PROGRESS WITH THE QUASI-3D MMF

Development of a New Q3D Algorithm

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I. Introduction

II. Outline of the Q3D algorithm

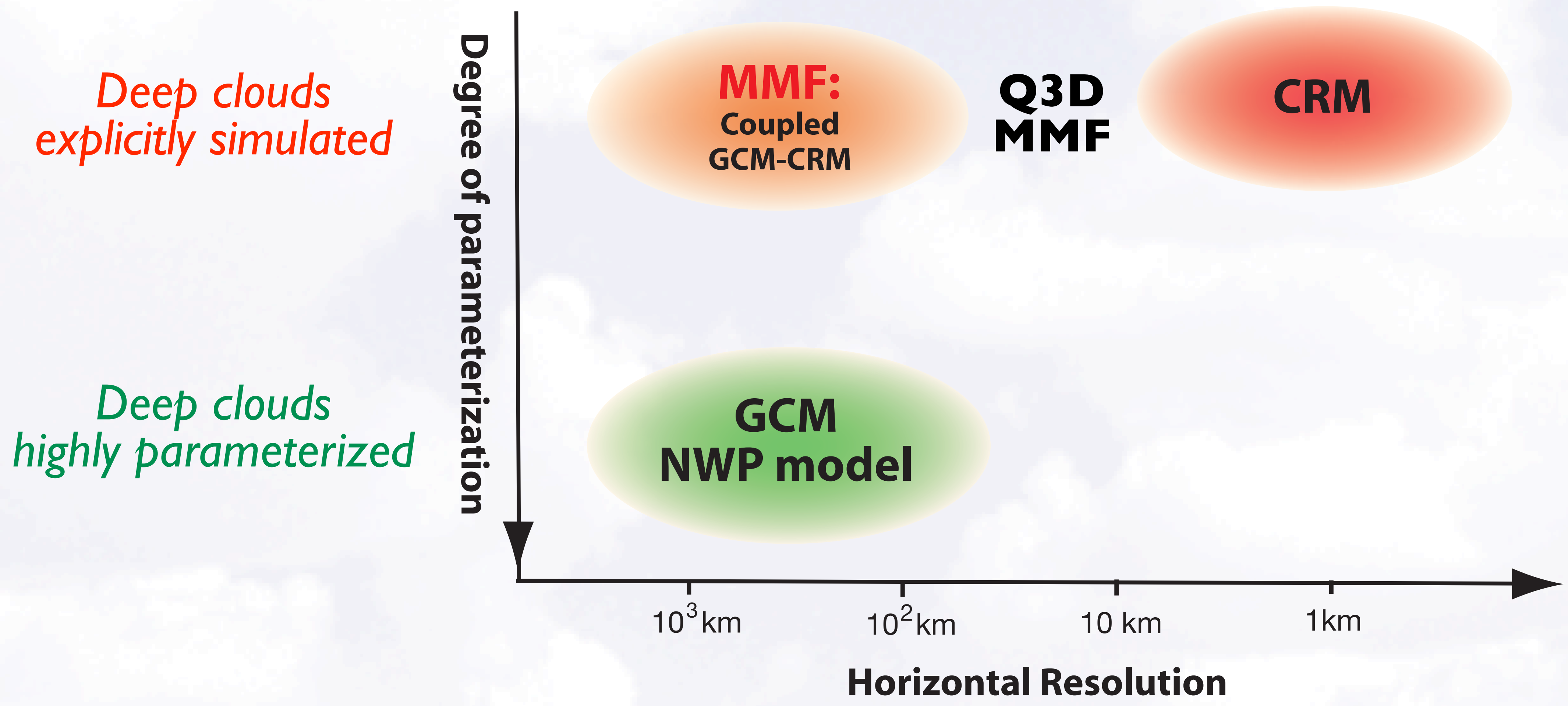
III. Sample results

IV. Summary and future plan

July 2009 CMMAP Team Meeting

MOTIVATION FOR
MULTI-SCALE MODELING FRAMEWORK (MMF)

- As far as the representation of deep clouds is concerned, we only have two kinds of model physics.
- Correspondingly, there have been only two families of 3D models (besides LES).



- MMF uses the CRM physics while maintaining the conventional resolution of GCM.
- Q3D MMF is an attempt to make MMF and 3D CRM a single family of models.

We are not alone in facing this kind of problem.

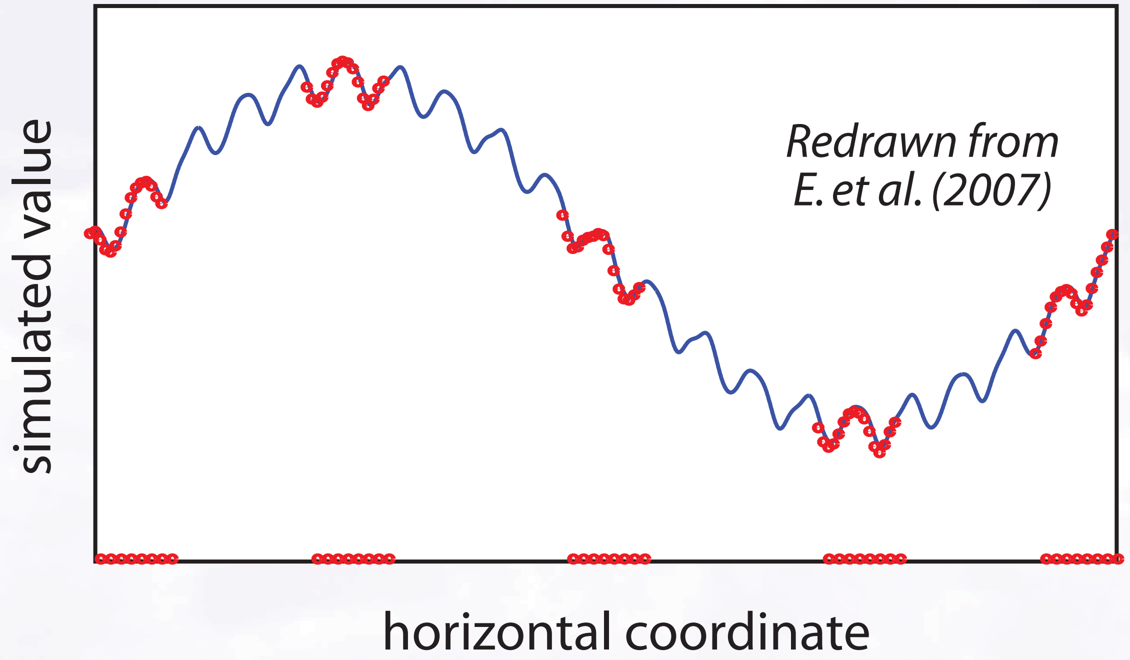
HETEROGENEOUS MULTISCALE MODELING (HMM)

A new approach in applied mathematics to solve multi-physics problems

"To design combined macroscopic-microscopic computational methods that are much more efficient than solving the full microscopic model.."
-- E et al. (2007)

The efficiency is gained by ***localization*** of the microscopic problem,

assuming either the defects of the macroscopic model appear only locally,
or the gross features of the microscopic solution vary macroscopically.

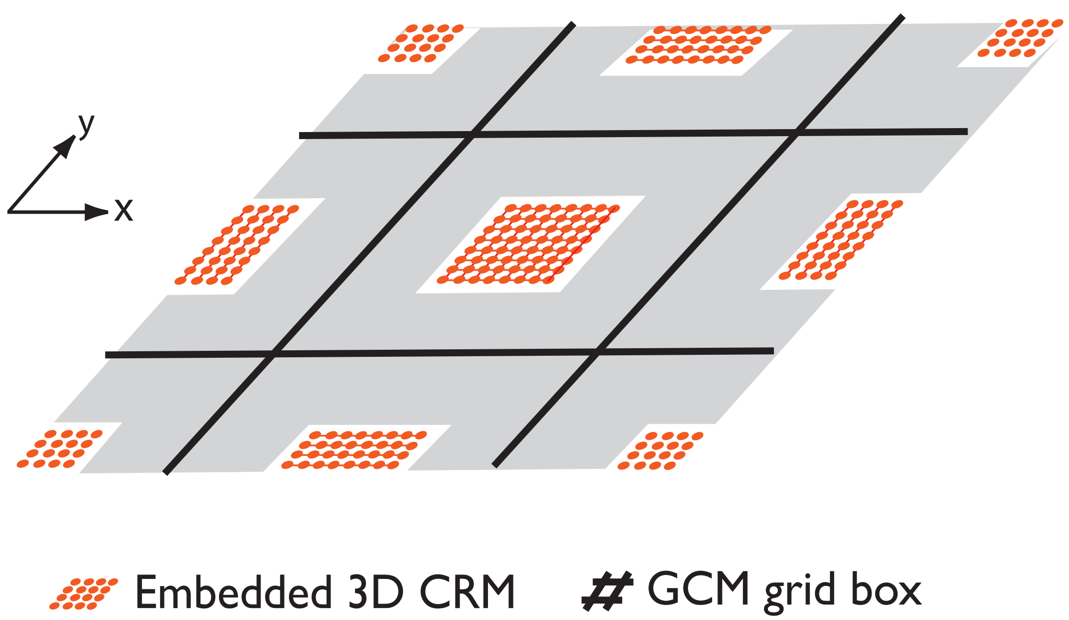


The microscopic model is used for **better representation of the gross features** of microscopic processes rather than their details.

3D & 2D MMF

3D MMF

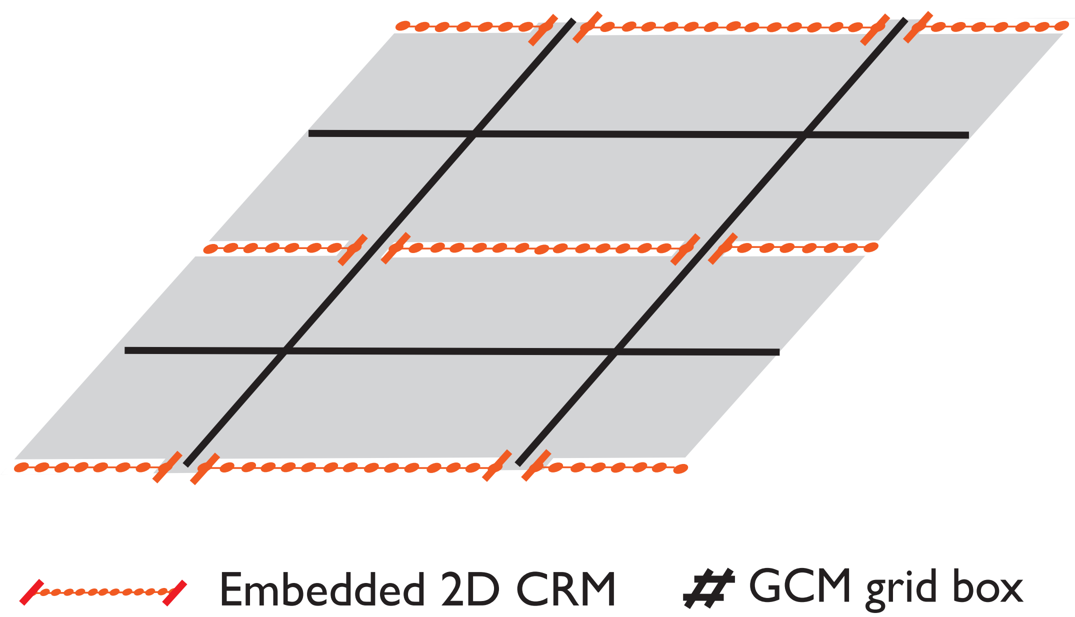
Khairoutdinov and Randall (2005)



Sacrifices representation of meso-scale processes

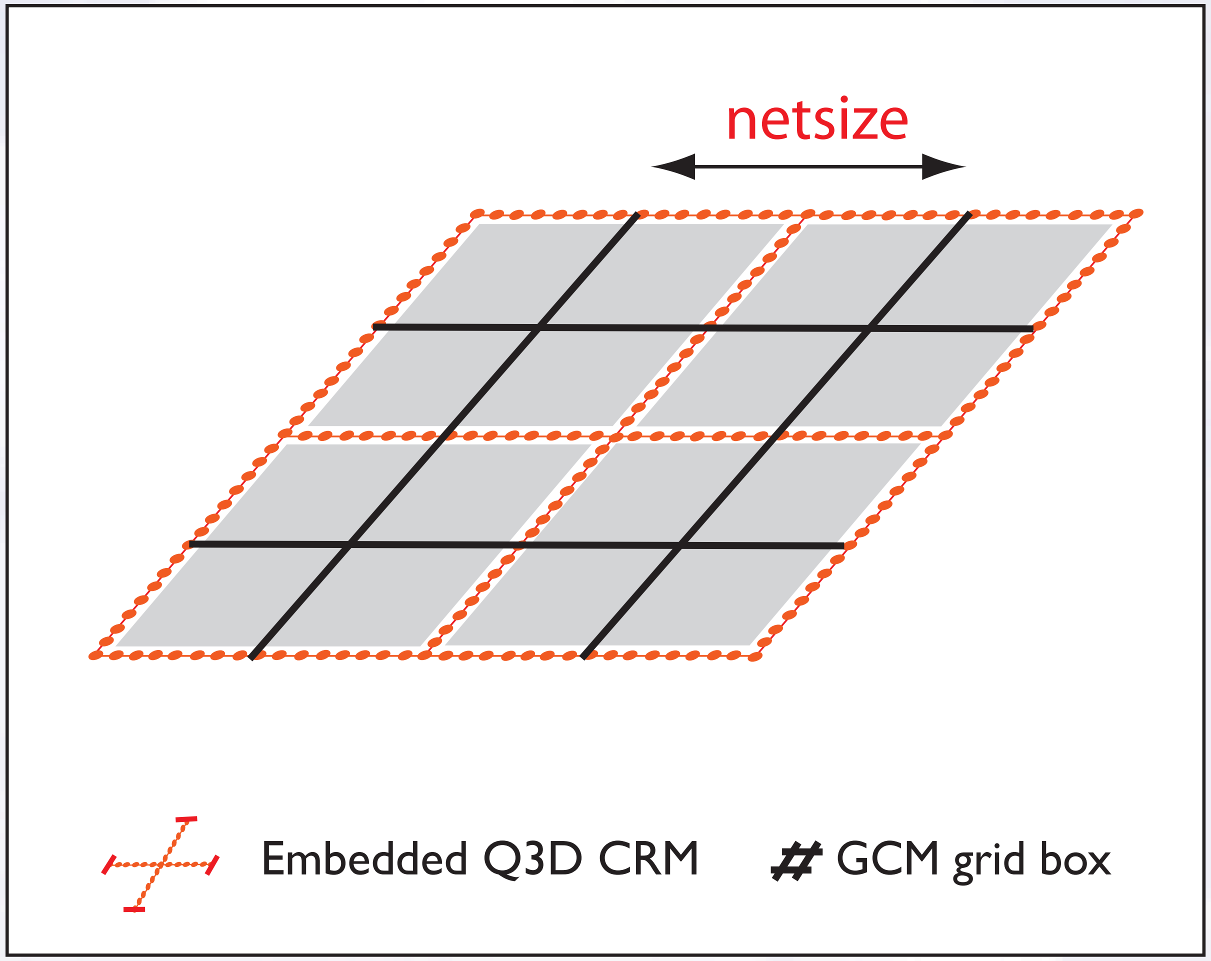
2D MMF
(prototype MMF)

Grabowski (2001)
Khairoutdinov and Randall (2001)



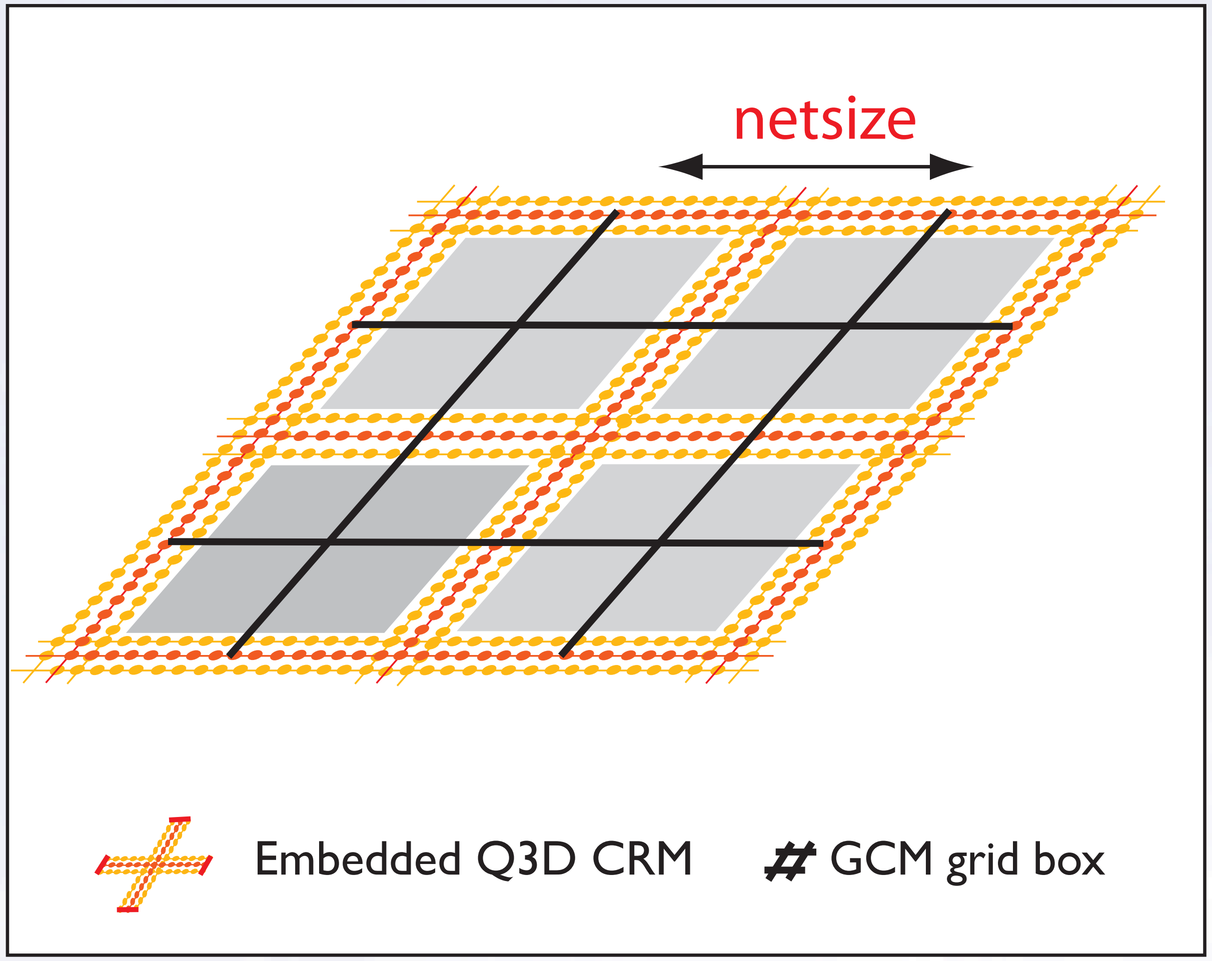
Sacrifices representation of 3D dynamics

PROTOTYPE Q3D MMF

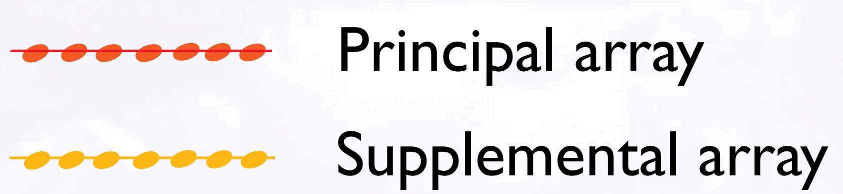


- The grid point arrays are extended beyond the individual GCM grid boxes.
- Perpendicular grid-point arrays are introduced to represent the netsize-scale three dimensionality.
- 3D predictions are made only at the intersections. This introduces singularity and netsize-scale inhomogeneity.

