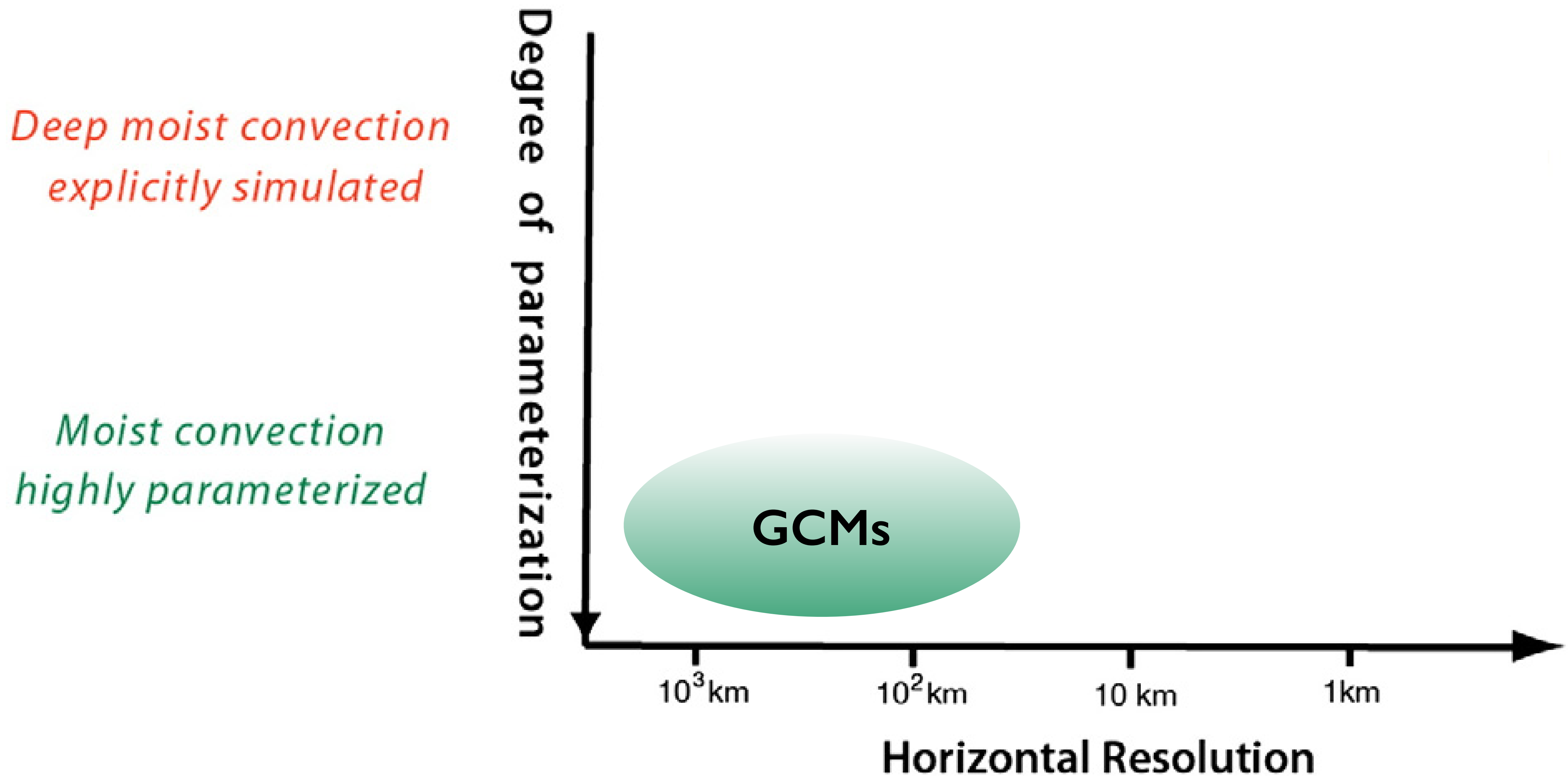

Gliding Into the Grey Zone
David Randall

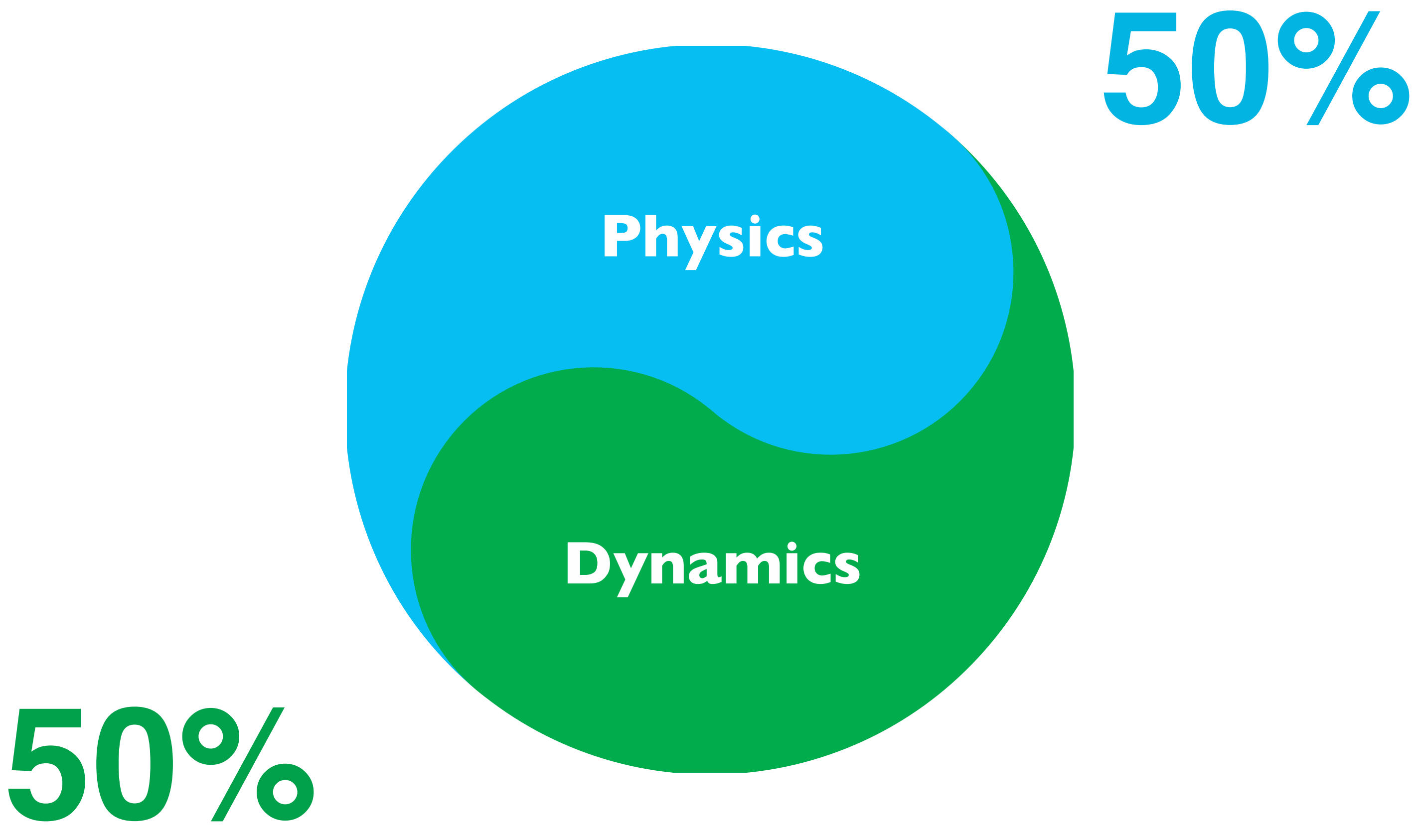
CMMAP

Reach for the sky.

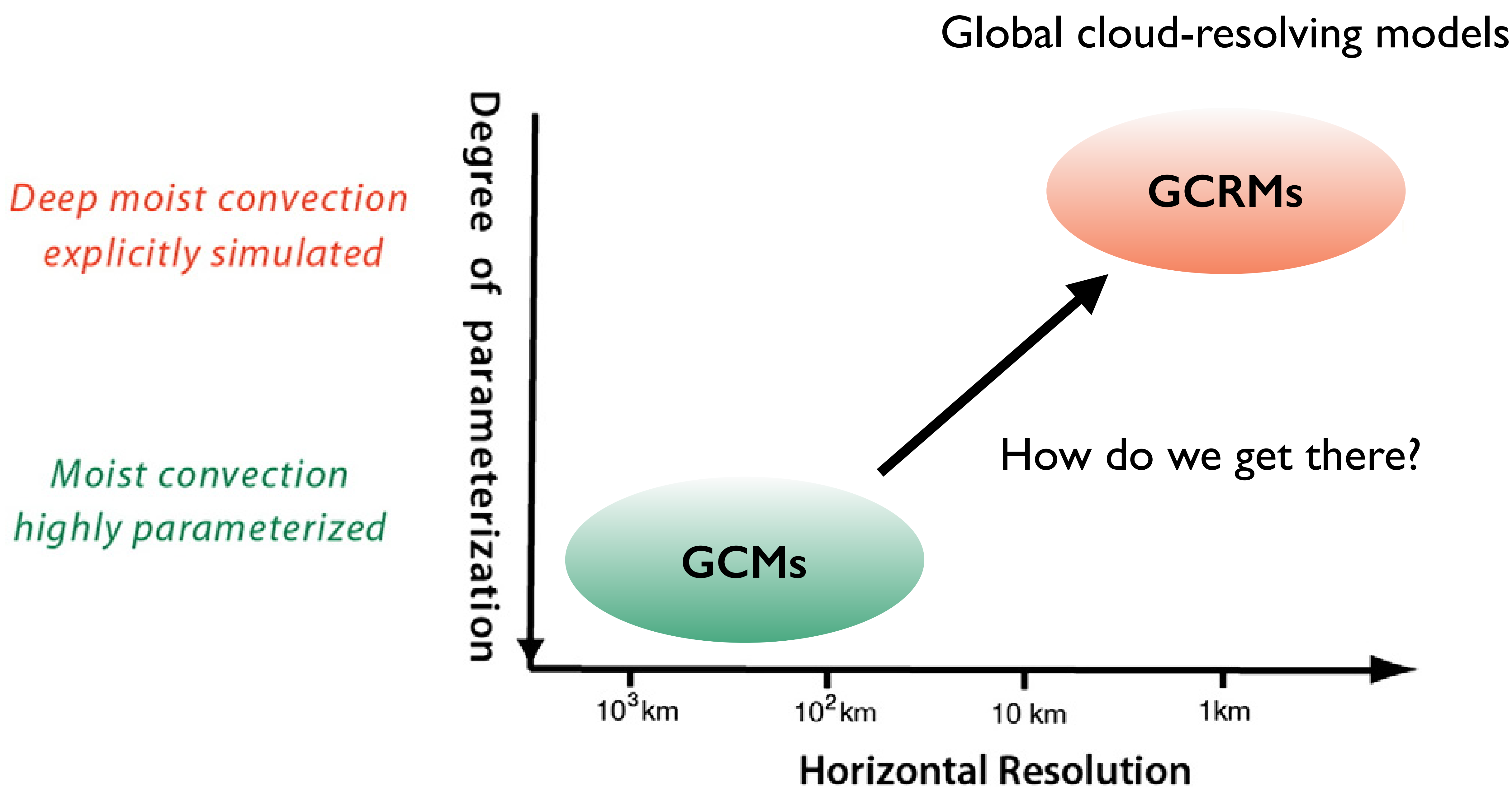
Global modeling landscape, 2000



Where does the computer time go?



Global modeling landscape, 20XX



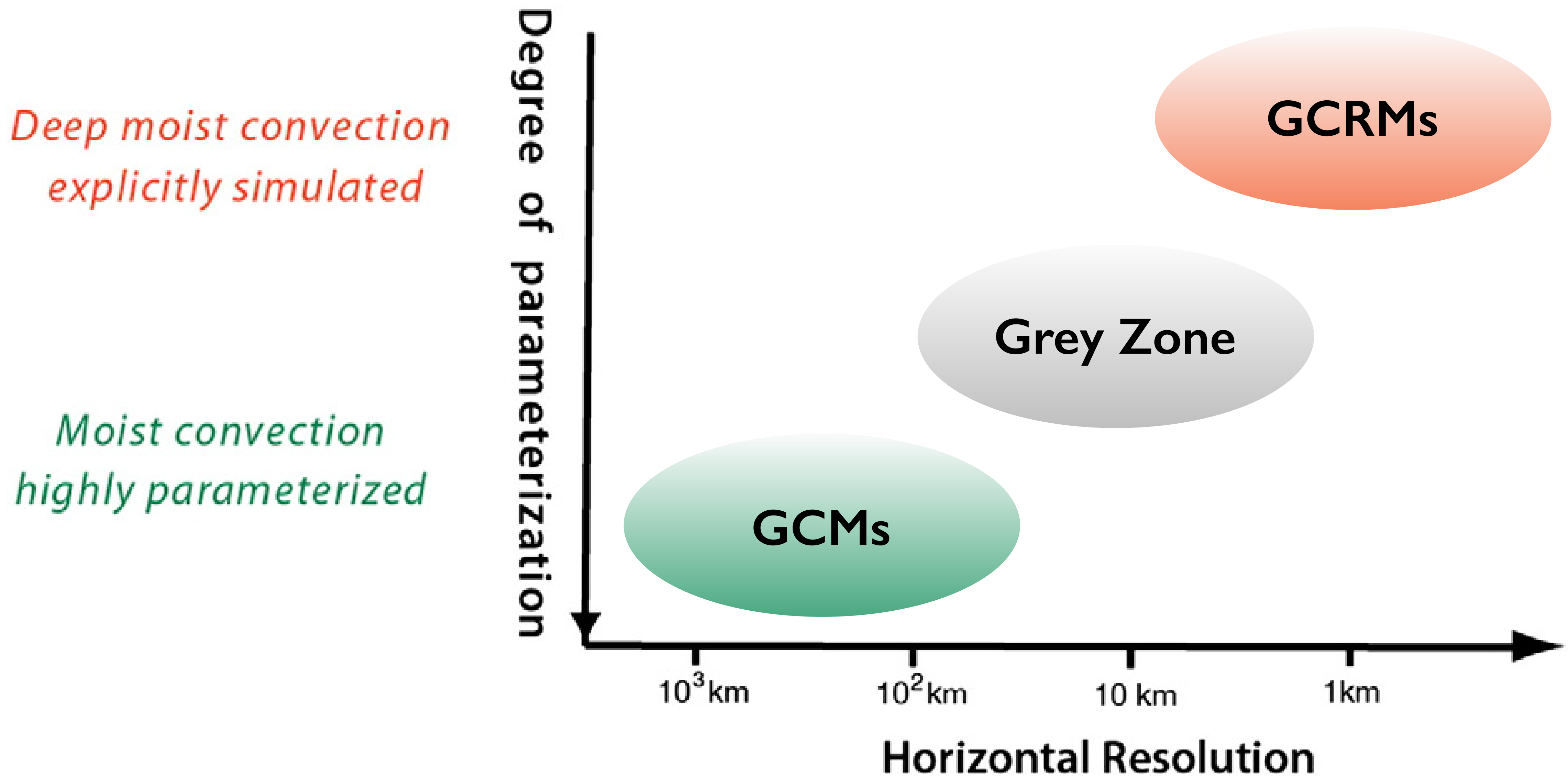

Resolve clouds?
Modest increases in resolution don’t improve the simulation of cloud processes.
A cloud-resolving model needs a horizontal grid-spacing of 4 km or finer.

Believe it or not?

- A future version of the CESM
- IPCC-class simulation (one century or more)
- Atmospheric horizontal grid spacing of 4 km or finer everywhere

By the time of iCAS 2025?

