

Precipitation Equations and Quantitative Analysis

Xiaofan Li

NOAA/NESDIS/SCMD/EMB

Issues

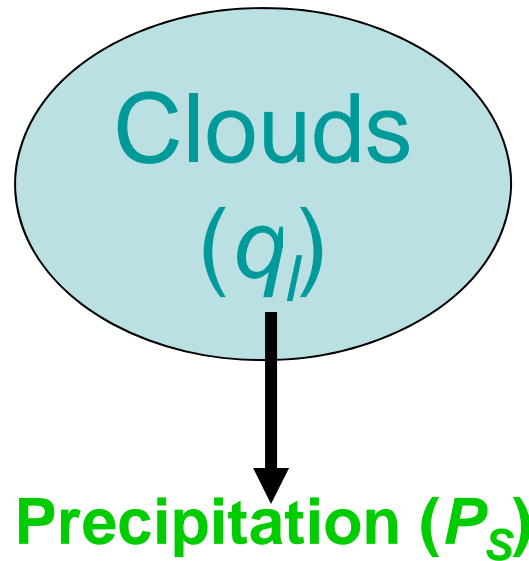
- What is quantitative relationship between surface rainfall and thermodynamic processes?
- If observational data (satellite-retrieved data) are available, how is precipitation statistics analyzed quantitatively? How is precipitation efficiency defined and estimated properly? What is requirement of quality of observed initial conditions for quantitative precipitation forecast/simulation?

PS=?

Motivation

- Establish a framework for quantitatively identifying dominant thermodynamic and cloud processes associated with precipitation

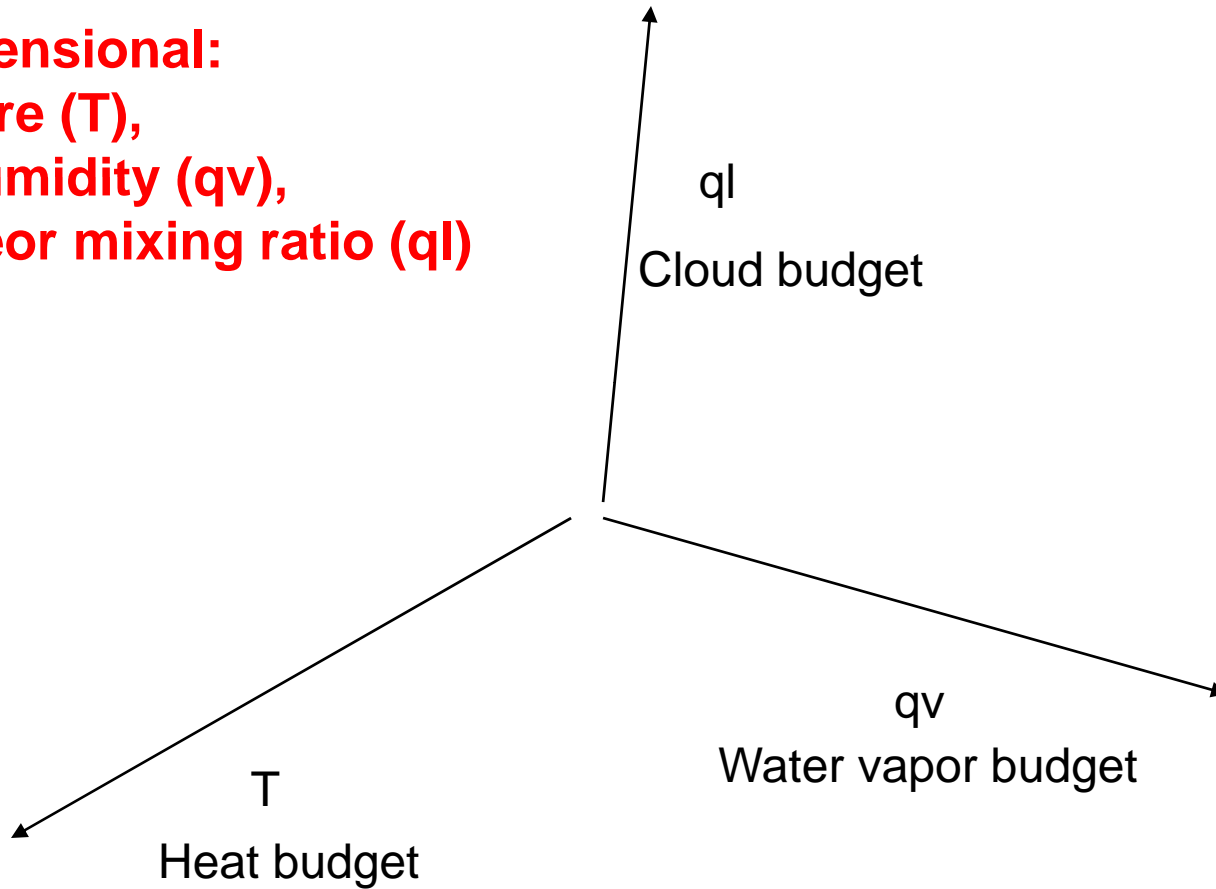
Environments (T, q_v)



Environments

Precipitation Physical Space

**Three-Dimensional:
Temperature (T),
specific humidity (qv),
Hydrometeor mixing ratio (ql)**



Mass-Integrated Cloud Budget

$$P_S - Q_{CM} = Q_{WVS} = Q_{WVOUT} + Q_{WVIN}$$

Surface rain rate (P_S) is a diagnostic quantity

$$Q_{CM} = -\frac{\partial[q_l]}{\partial t} - [u \frac{\partial q_l}{\partial x}] - [w \frac{\partial q_l}{\partial z}]$$

Local hydrometeor change and convergence rate

$$Q_{WVOUT} = [P_{CND}] + [P_{DEP}] + [P_{SDEP}] + [P_{GDEP}]$$

Cloud sources/water vapor sinks: vapor condensation and depositions

$$Q_{WVIN} = -[P_{REVP}] - [P_{MLTG}] - [P_{MLTS}]$$

Cloud sinks/water vapor sources: evaporation of rain, snow, and graupel

Q_{WVS} is cloud microphysical processes including cloud sources and sinks

Local hydrometeor change is determined by hydrometeor convergence, precipitation rate, and cloud sources and sinks.