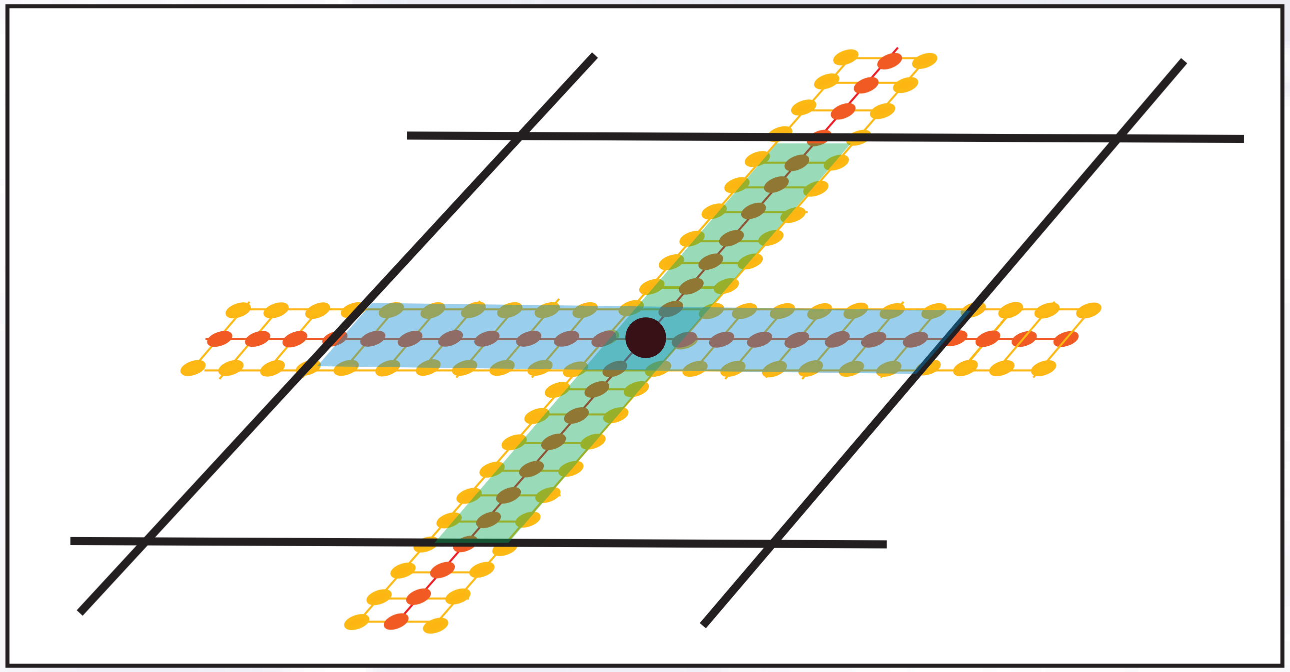
CURRENT Q3D MMF



- Uses two perpendicular sets of channels, each of which consists of three grid-point arrays.

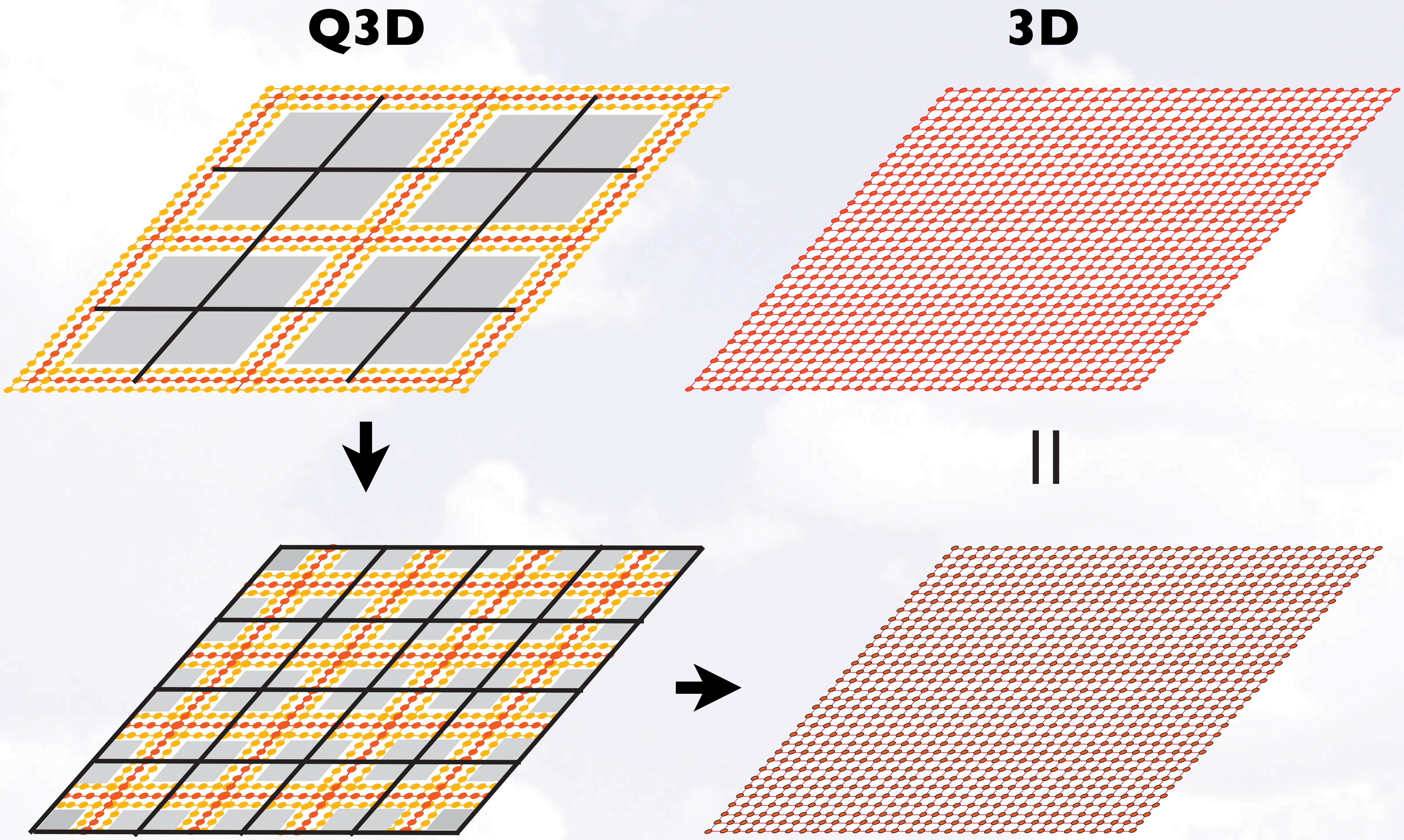


THREE-WAY COUPLING BETWEEN PERPENDICULAR CHANNELS AND GCM



- Channels intersect only virtually.
- Virtually intersecting channels are coupled through mutual relaxations of major prognostic variables averaged over the netsize segment of each channel.
- The average of the two segments is further coupled with the GCM through mutual relaxation.

CONVERGENCE OF THE Q3D MMF TO THE 3D CRM AS THE GCM GRID SIZE DECREASES



Q3D MMF is an attempt to make MMF and 3D CRM a single family of models.

STRUCTURE OF THE Q3D CRM

Based on the 3D anelastic vorticity equation model of
Jung and Arakawa (2008).

- Nonhydrostatic anelastic 3D model
- Prognostic variables:
  - Horizontal components of vorticity
  - Vertical component of vorticity (*at a certain height*)
  - *Horizontally uniform* part of horizontal velocity (*at a certain height*)
  - Potential temperature
  - Mixing ratios of various phases of water
- 3D elliptic (or parabolic) equation is solved for vertical velocity
- Physics:
  - Bulk ice-phase microphysical parameterization
  - Radiation parameterization
  - Turbulence parameterization (1st-order closure)

THREE-DIMENSIONAL TERMS IN THE BASIC EQUATIONS

$\underline{(\ )}$: 3D effect due to either $v \neq 0$ or $\partial/\partial y \neq 0$

- Continuity equation: $\dfrac{\partial}{\partial x}(\rho_0 u) + \underline{\dfrac{\partial}{\partial y}(\rho_0 v)} + \dfrac{\partial}{\partial z}(\rho_0 w) = 0$

  w-equation: $\left(\dfrac{\partial^2}{\partial x^2} + \underline{\dfrac{\partial^2}{\partial y^2}}\right) w + \dfrac{\partial}{\partial z}\left[\dfrac{1}{\rho_0}\dfrac{\partial}{\partial z}(\rho_0 w)\right] = -\dfrac{\partial \eta}{\partial x} + \underline{\dfrac{\partial \xi}{\partial y}}$, where $\underline{\xi \equiv -\dfrac{\partial v}{\partial z} + \dfrac{\partial w}{\partial y}}, \eta \equiv \dfrac{\partial u}{\partial z} - \dfrac{\partial w}{\partial x}$

- Equation for scalar variable, q: $\rho_0 \dfrac{\partial q}{\partial t} = -\left[\dfrac{\partial}{\partial x}(\rho_0 uq) + \underline{\dfrac{\partial}{\partial y}(\rho_0 vq)} + \dfrac{\partial}{\partial z}(\rho_0 wq)\right] + S_q$

  (potential temperature and mixing ratios of various phases of water)

- Vorticity equation:

$$\underline{\frac{\partial \xi}{\partial t} = -\left[\frac{\partial}{\partial x}(u\xi) + \frac{\partial}{\partial y}(v\xi) + \frac{\partial}{\partial z}(w\xi)\right] + \xi\frac{\partial u}{\partial x} + \eta\frac{\partial u}{\partial y} + \zeta\frac{\partial u}{\partial z} + \frac{\partial B}{\partial y} + \ldots}$$

$$\frac{\partial \eta}{\partial t} = -\left[\frac{\partial}{\partial x}(u\eta) + \underline{\frac{\partial}{\partial y}(v\eta)} + \frac{\partial}{\partial z}(w\eta)\right] + \eta\frac{\partial v}{\partial y} + \underline{\xi\frac{\partial v}{\partial x} + \zeta\frac{\partial v}{\partial z}} - \frac{\partial B}{\partial x} + \ldots$$

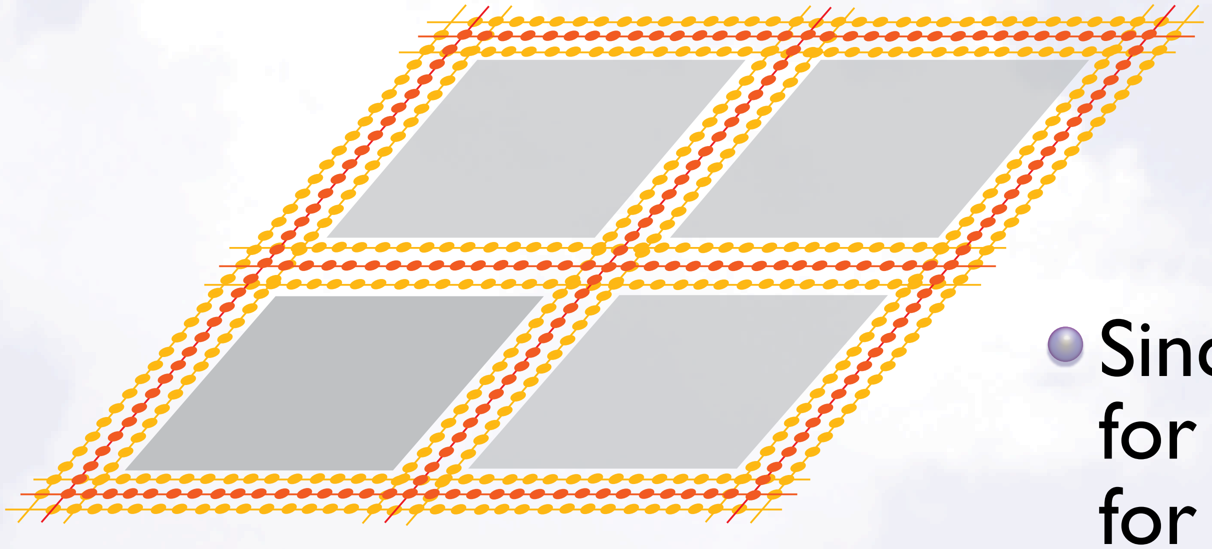
Underlined Terms

2D model: entirely neglected

Prototype Q3D model: statistically or hypothetically estimated

Current Q3D model: explicitly predicted on the Q3D principal arrays

QUASI-3D ALGORITHM



- The algorithm is basically that of limited-area modeling applied to the unshaded area.
- Since the area is so narrow, it is crucial for the lateral boundaries to be non-rigid for both advection and dynamics.

Separation of the fields

The algorithm separates the fields into "background" and "deviation". For example,

