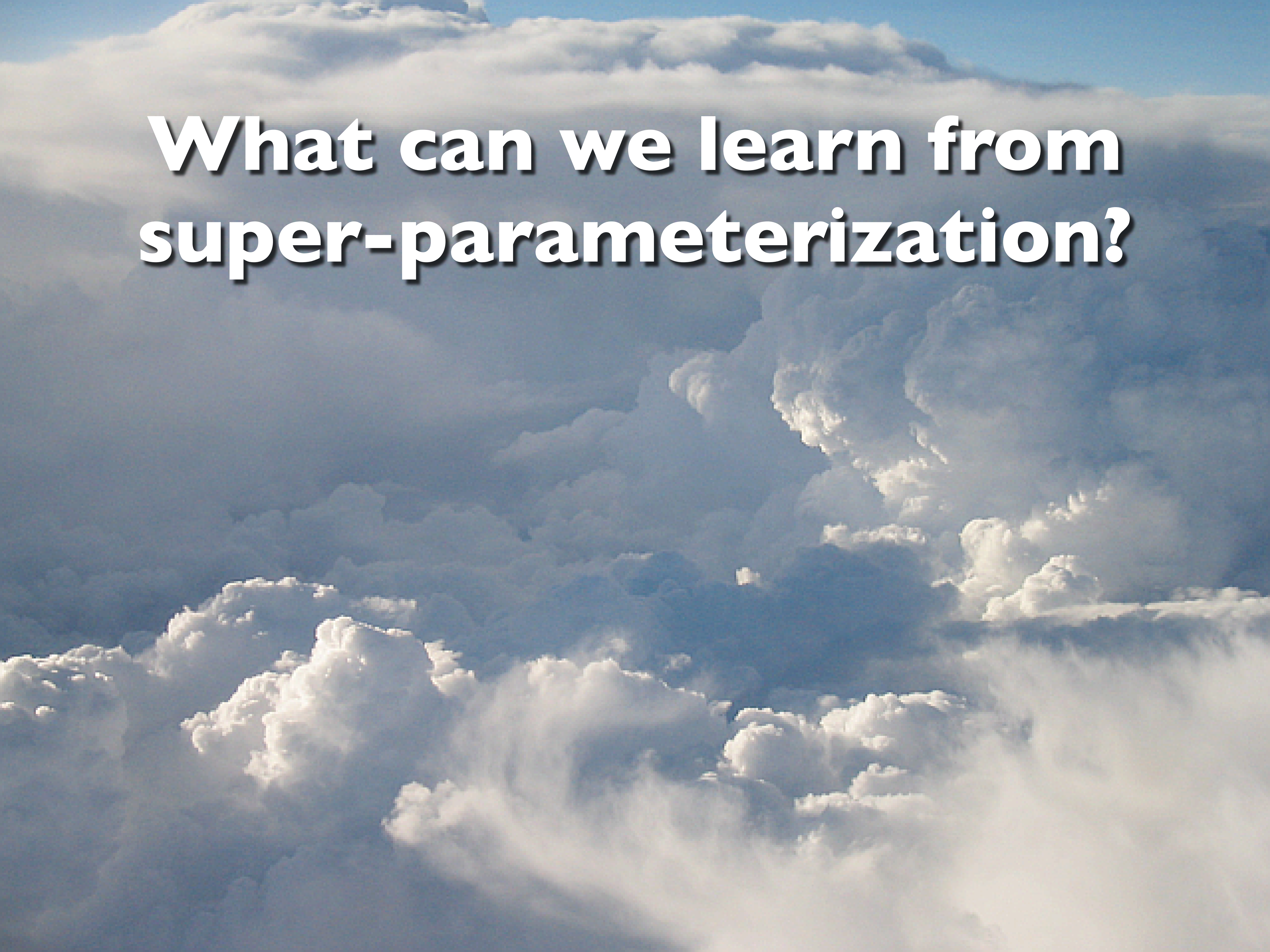
What can we learn from super-parameterization?



Acknowledgments

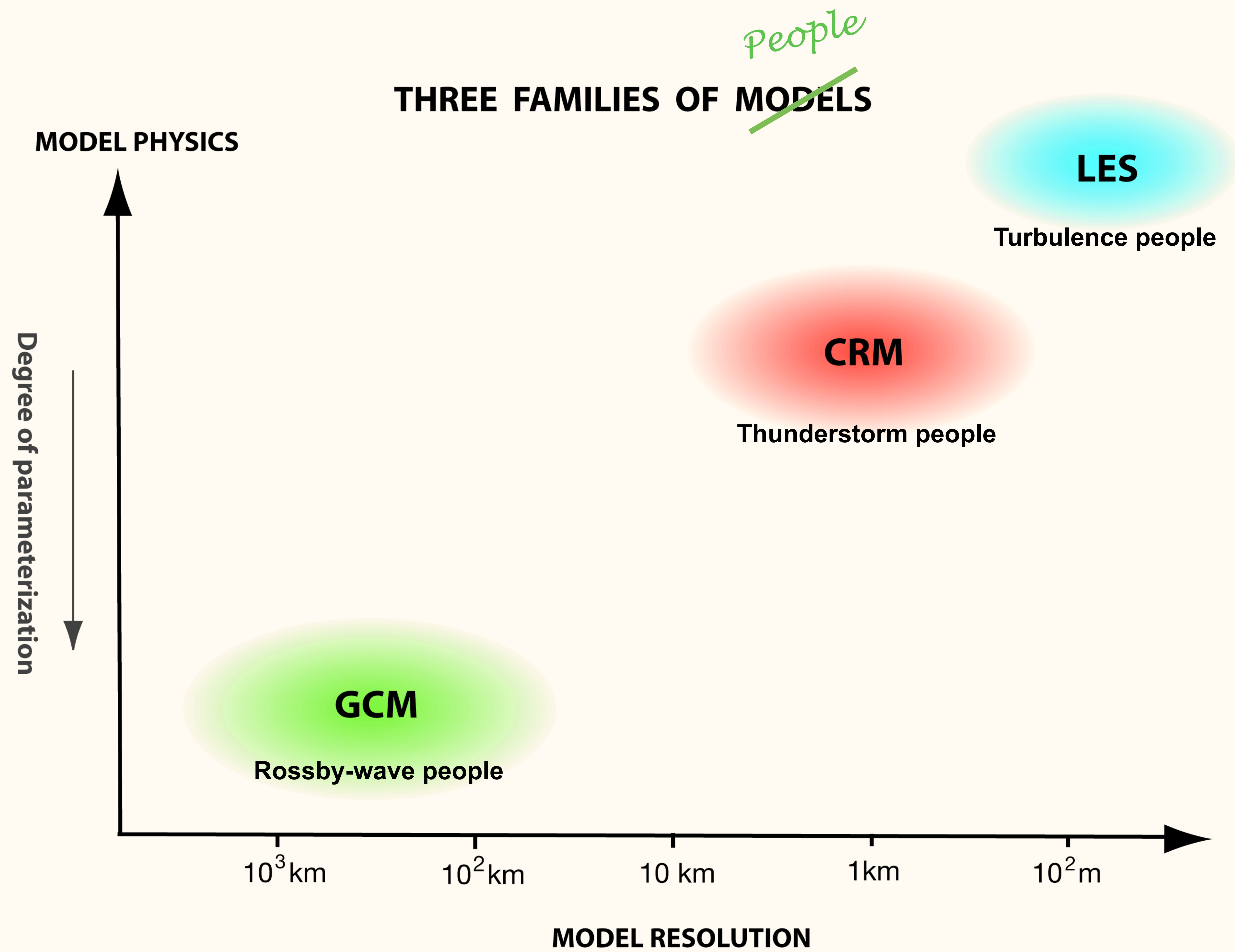
Marat Khairoutdinov

Charlotte DeMott

Why build GCMs?

- Prediction
  - NWP
  - Seasonal to interannual prediction
  - Climate change simulations
- Academic applications
  - Numerical experiments (e.g., what Isaac Held showed)
  - Synthesis
    - Learning by coupling -- Lots of interesting questions arise
    - Interdisciplinary connections

The GCM as Scientific Water Hole



Slide from A Arakawa

A Disconnect at the Water Hole

- **What cloud-observers measure, GCMs don't simulate.**
- **What cloud-resolving models simulate, GCMs don't simulate.**

Addressing the disconnect

- **Tests with SCMs, CRMs, and LESMs, through case studies based on field experiments**
- **A harmonic convergence of GCMs and CRMs**

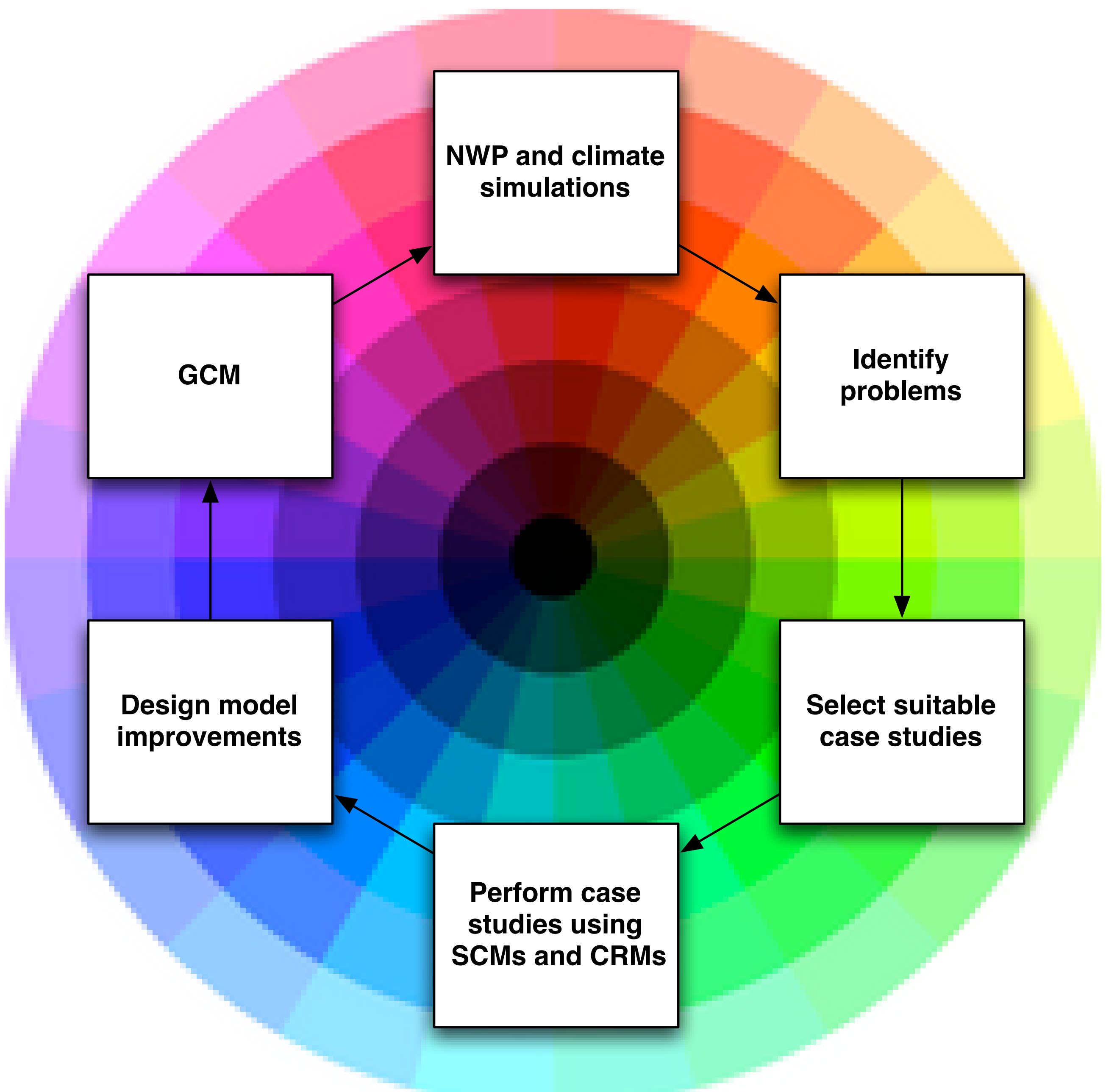


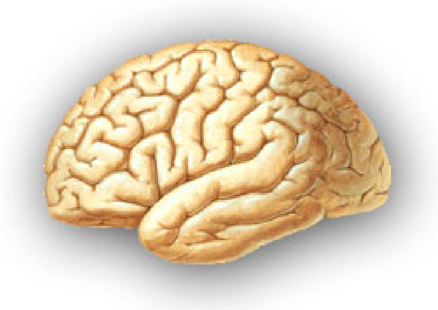
Diagram from Christian Jakob

Lamentations

(A short list of problems with current cloud parameterizations)

- **Statistics of cloud-dynamical processes are inadequately understood.**
  - ★ **"Closures"**
  - ★ **"Triggering"**
  - ★ **Mesoscale organization**
- **Microphysics is very rudimentary.**
  - ★ **Required input is not available.**
  - ★ **Basic understanding is weak, esp for ice clouds.**

Working together to solve the cloud problem



Applied Mathematicians **Atmospheric Scientists**

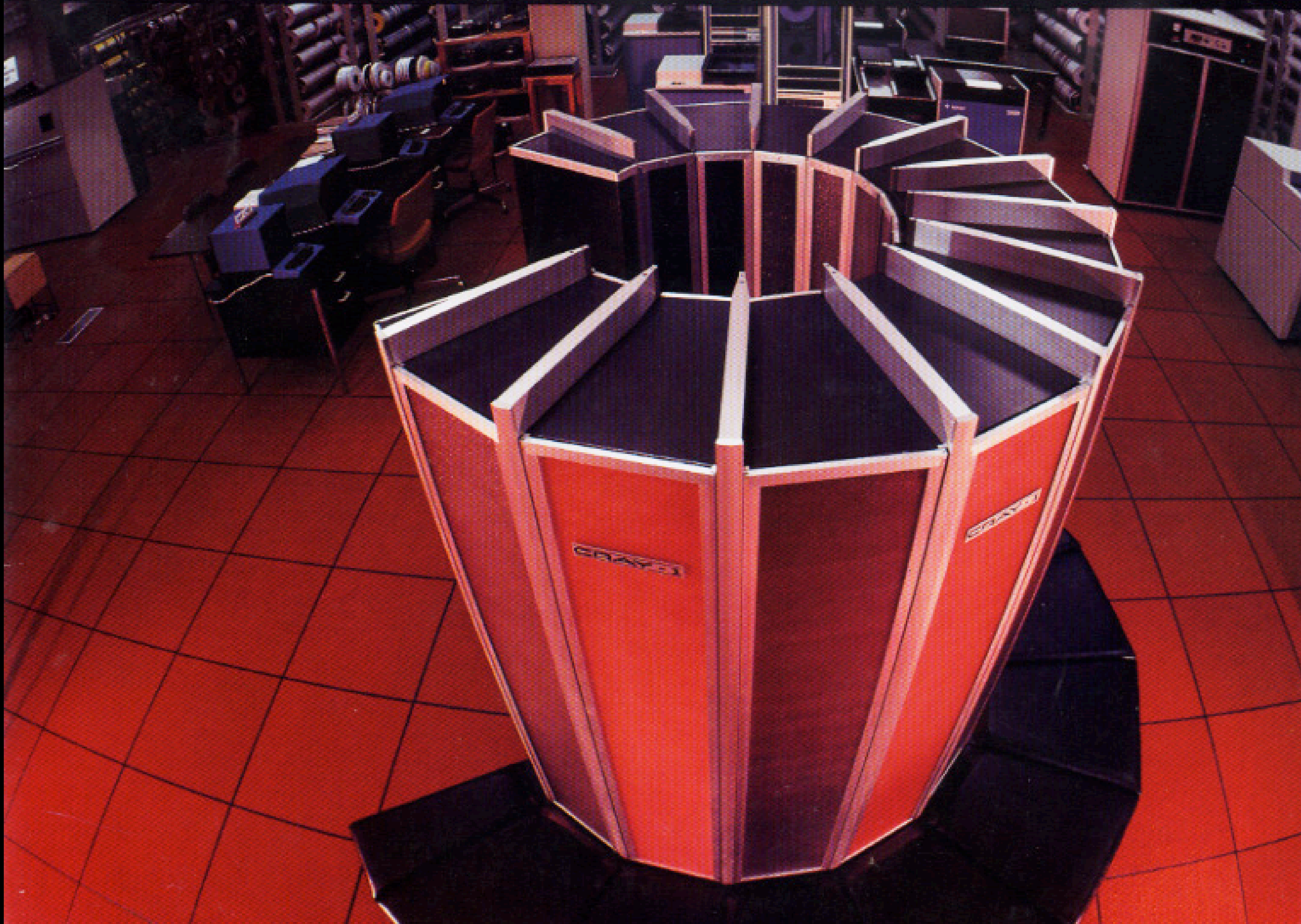
Step back.

