TOWARD UNIFICATION OF MULTISCALE MODELING OF THE ATMOSPHERE

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collaborating with

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Vilhelm Bjerknes (1904)

Pointed out that a necessary condition for the rational solution of forecasting problem is

"A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another."

Here he distinguished the laws for changes

"from degree to degree in meridian and from hour to hour in time"

from those for changes

"from millimeter to millimeter and from second to second."

Numerical modeling of the atmosphere has been a struggle for finding such laws, and ***still is****.*

RATIONALE FOR THE THEME OF THIS TALK

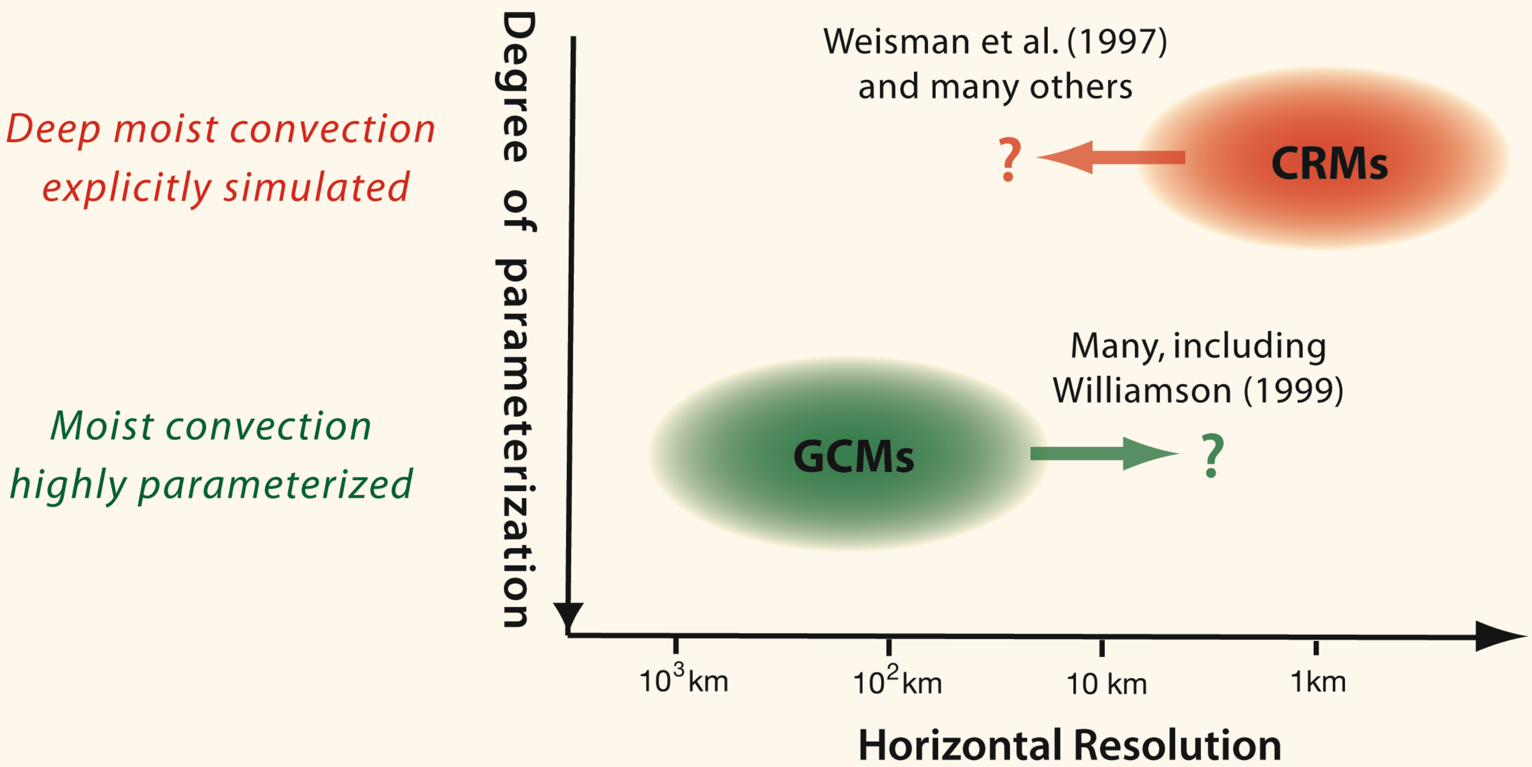
As far as representation of deep moist convection is concerned,

we have only two kinds of model physics :

highly parameterized and *explicitly simulated*.

TWO FAMILIES OF ATMOSPHERIC MODELS

(besides those models that explicitly simulate turbulence, such as DNS and LES.)



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

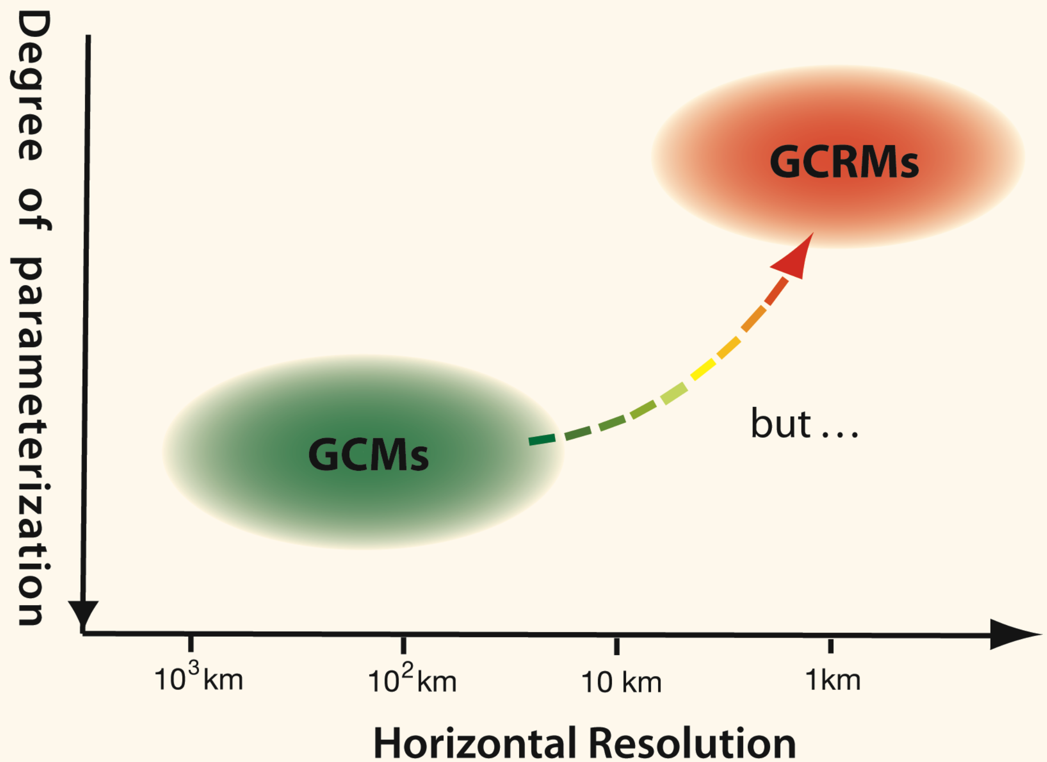
the scale of the grid on which it is based. "

