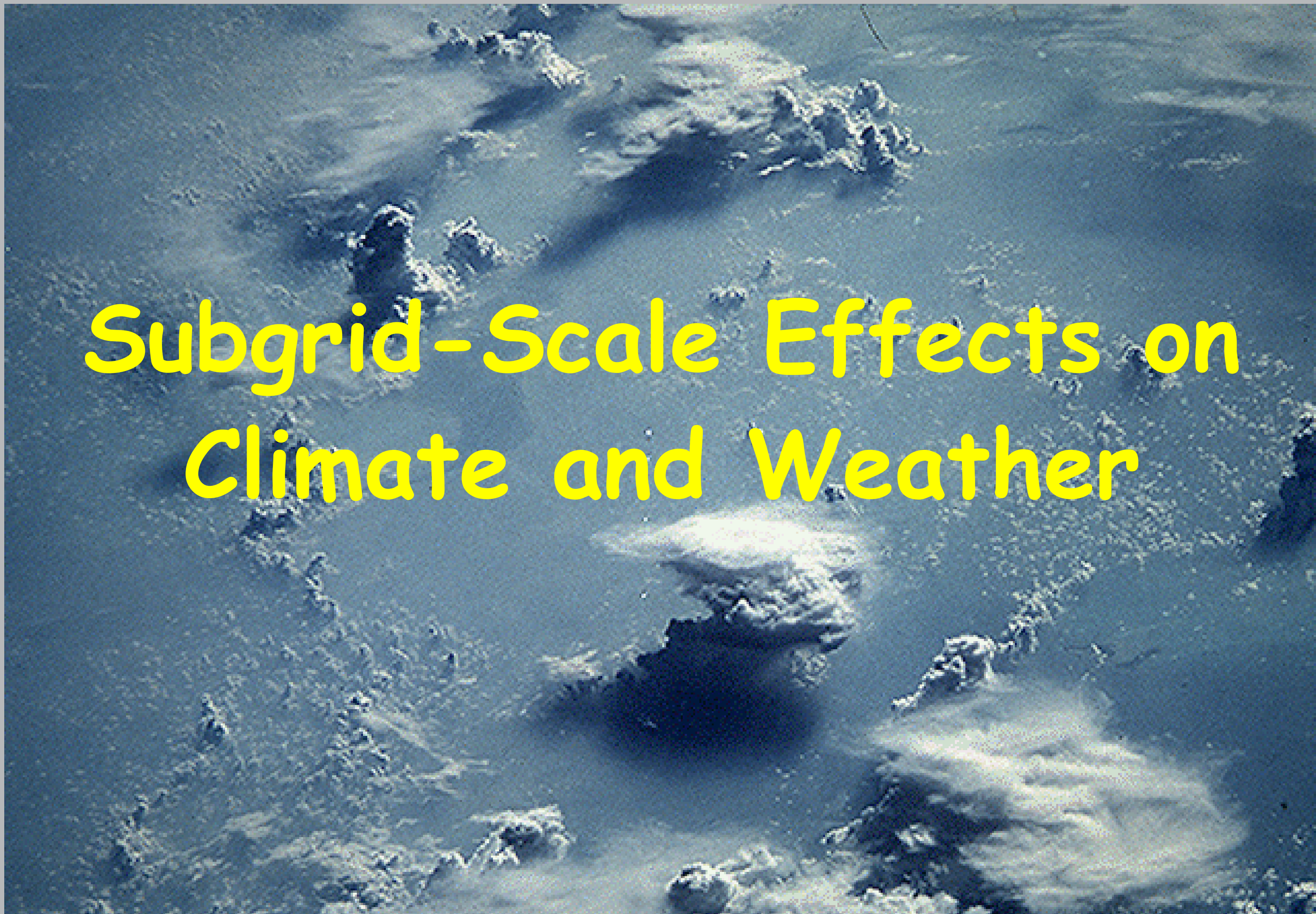
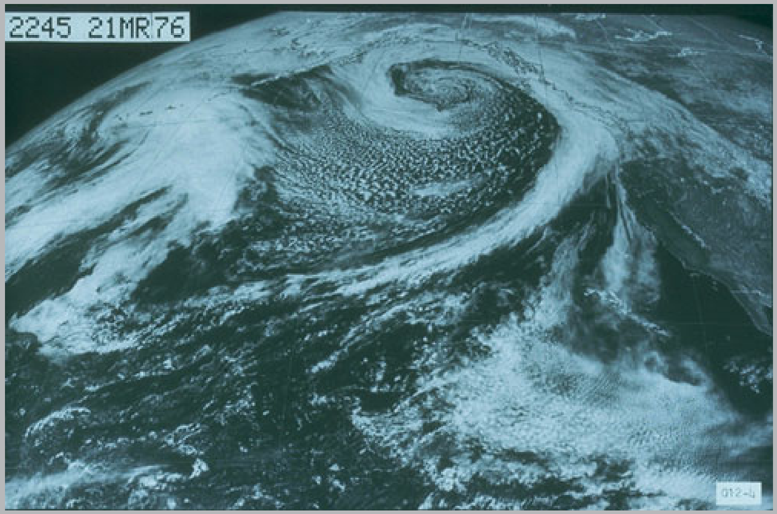
Subgrid-Scale Effects on Climate and Weather



The problem that will not die

Deficiencies in the representation of *cloud-dynamical* processes in climate models drive much of the uncertainty surrounding predictions of climate change.



This was true 30 years ago, it's true now, and at the rate we are going it will still be true 30 years from now.

What are we doing about this?

What can we do about this?

What is a parameterization? (1)

The basic physical equations describe the behavior of the atmosphere on small scales.

From these we derive equations describing the behavior of the system on larger scales.

The equations that govern the large scale contain terms that represent the effects of smaller-scale processes.

What is a parameterization? (2)

A parameterization is a “parametric representation” of the effects of small-scale processes on large-scale processes, formulated in terms of large-scale processes only.

Control

Large-scale processes → Small-scale processes

Small-scale processes → Large-scale processes

Feedback

Parameterizations are physically based as far as possible, but involve uncertain “closure assumptions” that cannot (for now) be fully derived from the (known) basic physical equations that describe the behavior of the system on fine scales.

Irony

Even though the basic equations describe the small-scale processes, in practice it is the small-scale processes that are incorporated through the use of uncertain closure assumptions.

We try to represent the small-scale processes without using the (known) equations that govern them. We try to solve the problem with our hands tied behind our backs.

Why do we develop parameterizations?

- ***Science.*** **For many of us, parameterization is an end in itself. It is a beautiful problem and a fascinating challenge.**

  Our ability to parameterize *measures our understanding* of the interactions among diverse scales of motion. To parameterize is to "explain."

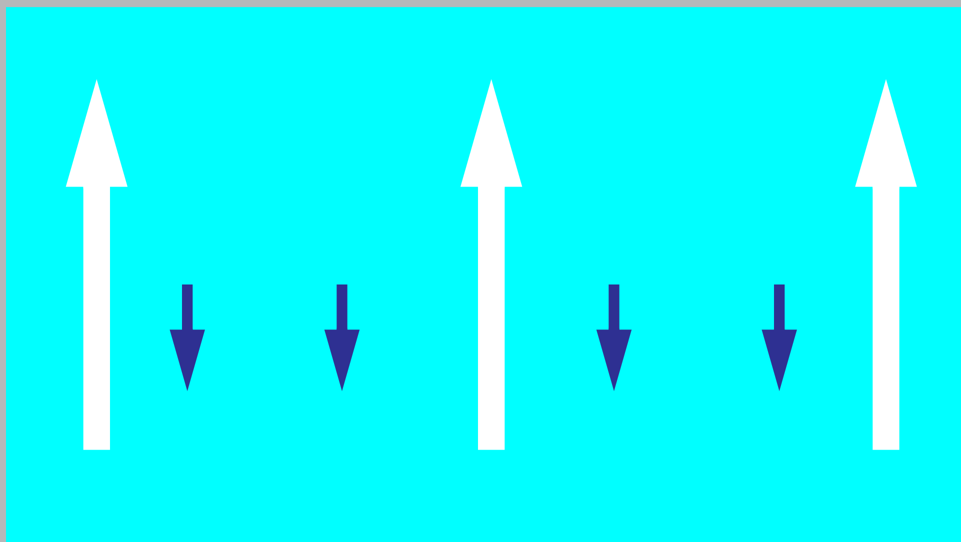
- ***Engineering.*** **We lack the computer power to perform direct simulations of all of the important scales of motion. There are large and influential communities for whom parameterizations are merely tools that are needed so that models can generate *quantitatively accurate* answers to questions.**

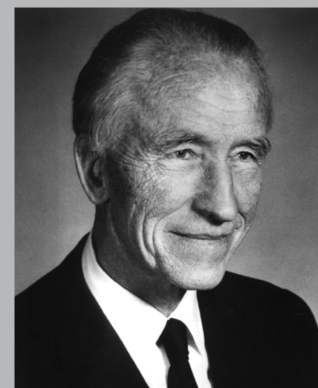
Will the Earth's climate become warmer? How much? When?

