Recent Progress in Cloud-Resolving Modeling

Detlev Majewski* and Evgeny Jadin†

Abstract

This paper provides a brief review and discussion of the recent main progress in the development of cloud-resolving model simulation. The dynamic and thermodynamic studies linked with convection development and precipitation processes have contributed effective solution to the numerical models for estimation of surface rainfall budget. Research on Cloud Resolving modeling has gone through several developmental phases since 1980s and has claimed remarkable success recently despite several challenges yet on the way to perfection. A significant improvement was seen after the introduction of new cloud ratio (IWP/LWP) to derive tendency equation. However, the introduction of three vorticity vectors brought revolutionary changes in analytic process of 2D and 3D cloud-resolving model simulation data. They have several added advantages over PV/H in terms of understanding the causes for development of cloud clusters and super cloud clusters, differentiation of secondary circulation from dominant horizontal one. Non-conservative nature of vorticity vectors has provided the convenient pathway to their wider use in understanding meso-scale convective precipitation mechanism. The progress in modeling the cloud resolving process has been discussed in topical manner rather than following the chronological order.

Precipitation processes

Environment, cloud, and surface rainfall are three major factors in precipitation processes. However, most of process studies associated with precipitation have conducted water vapor budget and cloud budget separately. The water vapor budget links atmospheric environmental conditions including major water vapor convergence and surface evaporation to condensation and deposition whereas the cloud budget present relationship between rain rate and cloud microphysical processes. The surface rain rate is excluded in the water vapor budget whereas it is included in the cloud budget. Gao et al. (2005a) combined the water vapor budget and cloud budget by eliminating cloud microphysical processes to derive a diagnostic equation for surface rain rate. In their surface rainfall budget, the surface rain rate is determined by local water vapor change, water vapor convergence, surface evaporation flux, local hydrometeor change, and hydrometeor exchanges from surroundings. This is the first time that environment, cloud, and surface rainfall are included in one budget, which lays down foundation for precipitation study. Scientists can use this infrastructure to quantitatively identify dominant processes for production of surface rainfall. The surface rainfall budget has been successfully applied to study precipitation efficiency (Sui et al. 2007), role of surface evaporation in precipitation processes (Cui and Li 2006), and convective and stratiform rainfall (Gao et al. 2006d; Ping et al. 2007a) and their diurnal variations (Cui 2008). Sui et al. (2007) analyzed surface rainfall budget to identify water vapor sources for precipitation, found that all terms in surface rainfall budget could serve as moisture sources for precipitation under certain circumstances, define new precipitation efficiency that includes all water vapor and cloud sources for rainfall, and assure precipitation efficiency in a physically meaningful range of 0-100 %. This

* German Meteorological Service, Frankfurter Strasse 135, 63067 Offenbach. Germany
† P.P. Shirshov Institute of Oceanography, Rusian Academy of Sciences

complete analysis of precipitation efficiency only can be conducted in this framework. Cui and Li (2006) analyzed time-mean surface rainfall budgets in the tropical deep convective regime and showed that the water vapor is pumped from the ocean surface over rainfall-free regions through surface evaporation and is transported to convective regions to feed surface rainfall. Cui (2008) calculated surface rainfall budgets associated with convective and stratiform rainfall and found that more vapor convergence yields higher convective rain rate and that more vapor convergence and more local vapor loss cause higher stratiform rain rate in early morning than in afternoon. Thus, the surface rainfall budget proposed by Gao et al. (2005a) have been demonstrated to make major contributions in better understanding of precipitation processes quantitatively through building a research platform in which large-scale environment, cloud, and precipitation are analyzed in a unified point view.

