Counting the clouds

A look ahead

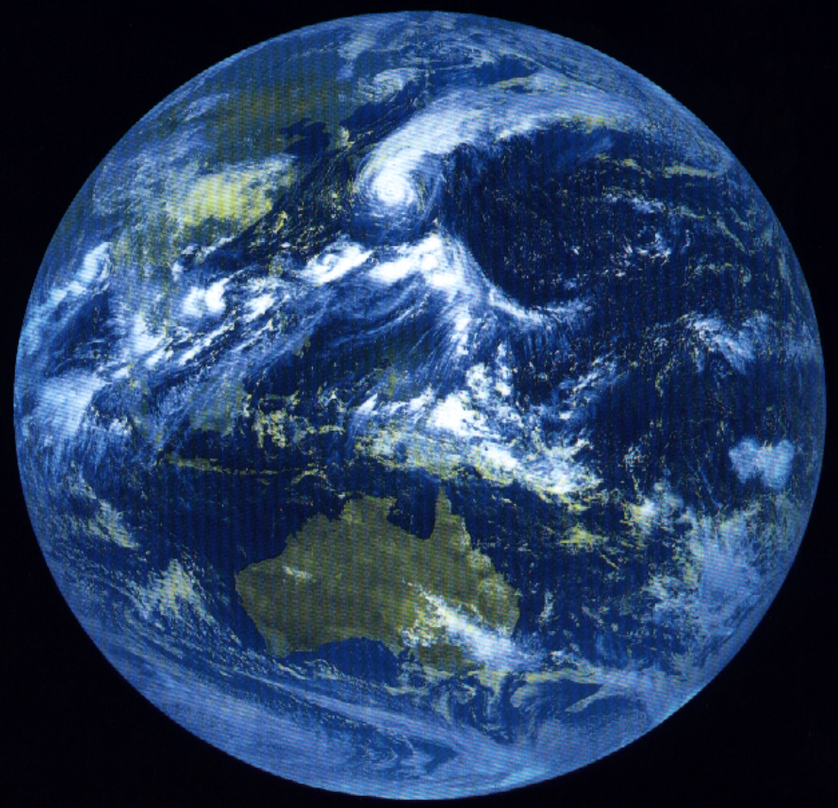
Clouds Are Central to the Earth Sciences

- Climate change
- Weather prediction
- The water cycle
- Global chemical cycles
- The biosphere

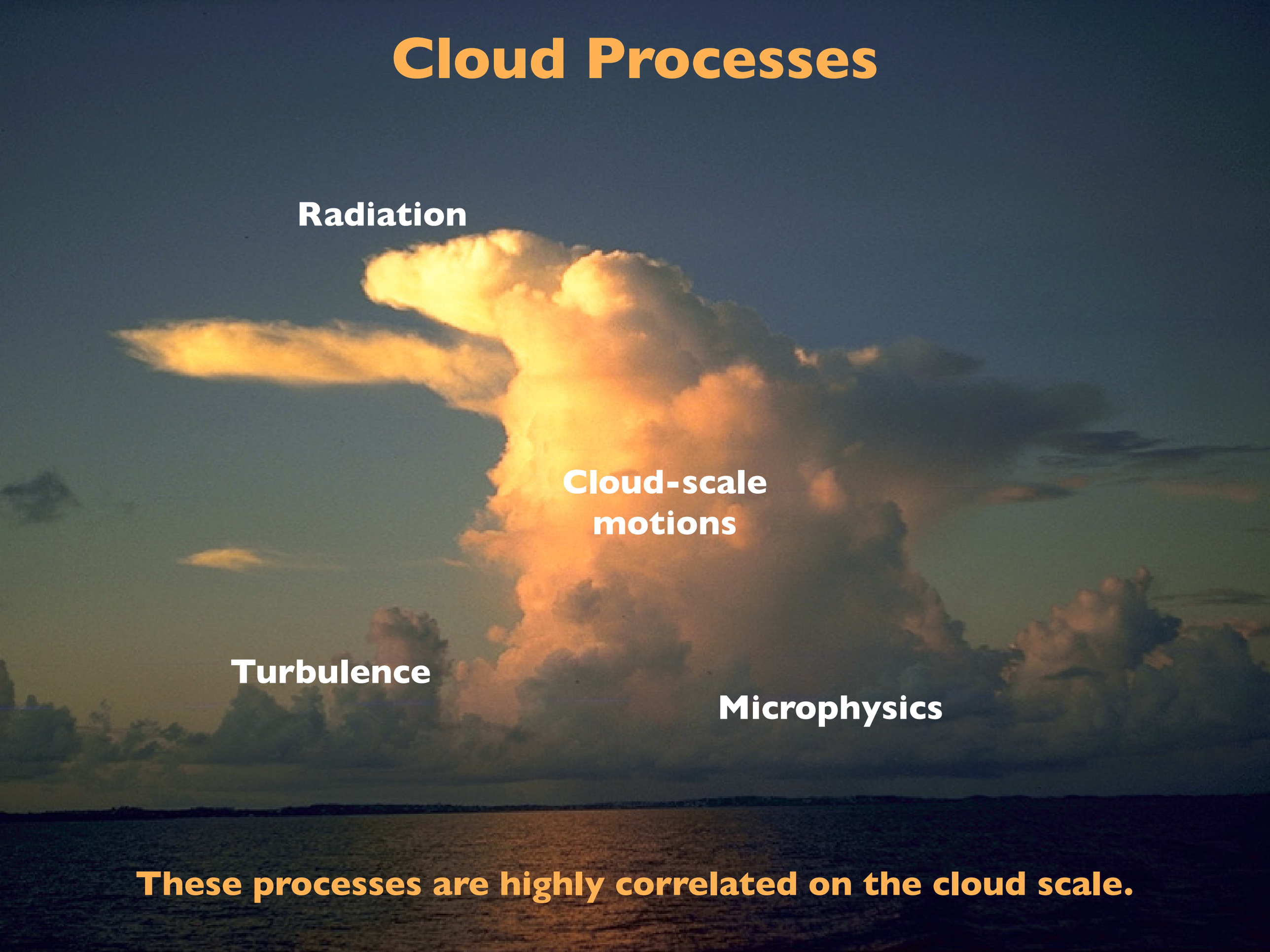
We are being held back in all of these areas by an inability to simulate the global distribution of clouds and their effects on the Earth system.

Multiple scales

- Cross-sectional area of medium-size cumulus cloud: ~ 10 km^2
- Surface area of the Earth: ~ 5 x 10^8 km^2