Will it rain in Santa Monica today? How much? When?

In the beginning there were hot towers

Bjerknes (1938) taught us that cumulus convection prefers to organize itself in the form of narrow, strong updrafts embedded in a broad, slowly subsiding environment.





Riehl and Malkus (1958) deduced from observations that such hot towers play an essential role in the vertical transport of energy.

"The environment"

Bjerknes conclusion that the convective updrafts must occupy a very small fraction of a "large-scale" area implies that the thermodynamic properties of the slowly subsiding environment are very nearly the same as those of the large-scale mean.

This idea has been extensively used in cumulus parameterizations based on the mass-flux concept, first developed by Akio Arakawa and colleagues in the 1960s and 70s, and now ubiquitous.

Hot towers and cold showers

Some of the precipitation formed in convective towers falls through unsaturated air adjacent to the towers. As it evaporates, this precipitation cools and moistens the environment.

Evaporative cooling and precipitation loading drive convective-scale downdrafts, which further cool and moisten the environment.

Parameterizations of these effects have been proposed by Johnson, Cheng and Arakawa, and others.

Stratiform clouds

In 1960, Smagorinsky proposed a parameterization of stratiform cloudiness based on relative humidity. The mechanics of cloud formation were not addressed.

Following Smagorinsky, early parameterizations of stratiform clouds were formulated in terms of "large-scale saturation," still without addressing the specific mechanisms of cloud formation.

Convectively generated stratiform clouds

Arakawa and Schubert (1974) proposed a cumulus parameterization that explicitly recognized convective detrainment of condensed water as a source of stratiform clouds. This cloud formation “hook” went un-used for more than a decade.

During the 1970s and 80s, cumulus parameterizations were tested without accounting for the effects of attendant stratiform clouds.

Predicting condensed water

Following the lead of Sundqvist, large-scale modelers began to predict the spatial distribution of condensed water, during the 1980s and 90s.

Most of these models now include an explicit convective source term for the condensed water of stratiform clouds, using the hook put in place by Arakawa and Schubert almost thirty years ago.

Tiedtke (1993) developed a comprehensive parameterization that includes a prognostic equation for cloud area, in addition to prognostic condensed water. Cumulus detrainment acts as a source of both condensed water and cloud area.

Prognostic cloud parameterizations have led to major improvements in both NWP scores and climate simulations, and are now widely used. This is progress.

Mesoscale organization

Meanwhile, everybody knows that the mesoscale is out there.

Two views of the mesoscale

- Houze and colleagues emphasize anvil precipitation and anvil vertical motions. The mesoscale system is viewed a thermodynamically active extension of the cumulus system.

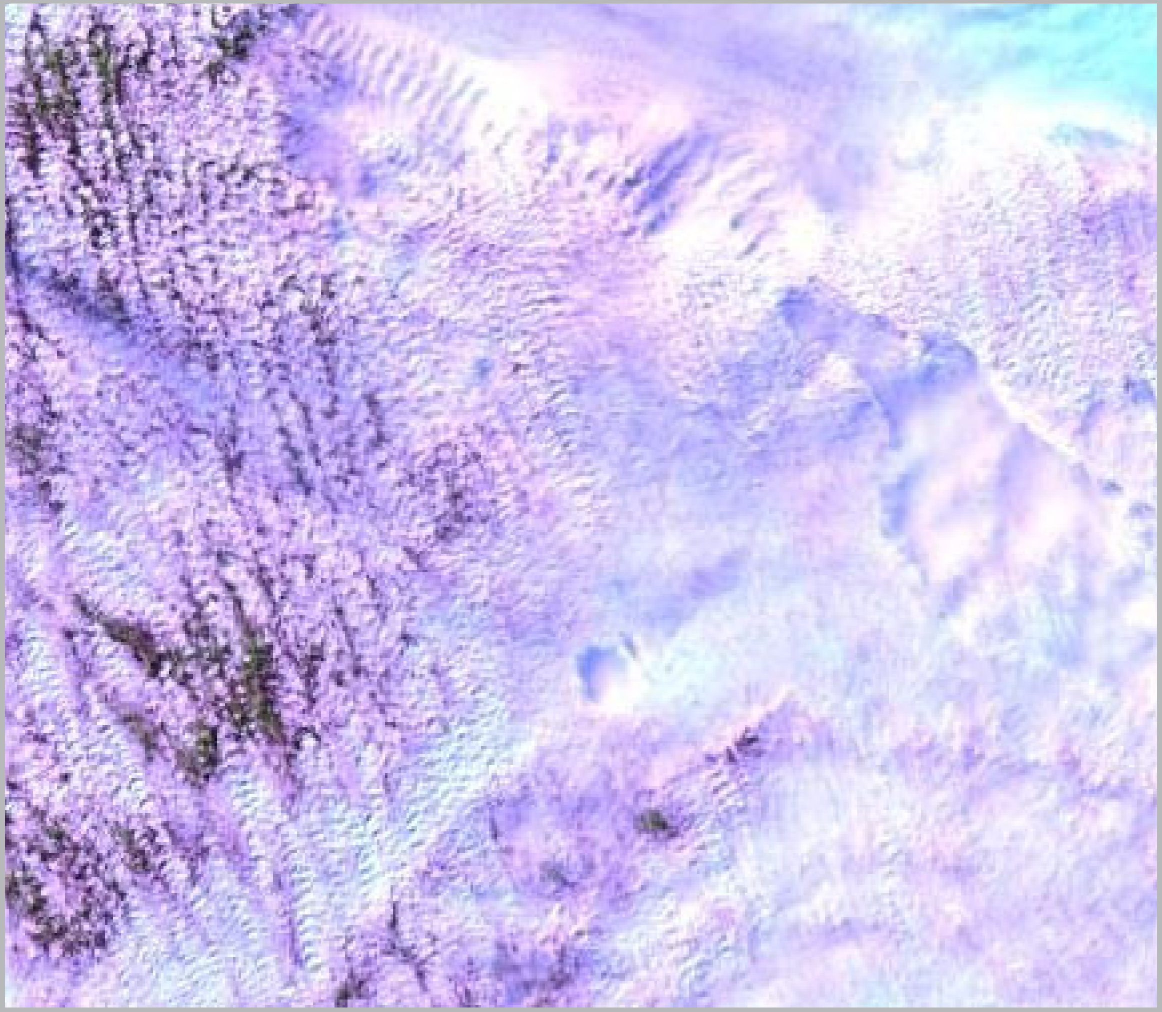
- Moncrieff and colleagues emphasize the dynamical organization of mesoscale systems, including their momentum fluxes and their geometrical structures.

The reality includes both sets of phenomena (and more).

GCMs are just beginning to include these processes.

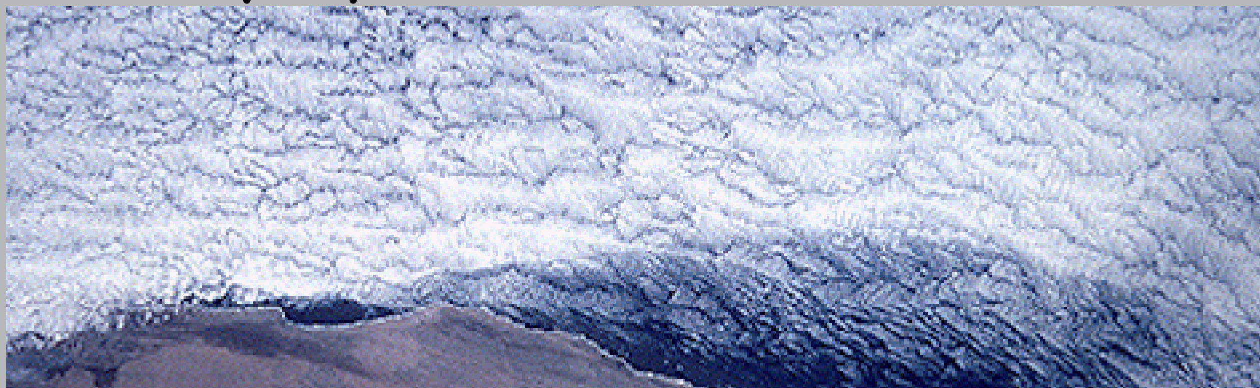
Virtually all clouds are turbulent

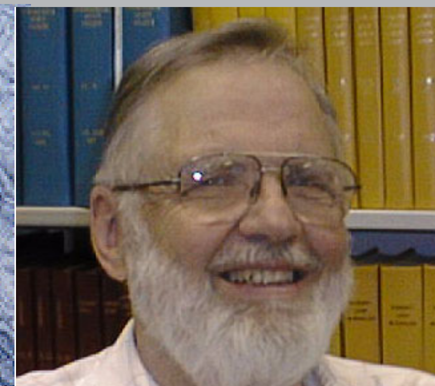
Turbulence is one of the most important processes influencing fractional cloud cover.



