Q3D MMF: A New Generation of Superparameterization

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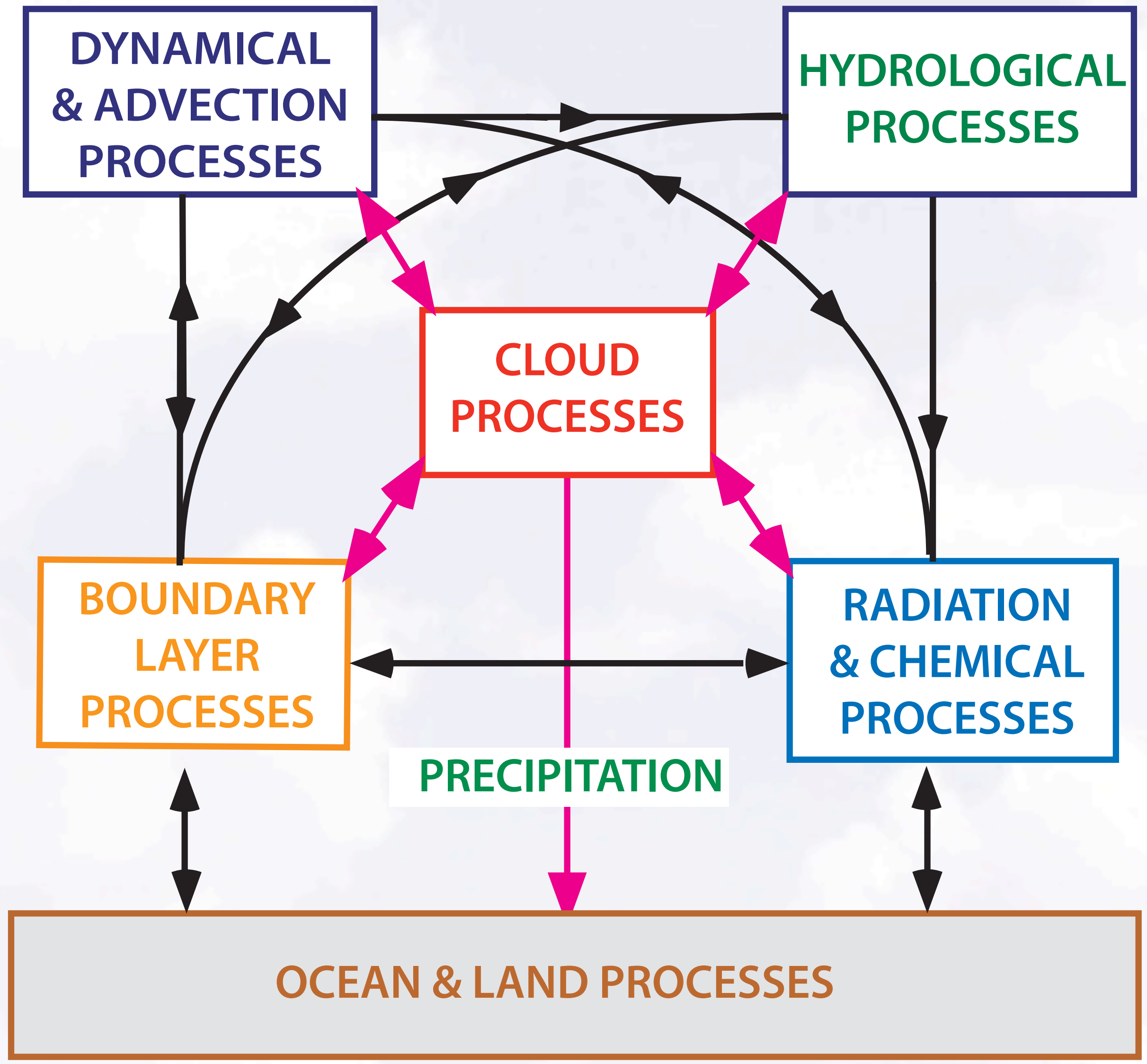
CMMAP

Reach for the sky.

January 2014 CMMAP Team Meeting

Modeling the Moist-convective Atmosphere

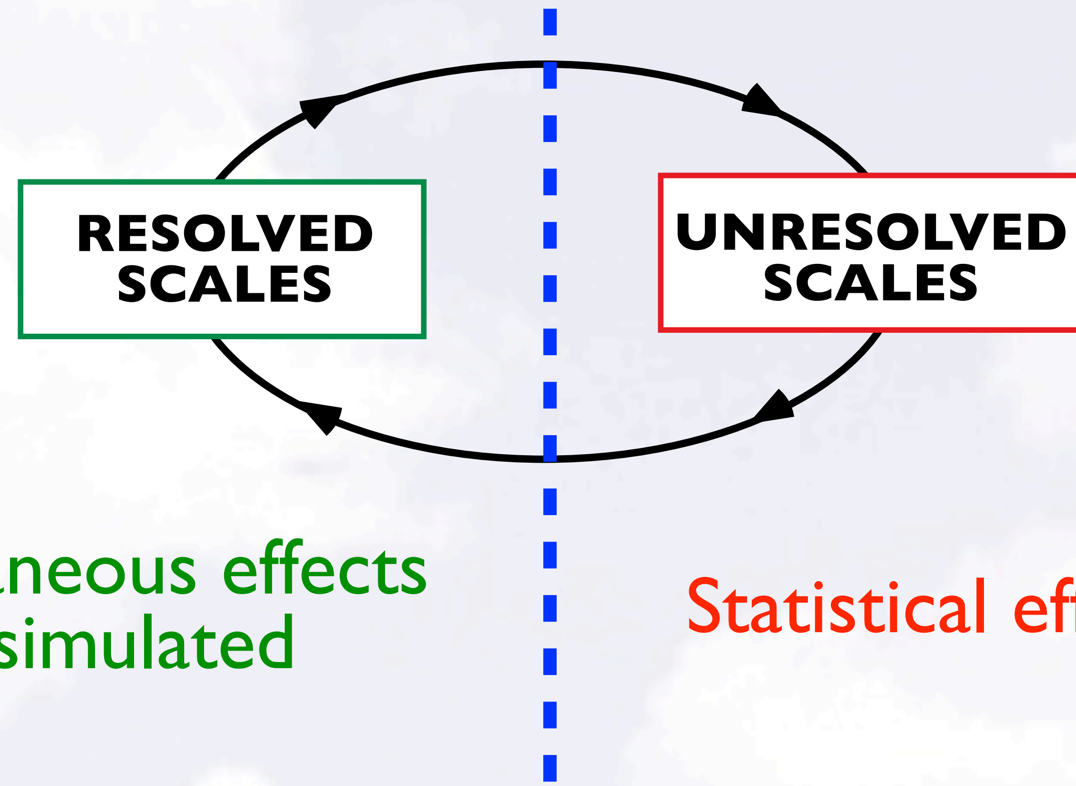
Clouds and their associated processes play crucial roles in the climate system



Arakawa (2004)

It is extremely challenging to formulate the net effects of these complicated interactions for use in climate models.

Truncation of Continuous System in Modeling



Local and instantaneous effects are explicitly simulated

Statistical effects are estimated

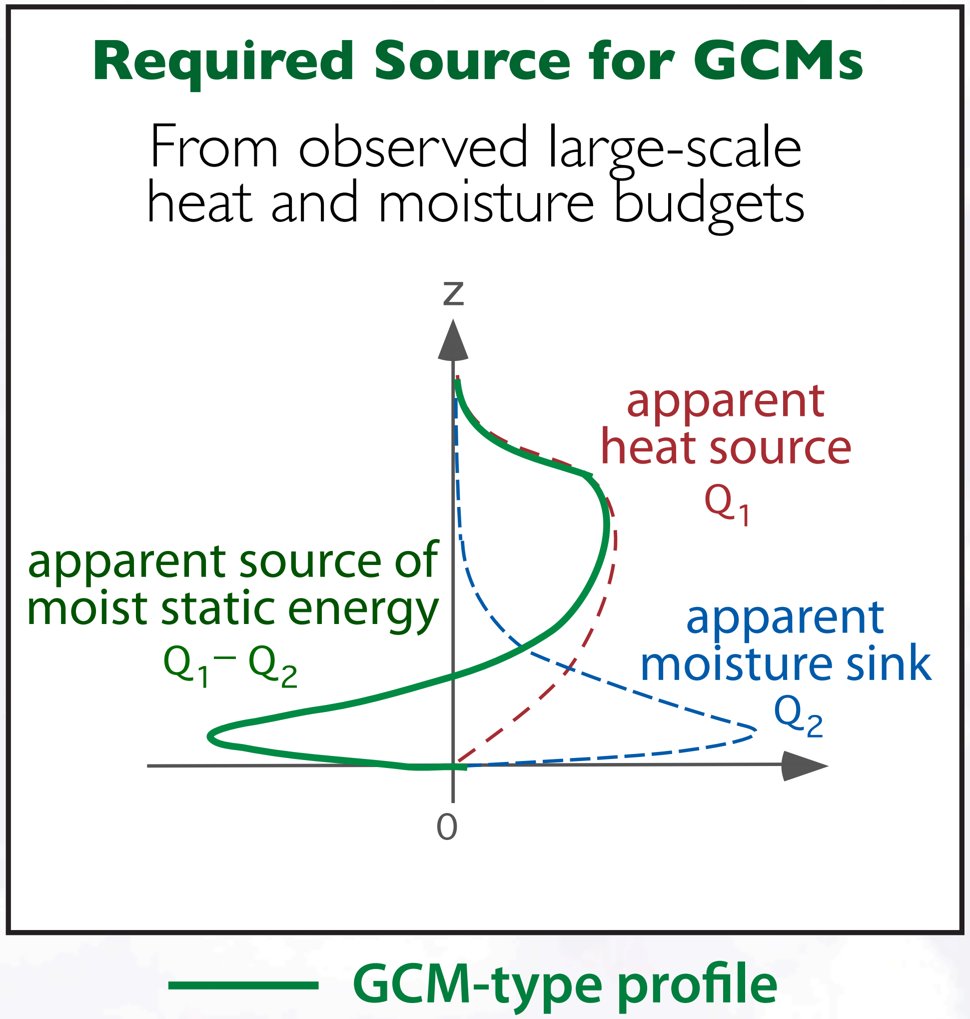
truncation

Depending on where truncated, atmosphere models are separated into two groups (as far as the representation of deep moist convection is concerned):

- **High-resolution models (CRMs)**
  moist convective processes are explicitly simulated
- **Low-resolution models (Conventional GCMs and NWP models)**
  moist convective processes are highly parameterized

Required Sources (for Low Resolution Models) *vs.* Real Sources (for High Resolution Models)

Typical Profiles of Moist Static Energy Source due to Deep Convection



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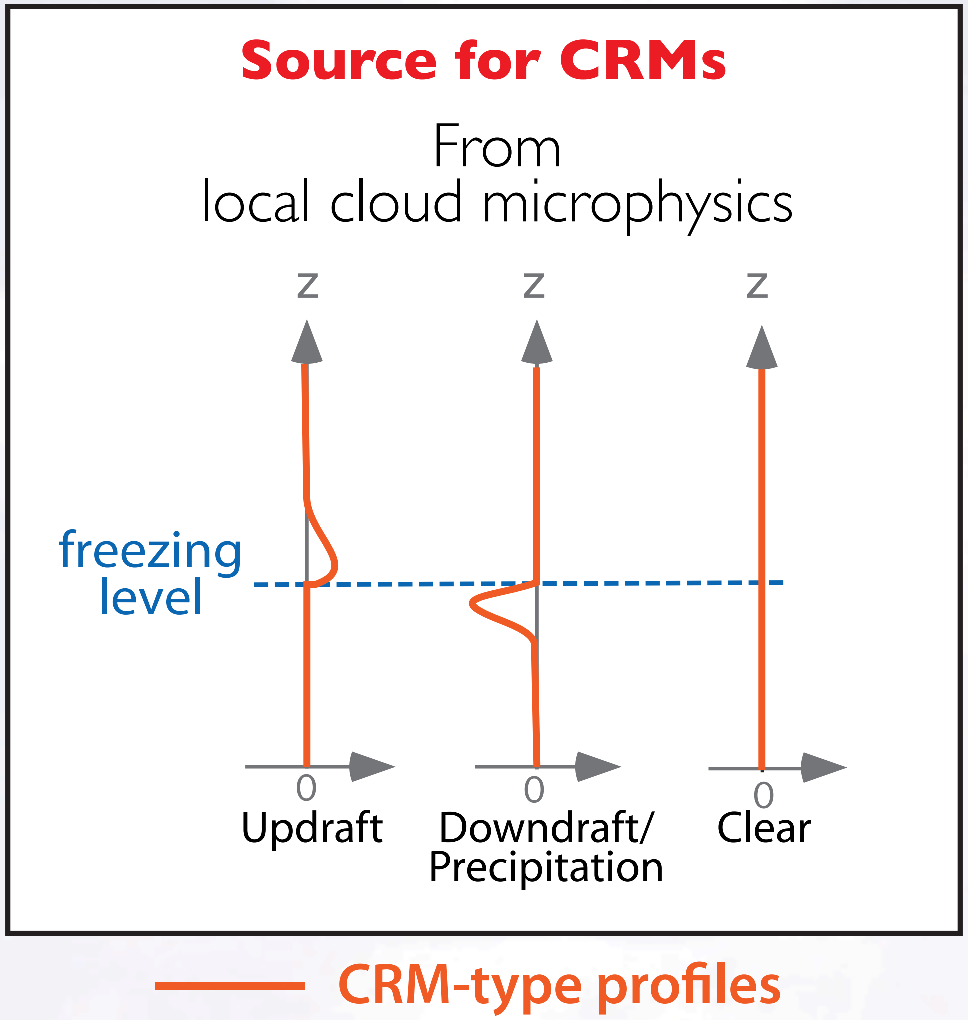
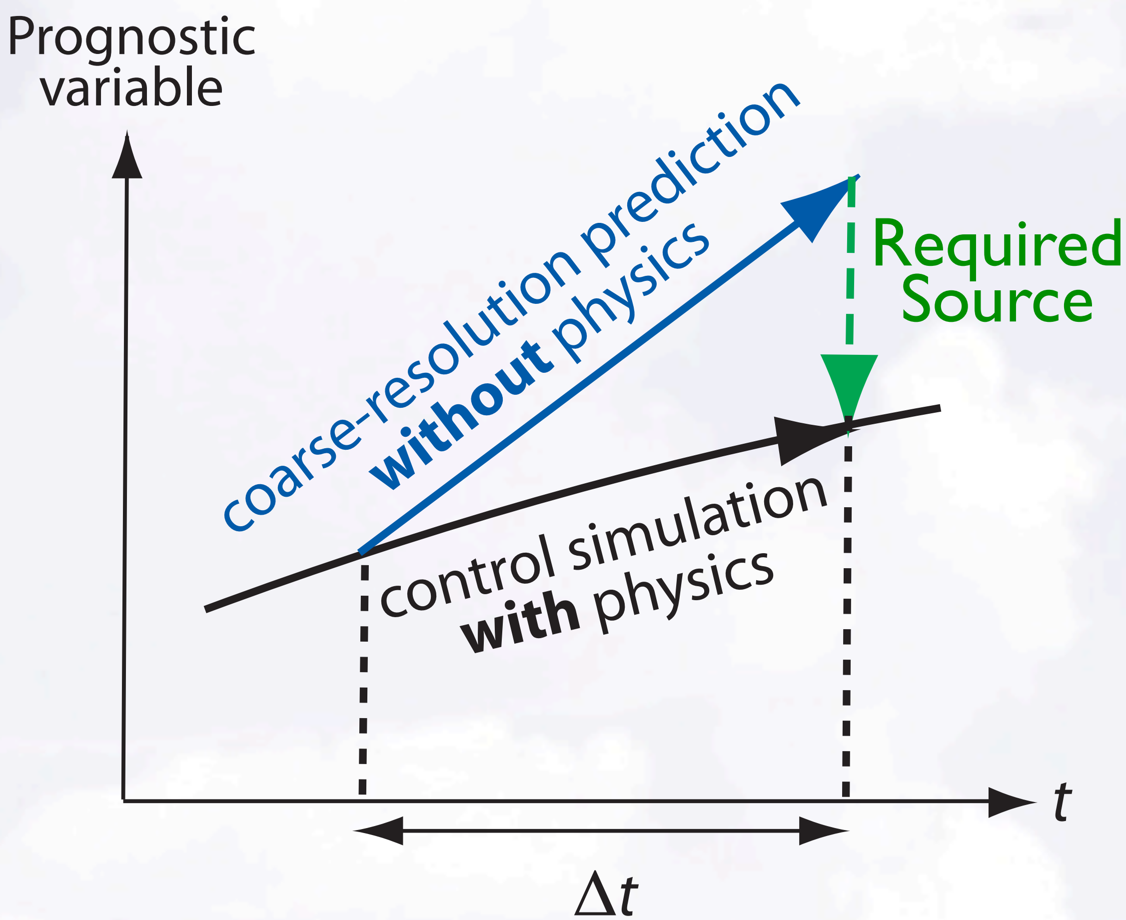