Global modeling landscape, 20XX

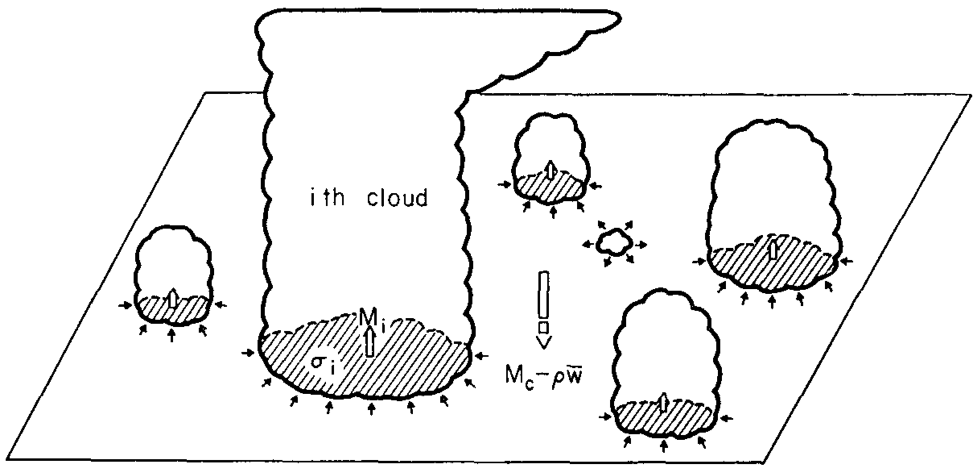


In the Grey Zone:

- The grid is too coarse to resolve even large cumulus clouds.
- The grid is too fine for use with cumulus parameterizations.

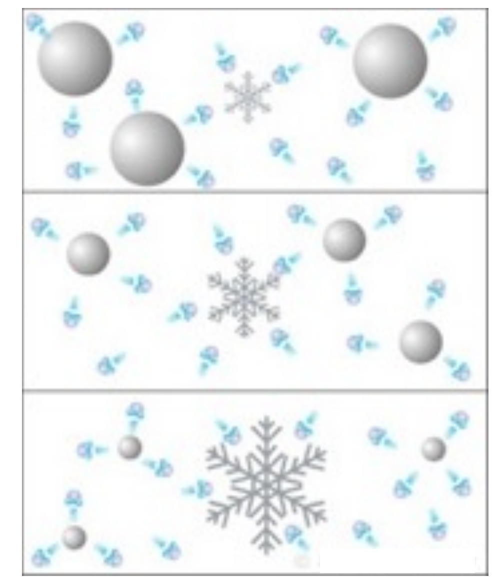
The grey zone starts near dx = 25 km.

Parameterizations Must Be Scale-Dependent.



GCM

Increasing resolution



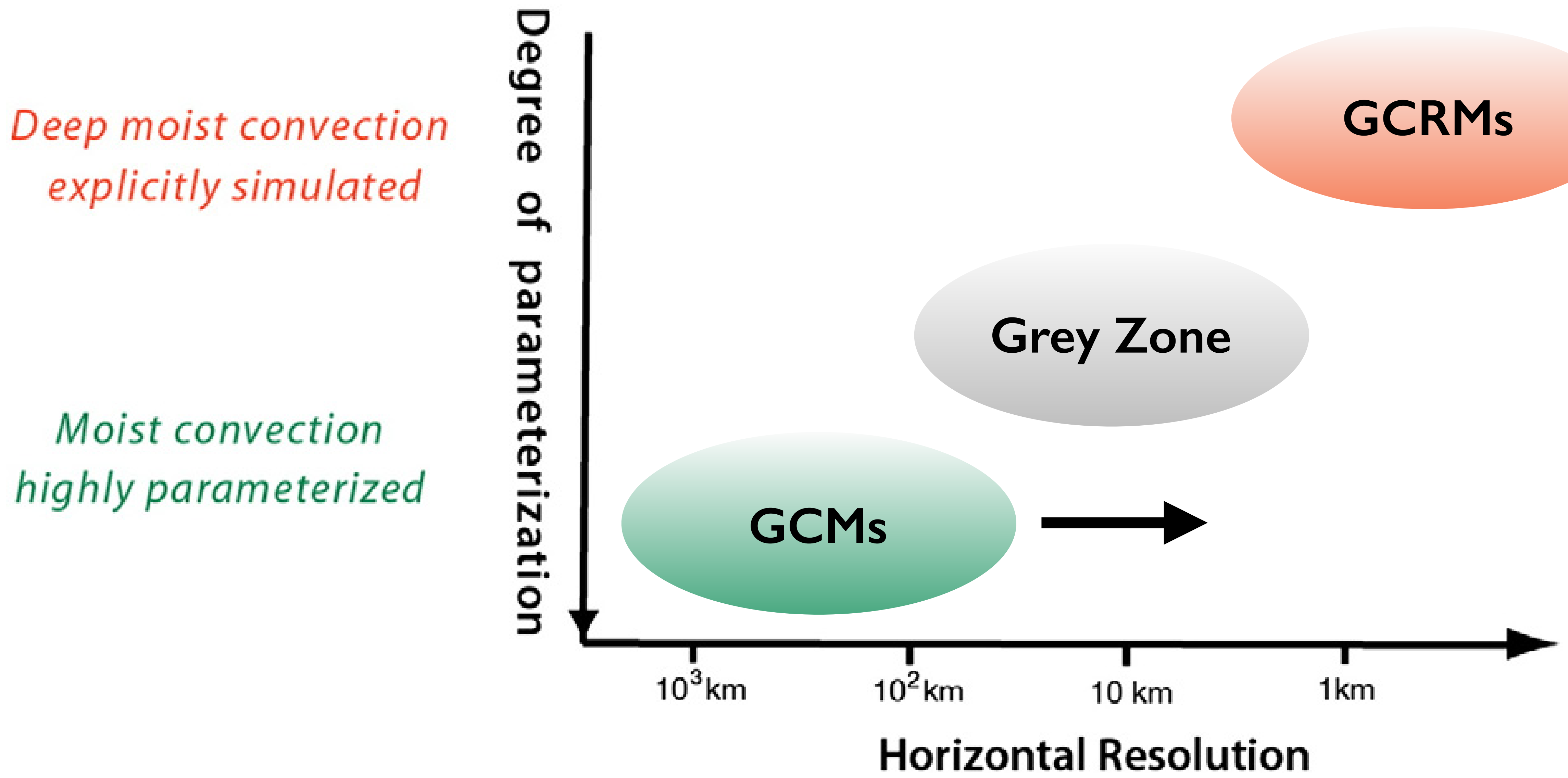
CRM

Parameterizations for low-resolution models are designed to describe the collective effects of many clouds, including strong convective transports.

Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

One way forward

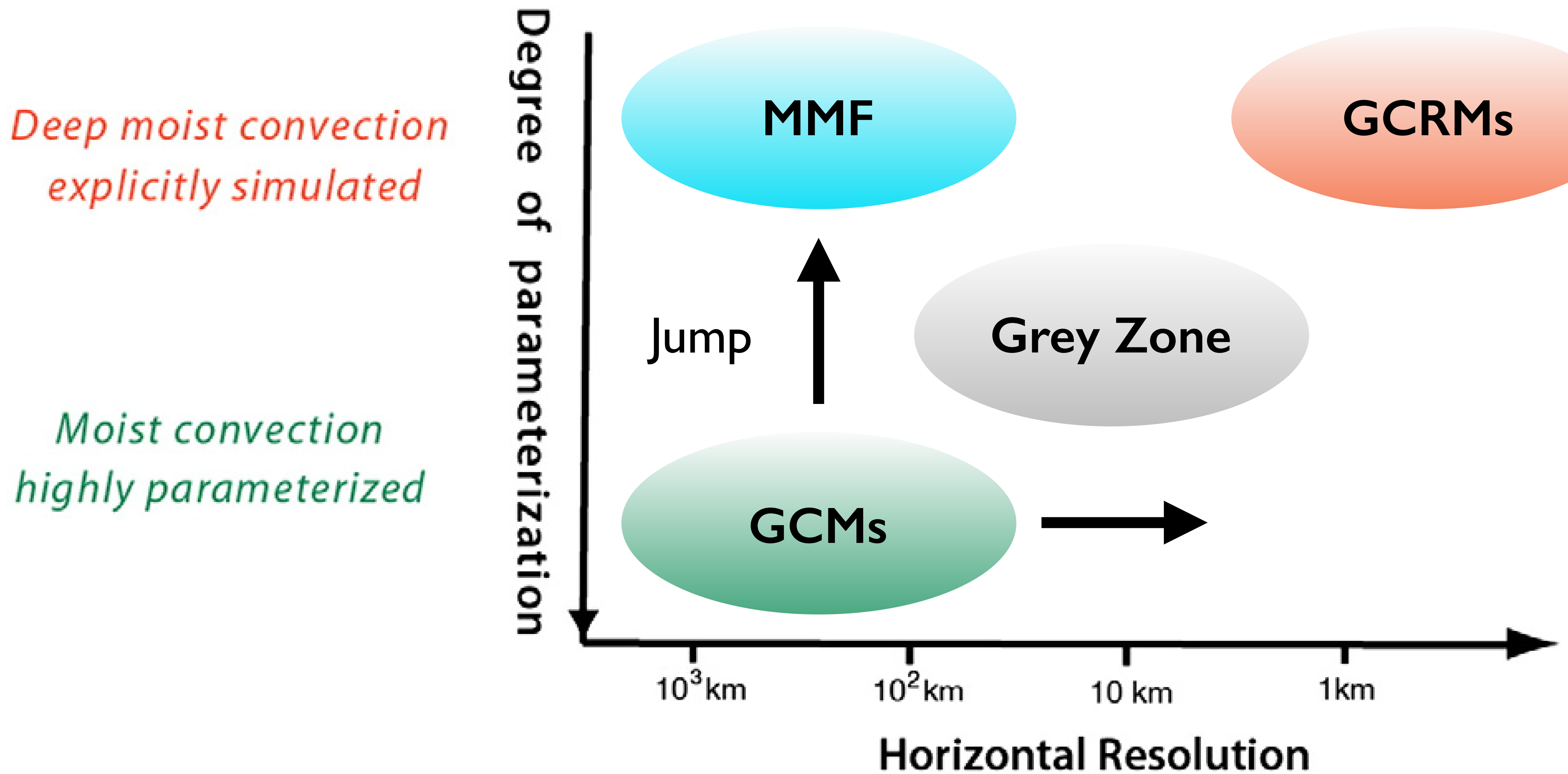
Discussed by Justin Small on Monday morning



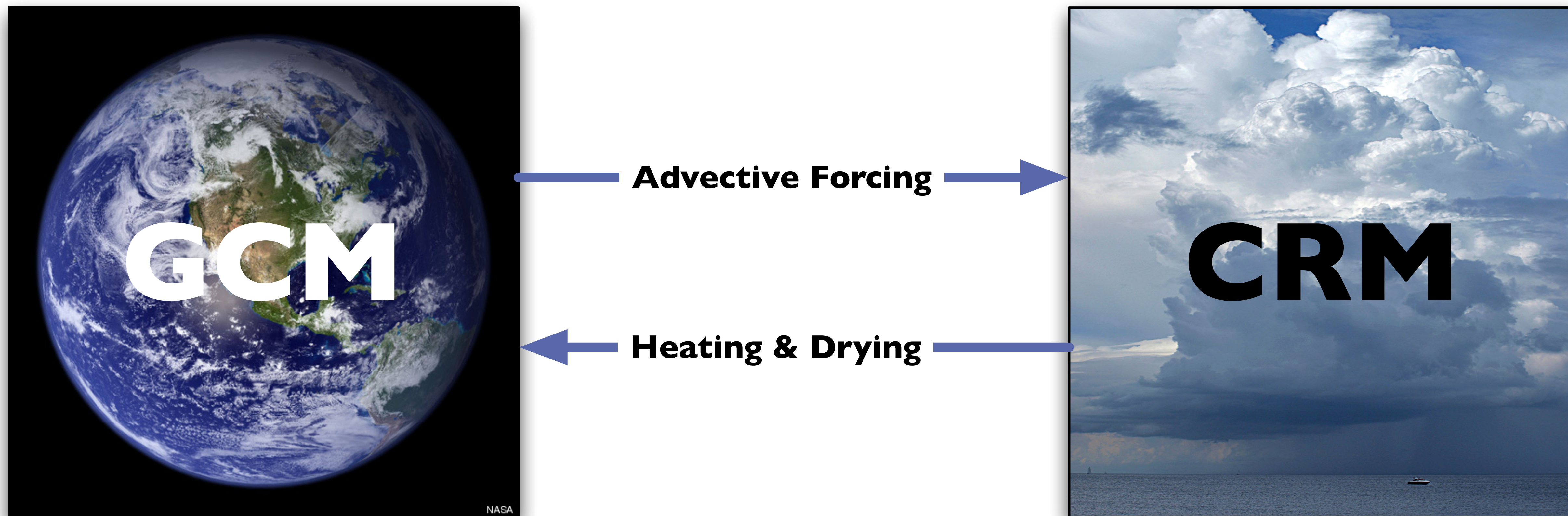
What happens if we make the grid finer without changing the parameterizations?

- The fluid dynamics is better resolved.
- Topography and coastlines become more realistic.
- Tropical cyclones start to appear.
- But when we enter the grey zone, the low-resolution parameterizations become *scale-inappropriate*.

What if we jump up instead?



Multiscale Modeling Framework (MMF)



"Super-Parameterization"

The CRMs are 2-dimensional and use periodic boundary conditions.

Each CRM runs continuously.

The CRMs do not communicate with each other except through the GCM, so *the model is "embarrassingly parallel."*


Dynamics
Physics

Warning:
The next slide has equations.

The choreography

$$\frac{\widetilde{q_G^{n+1}} - q_G^n}{\Delta t_G} = B_G$$

GCM adiabatic processes

$$\frac{q_C^{m+1} - q_C^m}{\Delta t_C} = B_C + S_C + \left(\frac{\widetilde{q_G^{n+1}} - \left\langle q_C^n \right\rangle}{\Delta t_G} \right)$$

GCM advective forcing of CRM

$$\frac{q_G^{n+1} - q_G^n}{\Delta t_G} = B_G + \frac{\left\langle q_C^{n+1} \right\rangle - \widetilde{q_G^{n+1}}}{\Delta t_G}$$

$$= B_G + \frac{\left\langle q_C^{n+1} \right\rangle - \left(q_G^n + B_G \Delta t_G \right)}{\Delta t_G}$$

$$= \frac{\left\langle q_C^{n+1} \right\rangle - q_G^n}{\Delta t_G}$$

CRM feedback to GCM

The CRM can’t drift away from the GCM.

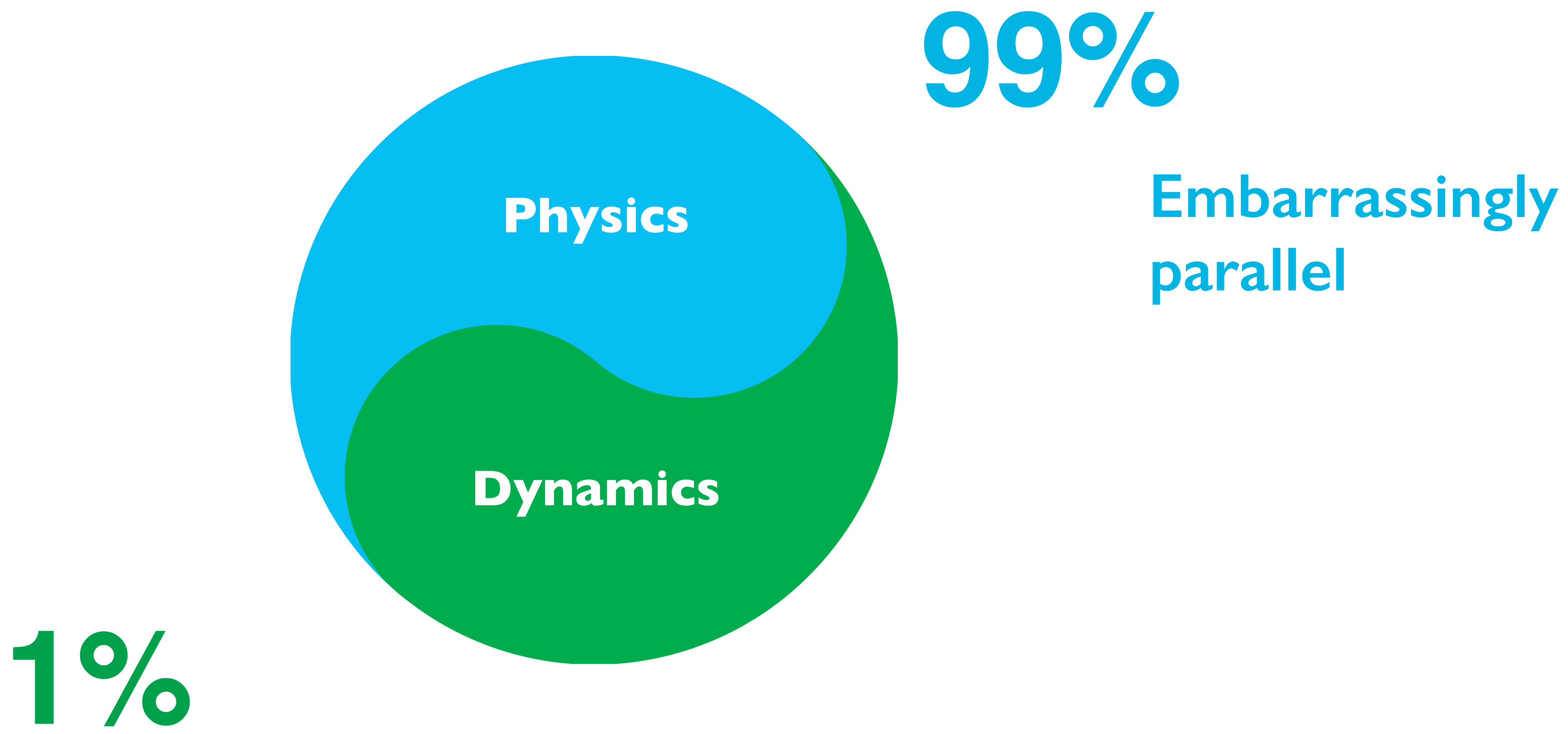
SP-CAM

An MMF based on the Community Atmosphere Model is able to simulate lots of things that the conventional CAM has trouble with.