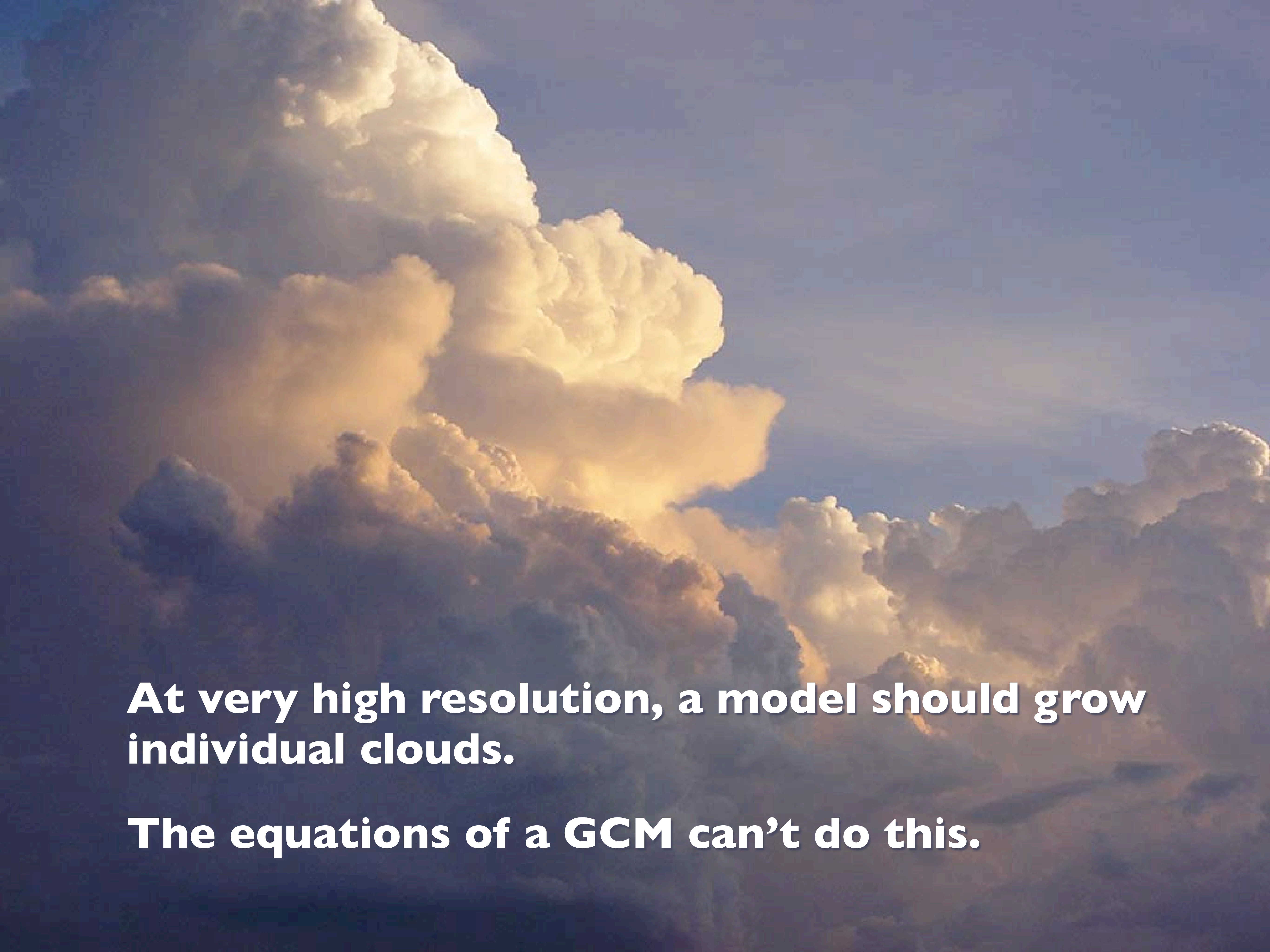
There have been no *revolutionary* changes in climate model design since the 1970s.

Meanwhile, computing power has increased by a factor of a *million*.

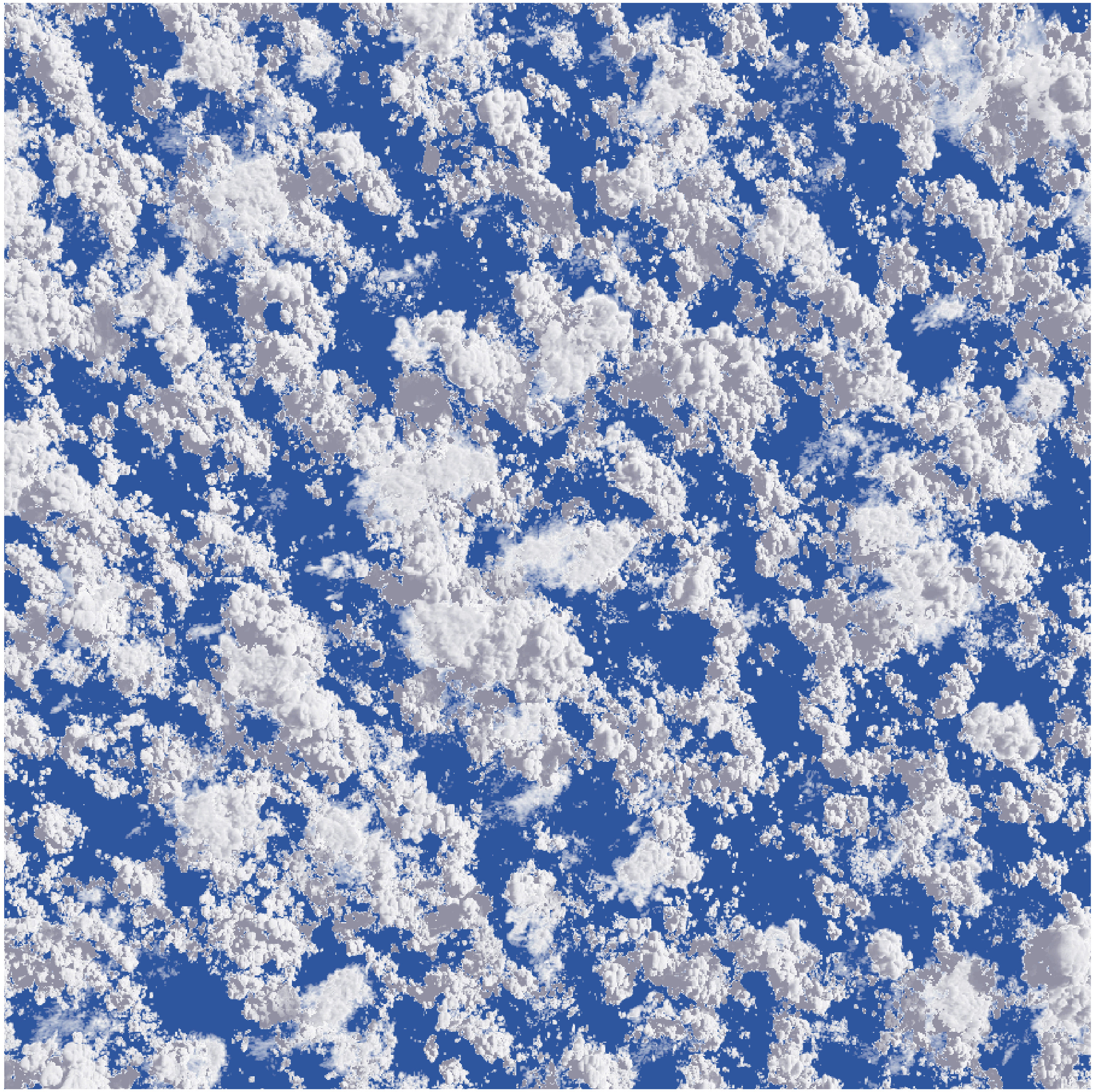
The CRAY-1 S Series of Computers

Cray Research, Inc.



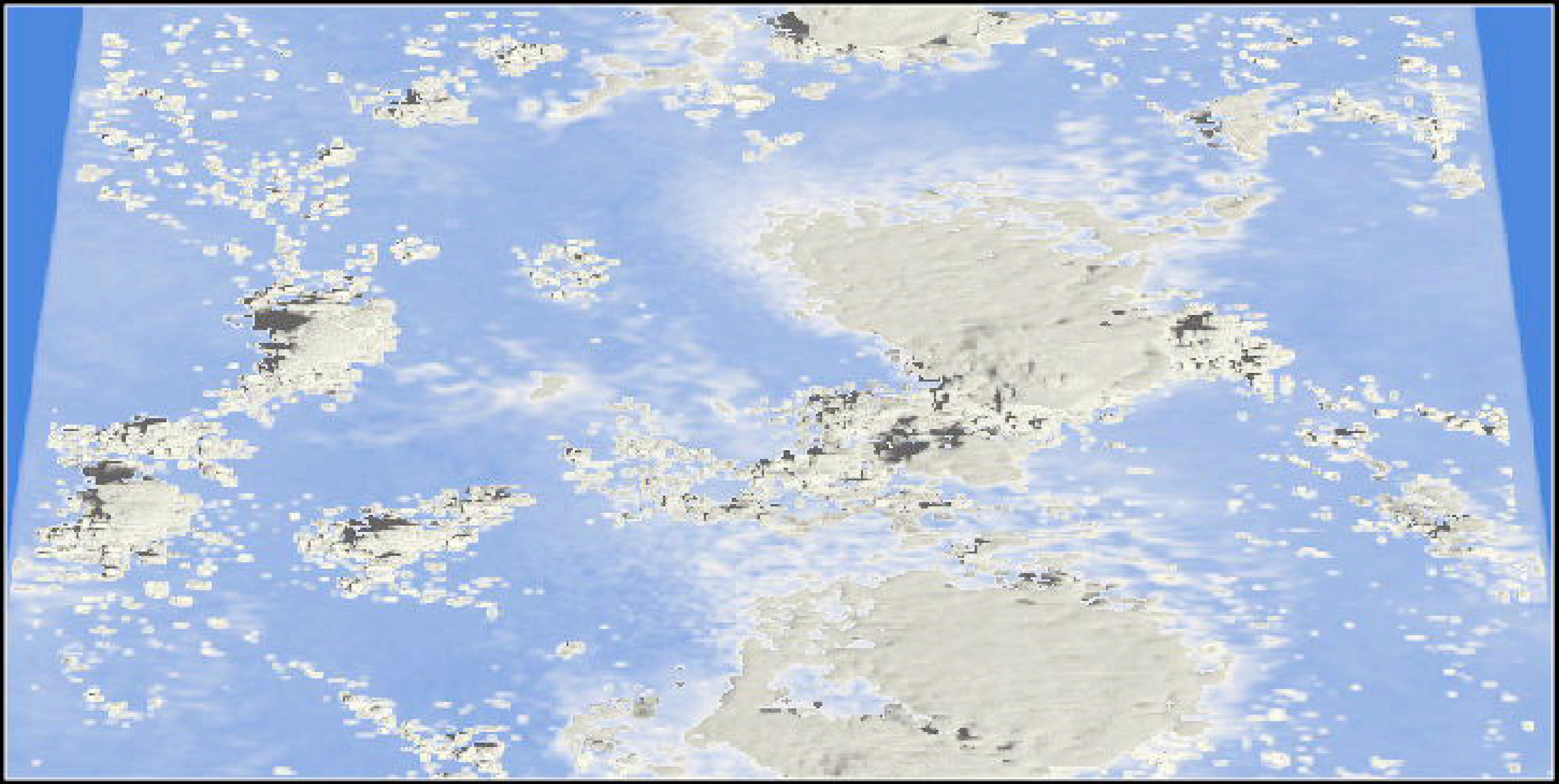

At very high resolution, a model should grow individual clouds.
The equations of a GCM can't do this.

Cloud-Resolving Models



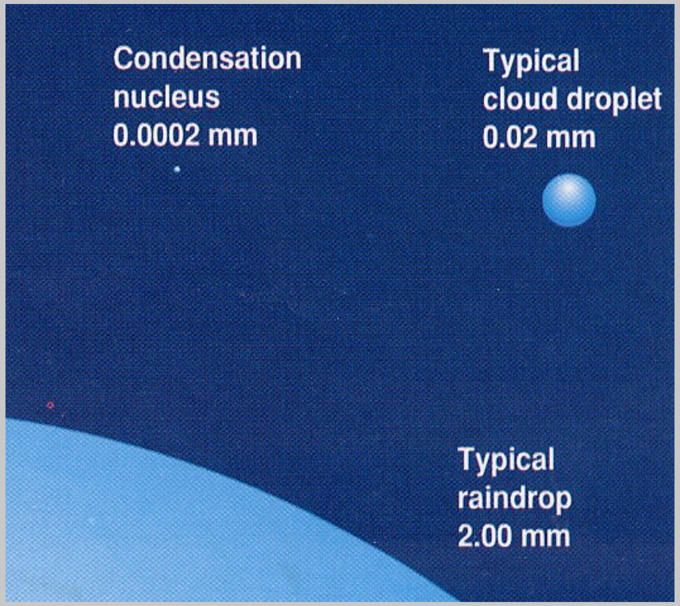
Partial differential equations --> Clouds

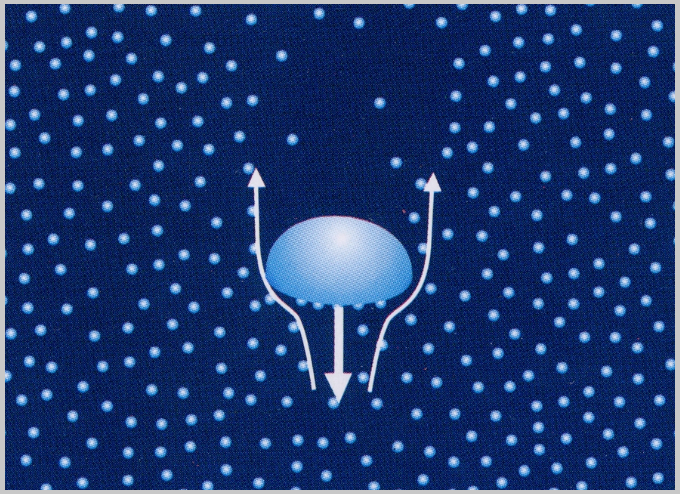
A cloud simulation performed with a CSRM, as viewed from space



Note the wide range of spatial scales in the cloud system.

Limitations of CSRMs





- Microphysics must still be parameterized.
- Turbulence and shallow convection must still be parameterized.
- Radiative transfer must still be parameterized.

Strengths of CSRMs

With a CSRM, mesoscale and cloud-scale dynamics are explicitly simulated, so that microphysics, turbulence, and radiation become the "tall pegs."

- **A CSRM is a much better framework for microphysics parameterization than a GCM.**
- **A CSRM is a much better framework for turbulence parameterization than a GCM.**
- **A CSRM is a much better framework for radiation parameterization than a GCM.**

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 $10^4 x 10^2$ = **10^6** times larger than with today's lower-resolution models.

A dream no more.

Our friends at the Frontier Research Center for Global Change, in Japan, are helping us to find the path forward.

They are helping us in much the same way that Toyota helped General Motors.

