Computational Challenges for Dynamic Earth System Models

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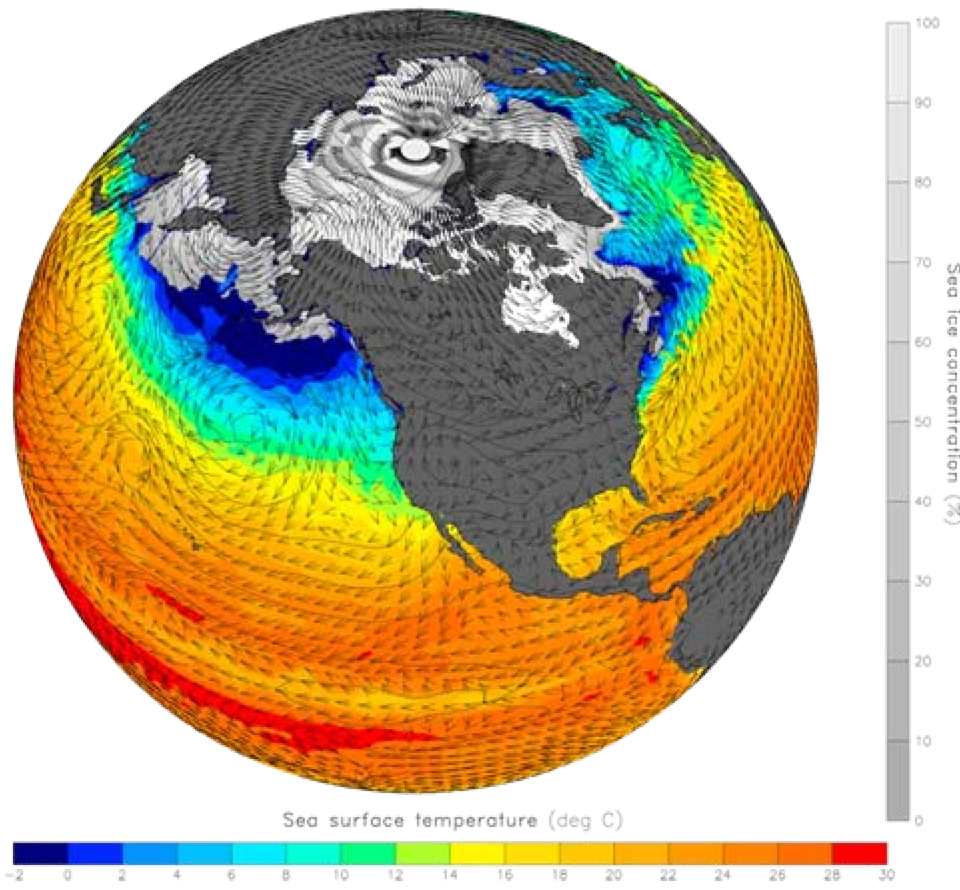
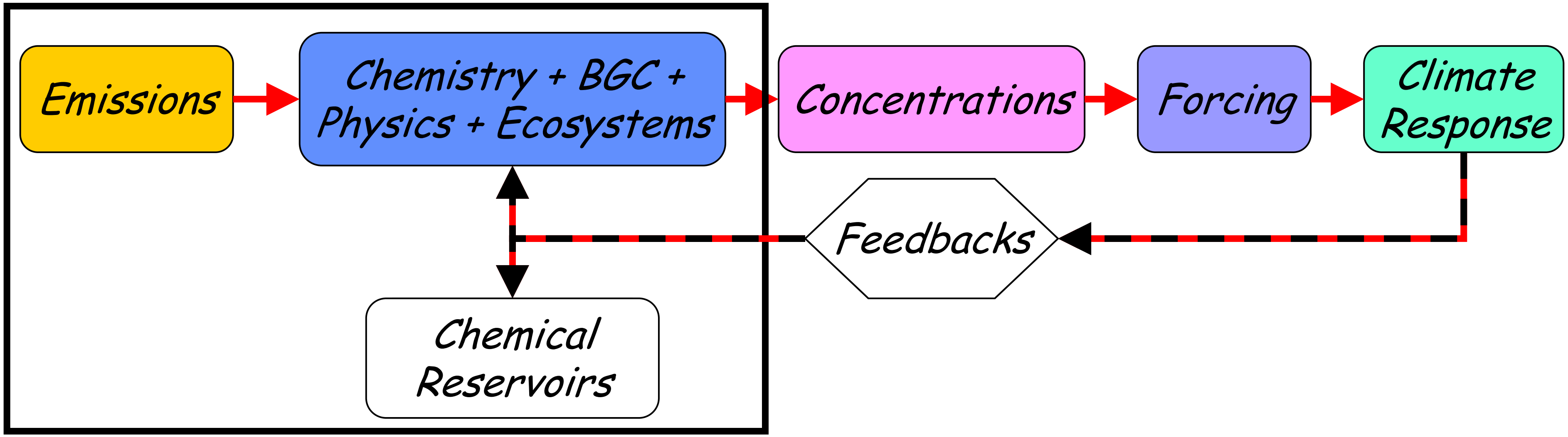
Topics

- **Extension of climate models to Earth system models**
- **Computational requirements for Earth system models**
- **Higher fidelity of water cycle with increasing spatial resolution**
- **Computational demands of increasing spatial resolution**
- **Grand challenges in oceanic biogeochemical cycles**



Simulating the coupled Earth system

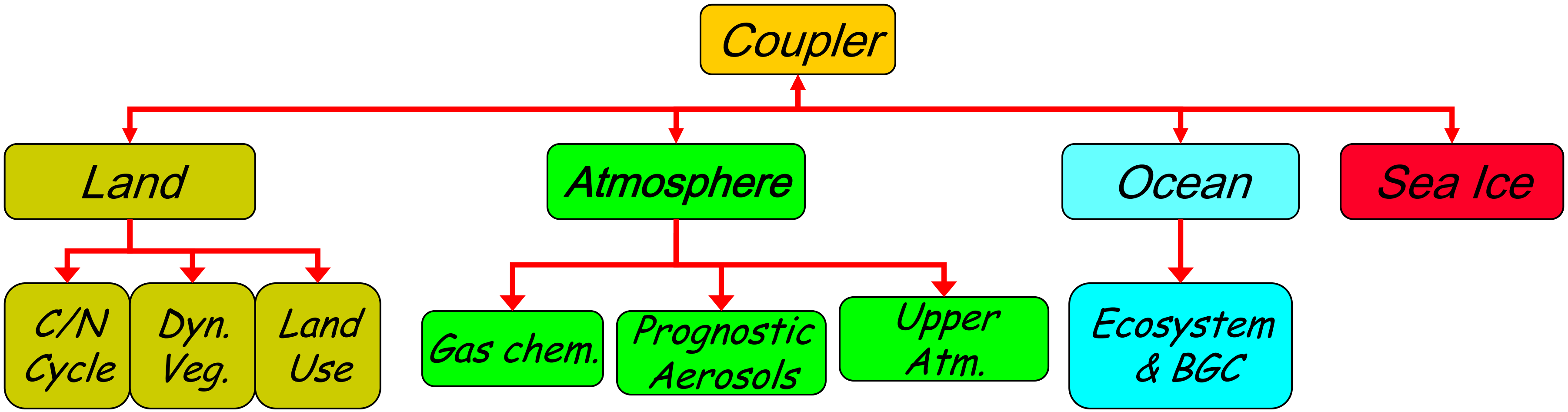


- In the past, we have generally used offline models to predict concentrations and read these into models.

- This approach is simple to implement, but
  - It cuts the feedback loops.
  - It eliminates the chemical reservoirs.

- The next generation of models will include these interactions.

CCSM4: 1st generation Earth System Model



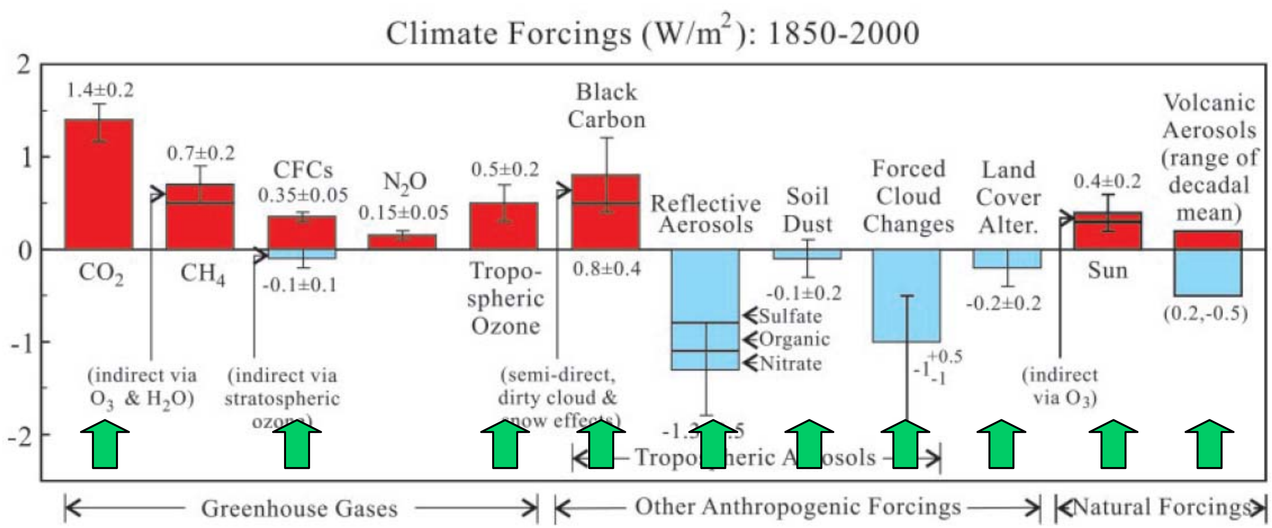
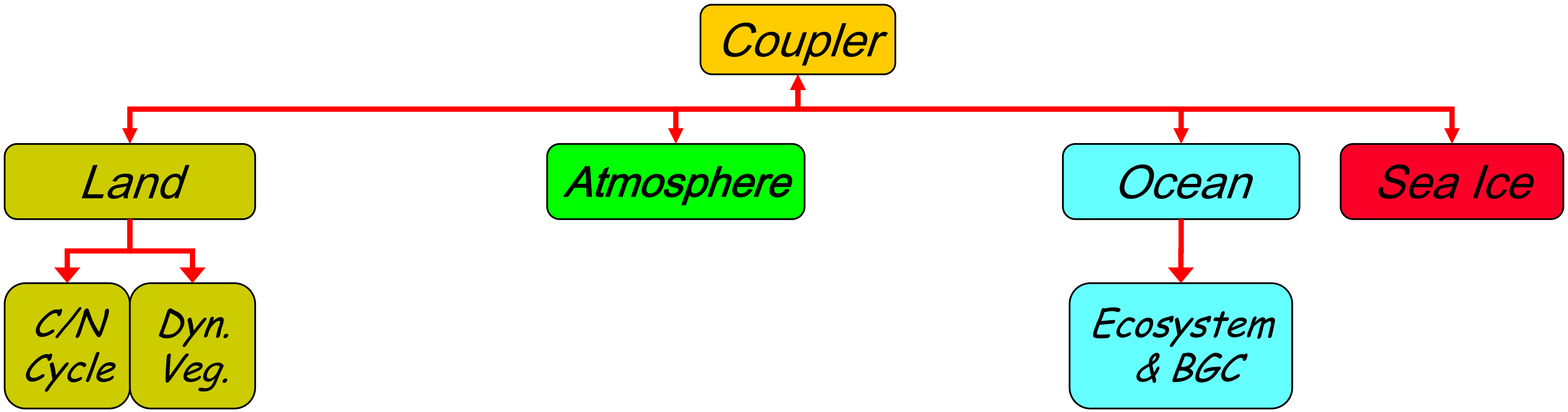