Turbulence and radiation

Lilly (1968) recognized the tight interactions among cloudiness, turbulence, and radiation, in his classic study of boundary-layer clouds.





A few GCMs are incorporating Lilly's ideas now, still for boundary-layer clouds. *This means coupling parameterizations together, making the models less modular. GCMs should be as modular as possible, but not more so.*

Turbulence-radiation interactions are also at work in most other types of clouds, e.g. cirrus, but large-scale models do not yet take this into account.

Microphysical processes

Microphysical processes include precipitation falling through lower-level clouds (“microphysical overlap”).

Microphysical processes closely interact with dynamical processes, e.g. through the formation of downdrafts.

The properties of the cloud particles are strongly influenced by the ambient aerosols, which in turn depend on chemical processes in the atmosphere.

Microphysics and radiation

The radiative transfer problem has now been "solved" in the sense that accurate radiative fluxes can be computed, even for cloudy skies, given accurate input.

The required input is the main issue. **It includes information about cloud geometry (e.g. "radiative overlap") and about the nature of the cloud particles.**

Overwhelming complexity

- Convective updrafts and downdrafts
- Mesoscale anvils and mesoscale dynamical systems
- A slowly subsiding environment
- Tightly coupled radiative and turbulent processes
- Strong dependence of radiation on microphysical parameters
- Cloud overlap in the radiative and microphysical senses.
- Aerosol effects

Some of the weaknesses of current parameterizations

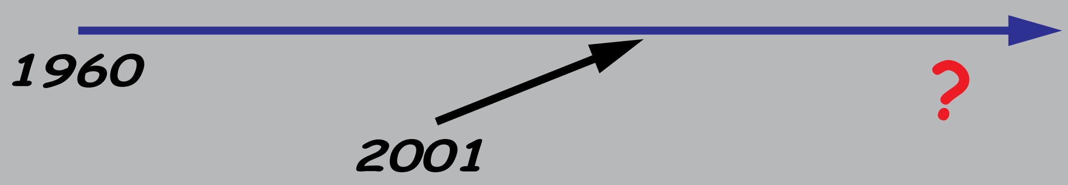
- Interactions of deep convection with the boundary layer are drastically oversimplified in all cases.
- Fractional cloudiness, cloud radiative overlap, and cloud microphysical overlap are inadequately represented.
- Coupling of radiative, turbulent, and microphysical processes is mostly ignored.
- Mesoscale organization is completely ignored in most cases.
- Convectively generated gravity waves are ignored in almost all cases.
- Cloud microphysical processes are oversimplified.

Parameterizability

Can we really parameterize all of this complexity with quantitative accuracy?

Well maybe, but it's going to take another 100 years.

We have already been working on it for about 40 years, and we are still in the early stages of the project.

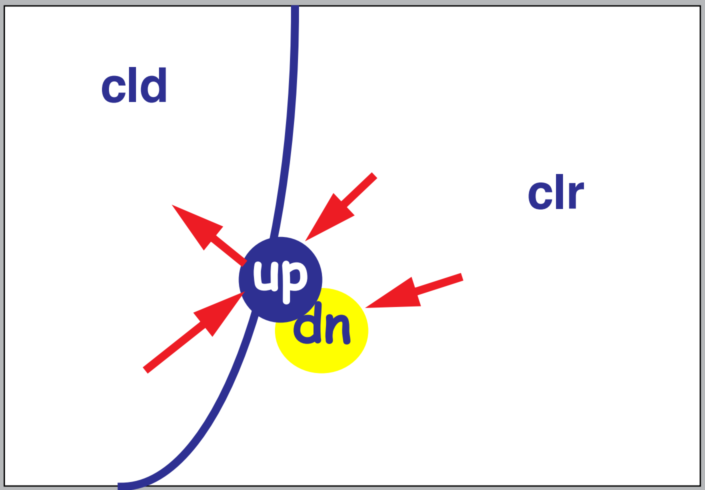


"Cloud parameterization is a very young subject."

-- Akio Arakawa
December 2001

Sketch of a current approach

(An extension of Tiedtke's parameterization)



Convective updrafts and downdrafts coexist with a partly cloudy environment.

The clear and cloudy regions have different thermodynamic properties and different vertical velocities. The cloudy region is turbulent, while the clear region is not.

How can we implement this?

- **Lots of prognostic variables representing subgrid-scale variability on multiple scales:**

Water vapor and temperature in clear and cloudy regions

Cloud water and cloud ice mixing ratios in cloud

Fractional area covered by stratiform cloud

Rain and snow mixing ratios

Cumulus mass flux

Mesoscale mass flux

Turbulent fluxes, variances, etc., in multiple regions

- **Closure assumptions:**

Joint probability distributions have particular shapes

Mixing between (or within) subdomains occurs in particular ways

Two measures of complexity

- **Numerical complexity.** A parameterization of the type outlined above can easily include as many prognostic degrees of freedom as a high-resolution cloud model. What to leave in? What to leave out?

- **Conceptual complexity.** The parameterization outlined above is *conceptually more complicated* than a high-resolution cloud model, in that we substitute a statistical theory (closure assumptions, etc.) for the relatively straightforward governing equations of a cloud model.

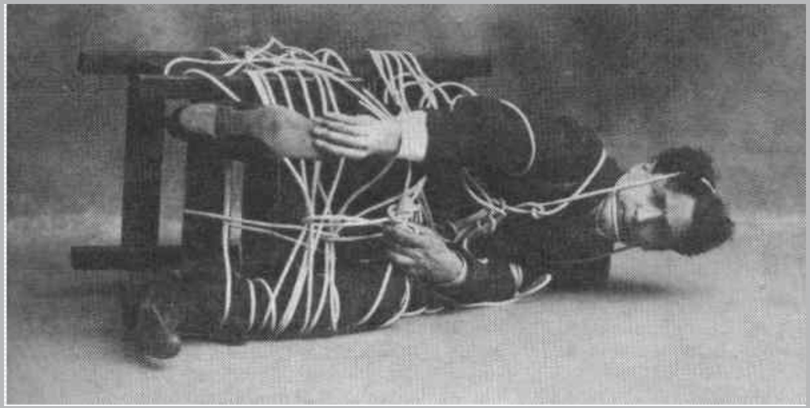
  To "explain" is to deduce complicated specifics from simple general principles. The more complicated a parameterization is, the less it can explain.

Can we really parameterize these complex phenomena with quantitative accuracy?

We may hope that it is possible to make a parameterization that is much more realistic than what we have today, but not much more complicated (in the numerical and/or conceptual senses).

There is no guarantee that this is possible.

I doubt that it is possible.



Enter an important new tool:
Cloud-system-resolving models

CSRMs are “Cloud-System Resolving Models,” with resolutions fine enough to represent individual cloud elements, and space/time domains large enough to encompass many clouds over many cloud lifetimes. CSRMs can be driven by observations of large-scale weather systems.

SCMs are “Single-Column Models,” which are the column-physics components of GCMs, surgically extracted from their host GCMs and driven by observations of large-scale weather systems.

GCM

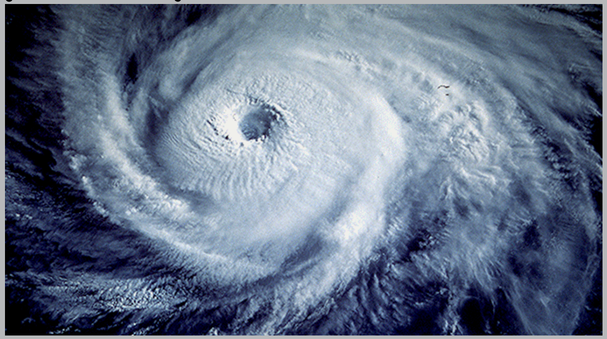
Simulated large-scale dynamics $\rightleftarrows$ Parameterizations

SCM/CSRM

Observed large-scale dynamics $\rightarrow$ Parameterizations or CSRM

Background on CSRMs

The earliest CSRM was developed by Yamasaki during the 1970s, to study tropical cyclones.