Tropical Clusters and Associated Microphysical Processes

Observational studies using satellite measurements reveal that westward-moving cloud clusters are embedded within the eastward-moving super cloud cluster (e.g., Nakazawa 1988; Lau et al. 1991; Sui and Lau 1992). Numerical models including CRMs have been employed to investigate the physical processes controlling the formation, development, and propagation of cloud clusters and super cloud clusters (e.g., Lau et al. 1989; Numaguti and Hayashi 1991; Chao and Lin 1994; Yano et al. 1995). The westward movement of cloud clusters in the satellite images is the reflection of the horizontal advection of anvil clouds driven by the mean flow and the creation of new cells to the west of the old clouds within a convectively active phase of the intraseasonal oscillation during TOGA COARE (Wu and LeMone 1999). The new cloud clusters are generated at the leading edge of a propagating cold pool. The condensational heating associated with the constituent cloud clusters initiates an overall tropospheric-deep gravity wave. The cumulative cluster-induced wave effects lead to the development of new cloud clusters (Peng et al. 2001). The development of the new cloud at the western edge of the existing cloud cluster before merging may account for the westward propagation of cloud cluster group, while the advection of the maximum total hydrometeor mixing ratio by the westerly winds after merging may cause the eastward propagation of individual cloud clusters. Two eastward-moving cloud clusters merge into westward-moving cloud clusters under the environment of vertical wind shear. Merged clouds display notable growth in the eastern edge, indicating that merging processes enhance convection (Ping et al. 2008) and surface rainfall (Tao and Simpson 1984, 1989b). The development of the new cloud at the western edge of the existing cloud cluster before merging may account for the westward propagation of cloud cluster group, while the advection of the maximum total hydrometeor mixing ratio by the westerly winds after merging may cause the eastward propagation of individual cloud clusters.

The microphysical processes play an important role in the simulations of cloud systems. The ice phase is crucial for the development of light precipitation associated with stratiform clouds in the short-term (less than 1 day) CRM simulations show (e.g., Yoshizaki 1986; Nicholls 1987; Fovell and Ogura 1988; Tao and Simpson 1989; McCumber et al. 1991; Tao et al. 1991; Wu and Moncrieff 1996), whereas the effects of cloud microphysics on the temperature and moisture profiles could be significant in the long-term (more than 1 week) CRM simulations (e.g., Grabowski et al. 1999). The effects of ice microphysics could extend to cloud radiative processes (Wu et al. 1999), stratiform clouds, propagation speeds, and life cycles (Grabowski and Moncrieff 2001; Grabowski 2003). Comparing with the experiment with ice hydrometeors, the experiment without ice hydrometeors produces a larger amount of cloud water and a smaller surface rain rate due to the exclusion of vapor deposition processes, and a colder and moister state due to the smaller heating rate and smaller consumption of vapor (Gao et al. 2006d). A new way to study ice and water microphysics is developed by Sui and Li (2005) by defining the cloud ratio as the ratio of the ice water path (IWP) to the liquid water path (LWP) and deriving tendency equation of the cloud ratio. The tendency of the cloud ratio is mainly controlled by the processes related to the vapor condensation and deposition during the genesis and decay stages of cloud systems, whereas the tendency is determined by the conversion between water and ice clouds through the melting of graupel and accretion of cloud water by precipitation ice during the mature stage.

