QUASI-3D MMF and Global CRM

Akio Arakawa

I. Unification of Physics between GCM and CRM

1. Introduction - motivation and goal
2. Strategy for development of a quasi-3D algorithm
3. Current major issues

II. Unification of Dynamics between GCM and CRM

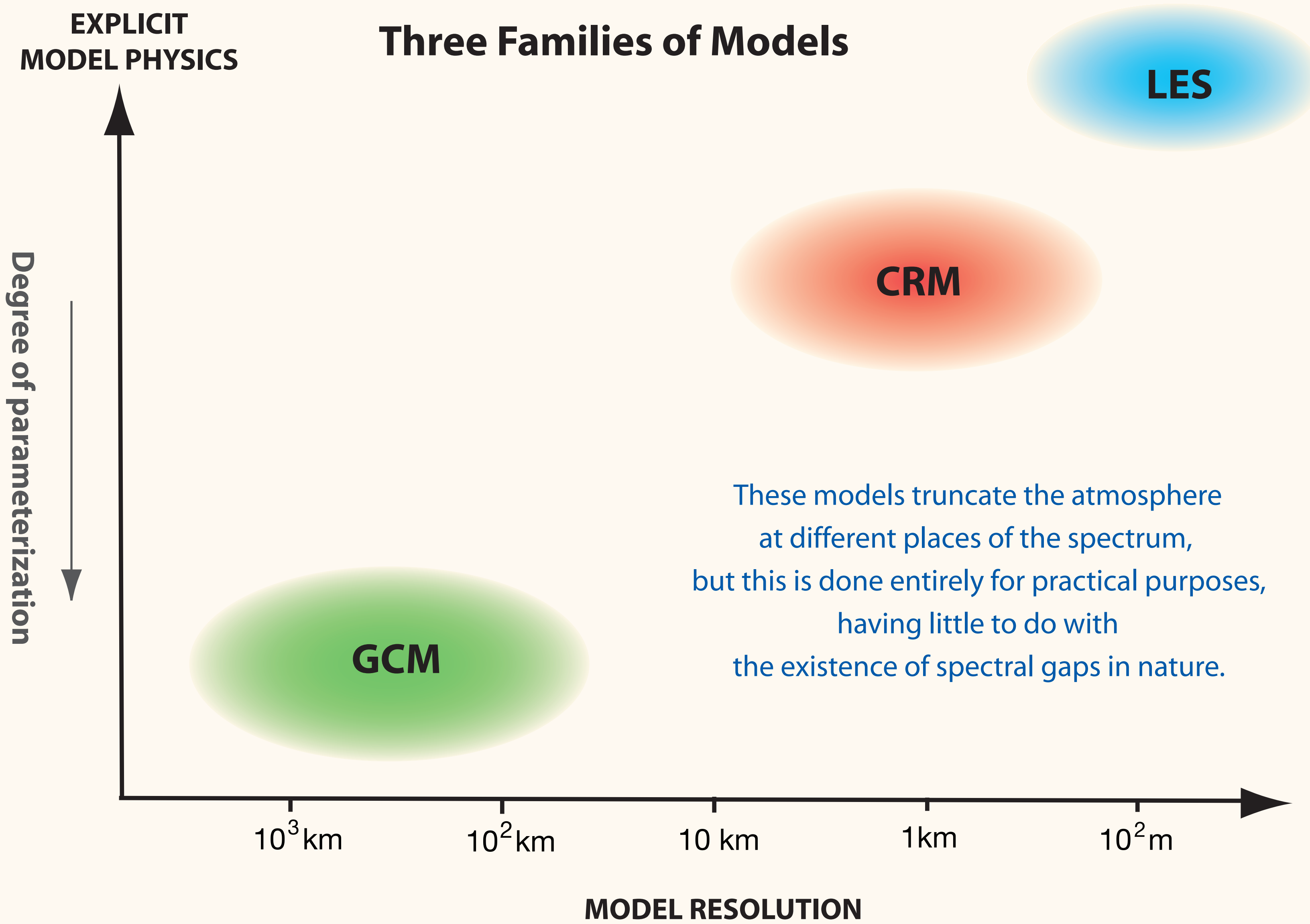
Joon-Hee Jung

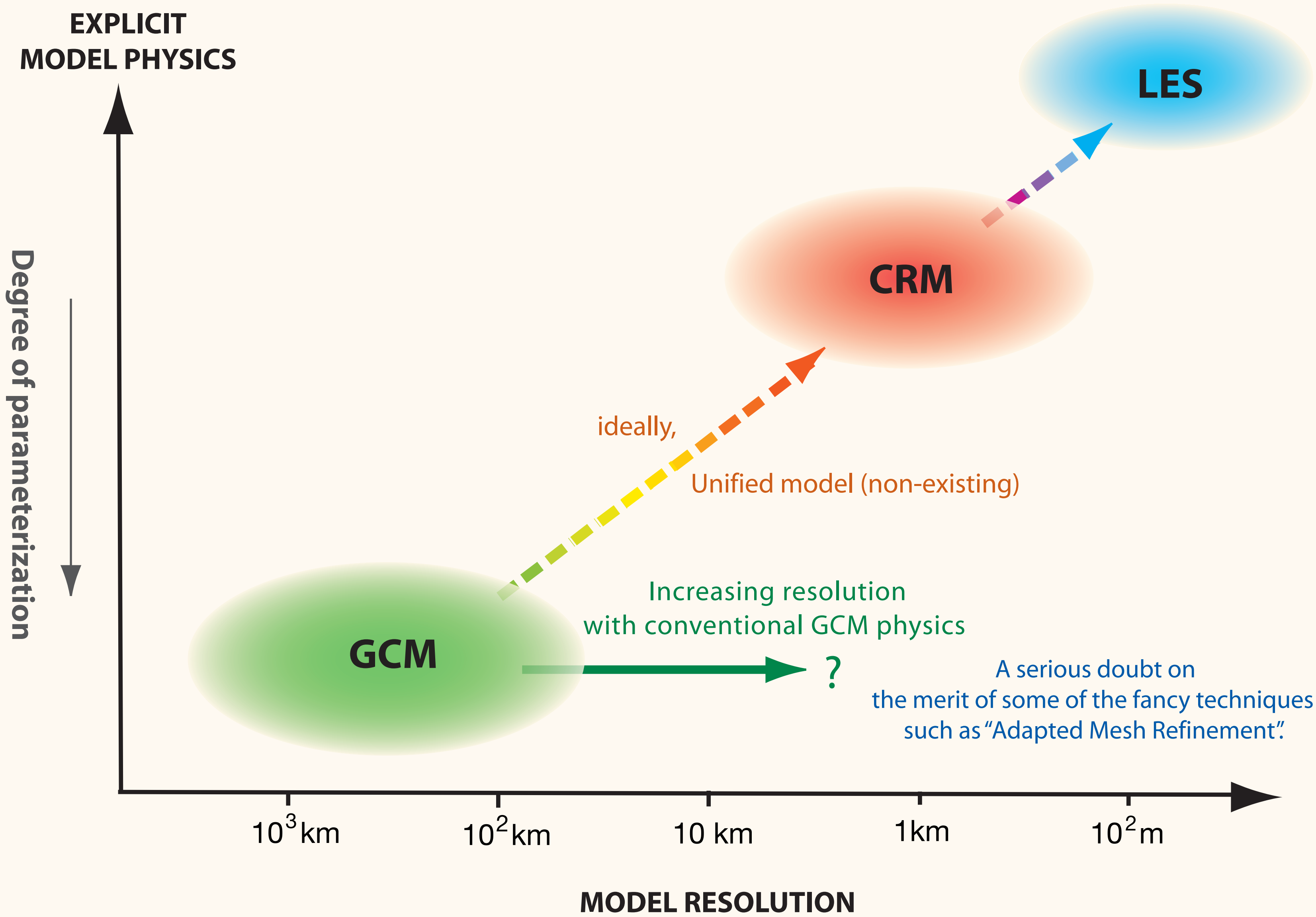
Results of preliminary experments and future plans

