than 300 km and the time scale is a few hours, since the simulations are greatly affected by uncertainties in initial conditions with the ranges of observational errors. Accurate precipitation and cloud simulations on daily time scales are associated with accurate simulations of water vapor processes. However, even accurate simulations of water vapor processes cannot guarantee accurate precipitation and cloud simulations on hourly time scales because of the dominance of cloud processes on simulations. The results imply that it is very difficult for the current modeling framework, given the quality of initial conditions, to produce meaningful quantitative precipitation forecasts on fine temporal and spatial scales.

Acknowledgements. The authors thank Dr. W.-K. Tao at NASA/GSFC for his two-dimensional cloud-resolving model and two anonymous reviewers for their constructive comments. This work is supported from the National Key Basic Research and Development Project of China (2009CB421505), the National Natural Sciences Foundation of China (40775031), and the Project (No. 2008LASW-A01).

REFERENCES

Cess, R. D., and Coauthors, 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res.*, **95**, 16 601–16 615.

Cess, R. D, and Coauthors, 1991: Interpretation of snow-climate feedback as produced by 17 general circulation models. *Science*, **253**, 888–892.

Cheng, A., and K.-M. Xu, 2006: Simulation of shallow cumuli and their transition to deep c onvecitve clouds by cloud-resolving models with different their-order turbulence closures. *Quart. J. Roy. Meteor. Soc.*, **132**, 359–382.

Chou, M.-D., and M. J. Suarez, 1994: An efficient thermal infrared radiation parameterization for use in general circulation model. NASA Tech. Memo. 104606, Vol. 3, 85pp. [Available from NASA/Goddard Space Flight Center, Code 913, Greenbelt, MD 20771.]

Chou, M.-D., D. P. Kratz, and W. Ridgway, 1991: Infrared radiation parameterization in numerical climate models. *J. Climate*, **4**, 424–437.

Chou, M.-D., M. J. Suarez, C.-H. Ho, M. M.-H. Yan, and K.-T. Lee, 1998: Parameterizations for cloud overlapping and shortwave single scattering properties for use in general circulation and cloud ensemble models. *J. Atmos. Sci.*, **55**, 201–214.

Cui, X., and X. Li, 2006: Role of surface evaporation in surface rainfall processes. *J. Geophys. Res.,* **111**, D17112, doi: 10.1029/2005JD006876.

Donner, L. J., C. J. Semen, and R. S. Hemler, 1999: Three-dimensional cloud-system modeling of GATE convection. *J. Atmos. Sci.*, **56**, 1885–1912.

Gao, S., and X. Li, 2008a: *Cloud-Resolving Modeling of Convective Processes*. Springer, Dordrecht, 206pp.

Gao, S., and X. Li, 2008b: Impacts of initial conditions on cloud-resolving simulations. *Adv. Atmos. Sci.*, **25**, 737–747, doi: 10.1007/s00376-008-0737-6.

Gao, S., X. Cui, Y. Zhu, and X. Li, 2005: Surface rainfall processes as simulated in a cloud resolving model. *J. Geophys. Res.*, **110**, D10202, doi: 10.1029/2004JD005467.

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., 2003: MJO-like coherent structures: Sensitivity simulations using the cloud-resolving convection parameterization (CRCP). *J. Atmos. Sci.*, **60**, 847–864.

Grabowski, W. W., X. Wu, M. W. Moncrieff, and W. D. Hall, 1998: Cloud-resolving model 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.

Guichard, F., J.-L. Redelsperger, and J.-P. Lafore, 2000: Cloud resolving simulations of convective activity during TOGA-COARE: Sensitivity to external sources of uncertainties. *Quart. J. Roy. Meteor. Soc.*, **126**, 3067–3095.

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

Khairoutdinov, M. F., and D. A. Randall, 2003: Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. *J. Atmos. Sci.*, **60**, 607–625.

Krueger, S. K., Q. Fu, K. N. Liou, and H.-N. S. Chin, 1995: Improvement of an ice-phase microphysics parameterization for use in numerical simulations of tropical convection. *J. Appl. Meteor.*, **34**. 281–287.