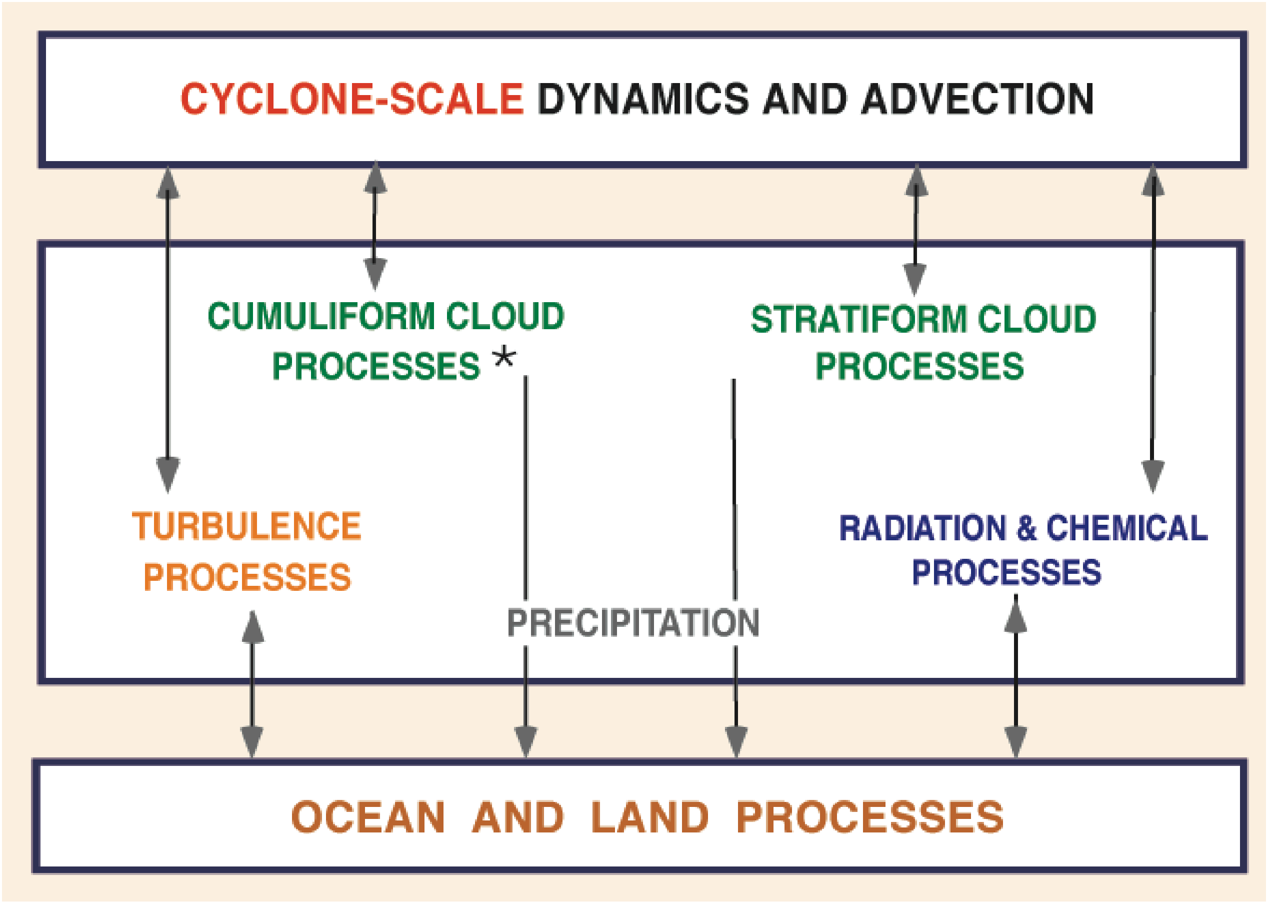
Figure from Hiroaki Miura

The World's First GCRM

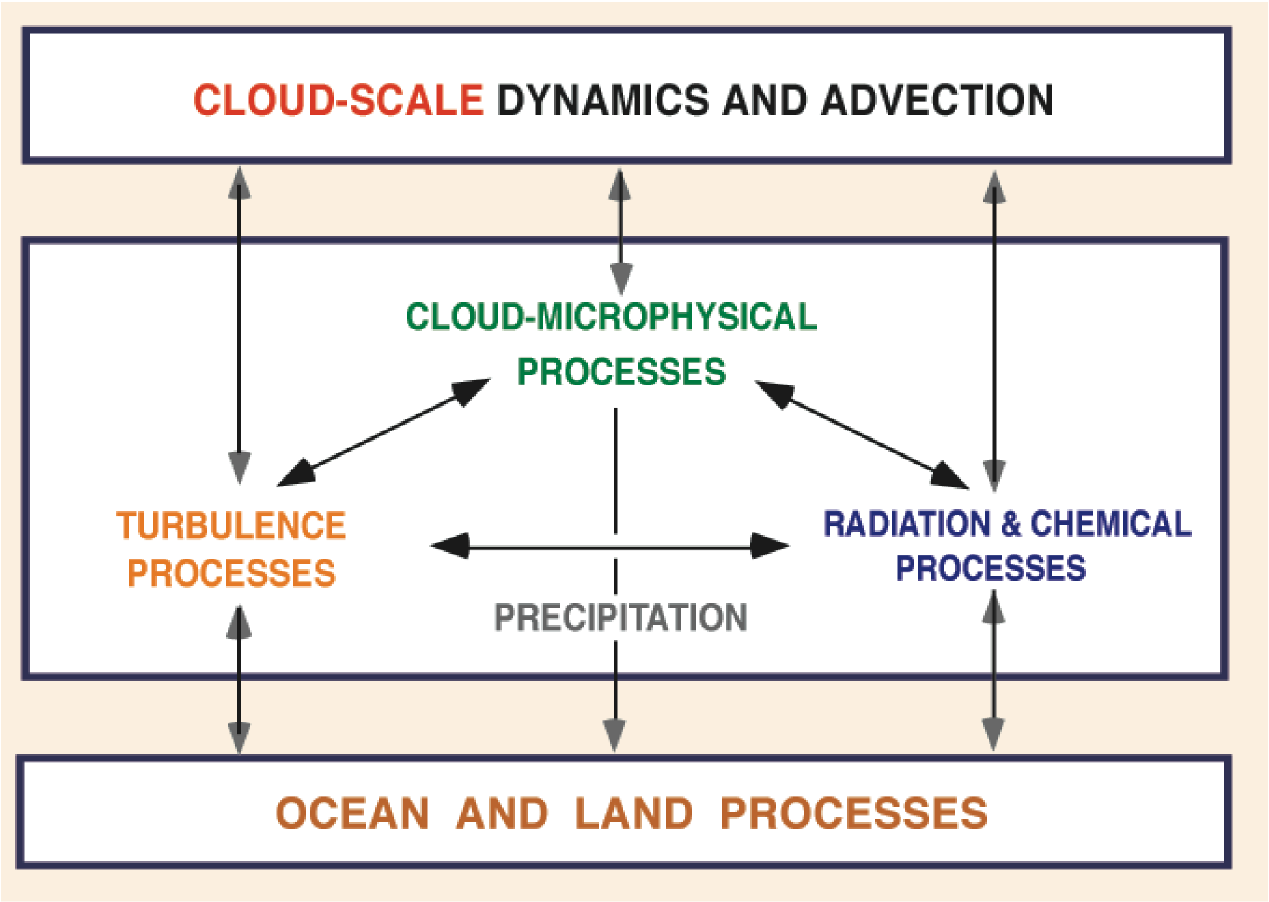
- 3.5 km cell size, ~10^7 columns
- Top at 40 km
- 54 layers, ~10^9 total cells
- State ~ 1 TB
- 15-second time step
- ~10 simulated days per day on half of the Earth Simulator (2560 CPUs, 320 nodes), close to 10 real TF.
- ~ 1 TF-day per simulated day

Physical interactions

Conventional GCM



GCRM



Slide from A. Arakawa.

Applications of GCRMs

- Parameterization development
  - For the first time, we will be able to simulate interactions from the global scale to the cloud scale.
- Numerical weather prediction
- Climate simulation
  - An annual cycle, coupled to the ocean, by 2011
  - Time slices
  - Anthropogenic climate change

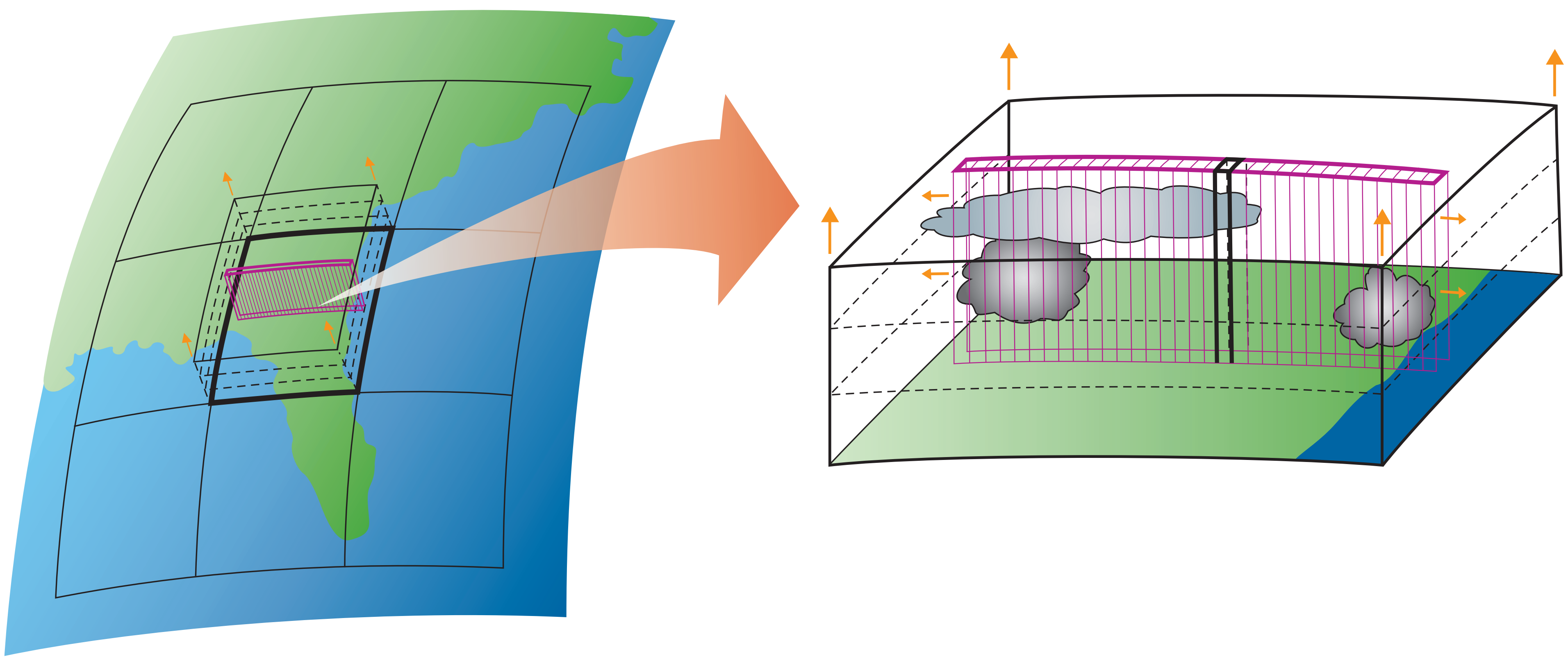
A bridge to GCRM climate simulation

GCRM climate

Current climate models

Super-Parameterization

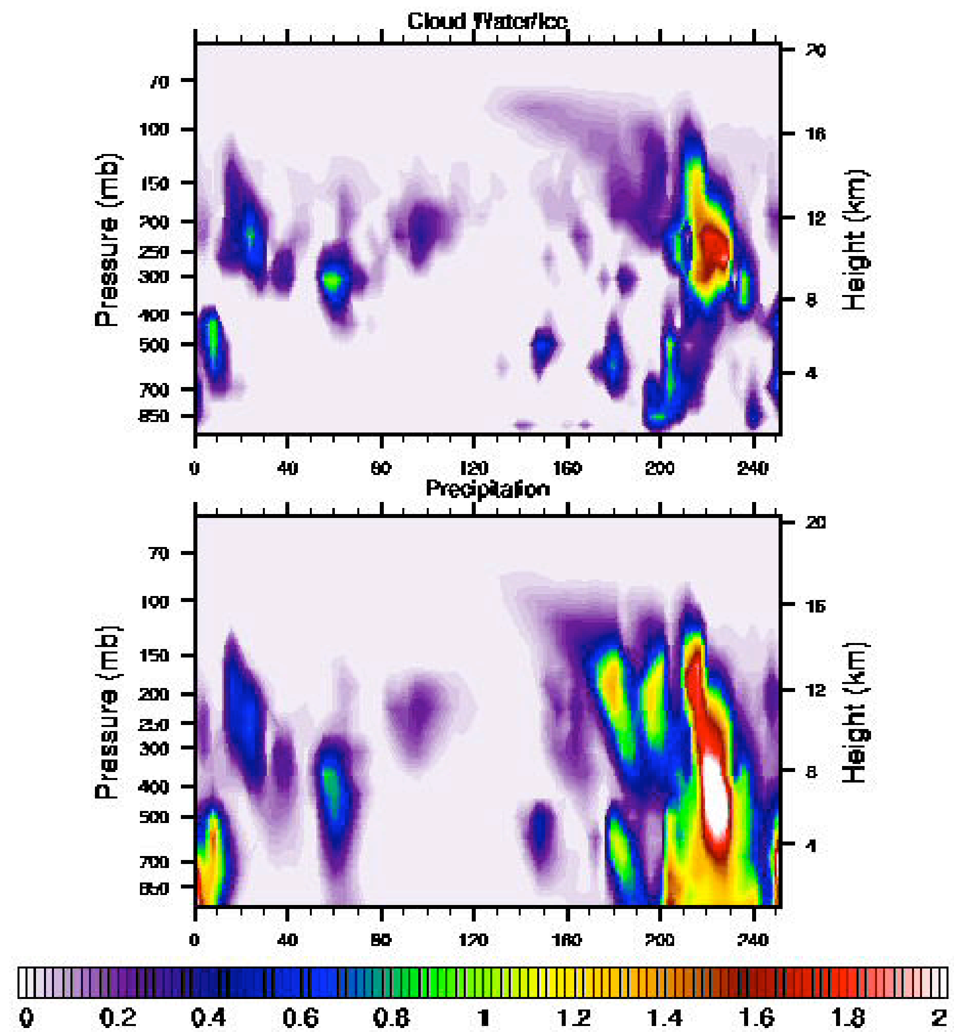
(aka MMF)



This idea was proposed and first tested by Wojciech Grabowski.

Compared to what?

Super-Parameterizations	Conventional Parameterizations
2D or Quasi-3D	1D
Periodic boundary conditions	Boundary whats?
Shallow convection and turbulence must be parameterized.	Same
Microphysics is simplified but the required input is in pretty good shape.	Microphysics even simpler, and the required input (e.g., local vertical velocity) is not available.



"It's low-resolution, but at least it uses the right equations."

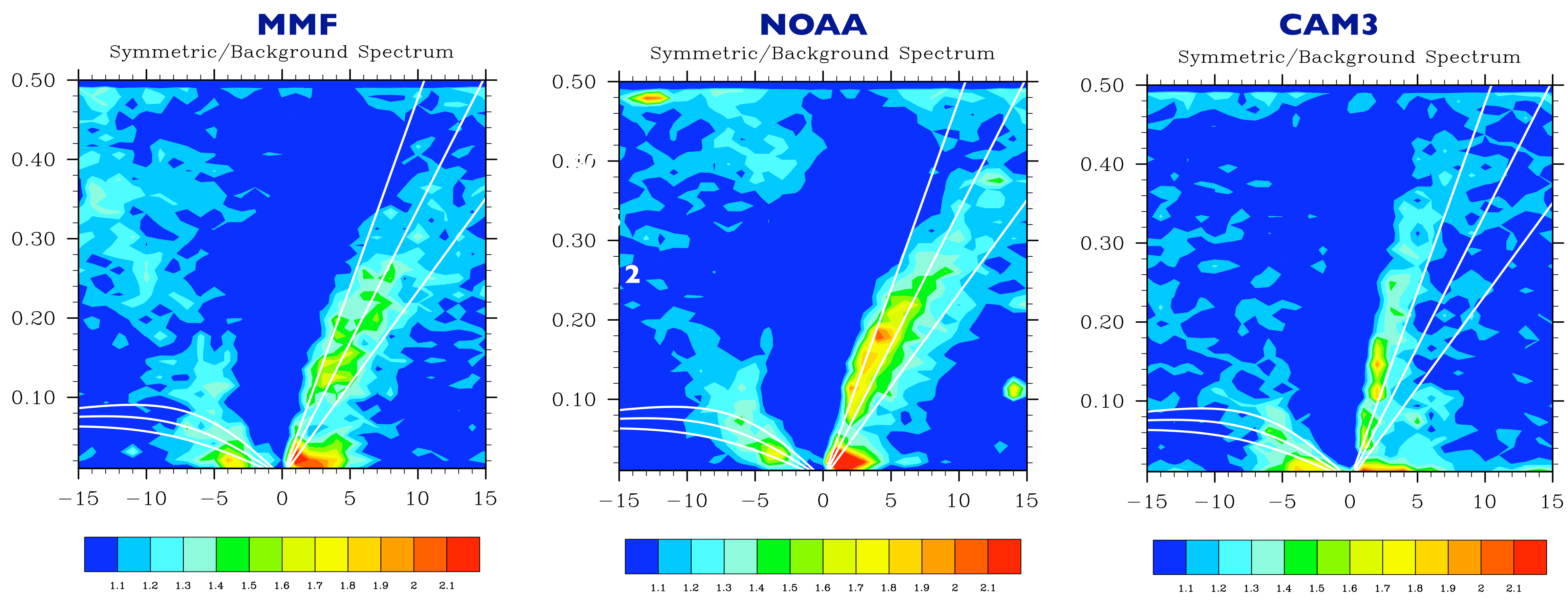
-- Bjorn Stevens

An AMIP-style experiment with the Super-CAM

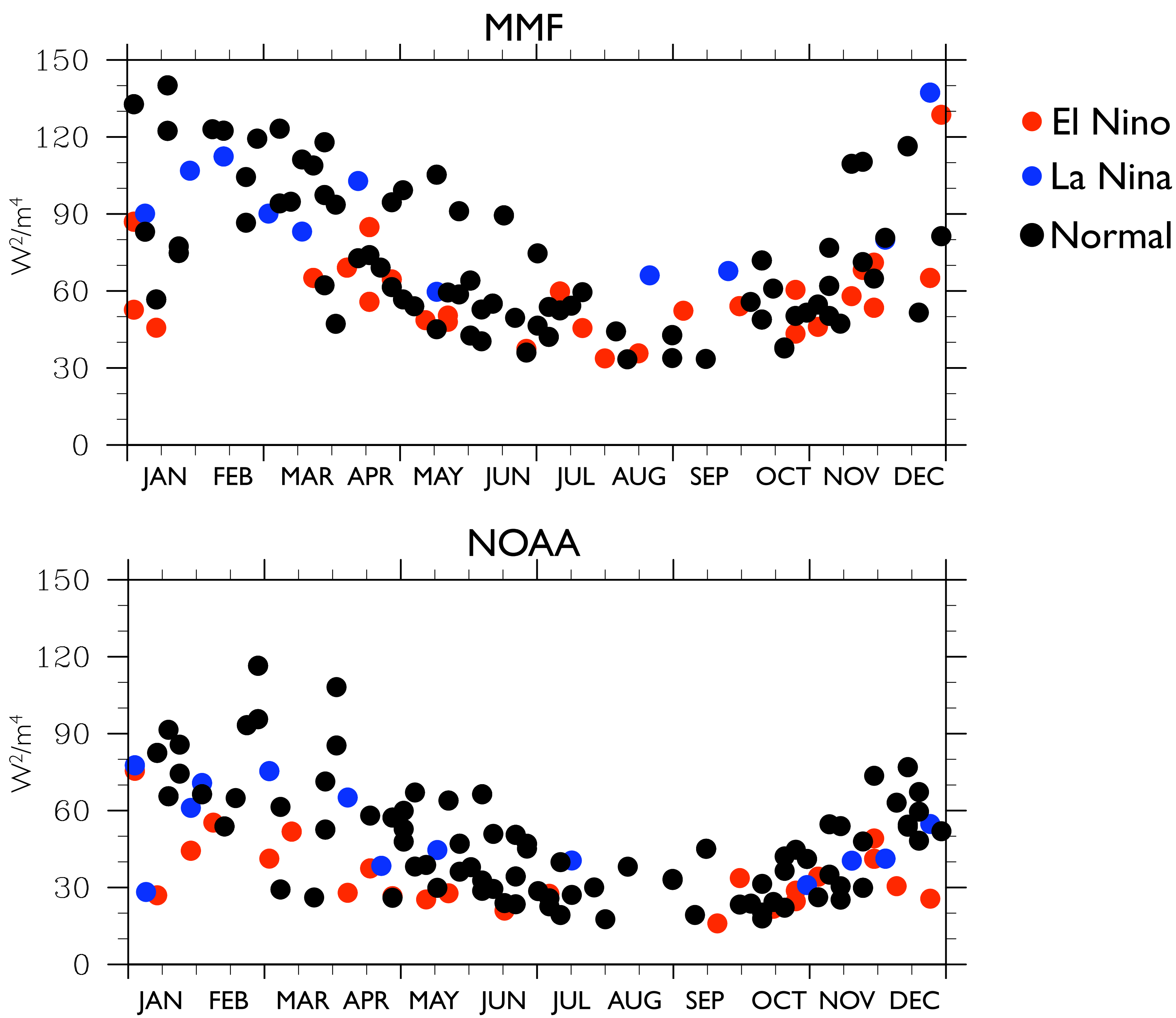
Prescribed monthly-mean observed SST and ice

September 1985 to August 2001 (16 years)