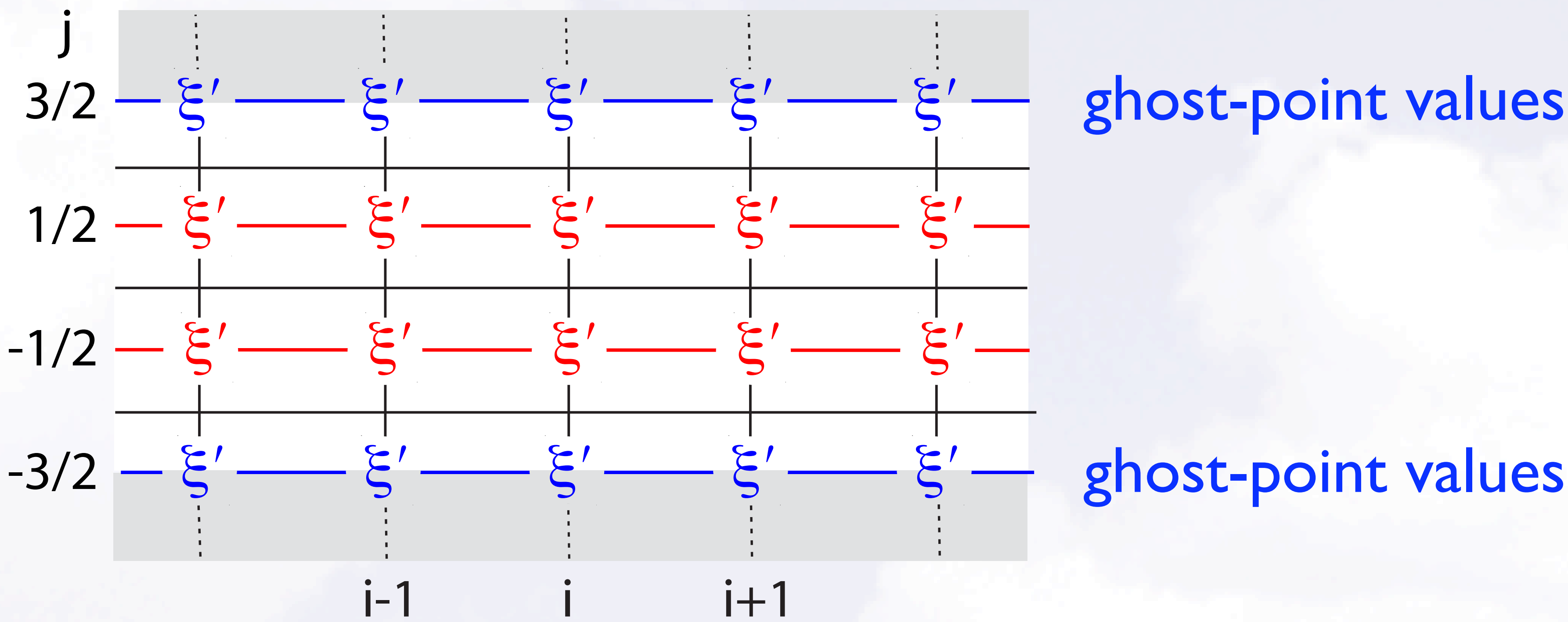
$$q = \bar{q} + q'$$

background field interpolated from GCM

deviation

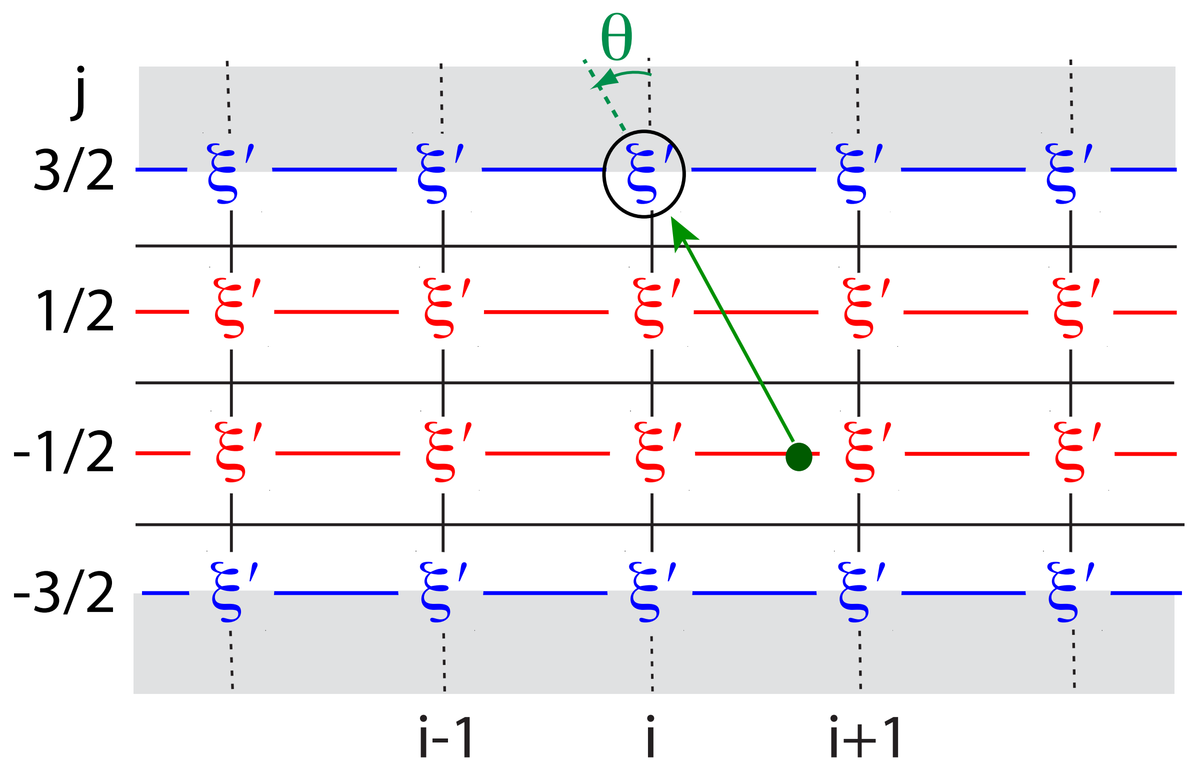
Lateral boundary condition - Basic requirements

(for ξ' as an example)



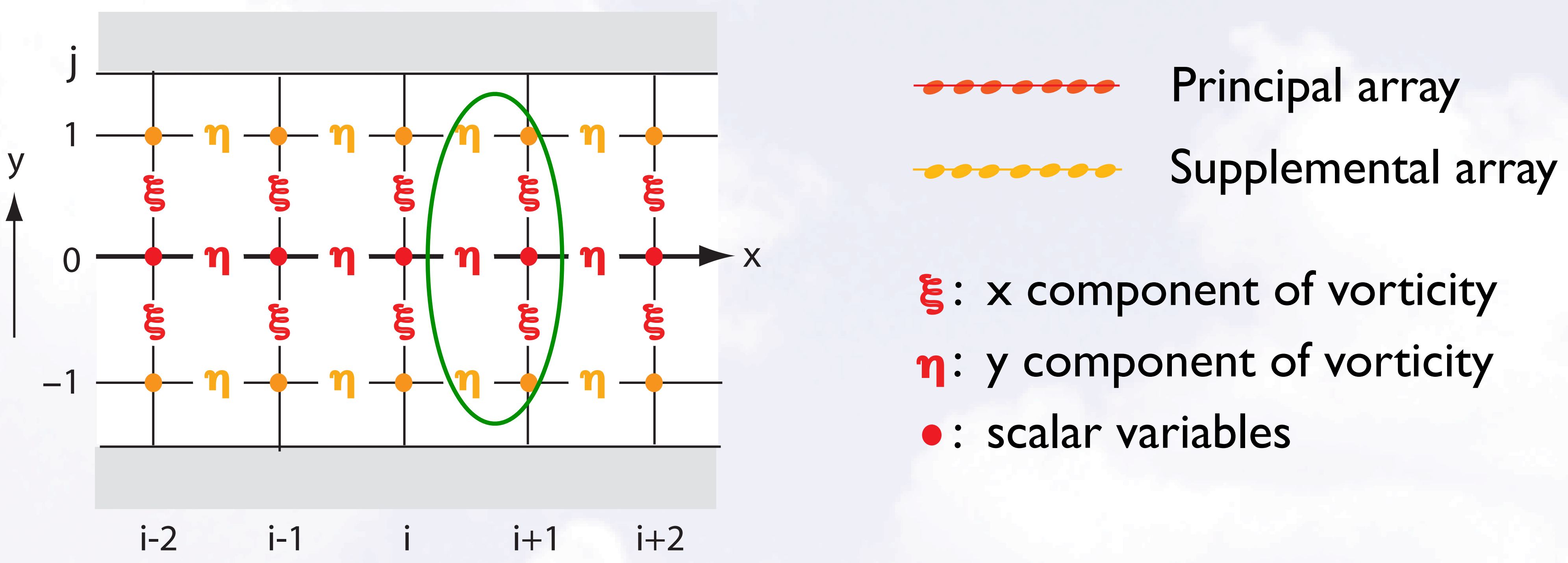
- The lateral boundary condition is implemented through assigning ghost-point values.
- Stability is the most fundamental issue, but that is not all.
- For the lateral boundary condition not to distort the statistics of the solution, it is important for the ghost-point values to have a PDF similar to that of the solution.

Lateral boundary condition - The approach



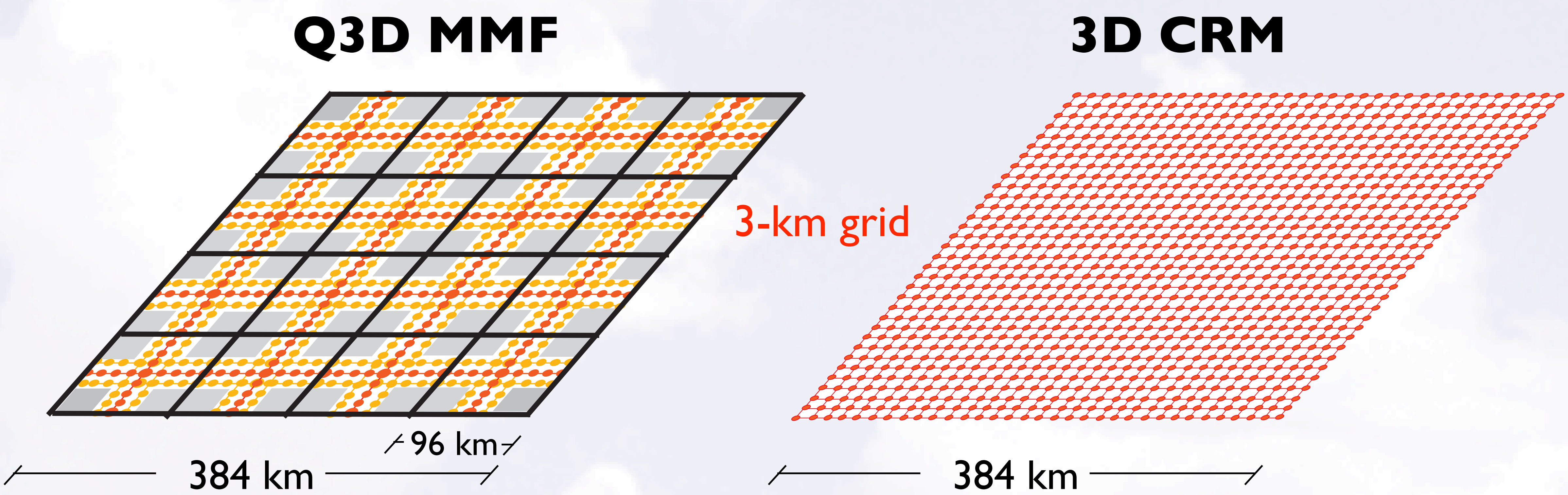
- An easy way to let the ghost-point values have a PDF similar to that of the solution is to "borrow" the values at one of the internal grid-point arrays.
- If the ghost-point values at j=3/2 are highly correlated with the values at j=1/2 with the same i, the situation at an inflow point is similar to the use of an unstable downstream scheme.
- We therefore use the values at j=-1/2 as shown in the figure.
- If θ is zero, the boundary condition becomes cyclic ("cyclic Q3D", CQ3D).
- The CQ3D is being used as a base model to implement more elaborated lateral boundary condition.

Controlling the imbalance of the degrees of freedom between the vorticity components



- As in the 3D model, a staggered grid is used for the vorticity components.
- The staggered grid, however, can introduce an imbalance of the degrees of freedom between the vorticity components.
- This imbalance can easily cause instability of the solution.
- Such imbalance is controlled by not allowing the full degree of freedom for supplemental prognostic variables.

EXPERIMENTAL STRATEGY



- Construct a Q3D MMF in which a Q3D CRM is coupled with an idealized GCM.
- Compare the results of Q3D MMF with those of the straightforward application of the 3D CRM.

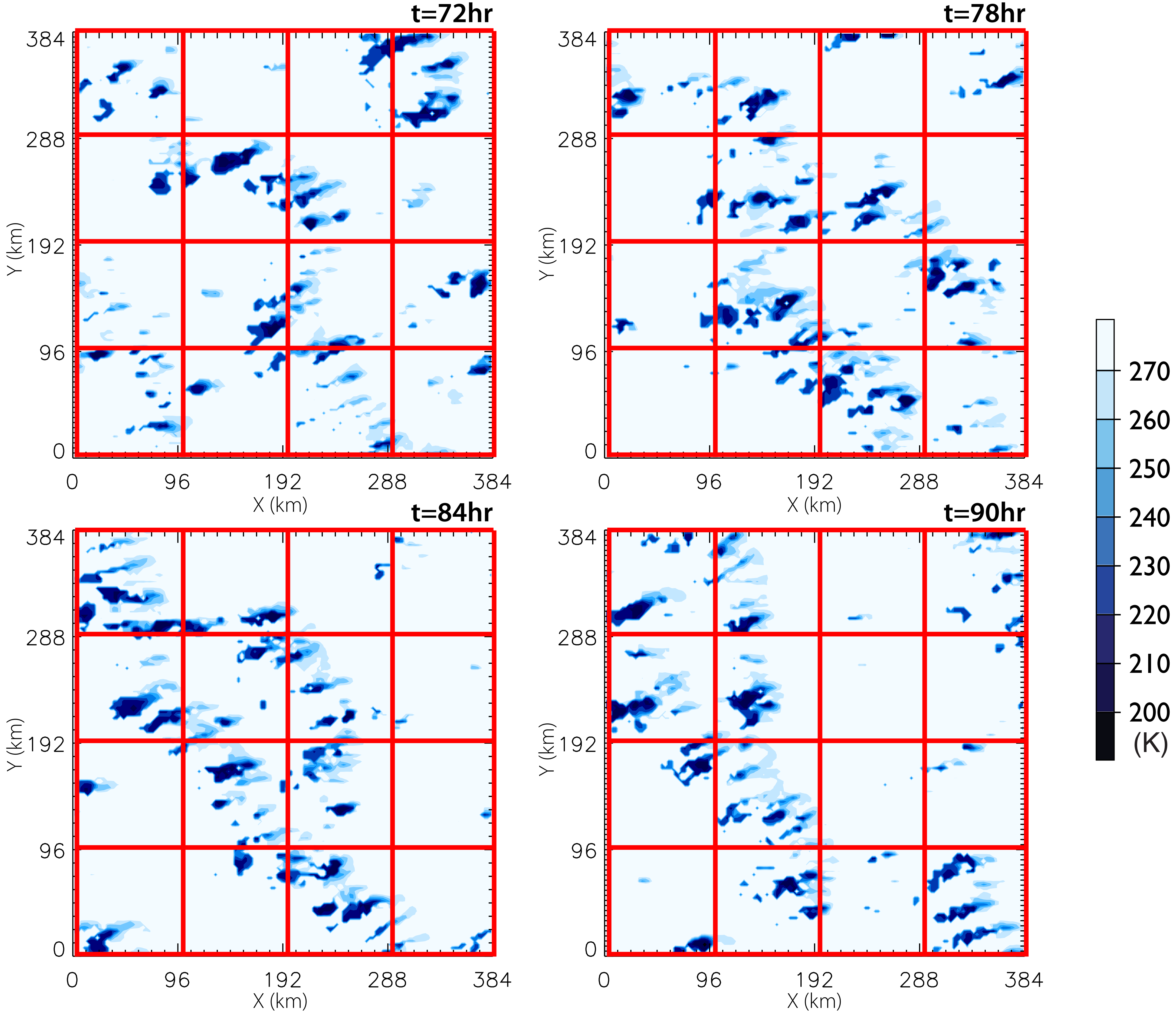
BENCHMARK SIMULATION WITH VVCM

- 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

4-day simulation is made.

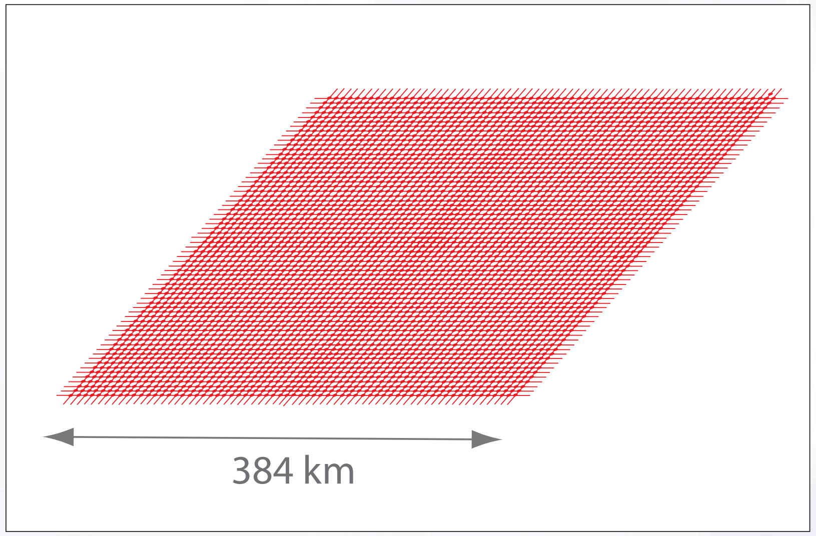
BENCHMARK SIMULATION

Cloud Top Temperature

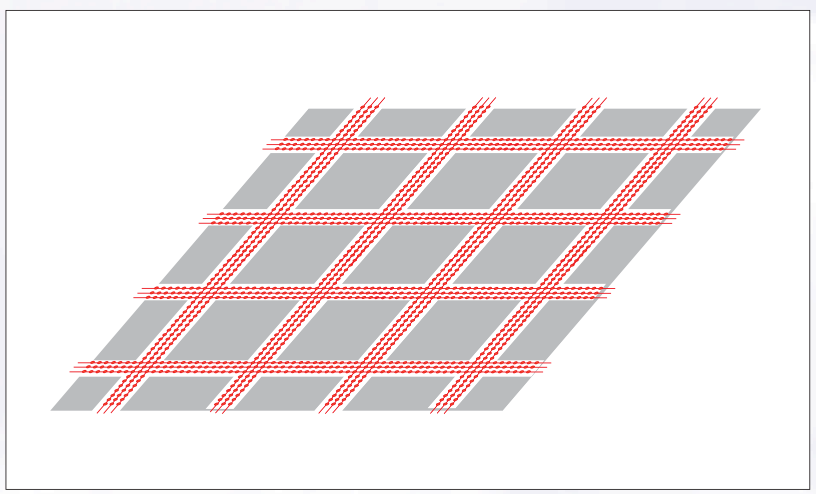


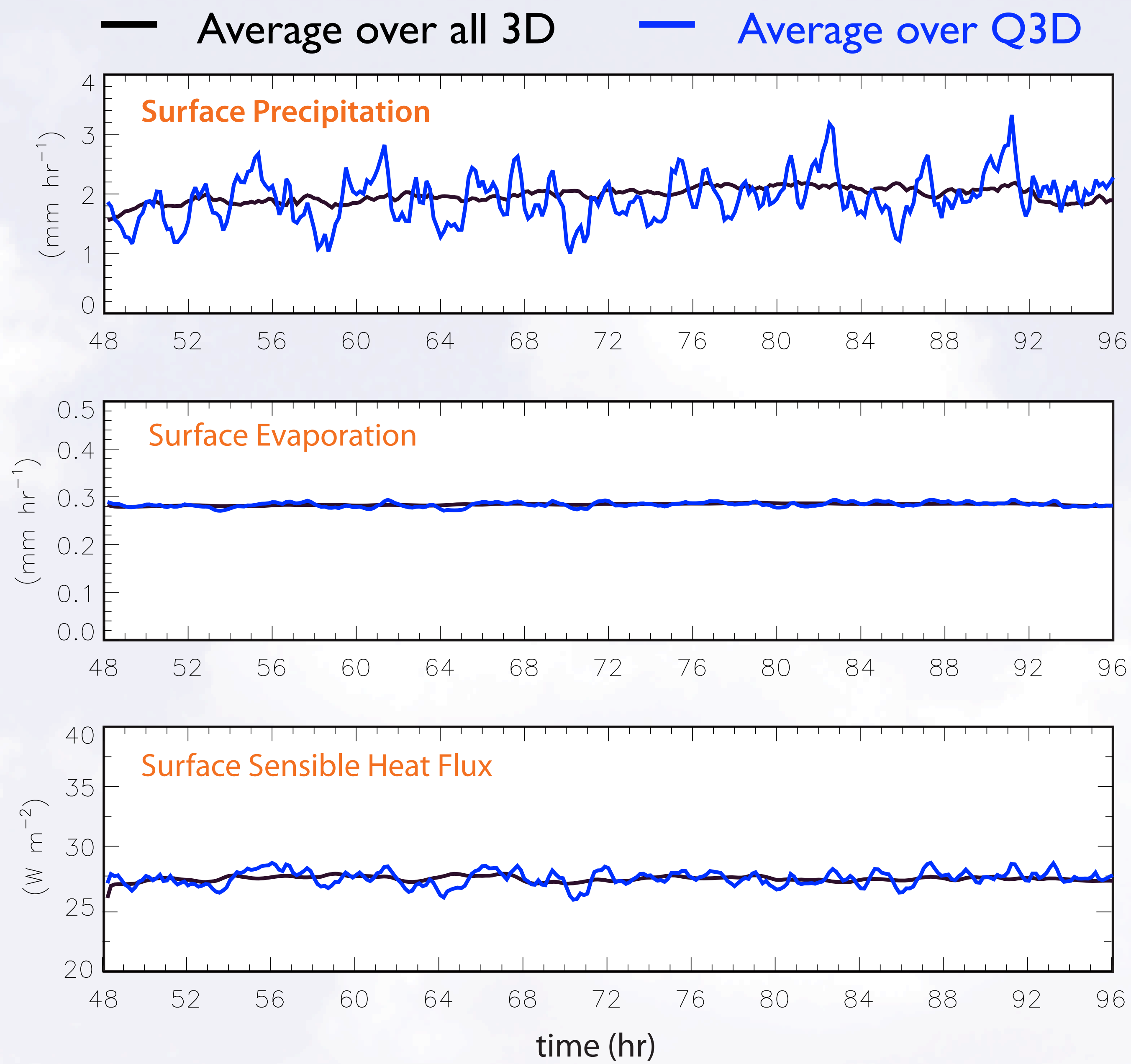
AN EXAMPLE OF SAMPLING ERROR DUE TO THE USE OF Q3D GRID