Li, X., C.-H. Sui, K.-M. Lau, and M.-D. Chou, 1999: Large-scale forcing and cloud-radiation interaction in the tropical deep convective regime. *J. Atmos. Sci.*, **56**, 3028–3042.

Li, X., S. Zhang, and D.-L. Zhang, 2006: Thermodynamic, cloud microphysics and rainfall responses to initial moisture perturbations in the tropical deep convective regime. *J. Geophys. Res.*, **111**, D14207, doi: 10.1029/2005JD006968.

Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.*, **22**, 1065–1092.

Petch, J. C., 2004: The predictability of deep convection in cloud-resolving simulations over land. *Quart. J. Roy. Meteor. Soc.*, **130**, 3173–3187.

Petch, J. C., 2006: Sensitivity studies of developing convection in a cloud-resolving model. *Quart. J. Roy. Meteor. Soc.*, **132**, 345–358.

Petch, J. C., and M. E. B. Gray, 2001: Sensitivity studies using a cloud-resolving model simulation of the tropical west Pacific. *Quart. J. Roy. Meteor. Soc.*, **127**, 2287–2306.

Petch, J. C., A. R. Brown, and M. E. B. Gray, 2002: The impact of horizontal resolution on the simulations of convective development over land. *Quart. J. Roy. Meteor. Soc.*, **128**, 2031–2044.

Petch, J. C., P. N. Blossey, and C. S. Bretherton, 2008: Differences in the lower troposphere in two- and three-dimensional cloud-resolving model simulations of deep convection. *Quart. J. Roy. Meteor. Soc.*, **134**, 1941–1946.

Phillips, V. T., and L. J. Donner, 2006: Cloud microphysics, radiation and vertical velocities in two- and three-dimensional simulations of deep convection. *Quart. J. Roy. Meteor. Soc.*, **132**, 3011–3033.

Rutledge, S. A., and P. V. Hobbs, 1983: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. Part VIII: A model for the "seeder-feeder" process in warm-frontal rainbands. *J. Atmos. Sci.*, **40**, 1185–1206.

Rutledge, S. A., and P. V. Hobbs, 1984: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. Part XII: A diagnostic modeling study of precipitation development in narrow cold-frontal rainbands. *J. Atmos. Sci.*, **41**, 2949–2972.

Satoh, M., H. Tomita, H. Miura, S. Iga, and T. Nasumo, 2005: Development of a global resolving model—A multi-scale structure of tropical convections. *Journal of the Earth Simulator*, **3**, 1–9.

Soong, S. T., and Y. Ogura, 1980: Response of tradewind cumuli to large-scale processes. *J. Atmos. Sci.*, **37**, 2035–2050.

Soong, S. T., and W. K. Tao, 1980: Response of deep tropical cumulus clouds to mesoscale processes. *J. Atmos. Sci.*, **37**, 2016–2034.

Tao, W.-K., and J. Simpson, 1993: The Goddard Cumulus Ensemble model. Part I: Model description. *Terr. Atmos. Oceanic Sci.*, **4**, 35–72.

Tao, W.-K, J. Simpson, and M. McCumber, 1989: An ice-water saturation adjustment. *Mon. Wea. Rev.*, **117**, 231–235.

Tomita, H., H. Miura, S. Iga, T. Nasuno, and M. Satoh, 2005: A global cloud-resolving simulation: Preliminary results from an aqua planetary experiment. *Geophys. Res. Lett.*, **32**, L08805, 10.1029/2005GL022459.

Wentz, F. J., C. Gentemann, D. Smith, and D. Chelton, 2000: Satellite measurements of sea surface temperature through clouds. *Science*, **288**, 847–850.

Xu, K.-M., and Coauthors, 2002: An intercomparison of cloud resolving models with the Atmospheric Radiation Measurement summer 1997 Intensive Observation Period data. *Quart. J. Roy. Meteor. Soc.*, **128**, 593–624.