THE CONVERGENCE PROBLEM

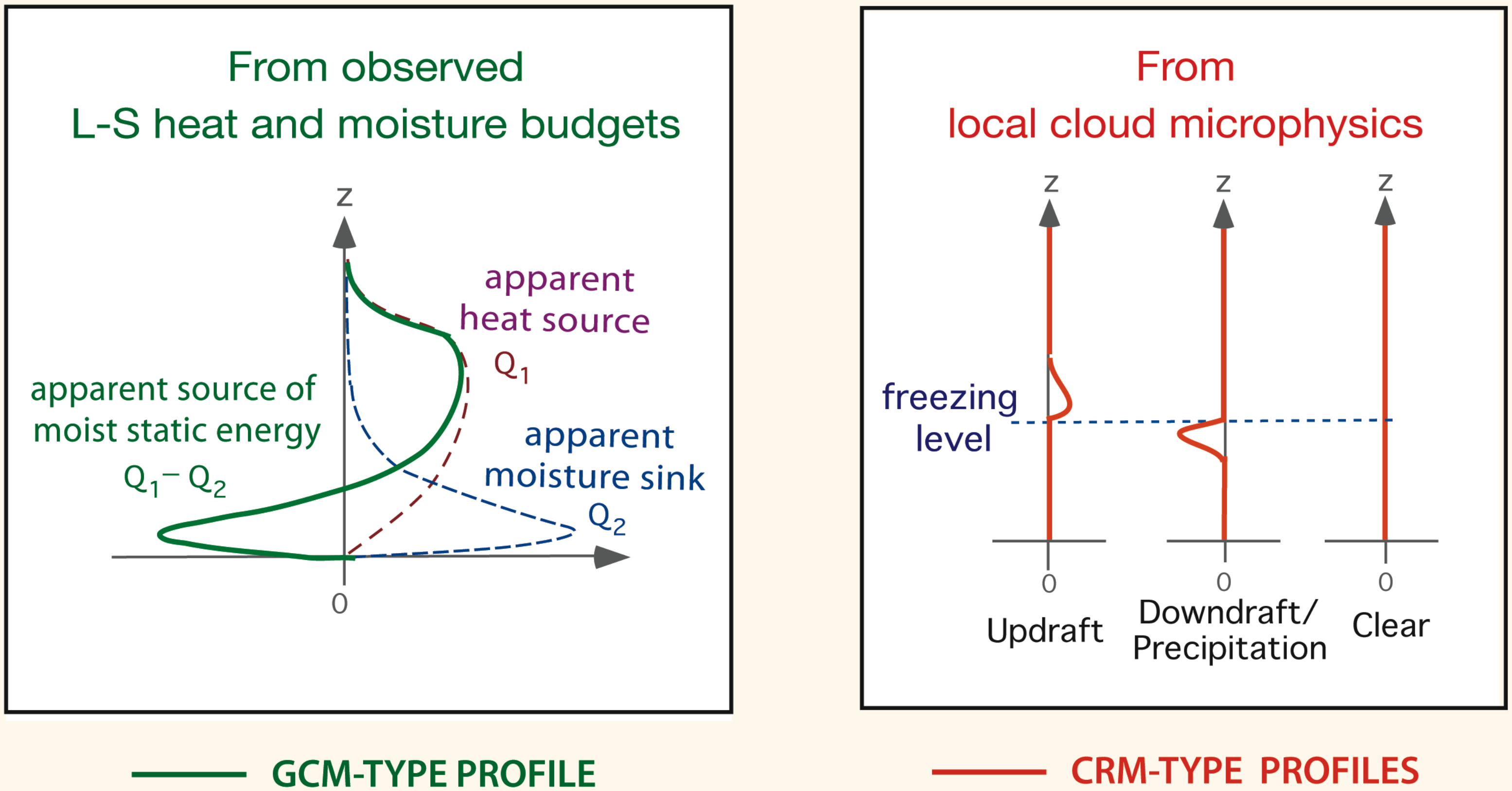
Our problem is more demanding than just a convergence;

the GCM should converge to a physically meaningful system,

e.g., a global CRM (GCRM).



SCHEMATIC ILLUSTRATION OF MOIST STATIC ENERGY SOURCE UNDER TYPICAL TROPICAL CONDITIONS



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 not a purely statistical problem as we have seen.
- It is not a purely physical/dynamical problem because it is a formulation of *subgrid-scale processes* required in a truncated system.
- It is not a purely computational problem as a higher resolution does not automatically improve the overall results.

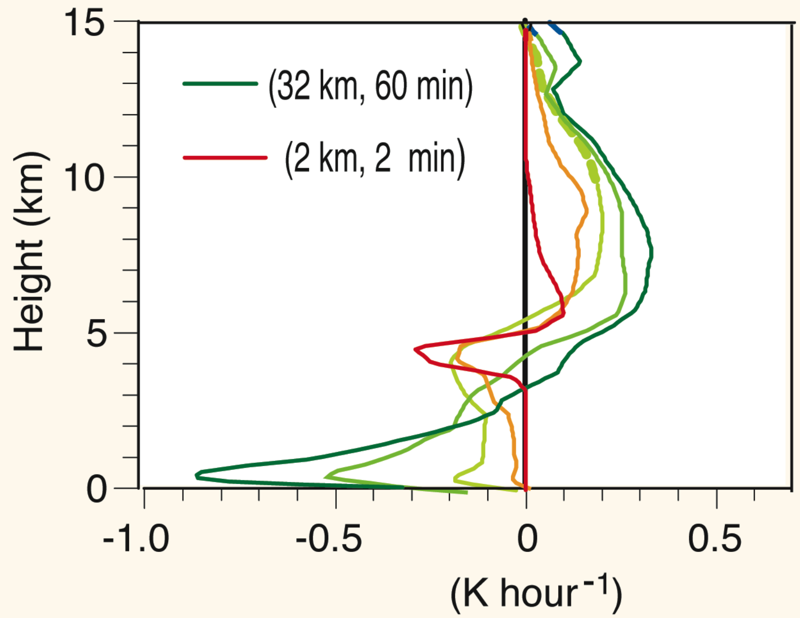
A complete theory of cumulus parametrization must address all of these aspects in a consistent manner, including the transion between the GCM-type and CRM-tupe profiles.