Resolution Dependency of Model Physics

"Required Sources" ➡ "Real Sources"

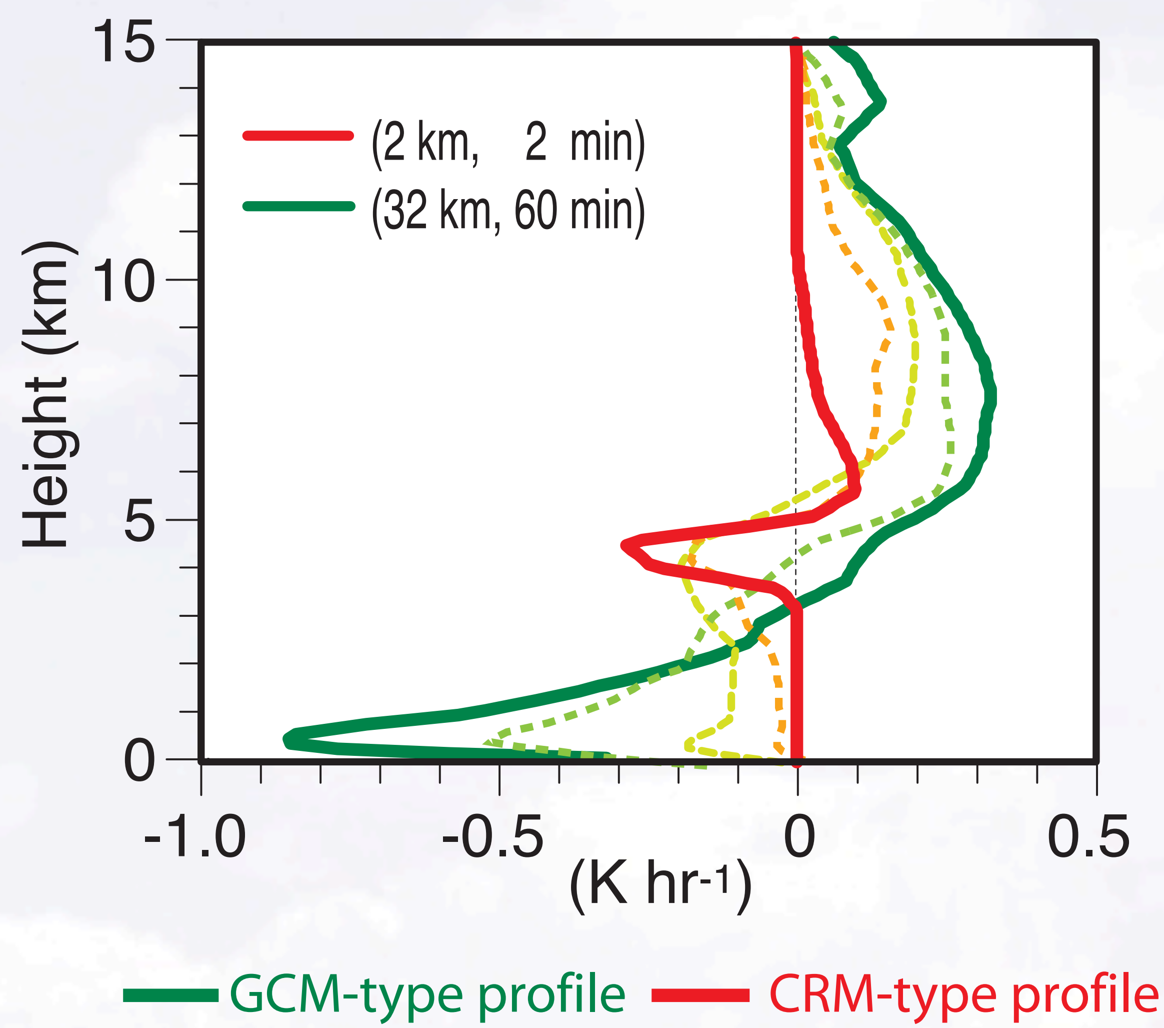
Jung and Arakawa, 2004

Budget analyses of CRM-simulated data applied to various space/time intervals with and without a component (or components) of model physics



Required Source: "source" due to the missing physics required for the coarse-resolution version of the model

Average Profiles of "Required" Source for Moist Static Energy



A smooth transition between the two types of profiles as the resolution changes.

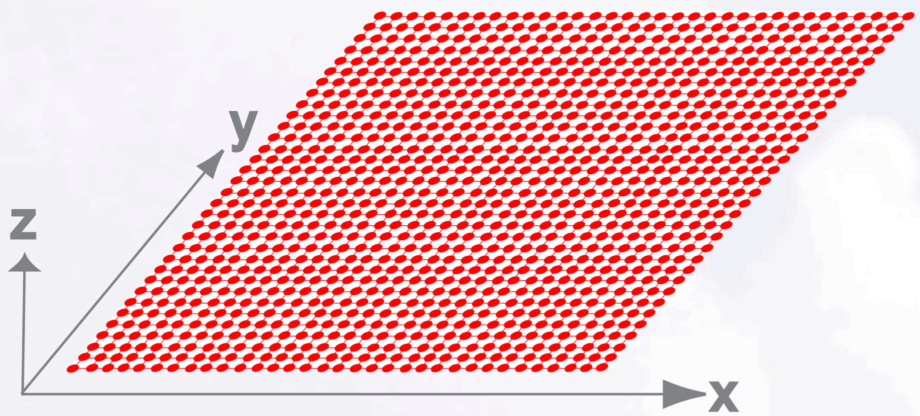
A New Approach: “Resolve Everything”

Arakawa (2004)

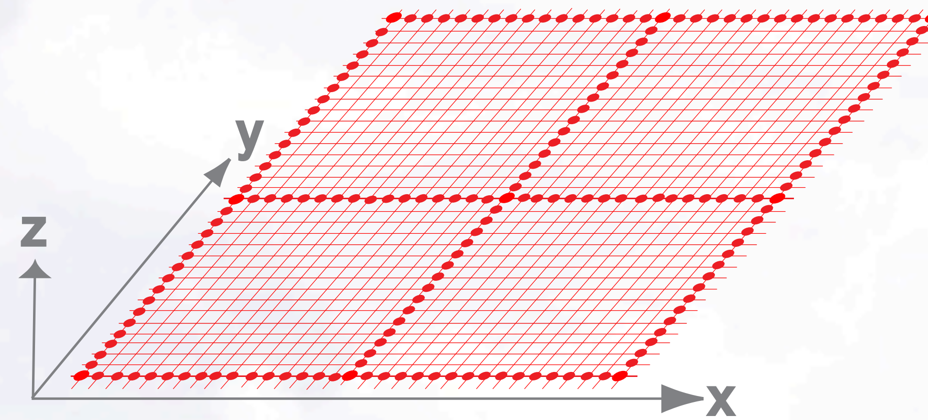
Modeling Framework that satisfies the following requirements:

- It can be used as a global 3D CRM;
- It is flexible enough to include less-expensive options;
- It is based on the same formulation of model physics for all options.

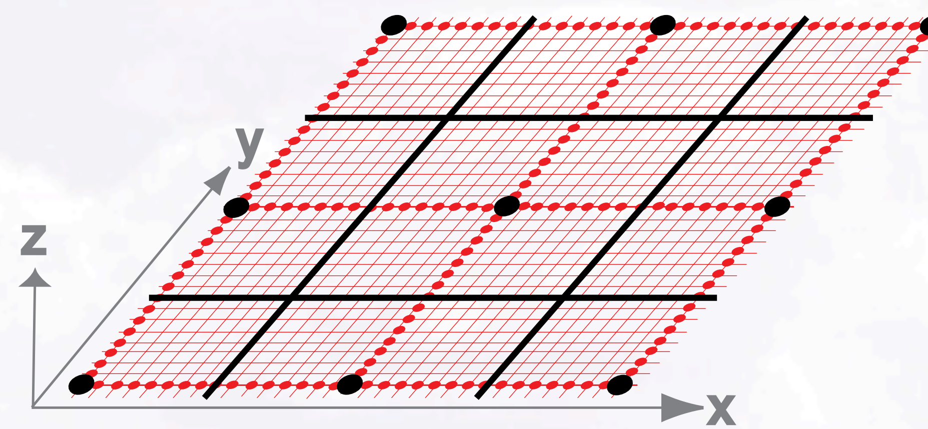
Original 3D CRM



Q3D CRM (less dense network)



Prototype Q3D MMF



GCMs have uniform grid-point distributions for large scales;

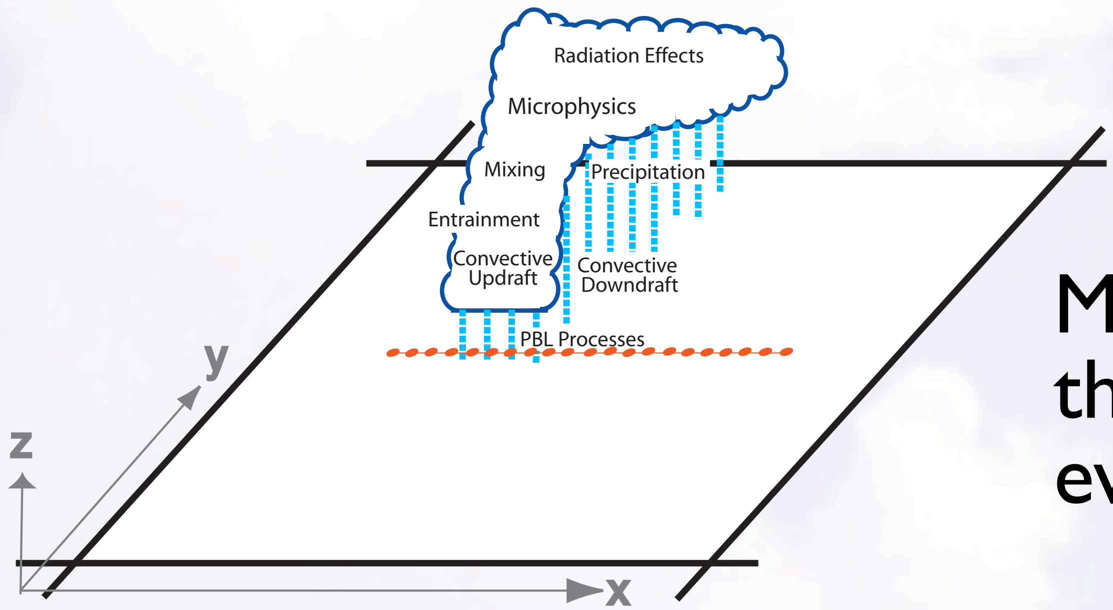
Good to maintain compatibility with conventional GCMs.

Multiscale Modeling Framework (MMF)

"Cloud Resolving Convective Parameterization" or "Superparameterization"

Approach trying to improve the representation of cloud processes by using the simulated statistics of 2D CRM.

Grabowski & Smolarkiewicz (1999), Khairoutdinov & Randall (2001), and many others.



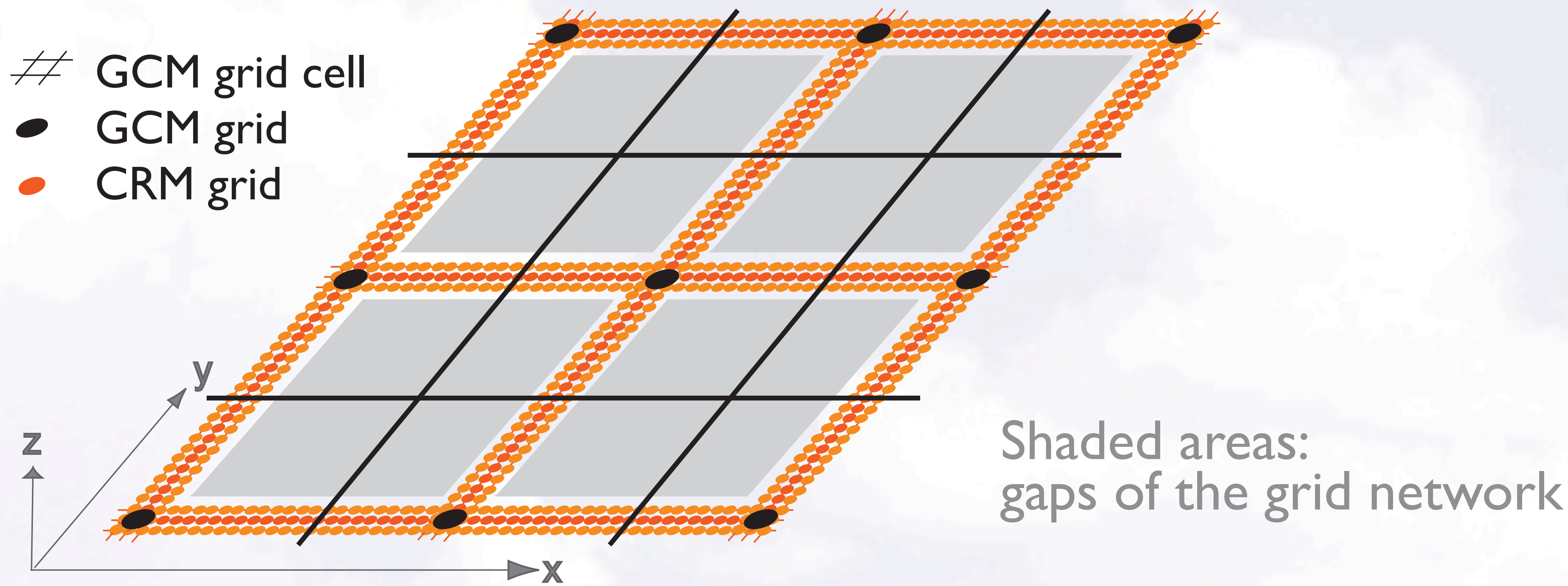
Many studies have shown the ability of the MMF to simulate various atmospheric events with a wide range of time scales.

