The Evolution of Complexity in GCMs

Types of Complexity

- Conceptual Complexity
  - Understanding the model
  - Maintaining the code
- Coupling Complexity
  - Broad variety of components
  - Coupling of components per se
  - Realism limited by weakest component
- Numerical Complexity
  - Number of numbers
  - Analysis and visualization

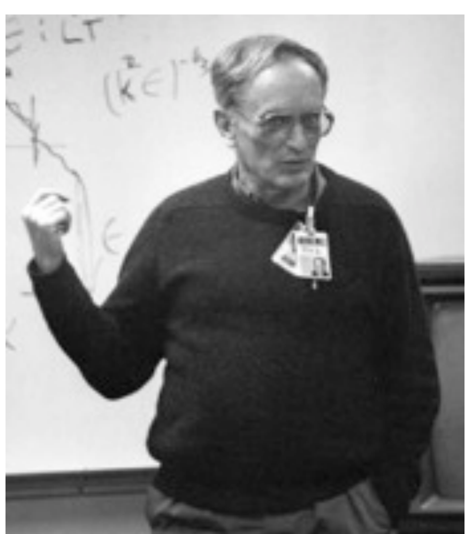
Very high-resolution models are conceptually simpler but numerically more complicated.

The Dawn of Global Modeling

Ancestral Models

- **The GFDL model**
  - **First cumulus parameterization**
  - **"Bucket" model for the land surface**
  - **Relatively high vertical resolution**
- **The UCLA model**
  - **Conservative numerical methods**
  - **Mass-flux convection**
  - **Predicted clouds**
- **The Livermore model**
  - **Short lifetime**
  - **Presssure as the vertical coordinate**
  - **Unrealistically strong horizontal smoothing**
- **The NCAR model**
  - **Height as the vertical coordinate**
  - **First version did not predict the distribution of water vapor**

The 1960s



Global modeling in the 60s

- Purely academic
- Modest funding
- Finite differences everywhere
- First coupled ocean-atmosphere model
- Early studies of predictability
- First work on data assimilation

Global modeling in the 70s

- More global modeling centers are set up
- First simulations of annual cycles
- Global NWP begins
- Vector computing
- More simulations of global warming
- “Climate simulation” usually means a perpetual January with prescribed SSTs
- Cloud feedbacks are identified as a key issue
- Satellite data increases in importance for both NWP and climate model evaluation

During the 1980s

Hilding Sundqvist argues for predicting cloud water and ice.

Coupled ocean-atmosphere models become more mature.

The CCM is born.

