THE ROLE OF SUPER-PARAMETERIZATION IN THE CLOUD PARAMETERIZATION PROBLEM

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A PRELIMINARY TEST OF SUPER-PARAMETERIZATION IN AN IDEALIZED FRAMEWORK

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Historical Assessment

Arakawa, A., 2003: The Cumulus Parameterization Problem: Past, Present, Future
(To be submitted to JC)

- GCMs that use cumulus parameterizations constructed with quite different rationale can still produce "comparable" results.
- Thus, cumulus parameterization did not seem to be too demanding problem.
- All surviving cumulus parameterizations can do the simple basic task:
  Providing a negative feedback to large-scale destabilization.
- This negative feedback tends to hide model differences and deficiencies, especially when SST is fixed.

We cannot continue to rely on this kind of "luck"
in future climate models
as the objectives of cumulus parameterization expand.

OBJECTIVES OF CUMULUS PARAMETERIZATION

Classical Objective

Vertical distributions of cumulus heating (cooling) and cumulus drying (moistening).

Nonclassical Objectives

(i) Generation, transport and mixing of liquid and ice phases

(ii) Interactions with the subcloud layer

(iii) Interactions with radiation

(iv) Mechanical interactions with the mean flow

↓

Unified cloud (or even unified physics) parameterization

DILEMMA

- Unified cloud parameterization is an extremely challenging scientific problem of scale interactions in the moist atmosphere.
- It is a crucially important engineering problem in weather and climate predictions, for which quick answers are needed.

The struggle in our mind
between the scientific and engineering aspects
is at least partially responsible for
the slow progress of each in the past.

Now it is the time to recognize the two as separate (but complementary) aspects.

Scientific aspect ⟷ **Engineering aspect**

↑ ↑

maximum use of brain power | maximum use of computer power

Parameterize everything! | Resolve everything !

MAJOR PROBLEMS IN CONVENTIONAL MODEL PHYSICS

Major Conceptual Problems

(a) Artificial scale separation by discretization

Discretization introduced for computational purpose separates scales for explicit processes, which can be highly transient, and implicit (parameterized) processes, which can only be near statistical equilibrium. This is especially serious for processes involving clouds.

(b) Incomplete interactions between different physical processes

Due to the modular structure of models, different physical processes (cloud microphysics, radiation, turbulence, etc.) interact mainly through resolved scales, missing most of their small-scale transient interactions.

(c) Non-convergence to "real physics"

Conventional model physics does not converge to local and instantaneous "real physics" as the grid size and time interval approach zero.

The Most Fundamental Technical Problem

Lack of an appropriate cloud-system model (as opposed to a model for individual clouds) to be used as a basic framework

"REAL SOURCES" vs. "REQUIRED SOURCES"

(For prognostic variable $\square$)

Local and instantaneous governing equation:

$$\frac{\partial \square}{\partial t} = \square \ \mathbf{V} \cdot \square \ \square \quad + \text{"real sources"} \qquad (1)$$

Model's governing equation:

$$\frac{\partial \overline{\square}}{\partial t} = \square \ \overline{\mathbf{V}} \cdot \square \ \overline{\square} \quad + \text{"required sources"} \qquad (2)$$

$\overline{}$: space/time averaging

For (2) to be consistent with $\overline{(1)}$,

$$\text{"required sources"} = \overline{\text{"real sources"}} + \overline{\mathbf{V}} \cdot \square \ \overline{\square} \ \square \ \overline{\mathbf{V} \cdot \square \ \square}$$

implicit component of advection

(diffusive, penetrative, or . . .)

Thus, "required physics" is

more than the time/space average of "real physics".

"REAL CLOUD-MICROPHYSICAL SOURCES

vs.

"REQUIRED CLOUD-MICROPHYSICAL SOURCES

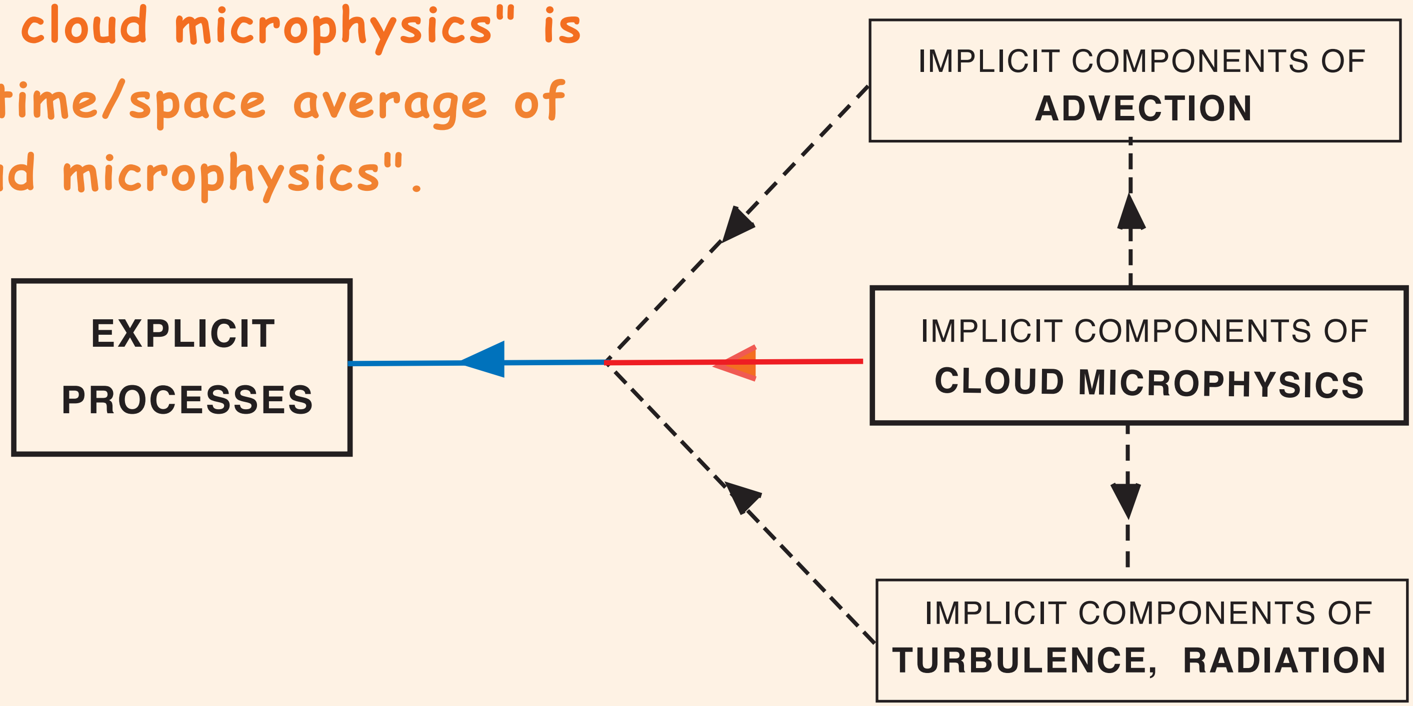
Similarly to the total physics case,

"required cloud-microphysical sources"

