Modeling the Moist-convective Atmosphere with a Q3D MMF

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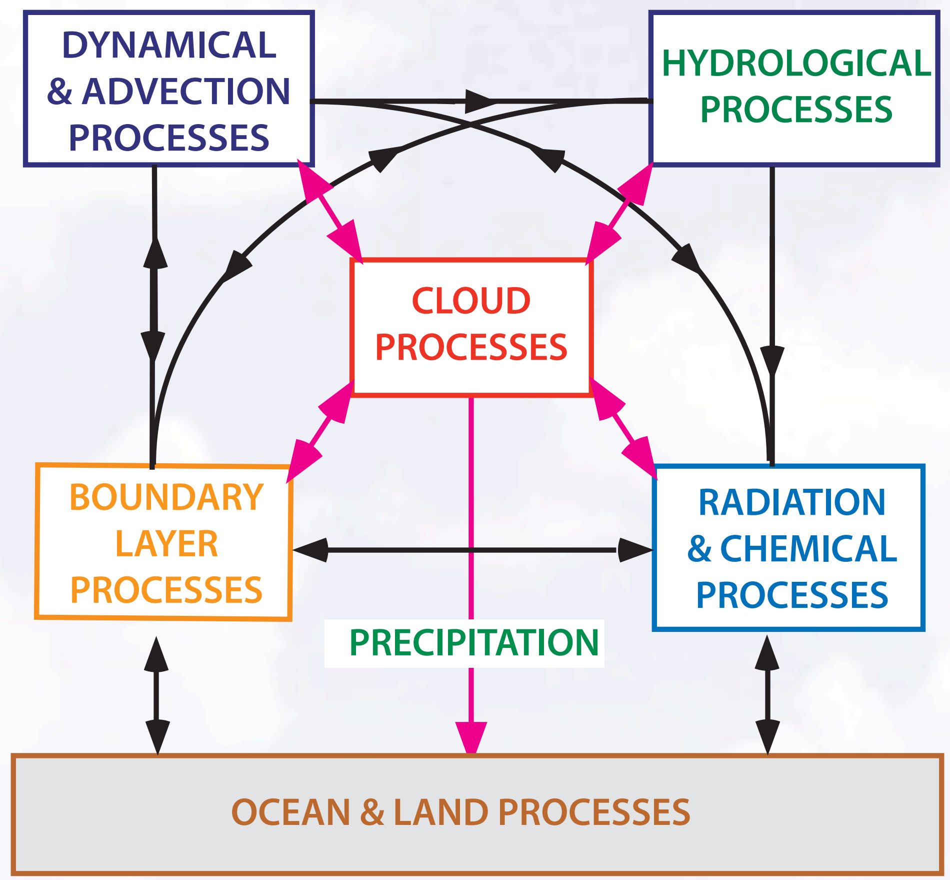
Modeling the Moist-convective Atmosphere

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

Two-way interactions take place on cloud-scale



Taken from Arakawa (2004)

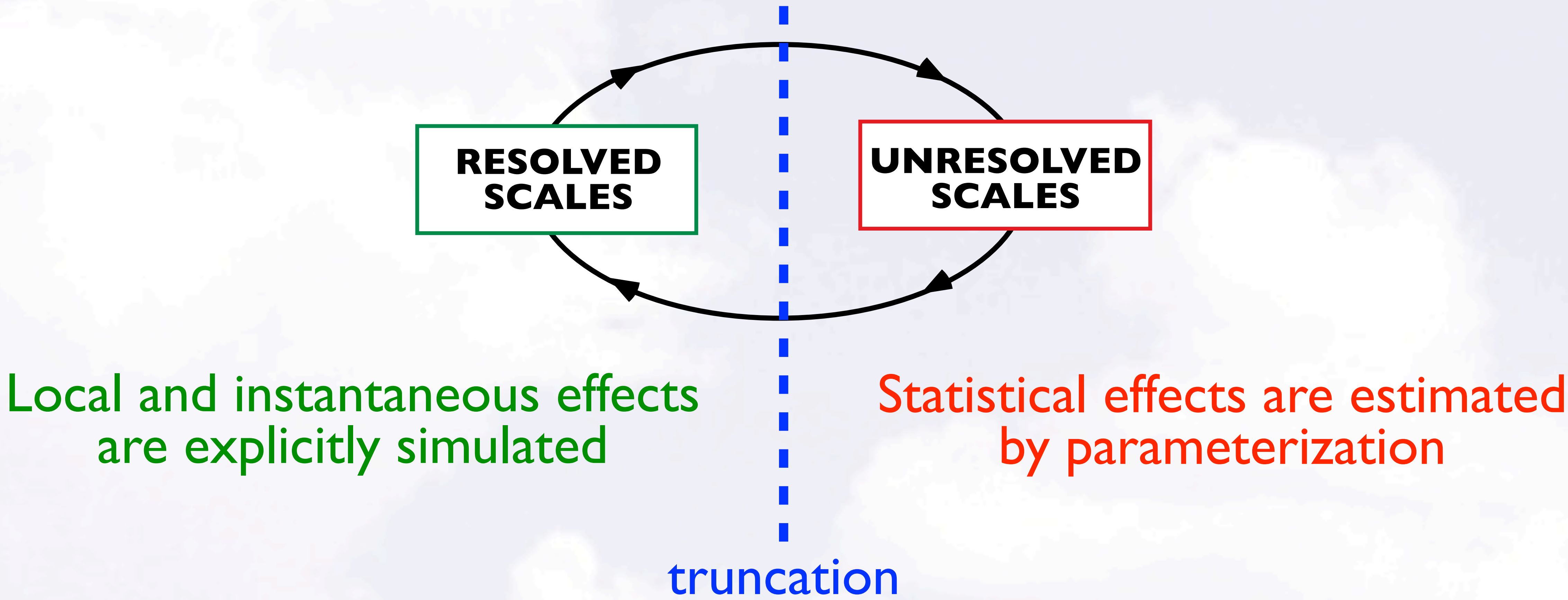
It is extremely challenging to formulate the net effects of these complicated interactions for use in climate models.

Multiscale Aspect of the Moist-convective Atmosphere

Satellite Image Showing Clusters of Clouds

Lots of details as well as large-scale features

Truncation of Continuous System in Modeling



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

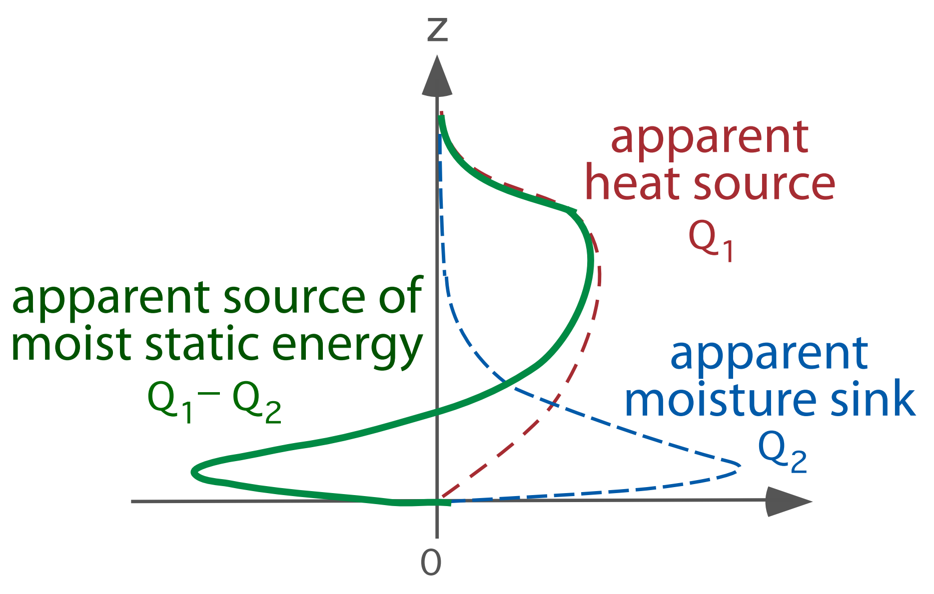
- **Low-resolution models (Conventional GCMs and NWP models)**
  moist convective processes are highly parameterized
- **High-resolution models (CRMs)**
  moist convective processes are explicitly represented

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

Typical Profiles of Moist Static Energy Source due to Deep Convection

Required Source for GCMs

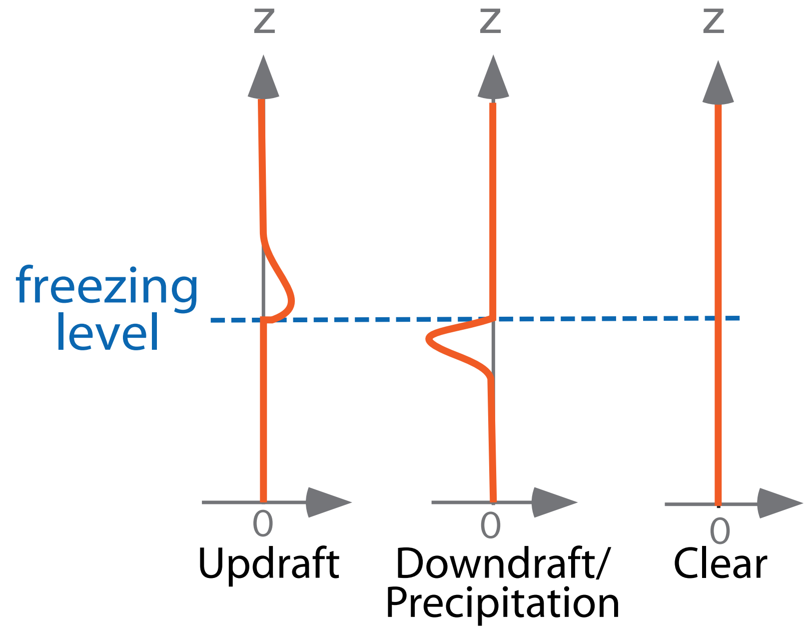
From observed large-scale heat and moisture budgets



GCM-type profile

Source for CRMs

From local cloud microphysics



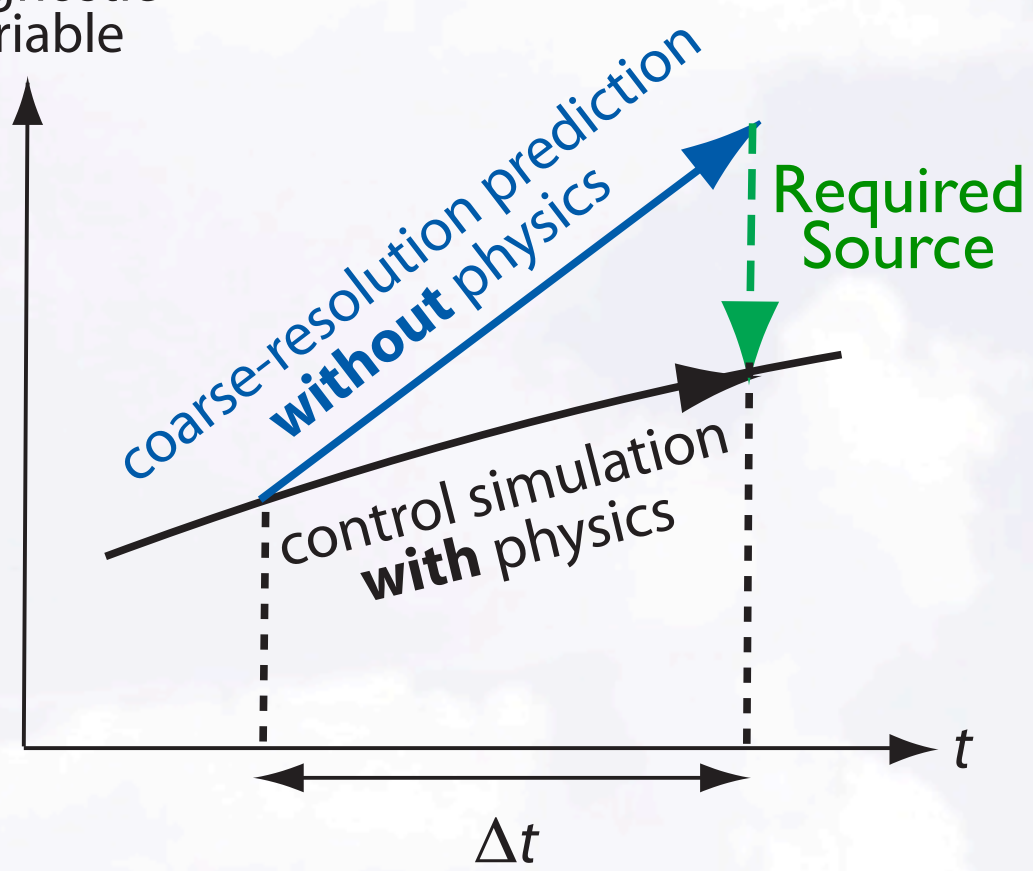
CRM-type profiles

The conventional formulation of model physics is valid only for a specific range of resolutions
(i.e., non-convergence of required source to real source).

