TOWARD UNIFICATION OF GENERAL CIRCULATION AND CLOUD-RESOLVING MODELS

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RATIONALE FOR THE THEME OF THIS TALK

As far as representation of deep moist convection is concerned,

we have only two kinds of model physics :

highly parameterized,

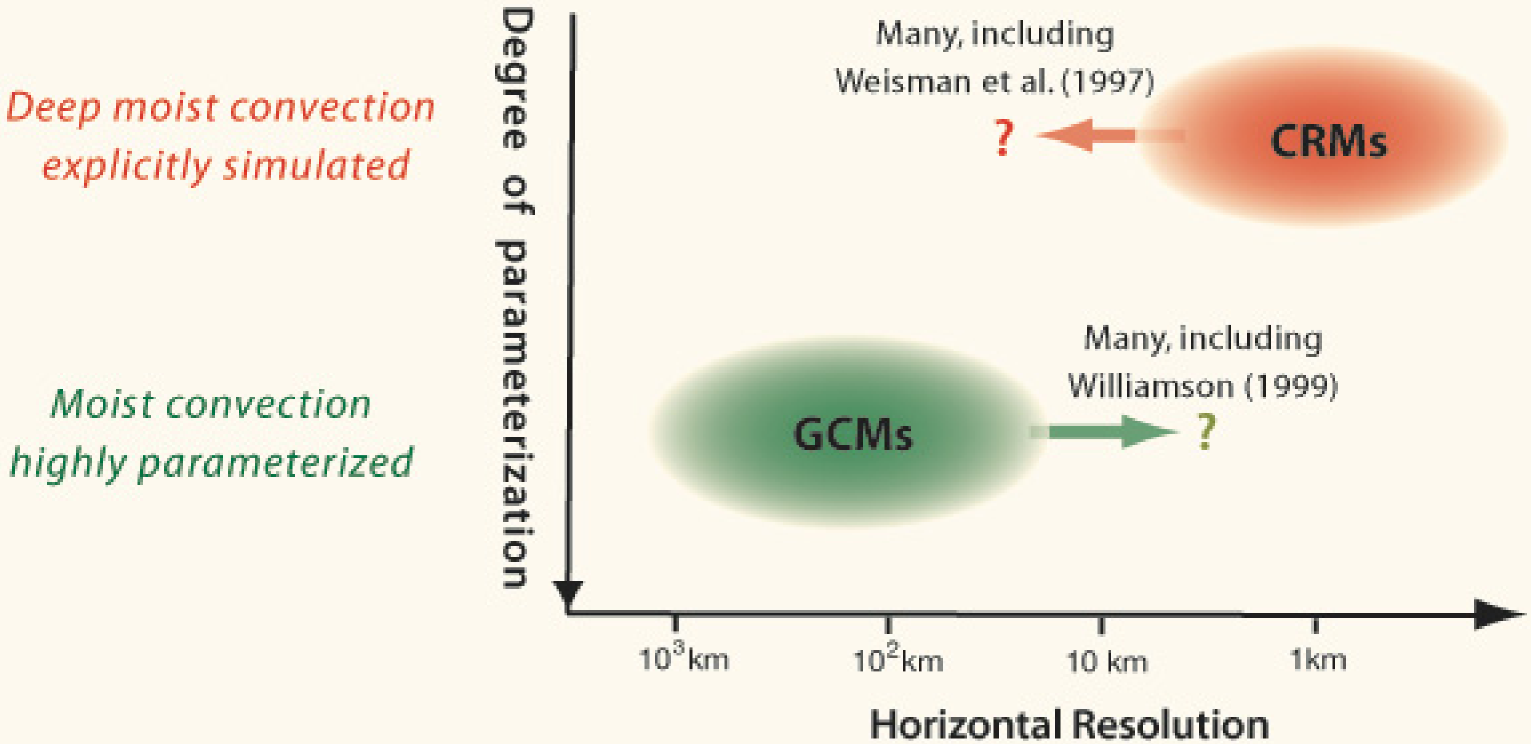
and

explicitly simulated.

Correspondingly,

THERE ARE TWO FAMILIES OF ATMOSPHERIC MODELS

(besides those models that explicitly simulate turbulence)



WILLIAMSON, D. J. , 1999

For the upward branch of the Hadley circulations simulated by the NCAR CCM2 :

- When the resolutions are increased for both dynamics and parameterizations,

  → No sign of convergence;

- When the resolution is increased only for dynamics,

  → Convergence;

  However, the result is similar to that when the coarse resolution is used for both.

He then raised a serious question:

> *“ . . . are the parameterizations correctly formulated ? . . .*
> *The parametrization should explicitly take into account*
> *the scale of the grid on which it is based. ”*

Similar questions are also raised by

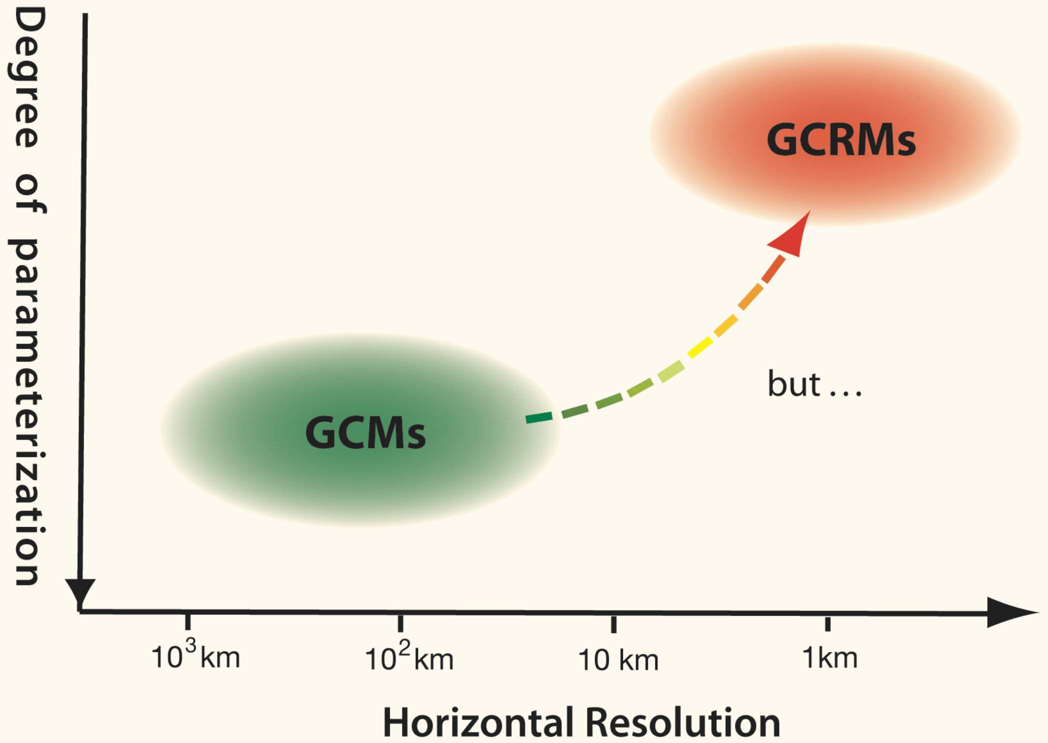
Skamarock and Klemp (1993) and Buizza (2010).

