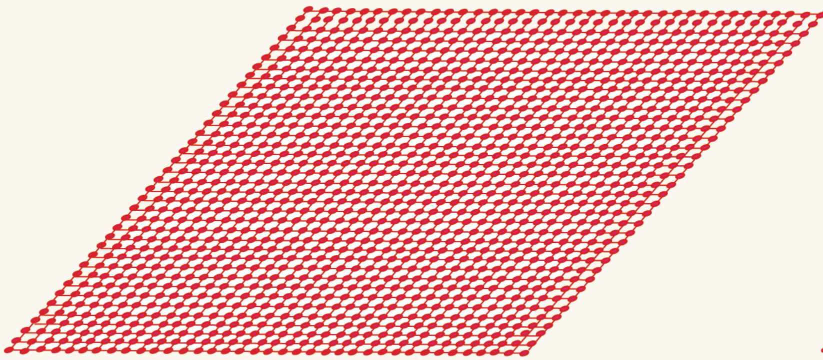
DEVELOPMENT OF Q3D MMF

Akio Arakawa and Joon-Hee Jung

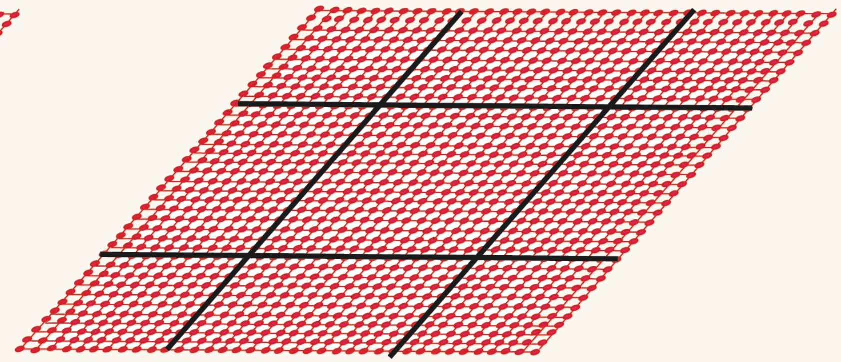
CMMAP Team meeting   July 30, 2008

FOUR KINDS OF HORIZONTAL GRID WE HAVE WORKED ON

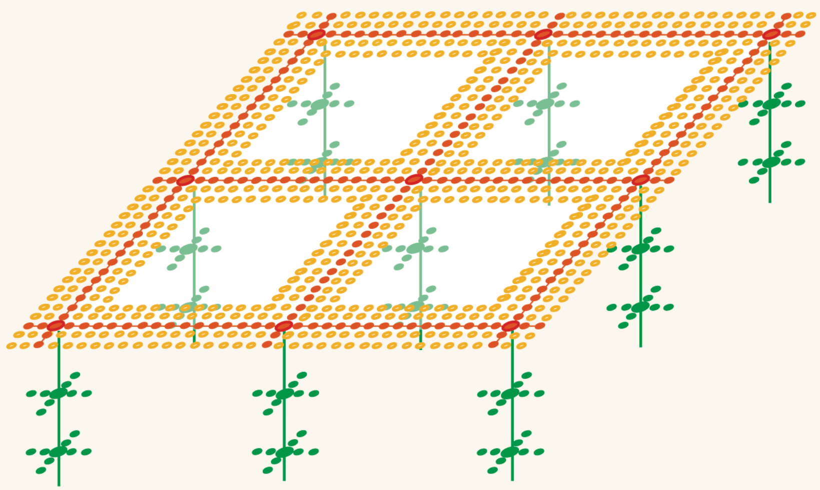
3D CRM



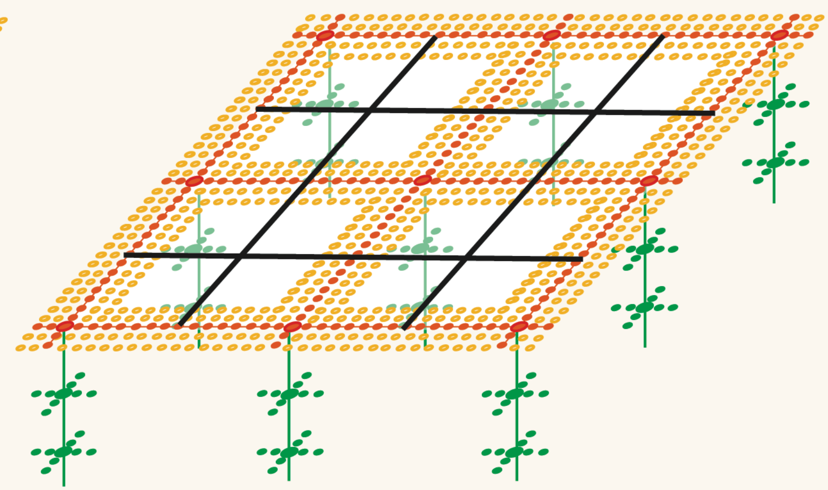
3D MMF



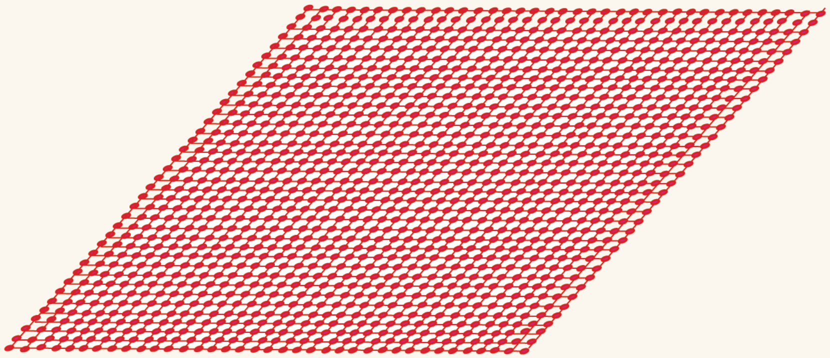
Q3D CRM



Q3D MMF



3D CRM



Used for Benchmark Simulation

Domain size :

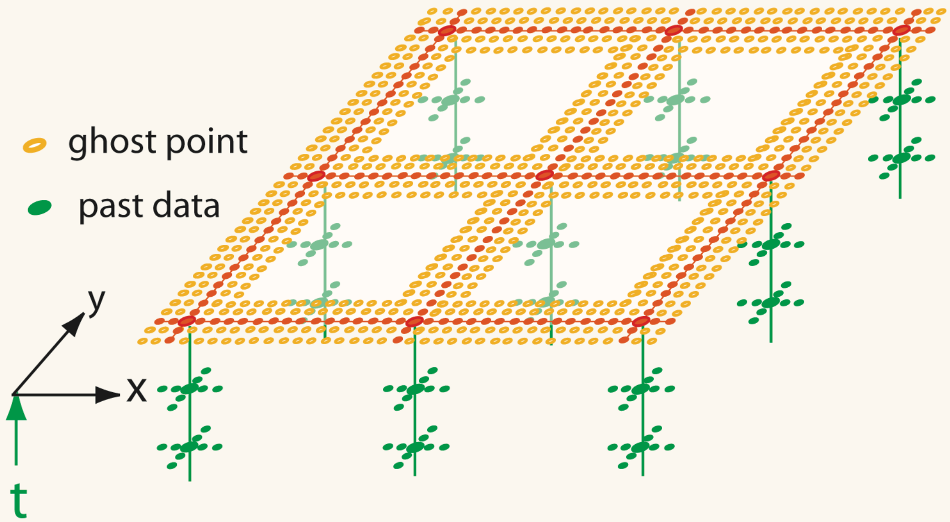
384km x 384km with cyclic condition

(Four times larger than what is shown here.)

- Due to the lack of mean vertical motion for such a small domain, a horizontally-uniform large-scale forcing based on typically observed Q1 and Q2 is imposed.
- Domain-averaged and local profiles are nudged to reference profiles.

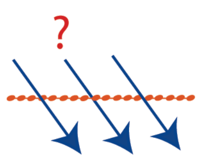
(These are done also in Q3D MMF.)

Q3D CRM



Used for development of Q3D algorithm

Q3D ADVECTION



Uses estimated values at ghost-points.

- *For the cloud-organization scale :*

  Based on identification of cloud regime using the past data at the intersections

- *For the local cloud scale:*

  Basically 2D with a hypothetical structure such as isotropy

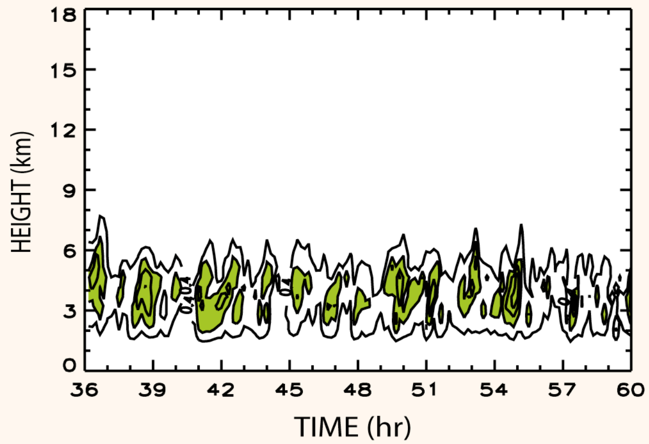
Major issues addressed : Global and local stability, handling the singularity, . . .

TEST OF Q3D ADVECTION

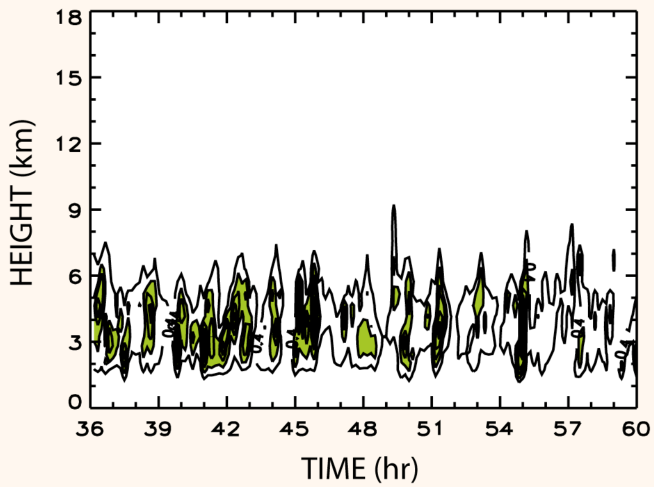
With θ and velocity components prescribed at all Q3D grid points

Example : Variance of liquid water mixing ratio

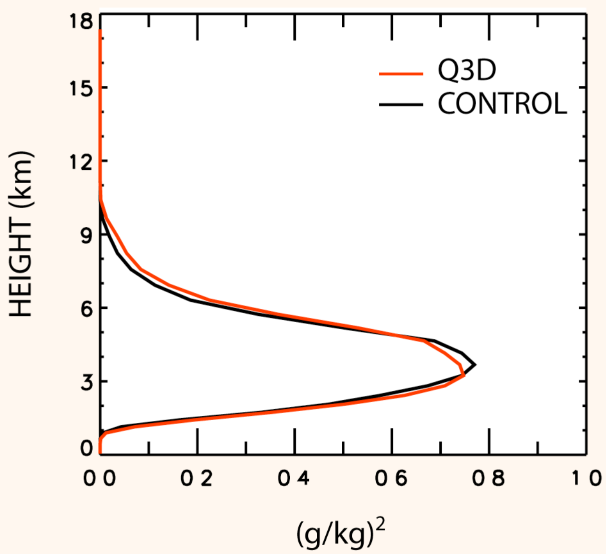
BENCHMARK (3D)



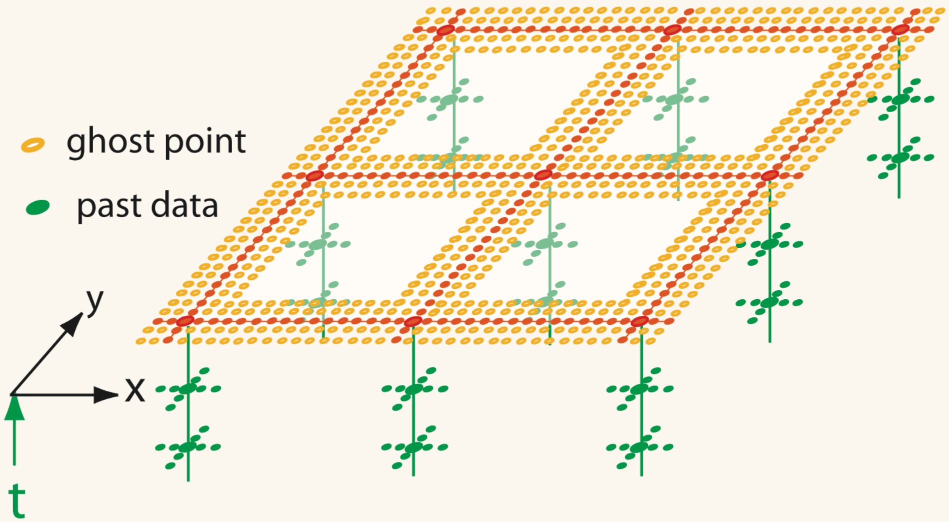
Q3D



Time Average



Q3D CRM

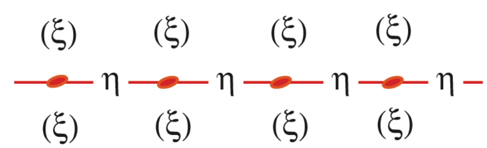


Used for development of Q3D algorithm

Q3D DYNAMICS

Additional major issues addressed :