Empirical Evidence for the Transition of Model Physics

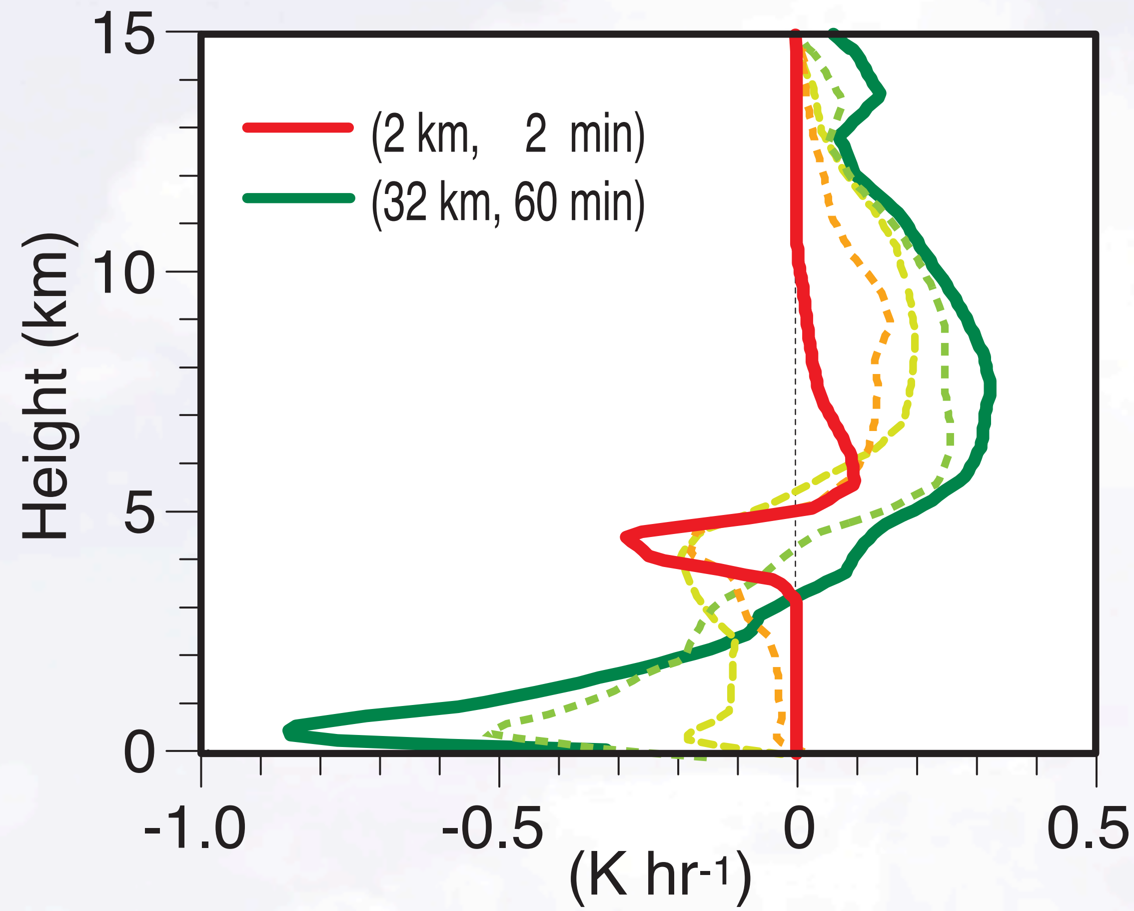
Jung and Arakawa, 2004

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

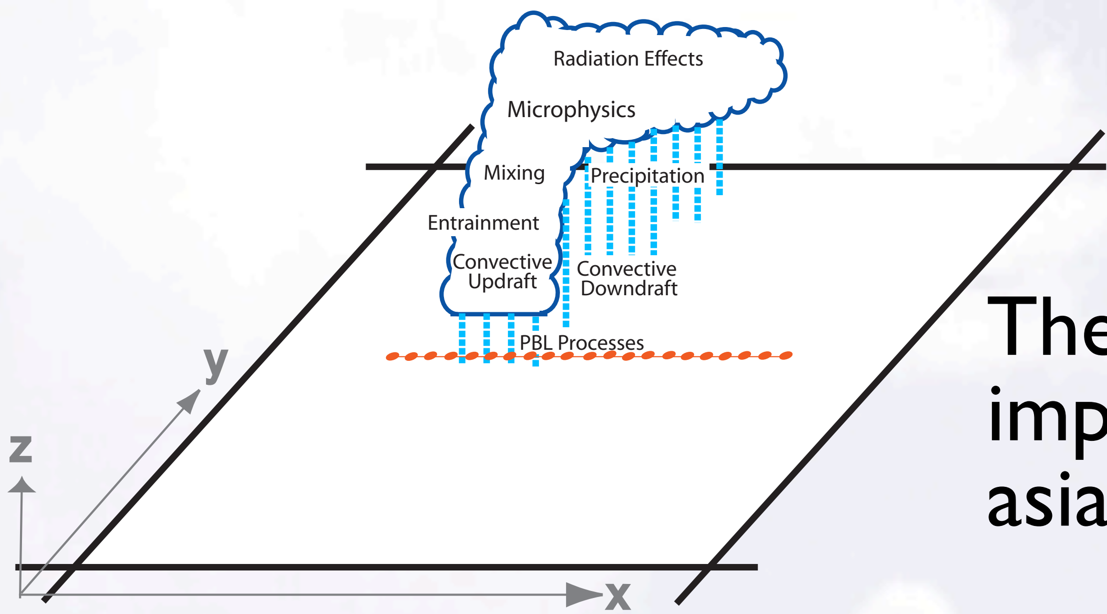
Average Profiles of "Required" Source for Moist Static Energy



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

Multiscale Modeling Framework (MMF)

A new approach trying to improve the representation of cloud processes by using the simulated statistics instead of the conventional parameterization.



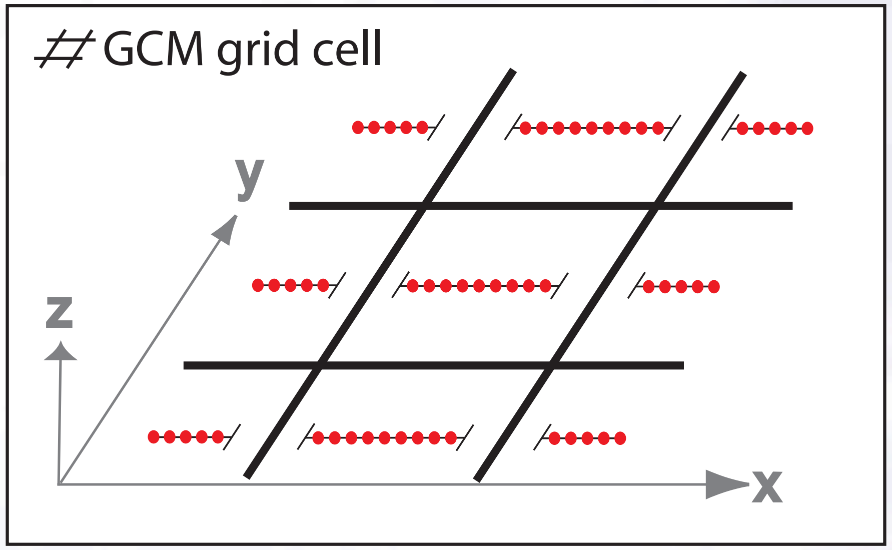
The prototype MMF has been shown to improve the representation of diurnal cycle, asian monsoon, and MJO.

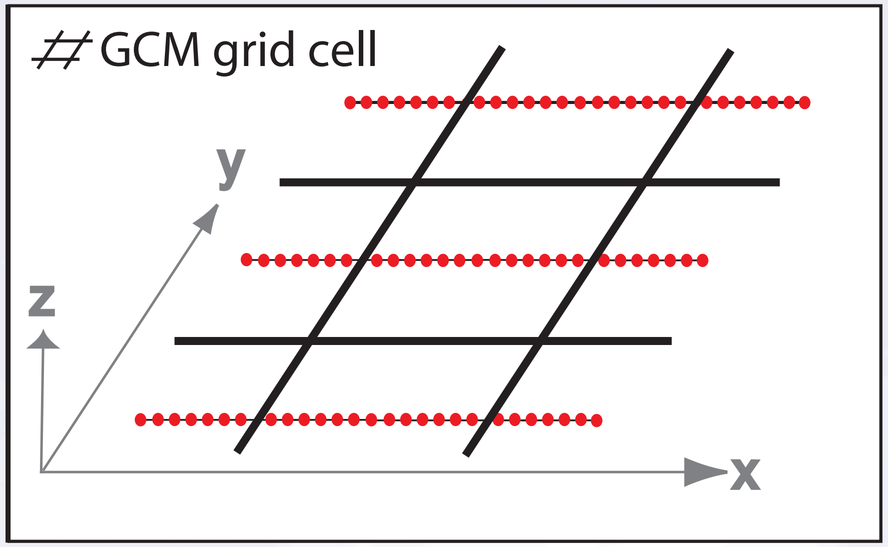
But, there are inherent limits:

- No three-dimensionality
- Need to choose a particular direction for the CRM
- Confinement of CRM with a cyclic boundary condition

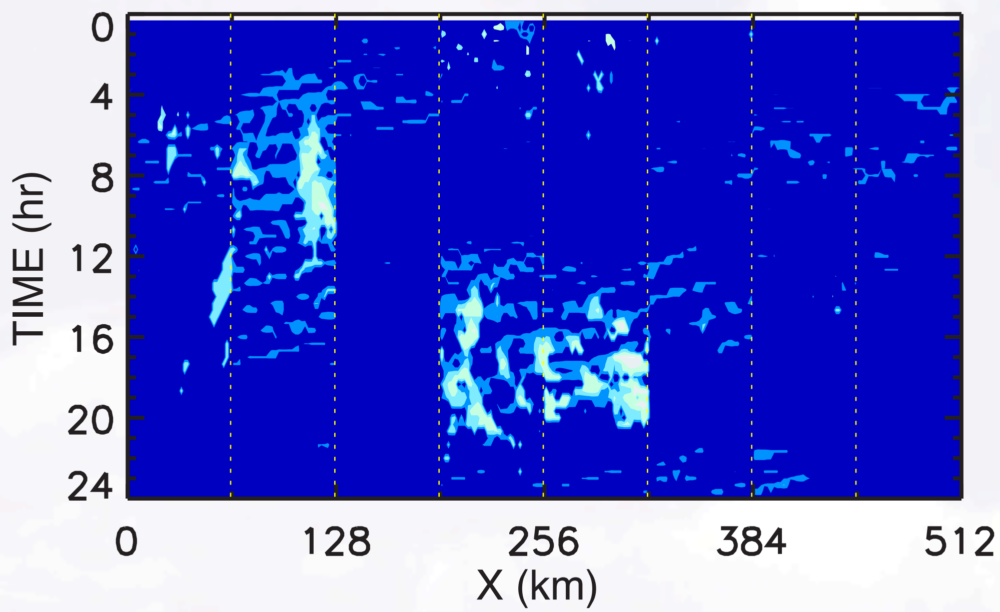
Convergence of required source to real source is not expected.

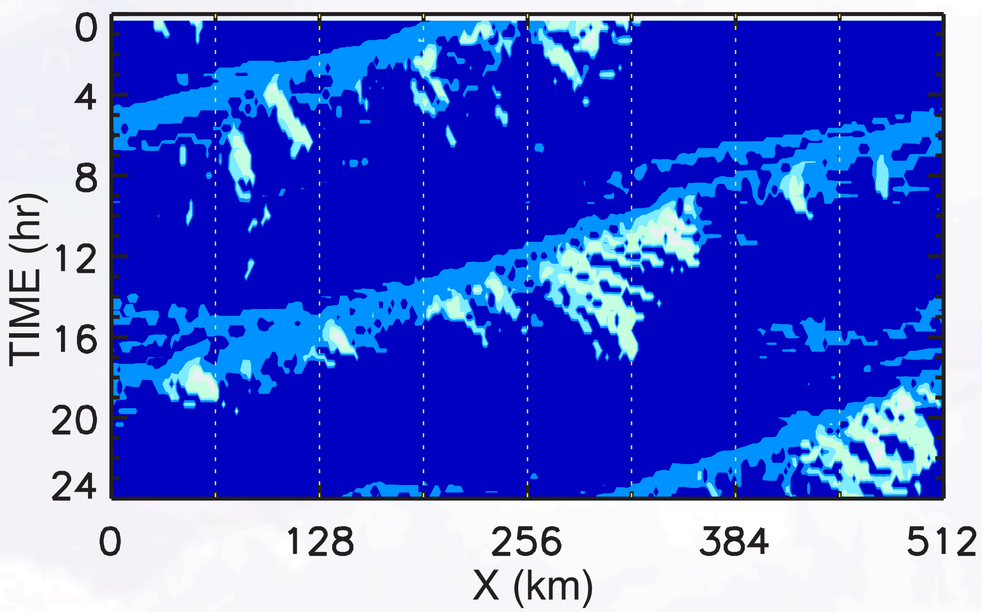
Embedded 2-D CRM *vs.* Extended 2-D CRM





Idealized test by Jung and Arakawa (2005)
Examples of simulated cloud top temperature

