Research Objective:

Development of a Q3D MMF

Incorporation of Topography into the Q3D MMF

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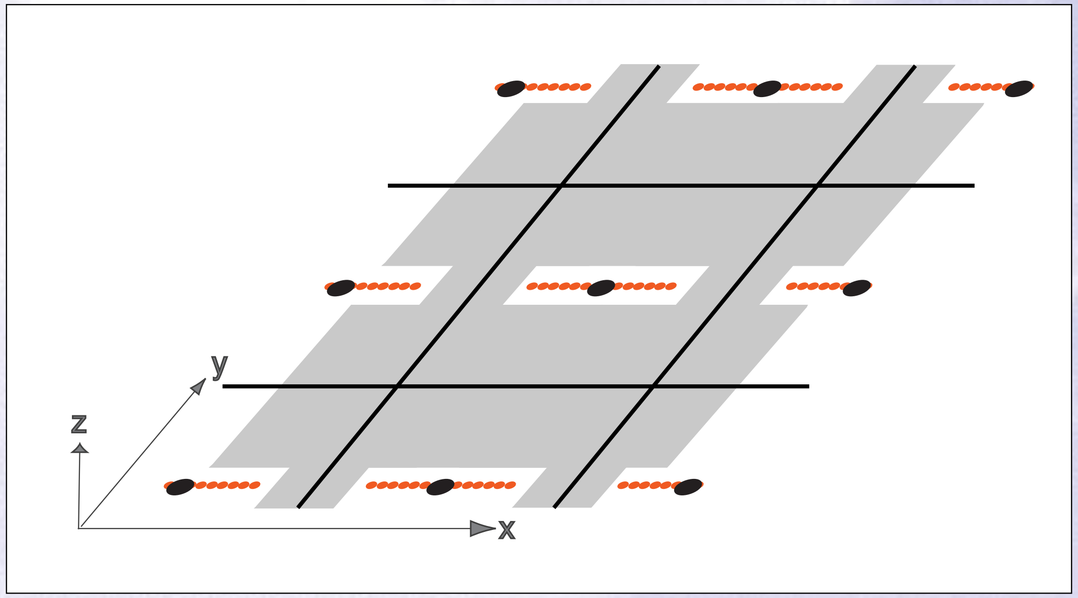
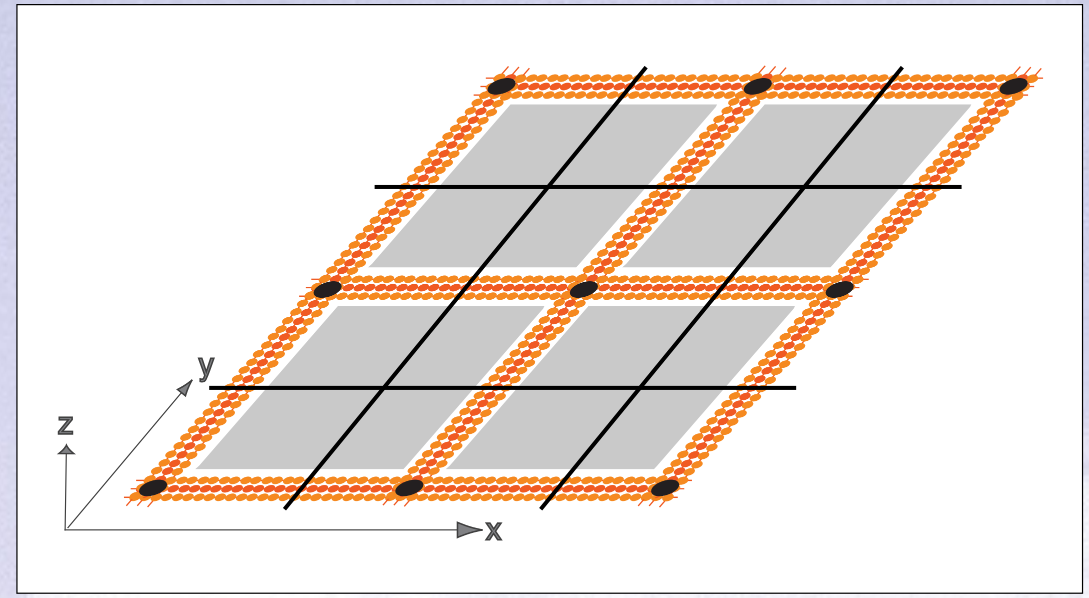
Quasi 3-D Multi-scale Modeling Framework

Original MMF



Q3D MMF

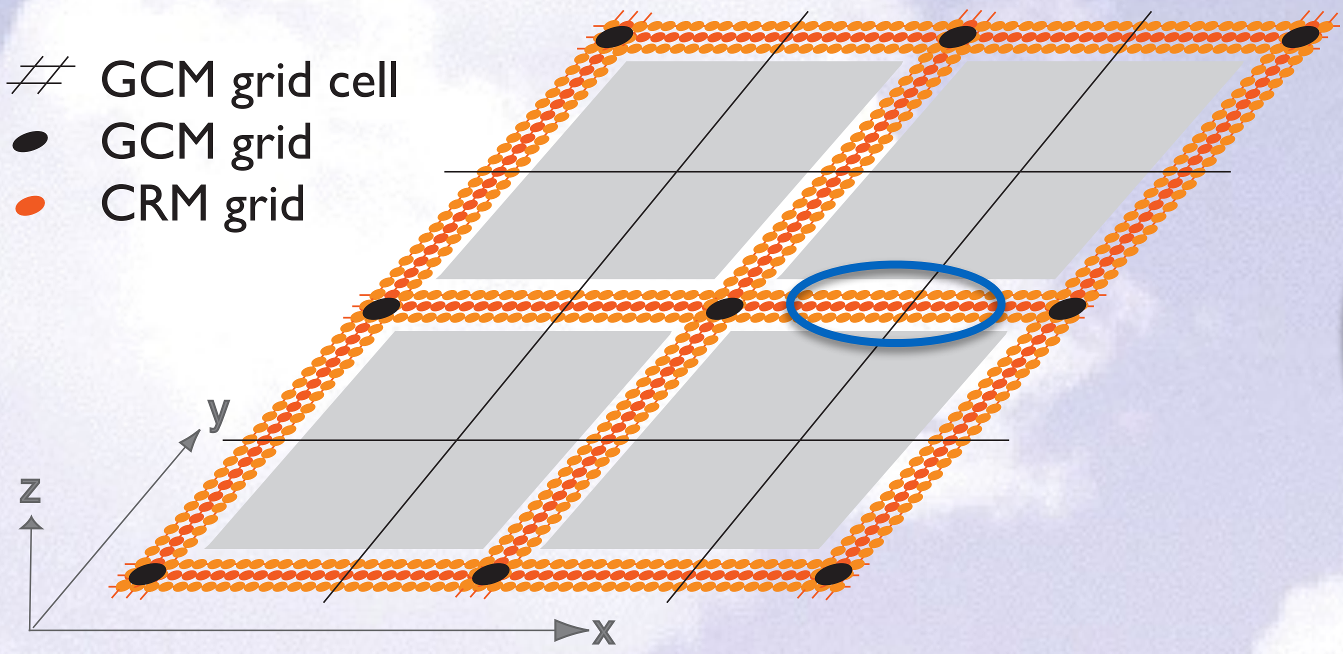


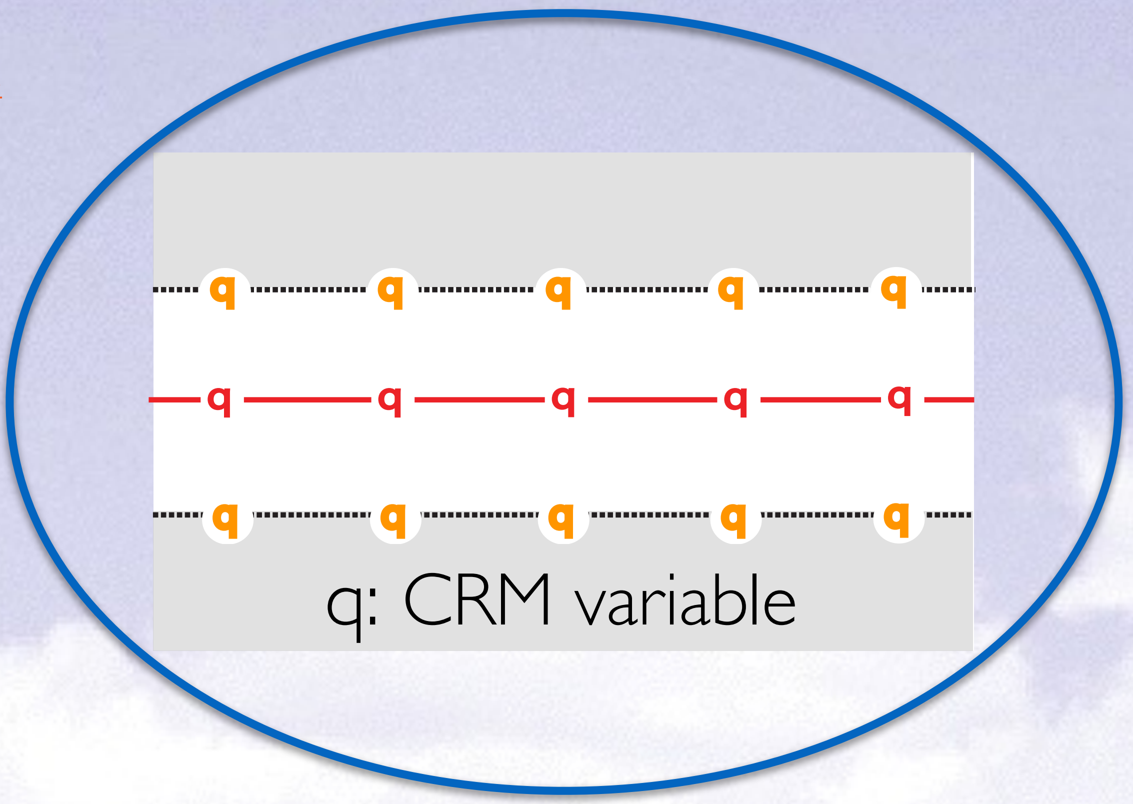
GCM grid cell · GCM grid · CRM grid for prediction · CRM ghost-grid

Shaded areas: gaps of the grid network

- CRMs are extended beyond the GCM grid columns, eliminating the periodic boundary conditions.
- Two perpendicular sets of CRMs are used.
- 2-D CRMs are replaced with 3-D CRMS applied to narrow channel-domains.

