DEVELOPMENT OF A NEW QUASI-3D ALGORITHM

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I. Introduction

III. Old and new Q3D grids

III. Outline of the new Q3D algorithm

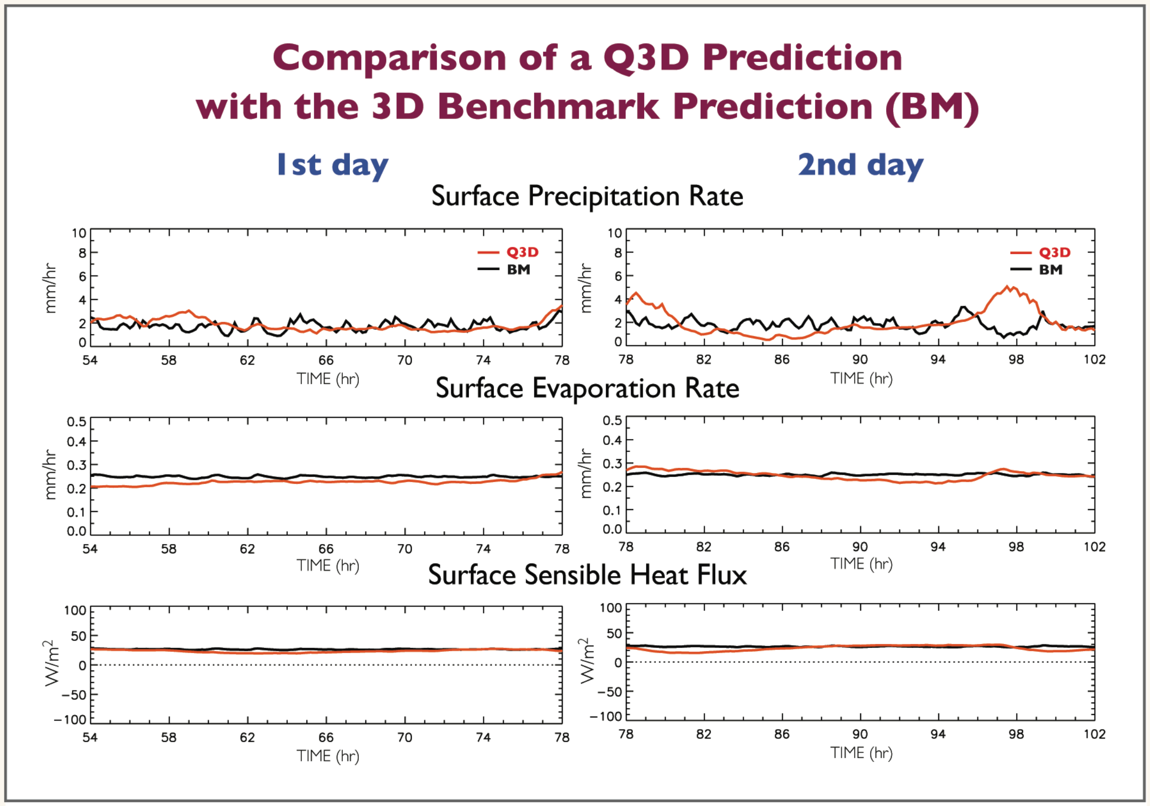
IV. Sample results

V. Summary and future plan

January 2009 CMMAP Team Meeting

At the last CMMAP Team Meetimg,
we presented the following summary and future plan:

- 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.



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- 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.

- To predict propagation of 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 . .

During the last 6 months, we have constructed a drastically new version of Q3D algorithm.

Three-Dimensional Terms in the Basic Equations

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

- Continuity equation

$$\frac{\partial}{\partial x}(\rho_0 u) + \underline{\frac{\partial}{\partial y}(\rho_0 v)} + \frac{\partial}{\partial z}(\rho_0 w) = 0$$

w-equation

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

- Equations for scalar variable, q (including θ and mixing ratios of various phases of water)

$$\frac{\partial}{\partial t}(\rho_0 q) + \frac{\partial}{\partial x}(\rho_0 u q) + \underline{\frac{\partial}{\partial y}(\rho_0 v q)} + \frac{\partial}{\partial z}(\rho_0 w q) = \rho_0 S_q$$

- Vorticity equation

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

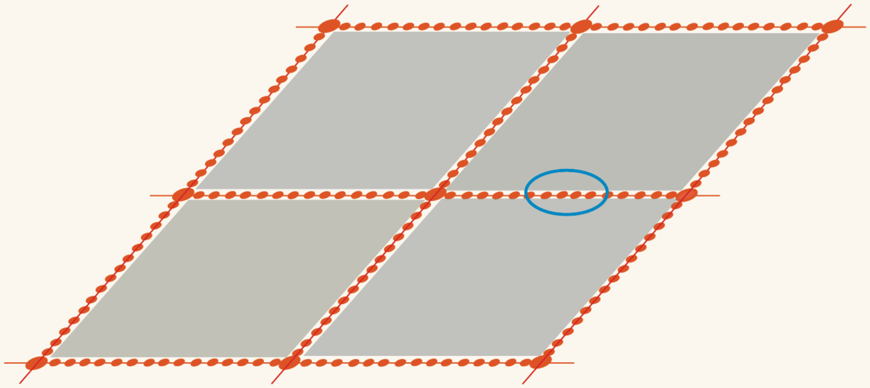
$$\frac{\partial \eta}{\partial t} = -\left[\frac{\partial}{\partial x}(u\eta) + \underline{\frac{\partial}{\partial y}(v\eta)} + \frac{\partial}{\partial z}(w\eta)\right] + \eta\frac{\partial v}{\partial y} + \underline{\xi\frac{\partial v}{\partial x} + \zeta\frac{\partial v}{\partial z}} - \frac{\partial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