Mass-Integrated Water Vapor Budget

$$Q_{WVT} + Q_{WVF} + Q_{WVE} = Q_{WVS}$$

$$Q_{WVT} = -\frac{\partial [q_v]}{\partial t} \quad \text{Local atmospheric drying/moistening}$$

$$Q_{WVF} = -[\bar{u}^o \frac{\partial \bar{q}_v}{\partial x}] - [\bar{w}^o \frac{\partial \bar{q}_v}{\partial z}] - [\frac{\partial (u' q_v')}{\partial x}] \quad \text{Water vapor convergence/divergence}$$

$$-[\bar{u}^o \frac{\partial q_v'}{\partial x}] - [\bar{w}^o \frac{\partial q_v'}{\partial z}] - [w' \frac{\partial \bar{q}_v'}{\partial z}]$$

$$Q_{WVE} = E_s \quad \text{Surface evaporation}$$

Local water vapor change rate is determined by water vapor convergence, surface evaporation, and vapor condensation and depositions.

Mass-Integrated Heat Budget

$$S_{HT} + S_{HF} + S_{HS} + S_{LHLF} + S_{RAD} = Q_{WVS}$$

$$S_{HT} = \frac{c_p}{L_v} \frac{\partial [T]}{\partial t} \quad \text{Local atmospheric warming/cooling}$$

$$S_{HF} = \frac{c_p}{L_v} \left[\frac{\partial}{\partial x} (\bar{u}^o + u') T' + \pi \bar{u}^o \frac{\partial \bar{\theta}^o}{\partial x} + \pi \bar{w}^o \frac{\partial}{\partial z} (\bar{\theta} + \theta') + \pi w' \frac{\partial \bar{\theta}}{\partial z} \right] \quad \text{Heat convergence/divergence}$$

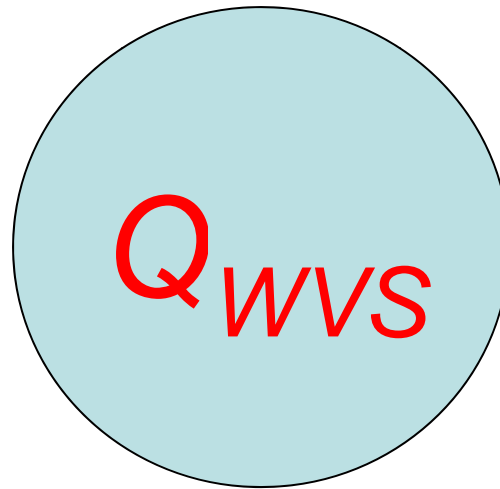
$$S_{HS} = -\frac{c_p}{L_v} H_s \quad \text{Surface sensible heat}$$

$$S_{LHLF} = -\frac{L_f}{L_v} \langle P_{18} \rangle \quad \text{Latent heat due to ice-related processes (P}_{18}\text{)}$$

$$S_{RAD} = -\frac{1}{L_v} \langle Q_R \rangle \quad \text{Radiative heating/cooling}$$

Local thermal change rate is determined by heat convergence, surface sensible heat, latent heat, and radiative heating.

Three Mass-Integrated Budgets
are linked by



Water vapor-related Precipitation equation is derived by combining cloud budget with water vapor budget

$$P_S = Q_{WVT} + Q_{WVF} + Q_{WVE} + Q_{CM}$$

Thermally-related Precipitation equation
is derived by combining cloud budget
with heat budget

$$P_S = S_{HT} + S_{HF} + S_{HS} + S_{LHLF} + S_{RAD} + Q_{CM}$$

Outline

- **Precipitation Statistics**
- **Diurnal Cycle of Rainfall**
- **Sensitivity of precipitation simulation to uncertainty of initial conditions**

Cloud Resolving Model

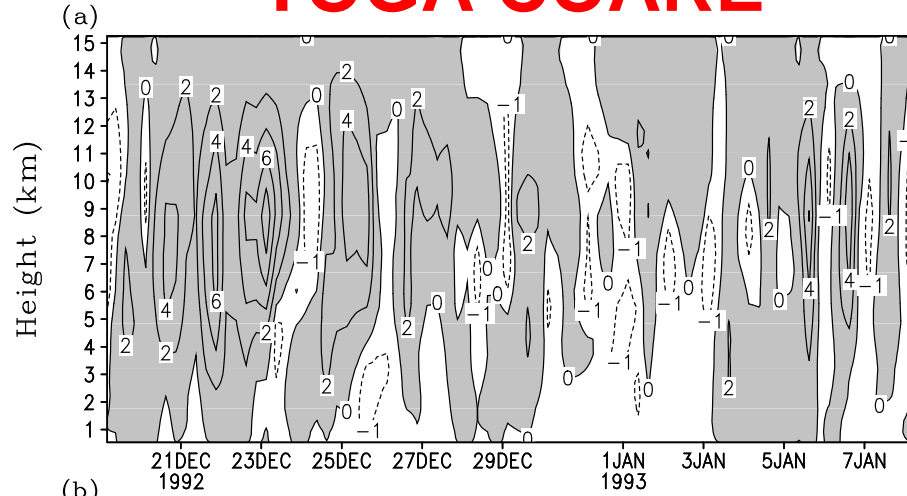
- Non-hydrostatic and Anelastic (Tao and Simpson 1993)
- Prognostic equations for T , q_v , q_c , q_r , q_i , q_s , q_g
- Radiation (Chou and Suarez 1994, Chou et al. 1998)
- Cloud Microphysics (Rutledge and Hobbs 1983 1984, Lin et al. 1983, Tao et al. 1989, Krueger et al. 1995)
- Turbulence Closures
- Imposed spatial-uniform large-scale vertical velocity, zonal wind, SST, horizontal temperature and moisture advections

Cloud Resolving Model

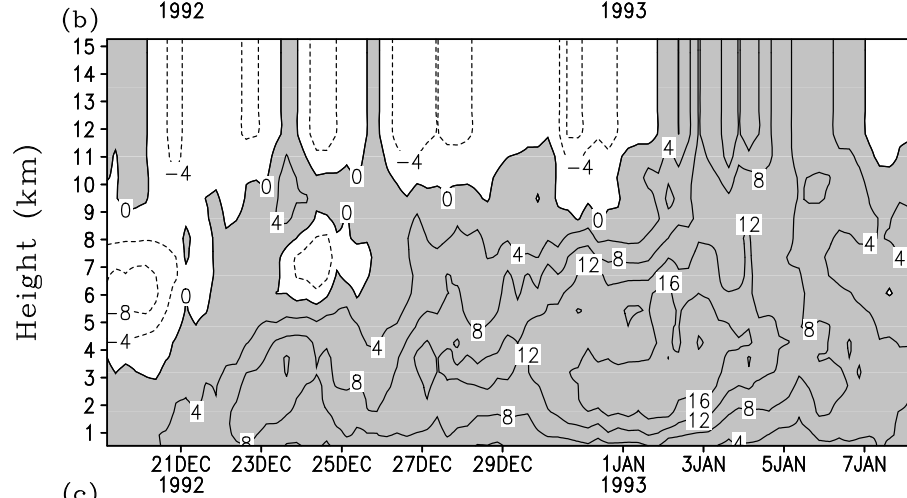
- Two dimension: x-z
- Domain: 768 km
- Horizontal Resolution: 1.5 km
- Vertical resolution: 33 vertical levels
- Time step: 12 Seconds