Decomposition of Variables in the CRM





Decomposition of variable: $q = \overline{q} + q'$

$\overline{q}$: background is interpolated from GCM

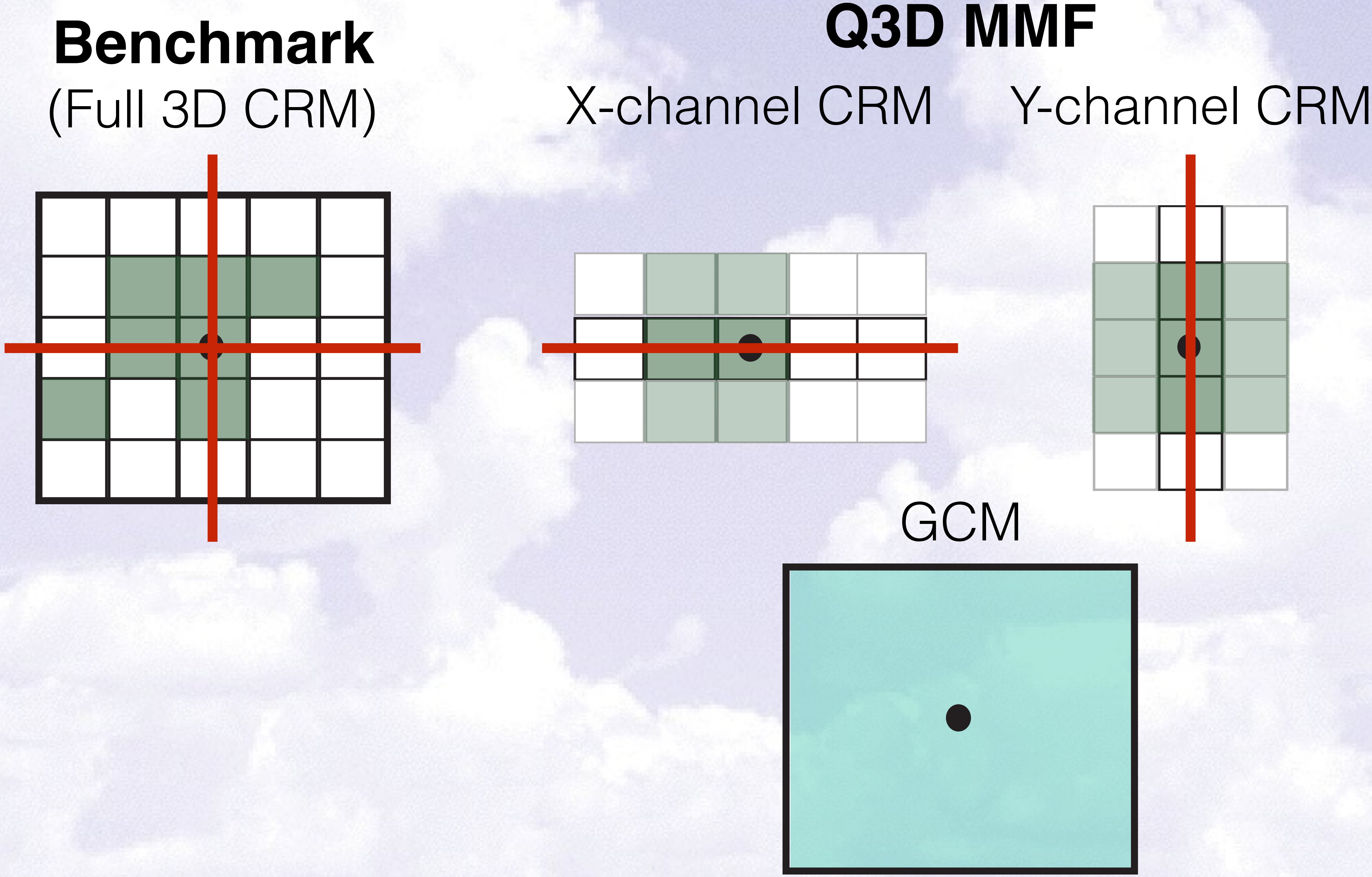
q' : deviation is cyclic across the channel

The CRM recognizes the inhomogeneity across the channel, which is predicted by the GCM.

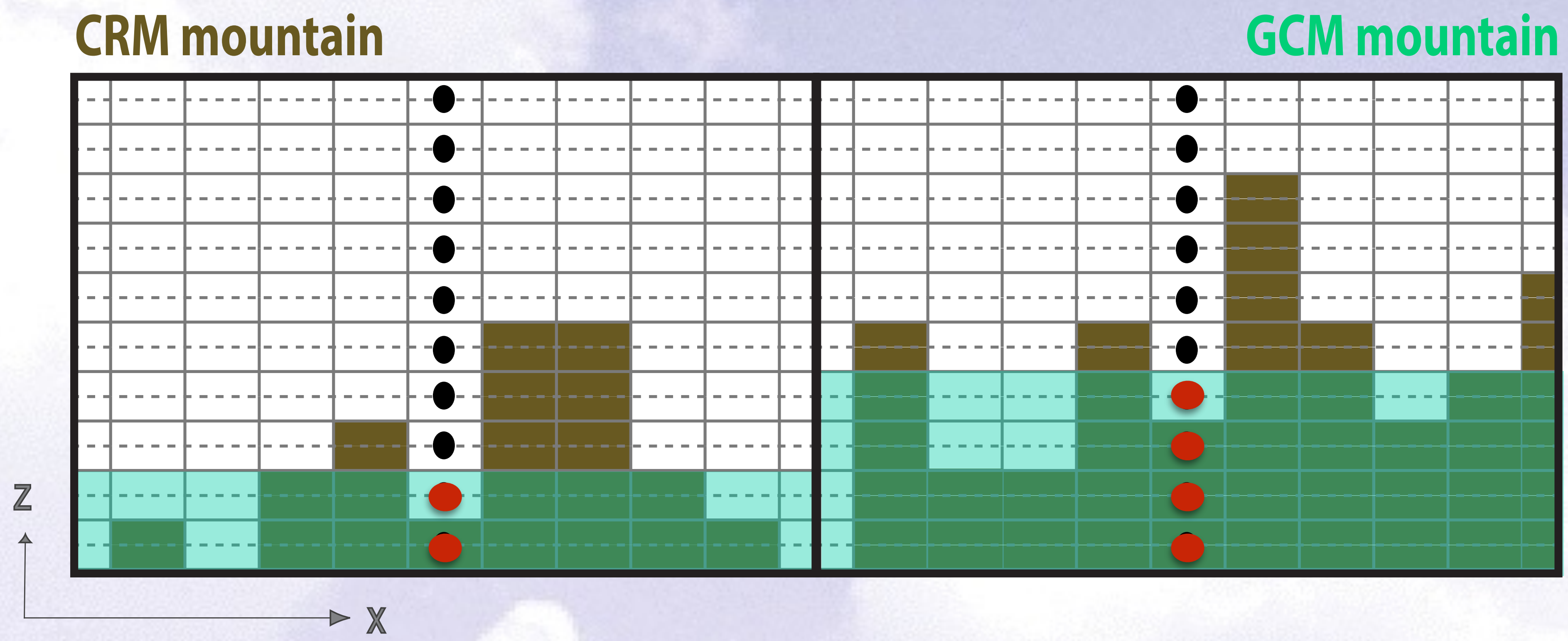
"Quasi-3-D"

Representation of Topography in the Q3D MMF

In the base model, topography has been implemented using the block-mountain method of Wu and Arakawa (2011).



How to determine the background field where the GCM prediction is not available?



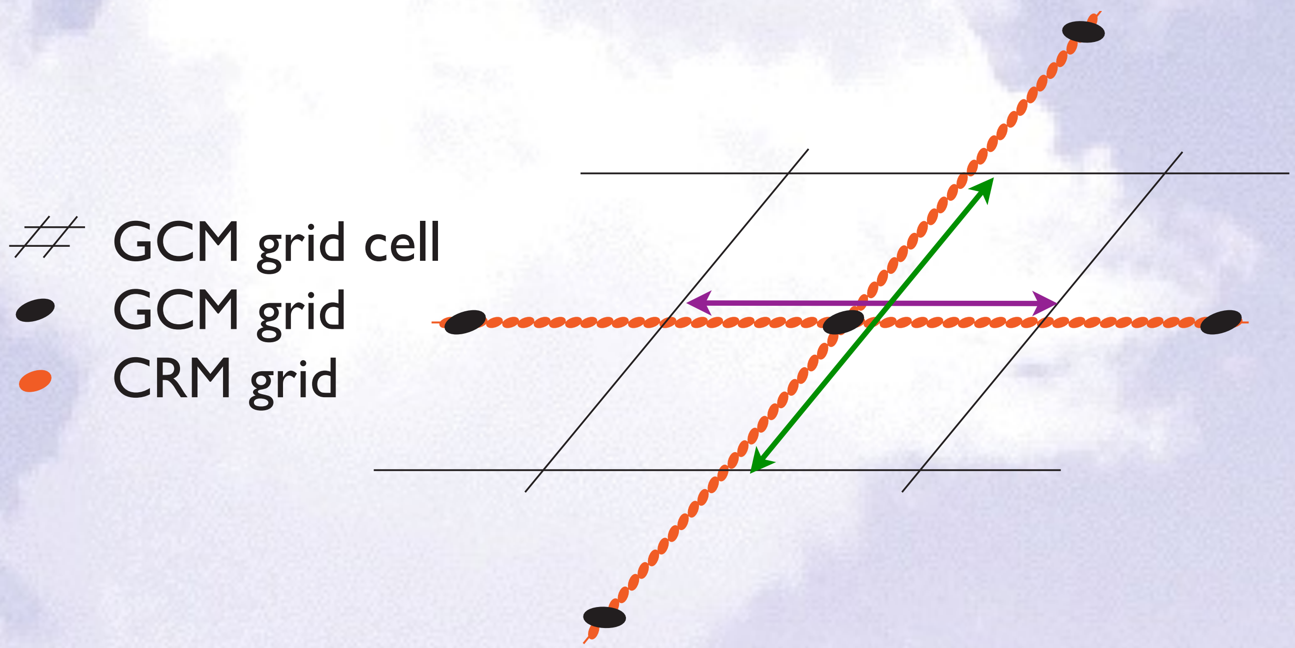
Use of "virtual" GCM values

- Water species are assigned to zero.
- Potential temperature and moisture are determined from the vertical extrapolation of the GCM prediction or the horizontal average of the CRM prediction.
- Large-scale circulations follow the kinematic condition.

to obtain smoothly distributed background fields

Coupling between the GCM and CRM components

Feedback: CRM effects on GCM



CRM effects:

mean diabatic effects +
mean ***eddy effects*** of advective and dynamical processes

- The CRM feedback is averaged only from available data, i.e., data from mountain-free CRM grid points.
- When only a portion in the segment is used for the average, the GCM and CRM components should be loosely coupled.
- The feedback is multiplied by the coupling strength ratio, *r*

$$r = \frac{\textit{number of mountain-free CRM grid points}}{\textit{number of total CRM grid points in the segment}}$$

Coupling between the GCM and CRM components
(Continued.)