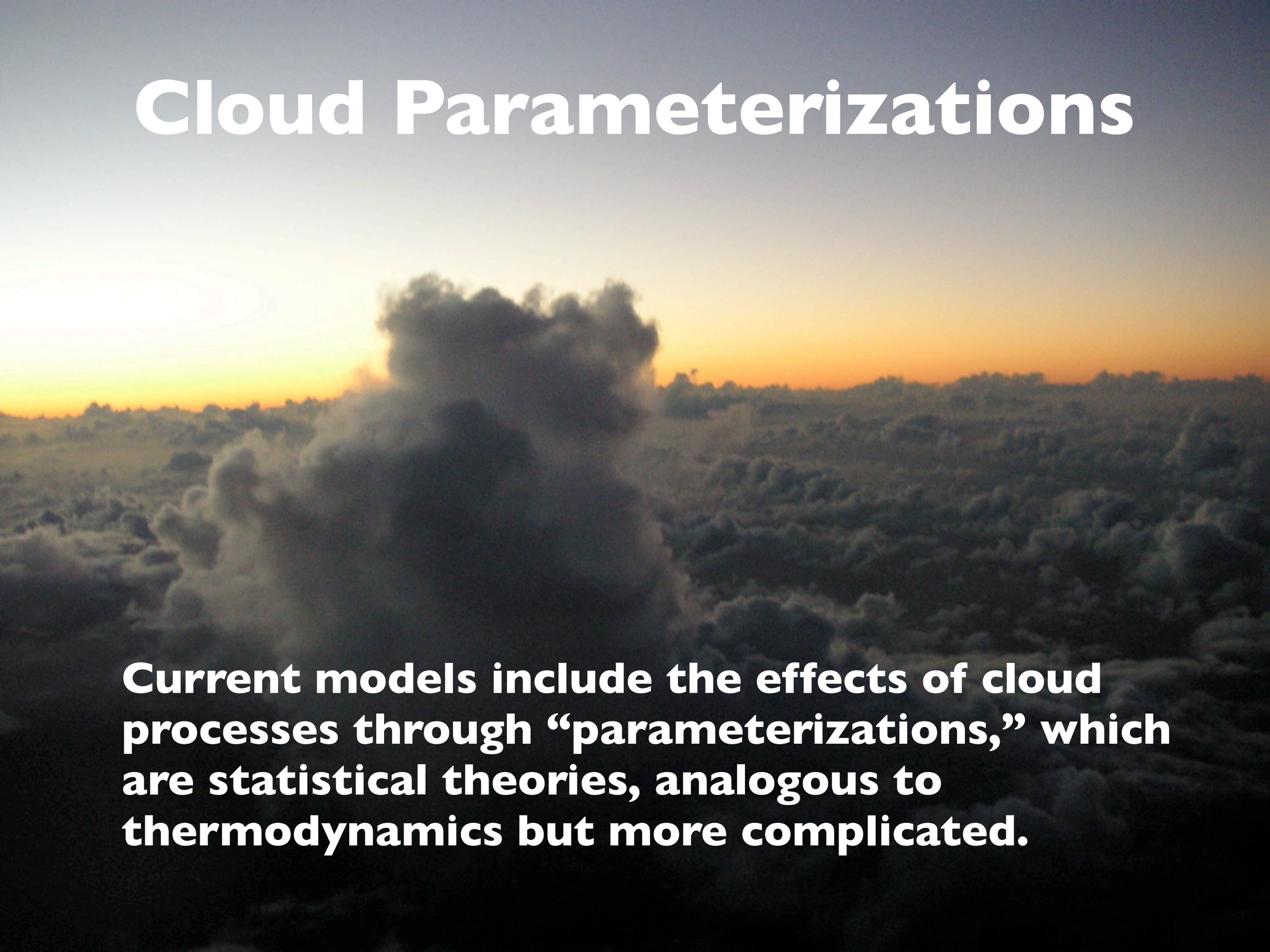


Cloud Processes



These processes are highly correlated on the cloud scale.

Cloud Parameterizations



Current models include the effects of cloud processes through "parameterizations," which are statistical theories, analogous to thermodynamics but more complicated.

What have we accomplished over the past 30 years?

Then	Now
Clouds predicted in some GCMs	Clouds predicted in all GCMs
Hydrologic cycle and radiatively active clouds modeled independently	Hydrologic cycle and radiatively active clouds linked in some models
Cloud parameterizations untested	Cloud parameterizations tested against field data -- ARM key here
Earth Radiation Budget unknown	ERB well observed and thoroughly tuned in models
Models simulate cloud feedbacks on climate change, but nobody knows whether or not they are realistic.	No change.

Cruising along

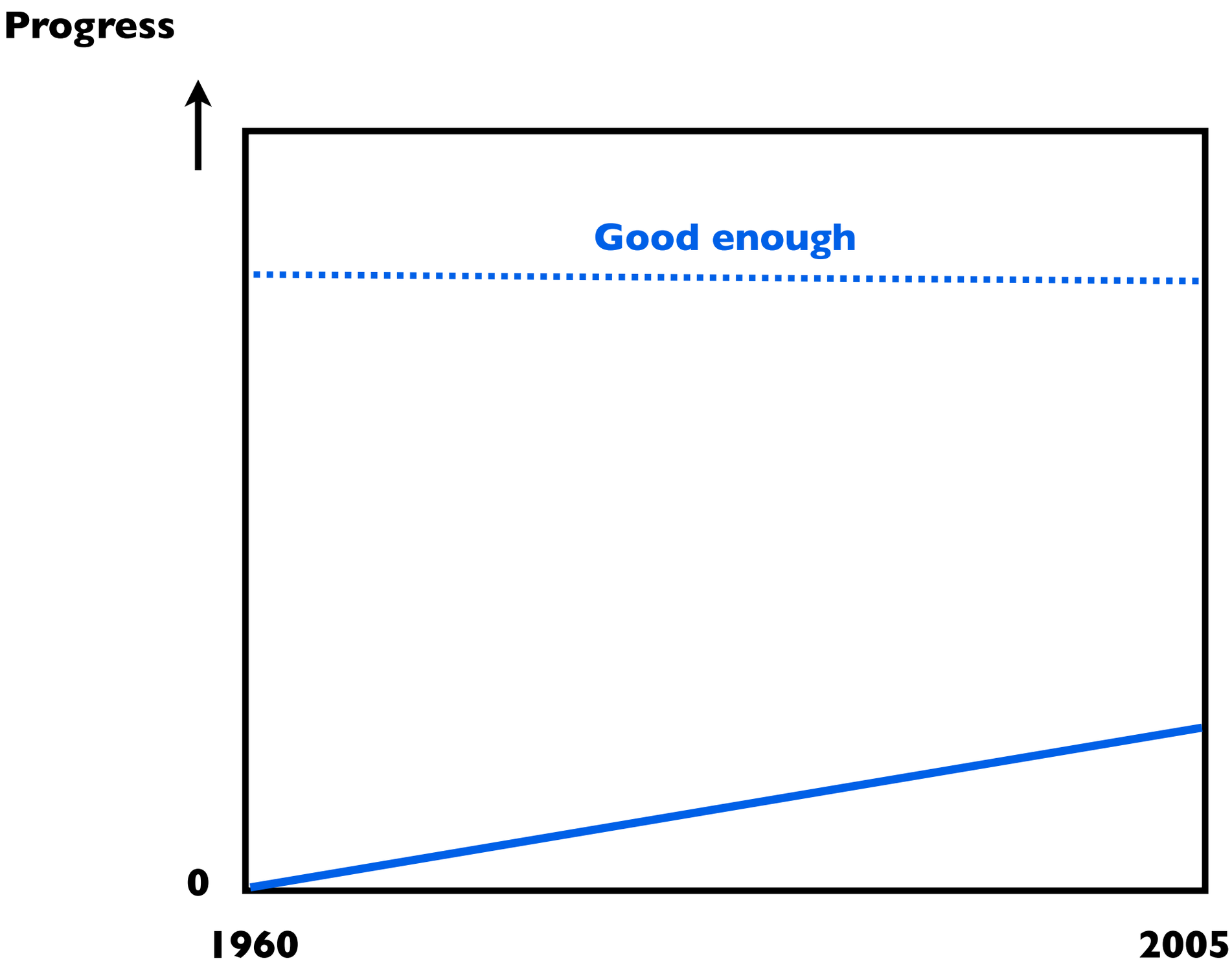
There have been no *revolutionary* changes in climate model design since the 1970s.

- Same dynamical equations
- Comparable resolution
- Similar parameterizations
- A modest extension of the included processes

And the models are a bit better.

Meanwhile, a computing revolution has occurred.