TOGA COARE

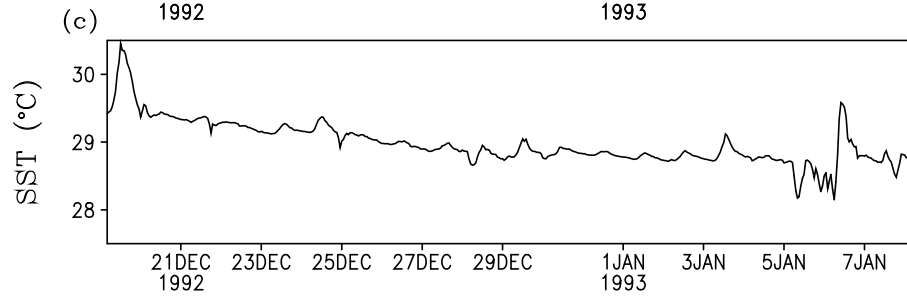
W



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SST



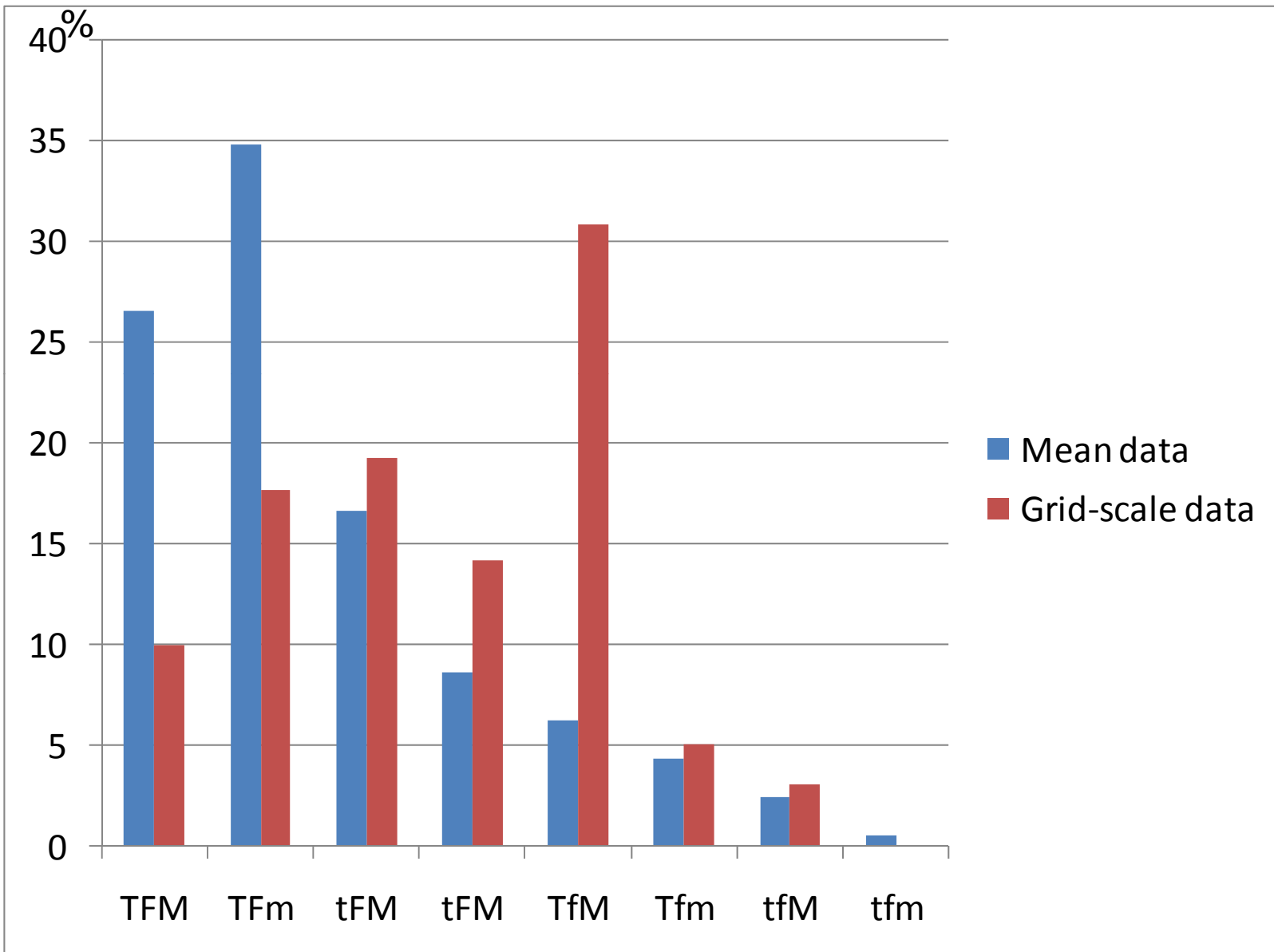
Precipitation Statistics

Precipitation Equation

- Q_{WVT} can be positive or negative
- Q_{WVF} can be positive or negative
- Q_{CM} can be positive or negative
- Eight rainfall types with different Q_{WVT} , Q_{WVF} , and Q_{CM}

Water vapor-related Precipitation equation

Rainfall type	Description
TFM	Water vapor convergence, local atmospheric drying, and hydrometeor loss/convergence
TFm	Water vapor convergence, local atmospheric drying, and hydrometeor gain/divergence
tFM	Water vapor convergence, local atmospheric moistening, and hydrometeor loss/convergence
tFm	Water vapor convergence, local atmospheric moistening, and hydrometeor gain/divergence
TfM	Water vapor divergence, local atmospheric drying, and hydrometeor loss/convergence
Tfm	Water vapor divergence, local atmospheric drying, and hydrometeor gain/divergence
tfM	Water vapor divergence, local atmospheric moistening, and hydrometeor loss/convergence
tfm	Water vapor divergence, local atmospheric moistening, and hydrometeor gain/divergence