Relaxation: GCM effects on CRM

To guarantee the compatibility between the GCM and CRM solutions, the large-scale solution of CRM is relaxed to the GCM prediction.

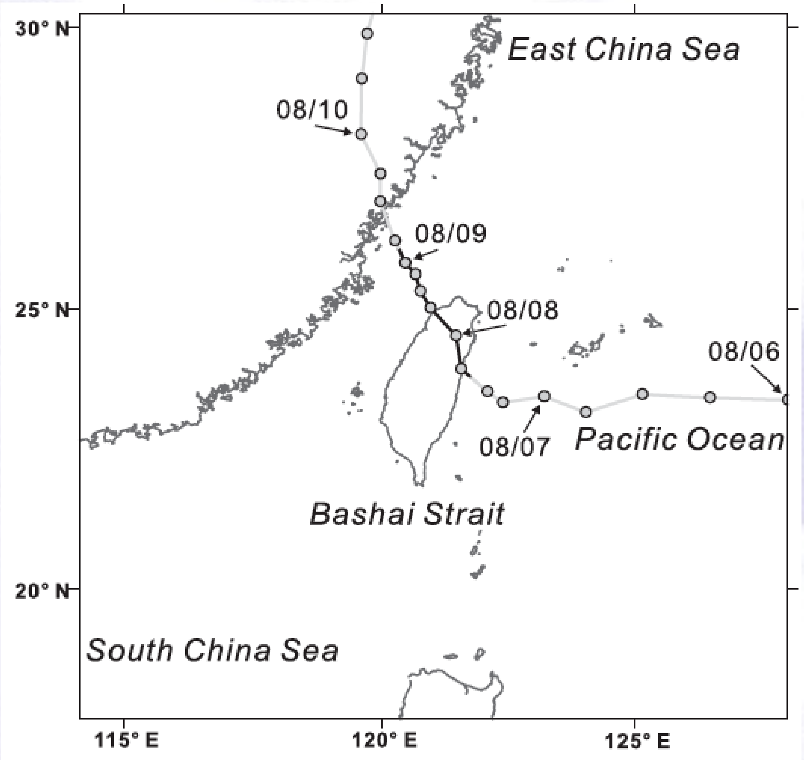
Relaxation time scale = Horizontal advection time scale (~ d/V)

d : GCM grid distance
V : characteristic wind speed

- When only a portion in the channel segment is free of mountain, the GCM and CRM components should be loosely coupled.
- The relaxation time scale is multiplied by the **inverse** of the coupling strength ratio (i.e., larger time scale indicates weaker coupling).

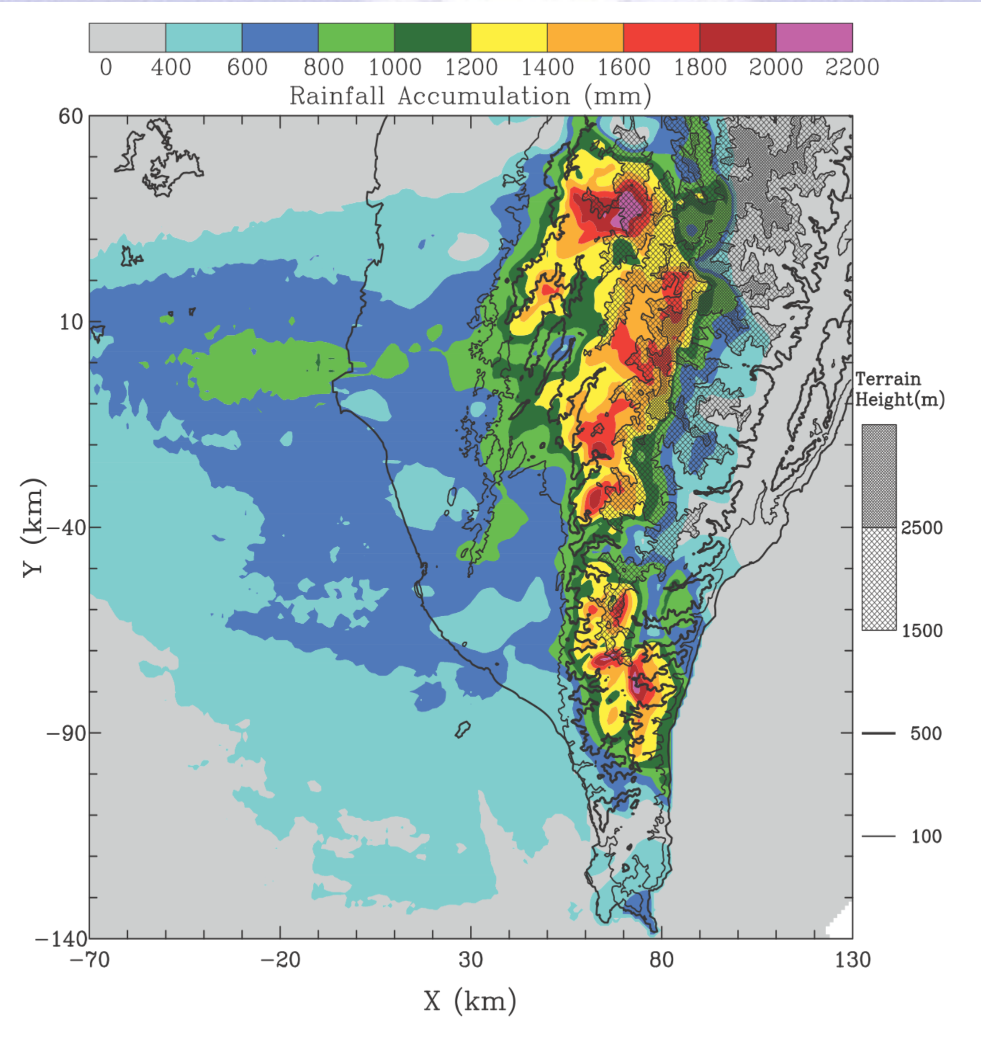
Benchmark for the Q3D MMF Test

Track of Typhoon Morakot (2009)



Accumulated Precipitation

(Radar-derived accumulation for 36 hr)



A good example of orographic enhancement of precipitation

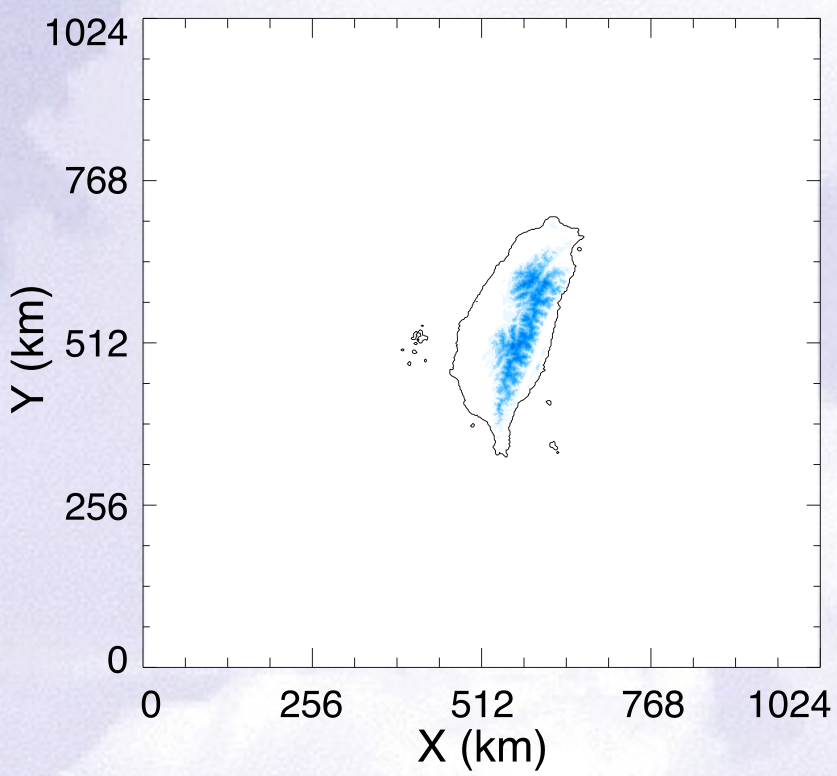
Distribution and Mechanism of Orographic Precipitation Associated with Typhoon Morakot (2009) by Yu and Cheng (2013, JAS)

Benchmark for the Q3D MMF Test (Continued.)

Idealized Simulation of the Orographic Precipitation Associated with Typhoon Morakot

(Without the typhoon itself: similar to Wu's high-resolution simulation)

3D Simulation by VVM



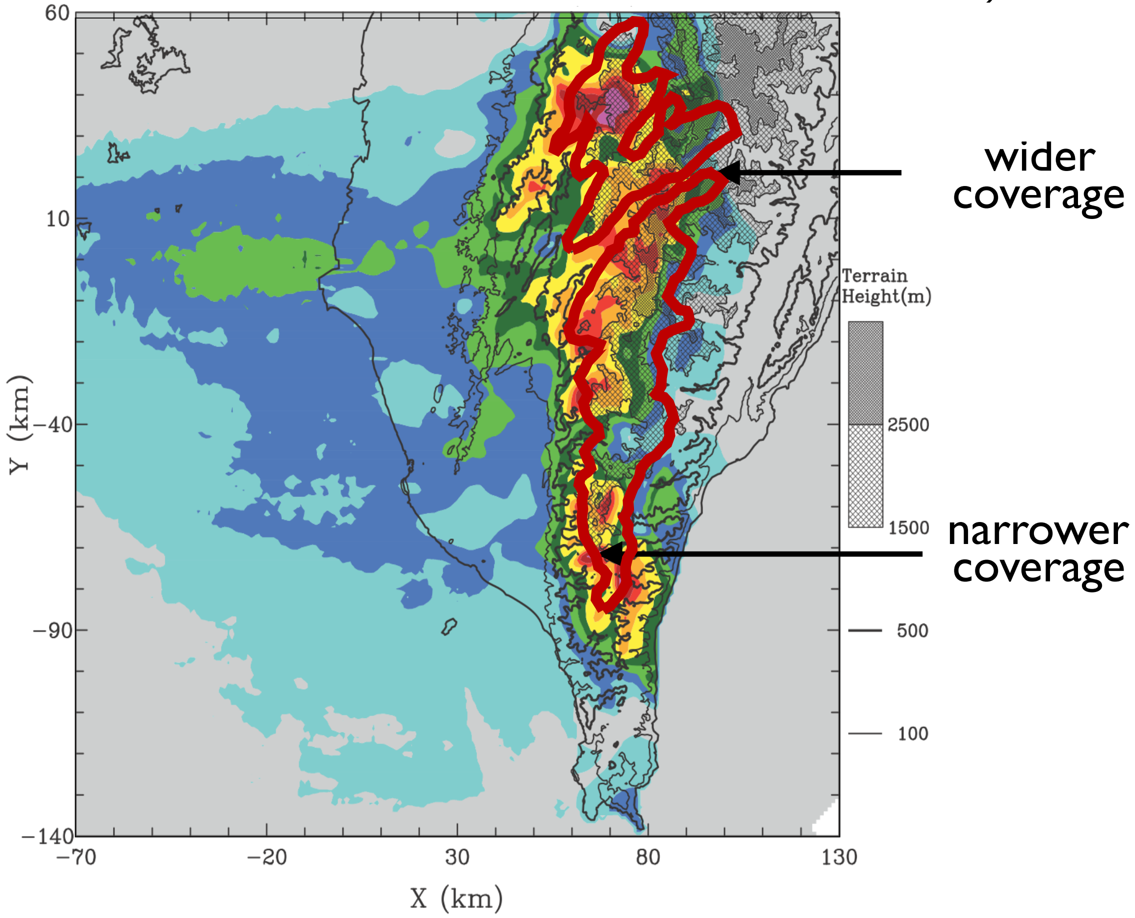
- **Initial soundings:** 36-hr averaged upstream profiles during Morakot
- **Initial wind field:** 20 m/s southwesterly wind
- **Domain size:** 1024 km x 1024 km x 32 km
- **Horizontal resolution:** 2 km
- **Vertical resolution:** 200 m below 4-km & stretched up (50 levels)
- No radiation, No Coriolis force, No sensible heat flux