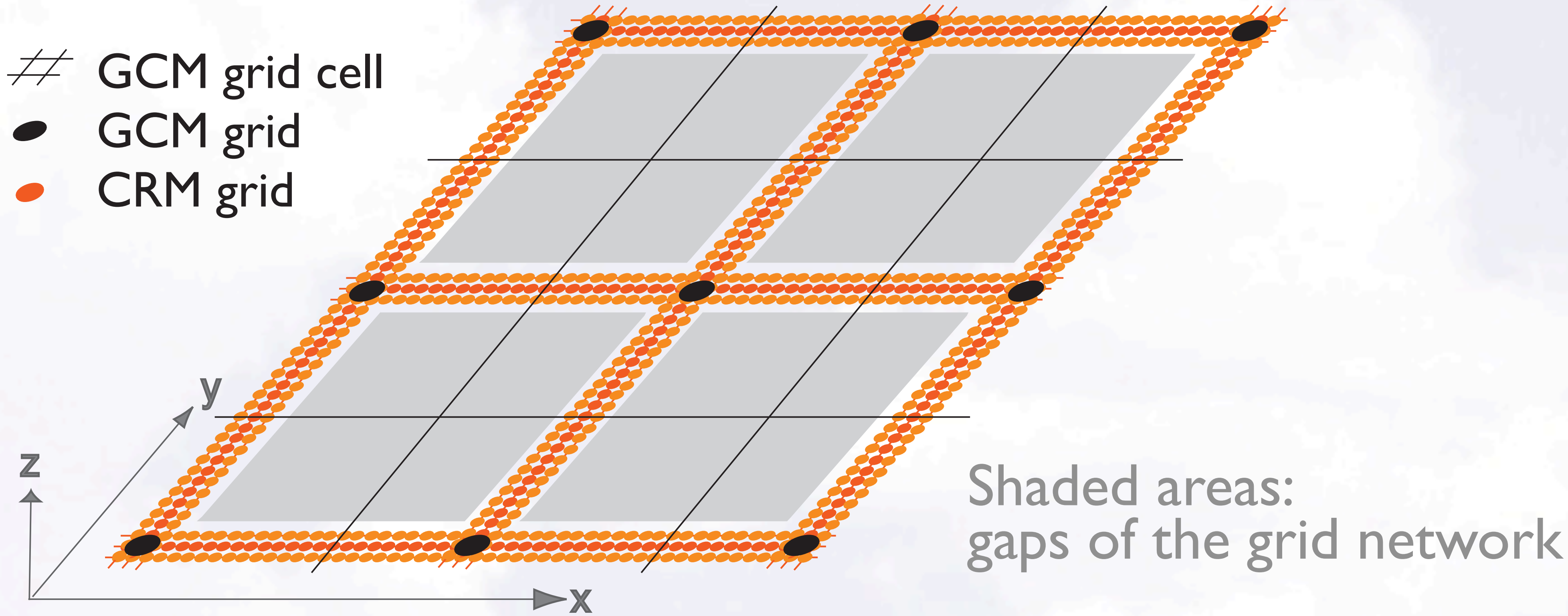




In the embedded MMF, clouds cover a relatively smaller area and thus their time-space averaged activity is weaker.

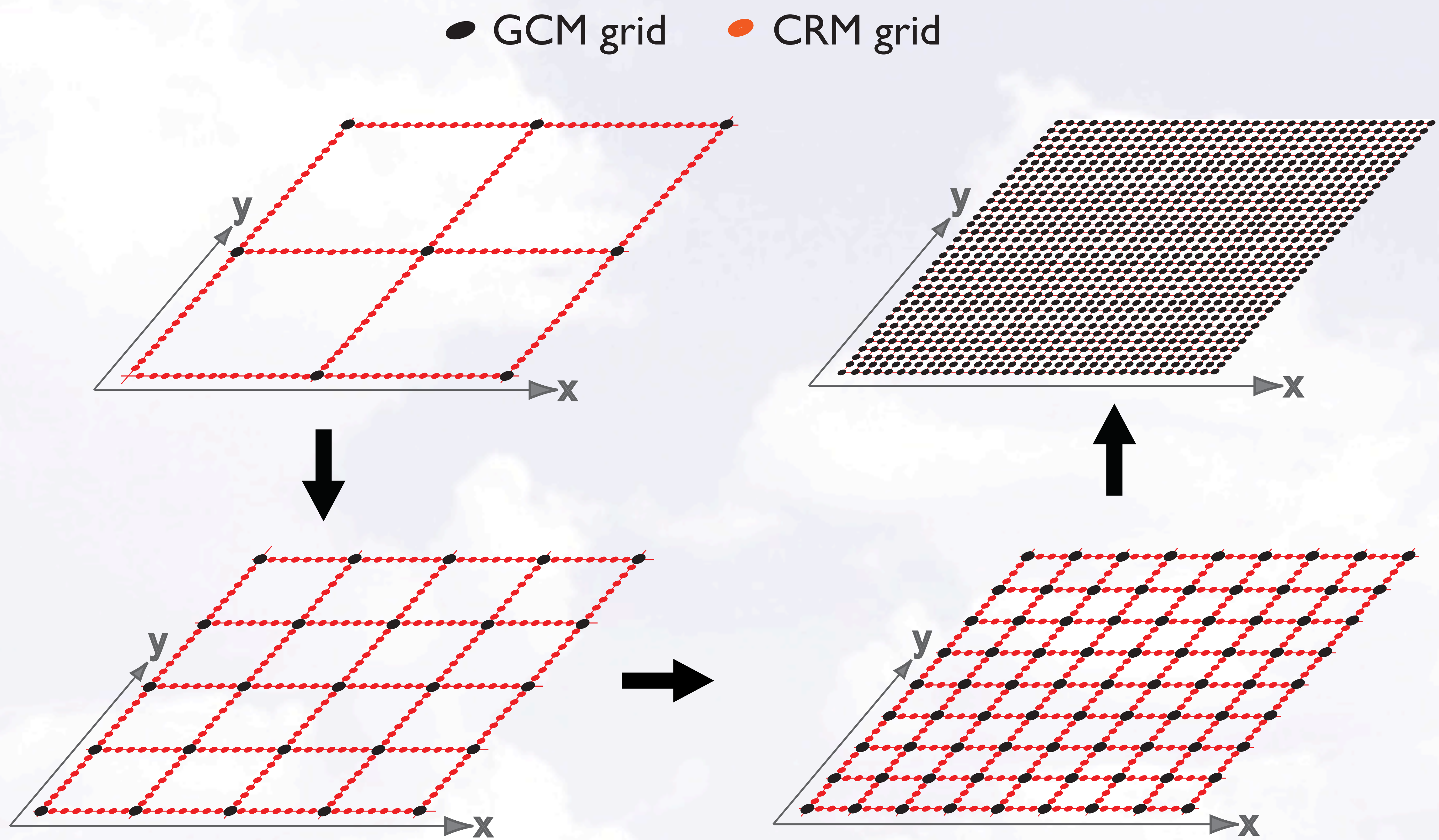
Quasi 3-D MMF

An attempt to broaden the applicability of MMF without necessarily using a fully three-dimensional CRM



- A combination of a GCM grid and two perpendicular sets of cloud-resolving grid channels.
- Perpendicular channels interact through the GCM.
- At all CRM grid points, formally 3-D predictions are made.

Convergence of the Quasi 3-D Grid System to a 3-D Grid



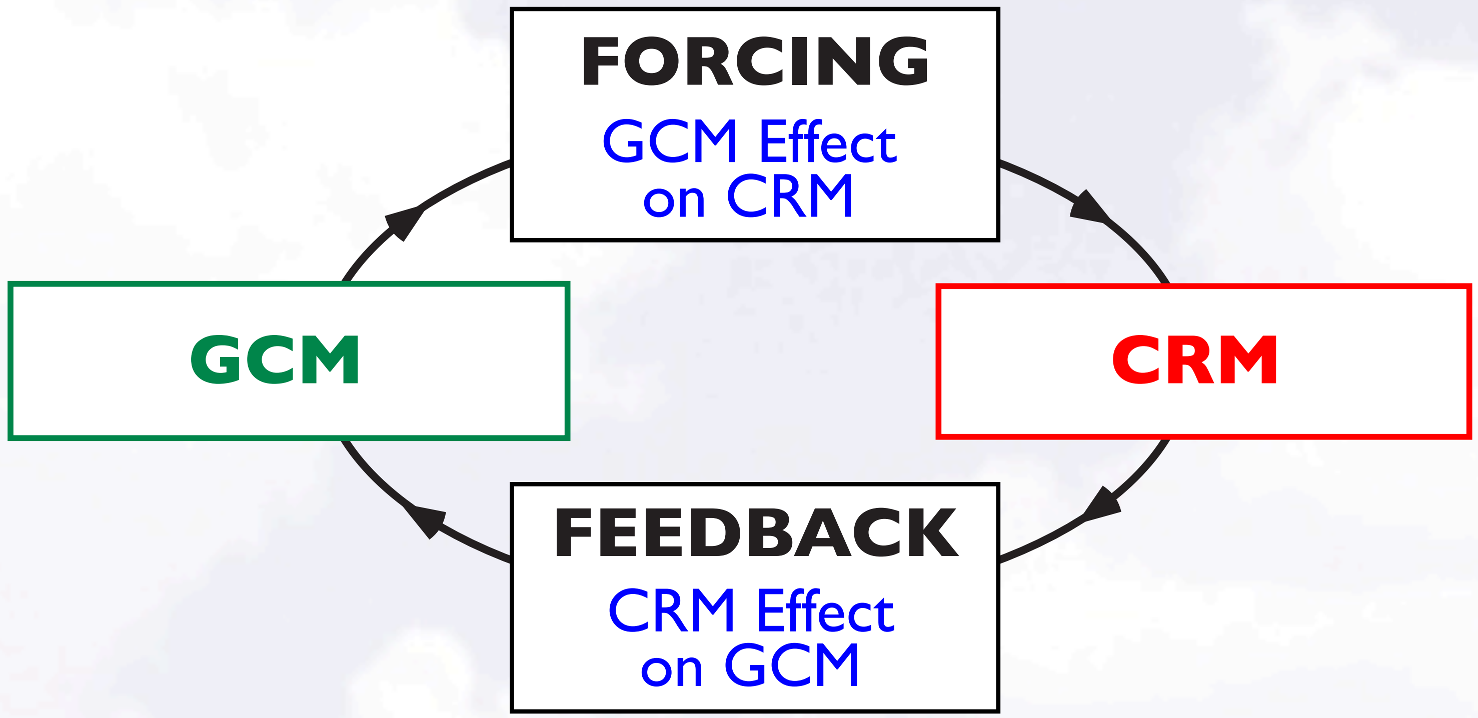
GCM grid size can be freely chosen without changing the formulation of model physics.

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 CRM.
  - Bulk three-phase microphysical parameterization
  - Radiation parameterization
  - Turbulence parameterization (1st-order closure)
- Only large-scale condensation is included in GCM.

Coupling the GCM and CRM Components



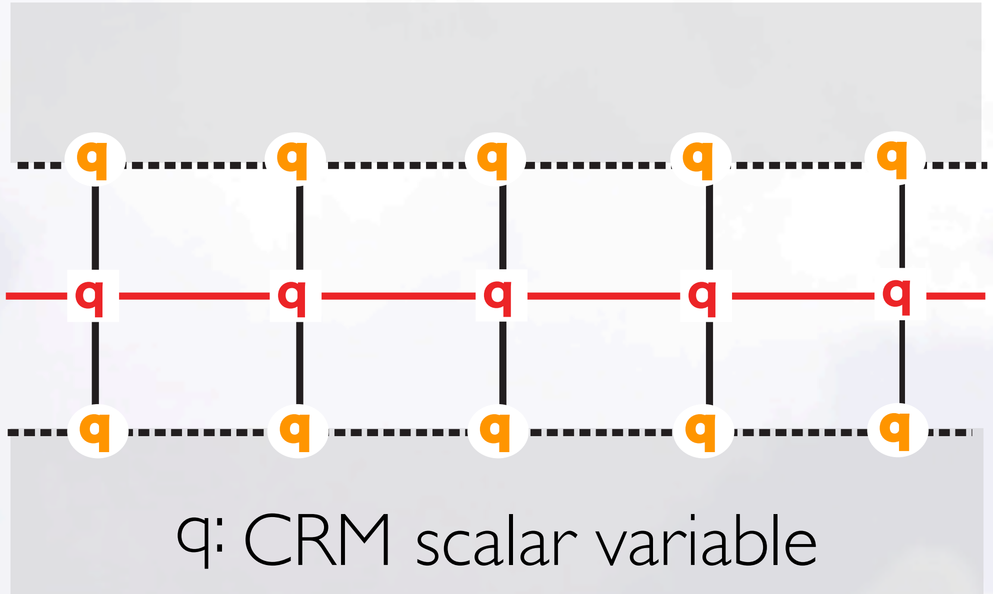
MMF (Q3D MMF) inherits the structure of the conventional GCMs, while the conventional cumulus parameterization is replaced with explicit simulations of cloud-scale processes.