THE CONVERGENCE PROBLEM

Our problem is more demanding than just a convergence;

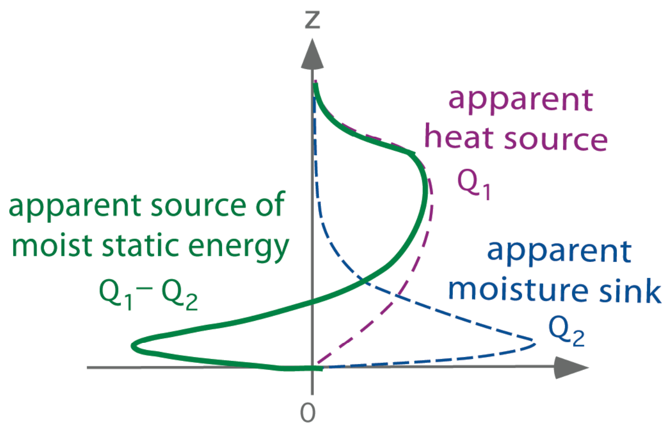
the GCM should converge to a physically meaningful system

such as a global CRM (GCRM).

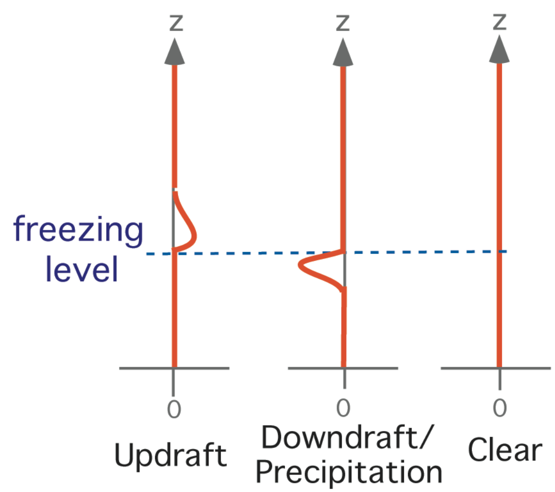


SCHEMATIC ILLUSTRATION OF MOIST STATIC ENERGY SOURCE UNDER TYPICAL TROPICAL CONDITIONS

From observed
L-S heat and moisture budgets



From
local cloud microphysics



GCM-type profile

CRM-type profile

Any space/time/ensemble average of the profiles in the right panel does NOT give the profile in the left panel.

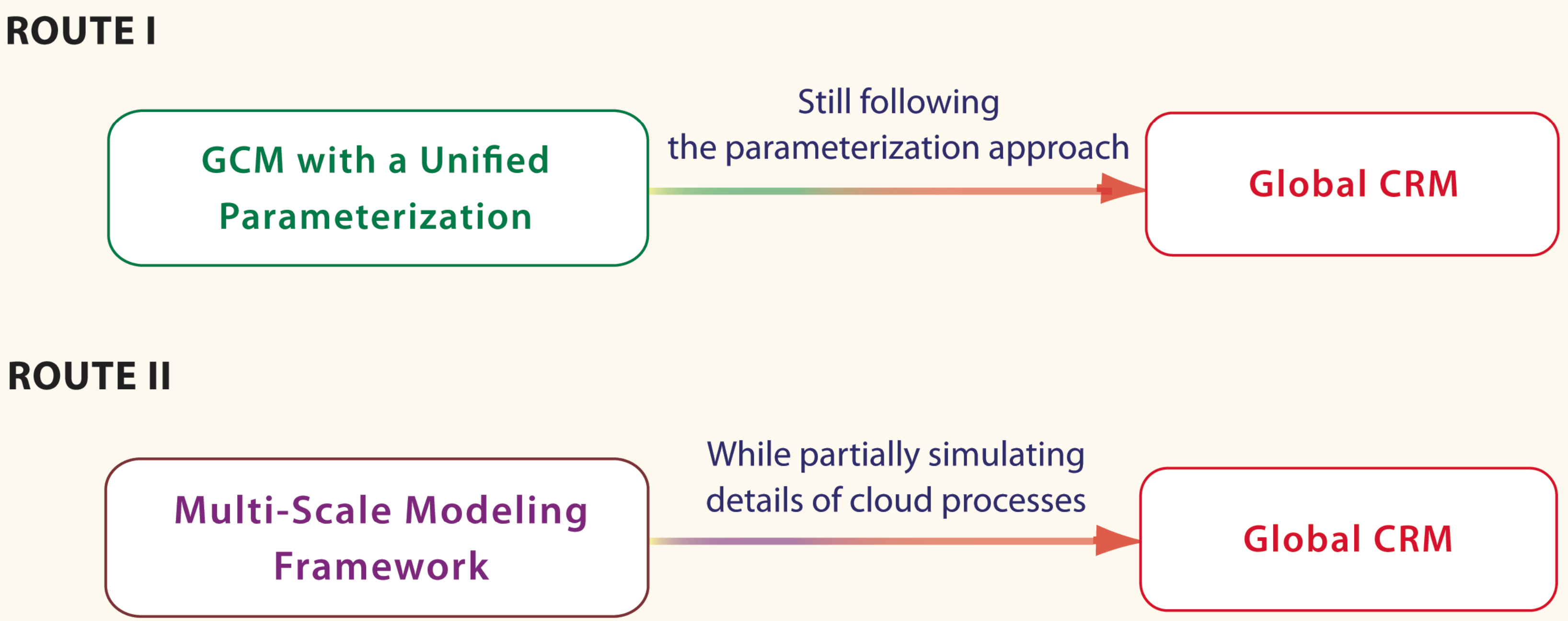
THE CUMULUS PARAMETERIZATION PROBLEM

- It is more than a statistical theory of cloud microphysics as we have seen.
- It is not a purely physical/dynamical problem because it is needed as a consequence of mathematical truncation.
- It is not a purely mathematical problem as a higher resolution or an improved numerical method does not automatically improve the overall results.

A complete theory of cumulus parametrization must address all of these aspects in a consistent manner, including the transition between the GCM-type and CRM-type profiles.