Model is integrated for 12 hrs.
This simulation is used as a benchmark for the Q3D MMF test.

Benchmark for the Q3D MMF Test (Continued.)

Observed Precipitation

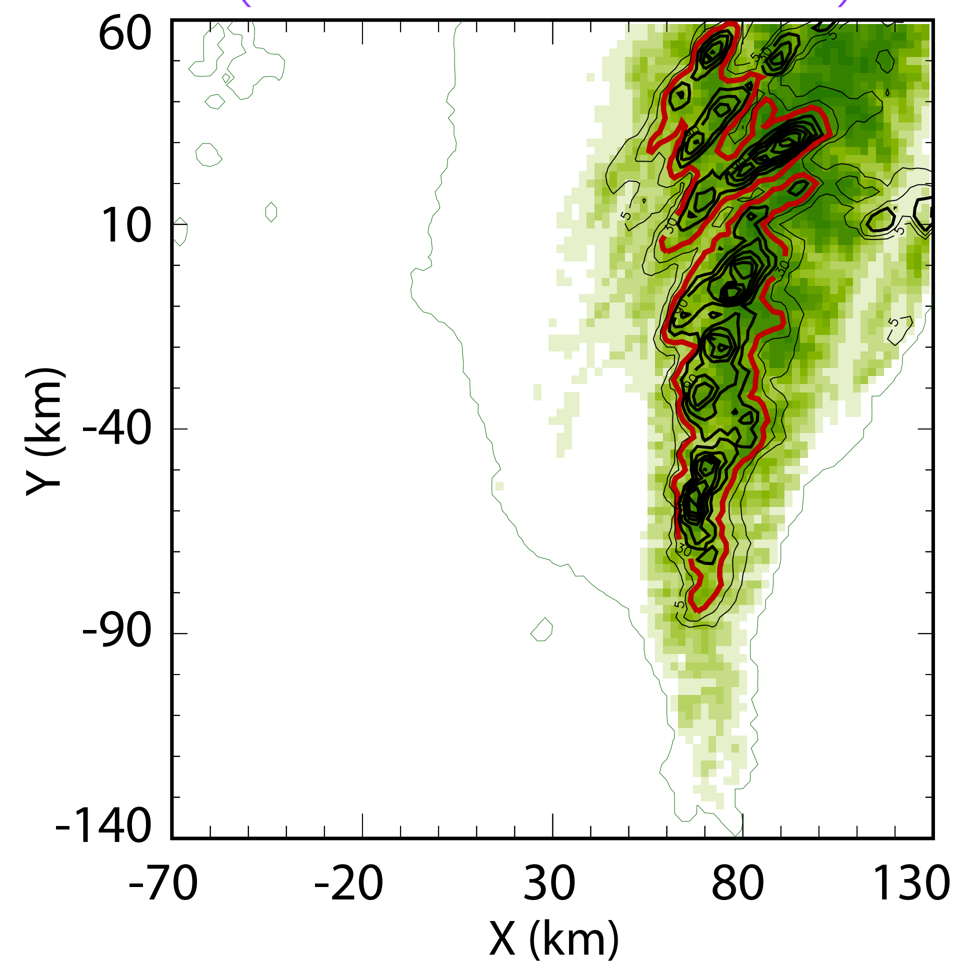
(Radar-derived accumulation for 36 hr)



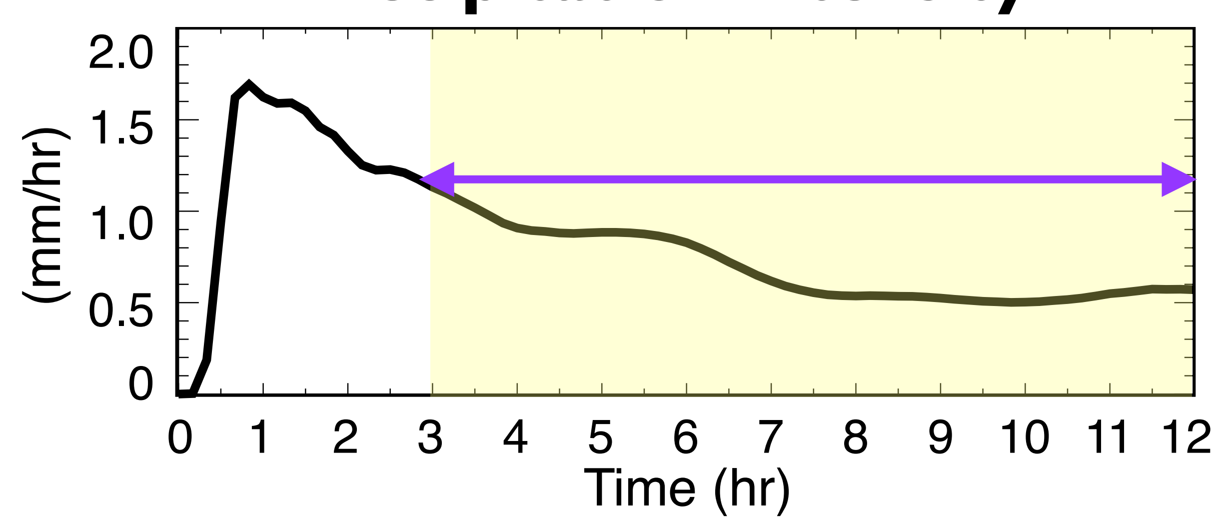
Yu and Cheng, 2013 (JAS)

Simulated by the 3D CRM

(Accumulated for 9-hr)



Precipitation Intensity



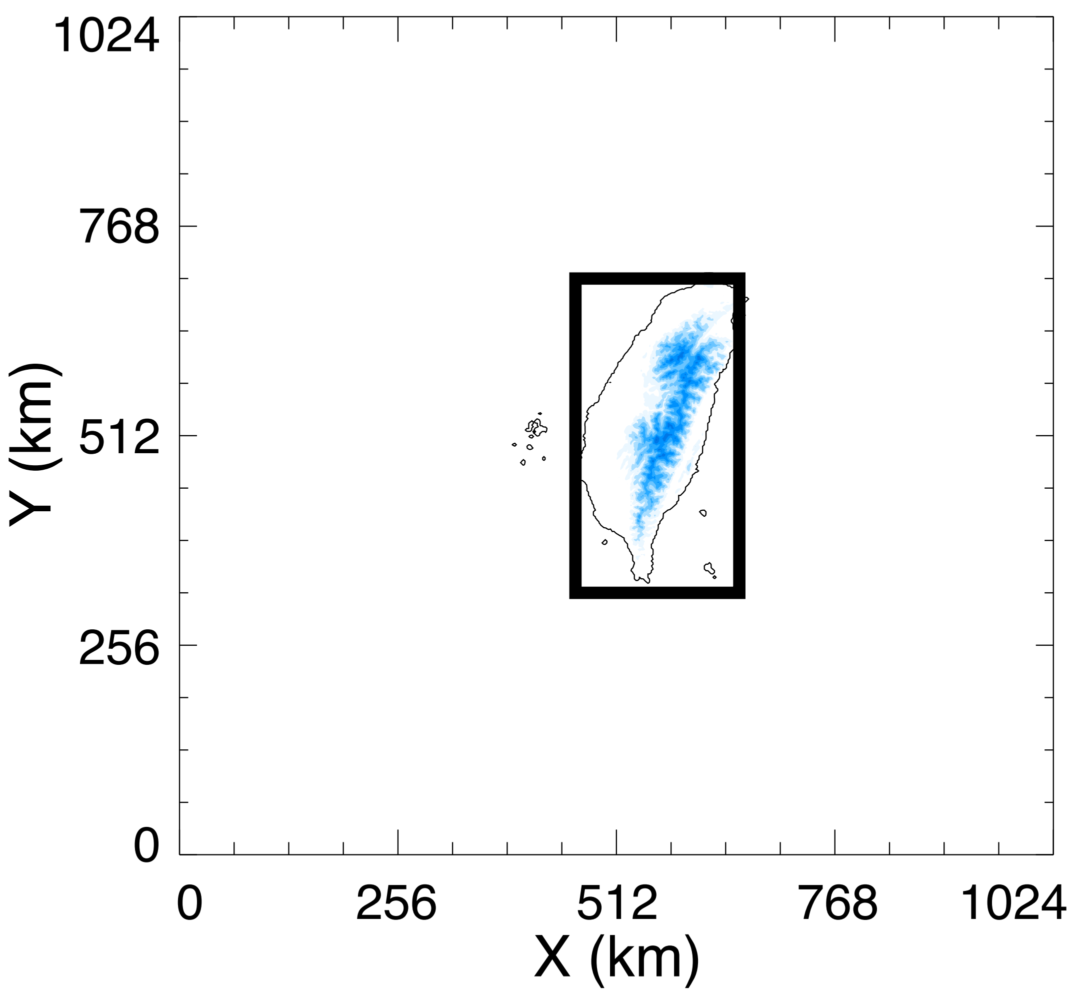
Not expected to simulate
typhoon background precipitation