twisting terms

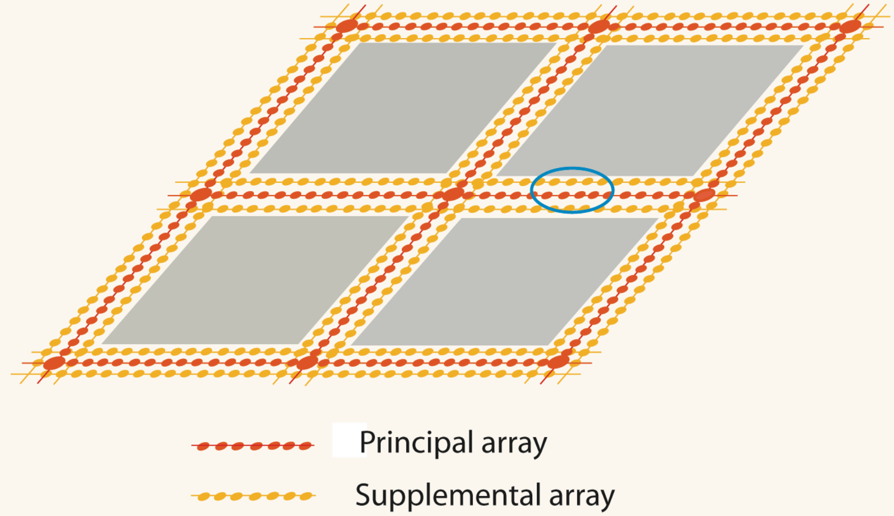
Underlined Terms

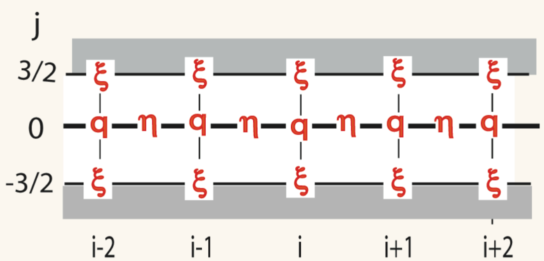
- *2D model : entirely neglected*
- *Old Q3D model : statistically or hypothetically estimated*
- *New Q3D model : explicitly predicted on the Q3D principal arrays.*

Old Q3D Grid

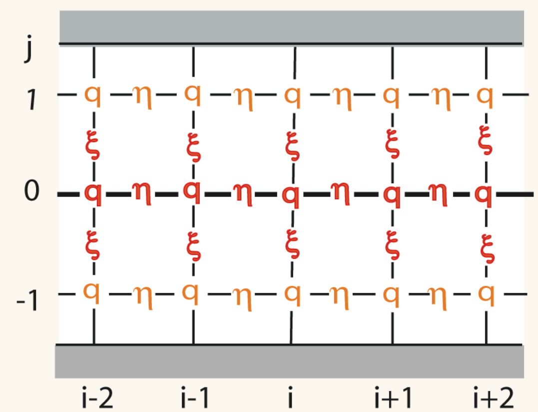


New Q3D Grid





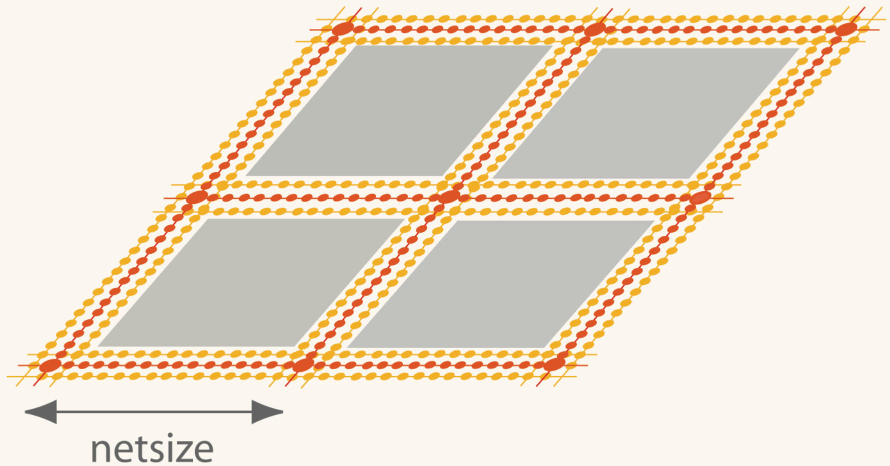
Except for ξ , normal gradients are estimated entirely through statistical/hypothetical relations.