- *Elimination of the imbalance of the degree of freedom between the two vorticity components: only the average across the array is prognostically determined.*



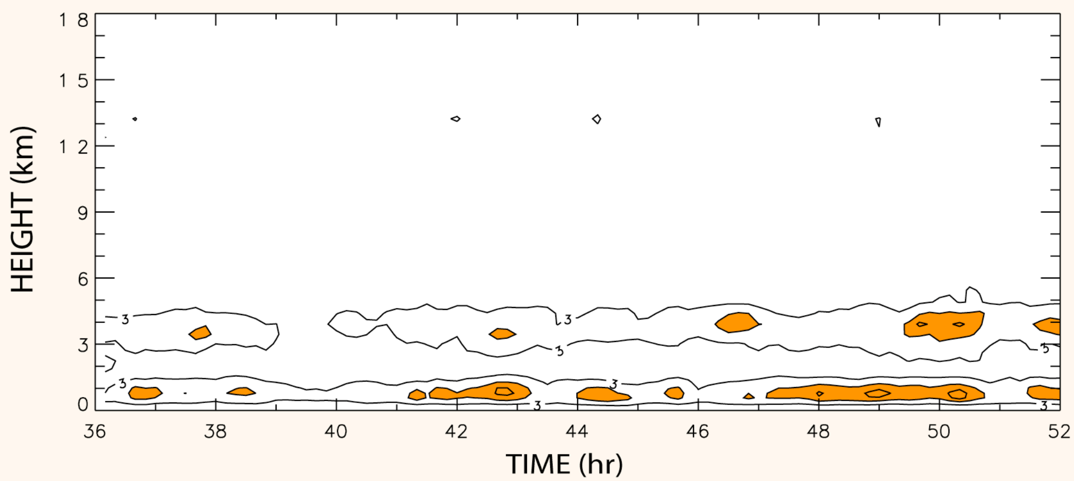
- *Estimation of the twisting term (a purely 3D problem) ;*
- *Solving the 3D w-equation, . . .*

TEST OF Q3D DYNAMICS (FULLY-PROGNOSTIC)

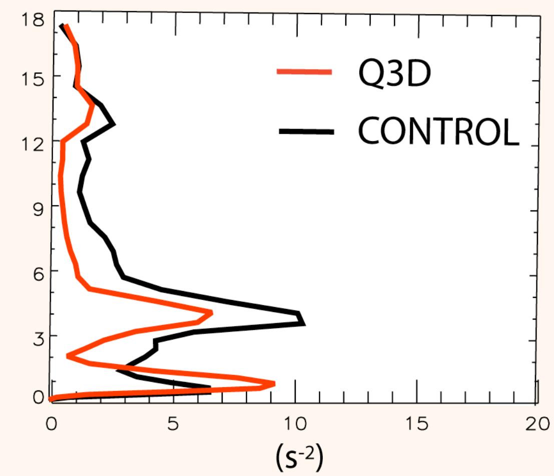
(Still without coupling with the GCM)

Example : X-Array Variance of the y-component of vorticity

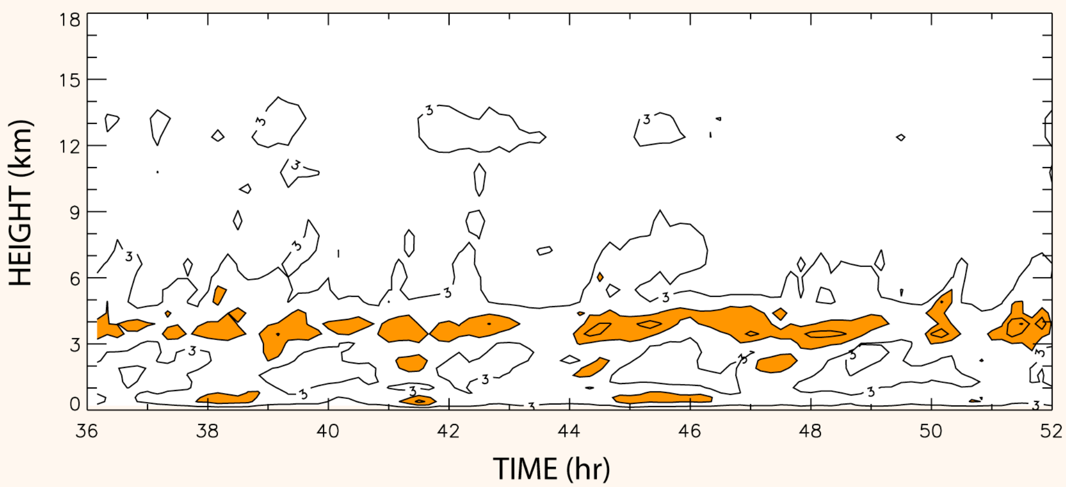
Q3D



Time Average



CONTROL (3D)

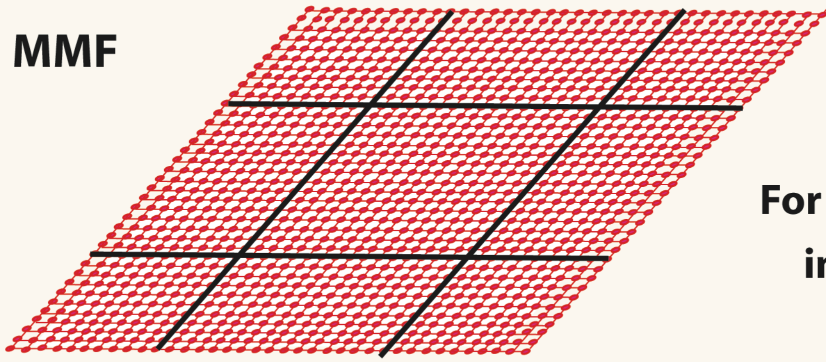


While prediction of the vorticity variance was reasonably successful, prediction of the horizontal velocity variance was totally unsuccessful.

It blew up later !

- There was a hope that the problem in the Q3D CRM may be less serious in the Q3D MMF, in which the Q3D CRM is coupled with a GCM to better control large-scale dynamics.
- Coupling with the GCM, however, introduces its own problem regardless of the dimensionality of the CRM.

3D MMF



For testing various methods of coupling independent of the dimensionality.

- The CRM in this case is a "perfect" GCM by itself so that the GCM component should play only a passive role.
- A similar situation exists in the Q3D MMF, in which the Q3D CRM can be a GCM.

This is in a sharp contrast to the situation in the prototype MMF.

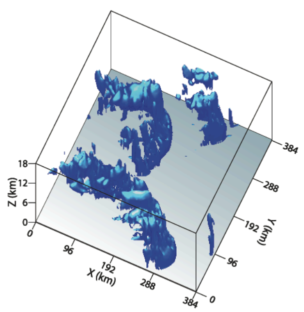
TWO BASIC APPROACHES FOR COUPLING

I. Coupling through processes (such as advection, condensation, . . .)

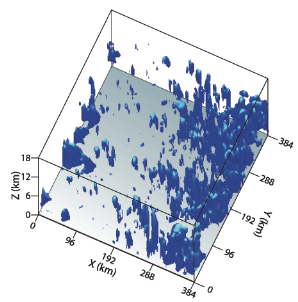
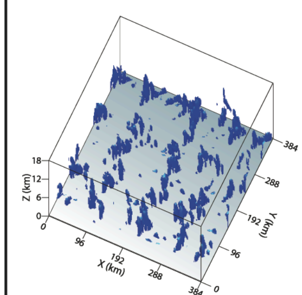
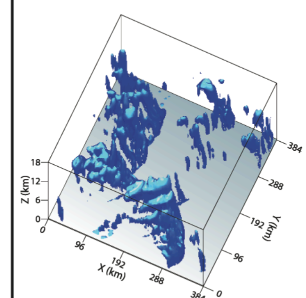
(Parallel to the traditional cumulus parameterization)

II. Mutual relaxation of prognostic variables

BENCHMARK



3D MMF RESULTS WITH DIFFERENT COUPLING METHODS

<table>
<tr><td>FORCING</td><td rowspan="3">PROCESS</td><td>PROCESS</td><td rowspan="2">RELAXATION</td></tr>
<tr><td>VORTICITY FEEDBACK</td><td>RELAXATION</td></tr>
<tr><td>THERMAL FEEDBACK</td><td>PROCESS</td><td>PROCESS</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
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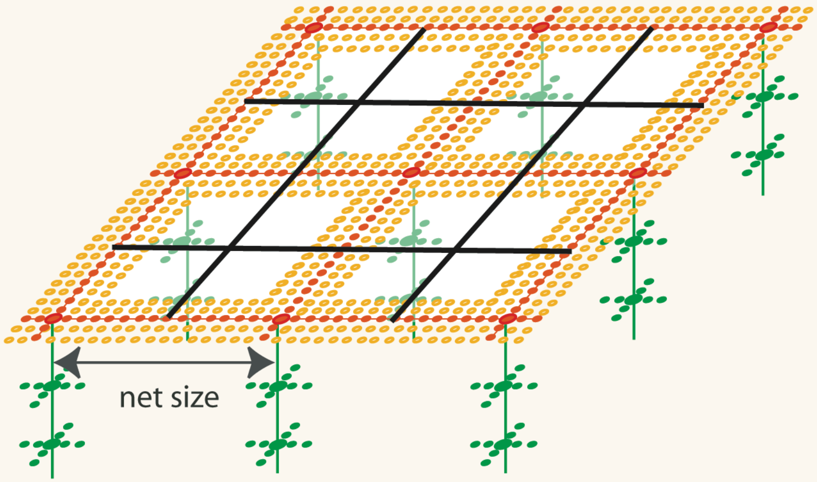
Q3D MMF – Our Goal



The coupling method we have chosen

- Thermodynamic variables
  - Forcing through relaxation
  - Instantaneous updating of the GCM by the CRM mean.
- Vorticity components

  Slow mutual relaxation

Considerable efforts have been spent to computationally "stabilize" the algorithm.

Recent Progress in the Development of Q3D MMF

"FIRST Q3D MMF SIMULATION IN A TEST MODE"

CMMAP Team meeting July 30, 2008

Benchmark Simulation with VVM

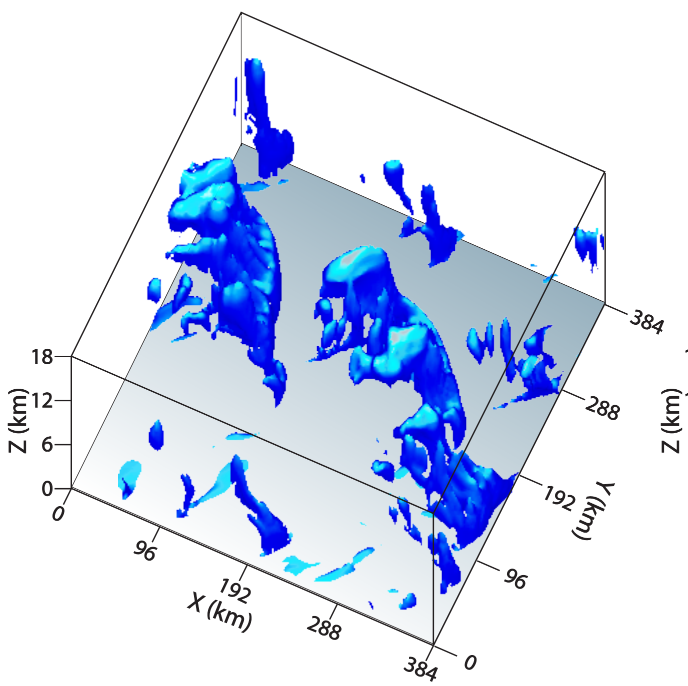
- Domain size: 384 km x 384 km x 18 km
- Horizontal resolution: 3 km
- Vertical resolution: 34 layers with a stretched vertical grid
- Lower boundary: ocean surface with a fixed temperature
- Idealized tropical condition: based on a GATE Phase-III mean sounding and a wind profile during TOGA COARE
- Large-scale forcing: prescribed cooling and moistening tendencies
- Perturbation: random temperature perturbations into the lowest layer

VVM: Vector Vorticity Model (Jung and Arakawa, 2008)