EVIDENCE FOR THE TRANSITION OF MODEL PHYSICS

Jung and Arakawa (2004)

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

Average Profiles of "REQUIRED" Source for Moist Static Energy

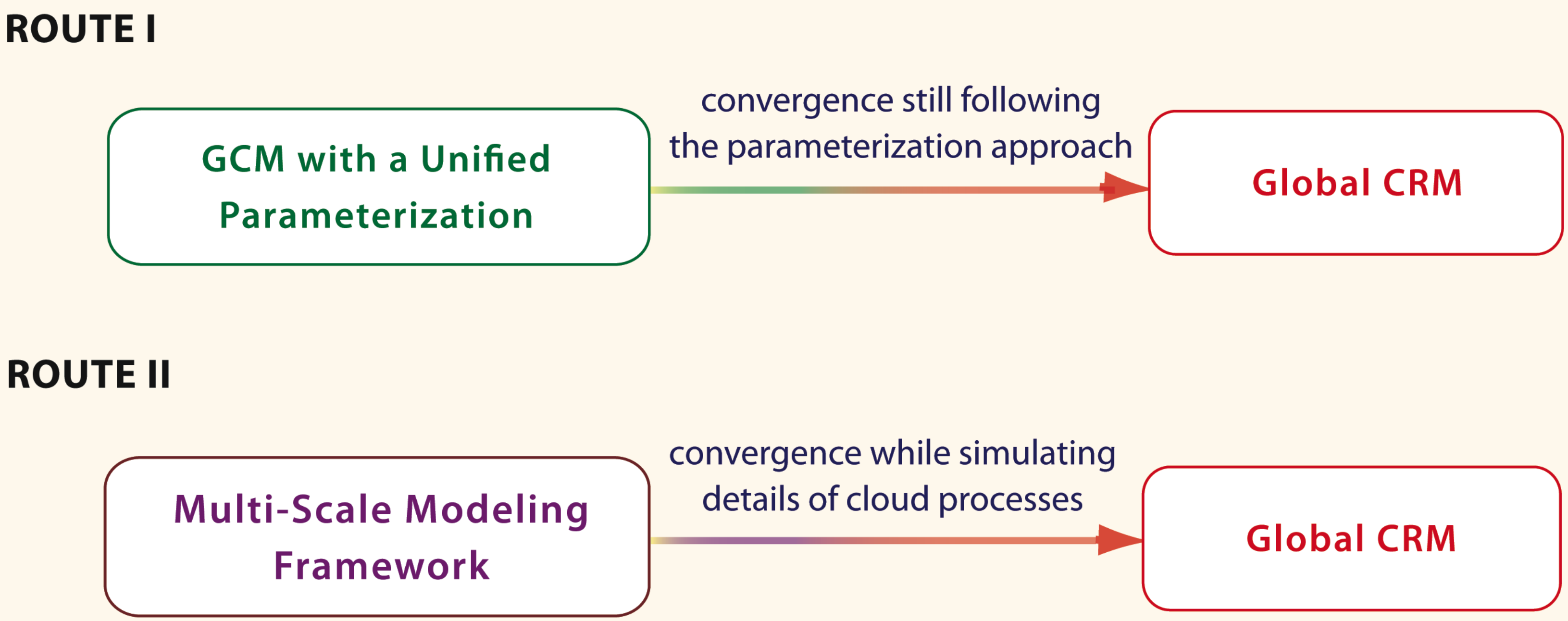


GCM-type profile

CRM-type profile

UNIFICATION OF GCM AND CRM

Two possible routes to achieve the unification:



ROUTE I :

UNIFICATION THROUGH A UNIFIED PARAMETERIZATION

Starting Point :

*"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

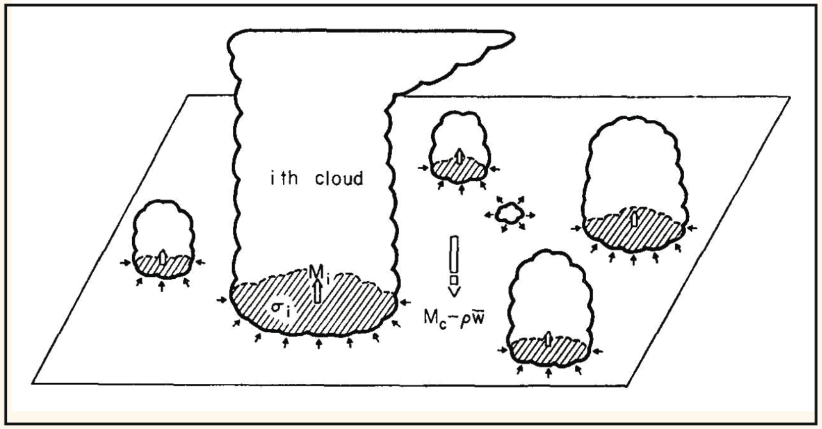
NOT small enough

⇒ Should include parameterization of mesoscale processess

NOT large enough

⇒ Should include a stochastic component

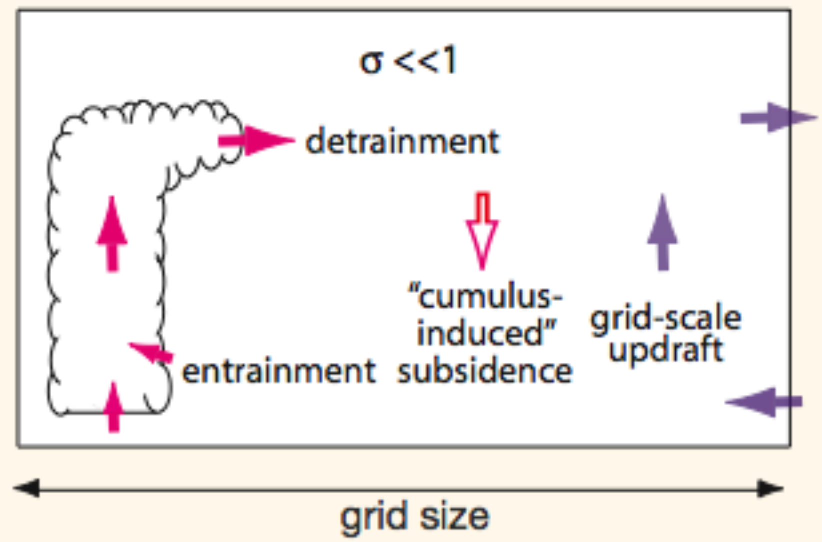
Should converge to a CRM, as discussed



ASSUMPTION OF SMALL FRACTIONAL CLOUD COVER

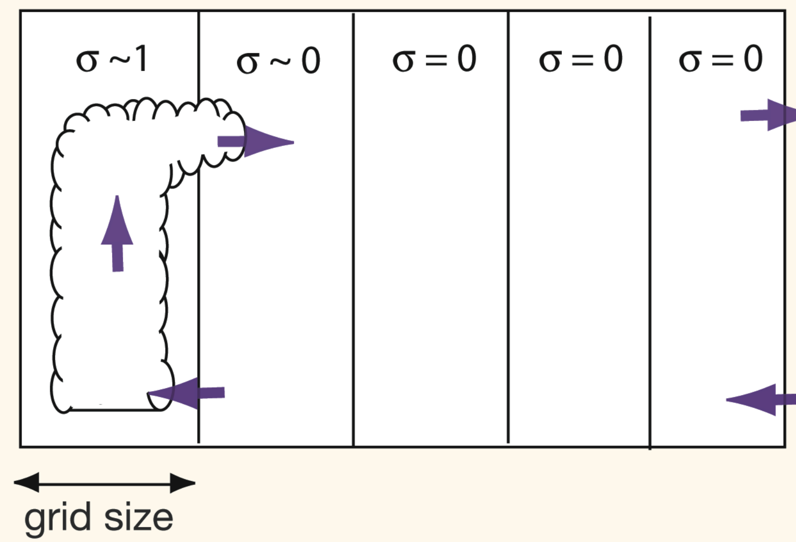
- Specifically, AS assumes σ << 1, where σ is the fractional area covered by *all convective clouds* in the grid cell.