1. Experimental strategy, design and settings
2. Experimental Results
3. Future Plans.

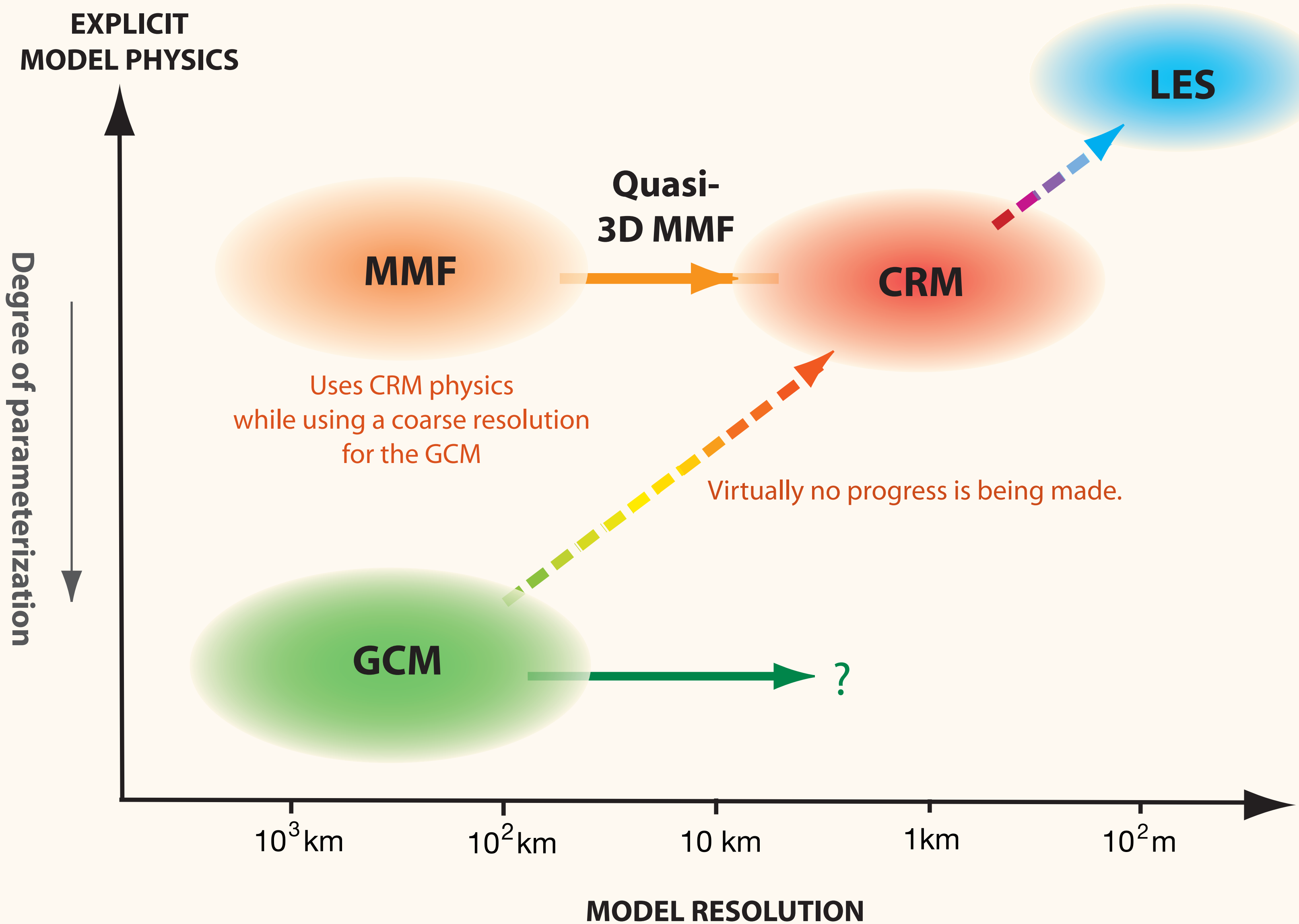
MOTIVATION AND GOAL

- Use of a discrete model can be justified only when its solution converges to the solution of the original system as the resolution is refined.
- When truncation is made in or near an energetically-active range of the spectrum, model physics must also be changed as the resolution changes.
- At present, there is no unified formulation of model physics that automatically provides such changes.
- Since the original system is 3D, a converging framework must be at least quasi-3D.

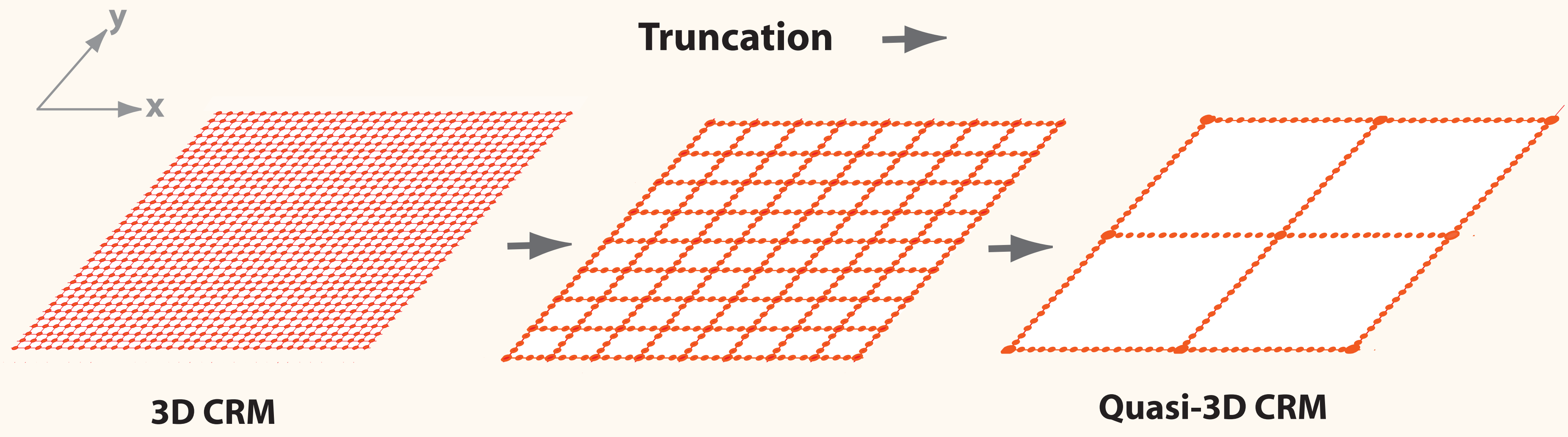

EXPLICIT
MODEL PHYSICS
Three Families of Models
LES
CRM
Degree of parameterization
These models truncate the atmosphere
at different places of the spectrum,
but this is done entirely for practical purposes,
having little to do with
the existence of spectral gaps in nature.
GCM
10³km
10²km
10 km
1km
10²m
MODEL RESOLUTION