Krueger, Arakawa, and Xu began applying CSRMs to the parameterization problem in the mid 1980s.

Today there are dozens of CSRMs, at various centers around the world.

Until recently CSRMs were 2D in order to limit the computational expense, but with today's computers 3D CSRMs are quite practical for many applications.

How can we use CSRMs?

- To develop parameterizations

No

- To confront models with data in order to answer some of the questions about parameterizations (*e.g.*, “Is this assumption right?”)

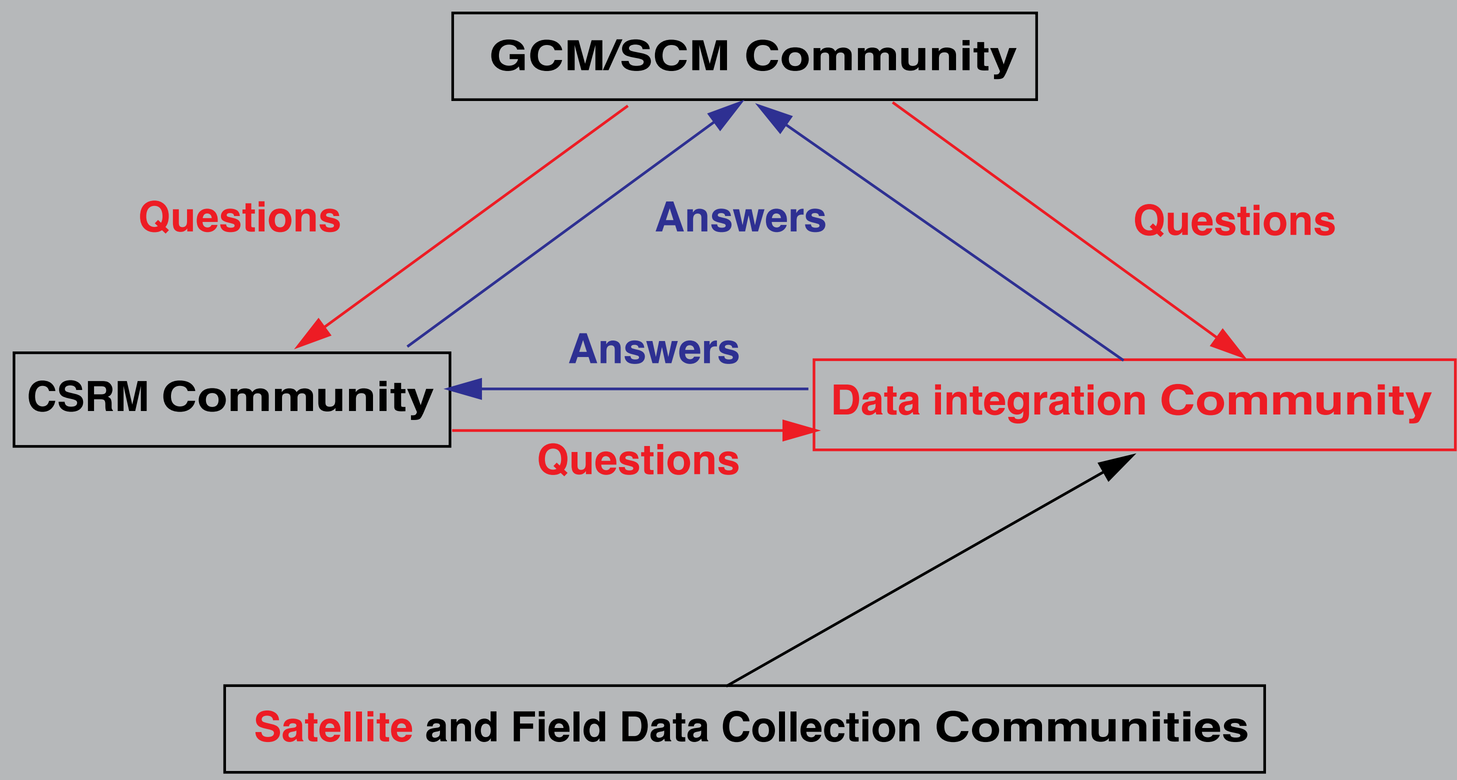
Yes

- To compute detailed answers to idealized questions

Yes

- Anything else?

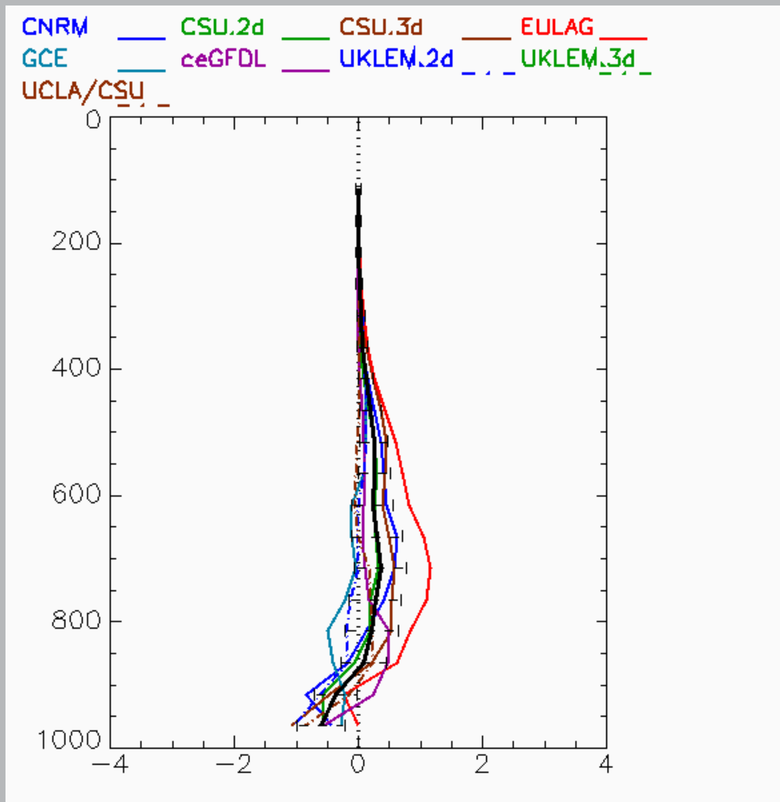
The GCSS Process

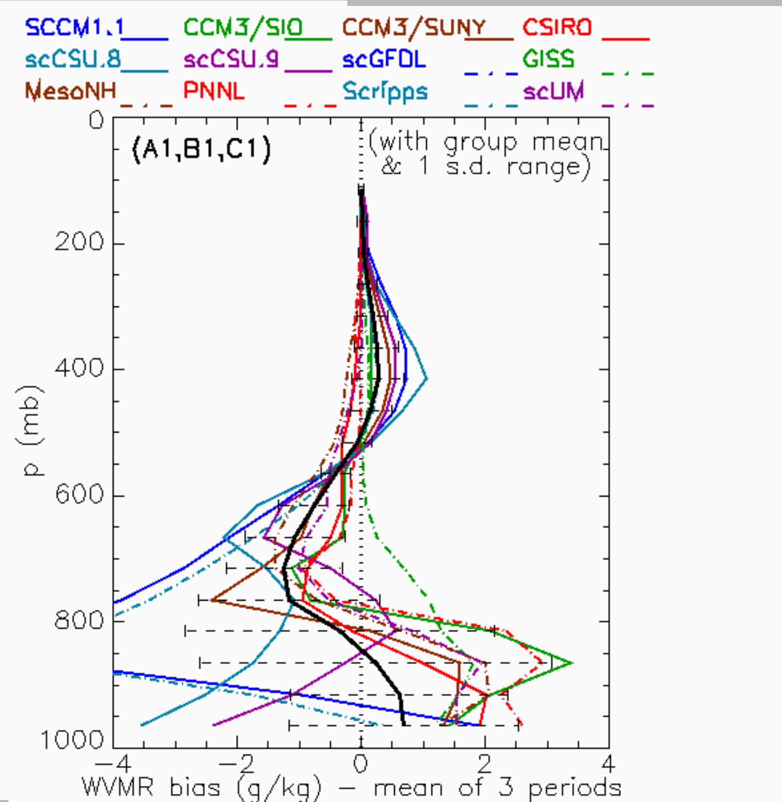


CSRMs give better results than SCMs

One would hope so, considering that the computational cost of running a CSRM is hundreds or thousands of times greater than that of running an SCM.