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

A 1st generation Earth system model



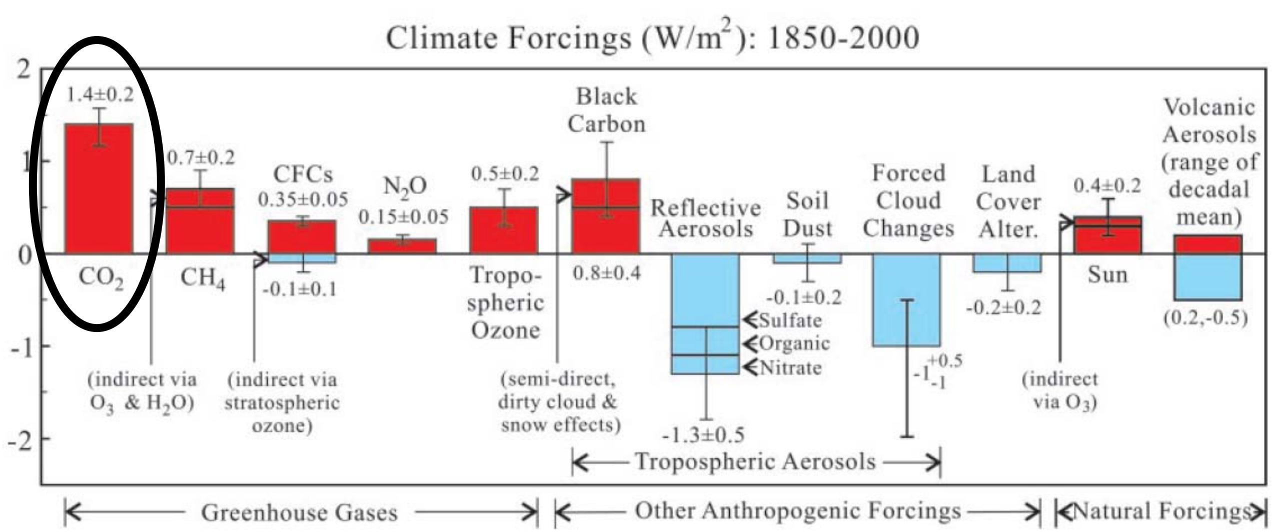
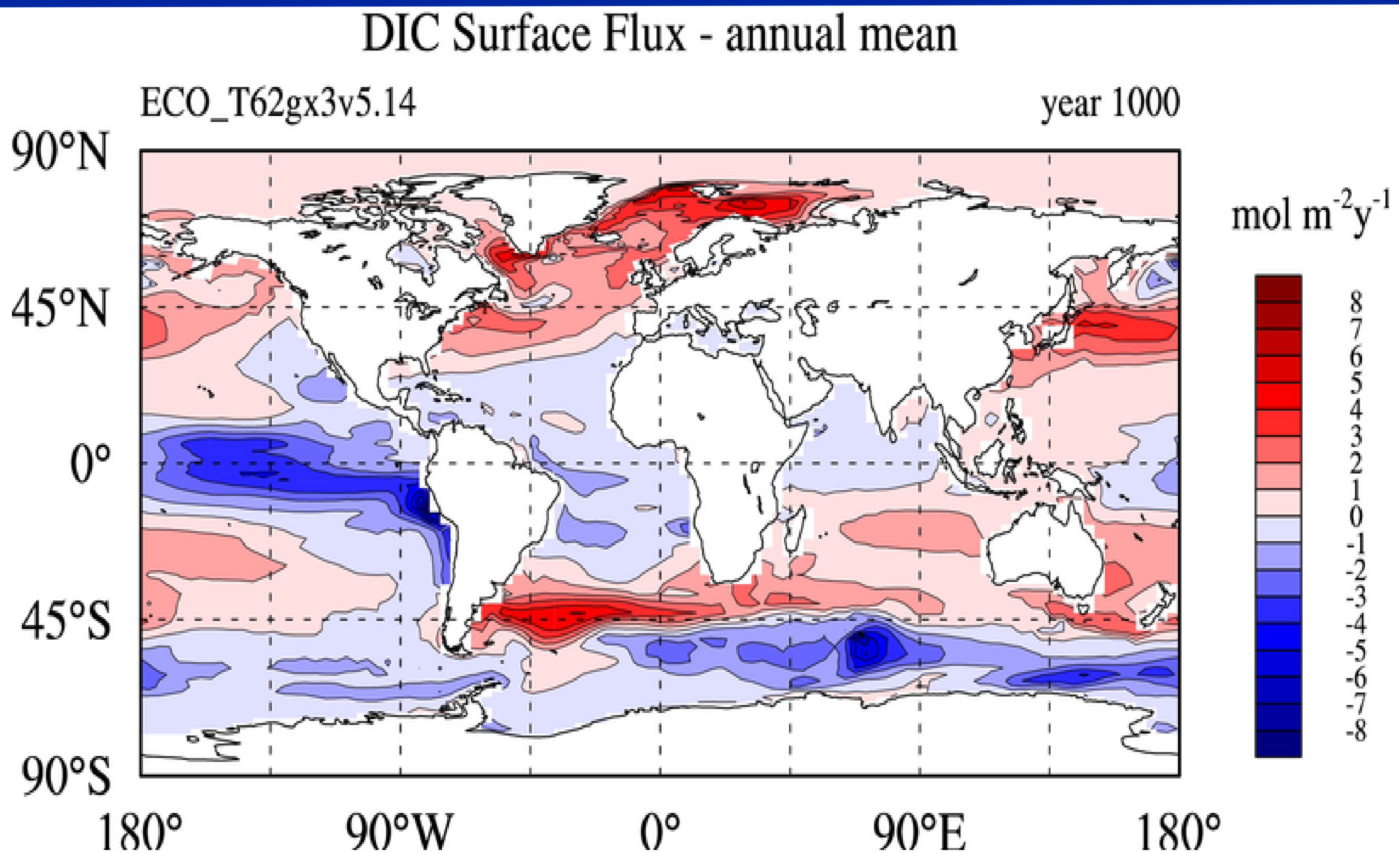


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

Flux of CO_2 into the world oceans

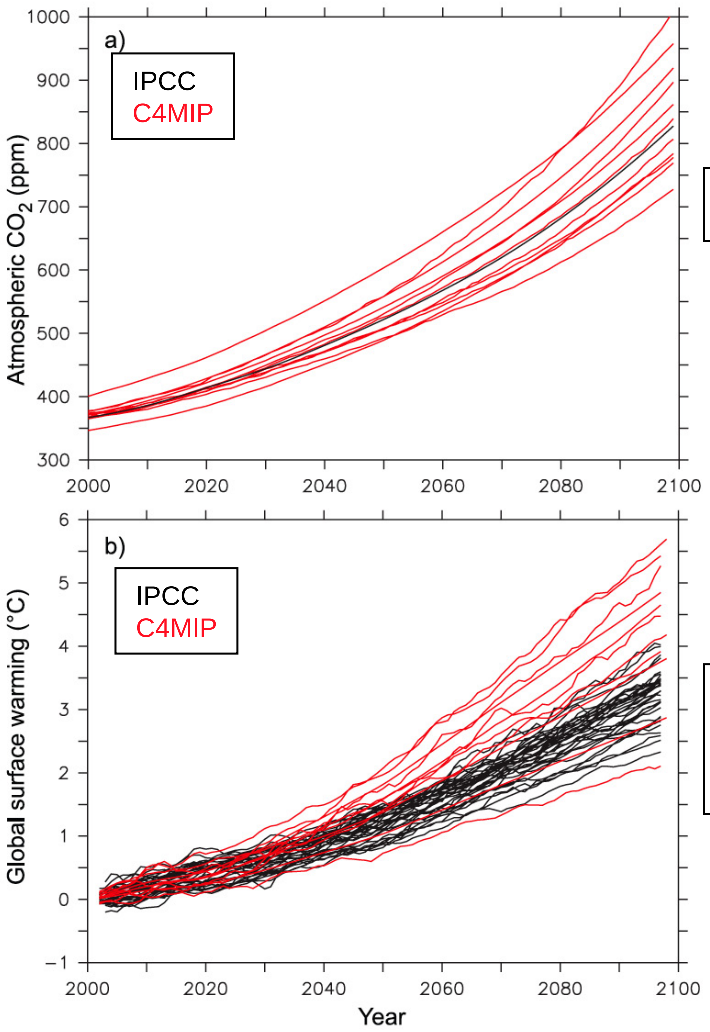
(Ocean ecosystem model)



Moore, Doney, and Lindsay

- Earth system models simulate exchange of CO_2 with ocean and land.

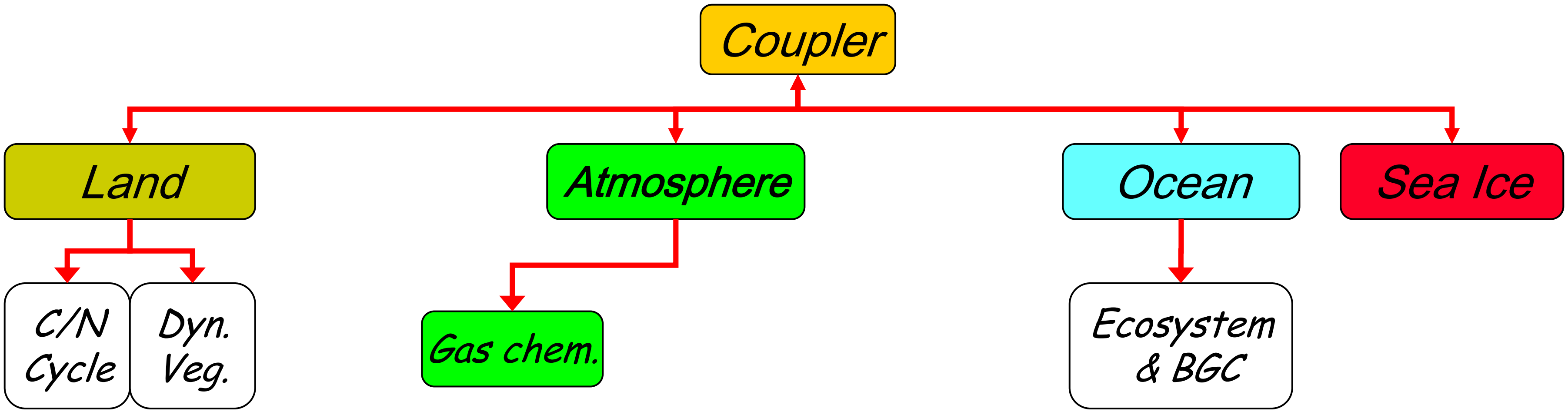
Effects of carbon-cycle feedbacks



- Carbon cycle has positive feedback on CO_2.

