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Temporal and Spatial Scale Dependence of Precipitation Analysis over the Tropical Deep Convective Regime

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ABSTRACT

Data from Goddard cumulus ensemble model experiment are used to study temporal and spatial scale dependence of tropical rainfall separation analysis based on cloud budget during Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE). The analysis shows that the calculations of model domain mean or time-mean grid-scale mean simulation data overestimate the rain rates of the two rainfall types associated with net condensation but they severely underestimate the rain rate of the rainfall type associated with net evaporation and hydrometeor convergence.

Key words: cloud microphysical budget, temporal and spatial scale, rainfall partitioning analysis

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1. Introduction

Precipitation is highly temporally and spatially dependent due to different thermodynamic, water vapor, and cloud microphysical processes. The precipitation could vary from diurnal timescale (e.g., Gao and Li, 2010), synoptic timescale (e.g., Wang et al., 2009; Shen et al., 2011) to climate timescale (e.g., Gao, 2008). Precipitation systems have a typical life span with the development stage dominated by convective rainfall and the decay phase dominated by stratiform rainfall. Convective rainfall corresponds to vapor convergence, while the stratiform rainfall corresponds to hydrometeor advection associated with dynamic processes (e.g. Li and Gao, 2011). To accurately estimate temporally and spatially averaged thermodynamic properties, which may be used in cumulus parameterization for large-scale models, the contributions to averaged properties from grid-scale properties should be properly accounted for. For example, accurate separation of rainfall source into precipitation and moistening local atmosphere measured by precipitation efficiency could be a key part for cumulus parameterization processes. As we can see from this study later, the precipitation efficiency estimated from averaged data could be significantly different from that calculated from grid-scale data. The contributions to averaged data from grid-scale data can be analyzed based on surface rainfall budget (e.g. Shen et al., 2010) and cloud budget (e.g. Li et al., 2011). Shen et al. (2010) showed an important role vapor convergence plays in production of precipitation in their separation study from precipitation processes. Li et al. (2011) revealed that all three rainfall types partitioned by cloud budget have important contribution to total rainfall in their partitioning examination from cloud microphysical processes. Thus, the rainfall separation analysis reveals important roles various physical processes play in production of precipitation during the convective development, which leads to enhancement of understanding precipitation processes and improvement of quantitative precipitation estimation and forecast.

Cloud microphysical processes are directly responsible for production of precipitation. Temporal evolution and spatial distribution of rainfall processes may lead to an offset between net condensation and net

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Table 1. Model setups.

Large-scale forcing	Vertical velocity, zonal wind, and horizontal advection over the Intensive Flux Array (IFA) region and sea surface temperature measured at the Improved Meteorological (IMET) surface mooring buoy (1.7°S, 156°E) (Weller and Anderson, 1996) during TOGA COARE [see Fig. 1 in Li et al. (2011)]
Prognostic equations	Potential temperature, specific humidity, five hydrometeor species, and perturbation zonal wind and vertical velocity.
Basic model parameters	Model domain of 768 km, grid mash of 1.5 km, time step of 12 s, and 33 vertical layers.
Lateral boundary conditions	cyclic
Experiment integration	0400 LST 22 December 1992 - 0400 LST 08 January 1993
Reference	Gao and Li (2008a) and Li and Gao (2011)

evaporation and between hydrometeor advections in averaged calculation of cloud budget, implying temporal and spatial scale dependence of rainfall partitioning analysis. Large temporal and spatial fluctuations of precipitation may cause significant differences between temporally and spatially averaged calculations in cloud microphysical budgets associated with production of precipitation. To evaluate sensitivity of rainfall analysis to temporal and spatial scale for data average, we conduct a rainfall analysis using spatially averaged data and temporally averaged grid-scale data and compare the results with grid-scale analysis from Li et al. (2011) during TOGA COARE. Model and experiment are briefly discussed in the next section. The results are presented in section 3. A summary is given in section 4.