- Then prediction of grid-scale averages of sensible and latent heat essentially becomes prediction of them in the cloud environment.



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

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



Bimodal distributioon of σ (Krueger 2002)

CRM SIMULATIONS USED FOR ANALYSIS

To visualize the problems in conventional cumulus parametrization,

CRM-simulated data are analyzed.

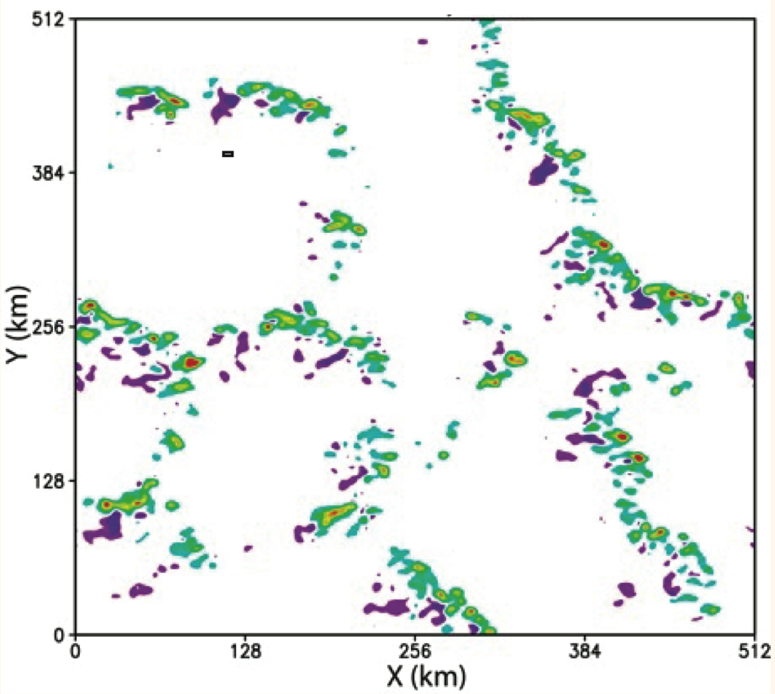
Model : 3D vorticity equation model of Jung and Arakawa (2008)

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

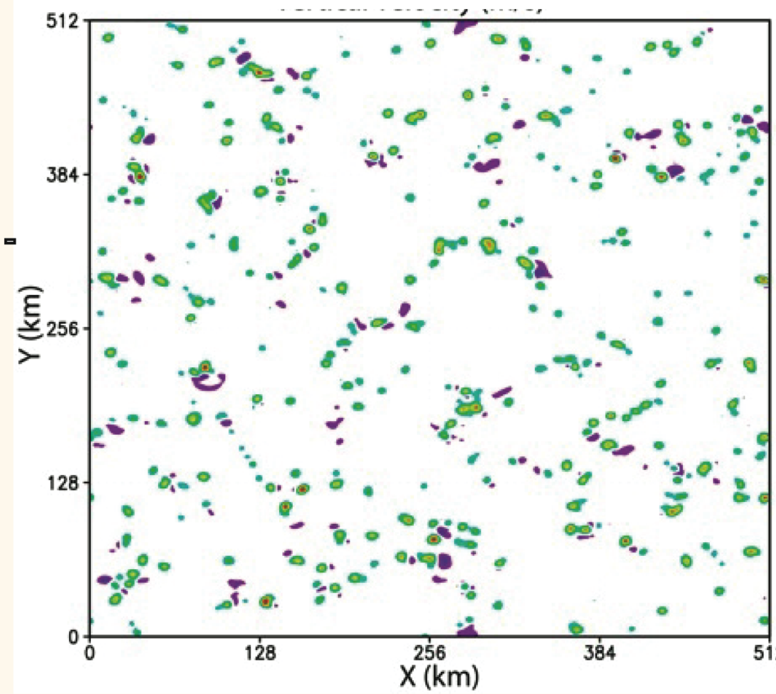
Snapshots of vertical velocity w at 3 km height