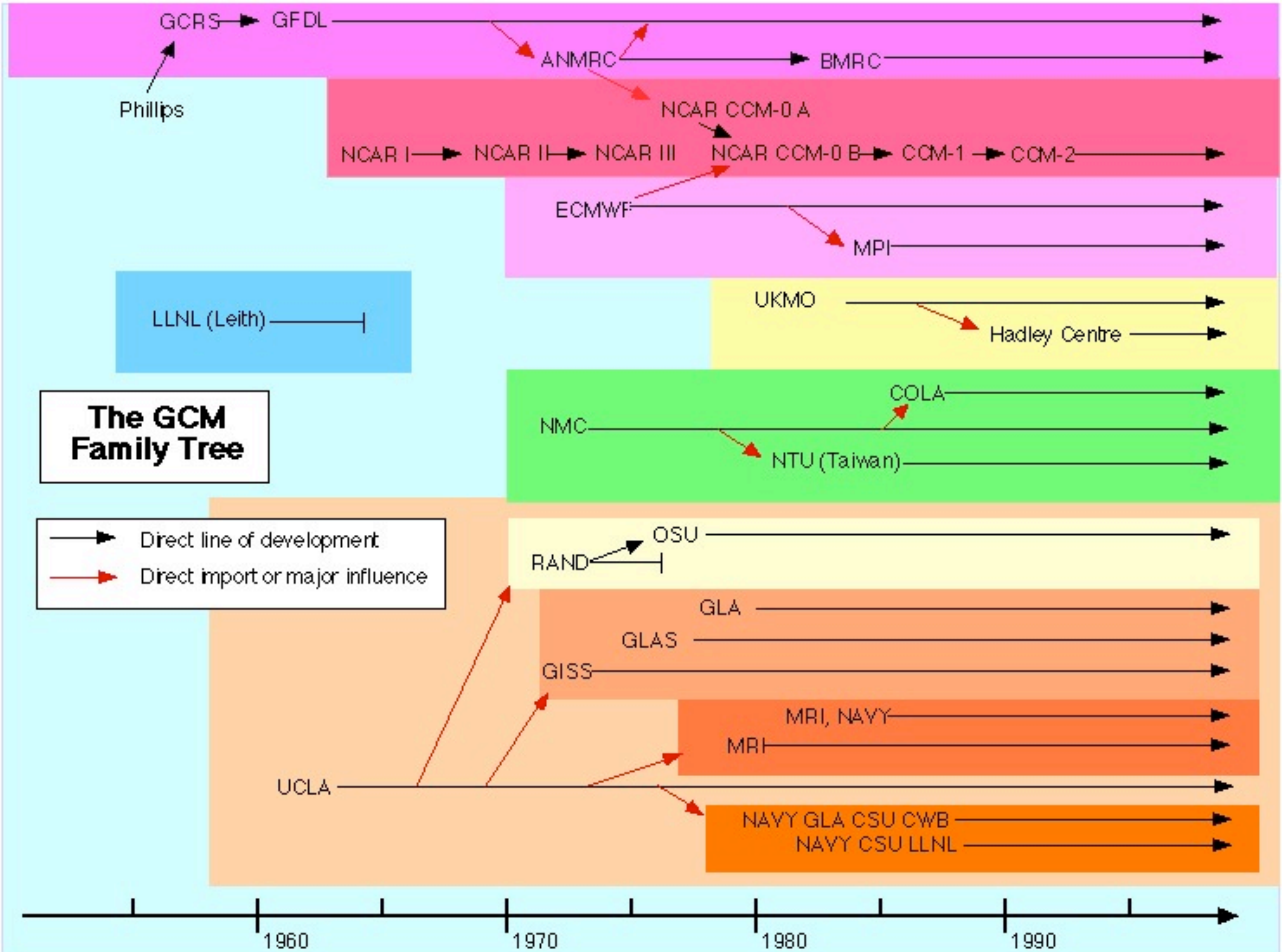
Global warming becomes a political cottage industry.

Land-surface modeling gets a higher profile.

The spectral method becomes popular.

The Earth's radiation budget gets more attention.