But, there are inherent limits:

- Confinement of CRMs with cyclic boundary conditions
- Use of 2D CRMs
- Need to choose a particular direction for the 2D CRMs

Q3D MMF

Eliminates or reduces the inherent problems of the prototype MMF



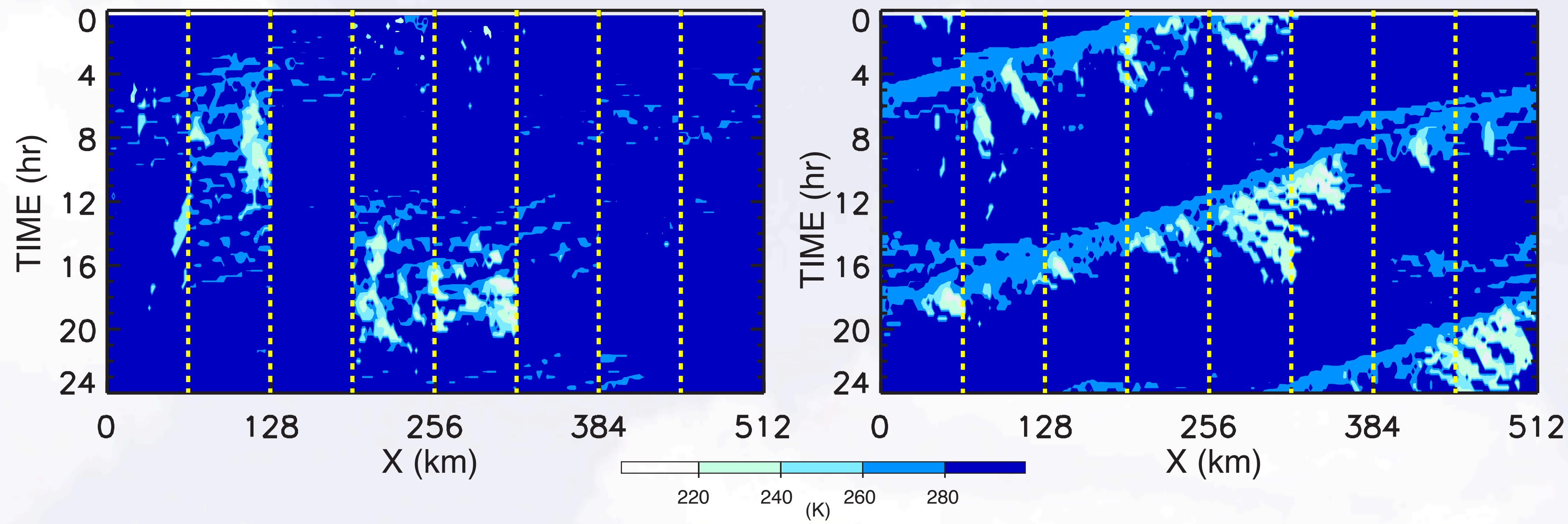
- The CRMs are extended beyond the GCM grid cell rather than confined.

Embedded CRM *vs.* Extended CRM

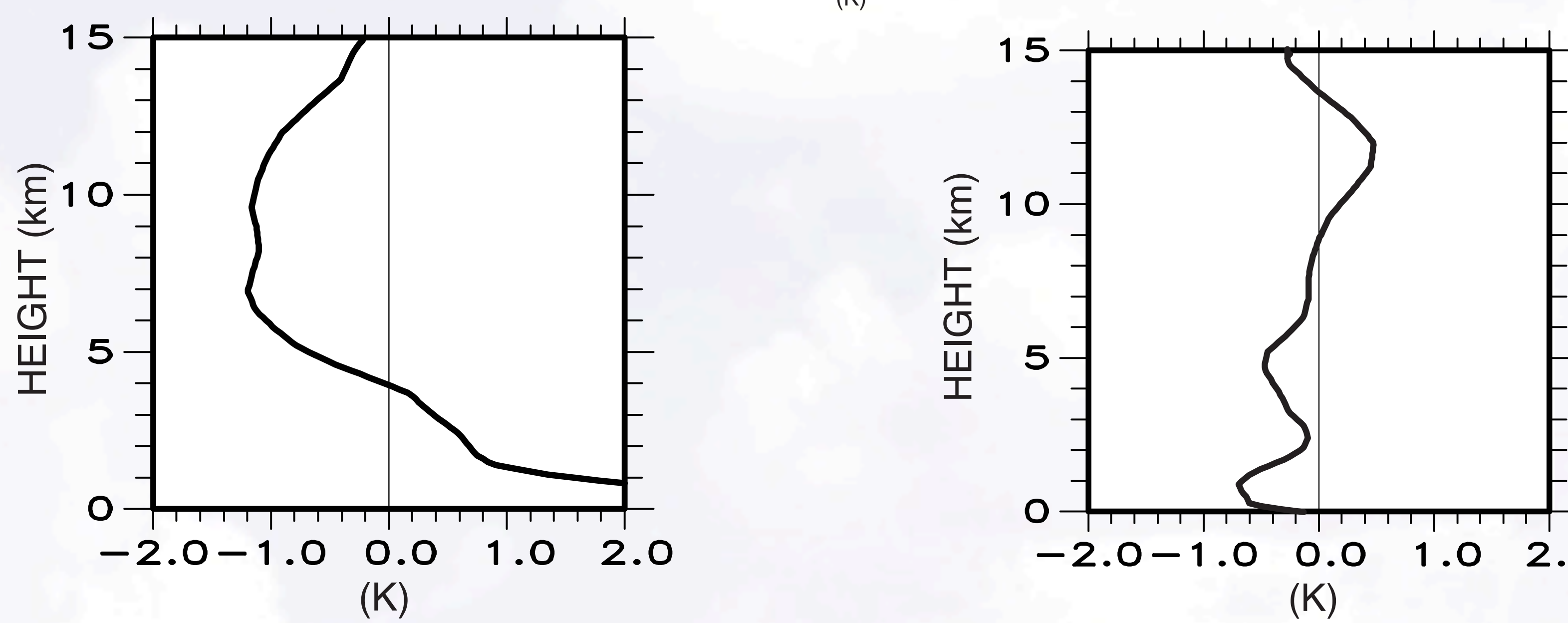
Idealized test by Jung and Arakawa (2005)

Embedded CRM | **Extended CRM**

Simulated Cloud Top Temp.



Systematic Errors of Moist Static Energy

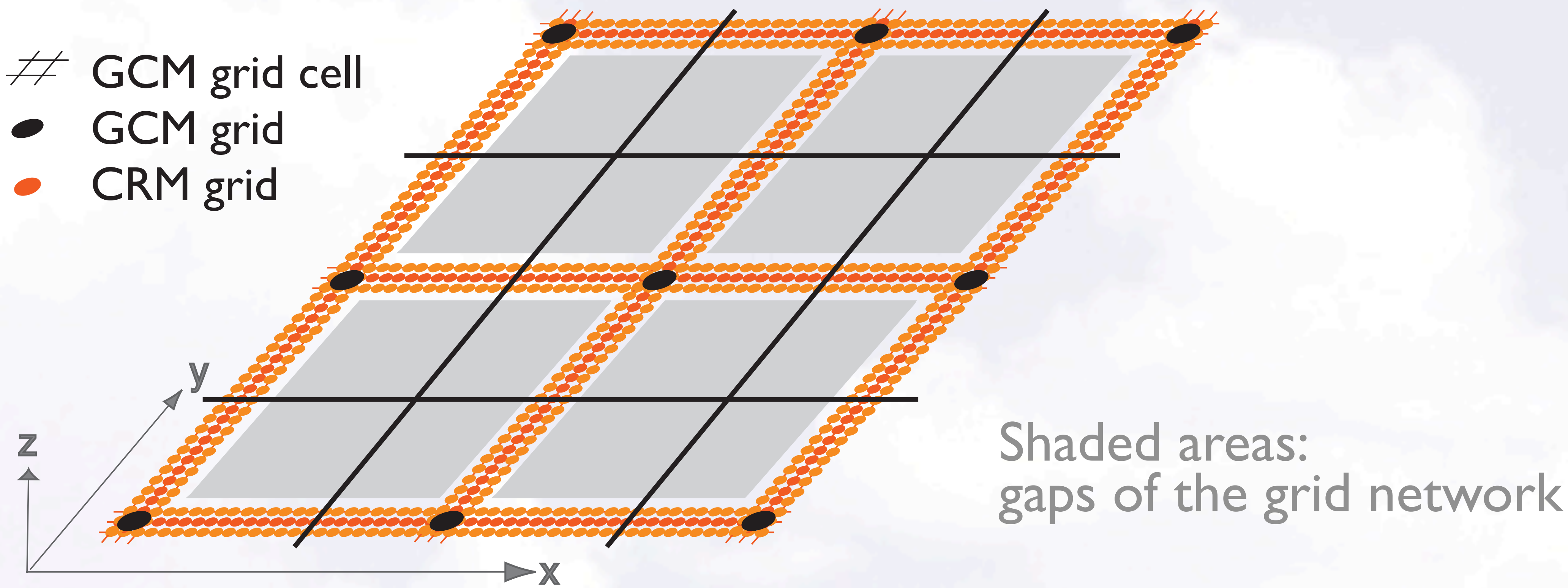


However, the prototype MMF can still simulate the propagation of cloud systems *primarily controlled by large scales.*

e.g., Pritchard et al. (2011); Grabowski (2006); Jung and Arakawa (2006)

Q3D MMF

Eliminates or reduces the inherent problems of the prototype MMF



- The CRMs are extended beyond the GCM grid cell rather than confined.
- The 2D CRMs are replaced with 3D CRMs.
- Two perpendicular sets of CRMs are used, *which interact through the GCM.*

Dynamics and Physics of the Q3D MMF

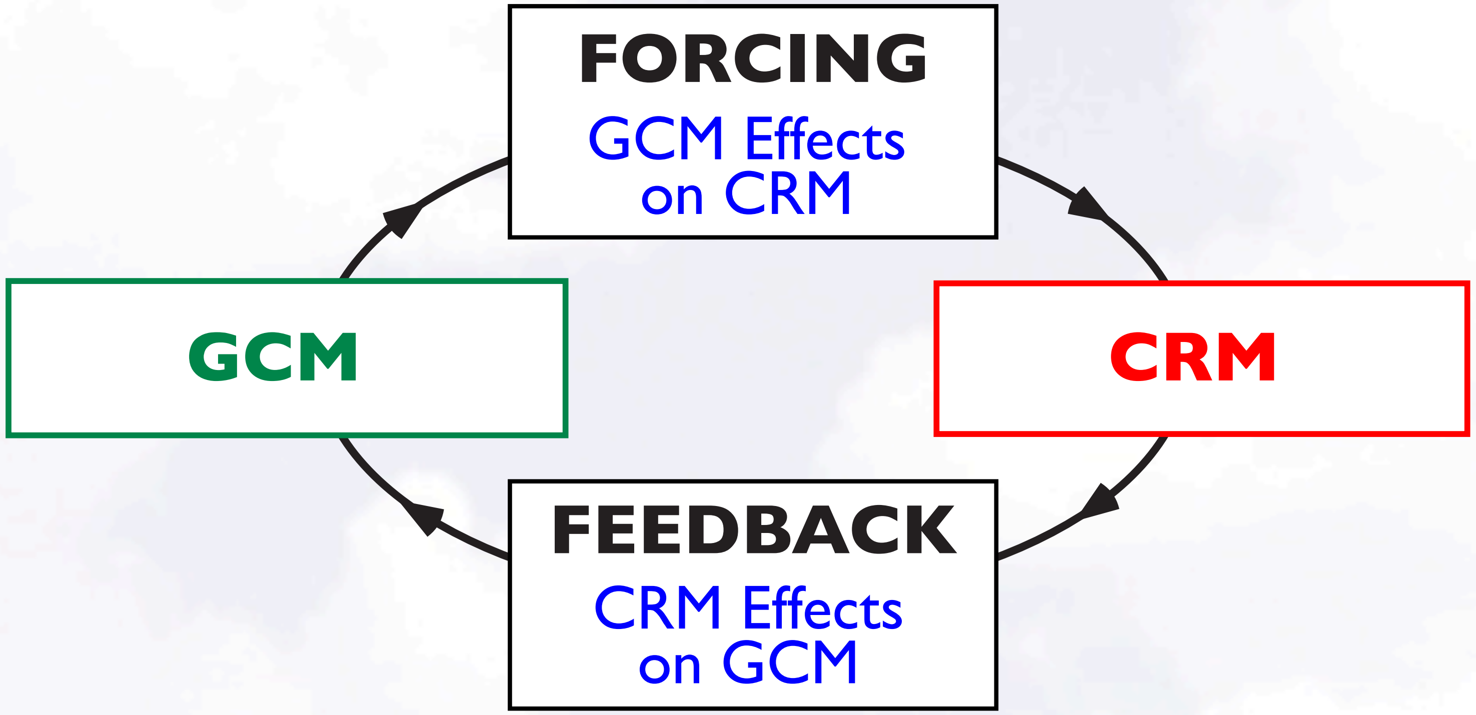
Based on the model of Jung and Arakawa (2008).

- Dynamics cores of GCM and CRM are basically same.
  - Nonhydrostatic anelastic 3-D model
  - Use of the vector vorticity equation for dynamics
  - 3-D elliptic equation is solved for vertical velocity
- All physical processes are included in the CRM.
  - Bulk three-phase microphysical parameterization
  - Radiation parameterization
  - Turbulence parameterization (1st-order closure)
- Only large-scale condensation is included in the GCM.

