TOWARD UNIFICATION OF GENERAL CIRCULATION AND CLOUD-RESOLVING MODELS

Akio Arakawa

Department of Atmospheric and Oceanic Sciences
University of California, Los Angels, California

1. Introduction
2. Route I: Unification through a generalized parameterization
3. Route II: Unification through a multi-scale modeling framework
4. Summary and conclusion

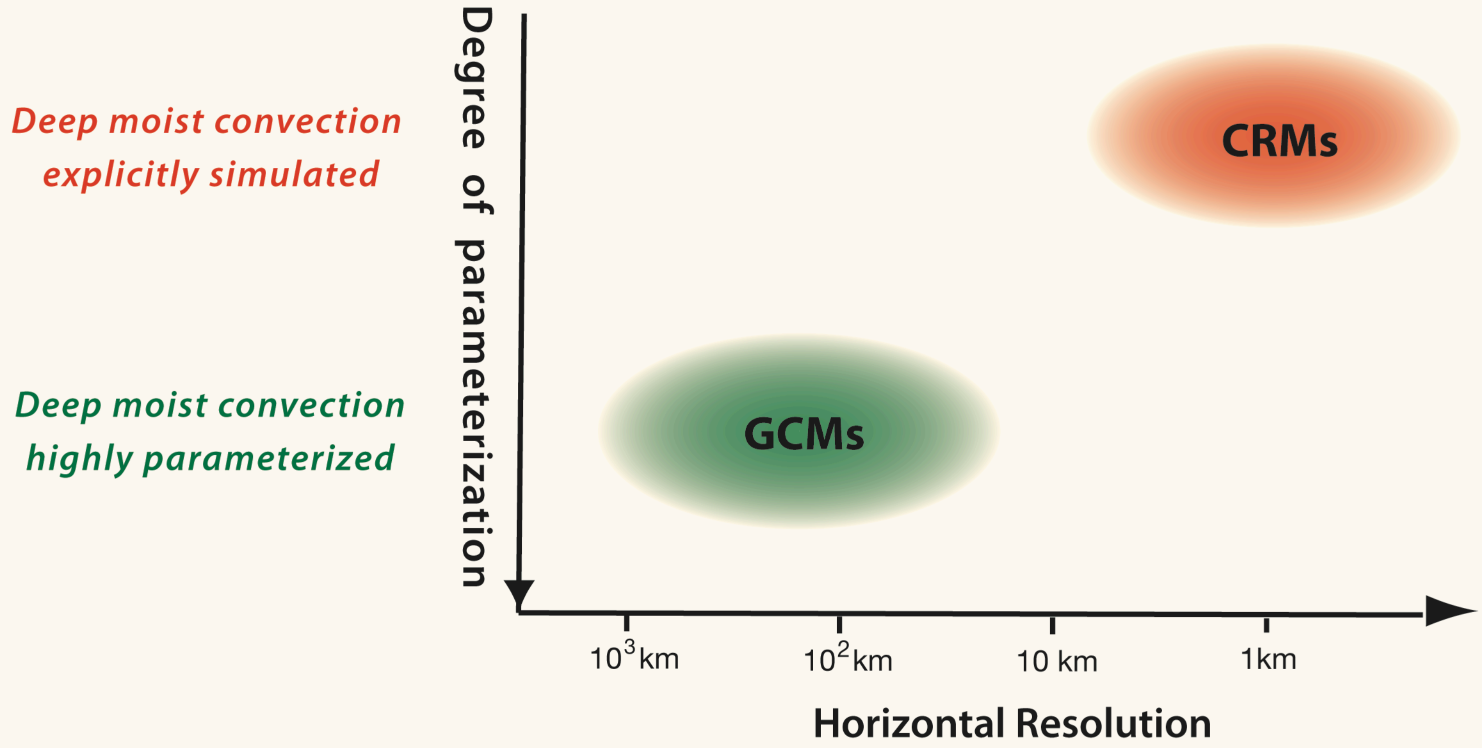
1. INTRODUCTION

"Despite the best efforts of our community, . . . the problem (of cloud modeling) remains largely unsolved . . . The need for more realistic simulations of the role of clouds in climate is so urgent, so critical, that we must pursue all available routes to progress" – Randall *et al.* (2003).

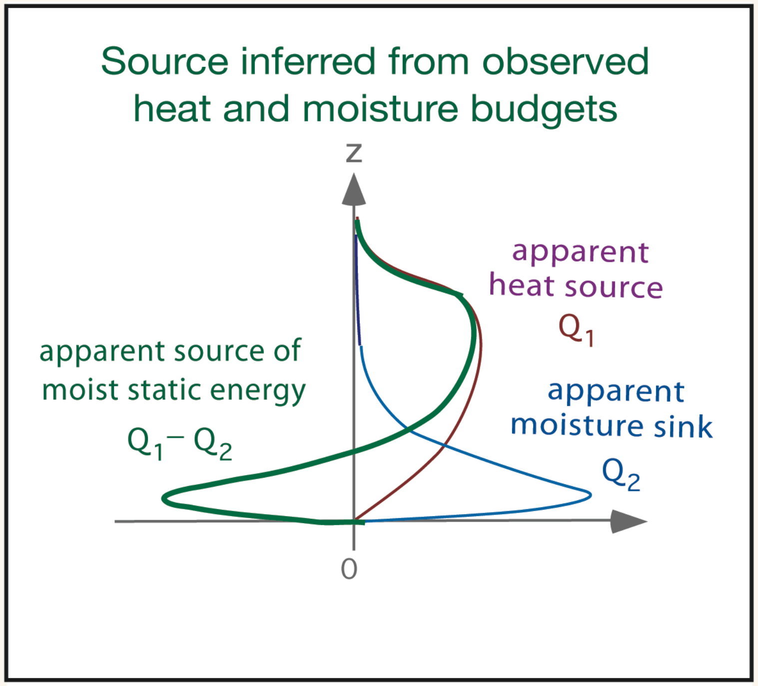
As far as representation of deep moist convection is concerned,
we only have two kinds of model physics:
highly parameterized and explicitly simulated.

TWO FAMILIES OF ATMOSPHERIC MODELS

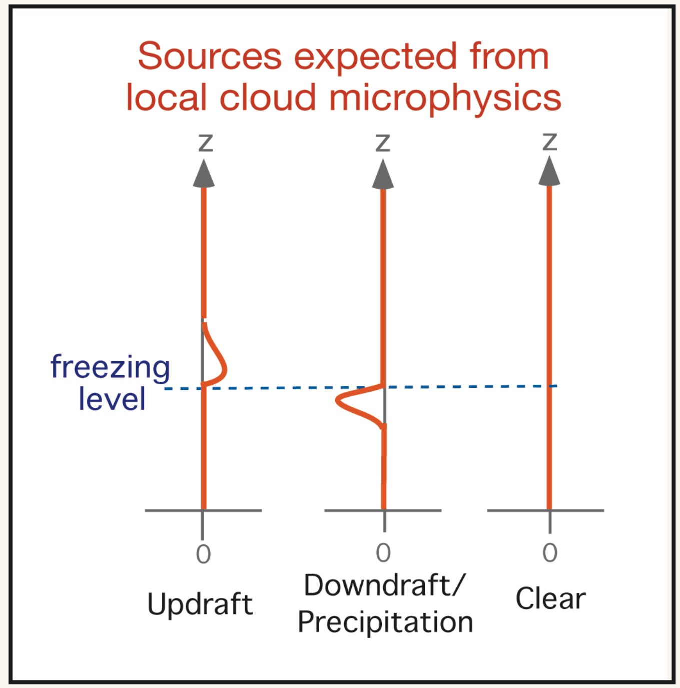
(besides LES and higher-resolution models)



TYPICAL VERTICAL PROFILES OF MOIST STATIC ENERGY SOURCE DUE TO DEEP CONVECTION



GCM-TYPE PROFILE

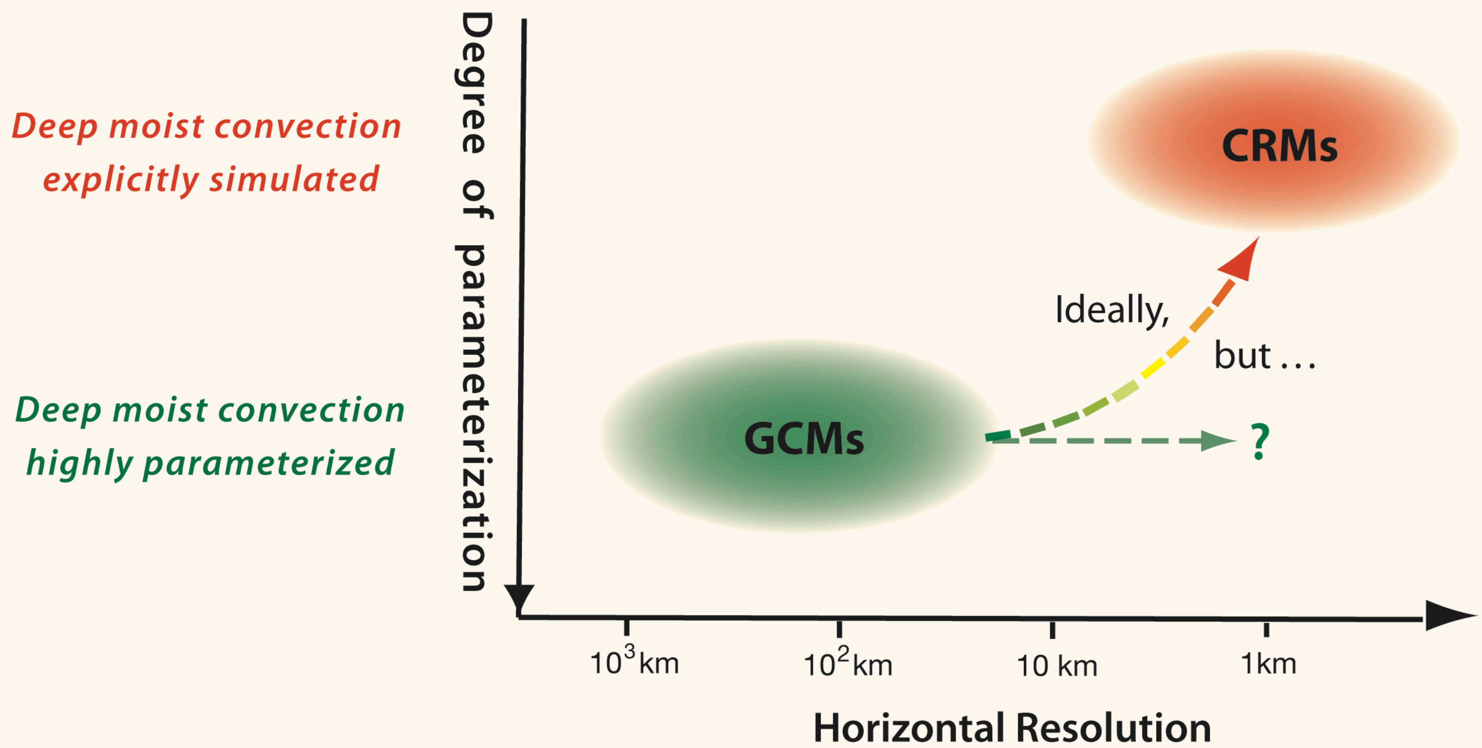


CRM-TYPE PROFILES

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

TWO FAMILIES OF ATMOSPHERIC MODELS

(besides LES and higher-resolution models)