w > 0.5 m/s
w < -0.5 m/s

With Shear



Without Shear

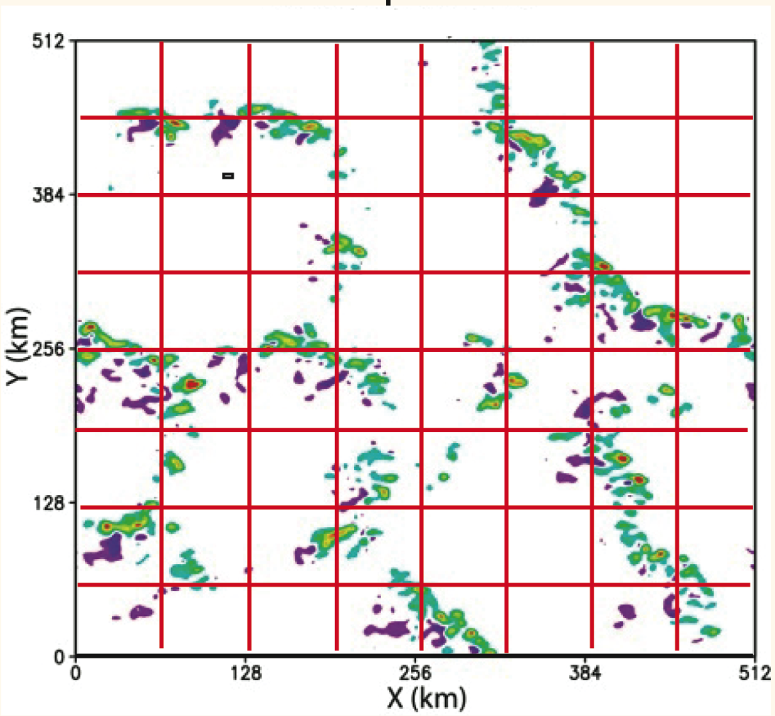


SUB-DOMAINS USED FOR ANALYZING THE GRID-SIZE DEPENDENT STATISTICS OF CRM DATA

The domain size used for prediction : 512 km

The sub-domain size used for analysis : (512 km) / n, n=2, 4, 8, . . , 256

Example: n = 8



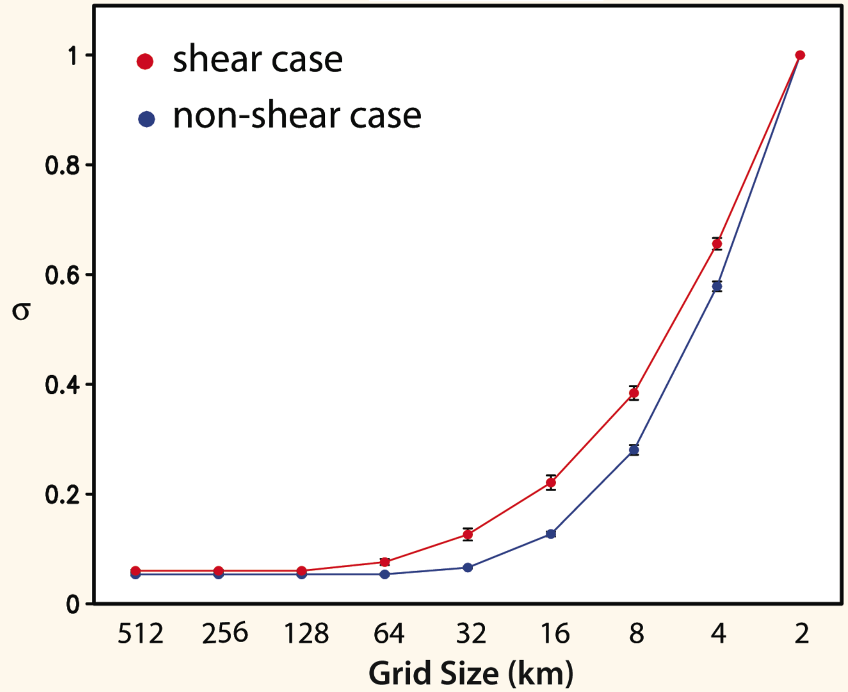
These sub-domains are treated as different members of the ensemble for that resolution.

FRACTIONAL CLOUD COVER, σ,

measured by the number of grid points that satisfy w>0.5 m/s

normalized by the total number of grid points in the sub-domain

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



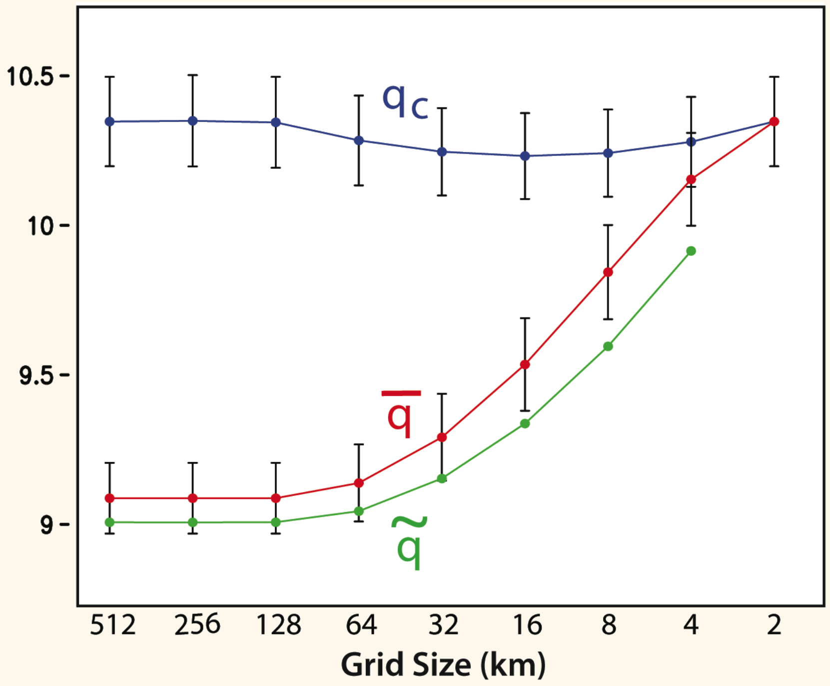
σ<<1 is a good approximation

ONLY for large grid sizes.

GRID-SIZE DEPENDENCE OF MEAN WATER-VAPOR MIXING RATIO

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

The shear case



$(\ )_c$: Mean over all grid points in the sub-domain that satisfy w > 0.5 m/s ("cloud-value")

$\overline{(\ )}$: Mean over all grid points in the sub-domain ("grid-scale value")

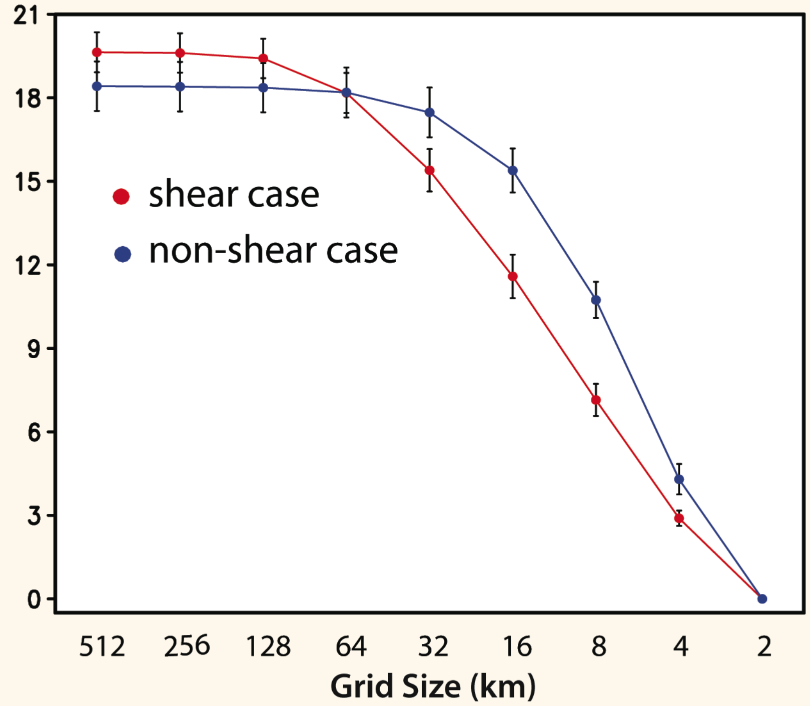
$\widetilde{(\ )}$: Mean over all grid points in the sub-domain that satisfy w < 0.5 m/s ("environment value")

$\overline{q} \approx \tilde{q}$ *is not an approximation for small grid sizes.*

GRID-SIZE DEPENDENCE OF

EDDY TRANSPORT OF WATER-VAPOR MIXING RATIO, $\overline{wq} - \overline{w}\,\overline{q}$

Ensemble averages at 3km height *excluding* $\sigma = 0$ sub-domains



If formulated with a large grid size in mind,

the eddy transport is SERIOUSLY OVERESTIMATED for small grid sizes.

A DESIGN OF THE UNIFIED CUMULUS PARAMETRIZATION

Definitions

M : Total "eddy" mass flux given by $M \equiv \rho\sigma(w_c - \overline{w})$ (1)

w_c^* : w calculated by an embedded plume model

- The simplest choice to satisfy $w_c \to w_c^*$ as $\sigma \to 0$, $w_c \to \overline{w}$ as $\sigma \to 1$:

$$w_c = (1-\sigma) w_c^* + \sigma \overline{w} \quad (2)$$

Similarly, $\Psi_c = (1-\sigma)\Psi_c^* + \sigma\overline{\Psi}$ (3)

- Substituting (2) into (1),

$$M = \rho\sigma(1-\sigma)\left(w_c^* - \overline{w}\right) \quad (4)$$

- The simplest choice to satisfy $M \to 0$ as $\sigma \to 0$: $M = (1-\sigma)M_0$ (5)

M_0 is M that is expected when $\sigma \approx 0$, which can be determined as in the conventional mass-flux schemes.