= "real cloud-microphysical sources" (with an overbar)

\+ implicit components of advection, turbulence & radiation effects *induced by cloud microphysics*

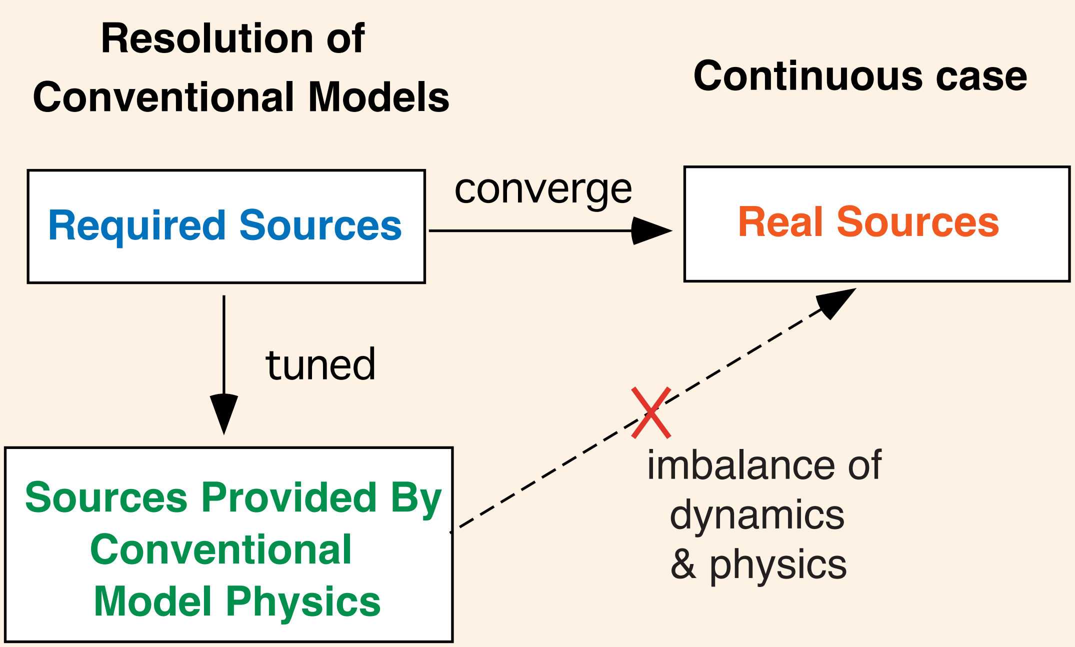
Thus, "required cloud microphysics" is more than the time/space average of "real cloud microphysics".



THE CONVERGENCE PROBLEM

Justification for use of a discrete model relies on the hope that its solution converges to the true solution as the resolution is refined.

- "Required sources" for a discrete model to be correct are more than the time/space means of local instantaneous sources ("real sources").
- Naturally, "required sources" converge to the "real sources" as the resolution is refined.
- Conventional model physics is designed and tuned to provide "required sources" for a particular resolution, not those as functions of resolution.



An Example of Non-Convergence

A simple cumulus parameterization (no detrainment, no downdraft, etc.)

Cumulus warming: $Q_{1c} \sim M_c\, \partial s/\partial z$

Cumulus drying: $Q_{2c} \sim -M_c\, L\, \partial q/\partial z$

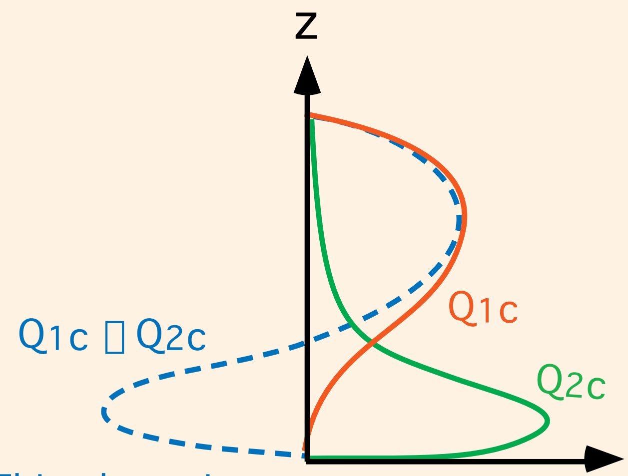
M_c: cumulus-induced subsidence

s: dry static energy

Source of moist static energy:

$Q_{1c} - Q_{2c} \sim M_c\, \partial h/\partial z$

h: moist static energy

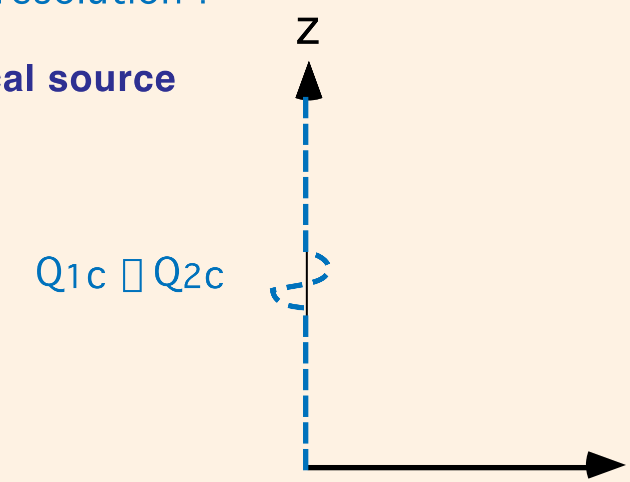


This shape is independent of resolution !

Real (i.e.,local & instantaneous) cloud-microphysical source of moist static energy

$Q_{1c} - Q_{2c} \sim 0$

except where ice-phase is involved.