Expected to simulate
precipitation due to upslope lifting

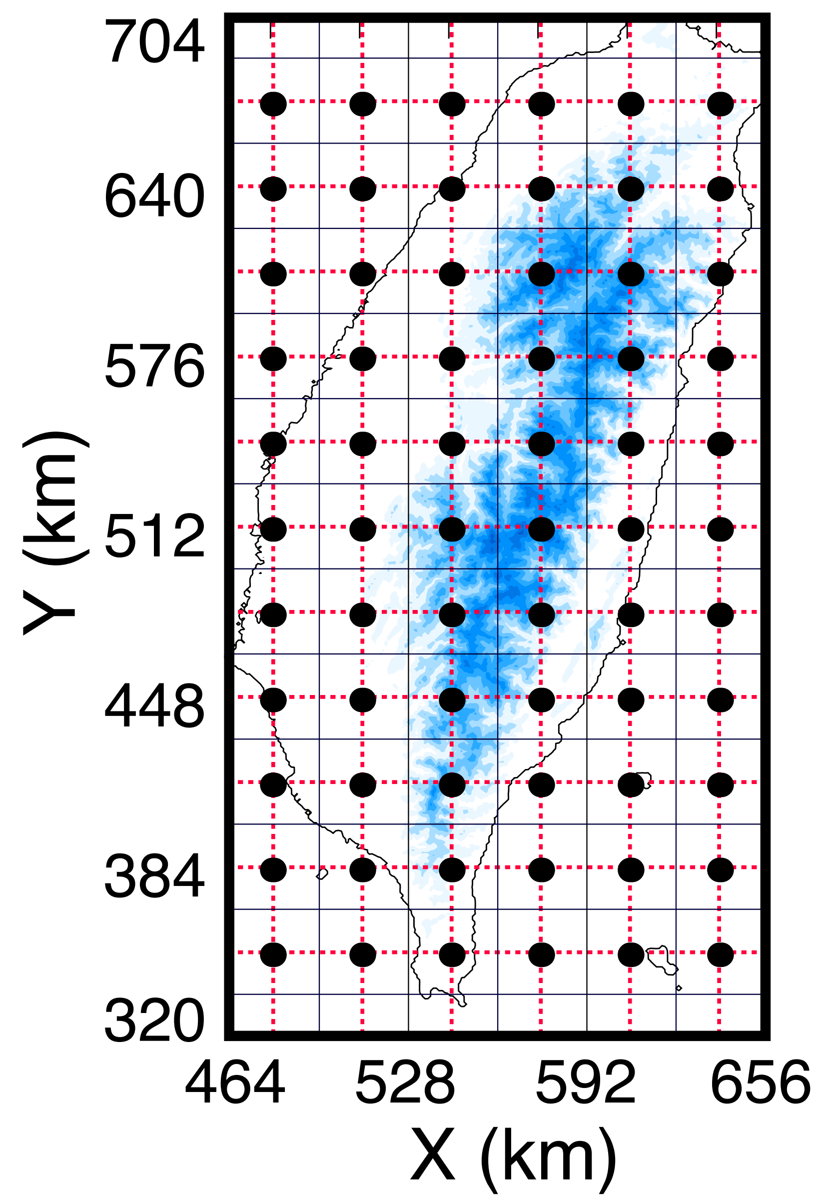
The 3D CRM is able to capture the characteristic orographic precipitation pattern.

Q3D MMF Simulation

Q3D MMF simulation starts from the realization of Benchmark at t = 3hr.



GCM grid size = 32 km

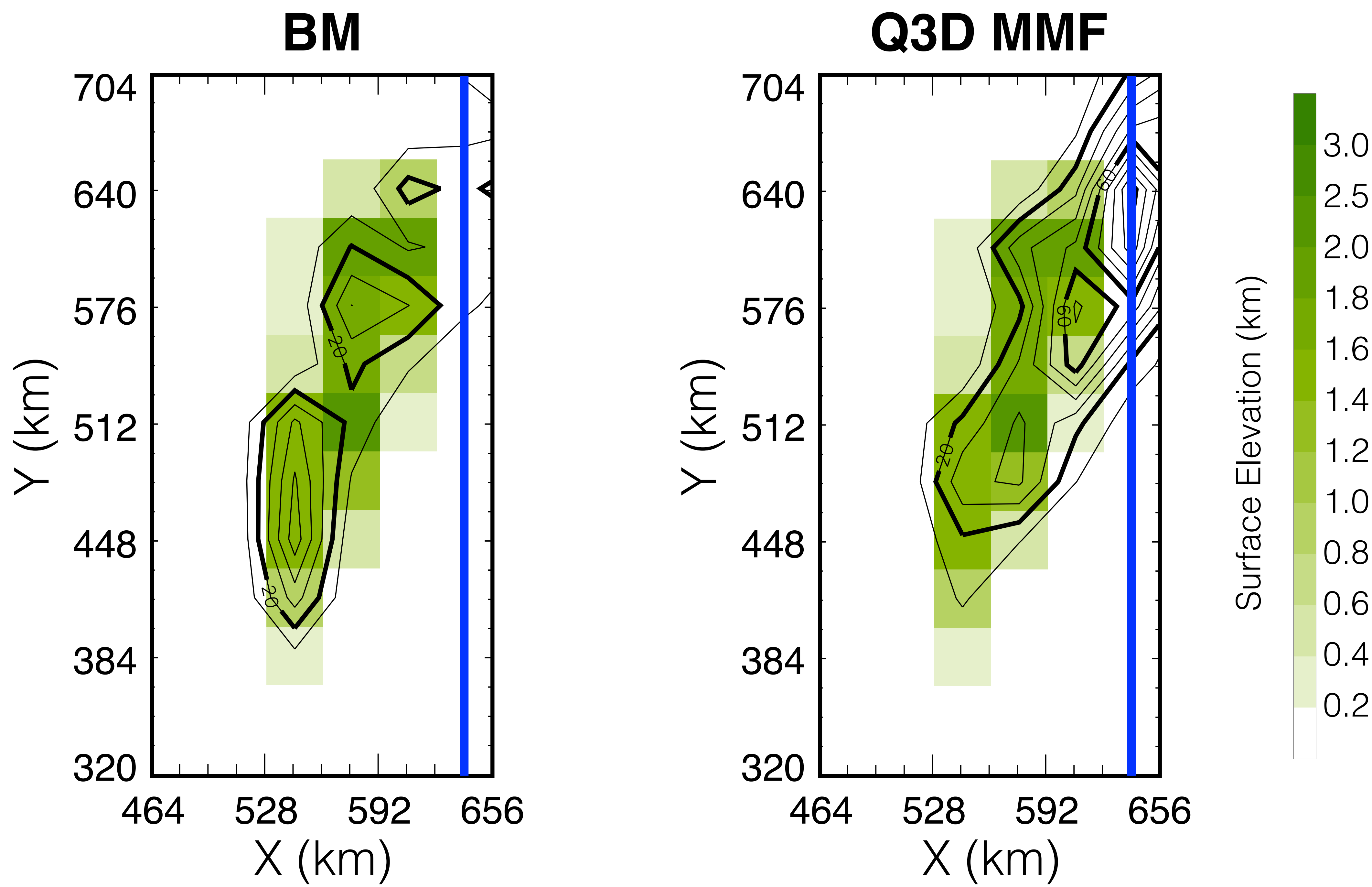


Q3D MMF Simulation Results

Surface Precipitation

(Accumulated for 8 hours)

GCM grid size = 32 km

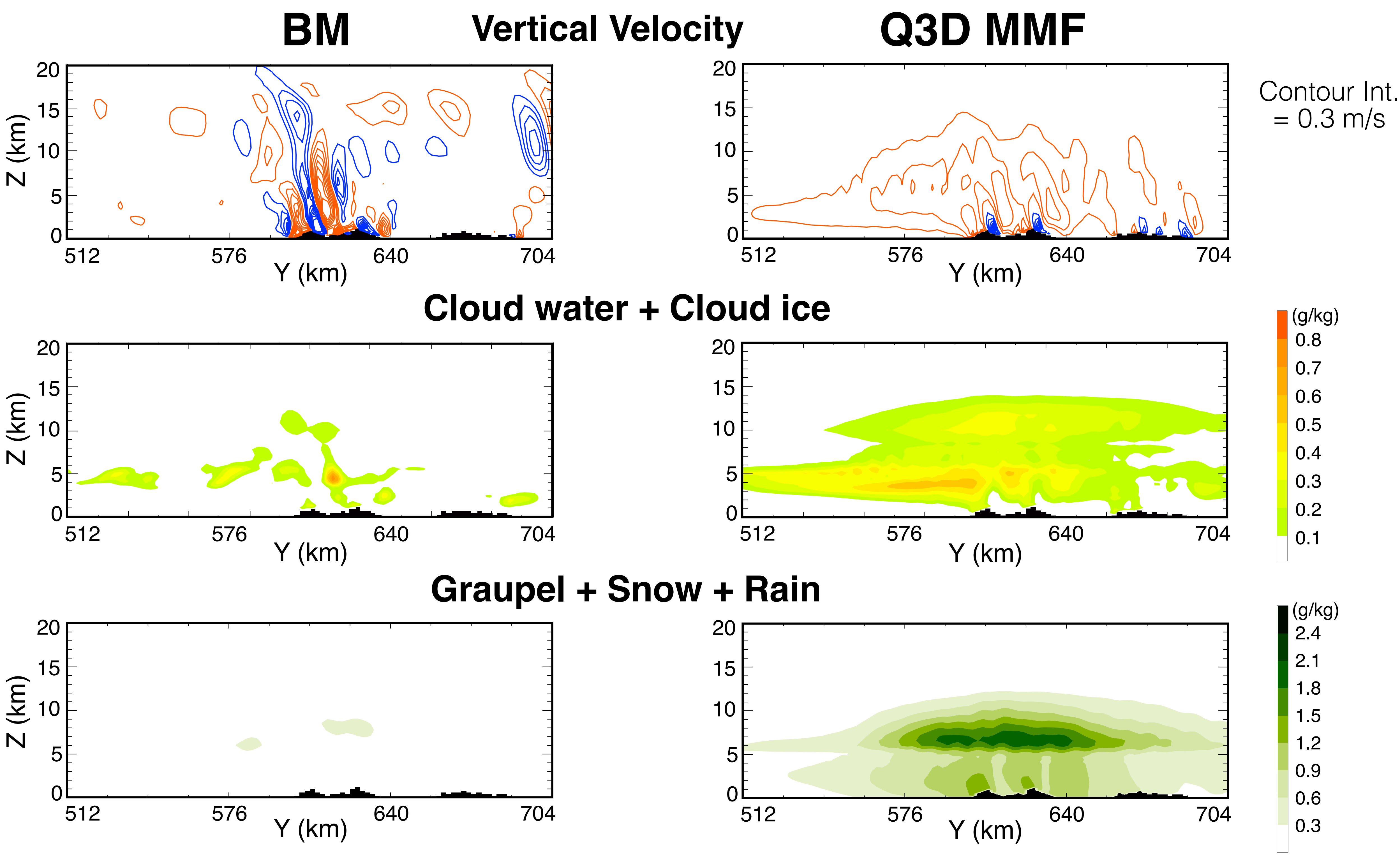


Strong discrepancy between BM and Q3D MMF results

Q3D MMF Simulation Results (Continued.)