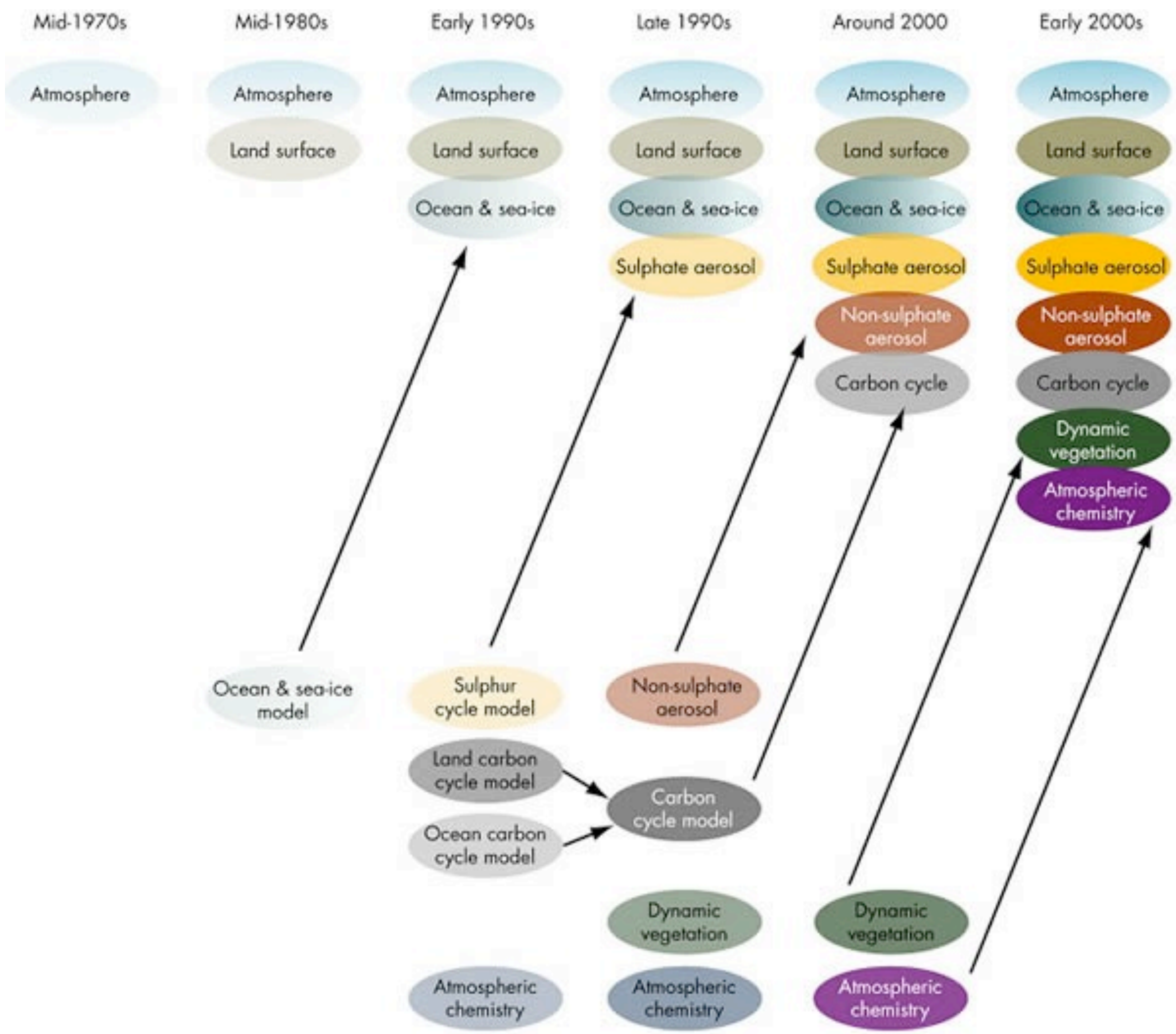
True climate simulation begins.


GCRS
GFDL
ANMRC
BMRC
Phillips
NCAR CCM-0 A
NCAR I
NCAR II
NCAR III
NCAR CCM-0 B
CCM-1
CCM-2
ECMWF
MPI
LLNL (Leith)
UKMO
Hadley Centre
The GCM Family Tree
COLA
NMC
NTU (Taiwan)
Direct line of development
Direct import or major influence
OSU
RAND
GLA
GLAS
GISS
MRI, NAVY
MRI
UCLA
NAVY GLA CSU CWB
NAVY CSU LLNL
1960
1970
1980
1990

Global modeling in the 90s

- The Age of Intercomparison begins
- Reanalysis gets under way
- Semi-Lagrangian advection becomes popular
- Parameterization testing becomes organized
- The carbon cycle gets attention
- Aerosols become widely appreciated
- The IPCC begins its work
- Operational seasonal prediction with coupled models begins
- Global modeling goes corporate

Broader and Deeper (?)



Global modeling in the 00s

- Massively parallel computing
- Very-high-resolution global models
- Carbon feedbacks
- Ice sheets

Dynamics

- Governing equations
- Horizontal, vertical, and temporal
- Spectral vs. finite-difference (F ➳ S ➳ F)
- Vertical coordinate
- Accuracy (a very vague concept)
- Stability
- Computational modes
- Conservation
- Speed
- Simplicity

Parameterizations Increase Conceptual Complexity

The fundamental principles of fluid dynamics, radiative transfer, etc., are relatively simple. They apply locally, at a point.

Because of limited computer resources, AGCMs are formulated to describe averages over finite volumes -- not at points.