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 effect on CRM

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

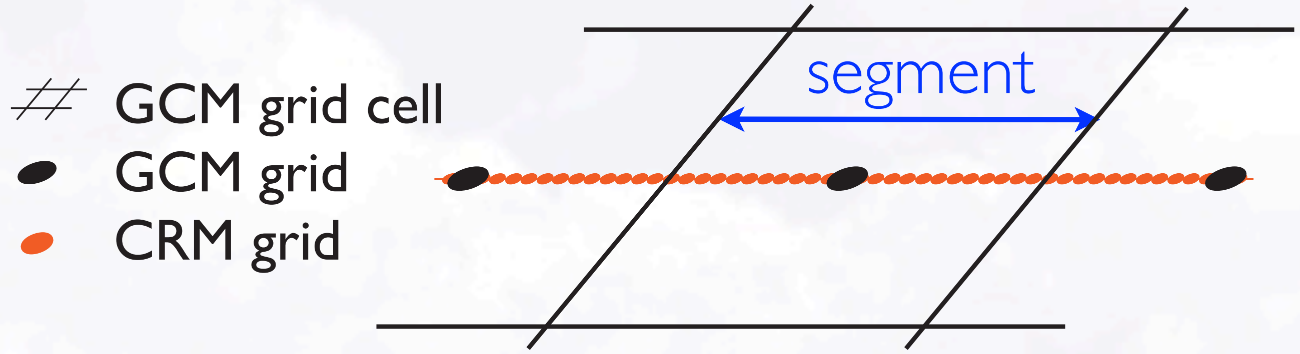


Decomposition of variable: $q = \overline{q} + q'$

$\overline{q}$: 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 relaxation time scale 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.

- What determines the relaxation time scale?
  (Will be answered along with the sensitivity test results later)

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

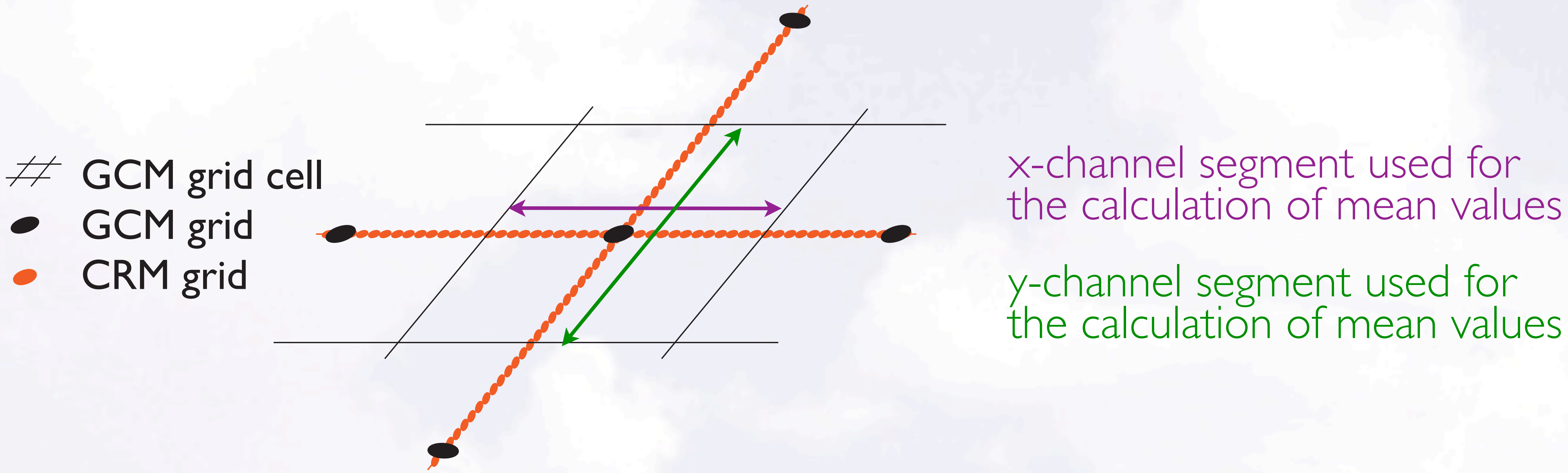
- Having uniformly distributed grid network, the GCM is supposed to simulate well-behaved three-dimensional large-scale features. The large-scales simulated by the GCM and CRM should be sufficiently close to each other.

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

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

Feedback: CRM effect on GCM

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



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 through the dynamics-convection interaction

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

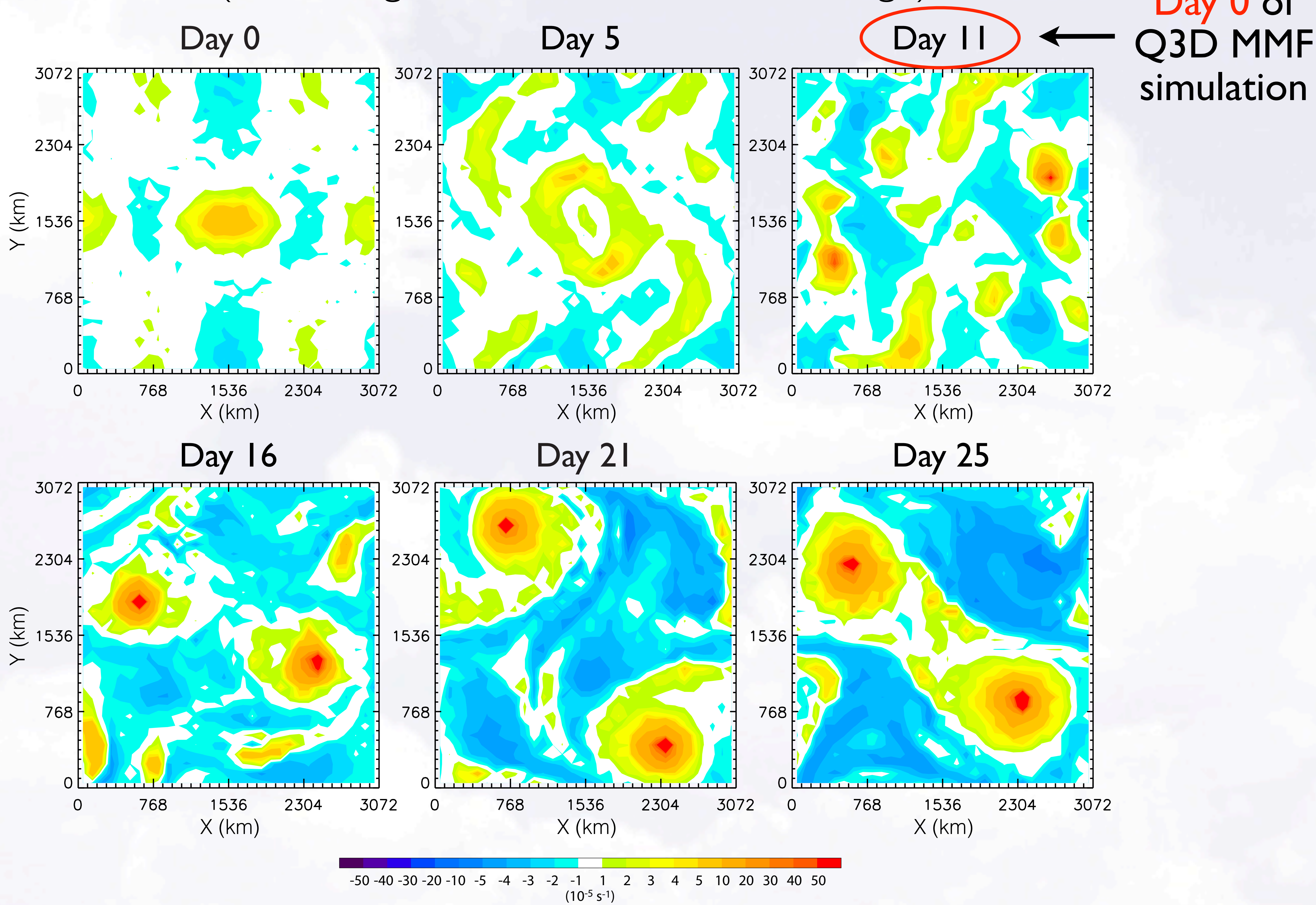
  Horizontal domain: 3072 km x 3072 km, Vertical domain: 30 km
  Horizontal grid: 3 km, Vertical grid: 0.1 ~ 1.7 km (stretched grid)
  f-plane: $f_0 = 1 \times 10^{-4}\ s^{-1}$
  Prescribed radiative cooling rate
  SST = 302 K
  Periodic boundary condition

- **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:

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

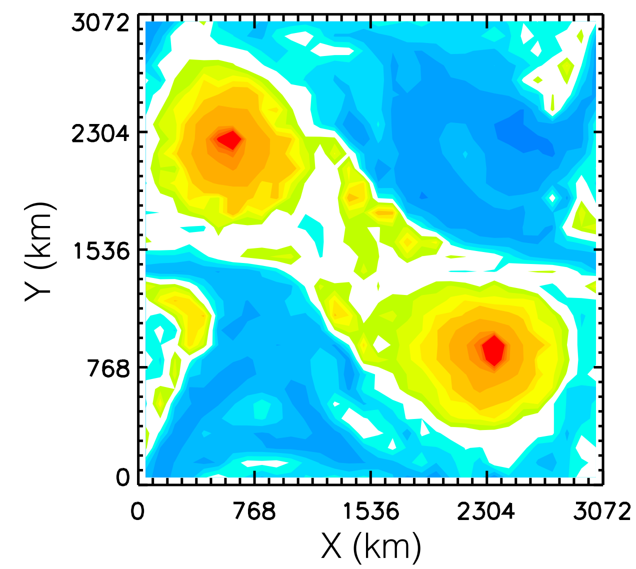
This ratio becomes smaller if the GCM resolution is coarser or the CRM resolution is finer.

Sensitivity to the Relaxation Timescale

Simulated Vertical Component of Vorticity (Day 14)

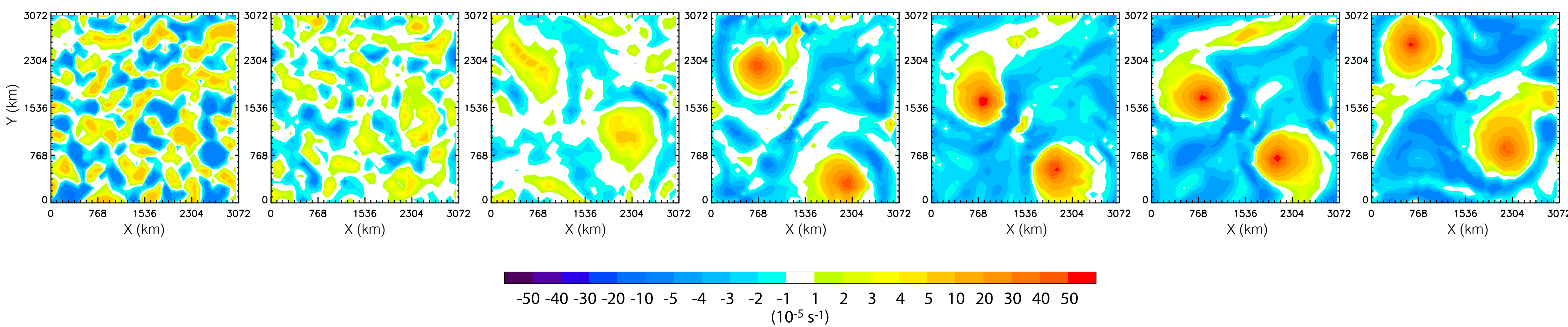
Height ~ 3 km
d_{GCM} = 96 km

BM



Q3D MMF

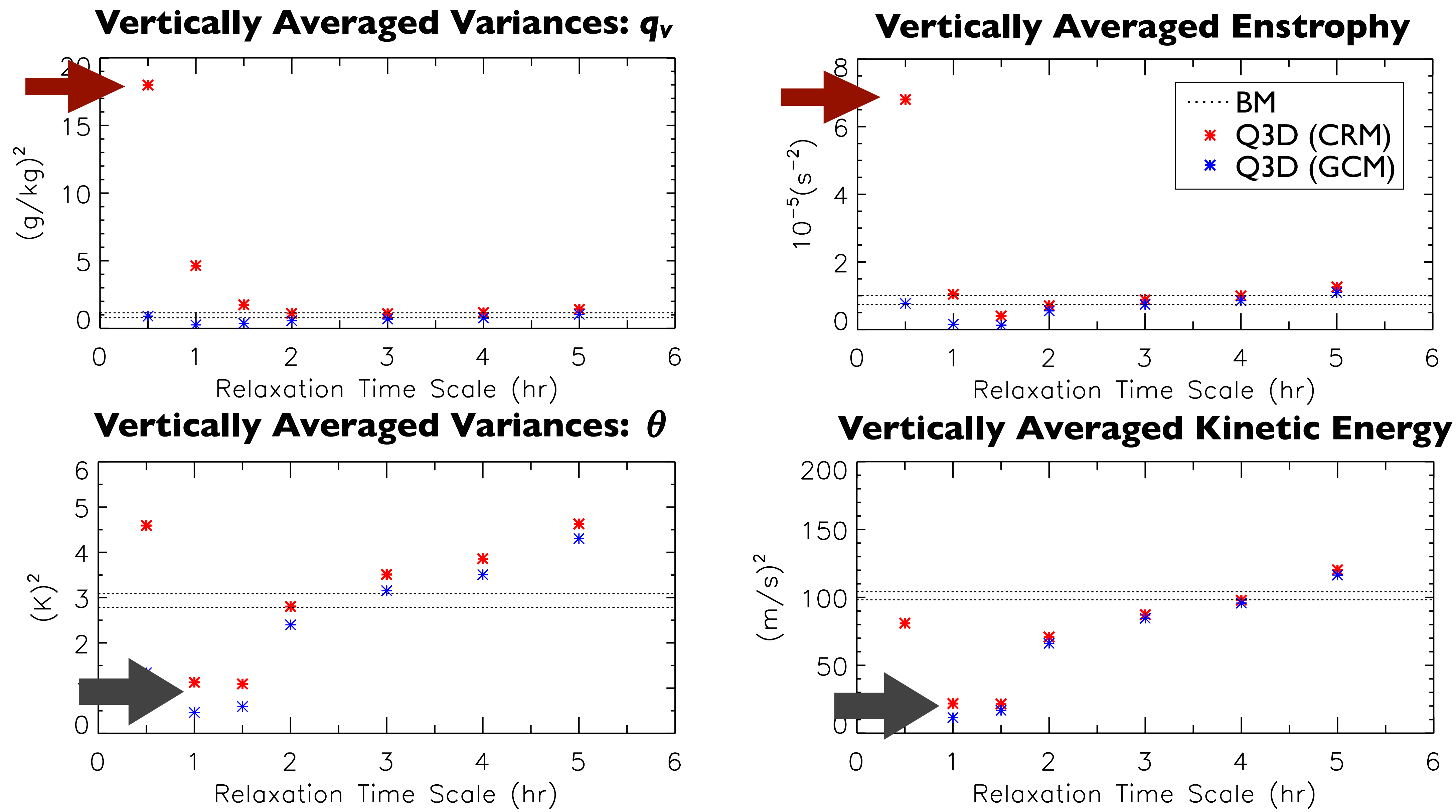
Timescale=0.5hr | Timescale=1hr | Timescale=1.5hr | Timescale=2hr | Timescale=3hr | Timescale=4hr | Timescale=5hr



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

What determines the critical time scale for segment relaxation?

