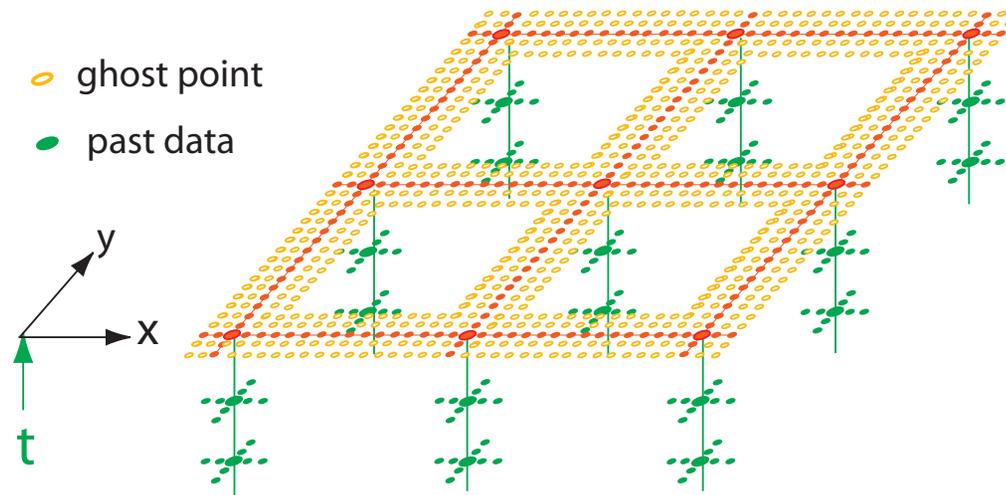


DEVELOPMENT OF Q3D MMF

Akio Arakawa and Joon-Hee Jung

EAP meeting September 29, 2008

Q3D CRM



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.

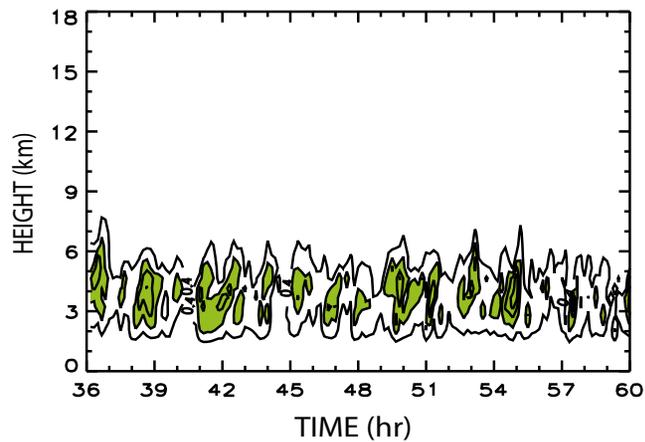
Major issues addressed: Global and local stability, handling the singularity, ...

TEST OF Q3D ADVECTION

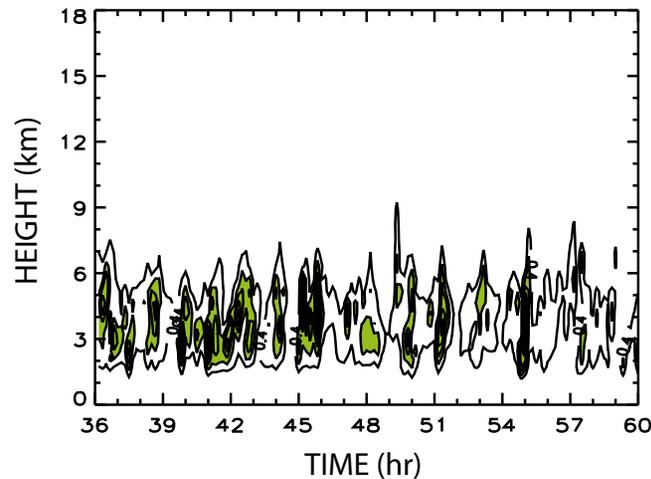
With θ and velocity components prescribed at all Q3D grid points.

Example: Variance of liquid water mixing ratio

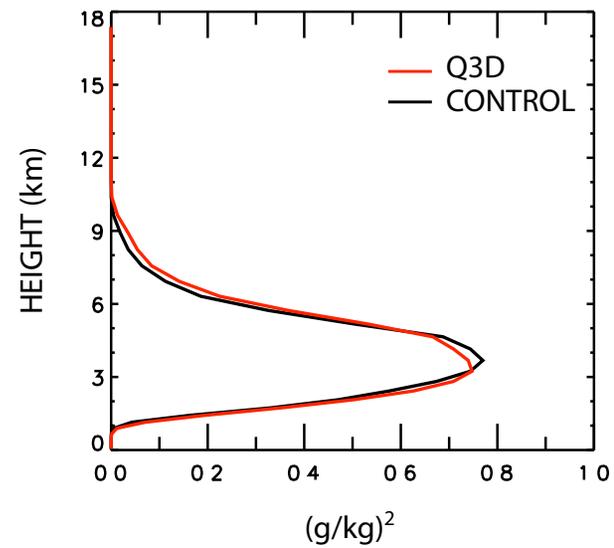
BENCHMARK (3D)



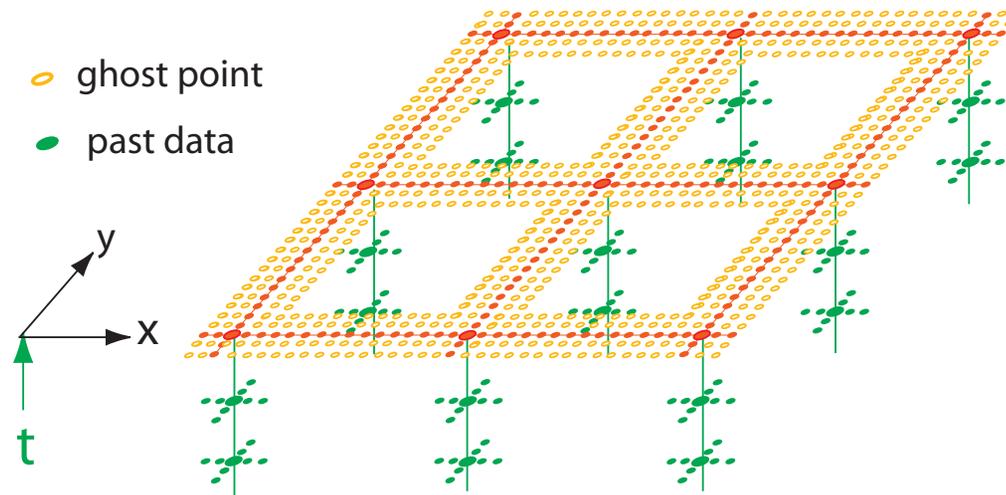
Q3D



Time Average



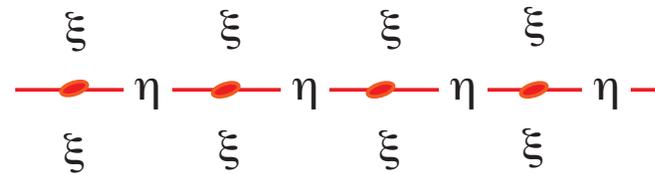
Q3D CRM



Q3D DYNAMICS

Additional issues addressed:

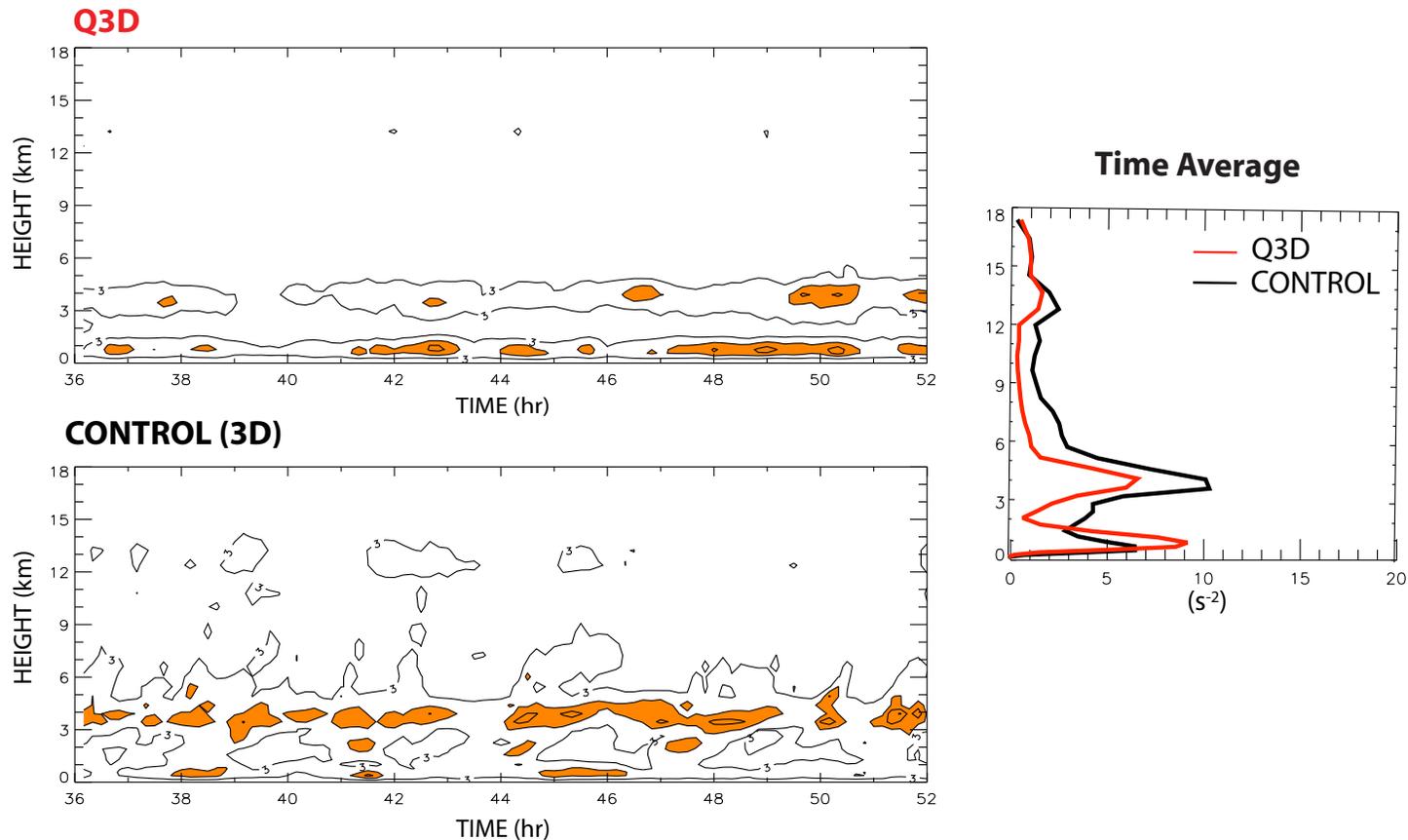
- Elimination of the imbalance of the degree of freedom between the two vorticity components: only the average across the array is prognostically determined.
- Estimation of the twisting term (a purely 3D problem),
- Solving the 3D w -equation,



TEST OF Q3D DYNAMICS (FULLY-PROGNOSTIC)

Still without coupling with the GCM.