What’s different?

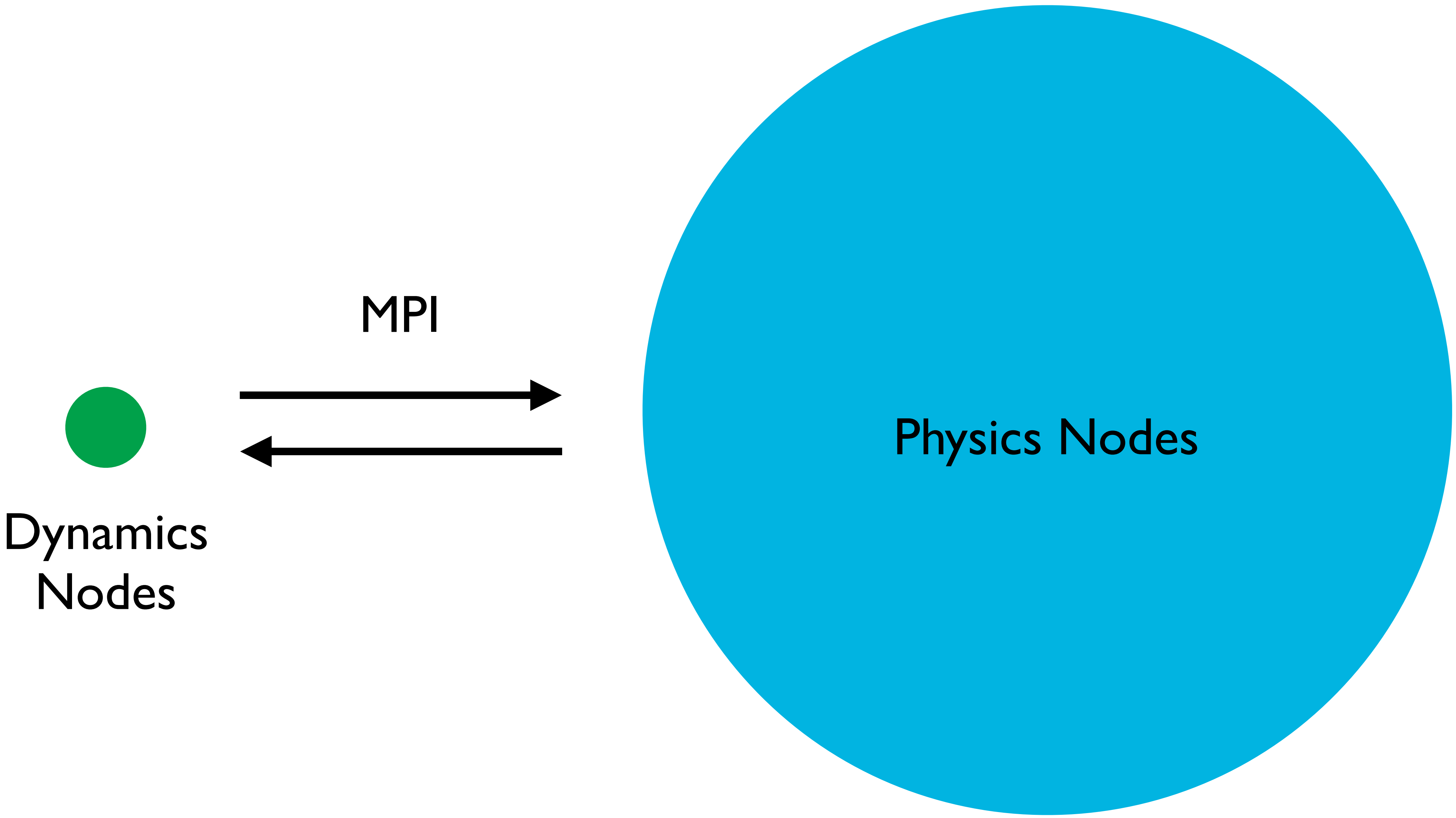
- The equation of motion
  - No closure assumptions
  - No triggers
  - Mesoscale organization
- High-resolution physics on the CRM grid
- CRM memory
  - Delay in convective response
  - Sensitive dependence on initial conditions
- Increased computational cost

How an MMF uses the computer time



The CPU time needed is much greater than for a conventional model,
but the wall-clock time required can be the same as that of a conventional model.

Minimizing the Wall-Clock Time



Unfortunately, this is difficult with the current CESM.

Balaji's approach would make it much easier.

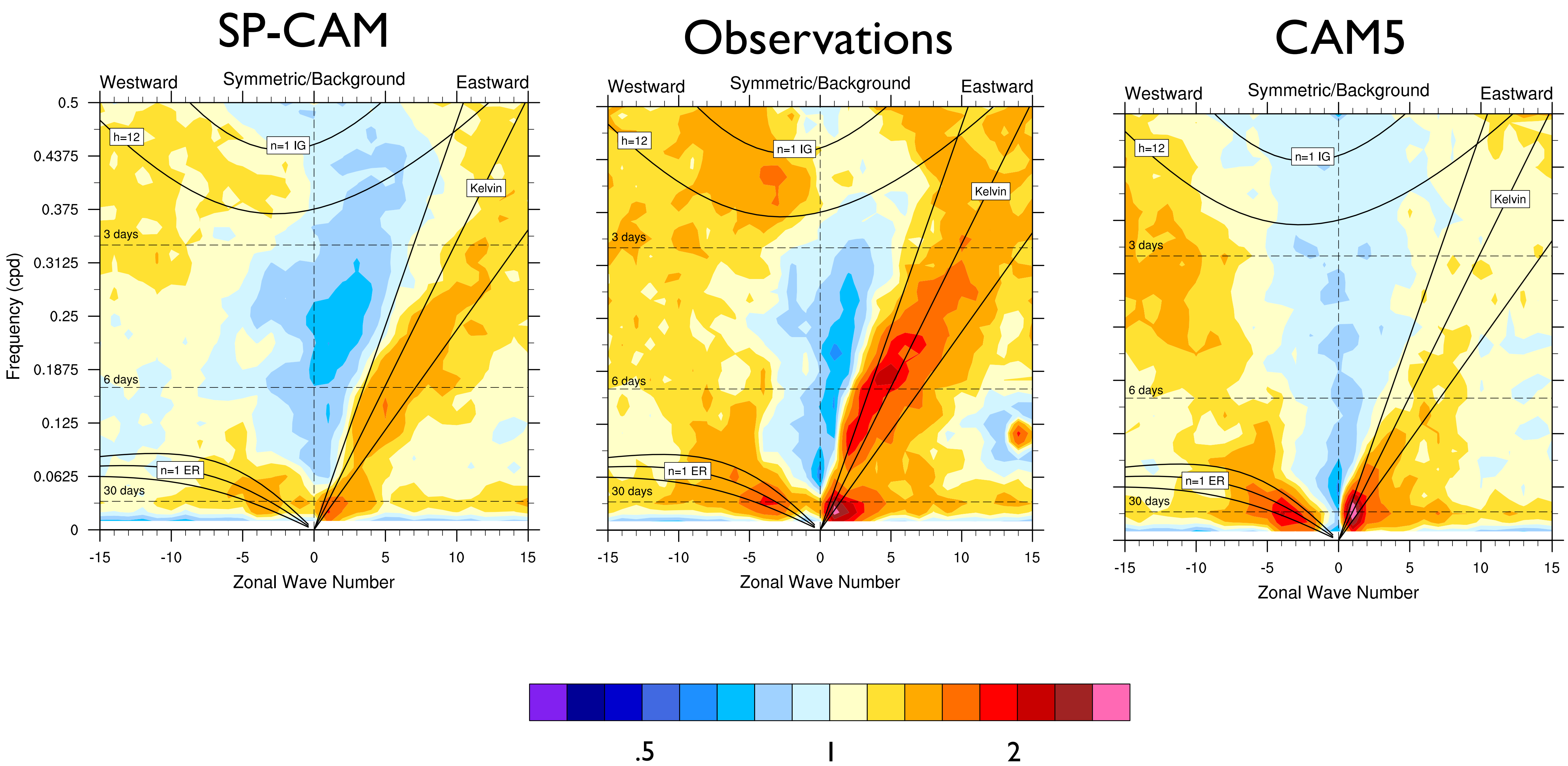
Focus: Variability

- Diurnal cycle
- African Easterly Waves
- Tropical cyclones
- Monsoon fluctuations
- The MJO
- ENSO
- Climate change

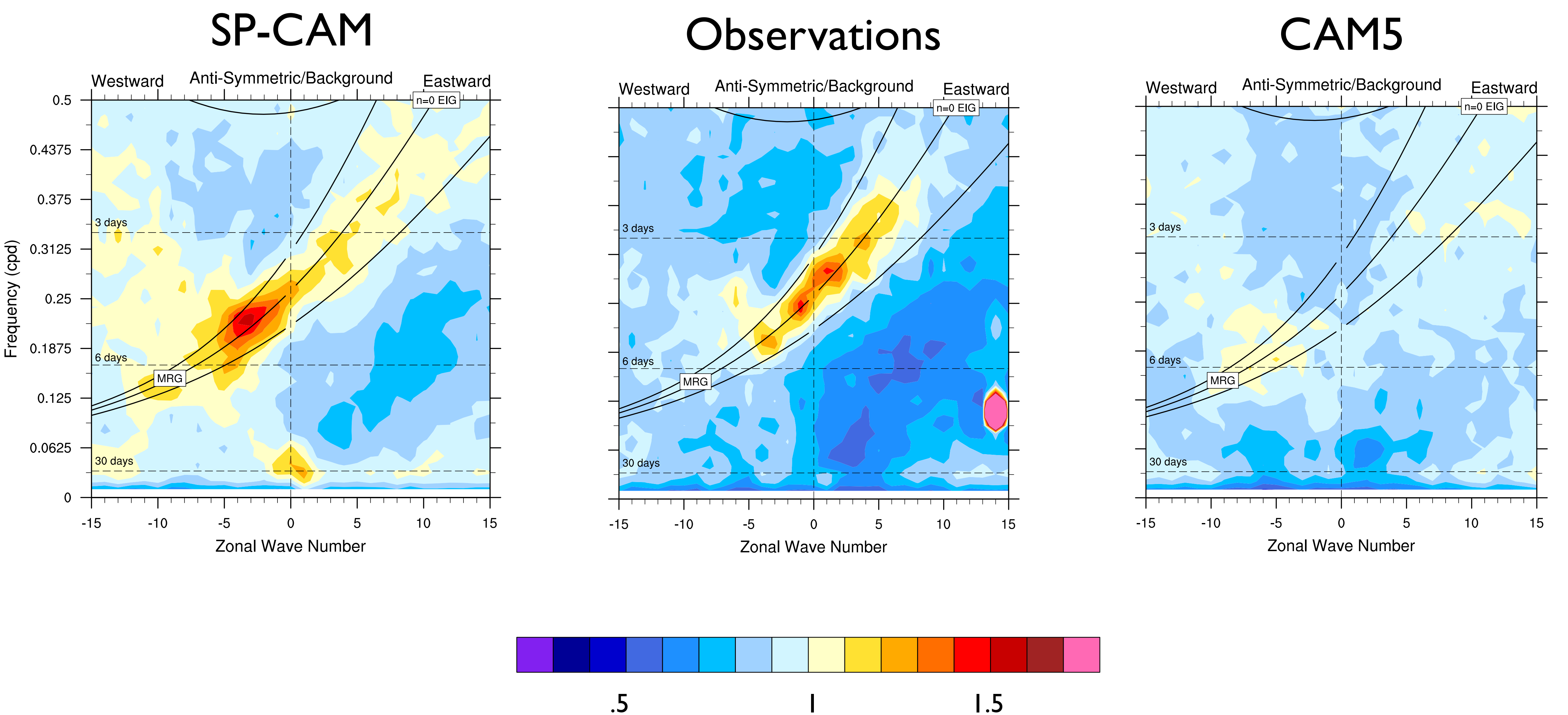
http://www.cmmap.org/research/pubs-mmf.html

~100 papers

Symmetric


SP-CAM
Observations
CAM5
Westward
Symmetric/Background
Eastward
Frequency (cpd)
0.5
0.4375
0.375
0.3125
0.25
0.1875
0.125
0.0625
0
h=12
n=1 IG
Kelvin
3 days
6 days
30 days
n=1 ER
-15
-10
-5
0
5
10
15
Zonal Wave Number
.5
1
2

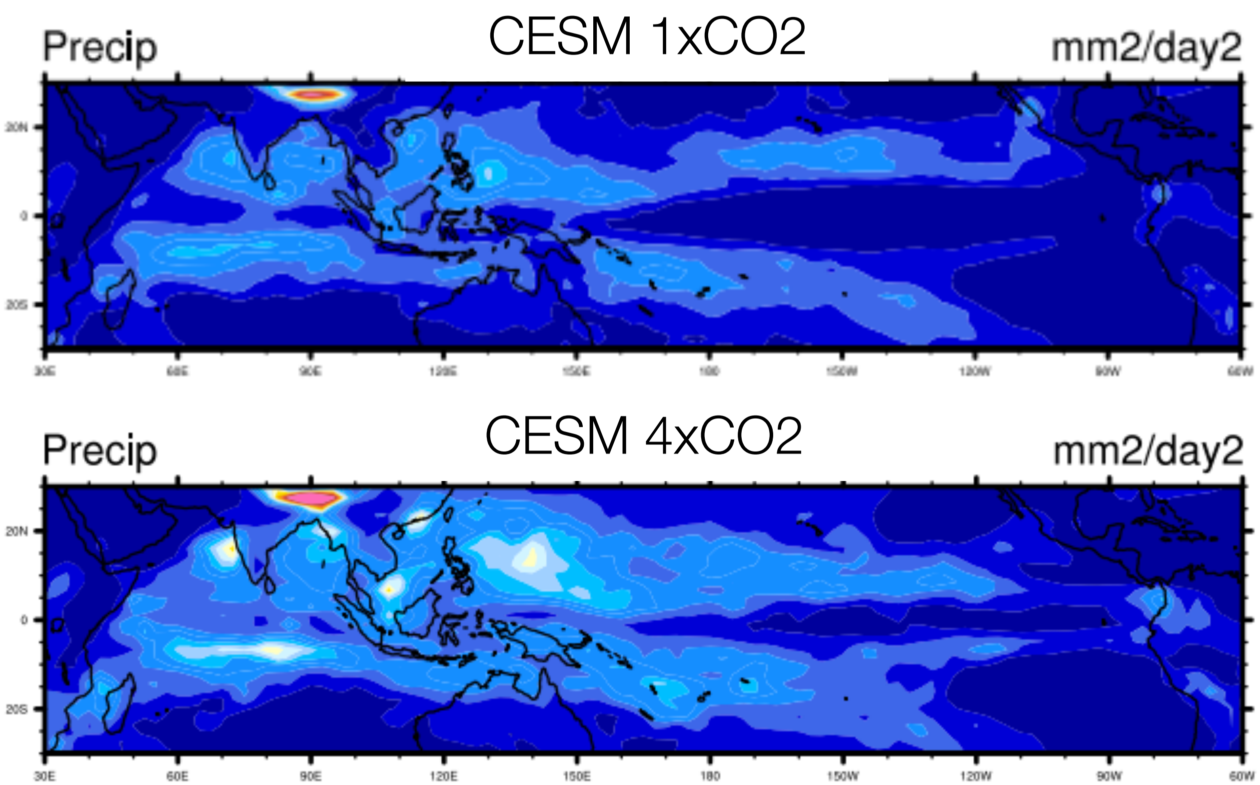
Asymmetric


SP-CAM
Observations
CAM5
Westward
Anti-Symmetric/Background
Eastward
n=0 EIG
3 days
6 days
30 days
MRG
Frequency (cpd)
0.5
0.4375
0.375
0.3125
0.25
0.1875
0.125
0.0625
0
-15
-10
-5
0
5
10
15
Zonal Wave Number
.5
1
1.5

How will the MJO change in a warmer climate?