Model domain mean data

	TFM	TFm	tFM	tFm	TfM	Tfm	tfM	tfm
PRA (%)	26.572	34.789	16.627	8.631	6.207	4.301	2.387	0.486
P_S (mm h ⁻¹)	0.895	0.717	0.360	0.261	0.375	0.243	0.120	0.057
Q_{WVT}	0.217	0.338	-0.219	-0.175	0.220	0.309	-0.134	-0.078
Q_{WVF}	0.343	0.346	0.271	0.349	-0.151	-0.132	-0.077	-0.058
Q_{WVE}	0.200	0.201	0.189	0.167	0.194	0.201	0.230	0.232
Q_{CM}	0.136	-0.168	0.118	-0.080	0.112	-0.135	0.100	-0.039

Contribution of rainfall in each mean rainfall type (Blue: mean data; green: grid-scale data)

	TFM	TFm	tFM	tFm	TfM	Tfm	tfM
TFM	12.264	9.567	11.117	7.767	7.282	6.721	4.376
TFm	15.675	21.716	14.375	17.990	15.895	19.338	7.330
tFM	19.016	19.390	22.063	16.600	19.181	15.170	18.153
tFm	12.174	16.168	11.294	17.166	12.667	20.108	10.091
TfM	33.983	25.403	33.589	31.165	37.194	27.628	44.101
Tfm	3.321	5.292	4.551	6.159	4.642	8.164	10.502
tfM	3.567	2.465	3.012	3.153	3.138	2.871	5.446

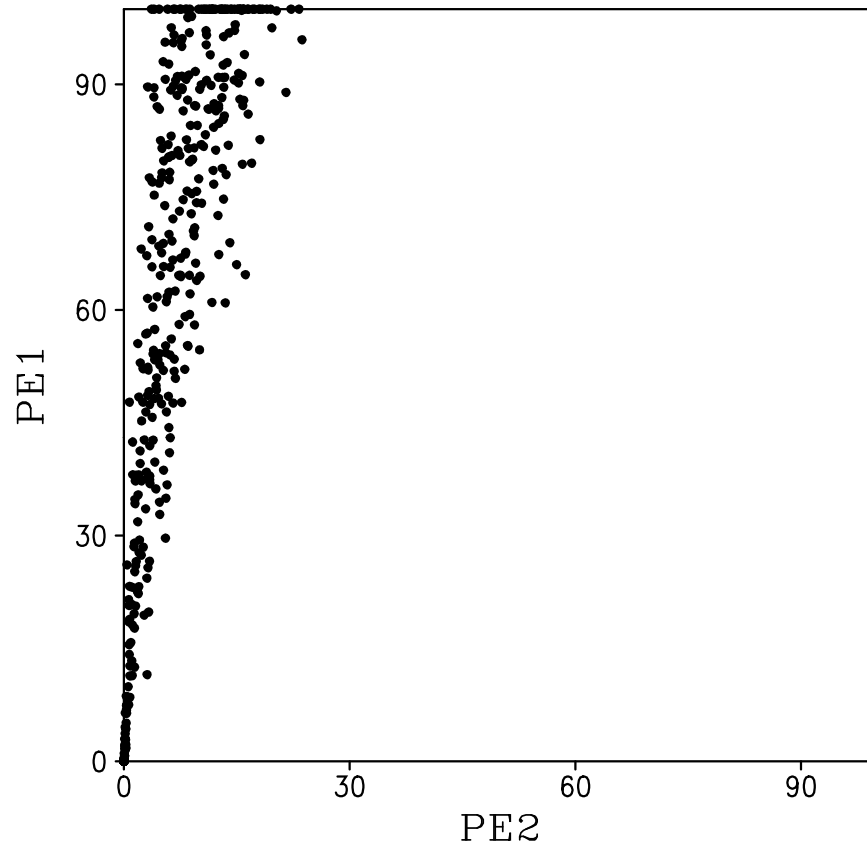
Issue

- The precipitation statistics is spatial-scale dependent
- Significant contributions from rainfall with water vapor divergence, hydrometeor change/convergence and local atmospheric drying/moistening should be included in current cumulus parameterization schemes

Large-scale precipitation efficiency (*LSPE*) based on the water vapor related precipitation equation