Normal gradients are explicitly predicted on the principal array and at the inner side of the supplemental array.

OUTLINE OF THE NEW Q3D ALGORITHM

- Basically that of limited-area modeling for the unshaded area below
- Since the area is so narrow except near the intersections, we have to pay special attentions to the design of the algorithm.



Separation of the fields

For the variable q, for example, $q = \overline{q} + q'$, where

$\overline{q}$: Background field obtained by interpolation of the GCM variables

q' : Deviation from the background

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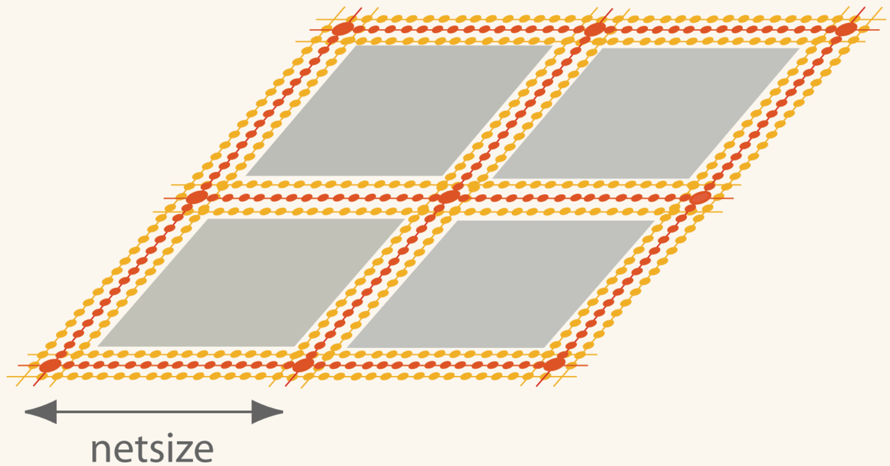
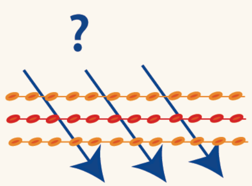
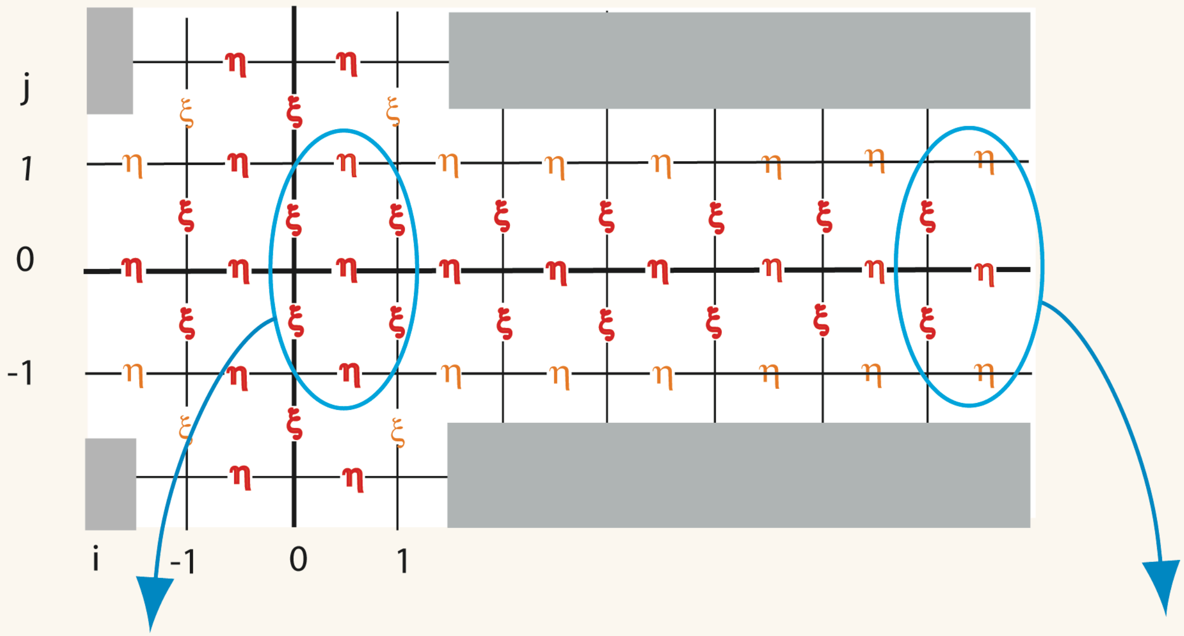


Major issues we have addressed:

1. Controlling the extra degree of freedom of the vorticity components
2. Computational design of advection in the normal direction
3. Statistical estimation of gradients at the boundaries
4. Controlling the singularity at the intersections and netsize circulation