Are we doing OK?



Can't we just "tune" the clouds?

Parameterizations contain parameters.

With a few exceptions, the parameters are not expected to be universal constants, but they are nevertheless assigned constant values.

***Tuning* consists of adjusting the unobserved (or unobservable) parameters *after the fact* to improve agreement with observations.**

Tuning is necessary, but it does not qualify as scientific work.

Randall is a pessimist.

Randall is an optimist.

Models simulate cloud feedbacks on climate change, but nobody knows whether or not they are realistic.

- We will, eventually, find out whether or not they are realistic.
  - Simulated cloud feedbacks *are* subject to observational tests.
  - We have to wait for that.
- In the mean time, how can we get better results?
  - Computational power
  - Better parameterizations
  - Better parameterizations through computational power

Cloud-System Resolving Models (CSRMs)

- Cloud dynamics are directly simulated by solving the basic physical equations.
- The domain is large enough to contain many clouds.

Dreaming of a global CRM (GCRM)

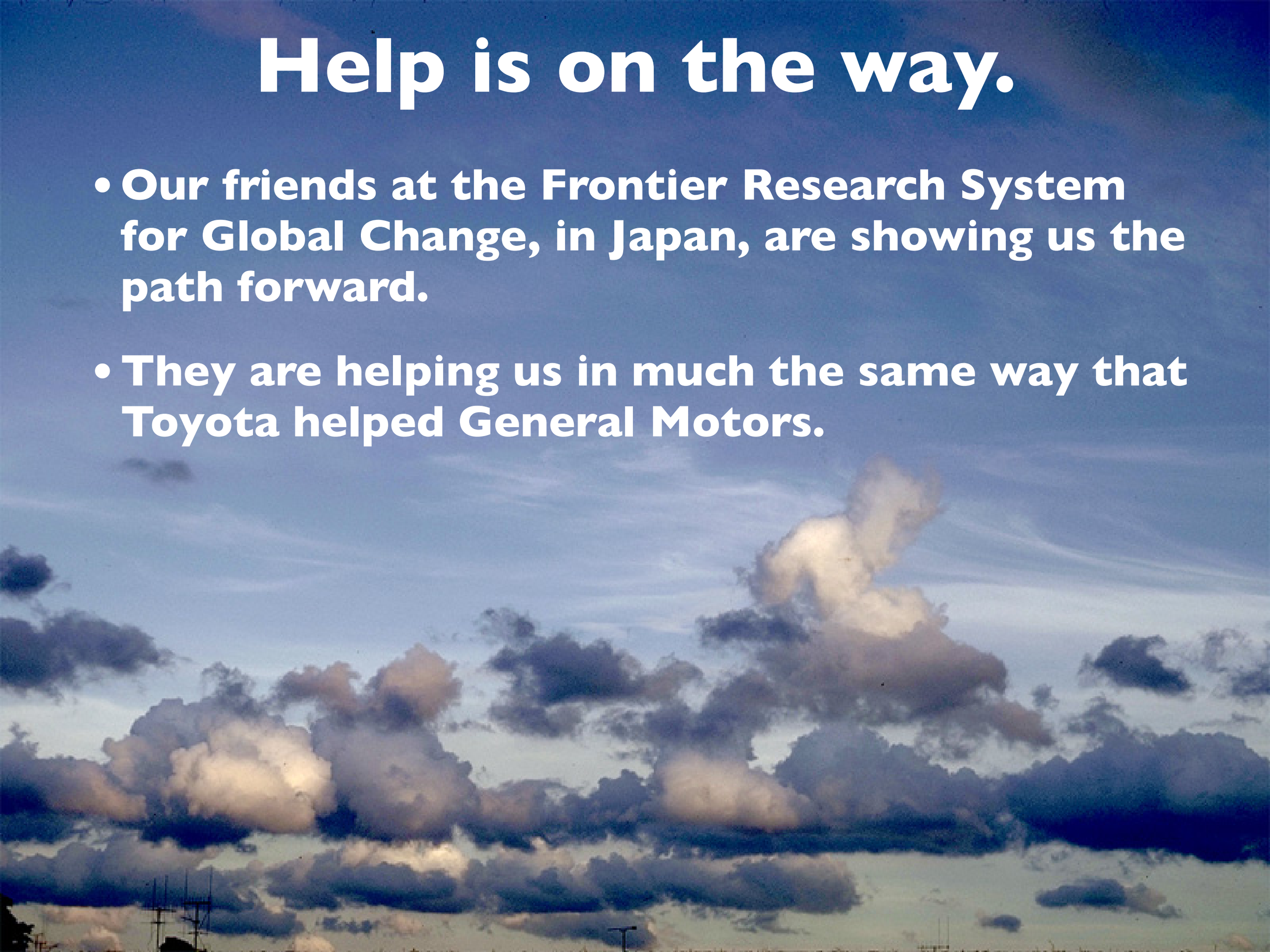
Current climate-simulation models typically have on the order of 10^4 grid columns, averaging about 200 km wide.

A global model with grid cells 2 km wide will have about 10^8 grid columns. The time step will have to be roughly 10^2 times shorter than in current climate models.

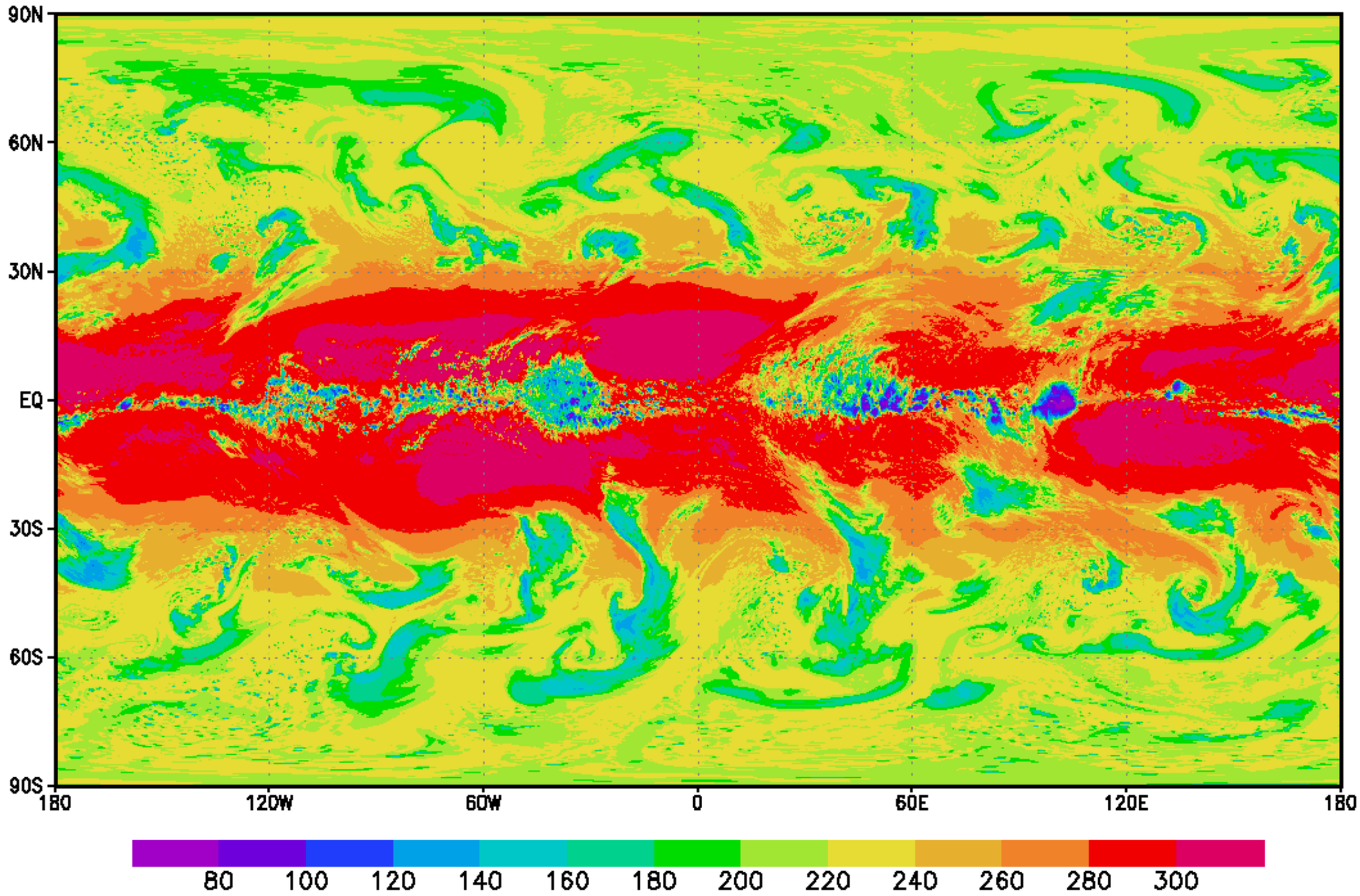
The CPU requirements will thus be $10^4 \times 10^2 = 10^6$ times larger than with today's lower-resolution models.