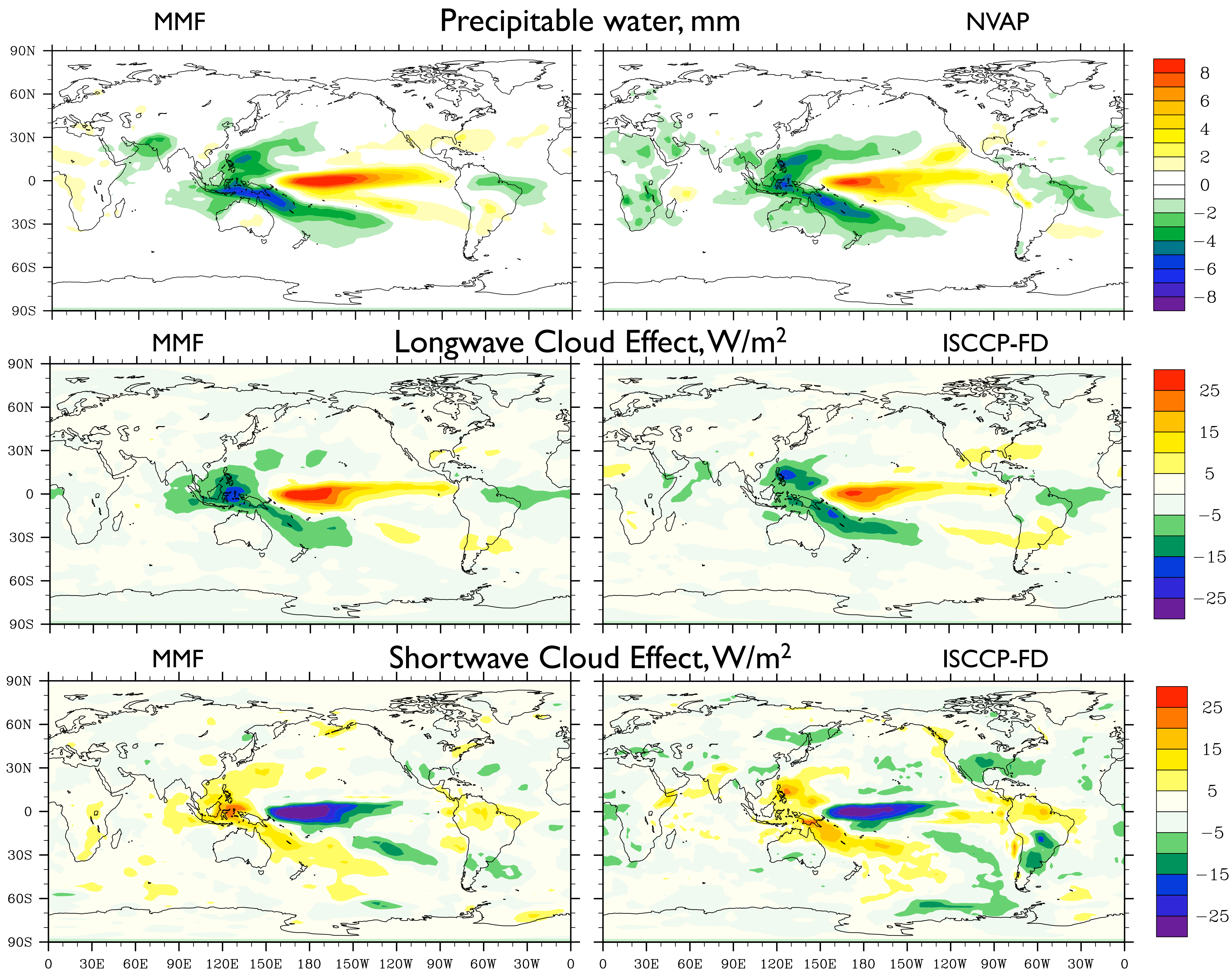
Outgoing Longwave Radiation



MJO-event OLR anomalies
1986-2003

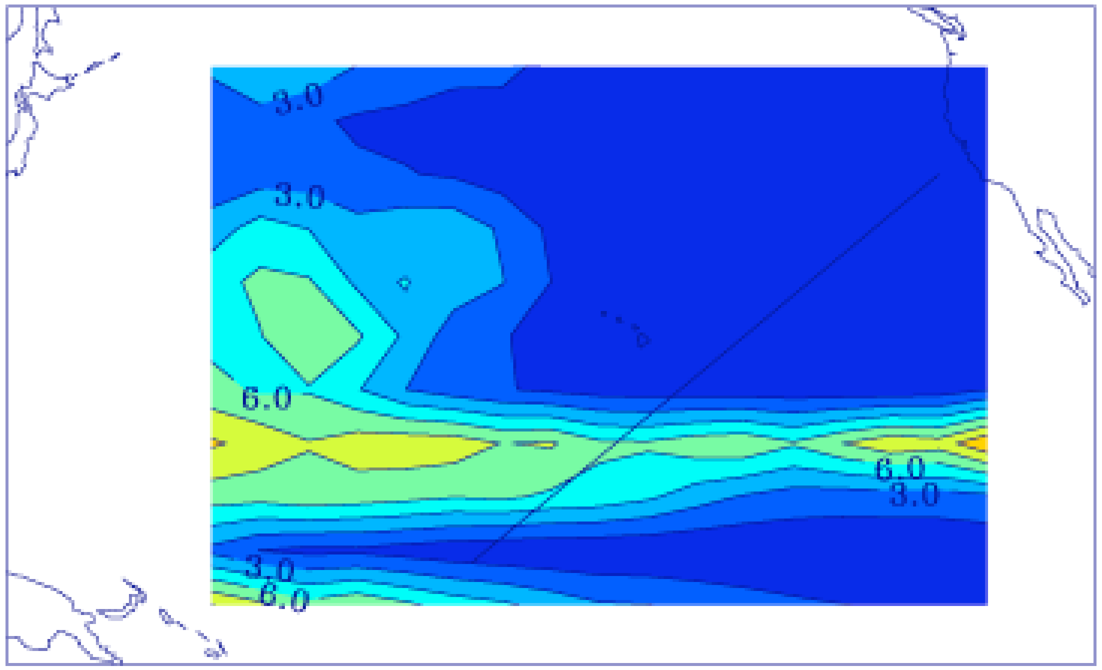


El Nino - La Nina Anomalies

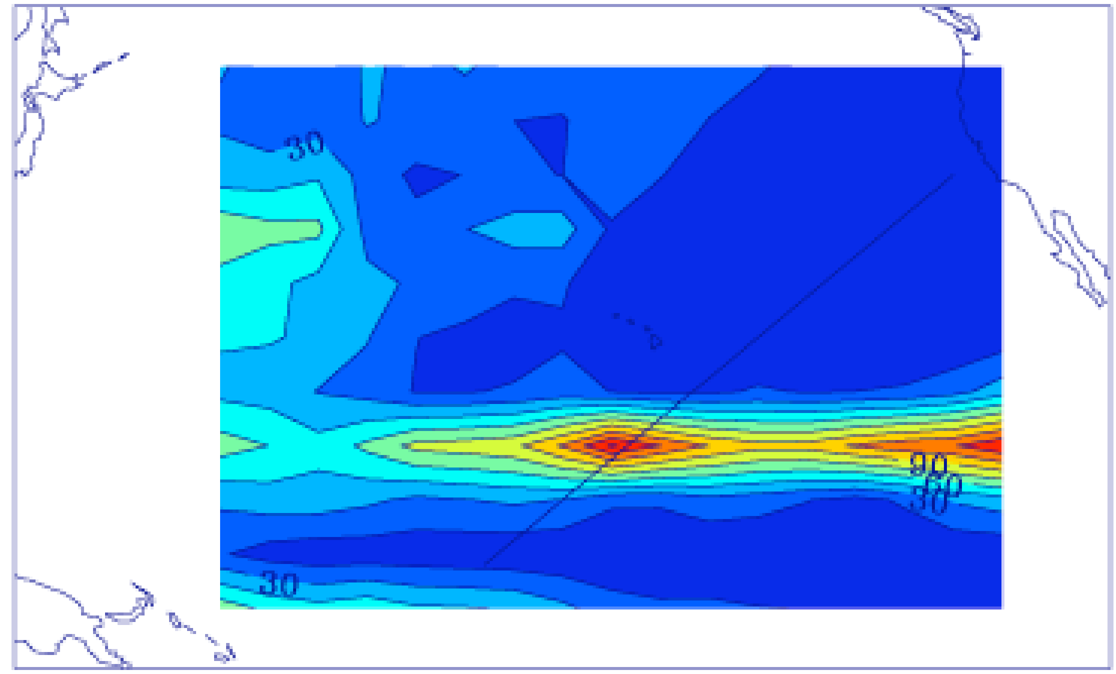


Precipitation rate

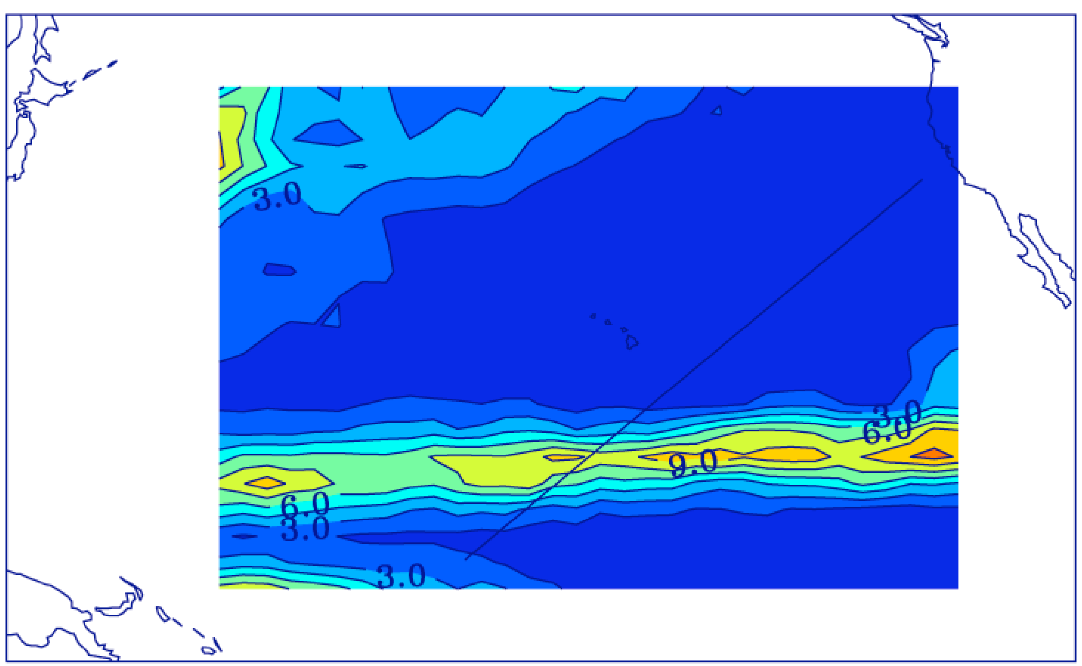
CAM3



MMF

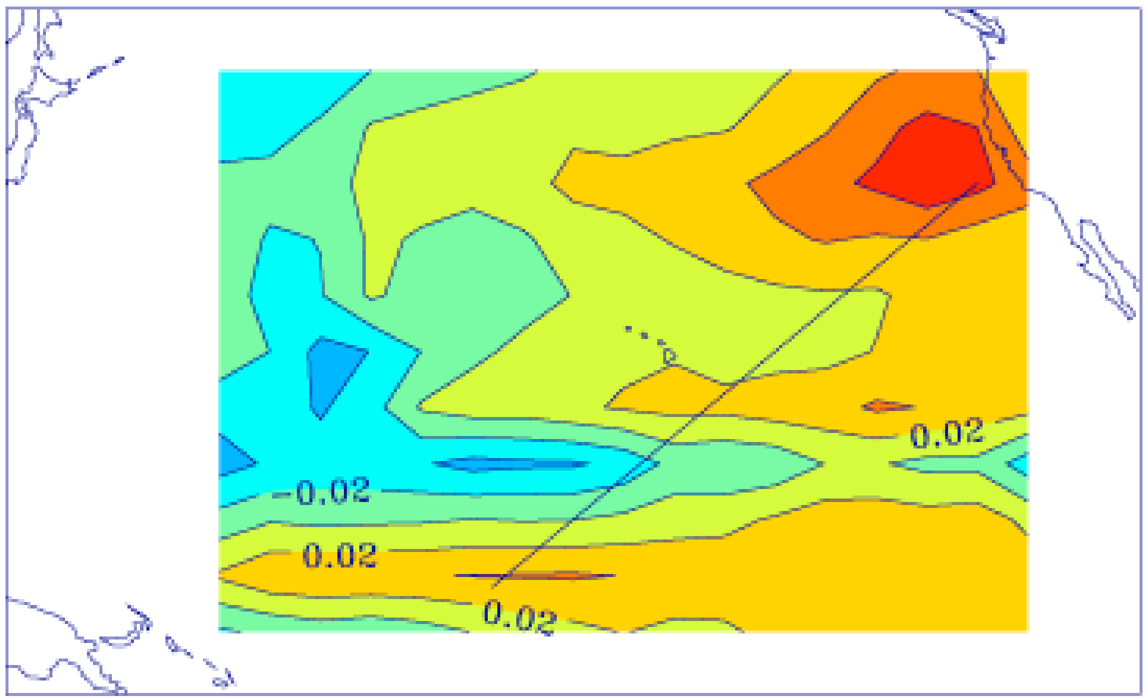


GPCP

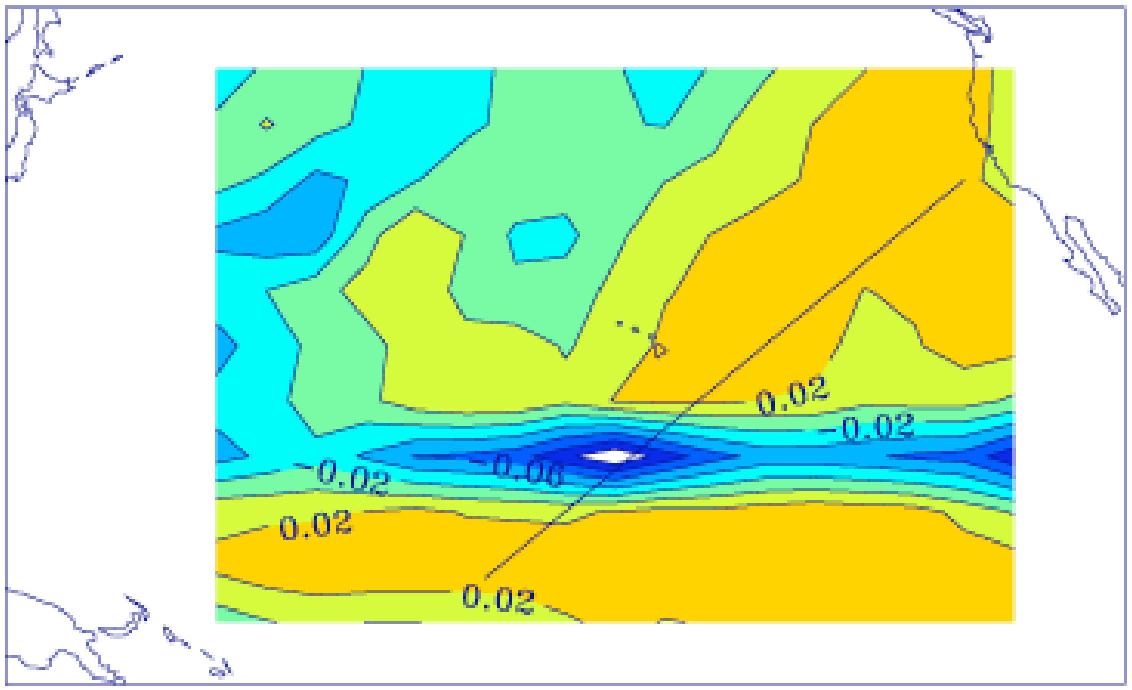


Vertical Velocity, 300 mb (Pa/s)