- The feedback increases surface temperatures.
- It increases range of uncertainty.

Tropospheric ozone



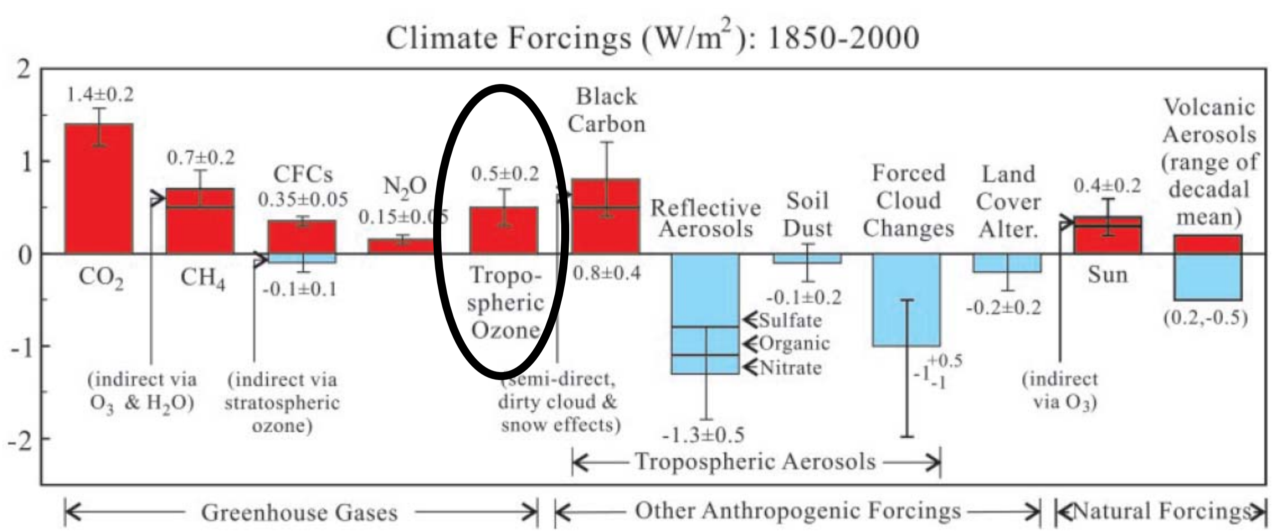
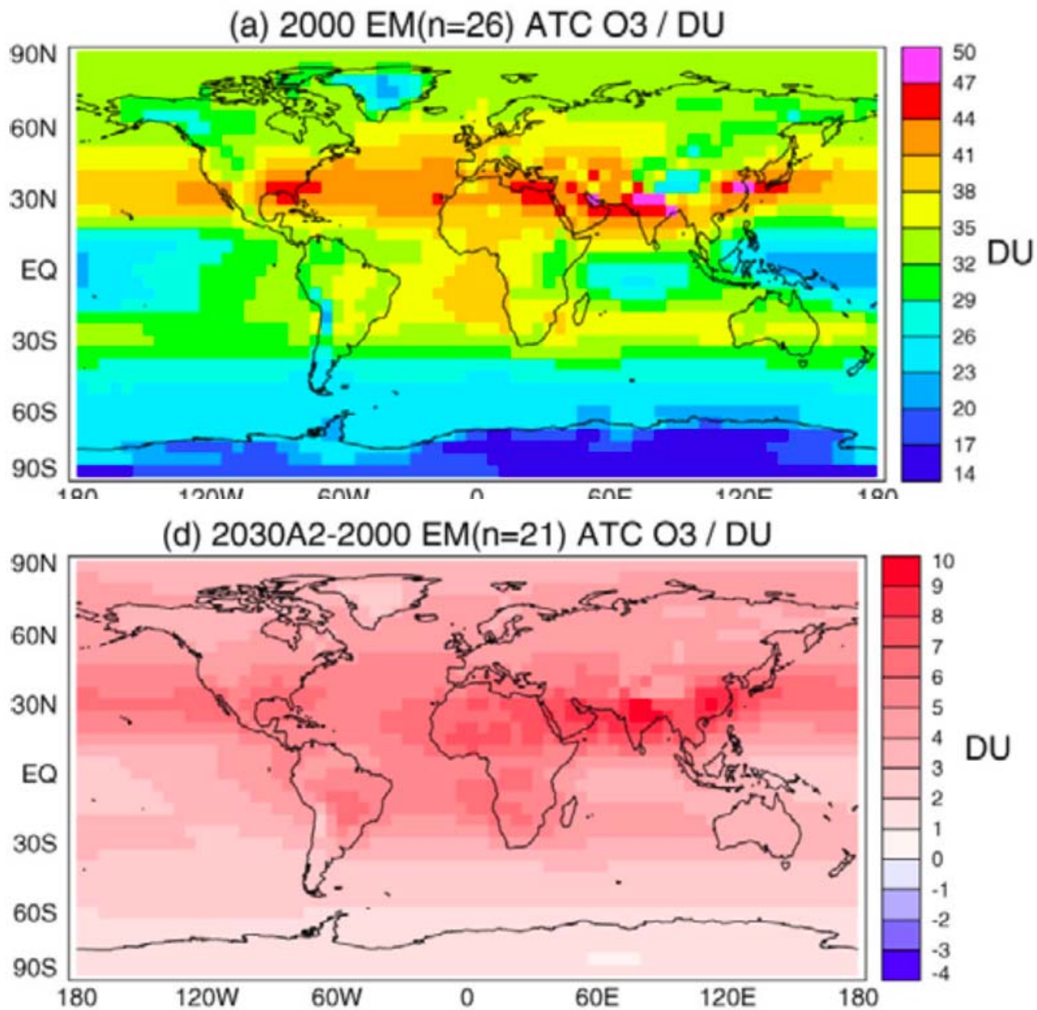


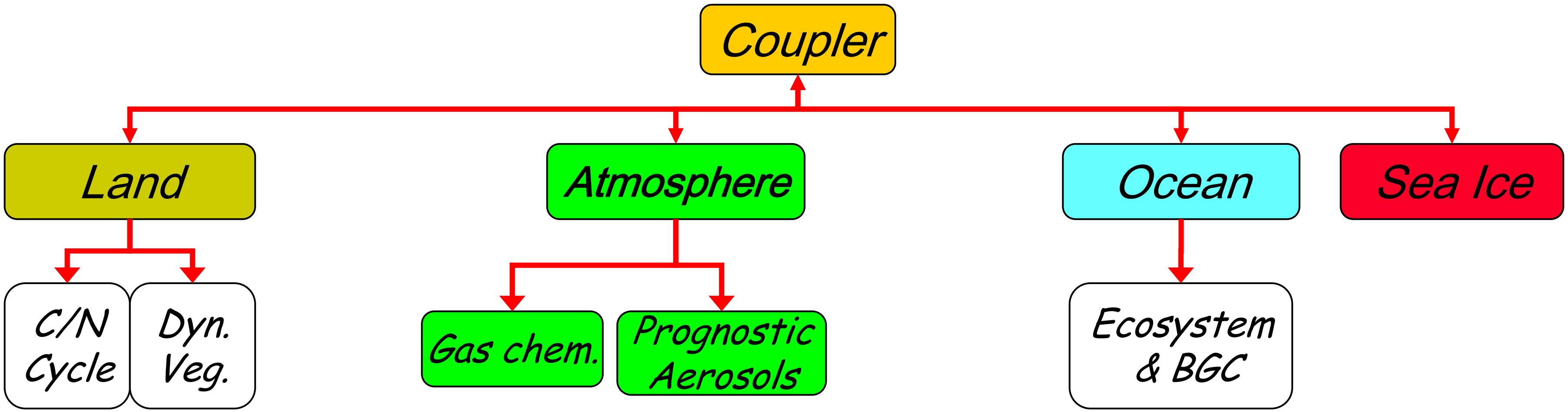
Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