UNIFICATION OF GCM AND CRM

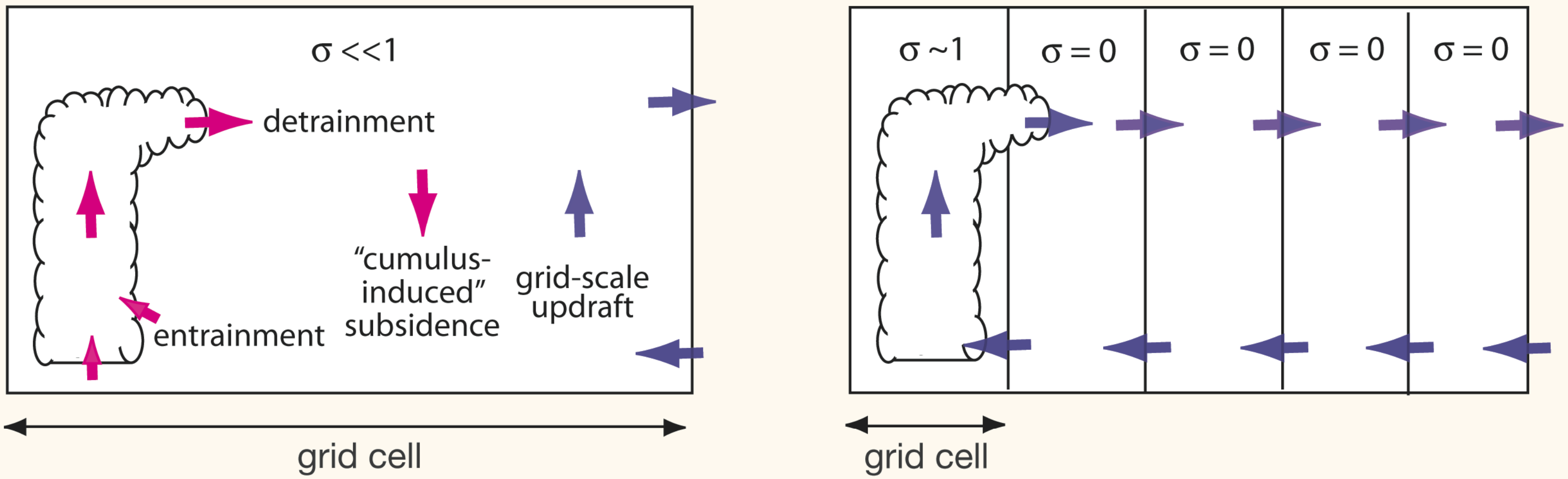
Two possible routes to achieve the unification:



ROUTE I: UNIFICATION THROUGH A UNIFIED PARAMETERIZATION

σ : the fractional area covered by *all convective clouds in a grid cell.*

- Most parameterization schemes assume σ << 1 *a priori*, either explicitly or implicitly.
- Then the temperature and water vapor to be predicted are essentially those.variables for the cloud environment.



- But, if cloud occupies the entire cell, there is no "environment" within the cell.

A key to open Route I is eliminating the assumption of σ << 1 .

CRM SIMULATIONS USED FOR ANALYSIS

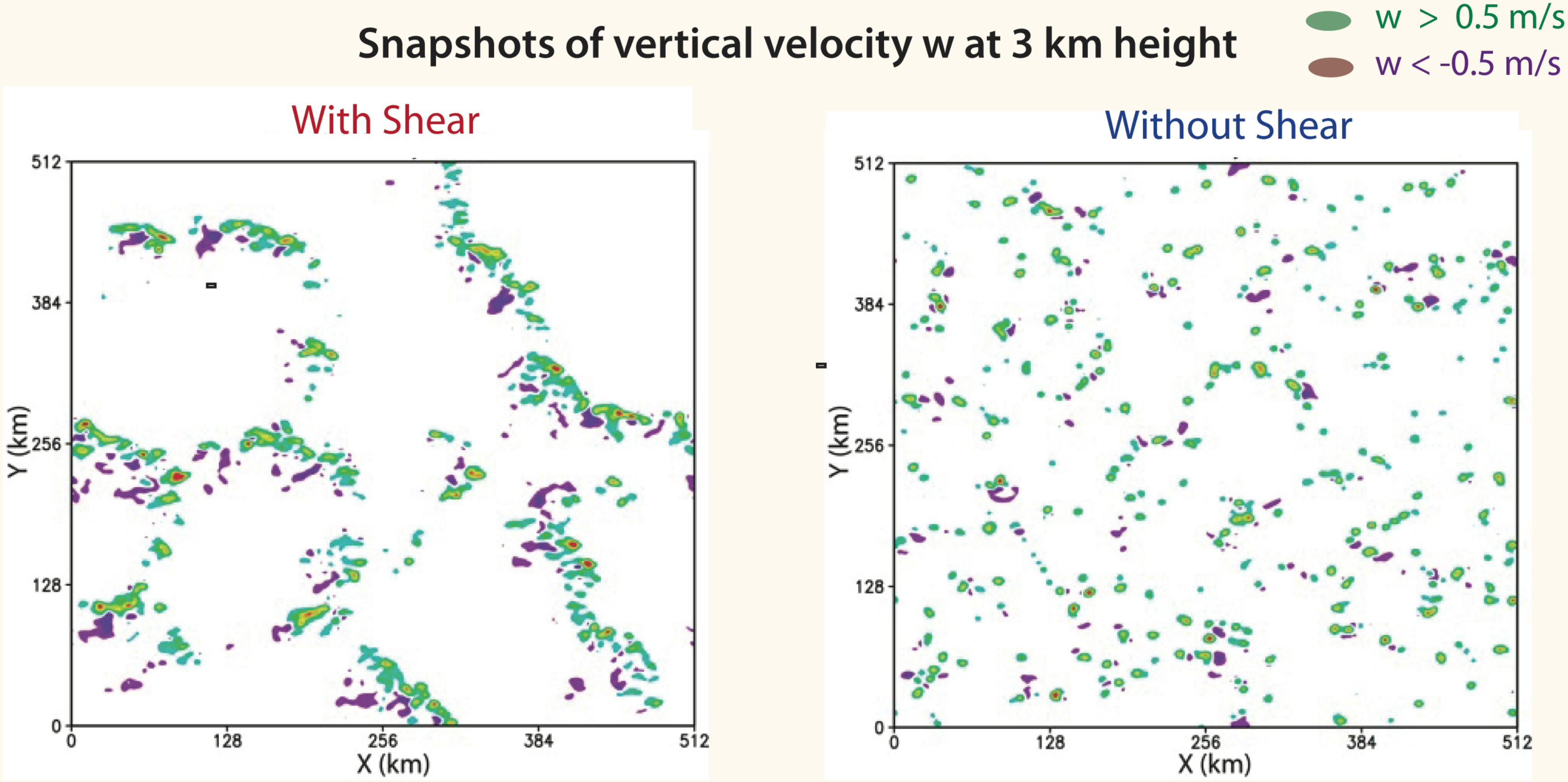
To visualize the problem raised above, we have analyzed datasets simulated by a CRM

Model : 3D vorticity equation model of Jung and Arakawa (2008)

Horizontal domain size : 512 km Horizontal grid size : 2km

Data used : last 2 hrs of two 24-hr simulations with 20-min intervals

Snapshots of vertical velocity w at 3 km height



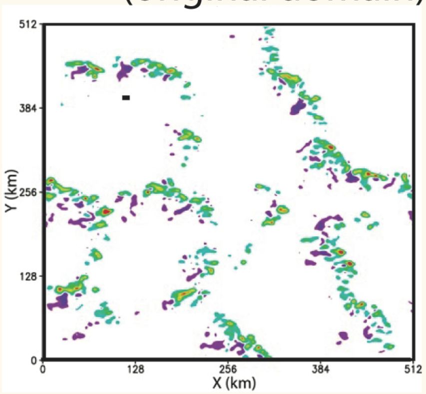
ANALYSIS OF GRID-SIZE DEPENDENT STATISTICS OF THE CRM DATA

The original domain is divided into sub-domains with the same size.