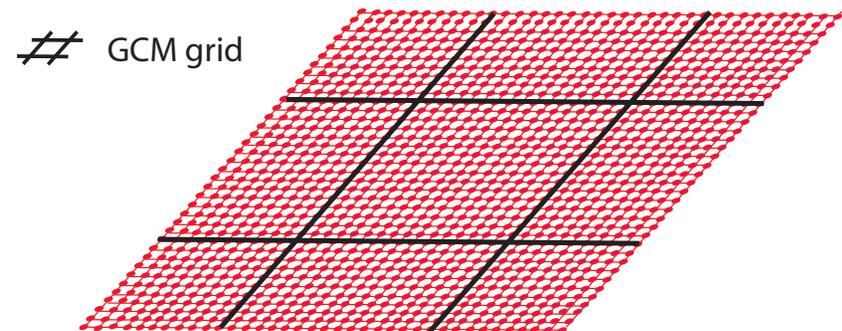
Example: X-array variance of the y-component of vorticity



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

- 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.

For testing various methods of coupling independent of the dimensionality, we used a 3D MMF.



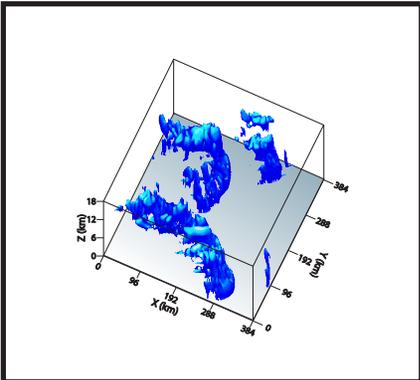
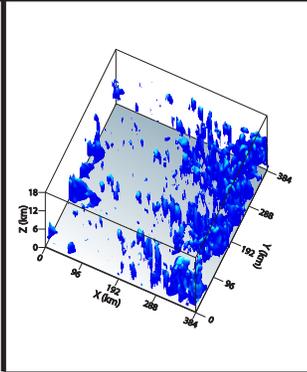
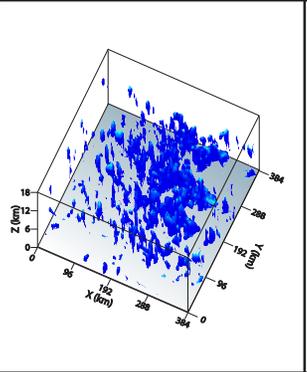
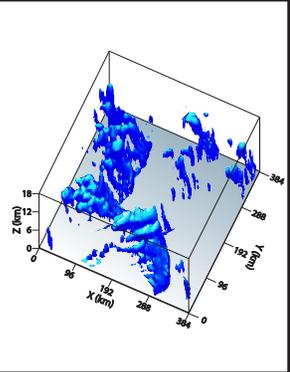
The CRM in this case is a “perfect” GCM by itself so that the GCM component should play only a passive role.

TWO BASIC APPROACHES FOR COUPLING

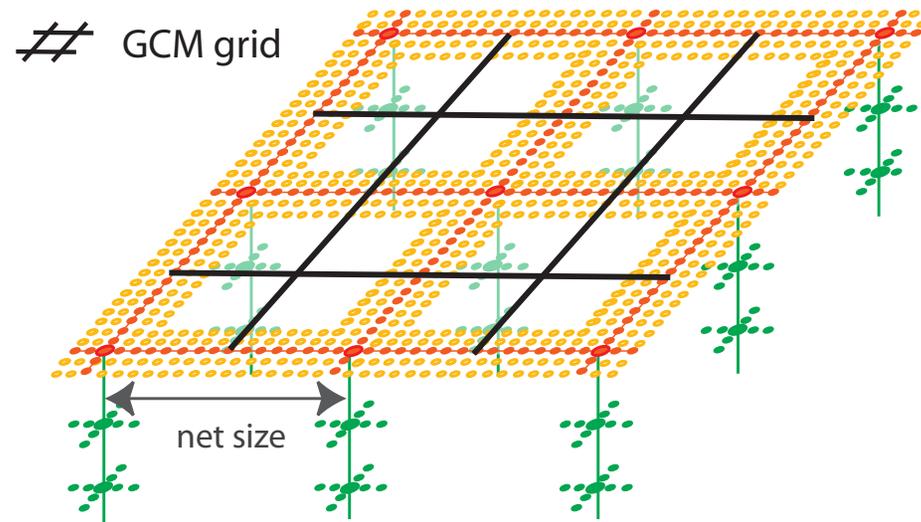
- I. **Coupling through processes** (such as advection, condensation, ...) (Parallel to the traditional cumulus parameterization)
- II. **Mutual relaxation** of prognostic variables

BENCHMARK

3D MMF RESULTS WITH DIFFERENT COUPLING METHOD

FORCING		PROCESS	
VORTICITY FEEDBACK	PROCESS	RELAXATION	RELAXATION
THERMAL FEEDBACK		PROCESS	PROCESS
			

Q3D MMF



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

Benchmark Simulation with VVCM

- **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

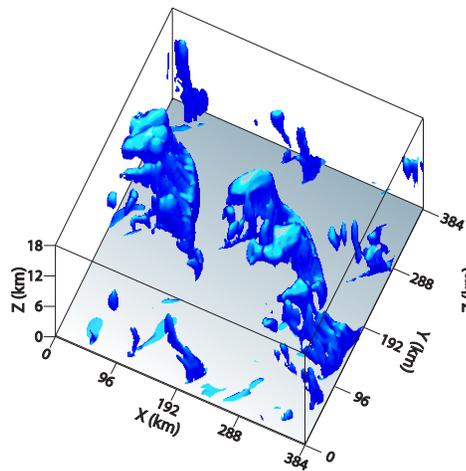
VVCM: Vector Vorticity Cloud Model (Jung and Arakawa, 2008)

Benchmark Simulation with VVCM

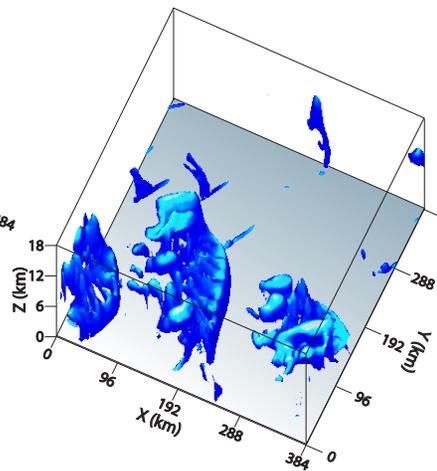
(An example of cloud development)

Isotomic Surface of Cloud Water Mixing Ratio

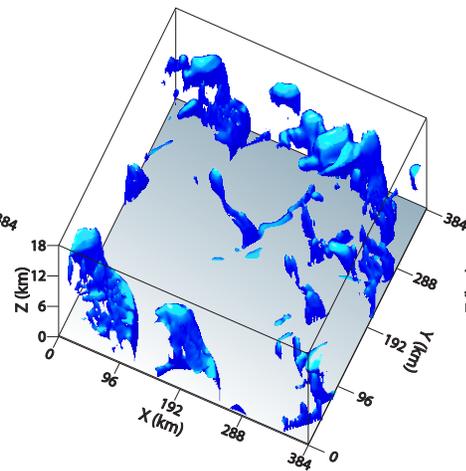
t=60 hr



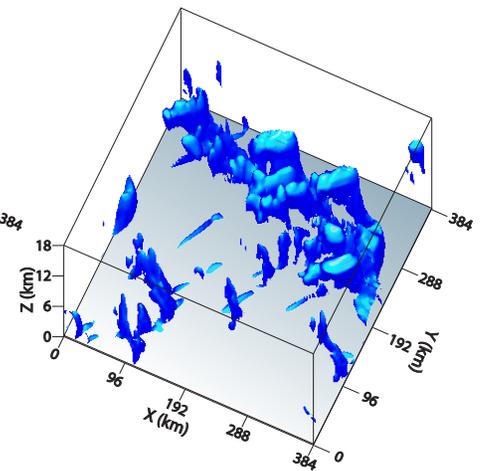
t=72 hr



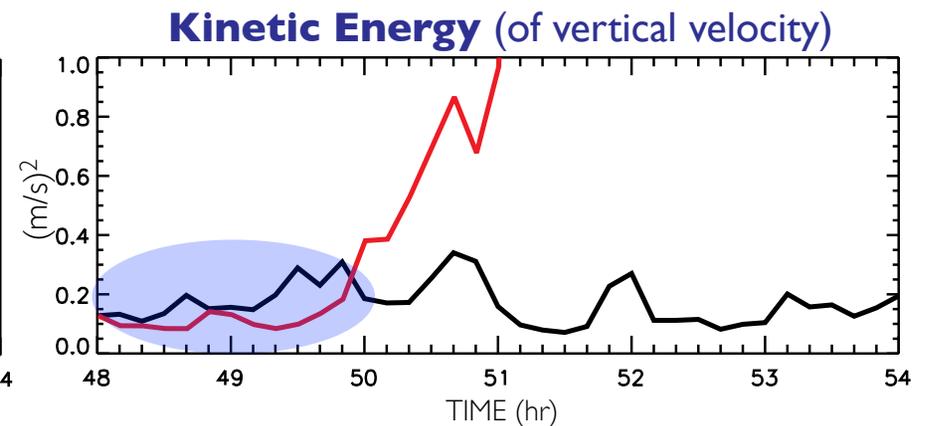
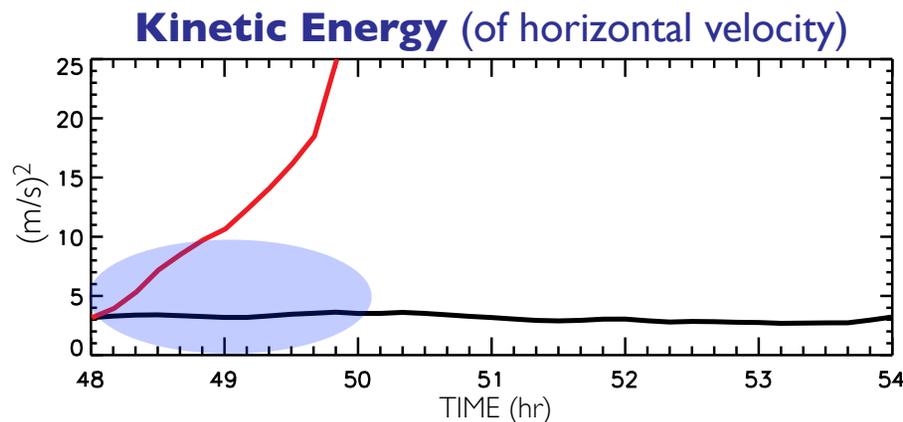
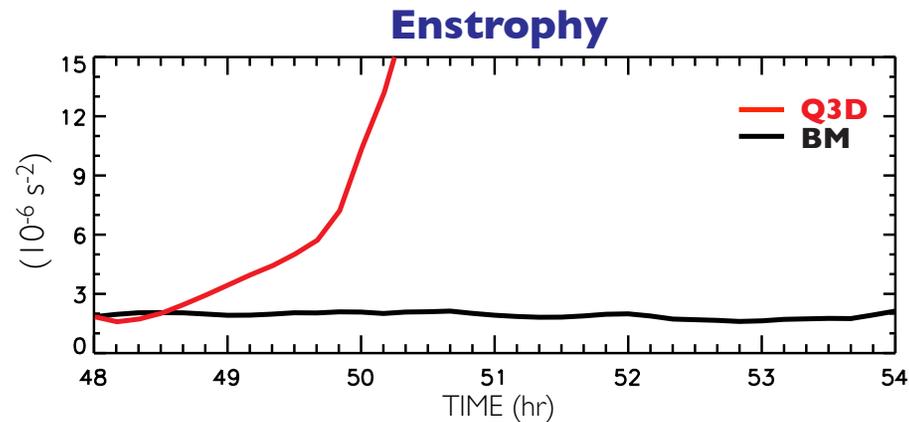
t=84 hr