GCSS and ARM have actually *demonstrated* that CSRMs give better results than SCMs, through a number of case studies.

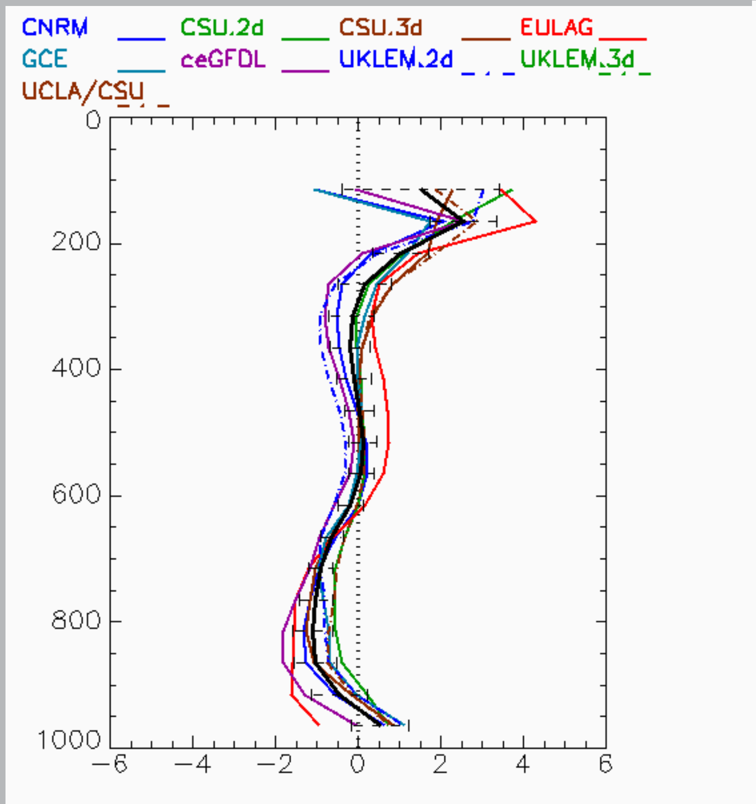


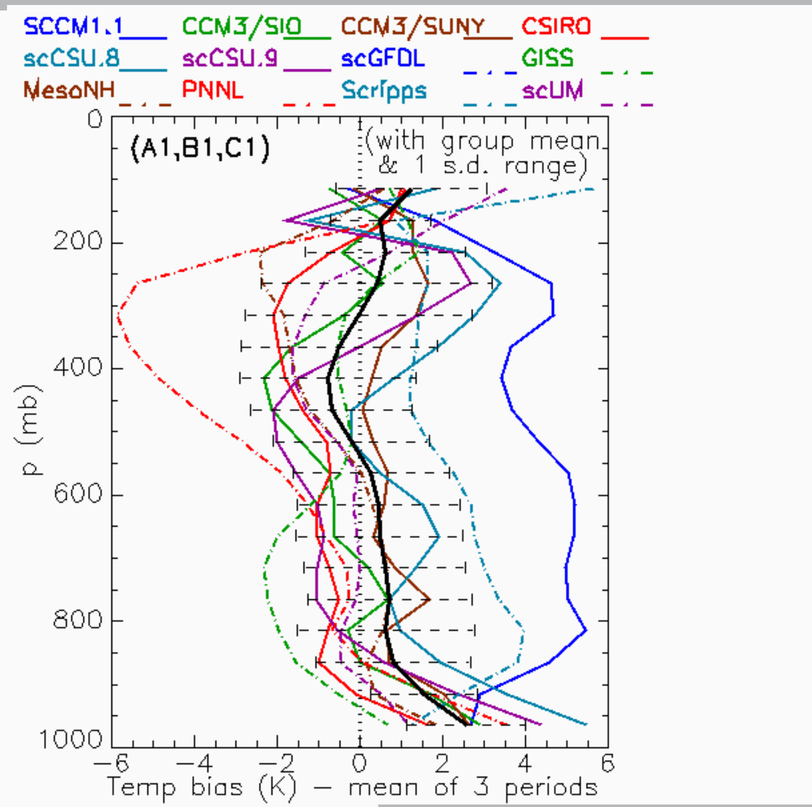


CSRMs

SCMs

Water vapor

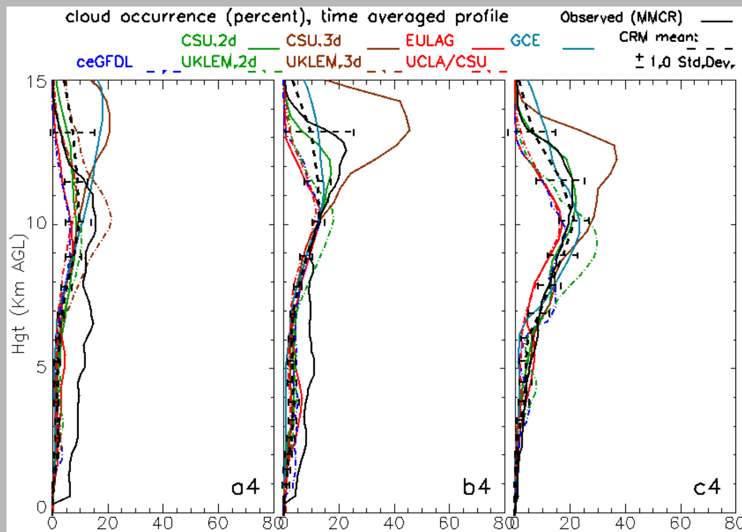


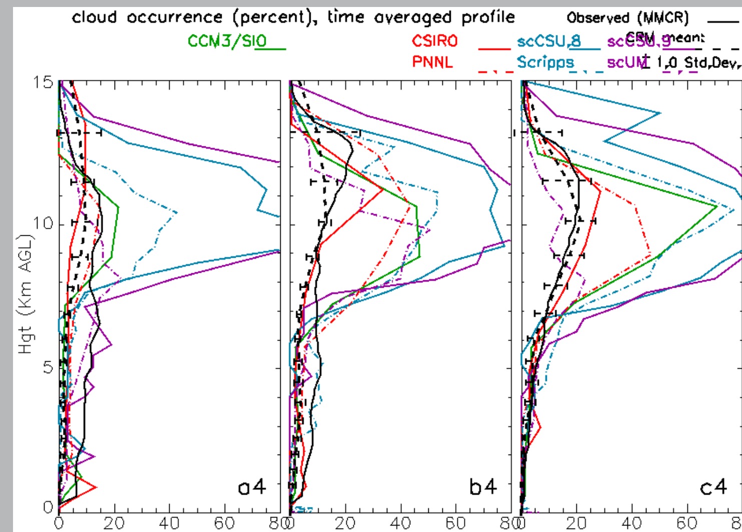


CSRMs

SCMs

Temperature





CSRMs

SCMs

Cloud occurrence

Blackbird:Users:randall:UCLA_IPAM:UCLA_IPAM.frame

Too bad we can't run a global CSRM

Existing climate simulation models typically have fewer than 10^4 grid columns, averaging about 200 km wide.

A global model with grid cells 2 km wide would have about 10^8 grid columns. The time step will have to be roughly 100 times shorter than in current climate models.

> In a few more decades such global CSRMs will become possible.
>
> This may solve the engineering problem.
>
> It may also help us to solve the scientific problem, which we will still be working on.

There is another approach, however...