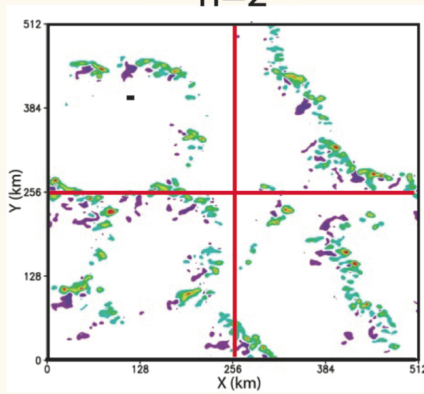
Size of sub-domains : (512 km) $/2^{n-1}$, n=1, 2, 3, 4, . . . , 9

Examples

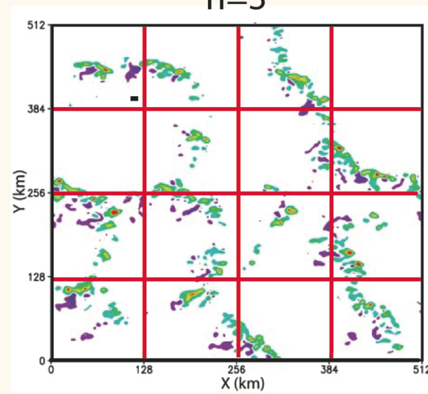
n=1 (original domain)



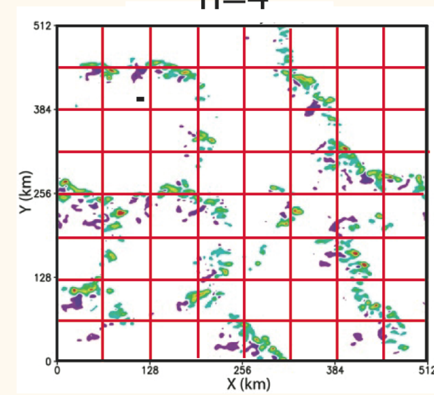
n=2



n=3



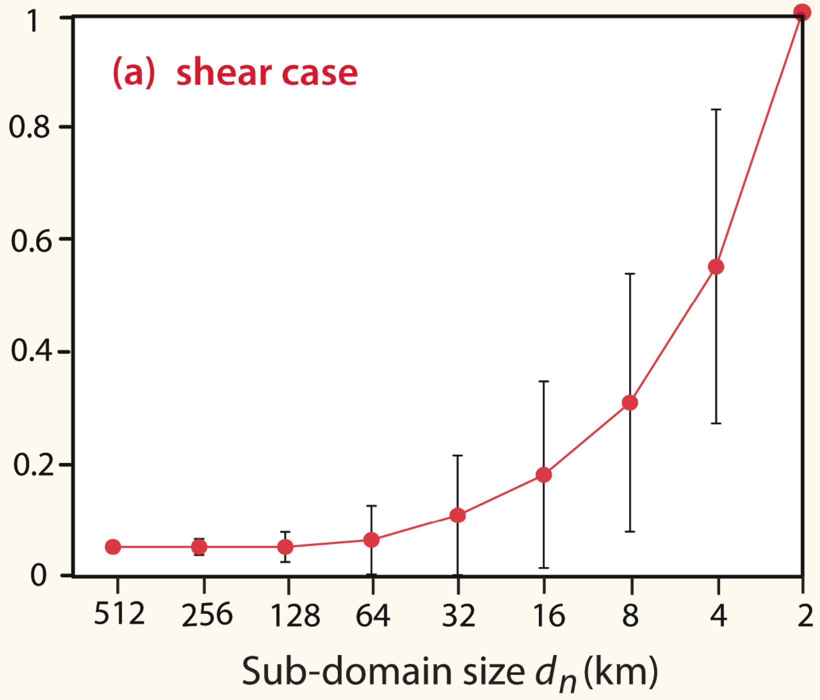
n=4

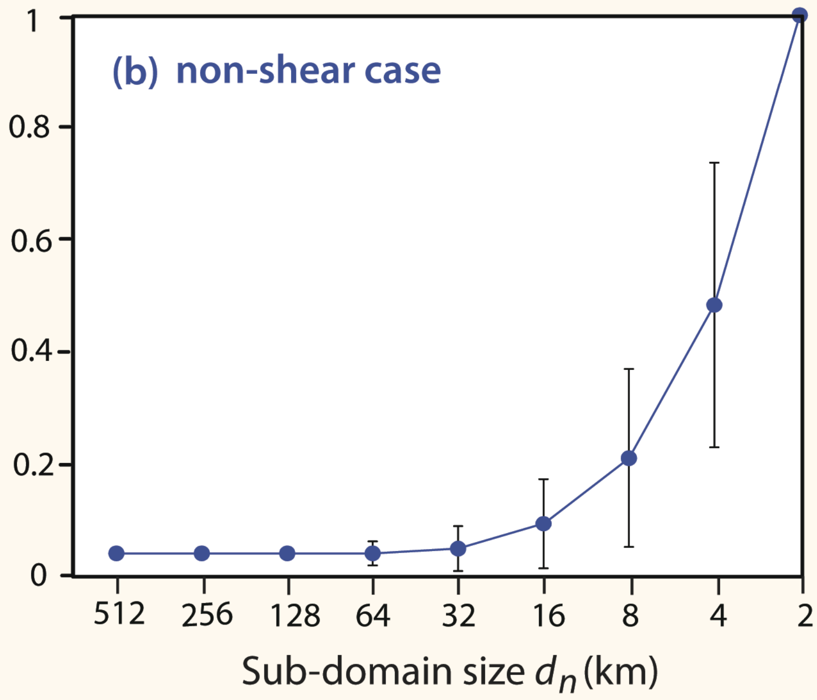


FRACTIONAL CLOUD COVER, σ

Measured by the normalized number of grid points that satisfy w>0.5 m/s.

Ensemble average at 3 km height *excluding* σ = 0 sub-domains



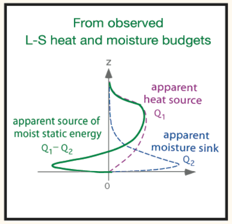


σ<<1 is a good approximation ONLY for large grid sizes.

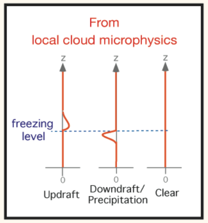
THE GOAL OF THE UNIFIED CUMULUS PARAMETRIZATION

Recall that the vertical eddy transport is responsible for the difference

between the GCM-type



and CRM-type



profiles.

THE GOAL

To formulate the vertical eddy transport

in a way that is applicable to any value of σ including $\sigma = 1$.

BASIC ASSUMPTIONS AND GRID-CELL AVERAGES

$\overline{(\ )}$: average over the entire grid cell

$(\ )_c$: cloud value $\widetilde{(\ )}$: environment value (not well defined when $\sigma \sim 1$)

We take water vapor mixing ratio q as an example.

- Assume that q_c and $\tilde{q}$ are horizontally uniform individually.
- At this stage, we neglect the effect of convective-scale downdraft.

$$\bar{q} = \sigma q_c + (1-\sigma)\tilde{q}$$

$$\bar{w} = \sigma w_c + (1-\sigma)\tilde{w}$$

$$\overline{wq} = \sigma w_c q_c + (1-\sigma)\tilde{w}\tilde{q}$$

Vertical eddy transport of q : $\overline{wq} - \bar{w}\bar{q} = \dfrac{\sigma}{1-\sigma}\left(w_c - \bar{w}\right)\left(q_c - \bar{q}\right)$

REQUIREMENT FOR CONVERGENCE

We have derived

$$\overline{wq} - \overline{w}\,\overline{q} = \frac{\sigma}{1-\sigma}\left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right)$$

Eddy transport by plumes

$$\left(\overline{wq} - \overline{w}\,\overline{q}\right)_P \equiv \frac{\sigma}{1-\sigma}\left(w_c^* - \overline{w}\right)\left(q_c^* - \overline{q}\right)$$

w_c^* , q_c^* : w_c , q_c determined by a cloud model such as a plume model

Obviously this cannot be applied to situations with large σ.