- The critical time scale is determined by the timescale of the mesoscale organization.

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

- For the development of the mesoscale organization, horizontal advection plays an important role.

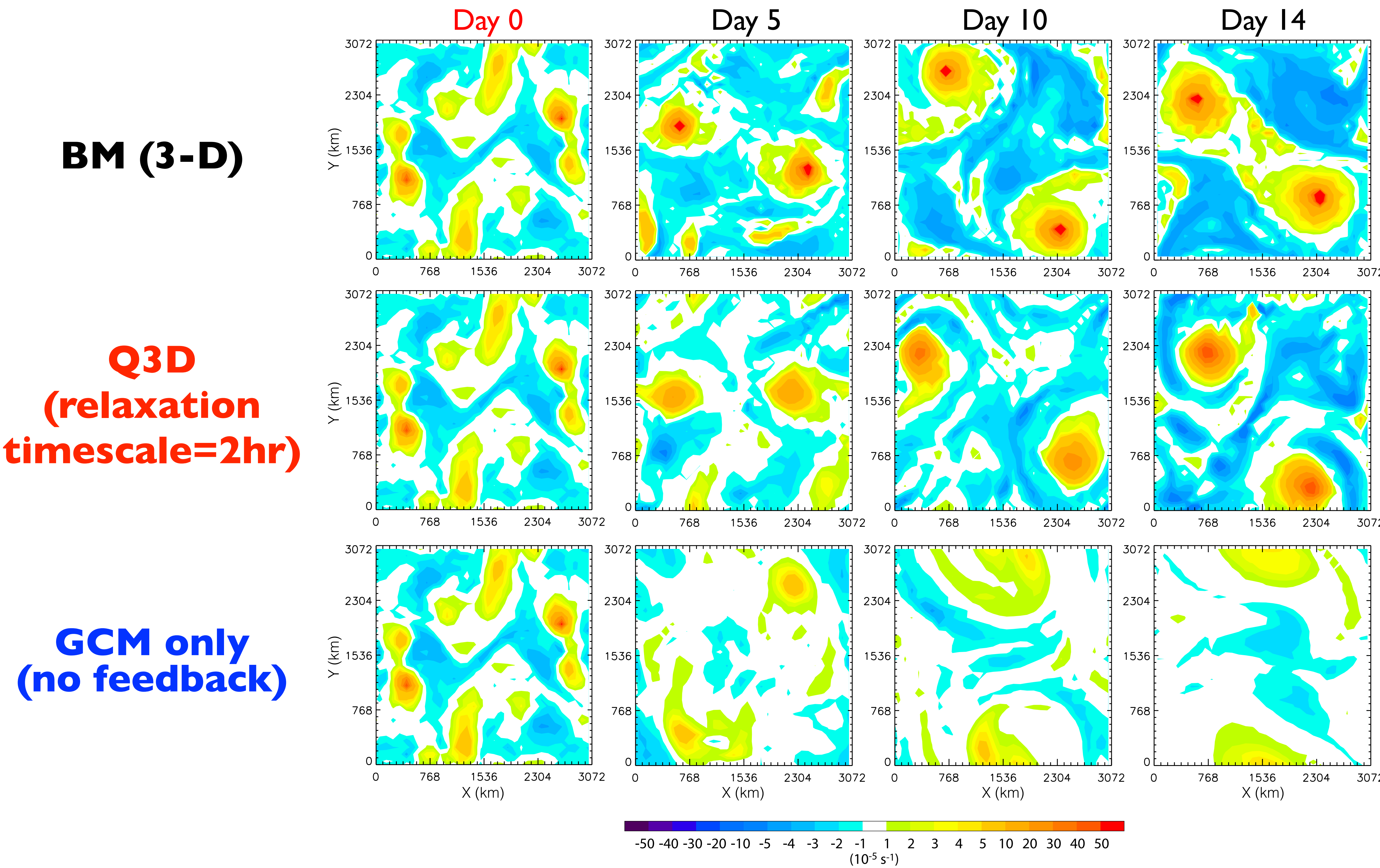
$$\text{Horizontal advection timescale for mesoscale} \lesssim \frac{d}{V}$$

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

If V~15 m/s and d=96km, the timescale $\lesssim$ 1.8 hr

Q3D MMF Simulation Results

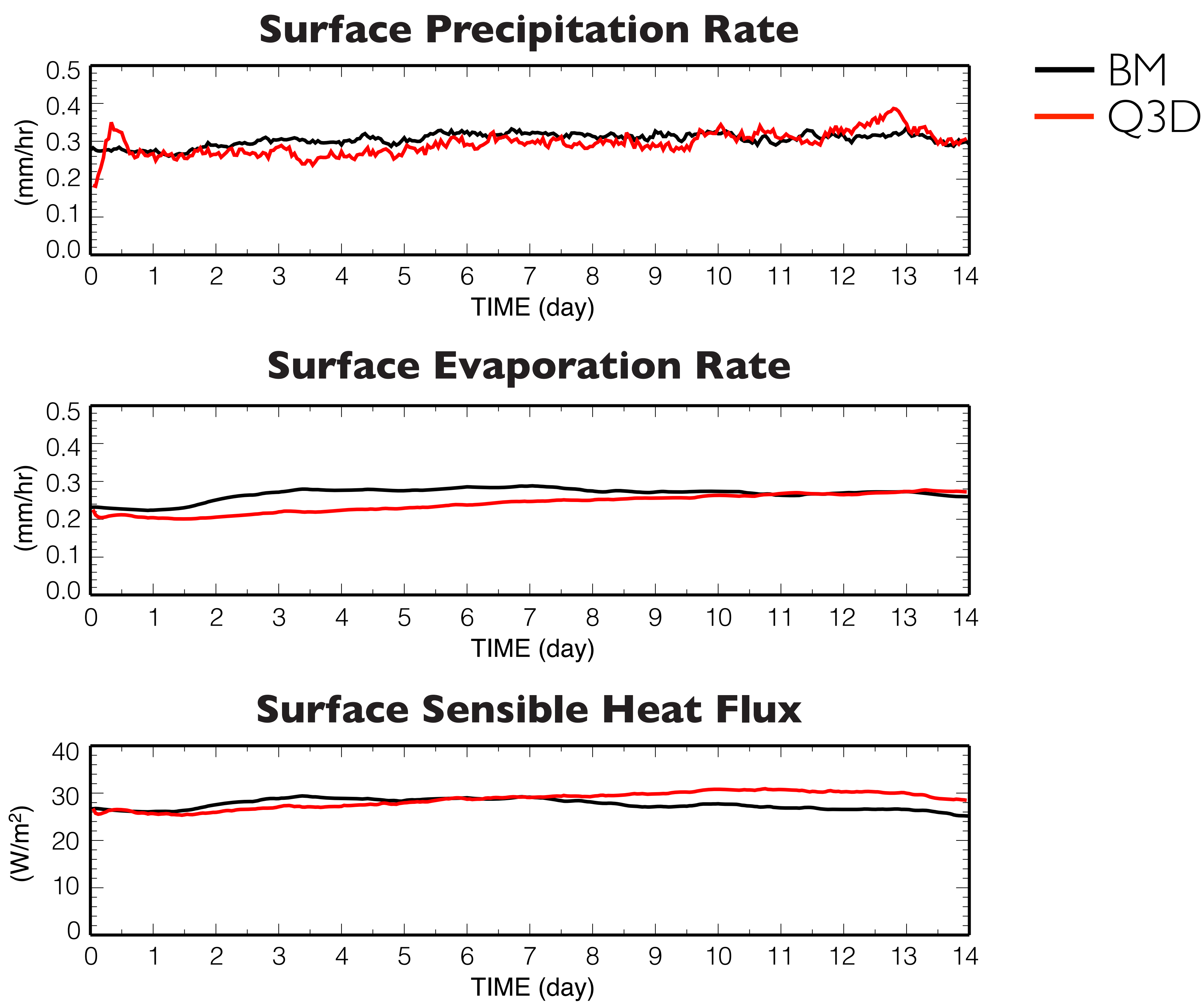
Vertical Component of Vorticity



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

Q3D MMF Simulation Results (Continued.)