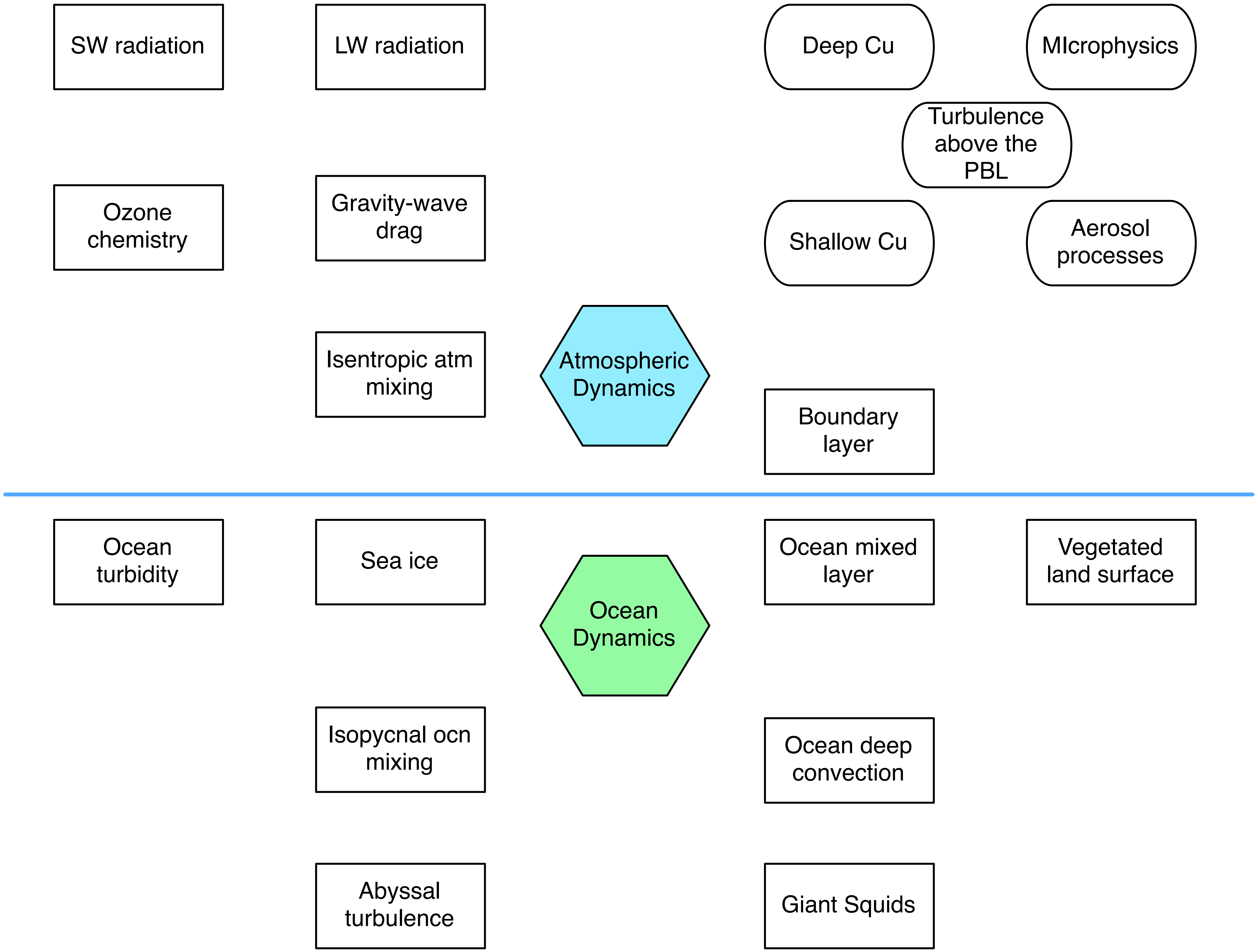
Because of nonlinearity, averaging introduces new unknowns, which are essentially statistics characterizing relevant aspects of the unresolved processes.

The fundamental principles cannot be directly applied to determine such statistics, except by going to higher spatial resolution.

Statistical theories, called parameterizations, are used instead.

The need to predict statistics over (large) finite volumes is a major and fundamental source of conceptual complexity.