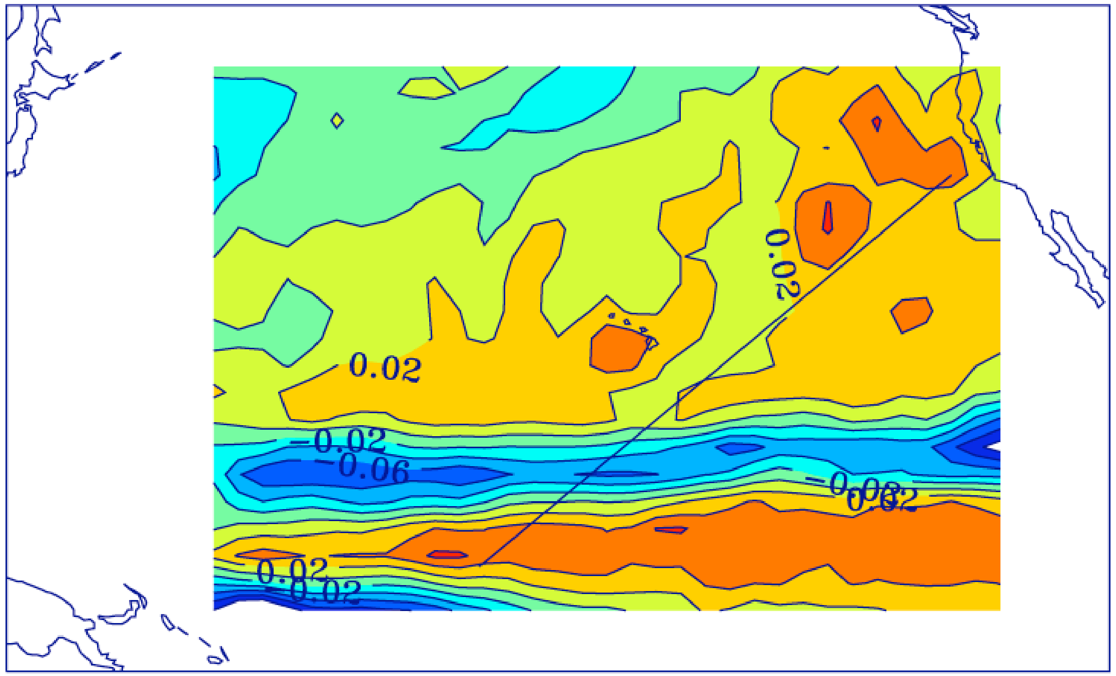
CAM3

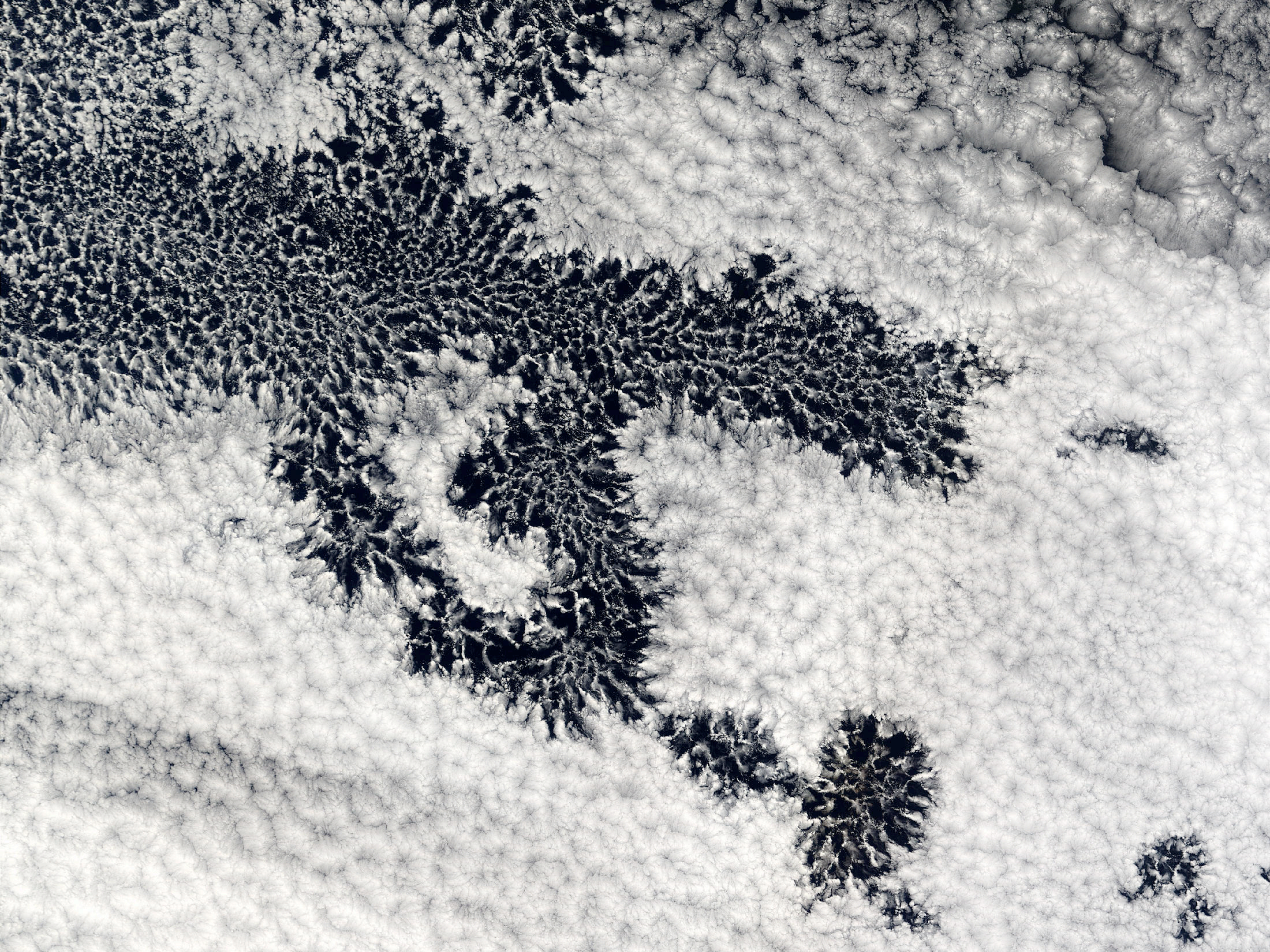


MMF

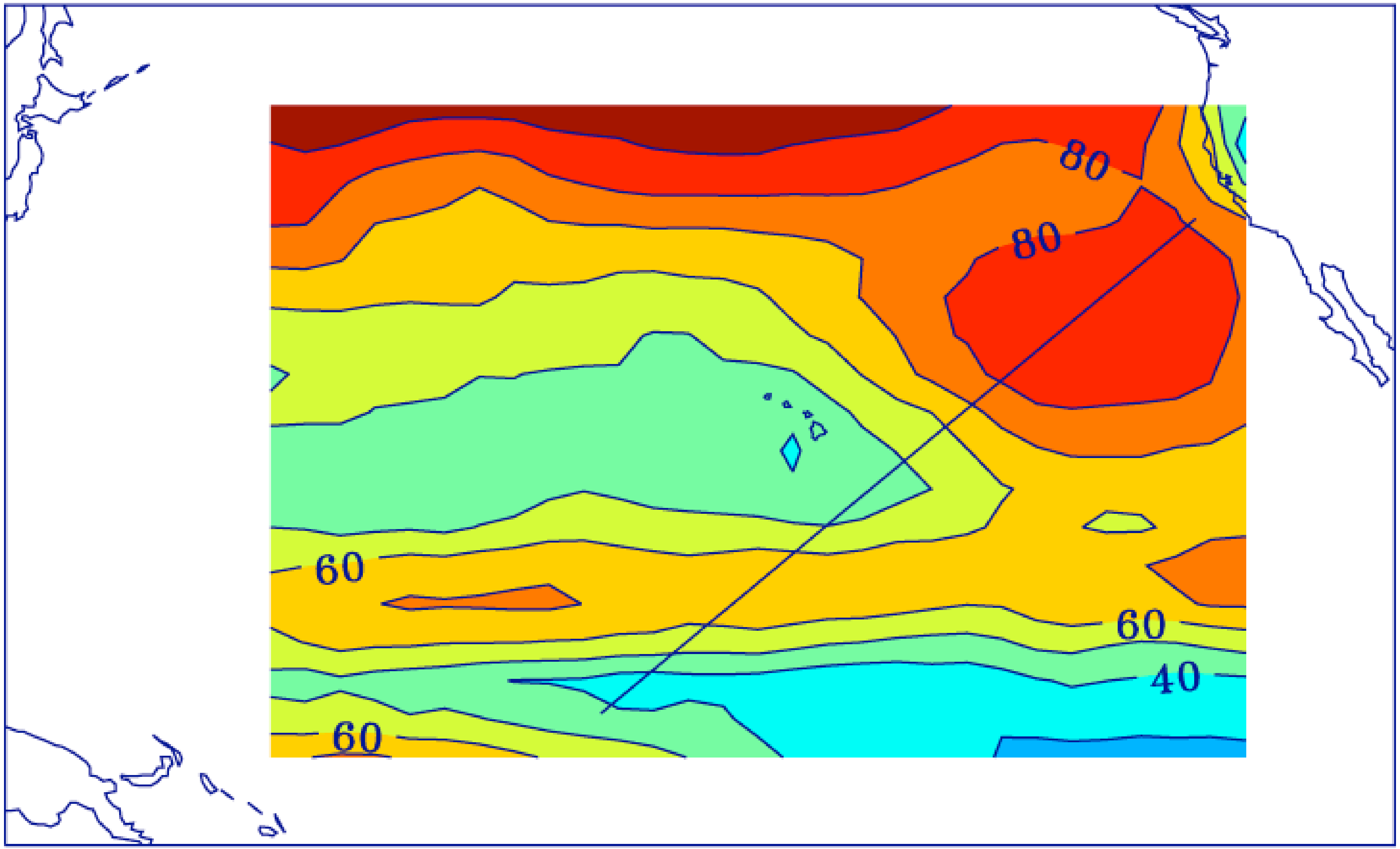


ERA40



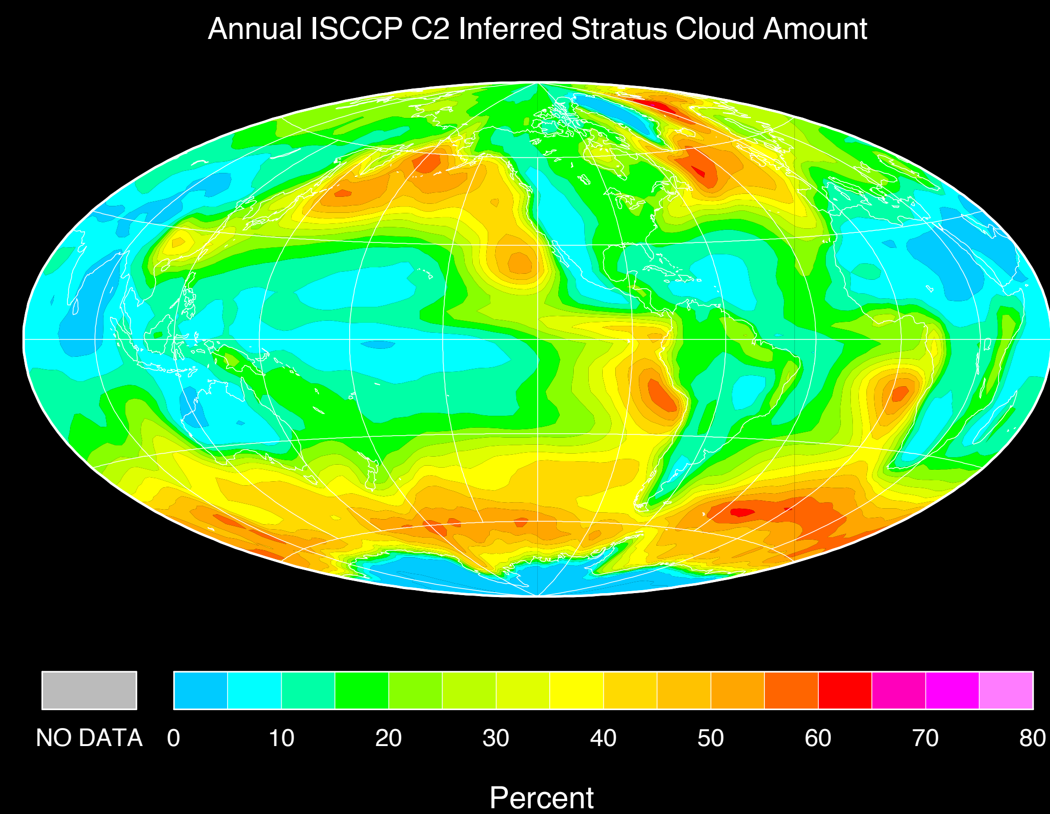


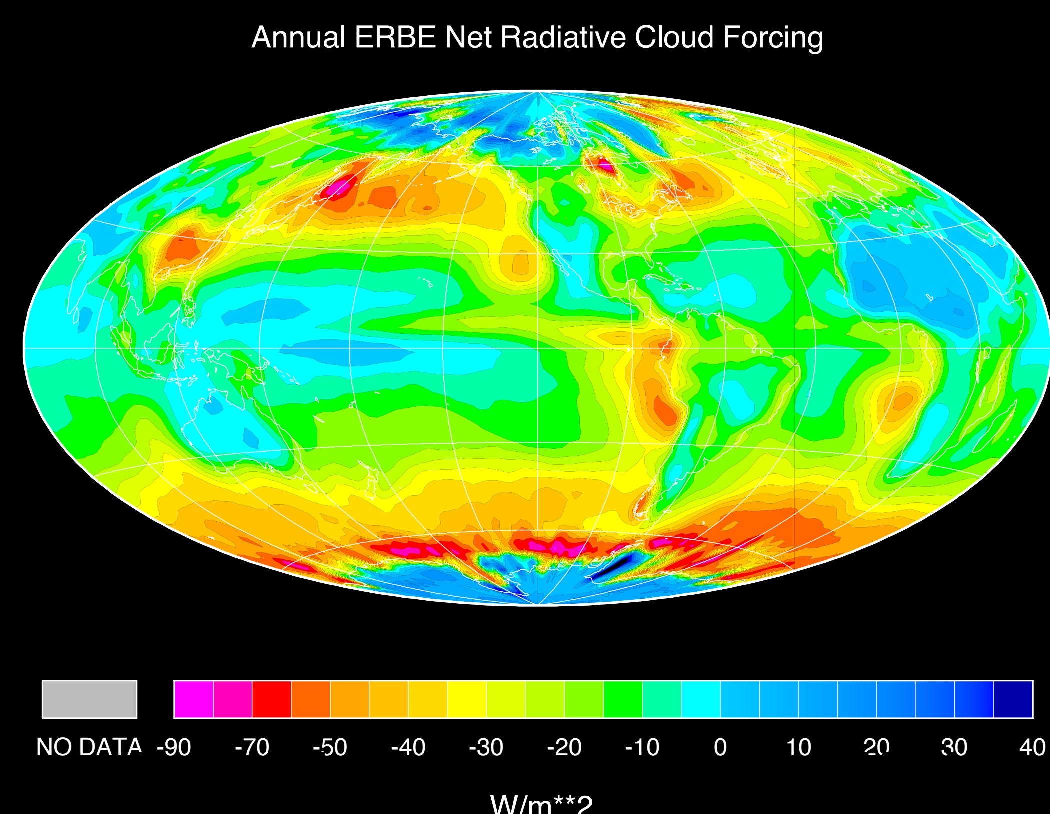
Summertime California Stratus

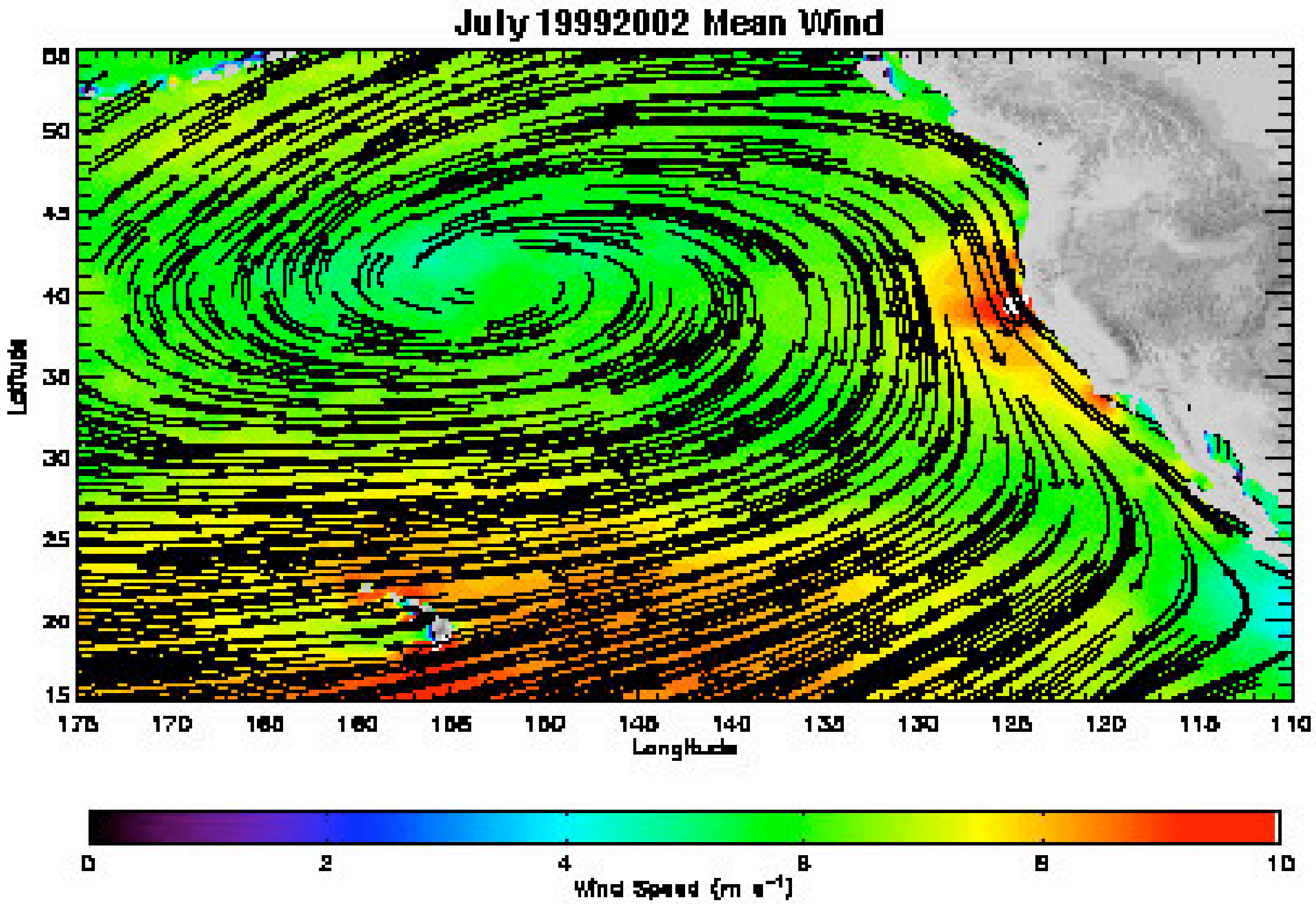


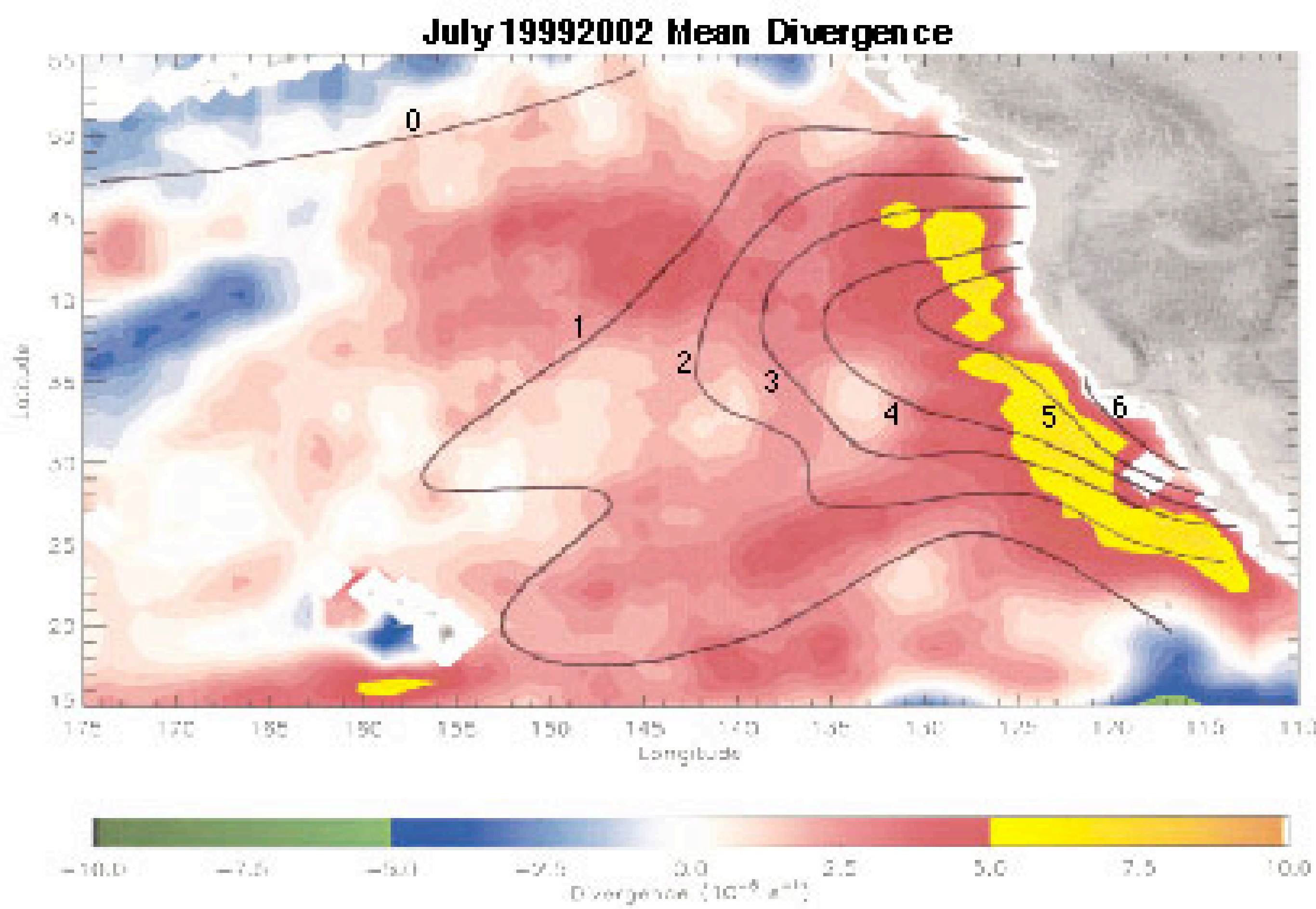
Mean cloud amount from the International Satellite Cloud Climatology Project