Vorticity Vectors

Gao et al. (2004, 2005, 2007b) and Gao (2007) introduced vorticity vectors in analysis of 2D and 3D cloud-resolving model simulation data. Convective (CVV) and moist (MVV) vorticity vectors are defined as cross products of absolute vorticity vector and equivalent potential temperature gradient, and absolute vorticity vector and specific humidity gradient, respectively whereas dynamic vorticity vector (DVV) is defined as cross product of absolute vorticity vector and wind vector. Some components of vorticity vectors are found to be highly correlated with cloud hydrometeors that represent convection. Potential vorticity (PV)/helicity (H) and their application to dynamics and thermodynamics have successfully enhanced understanding of atmospheric dynamic and thermodynamic processes associated with large-scale weather systems for several decades (e.g., Emanuel 1979; Cao and Cho 1995; Gao et al. 2002; Lilly 1986; Droegemeier et al. 1993), vorticity vectors have shown potential for application to convection and precipitation studies at convective scales. Vorticity vectors differ from PV/H in the following ways. First, vorticity vectors can be used in both 2D and 3D framework whereas PV/H only can be applied in 3D framework. In 2D framework, the dot products of relative vorticity and equivalent potential temperature gradient, relative vorticity and specific humidity gradient, and relative vorticity and wind are zero so that relative vorticity is excluded. Second, the linear correlation coefficients between vertical components of CVV/MVV and cloud hydrometeors are much larger than those between horizontal components of CVV/MVV and cloud hydrometeors whereas those coefficients between horizontal components of DVV and cloud hydrometeors are much larger than that between vertical component of DVV and cloud hydrometeors. The vertical components of CVV/MVV are represented by variances between horizontal components of relative vorticity associated with secondary circulations and horizontal gradients of equivalent potential temperature/specific humidity. The horizontal components of DVV are denoted by variances between horizontal components of relative vorticity and winds associated with secondary circulations. The secondary circulations are direct producers for clouds and precipitation. In contrast, PV is mainly contributed to by variance between vertical component of relative vorticity and vertical gradient of equivalent potential temperature whereas H is determined by covariances between horizontal components of relative vorticity and horizontal winds. Thus, the correlation between vorticity vectors and convection is higher than that between PV/H and convection mainly because vorticity vectors identify secondary circulations. Third, secondary circulations also included in PV/H, but their magnitudes are much smaller than those of horizontal circulations. Vorticity vectors can identify secondary circulations from dominant horizontal circulations. Fourth, vorticity vectors are not conserved whereas PV/H can be conserved under some conditions. Budget analysis shows that tendency of CVV/MVV are determined by interaction between vorticity and horizontal gradient of ice cloud heating/both ice and water cloud heating. Thus, CVV/MVV is associated with cloud microphysical processes. Therefore, vorticity vectors introduced by Gao et al. have straightforward physical meaning and directly capture convective signals, and have major contributions to better understanding of convective development and associated physical processes.

Tropical Diurnal Rainfall Variation

The diurnal rainfall variation is one of most important variabilities over the tropical ocean (e.g., Randall et al. 1991). The dominant diurnal signal is the nocturnal rainfall peak that occurs in the early morning. The enhancement of nocturnal rainfall could be a result of radiative forcing including the infrared cooling (Kraus 1963), the secondary circulation forced by the differences of radiative heating between cloudy and clear-sky regions (Gray and Jacobson 1977), the direct solar radiation–cloud interactions (Xu and Randall 1995), and direct interaction between radiation and convection (Liu and Moncrieff 1998). A recent observational analysis by Sui et al. (1997), however, found that the nocturnal rainfall peak is accounted for by the infrared cooling induced destabilization and decrease of saturation specific humidity associated with falling temperature during nighttime, which is consistent to Tao et al (1996), and is supported by numerical experiments which showed that the condensation rates associated with the diurnal variations are mainly contributed by the falling temperature during nighttime (Sui et al. 1998; Li 2004). The application of the surface rainfall equation and heat budget to the diurnal analysis reveals that the infrared radiative cooling after sunset and advective cooling associated with imposed large-scale ascending motion destabilizes the atmosphere and releases convective available potential energy to energize nocturnal convective development (Gao et al. 2008).

Coupled Atmosphere-Ocean CRMs

A 2D coupled atmosphere-ocean CRM has been developed to study the effect of fresh water flux and small-scale perturbations on the ocean mixed layer (Li et al. 2000). The coupled model consists of a CRM and an ocean circulation mixed-layer model developed by Adamec et al. (1981) with the mixing scheme of Niiler and Kraus (1977). Gao et al. (2006a) conducted a COARE simulation with coupled ocean-cloud resolving atmosphere model to analyze diurnal rainfall variations and found that a rainfall peak appears in the early morning when diurnal SST variation is weak whereas a rainfall maximum occurs in the afternoon when diurnal SST variation is strong. Gao et al. (2006c) further showed surface evaporation flux decreases with increasing SST and plays a negligible role in water vapor budget over rainfall regions. Atmospheric impacts on the ocean are important where oceanic impacts on the atmosphere are not in the tropical air-sea system on short timescales. Thus, the relationship between surface rain rate and SST over tropical cloudy areas is not physically important. Further estimates indicate that the surface evaporation flux and residual between moisture convergence and condensation could have the same order of magnitudes in daily-mean moisture budget. Ping et al. (2007b) performed a pair of sensitivity coupling experiments to study salinity effects on ocean mixed layer and revealed that the salinity effects increase ocean mixed-layer temperature and atmospheric precipitable water whereas they decrease atmospheric temperature. Gao and Zhou (2008) studied effects of diurnal variation of solar zenith angle on coupling system and found that the experiment with the time-invariant solar zenith angle produces a colder and drier atmosphere and a colder and saltier ocean mixed layer than the experiment with the diurnally-varied solar zenith angle does because the experiment with the time-invariant solar zenith angle has smaller solar heating, consumes more atmospheric water vapor through more condensation, and generates smaller thermal forcing through deeper mixed layer and more saline entrainment.