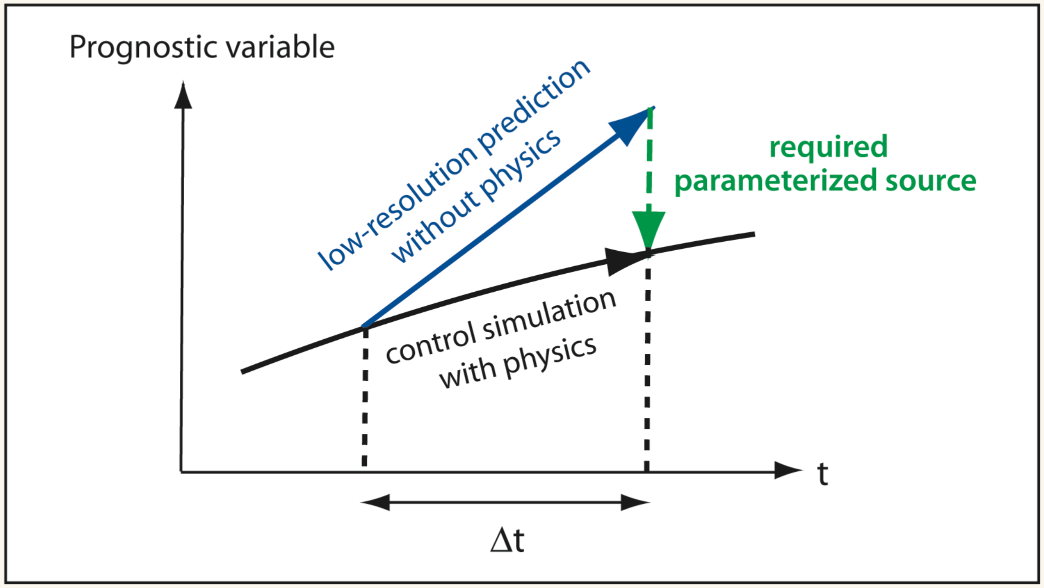


We cannot freely choose intermediate or highly heterogeneous resolutions.

The Resolution Dependence of Model Physics: Illustration from Nonhydrostatic Model Experiments

Jung and Arakawa, 2004, *JAS*

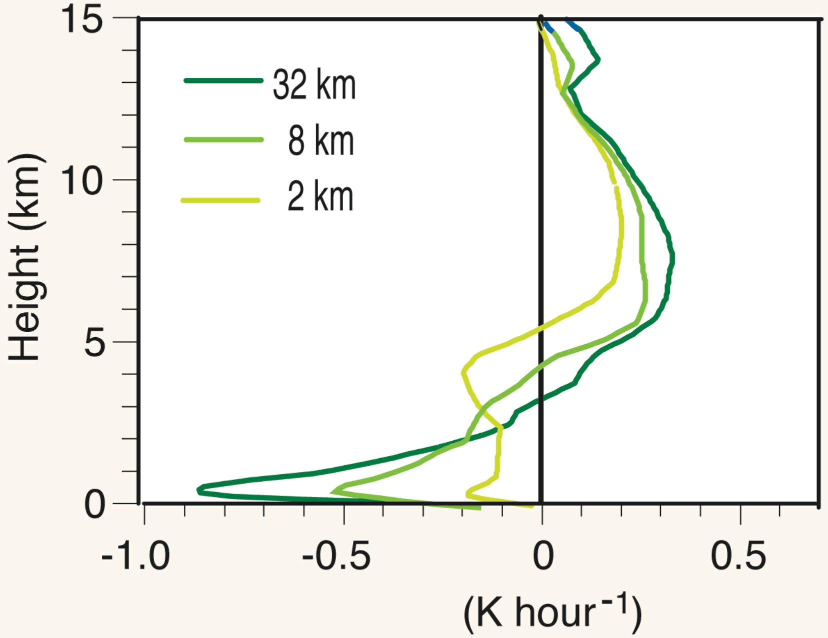
Budget analysis of CRM-simulated data with and without (a component of) model physics applied to various space/time intervals



Domain/Ensemble Average Profiles of

"*REQUIRED*" Source for Moist Static Energy due to Cloud Microphysics

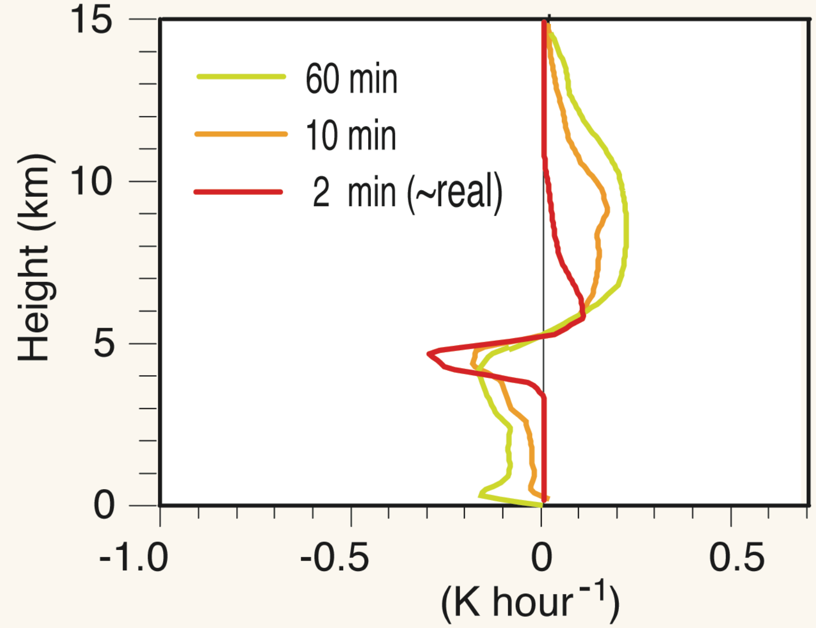
Horizontal resolution dependence
with 60 min physics time interval



GCM-type profile

Primarily due to eddy transport of water vapor

Physics time interval dependence
with 2 km horizontal resolution



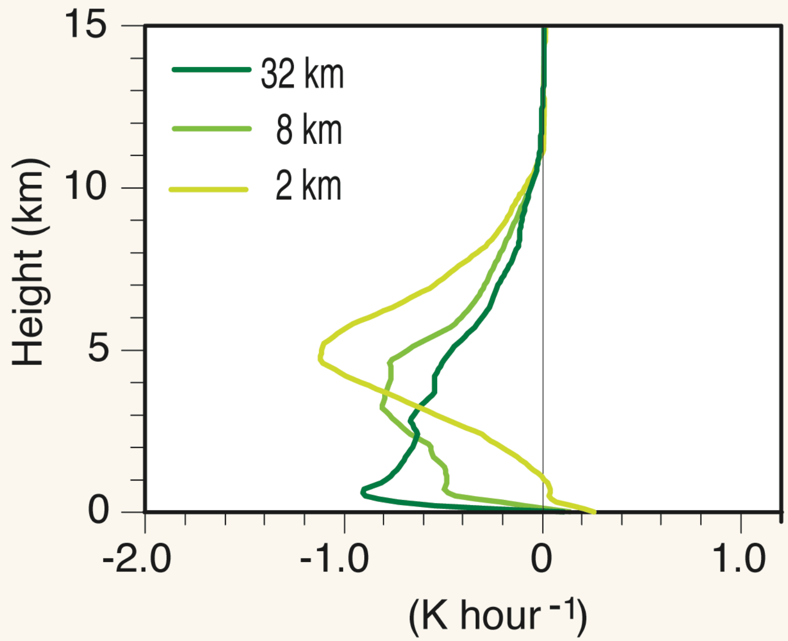
CRM-type profile

Primarily due to delayed freezing/melting

Domain/Ensemble Average Profiles of

"*REQUIRED*" Source for Total Water due to Cloud Microphysics

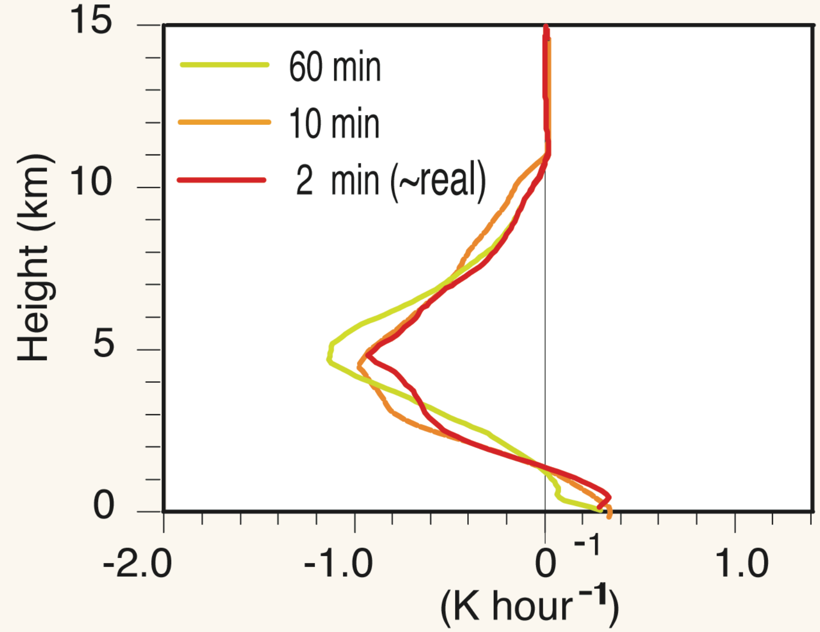
Horizontal resolution dependence
with 60 min physics time interval



GCM-type profile

Primarily due to eddy transport of water vapor

Physics time interval dependence
with 2 km horizontal resolution



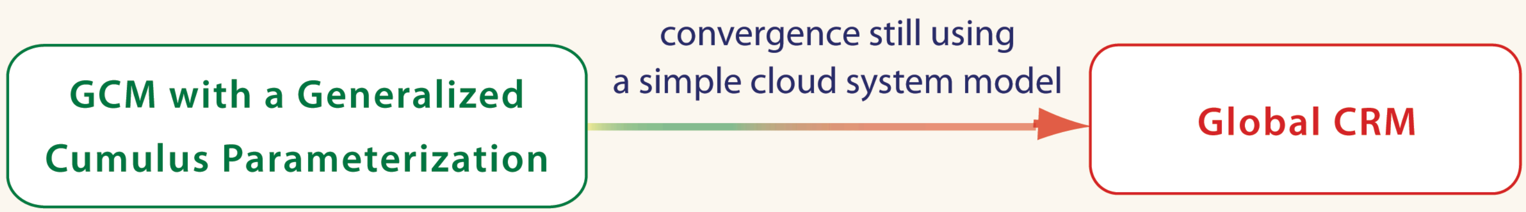
CRM-type profile

UNIFICATION OF GCM AND CRM

- The two models must share the same dynamics core.
- GCM physics must converge to CRM physics as the resolution is refined.

