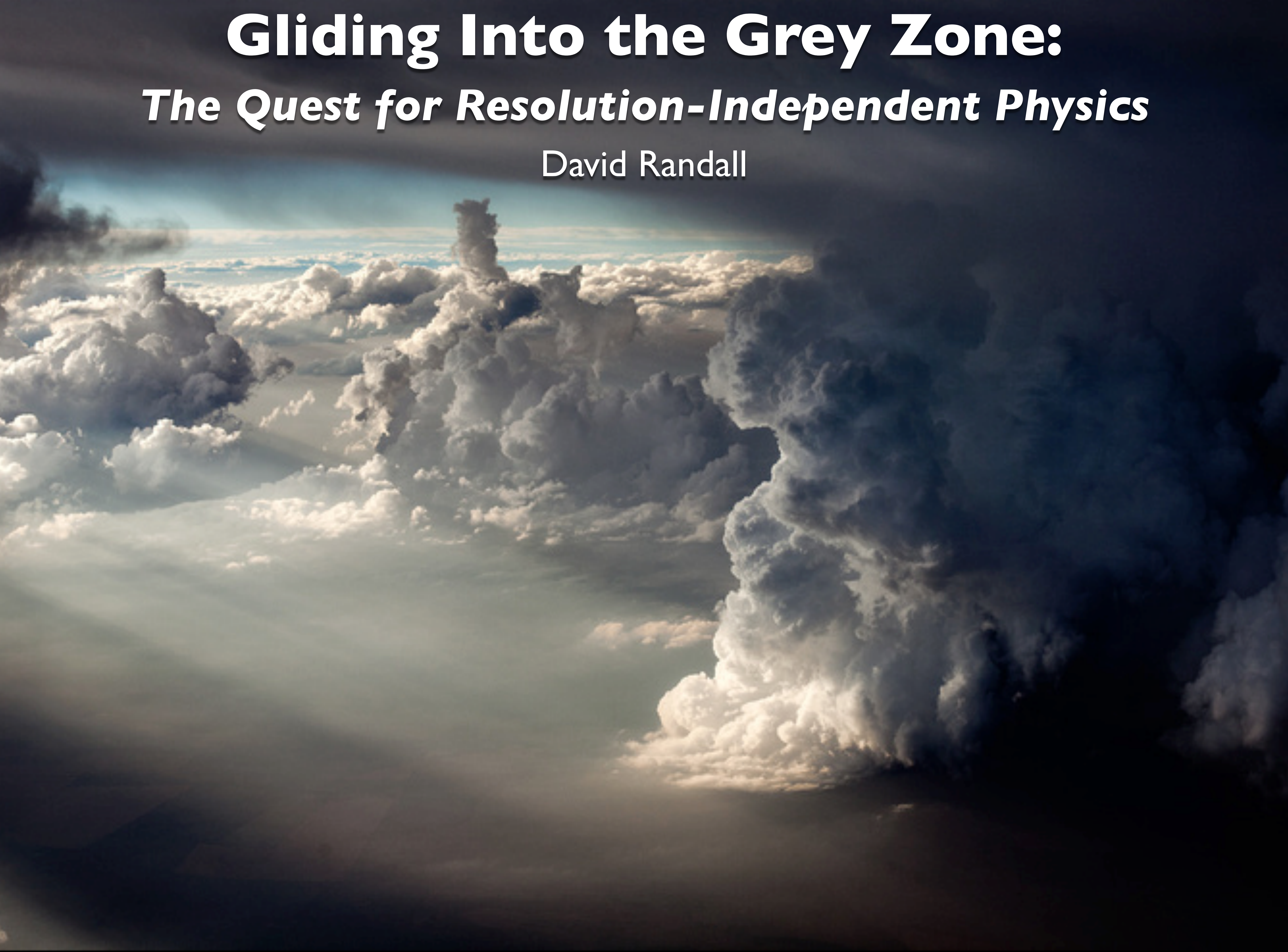


Gliding Into the Grey Zone:

The Quest for Resolution-Independent Physics

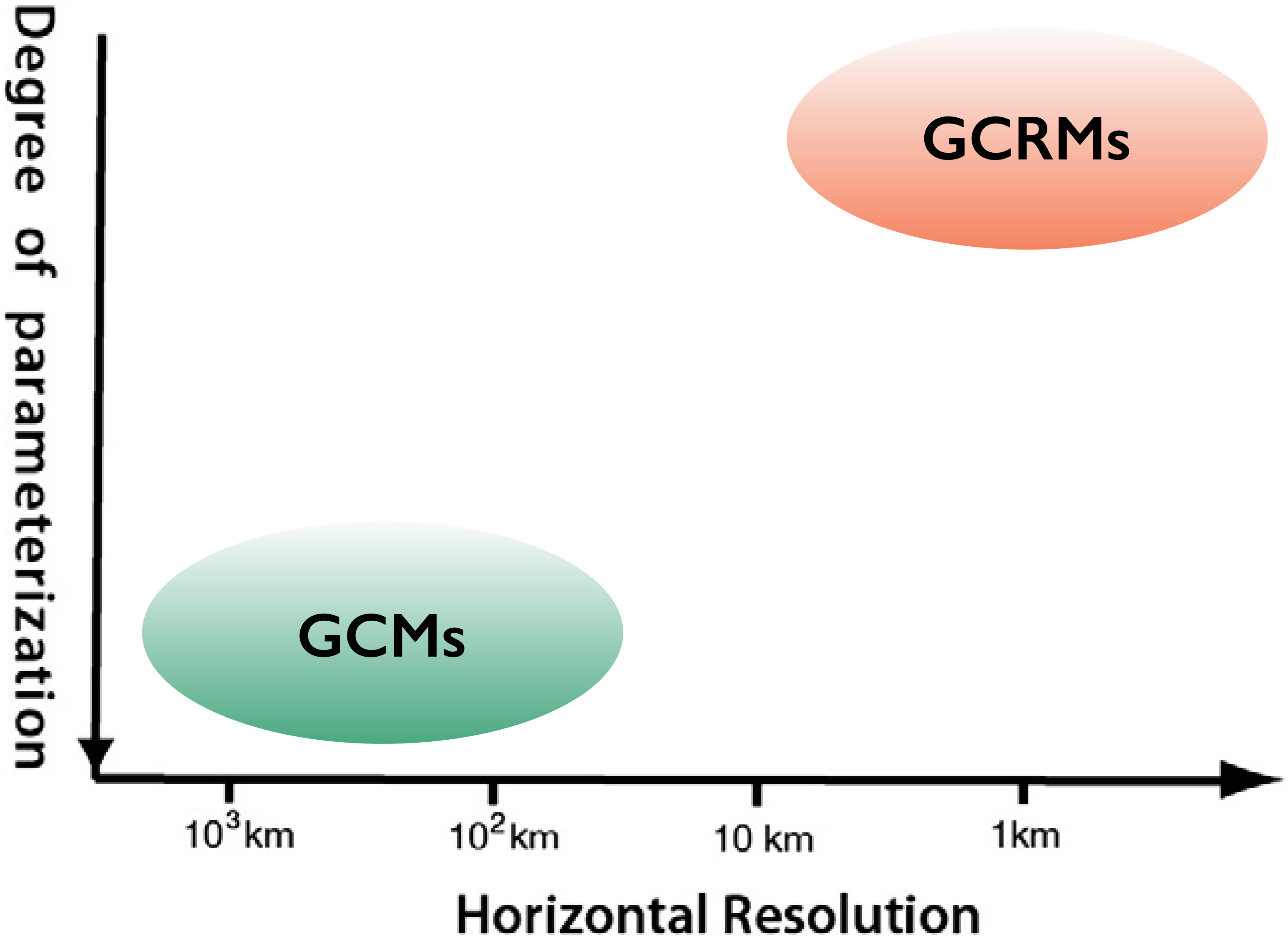
David Randall

Global modeling landscape, 20XX

Global cloud-resolving models

Deep moist convection explicitly simulated

Moist convection highly parameterized

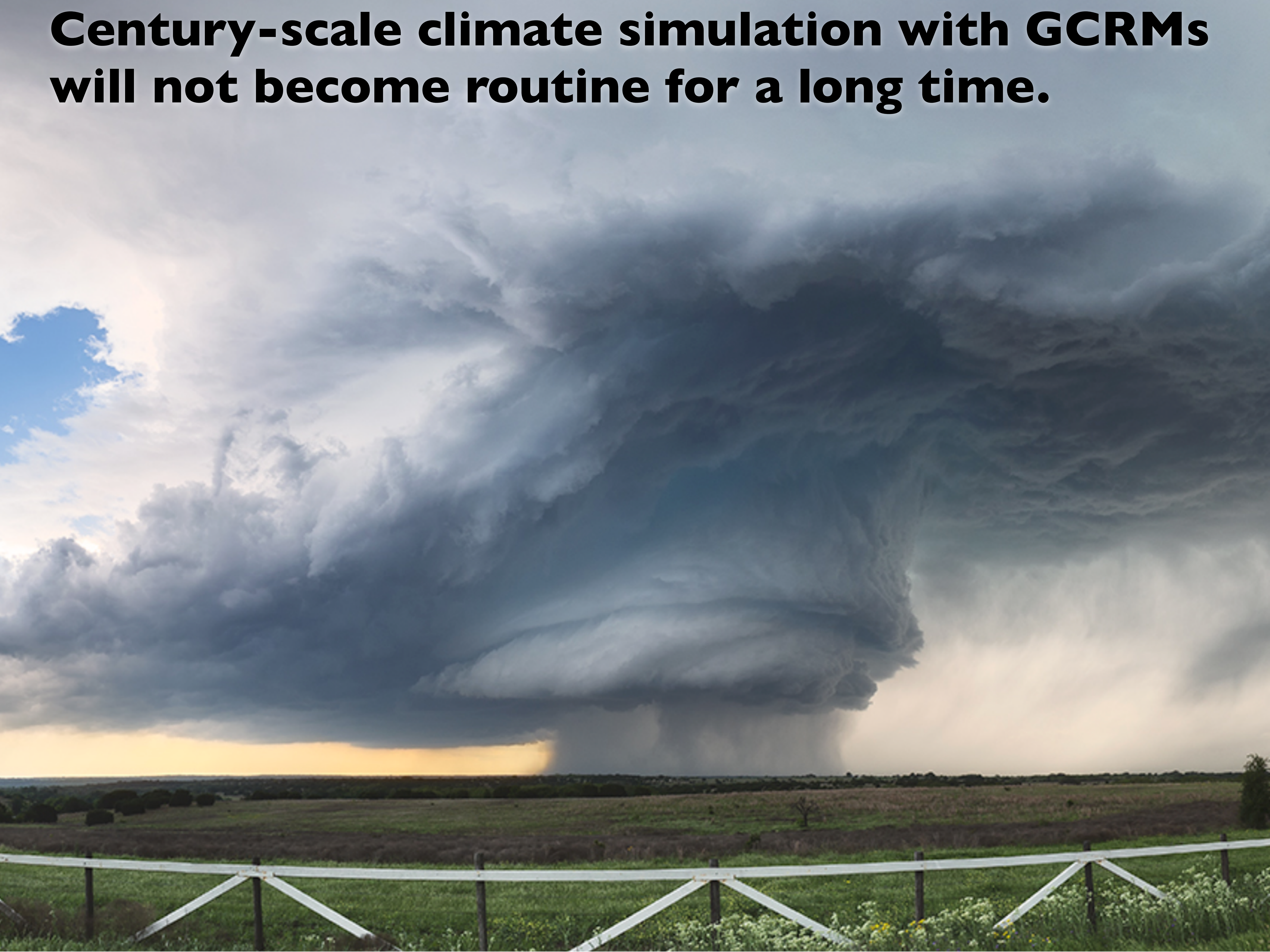


Resolve clouds?

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.

Century-scale climate simulation with GCRMs will not become routine for a long time.



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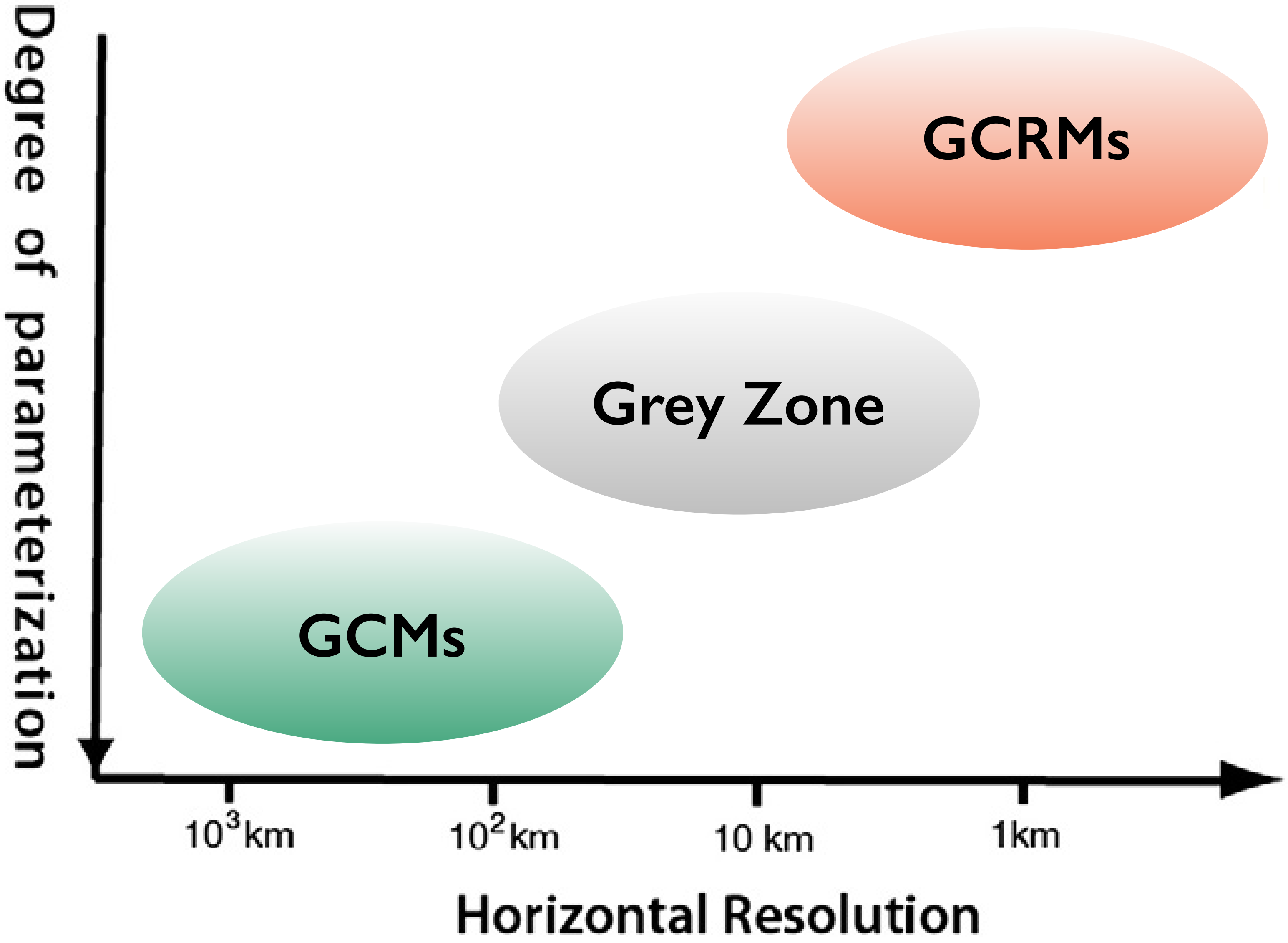
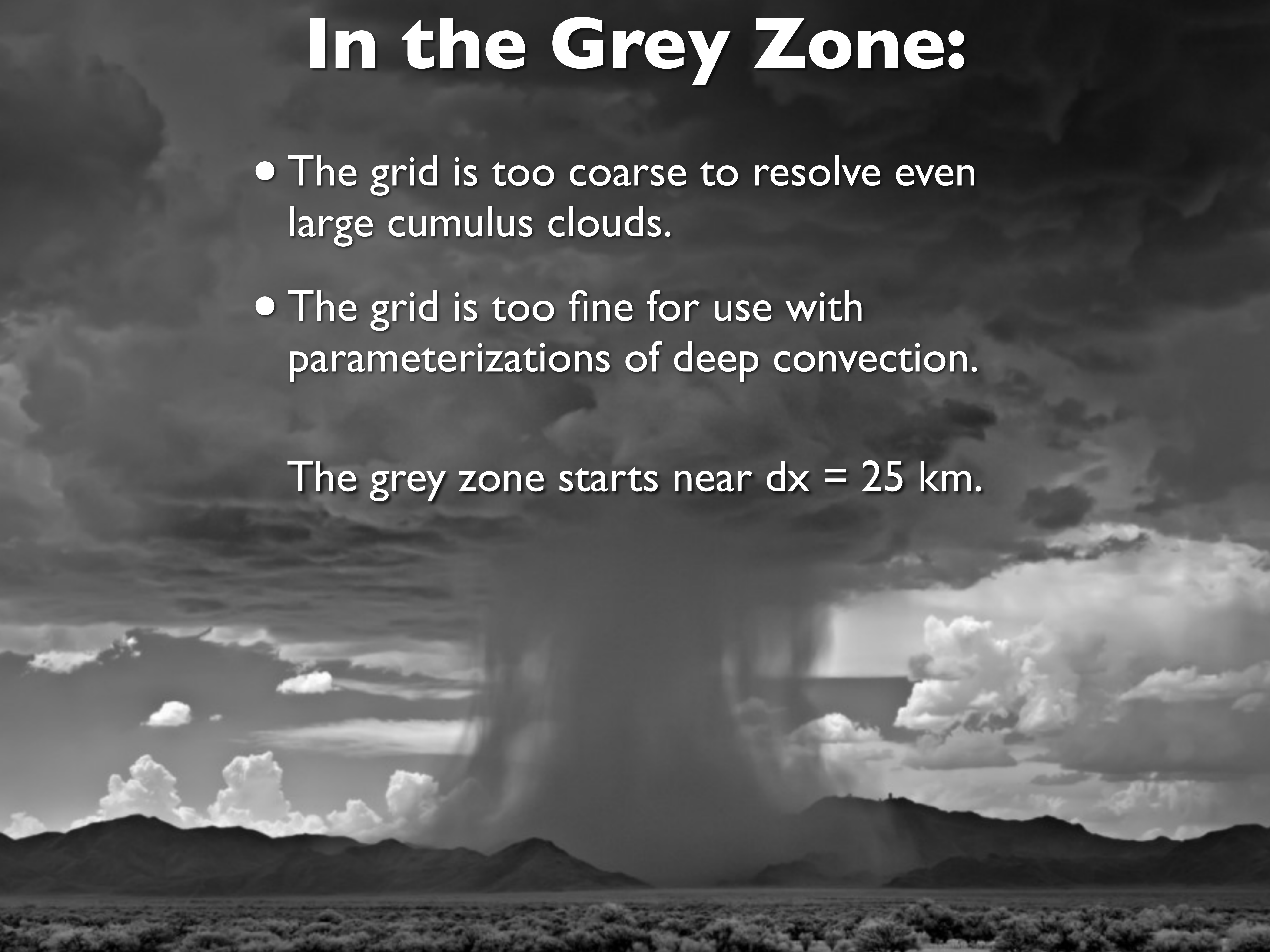