Tropical Climate Equilibrium States

Tropical climate is essentially determined by the nonlinear interactions of multiscale physical processes including the large-scale and cloud dynamics, cloud microphysics, radiative and surface processes, turbulence, and ocean. The convective-radiative equilibrium studies with the CRMs help to improve the understanding of these controlling processes (Nakajima and Matsuno 1988; Tao 2007). The simulations reach a cold and dry equilibrium state (Lau et al. 1993; Sui et al. 1994; Tompkins and Craig 1998) or a warm and humid state (Grabowski et al. 1996). The equilibrium states are insensitive to the initial conditions whereas they are sensitive to the minimum surface speed prescribed in the calculation of surface fluxes (Tao et al. 1999). The equilibrium thermodynamic states depend on the surface evaporation, where surface wind plays a central role. Small surface evaporation associated with weak surface winds produces a cold and dry equilibrium state whereas large evaporation associated with strong surface winds causes a warm and humid equilibrium state (Tao et al. 1999; Tompkins 2000). The vertical wind shear, minimum surface wind speed in the calculations of surface fluxes, and radiative heating determine thermodynamic quasi-equilibrium states (Shie et al. 2003). Gao et al. (2006b) analyzed cloud-resolving model simulation data during TOGA COARE and proposed a tropical heat/water cycling mechanism. Convection develops with the enhanced rainfall as a result of the consumption of water vapor, and the release of unstable energy which causes the local atmospheric drying and warming. The convection and rainfall are suppressed until the atmosphere becomes more stable with small unstable energy and low amount of water vapor. Unstable energy is generated and moisture is accumulated to rebuild a favorable environmental condition for the development of convection. The tropical heat/water cycling limits the deviation of thermodynamic state from its mean state and the life cycle of the clouds. Gao et al. (2007a) investigated effects of diurnal variations on tropical climate equilibrium states with integrations of cloud-resolving model to quasi-equilibrium states. The simulation with a time-invariant solar zenith angle produces a colder and drier equilibrium state than does the simulation with a diurnally varied solar zenith angle because the former simulation solar heating, more condensation, and consumes more moisture than the latter simulation does. The simulation with a diurnally varied sea surface temperature

(SST) generates a colder equilibrium state than does the simulation with a time-invariant sea surface temperature since the former simulation generates a colder temperature through less latent heating and more infrared cooling than the latter simulation does. Ping et al. (2007) examined radiative and microphysical effects of ice clouds on tropical climate equilibrium states by comparing an experiment without ice microphysics (ice microphysical and radiative effects) and an experiment without ice radiative effects with the control experiment with ice microphysics. The experiment without ice radiative effects produces a colder and drier equilibrium state than the two other experiments do through generating a larger IR cooling, a larger vapor condensation rate, and consuming a larger amount of water vapor. The ice radiative effects on thermodynamic equilibrium states are stronger than the ice microphysical effects do. Gao (2008) further investigated radiative effects of clouds (both water and ice clouds) on tropical climate equilibrium states and found that radiative effects of ice clouds on tropical climate equilibrium states are much stronger than those of water clouds. Thus, tropical climate equilibrium studies conducted by Gao et al. have important contributions in elucidated understanding of effects of diurnal variations and cloud radiation on tropical climate equilibrium states.

References

Adamec, D., R. L. Elsberry, R. W Garwood, and R. L. Haney, 1981: An embedded mixed-layer-ocean circulation model. Dyn. Atmos. Oceans, 6(2), 69-96.