Two Possible Routes to Achieve the Convergence :

ROUTE I



ROUTE II

2. ROUTE I :

UNIFICATION THROUGH A GENERALIZED PARAMETERIZATION

*"Consider a horizontal area - **large enough** to contain an ensemble of cumulus clouds but **small enough** to cover a fraction of a large-scale disturbance."*

– Arakawa & Schubert (1974)

In reality, grid boxes are

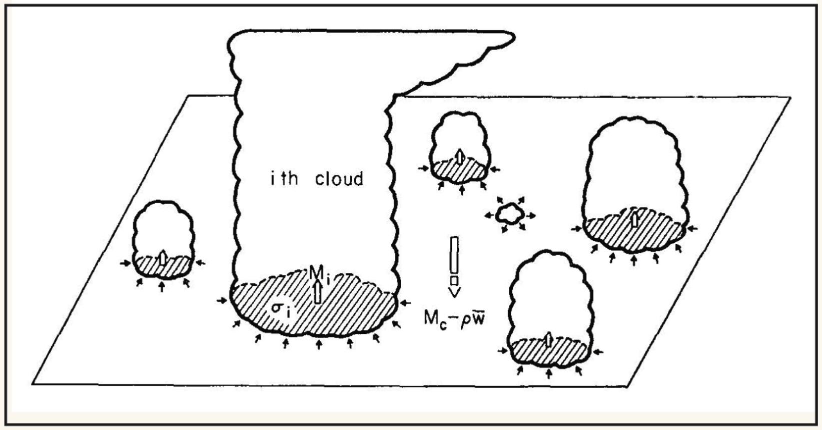
NOT small enough

⇒ Should consider mesoscale organization of clouds

NOT large enough

⇒ Should include a stochastic component,

Should converge to a CRM, as discussed

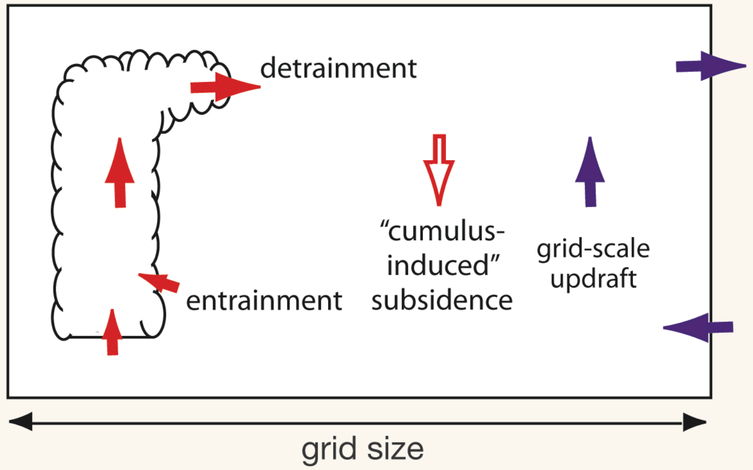


ASSUMPTION OF SMALL FRACTIONAL CLOUDINESS

As in RAS (Moorthi and Suarez 1992), consider one sub-ensemble at a time, each of which consists of clouds that are alike.

- AS further assumes $\sigma << 1$, where σ is the fractional area covered by *all* clouds in the grid cell.

- AS then showed that prediction of grid-scale mean is essentially prediction of the cloud environment.



A key to open this route is eliminating this assumption.

VERTICAL EDDY TRANSPORT DUE TO CUMULUS-INDUCED CIRCULATION

For a variable Ψ that is horizontally uniform both inside and outside of clouds, the eddy transport is approximately given by

$$\rho\left(\overline{w\Psi} - \overline{w}\,\overline{\Psi}\right) = M_c\left(\Psi_c - \overline{\Psi}\right).$$

$\overline{\Psi}$: Grid-scale value predicted by the GCM

Ψ_c : Cloud value predicted or diagnosed by an embedded plume model

M_c : Total cumulus mass flux $\rho\sigma w_c$

For the eddy transport to vanish as $\sigma \to 1$, $\overline{\Psi} \to \Psi_c$ must be satisfied.

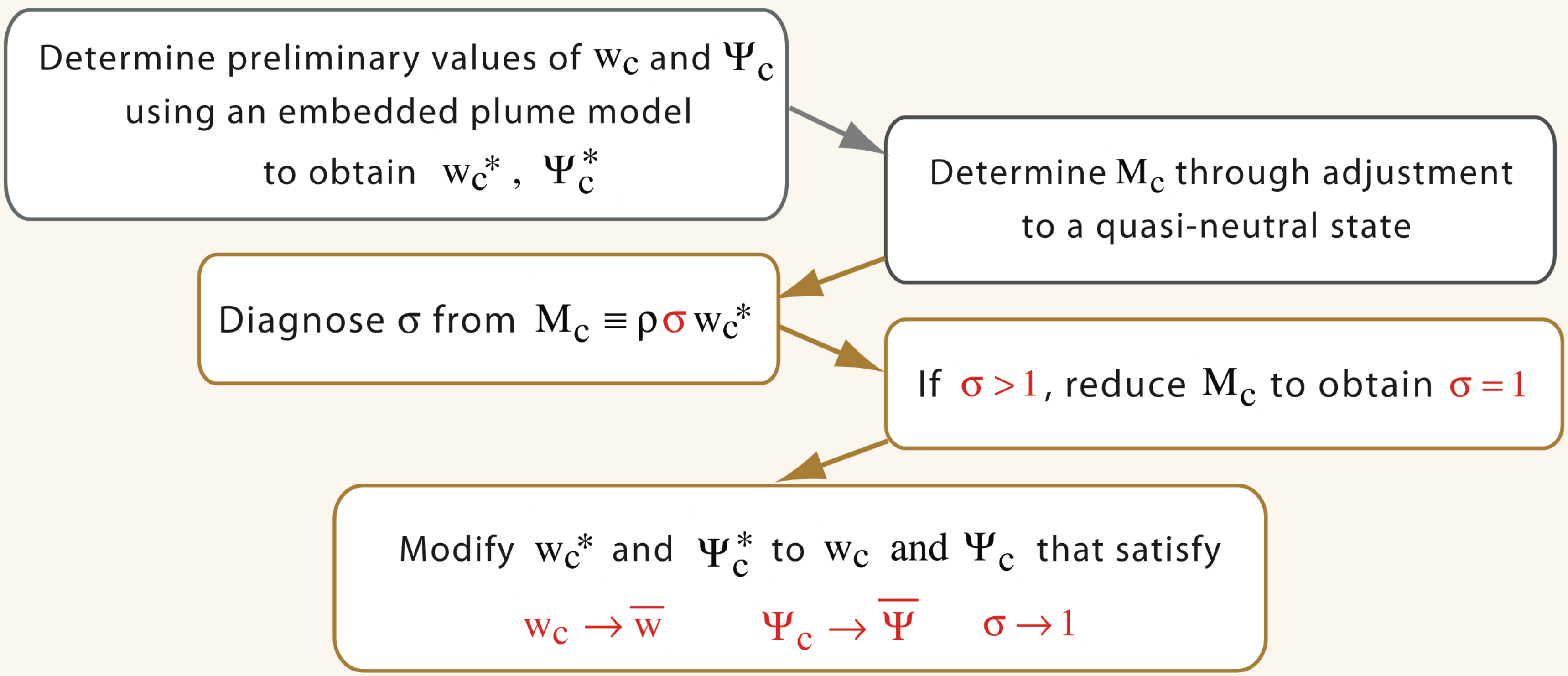
↑

quite different from
what the conventional parameterizations do

A ROADMAP FOR ELIMINATING THE ASSUMPTION $\sigma \ll 1$

$$\rho\left(\overline{w\Psi} - \overline{w}\,\overline{\Psi}\right) = M_c\left(\Psi_c - \overline{\Psi}\right)$$

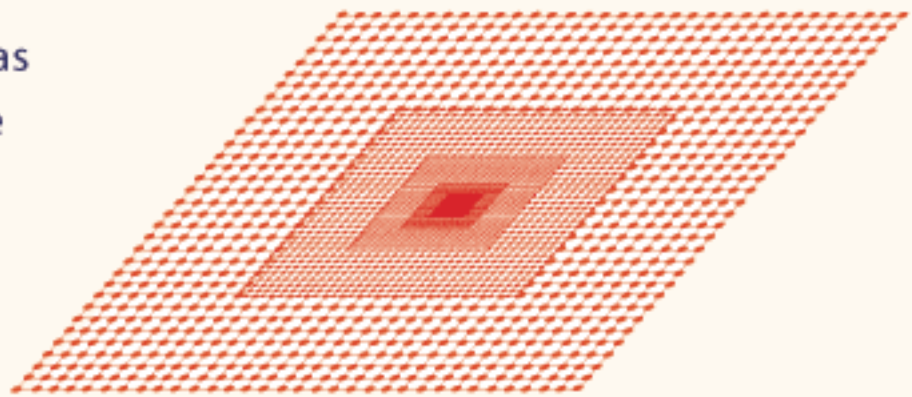
implicit dependence on σ



An ad hoc choice: $w_c = (1-\sigma)w_c^* + \sigma\overline{w}$, $\Psi_c = (1-\sigma)\Psi_c^* + \sigma\overline{\Psi}$