Marine Stratocumulus Clouds & Climate









QuikSCAT Data

Slide from Wayne Schubert

An amazingly sharp interface

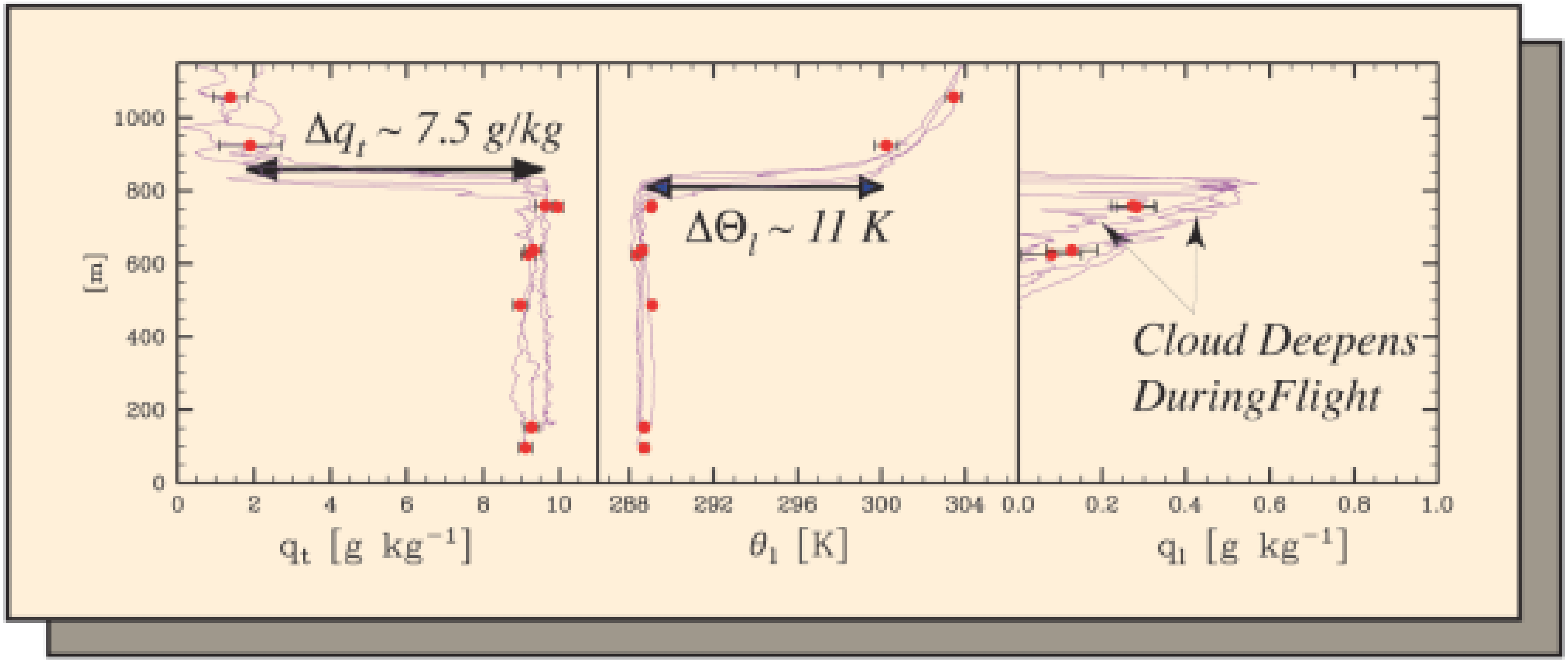
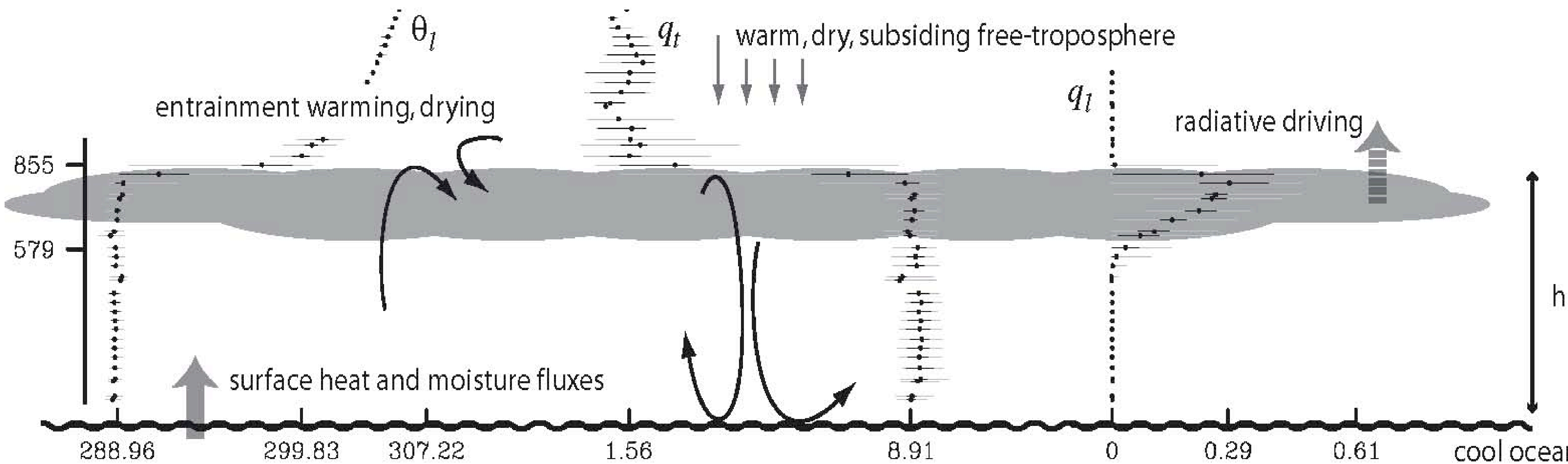
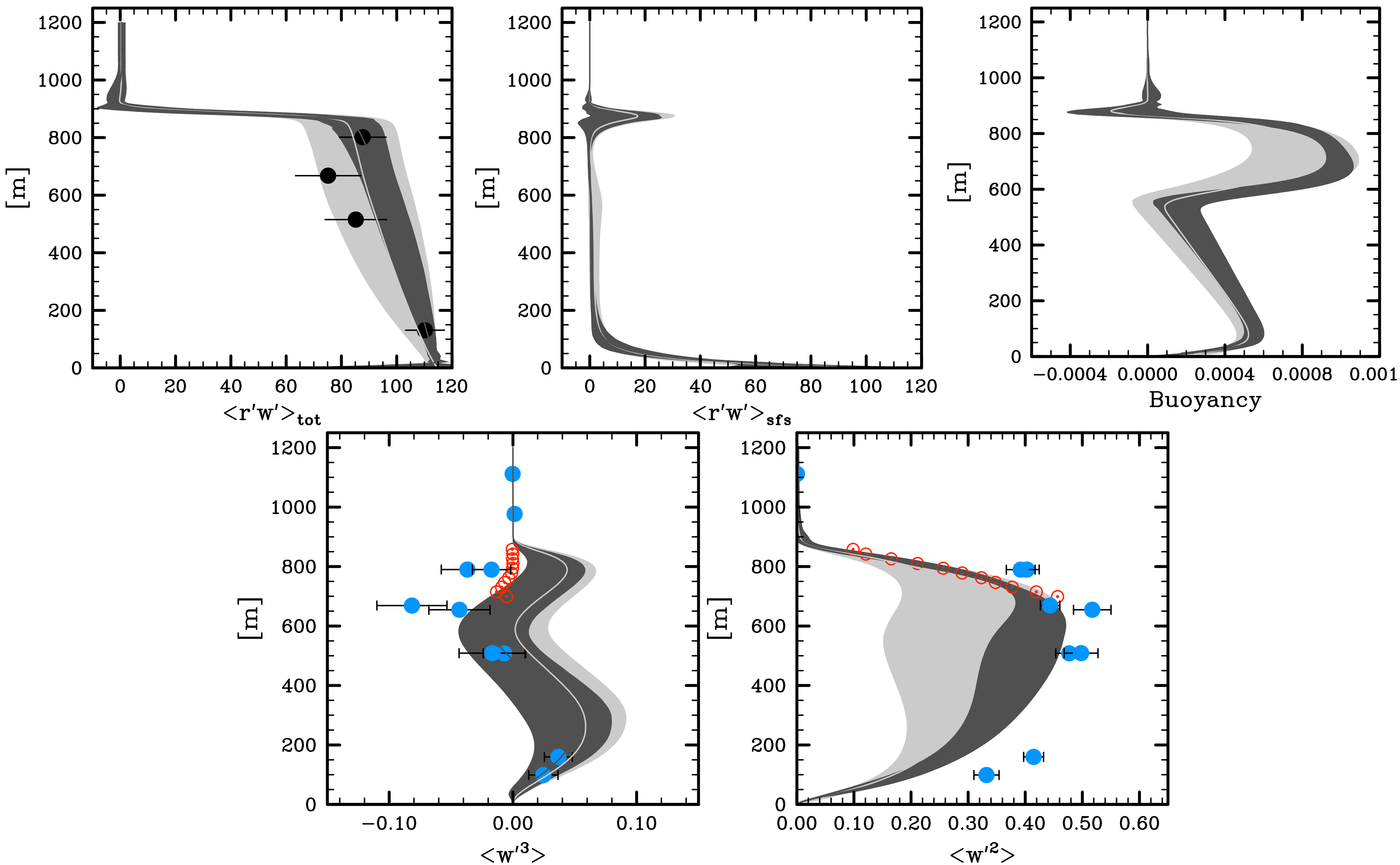


Figure from Stevens et al. (2003)