3D Grid used for
the benchmark simulation



Q3D Grid used in this study





The ratio of the number of grid points:

18.75 % in this case,

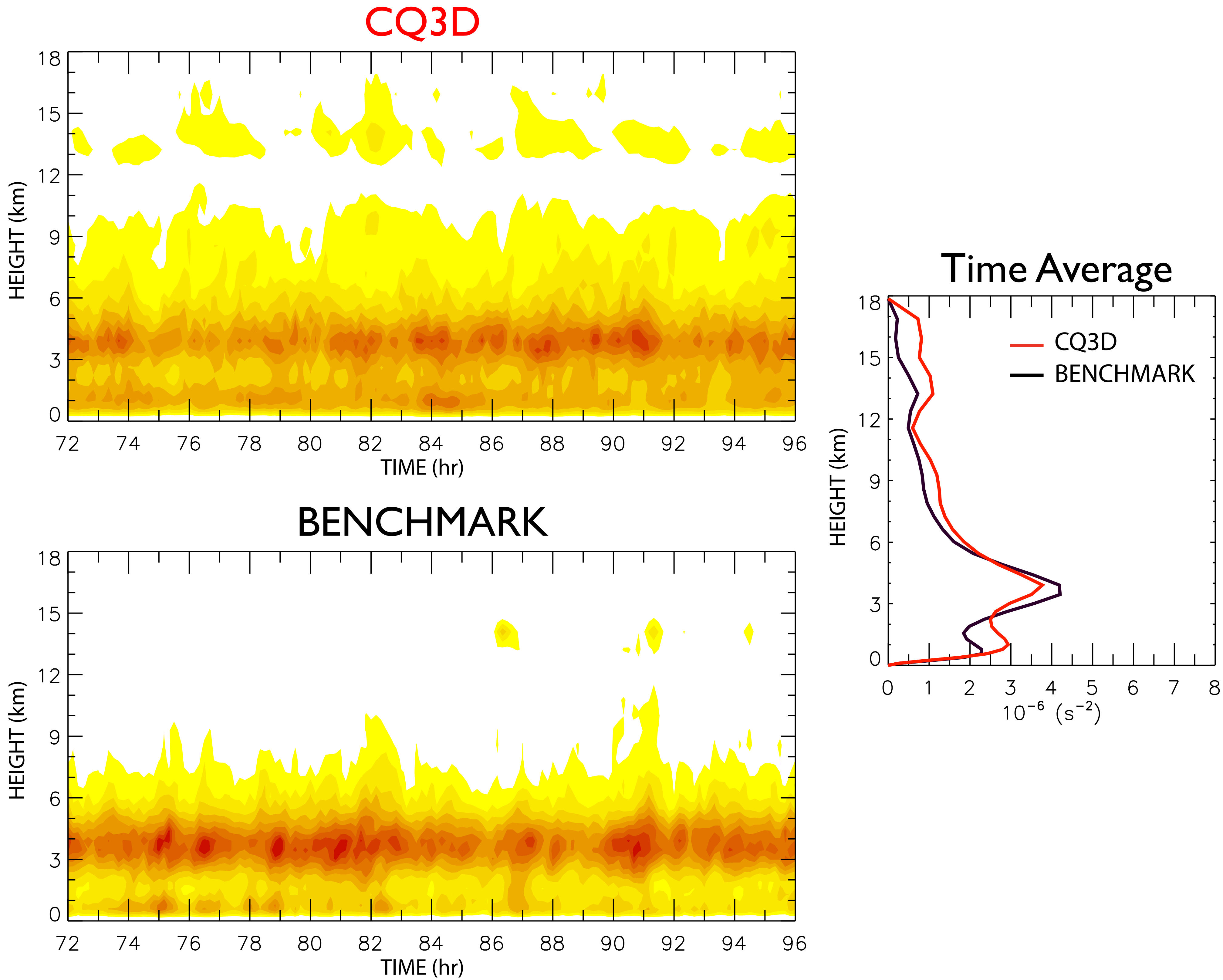
3 % if the GCM and CRM grid sizes are 200km and 1km, respectively.

No significant differences have been found for all variables as far as time averages are concerned.

SIMULATION RESULTS FROM CQ3D

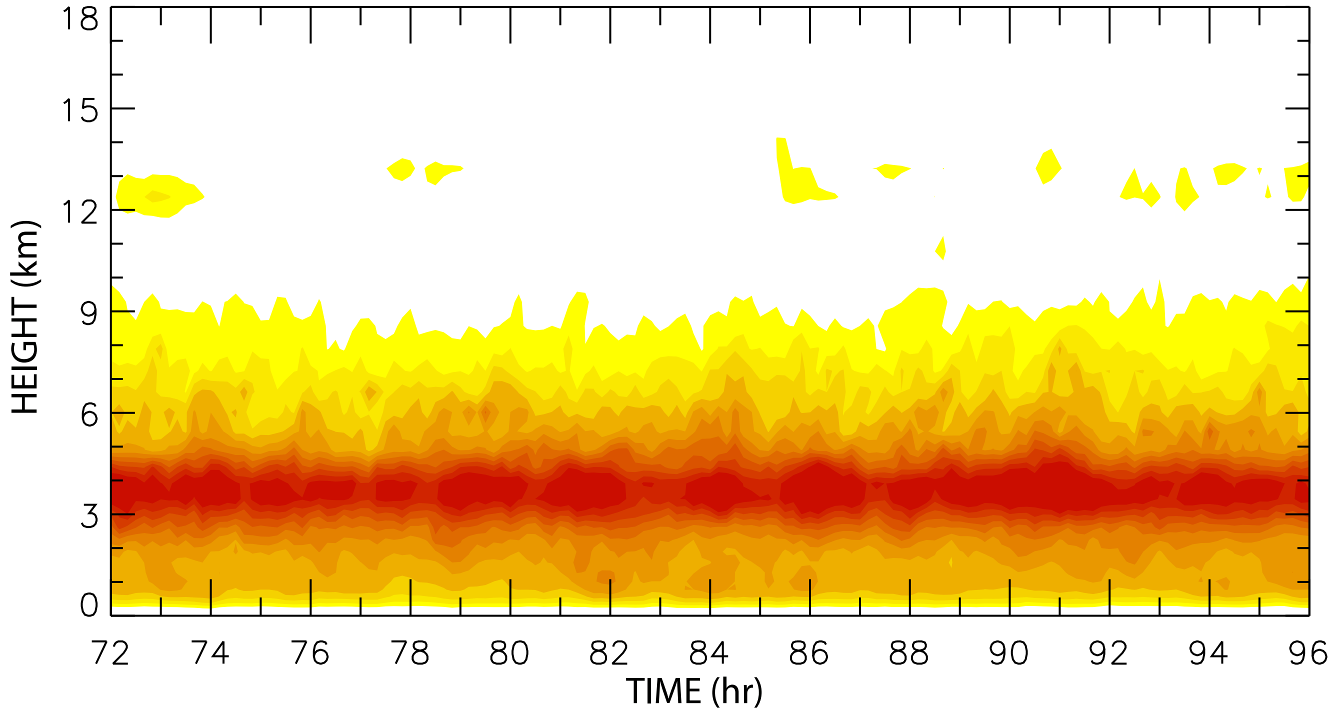
(Comparison is made for the last 1-day simulation.)