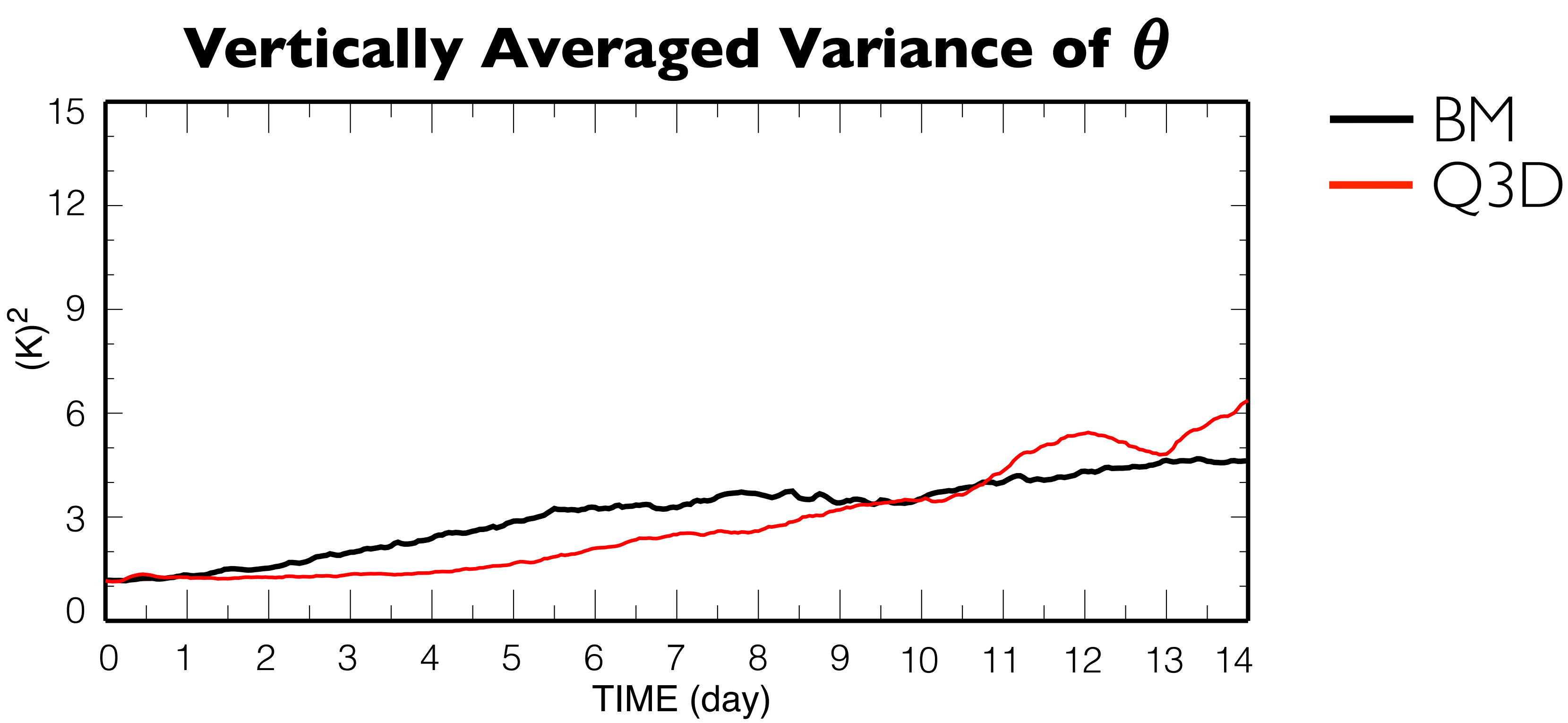
Domain Averages

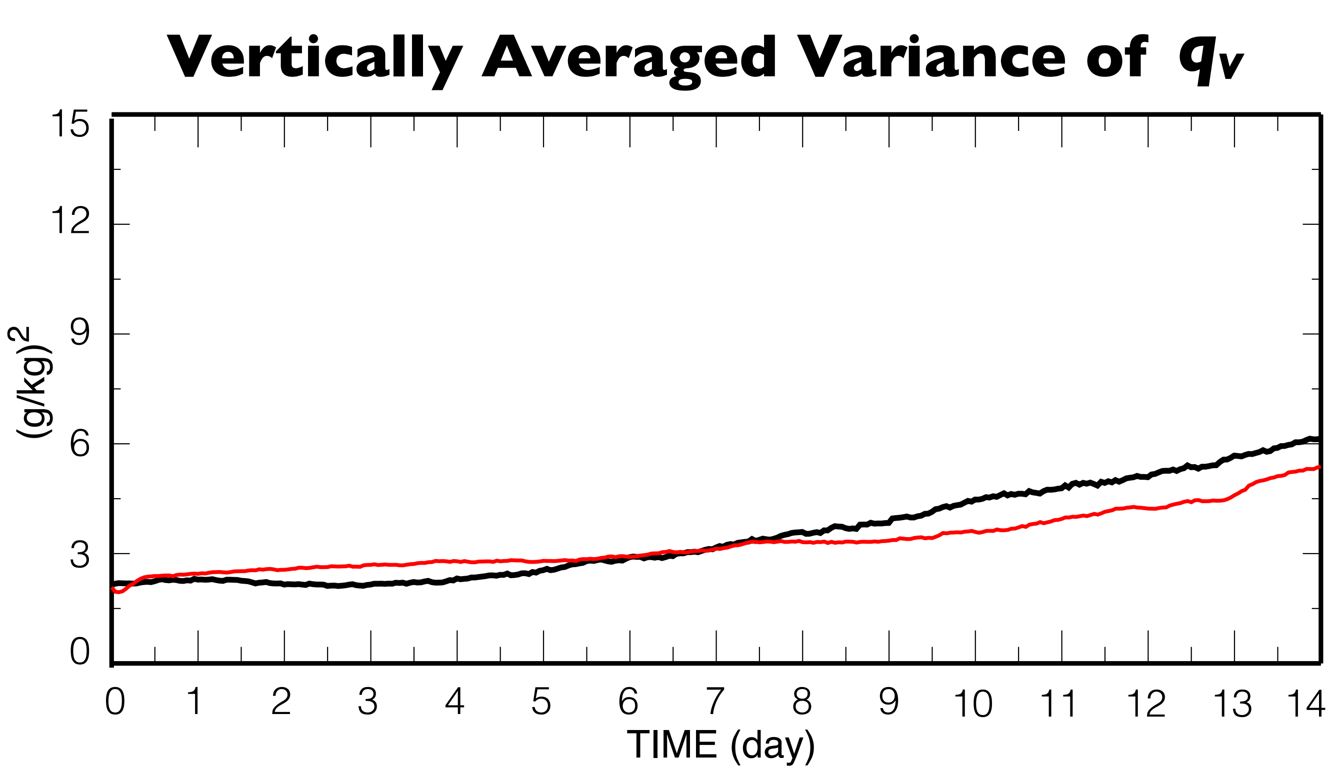


Comparable in general.

Q3D MMF Simulation Results (Continued.)

Variances

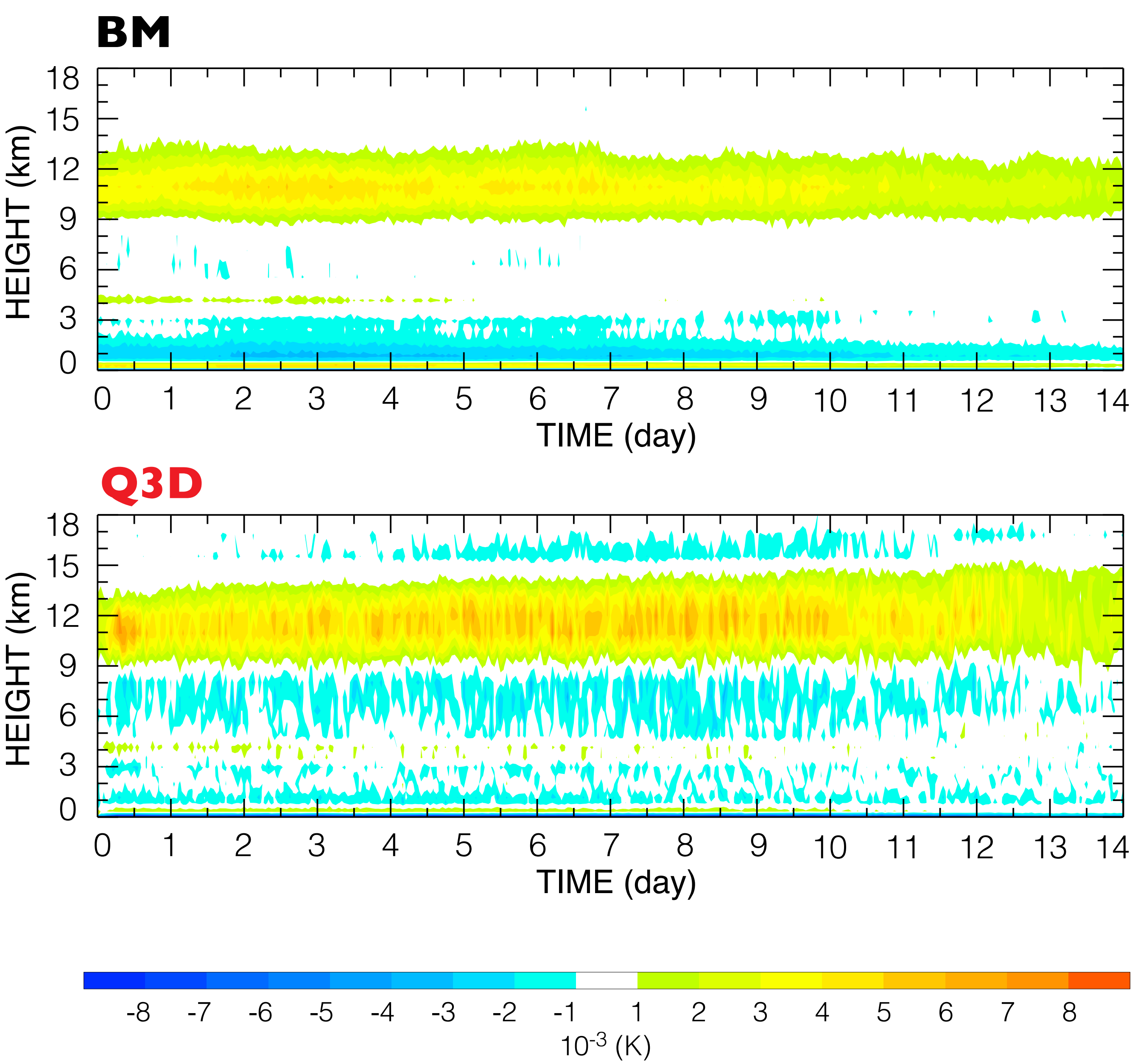


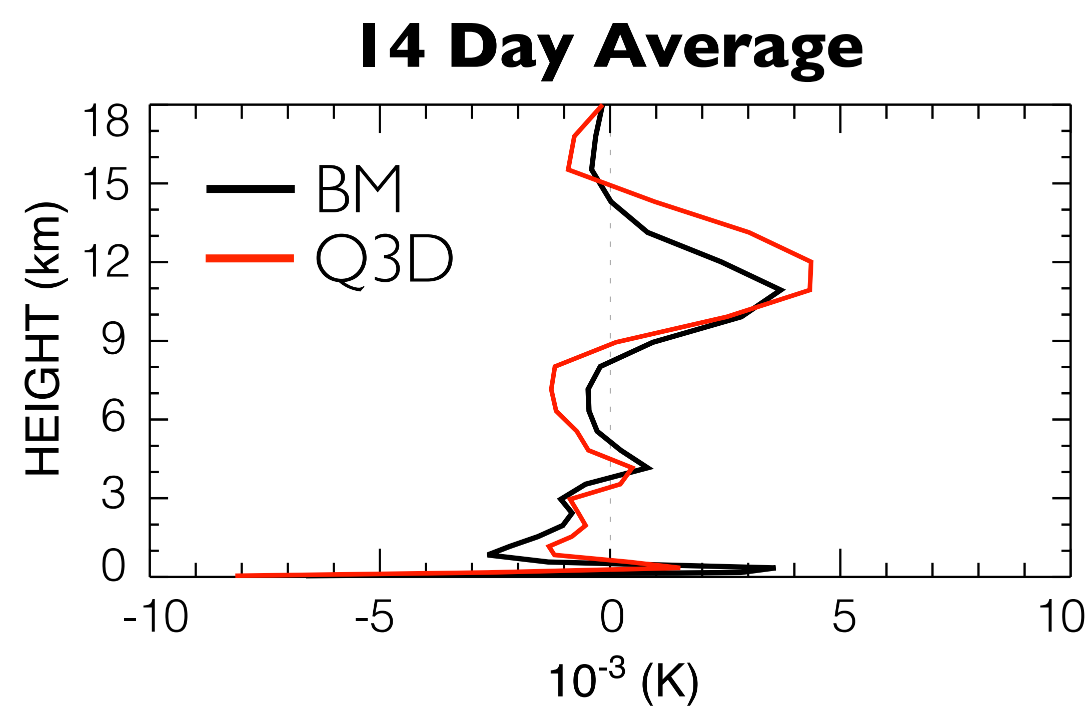


Q3D MMF Simulation Results (Continued.)