Super-Parameterizations

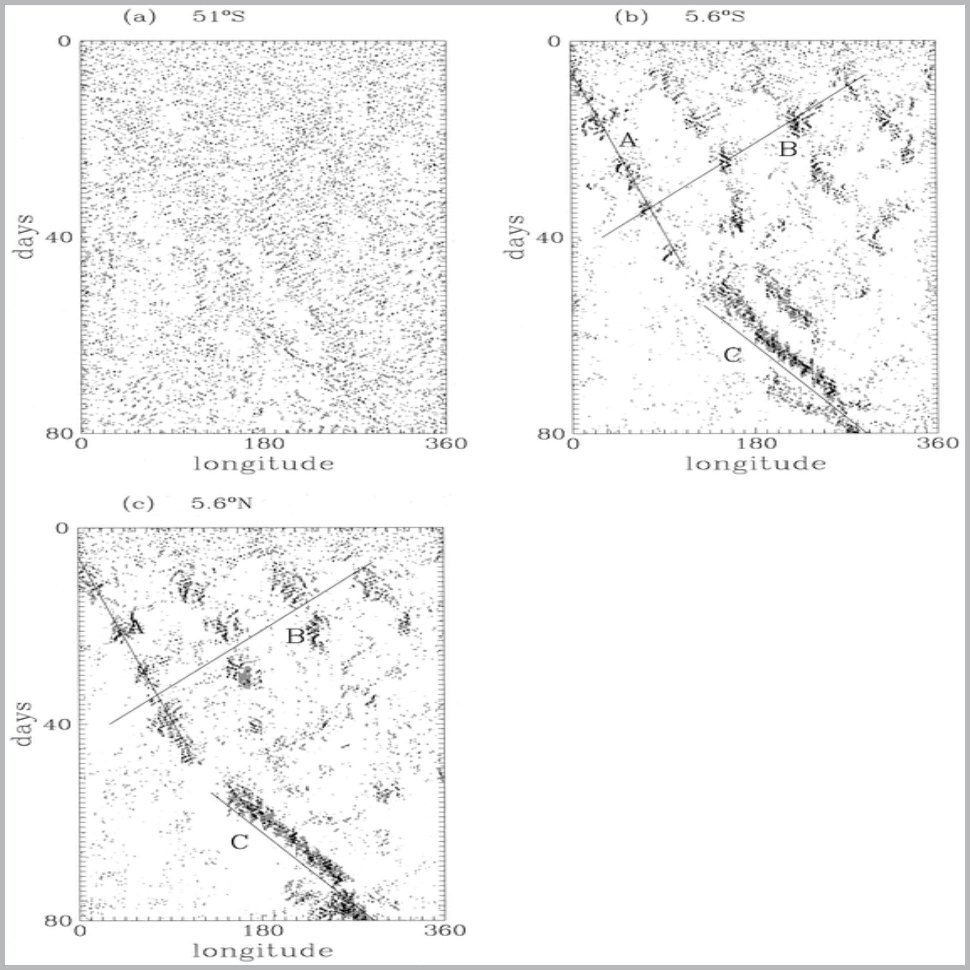
We can run a CSRM as a "super-parameterization" inside a GCM.

Wojciech "W" Grabowski of NCAR implemented a 2D CSRM inside a simplified global model with globally uniform SSTs, no mountains, etc.

Each copy of the CSRM represents a "sample" of the volume inside a GCM grid column.

Statistics computed using the CSRM are based on this "sample," in much the same way that statistics from an opinion poll are based on interviews with a sample of the population.

W obtains results that look physically realistic, e.g. a tropical MJO.



And so, inspired by W's idea...

Marat Khairoutdinov of CSU has embedded his 2D CSRM as a super-parameterization in the atmosphere sub-model of the Community Climate System Model (the "CAM" for short). This global model has realistic topography, SSTs, etc.

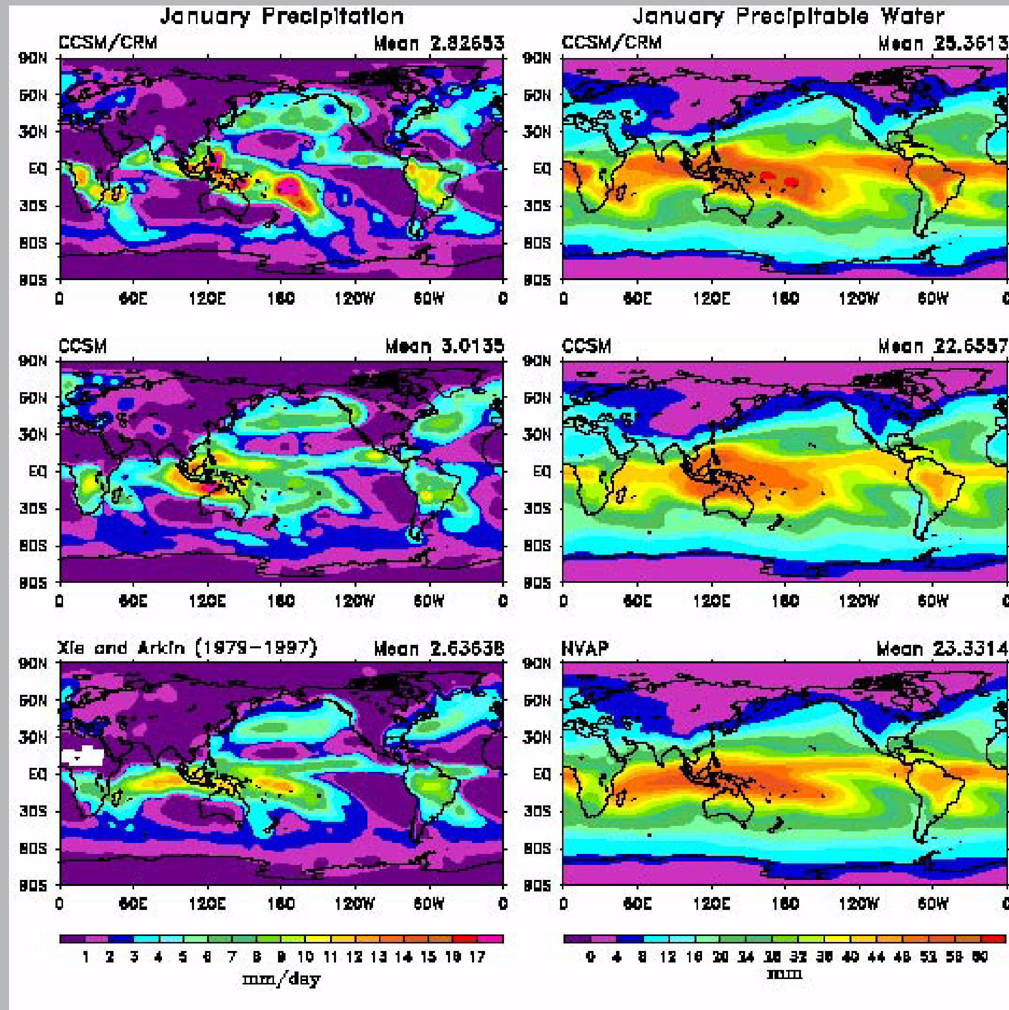
The CSRM takes the place of the stratiform and convective cloud parameterizations, and in the future will also replace the PBL parameterization.

Tests in the T42 CAM (GRL, 2001)