Variance of ξ $\left(10^{-6}\right)$

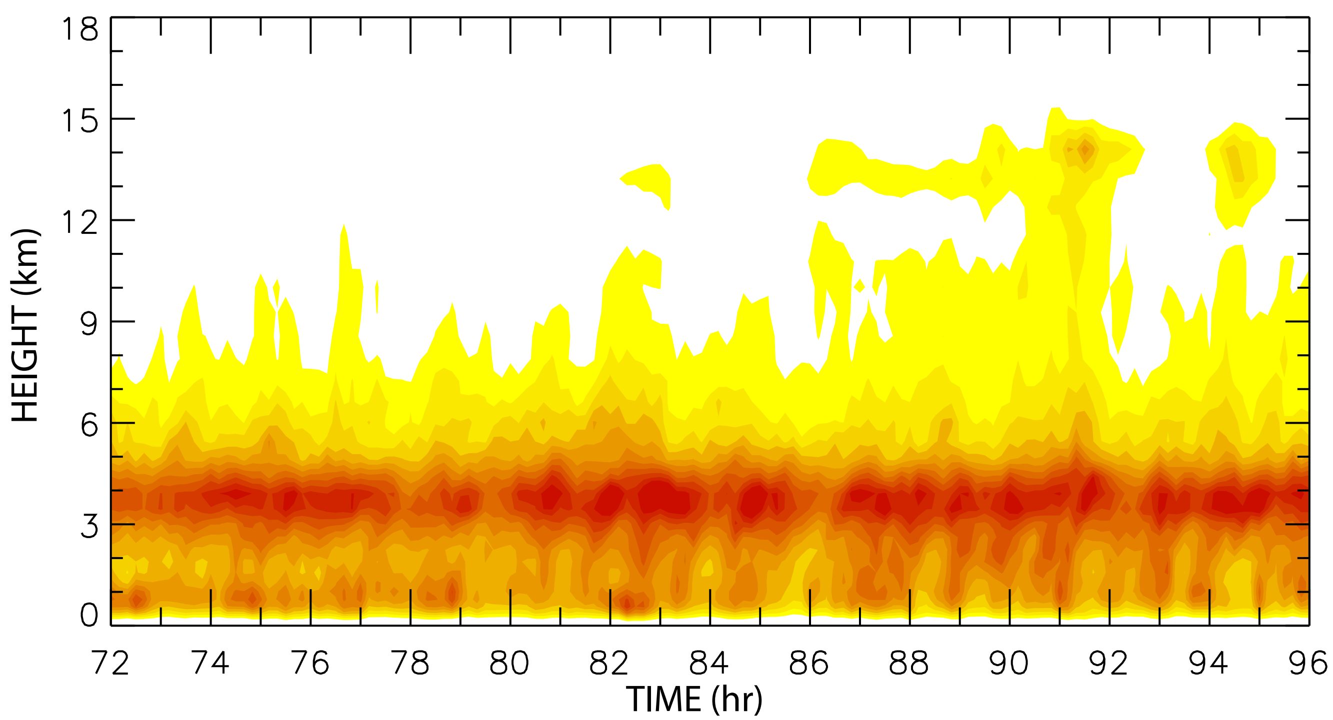


Variance of $\eta \left(10^{-6}\right)$

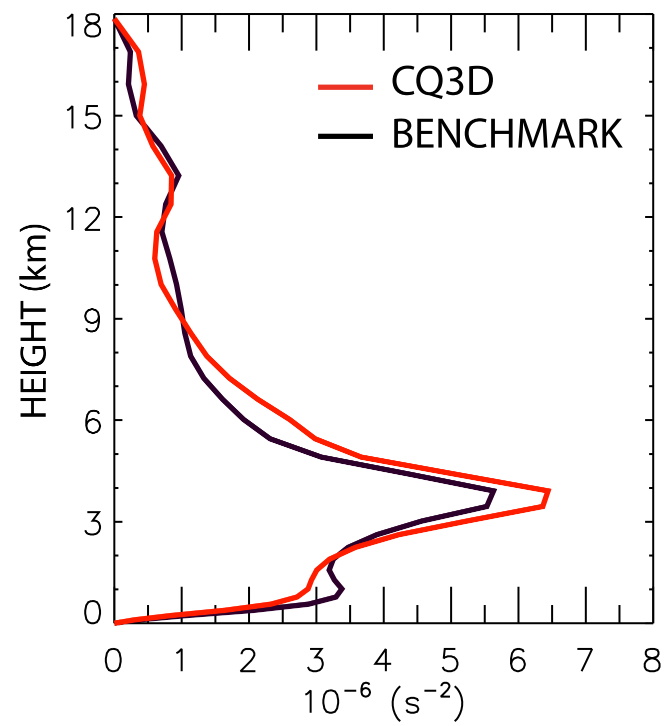
CQ3D



BENCHMARK

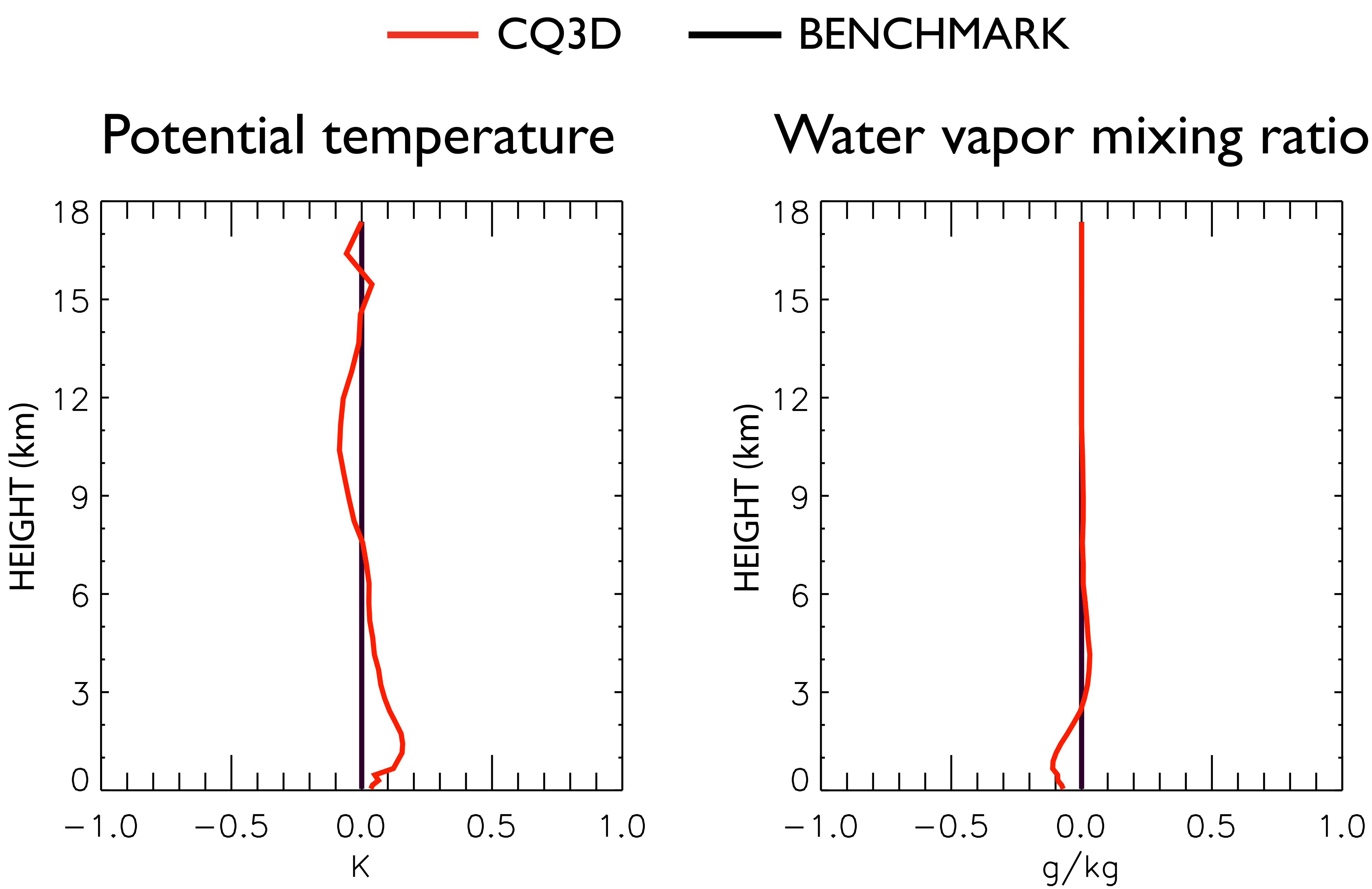


Time Average

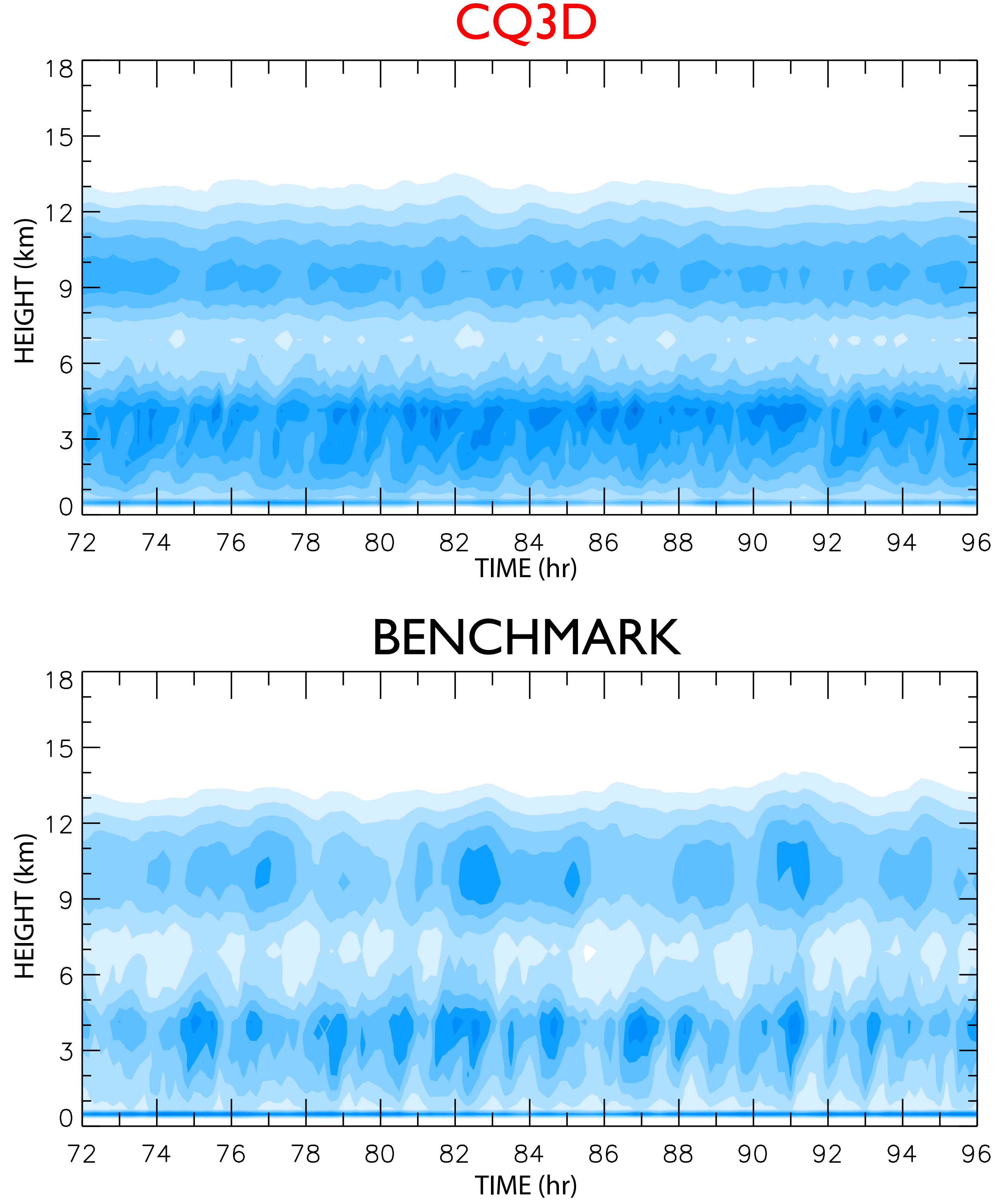


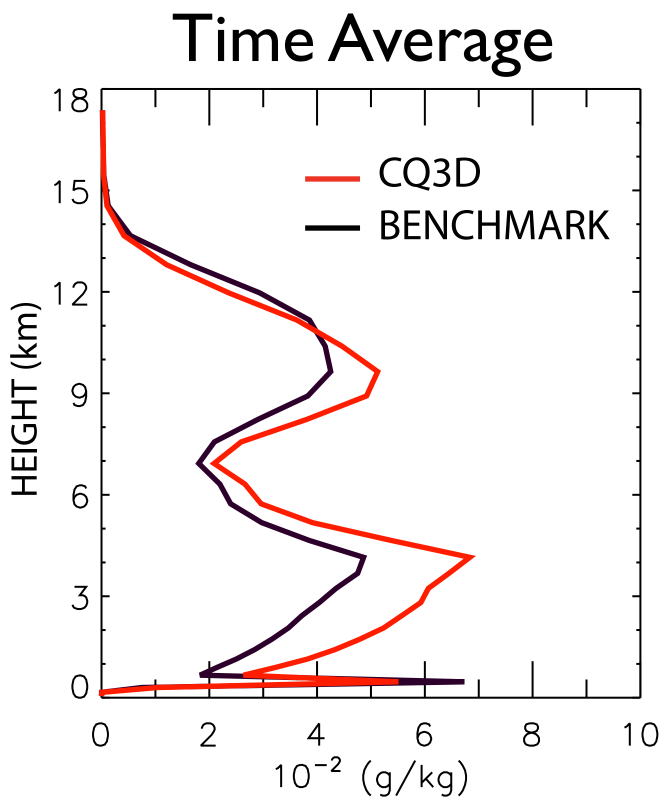
Network & time average

(Domain & Time average of BM is subtracted.)