2. Model and experiment

The data analyzed in this study comes from Gao and Li (2008b). The two-dimensional model setups are summarized in Table 1 and validation of model simulations against available observational data can be found in Gao and Li (2008b). Cloud budget can be written as

$$P_{\mathrm{S}} = Q_{\mathrm{NC}} + Q_{\mathrm{CM}}, \tag{1}$$

where

$$Q_{\mathrm{NC}} = ([P_{\mathrm{CND}}] + [P_{\mathrm{DEP}}] + [P_{\mathrm{SDEP}}] + [P_{\mathrm{GDEP}}]) - ([P_{\mathrm{REVP}}] + [P_{\mathrm{MLTG}}] + [P_{\mathrm{MLTS}}]) \,, \tag{1a}$$

$$Q_{\mathrm{CM}} = -\frac{\partial [q_5]}{\partial t} - \left[\frac{\partial}{\partial x}(uq_5)\right] \,. \tag{1b}$$

Here, P_{S} is surface rain rate; Q_{NC} is the net condensation, where $([P_{\mathrm{CND}}] + [P_{\mathrm{DEP}}] + [P_{\mathrm{SDEP}}] + [P_{\mathrm{GDEP}}])$ represents the cloud source term that consists of vapor condensation rate for the growth of cloud water ($[P_{\mathrm{CND}}]$), vapor deposition rates for the growth of cloud ice ($[P_{\mathrm{DEP}}]$), snow ($[P_{\mathrm{SDEP}}]$) and graupel ($[P_{\mathrm{GDEP}}]$) and $-([P_{\mathrm{REVP}}] + [P_{\mathrm{MLTG}}] + [P_{\mathrm{MLTS}}])$ denotes the cloud sink term that includes growth of vapor by evaporation of raindrop ($[P_{\mathrm{REVP}}]$), evaporation of liquid from graupel surface ($[P_{\mathrm{MLTG}}]$), and evaporation of melting snow ($[P_{\mathrm{MLTS}}]$); u is the zonal wind; q_5 is total hydrometeor mixing ratio (sum of mixing ratios of five cloud species); $[(\ )](=\int_{z_{\mathrm{b}}}^{z_{\mathrm{t}}} \bar{\rho}(\ )dz)$ is a mass integration, and z_{t} and z_{b} are the heights of the top and bottom of the model atmosphere, respectively. Cloud microphysical budget (1) shows that surface rainfall corresponds to net condensation (vapor condensation and deposition rates are larger than evaporation rates of precipitation hydrometeors) or net evaporation (evaporation rates of precipitation hydrometeors are larger than vapor condensation and deposition rates), and local hydrometeor tendency/advection (e.g., Li et al., 2011). According to cloud microphysical budget, rainfall can be partitioned into three types: CM, Cm, and cM. CM is the rainfall type associated with net condensation and hydrometeor convergence. Cm is the rainfall type related to net condensation and hydrometeor divergence. cM is the rainfall type that corresponds to net evaporation and hydrometeor convergence.

3. Results

In this short note, contribution of each rainfall type to total rainfall is first calculated using spatially averaged data and temporally averaged grid-scale simulation data, respectively (Table 2). The calculations of both model domain mean and time-mean grid-scale simulation data show that the rainfall types CM and Cm contribute equally to total rainfall, and their contributions are much larger than the contribution from the rainfall type cM. The rainfall contribution from CM is slightly larger than that from Cm in the calculations of model domain mean data, whereas it is slightly smaller than that from Cm in the calculations of time-mean grid-scale data. The rainfall contributions from CM and Cm in this study are larger than those in grid-scale data calculations, whereas the rainfall contribution from cM in this study is much smaller than that in grid-scale data calculations (Li et al., 2011; also see Table 2c), indicating that the rainfall partitioning analysis based on cloud budget is temporal and spa-

Table 2. Percentage of rain amount over total rainfall amount (PRA), mean cloud budgets (P_S, Q_{NC}, Q_{CM}) for CM, Cm, and cM calculated using (a) model domain mean data and (b) time-mean grid-scale data and (c) grid-scale data (Li et al., 2011). Units are % for PRA and mm h^{-1} for cloud budget.