MERITS OF THE GENERALIZED PARAMETERIZATION

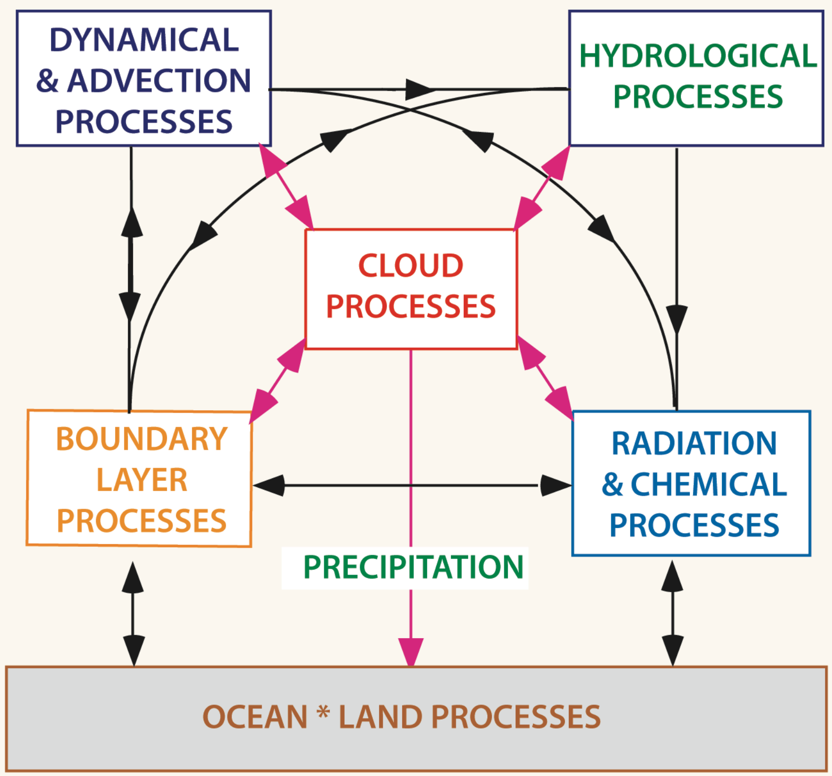
- A relatively minor modification of the existing parameterization schemes can drastically broaden their applicability.
- The error (measured by the difference from the CRM solution) can be made arbitrarily small by using a higher resolution without changing formulation of model physics.
- Multi-scale numerical methods, such as the multiply-nested grid and adaptive mesh refinement (AMR) methods, can be used with no problem of model physics.



While its practical merits are great, however, this route has its own limit as a "parameterization".

In particular,

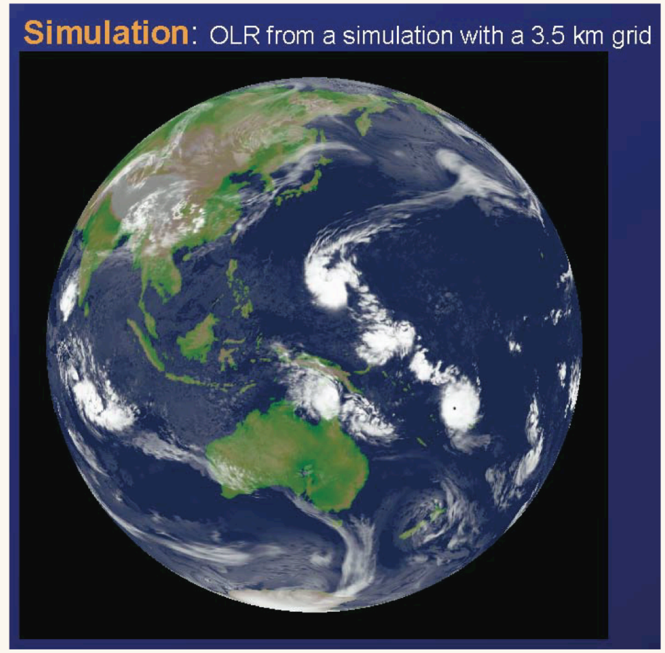
Realistically parameterizing all of these cloud-scale interactions is overwhelmingly complicated.



GLOBAL CLOUD-RESOLVING MODEL

With the recent development of computer technology, it is becoming feasible to simulate the global climate using a CRM (e.g., Sato et al. 2009).

There is no doubt that we should pursue this approach.



However, we cannot exclusively depend on this approach for all kinds of climate studies, which require longer or a number of runs with different focuses, different initial conditions and/or different external and internal conditions.

3. ROUTE II :

UNIFICATION THROUGH

MULTI-SCALE MODELING FRAMEWORK (MMF)

("Super-Parameterization")

A GCM in which cloud parameterization is replaced by

the statistical effects of cloud and associated processes

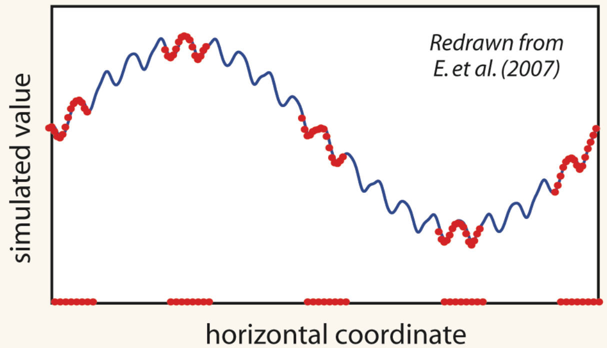
explicitly simulated by a CRM that is not neceessarily fully three-dimensional.

COMPARISON OF MMF AND HMM

The philosphy of MMF is similar to that of Heterogeneous Multiscale Modeling (HMM) :

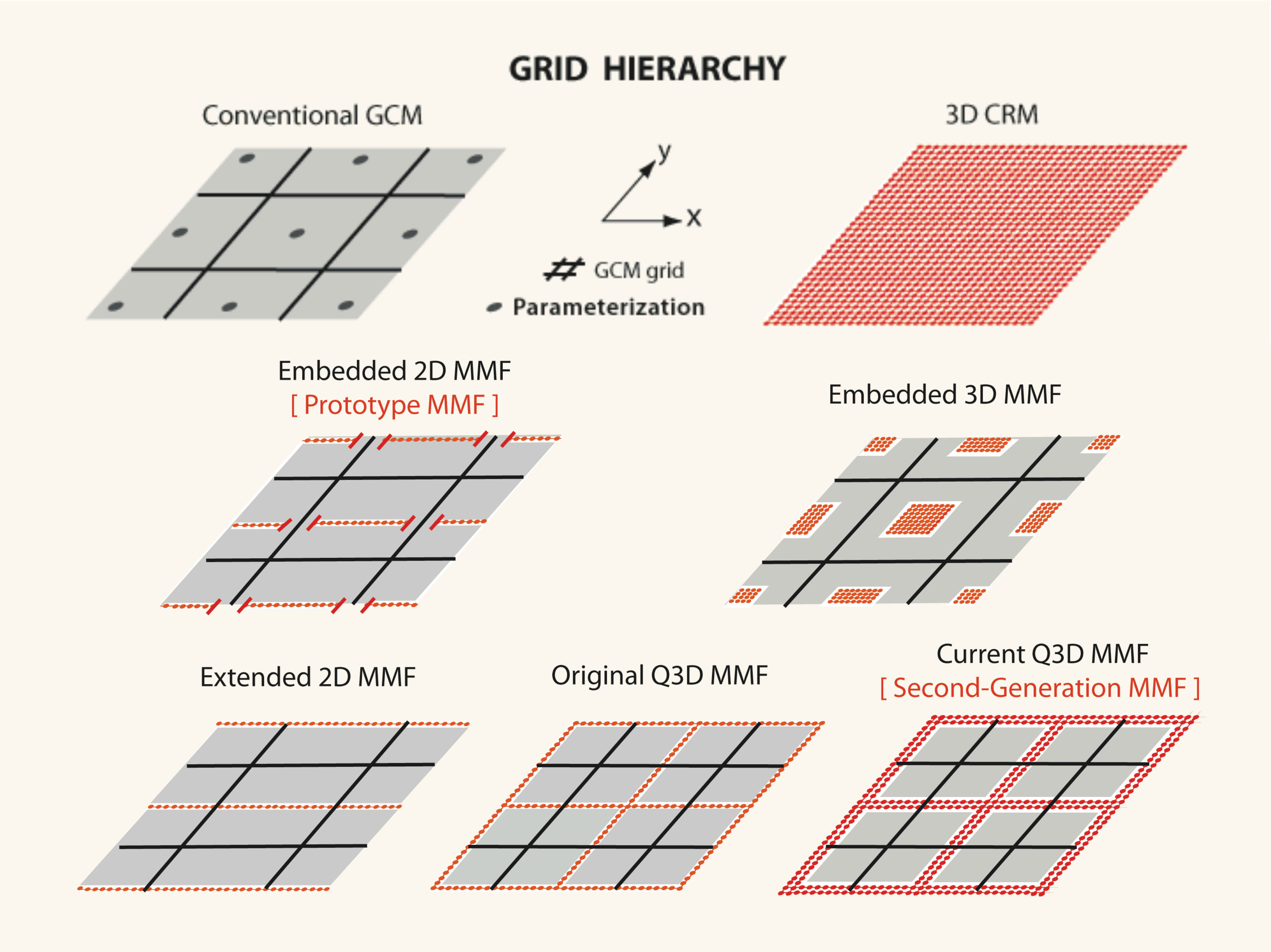
> *"To design combined macroscopic-microscopic computational methods that are much more efficient than solving the full microscopic model and at the same time give the information we need."* E *et al.* (2007)

In HMM the efficiency is typically gained by ***localization** of the microscopic model,* assuming that gross features of the microscopic solutions vary only macroscopically.



In MMF the efficiency is typically gained by *sacrificing full representation of 3D processes.*

Motivation: 2D CRMs are reasonably successful in simulating the thermodynamical effects of deep moist convection.