1. Controlling the Extra Degree of Freedom of the Vorticity Components



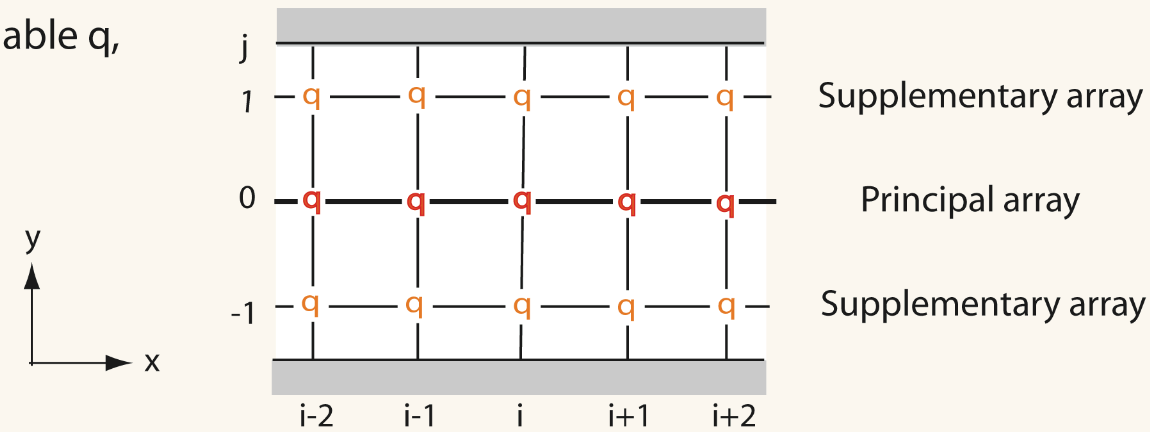
The structure of η in j is explicitly predicted.

The number of degrees of freedom of η in j is larger than that of ξ by the factor of 3/2.

- Away from the intersections, we modify the equations for $\eta'_{j=1}$ and $\eta'_{j=-1}$ in such a way that prediction of their sum is costrained while prediction of their difference is not modified.
- Prediction of η' at i = -1/2 and 1/2 are not modified.
- A smooth transition between the two.

2. Computational design of advection in the normal direction

For a scalar variable q,



The x direction

The upstream-weighted 3rd-order scheme of the original 3D model

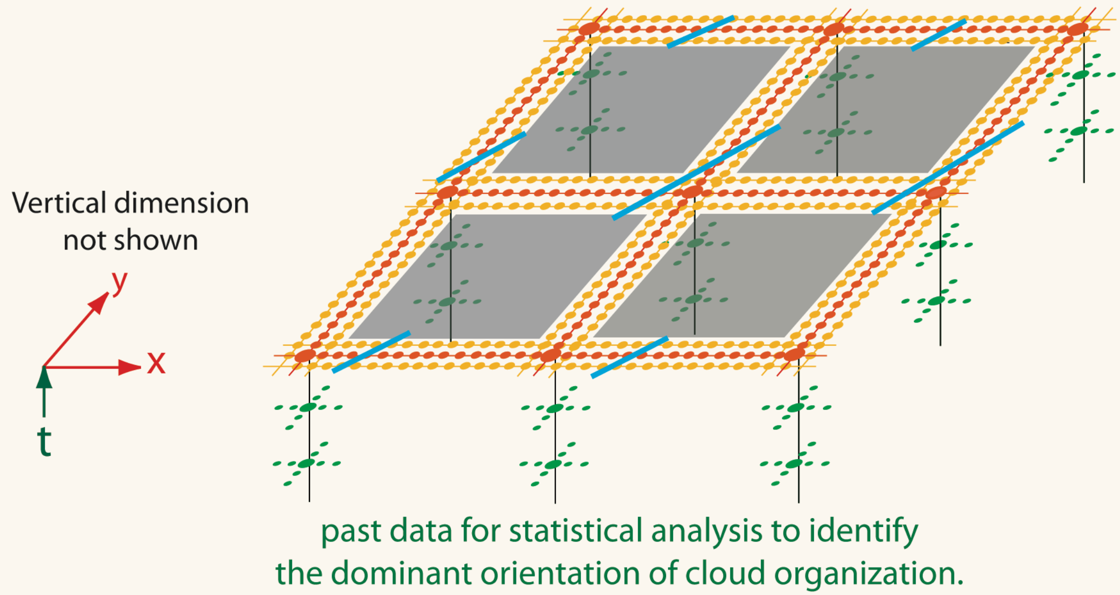
The y direction

On the principal array: The ghost-point values are chosen in such a way that the scheme effectively becomes a 2nd-order scheme.

On the supplemental arrays: The scheme has a room to increase its practical accuracy by statisticly estimating ghost-point values.

3. Statistical estimation of gradients at the boundaries

- To cover the advection of linearly organized clouds, the model has an option of analyzing the past data at and near intersections to identify the cloud regime being simulated.



- The analysis is a regression analysis of the relation between the two components of the gradient.
- If the correlation coefficient is high, the dominant angle inferred from the analysis is used in the design of inflow/outflow conditions.