GCM performs the overall prediction and should be considered as the principal component of the Q3D MMF.

Coupling the GCM and CRM Components

MMF (Q3D MMF) inherits the structure of the conventional GCMs.



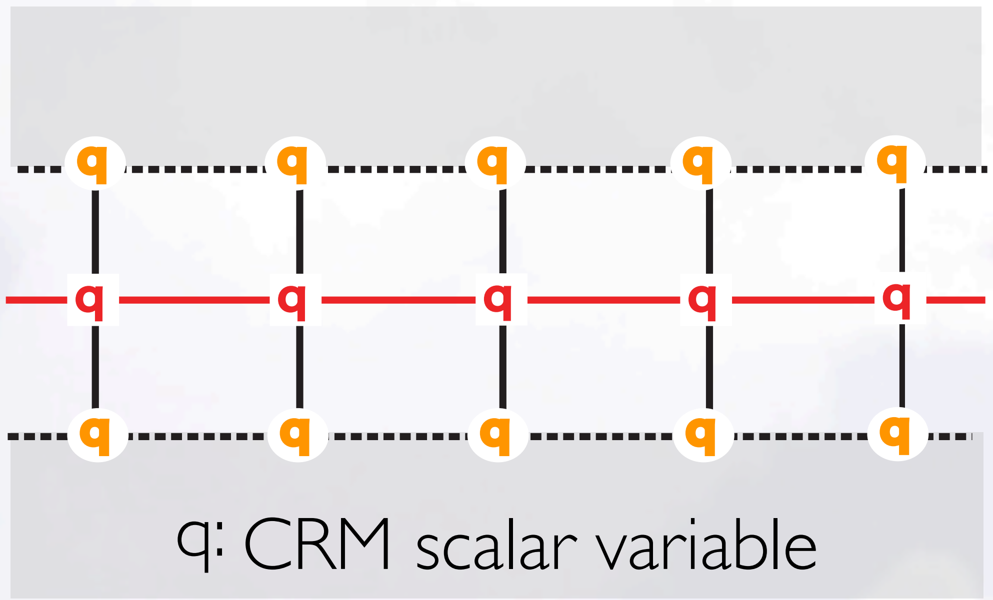
One of the most important objectives of the Q3D MMF is to achieve the unification of two families of atmosphere models. Having this objective in mind, the coupling between the GCM and CRM components is formulated.

Basic Requirements for Coupling in the Q3D MMF

- Having uniformly distributed grid network, the GCM is supposed to simulate well-behaved three-dimensional large-scale features. The large-scales simulated by the GCM and CRM should be sufficiently close to each other.

Forcing: GCM effects on CRM

- The CRM recognizes the horizontal inhomogeneity simulated by GCM through the lateral boundary condition.

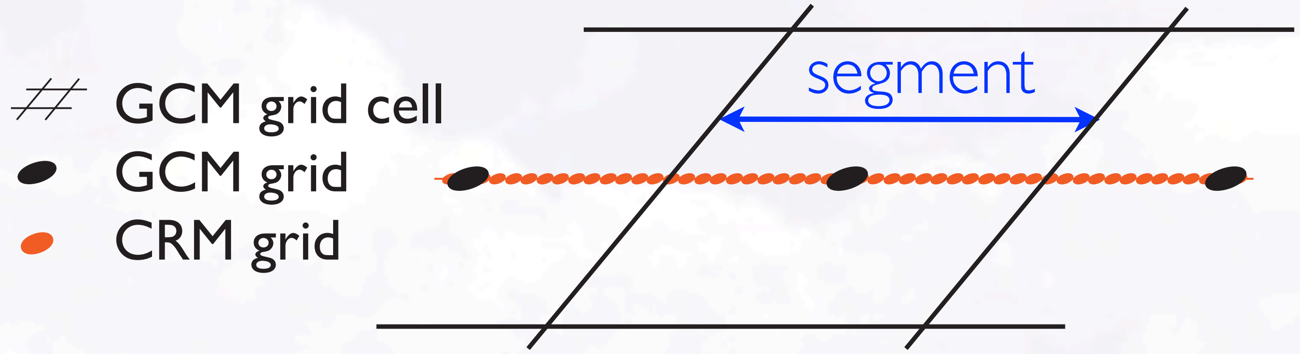


Decomposition of variable: $q = \overline{q} + q'$

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

q' : deviation is cyclic across the channel

- To guarantee the compatibility between the GCM and CRM solutions, the segment average of q is relaxed to the counterpart of $\overline{q}$.



Relaxation Timescale

- The time scale for the relaxation must be dependent on the resolution of GCM.

  When the GCM resolution is low, the relaxation time scale must be sufficiently long.

  When the GCM resolution is high, the relaxation time scale must be sufficiently short.

- The choice of relaxation timescale is important for the convergence of the Q3D MMF to a GCRM.

- More discussion will be given later with the sensitivity test results.

Basic Requirements for Coupling in the Q3D MMF (Continued.)

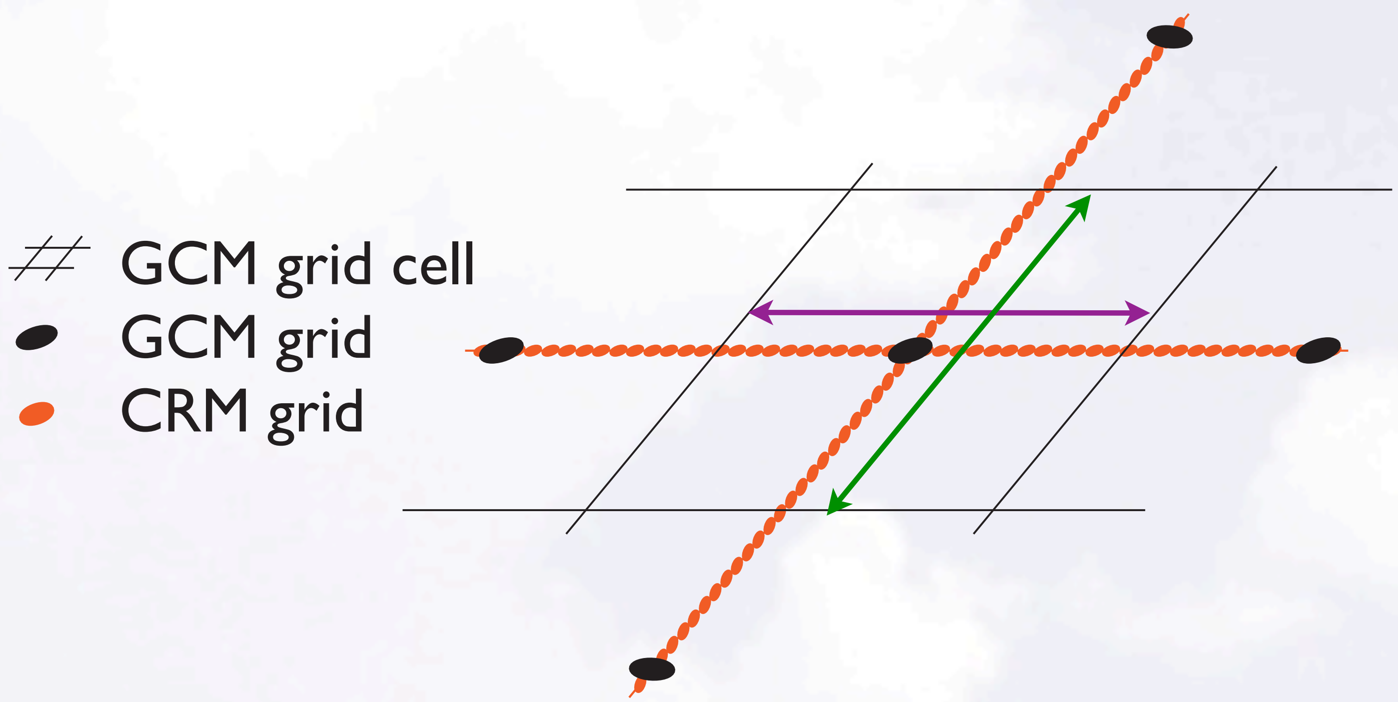
- Having uniformly distributed grid network, the GCM is supposed to simulate well-behaved three-dimensional large-scale features. The large-scales simulated by the GCM and CRM should be sufficiently close to each other.

- As for any parameterizations, the CRM is supposed to give only the statistical effects of sub-grid processes. Otherwise, double counting or spurious competition between the GCM and CRM solutions occurs.

  ➡ This is important in the Q3D MMF because the CRM grids extend over a GCM grid interval.

Feedback: CRM effects on GCM

Consists of the mean diabatic effects and the mean ***eddy effects*** of advective and dynamical processes simulated by the CRM



x-channel segment used for the calculation of mean values

y-channel segment used for the calculation of mean values

The CRM effects from two intersecting channels are averaged and assigned to a target GCM point.

An Idealized Benchmark Simulation

Transition of wave to vortices over the tropical ocean

- The benchmark simulation (BM) is performed with a fully three-dimensional CRM.

  Horizontal domain: 3072 km x 3072 km, Vertical domain: 30 km

  Horizontal grid: 3 km, Vertical grid: 0.1 ~ 1.7 km (stretched grid)

  f-plane: $f_0 = 1 \times 10^{-4}\ s^{-1}$

  Prescribed radiative cooling rate

  SST = 302 K

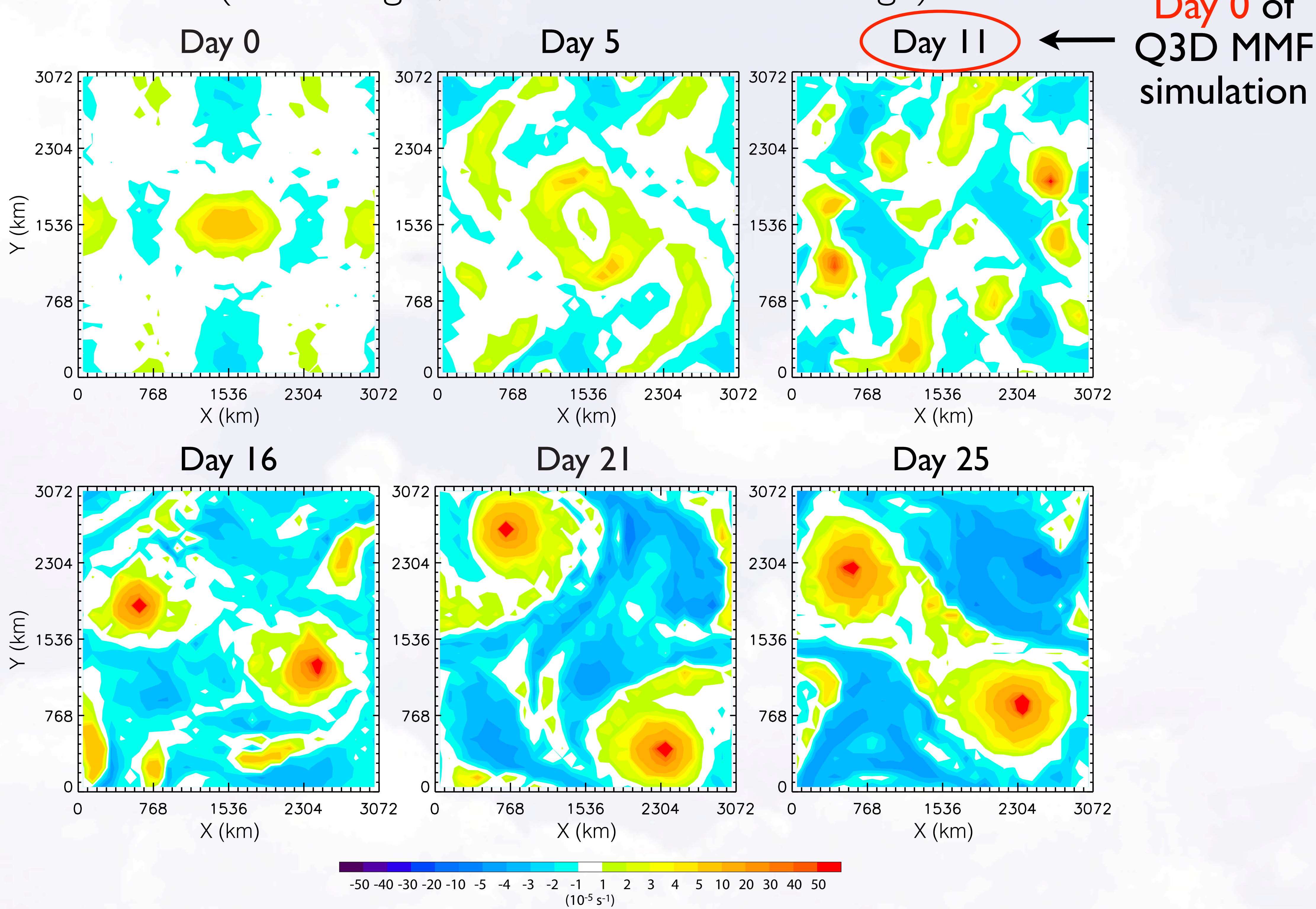
  Periodic boundary condition

- BM provides a reference for Q3D simulations and their initial conditions.

Benchmark Simulation

Vertical Component of Vorticity

(3-km height, 96km x 96km box average)



Initial vorticity pattern breaks down and two well defined vortices develop.

Test of Q3D MMF

(Horizontal domain: 3072 km x 3072 km, Vertical domain: 30 km)

CRM horizontal grid = 3 km (n = 1024)

GCM horizontal grid = 96 km (N = 32)

The channel width is 1-grid:

$$\frac{\text{\# of horizontal grid points of CRM in Q3D MMF}}{\text{\# of horizontal grid points of 3-D CRM (BM)}} = \frac{2 \times n \times N}{n \times n} = 6.25\ \%$$

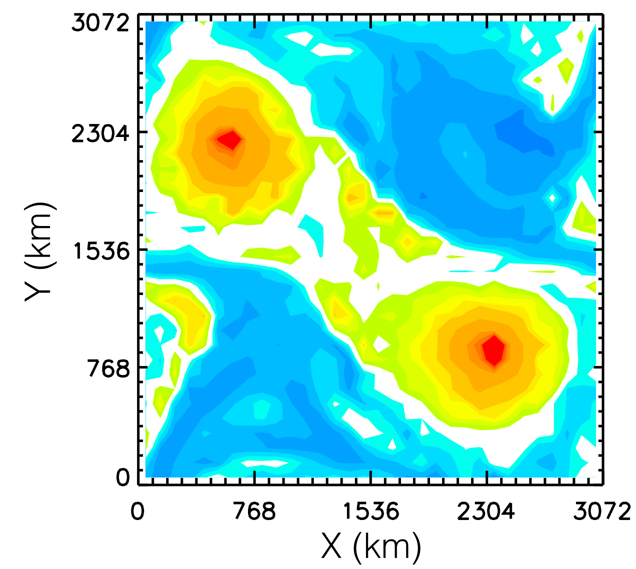
This ratio becomes smaller if the GCM resolution is coarser or the CRM resolution is finer.