Help is on the way.

- Our friends at the Frontier Research System for Global Change, in Japan, are showing us the path forward.
- They are helping us in much the same way that Toyota helped General Motors.

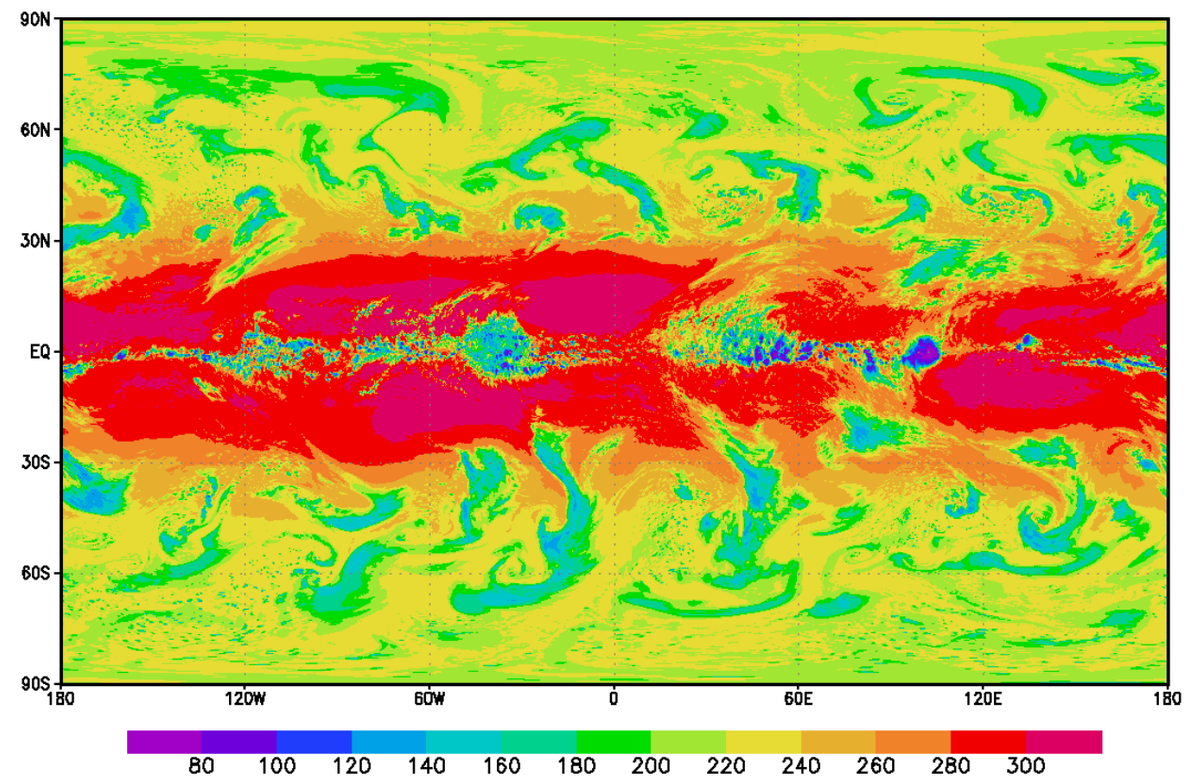


A dream no more.



The World's First GCRM

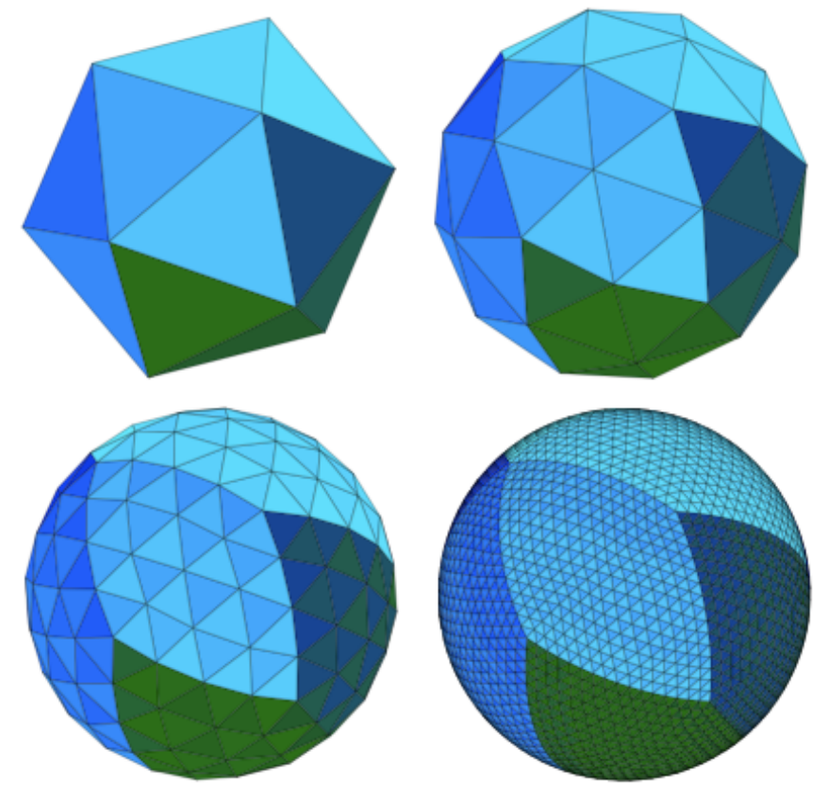
- Ocean-covered Earth
- 3.5 km cell size, ~10^7 columns
- 54 layers, ~10^9 total cells
- State ~ 1 TB
- Top at 40 km
- 15-second time step
- Spun up with coarser resolution
- 10 days of simulation
- ~10 simulated days per day on half of the Earth Simulator (2560 CPUs, 320 nodes), close to 10 real TF.
- ~ 1 TF-year per simulated year