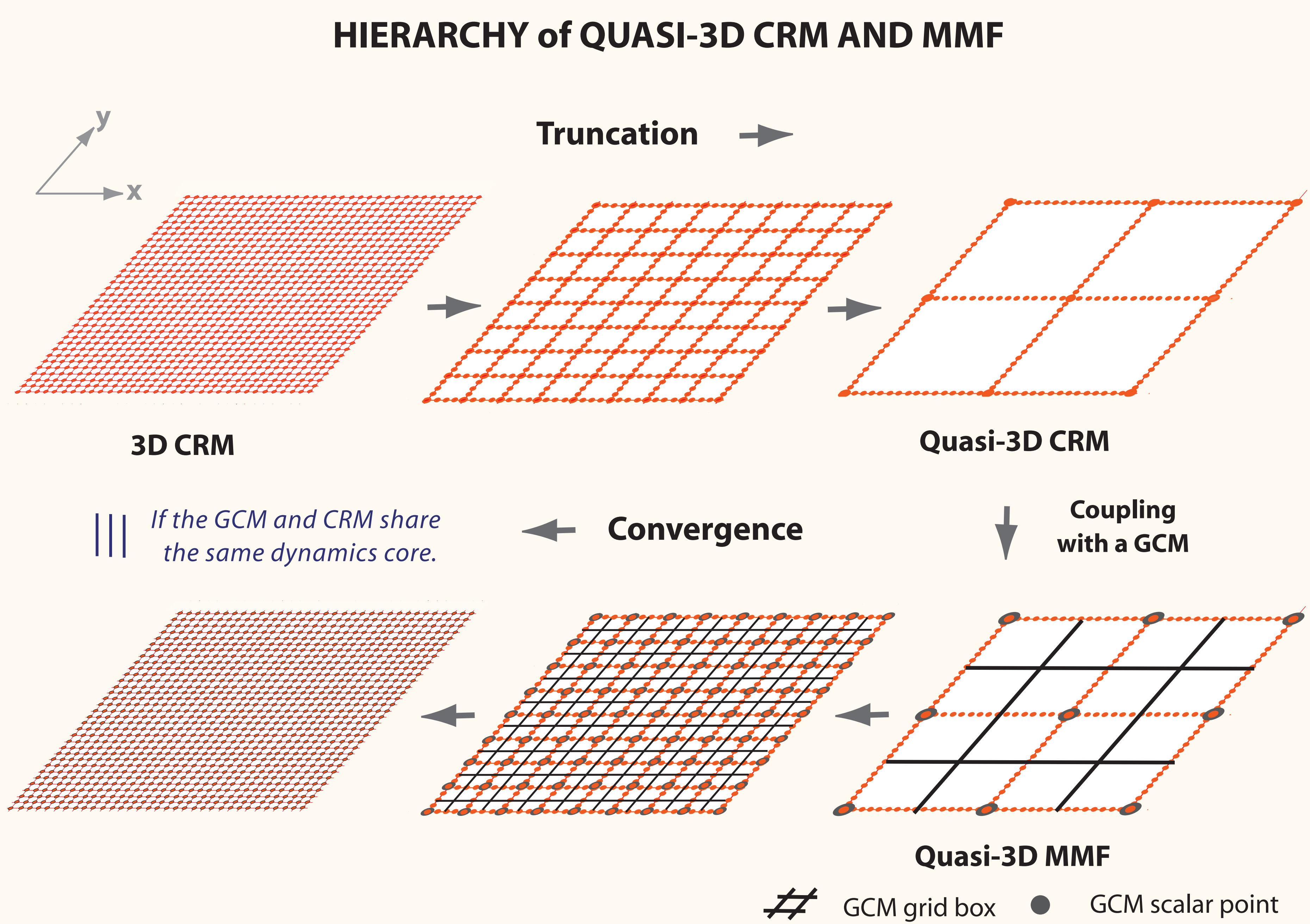


EXPLICIT
MODEL PHYSICS
Degree of parameterization
LES
CRM
ideally,
Unified model (non-existing)
GCM
Increasing resolution
with conventional GCM physics
?
A serious doubt on
the merit of some of the fancy techniques
such as "Adapted Mesh Refinement".
10^3 km
10^2 km
10 km
1km
10^2 m
MODEL RESOLUTION

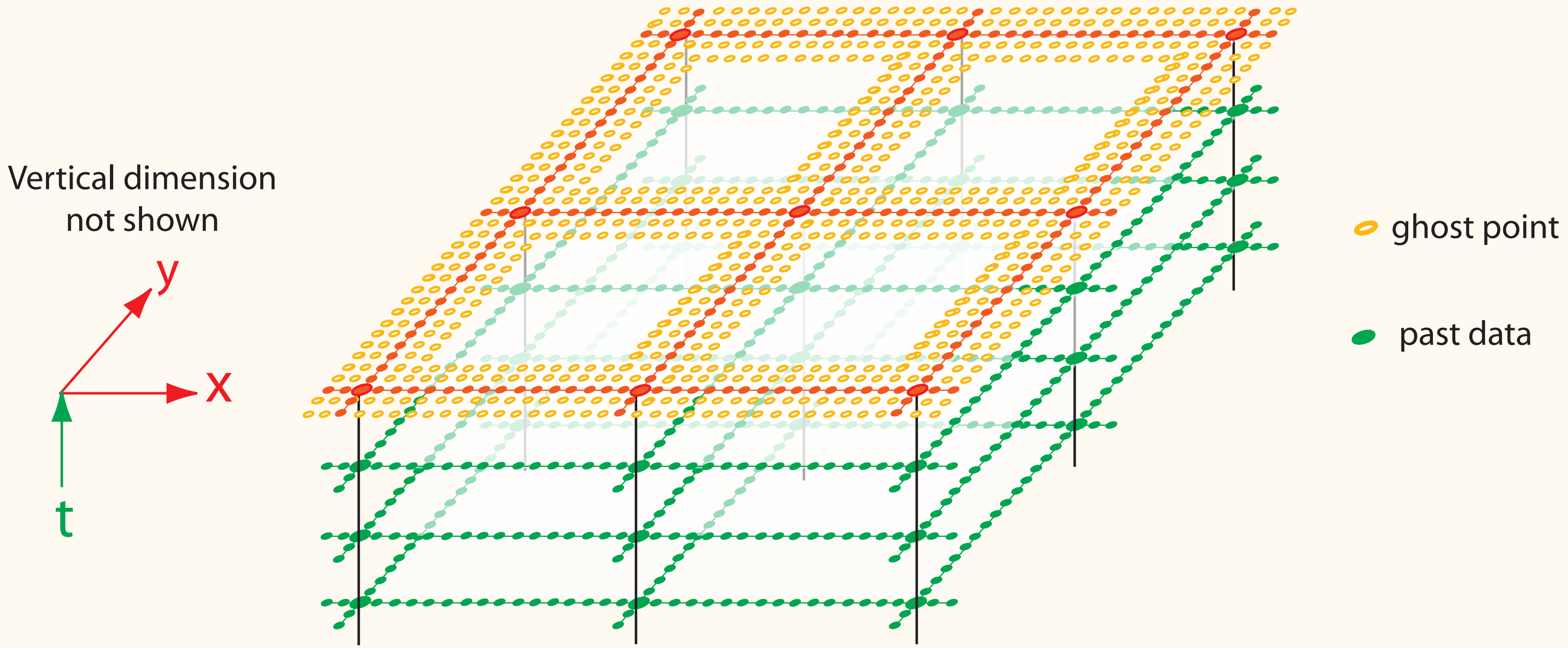

EXPLICIT
MODEL PHYSICS
Degree of parameterization
LES
Quasi-
3D MMF
MMF
CRM
Uses CRM physics
while using a coarse resolution
for the GCM
Virtually no progress is being made.
GCM
?
10^3 km
10^2 km
10 km
1km
10^2 m
MODEL RESOLUTION