		CM	Cm	cM
(a)	PRA	50.553	48.207	1.240
	P_S	0.182	0.174	0.004
	Q_{NC}	0.141	0.223	−0.003
	Q_{CM}	0.041	−0.049	0.007
(b)	PRA	48.853	49.147	2.000
	P_S	0.176	0.177	0.007
	Q_{NC}	0.114	0.250	−0.001
	Q_{CM}	0.063	−0.072	0.009
(c)	PRA	36.003	36.876	27.122
	P_S	0.130	0.133	0.098
	Q_{NC}	0.065	0.447	−0.158
	Q_{CM}	0.065	−0.314	0.256

Table 3. Percentage of rain amount over total rainfall amount (PRA), and cloud budgets (P_S, Q_{NC}, Q_{CM}) for CM, Cm, and cM calculated using (a) 6-km, (b) 24-km, and (c) 96-km averaged data. Units are % for PRA and mm h^{-1} for cloud budget.

		CM	Cm	cM
(a)	PRA	38.790	43.150	18.060
	P_S	0.140	0.156	0.065
	Q_{NC}	0.074	0.385	−0.096
	Q_{CM}	0.066	−0.230	0.161
(b)	PRA	39.195	51.985	8.820
	P_S	0.141	0.187	0.032
	Q_{NC}	0.088	0.331	−0.055
	Q_{CM}	0.053	−0.144	0.087
(c)	PRA	40.171	55.603	4.226
	P_S	0.145	0.200	0.015
	Q_{NC}	0.100	0.293	−0.028
	Q_{CM}	0.045	−0.093	0.044

tial scale dependent. The small rainfall contribution from cM here is partly due to the large offset in hydrometeor advection between raining stratiform and convective regions, and partly because cyclic later boundary conditions imposed in the model used in this short note. Although the rainfall contributions from CM and Cm are similar in the calculations of both mean data, the rainfall processes associated with CM and Cm are different. In CM, the net condensation and hydrometeor convergence rates are, respectively, higher and lower in the calculations of spatially averaged data than in the calculations of temporally averaged grid-scale data. In Cm, the net condensation and hydrometeor divergence rates are higher in the calculations of temporally averaged grid-scale data than in the calculations of spatially averaged data.

The rain rate of cM decreases from grid-scale data to mean data, suggesting that the rain rate of cM decreases as the temporal and spatial scales for data average increase. This can be demonstrated by the calculations of spatially averaged data in Table 3 as an example. The rain rates of cM are 0.065 mm h^{-1} for 6-km averaged data, 0.032 mm h^{-1} for 24-km averaged data, and 0.015 mm h^{-1} for 96-averaged data. The suppressed rainfall in cM results from the reduced hydrometeor convergence rate although the net evaporation rate decreases as well. The contribution from CM is smaller than that from Cm in the calculations of these spatially averaged data because of lower rain rate in CM compared to that of Cm. The contribution from Cm increases, but the contribution of CM barely changes as the spatial scale for data average increases. Thus, the suppressed contribution of cM corresponds to the enhanced contribution of Cm as the spatial scale for data averaged increases. The enhanced contribution of Cm corresponds to the suppressed hydrometeor divergence, while the net condensation rate decreases. The precipitation rate of CM is less sensitive to spatial scale for data average as a result of the offset between the enhanced net condensation and the suppressed hydrometeor convergence caused by the increased spatial scale for data average.

Although cM has minor rainfall contribution in mean calculations, grid-scale calculations show that about 20%–30% of rainfall for mean rainfall types CM and Cm originate from cM (Table 4). The grid-scale calculations reveal that all three rainfall types have important rainfall contributions, whereas the mean calculations may underestimate rainfall contribution from cM.