Super Param

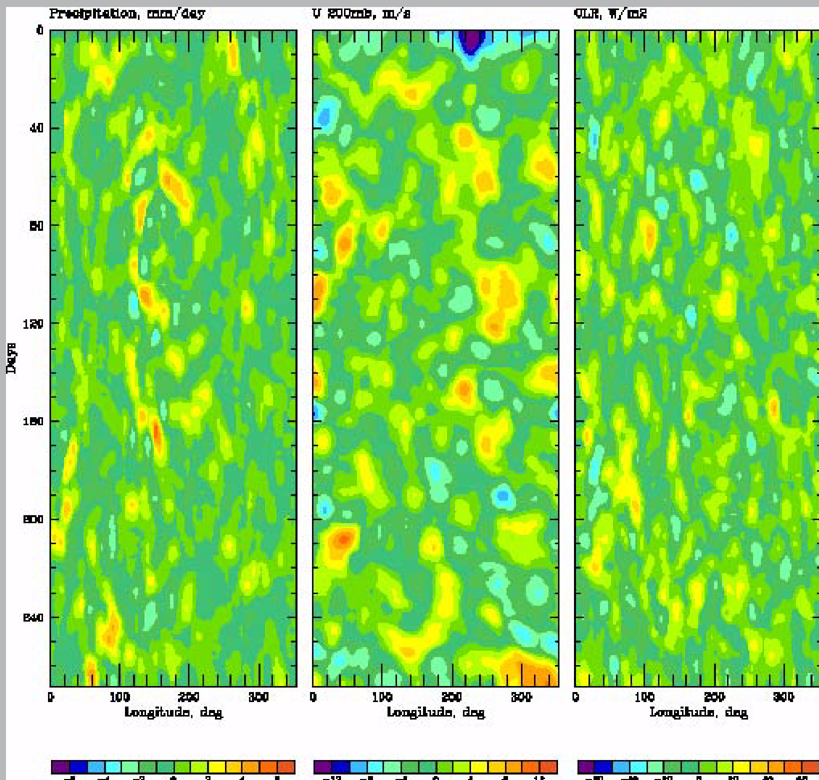
Control

Obs

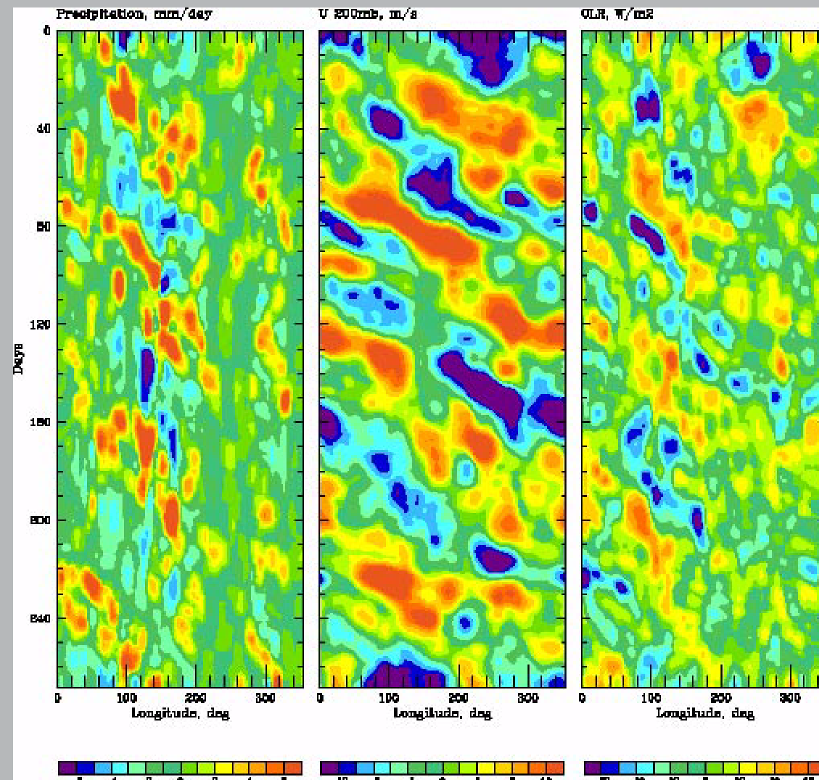


An MJO in the T21 CAM

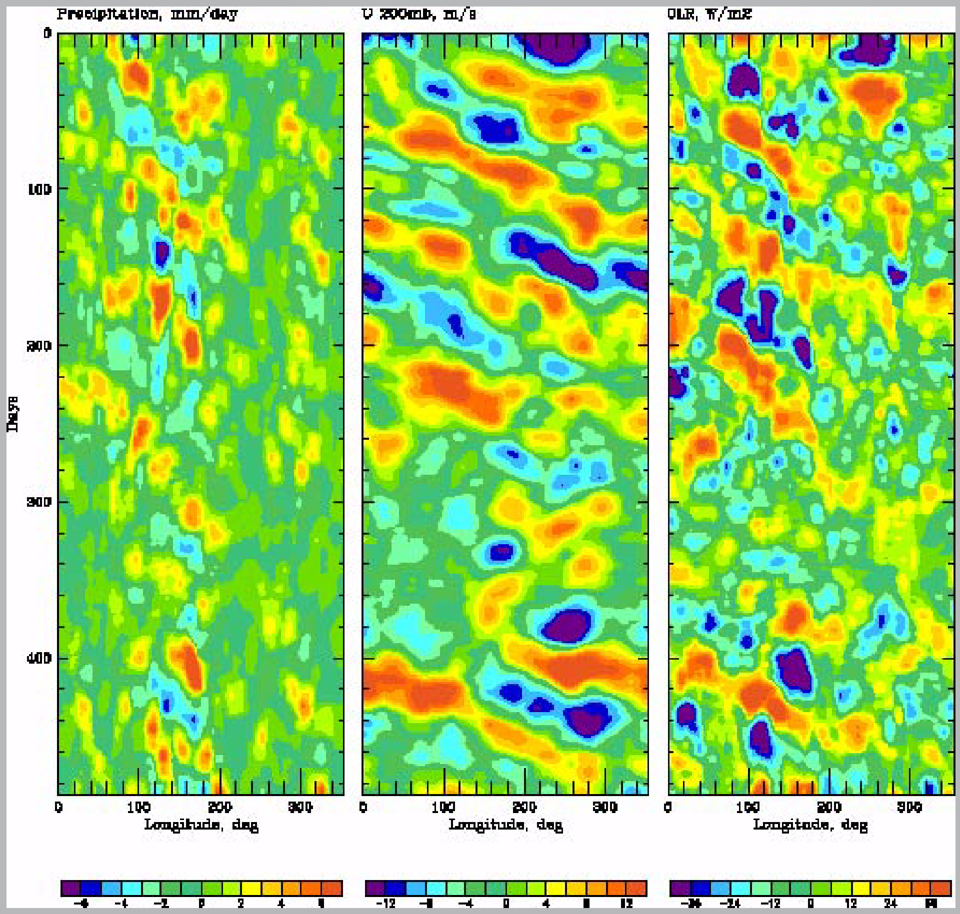
Control

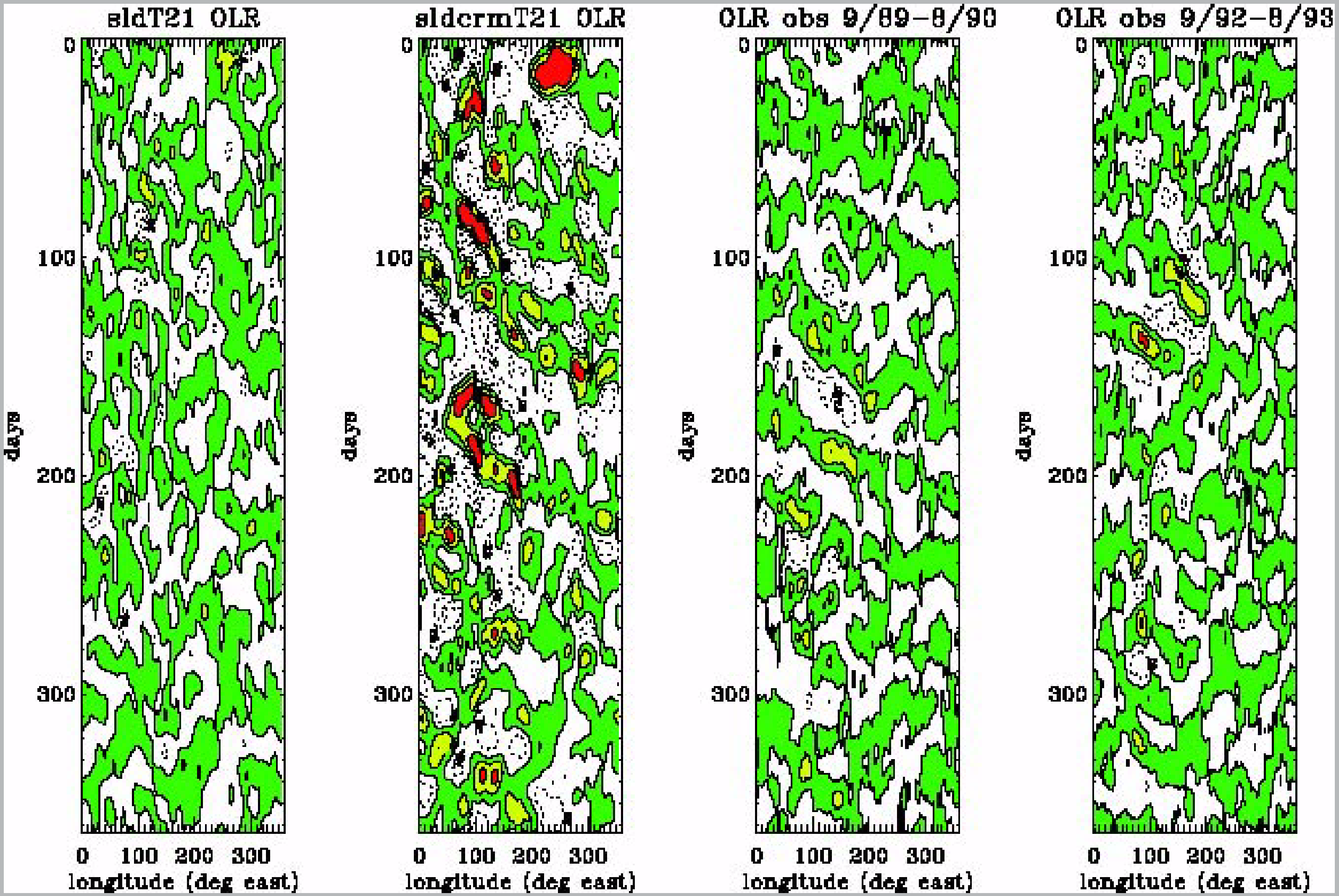


Experiment



Seasonal change...





sldT21 OLR
sldcrmT21 OLR
OLR obs 9/89-8/90
OLR obs 9/92-8/93
days
0
100
200
300
0 100 200 300
longitude (deg east)

What are we claiming?