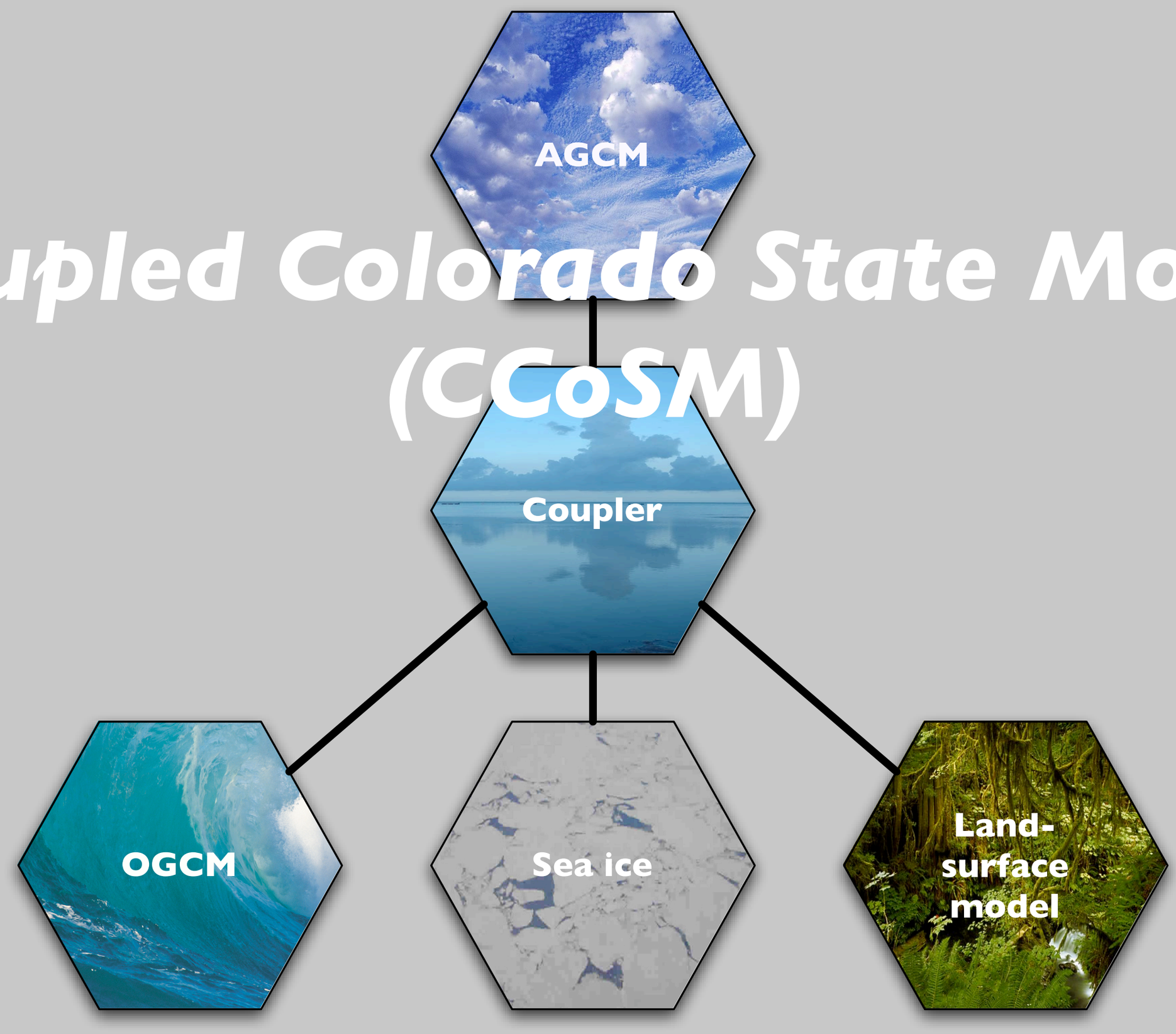
When I was doing my dissertation during the 1970s, a global atmospheric model consumed about 2.5 hours per simulated day, on an IBM 360/91.

Dynamics of the FRSGC GCRM

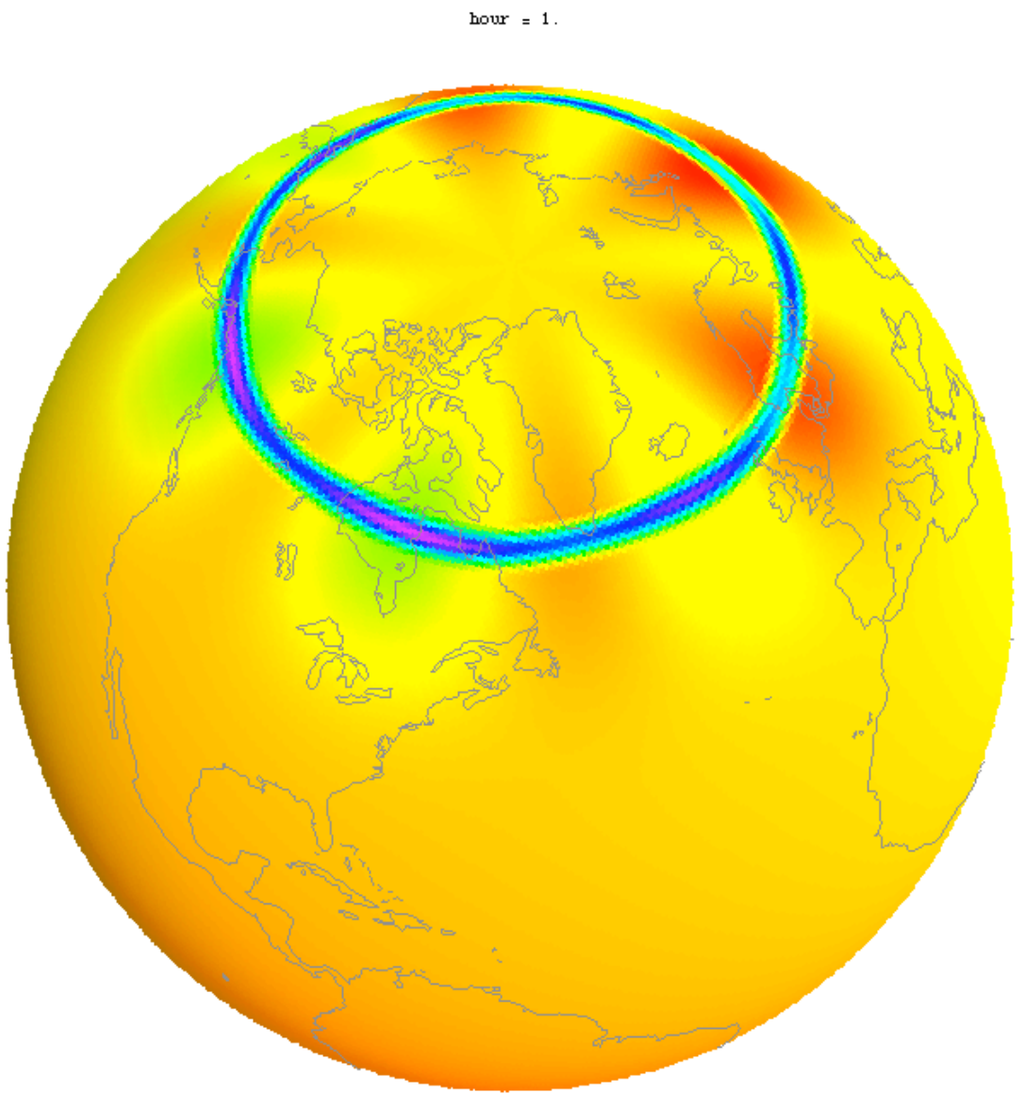
- **Horizontal discretization**
  - **Geodesic**
  - **Similar methods were developed here (*before* FRSGC) under SciDAC sponsorship**
- **Vertical discretization**
  - **High vertical resolution matched with improved physics**
  - **Non-hydrostatic -- like the UKMO model, or WRF**