GRID HIERARCHY
Conventional GCM
y
x
GCM grid
Parameterization
3D CRM
Embedded 2D MMF
[Prototype MMF]
Embedded 3D MMF
Extended 2D MMF
Original Q3D MMF
Current Q3D MMF
[Second-Generation MMF]

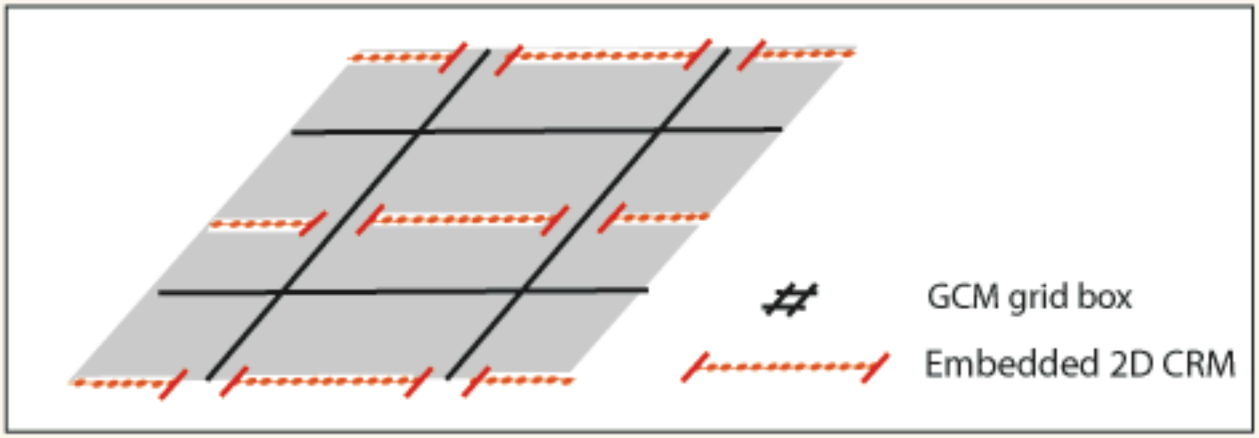
EMBEDDED 2D MMF [PROTOTYPE MMF]

"Cloud Resolving Convective Parameterization"

Grabowski & Smolarkiewicz (1999)
Grabowski (2001)

"Super-Parameterization"

Khairoutdinov and Randall (2001)
Randall et al. (2003)

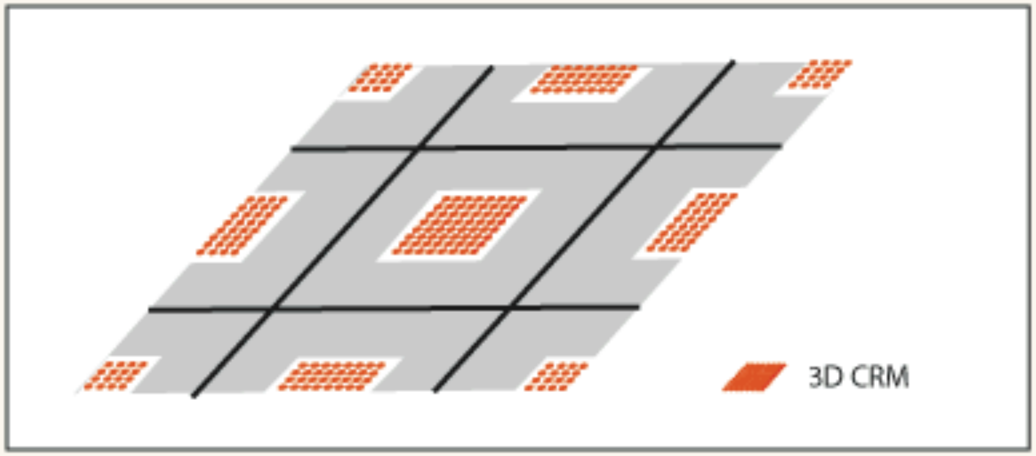


The prototype MMF has been shown to significantly improve climate simulation, including

- The Madden-Julian Oscillation (Benedict & Randall 2009, Thayer-Calder 2009);
- Low-cloud feedback on climate change (Wyant et al. 2006, 2009);
- Simulation of the coupled ocean-atmosphere system (Stan 2010).

EMBEDDED 3D MMF

Khairoutdinov and Randall (2005)



A tiny 3D CRM is embedded in each GCM grid cell - an HMM-like idea.

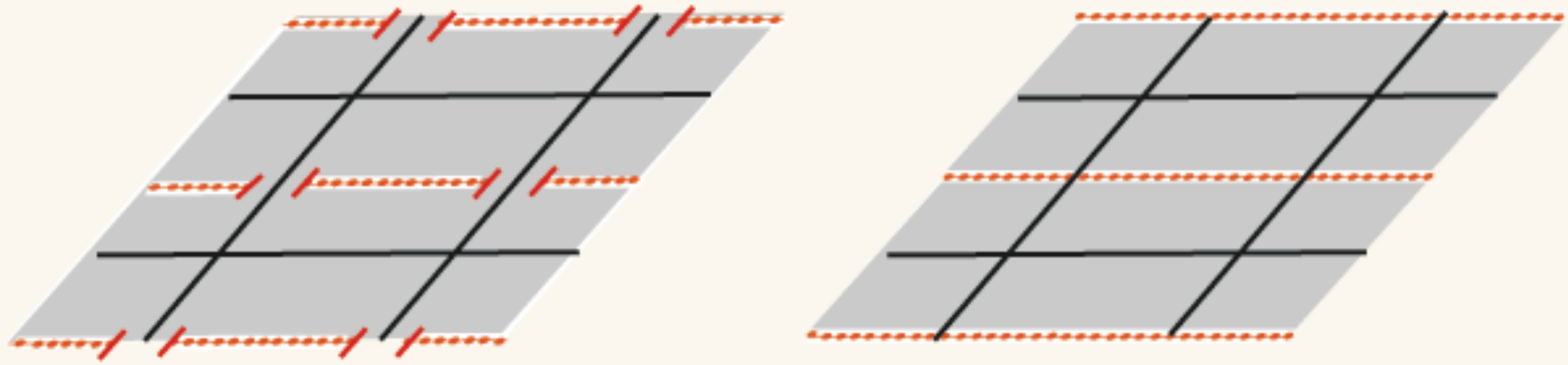
- For efficiency, CRMs must be very small so that there is no room for mesoscale organization of clouds.

- In both embedded 2D and 3D MMFs, neighboring CRMs can communicate only through the GCM.

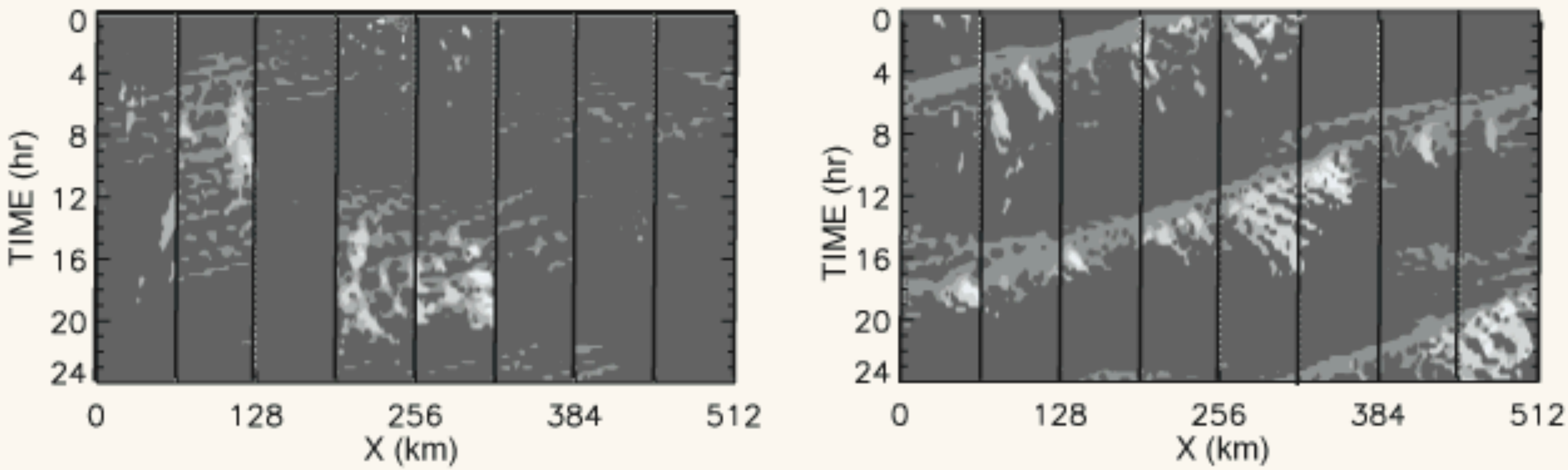
EMBEDDED VS. EXTENDED 2D MMF

Jung and Arakawa (2005)

Embedded **Extended**



Examples of simulated cloud top temperature

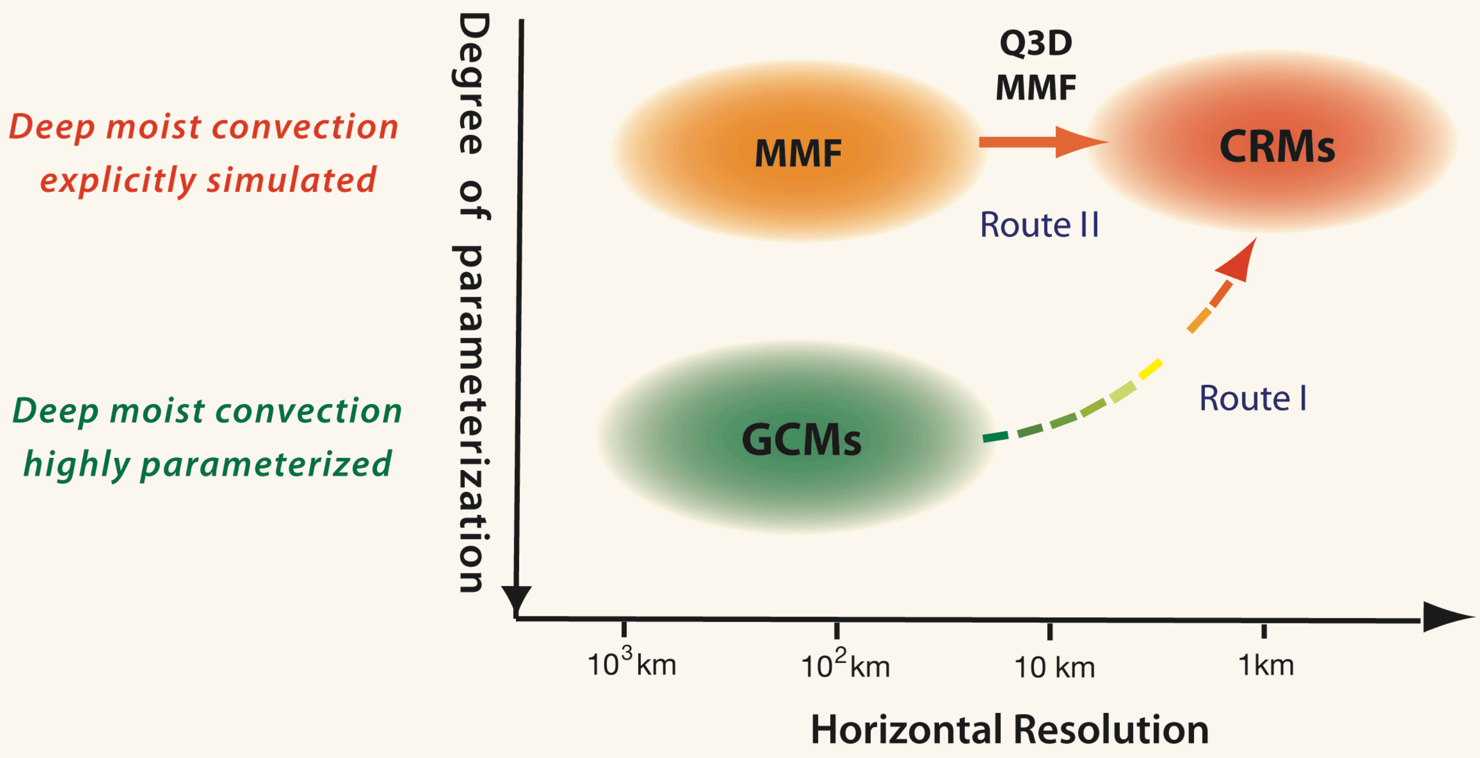


QUASI-3D (Q3D) MMF

Jung and Arakawa (2010)

An attempt to unify MMF and 3D CRM

by using a Q3D CRM, which partially includes 3D effects.