Cross Sections of Selected CRM Fields

(Averaged for 8 hours)



Unrealistic large-scale features

Elliptic Equation for Vertical Velocity

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)w+\frac{\partial}{\partial z}\left[\frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 w)\right]=-\frac{\partial \eta}{\partial x}+\frac{\partial \xi}{\partial y}$$

Consider an X-channel domain,

$$\frac{\partial \xi}{\partial y}=\frac{\partial \xi_{BG}}{\partial y}$$

due to the cyclic boundary conditions on the deviation fields

Can the background field (obtained from the GCM) properly represent the large-scale of the CRM near mountains?

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)w+\frac{\partial}{\partial z}\left[\frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 w)\right]=-\frac{\partial \eta}{\partial x}+\alpha\frac{\partial \xi}{\partial y}$$

where α = 1 (away from mountains)
= 0 (near mountains)

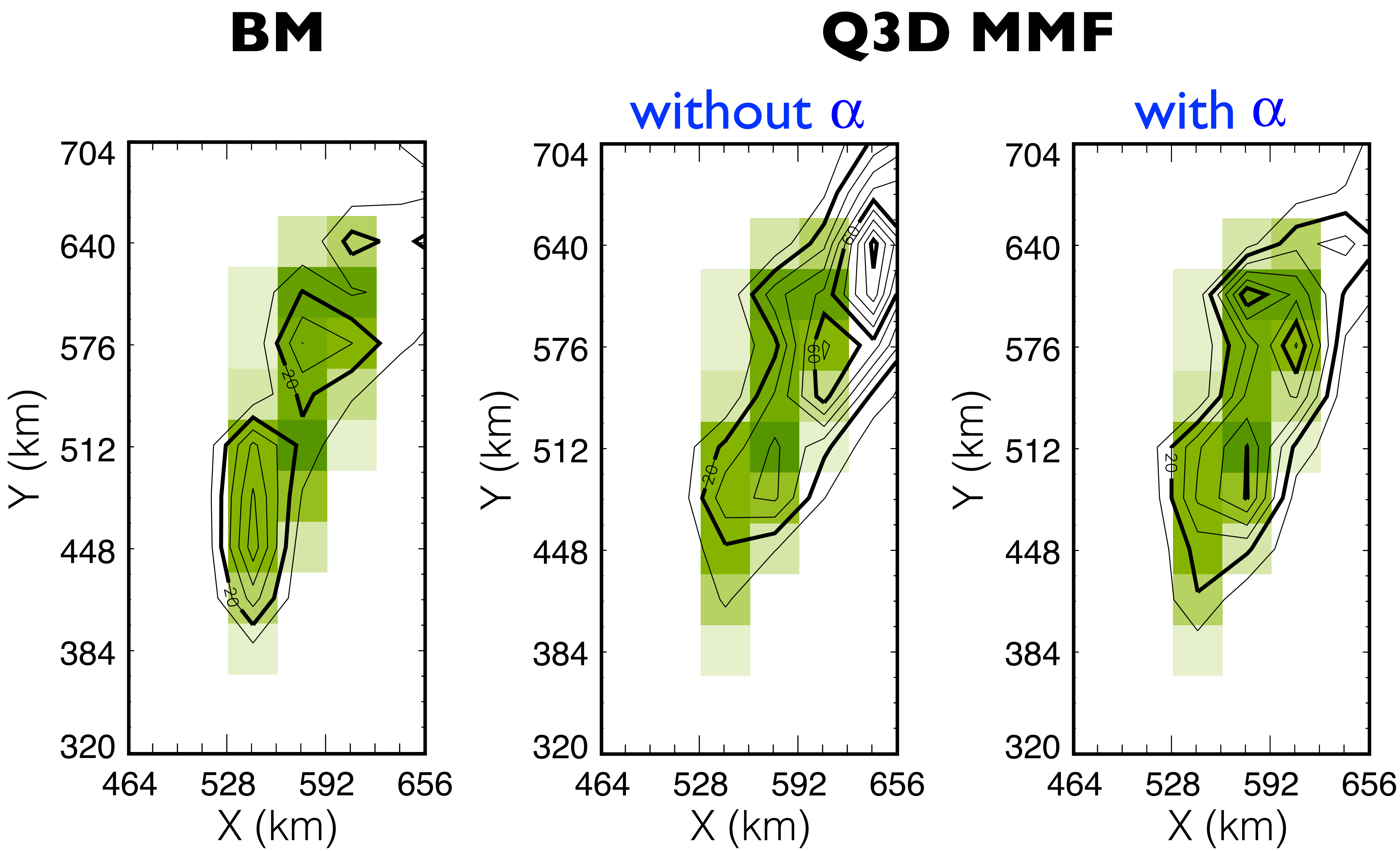
New algorithm reduces to the original algorithm as the surface elevation approaches zero.

Q3D MMF Simulation Results

Surface Precipitation

(Accumulated for 8 hours)

GCM grid size = 32 km

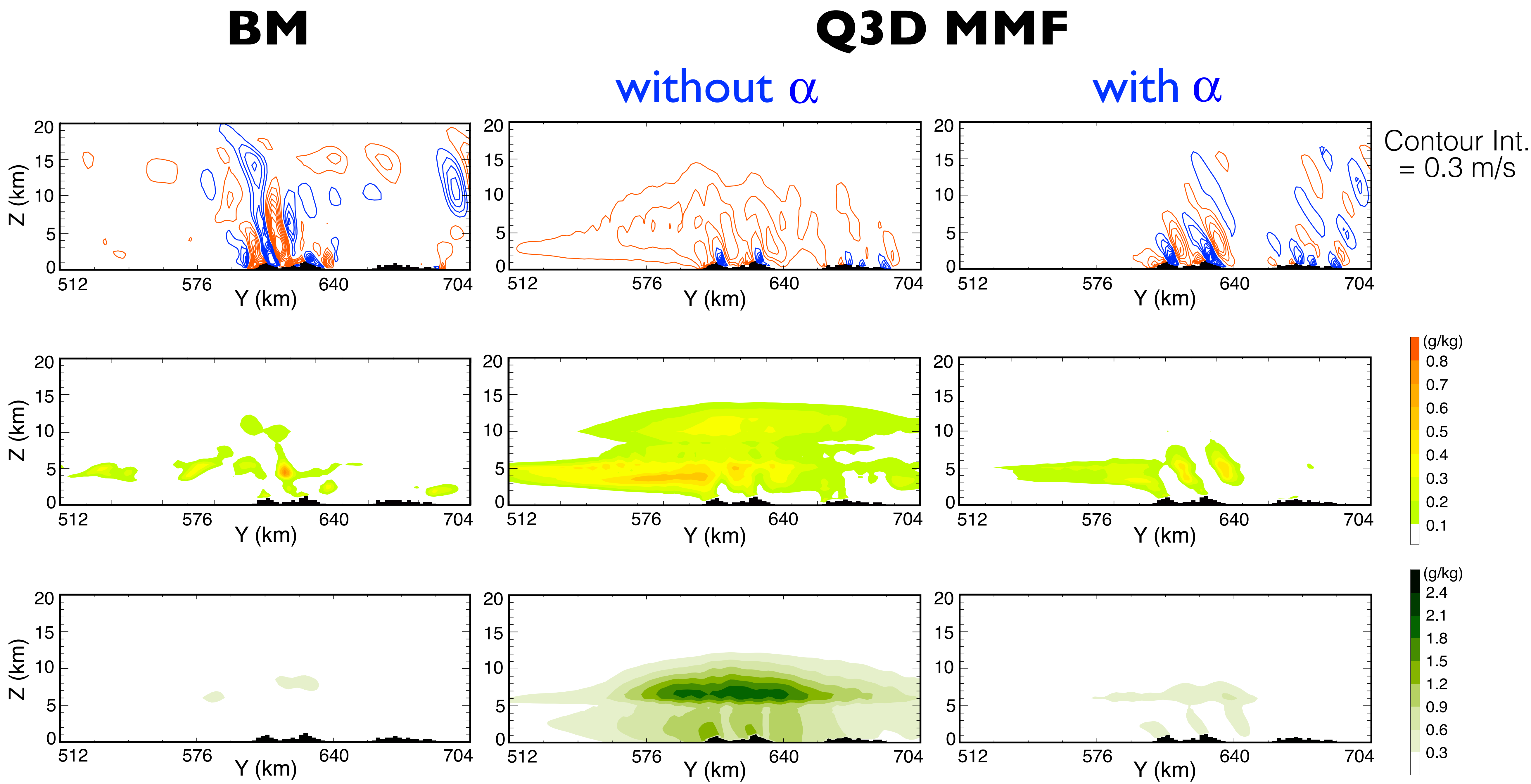


Unrealistic rainfall accumulation is not shown.

Q3D MMF Simulation Results (Continued.)

Cross Sections of Selected CRM Fields

(Averaged for 8 hours)



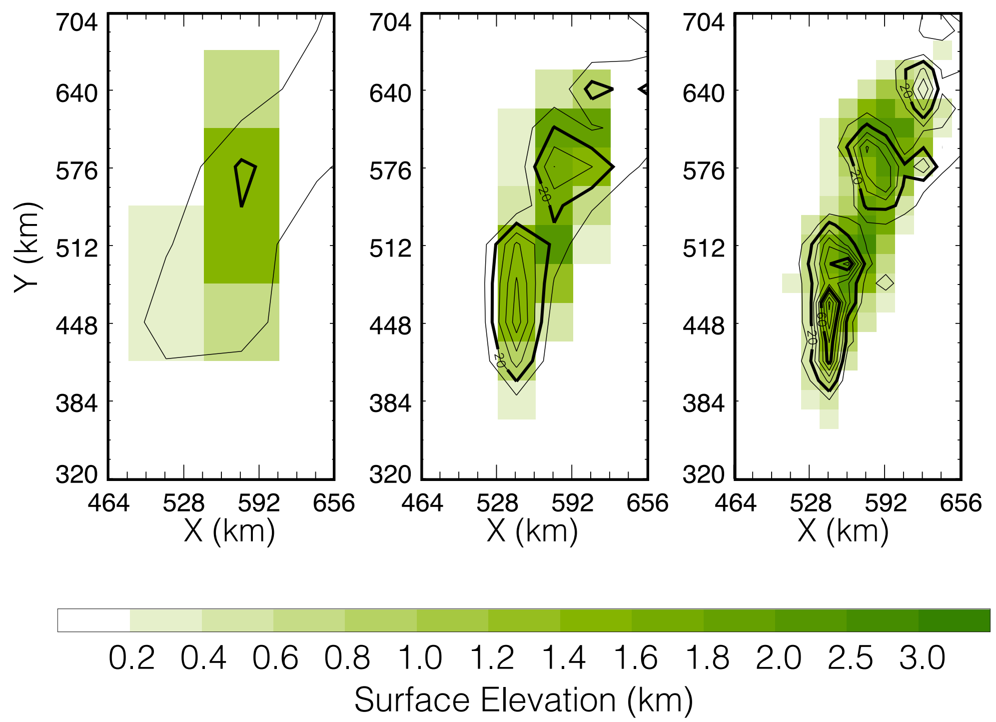
Unrealistic large-scale features do not appear.