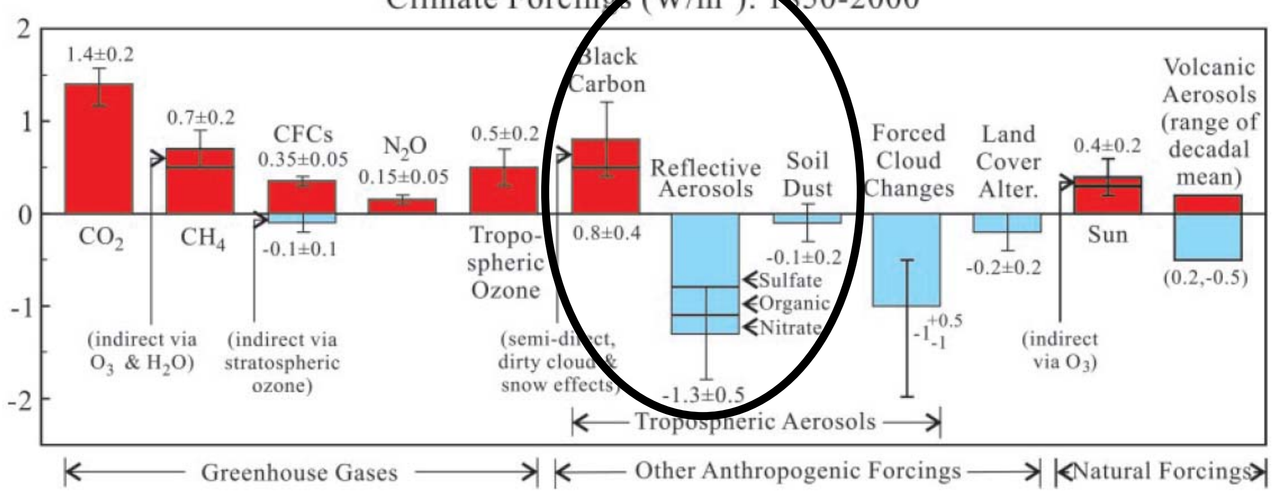
Tropospheric ozone: 21st century



IPCC AR4, 2007

Tropospheric aerosols

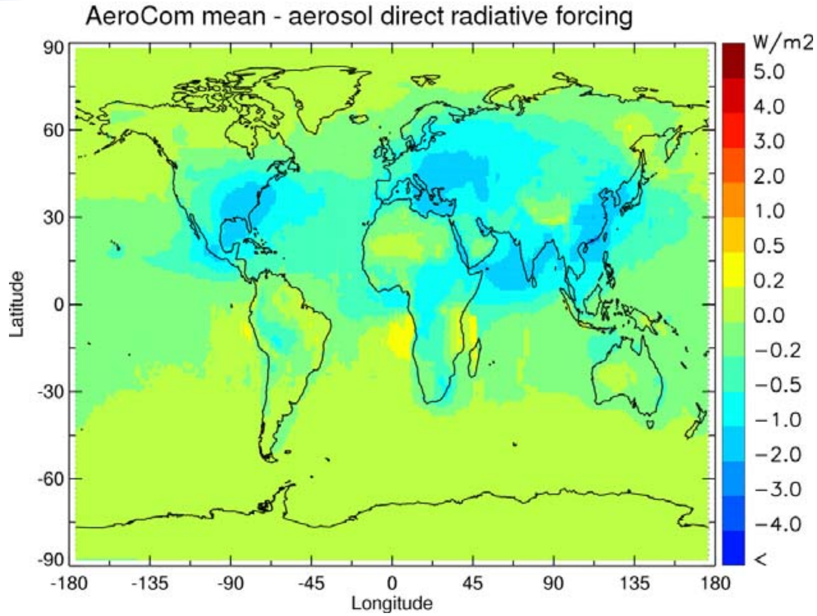


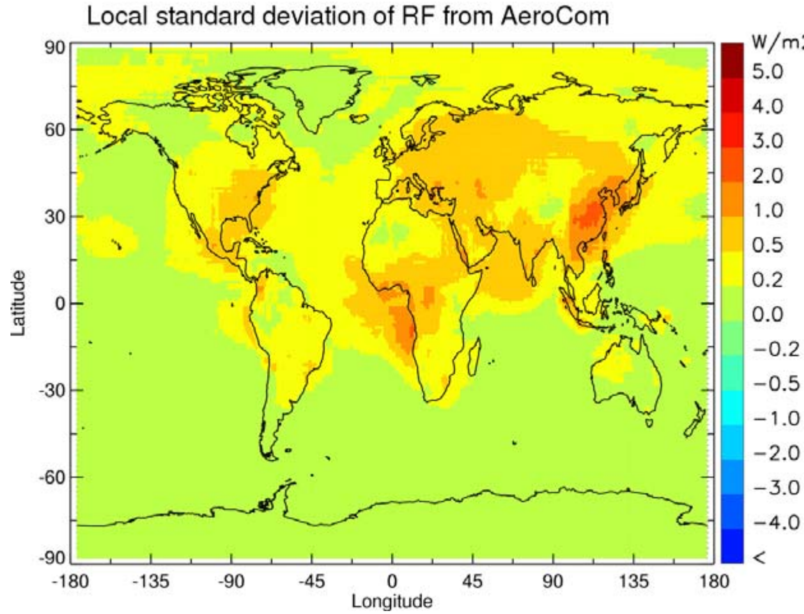


Climate Forcings (W/m^2): 1850-2000

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

Models of aerosol radiative forcing

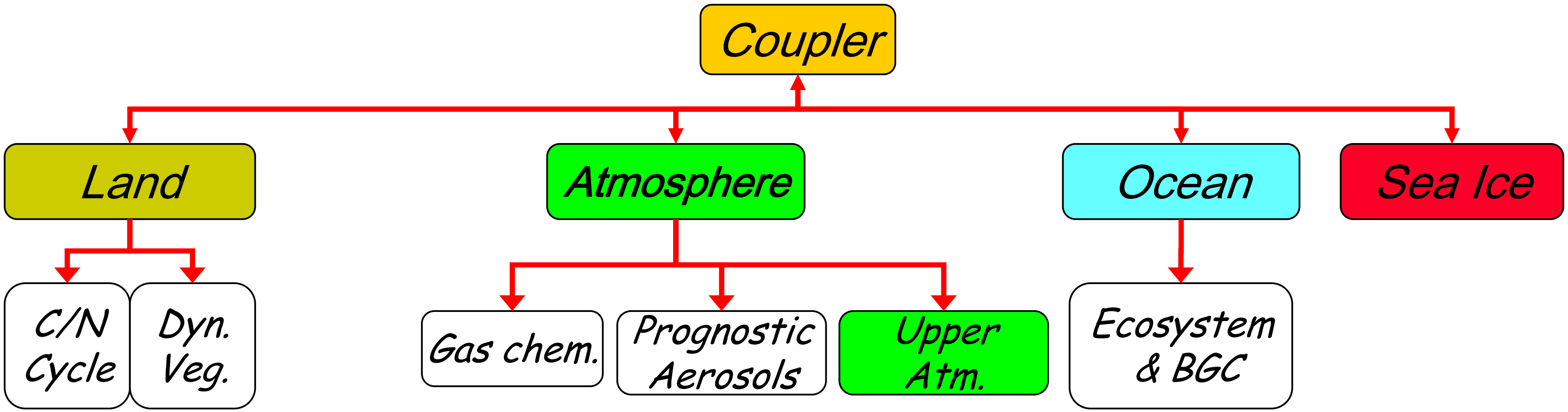




IPCC AR4, 2007

Species	Forcing (W m^{-2})
Sulfate	**–0.4 ± 0.2**
Fossil fuel organic carbon	**–0.1 ± 0.1**
fossil-fuel black carbon	**+0.2 ± 0.1**
Biomass burning	**0.0 ± 0.1**
Nitrate	**–0.1 ± 0.1**
mineral dust	**–0.1 ± 0.2**
Total	–0.5 ± 0.4

Solar forcing



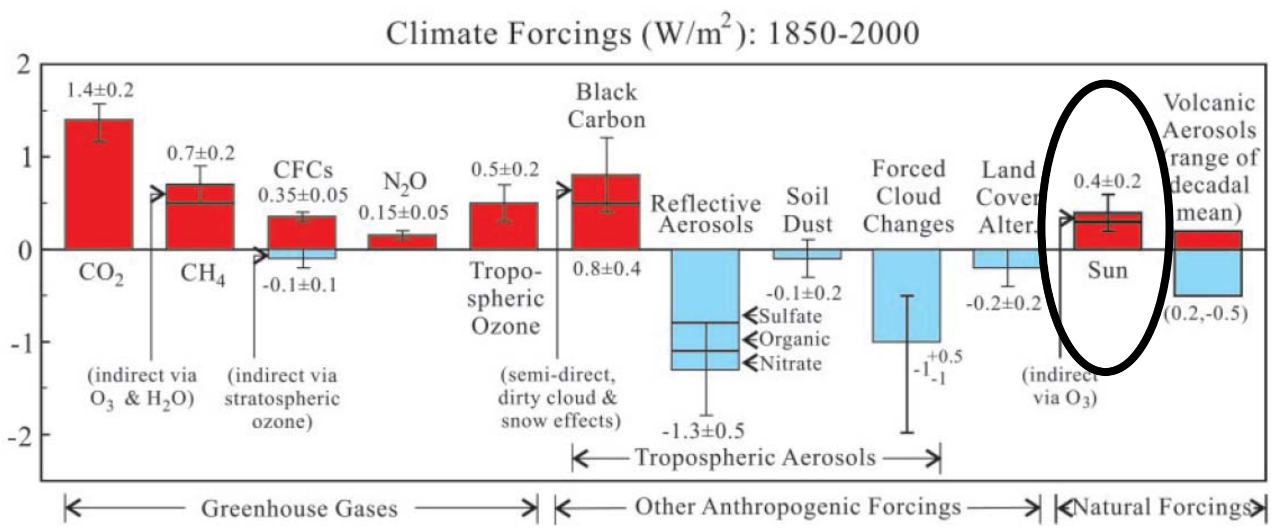
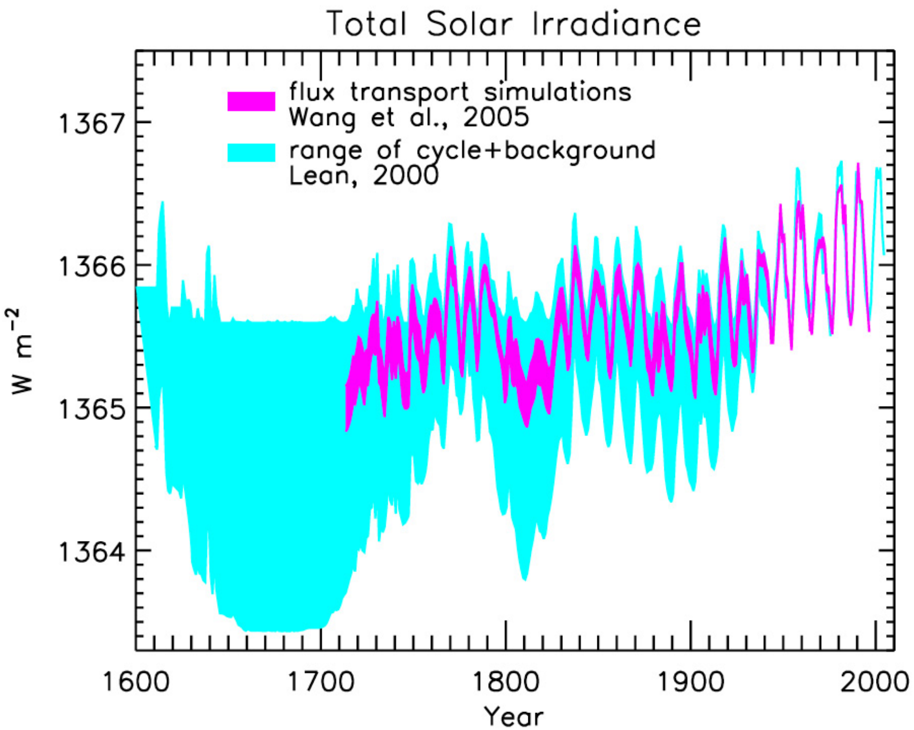
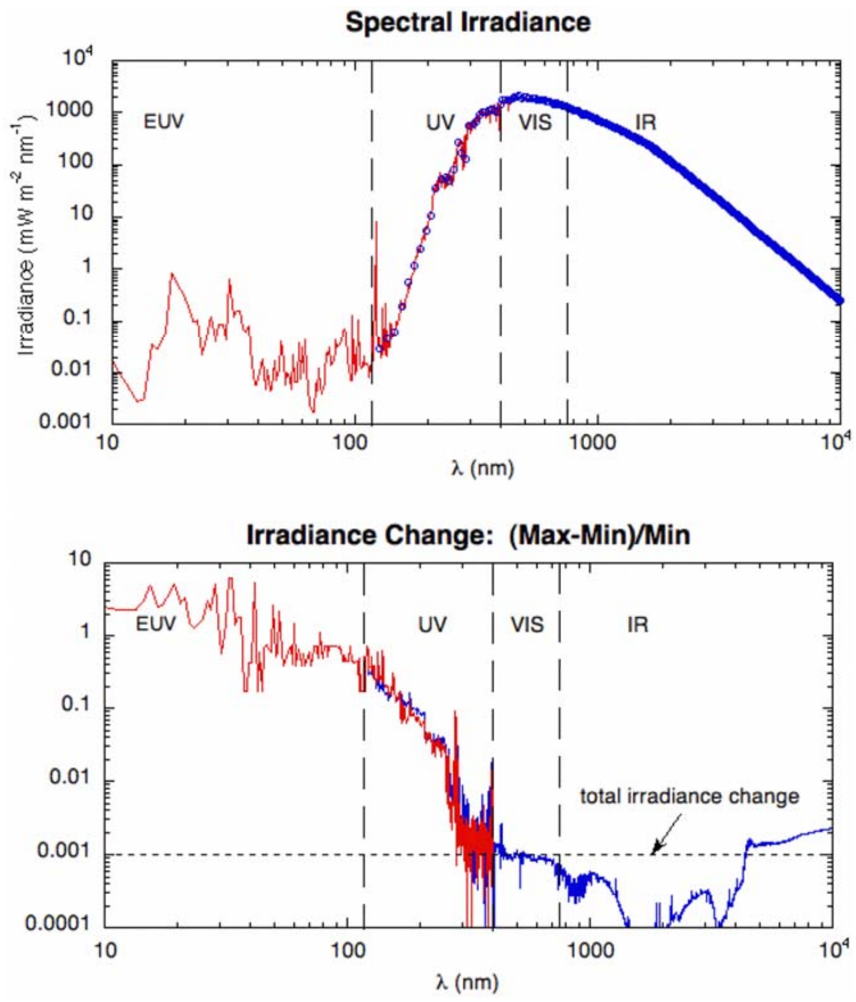