t=96 hr



“FIRST Q3D MMF SIMULATION IN A TEST MODE”



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

Considerable efforts have been spent to computationally “stabilize” the algorithm.

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

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

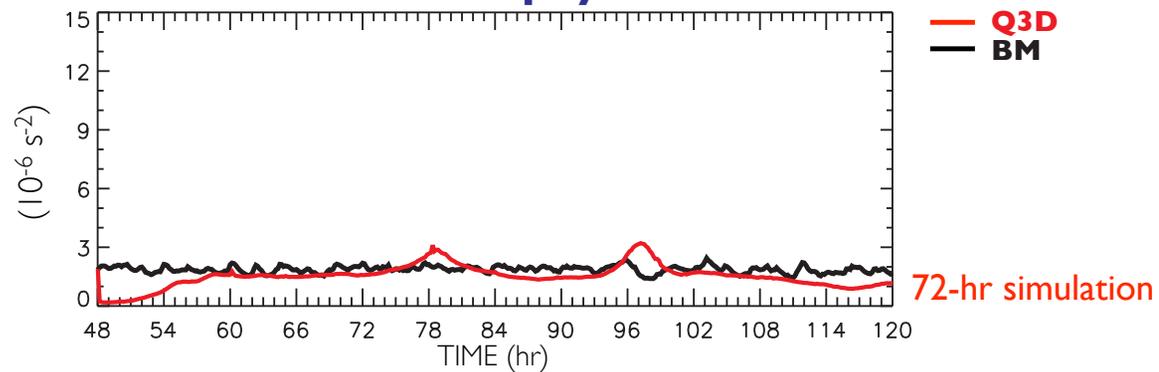
When the vorticity field is shear dominated (i.e. the vertical shear and vorticity are positively correlated), the mass-weighted domain integral of enstrophy decreases.

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

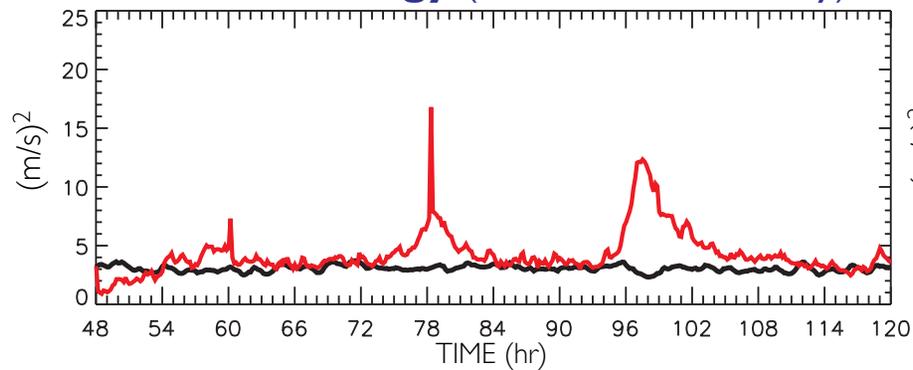
Q3D MMF SIMULATION

(with the selective damping)

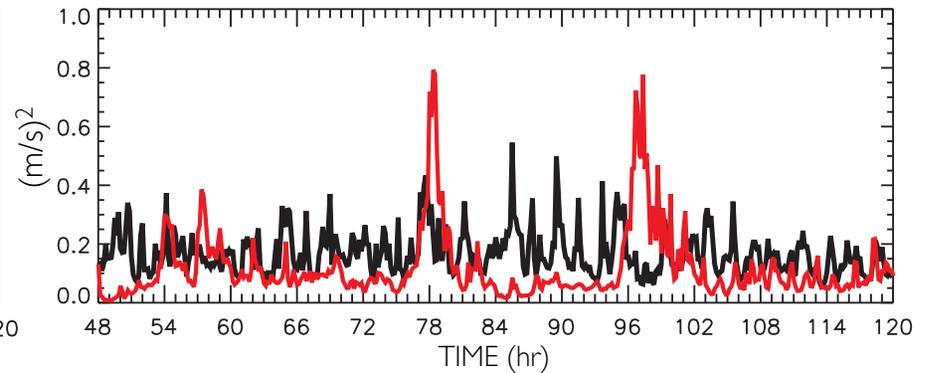
Enstrophy



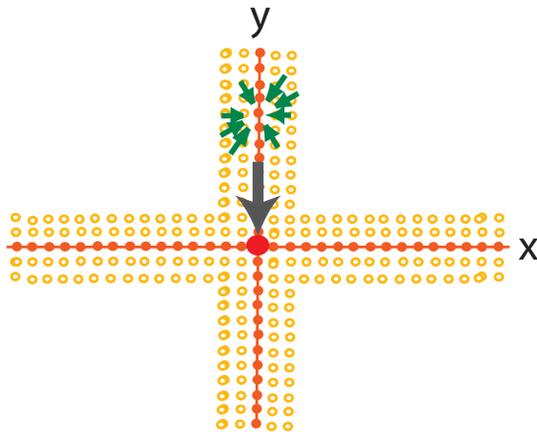
Kinetic Energy (of horizontal velocity)



Kinetic Energy (of vertical velocity)

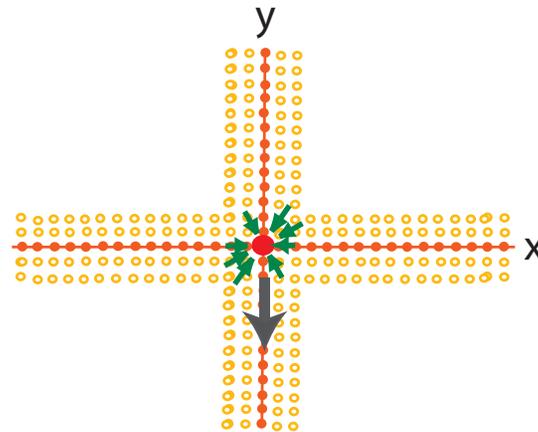


Passage of a strong convective system over an intersection point produces a spike in the total variance



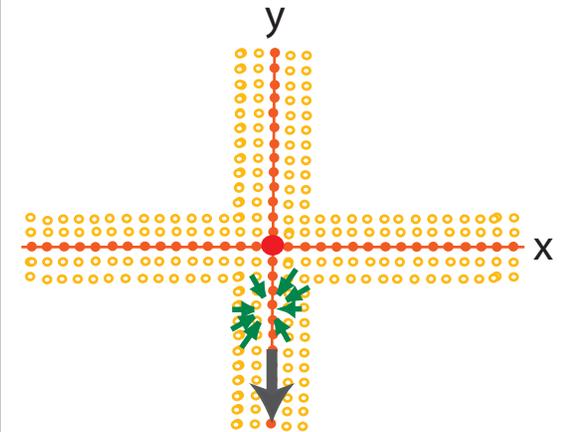
Variance is in y only.

The structure of the system in x is constrained.



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

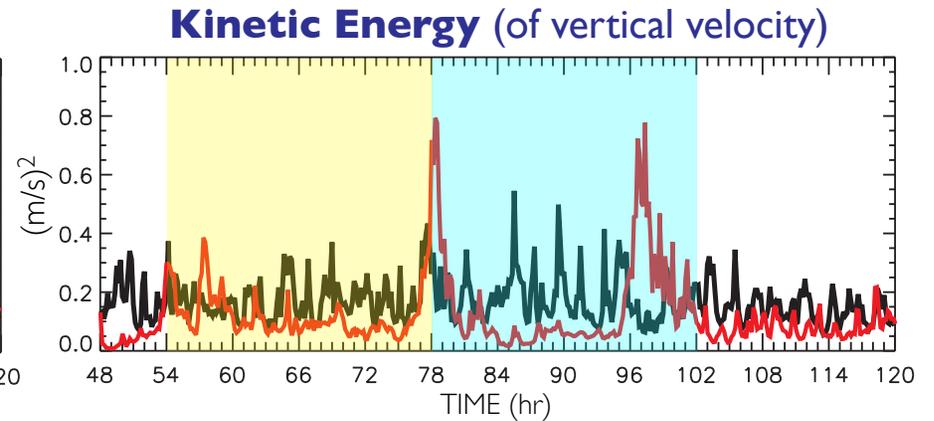
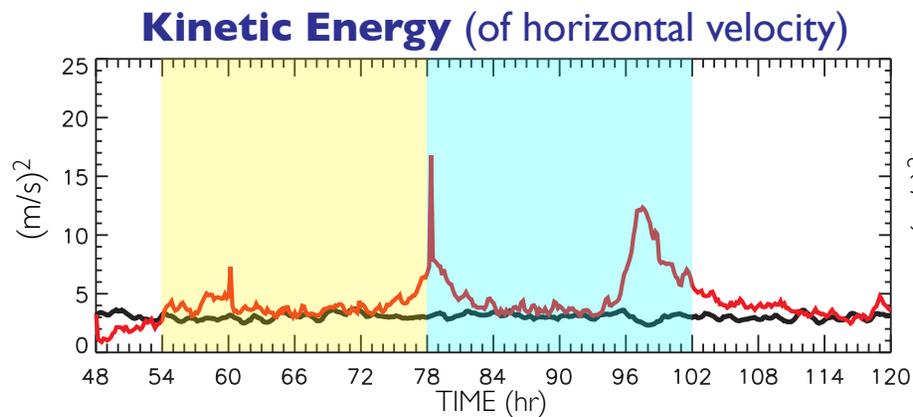
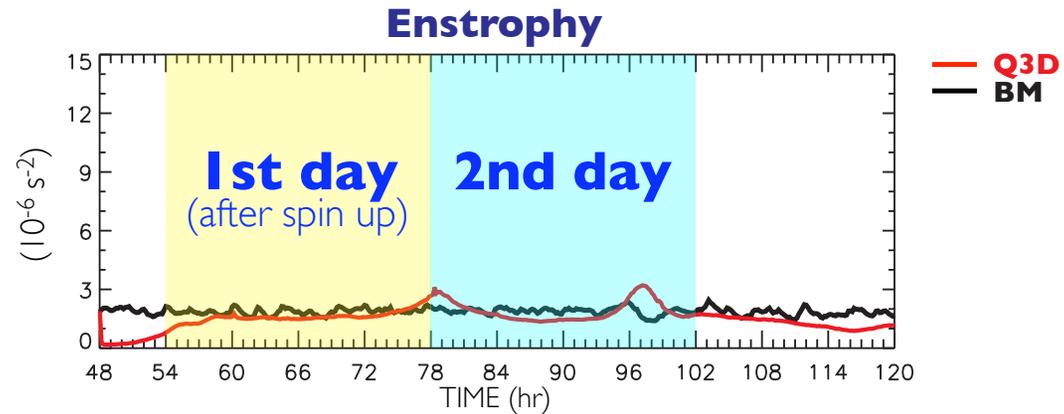
The structure of the system in x becomes free, suppressing convective activity on the x-axis by induced subsidence.