Sensitivity to the Relaxation Timescale

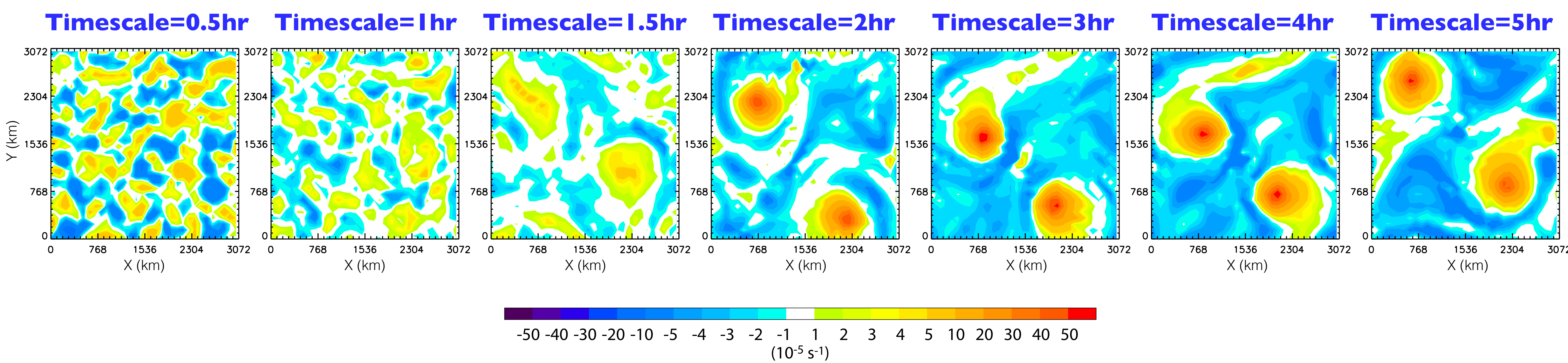
Simulated Vertical Component of Vorticity (Day 14)

Height ~ 3 km
d_{GCM} = 96 km

BM



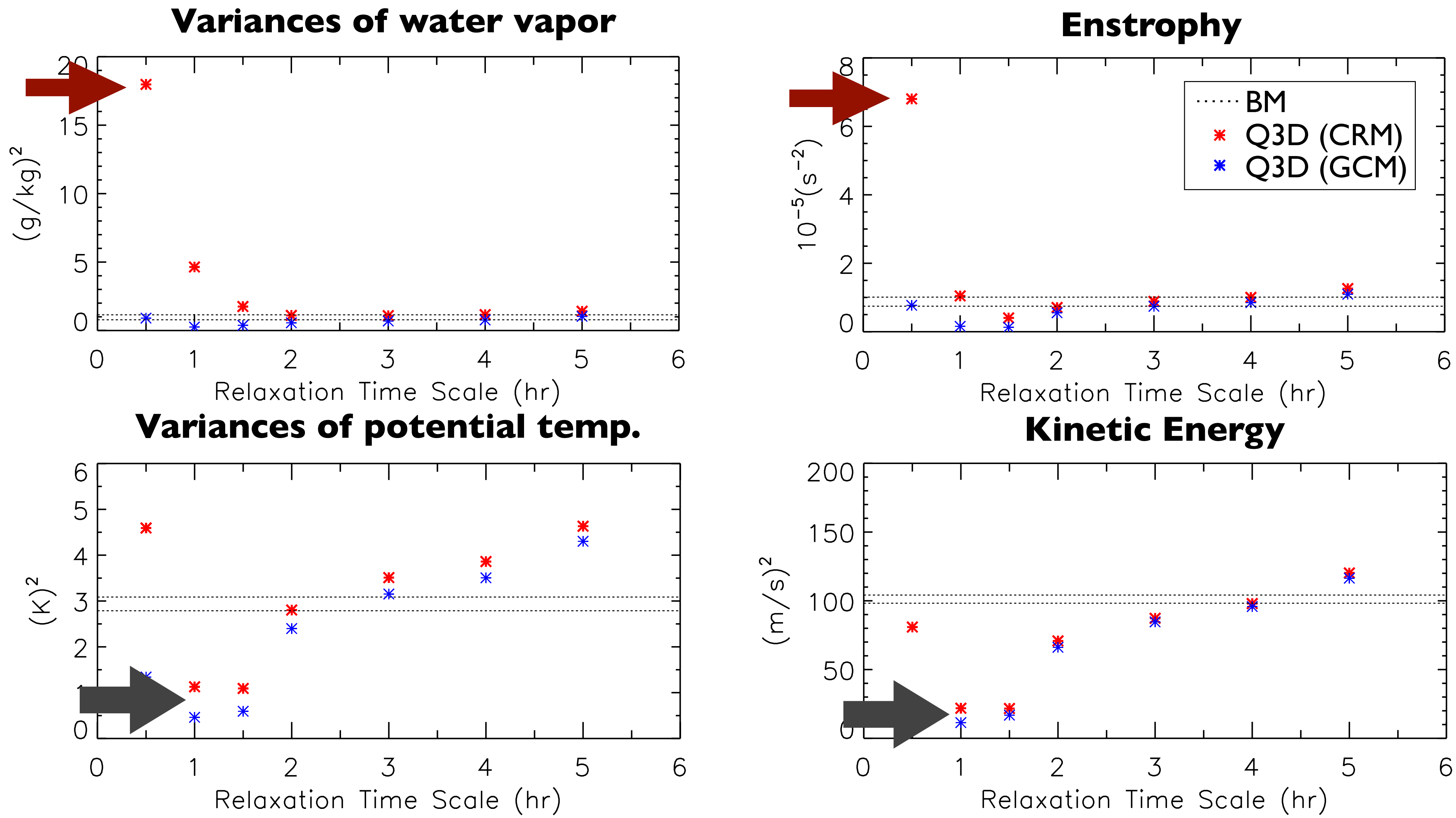
Q3D MMF



If the relaxation timescale is over a critical value (~1.5 hr), the prediction is relatively insensitive to the timescale.

Sensitivity to the Relaxation Timescale (Continued.)

(Averaged for 14 days)



- If the timescale is too short, the CRM is too strongly constrained by the GCM and loses its own local stabilization effect.
- If it is subcritical, the GCM still constrains the development of cloud organization in the CRM.
- If it is too long, the large-scales simulated by GCM and CRM are not sufficiently close to each other.

What to learn from the sensitivity test results?

- The critical time scale exists and it is the time required for the CRM to spontaneously develop mesoscale organization.

  "mesoscale": **intermediate scale** between the GCM-resolvable scale and cloud-scale

- The critical time scale can be determined by the time associated with horizontal advection because it plays an important role in the development of the mesoscale organization.

$$\text{Horizontal advection timescale for mesoscale } (\tau) \sim \frac{d}{V}$$

d : GCM grid size
V : characteristic magnitude of horizontal velocity

If V~15 m/s and d=96km, τ ~ 1.8 hr

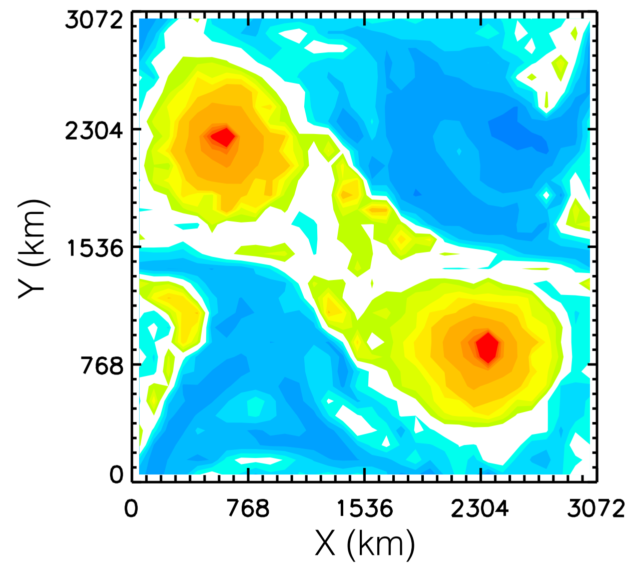
Sensitivity to the Relaxation Timescale (Continued.)

Advection Timescale Diagnosed from the CRM: $\tau(t)$

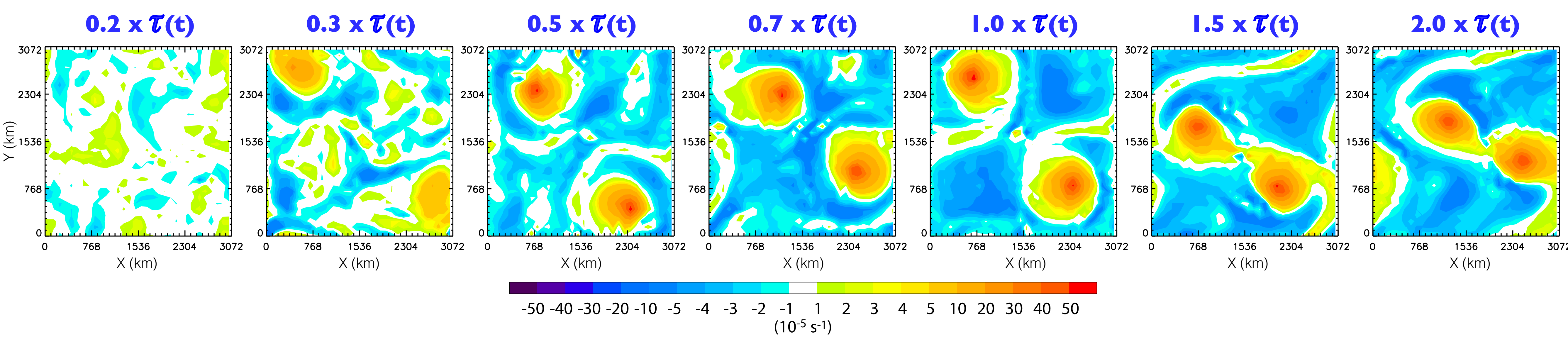
Simulated Vertical Component of Vorticity (Day 14)

Height ~ 3 km
d_{GCM} = 96 km

BM



Q3D MMF



Sensitivity to the Relaxation Timescale (Continued.)

Advection Timescale Diagnosed from the CRM: $\tau(t)$

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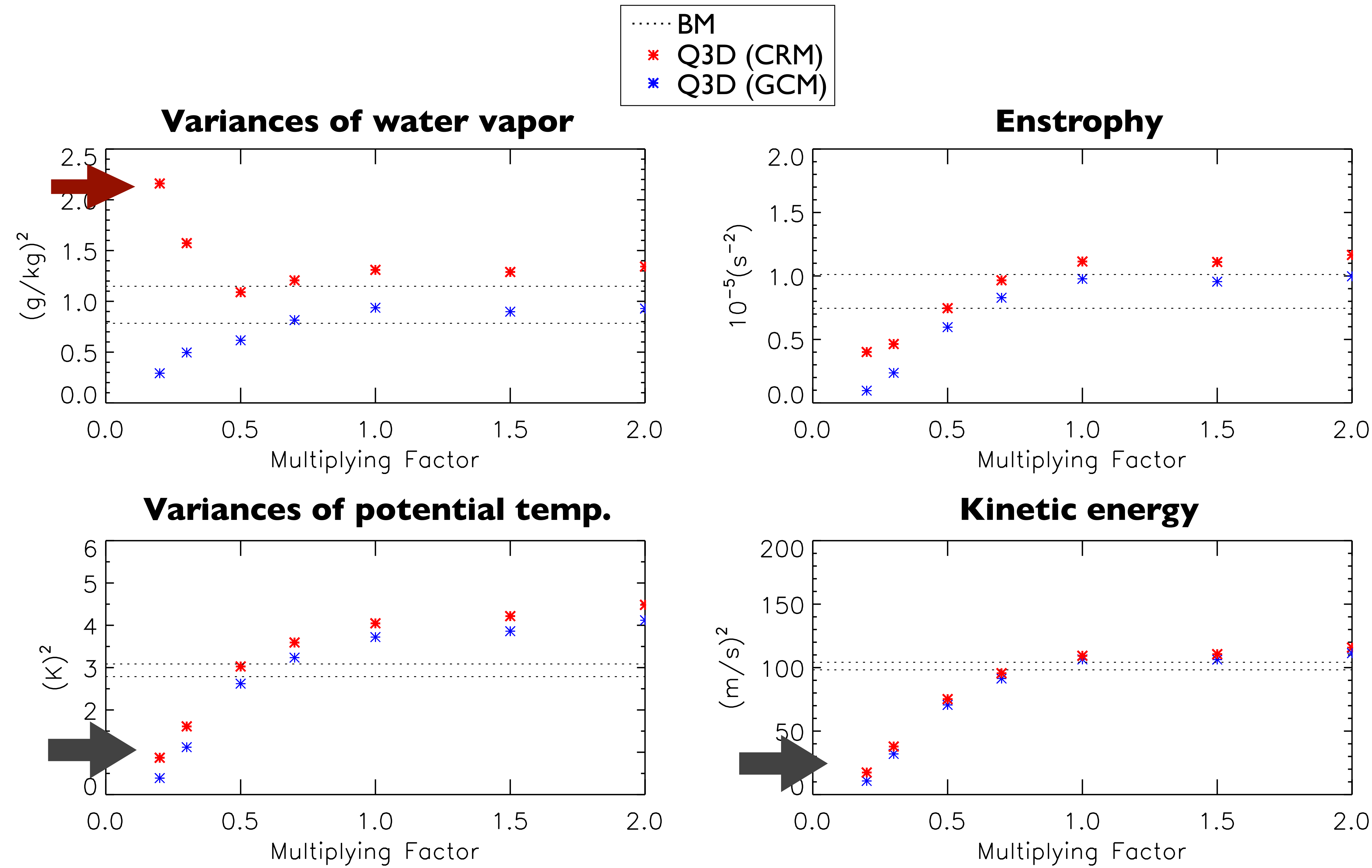
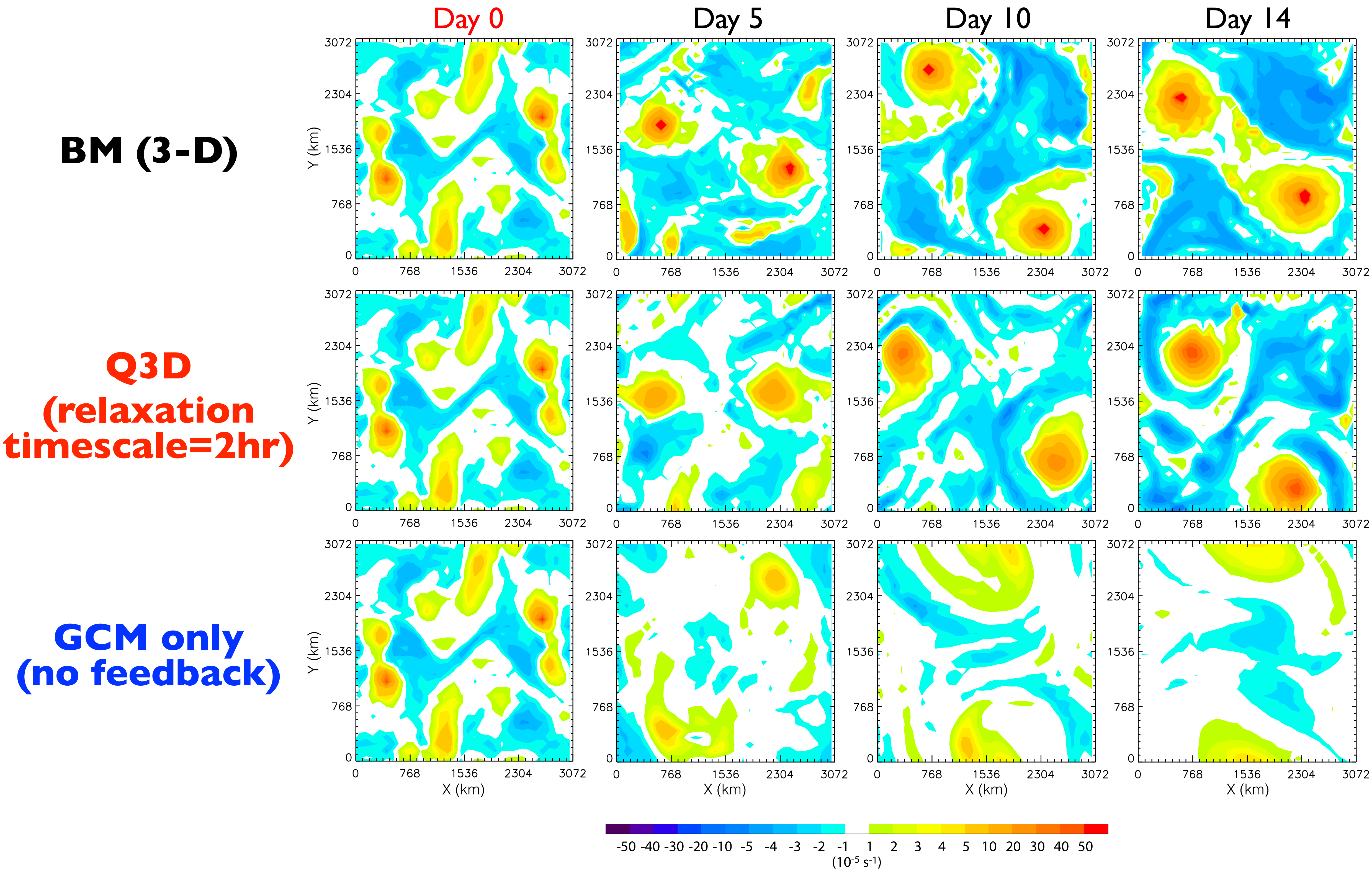