- From (4) and (5),

$$\sigma = \frac{M_0}{\rho\left(w_c^* - \overline{w}\right)}$$

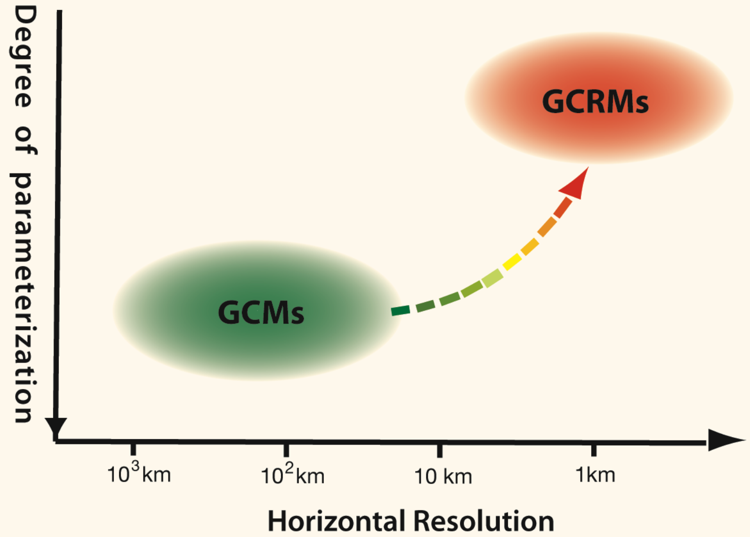
If $\sigma > 1$ (over-population), replace σ by 1.

Decrease M accordingly (delayed adjustment).

ANTICIPATED IMPACT OF THE UNIFIED 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.



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

Practical merits of the generalized parameterization are great.

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

MORE THINGS TO STRUGGLE WITH

- Having a good plume model is a key to success of the Route I.

- Unification with parameterization of stratiform clouds remains as an important issue.

- The parameterization should include a stochastic component, Including its resolution dependence.

  When $\sigma \sim 1$, the unified model is basically a CRM and can act as a ramdom-process generator by itself.

- The parameterization should predict a measure (or measures) of cloud organization. (as in Mapes 2010), including its resolution dependence.

  When $\sigma \sim 1$, cloud organization is explicitly predicted.

The convergence issue opens a broad area of modeling research.

ROUTE II :

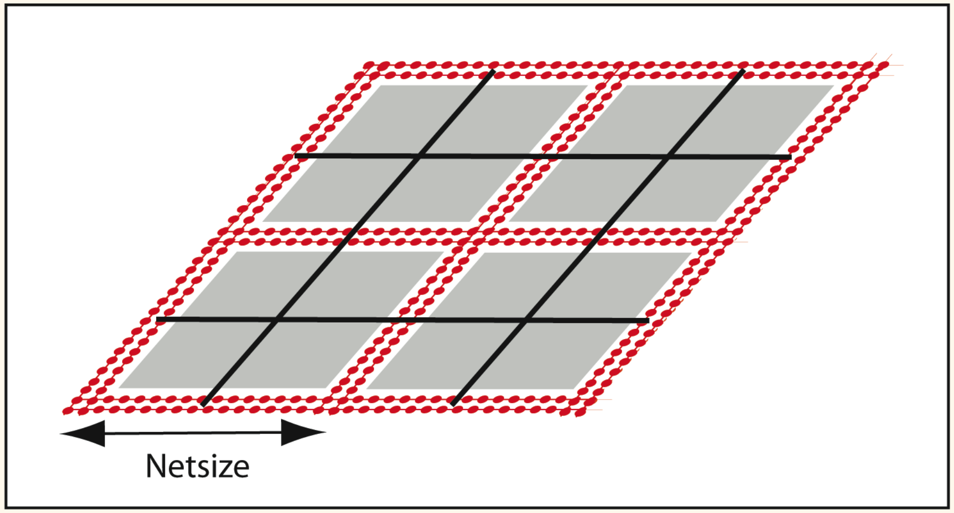
UNIFICATION THROUGH MULTI-SCALE MODELING FRAMEWORK (MMF)

("Super-Parameterization")

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

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

CURRENT Q3D MMF (SECOND-GENERATION MMF)

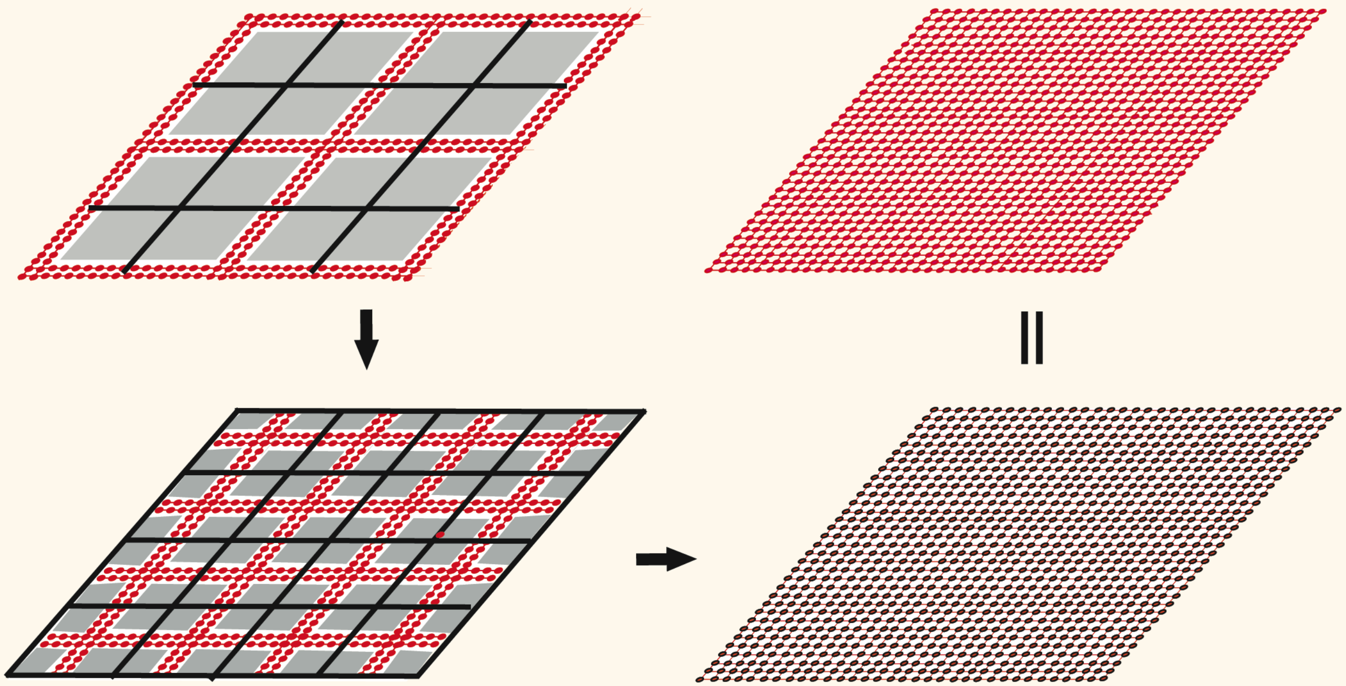


- The CRM domain consists of two perpendicular sets of channels.
- For efficiency, the width of channels is chosen to be narrow, barely enough to cover a typical cloud size.
- Thus, a channel contains only a few grid-point arrays. (In the above example, there are only two arrays.)