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

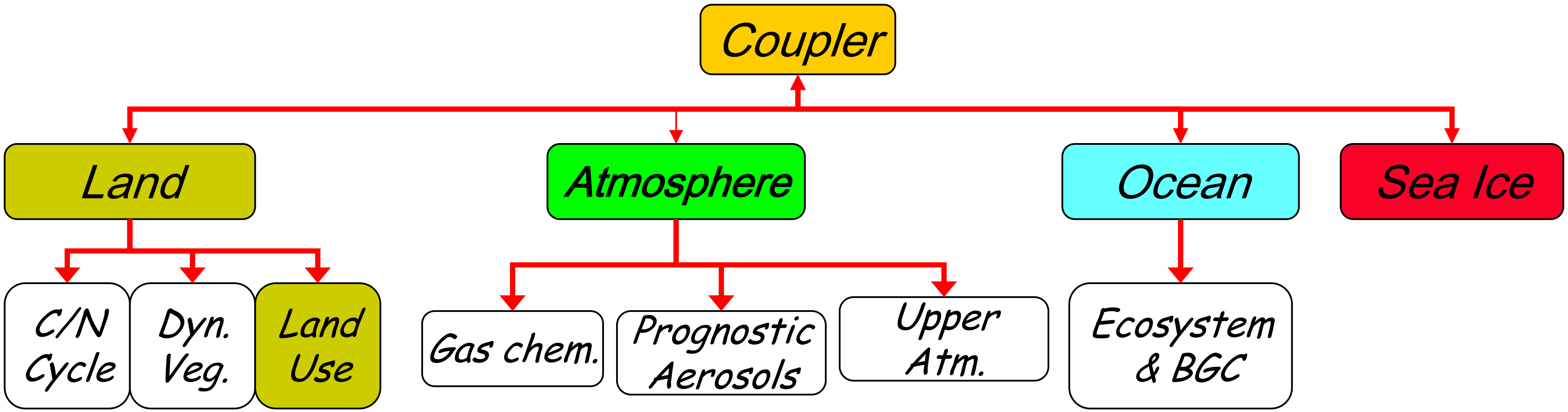
Solar variability and forcing



IPCC AR4, 2007



Agricultural land use



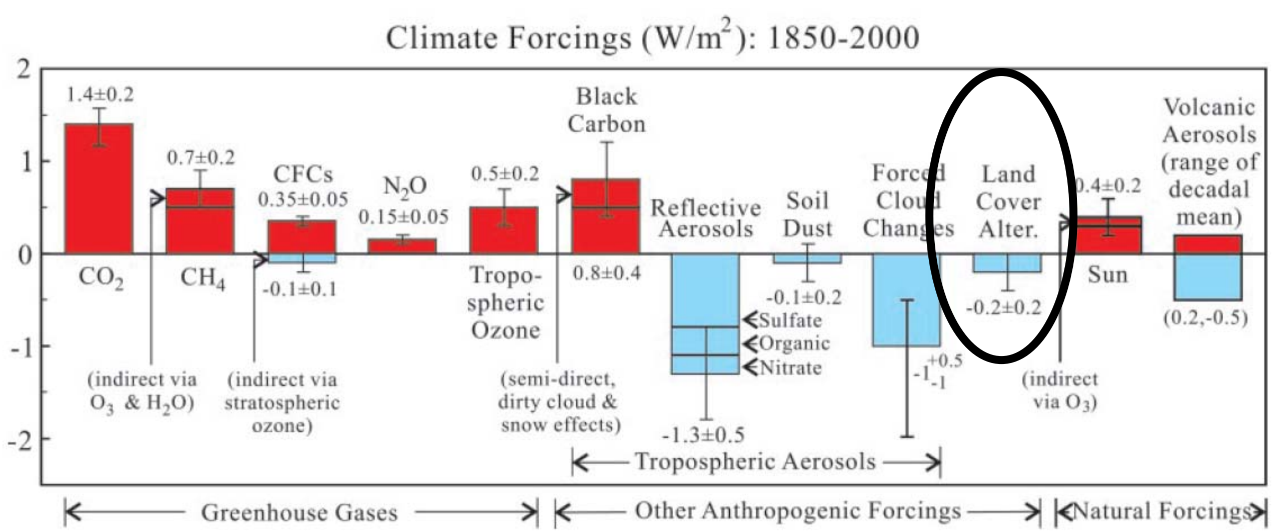
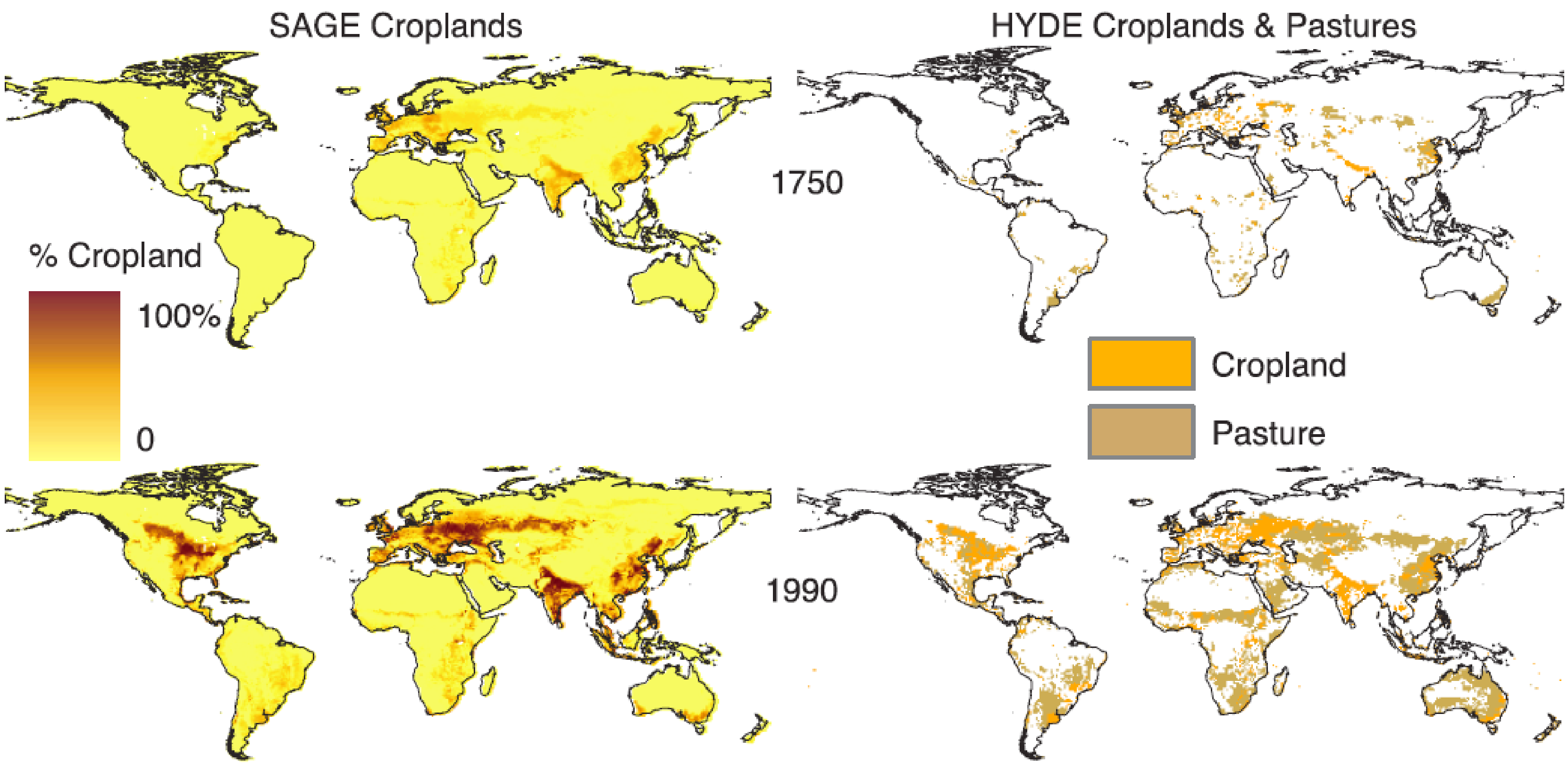


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

Evolution of agricultural land use



IPCC AR4, 2007

- Cropland has increased by factor of 5 to 6 relative to 1750.
- This effects both the carbon cycle and surface albedo.