Convergence requirement :

$$\lim_{\sigma\to 1} w_c = \overline{w} \qquad \lim_{\sigma\to 1} q_c = \overline{q}$$

This indicates that $\left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right)$ is the order of $(1-\sigma)^2$ (or higher).

The simplest choice : $\left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right) = (1-\sigma)^2\left(w_c^* - \overline{w}\right)\left(q_c^* - \overline{q}\right)$

Then,

$$\overline{wq} - \overline{w}\,\overline{q} = (1-\sigma)^2\left(\overline{wq} - \overline{w}\,\overline{q}\right)_P$$

INTERIM EVALUATION OF THE UNIFIED PARAMETERIZATION

Evaluation of the formal structure of the unified parameterization

We have derived
$$\overline{wq} - \overline{w}\,\overline{q} = \frac{\sigma}{1-\sigma}\left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right) \quad (1)$$

and made the choice :
$$\left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right) = (1-\sigma)^2\left(w_c^* - \overline{w}\right)\left(q_c^* - \overline{q}\right) \quad (2)$$

Then
$$\overline{wq} - \overline{w}\,\overline{q} = \sigma(1-\sigma)\left(w_c^* - \overline{w}\right)\left(q_c^* - \overline{q}\right) \quad (3)$$

We define "weighted ensemble mean" <X> by the weighted mean of X over all sub-domains of the same size with the weight σ.

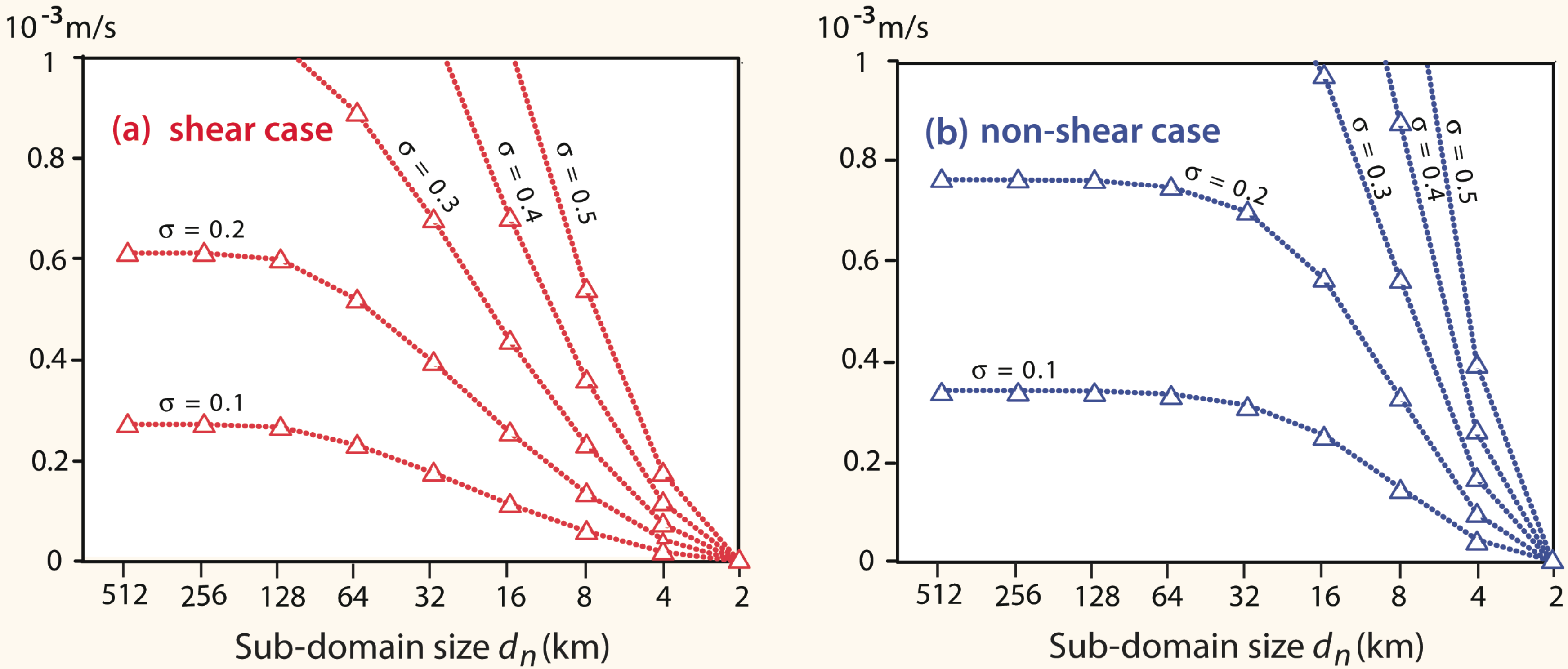
From <(1)>, <(2)> and <(3)>,

$$\left\langle \overline{wq} - \overline{w}\,\overline{q} \right\rangle = \frac{\left\langle \sigma(1-\sigma) \right\rangle}{\left\langle (1-\sigma)^2 \right\rangle}\left\langle \left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right) \right\rangle$$

Eddy Transport of Water Vapor Estimated with a Prescribed Constant σ

$$\left\langle \overline{wq} - \bar{w}\,\bar{q} \right\rangle = \frac{\left\langle \sigma(1-\sigma) \right\rangle}{\left\langle (1-\sigma)^2 \right\rangle} \left\langle \left(w_c - \bar{w}\right)\left(q_c - \bar{q}\right) \right\rangle$$

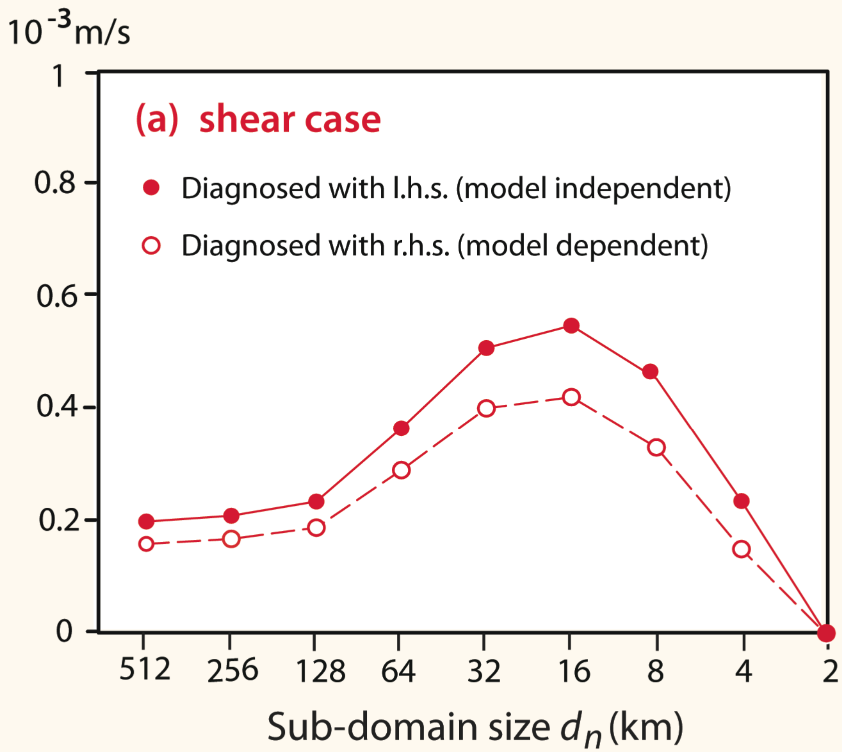
——— : Prescribed ——— : diagnosed from the dataset