DYNAMICS AND PHYSICS OF THE Q3D CRM

Based on 3D anelastic vector vorticity equation model
developed by Jung and Arakawa (2008)

Prognostic variables :

Horizontal vorticity components, ξ and η

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

Potential temperature, θ

Mixing ratios of various phases of water, q

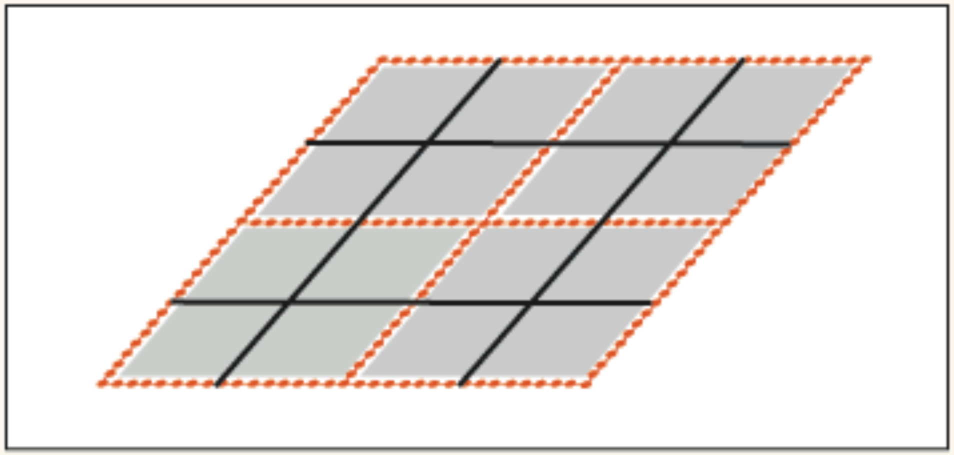
$\underline{(\ \ )}$: 3D effect in the y direction

Major diagnostic variable :

Vertical velocity w :

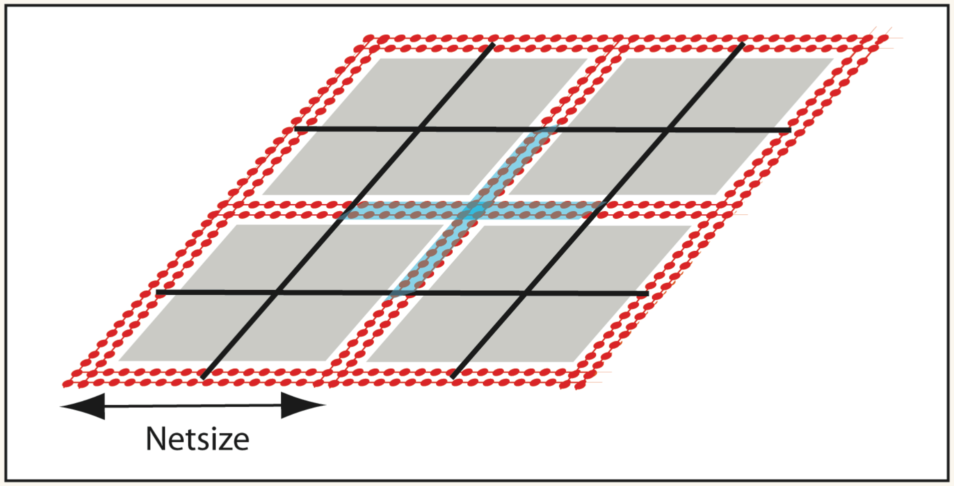
$$\left(\frac{\partial^2}{\partial x^2} + \underline{\frac{\partial^2}{\partial y^2}}\right)w + \frac{\partial}{\partial z}\left[\frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 w)\right] = -\frac{\partial \eta}{\partial x} + \underline{\frac{\partial \xi}{\partial y}}$$

ORIGINAL Q3D MMF



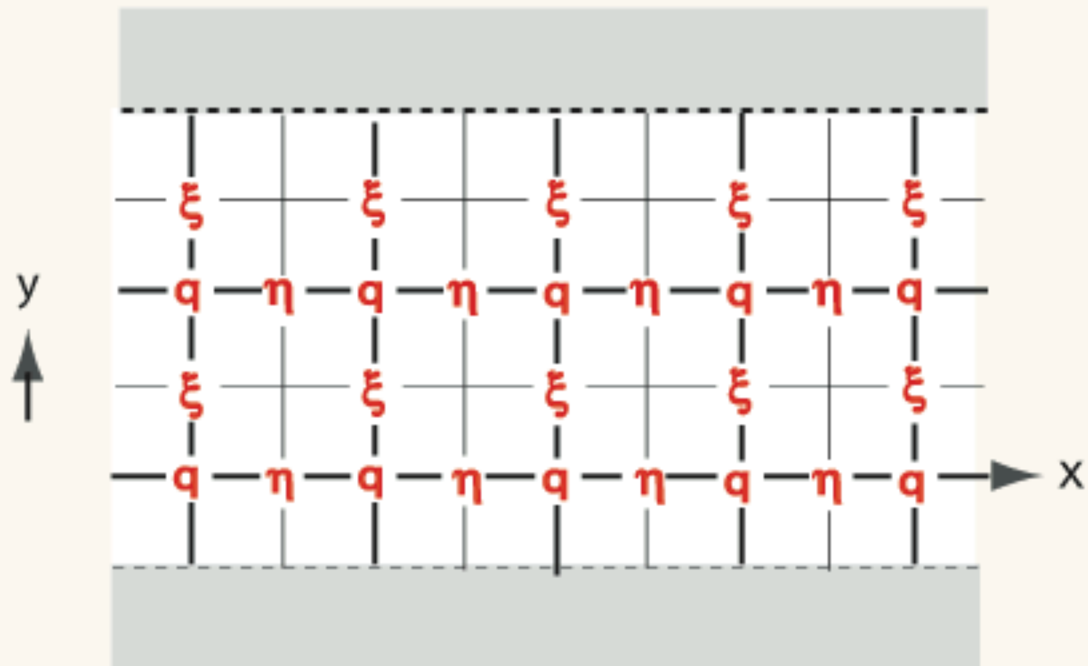
- Recognizes background anisotropy (typically due to the mean wind).
  - At each intersection, purely 3D prediction is made.
  - At other points, nomal gradients are estimated using the statistics of past data at the intersections.
- Was only partially successful due to the existence of singularity at the intersections.

CURRENT Q3D MMF [SECOND-GENERATION MMF]



- The CRM domain consists of a network of perpendicular channels each of which contains a few grid-point arrays. (In the above example, there are 2 arrays.)
- Perpendicular channels are coupled only through averages over channel segments of the netsize length (shown in blue) to avoid singularity.

Q3D GRID

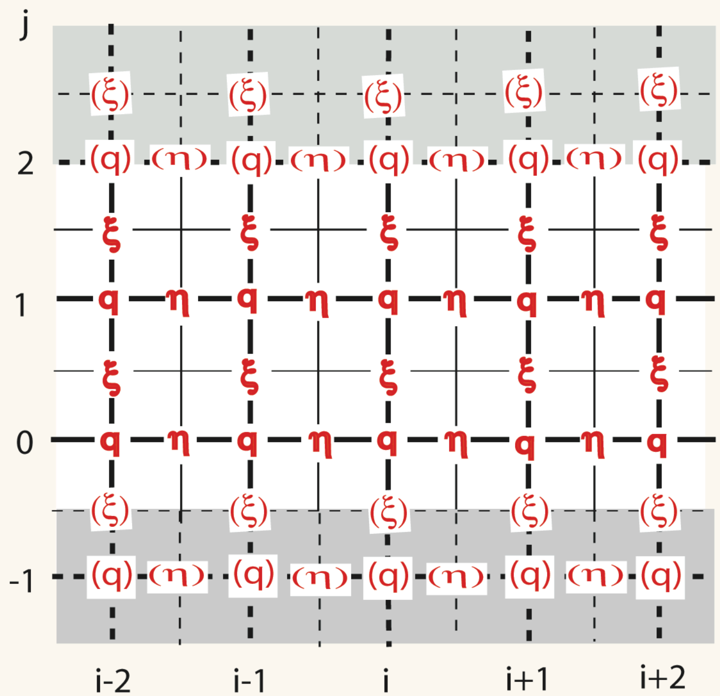


ξ, η and ζ : Vorticity components satisfying

$$\frac{\partial \xi}{\partial x} + \frac{\partial \eta}{\partial y} + \frac{\partial \zeta}{\partial z} = 0 ,$$

q : Scalar variables.