Computational burden: current models

Characteristics of CCSM3:

• ~1 quadrillion operations/simulated year

• Rate of simulation: 3.5 sim. years/day

• Ensemble size: 11,000 simulated years

• Computation cost: ~7 million CPU hours

• Output: 10 GB/simulated year

• Data volume for IPCC: ~100 TB

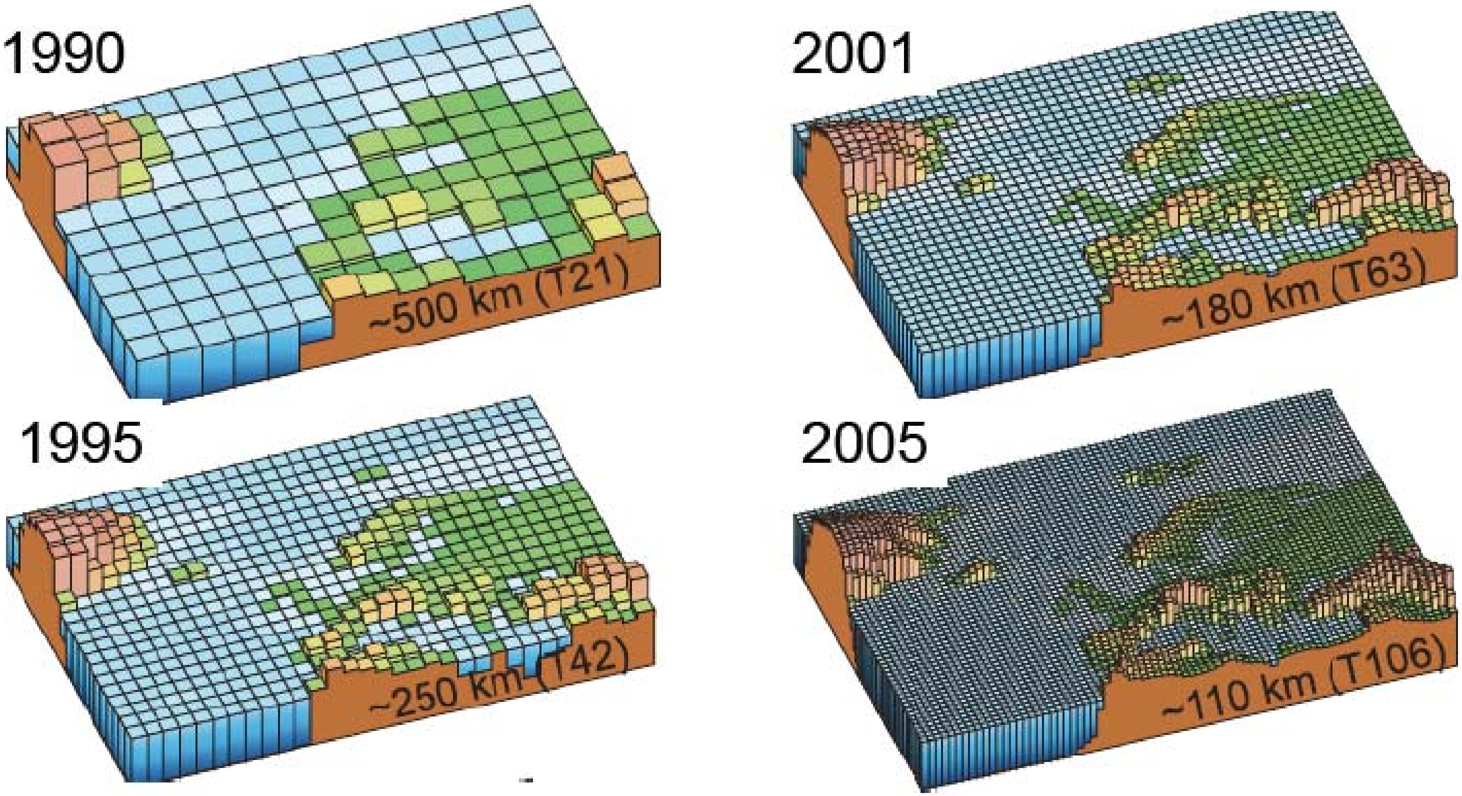
Computational burden: GCM to ESM

Process	Number	Cost
Chemistry	94	400 – 500% (Atmosphere)
Atmos. Res.→1º		5
Ocean BGC	25	250 – 375% (Ocean)
Land BGC	40	< 20% (Land)
Total	159	> 20 – 25 ≅ **Chemistry** **Resolution**

Other possible requirements could include:

- ***Increased ocean resolution to eddy permitting/resolving scales***
- ***Vertical resolution of the atmosphere for tropospheric processes***
- ***Addition of models for stratosphere and upper atmosphere***

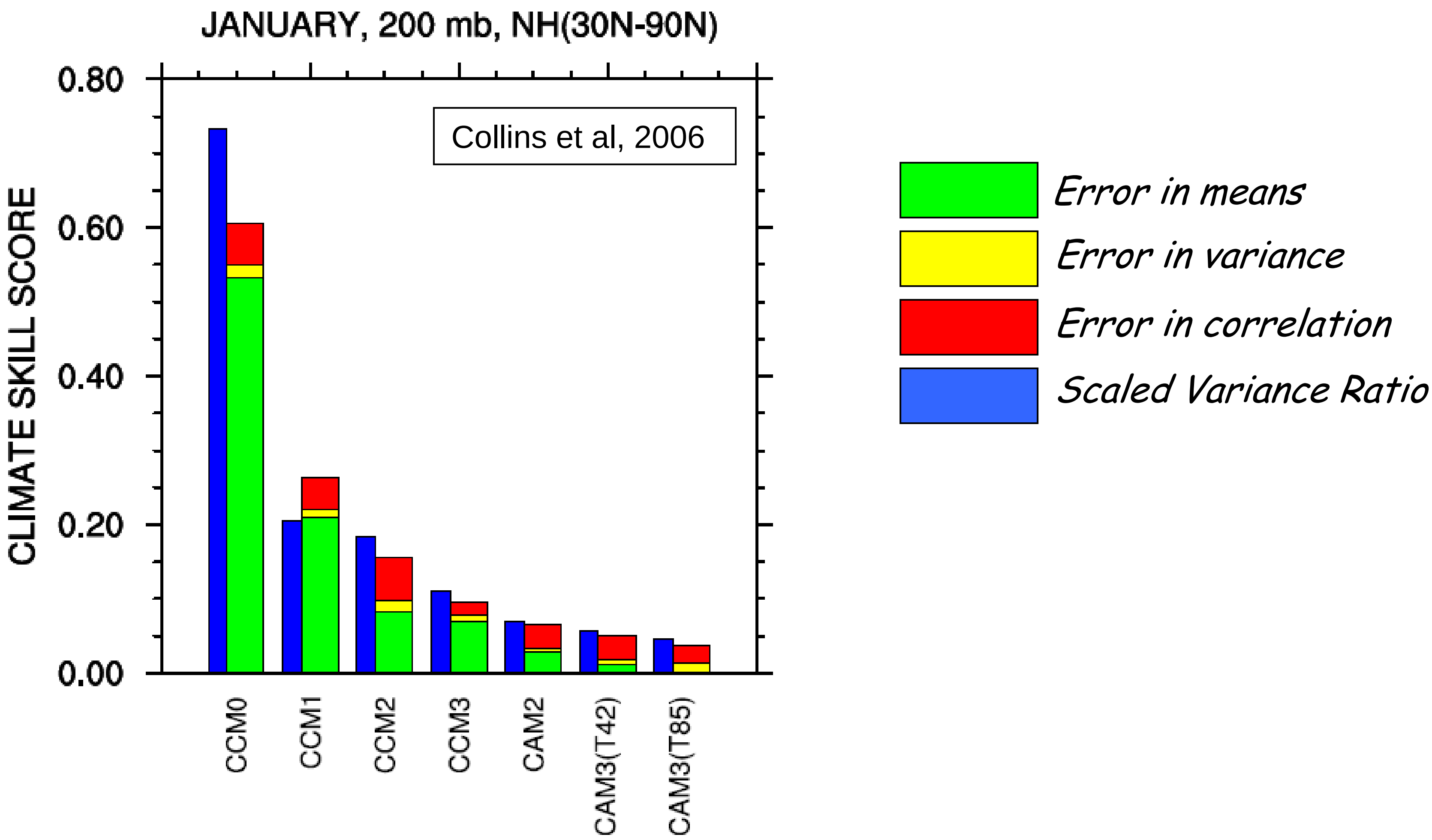
Resolution of climate models



IPCC AR4, 2007

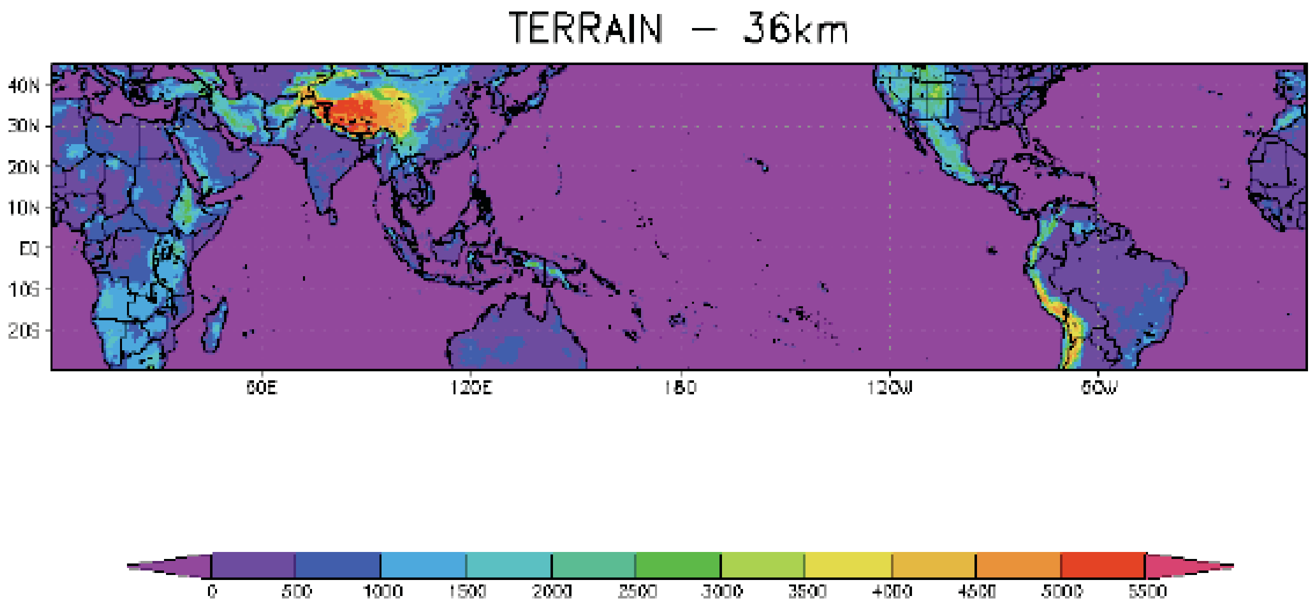
- Resolution has increased by a factor of 5.
- How does fidelity change with increased resolution?