HIERARCHY of QUASI-3D CRM AND MMF




HIERARCHY of QUASI-3D CRM AND MMF
Truncation
y
x
3D CRM
Quasi-3D CRM
Coupling
with a GCM
Convergence
If the GCM and CRM share
the same dynamics core.
Quasi-3D MMF
GCM grid box
GCM scalar point

Quasi-3D CRM : A prerequisite to a quasi-3D MMF



A 4D estimation/prediction problem

with a highly-anisotropic multi-resolution horizontal grid with singular points …

A treasure house of computational problems !

PATIENCE !

" If I have ever made valuable discoveries, it has been owing to patient attention, than to any other talent."

Sir Isaac Newton

CLOUD-RESOLVING ANELASTIC MODEL BASED ON THE 3D VORTICITY EQUATION

Prediction of scalar variables

Water substances (and tracer):

$$\rho_0 \frac{\partial q_x}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho_0 u q_x) + \frac{\partial}{\partial y}(\rho_0 v q_x) + \frac{\partial}{\partial z}(\rho_0 w q_x)\right] + S_{qx}$$

Potential temperature:

$$\rho_0 \frac{\partial \theta}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho_0 u\theta) + \frac{\partial}{\partial y}(\rho_0 v\theta) + \frac{\partial}{\partial z}(\rho_0 w\theta)\right] + S_\theta$$

Prediction of vorticity components

Horizontal components:

$$\rho_0 \frac{\partial \xi}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho_0 u\xi) + \frac{\partial}{\partial y}(\rho_0 v\xi) + \frac{\partial}{\partial z}(\rho_0 w\xi)\right] + \rho_0 \xi \frac{\partial u}{\partial x} + \rho_0 \eta \frac{\partial u}{\partial y} + \rho_0 \zeta \frac{\partial u}{\partial z} + S_\xi$$

$$\rho_0 \frac{\partial \eta}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho_0 u\eta) + \frac{\partial}{\partial y}(\rho_0 v\eta) + \frac{\partial}{\partial z}(\rho_0 w\eta)\right] + \rho_0 \eta \frac{\partial v}{\partial y} + \rho_0 \xi \frac{\partial v}{\partial x} + \rho_0 \zeta \frac{\partial v}{\partial z} + S_\eta$$

Vertical component:

$$(\rho_0 \zeta)_z = -\int_{z_T}^{z} \left[\frac{\partial(\rho_0 \xi)}{\partial x} + \frac{\partial(\rho_0 \eta)}{\partial y}\right] dz + (\rho_0 \zeta)_{z_T}$$

Determination of wind components

From anelasticity:

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

From the definition of vorticity:

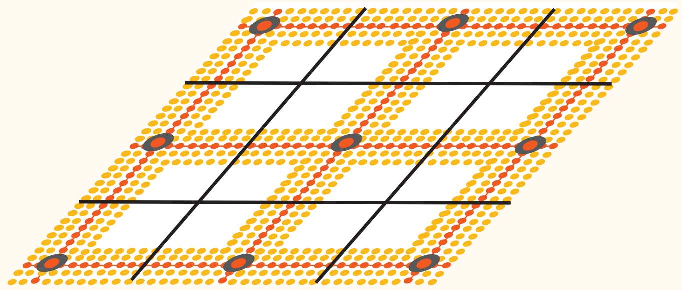
$$u = \int_{z_T}^{z} \left(\frac{\partial w}{\partial x} + \rho_0 \eta\right) dz + u_T(x,y,t) \qquad v = \int_{z_T}^{z} \left(\frac{\partial w}{\partial y} - \rho_0 \xi\right) dz + v_T(x,y,t)$$

A Problem with the Highly Anisotropic Grid :

Error imbalance between
explicitly -resolved tangential derivative and
statistically-estimated normal derivative.

The degree of imbalance is scale-dependent.

MULTI-SCALE REPRESENTATION OF VARIABLES



$$q = \bar{q} + \overbrace{q' + q''}^{q^*},$$

	$\bar{q}$	q'	q''
	BACKGROUND FIELD	COHERENT PART OF DEVIATION	NON-COHERENT PART OF DEVIATION
Typically,	synoptic-scale	cloud-system scale	cloud scale

DETERMINATION OF 3D STRUCTURES

$\bar{q}$

Determined by interpolatin
of GCM grid-point values

(Currently, this field is prescribed.)

q'

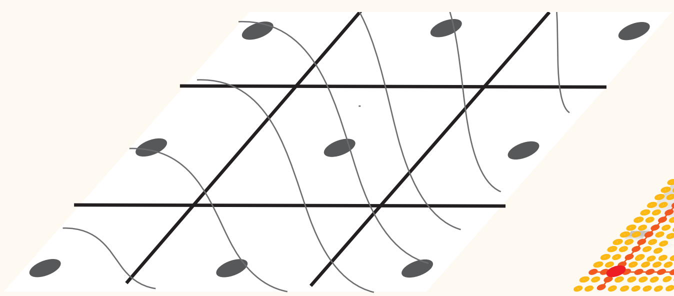
Along grid-point array:
1D Raynolds averaging of q^*