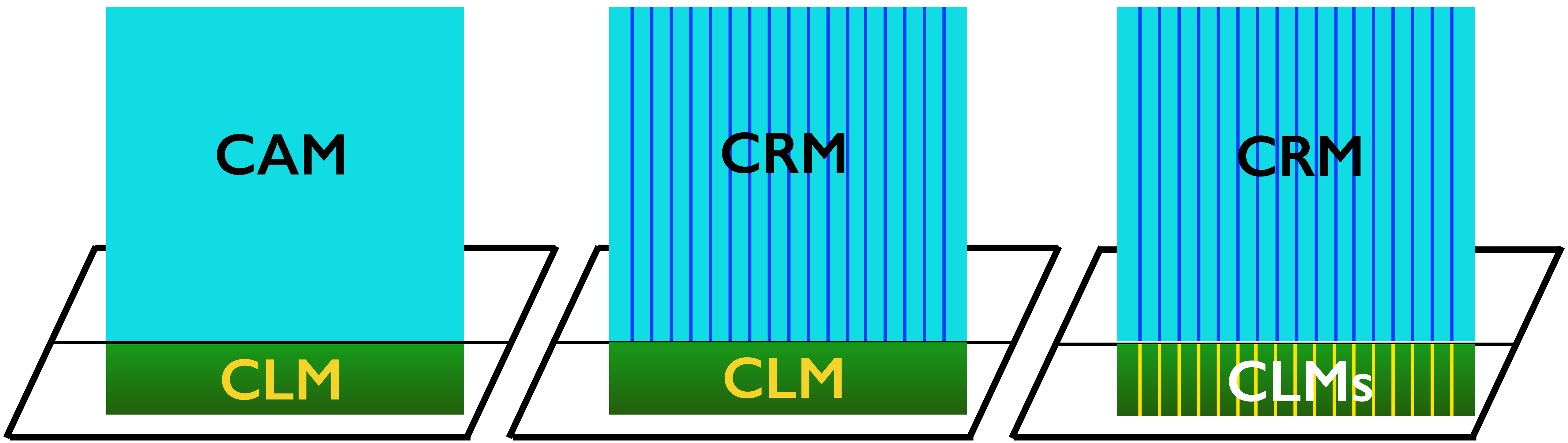
- Influence on tropical rainfall
- Coupling to the Asian Summer Monsoon
- Modulation of tropical cyclones

A tremendous future intensification of the MJO



Arnold, N., M. Branson, M. A. Burt, D. S. Abbot, Z. Kuang, D. A. Randall, and E. Tziperman, 2014: Significant consequences of explicit representation of atmospheric convection at high CO_2 concentration. *Proc. Nat. Acad. Sci.*, **111**, 10943-10948.

Three Ways to Couple the Atmosphere and the Land Surface



Single Atmosphere
Single Land

(standard CESM)

Multi-Atmosphere
Single Land

(SP-CESM)

Multi-Atmosphere
Multi-Land

(modified
SP-CESM)

Slide from Scott Denning

Why and how does it matter?

Atmosphere

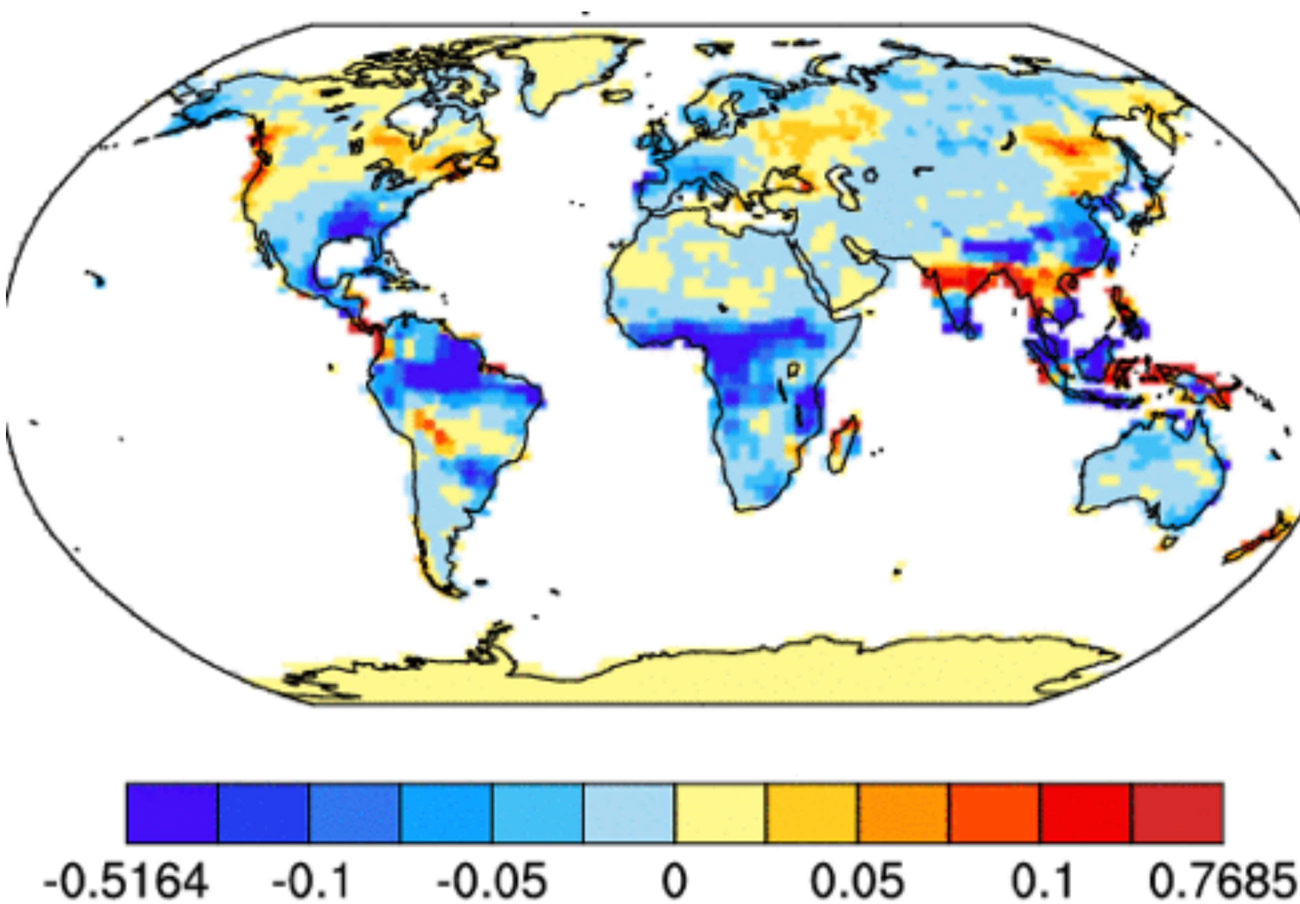
- Intense local rainfall
- Gustiness associated with local storms
- Cloud shadows

Surface

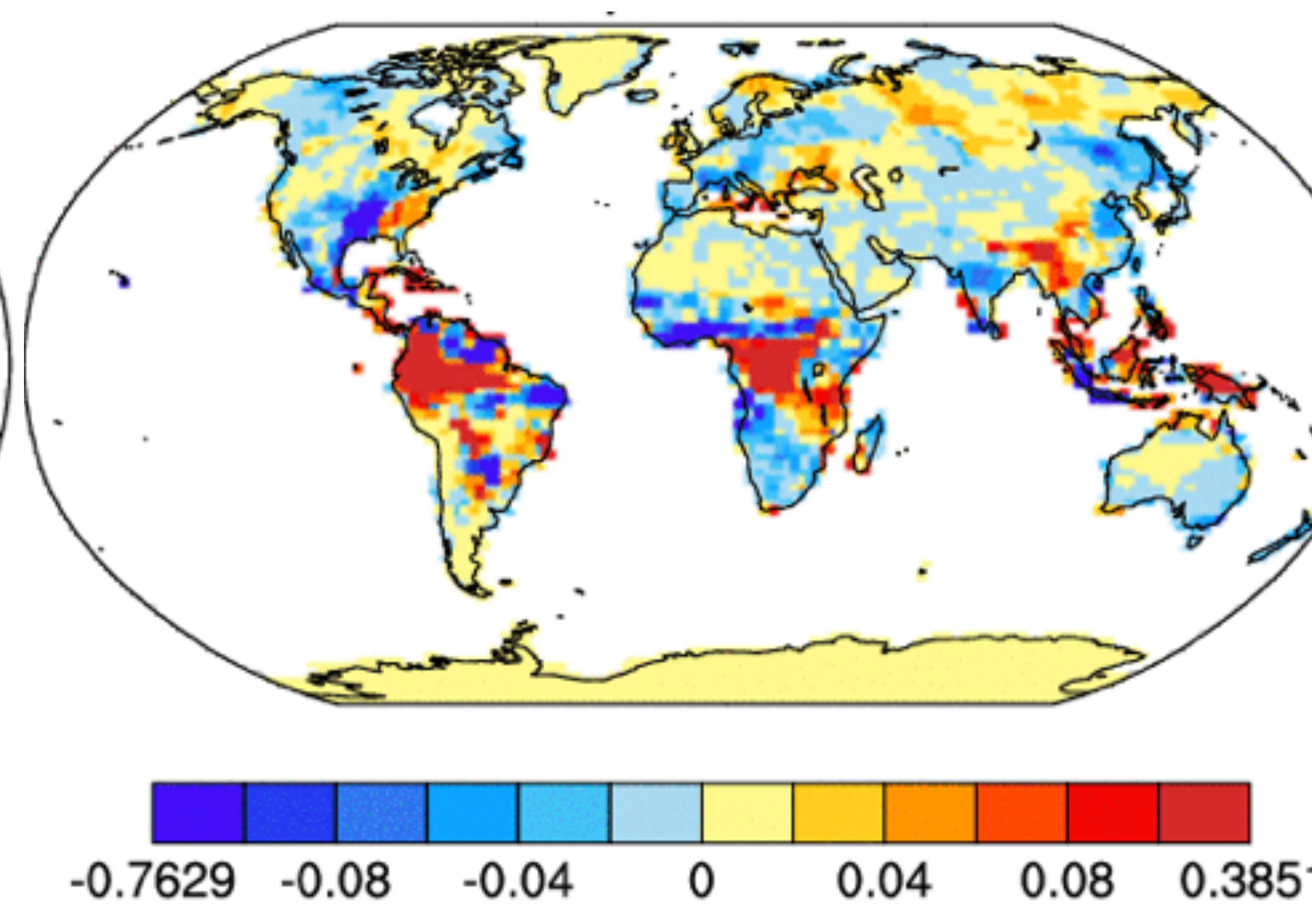
- Wet or warm spots
- Heterogeneous vegetation and soil types
- Lakes

Changes in Canopy Hydrology

Canopy Interception



Transpiration

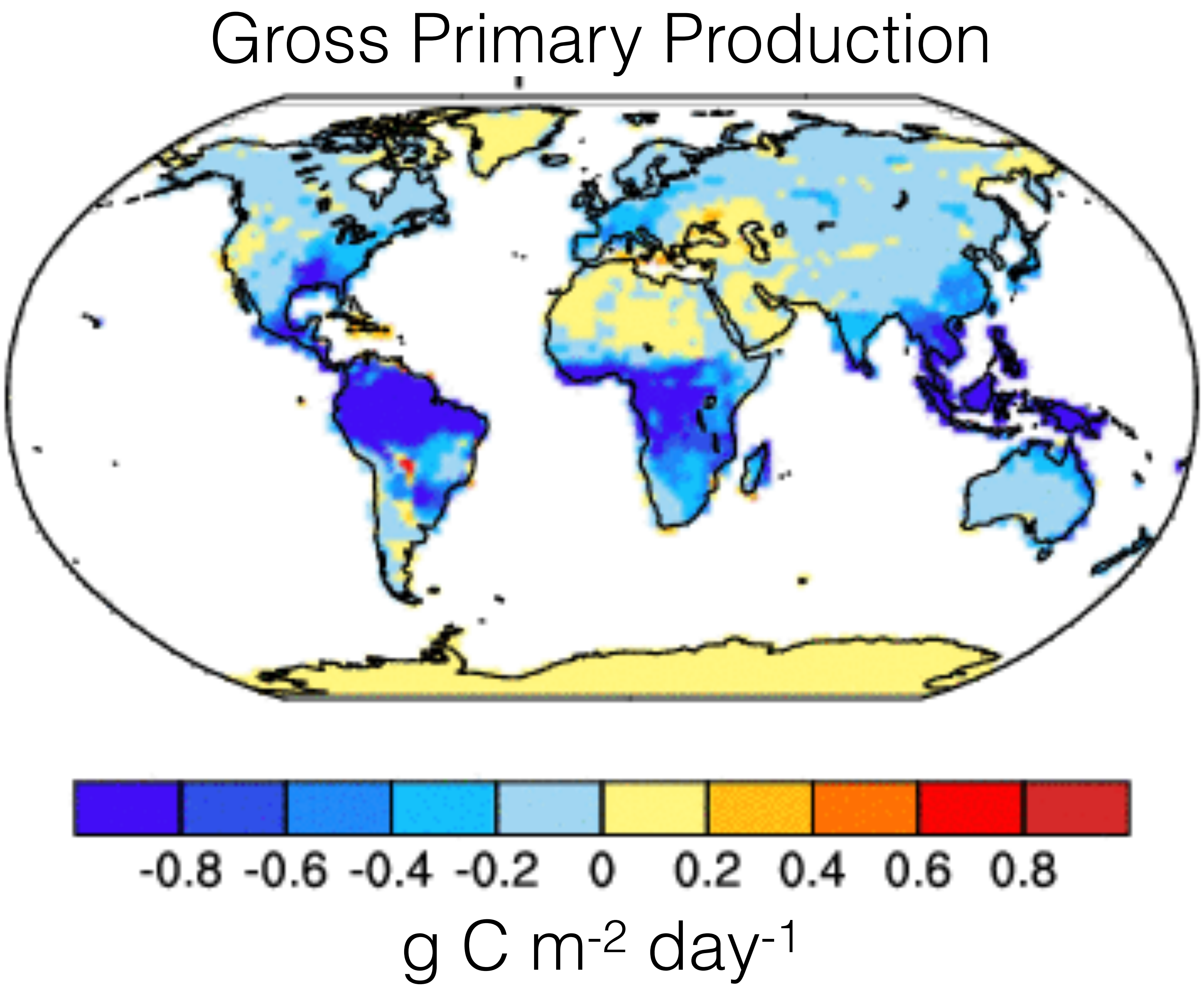


mm / day

Shift from canopy interception & evaporation to throughfall, infiltration, and transpiration, especially in the tropics