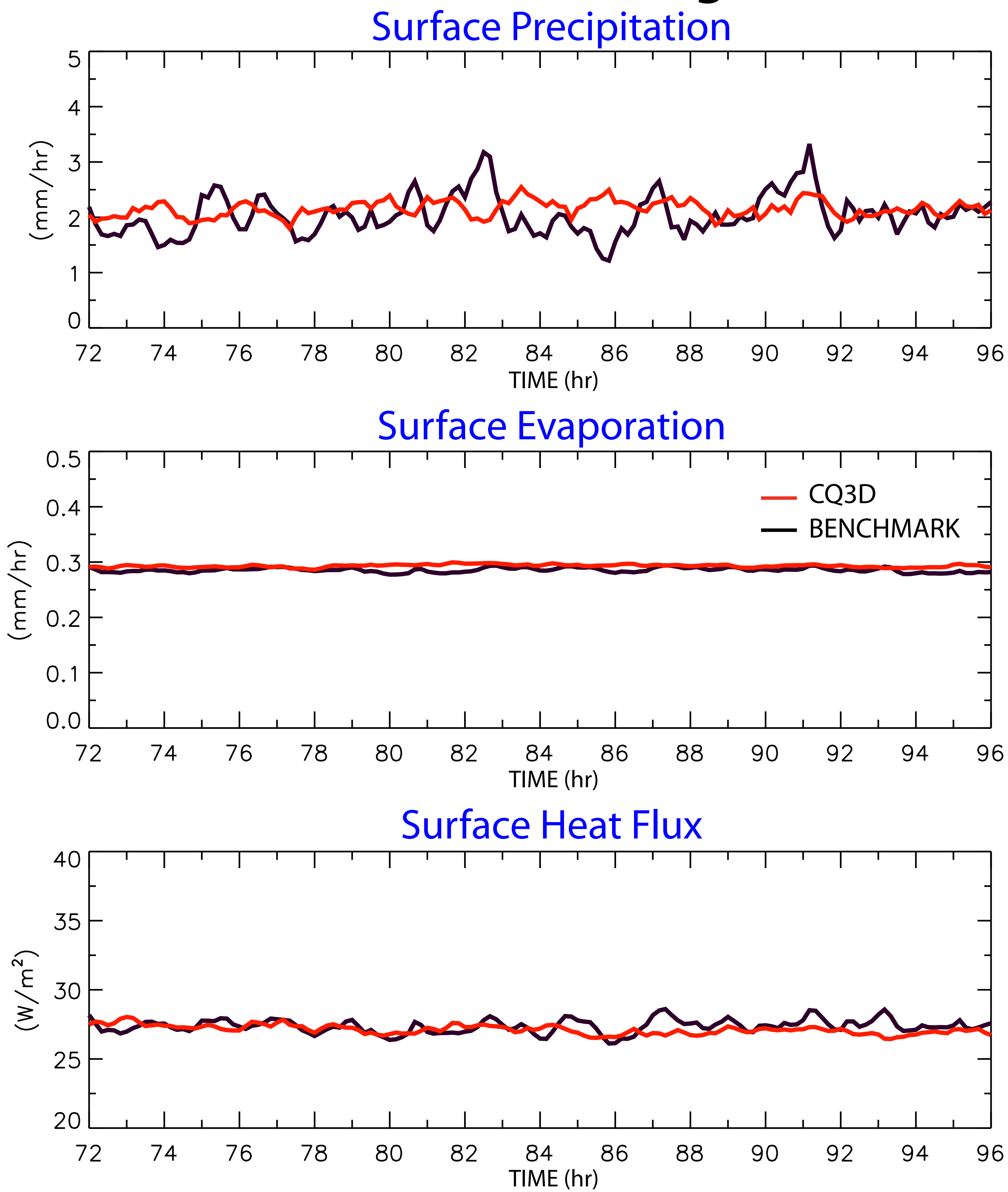


Network average of cloud water mixing ratio

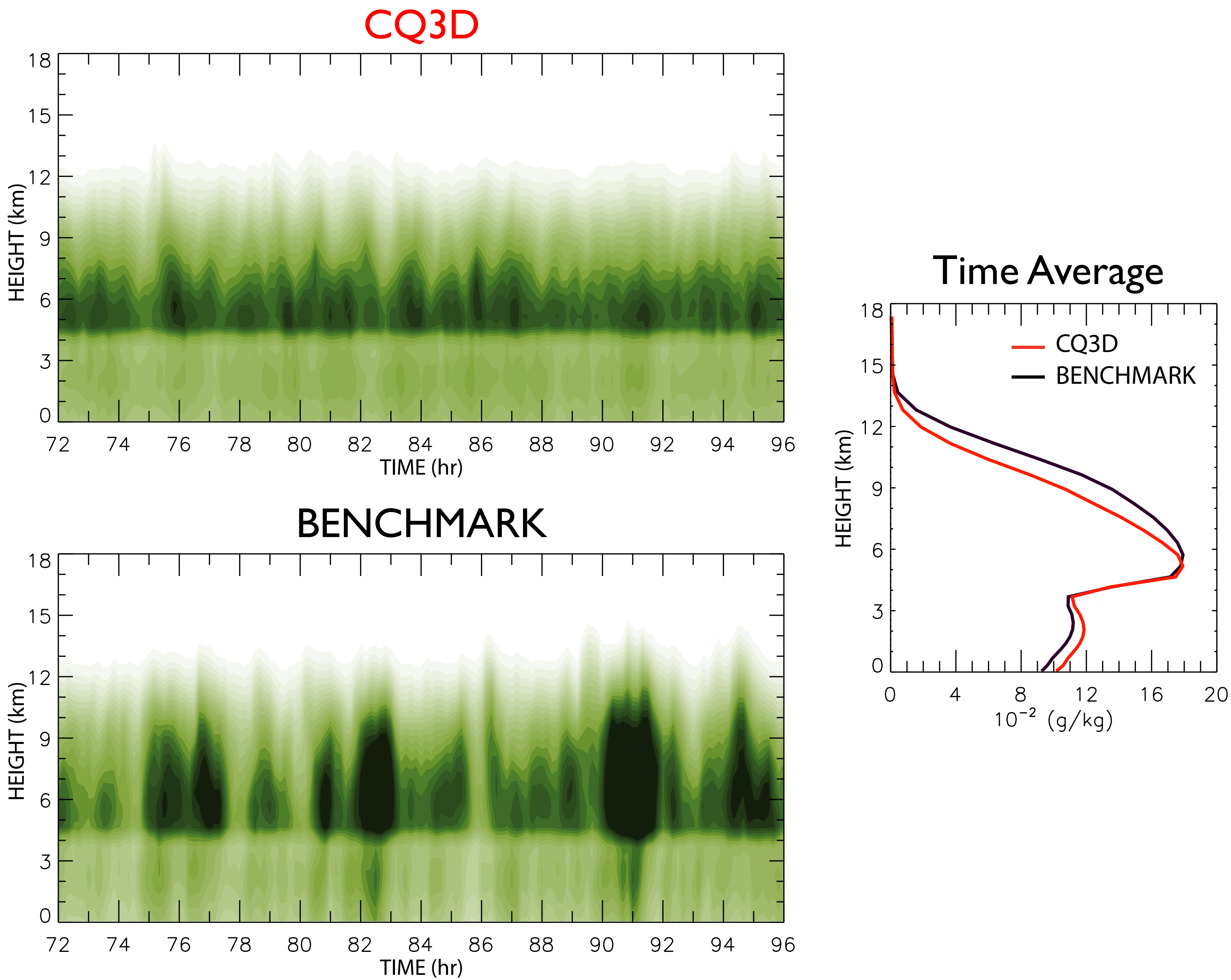




Network average

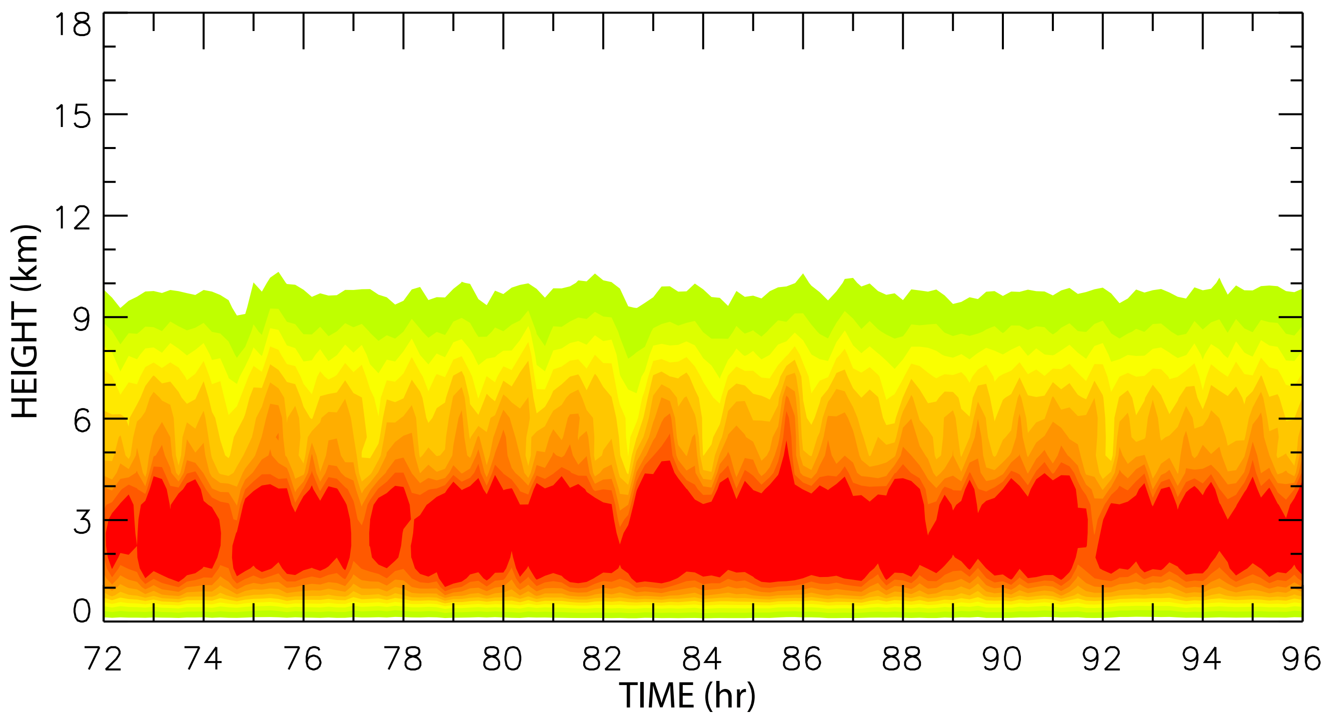


Network average of precipitant mixing ratio

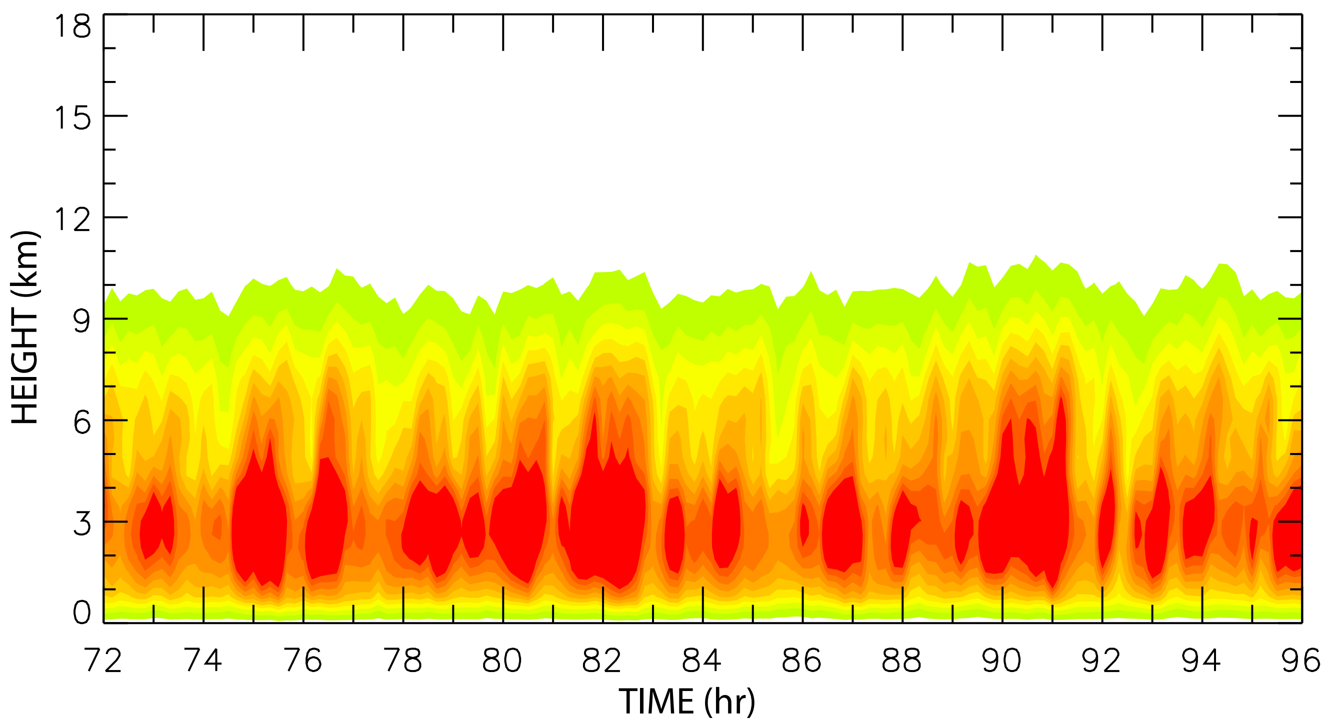


Covariance of q_v and w

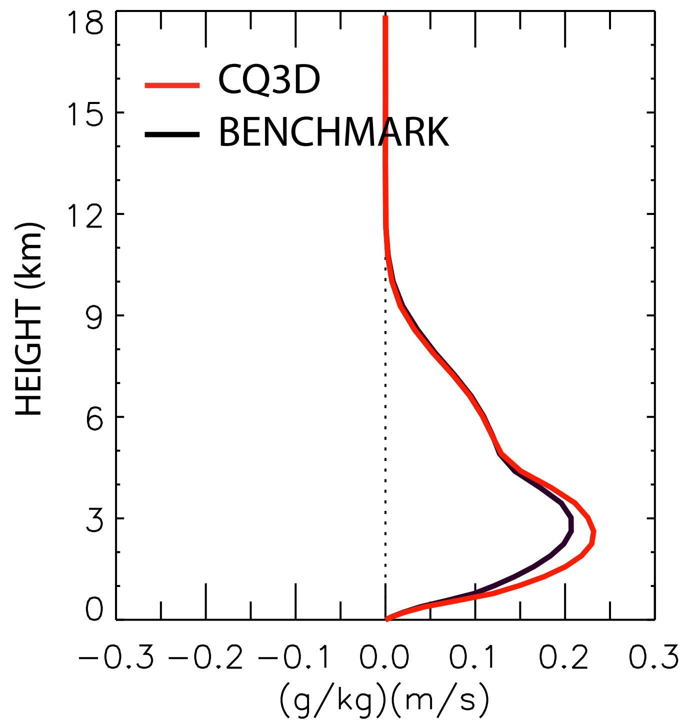
CQ3D



BENCHMARK

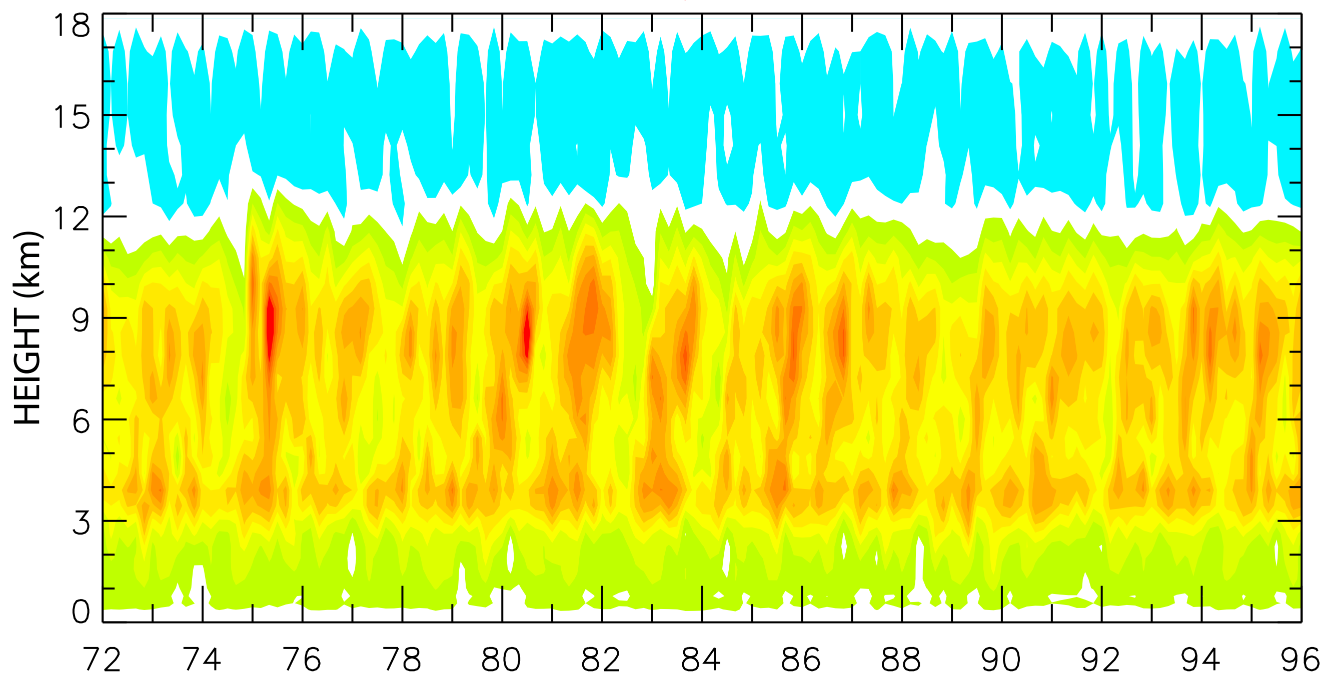


Time Average

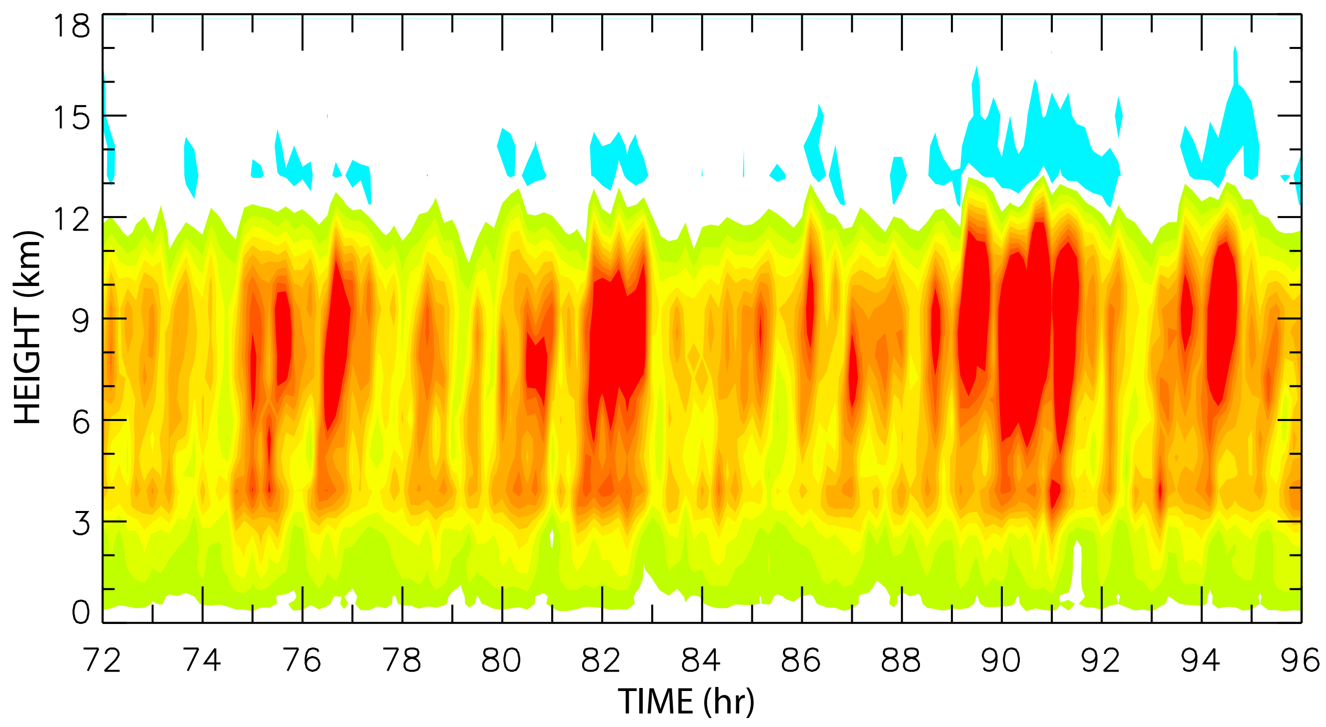


Covariance of θ and w

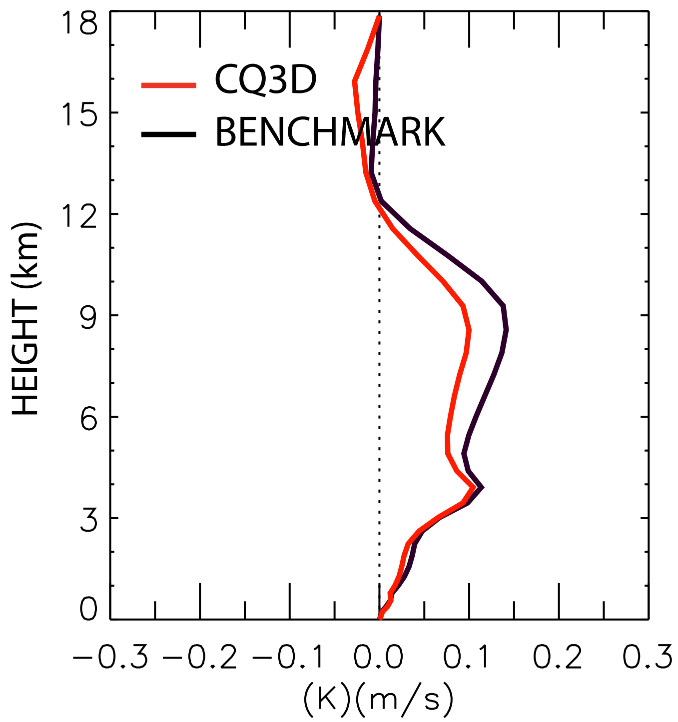
CQ3D



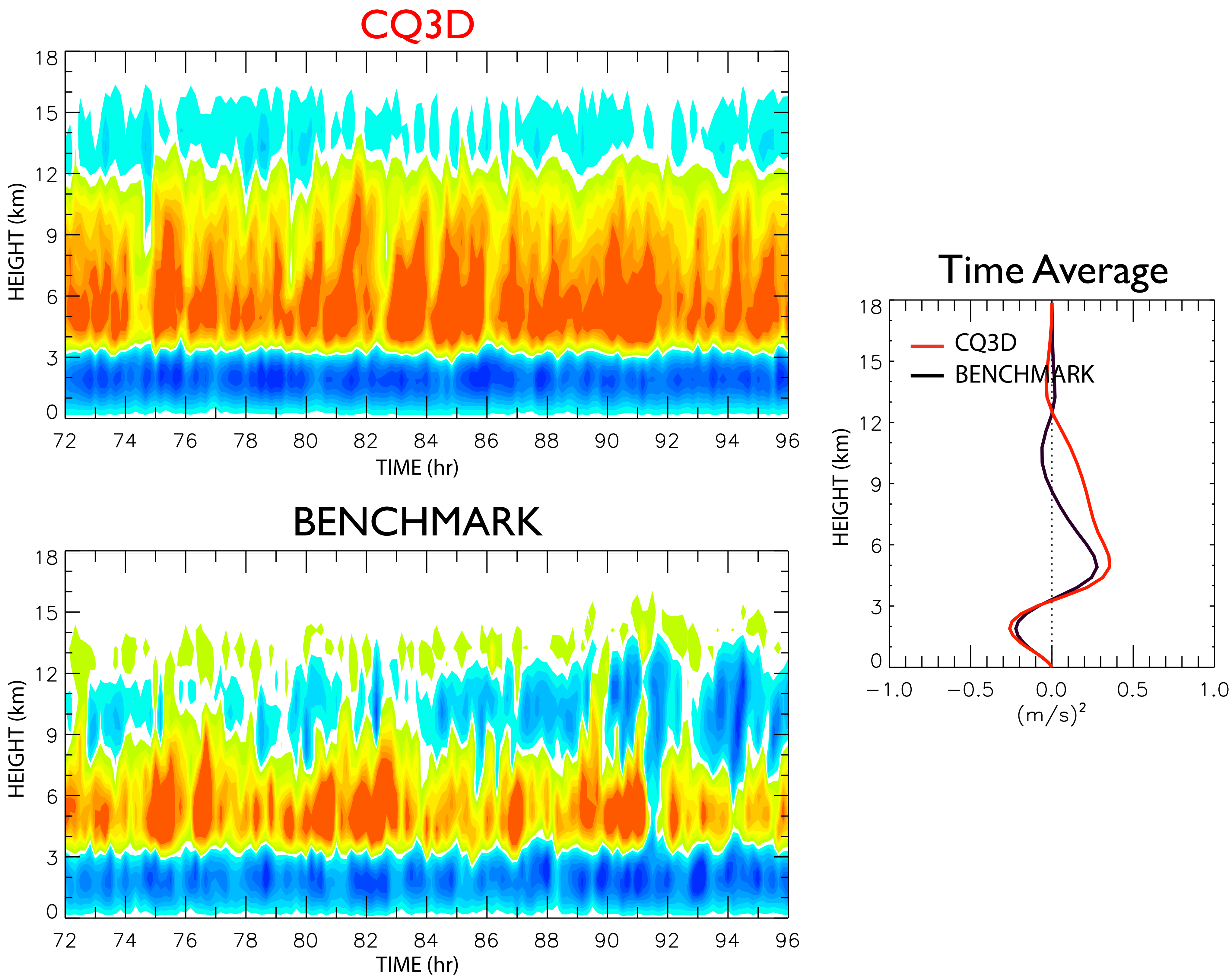
BENCHMARK



Time Average

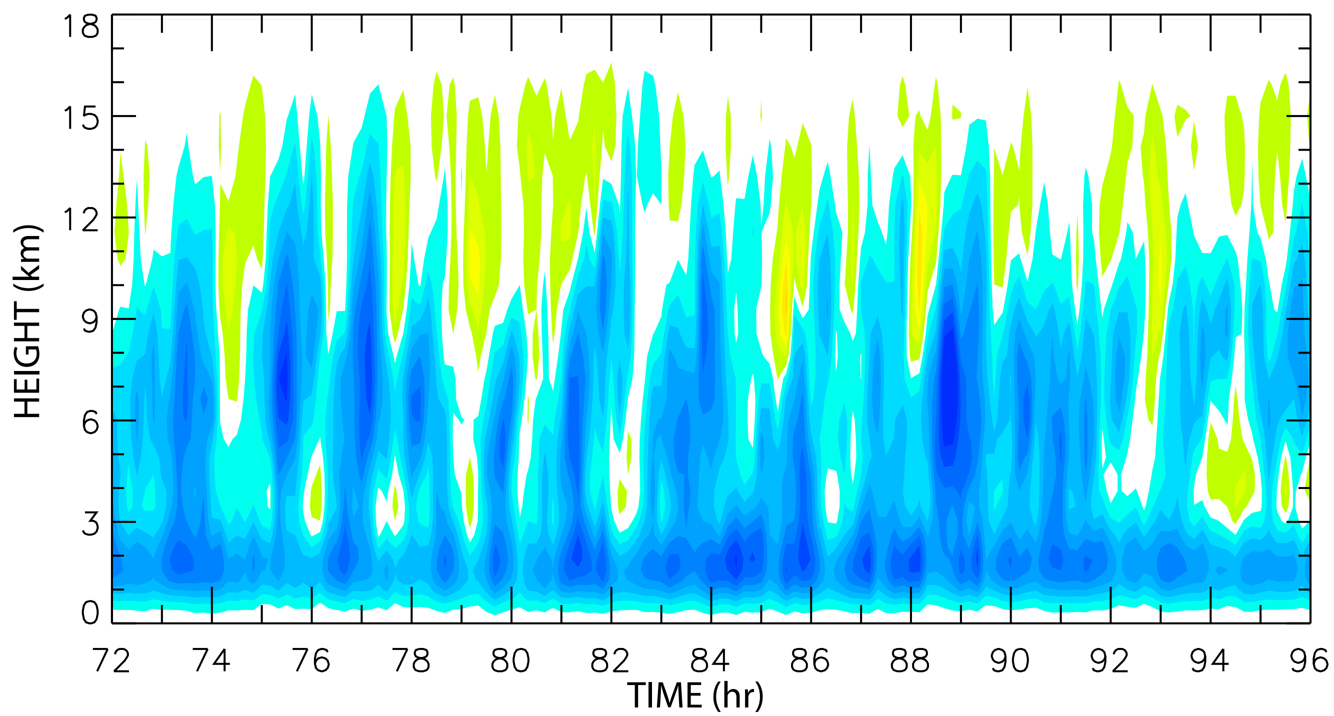


Covariance of u and w

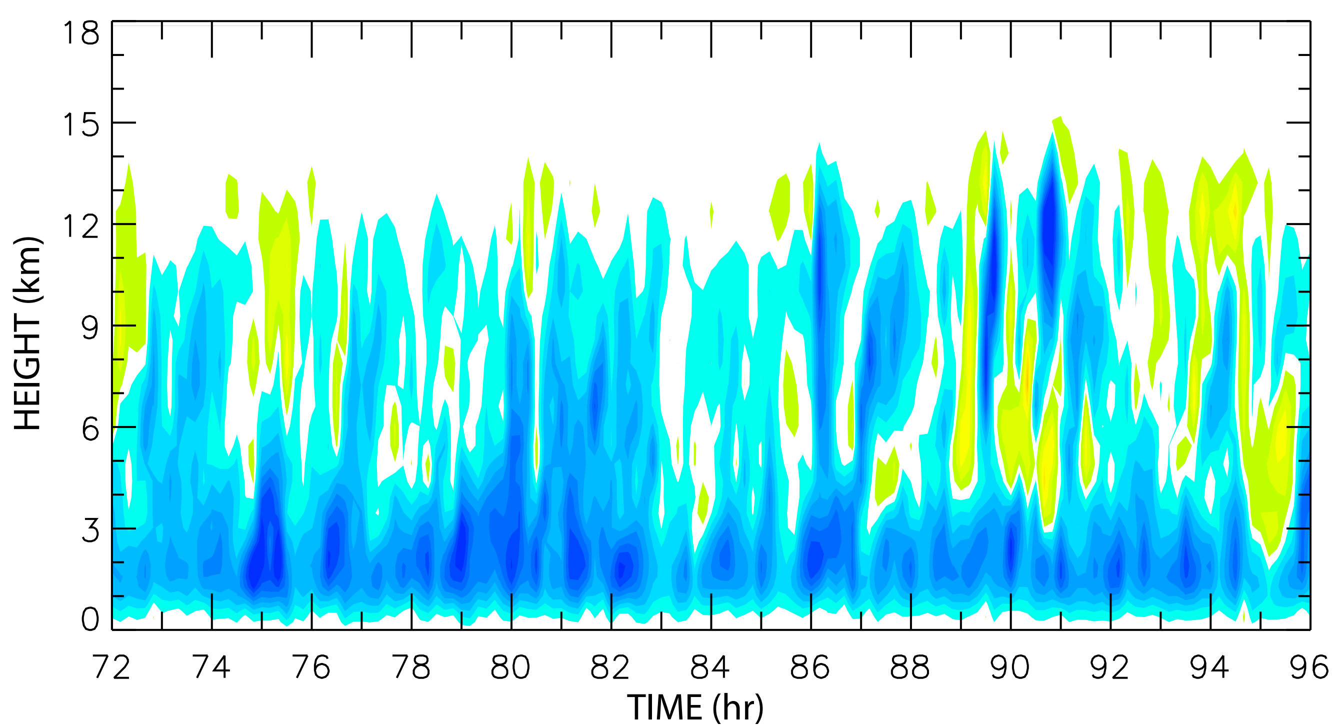


Covariance of v and w

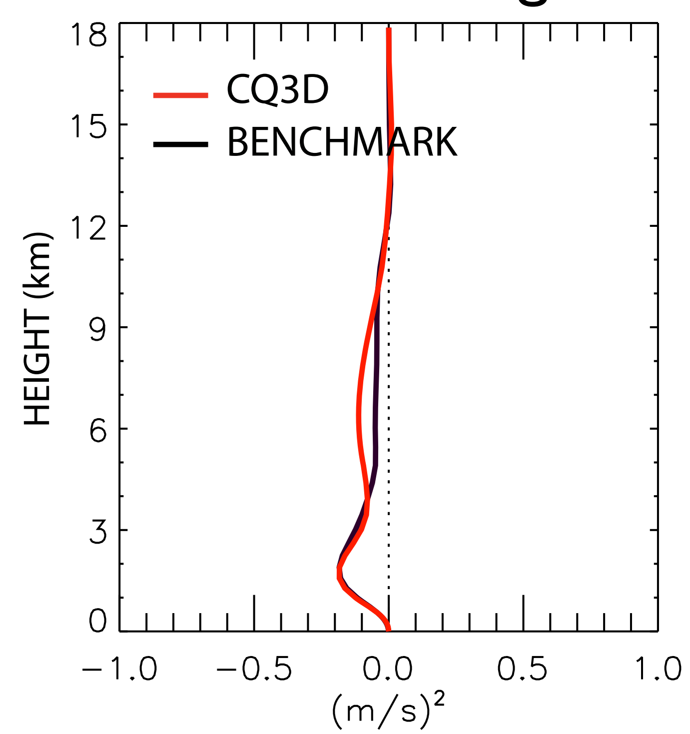
CQ3D



BENCHMARK

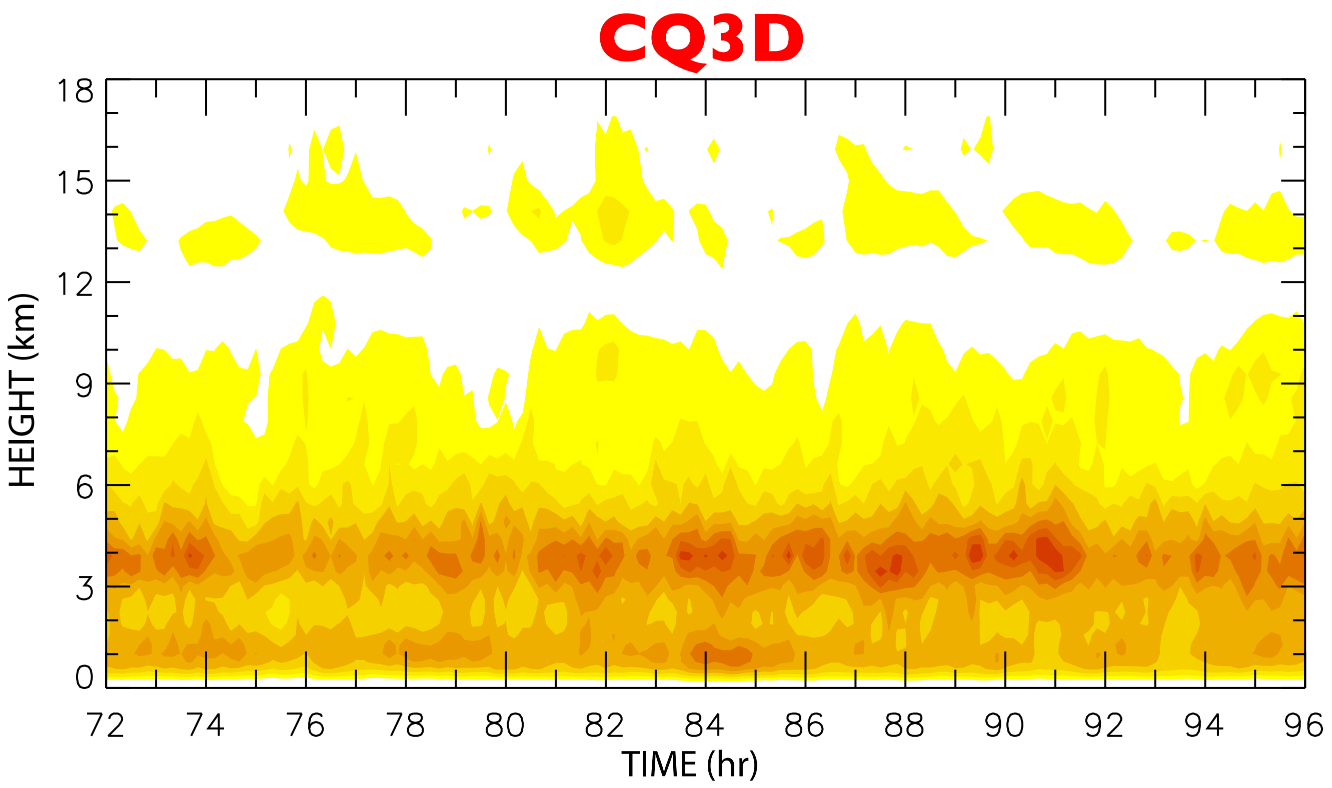


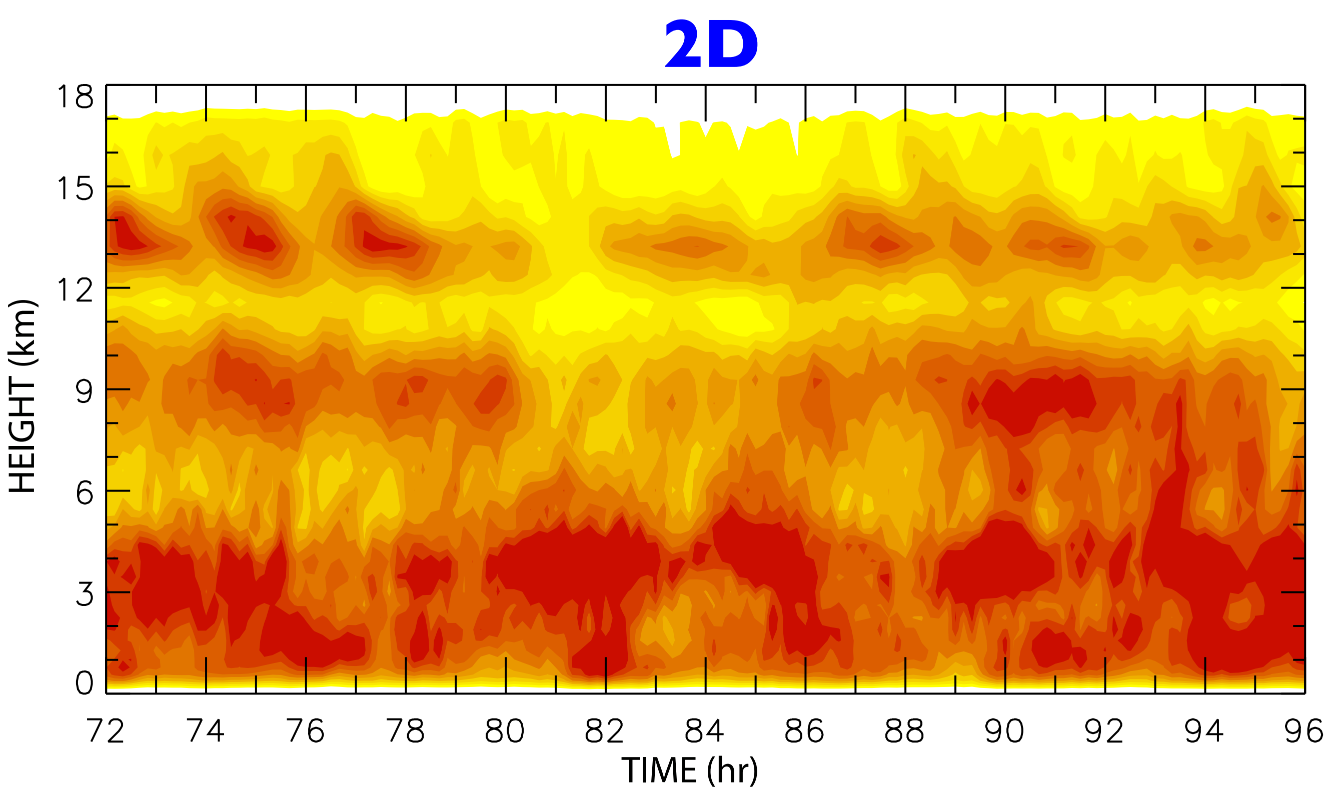
Time Average

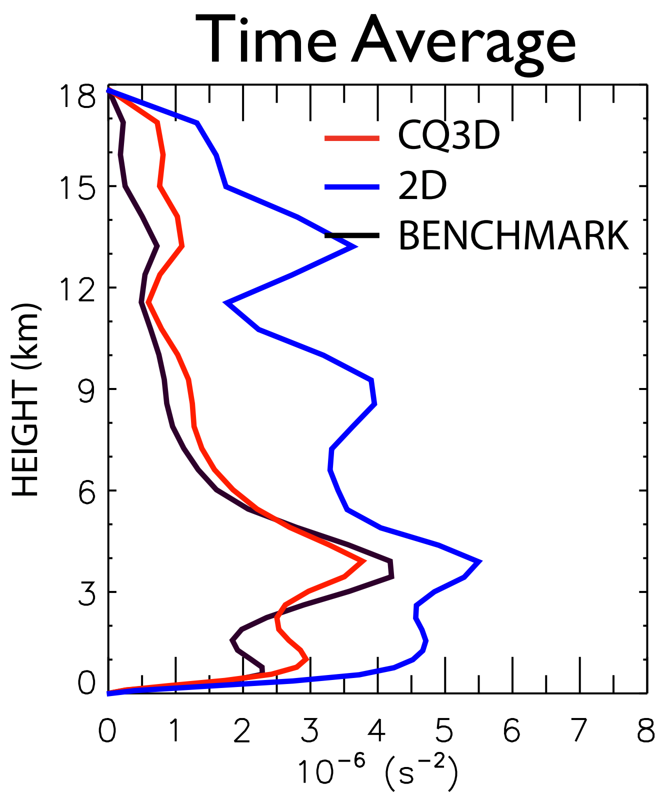


CQ3D vs. 2D

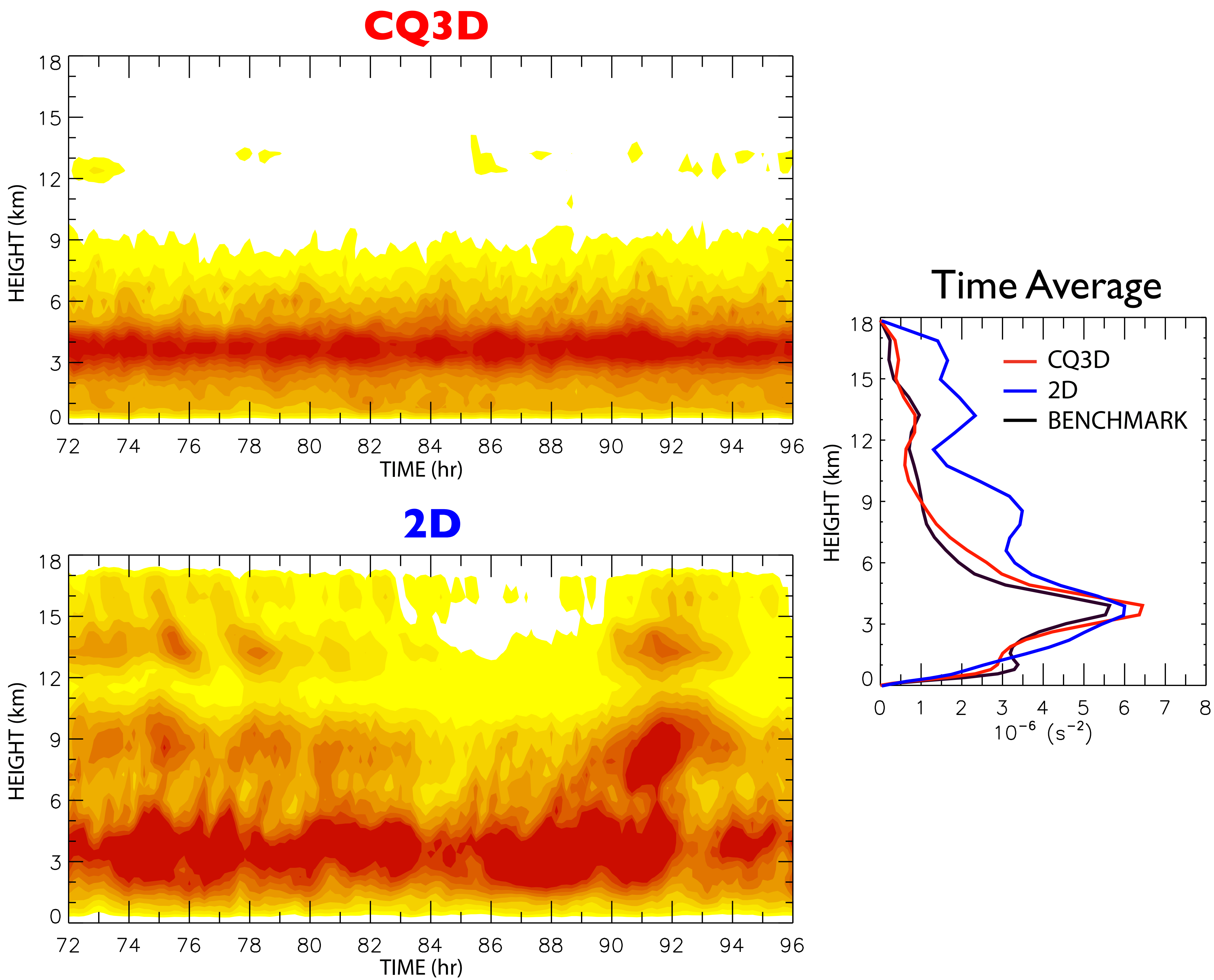
Variance of $\xi\ (10^{-6})$



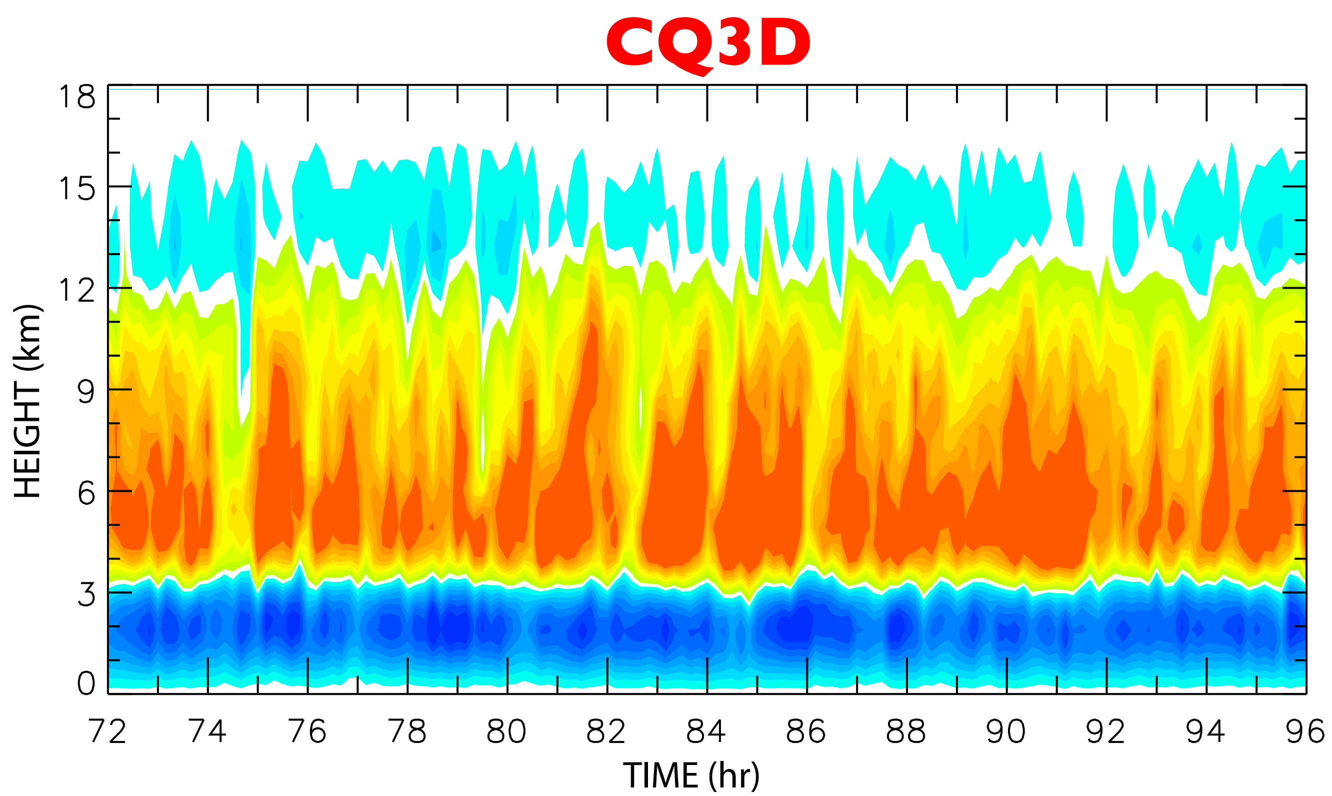


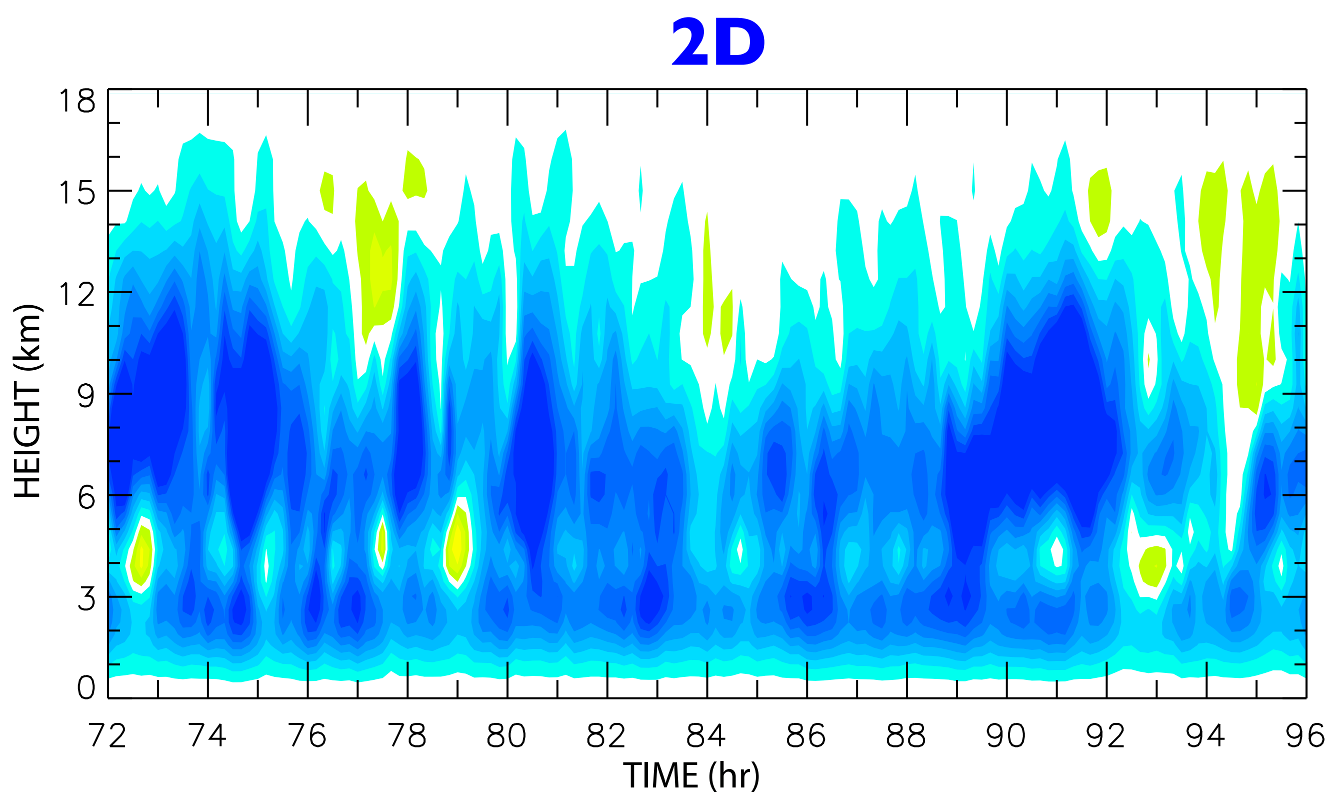


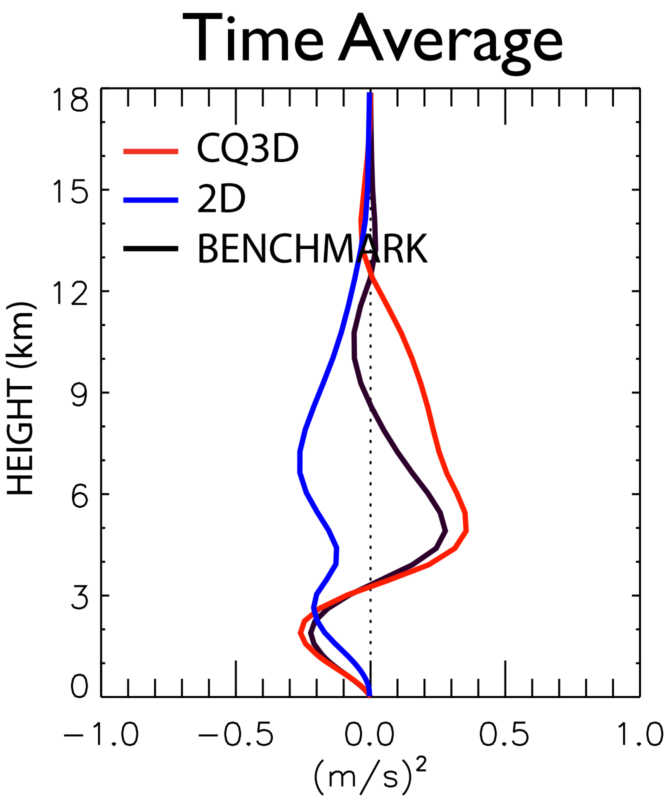
Variance of η $\left(10^{-6}\right)$



Covariance of u and w



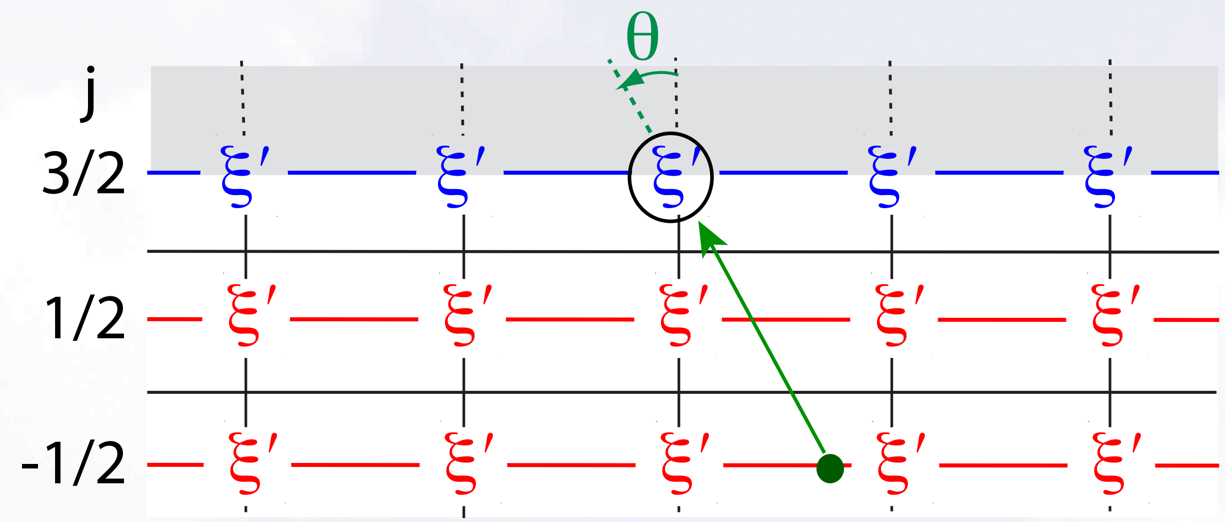


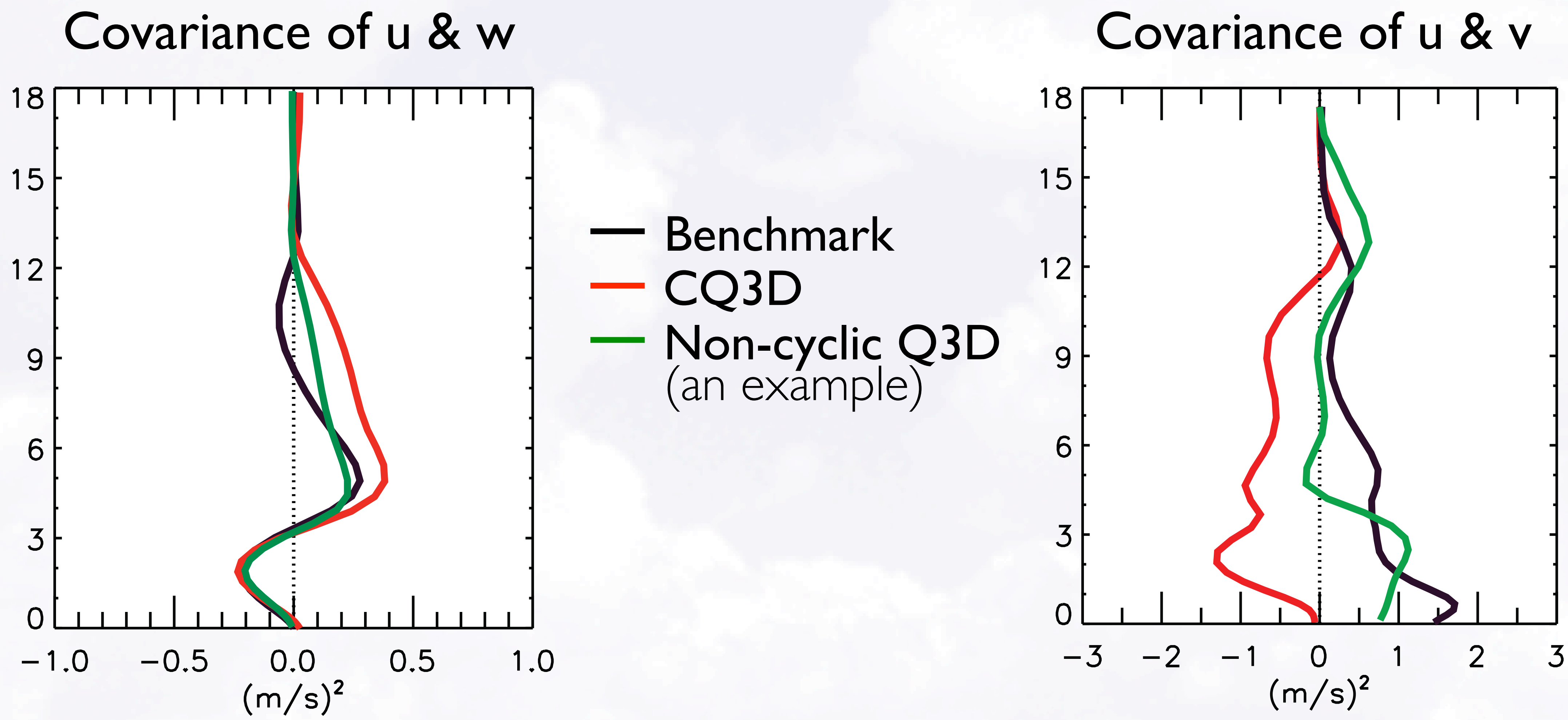


Preliminary tests of including the effect of orientation of cloud bands

SENSITIVITY TO THE ORIENTATION ANGLE, θ