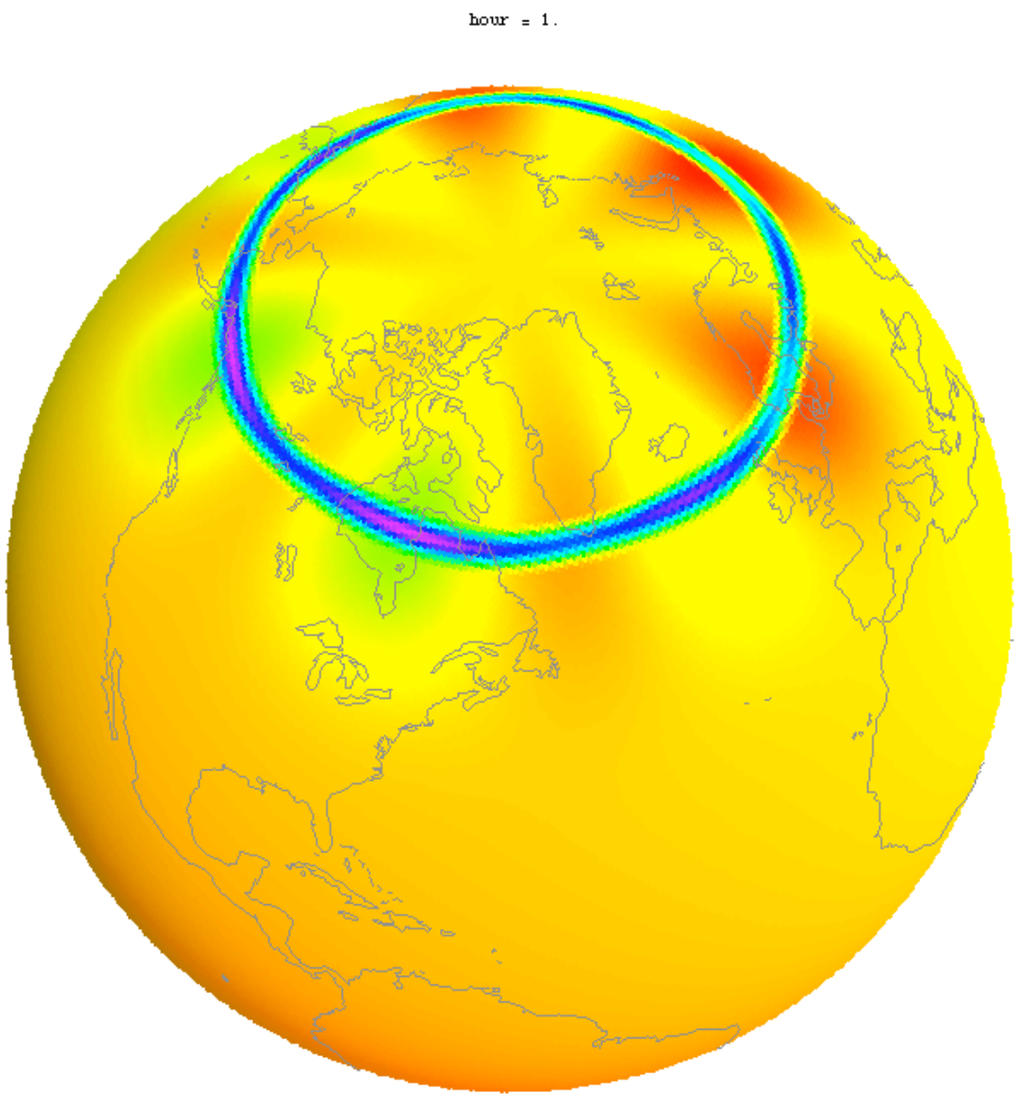


Coupled Colorado State Model (CCoSM)