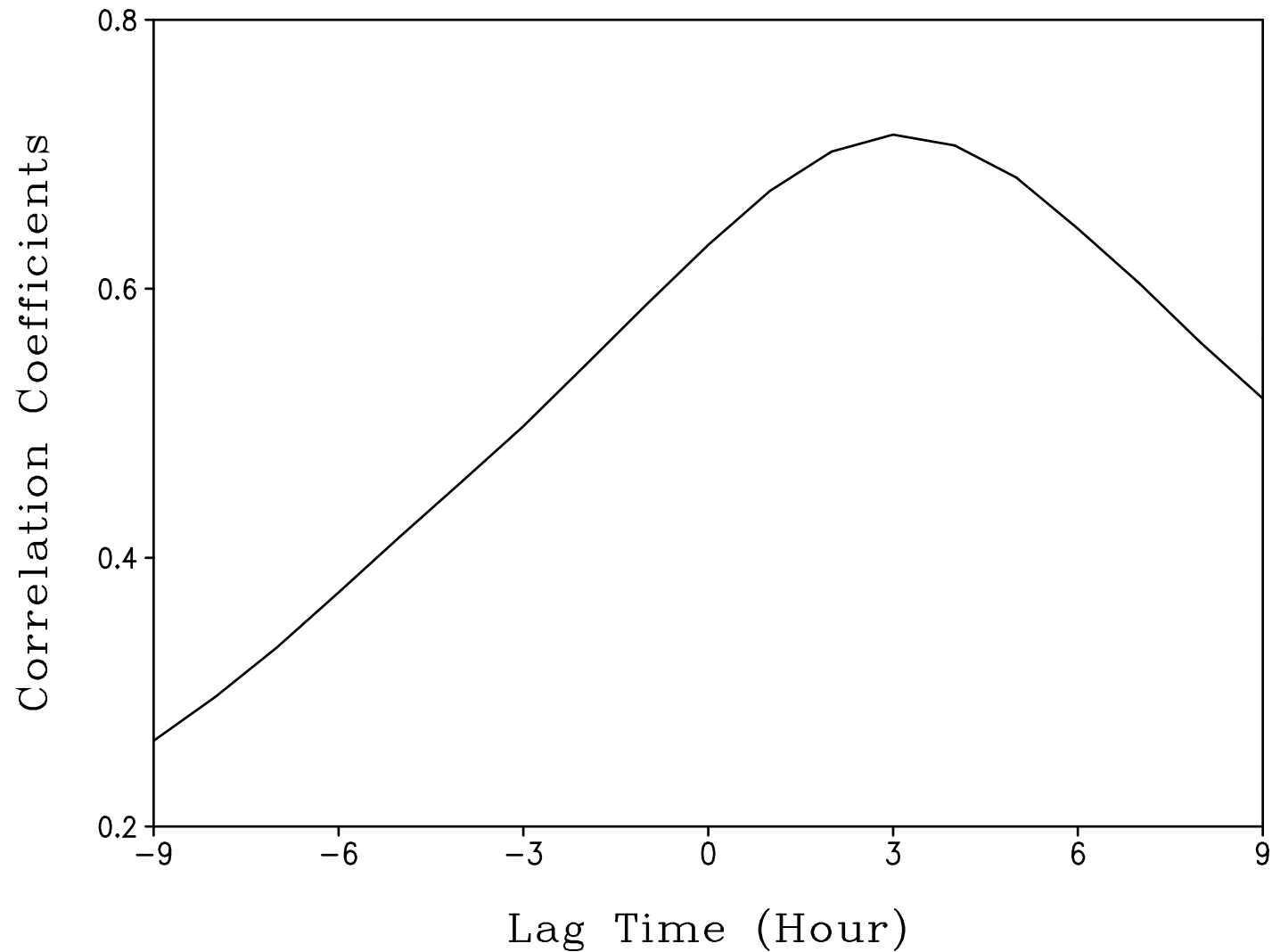
$$LSPE = \frac{P_s}{\sum_{i=1}^4 H(Q_i)Q_i}$$

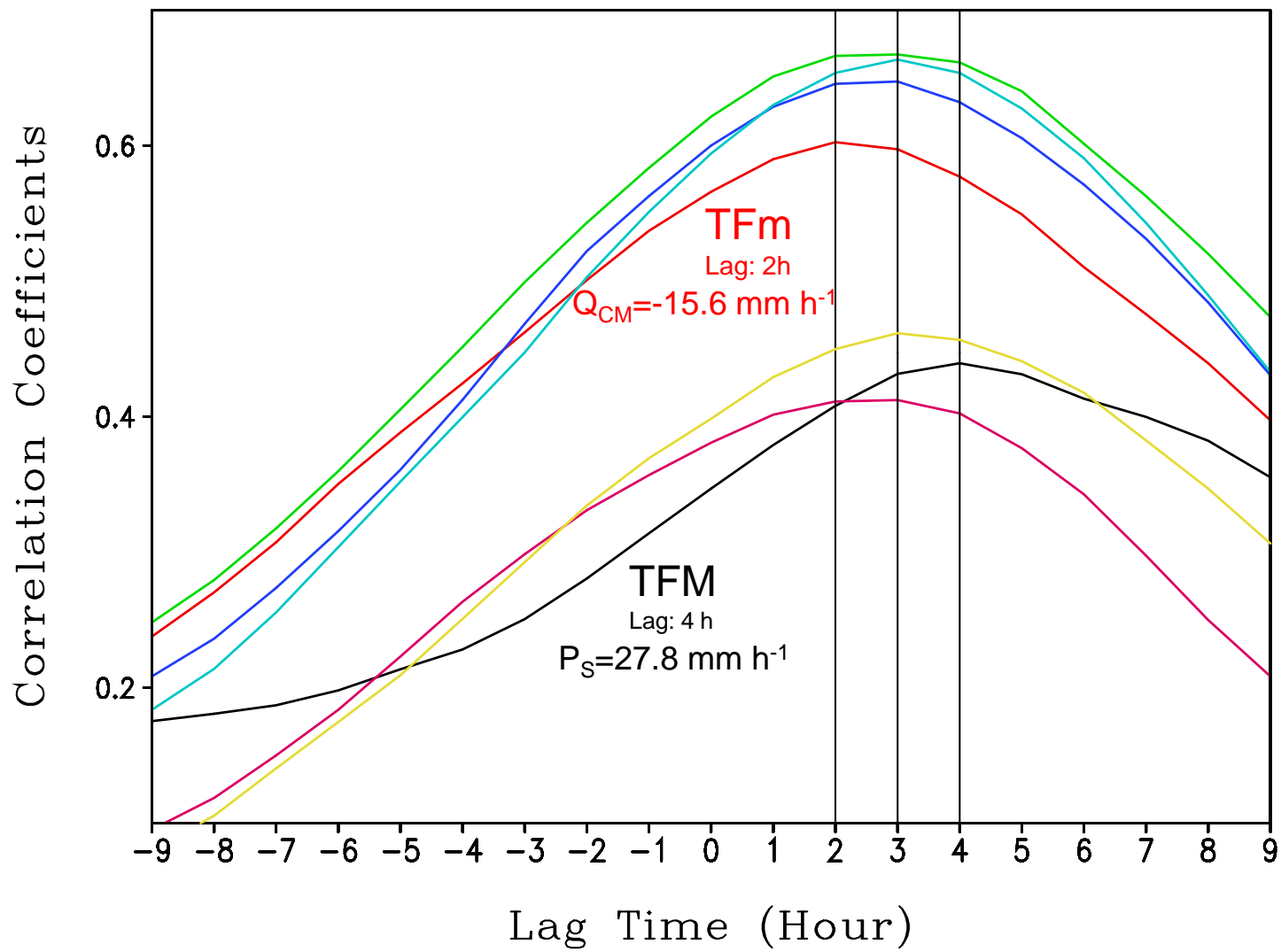
$$Q_i = (Q_{WVT}, Q_{WVF}, Q_{WVE}, Q_{CM})$$



Precipitation efficiency is calculated by accumulating rainfall sources from each model grid over the model domain in PE2, whereas it is calculated using model domain mean data in PE1.