LATERAL BOUNDARY CONDITION



- Lateral boundary condition is implemented through assigning appropriate values to the ghost points.
- Ghost point values are separated into two parts.
  For q, for example,

$$q \;=\; \overline{q} \;+\; q'$$

Background   Deviation

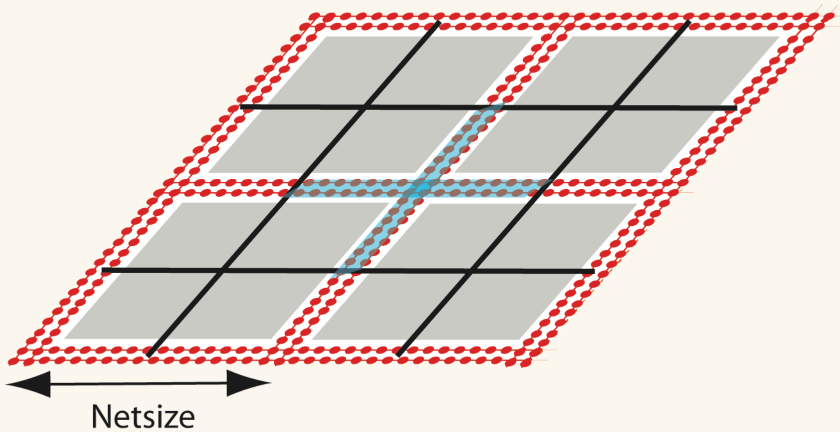
- Background values are obtained through interpolation from the GCM grid points.
- The ghost-point values of q′ should have statistics similar to that of the internal solution.
- An easy way to satisfy this is to "borrow" the values from one of the internal arrays.
- If $q'_2 = q'_1$, however, the solution is computationally unstable.

We thus assume that the distribution nomal to the channel is periodic for the deviations of all prognostic variables.

(For the above example, $q'_2 = q'_0$.)

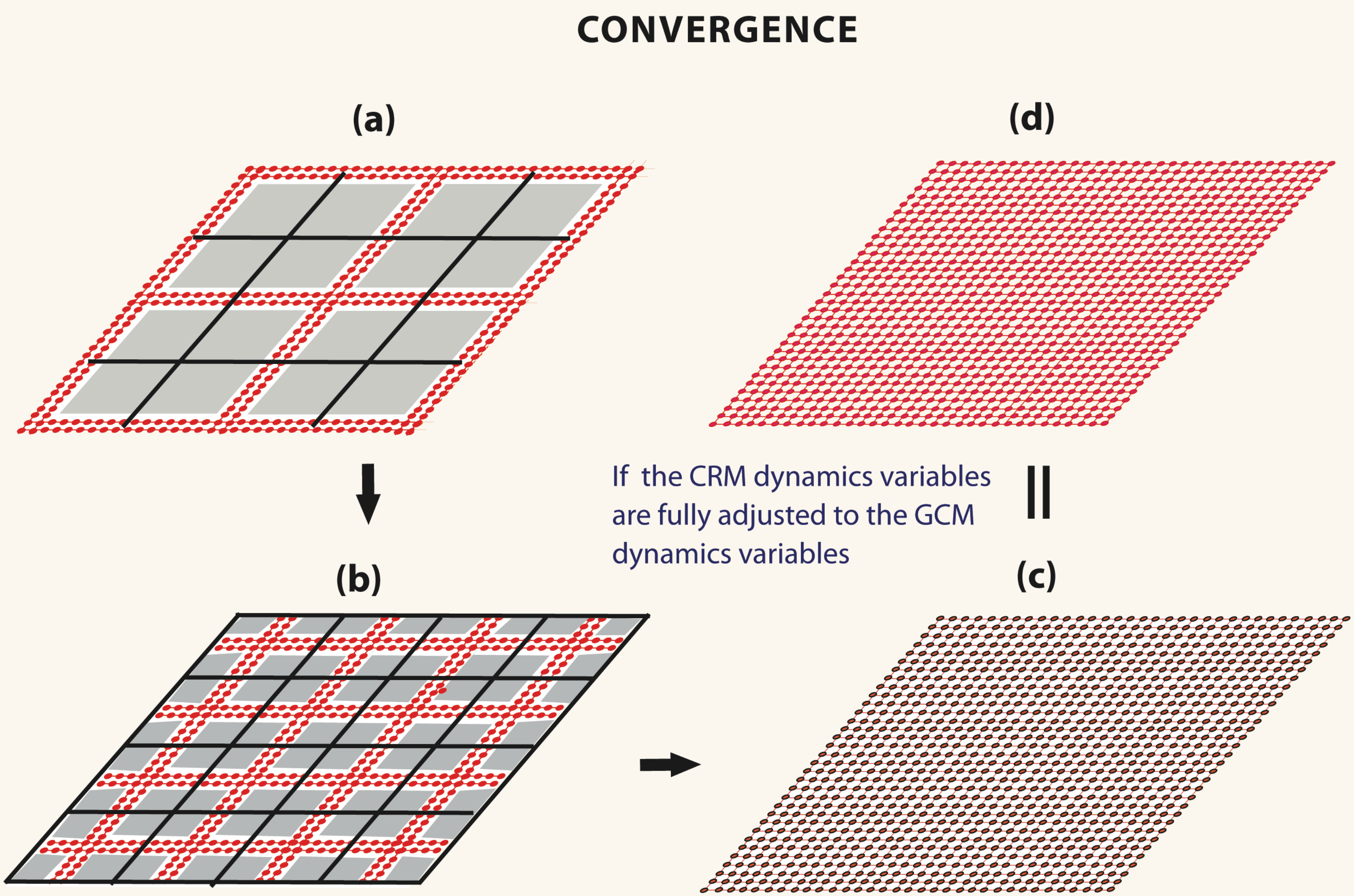
COUPLING OF THE Q3D CRM WITH A GCM

- The Q3D CRM is responsible for calculating the mean nonlinear effects of the "deviations" (e.g., eddy transport terms) and most of the diabatic effects.



- There is no "forcing" by the GCM on the CRM to avoid double counting. (Unparalleled to the conventional cumulus parameterization.)

- The netsize-averages of the CRM prognostic variables are adjusted to the GCM prognostic variables, loosely/tightly when the GCM resolution is low/high.

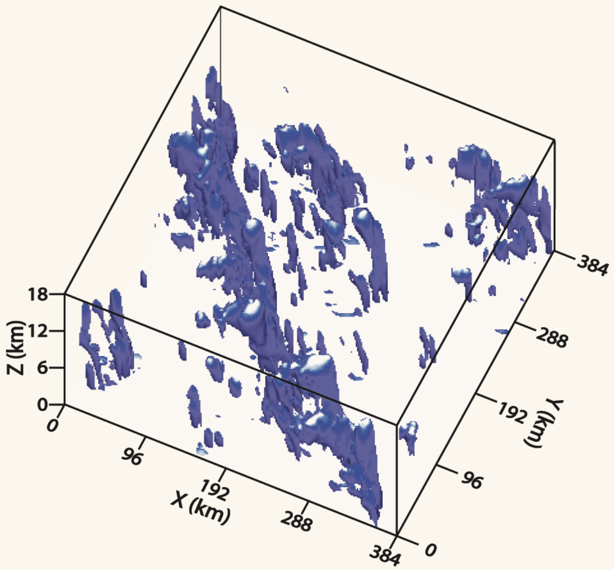

CONVERGENCE
(a)
(d)
If the CRM dynamics variables are fully adjusted to the GCM dynamics variables
(b)
(c)

Preliminary tests of Q3D CRM

- **Benchmark simulation (BM):**

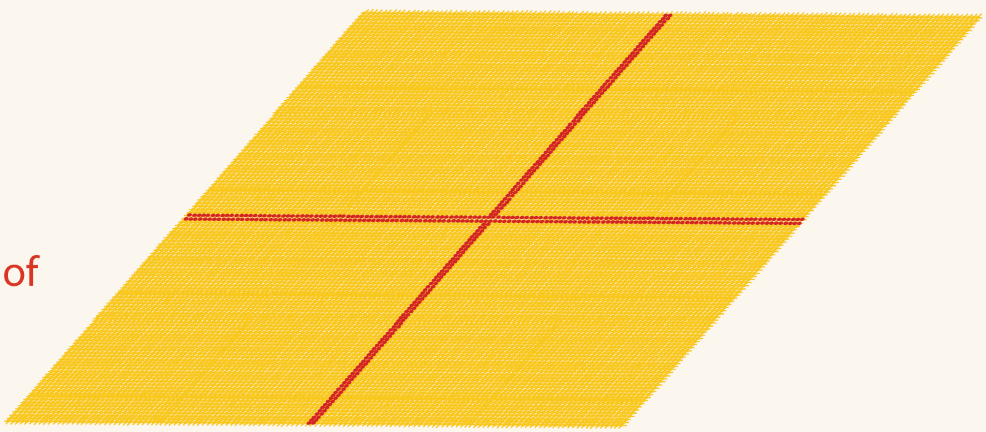
A straightforward application of a 3D CRM to a tropical condition