Q3D MMF Simulation Results (Continued.)

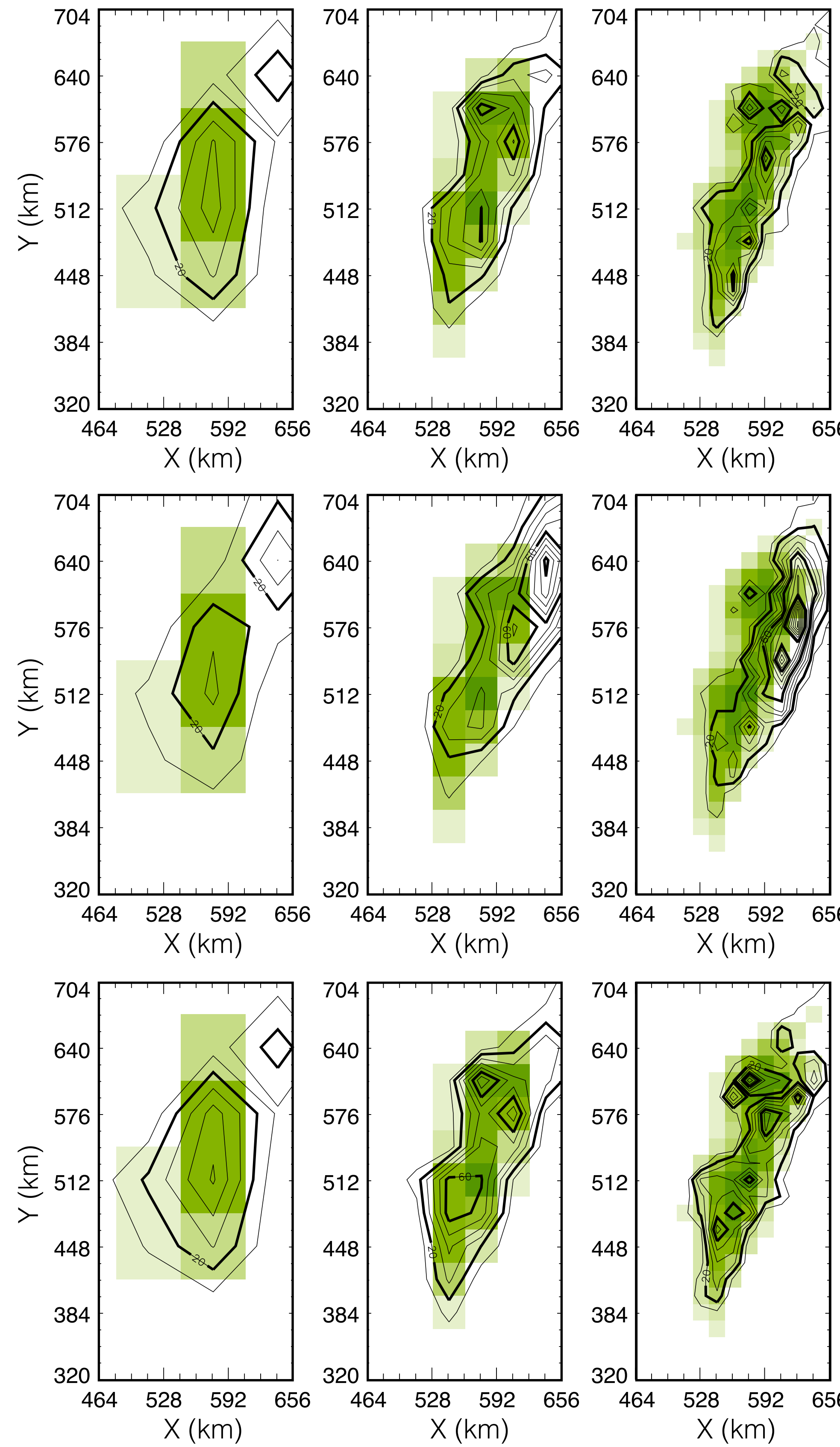
Surface Precipitation (Accumulated for 8 hours)

BM

d_{GCM}=64 km d_{GCM}=32 km d_{GCM}=16 km



For the simulation of orographic precipitation pattern, there is no significant difference between using 3-D and 2-D CRMs.



Q3D MMF

Using 3-D CRMs (with α)

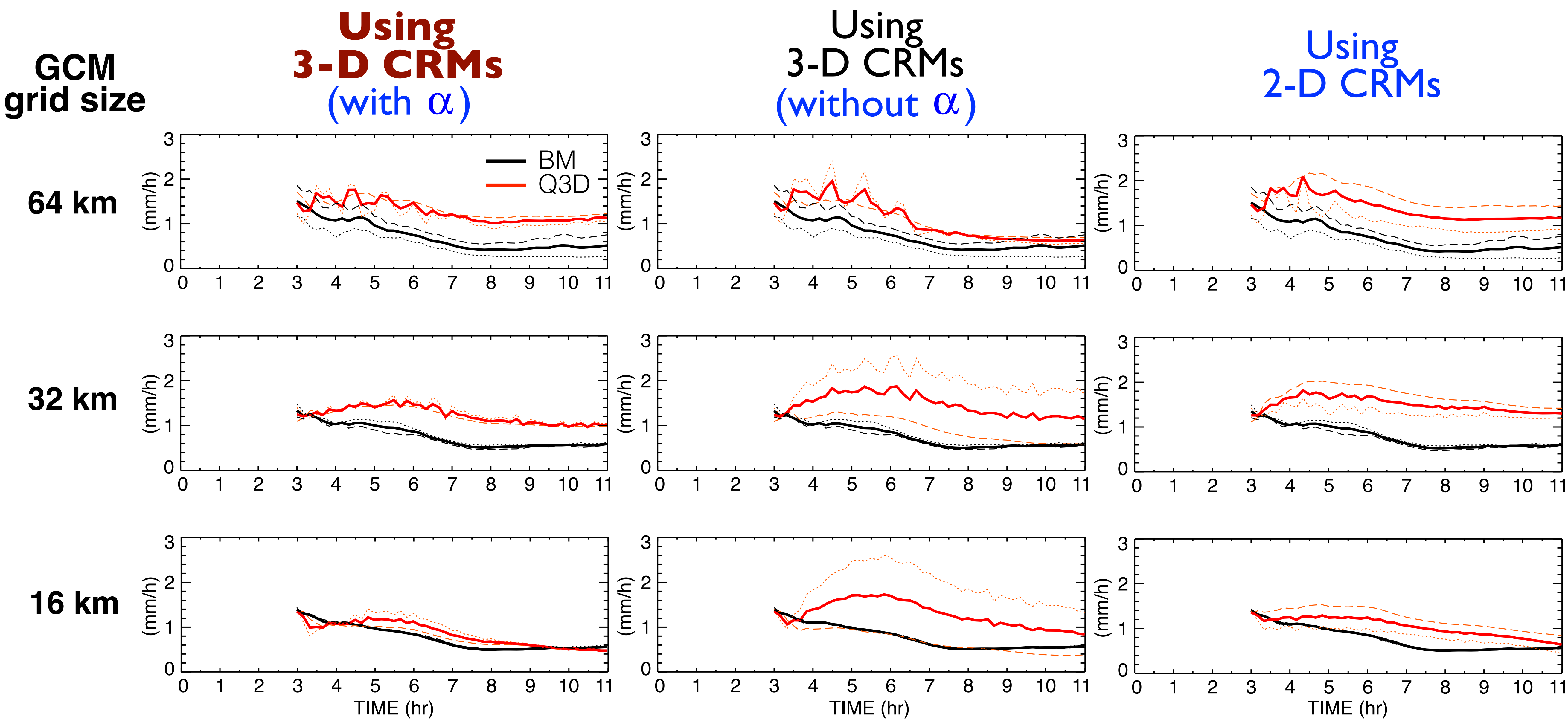
Using 3-D CRMs (without α)

Q3D MMF
Using 2-D CRMs

Q3D MMF Simulation Results (Continued.)

Domain Averaged Surface Precipitation Rates

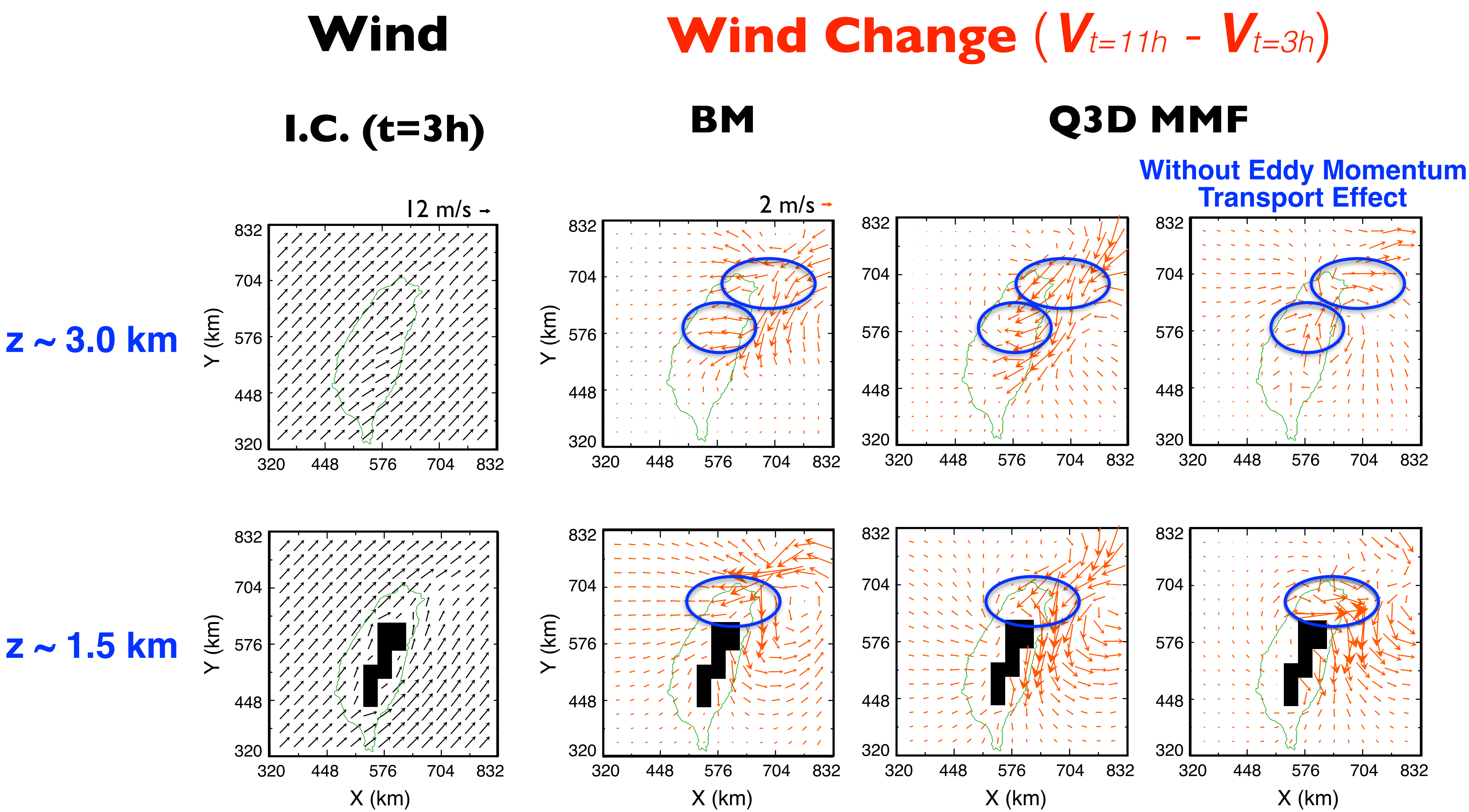
(Whole Island: x=464~656 km, y=320~704 km)