Cao, Z., and H. Cho, 1995: Generation of moist vorticity in extratropical cyclones. J. Atmos. Sci., 52, 3263-3281.

Chao, W. C., and S. J. Lin, 1994: Tropical intraseasonal oscillation, super cloud clusters, and cumulus convection schemes. J. Atmos. Sci., 51, 1282-1297.

Cui, X., 2008: A cloud-resolving modeling study of diurnal variations of tropical convective and stratiform rainfall. J. Geophys. Res., 113, D02113, doi: 10.1029/2007JD008990.

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

Droegemeier, K. K., and S. M. Lazarus, 1993: The influence of helicity on numerically simulated convective storms. Mon. Wea. Rev., 121, 2005-2029.

Emanuel, K. A., 1979: Inertial instability and mesoscale convective systems. Part I: Linear theory of inertial instability in rotating viscous fluids. J. Atmos. Sci., 36, 2425-2449.

Fovell, R. G., and Y. Ogura, 1988: Numerical simulation of a midlatitude squall line in two dimensions. J. Atmos. Sci., 45, 3846-3879.

Gao, S. 2007: A three dimensional dynamic vorticity vector associated with tropical oceanic convection. J. Geophys. Res., 112, doi: 10.1029/2006JD008247.

Gao, S., 2008: A cloud-resolving modeling study of cloud radiative effects on tropical equilibrium states. J. Geophys. Res., 113, D03108, doi: 10.1029/2007JD009177.

Gao, S., and Y. Zhou, 2008: Effects of diurnal variation of solar zenith angle on a tropical coupling system: A two-dimensional coupled ocean-cloud resolving atmosphere modeling study. Geophys. Res. Lett., 35, L15815, doi: 10.1029/2008GL034340.

Gao, S., T. Lei and Y. Zhou, 2002: Moist potential vorticity anomaly with heat and mass forcings in torrential rain system. Chin. Phys. Lett., 19, 878-880.

Gao, S., F. Ping, X. Li, and W.-K. Tao, 2004: A convective vorticity vector associated with tropical convection: A 2D cloud-resolving modeling study. J. Geophys. Res., 109, D14106, doi: 10.1029/2004JD004807.

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

Gao, S., X. Cui, Y. Zhou, X. Li, and W.-K. Tao, 2005b: A modeling study of moist and dynamic vorticity vectors associated with 2D tropical convection. J. Geophys. Res., 110, D17104, doi: 10.1029/2004JD005675.

Gao, S., F. Ping, and X. Li, 2006a: Cloud microphysical processes associated with the diurnal variations of tropical convection: A 2D cloud resolving modeling study. Meteor. Atmos. Phys., 91, 9-16.

Gao, S., F. Ping, and X. Li, 2006b: Tropical heat/water vapor quasi-equilibrium and cycle as simulated in a 2D cloud resolving model. Atmos. Res., 79, 15-29.

Gao, S., F. Ping, X. Cui, and X. Li, 2006c: Short timescale air-sea coupling in the tropical deep convective regime. Meteor. Atmos. Phys., 93, 37-44.

Gao, S., L. Ran, and X. Li, 2006d: Impacts of ice microphysics on rainfall and thermodynamic processes in the tropical deep convective regime: A 2D cloud-resolving modeling study. Mon. Wea. Rev., 134, 3015-3024.

Gao, S., Y. Zhou, and X. Li, 2007a: Effects of diurnal variations on tropical equilibrium states: A two-dimensional cloud-resolving modeling study. J. Atmos. Sci., 64, 656-664.

Gao, S., X. Li, W.-K. Tao, C.-L. Shie, and S. Lang, 2007b: Convective and moist vorticity vectors associated with three-dimensional tropical oceanic convection during KWAJEX. J. Geophys. Res., 112, D01104, doi:10.1029/2006JD007179.

Gao, S., X. Cui, and X. Li, 2008: A modeling study of diurnal rainfall variations during TOGA COARE., Adv. Atmos. Sci., Submitted.

Grabowski, W. W., 2003: Impact of ice microphysics on multiscale organization of tropical convection in two-dimensional cloud-resolving simulations. Q. J. Roy. Meteor. Soc., 129, 67-81.