4. Controlling the singularity at the intersections and netsize circulation

The model attempts to control these in two ways.

(1) Semi-local diffusion

Diffusion acting only on the grid points near the intersections.

(2) Selective Raleigh damping

Raleigh-type damping acting only on the vertical shear component of vorticity.

These are, however, only symtomatic treatments.

SAMPLE RESULTS

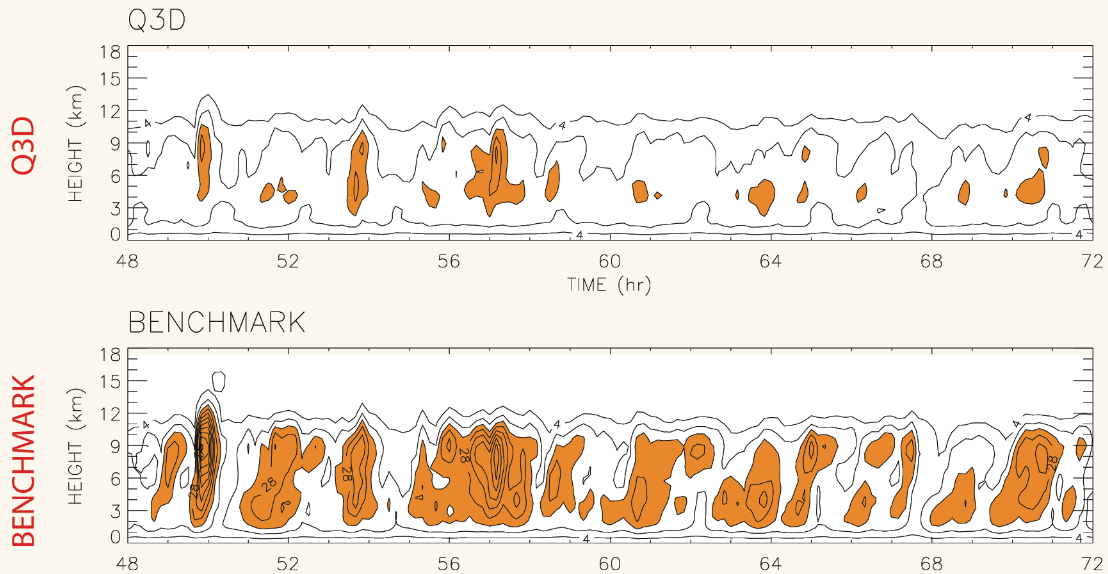
CRM grid size: 3 km GCM grid size : 96 km

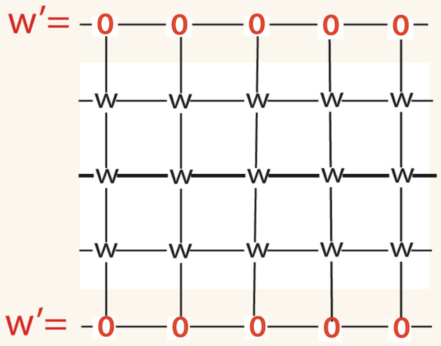
Domain size : 384 km

Several problems have been identified

Tests with prescribed ξ, η and θ (Not trivial because the w-equation must be solved)

Time sequences of horizontal variance of w





w is under-predicted probably because the boundary condition w = 0 is used at the boundaries.

We are testing different boundary conditions.

SAMPLE RESULTS

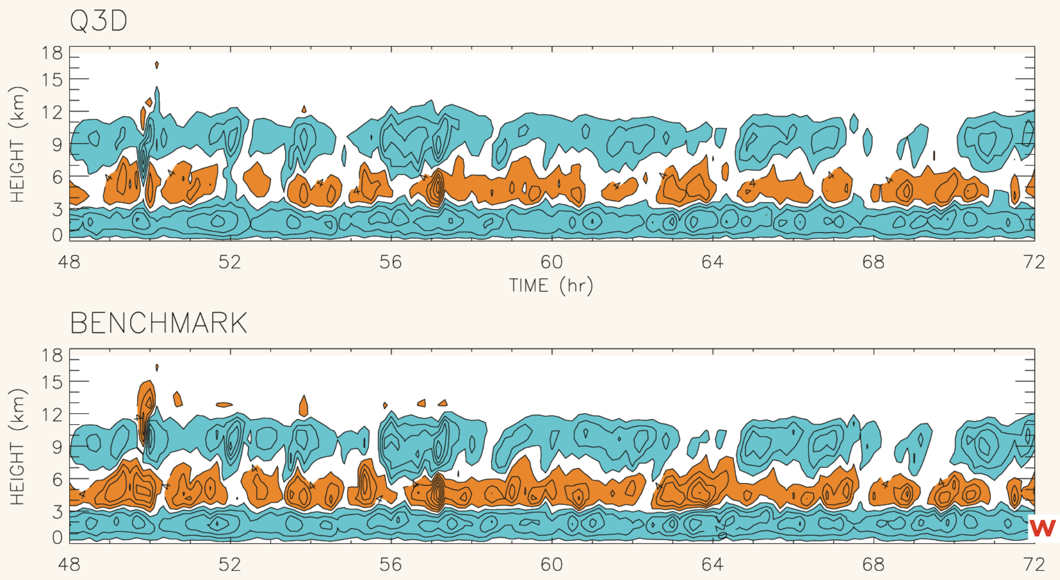
CRM grid size: 3 km GCM grid size : 96 km

Domain size : 384 km

Several problems have been identified

Tests with prescribed ξ, η and θ (Not trivial because the w-equation must be solved)

Time sequences of horizontal co-variance of u and w



This is encouraging .