The mean intensity of orographic precipitation is overestimated with the Q3D MMF. However, the error is reduced with the increase of GCM resolution.

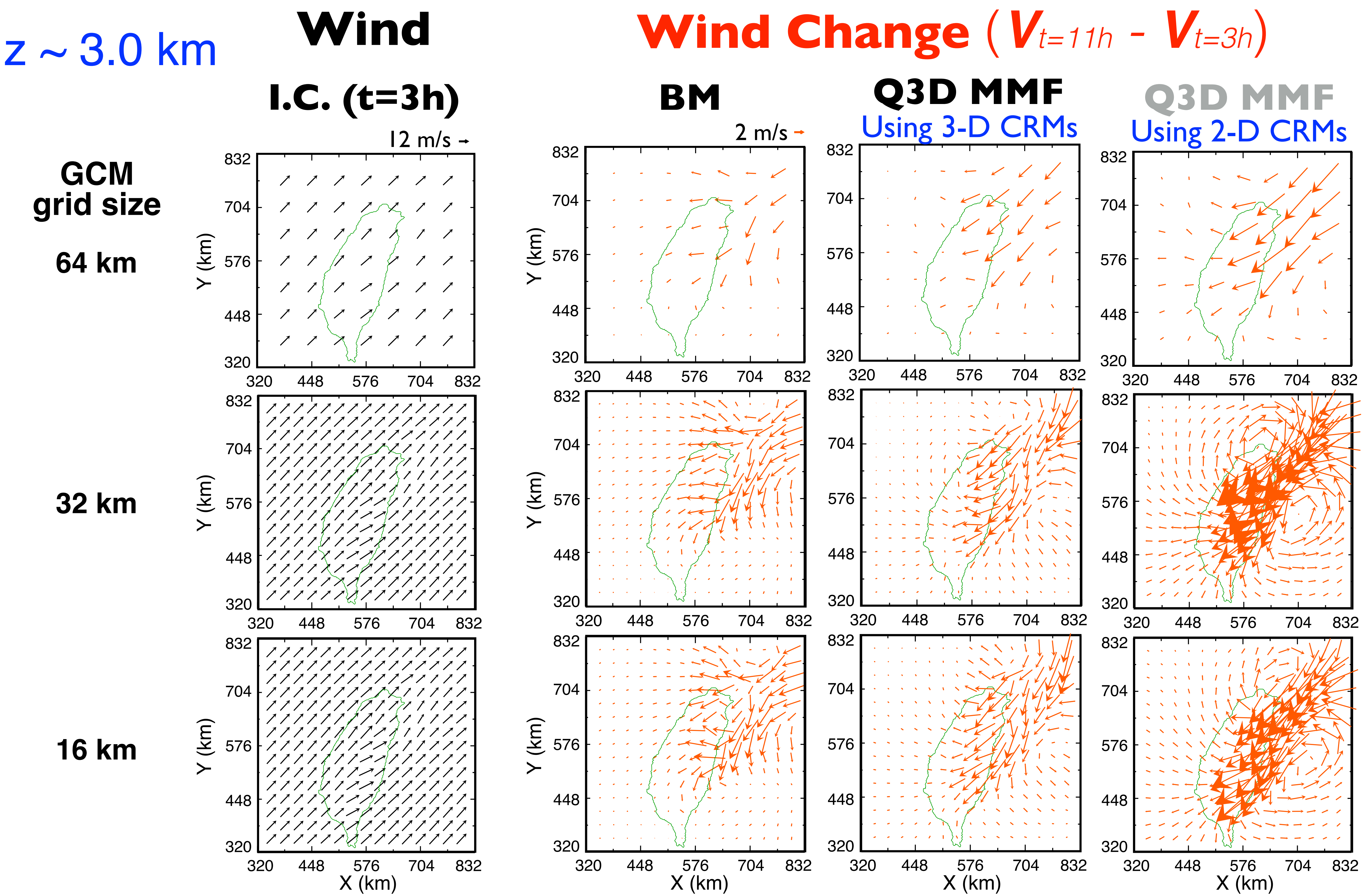
Q3D MMF Simulation Results (Continued.)

(GCM grid size = 32 km)



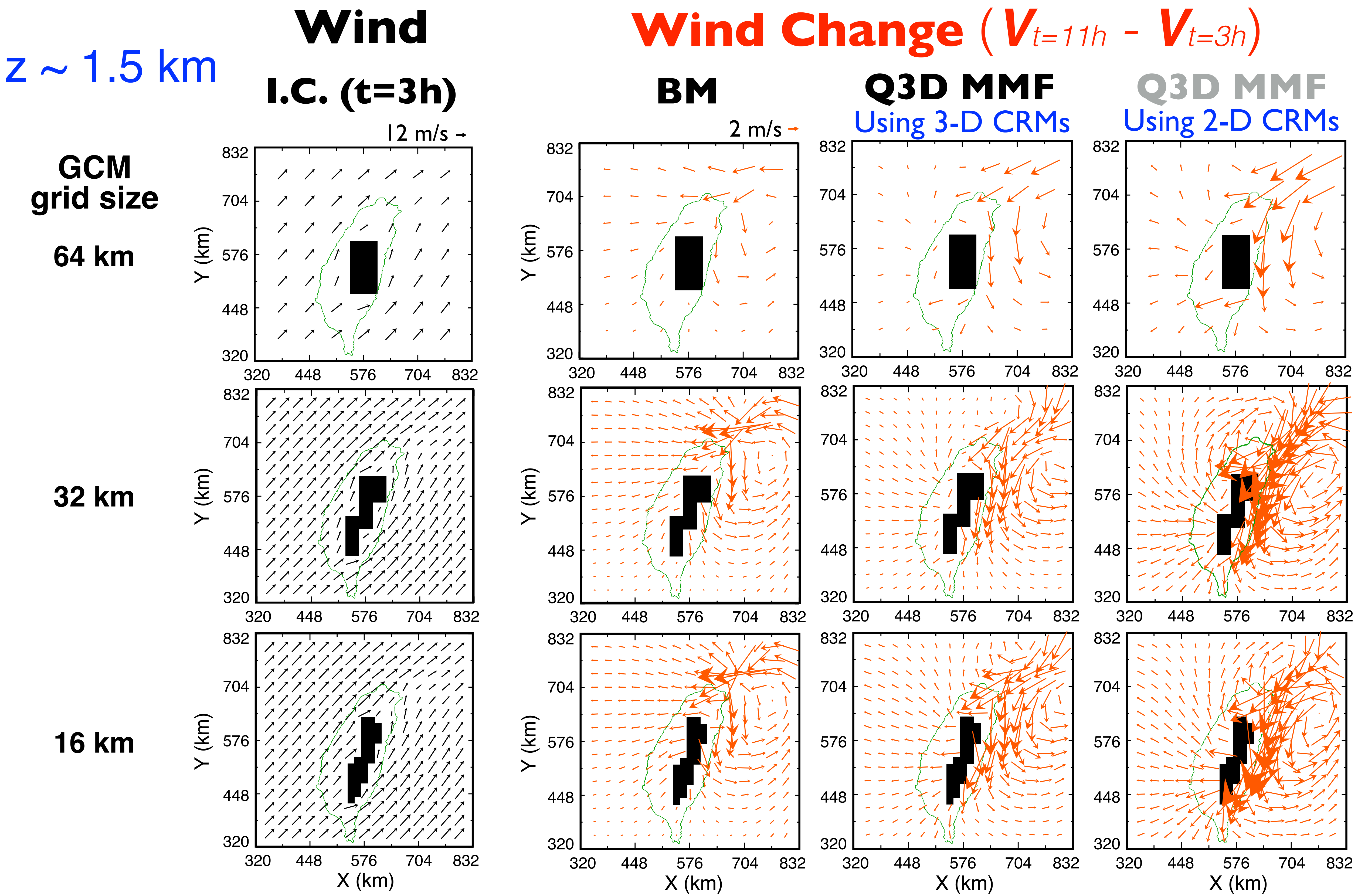
Orographic blocking is reasonably well simulated with the Q3D MMF.

Q3D MMF Simulation Results (Continued.)



For the simulation of circulation with topography, it is better to use 3-D CRMs (i.e., Q3D MMF).

Q3D MMF Simulation Results (Continued.)



For the simulation of circulation with topography, it is better to use 3-D CRMs (i.e., Q3D MMF).

Summary and Conclusion

- The Q3D MMF algorithm has been modified to incorporate surface topography.

- To evaluate the new algorithm, it is used to simulate the orographic precipitation enhancement during the passage of typhoon Morakot over Taiwan with idealized conditions.

- Comparisons between the simulation results of Benchmark and Q3D MMF confirm that
  - the Q3D MMF is able to simulate the orographic precipitation reasonably well, especially with a higher-resolution of the GCM, and
  - the Q3D MMF is able to simulate the circulation associated with topography well due to the use of 3-D CRMs (i.e., use of Q3D structure).