Eddy Transport Effect: $\Delta\theta$

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



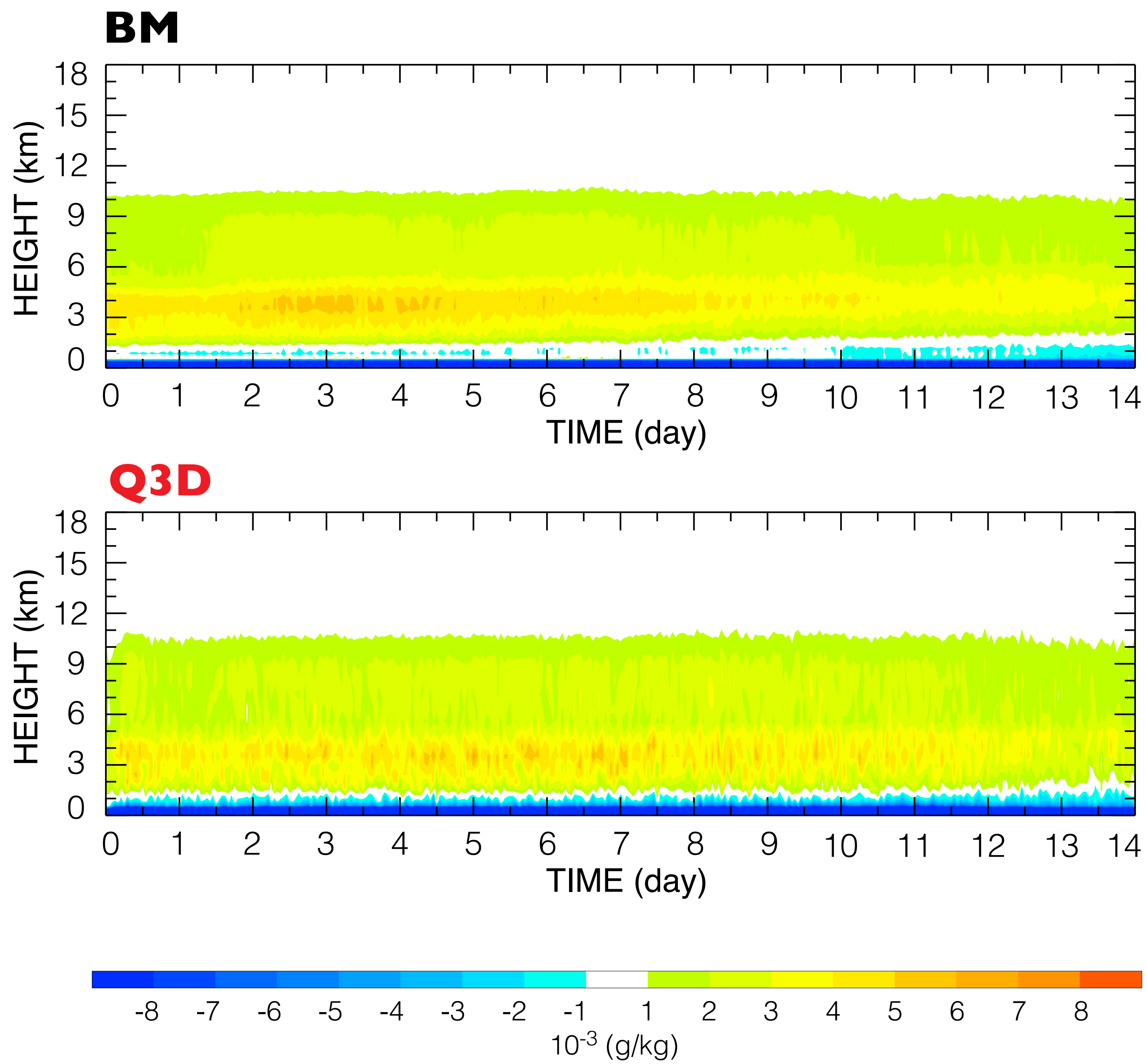


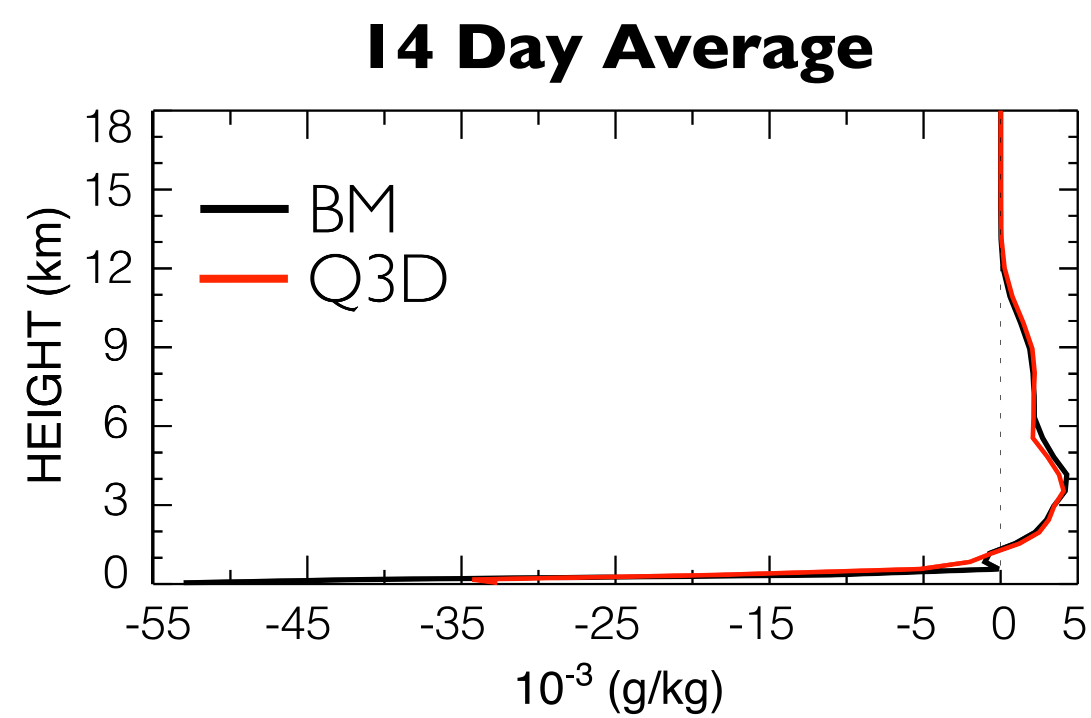
Main features are qualitatively well captured.

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





Use of 3-D CRM

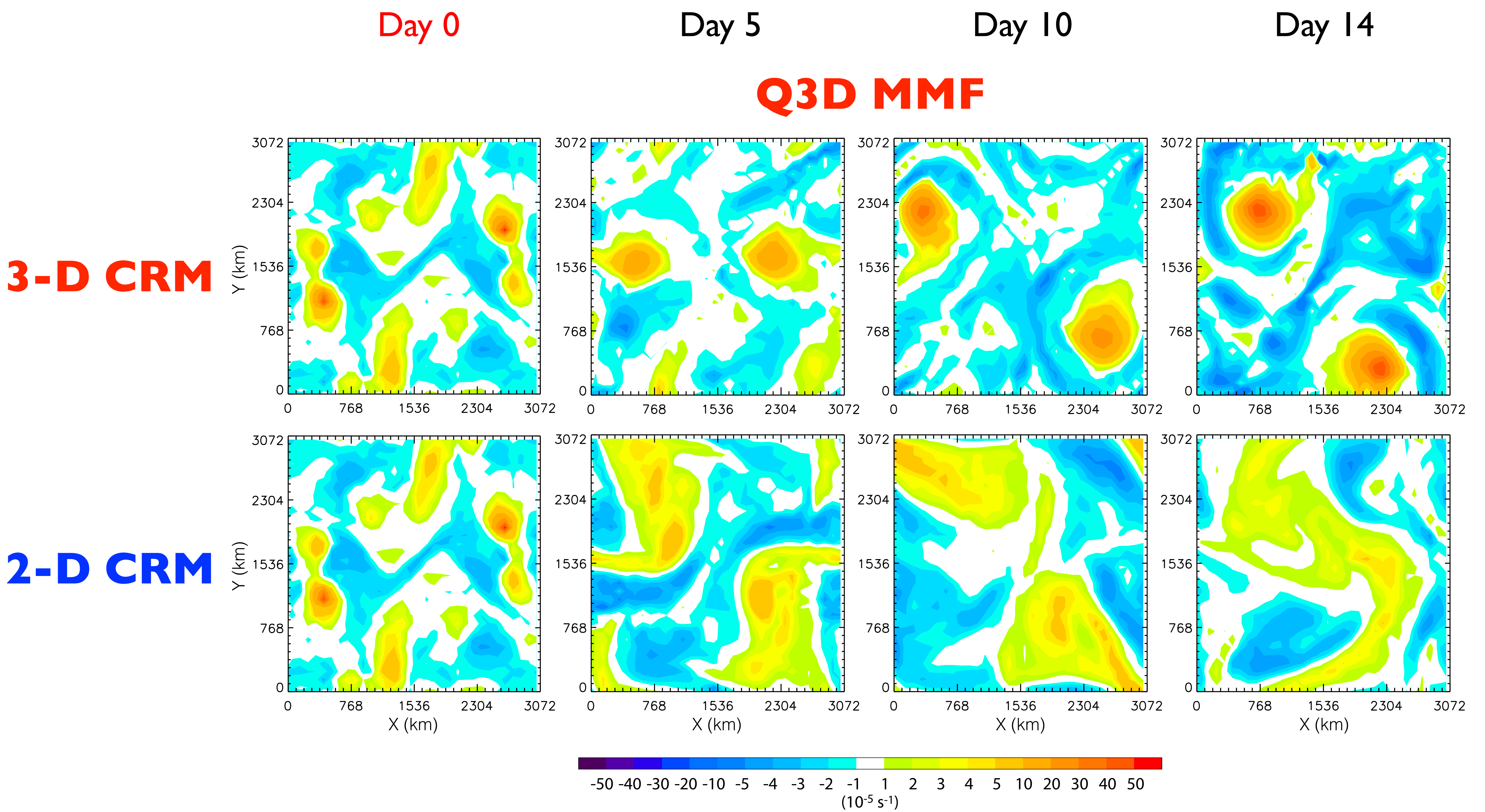
vs.

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

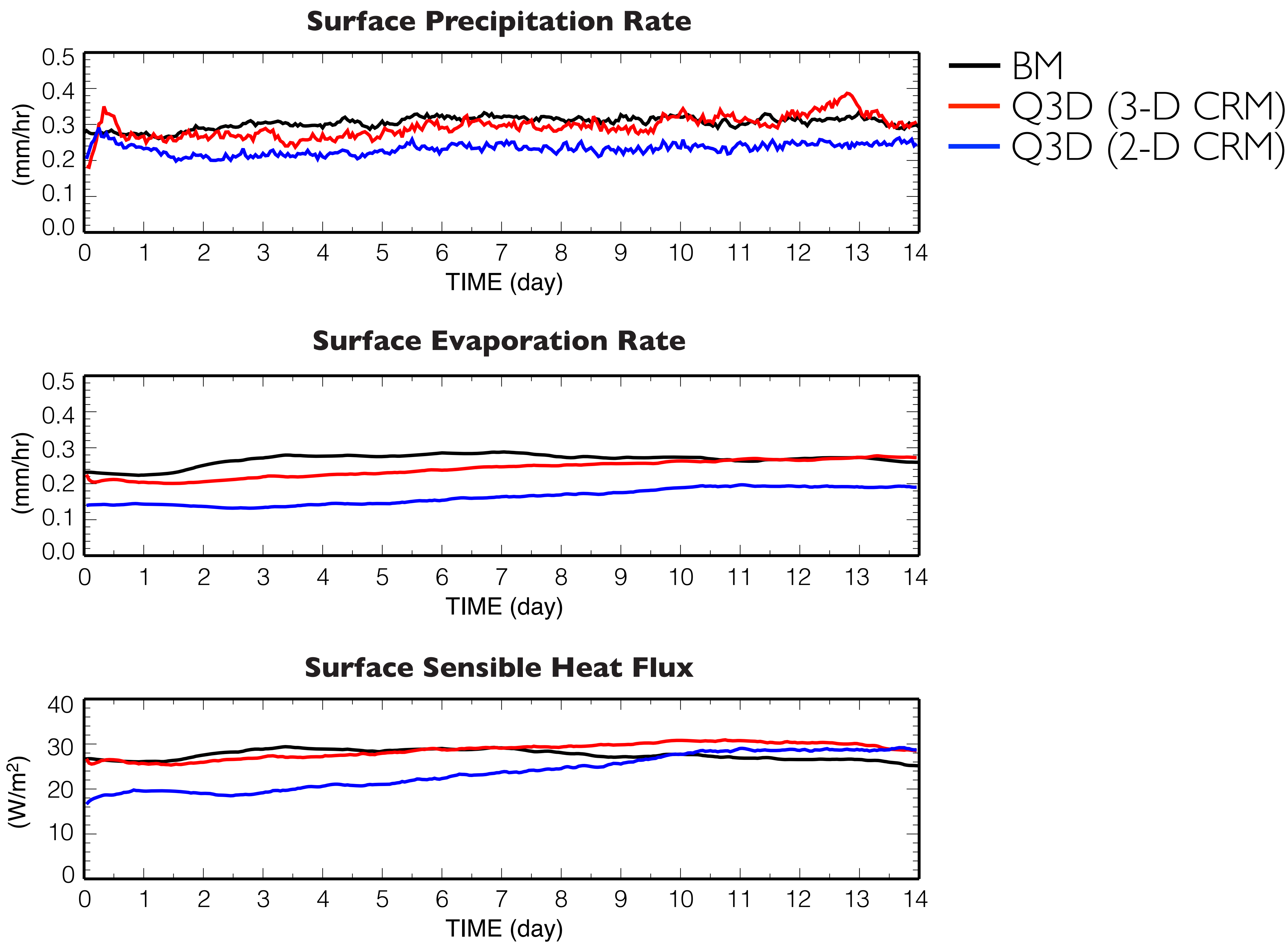
Vertical Component of Vorticity



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

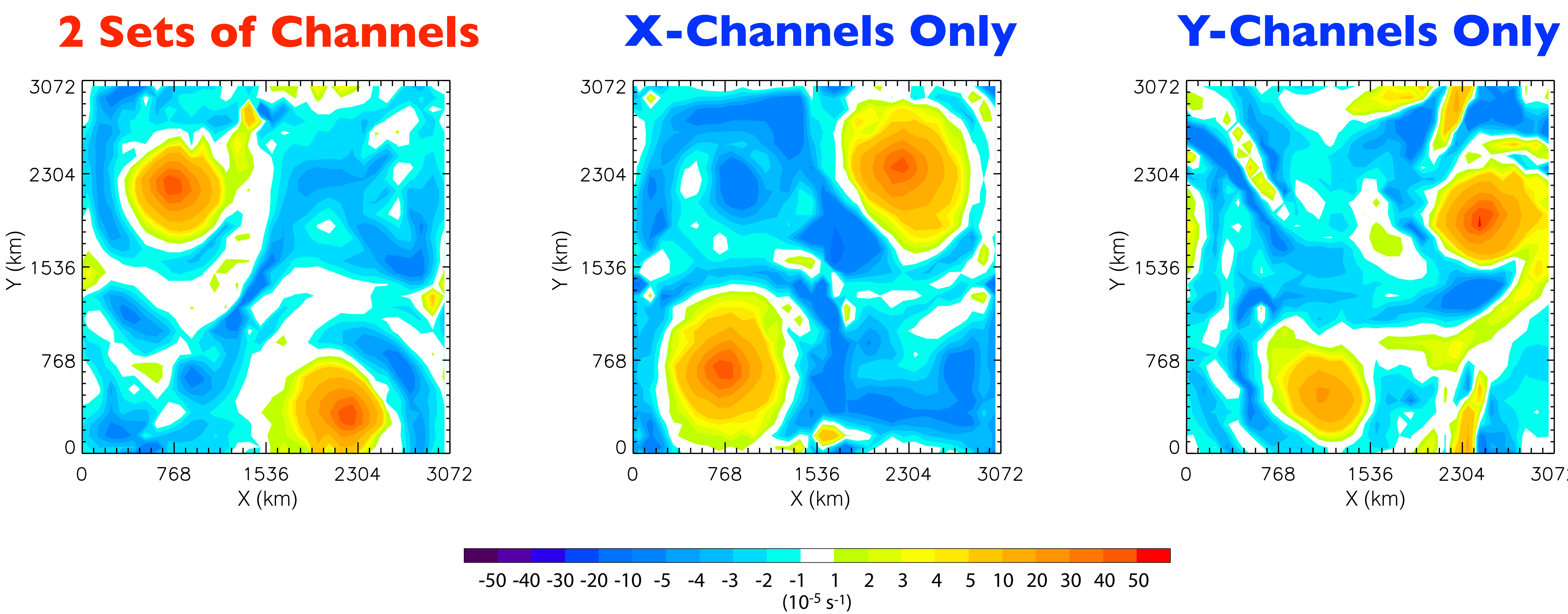
Use of Two Perpendicular Sets of Channels

vs.