Resolution Dependency of Model Physics

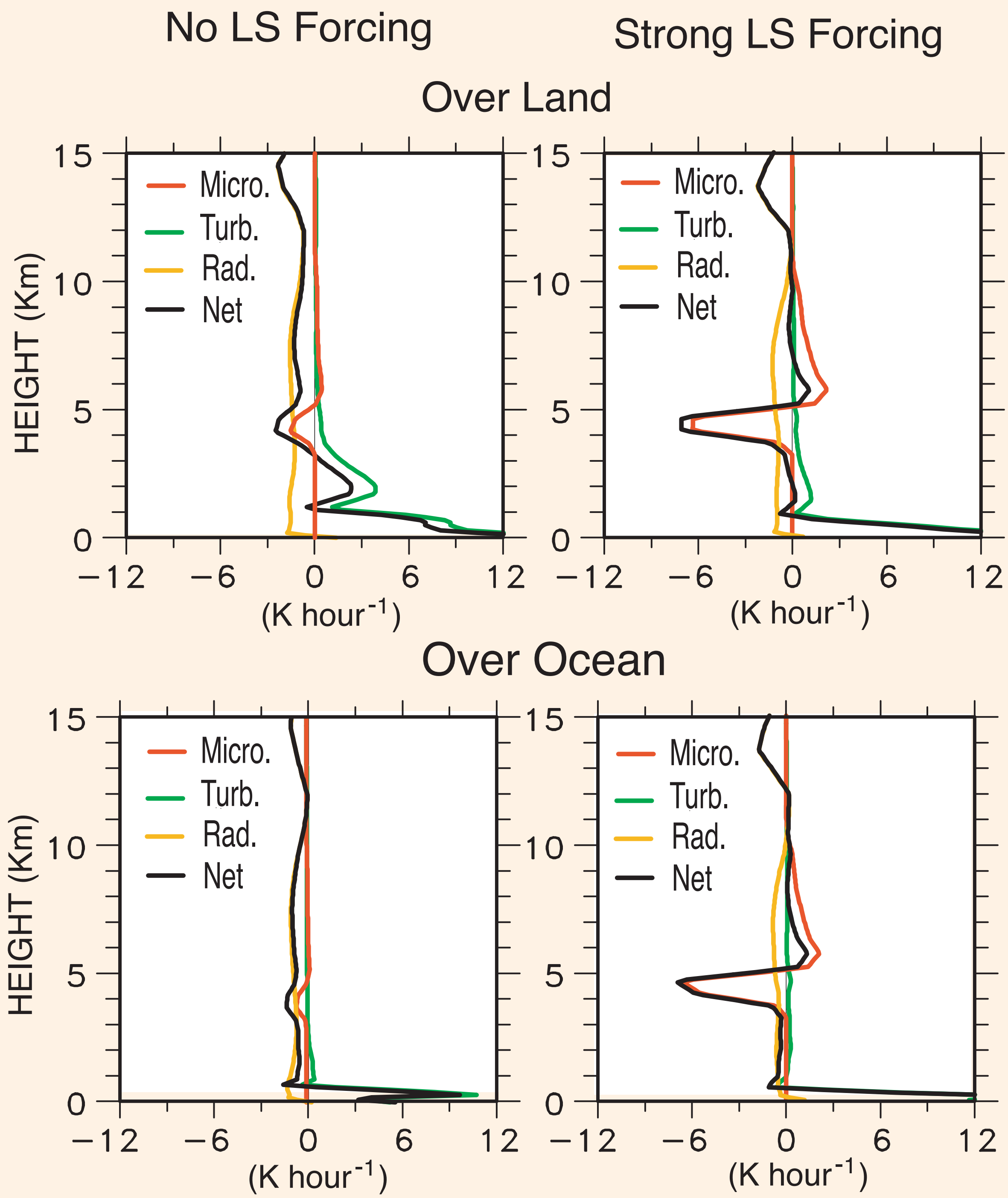
Inferred from Nonhydrostatic Model Experiments

(Jung and Arakawa 2002, submitted to JAS)

- APPLICATIONS OF UCLA/U-UTAH/CSU 2-D CRM to a variety of idealized tropical conditions
- CONTROL RUNS with 2-km horizontal resolution and full physics
- LOW-RESOLUTION RUNS WITH NO OR PARTIAL PHYSICS over a short time interval from selected realizations in CONTROL.
- DIAGNOSIS OF "REQUIRED SOURCES" for the low-resolution model to be correct as far as resolved scales are concerned

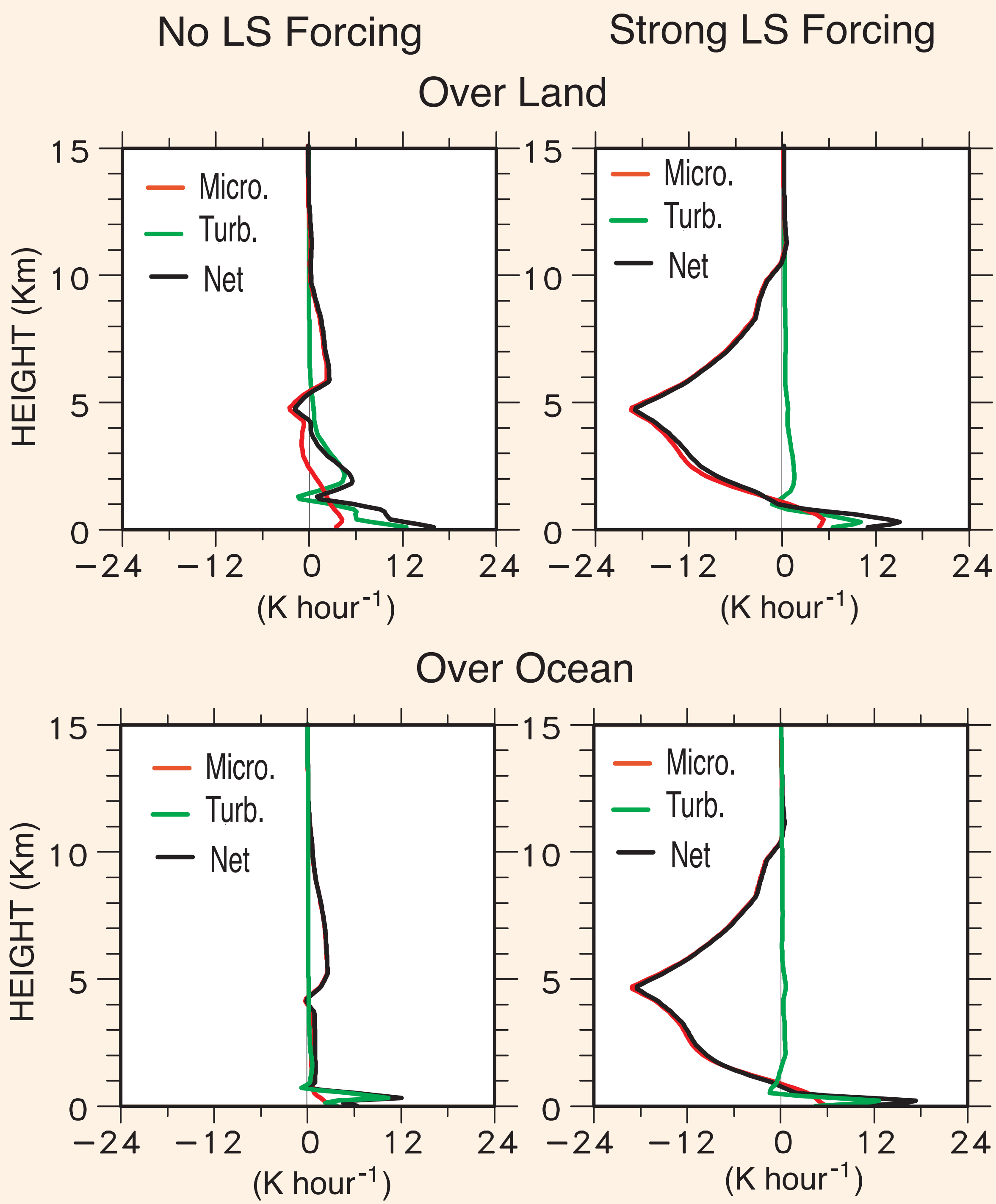
Time/Domain Average Profiles of "Real Sources"