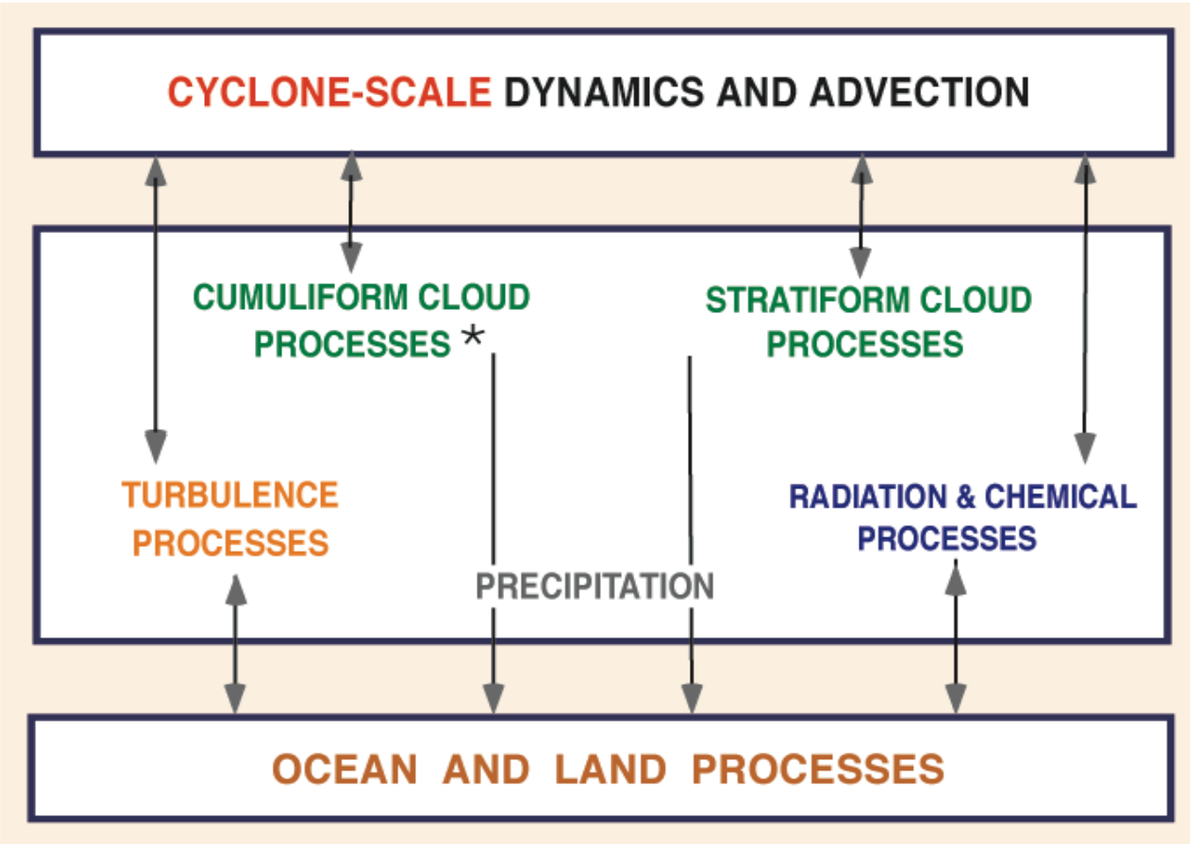
Vortex ring





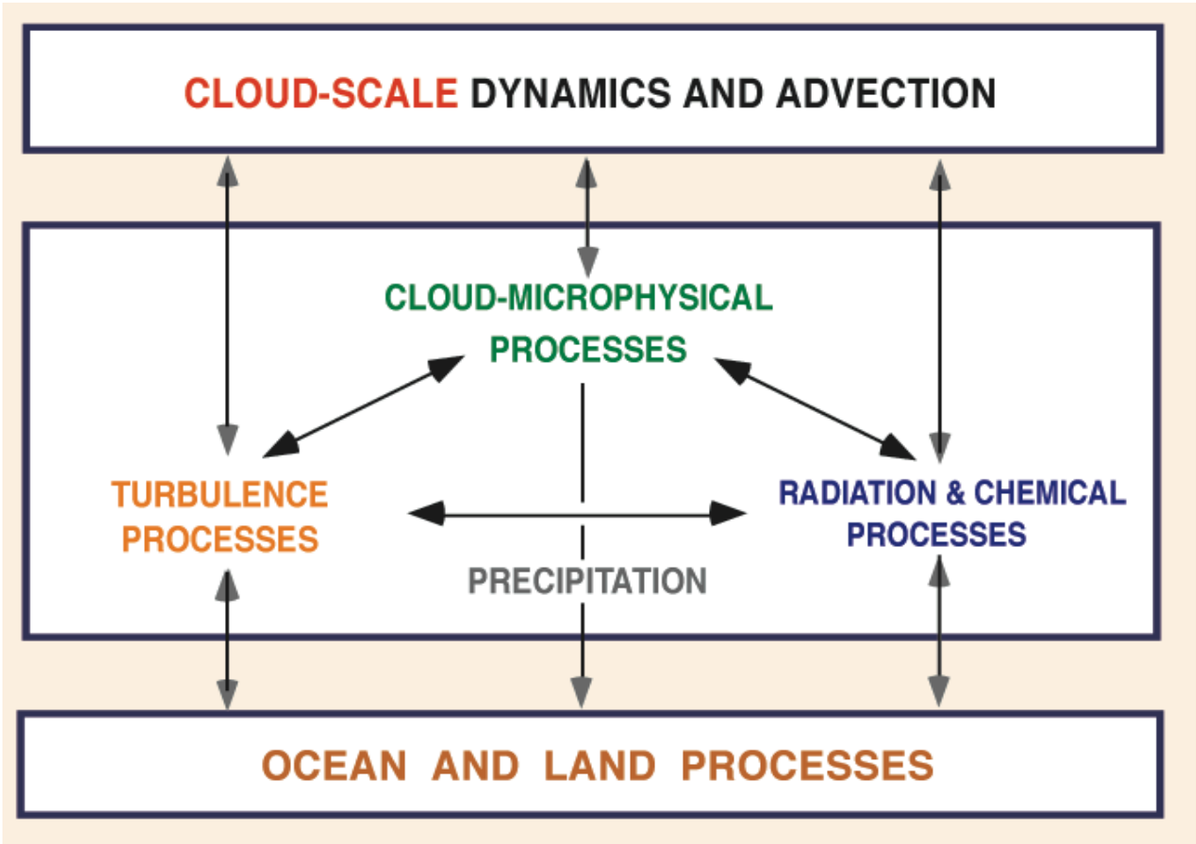
Physical interactions

Conventional GCM



Phoney modularity

GCRM



Something closer to true modularity

Testing a GCRM

- Idealized frameworks
- Regional simulations
  - ARM case studies
  - Evaluation alongside other models
- Weather forecasting
  - Initialization?
  - Use of emerging datasets

GCRM Applications

- Weather forecasting
  - Knowledge-transfer to NOAA
- Simulation of an annual cycle
  - About 10 days on a Cray X1-E
- An AMIP run
  - A few months on a Cray X1-E
- Coupled ocean-atmosphere simulations
  - A powerful way to test an atmosphere model
- Comparison with results from conventional models
  - Better parameterizations through computational power

Getting it right takes time.

The current generation of global models was born in the 1960s, and has reached maturity only recently.

- Operational global weather forecasting did not begin until the late 1970s.
- Until the 1980s, most “climate” simulations consisted of just a few simulated months, run with atmosphere-only models.
- Coupling with ocean models did not become widespread until the late 1980s.
- Systematic testing of parameterizations did not begin until the 1990s.