Model domain mean surface rain rate lags mean water vapor convergence by 3 hour

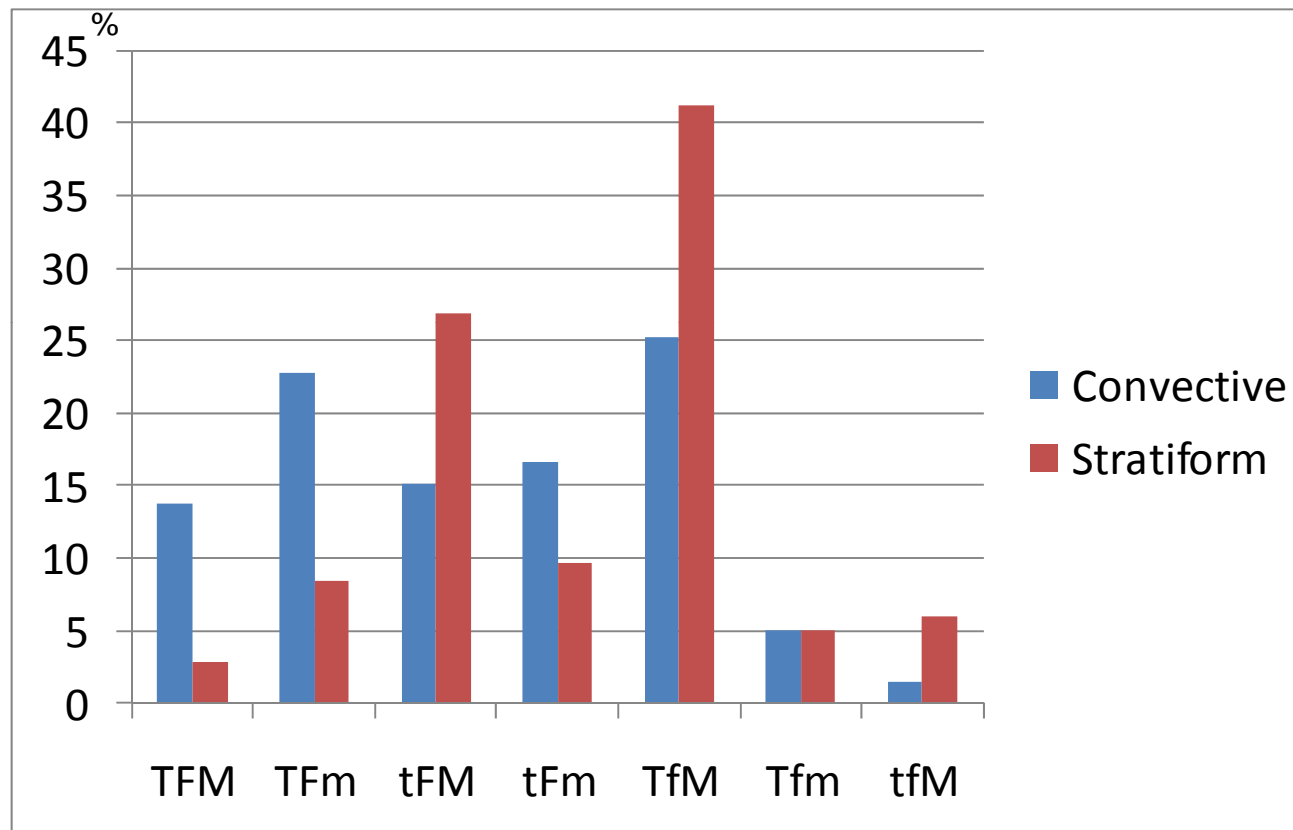




Convective-Stratiform rainfall separation scheme

- Radar reflectivity or rainfall intensity
- Tao et al. (1993): Convective rainfall:
Grids with larger rain rate than average in neighboring grids or grids with rain rate of larger than 20 mm h^{-1} .

Contributions from rainfall types for convective and stratiform rainfall



**Rainfalls with water vapor convergence contribute 68.3% to convective rainfall,
Rainfalls with water vapor divergence contribute 52.3% to stratiform rainfall**

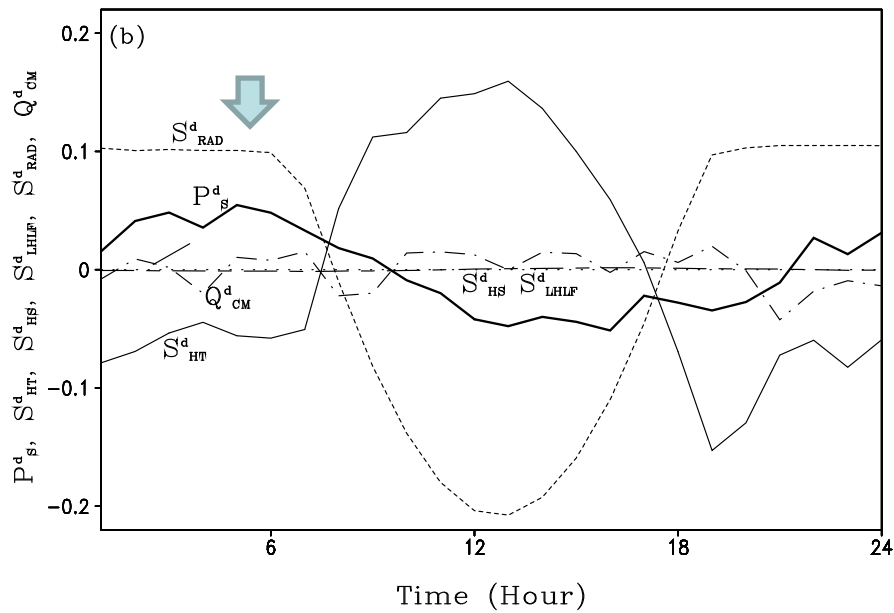
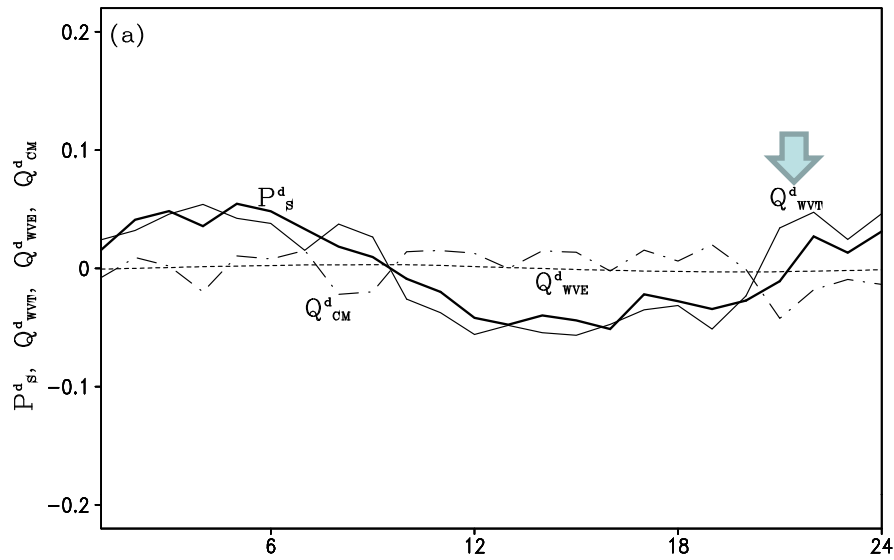
Issue