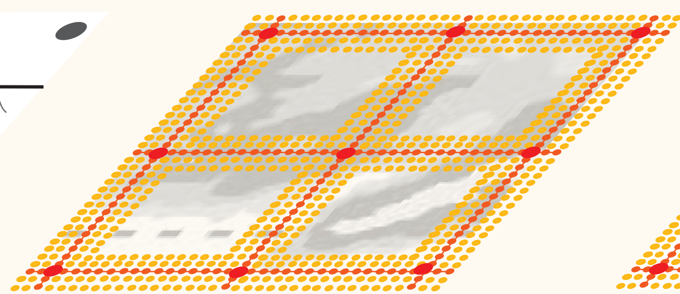
Normal to grid-point array:
By statistical Identification of cloud regime

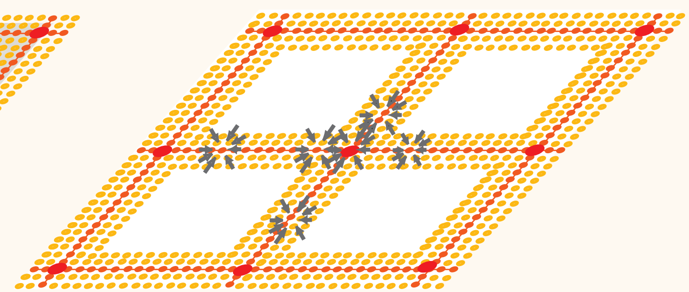
q''

Along grid-point array:
$q^* - q'$

Normal to grid-point array:
With a parameterization based on isotropy or inferred anisotropy





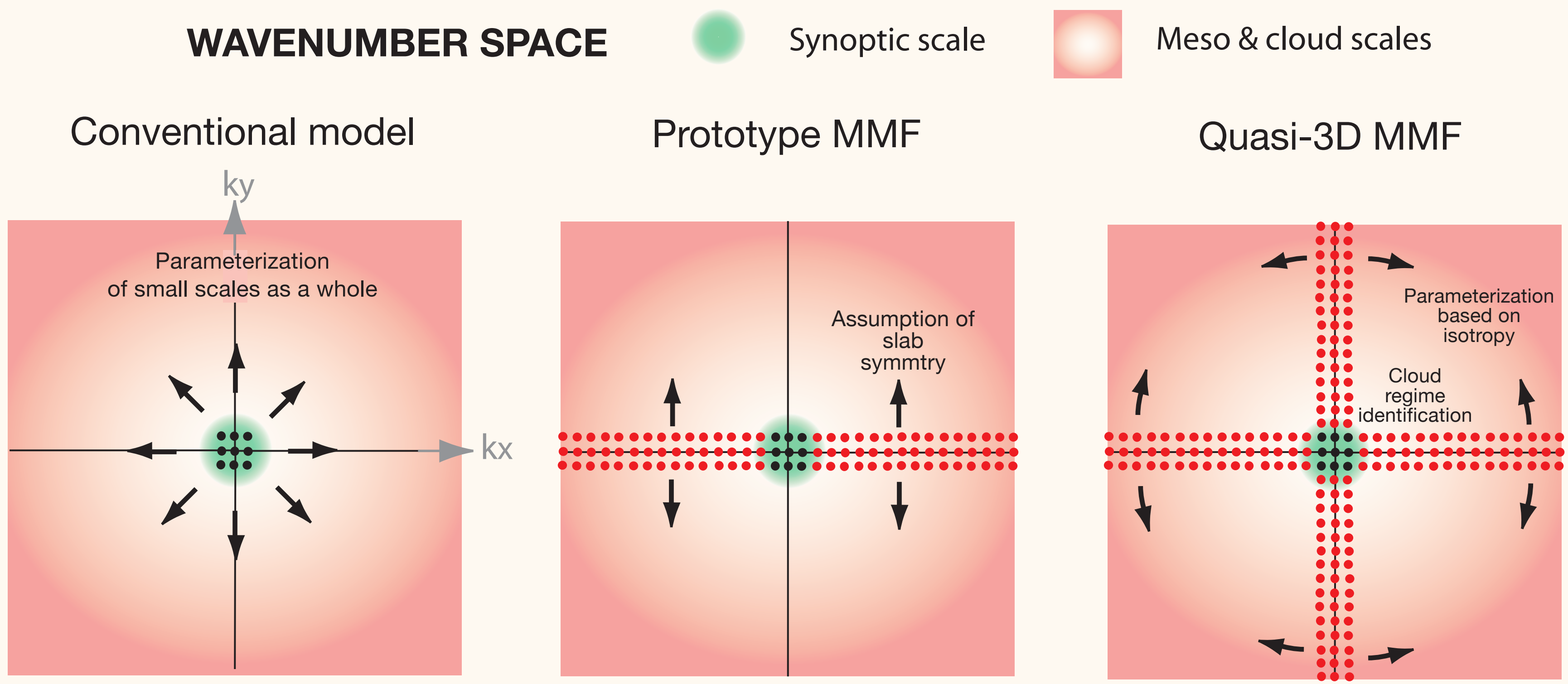


In CRMs with a horizontal resolutions of ≳1km,

parameterization problems still exist ***even for deep convection***

(due to the existence of the internal structure and ajacent small-scale processes such as entrainment, detrainment, convection in anvils, convective downdrafts, triggering due to surface inhomogeneities, etc.)