A bridge to GCRM climate simulation

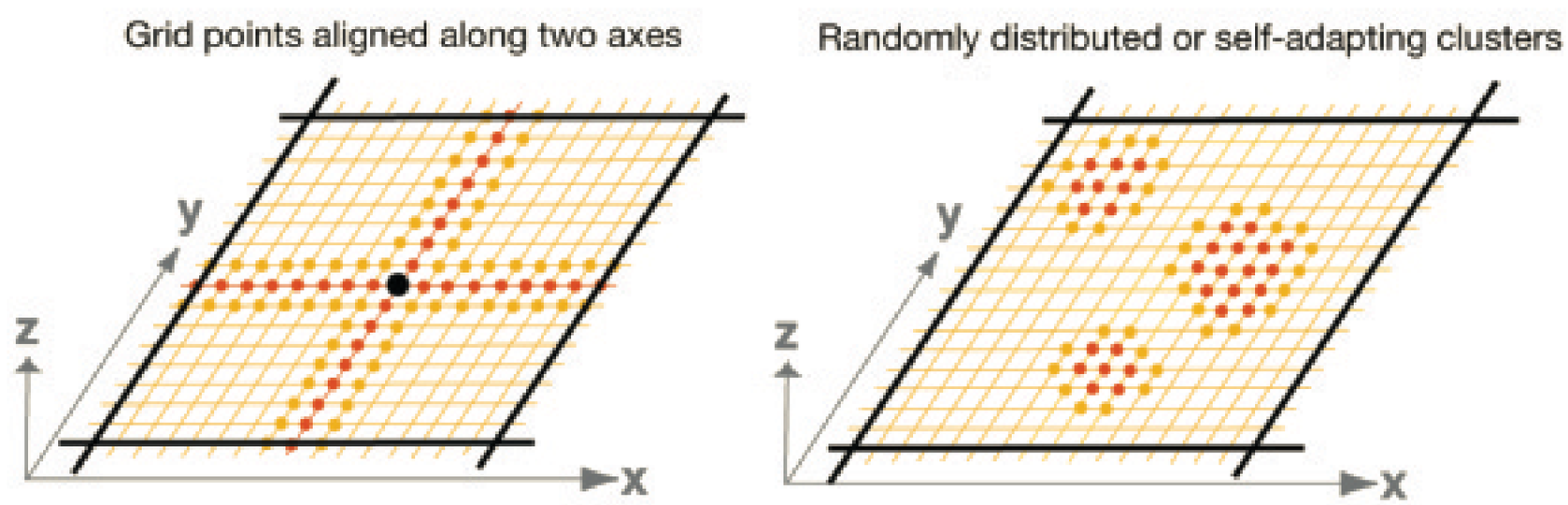
GCRM climate

Current climate models

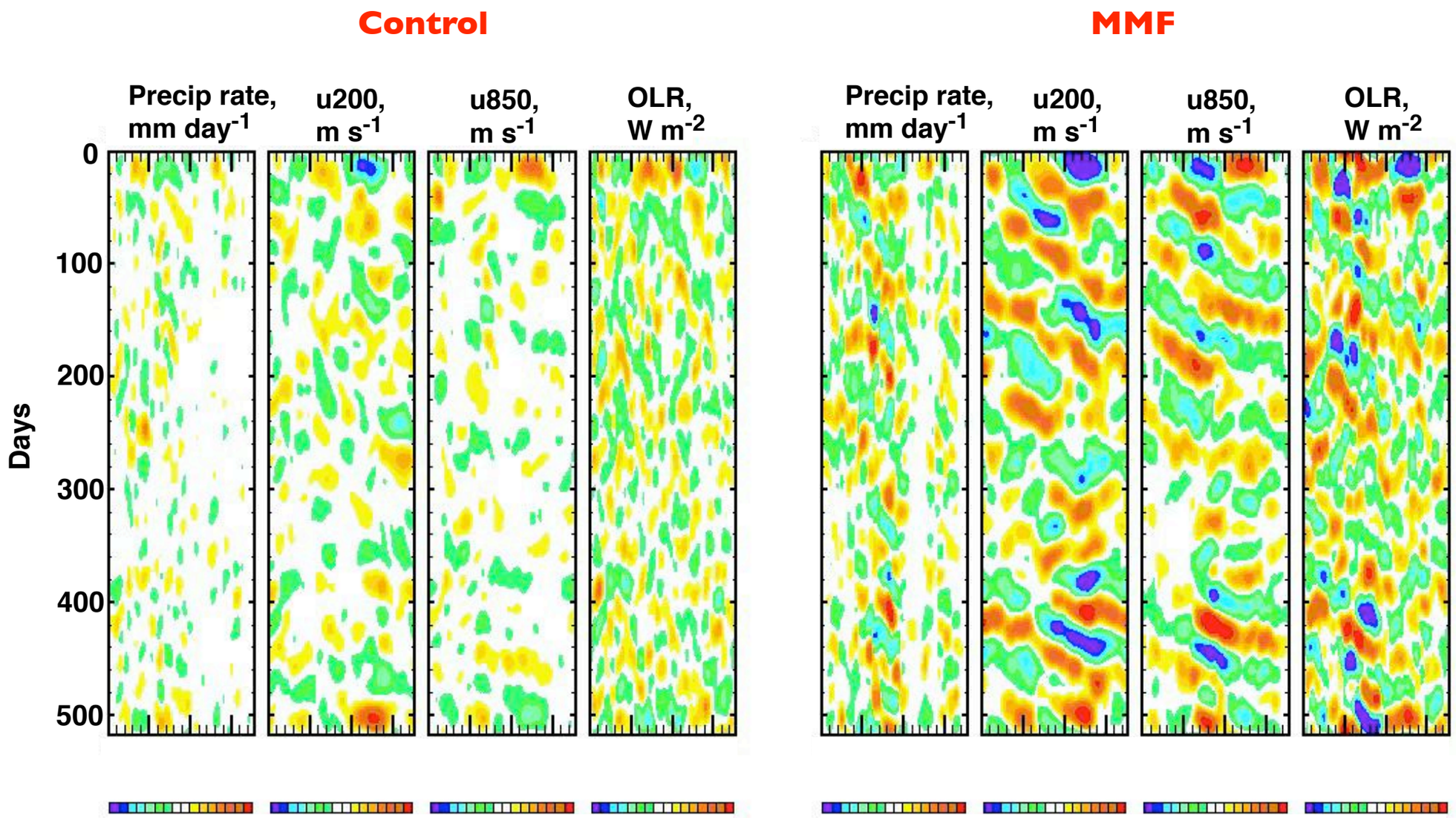
Multi-Scale Modeling Framework

(Supported by DOE's ARM program)

Examples

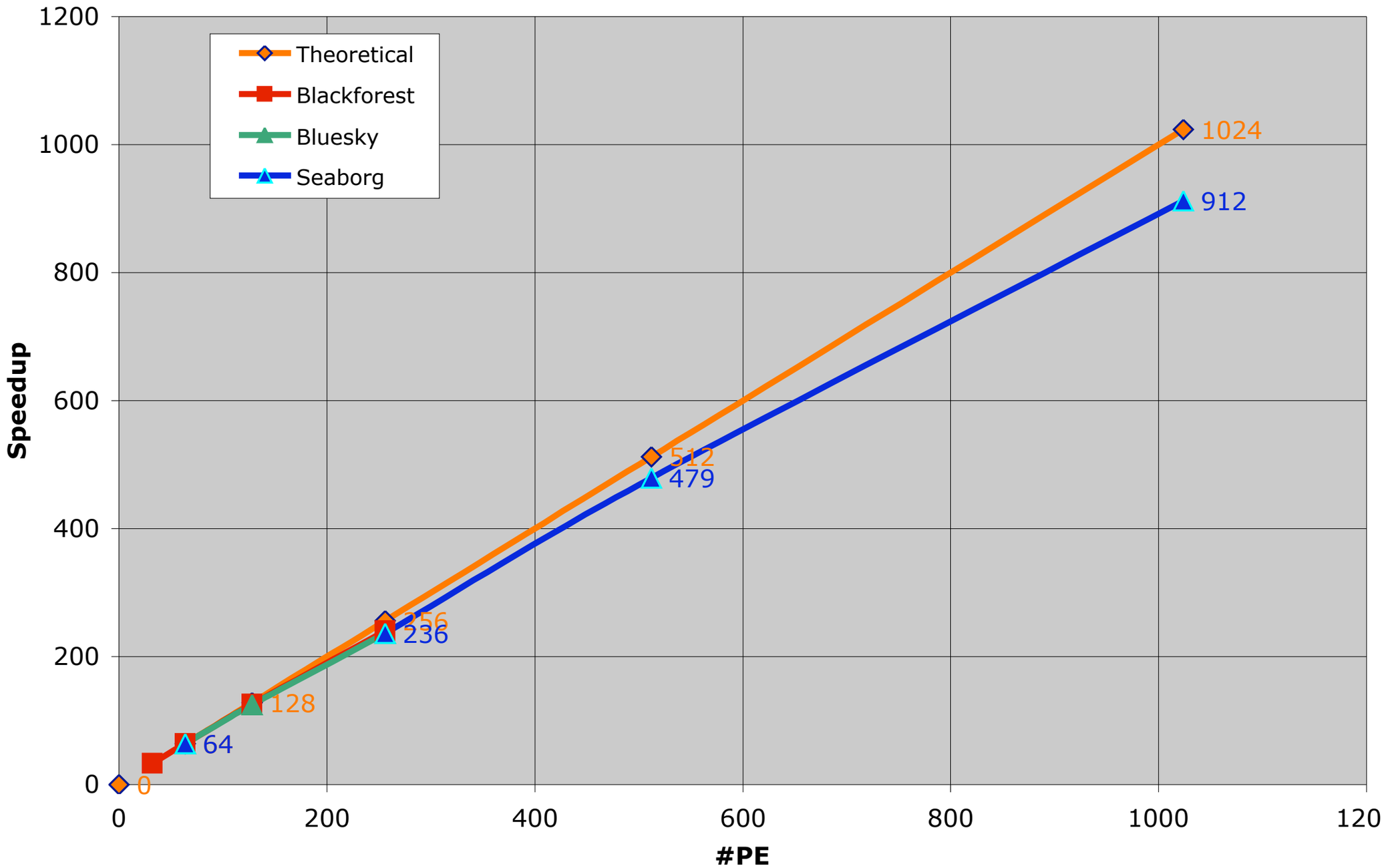


Physical errors due to parameterization are replaced by sampling errors, which can be made arbitrarily small.


Control
MMF
Precip rate, mm day-1
u200, m s-1
u850, m s-1
OLR, W m-2
Days
0
100
200
300
400
500

20-100 days

Scale away


Theoretical
Blackforest
Bluesky
Seaborg
Speedup
#PE
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
120
0
64
128
256
236
512
479
1024
912

What’s on the other side of the bridge?

What's on the other side of the bridge?

- Progress in computation
  - Moore's Law will give us a factor of about 10^6, we hope.
  - GCRMs will be used in true climate simulations.
- Progress in understanding: Future parameterizations
  - A new focus on microphysical processes
  - How many clouds?

Count the clouds