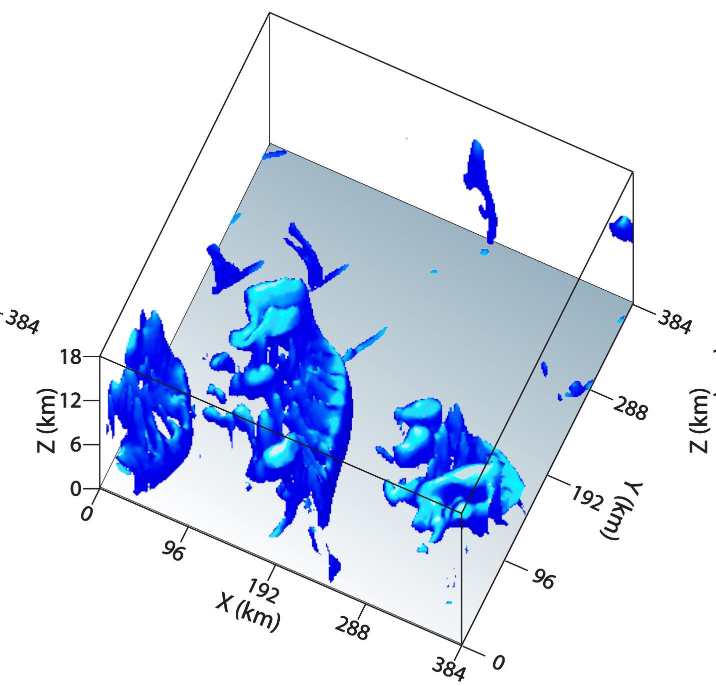
Benchmark Simulation with VVCM
(An example of cloud development)

Isotomic Surface of Cloud Water Mixing Ratio

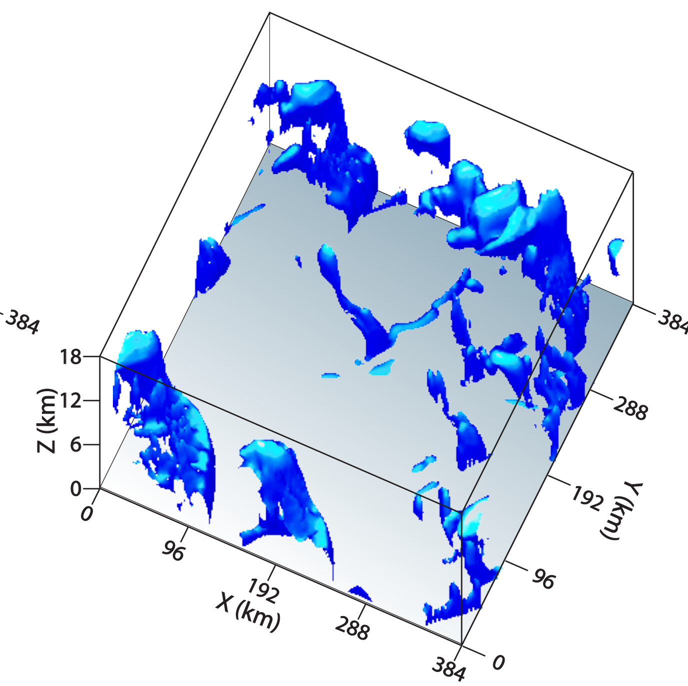
t=60 hr



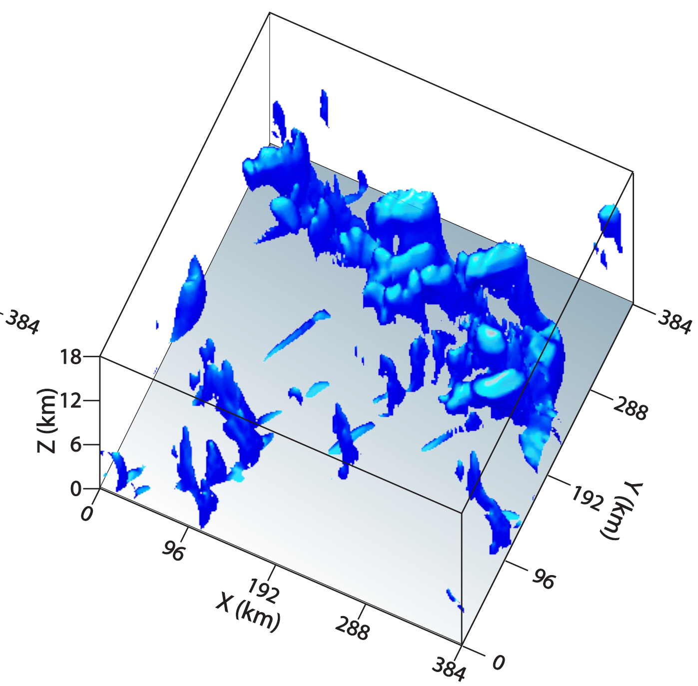
t=72 hr



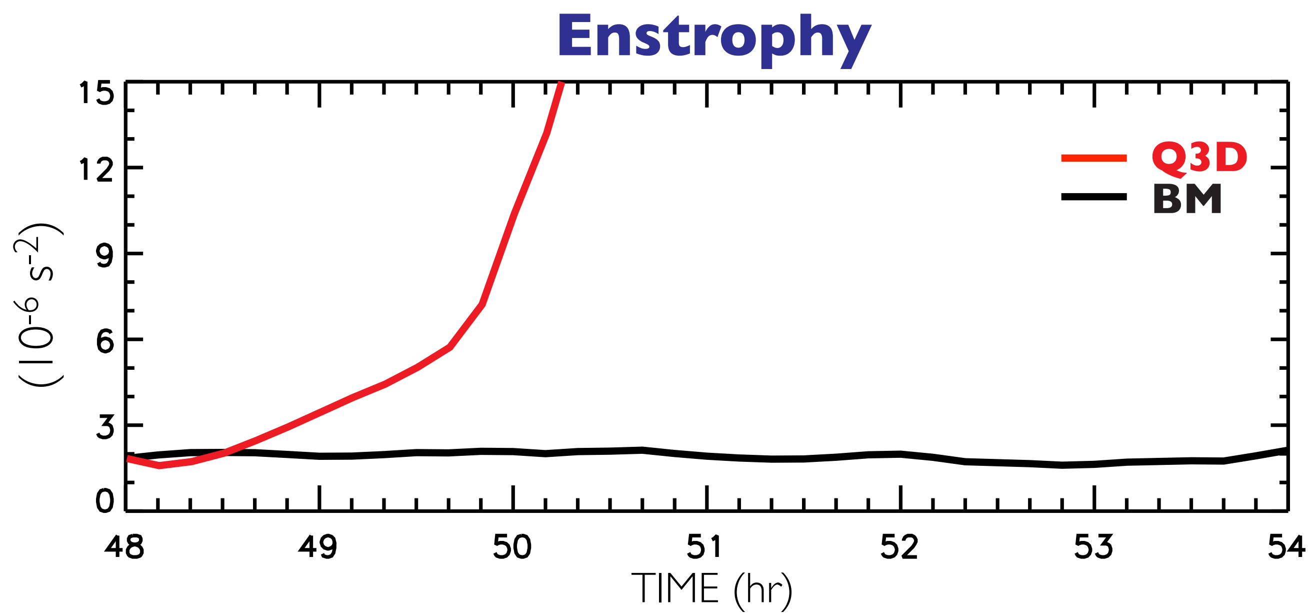
t=84 hr

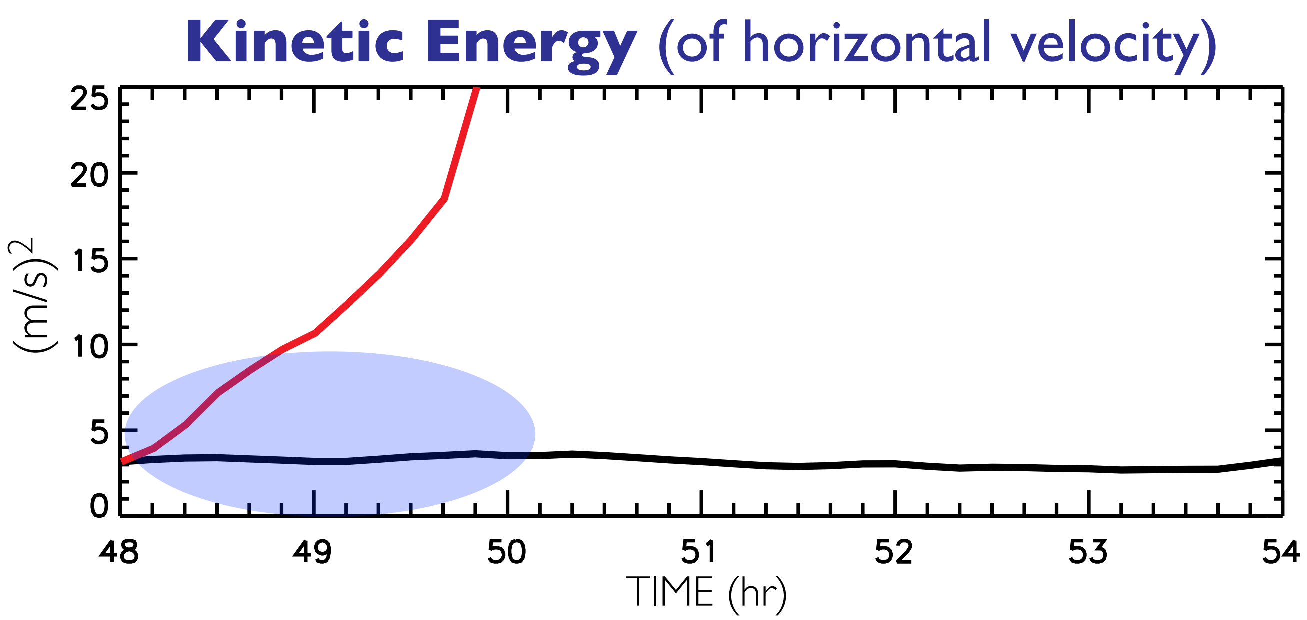


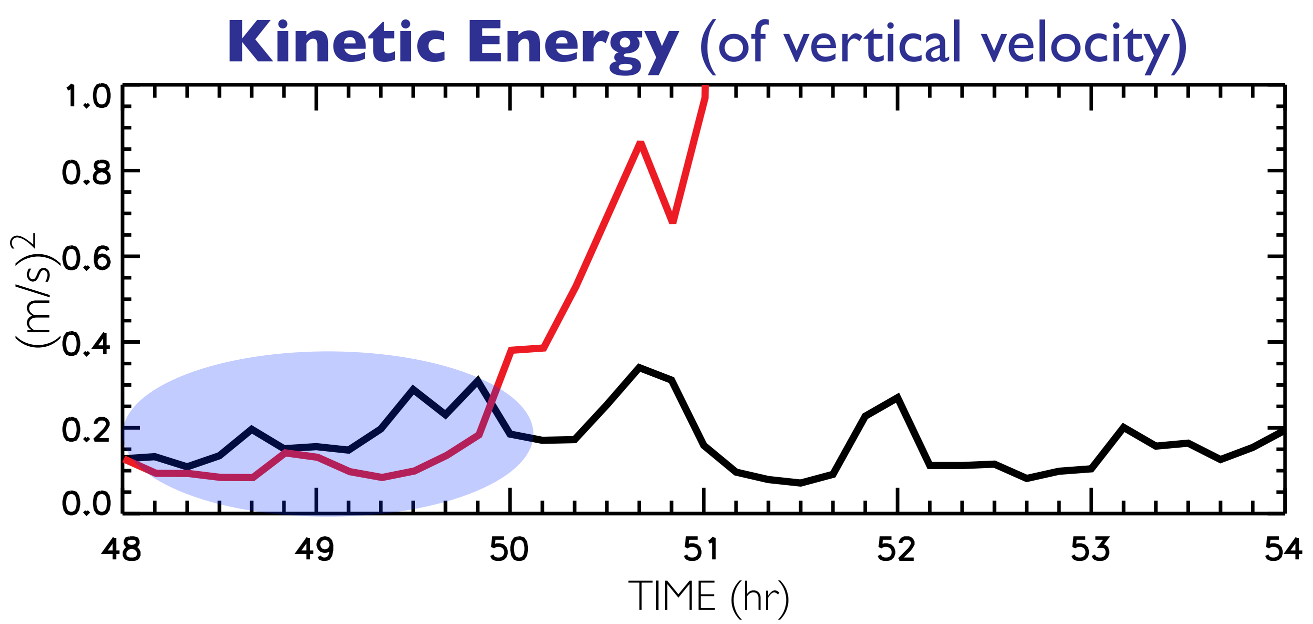
t=96 hr



Q3D MMF SIMULATION
(Results of the original version)







Kinetic energy of horizontal velocity grows faster than that of vertical velocity. This is mainly due to a spectral shift toward horizontally large scales.