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)

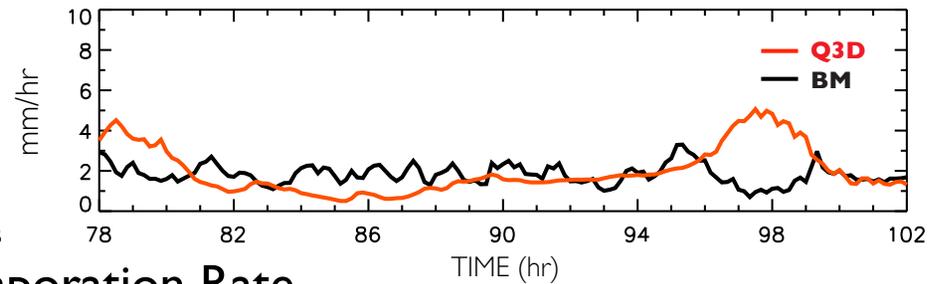
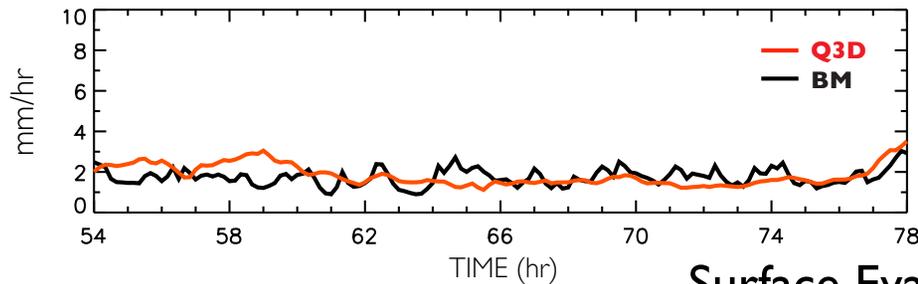


Comparison of a Q3D Prediction with the 3D Benchmark Prediction (BM)

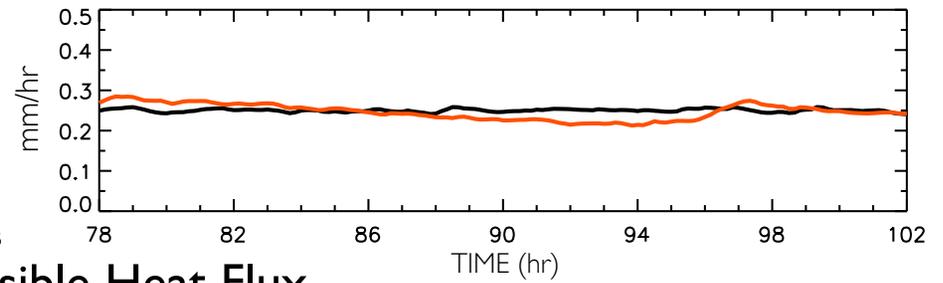
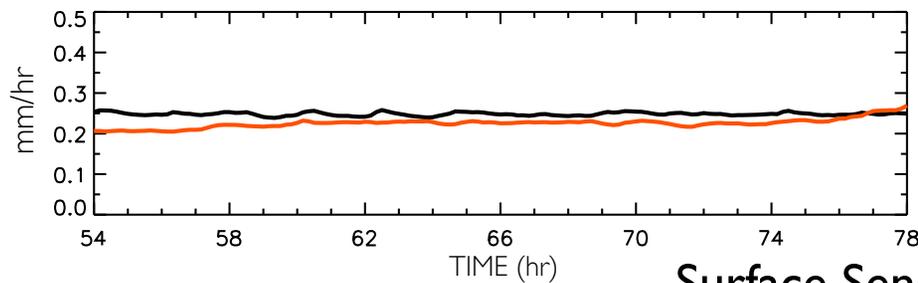
1st day

2nd day

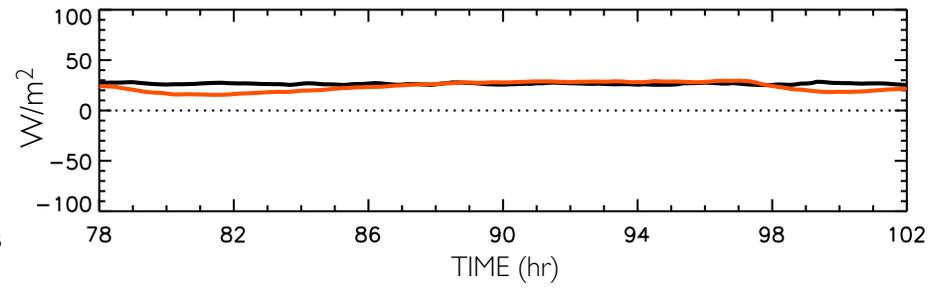
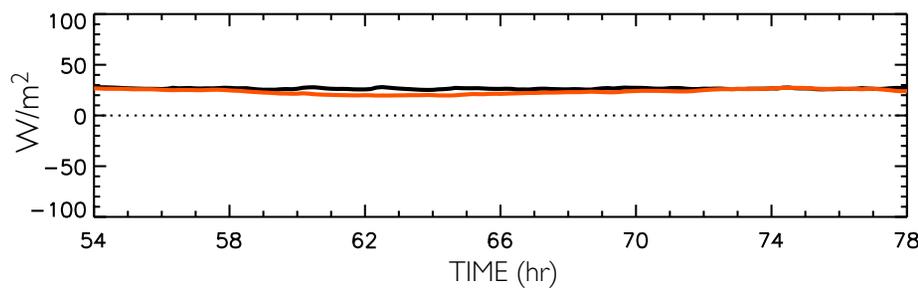
Surface Precipitation Rate



Surface Evaporation Rate

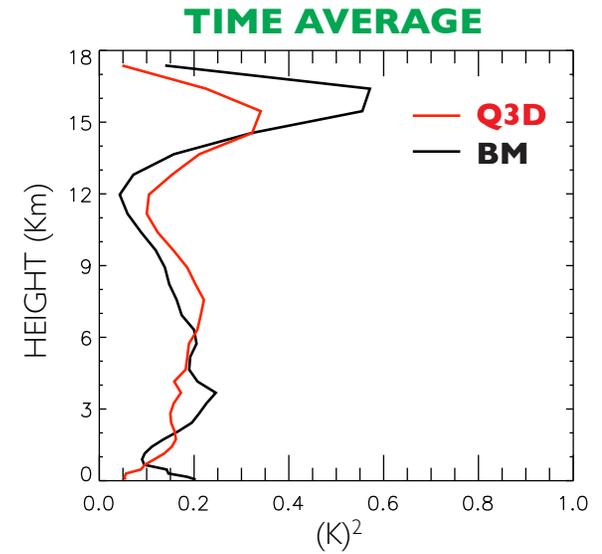
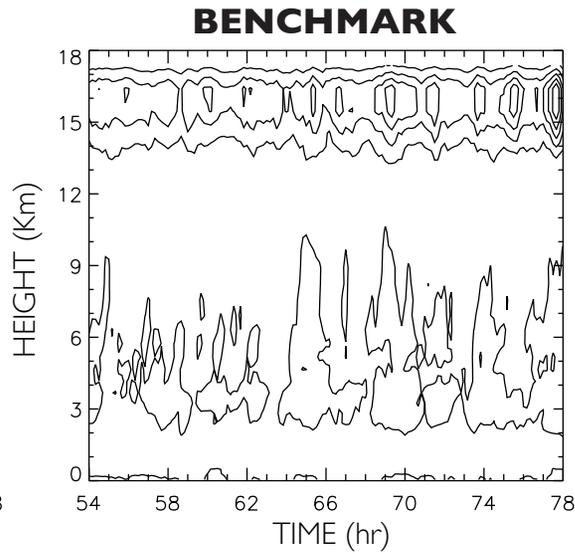
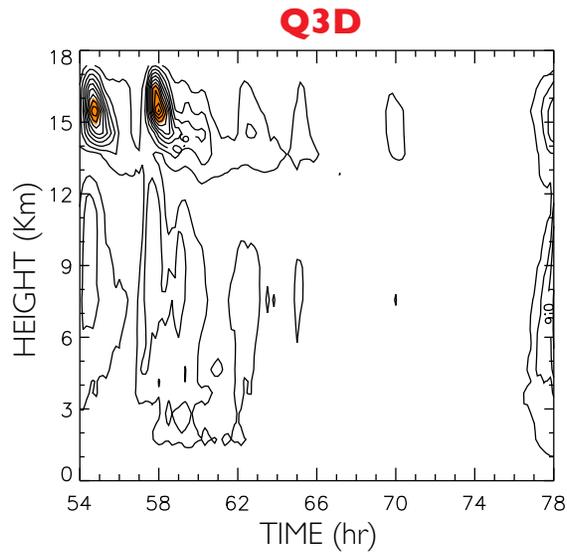