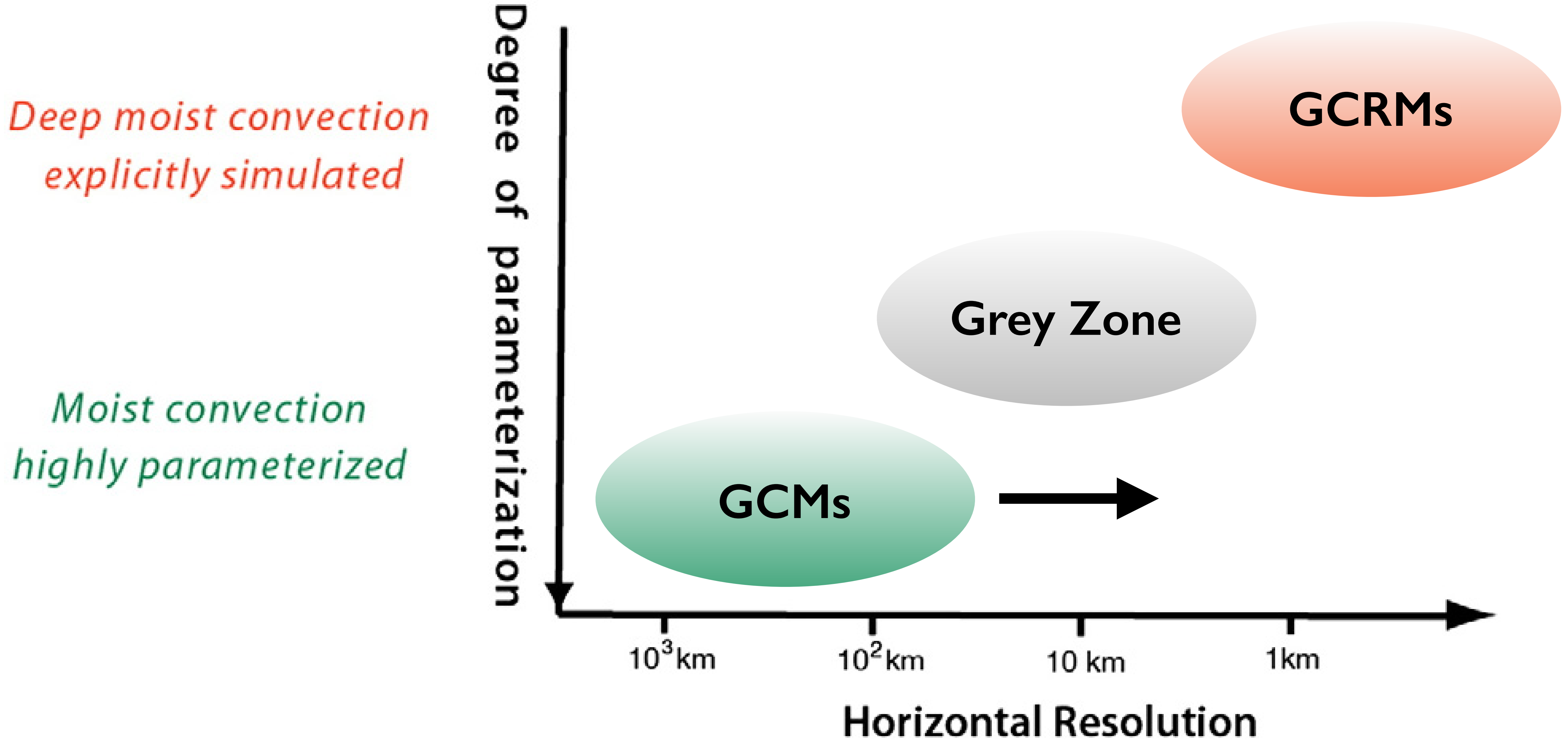


In the Grey Zone:

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

The grey zone starts near dx = 25 km.

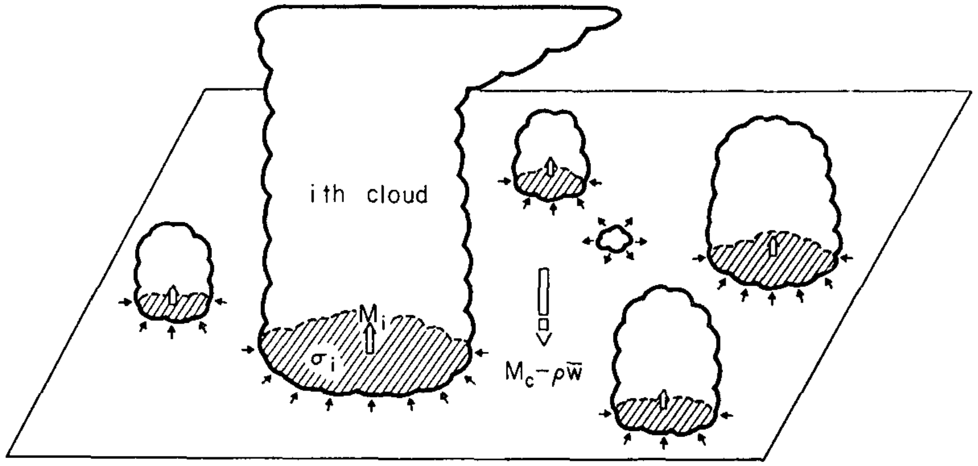
The path of least resistance: Don't change a thing.



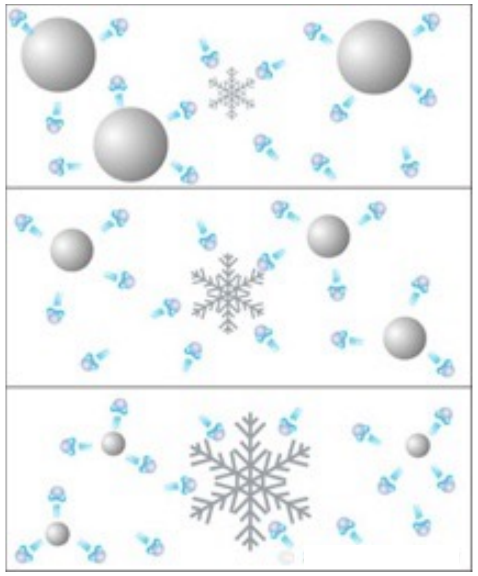
What happens if we make the grid finer without changing the parameterizations?

- 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*.

Parameterizations Must Be Scale-Dependent.



Increasing resolution



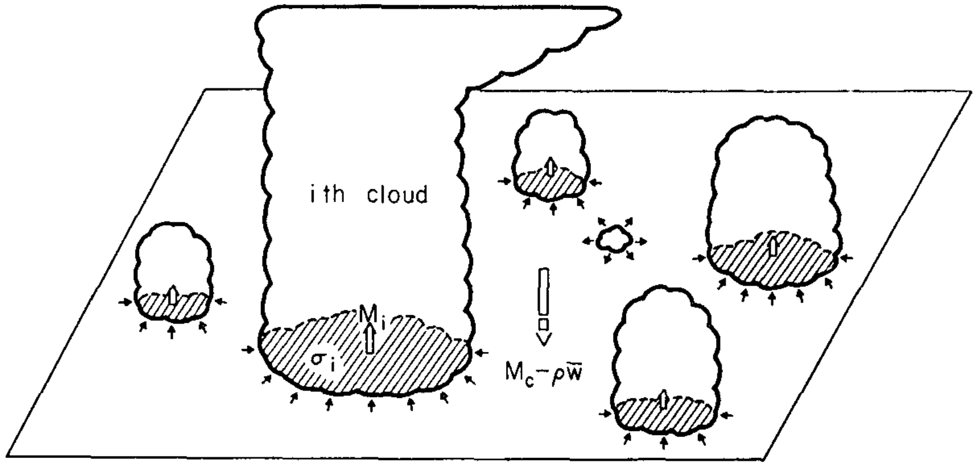
GCM

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.

Parameterizations Must Be Scale-Dependent.



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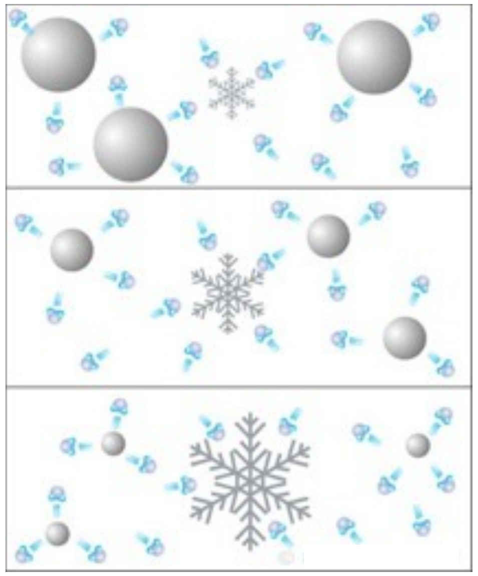