Grabowski, W. W., and M. W. Moncrieff, 2001: Large-scale organization of tropical convection in two-dimensional explicit numerical simulations. Q. J. Roy. Meteor. Soc., 127, 445-468.

Grabowski, W. W., M. W. Moncrieff, and J. T. Kiehl, 1996: Long-term behavior of precipitating tropical cloud systems: A numerical study. Quart. J. Roy. Meteor. Soc., 122, 1019-1042.

Gray, W. M., and R. W. Jacobson, 1977: Diurnal variation of deep cumulus convection. Mon. Wea. Rev., 105, 1171-1188.

Kraus, E. B., 1963: The diurnal precipitation change over the sea. J. Atmos. Sci., 20, 546-551.

Lau, K.-M., L. Peng, C.-H. Sui, and T. Nakazawa, 1989: Super cloud clusters, westerly wind bursts, 30-60 day oscillations, and ENSO: A unified view. J. Meteor. Soc. Japan, 67, 205-219.

Lau, K.-M., T. Nakazawa and C.-H. Sui, 1991: Observations of cloud cluster hierarchy over the tropical western Pacific. J. Geophys. Res. 96, 3197-3208.

Lau, K.-M., C.-H. Sui and W.-K. Tao, 1993: A preliminary study of the tropical water cycle using the Goddard Cumulus Ensemble model. Bull. Amer. Meteor. Soc. 74, 1313-1321.

Li, X., 2004: Cloud modeling in the tropical deep convective regime, in Observation, Theory, and Modeling of Atmospheric Variability. Edited by X. Zhu, pp. 206-223, World Sci., River Edge, N. J.

Li, X., C.-H. Sui, K.-M. Lau, and D. Adamec, 2000: Effects of precipitation on ocean mixed-layer temperature and salinity as simulated in a 2-D coupled ocean-cloud resolving atmosphere model. J. Meteor. Soc. Japan, 78, 647-659.

Lilly, D. K., 1986: The structure, energetics and propagation of rotating convective storms. Part II: Helicity and storm stabilization. J. Atmos. Sci., 43, 126-140.

Liu, C., and M. W. Moncrieff, 1998: A numerical study of the diurnal cycle of tropical oceanic convection. J. Atmos. Sci., 55, 2329-2344.

McCumber, M., W.-K. Tao, J. Simpson, R. Penc, and S.-T. Soong, 1991: Comparison of ice –phase microphysical parameterization schemes using numerical simulations of tropical convection. J. Appl. Meteor., 30, 985-1004.

Nakajima, K., and T. Matsuno, 1988: Numerical experiments concerning the origin of cloud clusters in the tropical atmosphere. J. Meteor. Soc. Japan, 66, 309-329.

Nakazawa, T., 1988: Tropical super clusters within intraseasonal variations over the western Pacific. J. Meteor Soc. Japan, 66, 823-839.

Nicholls, M. E., 1987: A comparison of the results of a two-dimensional numerical simulation of a tropical squall line with observations. Mon. Wea. Rev., 115, 3055-3077.

Niiler, P. P., and E. B. Kraus, 1977: One-dimensional models, in Modeling and Prediction of the Upper Layers of the Ocean, edited by E. B. Kraus, Pergamon, New York, 143-172.

Numaguti, A., and Y.-Y. Hayashi, 1991: Behavior of cumulus activity and the structures of circulations in an "aqua planet" model. Part I. The structure of the super cloud clusters. J. Meteor. Soc. Japan, 69, 541-561.

Peng, L., C.-H. Sui, K.-M. Lau, and W.-K. Tao, 2001: Genesis and evolution of hierarchical cloud clusters in a two-dimensional cumulus-resolving model. J. Atmos. Sci., 58, 877-895.

Ping, F., Z. Luo, and X. Li, 2007a: Microphysical and radiative effects of ice clouds on tropical equilibrium states: A two-dimensional cloud-resolving modeling study. Mon. Wea. Rev., 135, 2794-2802.