Surface Sensible Heat Flux

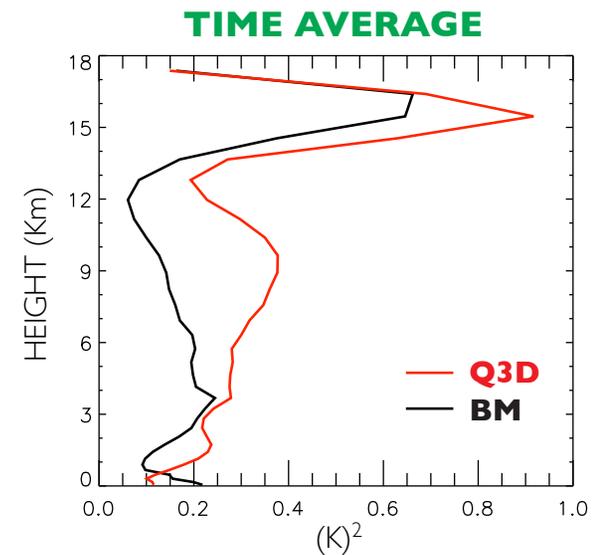
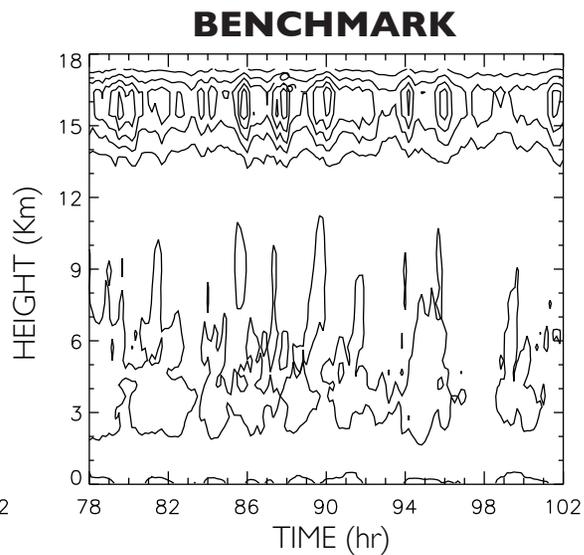
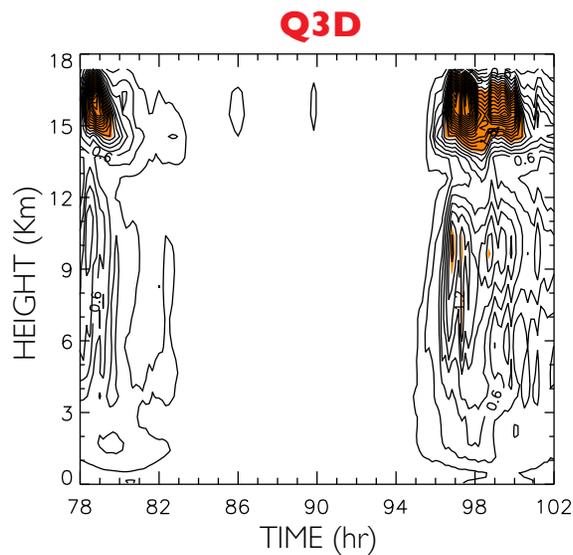


Variance of θ (Network averages)

1st day

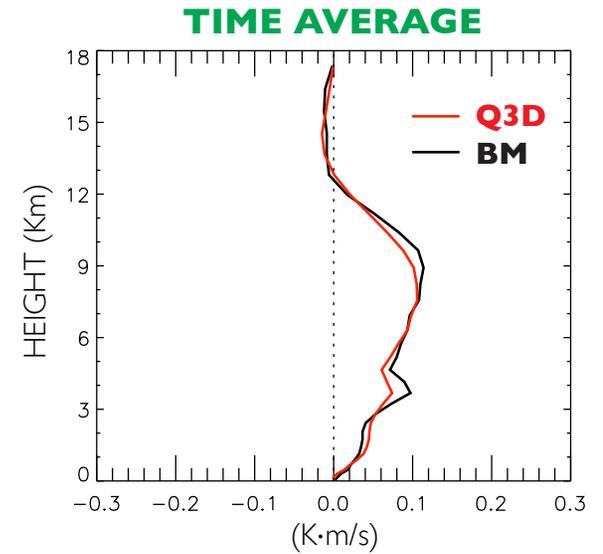
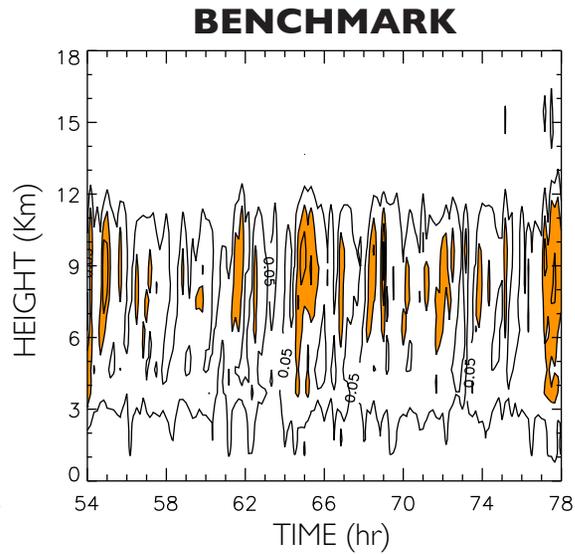
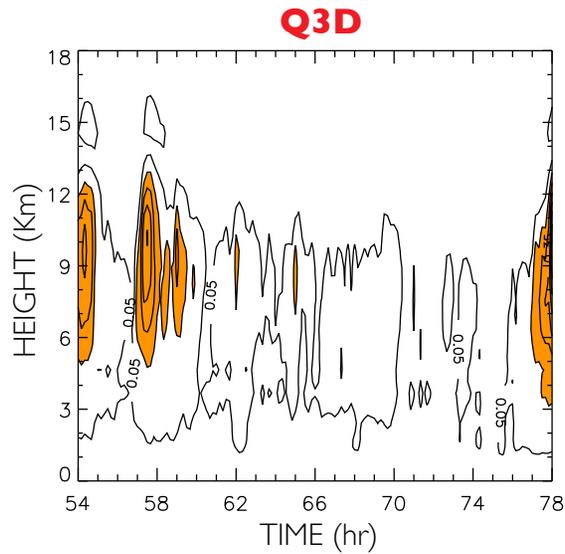


2nd day

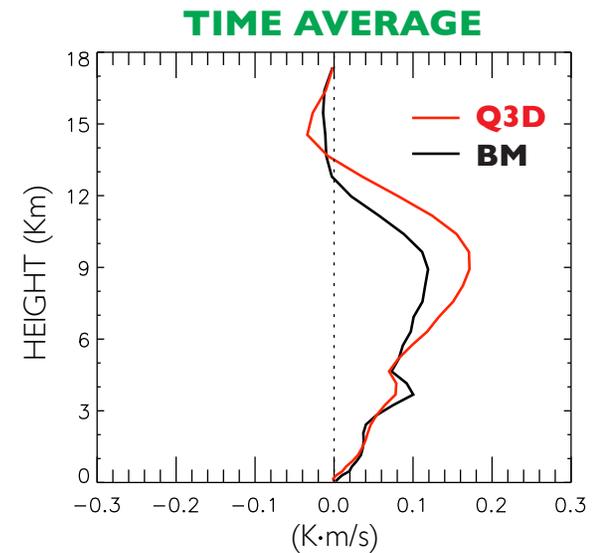
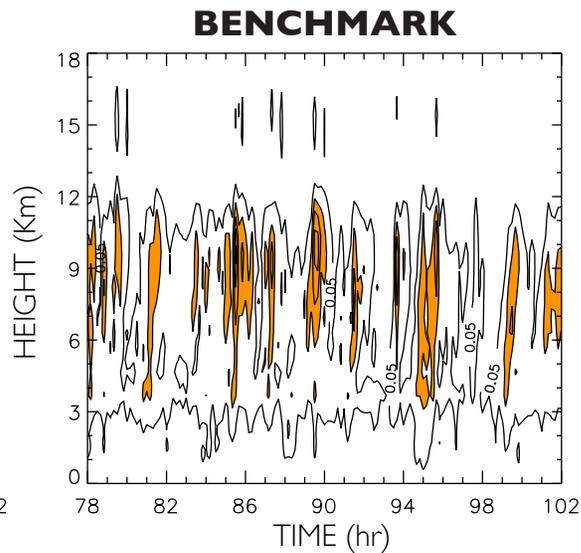
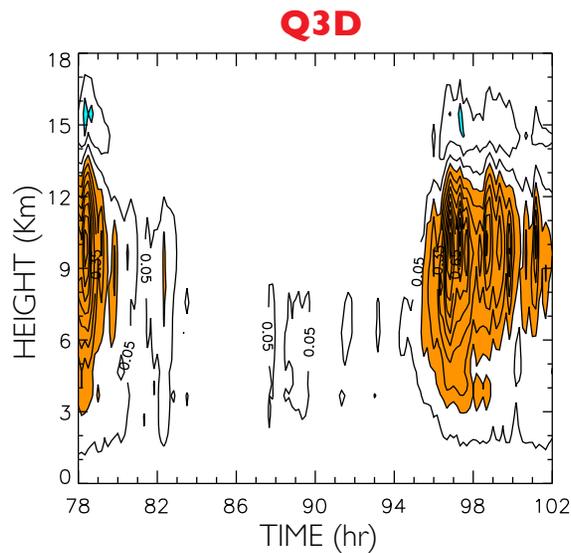


Covariance of w and θ (Network averages)