- Classic convective and stratiform rainfall separation schemes with rainfall or reflectivity intensity, which have been widely used in research and operational forecast, cannot distinguish between convective and stratiform rainfall properly

Diurnal Cycle of Rainfall

Background

- Diurnal variation of radiation leads to diurnal variation of rainfall.
- Nocturnal rainfall peak is caused by the decrease in saturation mixing ratio induced by IR radiative cooling (e.g., Tao et al. 1996).



Diurnal anomalies of surface rainfall equations from equilibrium model simulations imposed with zero large-scale vertical velocity and 29°C of sea surface temperature

Equations for describing diurnal rainfall cycle

$$\bar{P}_S^d \approx \bar{Q}_{WVT}^d$$

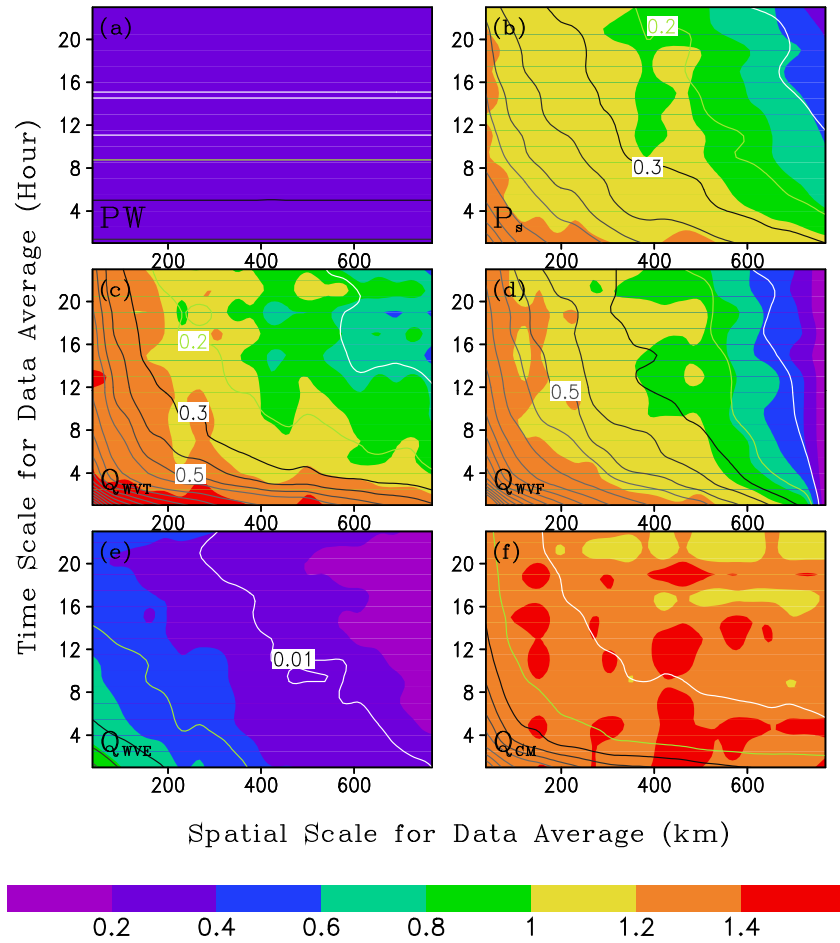
From vapor-related surface rainfall equation

$$\bar{P}_S^d \approx \bar{S}_{HT}^d + \bar{S}_{RAD}^d$$

From thermally-related surface rainfall equation

Sensitivity of precipitation simulation to uncertainty of initial conditions

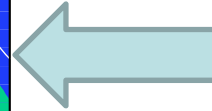
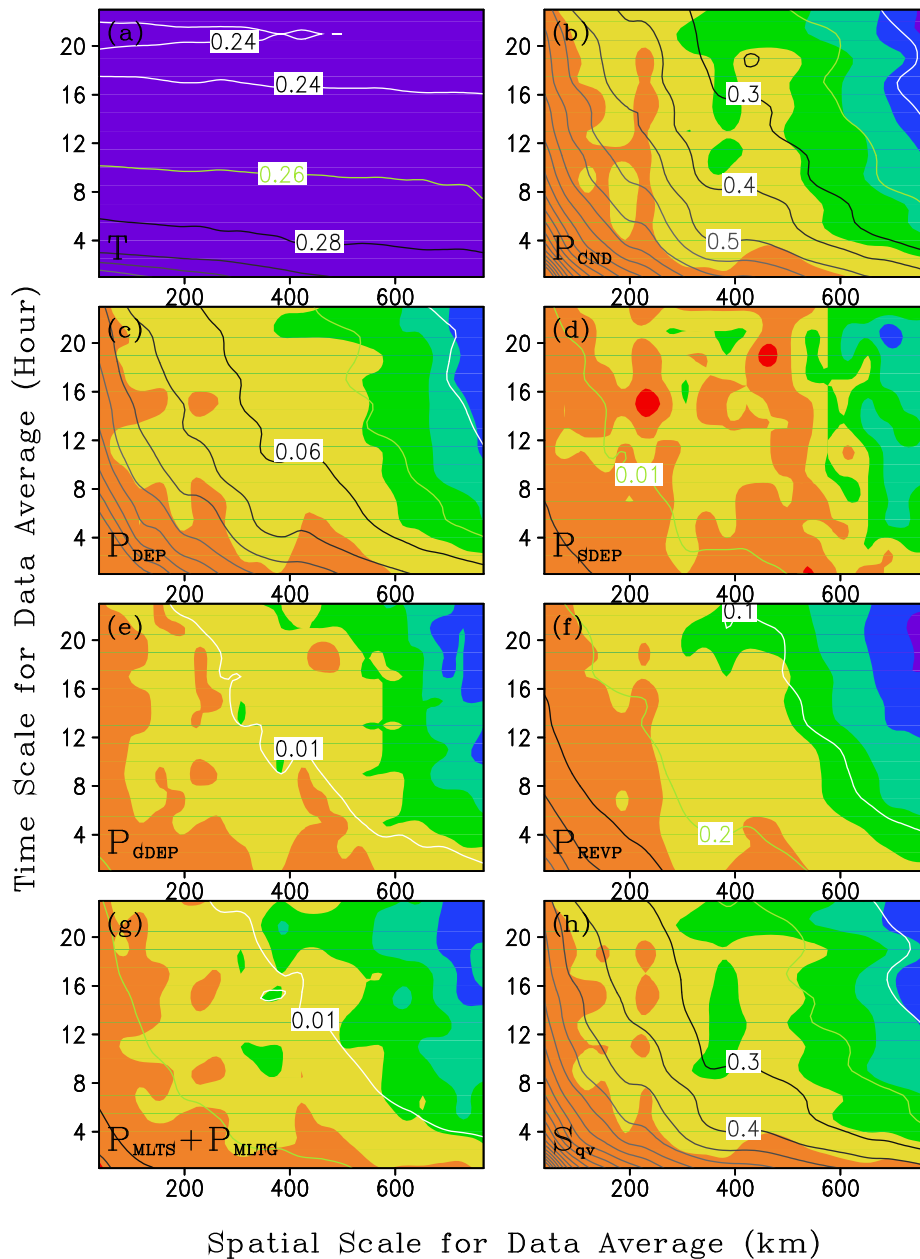
Errors of initial temperature and precipitable water are 0.5°C and 1 mm, respectively.