Selective Rayleigh Damping

Consider a system of the momentum equation with the Rayleigh friction given by

$$\frac{\partial u}{\partial t} = -k_u u, \quad \frac{\partial w}{\partial t} = -k_w w.$$

When $k_u = k > 0$ and $k_w = 0$, using the definition of vorticity, $\eta \equiv \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$

we obtain the vorticity equation given by *(considering only the damping term)*

$$\frac{\partial \eta}{\partial t} = -k \frac{\partial u}{\partial z}$$

We also obtain the enstrophy equation given by

$$\frac{1}{2}\frac{\partial \eta^2}{\partial t} = -k \frac{\partial u}{\partial z}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)$$

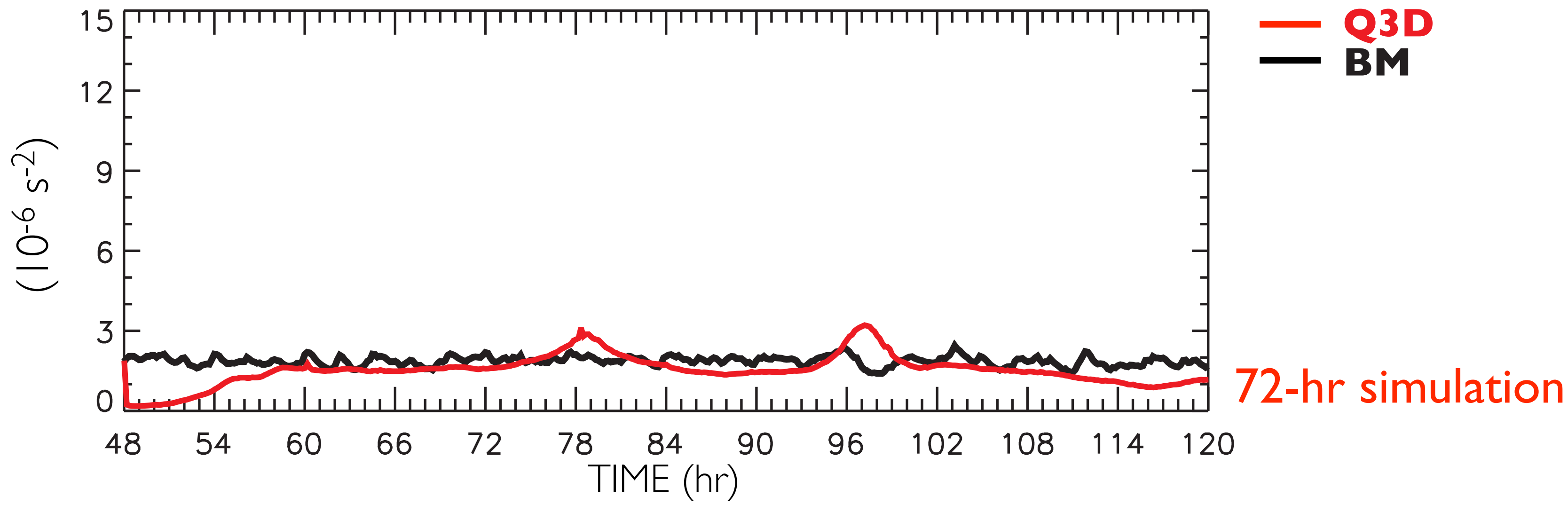
When the vorticity field is shear dominated (i.e. the vertical shear and vorticity are positively correlated), the mass-weighted domain integral of enstrophy decreases.

This selective damping is applied to
the deviation of vorticity from the background.

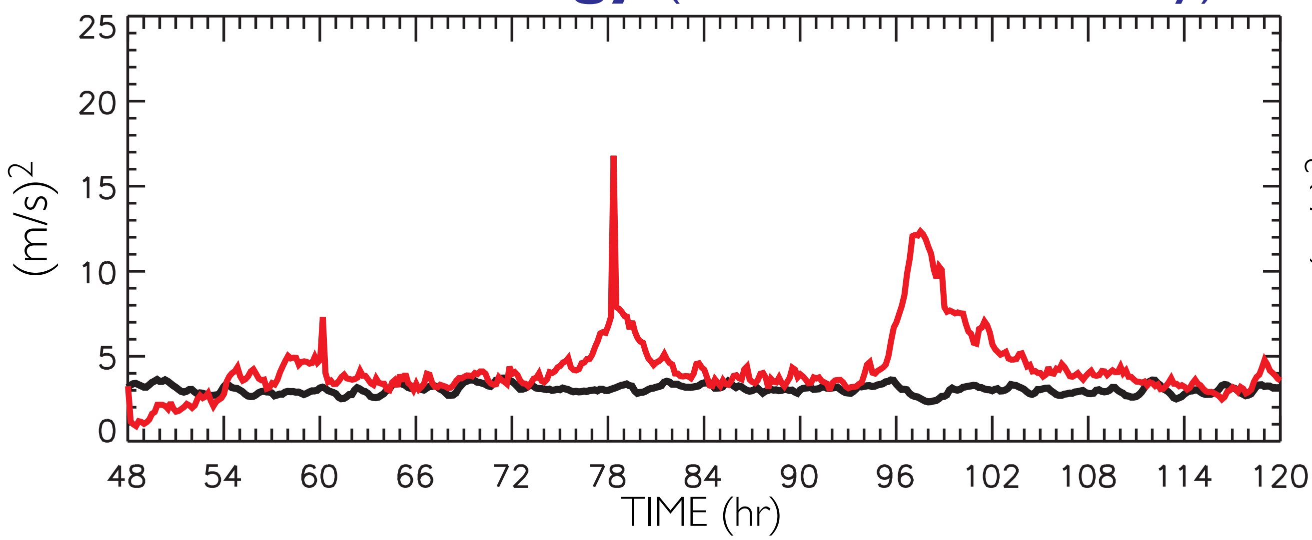
Q3D MMF SIMULATION

(with the selective damping)

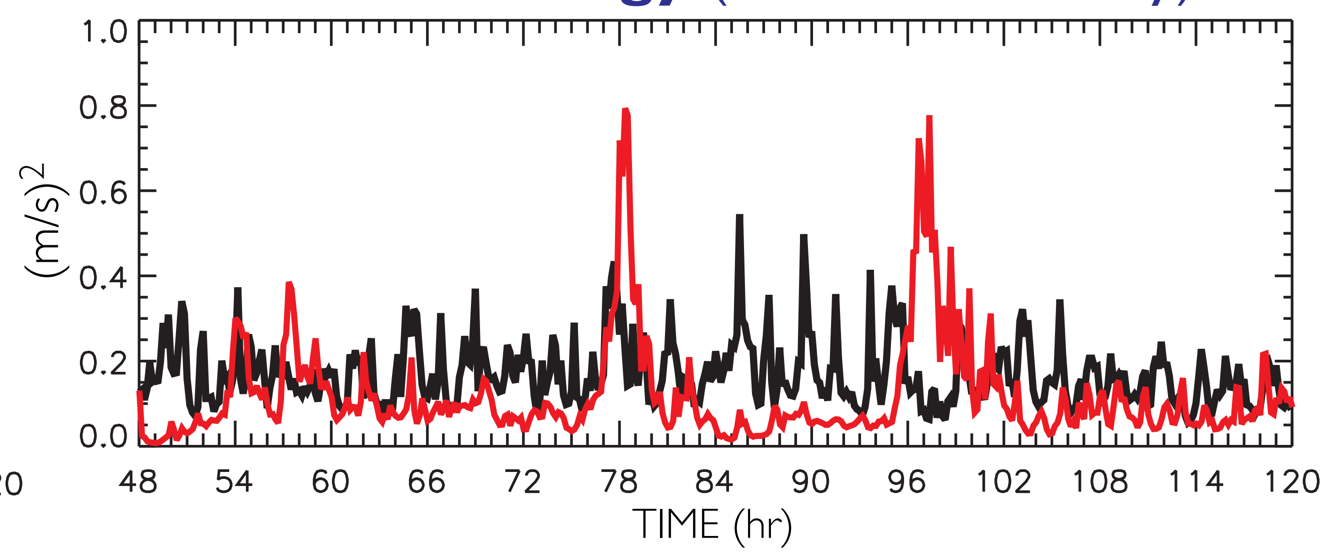
Enstrophy



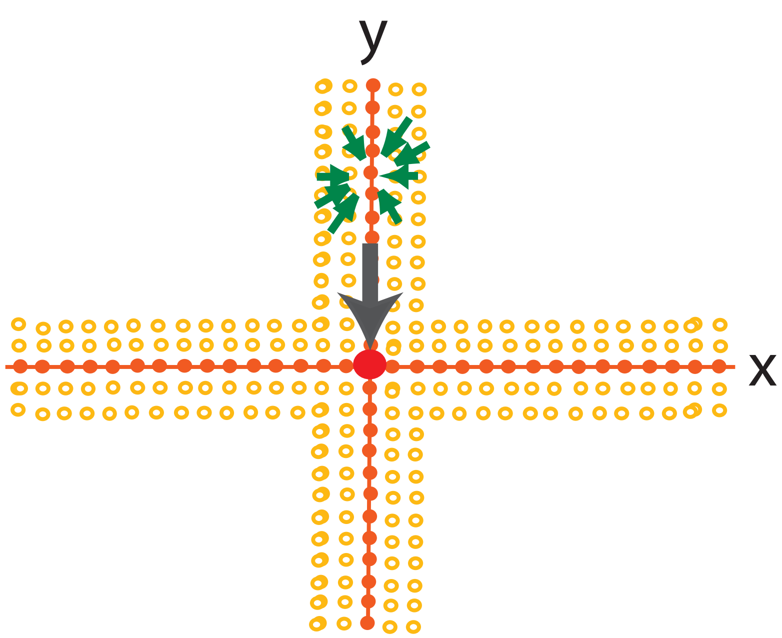
Kinetic Energy (of horizontal velocity)



Kinetic Energy (of vertical velocity)

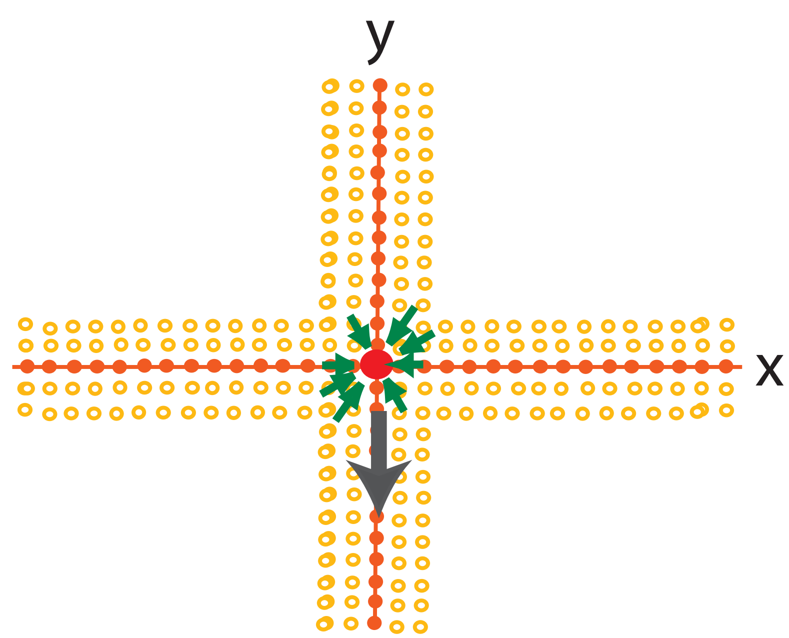


Passage of a strong convective system over an intersection point produces a spike in the total variance



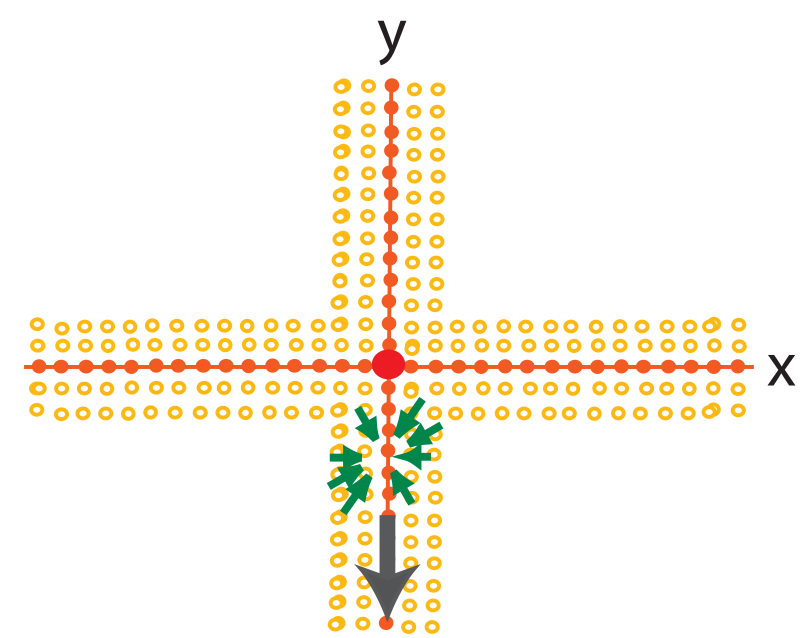
Variance is in y only.

The structure of the system in x is constrained.



Variance in x suddenly appears.
Variance in y does not change.

The structure of the system in x becomes free, suppressing convective activity on the x-axis by induced subsidence.