GCM

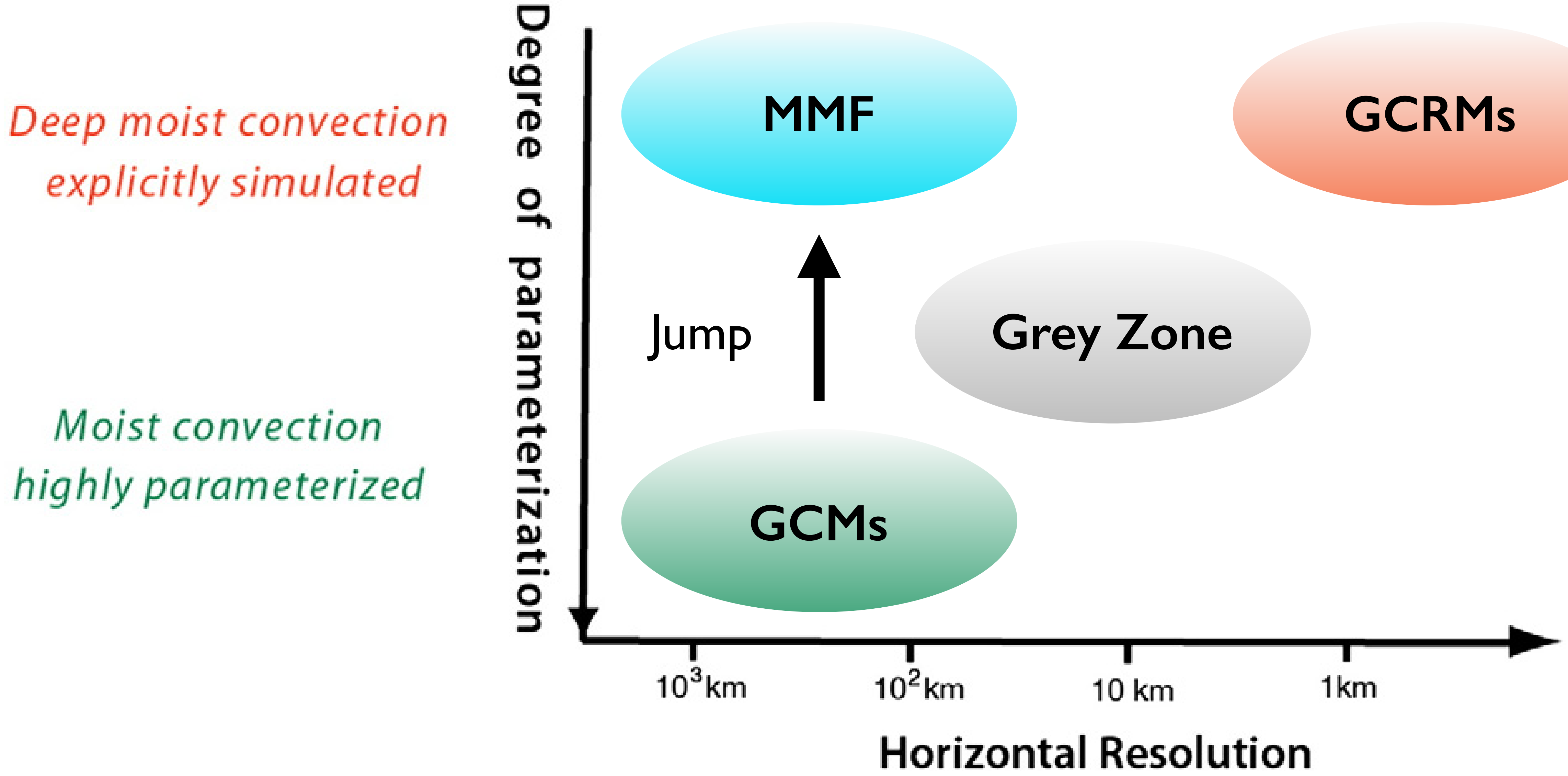
CRM

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

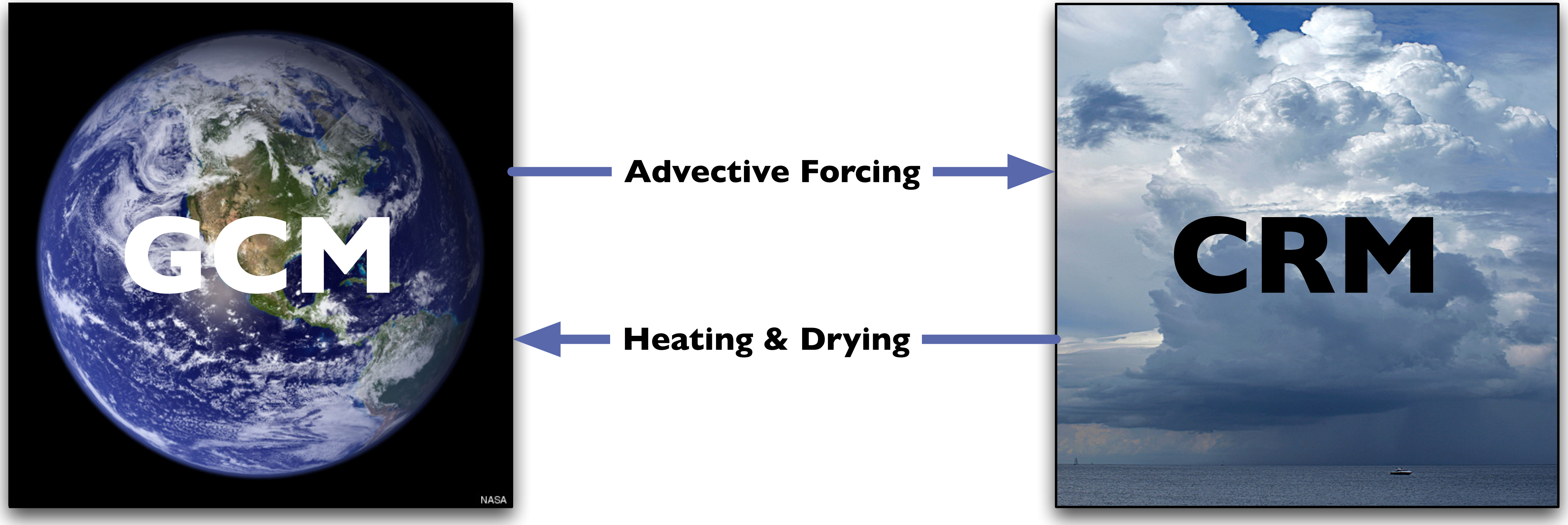
Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

So, should we just turn off the cumulus parameterization?

What if we jump up instead?



Multiscale Modeling Framework (MMF)



GCM

NASA

Advective Forcing

Heating & Drying

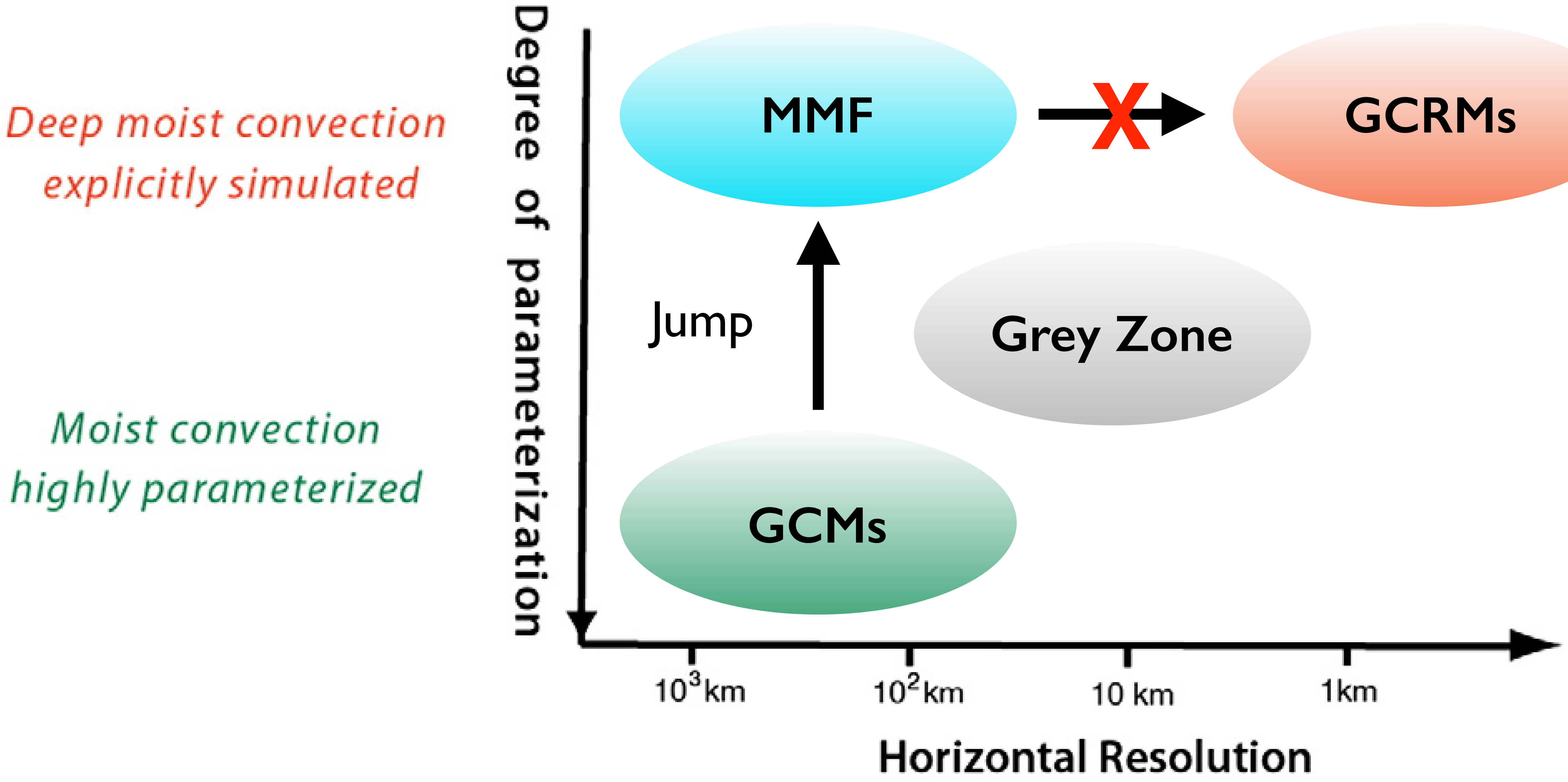
CRM

Use simplified cloud-resolving models as “super-parameterizations.”