Moist Static Energy



Time/Domain Average Profiles of "Real Sources"

Total Water Mixing Ratio

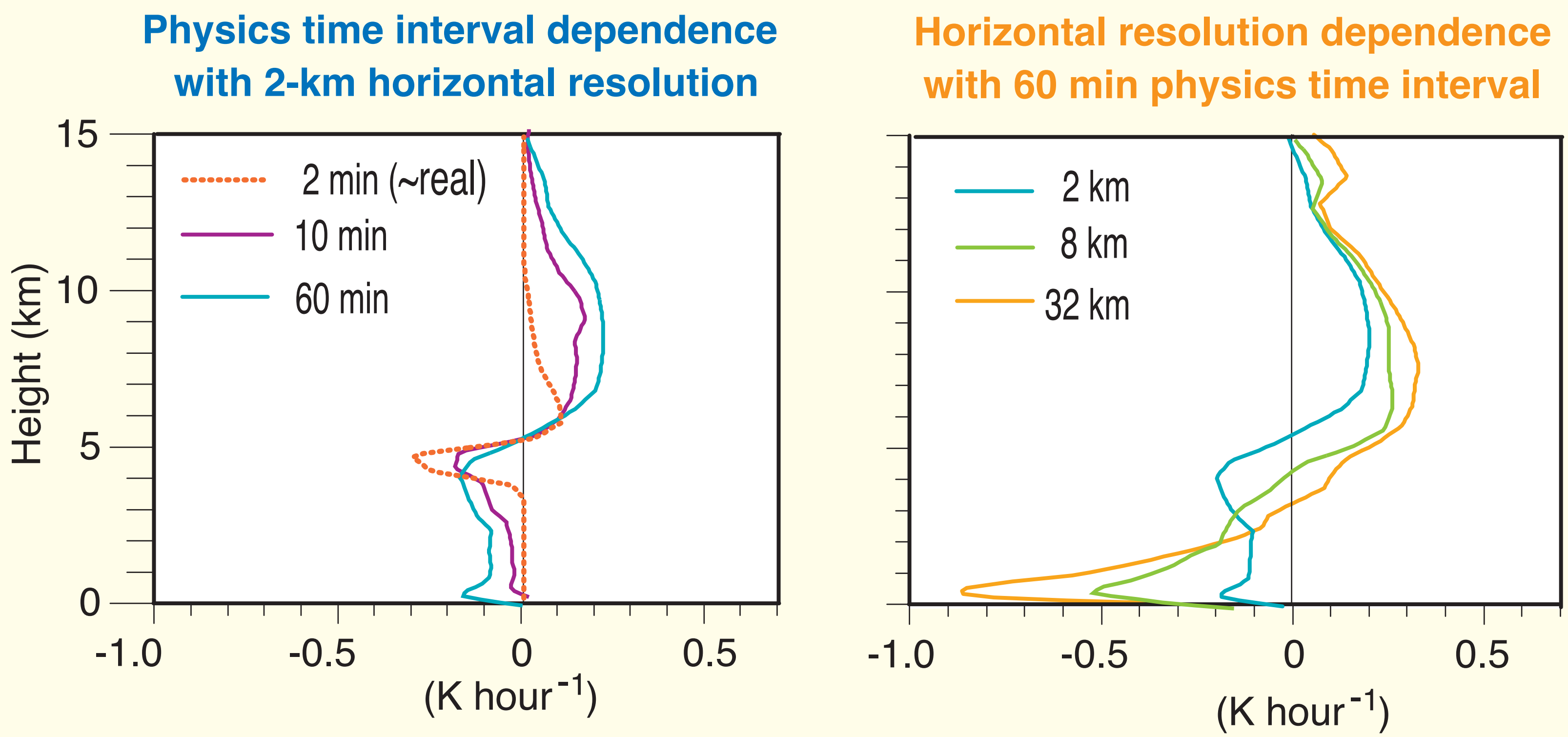


Domain/Ensemble Average Profiles of "Required Cloud-Microphysical Sources"

(From Jung and Arakawa 2002)

Strong LS forcing over land, late afternoon hours

Moist Static Energy



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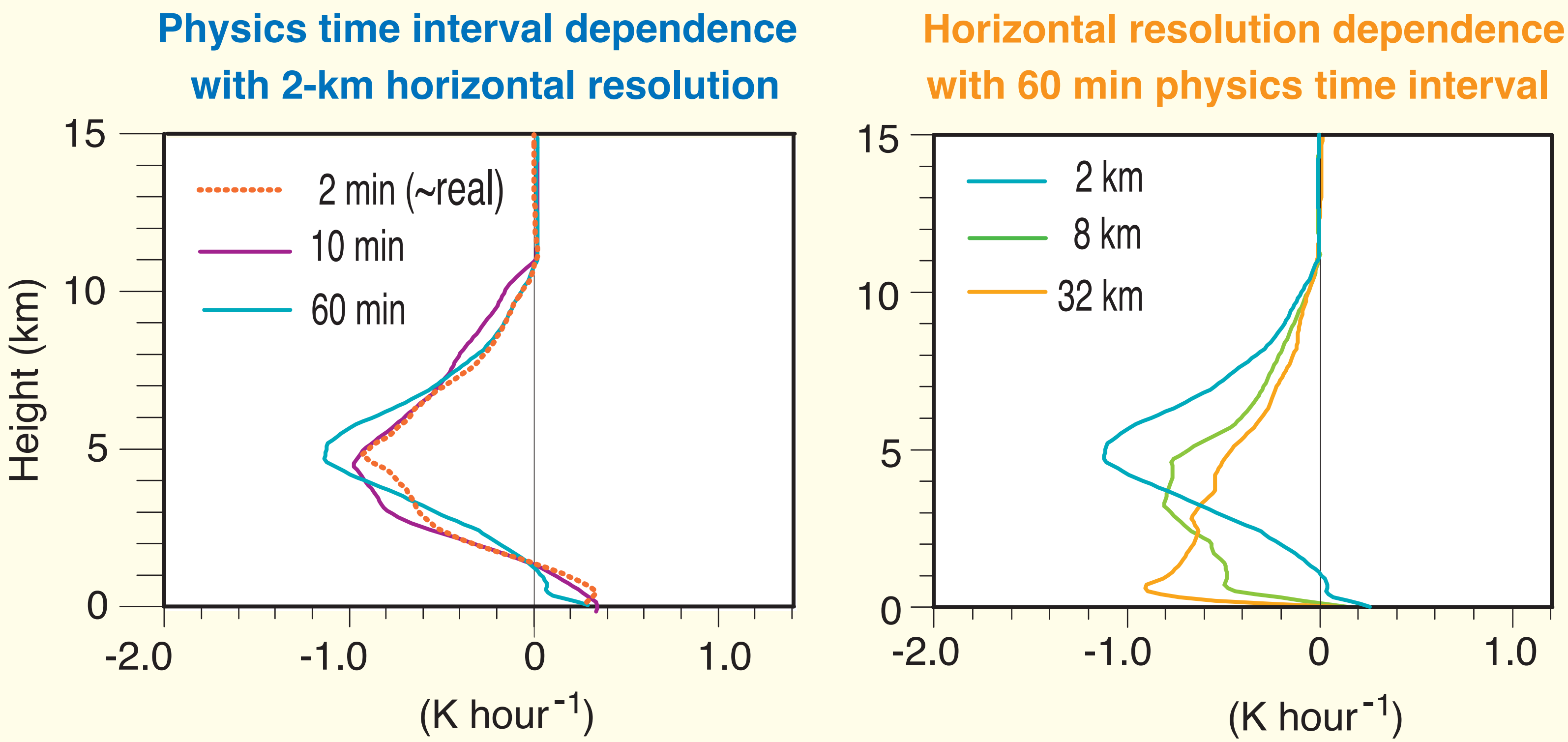