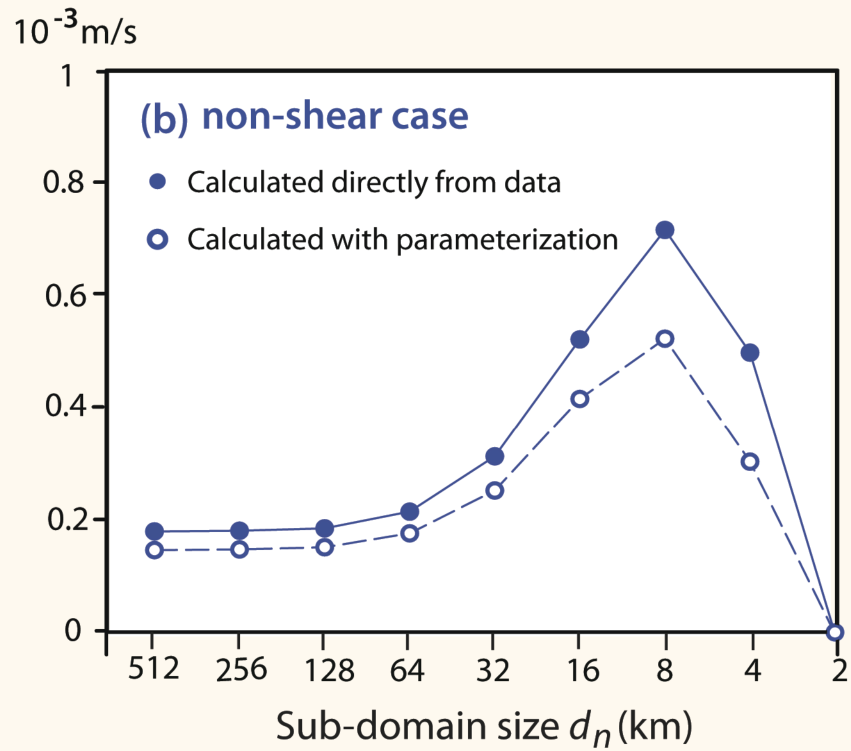


Estimated Eddy Transport of Water Vapor

$$\left\langle \overline{wq} - \overline{w}\,\overline{q} \right\rangle = \frac{\left\langle \sigma\left(1-\sigma\right)\right\rangle}{\left\langle \left(1-\sigma\right)^2 \right\rangle} \left\langle \left(w_c - \overline{w}\right)\left(q_c - \overline{q}\right)\right\rangle$$

——— : diagnosed from the dataset





DETERMINATION OF σ (TENTATIVE)

We have defined

$$\left(\overline{wq} - \overline{w}\,\overline{q}\right)_P \equiv \frac{\sigma}{1-\sigma}\left(w_c^* - \overline{w}\right)\left(q_c^* - \overline{q}\right)$$

w_c^* , q_c^* : w_c , q_c determined by a cloud model such as a plume model

Assume that the closure of conventional parameterization gives $\left(\overline{wq} - \overline{w}\,\overline{q}\right)_P$.

Then the l.h.s. is known so that

$$\sigma = \frac{\left(\overline{wq} - \overline{w}\,\overline{q}\right)_P}{\left(\overline{wq} - \overline{w}\,\overline{q}\right)_P + \left(w_c^* - \overline{w}\right)\left(q_c^* - \overline{q}\right)}$$

$$\sigma \to 0 \;\text{ as }\; \left(\overline{wq} - \overline{w}\,\overline{q}\right)_P \to 0 \qquad \sigma \to 1 \;\text{ as }\; \left(\overline{wq} - \overline{w}\,\overline{q}\right)_P \to \infty$$

This approach is in parallel to the reasoning used by Emanuel (1991)

in the sense that it combines the following two information :

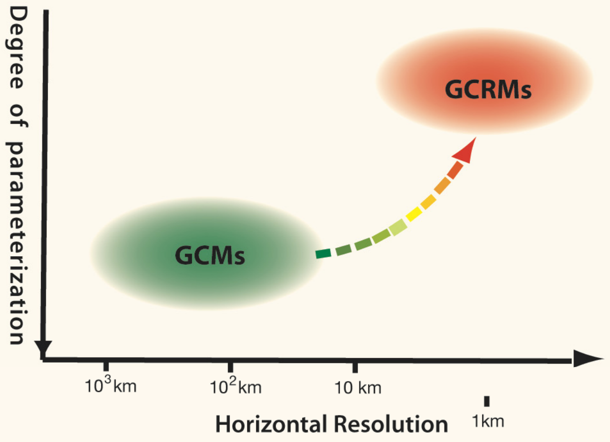
- Vertical profiles of cloud properties determined by a plume model
- *Total* vertical transport necessary for adjustment to a quasi-equilibrium

ANTICIPATED IMPACT OF THE UNIFIED PARAMETERIZATION

- If the GCM and CRM share the same dynamics core, a relatively minor modification of the existing parameterization schemes can drastically broaden their applicability.

- The error (measured by the difference from the CRM solution) can be made arbitrarily small by using a higher resolution.

- Thus multi-scale numerical methods, such as multiply-nested grids and adaptive mesh refinement, can be used with no problem of model physics.



- Having a good plume model is, however, a key to the success of the unified parameterization.

When successfully implemented,

practical merits of the unified parameterization will be great.

But after all ROUTE I has its own limit as a "parameterization".

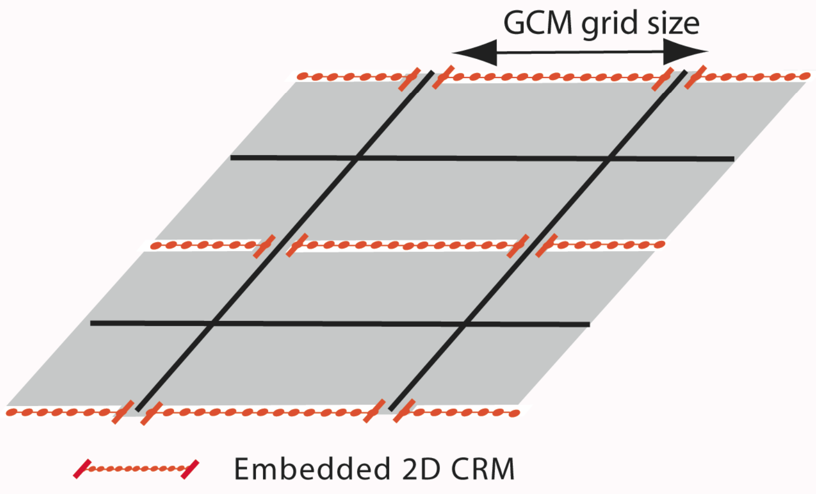
ROUTE II :

UNIFICATION THROUGH MULTI-SCALE MODELING FRAMEWORK (MMF)

- MMF recognizes that we currently have only two kinds of model physics.
- Correspondingly, MMF uses two grid systems, one for the GCM and the other for the CRM.
- The two systems are statistically coupled.
- Efficiency is gained by sacrificing full representations of cloud-scale 3D processes.