Slide from Scott Denning

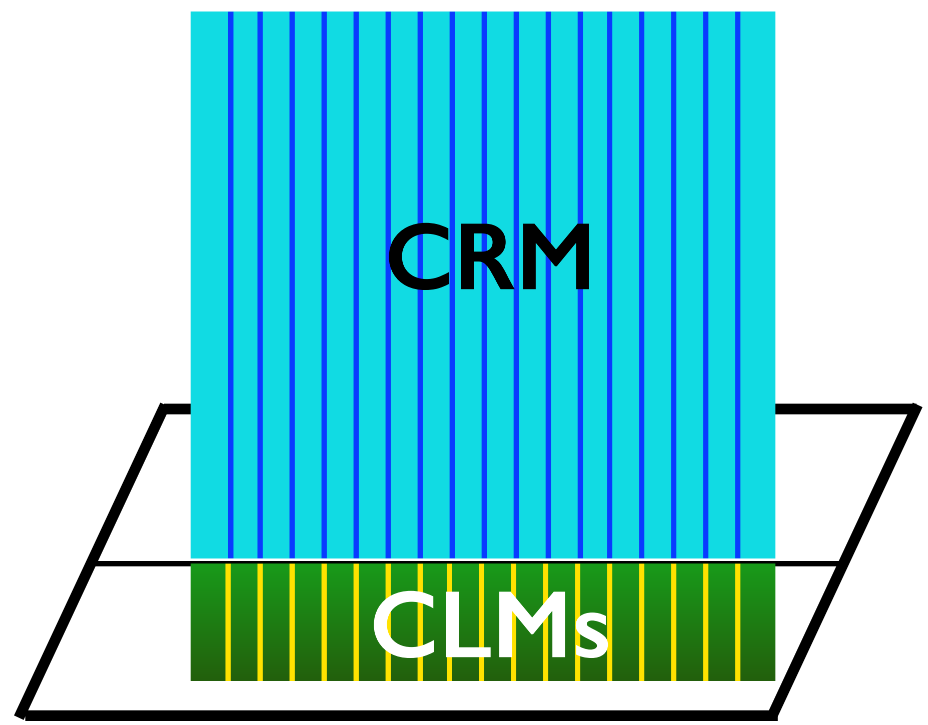
Changes in Photosynthesis



More moisture but less light over tropics

Slide from Scott Denning

Conceptually simple, but hard to code



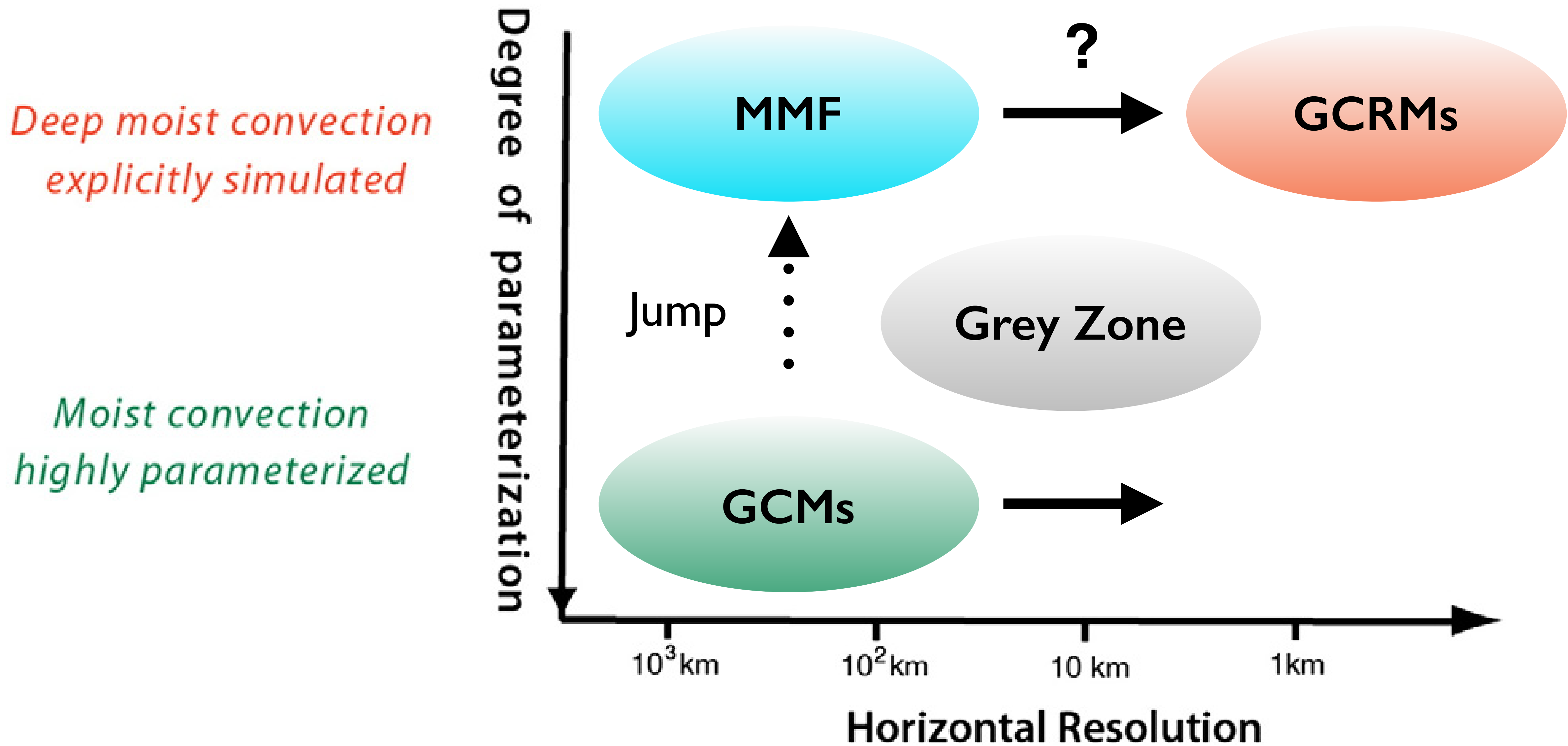
Marianna Vertenstein, Cheryl Craig, and Jim Edwards helped us to do this, but the CESM's coupler made it tricky.

Slide from Scott Denning

MMF community

1. Colorado State University
2. NASA Goddard Space Flight Center
3. University of Washington
4. NASA Langley Research Center
5. Lawrence Berkeley National Laboratory
6. Scripps Institution of Oceanography
7. Earth System Research Laboratory
8. National Center for Atmospheric Research
9. Pacific Northwest National Laboratory
10. Scripps Institution of Oceanography
11. State University of New York at Stony Brook
12. Massachusetts Institute of Technology
13. Indian Institute for Tropical Meteorology
14. Harvard University
15. University of Chicago
16. George Mason University
17. University of California at Irvine
18. ECMWF
19. University of Oxford
20. DOE's Accelerated Climate Model for Energy*

Unfortunately, the MMF can't take us past the grey zone.

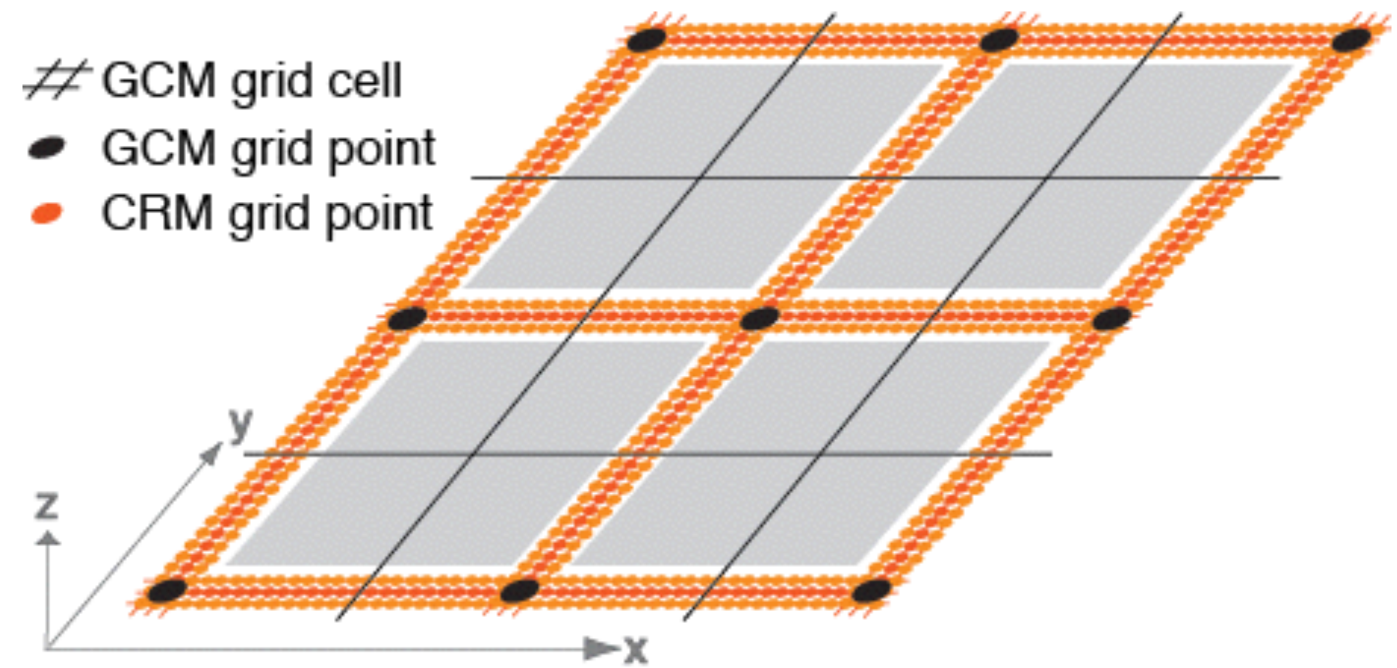


Cue the second-generation "Q3D" MMF

The two-dimensional grid of the original MMF is replaced by a minimally three-dimensional grid of CRM "channels."

The artificial periodic boundary conditions of the original MMF are eliminated, so that the CRM channels extend across GCM grid cell boundaries.

The new MMF is called "quasi-three-dimensional," or Q3D for short.

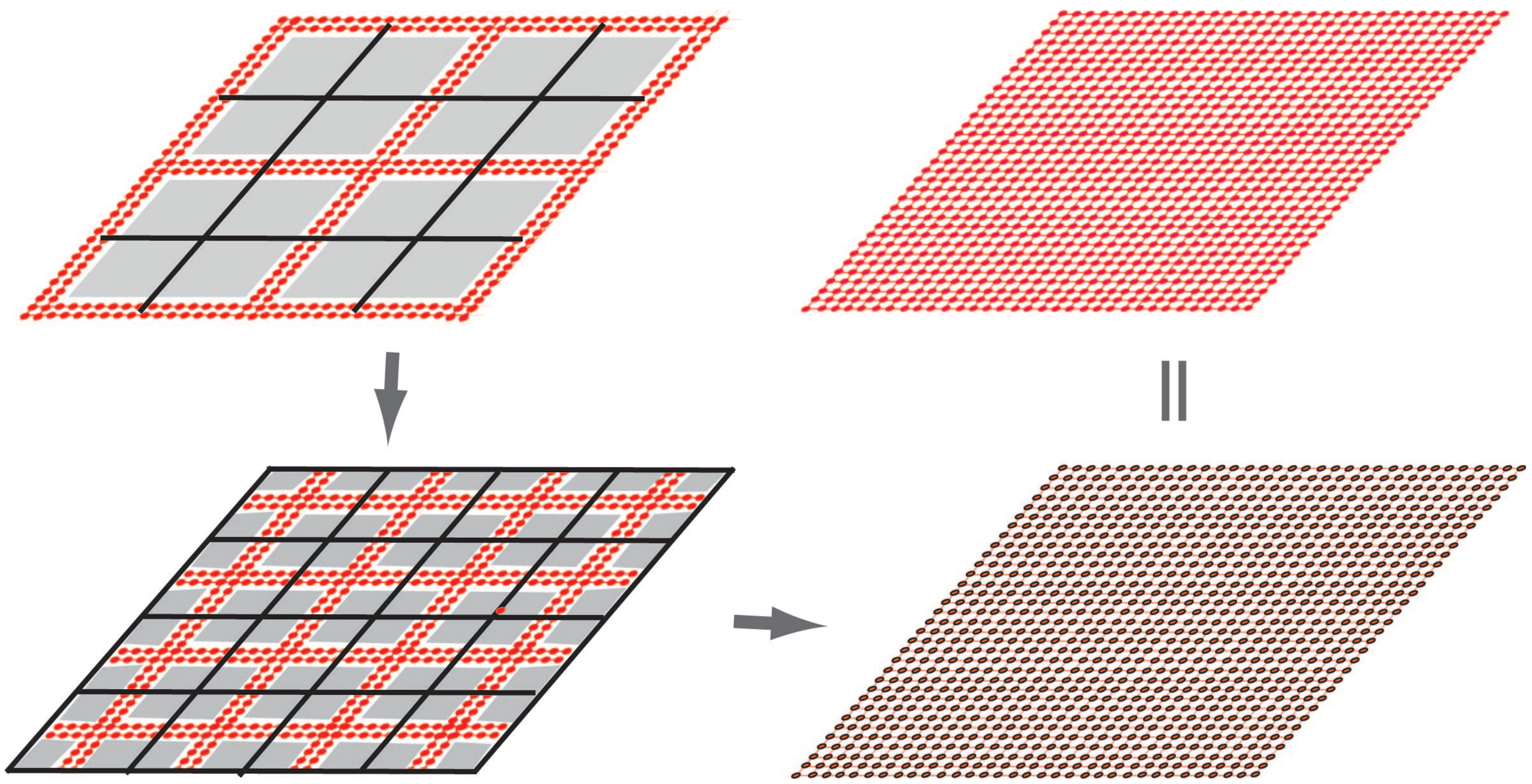


Allows convection to propagate across GCM cell boundaries.

Can include the effects of realistic topography.

Can simulate vertical momentum transport by both convection and waves.

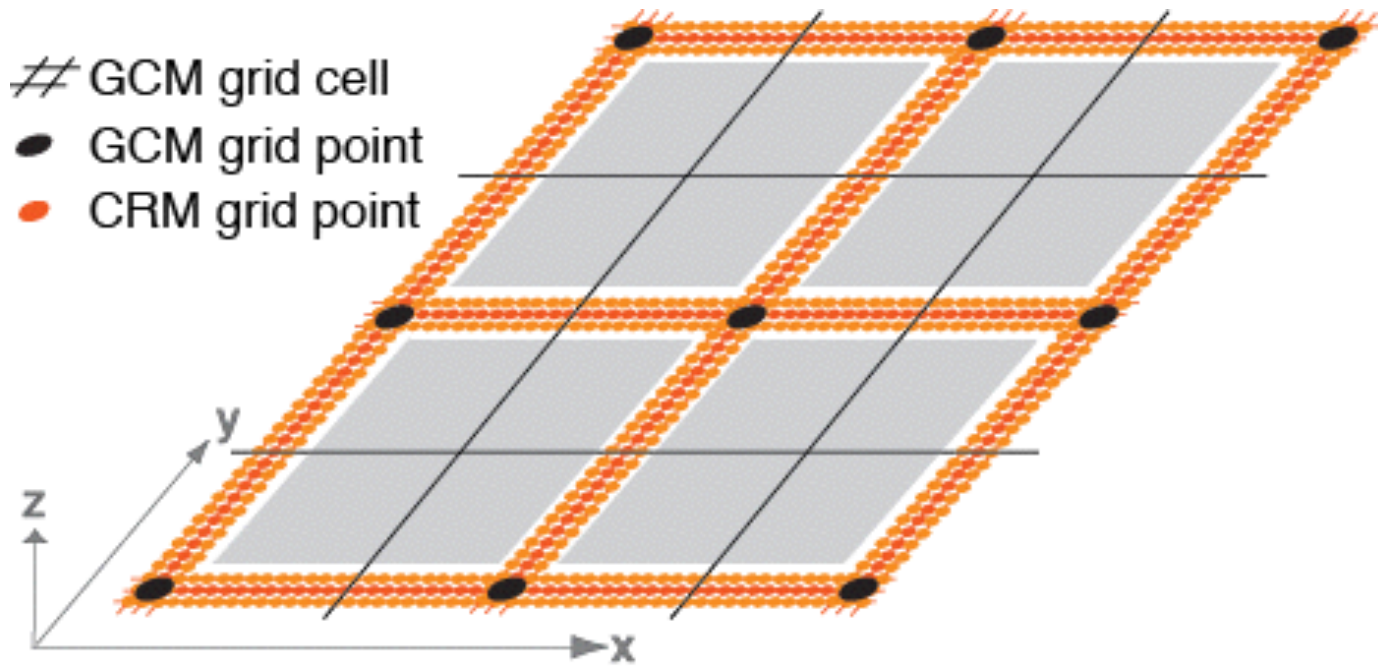
Convergence



As the GCM's grid is refined, the Q3D MMF converges to a global cloud-resolving model.