Temporal and spatial scale dependence of rainfall partitioning analysis implies that precipitation efficiency may be sensitive to temporal and spatial scale for data average. The precipitation efficiency defined in cloud microphysical budget can be expressed as

$$\mathrm{PE} = \frac{P_S}{H(Q_{NC})Q_{NC} + H(Q_{CM})Q_{CM}} \times 100\% \,, \quad (2)$$

where H is the Heaviside function, $H(F)$=1 when F >0, and $H(F)$=0 when $F\leqslant 0$. (2) is similar to cloud microphysics precipitation efficiency (CMPE) defined by Sui et al. (2007). The difference is the net condensation is a term in this study whereas the net condensation is separated into seven terms in Sui et al. (2007). In calculation of precipitation efficiency (2), only positive values of Q_{NC} and Q_{CM} are counted as rainfall sources. Thus,

Table 4. Percentage of rain amount over total rainfall amount (PRA) calculated using model domain mean simulation data for three mean rainfall types and PRA of rainfall types calculated using (a) model domain mean data and (b) time-mean grid-scale data for each mean rainfall type. Units: %.

			Rainfall type in model domain mean data		
			CM	Cm	cM
(a)	Mean data		50.553	48.207	1.240
	Rainfall type in grid-scale data	CM	38.905	33.243	24.943
		Cm	31.117	43.233	24.513
		cM	29.978	23.524	50.544
(b)	Mean data		48.853	49.147	2.000
	Rainfall type in grid-scale data	CM	39.606	32.373	37.191
		Cm	29.654	44.890	16.342
		cM	30.740	22.737	46.466

$$\mathrm{PE} = 100\% \text{ for CM} , \tag{2a}$$

$$\mathrm{PE} = \frac{P_{\mathrm{S}}}{Q_{\mathrm{NC}}} \times 100\% \text{ for Cm} , \tag{2b}$$

$$\mathrm{PE} = \frac{P_{\mathrm{S}}}{Q_{\mathrm{CM}}} \times 100\% \text{ for cM} . \tag{2c}$$

Positive values of both net condensation and hydrometeor loss/convergence make 100% of precipitation efficiency for CM. The precipitation efficiency of Cm generally increases as spatial and temporal scale for data average increases (Table 5). The precipitation efficiency of cM is less sensitive to spatial scale for data average when the spatial scale increases from 1.5 km to 96 km.

4. Summary

Temporal and spatial scale dependence of precipitation analysis is examined by analyzing the grid-scale simulation data on cloud microphysical budget during a selected period of TOGA COARE. The analysis of spatially averaged data and temporally averaged grid-scale data shows that the total rainfall originates mainly from raining regions with net condensation and hydrometeor convergence (CM) and with net condensation and hydrometeor divergence (Cm), while the contribution from raining regions with net evaporation and hydrometeor convergence (cM) is negligibly small. In contrast, the examination of grid-scale data from Li et al. (2011) revealed that all three rainfall types have important contributions to total rainfall. Further spatial-scale analysis using 6-km, 24-km, and 96-km averaged data reveals barely changed rainfall of CM, enhanced rainfall of Cm, and suppressed rainfall of cM. The calculations with mean data tend to overestimate the rain rates of CM and Cm but they severely underestimate the rain rate of cM. Therefore, caution should be exercised for application of results from precipitation analysis because of temporal and spatial scale dependence. An implication of temporal and spatial dependence of rainfall partitioning analysis is that the averaged data calculations significantly overestimate precipitation efficiency for Cm and cM because they underestimate rainfall sources.

Table 5. Precipitation efficiencies of Cm and cM calculated using grid-scale data from Li et al. (2011), data averaged over 6 km, 24 km, and 96 km, and model domain mean and time-mean grid-scale data. Units: %.

	Cm	cM
Grid-scale data	29.8	38.3
6-km averaged data	40.5	40.4
24-km averaged data	56.5	36.8
96-km averaged data	68.3	34.1
Model domain mean data	78.1	60.9
Time-mean grid-scale data	71.0	83.5

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