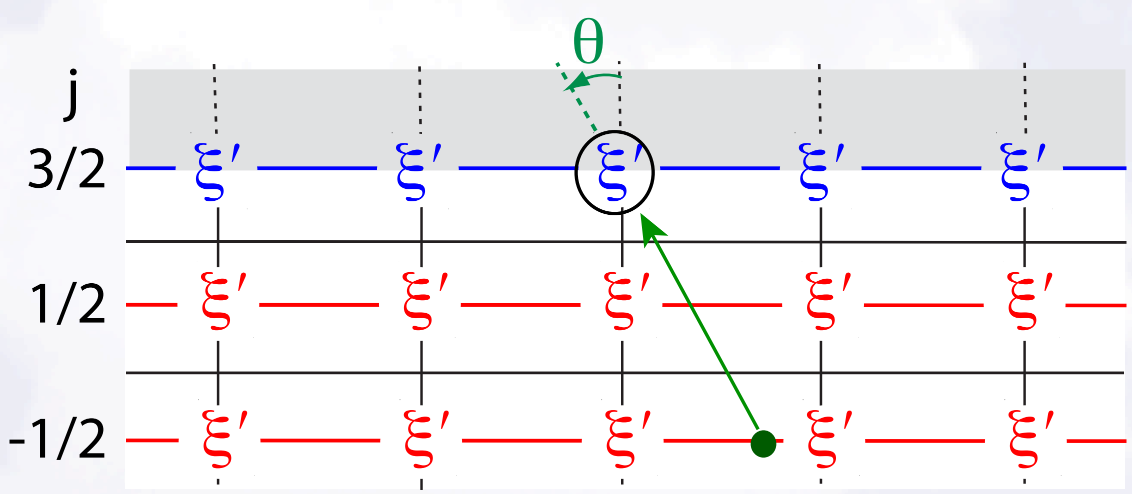
If it is well-defined, θ can be interpreted as an orientation angle of cloud bands.





STATISTICAL ESTIMATION OF θ AND ITS IMPLEMENTATION

If it is well-defined, θ can be interpreted as an orientation angle of cloud bands.



Basic assumption:

θ depends on cloud-regime, which changes only slowly in space and time.

- θ for the cloud-regime being simulated is determined through a regression analysis of the values of ξ' at j=1/2 and -1/2.
- Past data are used if necessary.
- If the regression analysis gives a poor correlation, θ is treated as a stochastic parameter.
- Implementation of θ follows an algorithm formally similar to that of the semi-Lagrangian scheme for advection.

SUMMARY AND CONCLUSIONS

- The new Q3D algorithm is computationally stable without any artificial diffusive/damping effects.

- Even without GCM coupling, agreement of CQ3D simulations with the benchmark simulation is generally very good for most of the variables.

  → Interactive coupling with the GCM must be tested with a wider domain so that the GCM can produce physically meaningful horizontal inhomogeneity.

- The biggest improvement from a corresponding 2D simulation appears in the vertical momentum transport given by the covariance of u and w.

- Preliminary tests indicate that including the effect of orientation of cloud bands can improve simulations of momentum transports.