Figure from Akio Arakawa

Status of the Q3D MMF



The method has been successfully tested in a regional model.

A global version is now under construction.

Randall, D. A., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003: Breaking the cloud-parameterization deadlock. *Bull. Amer. Meteor. Soc.*, **84**, 1547-1564.

Arakawa, A., 2004: The Cumulus Parameterization Problem: Past, Present, and Future. *J. Climate*, **17**, 2493-2525.

Jung, J.-H., and A. Arakawa, 2005. Preliminary Tests of Multiscale Modeling with a Two-Dimensional Framework: Sensitivity to Coupling Methods. *Mon. Wea. Rev.*, **133**, 649-662.

Jung, J.-H., and A. Arakawa, 2010: Development of a Quasi-3D Multiscale Modeling Framework: Motivation, basic algorithm and preliminary results. *J. Adv. Model. Earth Syst.*, Vol. 2, Art. #11, 31 pp.

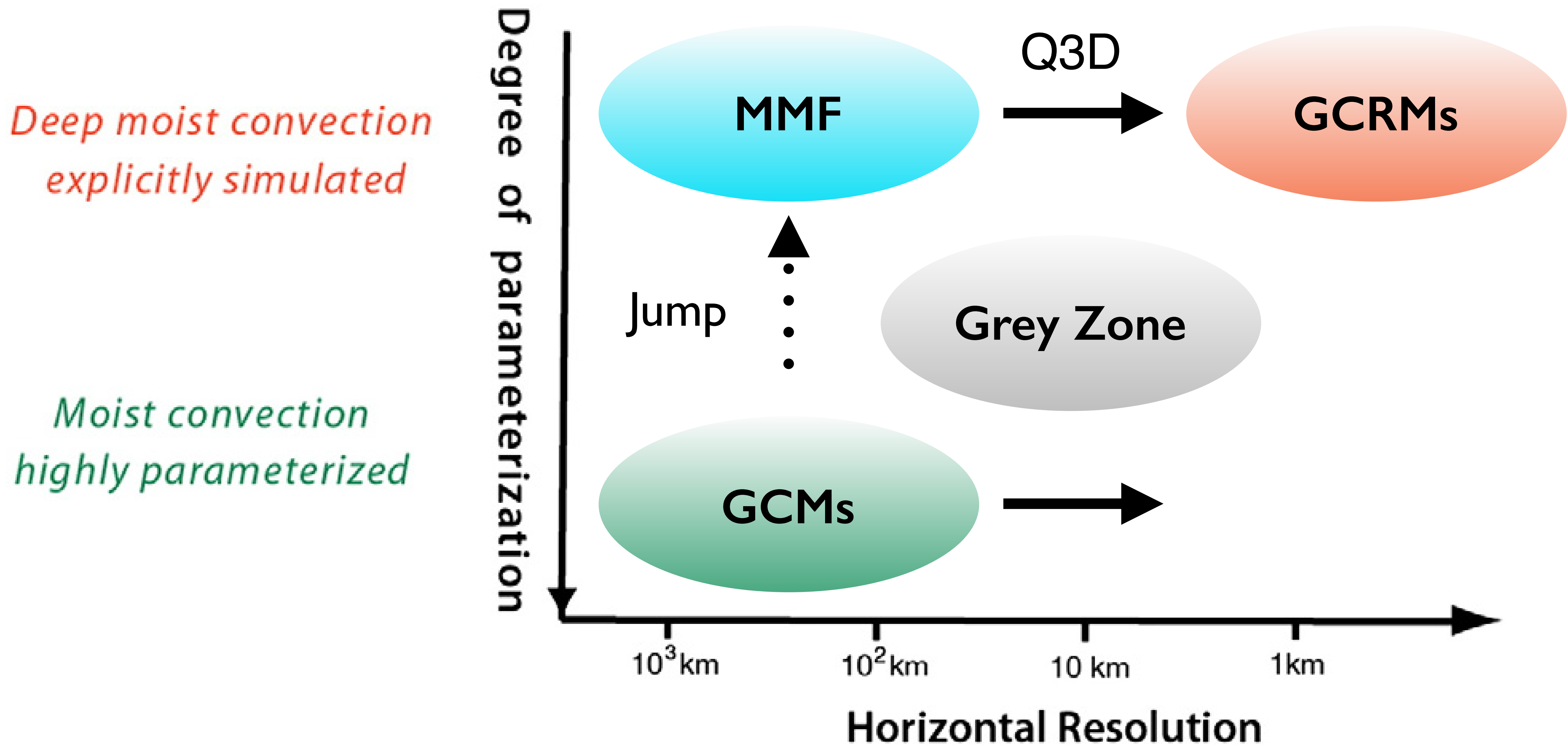
Arakawa, A., J.-H. Jung, and C. M. Wu, 2011: Toward Unification of the Multiscale Modeling of the Atmosphere. *Atmospheric Chemistry and Physics*, **11**, 3731-3742.

Jung, J.-H., and A. Arakawa, 2016: Simulation of Subgrid Orographic Precipitation with a 2-D Cloud-Resolving Model Embedded in a Coarser 3-D Grid. Submitted for publication.

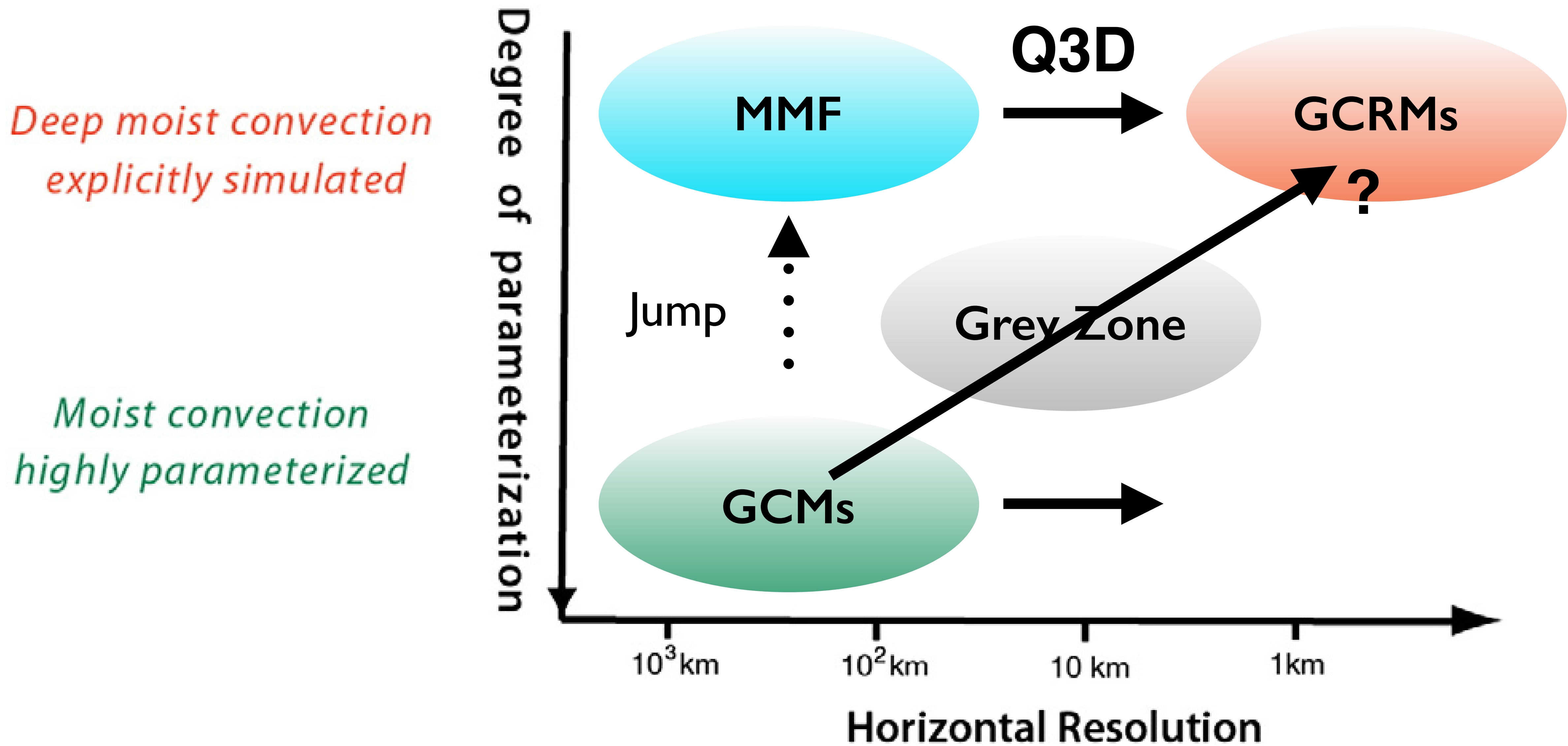
Jung, J.-H. and A. Arakawa, 2014: Modeling the moist-convective atmosphere with a Quasi-3-D Multiscale Modeling Framework (Q3D MMF). *J. Adv. Model. Earth Syst.*, **6**, 185-205.

Arakawa, A., and J.-H. Jung, 2011: Multiscale modeling of the moist-convective atmosphere -- A review. *Atmos. Res.*, **102**, 263-285.

The Q3D MMF can carry us past the grey zone.



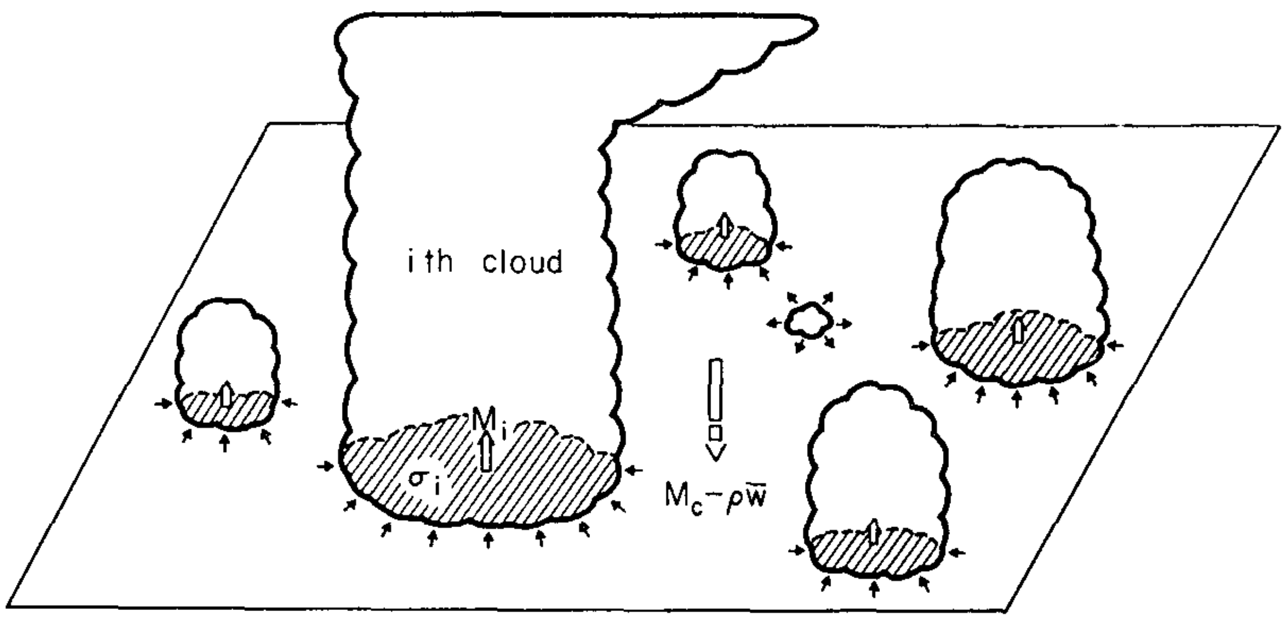
But is it possible to book a non-stop itinerary?



A "Unified Parameterization"

(unified in the sense that it can be used with any grid spacing)

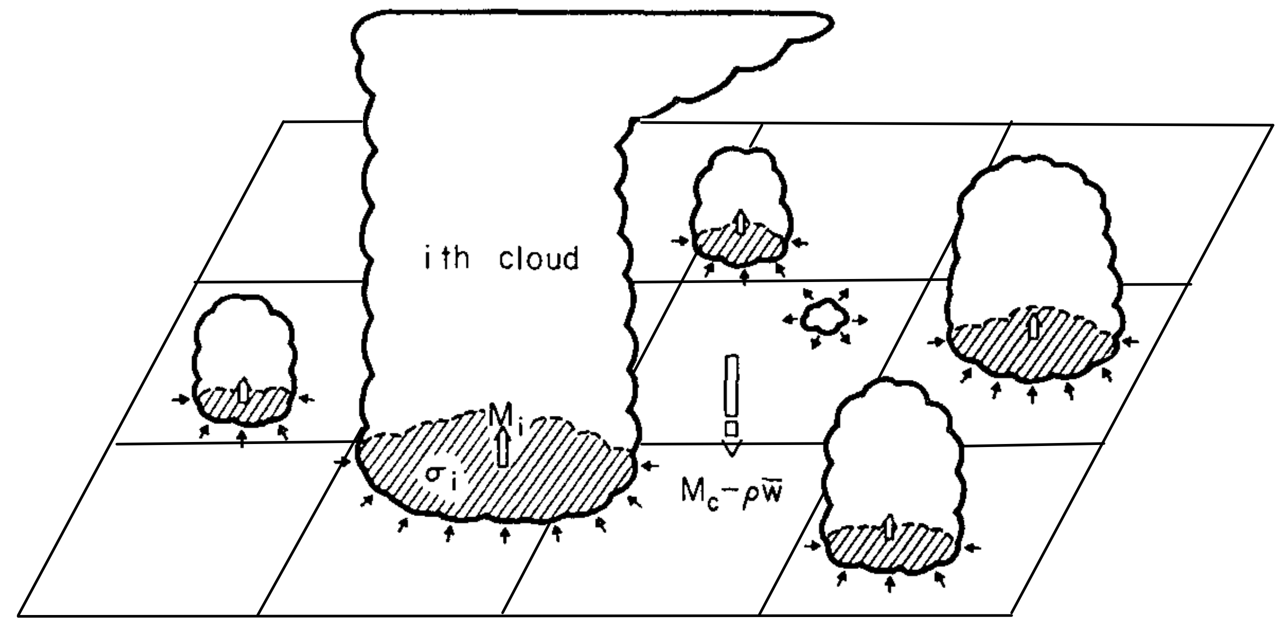
Low resolution



Updrafts are assumed to occupy a small fraction of each grid cell

Convective transport on *subgrid* scale

High resolution

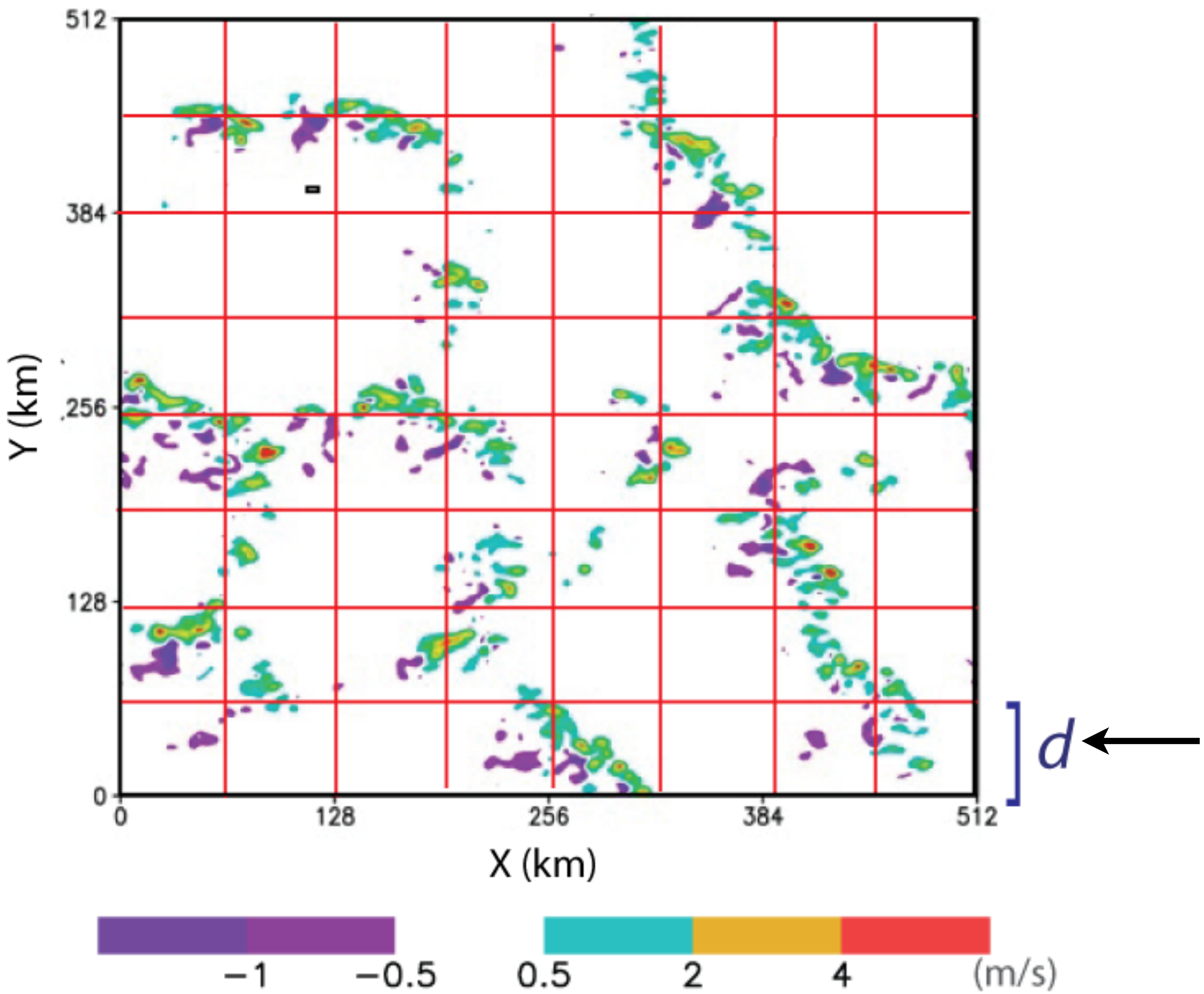


Some grid cells are almost filled by updrafts

Convective transport on *grid* scale

A unified parameterization must determine σ, the fraction of each grid cell that is occupied by convective updrafts and downdrafts.