SAMPLE RESULTS

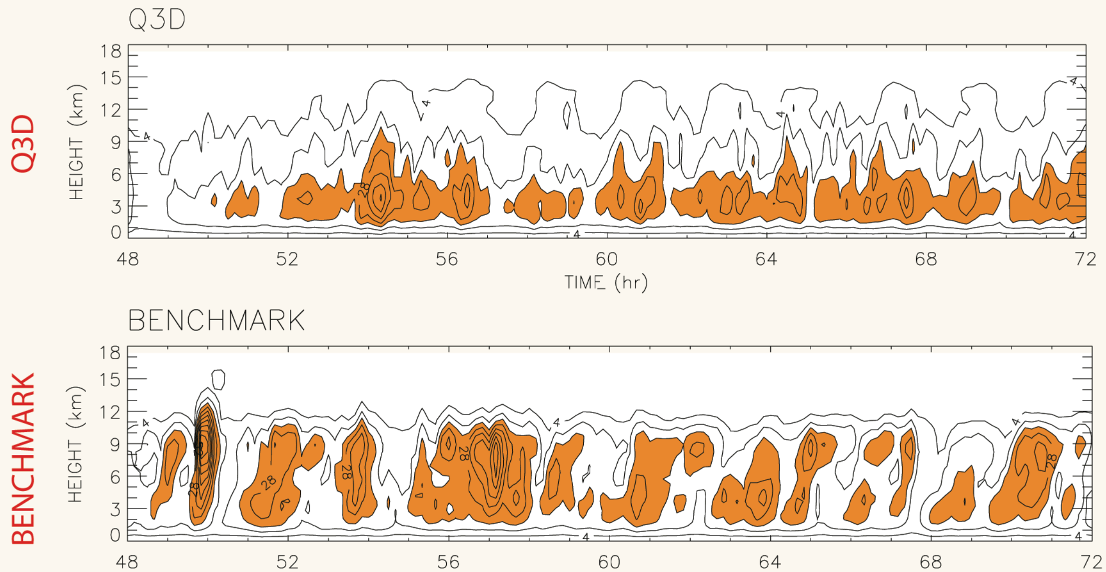
CRM grid size: 3 km   GCM grid size : 96 km