1st day



2nd day

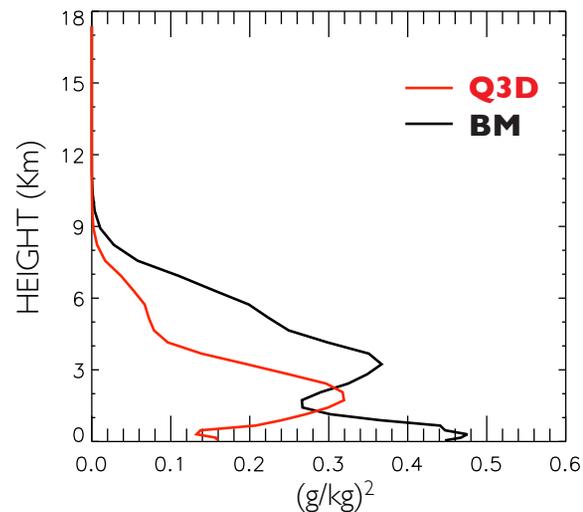
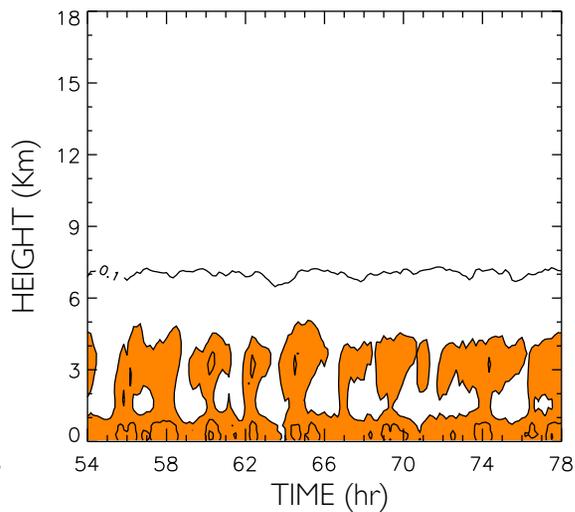
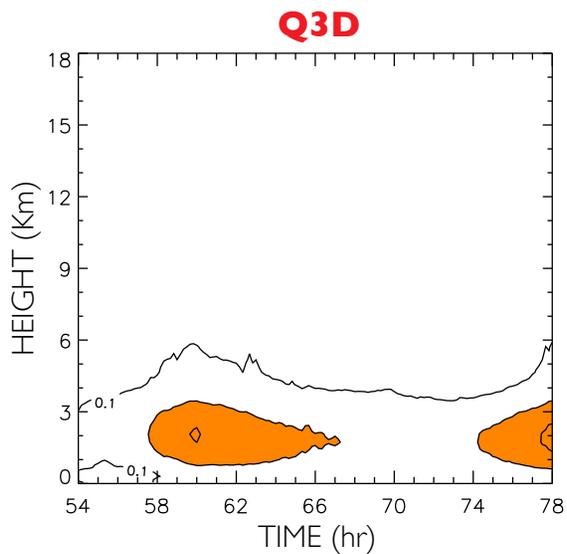


Variance of q_v (Network averages)

1st day

BENCHMARK

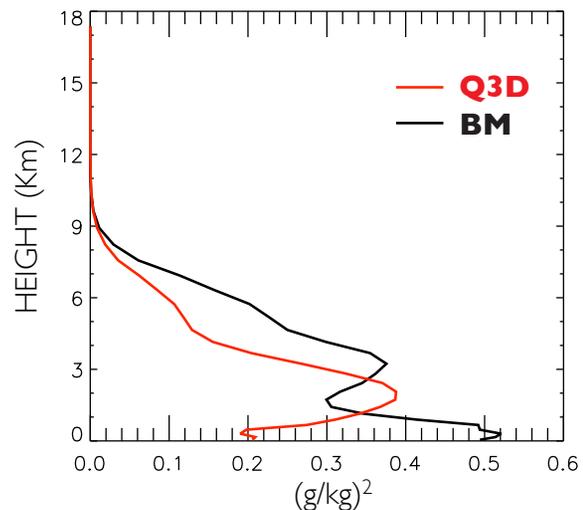
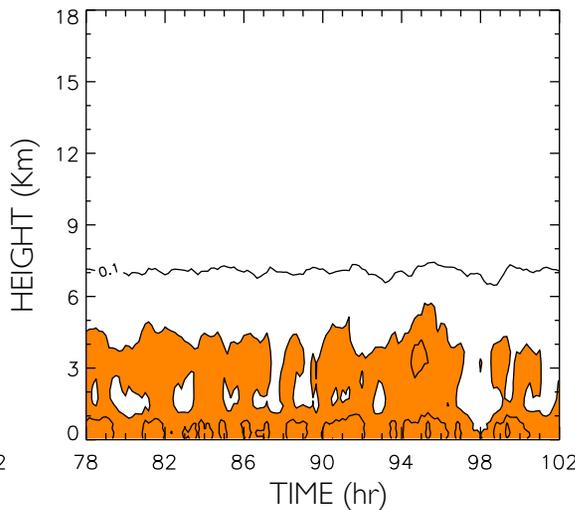
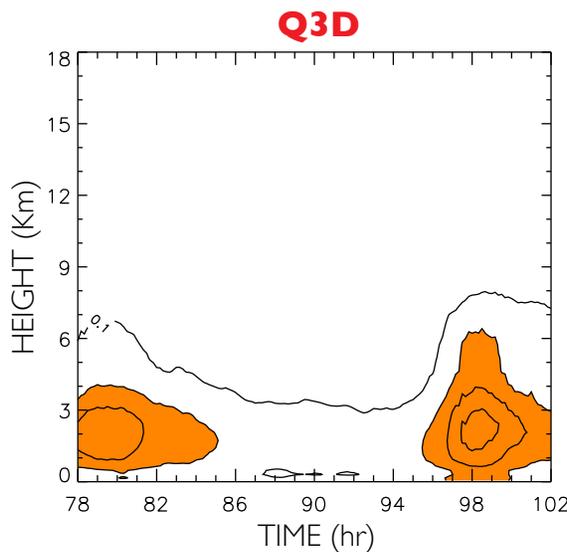
TIME AVERAGE



2nd day

BENCHMARK

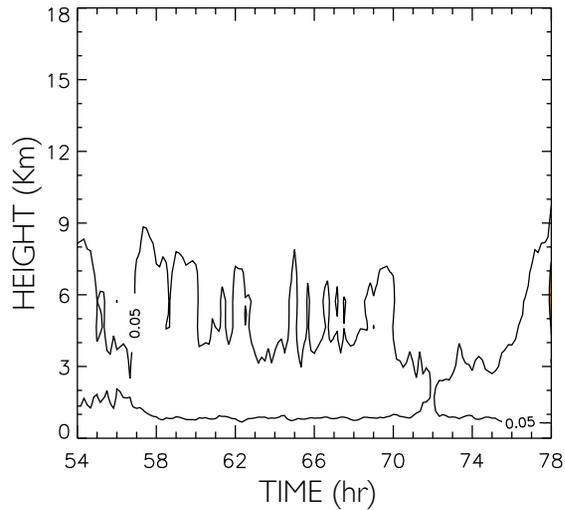
TIME AVERAGE



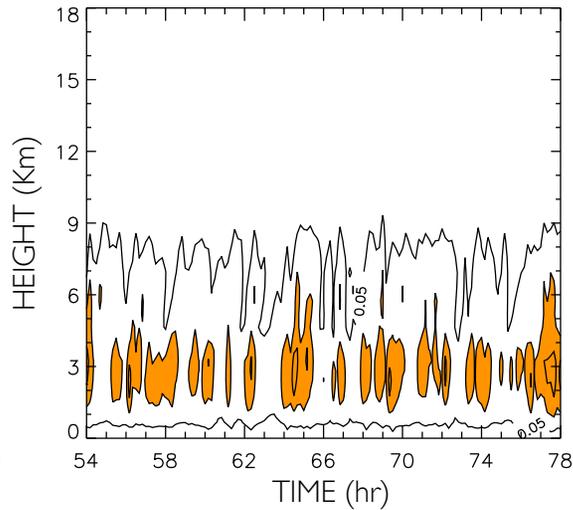
Covariance of w and q_v (Network averages)