Q3D MMF Simulation Results

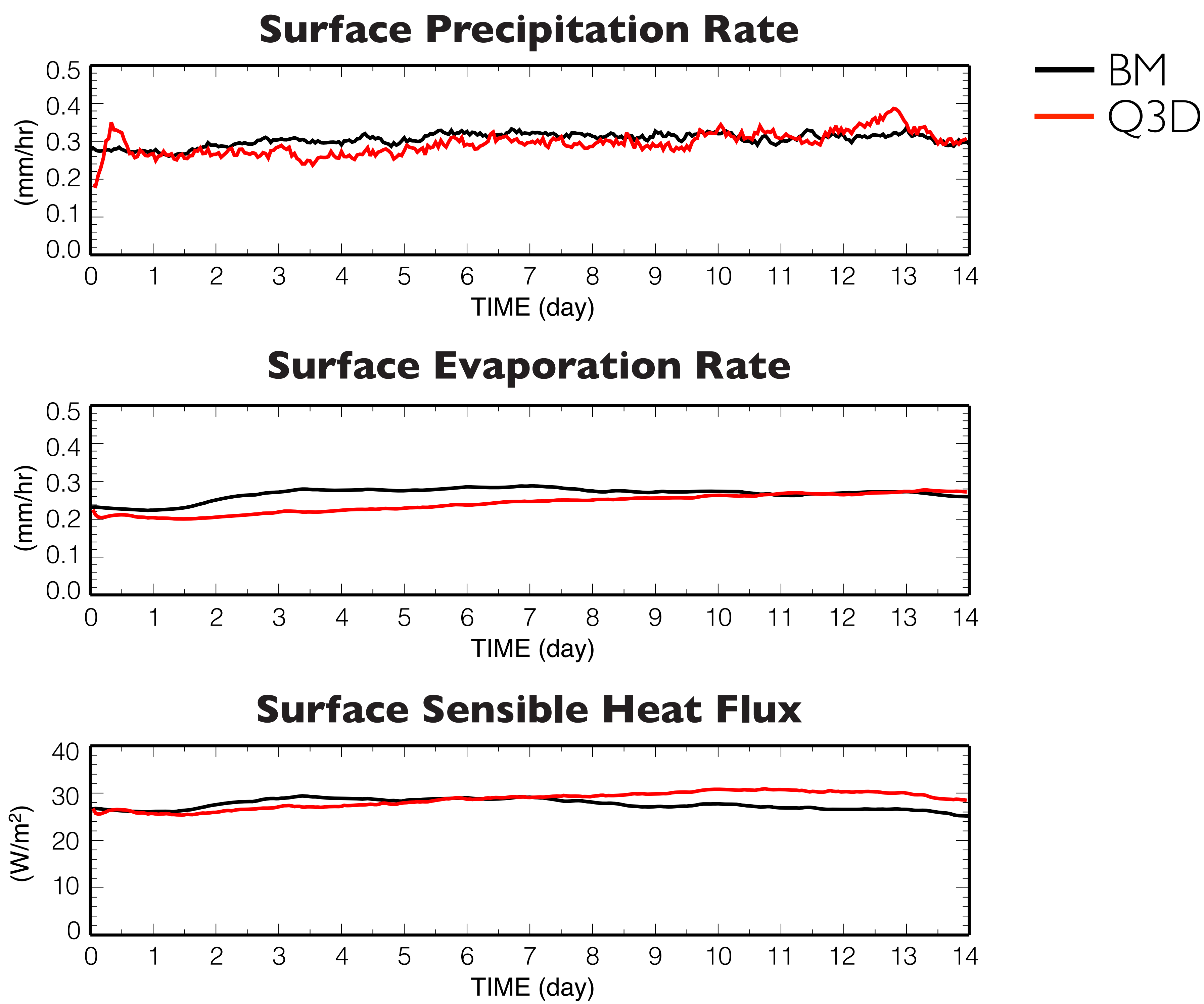
Vertical Component of Vorticity



Two intense vortices are developed and maintained in the Q3D simulation.

Q3D MMF Simulation Results (Continued.)

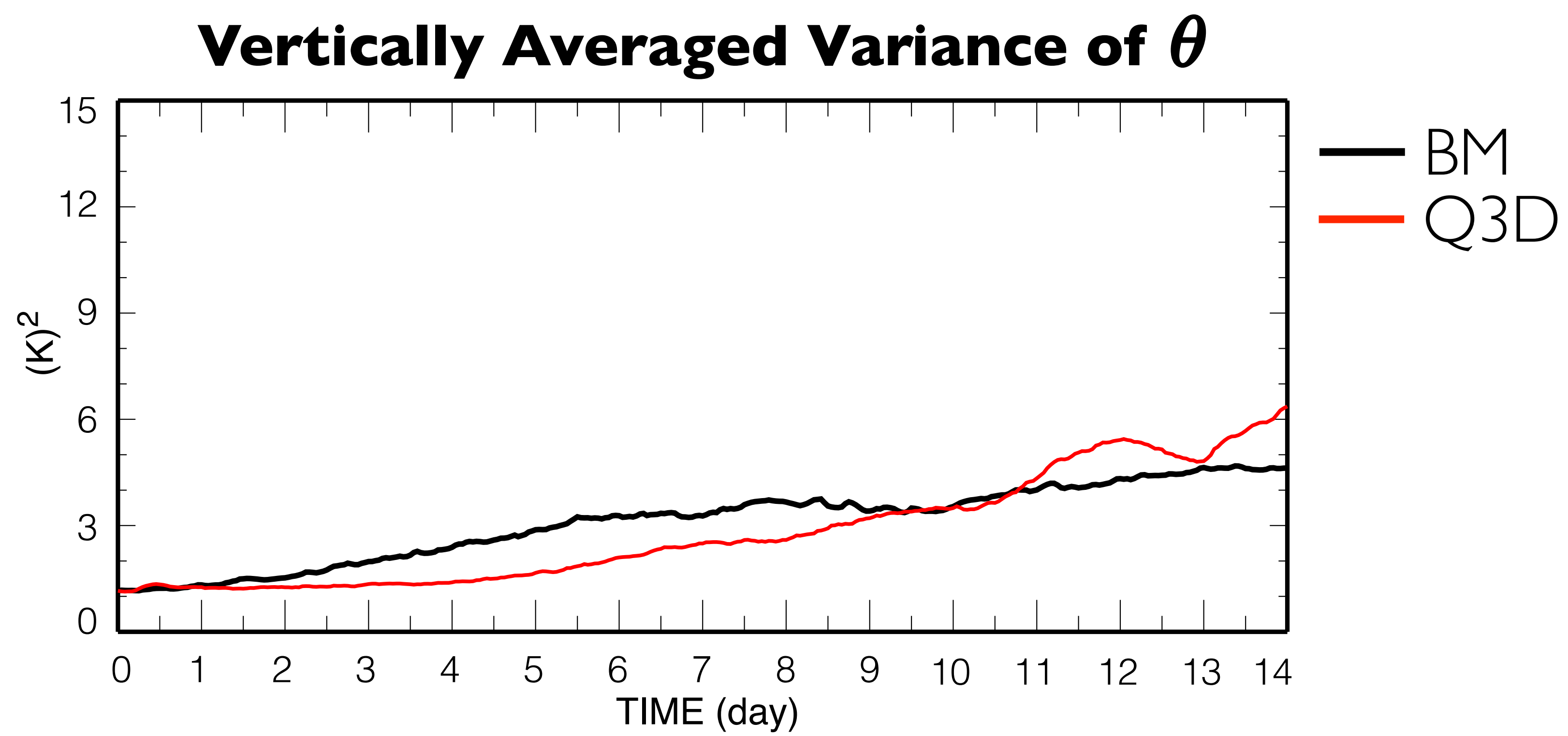
Domain Averages

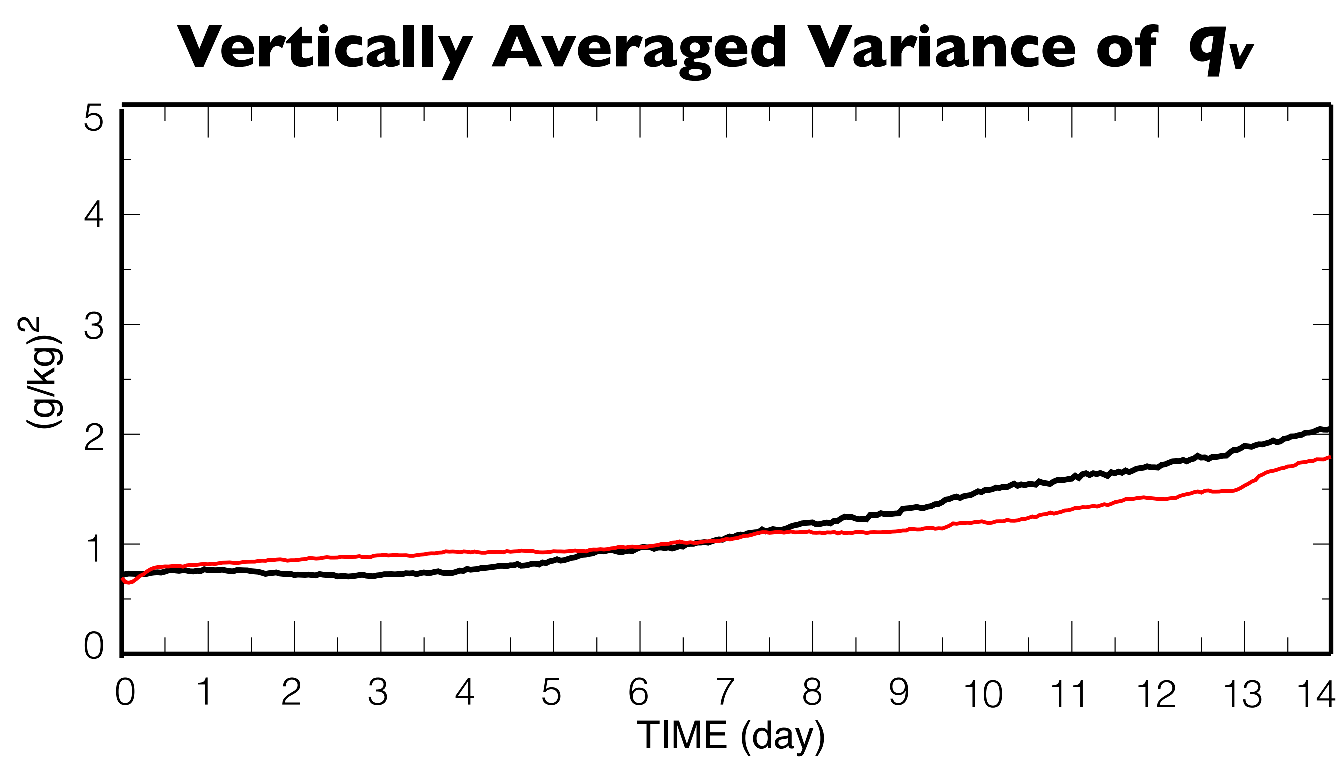


Comparable in general.

Q3D MMF Simulation Results (Continued.)