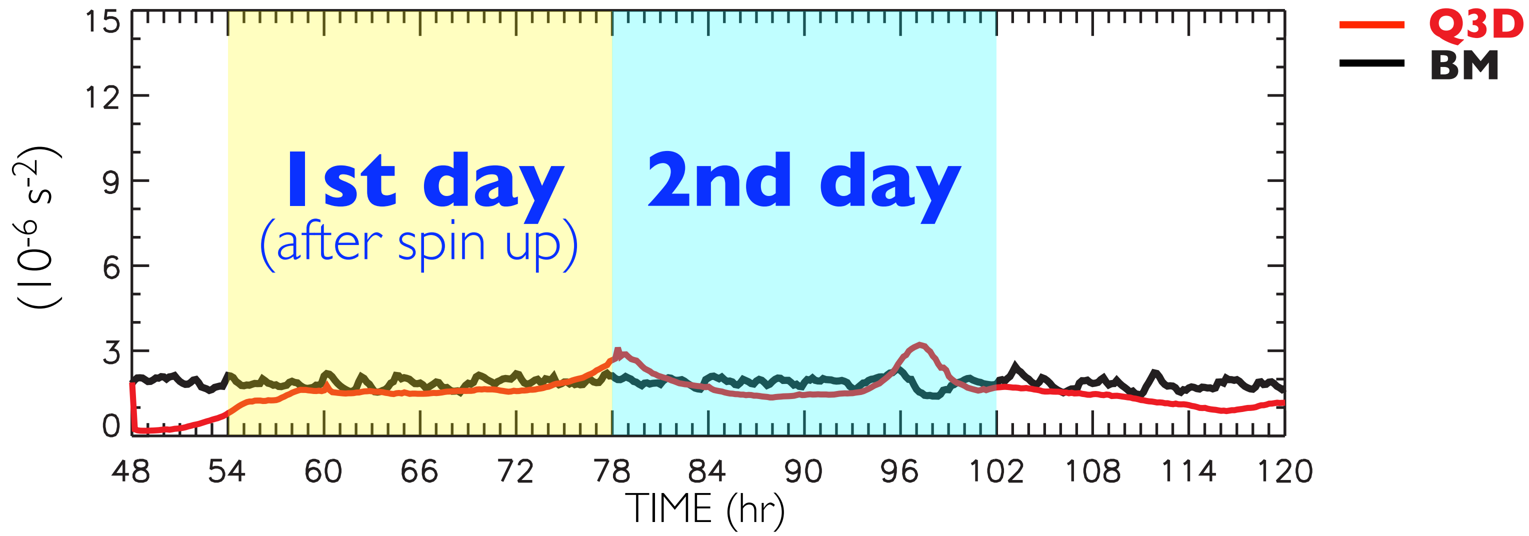


Variance is again in y only.

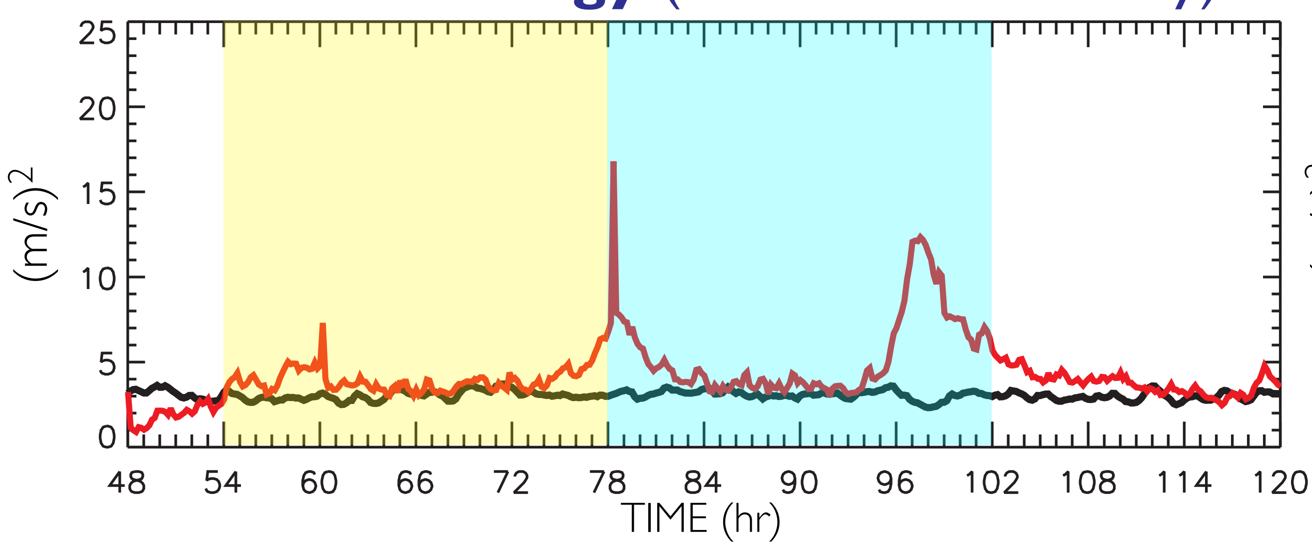
The structure of the system in x is again constrained, but the subsidence effect on the x-axis remains.

Comparison of a Q3D Prediction with the 3D Benchmark Prediction (BM)

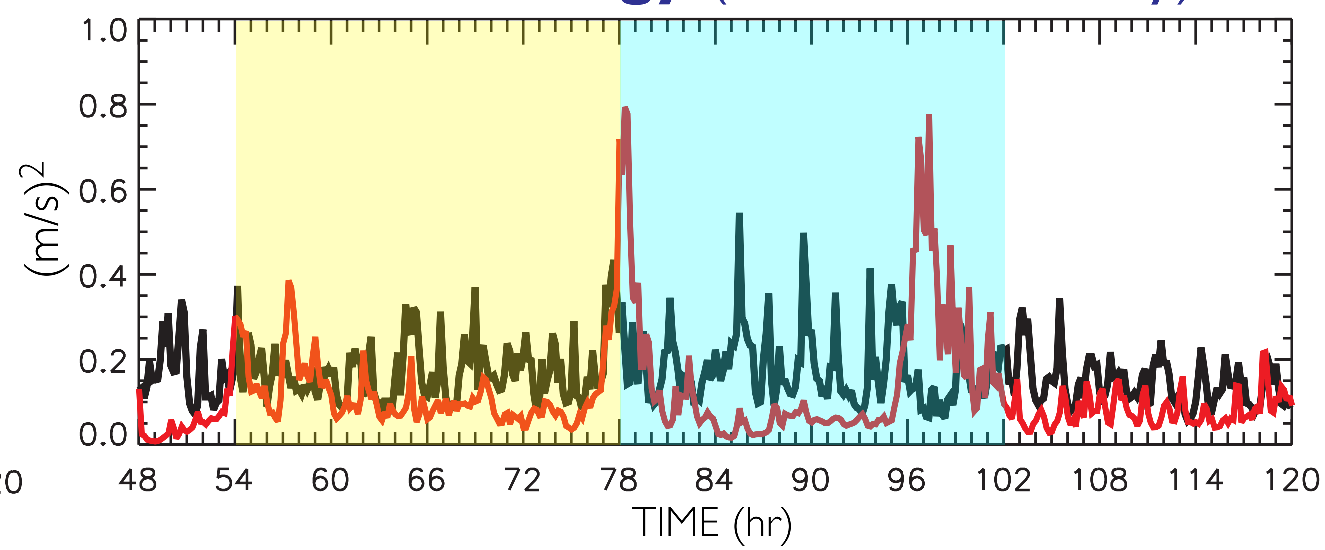
Enstrophy



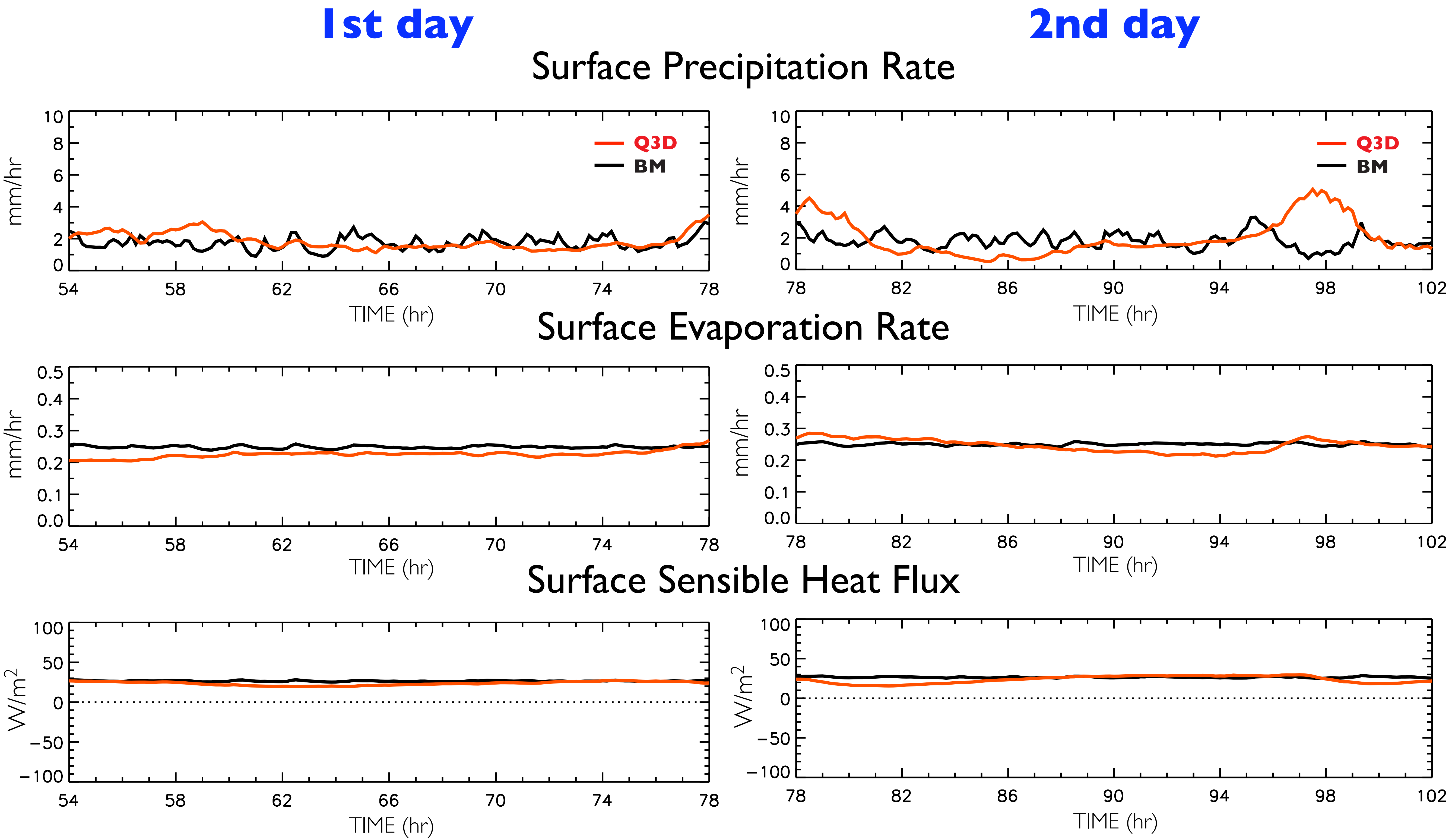
Kinetic Energy (of horizontal velocity)



Kinetic Energy (of vertical velocity)

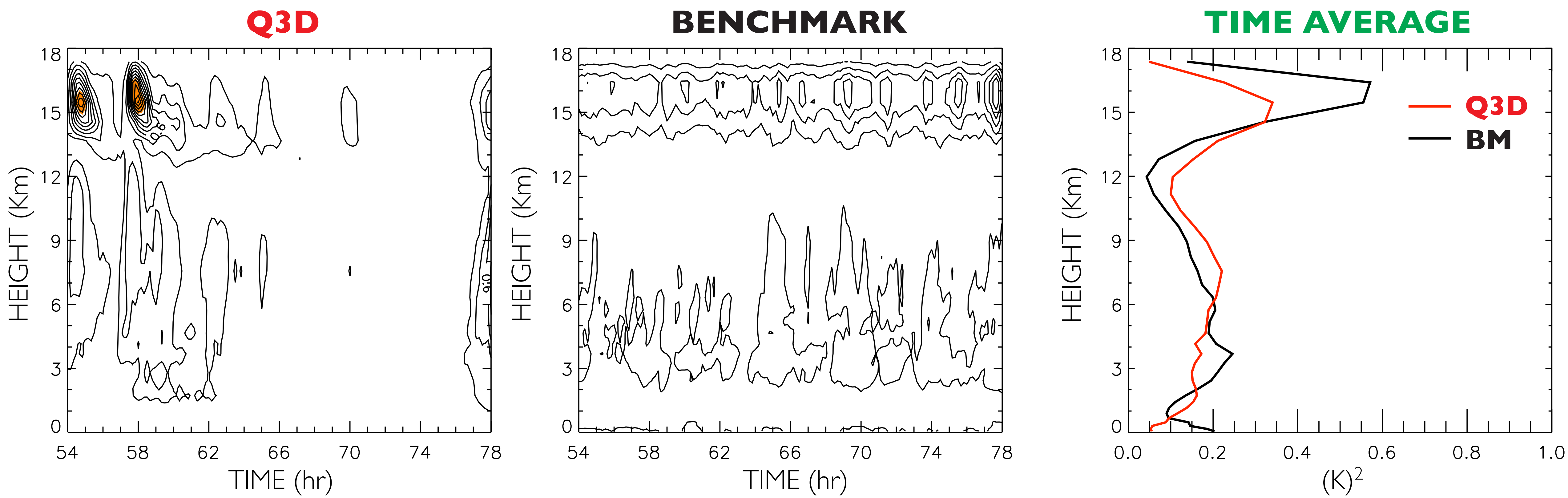


Comparison of a Q3D Prediction with the 3D Benchmark Prediction (BM)