Domain/Ensemble Average Profiles of "Required Sources due to Total Physics"

(From Jung and Arakawa 2002)

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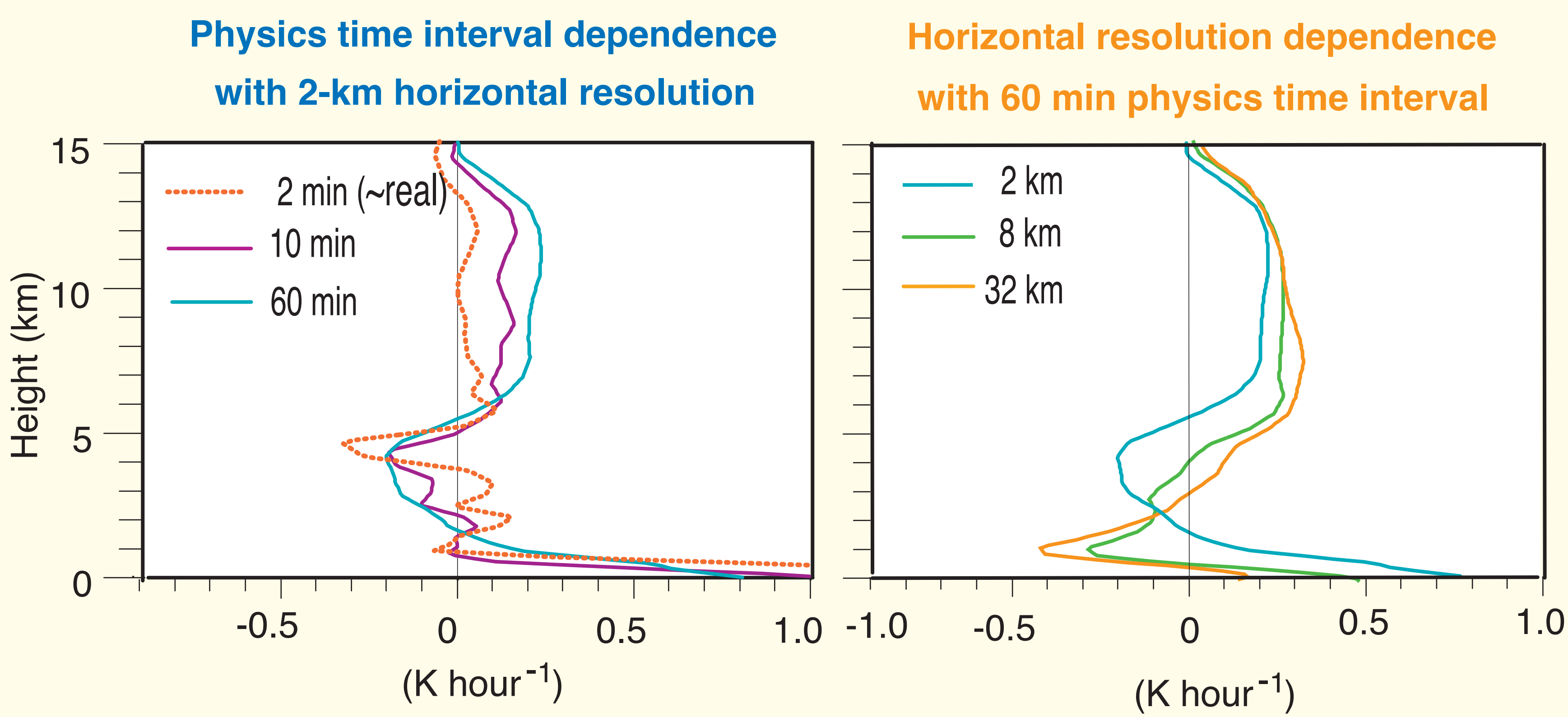
Moist Static Energy



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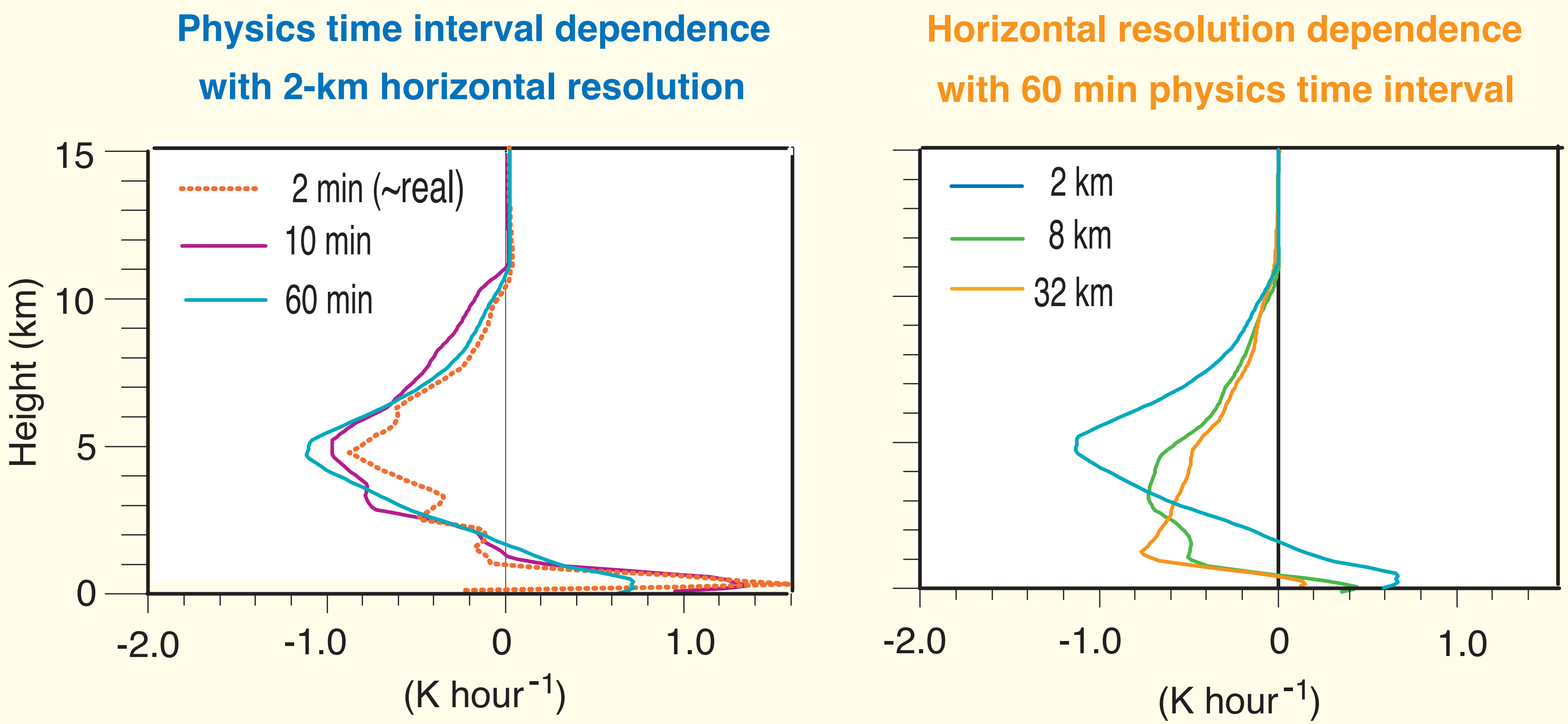