Domain size : 384 km   Grid size : 3 km



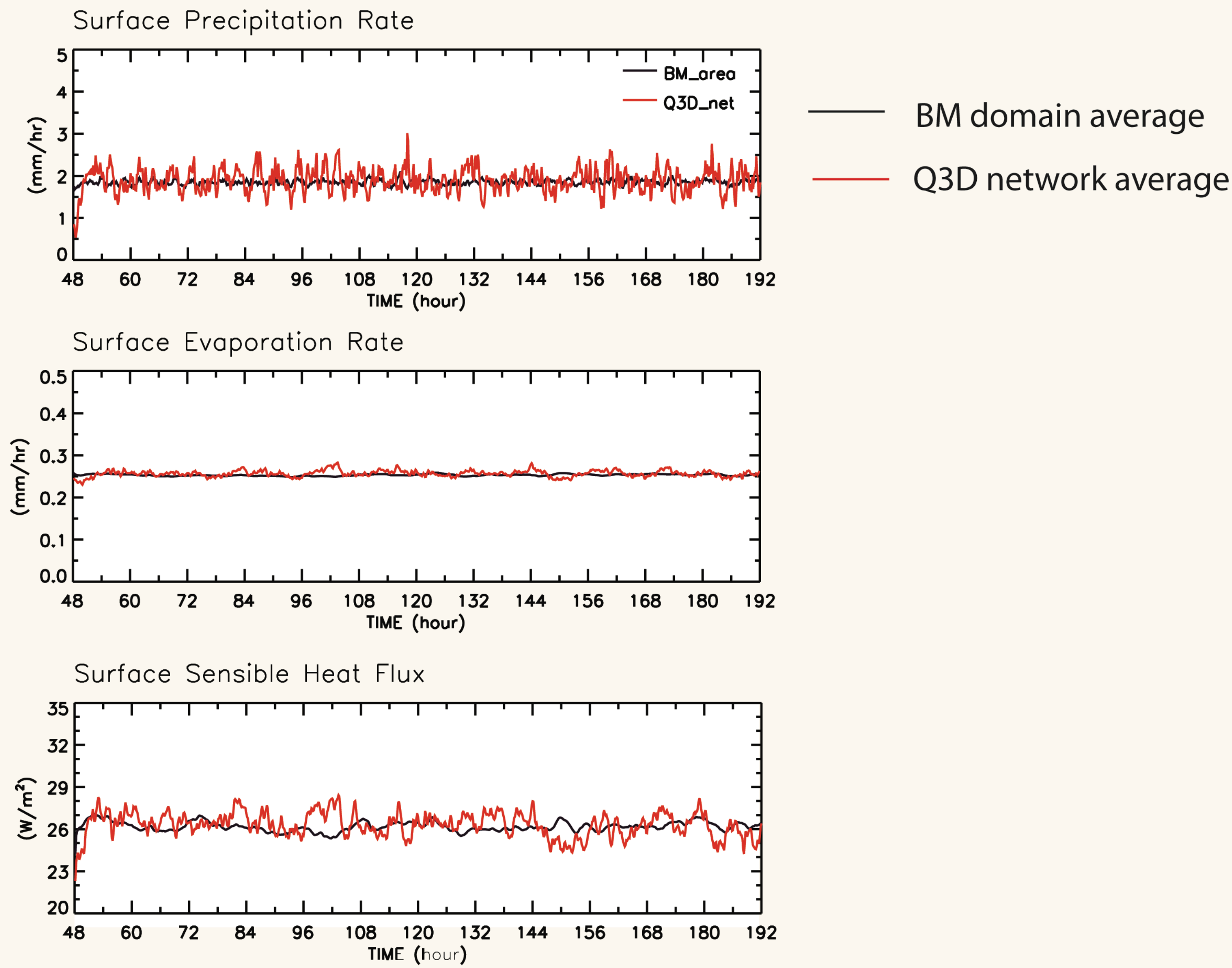
- **Q3D CRM**

Uses only two grid-point arrays in each channel and only one pair of channels for the entire domain

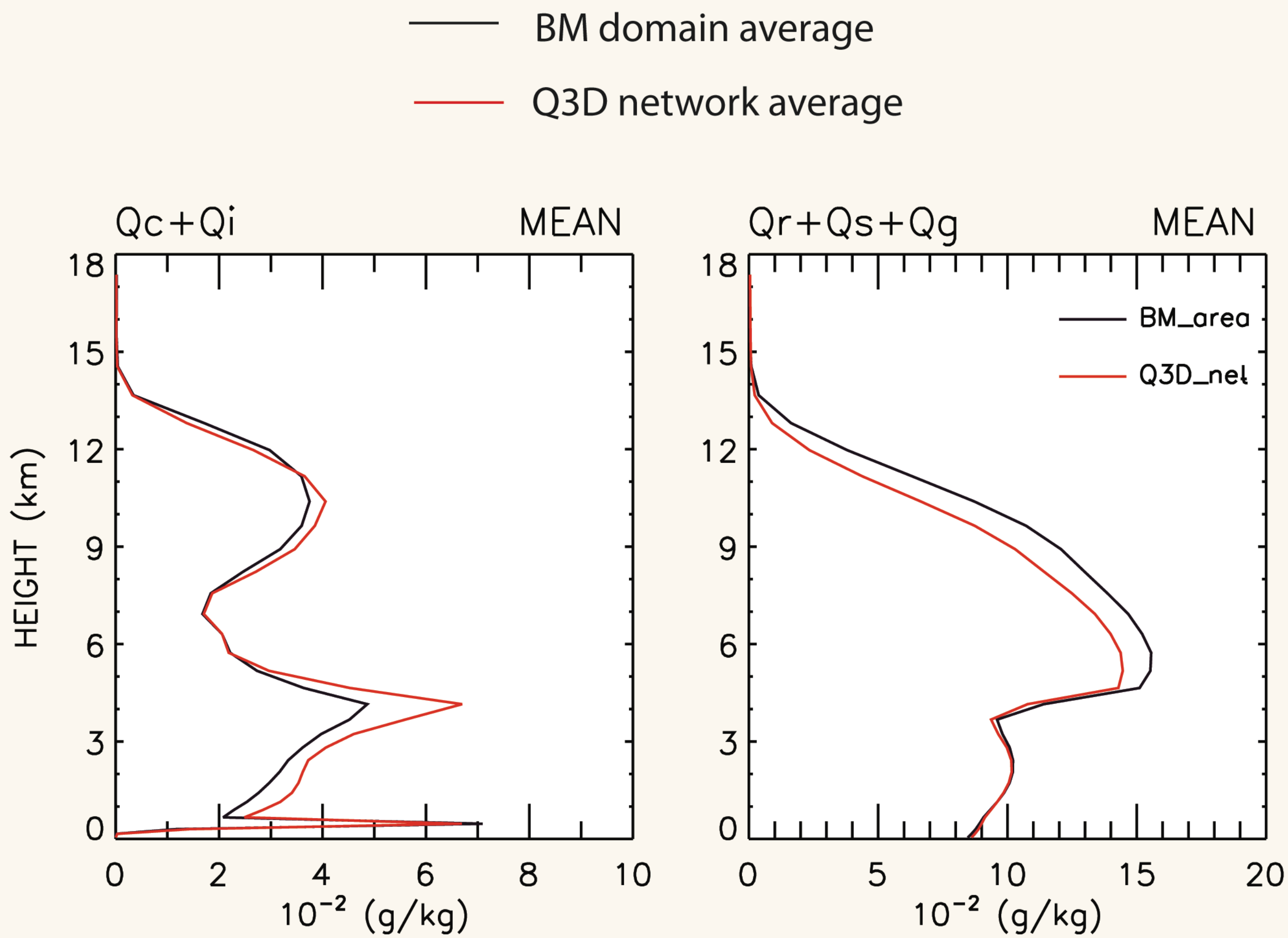


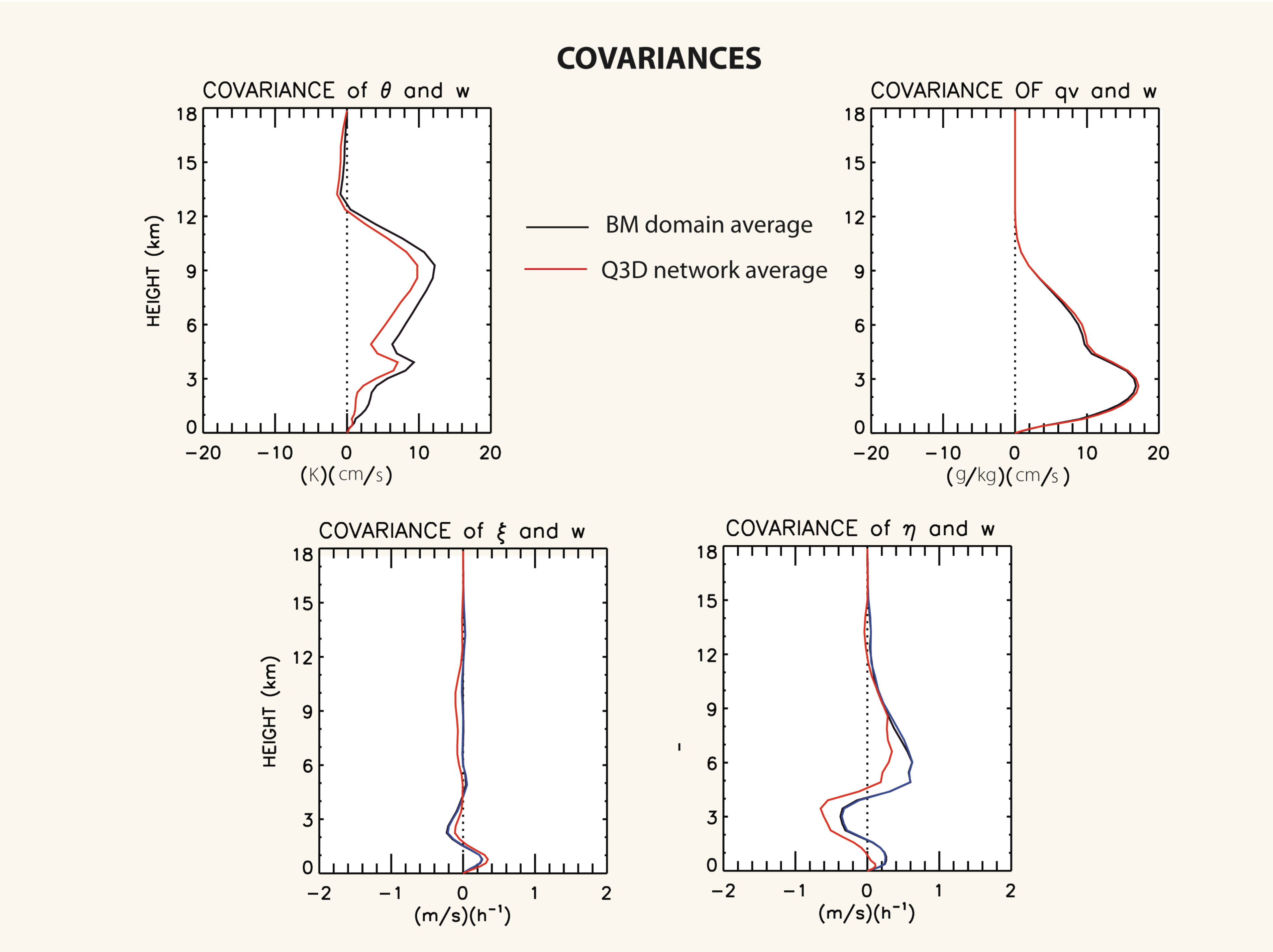
The ratio of the number of grid points of Q3D and 3D CRMs is 3%.

TIME SECTIONS OF SURFACE PREICIPITATION AND FLUXES



TIME-AVERAGED VERTICAL PROFILES OF CLOUD WATER AND PRECIPITANTS




COVARIANCES
COVARIANCE of θ and w
HEIGHT (km)
(K)(cm/s)
BM domain average
Q3D network average
COVARIANCE OF qv and w
(g/kg)(cm/s)
COVARIANCE of ξ and w
(m/s)(h⁻¹)
COVARIANCE of η and w
(m/s)(h⁻¹)

4. SUMMARY AND CONCLUSION

- General circulation and cloud-resolving models should be unified by sharing the same formulations of dynamics and physics so that the GCM can converge to a CRM as the resolution is refined.

- ROUTE I for unification is through relatively minor modifications of the existing cumulus parameterization schemes.

- ROUTE II for unification is through development of a numerical framework called the Q3D MMF, which also converges to a 3D CRM.

- The two routes are almost perfect complements for a broad range of the spectrum.

- Preliminary test results of the Q3D CRM are very encouraging.