SP-CAM

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

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

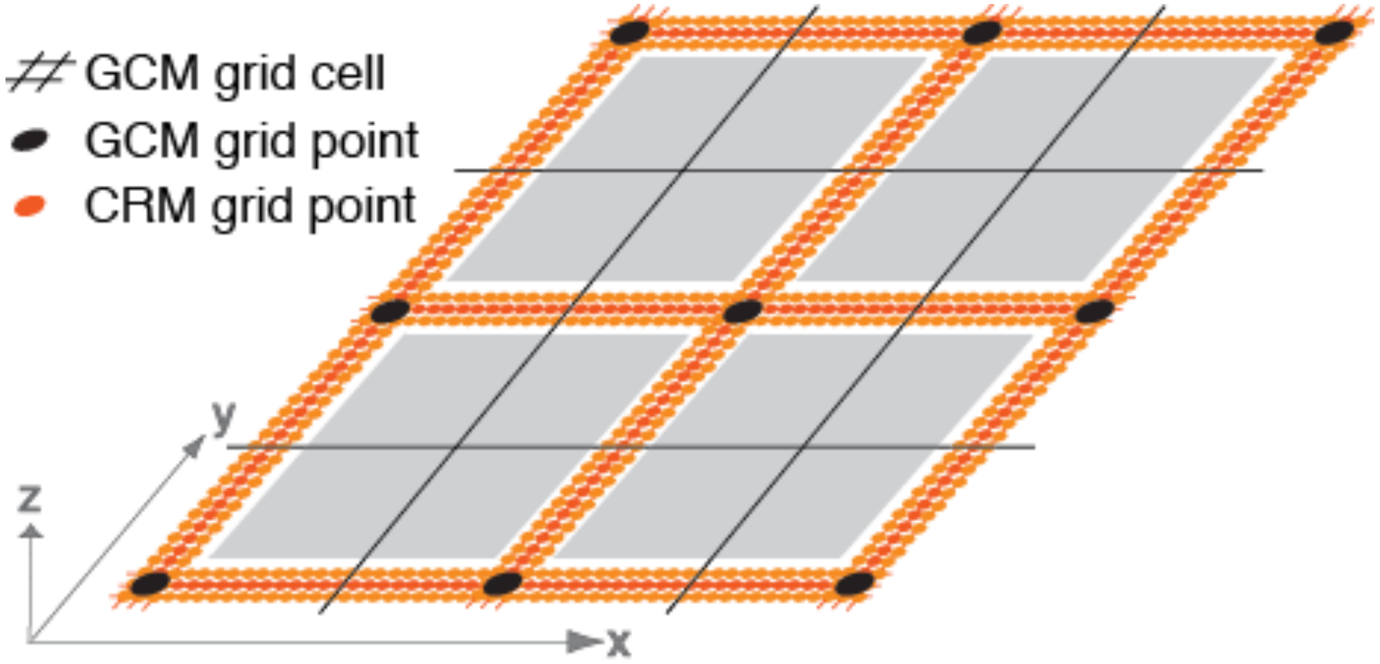


The Next-Generation MMF

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

The periodic boundary conditions of the original MMF are eliminated, so that the CRM channels extend "all the way around" the Earth.

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



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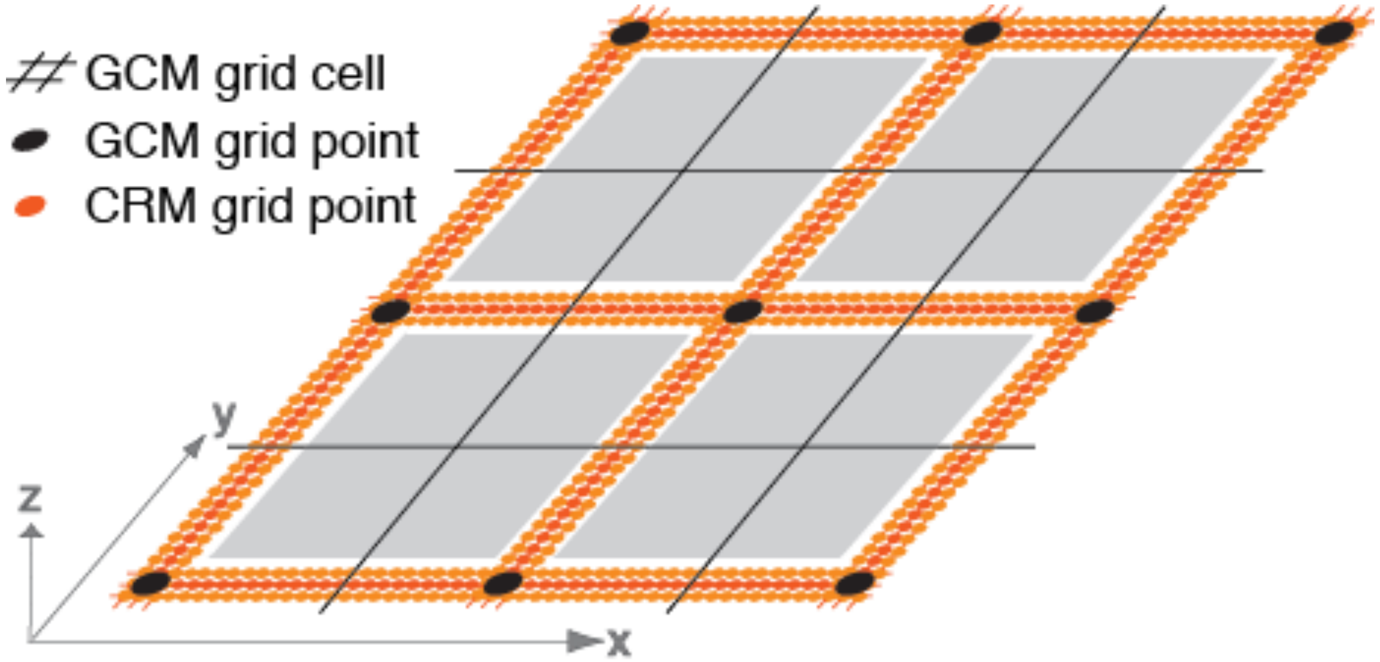
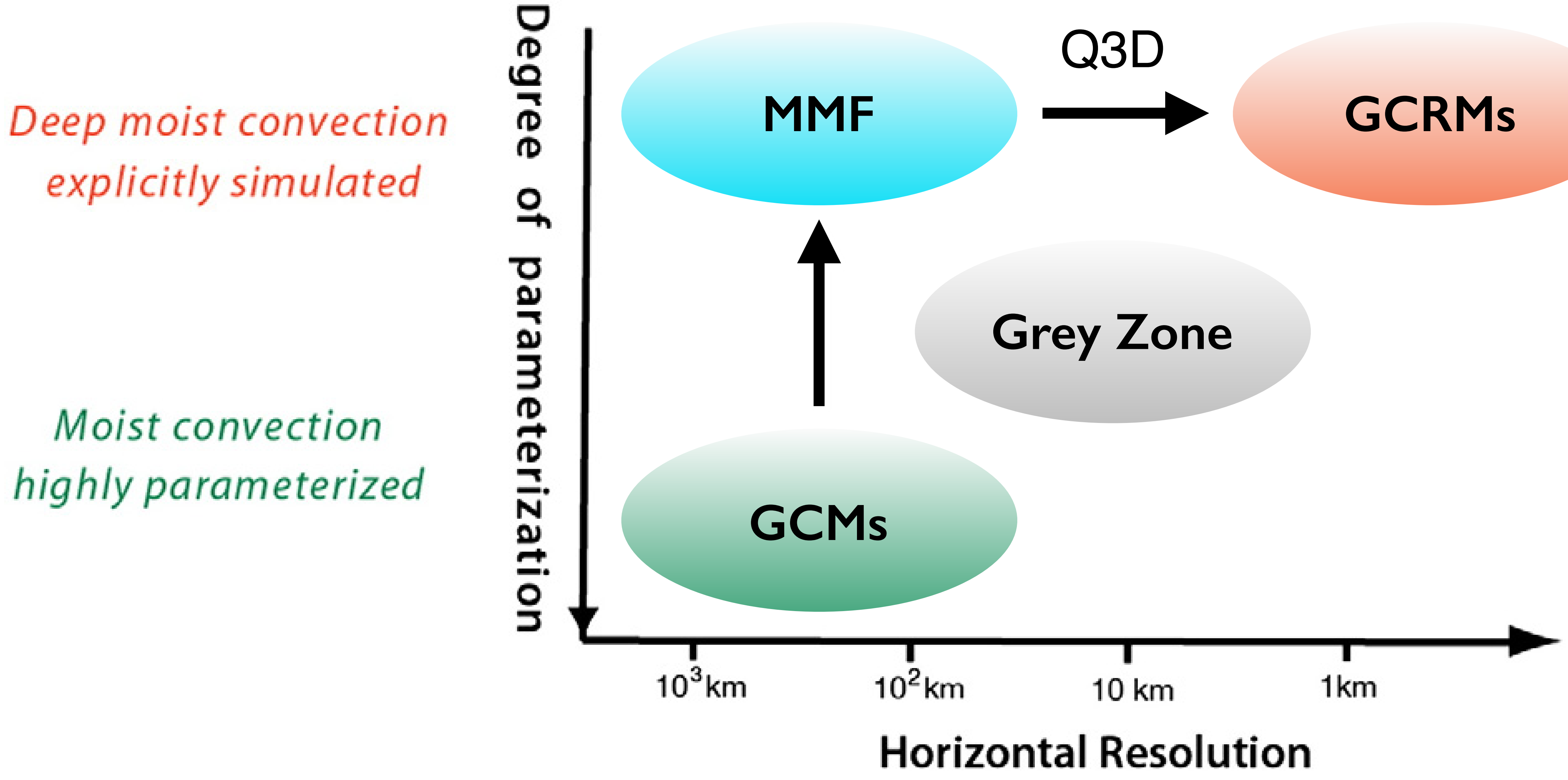
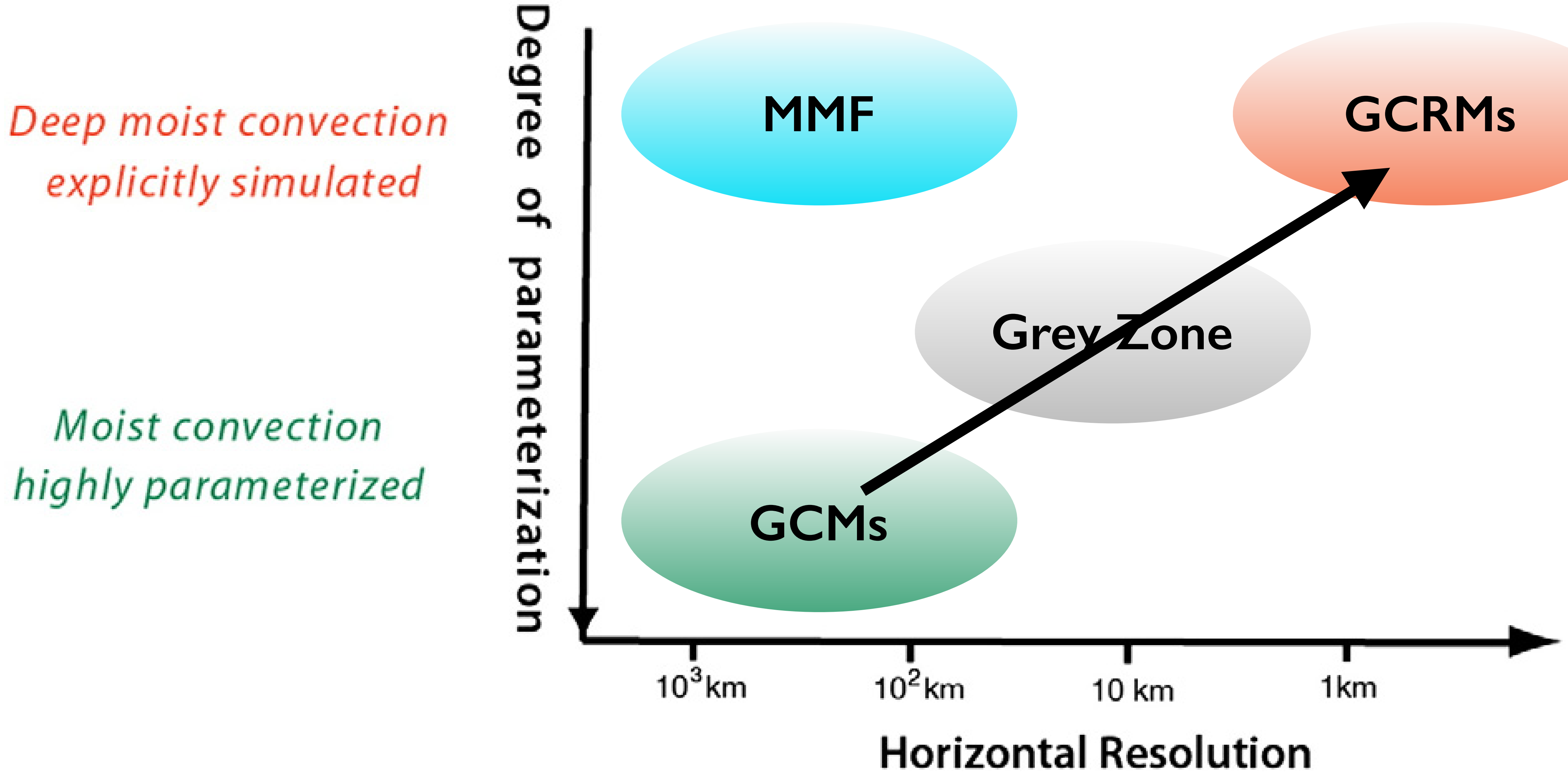