Use a CRM to suggest and test ideas.



Map of vertical velocity
3 km above the surface

Idealized simulation based on GATE data

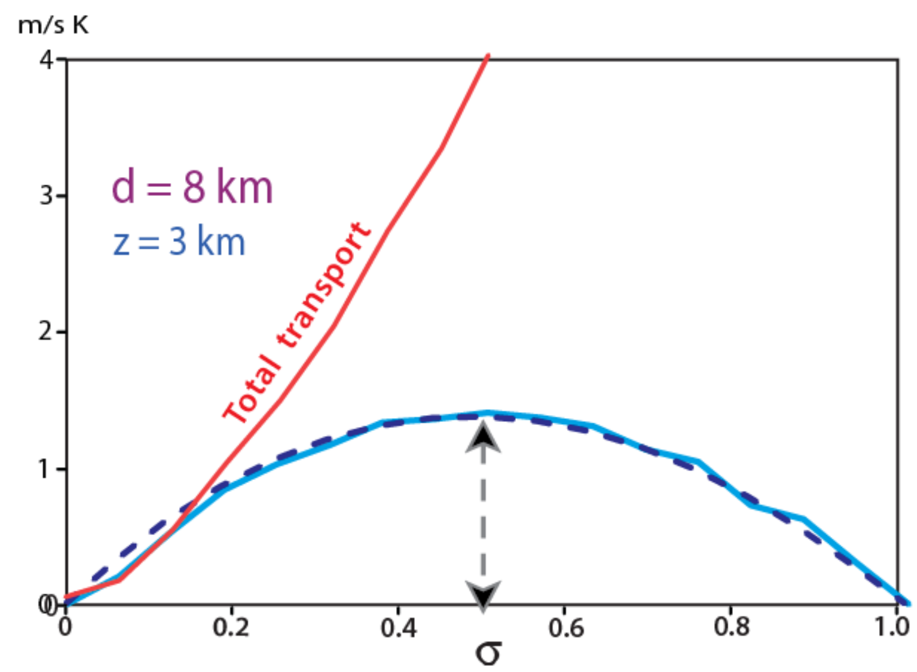
Compute σ as the fraction of each grid cell where w > 1 m/s.

Subdomain size, used to analyze dependence on grid spacing

Figure from Akio Arakawa

Flux partitioning as function of σ and d

Moist static energy transport



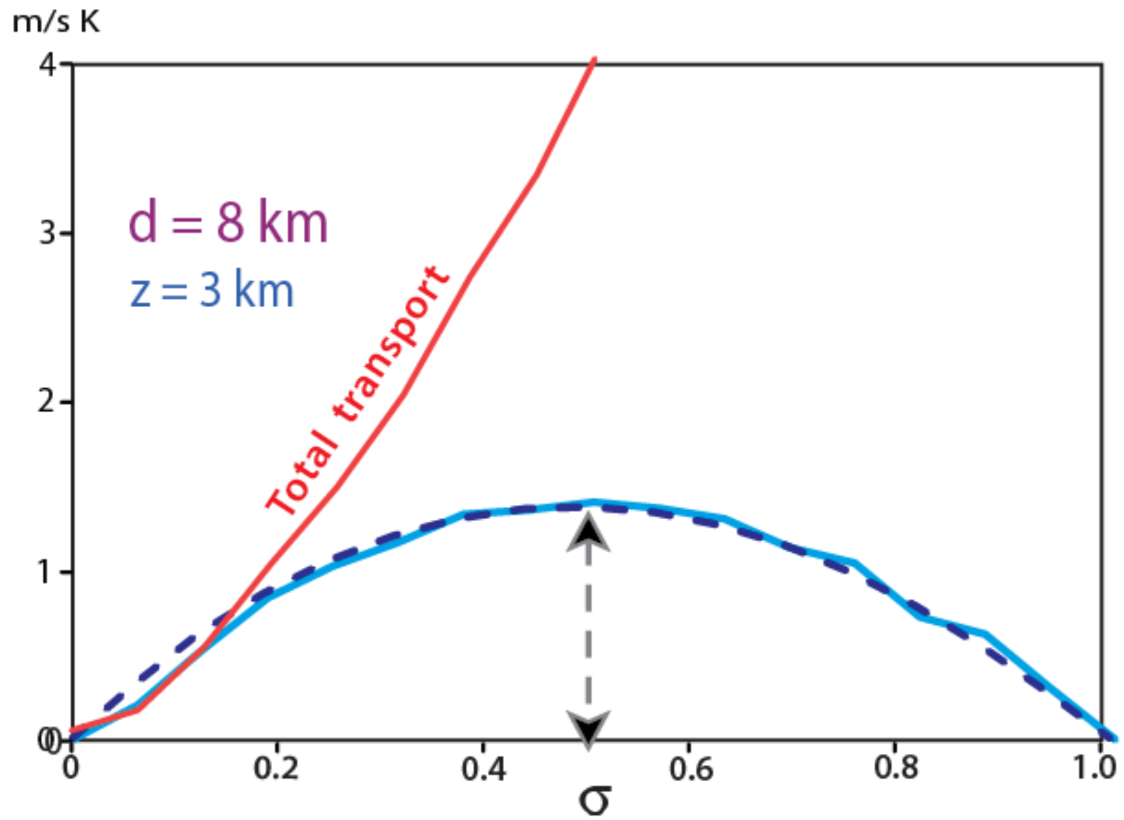
Blue data is SGS transport from CRM.

Dashed curve is based on a theory.

Note that large σ is only possible when the grid spacing is fine.

Figure from Akio Arakawa

Status of the Unified Parameterization



The unified parameterization is currently being tested in both CAM5 and NCEP's GFS.

Arakawa A., J.-H. Jung and C.-M. Wu, 2010: Toward unification of general circulation and cloud-resolving models. In *Proceedings of ECMWF workshop on non-hydrostatic modelling*, 8-10 November, 2010, 18 pp.

Arakawa, A., J.-H. Jung, and C. M. Wu, 2011: Toward Unification of the Multiscale Modeling of the Atmosphere. *Atmospheric Chemistry and Physics*, **11**, 3731-3742.

Arakawa, A., and C.-M. Wu, 2013: A Unified Representation of Deep Moist Convection in Numerical Modeling of the Atmosphere. Part I. *J. Atmos. Sci.*, **70**, 1977–1992.

Wu, C.-M., and A. Arakawa, 2014: A Unified Representation of Deep Moist Convection in Numerical Modeling of the Atmosphere. Part II. *J. Atmos. Sci.*, **71**, 2089–2103.


One more thing...
Chaotic Convection in SP-CAM

"Non-deterministic" clouds on unresolved scales are not fully controlled by the resolved-scale weather.

Deterministic parameterization

Non-deterministic parameterization

A deterministic parameterization simulates "expected values" or ensemble means.

A non-deterministic parameterization simulates individual realizations.

A super-parameterization is non-deterministic because the solution produced by the CRM is sensitively dependent on initial conditions.

Is there a way to explore the ensemble of possible realizations?

Doppelgängers

Instead of one CRM per GCM grid column, include N copies of the CRM.

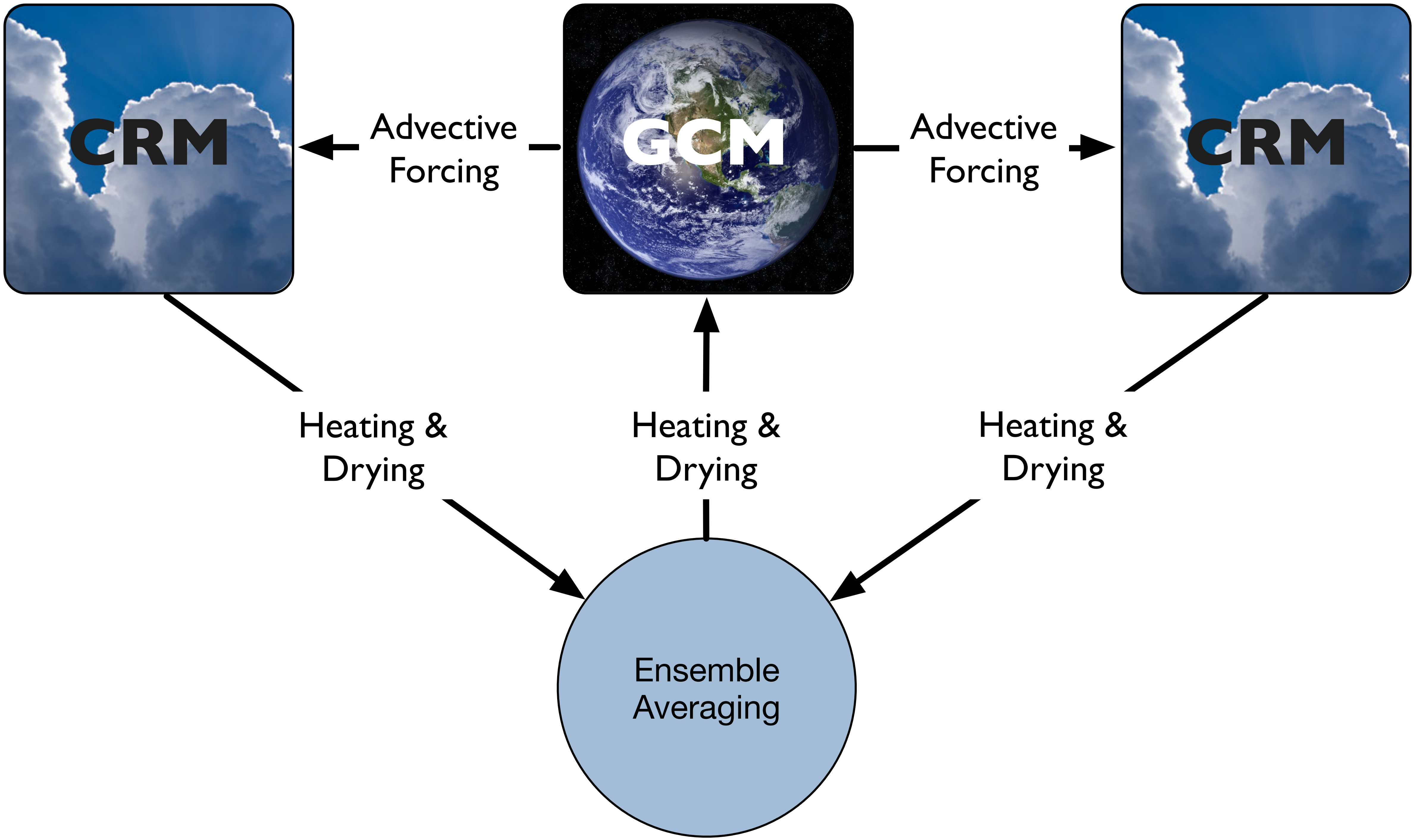
All copies see the same GCM weather.

The CRMs start from slightly different initial conditions.

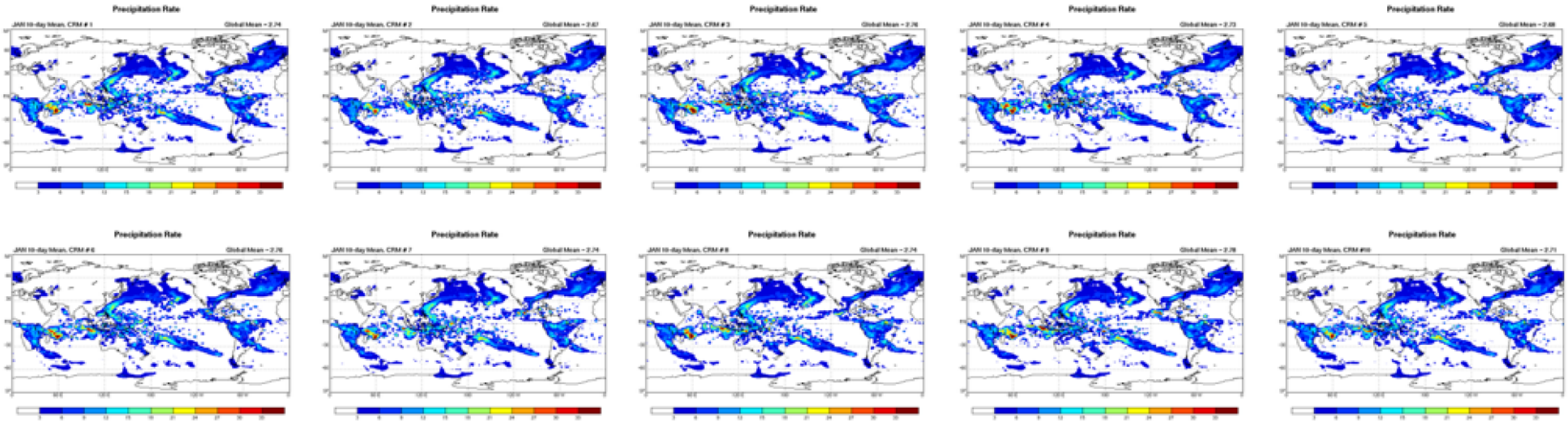
Each copy runs independently of the others.