LATERAL BOUNDARY CONDITION AND CONVERGENCE

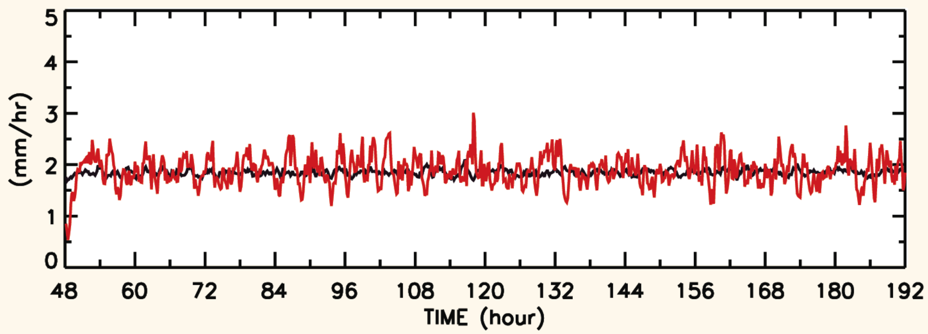
- Deviations from interpolated GCM values are assumed to be periodic across the channel.
- As the GCM grid size approaches the CRM grid size, the deviations vanish.

CONVERGENCE

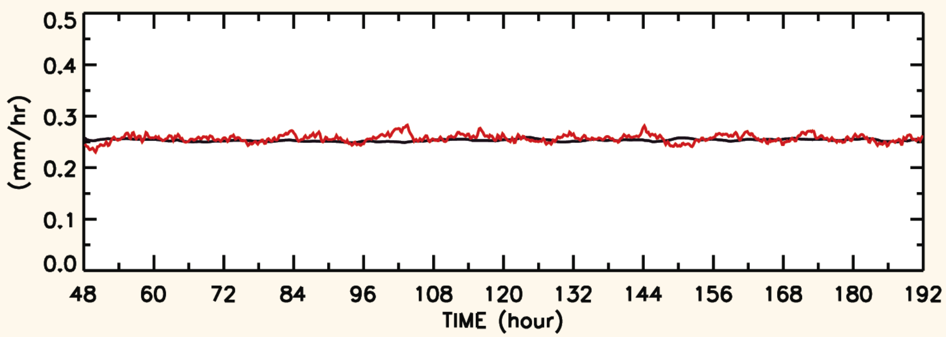


TIME SECTIONS OF SURFACE PREICIPITATION AND SURFACE FLUXES

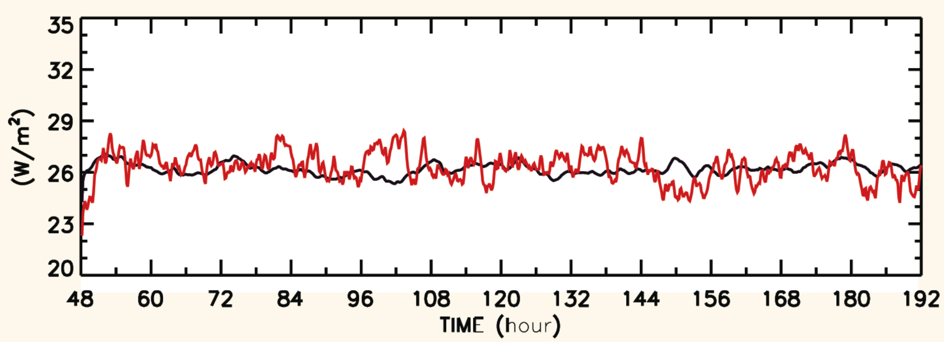
Surface precipitation rate



Surface evaporation rate



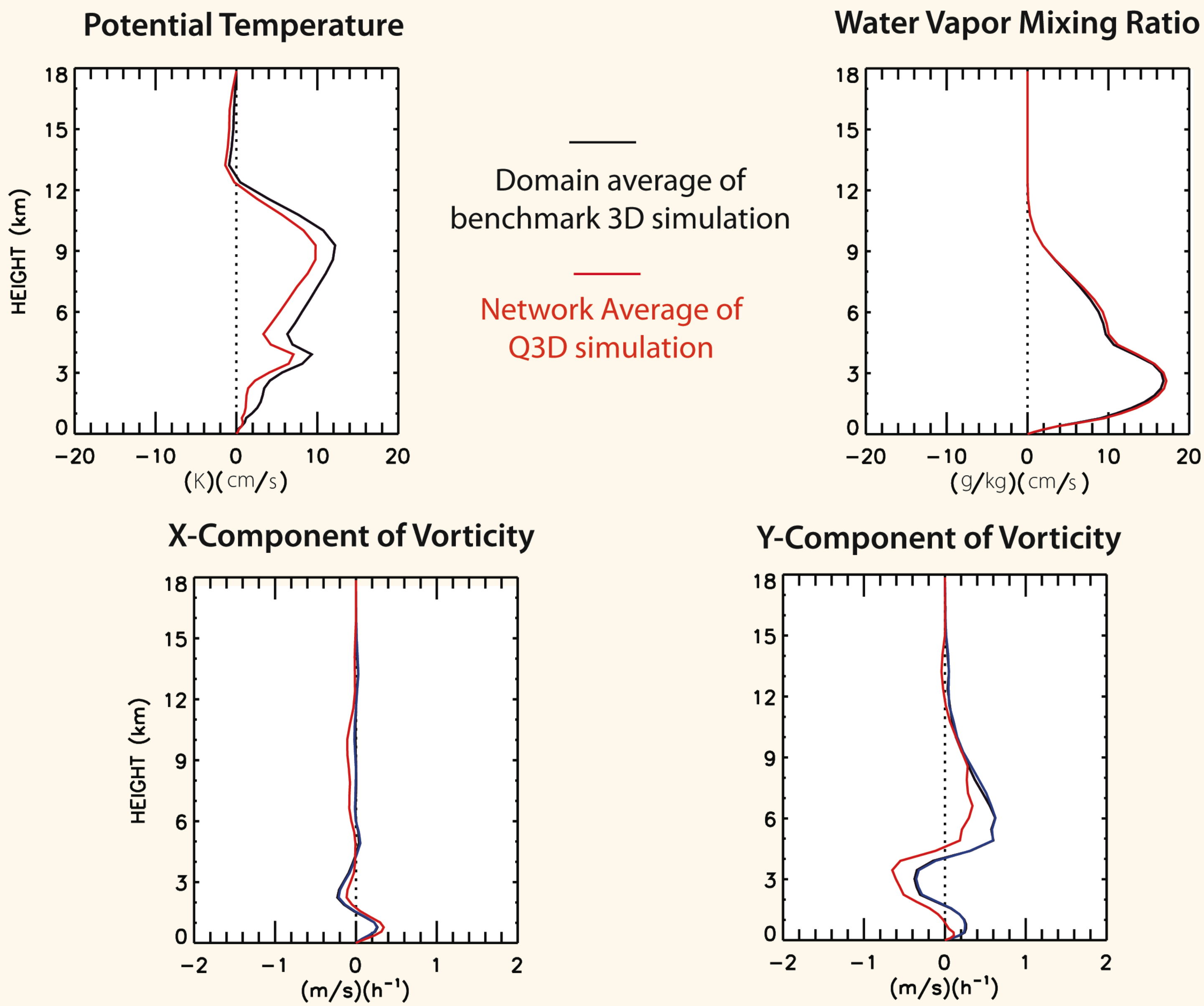
Surface sensibe heat flux



Domain average of benchmark 3D simulation

Network Average of Q3D simulation

AN EXAMPLE OF TIME-AVERAGED VERTICAL RANSPORTS