Additional parameterization problem exists in MMFs, which have cloud-scale resolution only in limited directions



Emphasis of the Development Work up to Now

$$q = \overline{q} + \overbrace{q' + q''}^{q^*},$$

"FILTERED" "NON-FILTERED"

q′

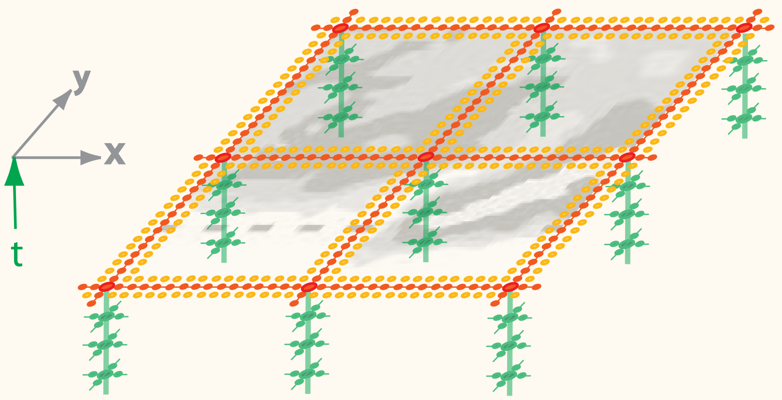
Along grid-point array:
1D Raynolds averaging of q *

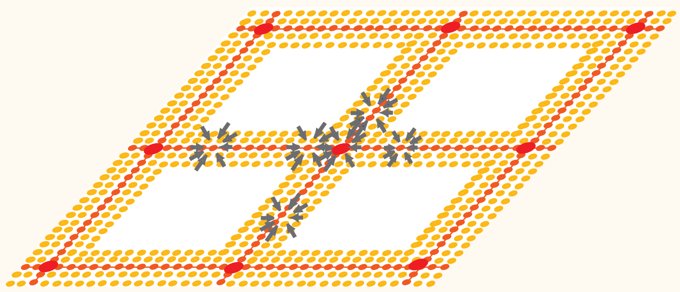
Normal to grid-point array:
By statistical Identification of cloud regime

q″

Along grid-point array:
$q^* - q'$

Normal to grid-point array:
With a parameterization based on isotropy or inferred anisotropy





- *Cloud regimes have longer spatial and temporal scales than individual clouds.*
- *Cloud regimes can be statistically inferred through regression analysis of past data at the intersection and neighboring points.*

Technical Problems in Quasi3D Advection

Computational problems

1. Global stability with 2-dimensional uniform current

2. Local stability with 3-dimensional non-uniform current

3. Control of singularity at intersections

4. Control of spurious trend

5. Control of noise

(6. Conservation)

Regression analysis of past data to identify cloud regimes

Solving 3D Elliptic Equation using the Quasi-3D Network

In anelastic models, 3D elliptic equation must be solved.

In momentum-equation models : for pressure

In vorticity-equation models : for vertical velocity

- *In our model*, the elliptic equation for w is converted to a parabolic equation whose equilibrium solution is the solution of the elliptic equation (mimicing the relaxation method).

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

- The second-order finite difference term is estimated based on ghost point values given by

w′ : Statistically estimated as in advection

w″ : Currently assumed to be zero

- No local deformation of the horizontal vorticity vector for cloud scale.

Problem with the Stretching and Twisting Terms in the Vorticity Equation

$$\rho_0 \frac{\partial \xi}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho_0 u\xi) + \frac{\partial}{\partial y}(\rho_0 v\xi) + \frac{\partial}{\partial z}(\rho_0 w\xi)\right] + \underline{\rho_0 \xi \frac{\partial u}{\partial x}} + \underline{\rho_0 \eta \frac{\partial u}{\partial y} + \rho_0 \zeta \frac{\partial u}{\partial z}} + S_\xi$$

$$\rho_0 \frac{\partial \eta}{\partial t} = -\left[\frac{\partial}{\partial x}(\rho_0 u\eta) + \frac{\partial}{\partial y}(\rho_0 v\eta) + \frac{\partial}{\partial z}(\rho_0 w\eta)\right] + \underline{\rho_0 \eta \frac{\partial v}{\partial y}} + \underline{\rho_0 \xi \frac{\partial v}{\partial x} + \rho_0 \zeta \frac{\partial v}{\partial z}} + S_\eta$$

stretching twisting

- These terms, which are responsible for enstrophy increase and energy cascade in 3D flow, are missing in 2D models.