Variances



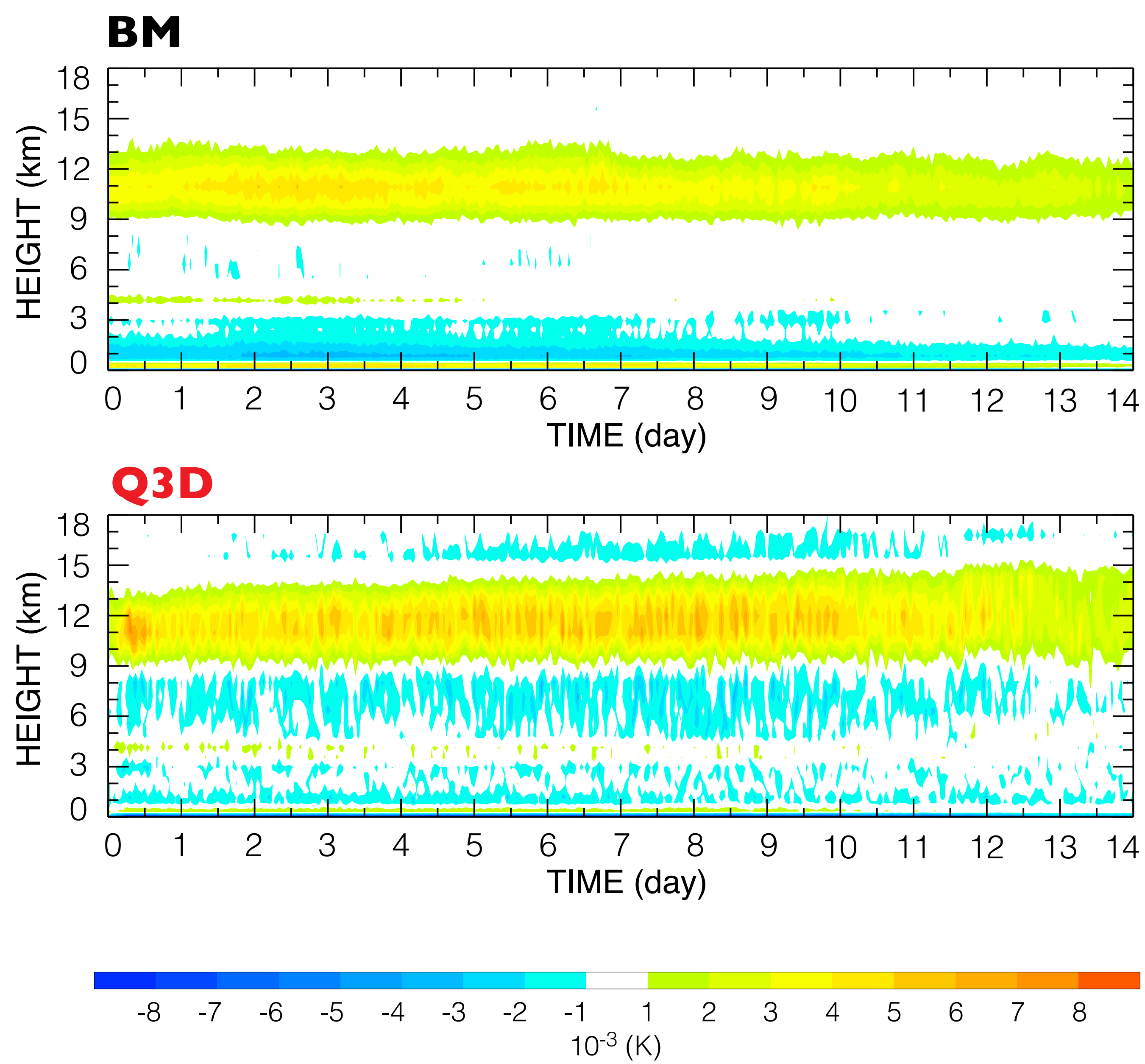


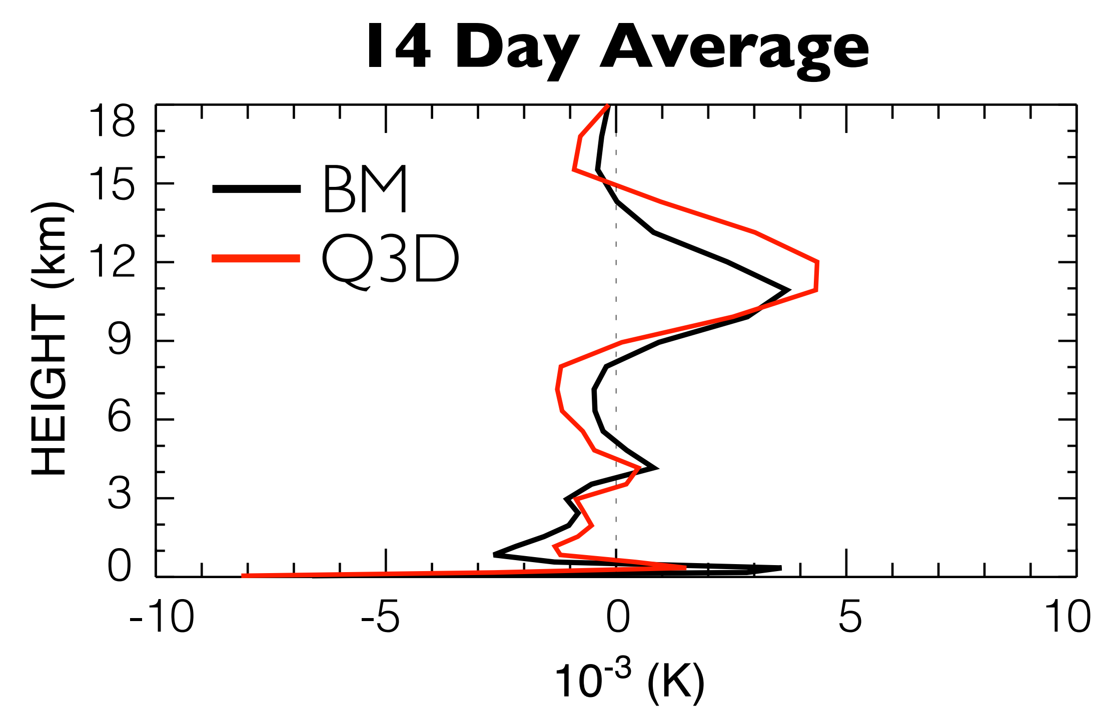
Intensities of the representative disturbance are well represented.

Q3D MMF Simulation Results (Continued.)

Eddy Transport Effect: $\Delta\theta$

Potential temperature change due to the convergence of the vertical eddy transports over one GCM time step



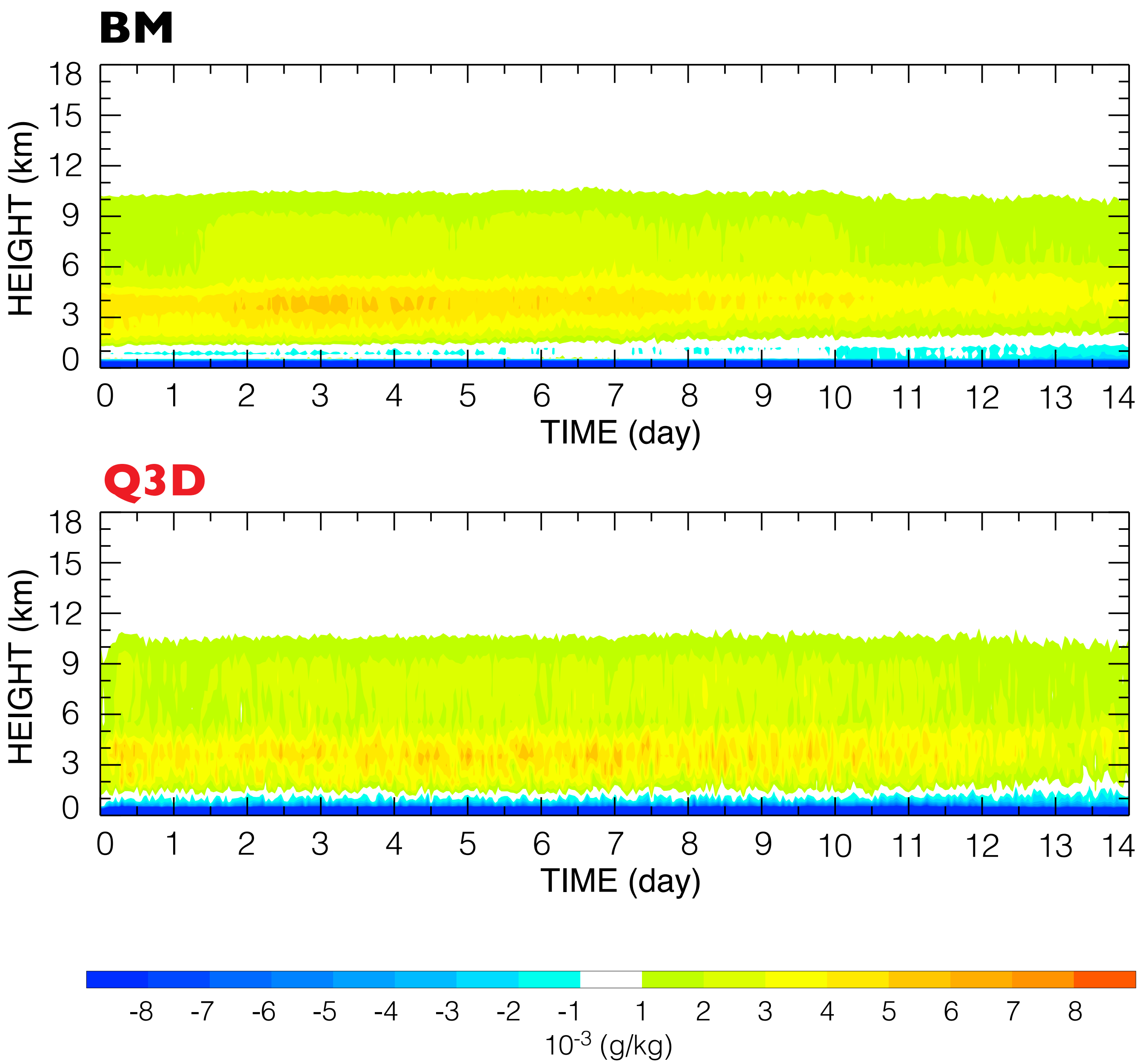


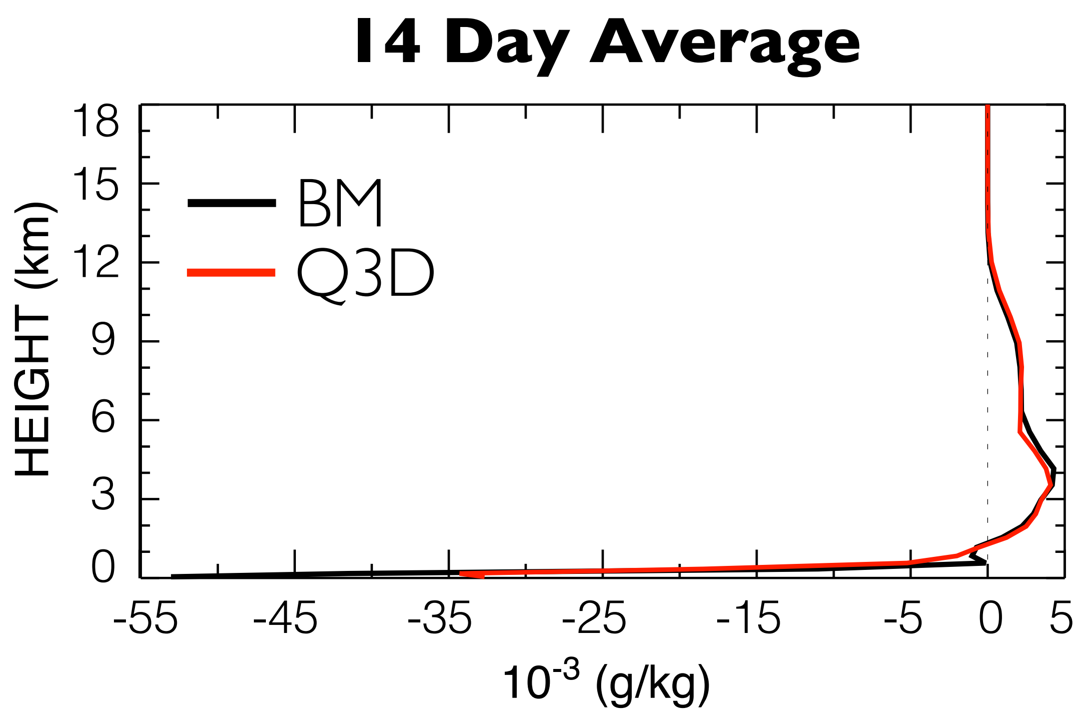
Main features are qualitatively well captured.

Q3D MMF Simulation Results (Continued.)

Eddy Transport Effect: Δq_v

Moisture change due to the convergence of the vertical eddy transports over one GCM time step

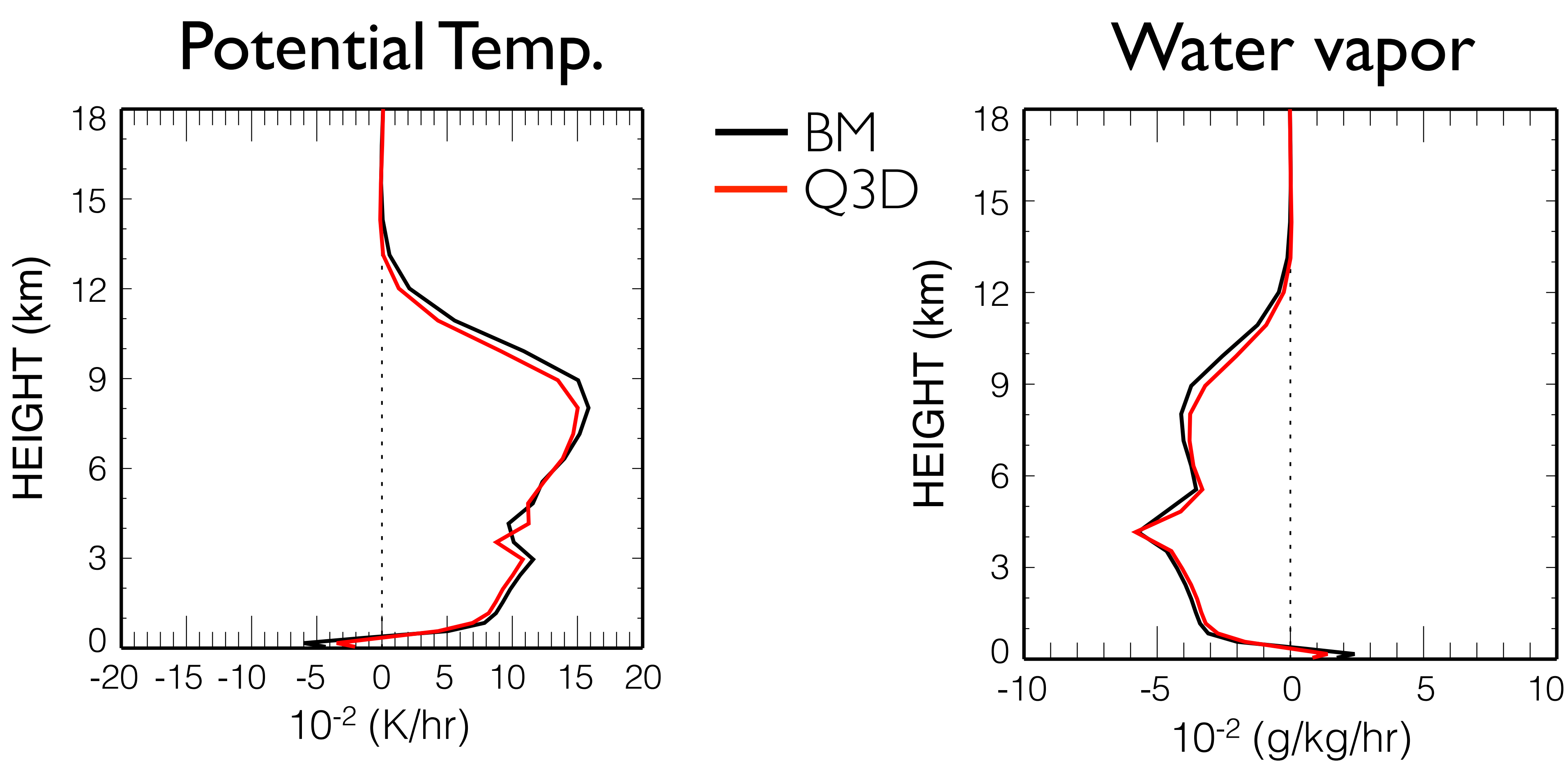




Q3D MMF Simulation Results (Continued.)