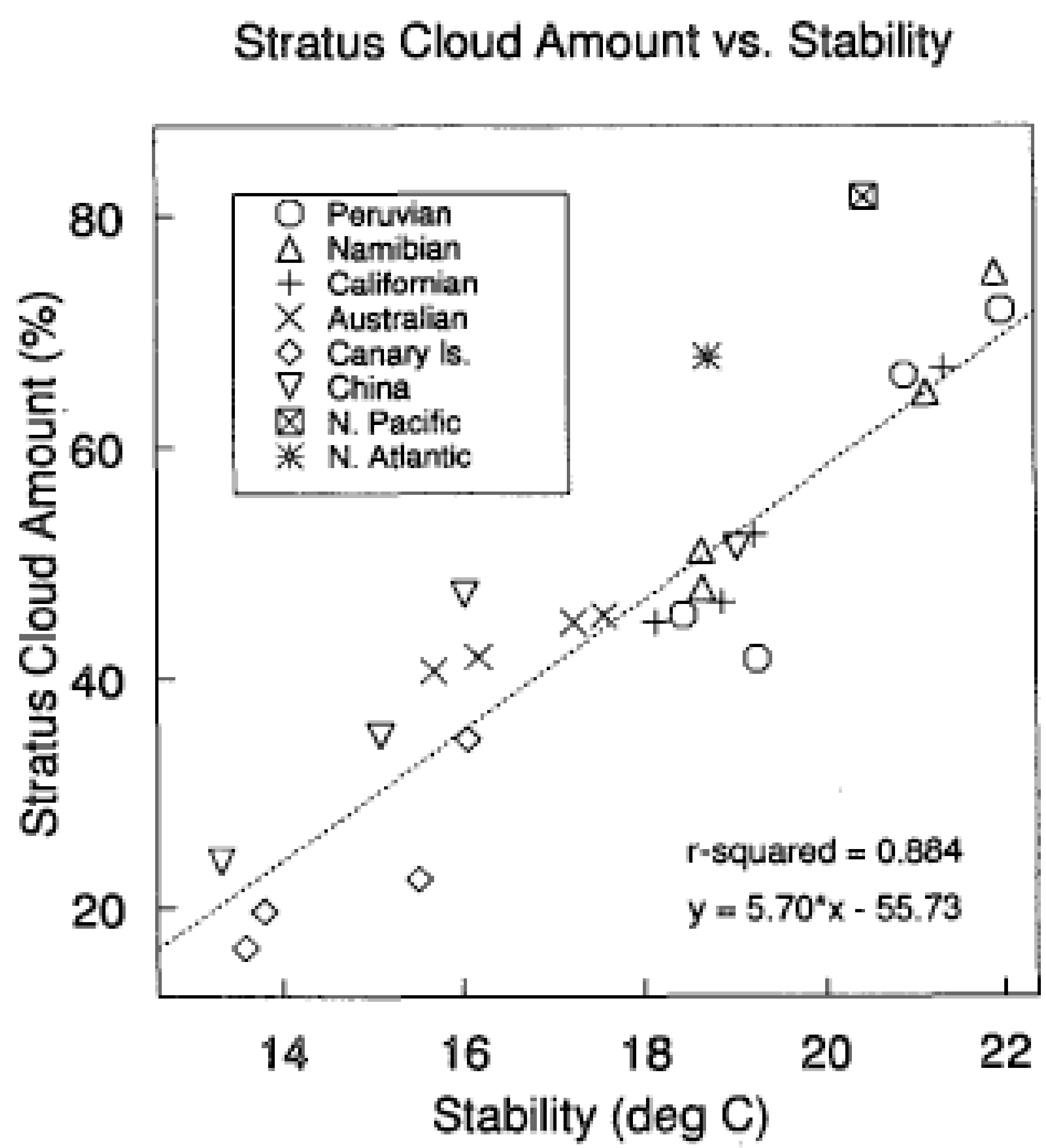
Slide from Bjorn Stevens

Radiatively driven turbulence below cloud top



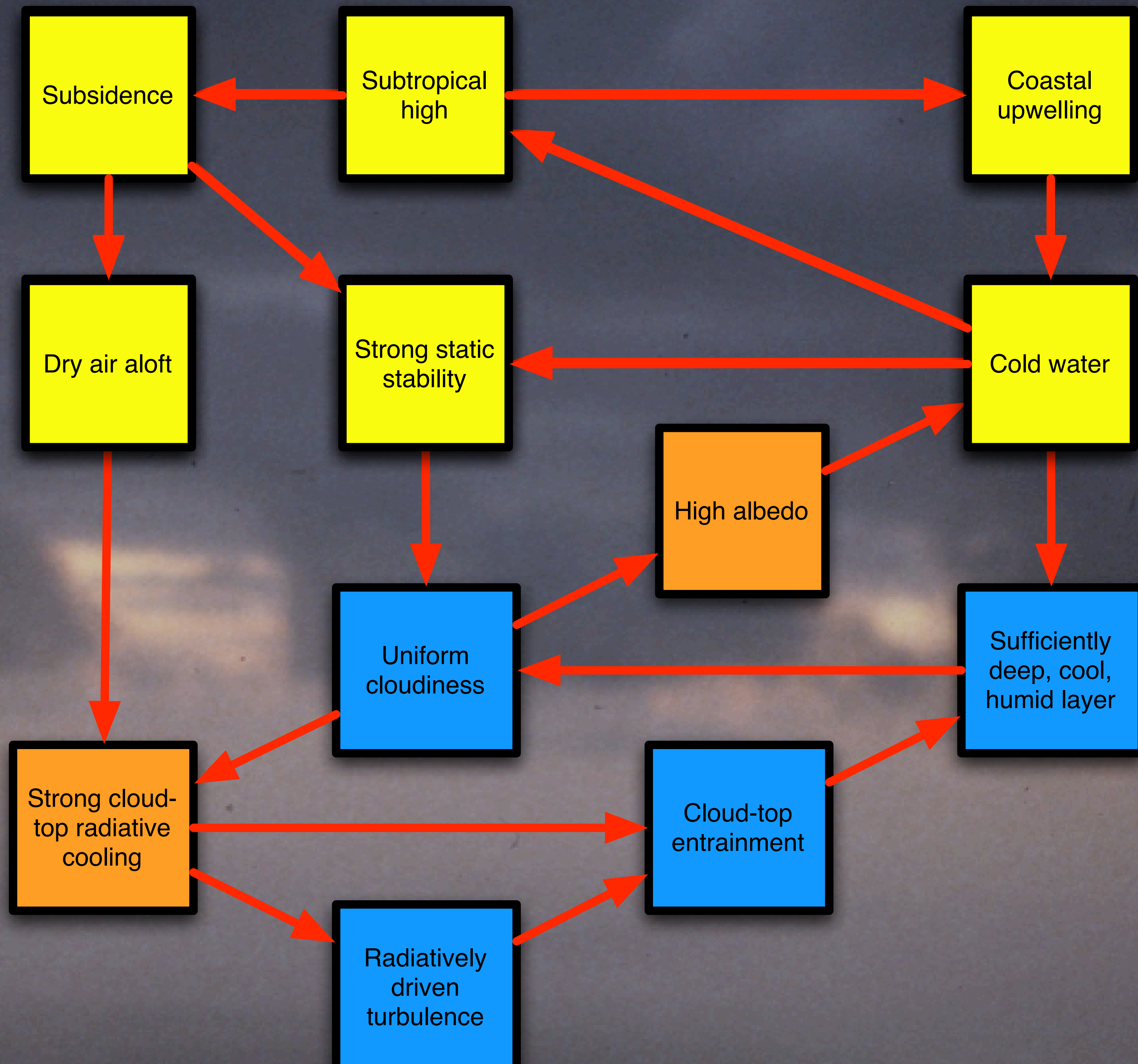
Slide from Bjorn Stevens

The Klein Line



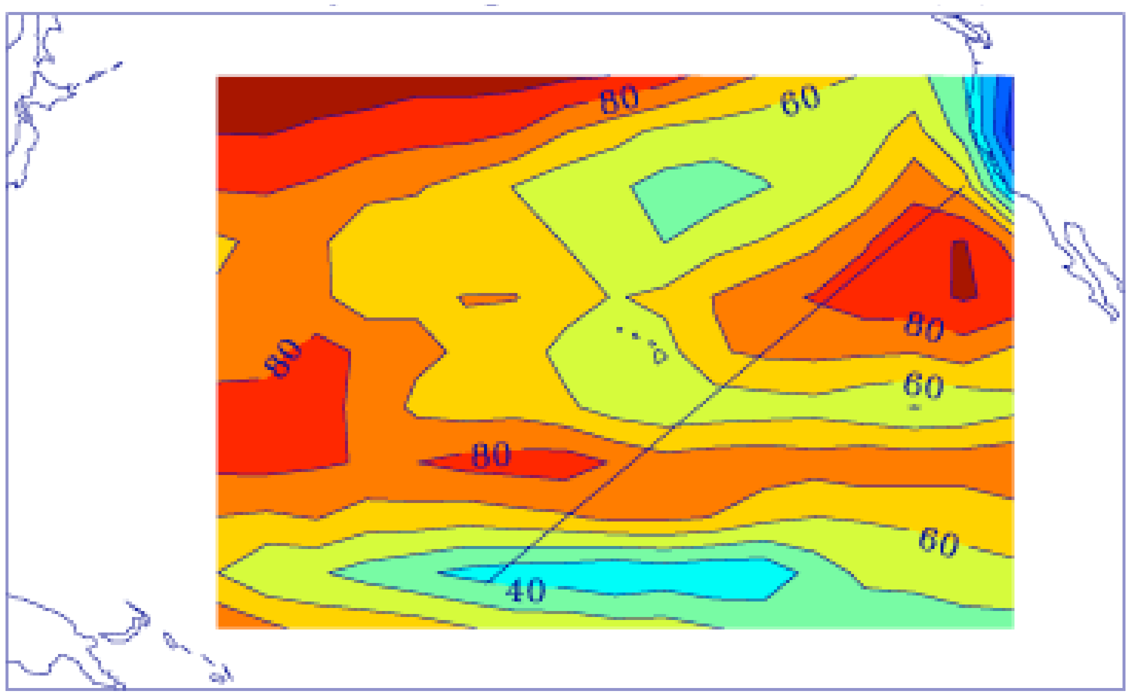
The Klein Line

- Physical explanation
  - Strong inversion inhibits mixing with dry air above, thus protecting the cloud
  - Details are complicated and controversial
- Input or output?
  - Klein line is macroscopic relationship
  - Parameterizations should represent microscopic processes
  - Klein line should be predicted, not built in by assumption

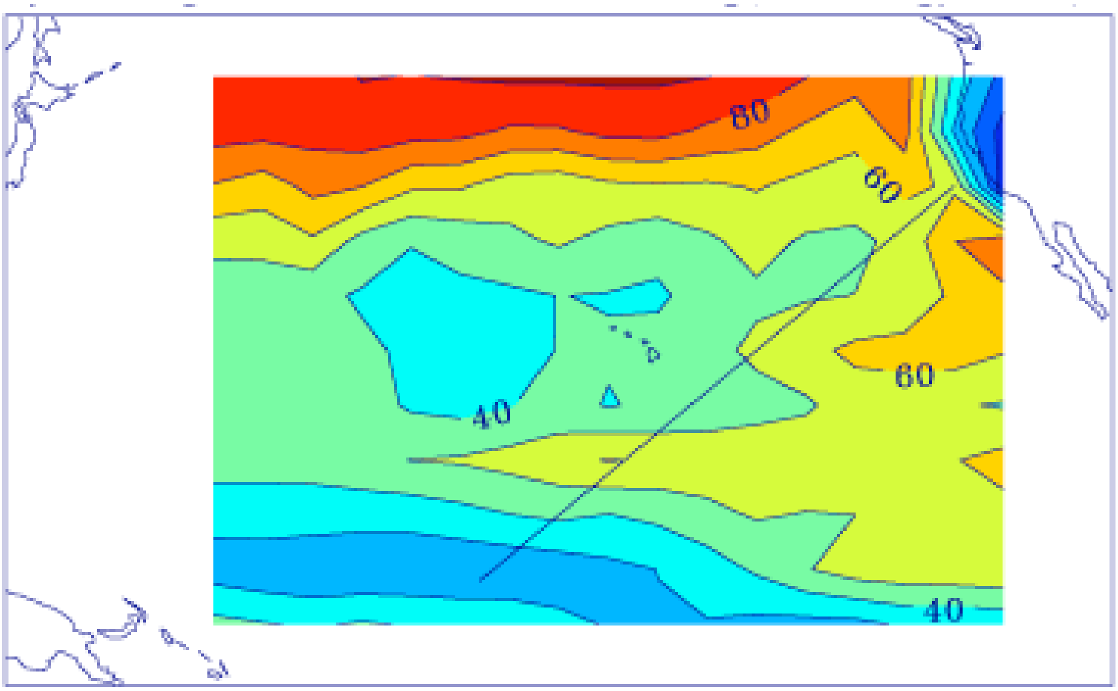

Subsidence
Subtropical high
Coastal upwelling
Dry air aloft
Strong static stability
Cold water
High albedo
Uniform cloudiness
Sufficiently deep, cool, humid layer
Strong cloud-top radiative cooling
Cloud-top entrainment
Radiatively driven turbulence

Making sausage

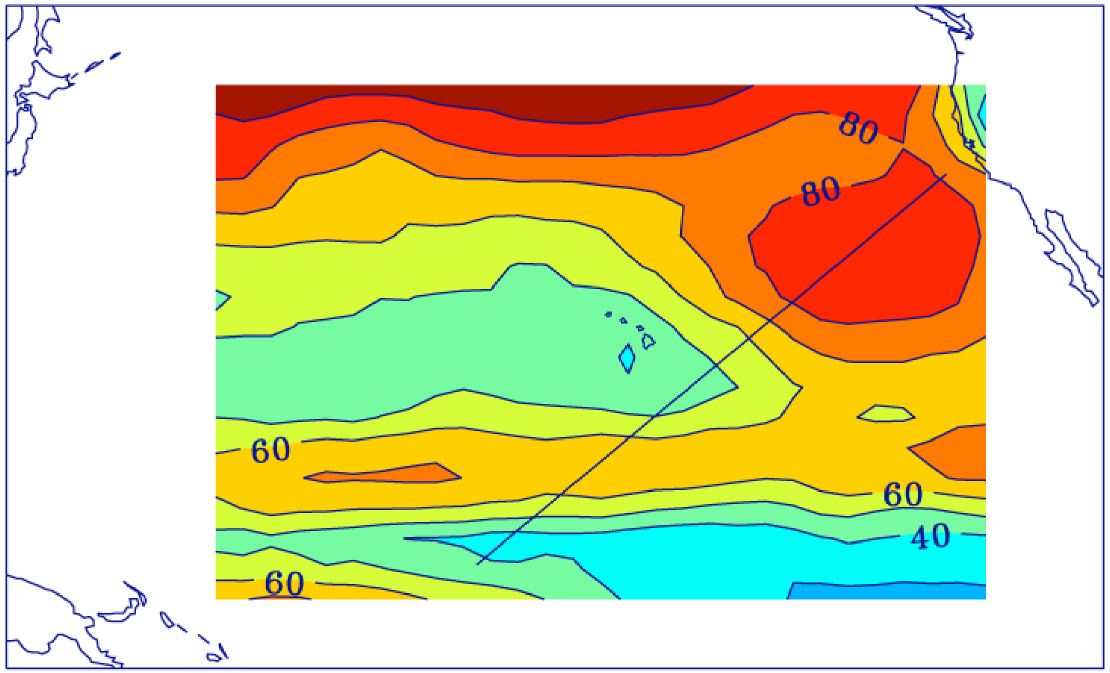
CAM3



MMF



ISCCP



Which simulation is better?

How do the two models produce marine Sc clouds?

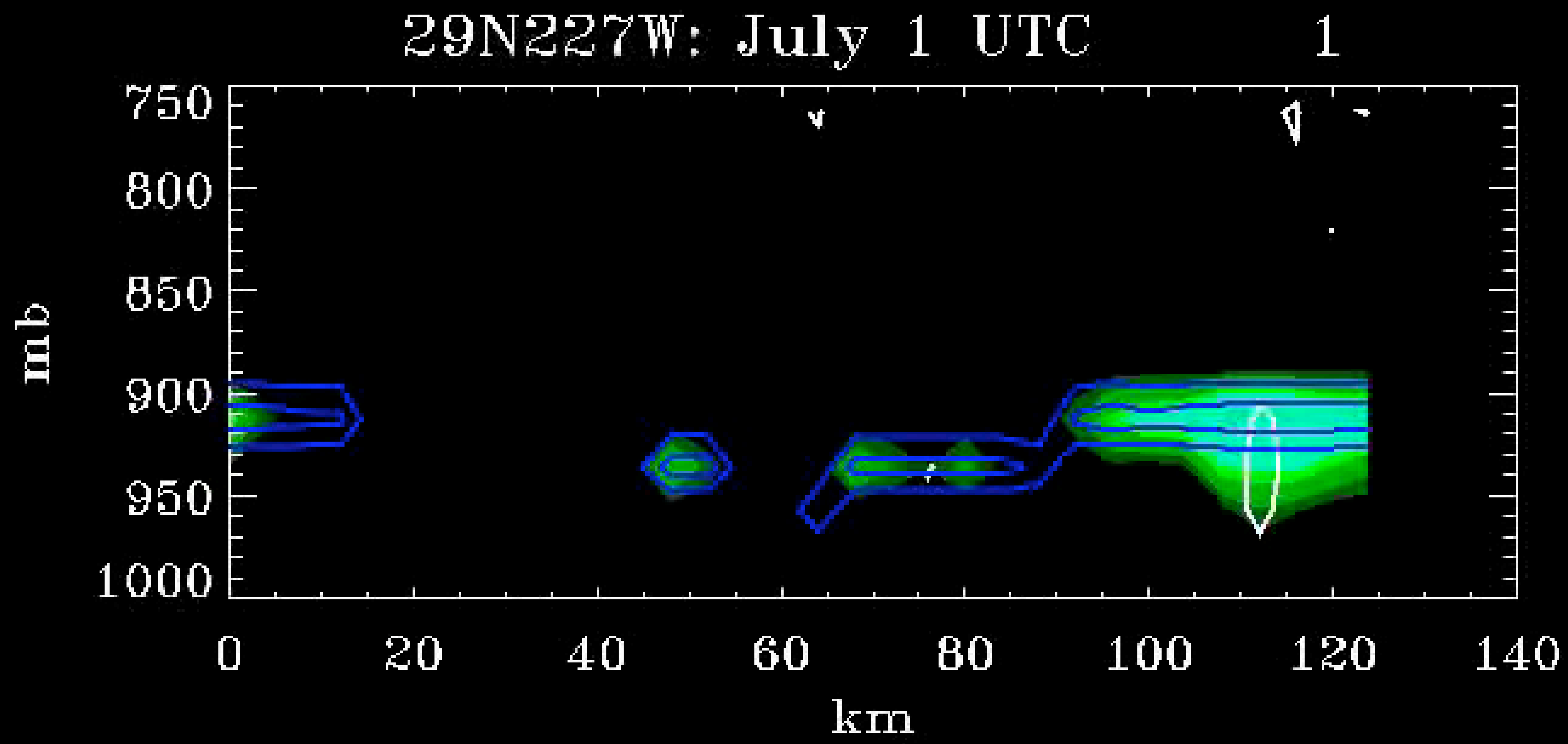
- **Standard CAM**

  Cloud is assumed to be located in the model layer below the strongest stability jump between 750 mb and the surface. If no two layers present a stability in excess of -0.125 K/mb, no cloud is diagnosed.

  - ***Klein Line is built in***
  - ***No information about moisture content!***

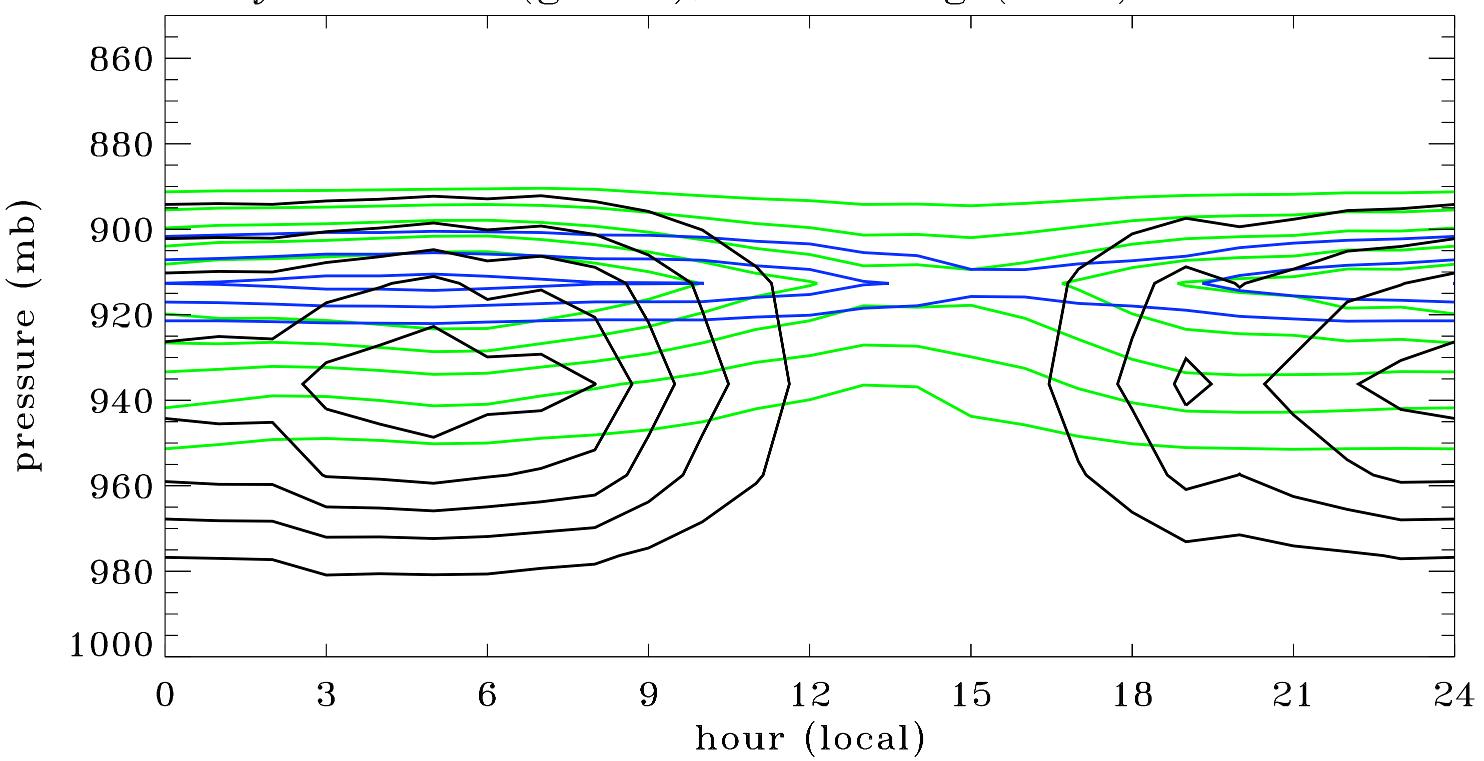
- **Super-CAM**

  Simply solves the right equations with low resolution.