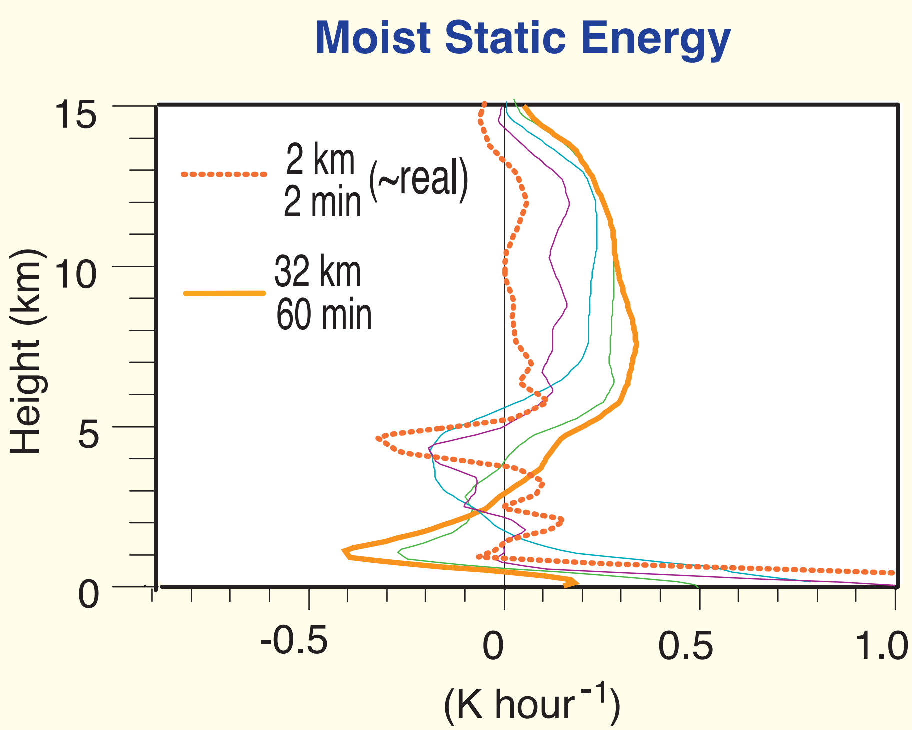
TWO BASIC PHYSICS

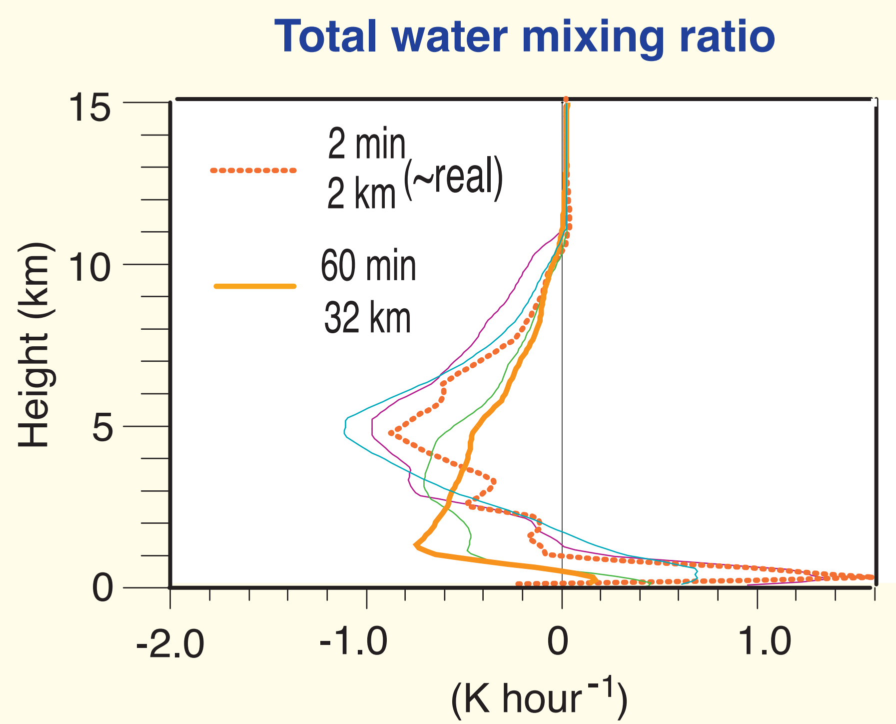
"Real physics" (approximately given by ·········)

Needs a good model for local & instantaneous physics

Idealized "parameterized physics" (approximately given by ——)

Needs a good model for cloud systems





Cloud Model as a Framework for Cloud Parameterization

Currently we only have

- **For cumuliform clouds based on column physics** (with typical examples)

cloud type / cloud model	single	sequential multiple	parallel multiple
none	Manabe et al., Betts & Miller		
simple	Kuo-type and most mass-flux schemes	Moorthi & Suarez	Arakawa-Schubert Ding & Randall
detailed	Most schemes for mesoscale models	Kreitzberg & Perkey	none

- **For stratiform clouds based on layer physics** (with typical examples)

  Sundqvist, Tiedke, etc.

- **For unified cumuliform and stratiform clouds**

  none

For the cloud parameterization problem,
we need a cloud-system model including
[cloud]-[environment], [cloud]-[cloud],
[cloud processes]-[other processes] interactions,
rather than a model for individual clouds.