Fidelity of atmospheric winds vs. resolution



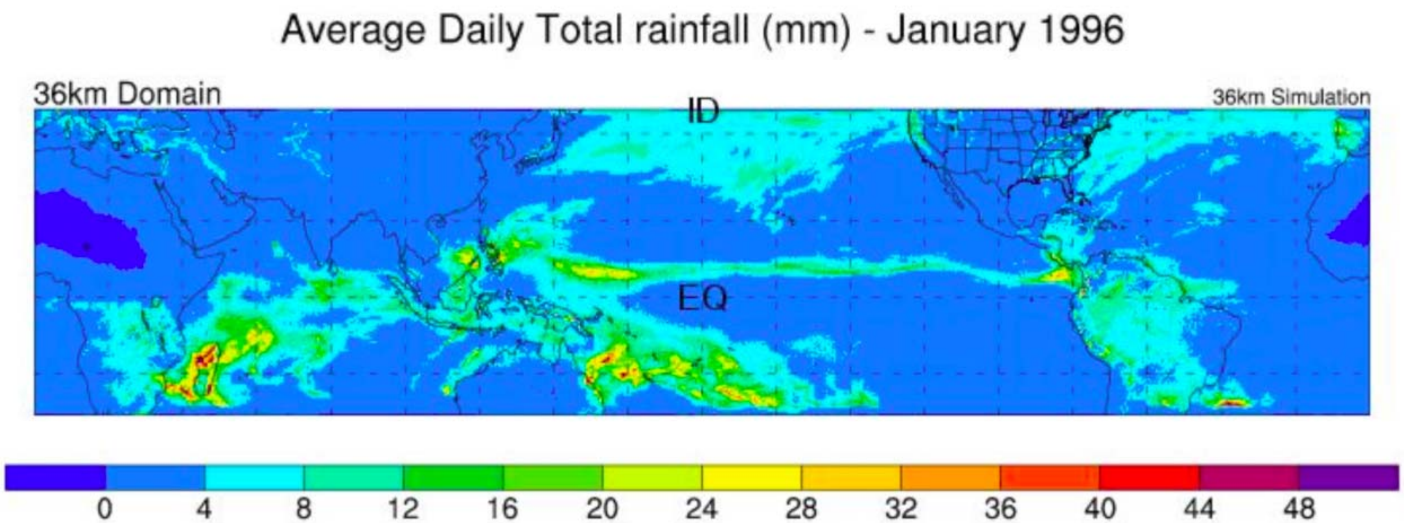
- The resolution of Community Model has increased by a factor of ~6.
- The fidelity of its simulated winds has improved by a factor of ~20.

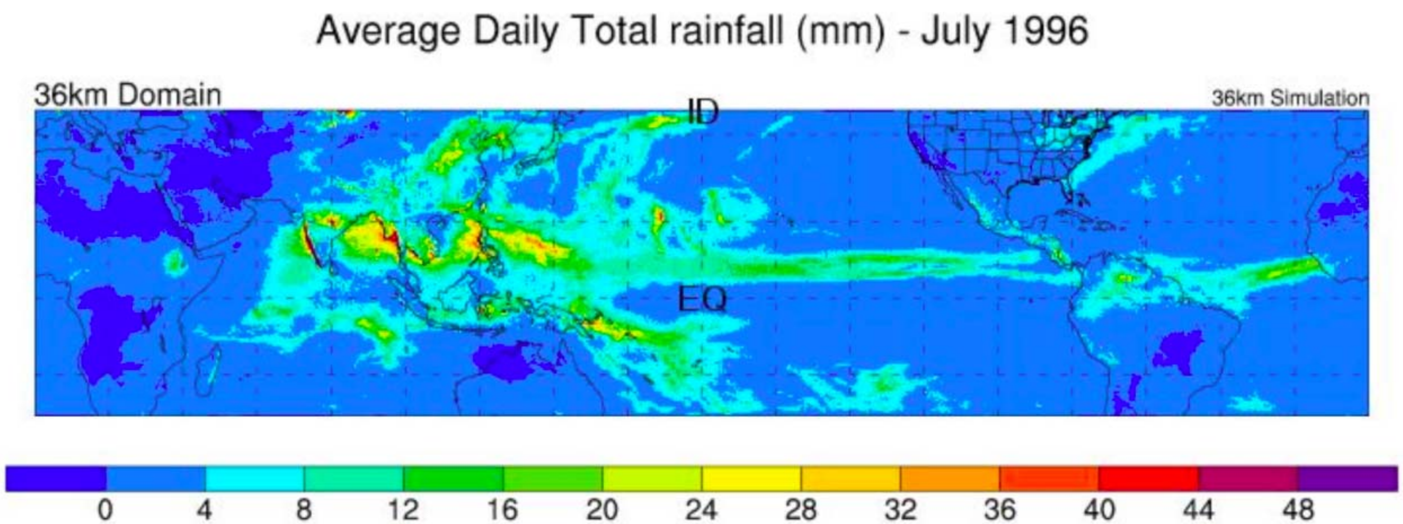
Nested regional climate configuration



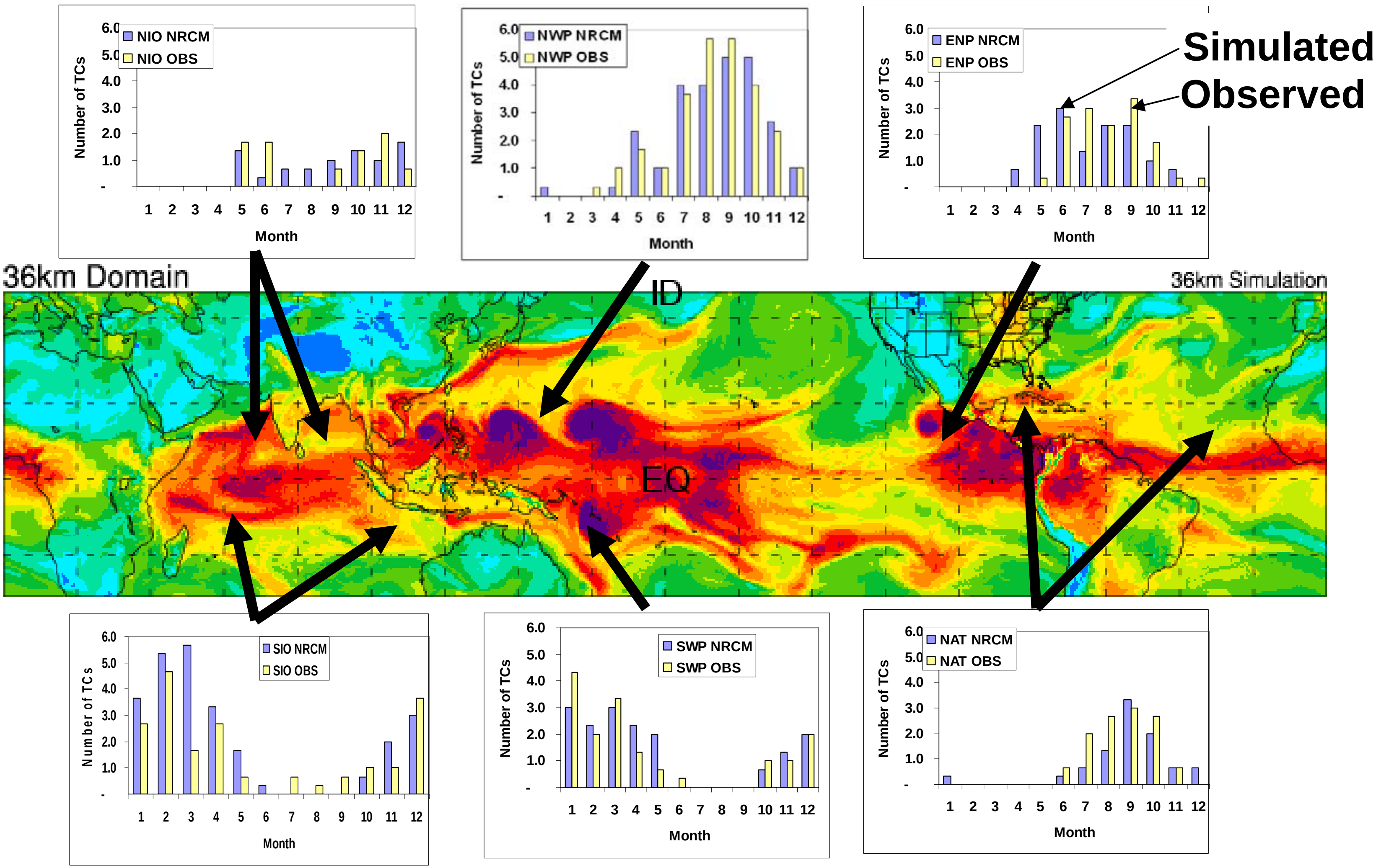
- Base model: Advanced Research version of WRF
- Meridional boundaries at 35S/45N are relaxed to NCEP reanalysis.
- 4 km and 12km grids nested in 36km outer grid.
- Kain-Fritsch cumulus scheme is used on 12 and 36km grids.
- Period of integration: Jan. 1, 1996 to Jan. 1, 2001