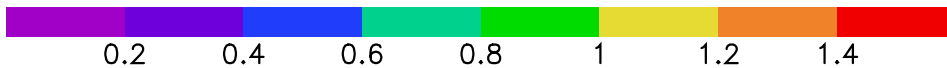
Background: ratio (RS ratio) of RMS difference to standard Deviation

RS<1 (cold color): the model simulation has a weak sensitivity to the uncertainty of the initial condition

Contour: RMS difference between Sensitivity experiments and the Control experiment

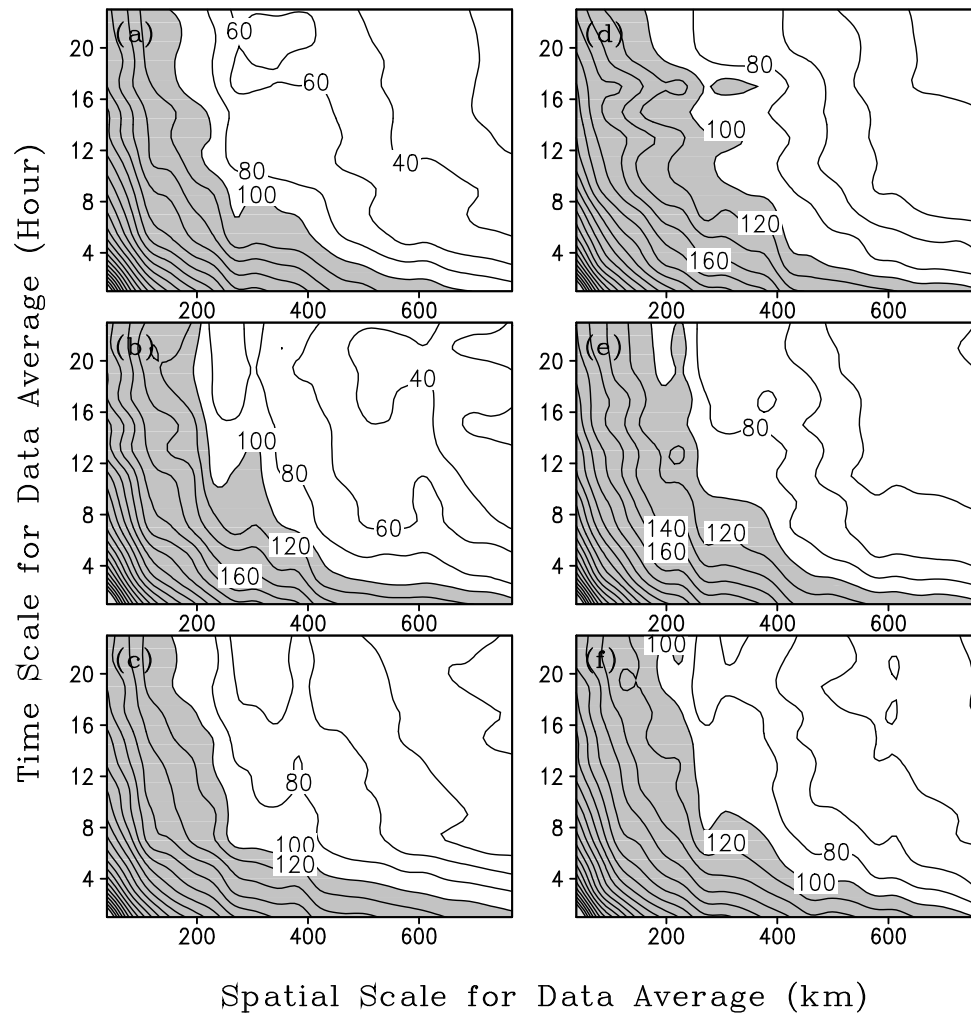


Condensation and depositions are a small residual between two large terms: specific humidity and saturation specific humidity



**Errors of initial temperature
and specific humidity are
0.2°C and 0.04gkg⁻¹,
respectively.**

Statistical error



Issue

- The quantitative precipitation simulation can be obtained at certain temporal (1 day) and spatial (500 km) scales due to the important impacts of water vapor processes.
- The tiny errors of initial conditions can lead to a significant error of precipitation simulation, raising concerns of whether the improvement of initial conditions can lead to accurate QPF.
- The precipitation simulations of weather events at synoptic scales can be simulated with significant errors, implying that the long term simulation at climate scale may be not physical meaningful.

Summary

- Surface rainfall equations are powerful tool for studying precipitation processes and related issues.
- The analysis of rainfall is spatial scale dependent.
- The model simulation may be much affected by cloud microphysical parameterization schemes. How cloud processes are presented in the model is a challenging issue due to spatial discontinuity of rainfall and nonlinearity of cloud processes.

Thank you!