- No major problems have been found in the new Q3D algorithm.

FUTURE PLANS (SHORT TERM)

- Finalize, implement and evaluate the algorithm for finding an optimum orientation angle of cloud bands and introducing stochastic effects.
- Simulated potential temperature variance tends to be large, presumably due to trapping of gravity waves into the channel. We will analyze and try to find a way to better control those waves (e.g., use of an absorbing lateral boundary condition for gravity waves.)
- Document the Q3D algorithm for publication and clean up the code.
- Parallelize the code.
- Still using an idealized but large domain, evaluate and refine the Q3D model with a truly interactive "GCM".

FUTURE PLANS (LONGER TERM)

Implementation of the Q3D CRM into global models

(require team effort)

- The global model can be either a vorticity-equation or a momentum-equation model.

  The latter case:

  The dynamical input to the Q3D CRM is through diagnosed vorticity.
  The dynamical output from the Q3D CRM is through diagnosed momentum.

- The horizontal coordinate of the Q3D can be a square grid even though the geodesic grid is used by the GCM.

  Reason:

  - The Q3D algorithm is more or less established for square grid.
  - It is difficult to handle a hexagonal staggered grid applied to a narrow channel while maintaining a balance in the degrees of freedom.
  - In the MMF approach, the output from the Q3D CRM is only through netsize averages.