Prototype MMF ("Super-Parameterization")

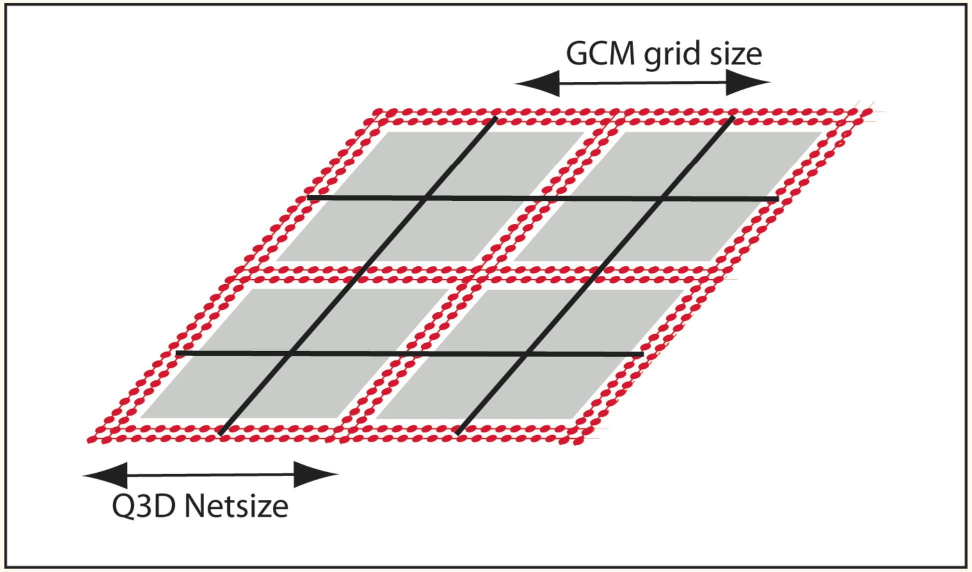
Grabowski 2001, Khairoutdinov and Randall 2001



This does not converge to a GCRM as the GCM grid size is refined.

Q3D MMF (SECOND-GENERATION MMF)

Jung and Arakawa (2010): Accepted by journalof AdvancedModeling of the Earth System (*JAMES)*



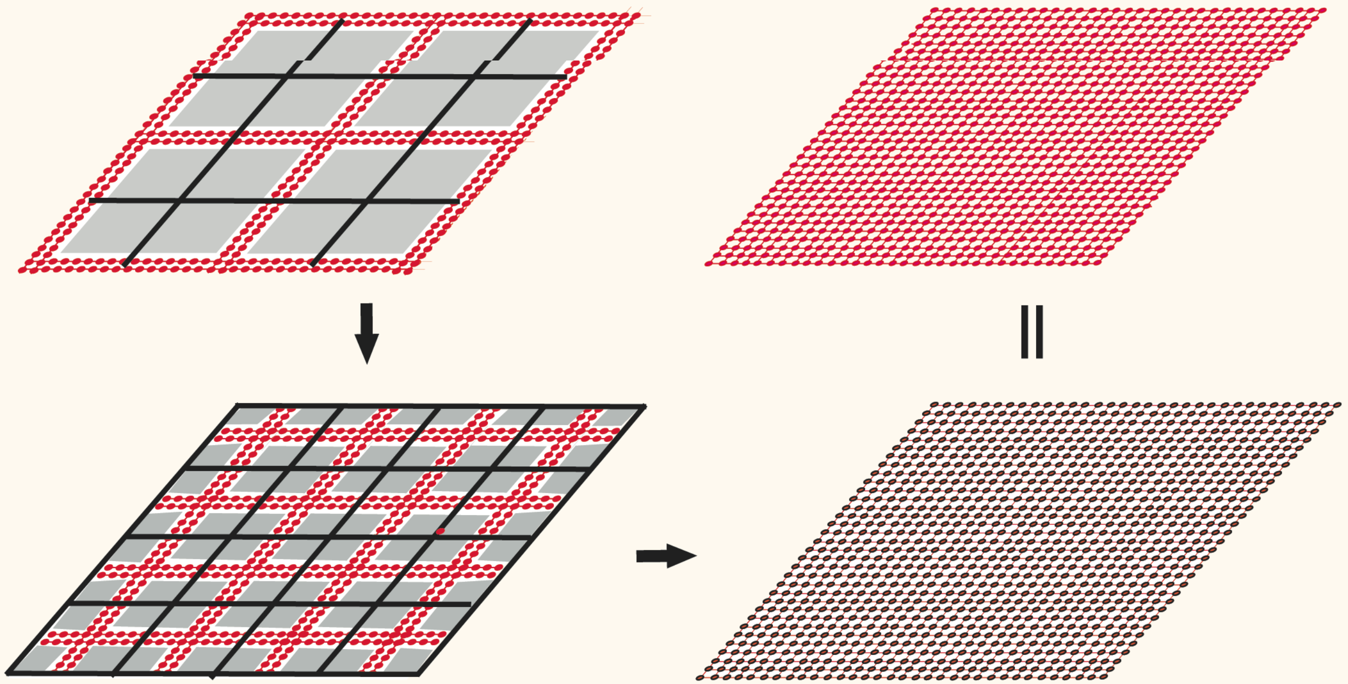
- The Q3D-CRM uses a gappy domain consisting of two perpendicular sets of channels.
- For efficiency, the width of channels is chosen to be narrow, barely enough to cover a typical cloud size.
- Thus, a channel contains only a few grid-point arrays. (In the above example, there are only two arrays.)