Domain size : 384 km

Several problems have already been identified

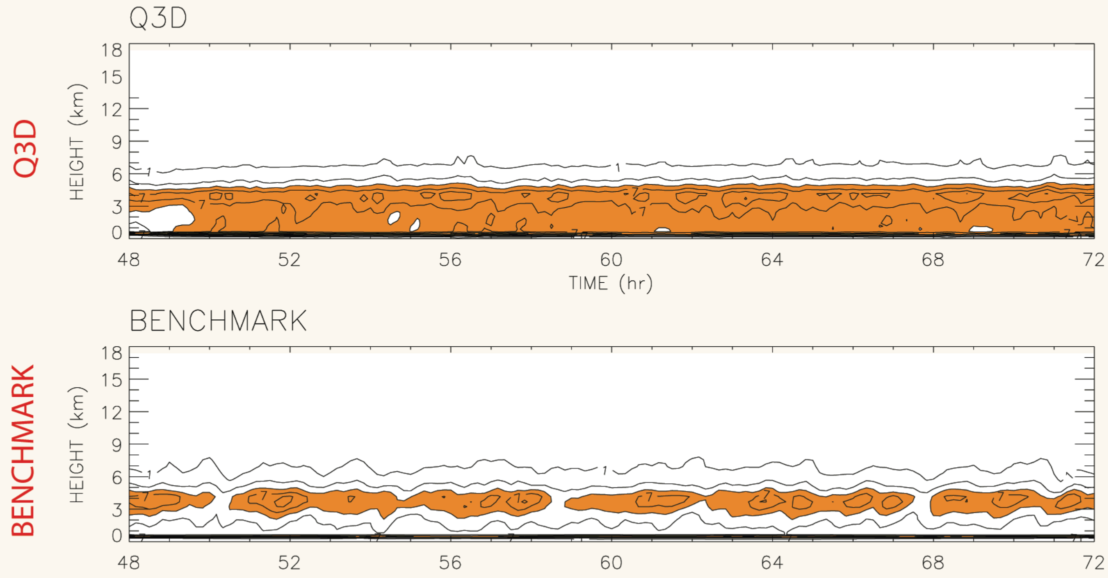
Tests with full model

Time sequences of horizontal variance of w

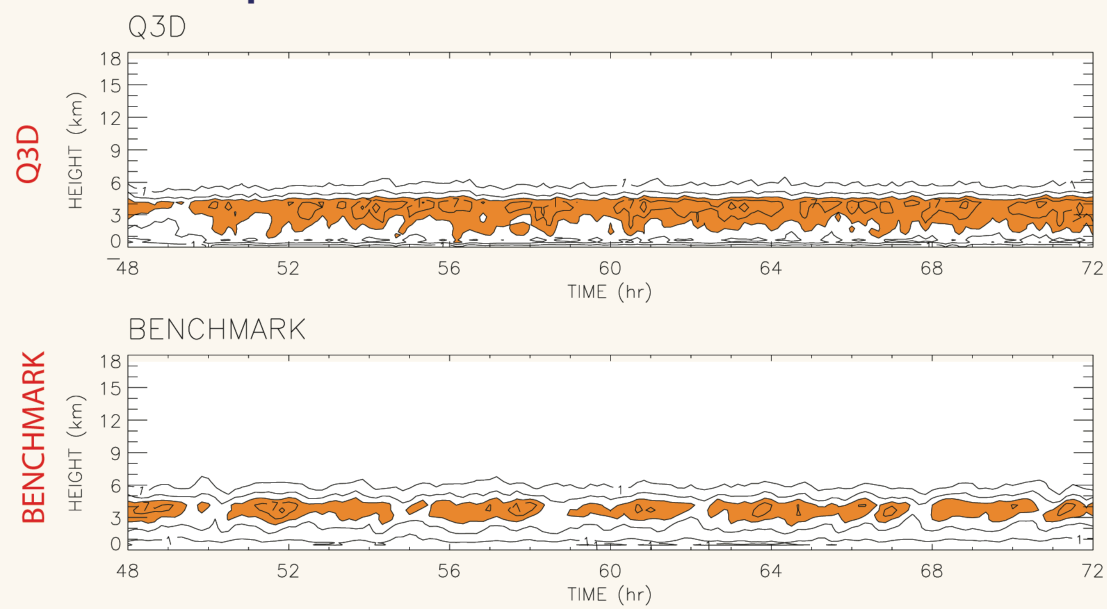


Convective activity is not sufficiently deep.

Time sequences of horizontal mean cloud water



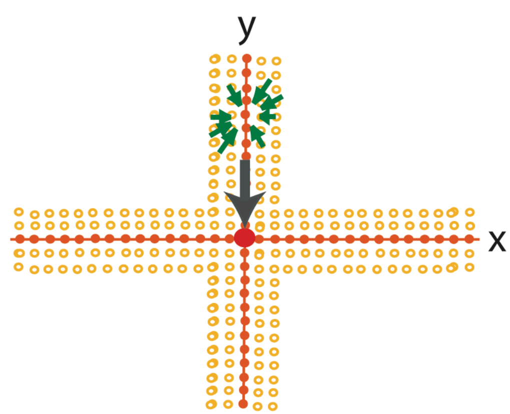
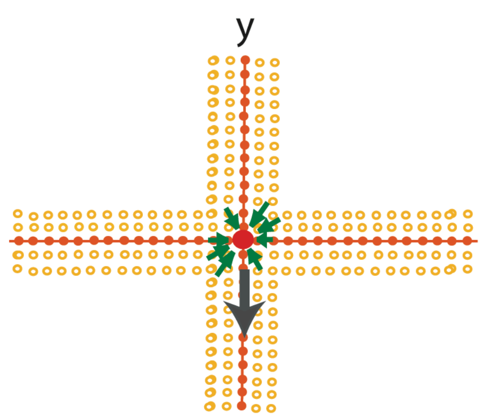
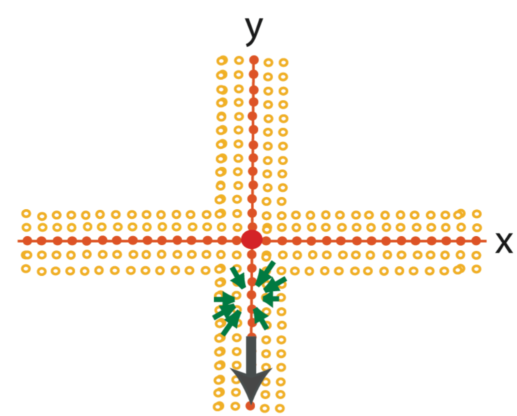
Time sequences of horizontal variance of cloud water



Low-level clouds are over-predicted especislly in the stratiform.

There is another reason why convective activity is underpredicted.

Passage of a strong convective system over an intersection point produces large-scale circulation on the other axis.

		
The structure of the system in x is constrained.	The structure of the system in x becomes free, suppressing convective ativity on the x-axis by induced subsidence.	The structure of the system in x is again constrained, but the lare-scale circulation on the x-axis remains.

Control of netsize-scale circulation is the most serious problem we now have.