The Q3D MMF allows convection to propagate across GCM cell boundaries.
It can include the effects of realistic topography.
It can simulate momentum transport by both convection and waves.
It converges to a GCRM as the GCM's grid is refined.
The idea has been tested in a regional model, and is now being tested in the CAM.

The Q3D MMF is resolution-independent.

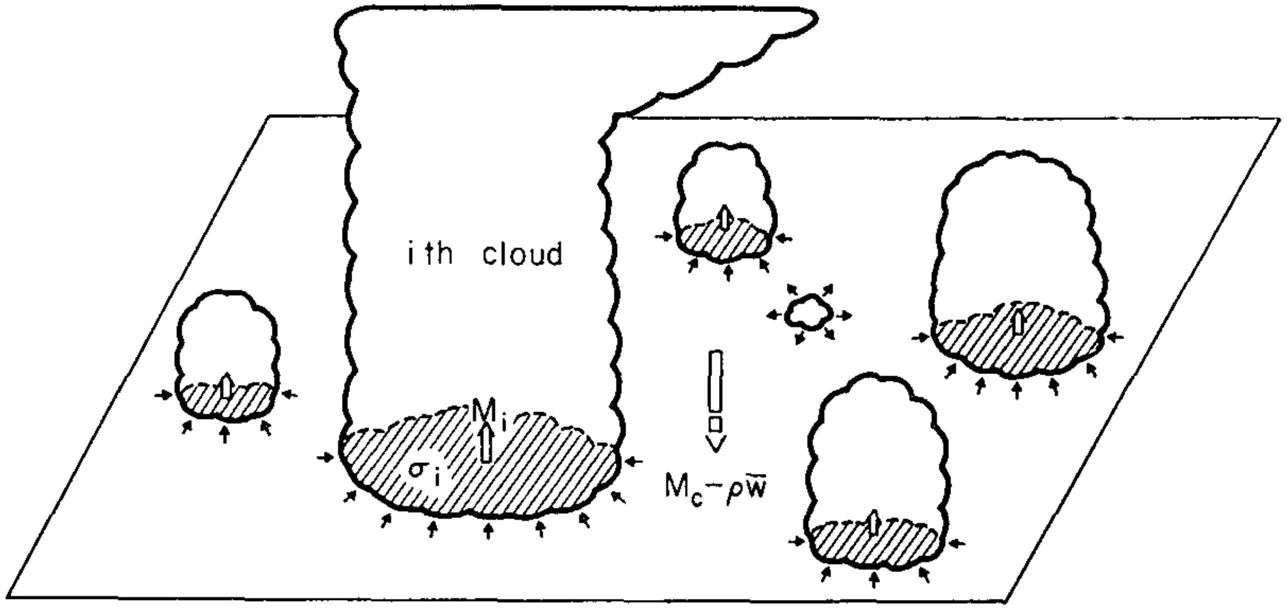


What about this more direct route?



Resolution-independent cumulus parameterizations

Low resolution

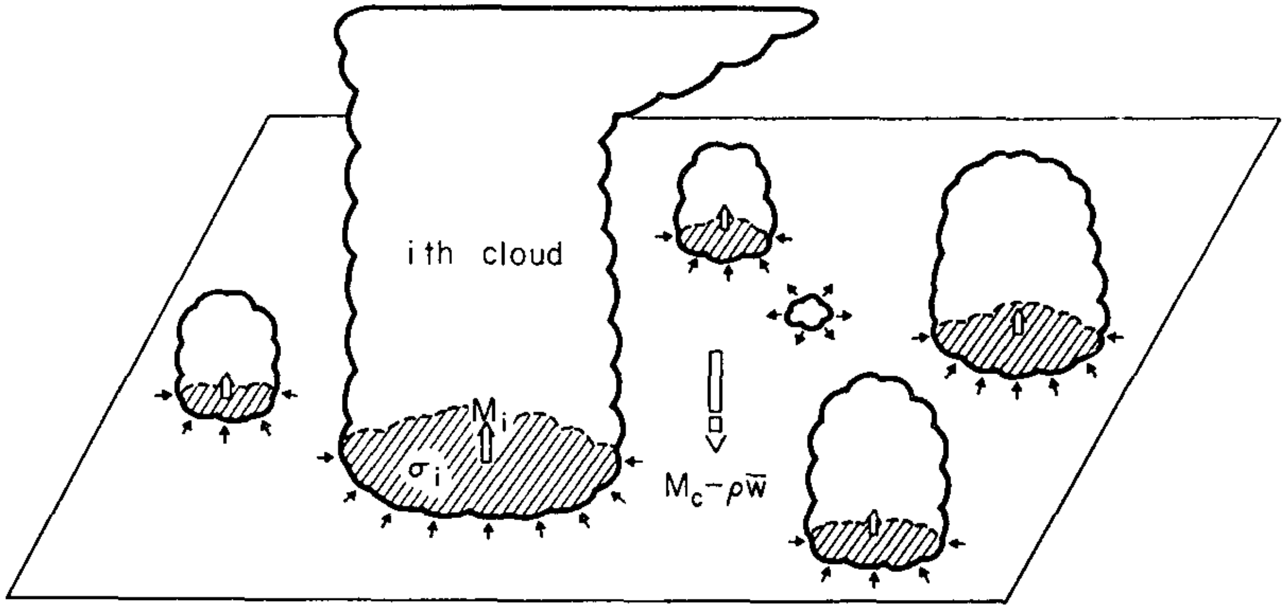


Updrafts are assumed to occupy
a small fraction of each grid cell.