**Even in the "traditional" approach,
a non-traditional cloud-system model is needed.**

**A brute-force approach, such as "super parameterization"
is required to satisfy the practical need
and to help developing appropriate cloud-system models.**

"Cloud-Resolving Convective Parameterization" or "Super-Parameterization"

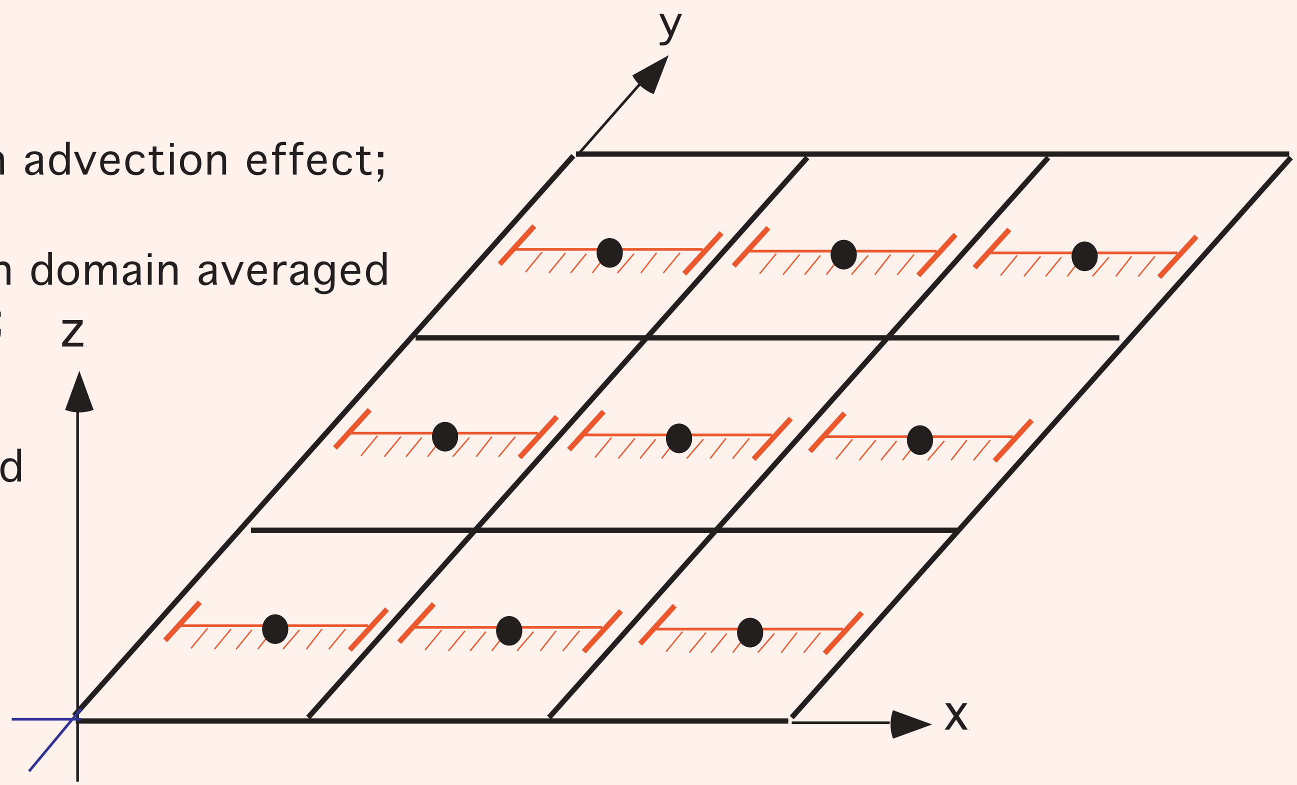
Grabowski (2001), Khairoutdinov and Randall (2001)

At the ● points:

GCM forces CSRM through advection effect;

CSRM forces GCM through domain averaged thermodynamic variables;

Velocity components of GCM and CSRM are nudged to each other.

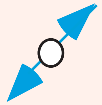


An excellent compromise between a global 3D CSRM and practicality.

However,

- Two neighboring CSRMs can communicate only through the GCM;
- As the GCM grid size approaches zero, each CSRM converges to a 1D cloud model with no vertical velocity.

A "Quasi-3D" Version with a Revised Coupling

At the  and  points:

GCM and two CSRM interact through velocity components sharing (approximately) the same fluxes.

At the ● point:

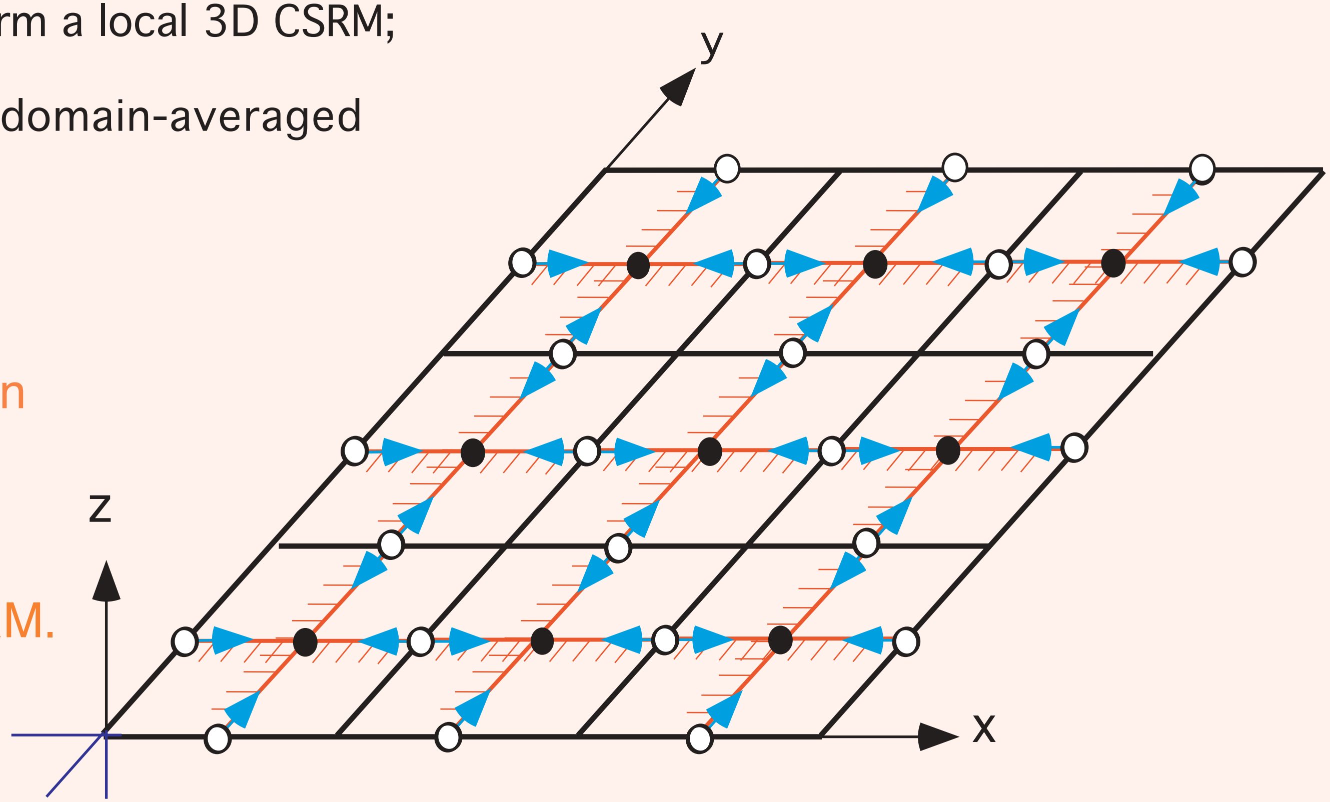
Two CSRM are coupled to form a local 3D CSRM;

CSRM forces GCM through domain-averaged thermodynamic variables.