1st day

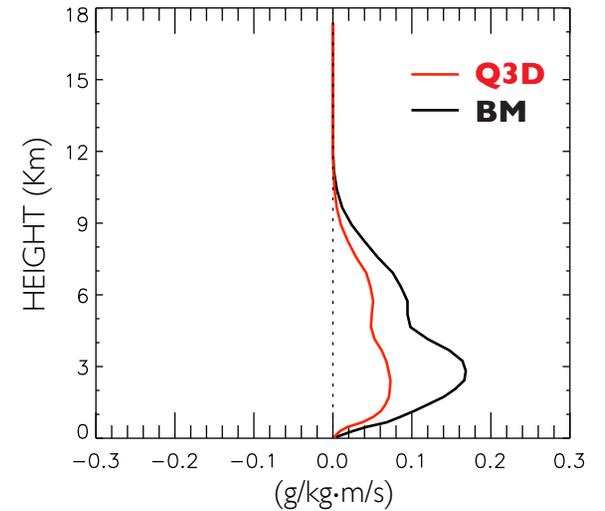
Q3D



BENCHMARK

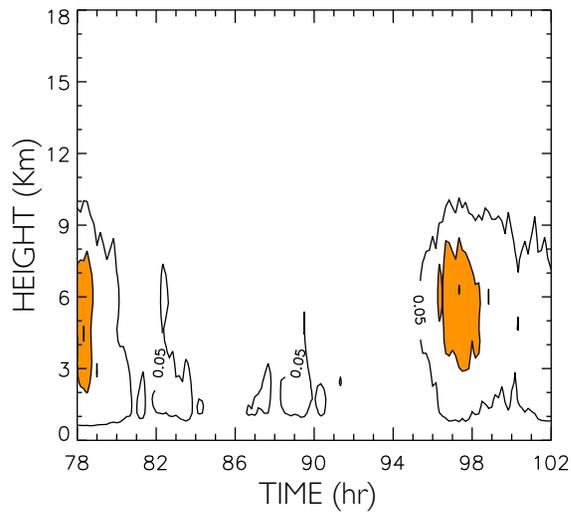


TIME AVERAGE

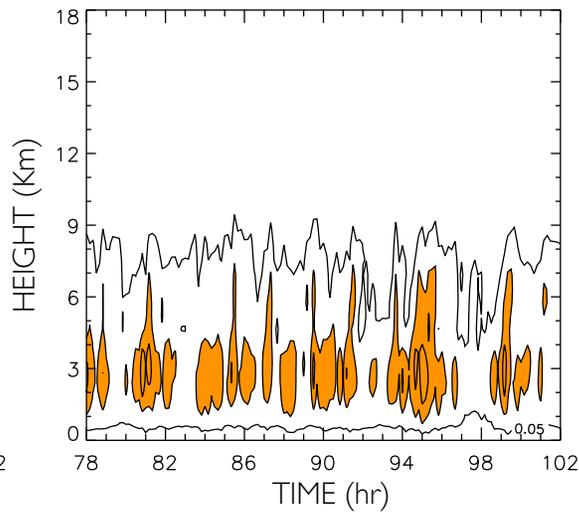


2nd day

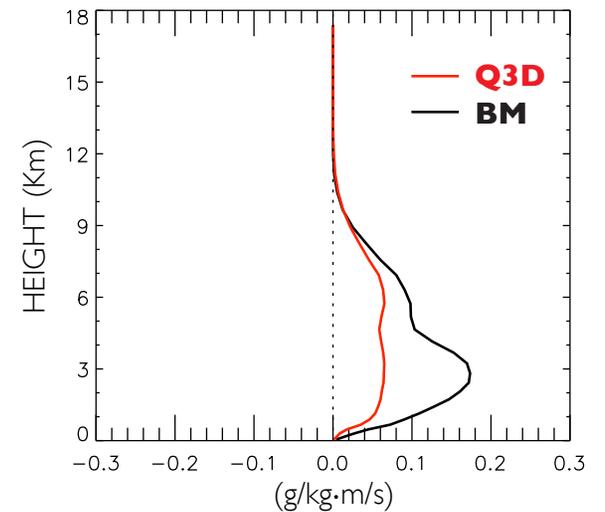
Q3D



BENCHMARK

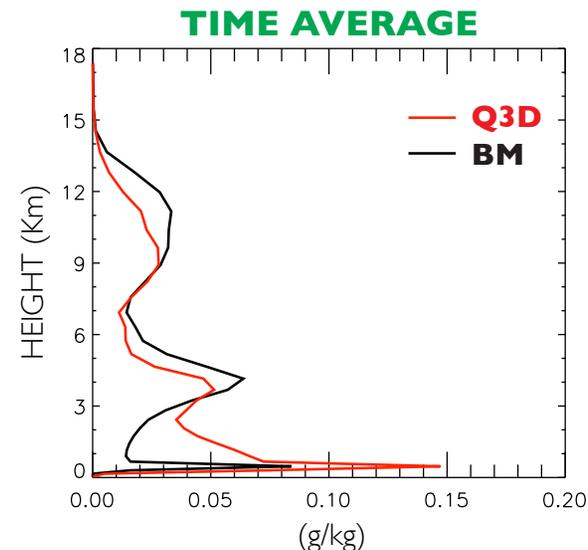
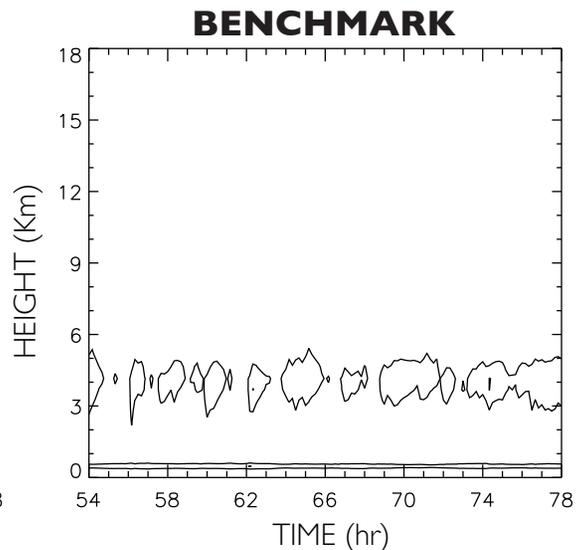
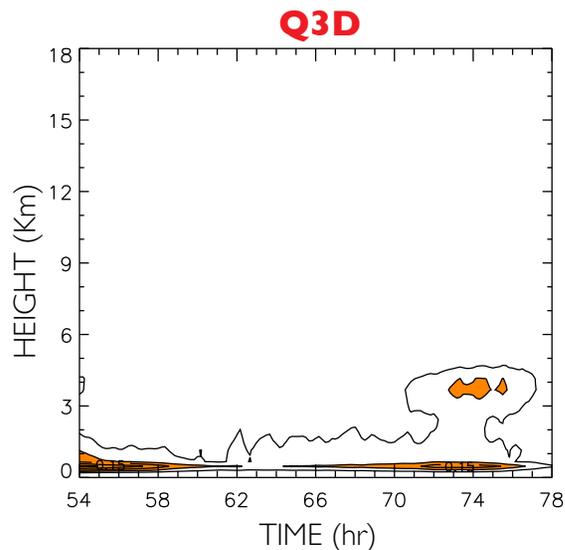


TIME AVERAGE

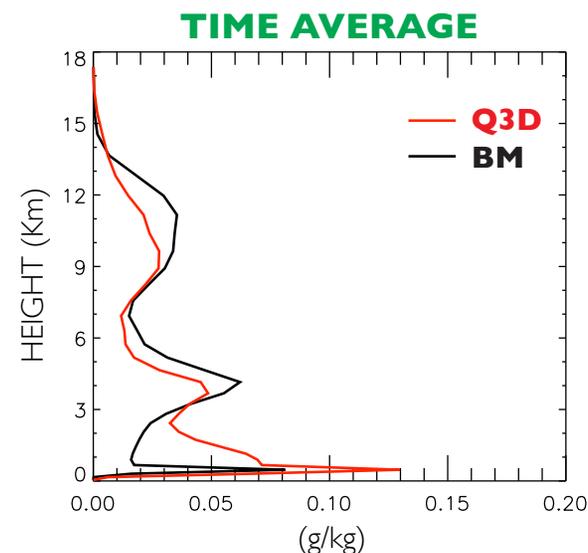
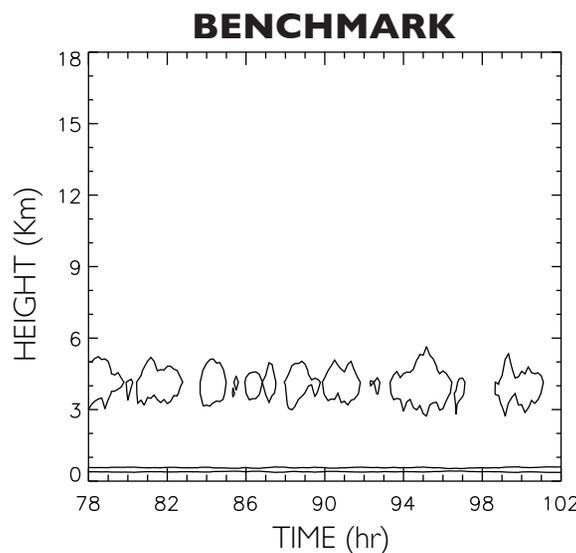
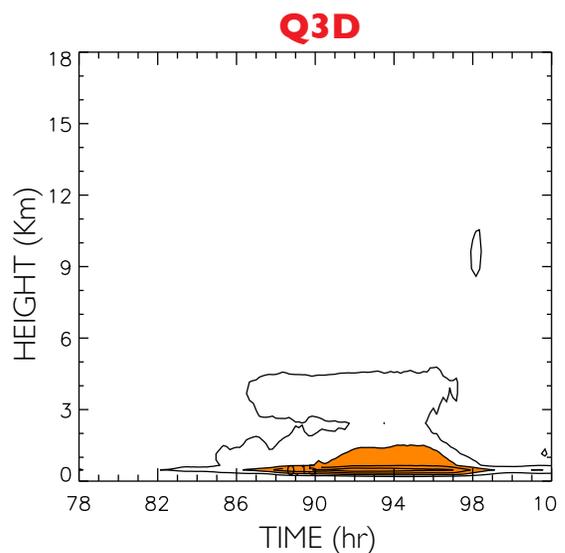


Sum of Cloud Liquid Water and Ice Mixing Ratios

1st day



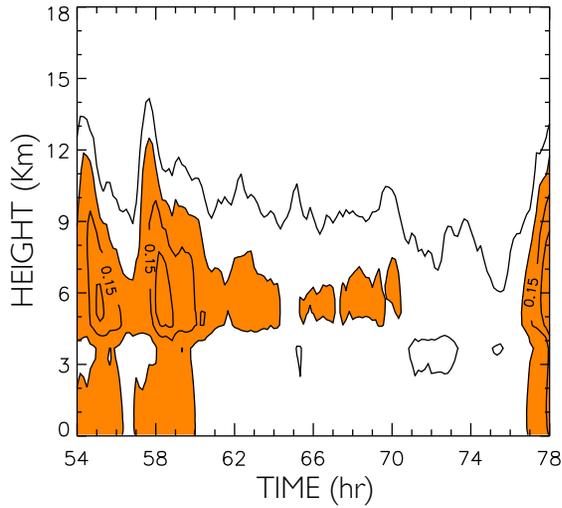
2nd day



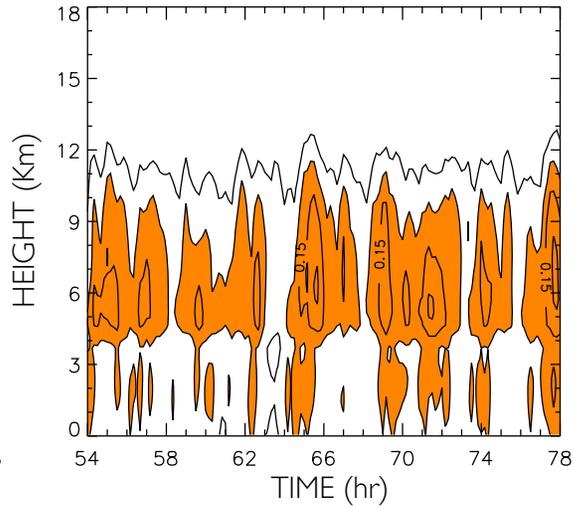
Sum of Rain, Snow, and Graupel mixing Ratios