MP-CAM

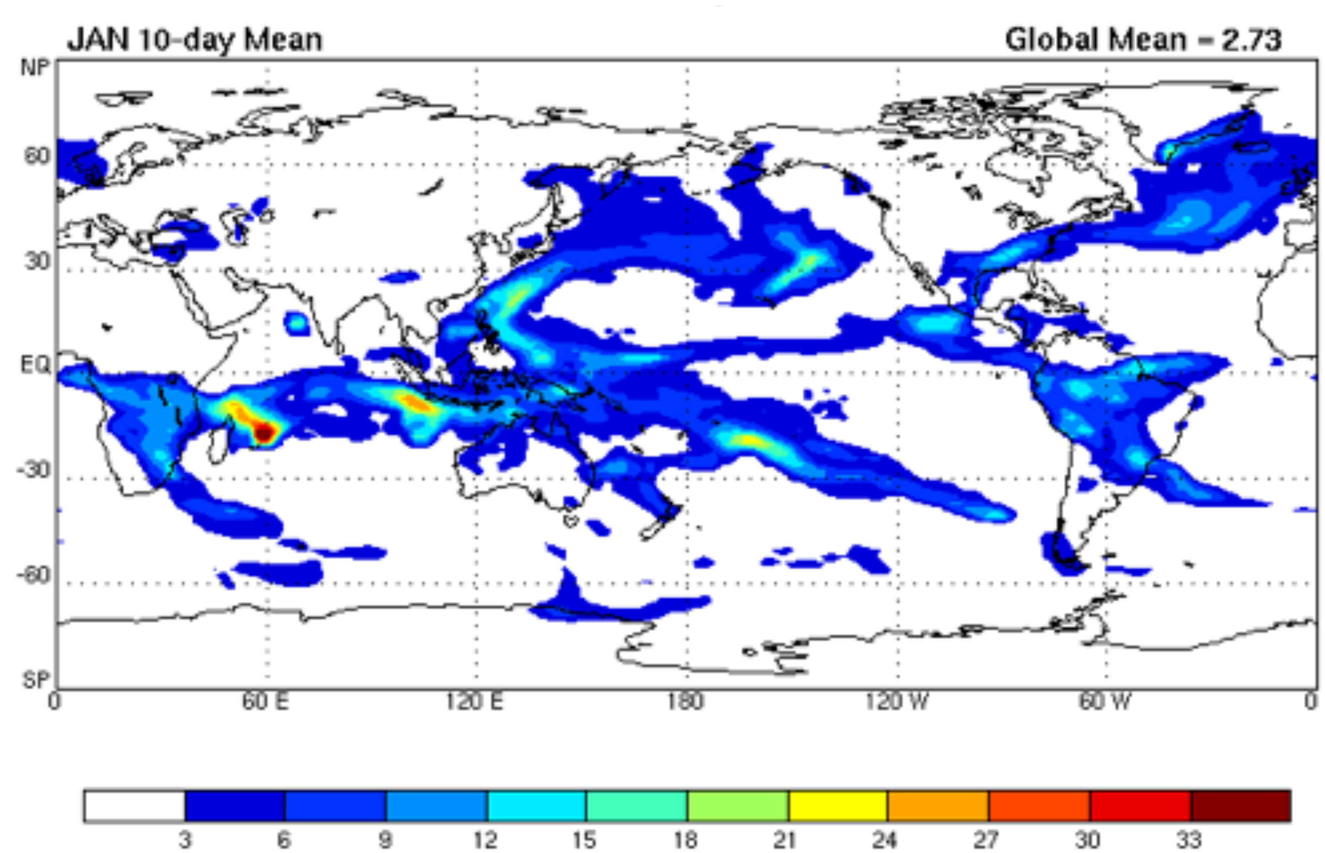
Illustrated for the case $N = 2$



This is what a deterministic parameterization tries to do.



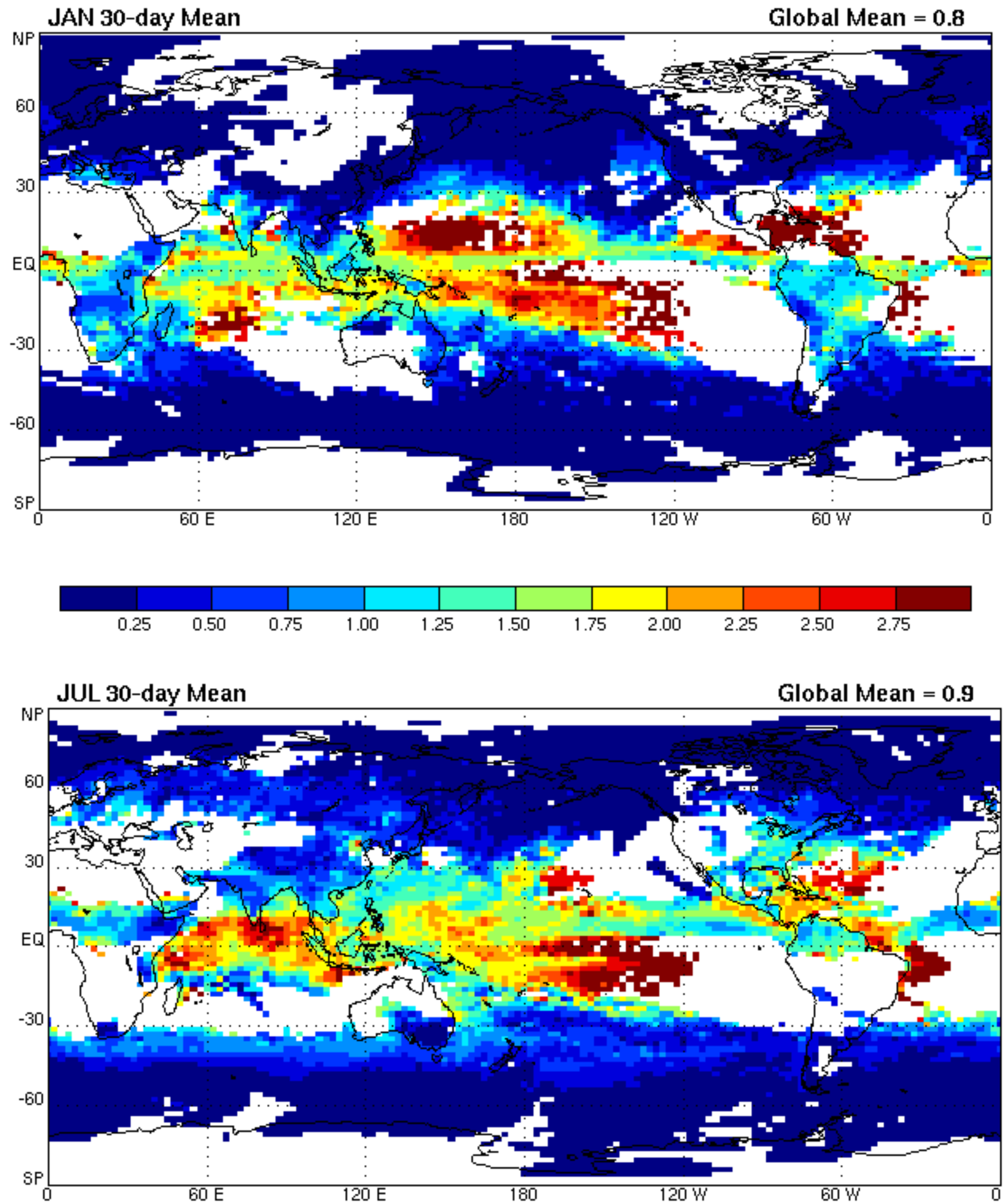
Individual realizations



Ensemble average

Where & when is strong precipitation predictable?

Standard dev / mean, sampled once per day where the daily mean > 5 mm day^{-1}

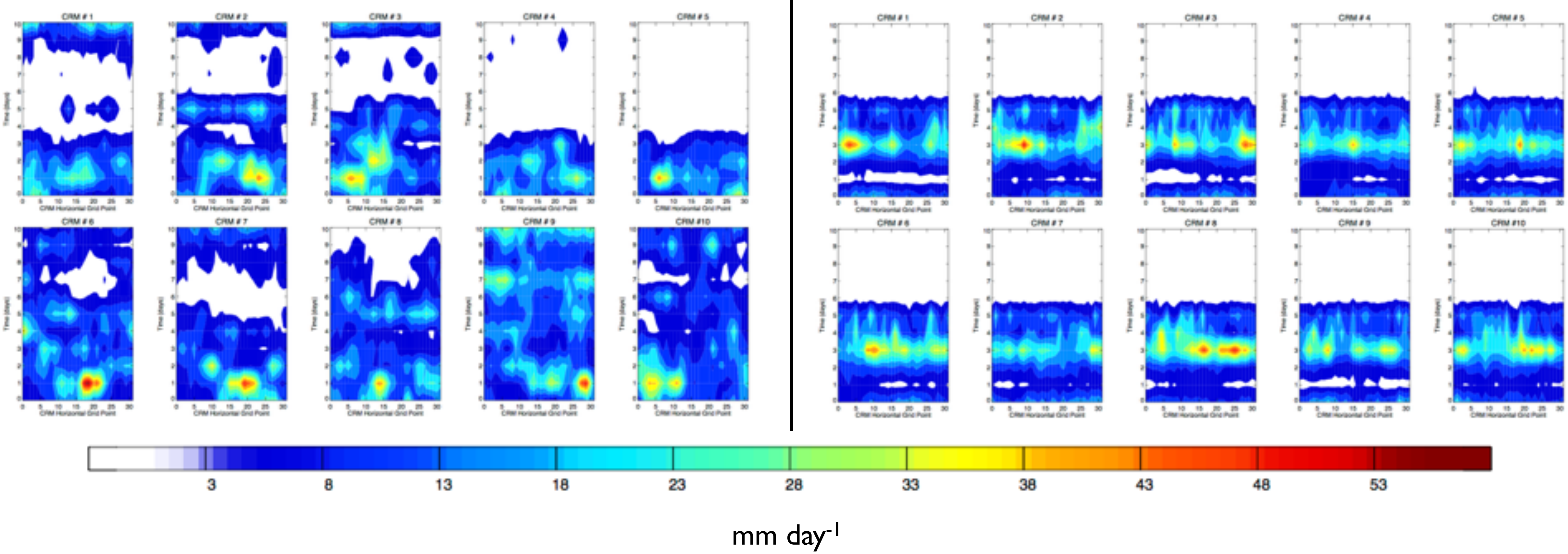


Ten days in the life of two selected GCM columns

These are Hovmöller diagrams, with time increasing upward.
The horizontal axis in each panel is horizontal distance in the CRM.

Ten realizations at a tropical point

Ten realizations at a midlatitude point

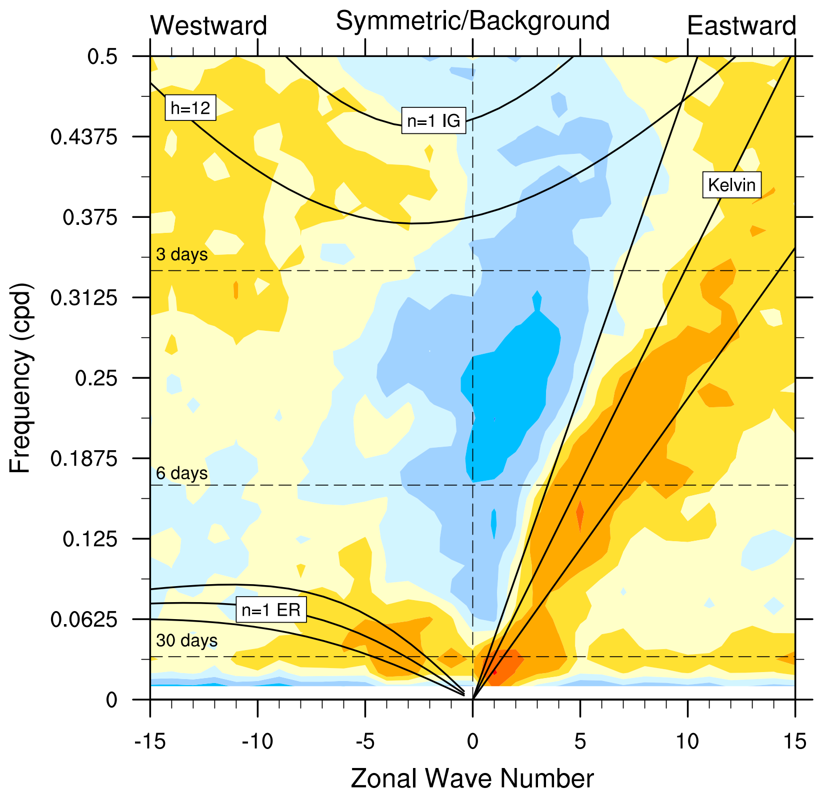


What I want to do with this

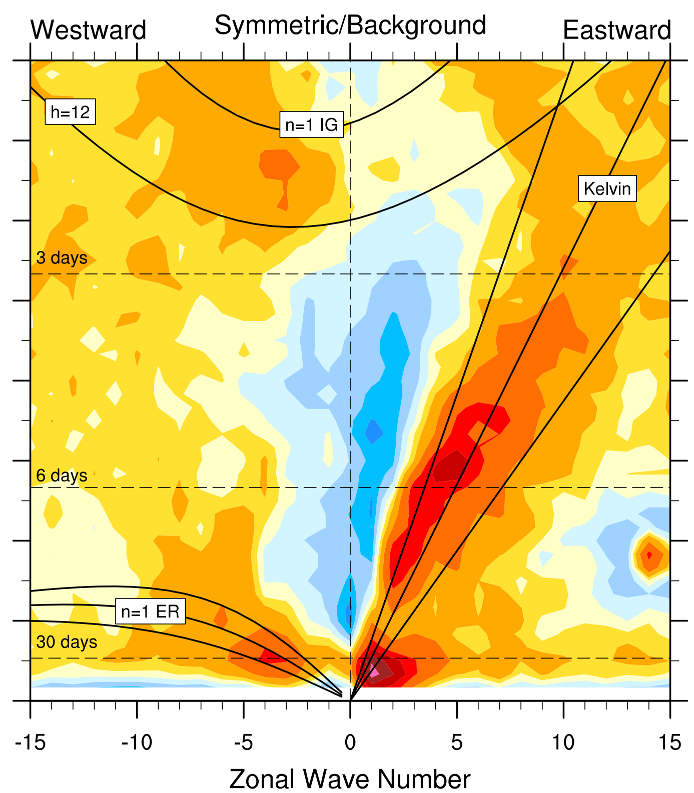
- Compare climate with ensemble-mean feedback to climate with feedback from one realization:
  - Systematic differences in extreme precipitation events?
  - Systematic differences in the MJO or other large-scale weather systems?
- Identify the specific weather regimes and physical mechanisms that are associated with strong but unpredictable convection.

Symmetric modes

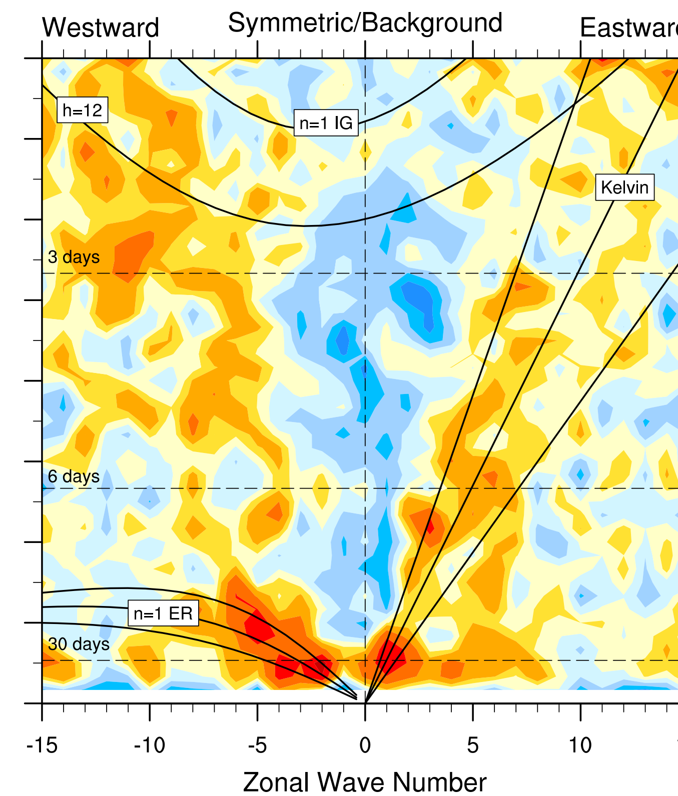
SP-CAM



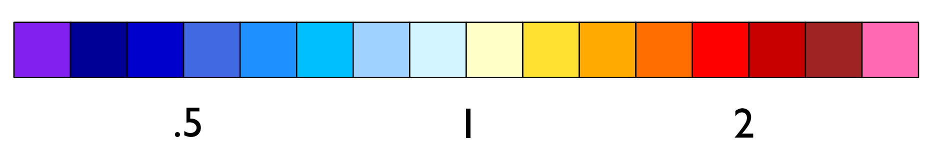
Observations



MP-CAM



Only 3 simulated years



Summary

- Current parameterizations are not applicable for grid spacings finer than about 25 km.
- The SP-CAM replaces the CAM physics with a CRM, and gains new powers as a result.
- The Q3D MMF can carry us across the grey zone, and converges to a global cloud-resolving model.
- The Unified Parameterization can cross the grey zone without using a CRM.
- The MP-CAM can be used to explore the physics of stochastic convection.

CMMAP

Reach for the sky.