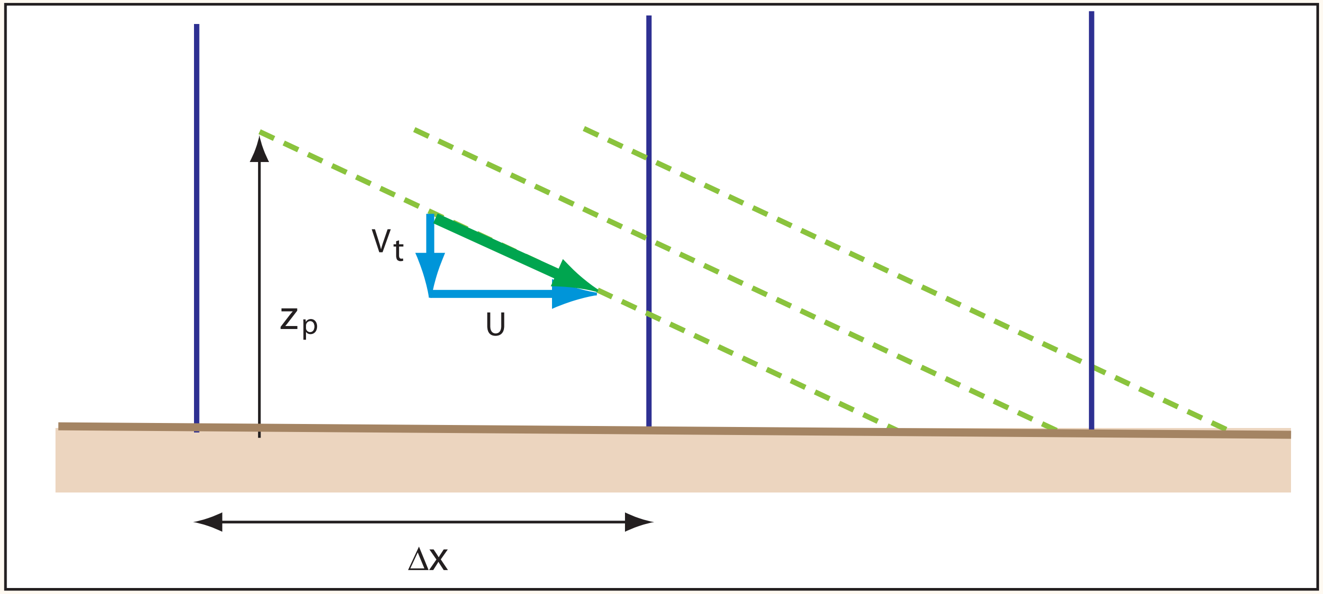
- The Q3D CRM includes these terms.
  - Fully for filtered scale (i.e., for cloud-system scale) vorticity;
  - Partially for non-filtered scale (i.e., individual cloud scale) vorticity by neglecting the effect of local deformation on this scale.

- The enstrophy increase and energy cascade must be balanced by dissipation on average. So far we have not found a satisfactory formulation of the dissipation for the quasi-3D network.

Dilemma

Too strong dissipation : Inactive dynamics
Too weak dissipation: Blowing up

Horizontal Advection of Precipitates in 3D CRM



If $\Delta x < \frac{U}{V_t} z_p \sim 10$ km, horizontal advection of precipitates must be explicitly formulated.

Lagrangian view: All precipitates in the column move into the next column before reaching ground.

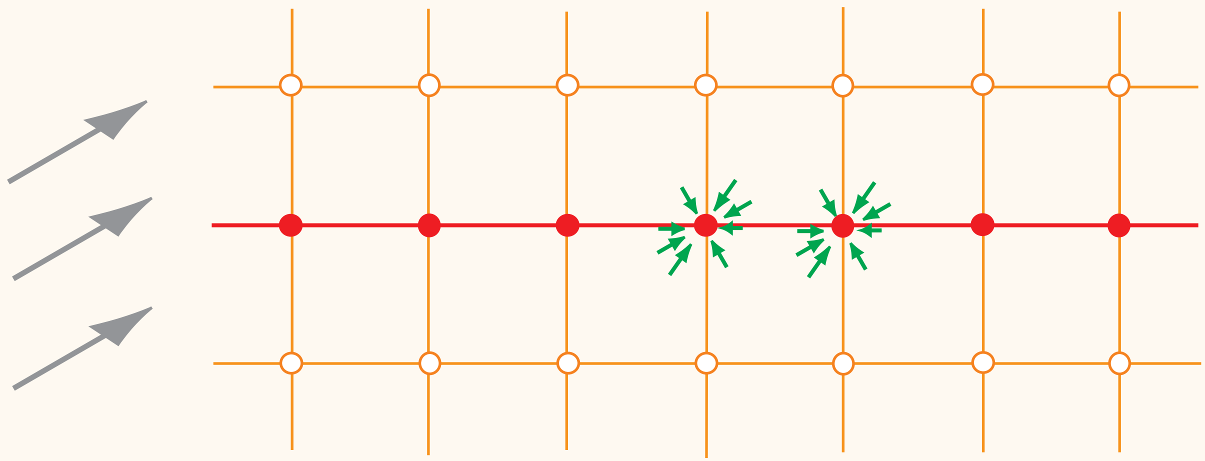
Eularian view: Air of the column is entirely replaced by the upwind-side precipitate-free air.

- If the precipitating system is poorly resolved (e.g., if $\Delta x \gtrsim 1$ km) by an Eulerian grid, serious dispersion error may qppear.
- Consequently, a significant part of the precipitates can be left in the original column, which tends to evaporate as a result of drier-air inflow.

Thus in a CRM with $1\ \text{km} \lesssim \Delta x < \frac{U}{V_t} z_p \sim 10\ \text{km}$, *the area average of precipitate due to convection tends to be under-predicted, and the humidity of the convective column tends to be over-predicted, eventually producing stratiform rain.*

These tendencies can be exaggerated in a Q3D CRM through

- Under-estimation of the precipitate mixing ratio at the up-wind side due to the use of statistics including non-precipitating cases.
- Overestimation of the normal component of velocity.



In our tets, generally the variance of water-vapor mixing ratio over the grid points tends to be over-predicted and those of rain/graupel mixing ratios tend to be under-predicted.

Unification of Dynamics between GCM and CRM

Two possibilities :

(1) Use of the fully-compressible nonhydrostatic system of equations for both.

(2) Use of a generalized anelastic system of equations for both, with compressibility included only for quasi-static motions.

neglected in the anelastic system

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0$$

$$\frac{\partial \rho}{\partial t} = \left(\frac{\partial \rho}{\partial p}\right)_{\theta} \frac{\partial p}{\partial t} + \left(\frac{\partial \rho}{\partial \theta}\right)_{p} \frac{\partial \theta}{\partial t}$$

compressibility — *Included with hydrostatic approximation*

thermal expansion — *fully included*

This system automsticly becomes the primitive equation model for large scales.