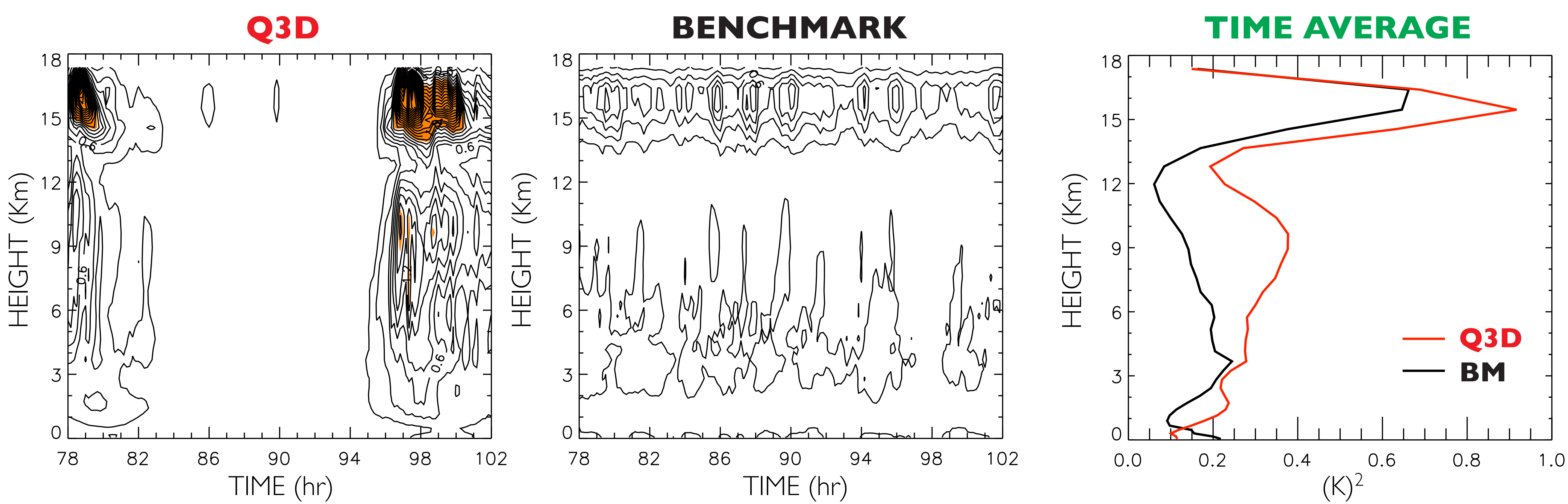


Variance of θ (Network averages)

1st day

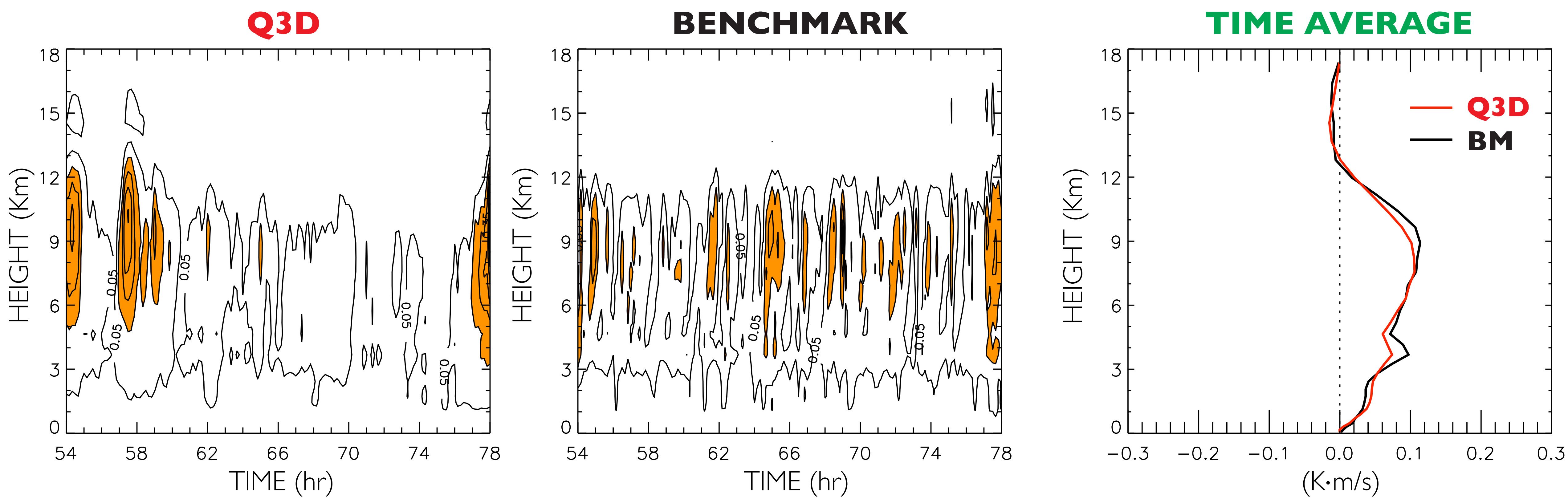


2nd day



Covariance of w and θ (Network averages)

1st day



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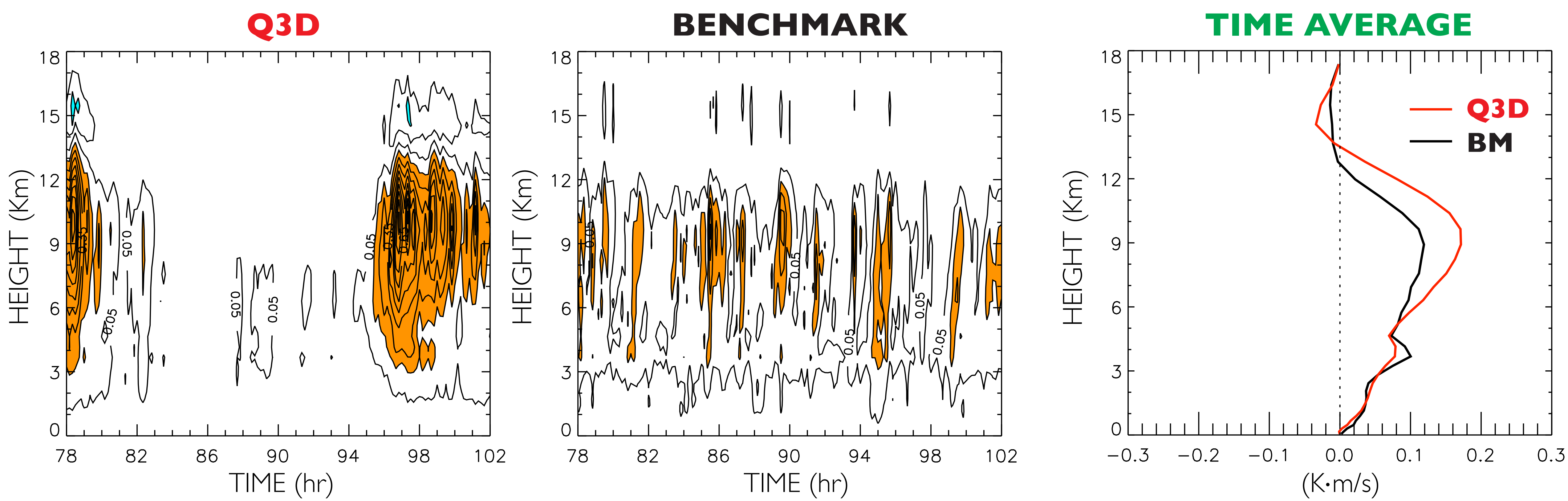
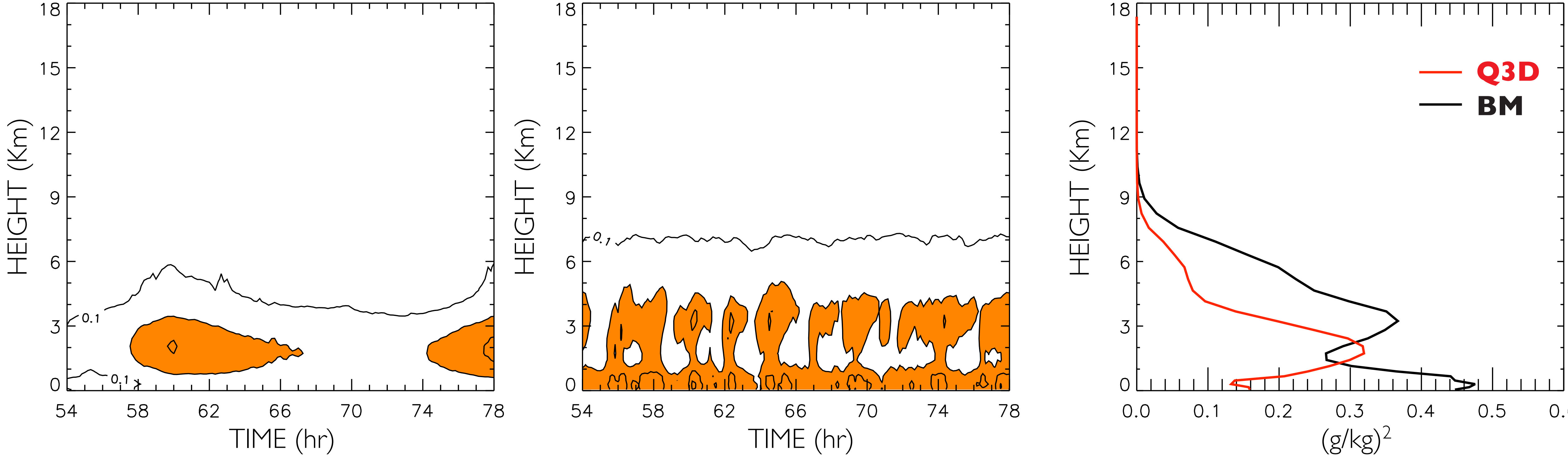


Variance of q_v (Network averages)

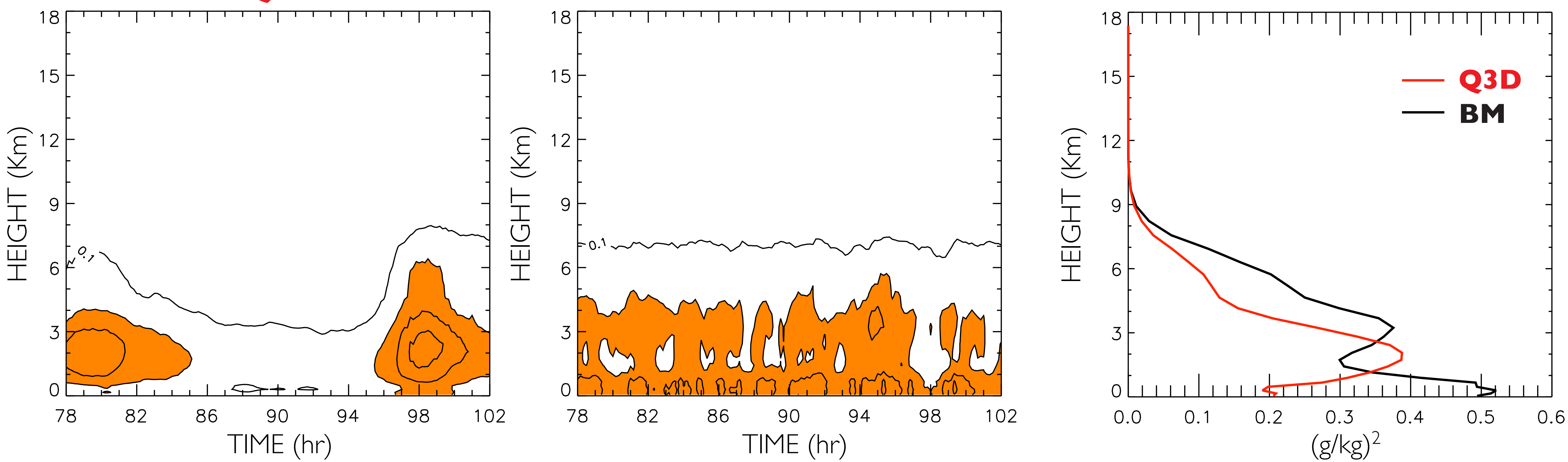
1st day

Q3D | BENCHMARK | TIME AVERAGE



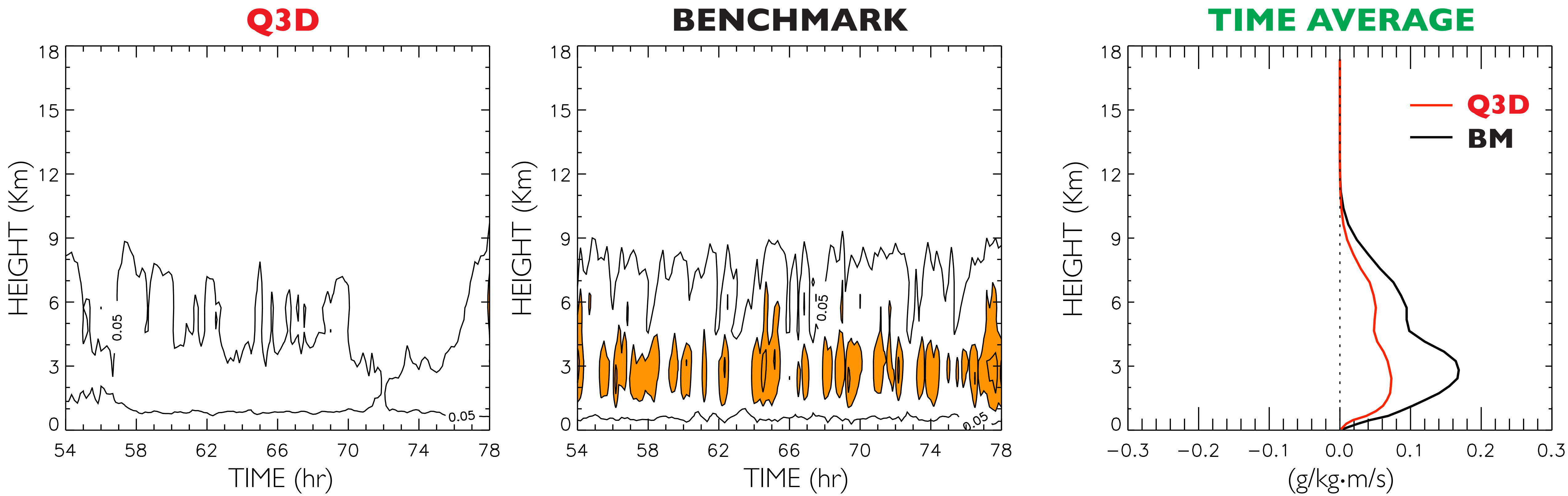
2nd day

Q3D | BENCHMARK | TIME AVERAGE



Covariance of w and q_v (Network averages)