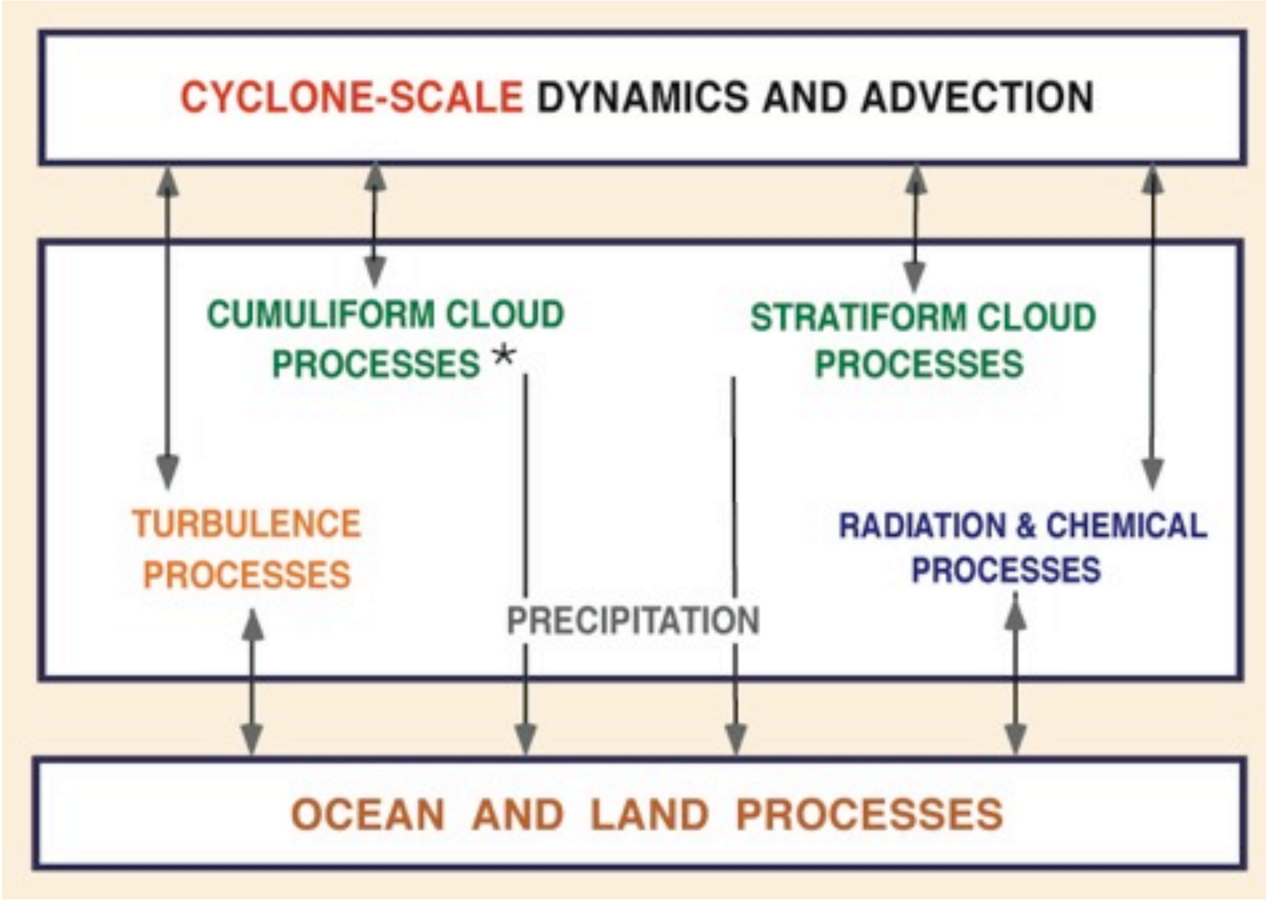
Players



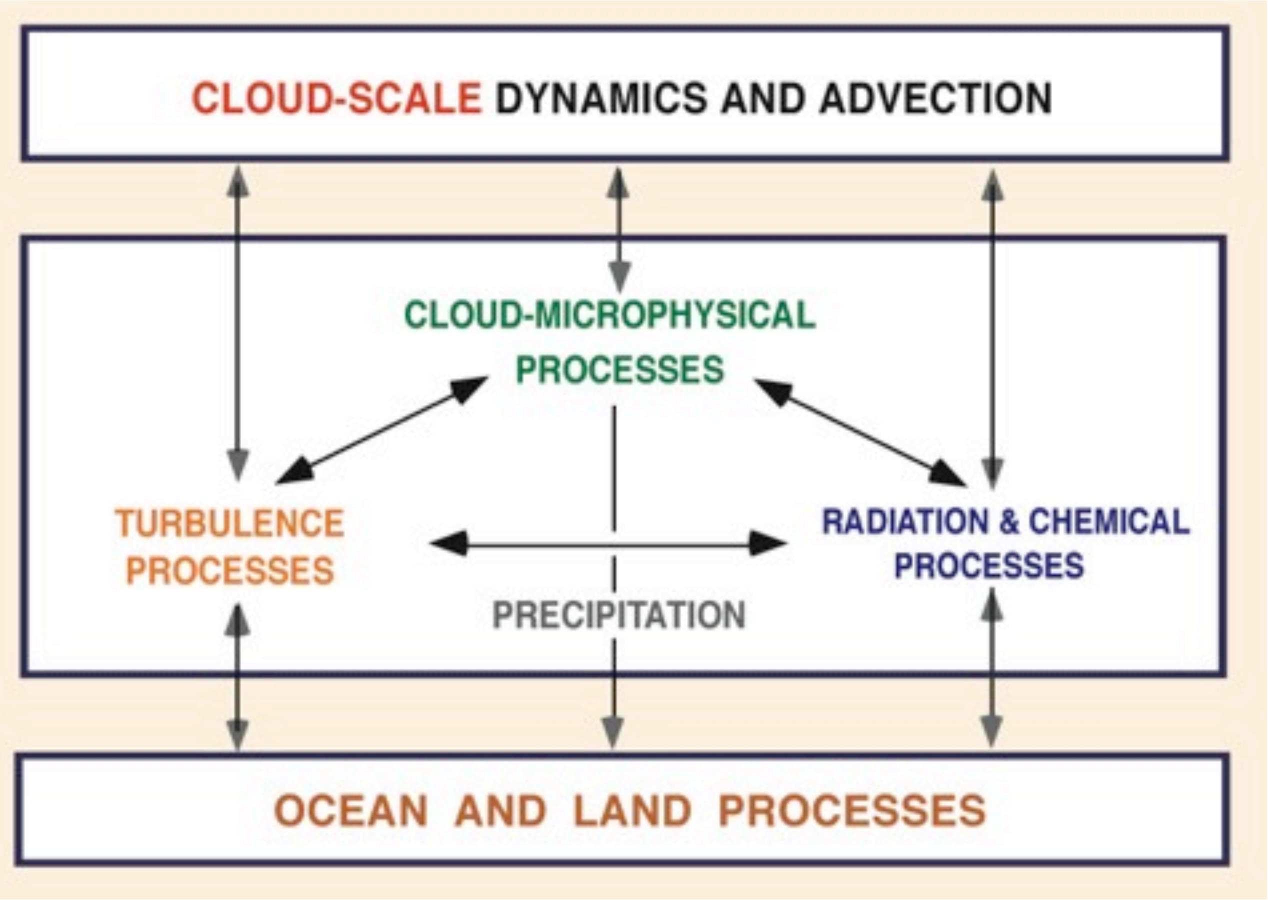
SW radiation
LW radiation
Deep Cu
MIcrophysics
Turbulence above the PBL
Ozone chemistry
Gravity-wave drag
Shallow Cu
Aerosol processes
Isentropic atm mixing
Atmospheric Dynamics
Boundary layer
Ocean turbidity
Sea ice
Ocean mixed layer
Vegetated land surface
Ocean Dynamics
Isopycnal ocn mixing
Ocean deep convection
Abyssal turbulence
Giant Squids

Physical interactions

Conventional GCM



GCRM



More modular

The role of computing power

- We can use as much as we can get -- 100 x every 10 years.
- We have recently crossed a threshold.
- Processor speed is now limited by energy consumption.
- Increased performance through more processors:
  - OK for larger ensembles with fixed resolution & run time.
  - OK for more resolution with fixed run time & ensemble size.
  - Not OK for longer runs with fixed resolution, e.g., ice ages.

Concluding Remarks

- Building GCMs is useful, even before you run them. The journey is the reward.
- It has taken about 50 years to reach our current modeling capability.
- Computers and GCMs co-evolve. Current technology trends are pushing models towards higher resolution.
- Explicit representation of deep convection is now possible, and will revolutionize the field.
- Nevertheless, conventional parameterizations will always be needed, because they represent our understanding of the system.