Ping, F., Z. Luo, and X. Li, 2007b: Effects of salinity on long-term atmospheric and oceanic variability. Atmos. Res., 84, 78-83.

Ping, F., Z. Luo, and X. Li, 2008: Kinematics, Cloud Microphysics, and spatial structures of tropical cloud clusters: A two-dimensional cloud-resolving modeling study. Atmos. Res., 88, 323-336.

Randall, D. A., Harshvardhan, D. A. Dazlich, 1991: Diurnal variability of the hydrologic cycle in a general circulation model. J. Atmos. Sci., 48, 40-62.

Shie, C.-L, W.-K. Tao, J. Simpson, and C.-H. Sui, 2003: Quasi-equilibrium states in the tropics simulated by a cloud-resolving model. Part I: Specific features and budget analysis. J. Climate, 16, 817-833.

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

Sui, C.-H. and K.-M. Lau, 1992: Multi-scale phenomena in the tropical atmosphere over the western Pacific. Mon Wea. Rev., 120, 407-430.

Sui, C.-H., and X. Li, 2005: A tendency of cloud ratio associated with the development of tropical water and ice clouds. Terr. Atmos. Oceanic Sci., 16, 419-434.

Sui, C.-H., K.-M. Lau, W.-K. Tao, and J. Simpson, 1994: The tropical water and energy cycles in a cumulus ensemble model. Part I: Equilibrium climate. J. Atmos. Sci., 51, 711-728.

Sui, C.-H., K.-M. Lau, Y. Takayabu, and D. Short, 1997: Diurnal variations in tropical oceanic cumulus ensemble during TOGA COARE. J. Atmos. Sci., 54, 639-655.

Sui, C.-H., X. Li, and K.-M. Lau, 1998: Radiative-convective processes in simulated diurnal variations of tropical oceanic convection. J. Atmos. Sci., 55, 2345-2359.

Sui, C.-H., X. Li, and M.-J. Yang, 2007: On the definition of precipitation efficiency. J. Atmos. Sci., 64, 4506-4513.

Tao, W.-K., 2007: Cloud Resolving Modeling. J. Meteor. Soc. Japan, 85, 305-330.

Tao, W.-K., and J. Simpson, 1989: Modeling study of a tropical squall-type convective line. J. Atmos. Sci., 46, 177-202.

Tao, W.-K., J. Simpson, and S.-T. Soong, 1991: Numerical simulation of a subtropical squall line over the Taiwan Strait. Mon. Wea. Rev., 119, 2699-2723.

Tao, W.-K., S. Lang, J. Simpson, C.-H. Sui, B. S. Ferrier, and M.-D. Chou, 1996: Mechanisms of cloud-radiation interaction in the Tropics and midlatitude. J. Atmos. Sci., 53, 2624-2651.

Tao, W.-K., J. Simpson, C.-H. Sui, C.-L. Shie, B. Zhou, K.-M. Lau, M. W. Moncrieff, 1999: Equilibrium states simulated by cloud-resolving models. J. Atmos. Sci., 56, 3128-3139.

Tompkins, A. M., 2000: The impact of dimensionality on long-term cloud resolving model simulations. Mon. Wea. Rev., 128, 1521–1535.

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.

Wu, X., and M. W. Moncrieff, 1996: Collective effects of organized convection and their approximation in general circulation models. J. Atmos. Sci., 53, 1477-1495.

Wu, X., and M. W. Moncrieff, 1999: Effects of sea surface temperature and large-scale dynamics on the thermodynamic equilibrium state and convection over the tropical western Pacific. J. Geophys. Res., 104, 6093-6100

Wu, X., and M. A. LeMone, 1999: Fine structure of cloud patterns within the intraseasonal oscillation during TOGA COARE. Mon. Wea. Rev., 127, 2503-2513.

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.

Yano, J.-I., J. C. McWilliams, M. W. Moncrieff, and K. A. Emanuel, 1995: Hierarchical tropical cloud systems in an analog shallow-water model. J. Atmos. Sci., 52, 1723-1742.

Yoshizaki, M., 1986: Numerical simulations of tropical squall-line clusters: Two-dimensional model. J. Meteor. Soc. Japan, 64, 469-491.