1st day



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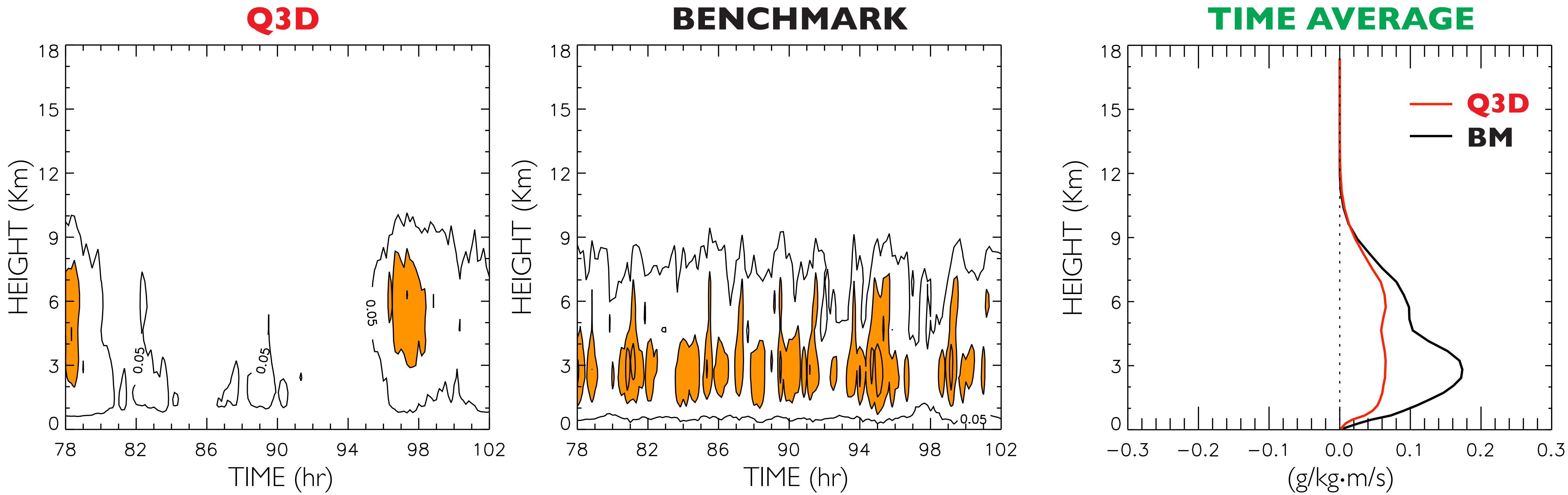
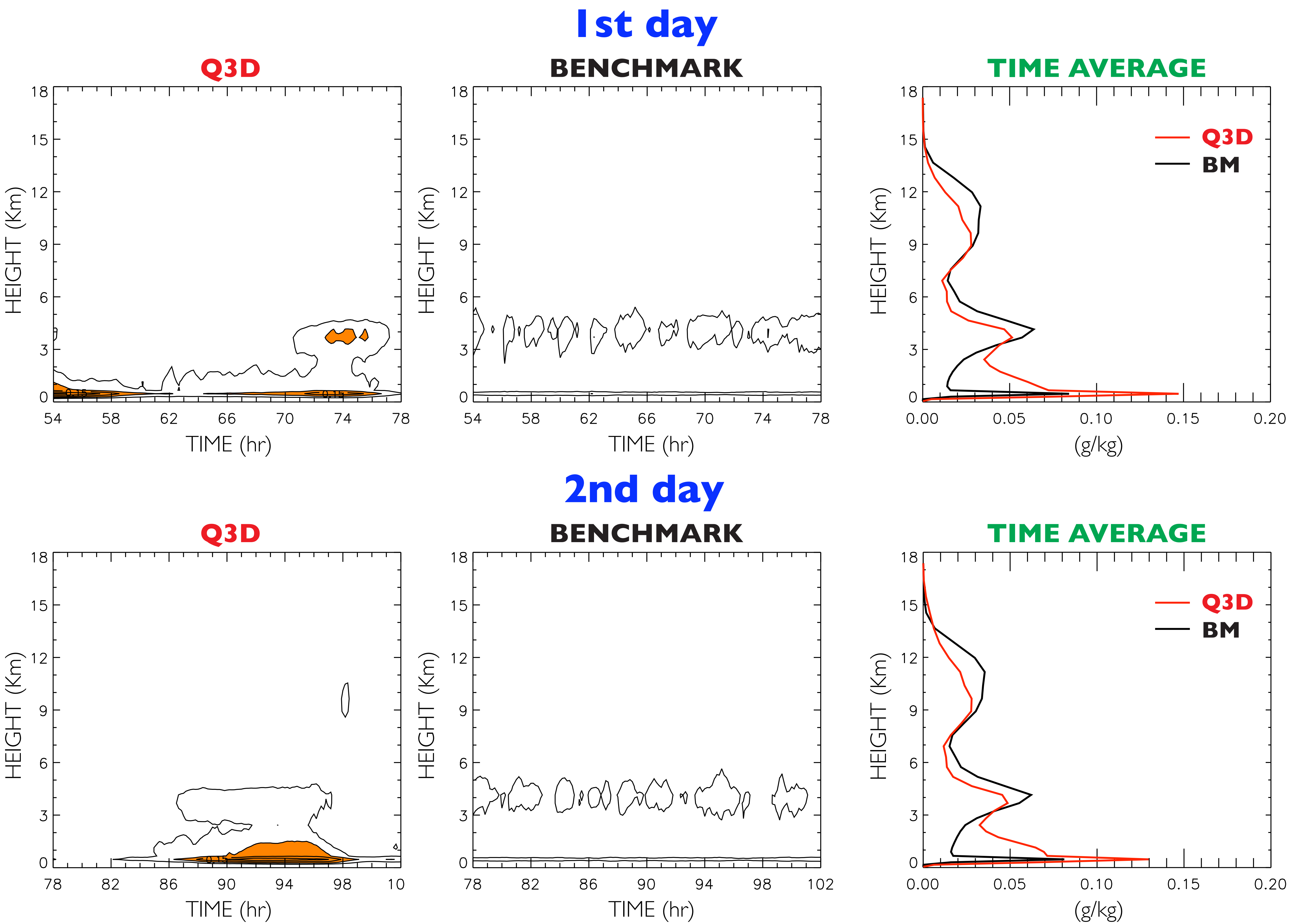
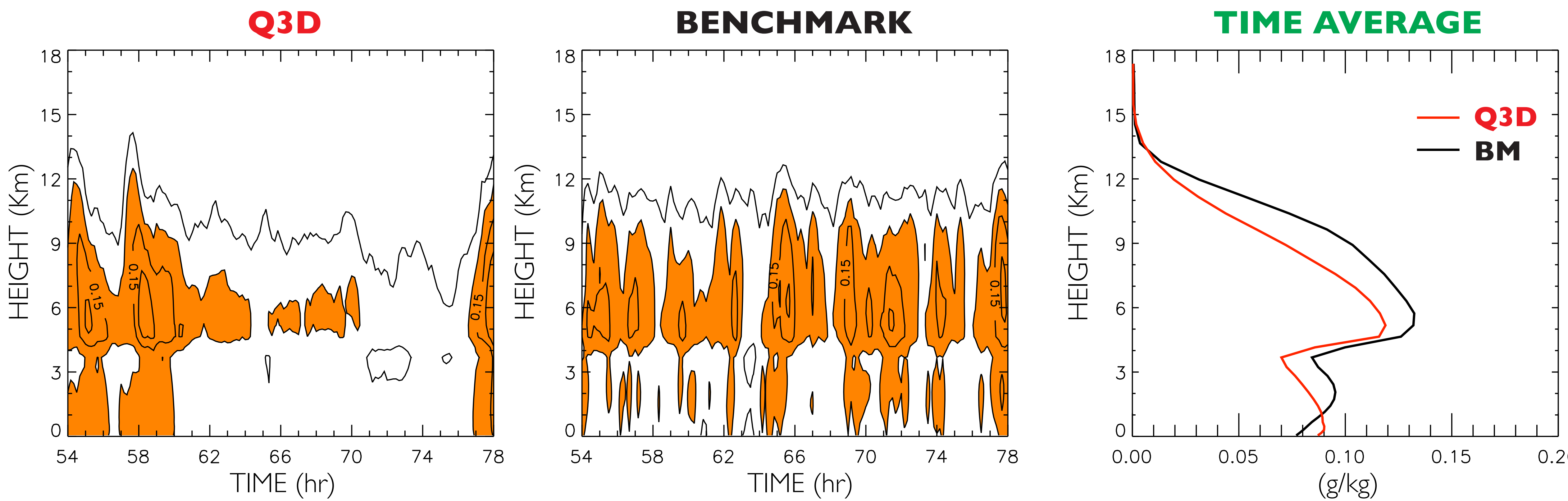