Advantages:

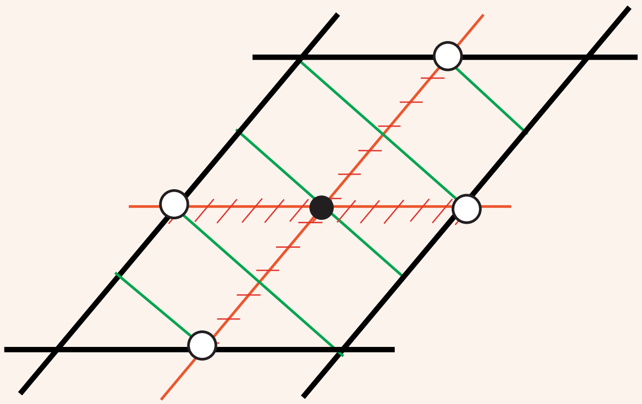
Relaxed boundary condition for the CSRMs.

Convergence of the entire system to a global 3D CSRM.



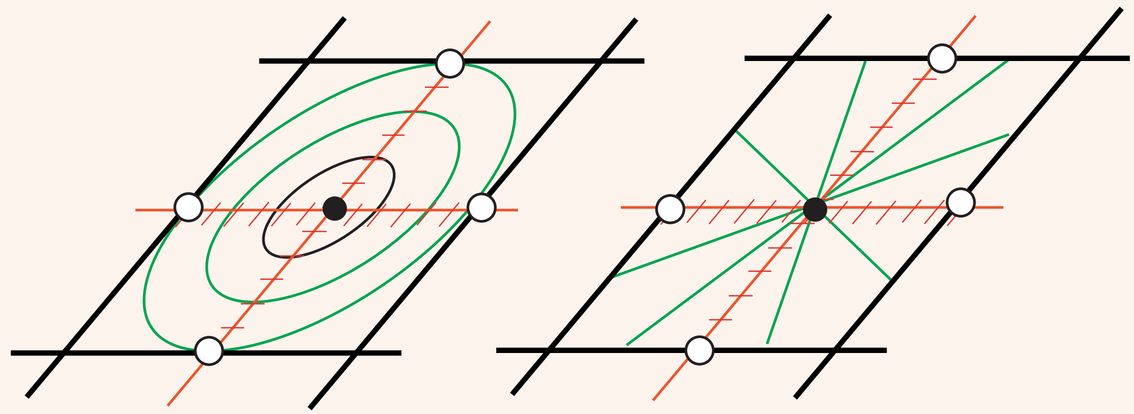
Patterns for the Largest-Scale within a GCM Grid Box
Recognizable by
the Quasi-3D Super-Parameterization

Propagating near-parallel flow
with arbitrary orientation

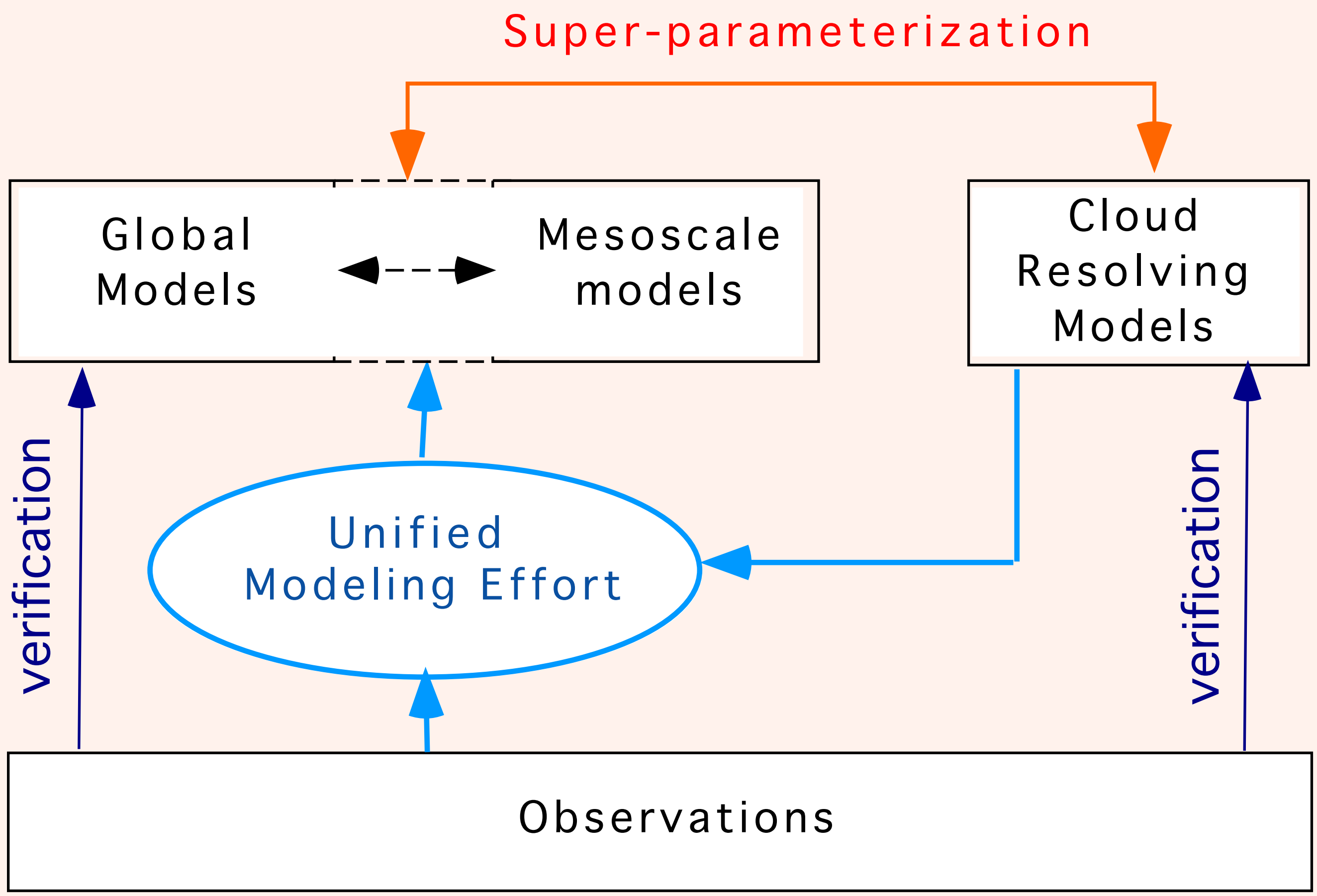


Advantageous from the point of view
of momentum transport

Stationary, nearly axi-symmetric flow



Advantageous from the point of view
of convergence to 3D CSRM



Beginning of a Great Challenge

in Atmospheric Science !