- Results to date suggest that super parameterizations can enable more realistic simulations of important climate processes such as the MJO. Much more work is needed.

- We have demonstrated, by example, that super-parameterizations can be incorporated into GCMs with a modest effort. Much more work is needed to define the best approach.

- There are many *a priori* reasons to believe that super parameterizations can provide more realistic and more reliable simulations of climate.

What do we get? (1)

- Explicit deep convection, including mesoscale organization (e.g., squall lines), downdrafts, anvils, etc.
- Explicit fractional cloudiness
- Explicit cloud overlap in the radiative sense
- Explicit cloud overlap in the microphysical sense
- Convective enhancement of the surface fluxes
- Possible explicit 3D cloud-radiation effects

What do we get? (2)

- Convectively generated gravity waves

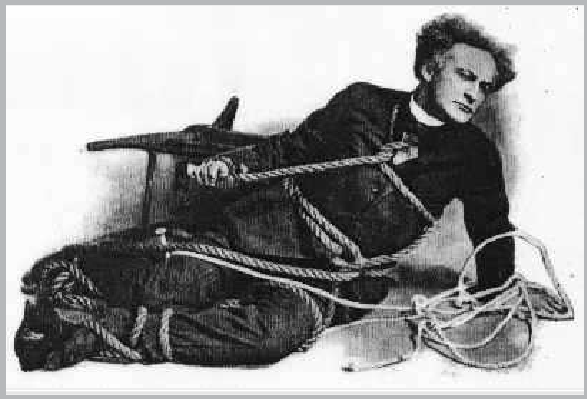
  Most of these benefits are valuable even in undisturbed weather regimes. Super parameterizations are not just for severe weather.

- The ability to compare global model results on the statistics of mesoscale and microscale cloud organization with observations from new platforms such as CloudSat

- The ability to assimilate cloud statistics based on high-resolution observations

What do we get? (3)

- The hybrid model can be used to generate more realistic simulations of climate, albeit at much higher cost.
- Results from the hybrid model can be compared with results from the same GCM run with conventional parameterizations.



What problems don't go away?

- Microphysics must still be parameterized.

  But the problem is more tractable with explicit cloud elements?

- Radiative transfer must still be parameterized.

  But some aspects of the problem are drastically simplified as already noted.

- Turbulence and small-scale convection must still be parameterized.

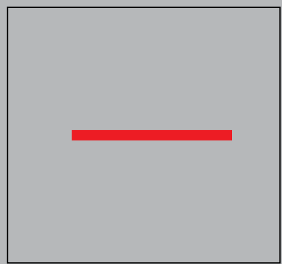
  But high resolution facilitates this too.

- Issues related to the numerical simulation of large-scale dynamics still remain.

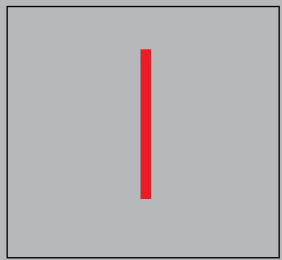
Issues (1)

- Consistency between the GCM and the CSRM?
- Communications between the GCM and the CSRM?
- Lower boundary conditions?
- Orientation and dimensionality of the CSRM?

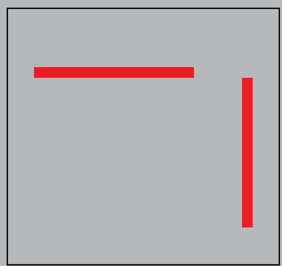
Orientation and dimensionality



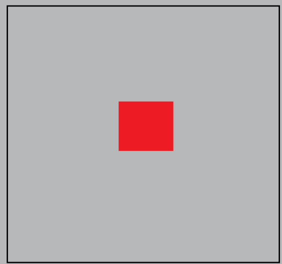
2D



Orientation?



Only a factor of 2



3D

Issues (2)

- Resolution of the CSRM?
- Lateral boundary conditions on the CSRM?
- CSRM communications *between* GCM grid columns?
- Everywhere, all the time?

and so on...

These are interesting problems.

None of them are show-stoppers.

It's only money

In our tests to date with the CAM, the embedded CSRM slows the model down by a factor of about 180.

A one-day simulation with CSRM embedded in a T42 GCM takes about one hour on 64 processors of an IBM SP.

> One copy of the CSRM takes ~30 secs per simulated day on one processor.
>
> Here we are running about ~100 copies of the CSRM on each processor.
>
> Therefore the one-day run takes about one hour per simulated day.
>
> The run time for the GCM itself is negligible.

With the configuration outlined above, a simulated century would take about four years of wall-clock time on 64 processors.

Rescued by massive parallelism

Because the CSRMs in different grid columns do not communicate, the calculation is “perfectly parallel.” Run time can be almost independent of the GCM’s resolution so long as we can keep allocating more processors.

Super-parameterizations thus provide a way to utilize more processors for a given GCM resolution -- we beat Amdahl’s Law by making the problem (a lot) bigger. Computer center directors will love it. With 1024 processors a simulated century would take about 3 months. Next year it will go twice as fast.

Ten years ago super-parameterizations would have been out of the question.

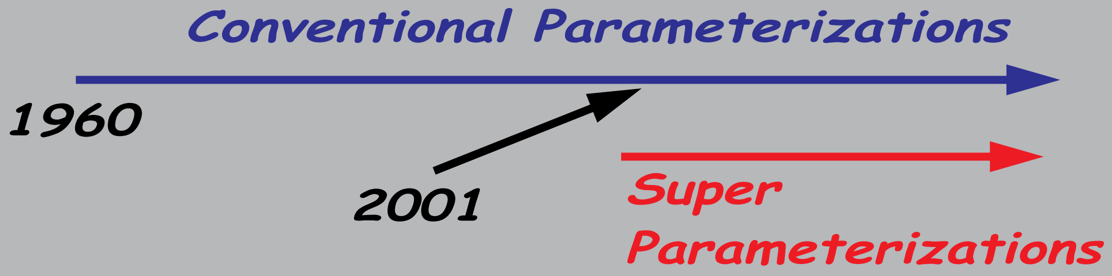
Today they are marginally possible.

By 2010 they will be very practical for some applications.

Continuing roles for conventional cloud parameterizations

- Conventional parameterizations will still be used wherever very large computing resources are not available.
- Conventional parameterizations will still be needed for very long simulations, e.g. of Milankovich cycles.
- Conventional parameterizations will still be needed as "encapsulations" of our (gradually improving) understanding of how clouds interact with the large-scale circulation.

The road
goes ever on.



And in the end

- **Conventional strategy:**

  As computer power increases, increase the global model's resolution, and alter parameterizations as necessary for consistency with the higher resolution. In 30 years or so, we arrive at a global CSRM

- **A crude alternative strategy:**

  As computer power increases over time, hold the GCM's resolution fixed, and "grow" the embedded CSRM. When the CSRM's domain size matches the GCM's grid-cell size, we have a global CSRM.

How can this approach be refined?

Summary and conclusions 1

- To take conventional parameterizations much beyond where we are now, it seems likely that we will have to make the parameterizations very, very complicated -- in some respects *more* complicated than CSRMs.

- When driven with observations, CSRMs produce much more realistic temperature, water vapor, and cloud distributions than SCMs.

- A CSRM can be used as a super-parameterization inside a GCM.

- Results to date suggest that super-parameterizations can give significantly more realistic climate simulations than conventional parameterizations do.

Summary and conclusions 2

- A GCM using a super-parameterization is two to three orders of magnitude more expensive than a GCM that uses conventional parameterizations.

- The good news is that a GCM with a super-parameterization can use thousands of processors with good computational efficiency.

- Super-parameterizations represent a distinctly new approach to climate simulation. They are not "more of the same, only better."

Climate-change simulations using a GCM with a super-parameterization are marginally feasible on today's most powerful machines, and will be much easier in just a few more years.

The cost of conducting such simulations is not out of line with the importance of the climate change problem.