Sum of Cloud Liquid Water and Ice Mixing Ratios

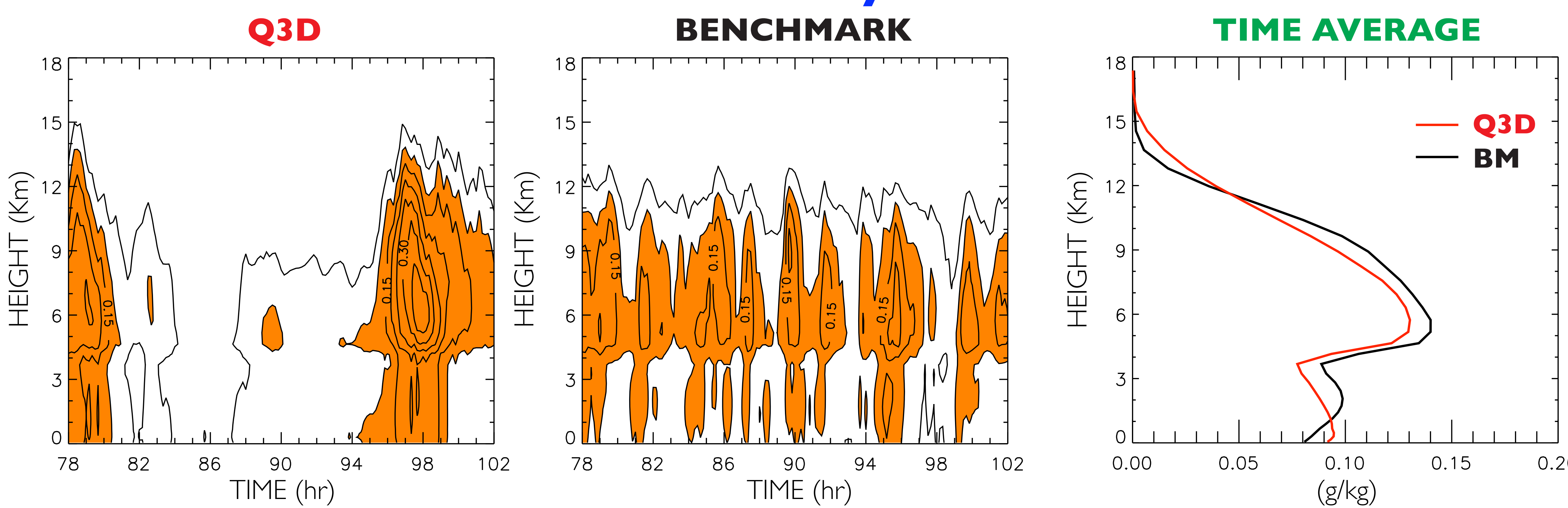


Sum of Rain, Snow, and Graupel mixing Ratios

1st day

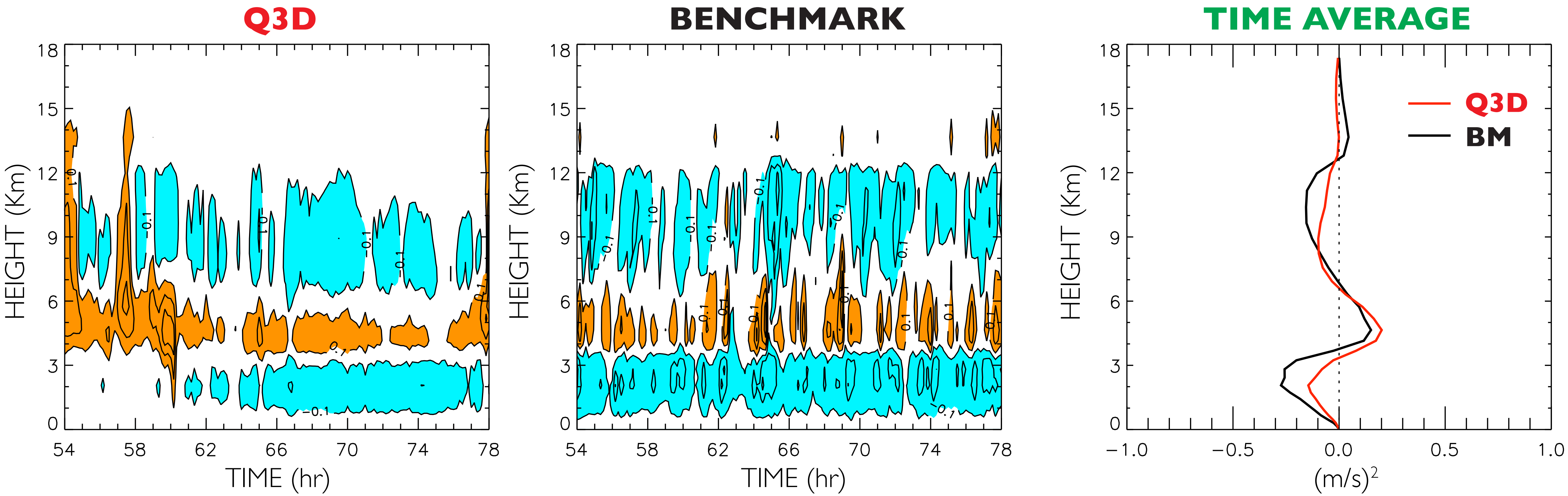


2nd day



Covariance of u and w (Network averages)

1st day



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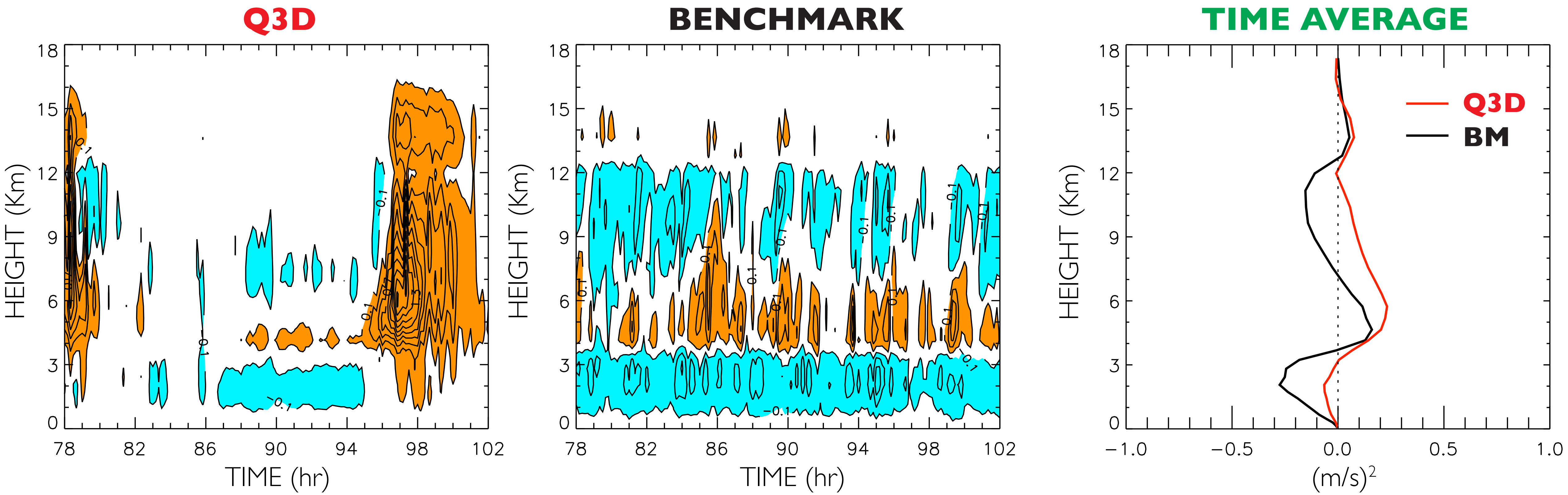


SUMMARY

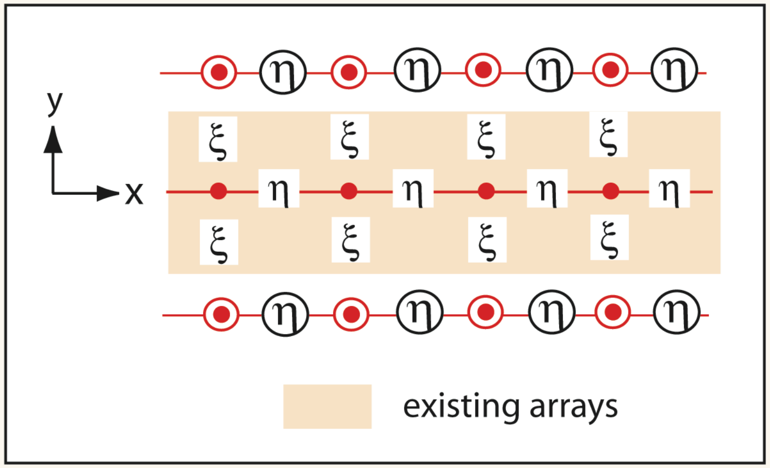
- We have worked on four kinds of grid, 3D CRM, Q3D CRM, 3D MMF and Q3D MMF. Using the fully-prognostic and fully-interactive Q3D MMF, we have entered the final phase of the work (as far as application to a small-domain is concerned).
- Q3D prediction tends to shift the spectrum toward horizontally larger scales, producing excessively strong horizontal velocity.
- Inclusion of the "selective damping" effectively controls computational instability associated with this shift.
- Encouraging results are obtained for the overall strengths of cloud-scale enstrophy and horizontal and vertical kinetic energy, surface precipitation and surface fluxes, the vertical profiles of buoyancy and momentum fluxes, and those of the network mean cloud water (except in the PBL) and precipitants.
- In spite of these successes, prediction of the mode of convective organization is unsuccessful. Instead of a propagating three-dimensional structure in the benchmark simulation, the model tends to choose a persistent organization along one direction with the largest interval in the other direction.

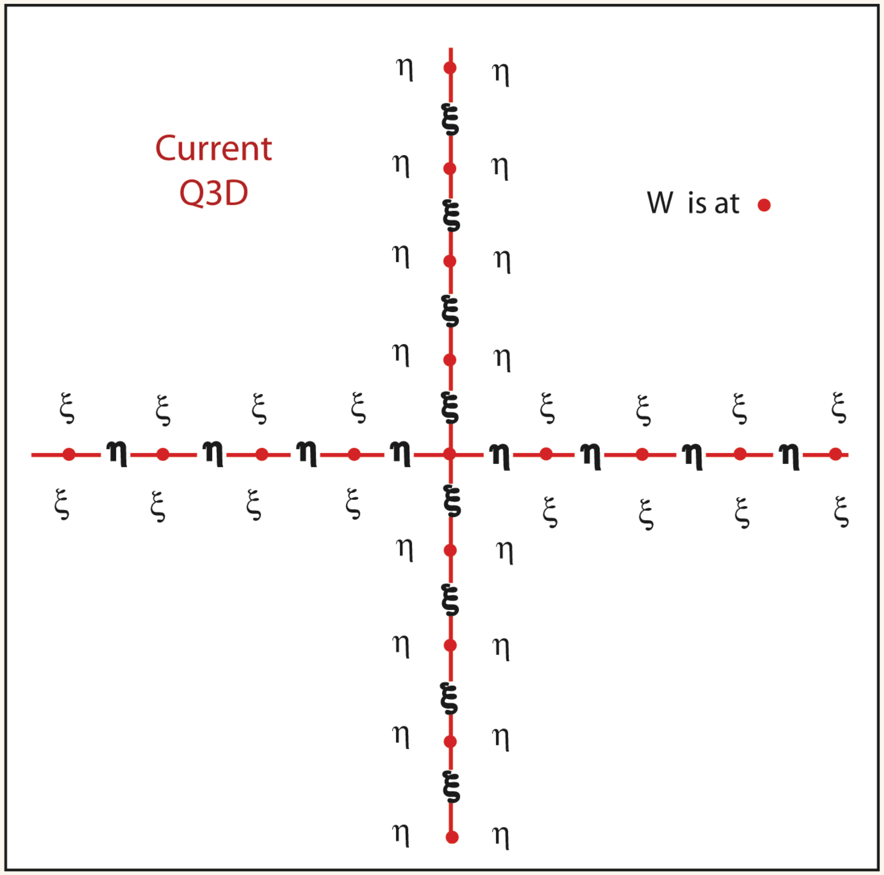
FUTURE PLAN

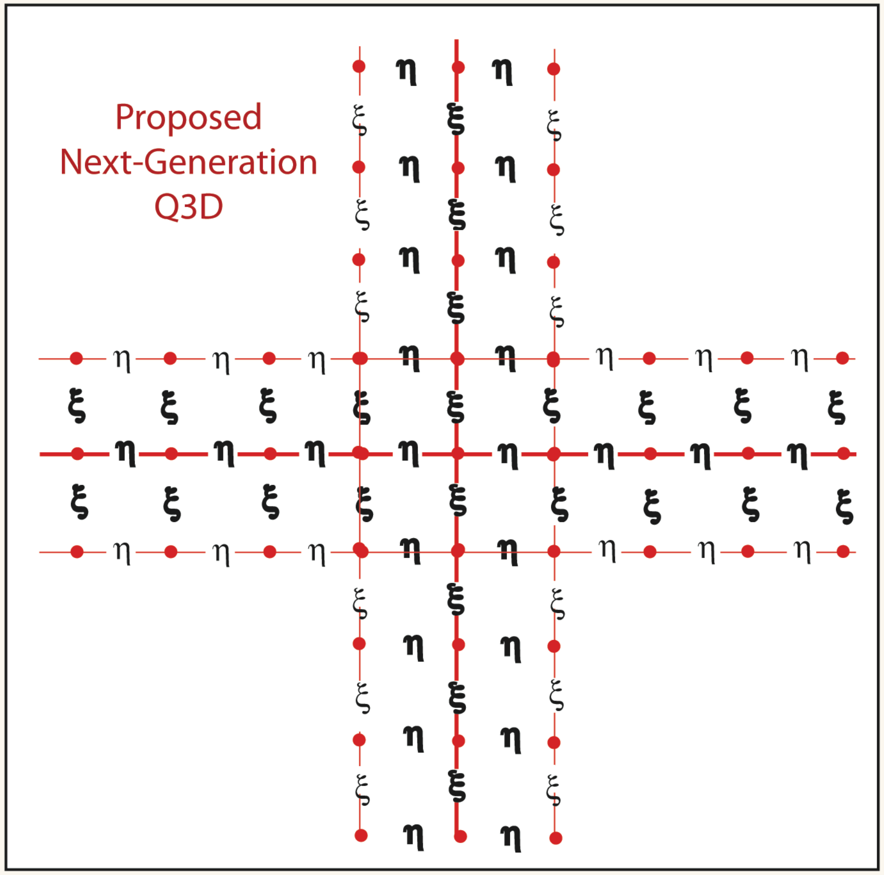
- We will continue to assess the strength and weakness of the current Q3D algorithm through more detailed and comprehensive analysis.

- Relatively poor prediction of the water-vapor variance can be attributed to the nudging of water vapor to a reference profile, a feature included even in the benchmark to guarantee realistic climatology. We will try to find an alternative.

- To predict propagation of organized clouds in the direction normal to a grid-point array, information on the asymmetry across the array is needed. Currently, the asymmetry is inferred using the statistics of the orientation of cloud organization. To explicitly predict the asymmetry, we look into the possibility of a next-generation Q3D MMF, which may use the grid below.







- An interactive degree of freedom across the array is added.
- For the array points, all terms in the w-equation are explicitly evaluated.

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

—— : Currently estimated either statistically or hypothetically.