1st day

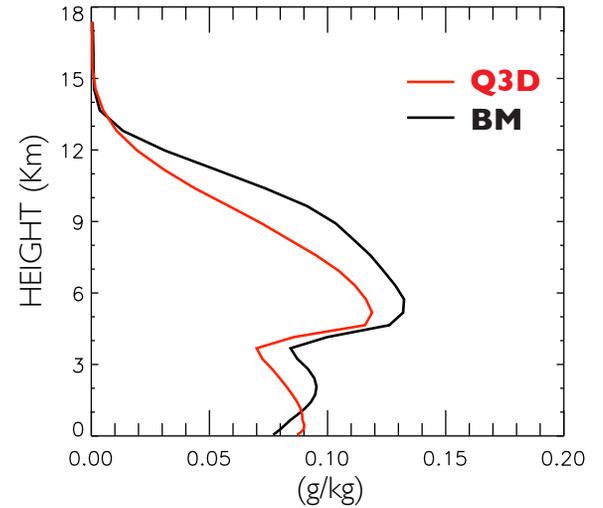
Q3D



BENCHMARK

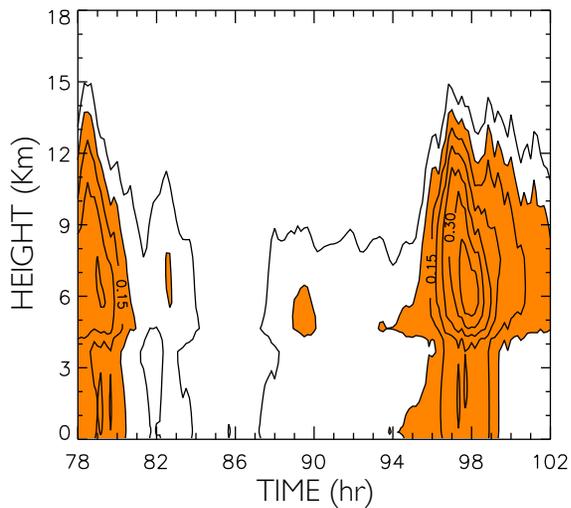


TIME AVERAGE

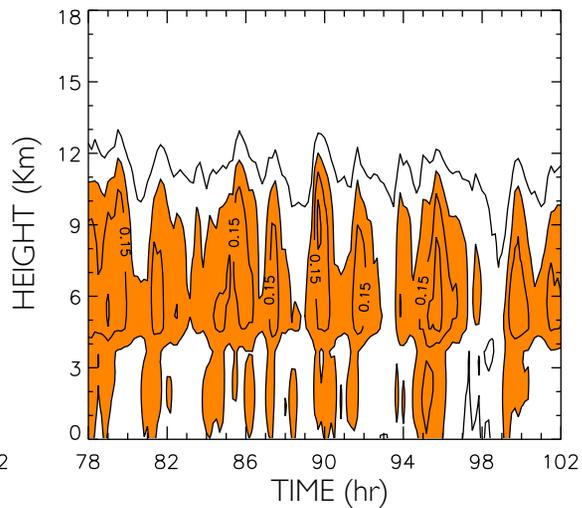


2nd day

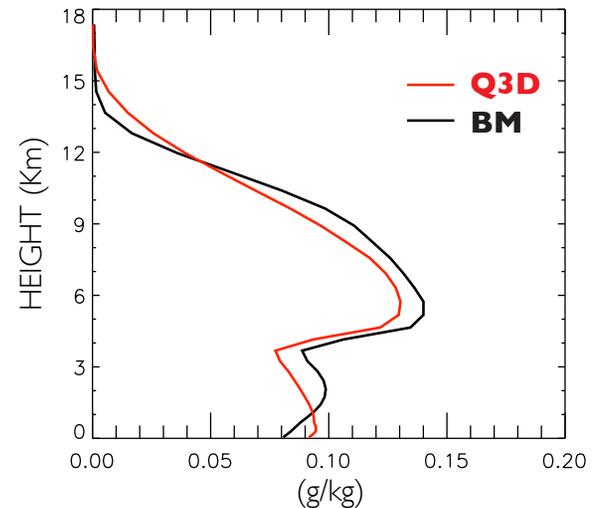
Q3D



BENCHMARK



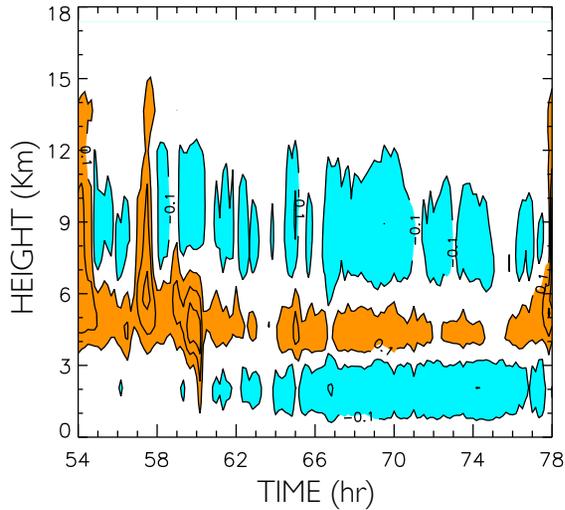
TIME AVERAGE



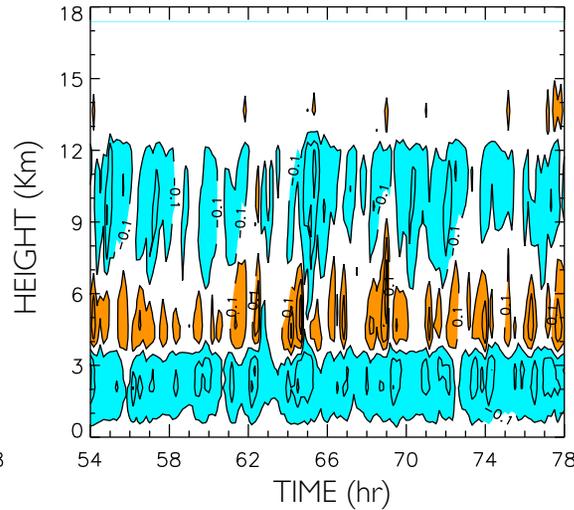
Covariance of u and w (Network averages)

1st day

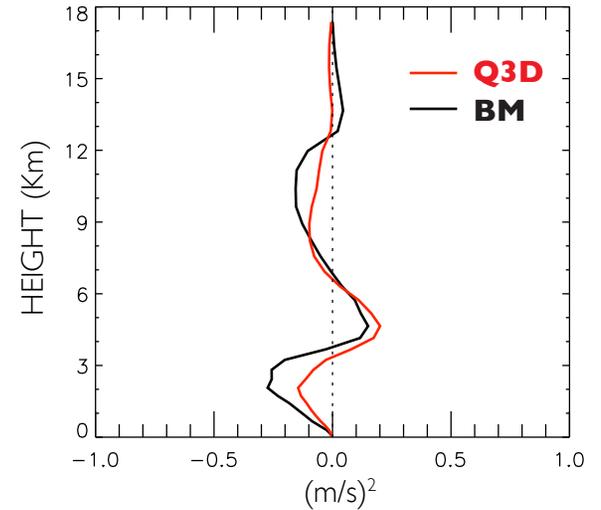
Q3D



BENCHMARK

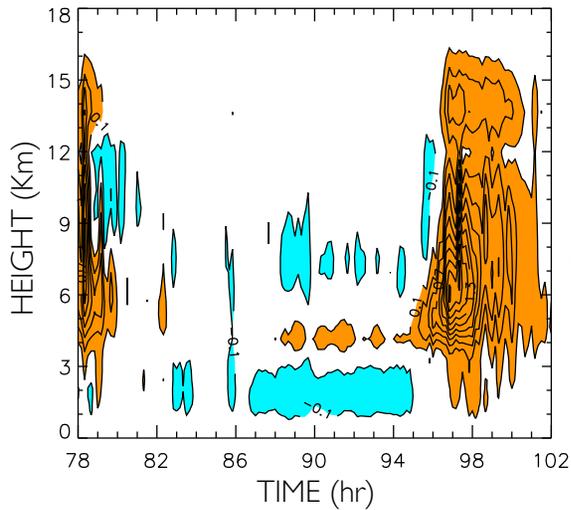


TIME AVERAGE

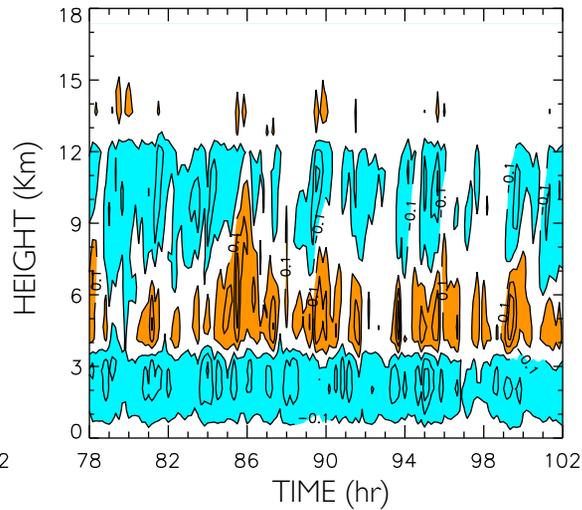


2nd day

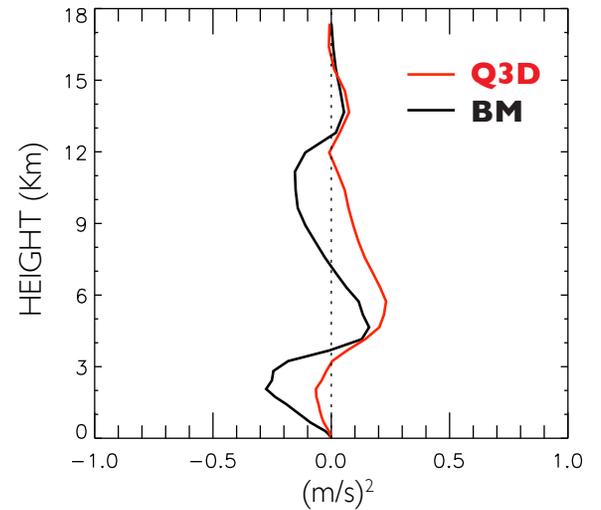
Q3D



BENCHMARK



TIME AVERAGE



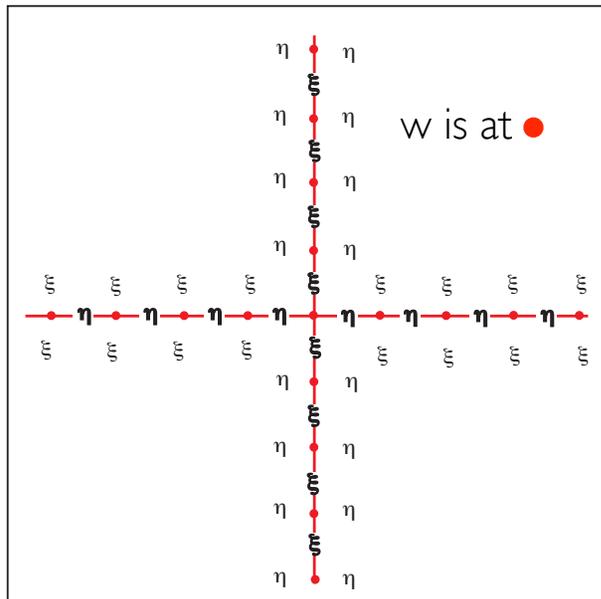
SUMMARY

- 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.

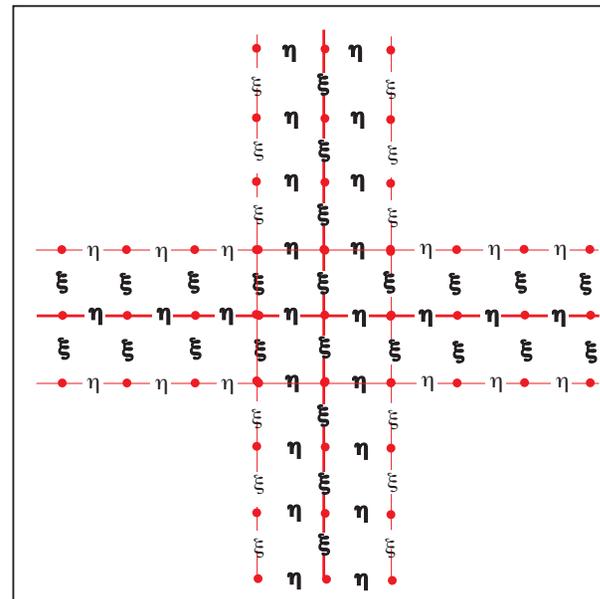
Work in Progress

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 are developing a next-generation Q3D MMF.

Current Q3D



Proposed Next-Generation Q3D



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

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

Currently estimated
either statistically or hypothetically.