Use of One-direction Channels

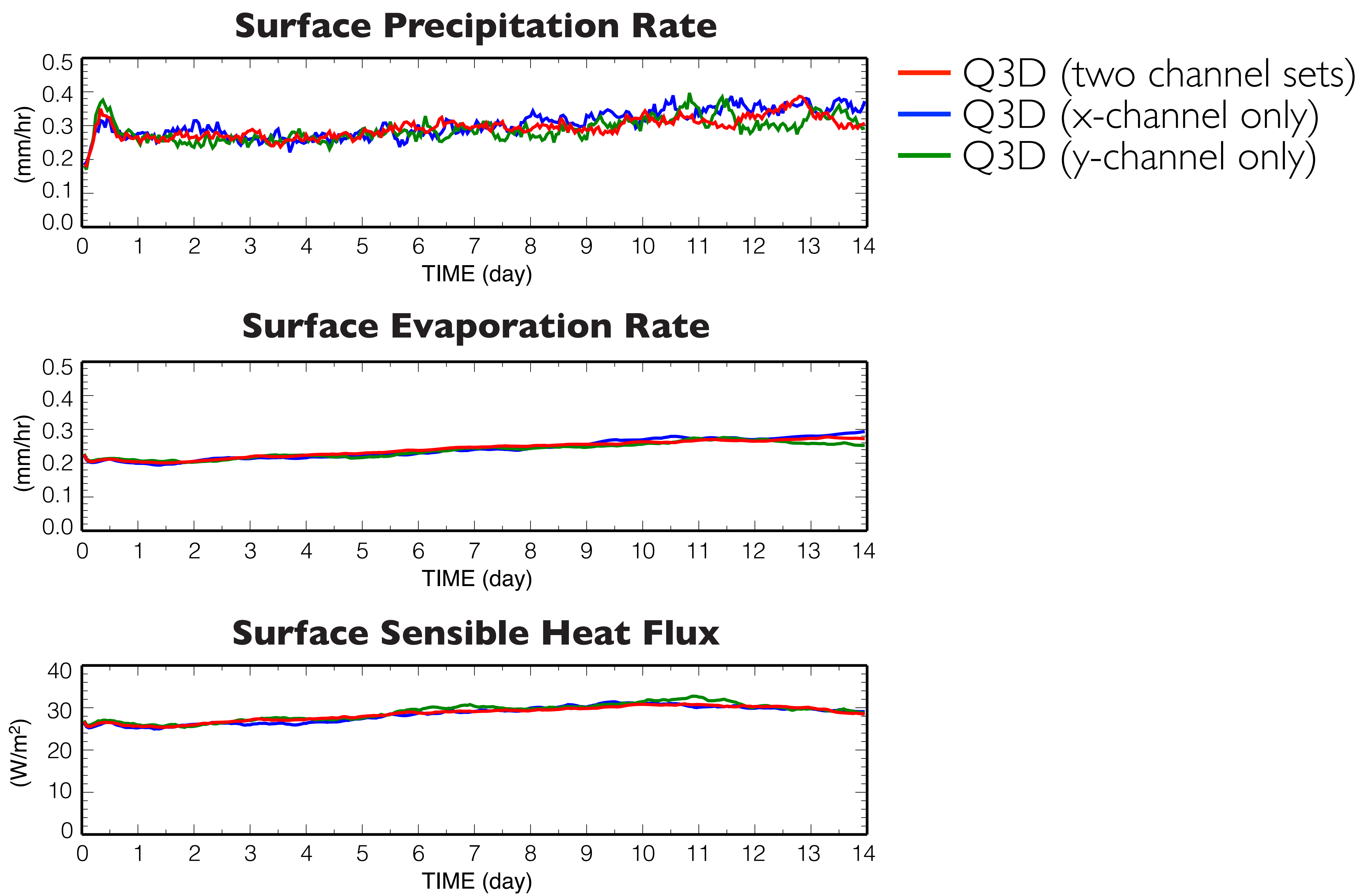
Two Perpendicular Sets of Channels vs. One-direction Channels

Vertical Component of Vorticity (day 14)



The location of two vortices is different from the standard Q3D MMF case.

Two Perpendicular Sets of Channels vs. One-direction Channels (Continued.)

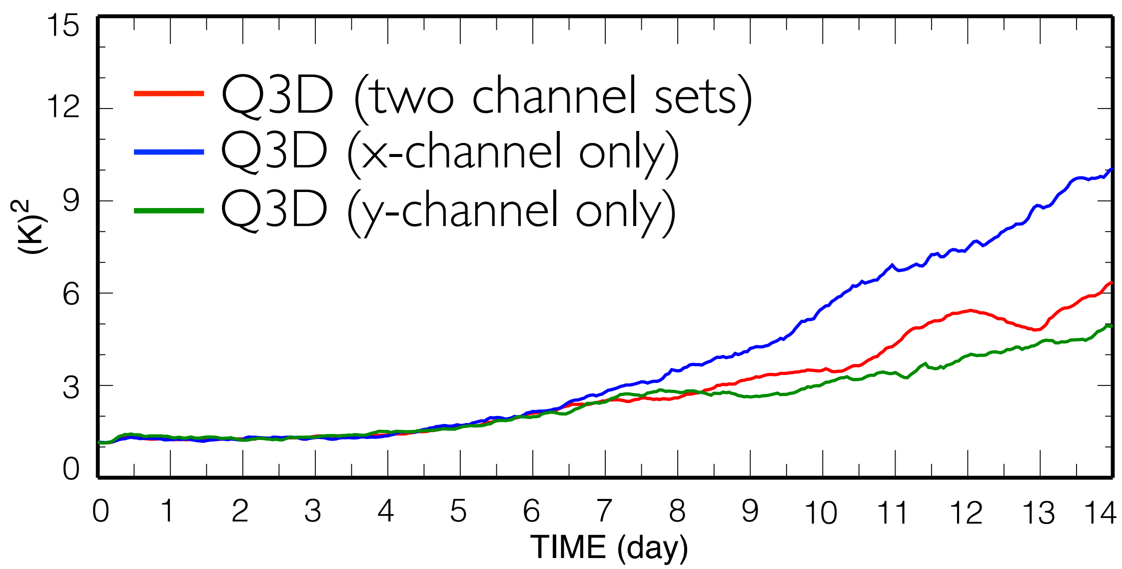


Precipitation and surface fluxes are quite similar each other.

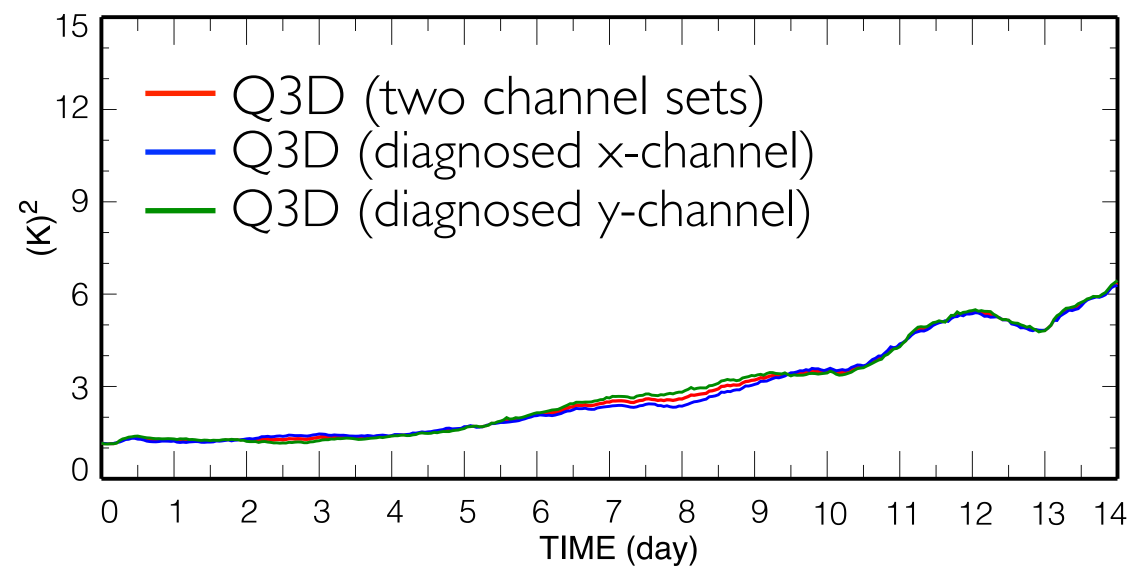
Two Perpendicular Sets of Channels vs. One-direction Channels (Continued.)

Variances

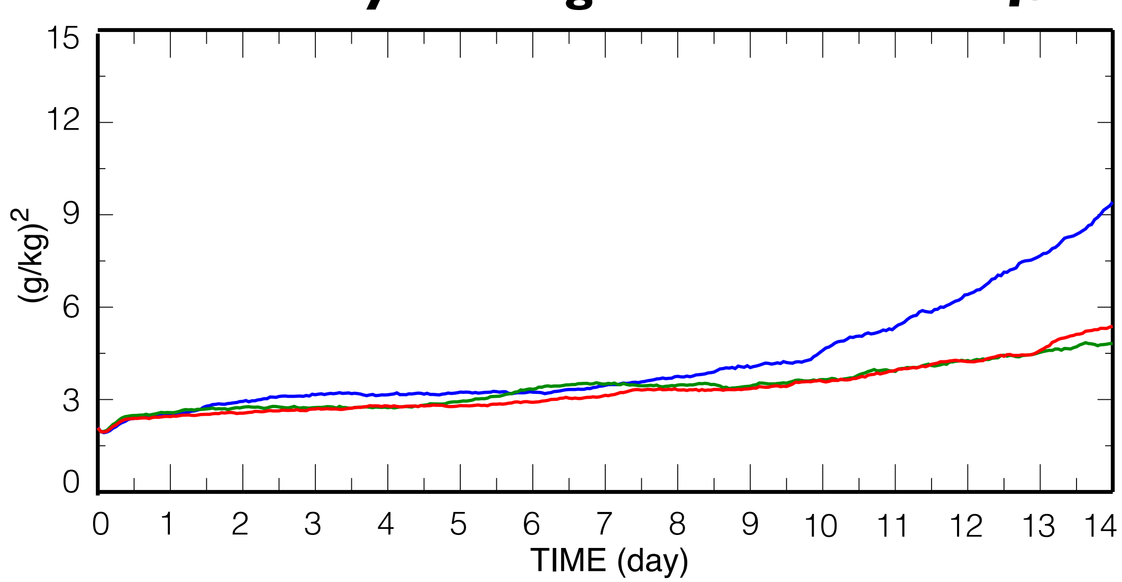
Vertically Averaged Variance of θ



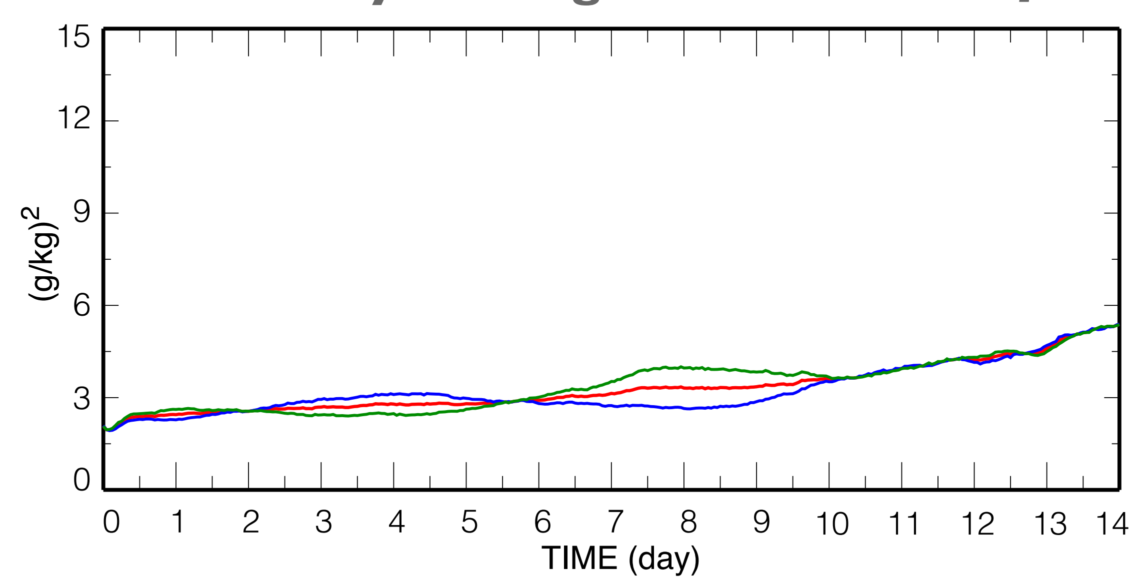
Vertically Averaged Variance of θ



Vertically Averaged Variance of q_v



Vertically Averaged Variance of q_v



The trends of the x- and y-channel solutions are more compatible with each other when the two channels are coupled.

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 effect on the CRM and the CRM effect 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 GCM and CRM are compatible.
- To evaluate the performance of Q3D algorithm, it is applied to an idealized experiment simulating the formulation of tropical cyclones, which is known to be a physically subtle event.
  - The encouraging simulation results show the potential of the Q3D MMF as the basic framework for future NWP and climate models.
  - The simulation results are rather sensitive to the relaxation timescale. But, since the timescale mainly depends on the GCM grid size (characteristic wind speed does not change much), the choice of timescale will not be a big problem.