14 Day Average

Microphysical Effects



Q3D MMF Simulation Results (Continued.)

Impact of Eddy Effects on Vorticity

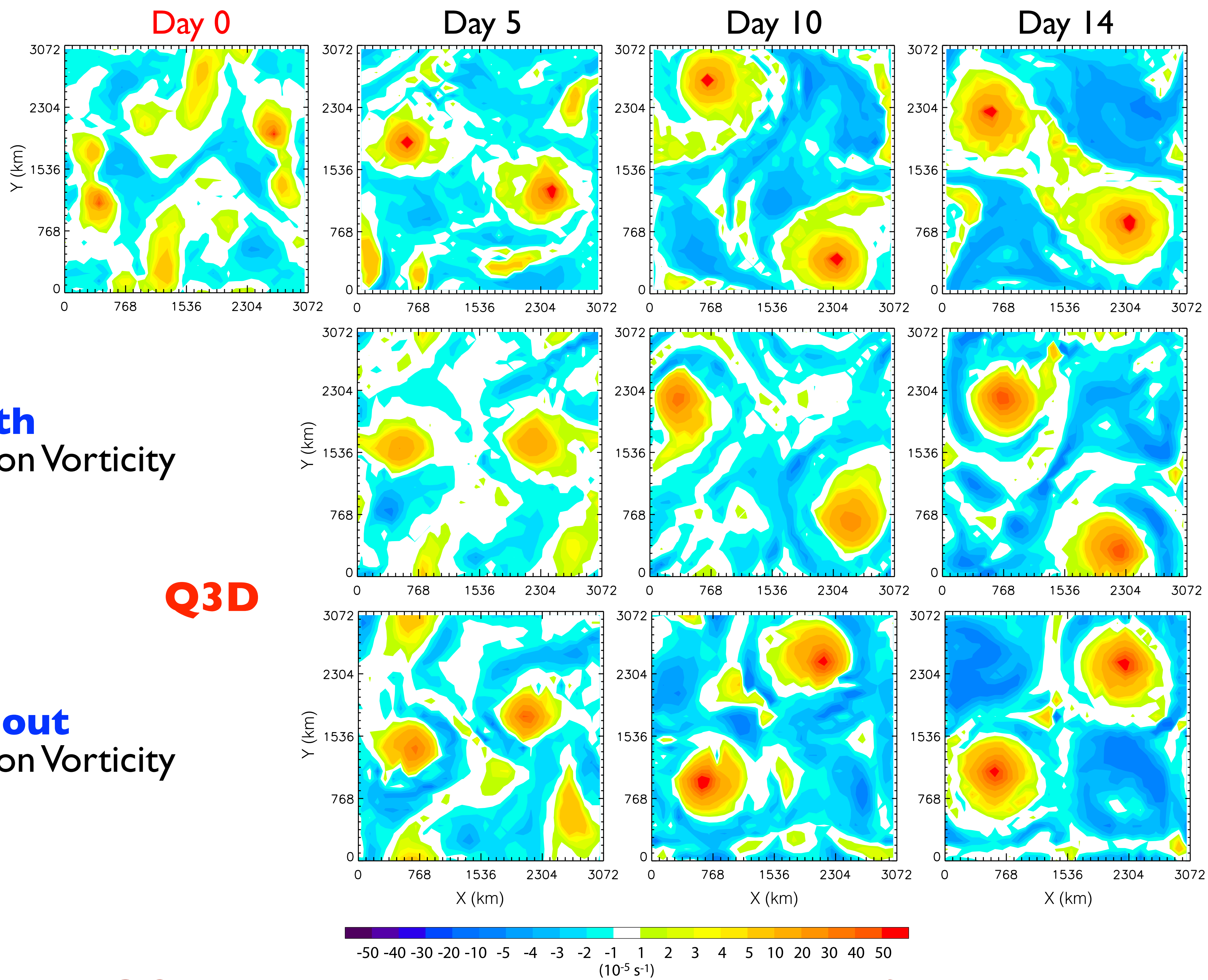
Vertical Component of Vorticity

BM (3-D)

With
Eddy Effects on Vorticity

Q3D

Without
Eddy Effects on Vorticity



With the effects, Q3D MMF captures the location of two vortices

Use of 3-D CRM

vs.

Use of 2-D CRM

(Still uses two perpendicular sets of cloud resolving channels, but does not recognize the inhomogeneity across the channel)

3-D CRM vs. 2-D CRM Test

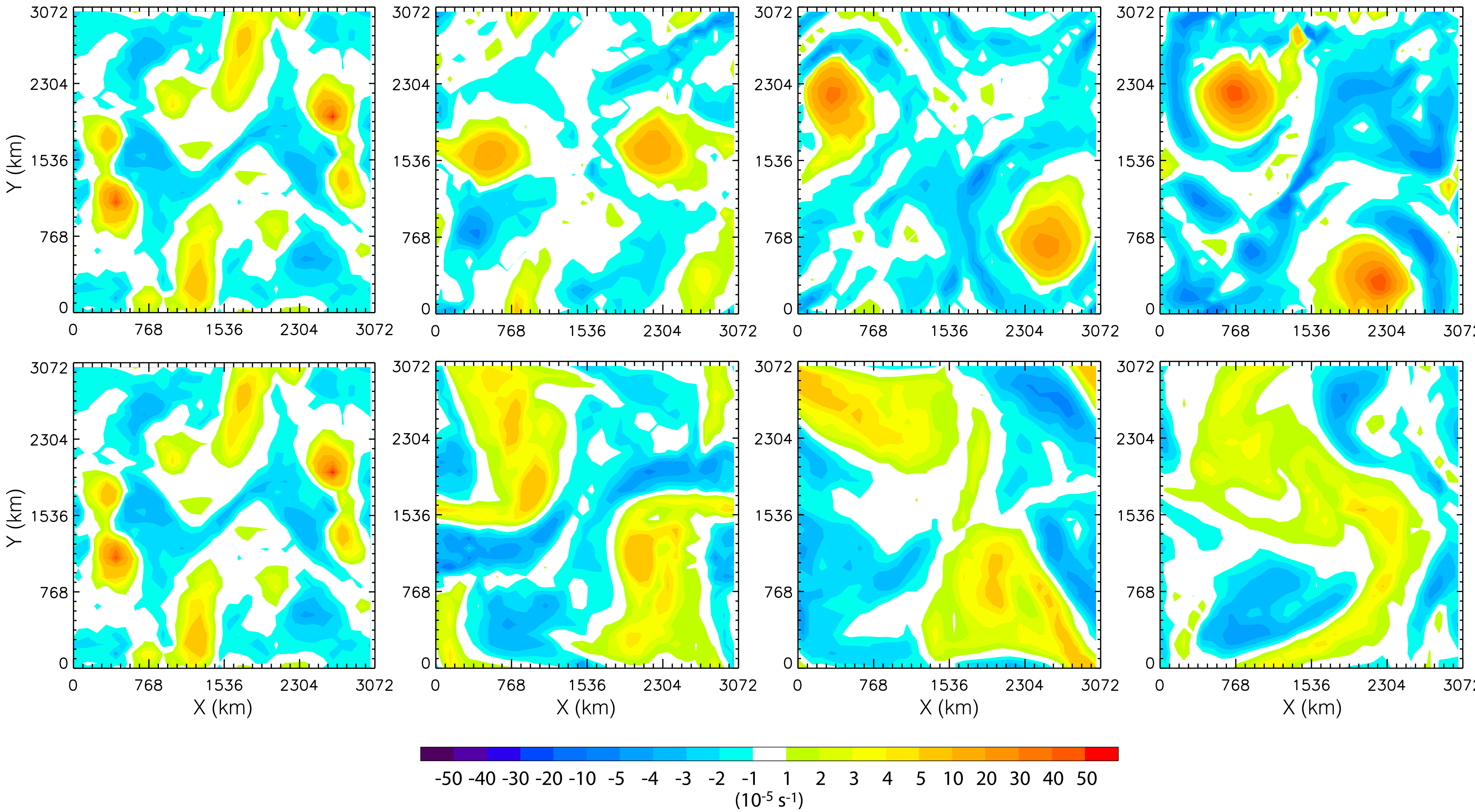
Vertical Component of Vorticity

Day 0 | Day 5 | Day 10 | Day 14

Q3D MMF

3-D CRM

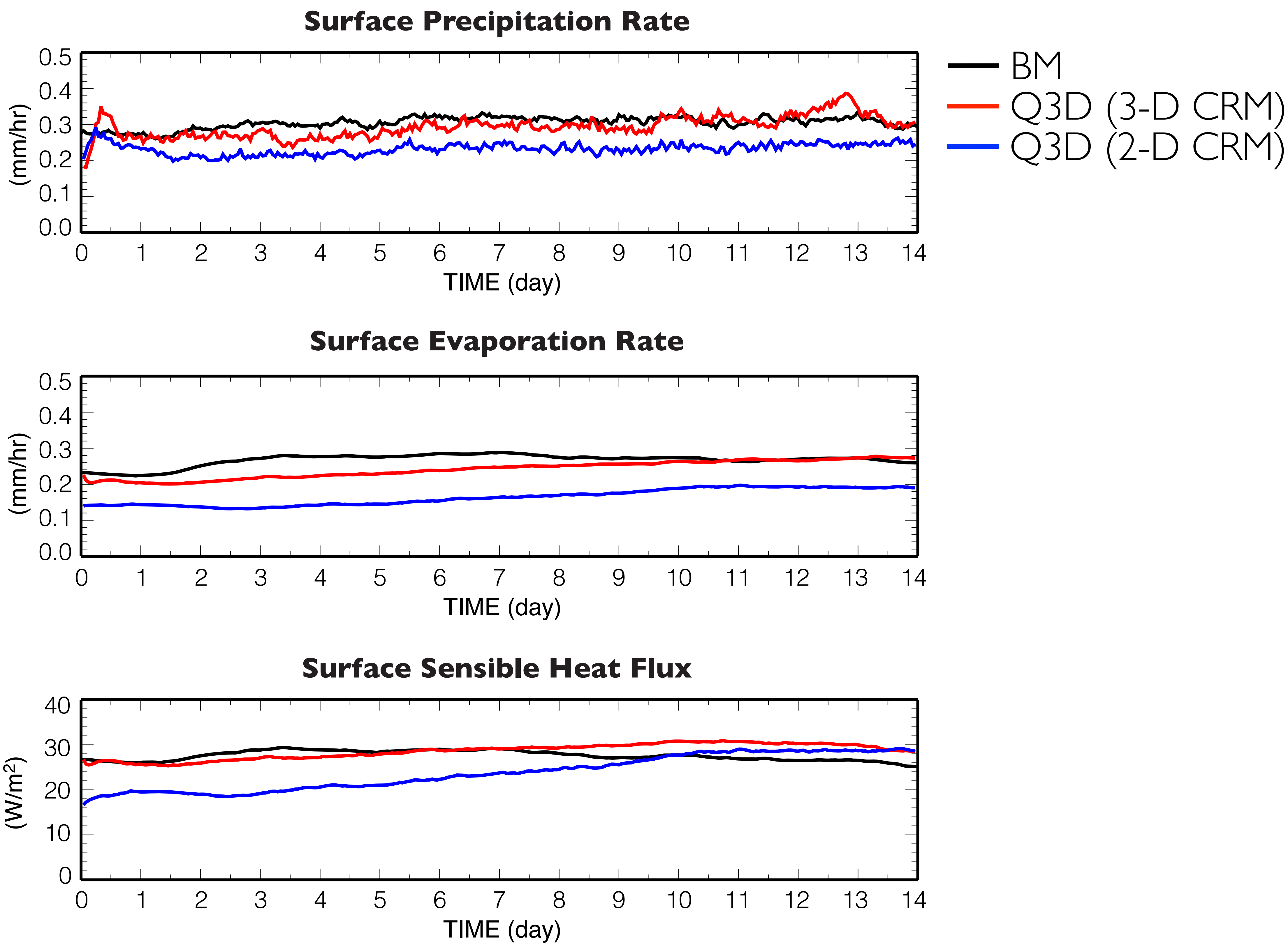
2-D CRM



The recognition of inhomogeneity across the channel through the lateral boundary condition makes the difference.

3-D CRM vs. 2-D CRM Test (Continued.)

Domain Averages



Considerably under-predicted in the 2-D case

Summary

- **As an attempt to overcome the limitations of the prototype MMF, a quasi 3-D MMF is constructed.**
  - To satisfy the convergence requirement, the CRM grid channels are extended beyond the GCM grid size.
  - The GCM effects on the CRM and the CRM effects on the GCM are formulated to eliminate the possibility of "double counting".
  - The current Q3D algorithm is computationally stable for a long-term integration as long as the solutions of GCM and CRM are compatible.

- **To evaluate the Q3D MMF, the model has been used to simulate the formation of tropical cyclones in an idealized domain.**
  - The simulation results are rather sensitive to the relaxation timescale. But, as long as this timescale is determined with the horizontal advective time scale, the Q3D MMF produces reasonable predictions.
  - The encouraging results suggest that it has potential as a basic framework for future numerical weather prediction and climate models.