Convective transport on *subgrid* scale

Resolution-independent cumulus parameterizations

Low resolution



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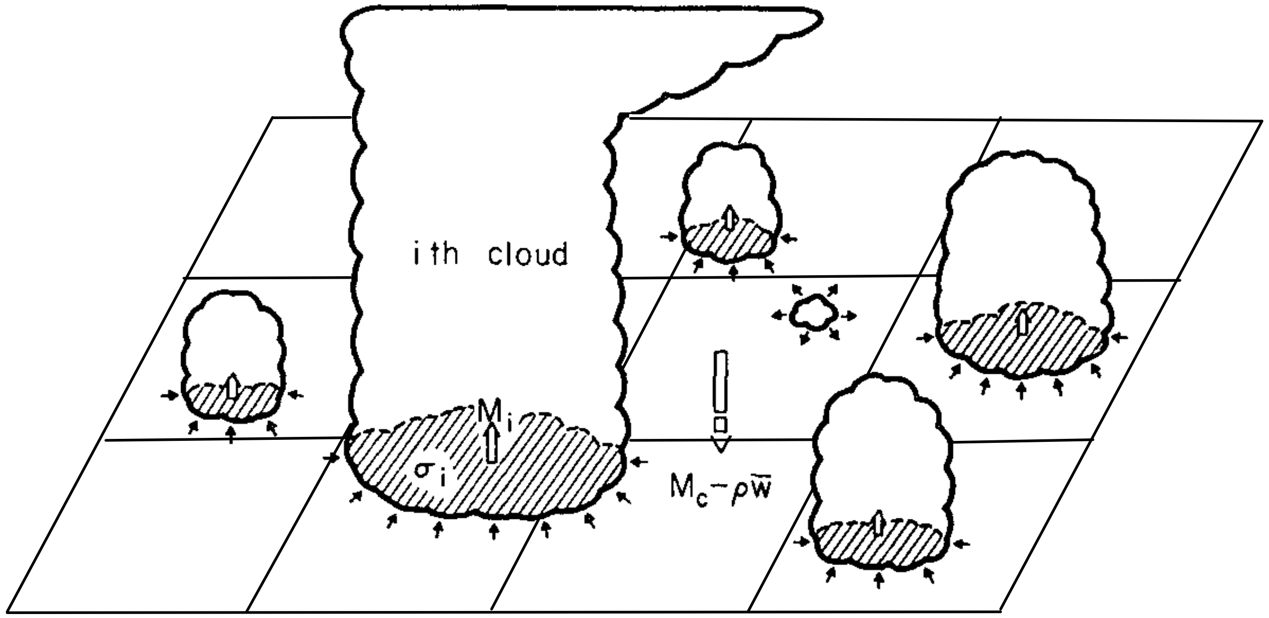
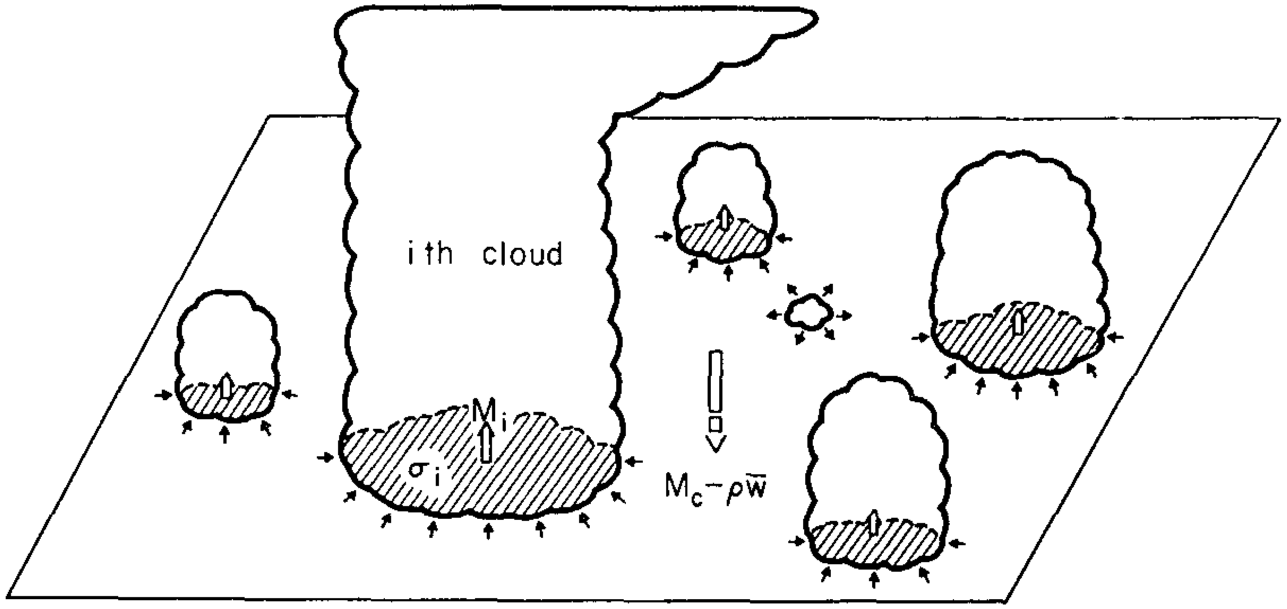


Some grid cells are
almost filled by updrafts.

Convective transport on *grid* scale

Resolution-independent cumulus parameterizations

Low resolution



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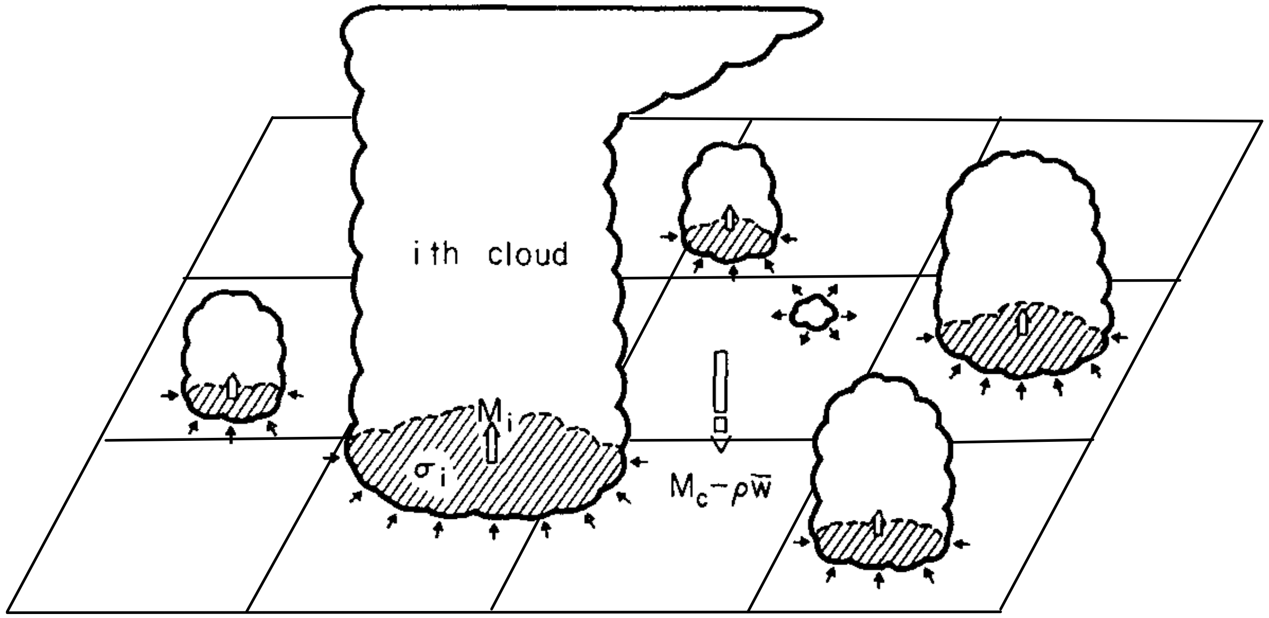