Summary

- We have developed a new Q3D algorithm that has a minimum degree of freedom for the 3D convective-scale dynamics.
- The 3D effect due to vorticity twisting seems to be well handled.
- The 3D effect due to advection also seems to be well handled although there is a room to improve inflow/outflow conditions.
- The convective-scale vertical velocity tends to be under-predicted. One of the cause for this seems to be the fixed (Dirichlet type) boundary condition for w at the boundary.
- The netsize-scale circulation also tends to suppress vertical velocity through subsidence..

Future Plan

- We will try to stabilize the model so that it does not have to depend on diffusion/damping for computational purpose.
- We need, however, to filter or damp the netsize-scale structure like

MULTISCALE METHODS

Comprehensive atmospheric modleing must ineviatably be multi-scale modeling because the model physics is resolution-dependent.

NESTED GRID

If "area of interest" can be defined in advance, we can apply cloud-resolving resolution only to such area(s).

Not for global climate models.

ADAPTIVE MESH REFINEMENT (AMR)

If "feature of interest" can be defined, higher resolution can be supplied where the model "thinks" it is needed.

Applications of this method have been to problems with no physics or those with a single fomulation of model physics.

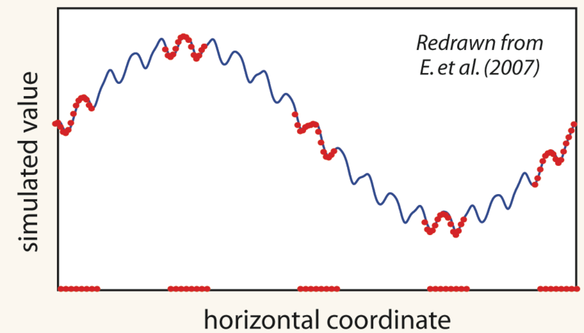
We need heterogeneous model physics for heterogeneous resolution.

HETEROGENEOUS MULTISCALE MODELING (HMM)

"To design combined macroscopic-microscopic computational methods that are much more efficient than solving the full microscopic model and at the same time give the information we need." (E *et al.* 2007)

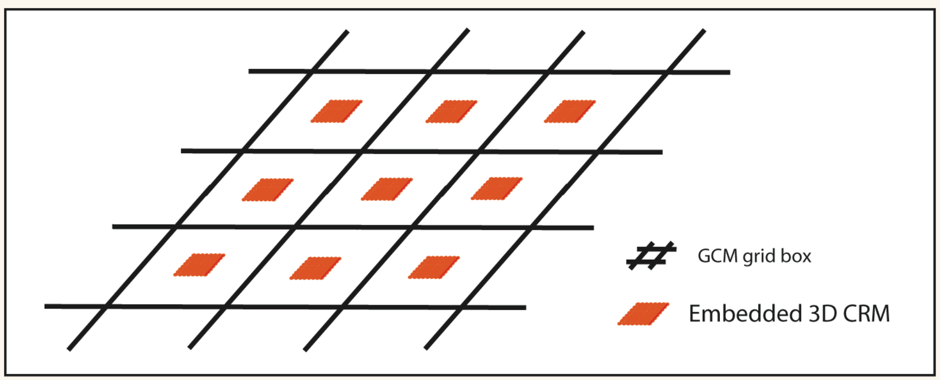
The efficiency is gained by ***localization*** of the microscopic problem,

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



3D MULTI-SCALE MODELIG FRAMEWORK

Khairoutdinov and Randall (2005)

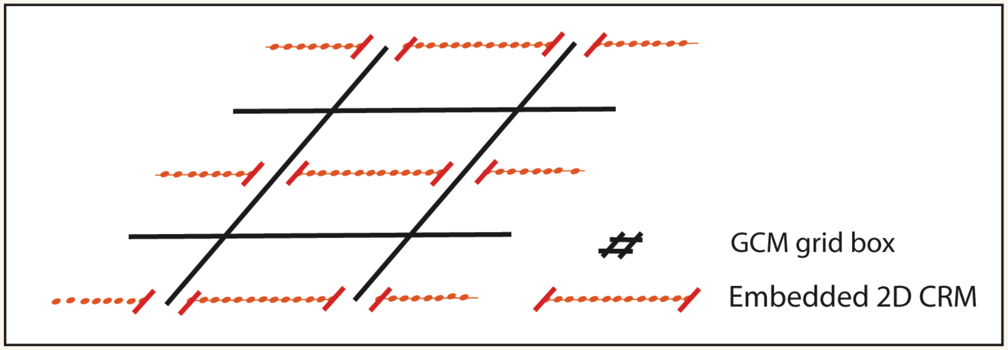


Success of these approaches crucially depends on the existence of a specral gap.

PROTOTYPE MULTISCALE MODELING FRAMEWORK

Grabowski (2001) Khairoutdinov and Randall (2001)

A unique idea by Grabowski *that takes advantage of the fact that 2D CRMs are reasonably successful in simulating deep clouds.*



Efficiency is gained by sacrificing three-dimensionality rather than localization.

QUASI-3D MULTISCALE MODELING FRAMEWORK