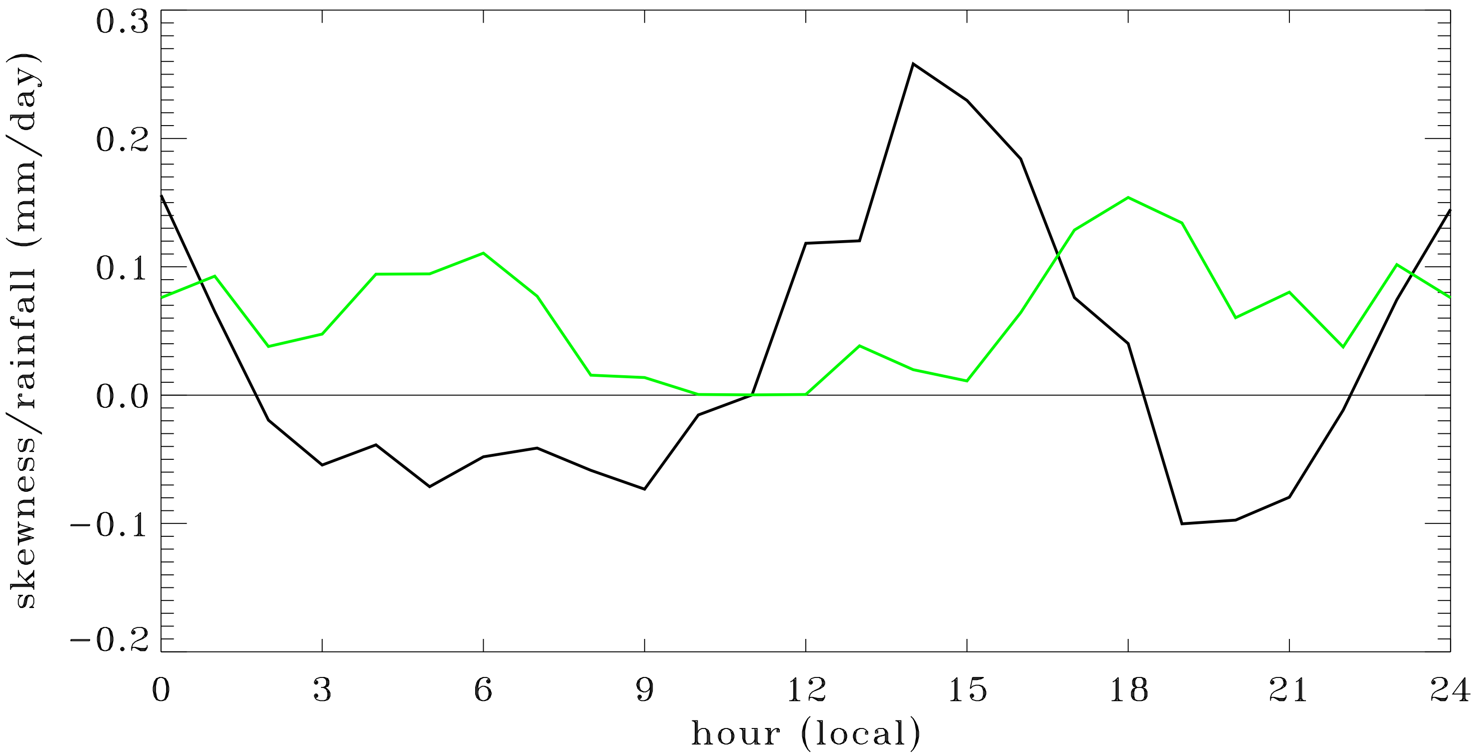


29N227W: July 1 UTC 1
750
800
850
900
950
1000
mb
0
20
40
60
80
100
120
140
km

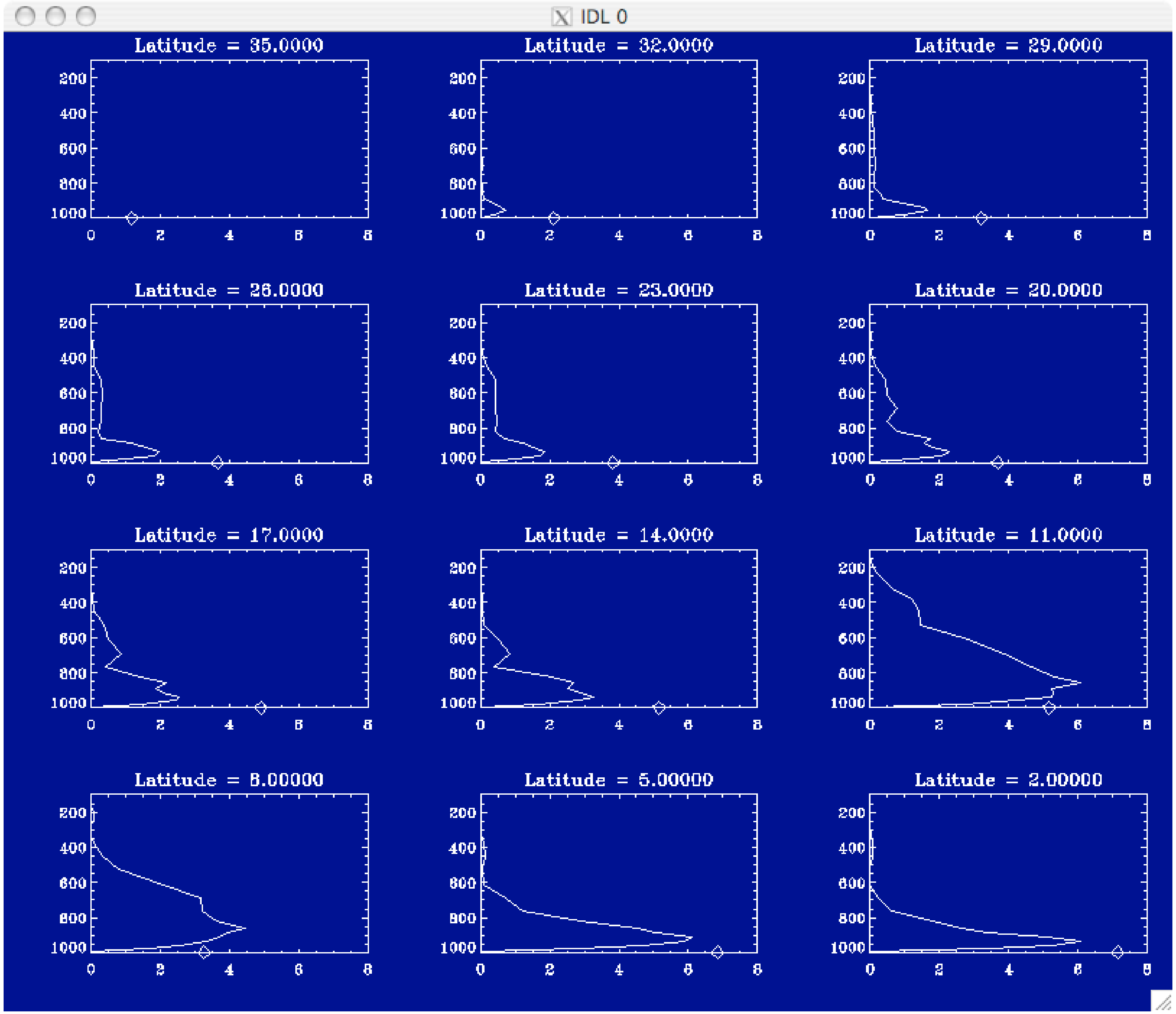
Mean diurnal cycle: CLW (green), IR cooling (blue), vertical motion (white)



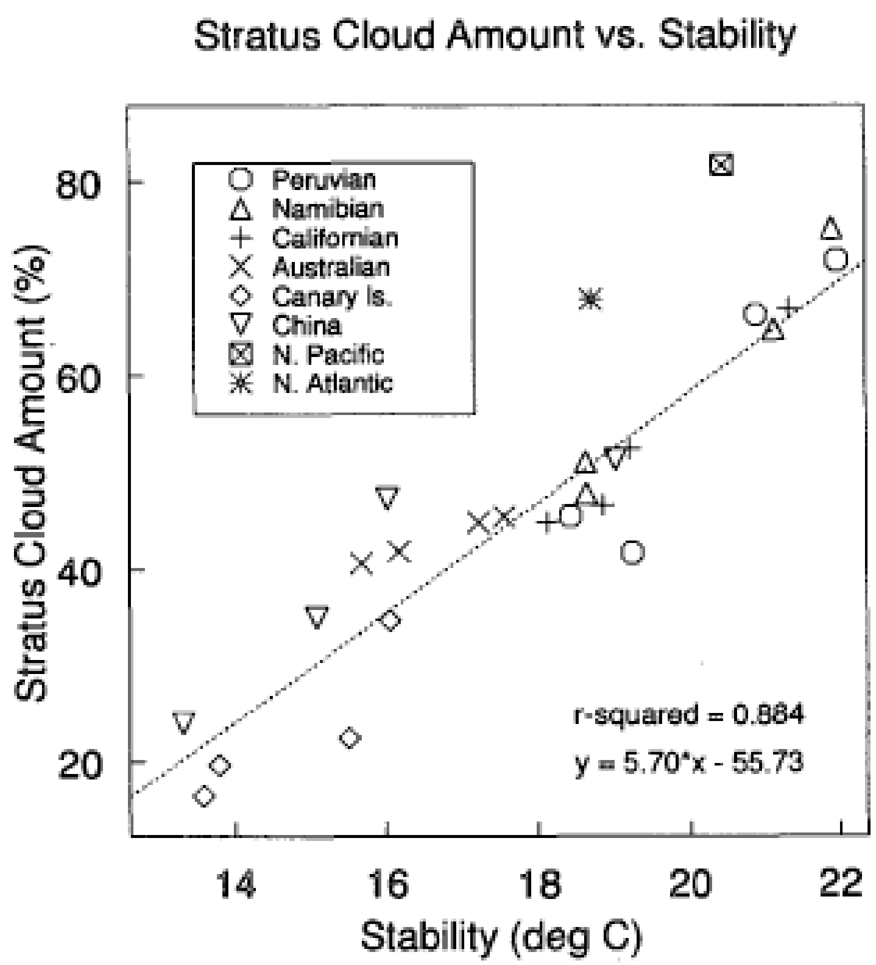
Mean below−cloud skewness and rainfall

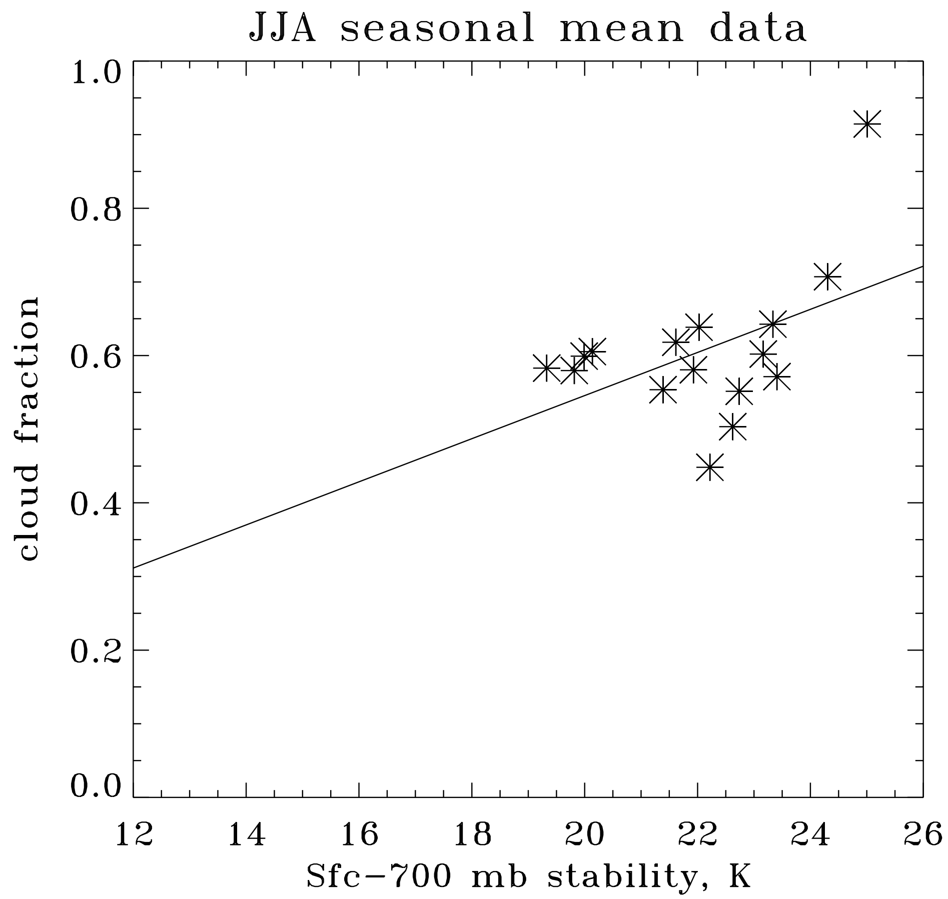


CRM-resolved moisture flux, and surface evaportion



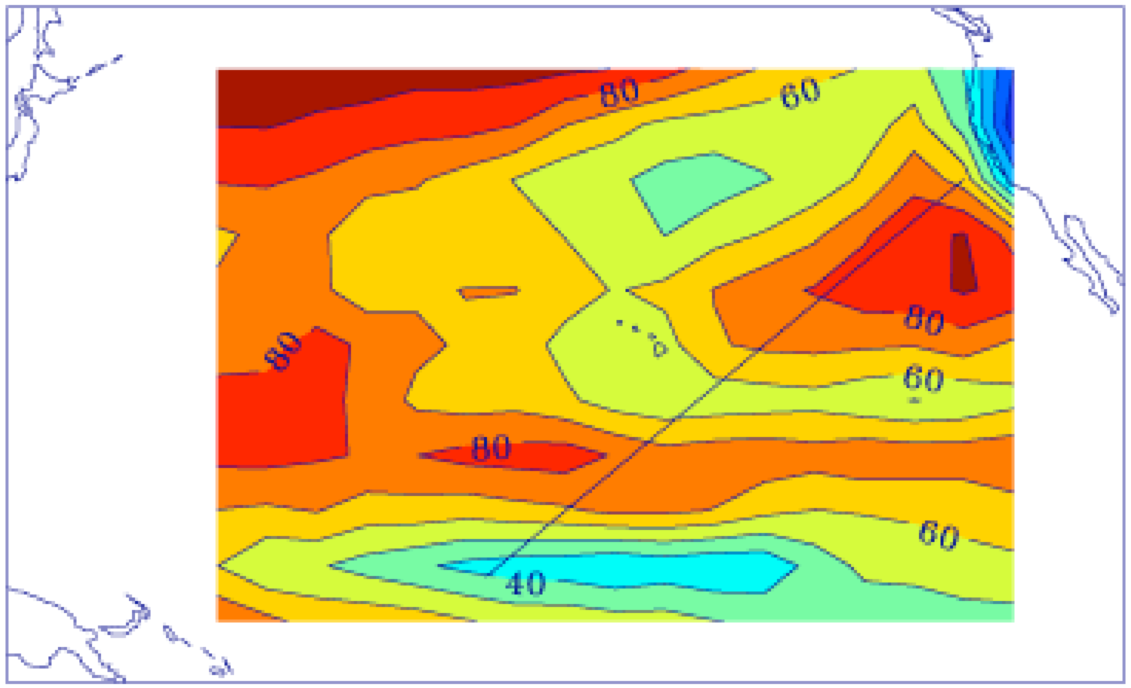
Back to the Klein line



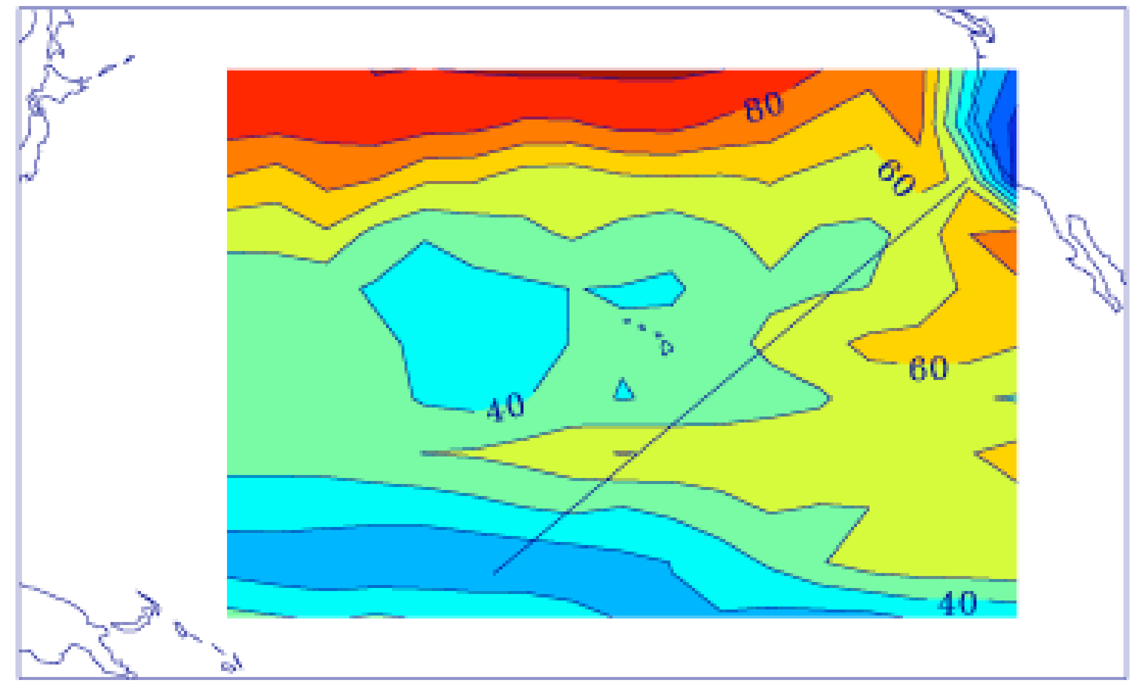


Cloud Cover (%)

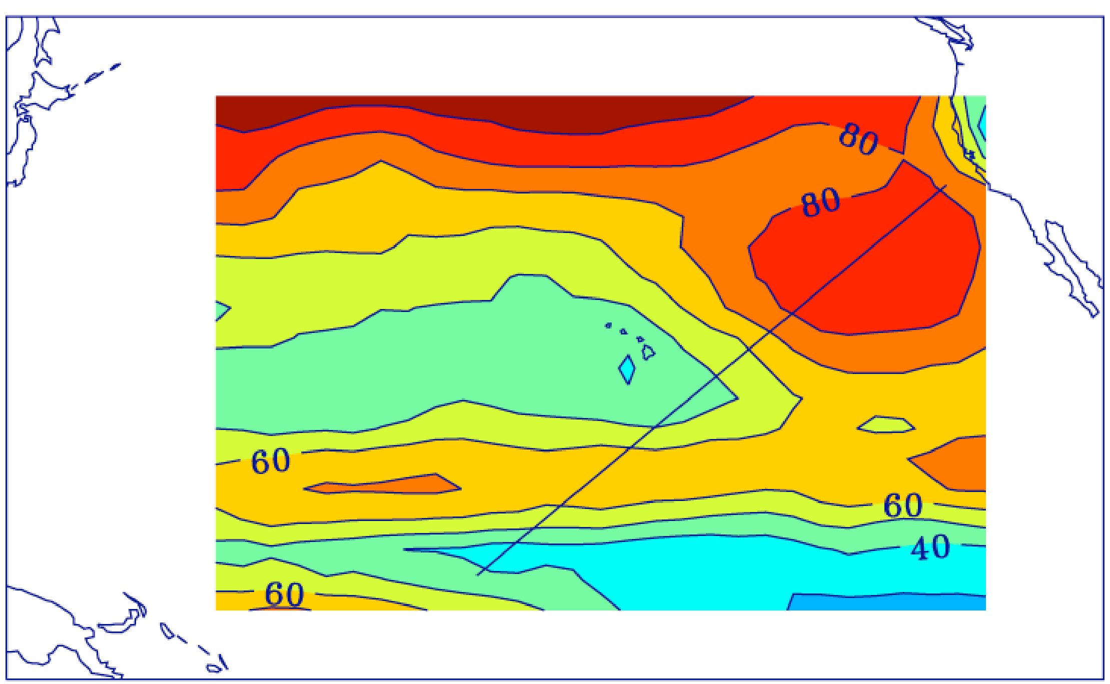
CAM3



MMF



ISCCP



Which simulation is better?

Concluding Remarks

- GCRMs and MMFs make it possible for cloud observers and GCM developers to compare apples with apples.
- When something doesn't work in a GCRM or an MMF, we can "look inside" to see how the simulation compares with observations.
- Focused efforts are under way to develop improved parameterizations for cloud-resolving models.
- Focused efforts are under way to develop a radically improved second-generation MMF.
- GCRMs are just appearing, but have a bright future.