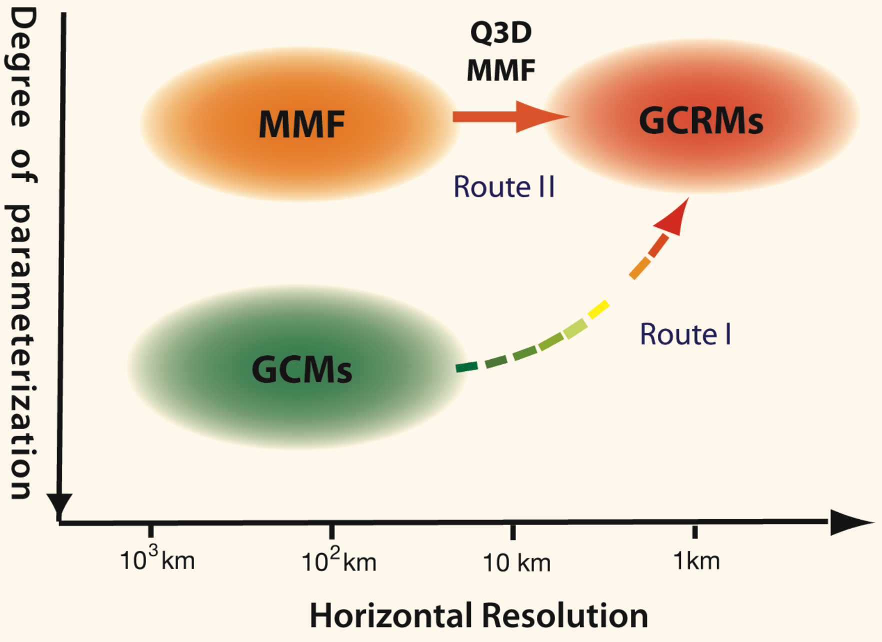


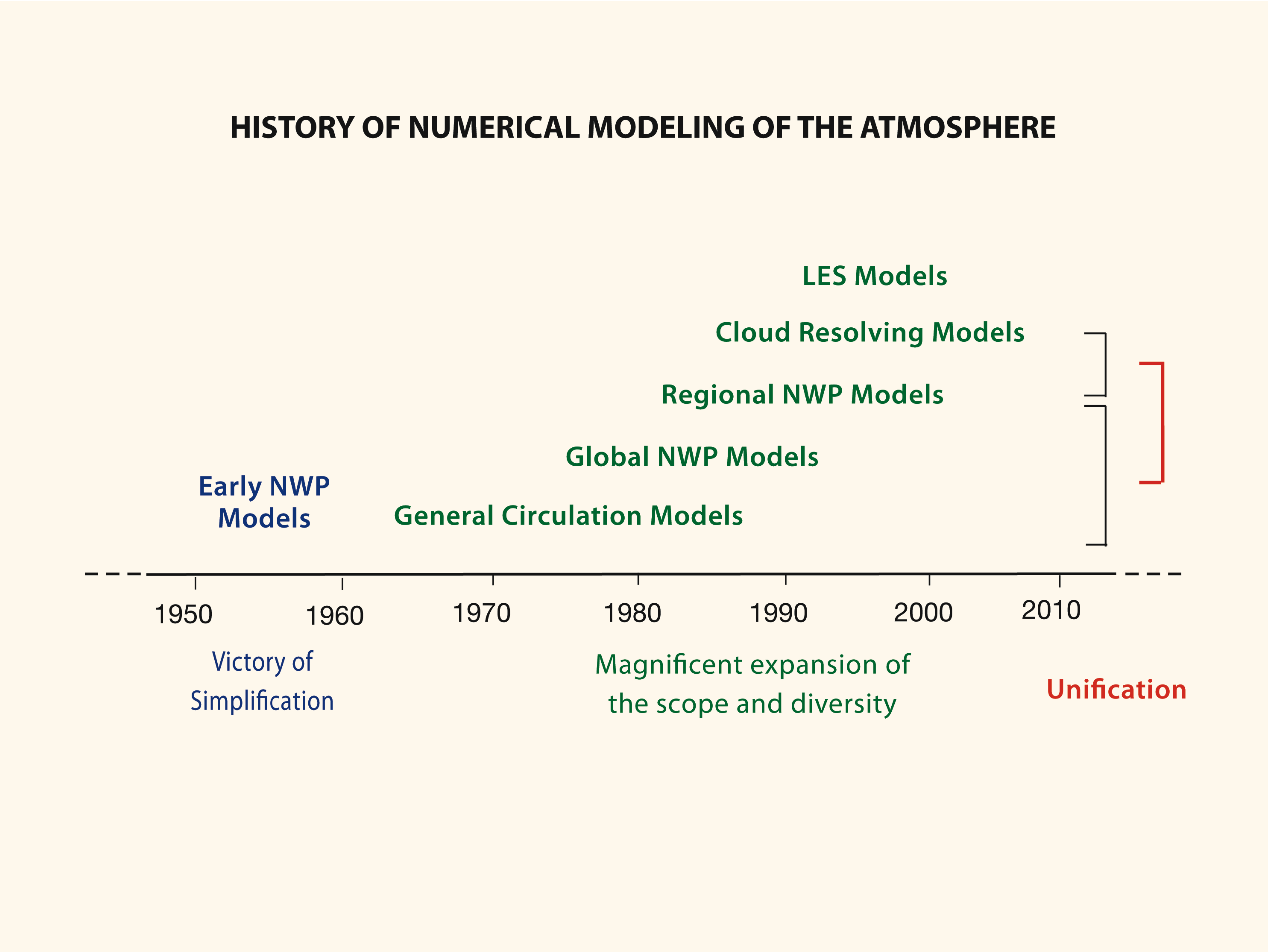
SUMMARY AND CONCLUSION

- 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.

- Our abillity of modeling the multi-scale role of cloud effects will significantly increase through comparisons of these routes with different grid sizes and GCRMs.





HISTORY OF NUMERICAL MODELING OF THE ATMOSPHERE
LES Models
Cloud Resolving Models
Regional NWP Models
Global NWP Models
Early NWP Models
General Circulation Models
1950
1960
1970
1980
1990
2000
2010
Victory of Simplification
Magnificent expansion of the scope and diversity
Unification