Some grid cells are
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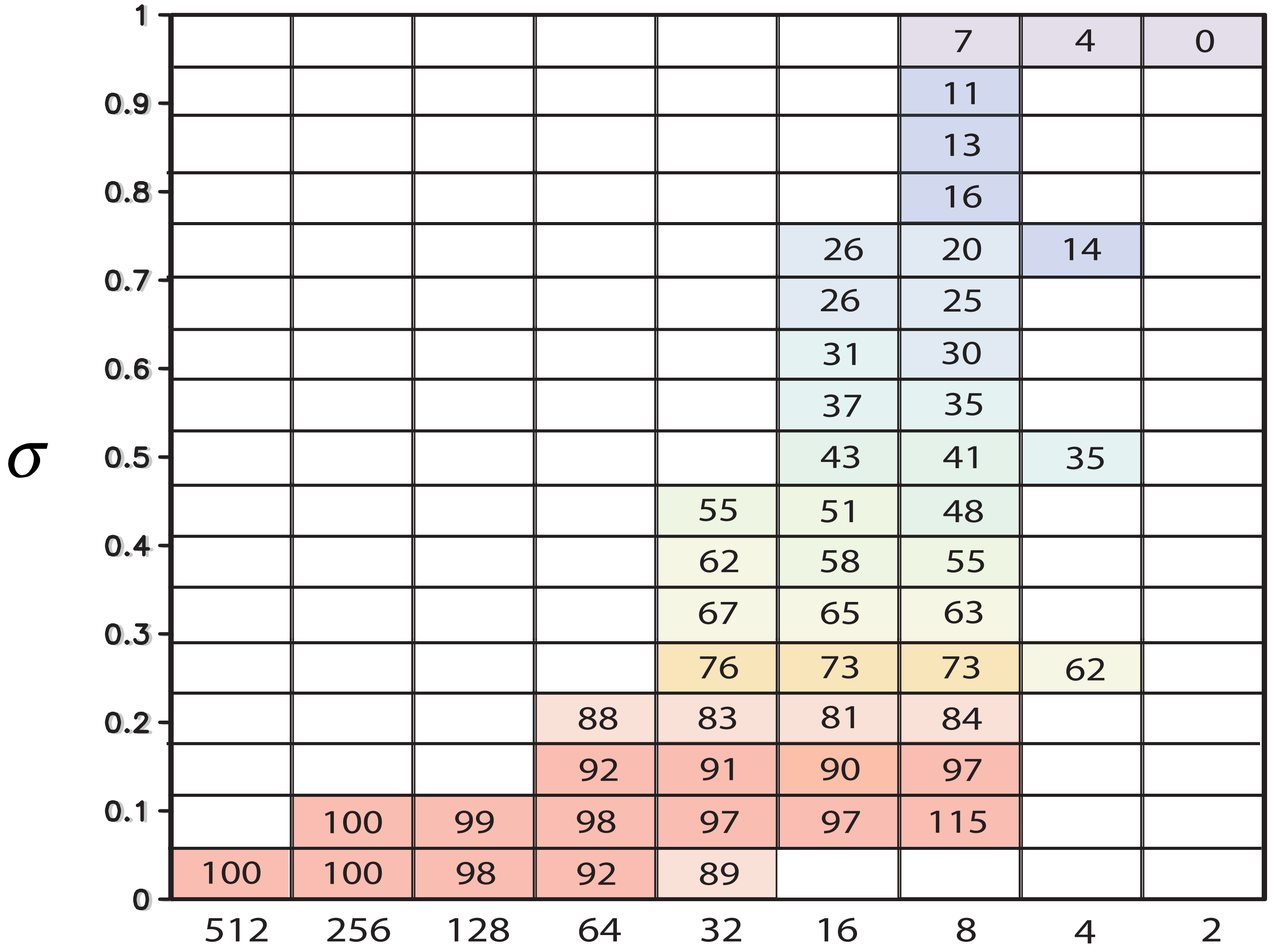
Convective transport on *grid* scale

A resolution-independent cumulus parameterization must determine σ,
the fraction of each grid cell that is occupied by convective updrafts.

Flux partitioning



						7	4	0
						11		
						13		
						16		
					26	20	14	
					26	25		
					31	30		
					37	35		
					43	41	35	
				55	51	48		
				62	58	55		
				67	65	63		
				76	73	73	62	
			88	83	81	84		
			92	91	90	97		
	100	99	98	97	97	115		
100	100	98	92	89				
512	256	128	64	32	16	8	4	2

horizontal grid spacing, km

Numbers and colors show percentage of the total flux due to unresolved processes.

The percentage depends mostly on σ, for a given grid spacing. For large σ, the percentage is small.

A parameterization of this type is being tested in both the CAM and the GFS.

Figure from Akio Arakawa

Higher-Order Closure
As a Replacement for Cumulus Parameterization?

$$\frac{\partial}{\partial t}\left(\rho_0\overline{\theta}\right)+\frac{\partial}{\partial x_j}\left(\rho_0\overline{u}_j\overline{\theta}+\rho_0\overline{u_j'\theta'}+\overline{H}_j\right)=\frac{\theta_0}{c_pT_0}\overline{Q}$$

$$\frac{\partial}{\partial t}\left(\rho_0\overline{u_i'\theta'}\right)+\frac{\partial}{\partial x_j}\left(\overline{u}_j\rho_0\overline{u_i'\theta'}+\overline{u_j'\rho_0u_i'\theta'}\right)$$

$$=-\rho_0\overline{u_i'u_j'}\frac{\partial\overline{\theta}}{\partial x_j}-\rho_0\overline{u_j'\theta'}\frac{\partial\overline{u}_i}{\partial x_j}+2\varepsilon_{i,j,k}\rho_0\overline{u_j'\theta'}\Omega_k$$

$$-\overline{\rho_0\theta'\frac{\partial}{\partial x_i}\left(\frac{\delta p'}{\rho_0}\right)}+\rho_0\frac{\overline{\left(\theta'\right)^2}}{\theta_0}g_i+\theta'\frac{\overline{\partial\Im'_{i,j}}}{\partial x_j}+\frac{\theta_0}{T_0}\frac{\overline{u_i'Q'}}{c_p}-\overline{u_i'\frac{\partial H'_j}{\partial x_j}}$$

These equations are resolution-independent and even process-independent.

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These equations are resolution-independent and even process-independent.

Unfortunately, the available closures are neither resolution-independent nor process-independent.

Higher-Order Closure
As a Replacement for Cumulus Parameterization?

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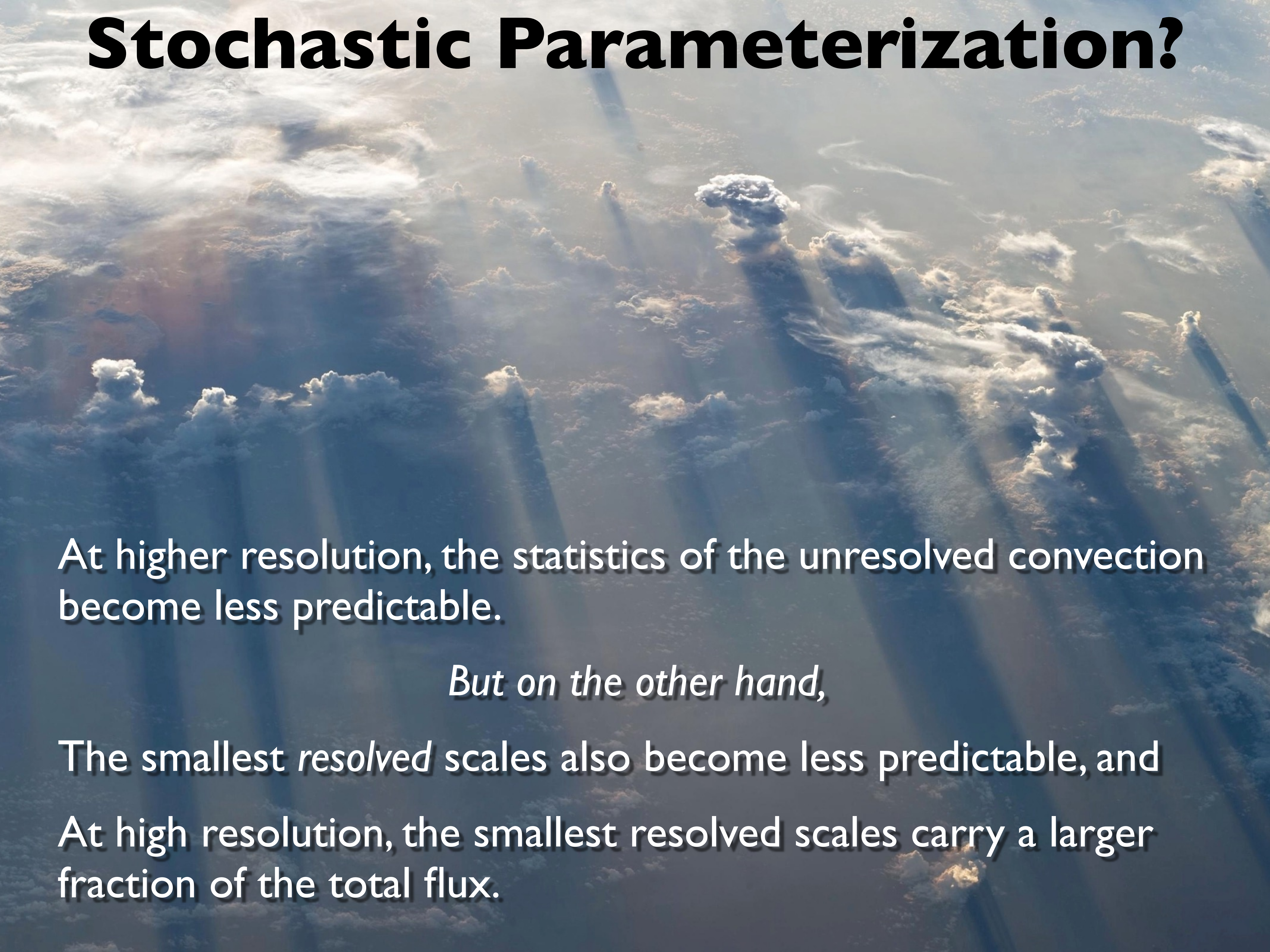
This approach is being tested in the CAM.

Stochastic Parameterization?



At higher resolution, the statistics of the unresolved convection become less predictable.

But on the other hand,

The smallest *resolved* scales also become less predictable, and

At high resolution, the smallest resolved scales carry a larger fraction of the total flux.

Summary of
Grey-Zone Modeling Strategies and/or Issues

- Don’t change a thing.
- Turn off the cumulus parameterization. Otherwise, don’t change a thing.
- Use super-parameterization.
- Use the Quasi-3D MMF.
- Use a resolution-independent cumulus parameterization.
- Use higher-order closure in place of a cumulus parameterization.
- Include stochastic effects?

It will take years to sort this out.