LATERAL BOUNDARY CONDITION AND CONVERGENCE

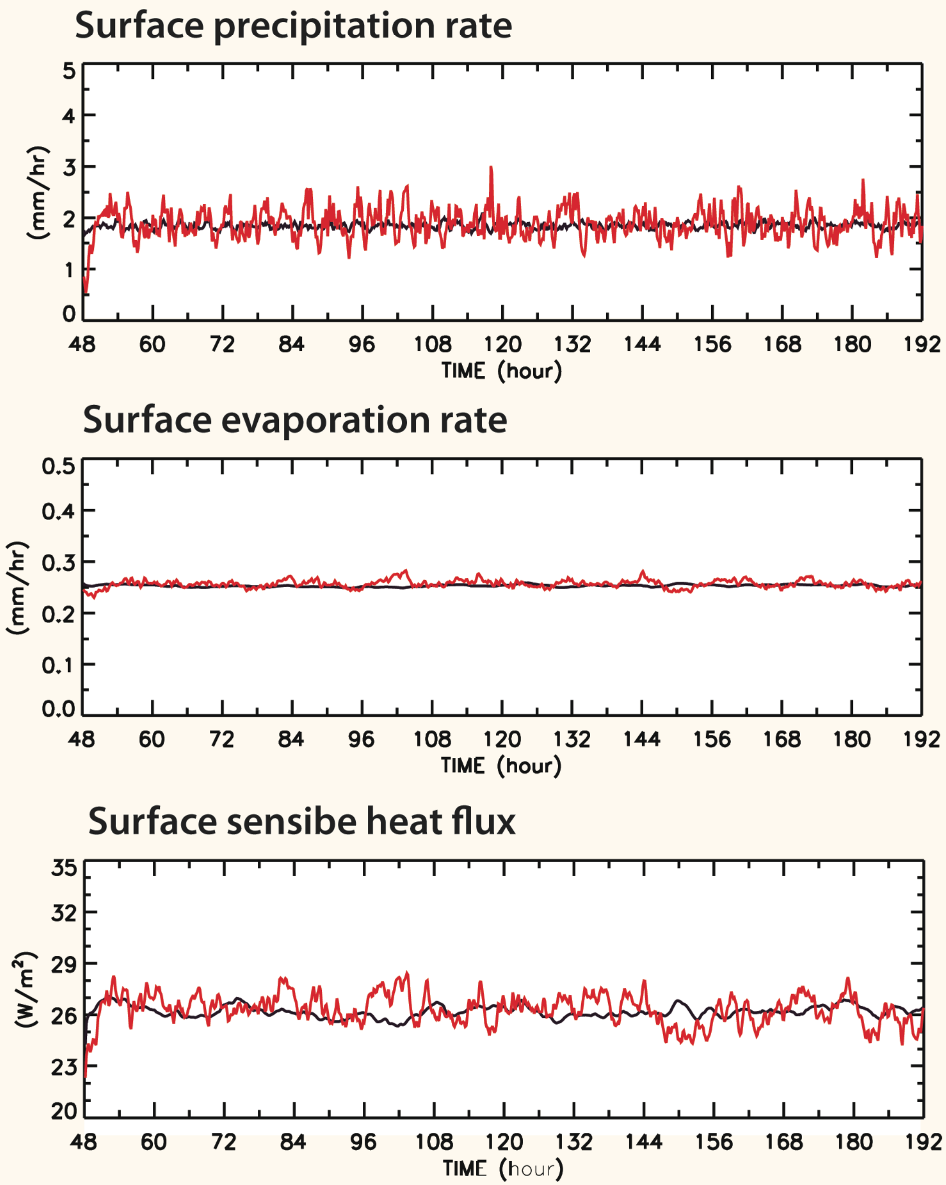
We let

- deviations from interpolated GCM values be periodic across the channel.
- the deviations vanish as the GCM grid size approaches the CRM grid size.

CONVERGENCE



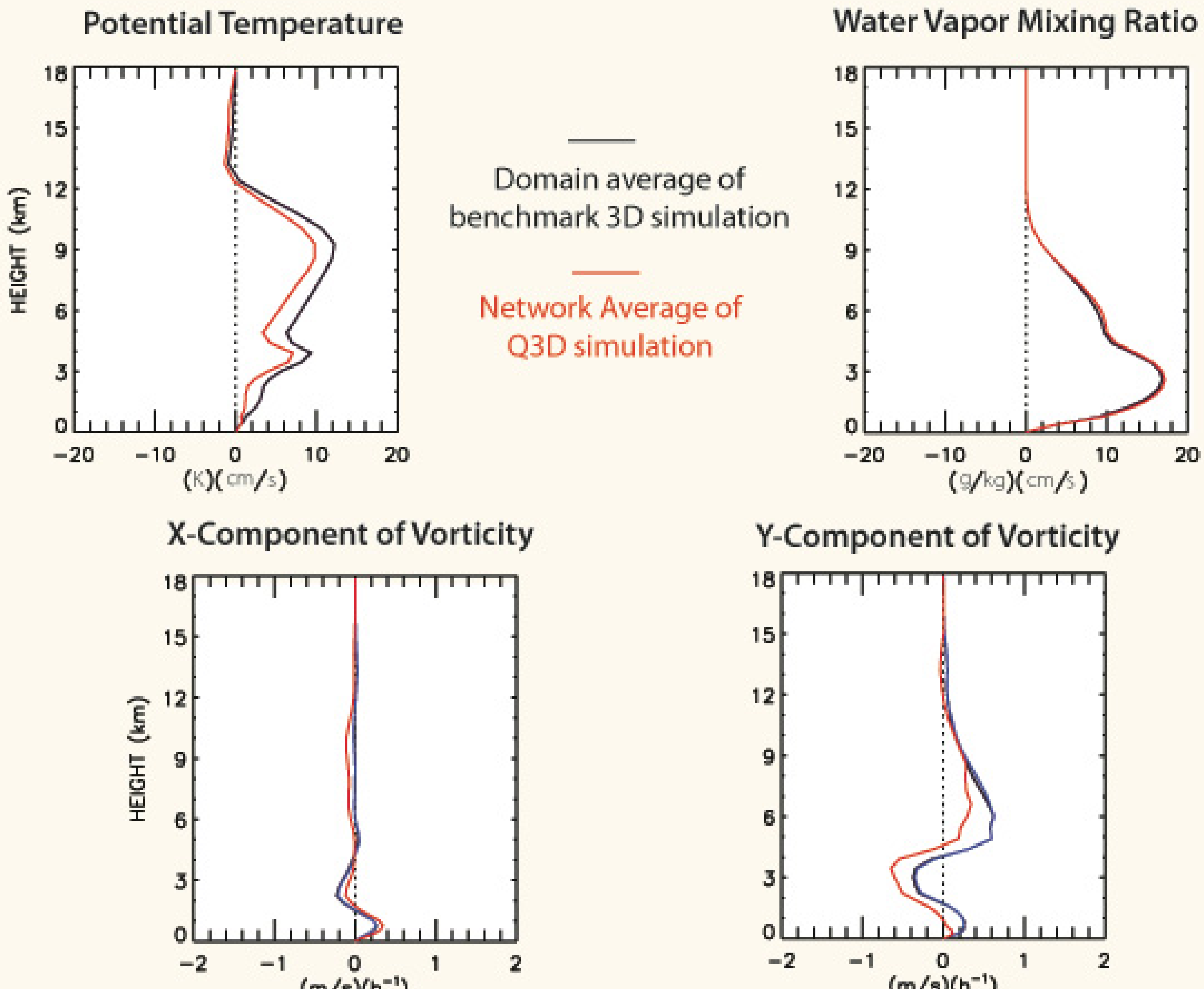
TIME SECTIONS OF SURFACE PRECIPITATION AND SURFACE FLUXES



Domain average of benchmark 3D simulation

Network Average of Q3D simulation

EXAMPLES OF TIME-AVERAGED VERTICAL RANSPORTS



SUMMARY AND CONCLUSION

- GCMs and GCRMs should be unified so that we can freely choose a resolution without changing formulation of model physics.

- We have discussed two possible routes for unification: ROUTE I and ROUTE II.

- ROUTE I is relatively simple and does not requirie much more computing resources beyond the conventional models.

- Although it is much more expensive, ROUTE II has great potential for more accurate NWP and climate simulations since various physical processes are coupled at cloud scale.