Nested Regional Model: Precipitation

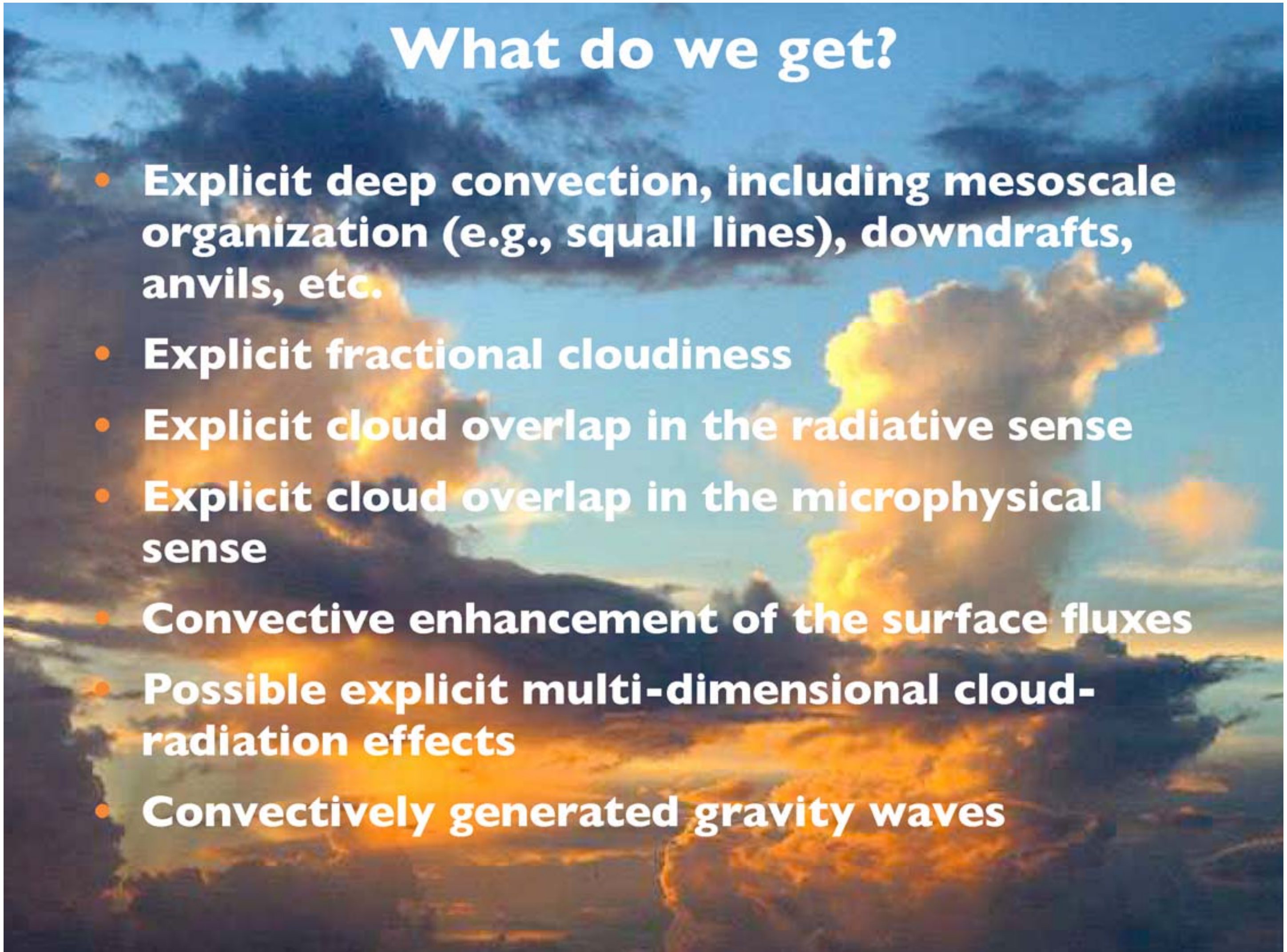




NRCM tropical cyclone simulation

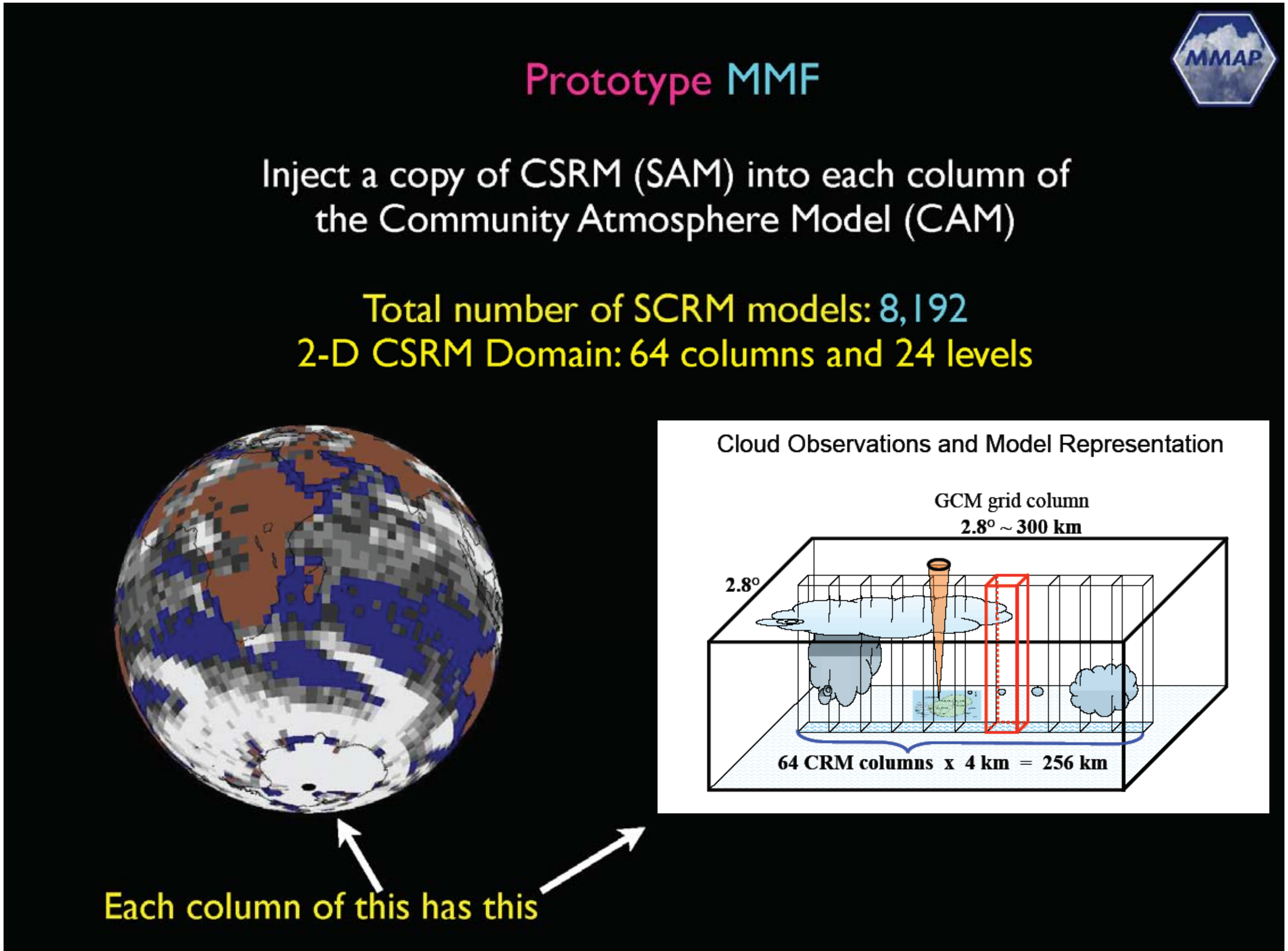


Reasons to resolve cloud processes



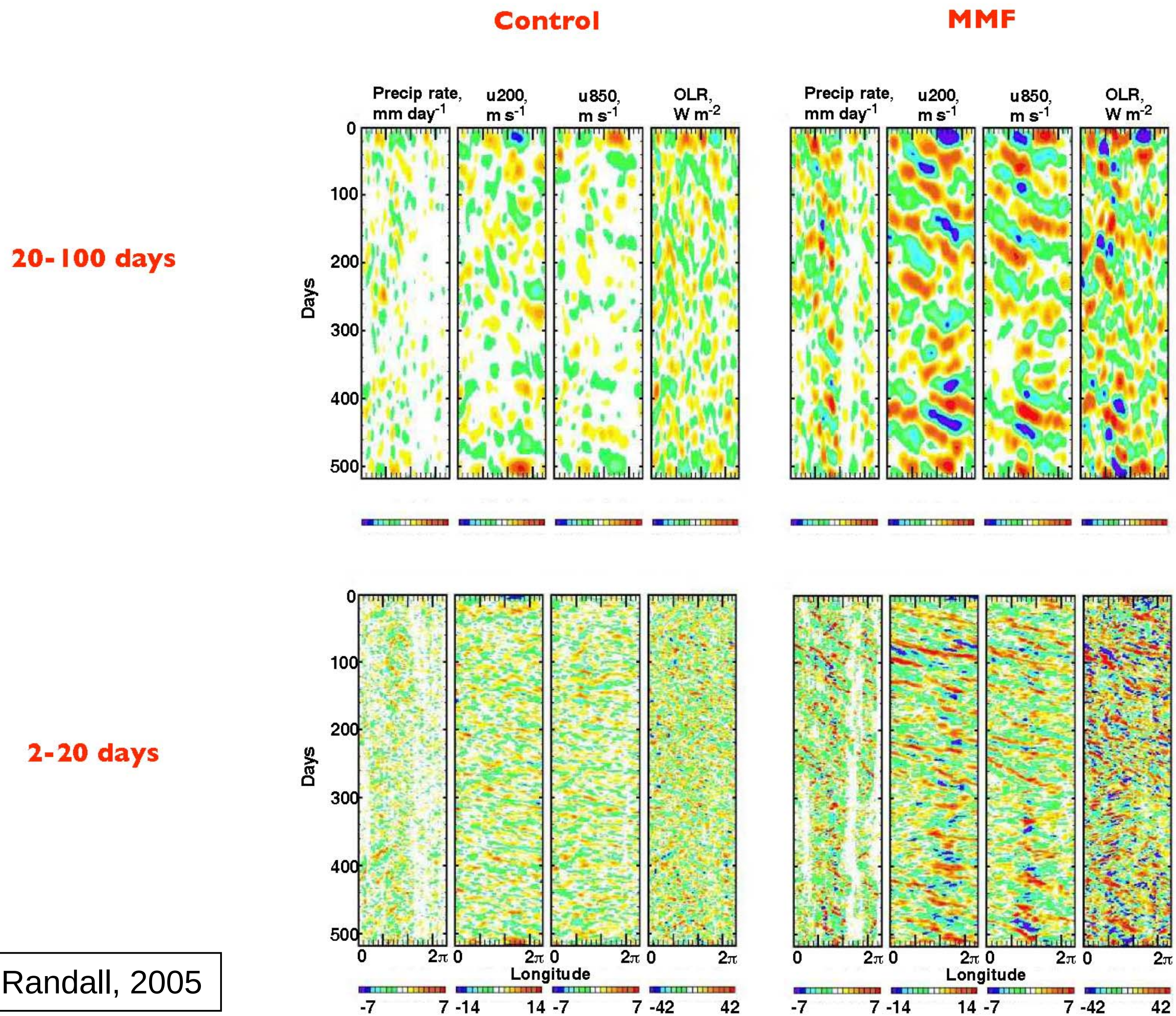
Randall, 2005

The multi-scale modeling framework



Randall, 2005

Improvements in cloud variability



Randall, 2005

Computational demand for increased atmospheric resolution

Table 2: Minimum sustained computational performance (in Tflop/s) required to integrate fvCAM 1000 times faster than real time and the relative percentages of the total operations in three main segments of the code.

Mesh Name	Horizontal Resolution Near Equator	Performance 1000x spdup (Tflop/s)	% total time in dynamics	% total time in filters	% total time in physics
B	200km	0.002	57%	2%	41%
C	100km	0.014	71%	3%	25%
D	50km	0.098	81%	4%	14%
E	25km	0.727	87%	5%	8%
F	12.5km	5.608	90%	6%	4%
G	6.25km	44.15	92%	6%	2%
H	3.13km	351.3	92%	7%	1%
I	1.57km	2809.7	92%	7%	1%

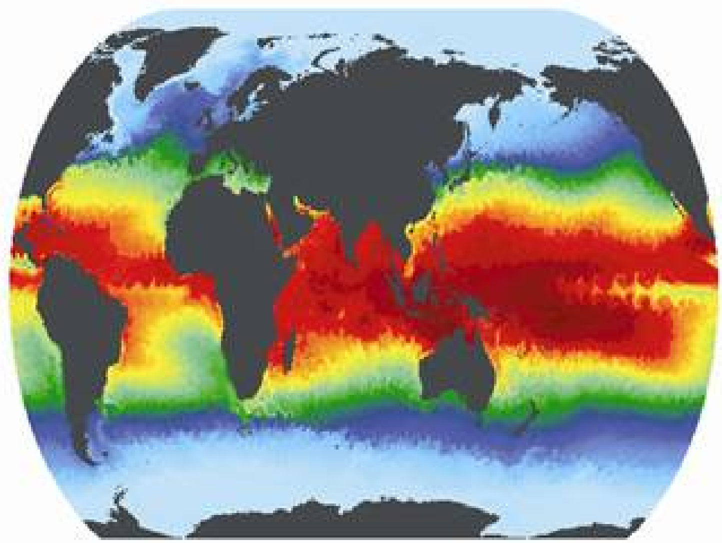
Wehner et al, 2006

Challenges in ocean modeling

- **Spatial scales of the flow**
  - — Boundary layers
  - — Scale of “weather systems” are ~10 smaller than atmosphere
- **Long equilibration time scale**
  - — Forcing occurs at sea surface
  - — Deep adjustment occurs on diffusive time scales
- **Irregular Domain**
  - — Complicated coastlines
  - — Multiply connected
  - — Narrow straits and passages

Temperature at 15m Depth

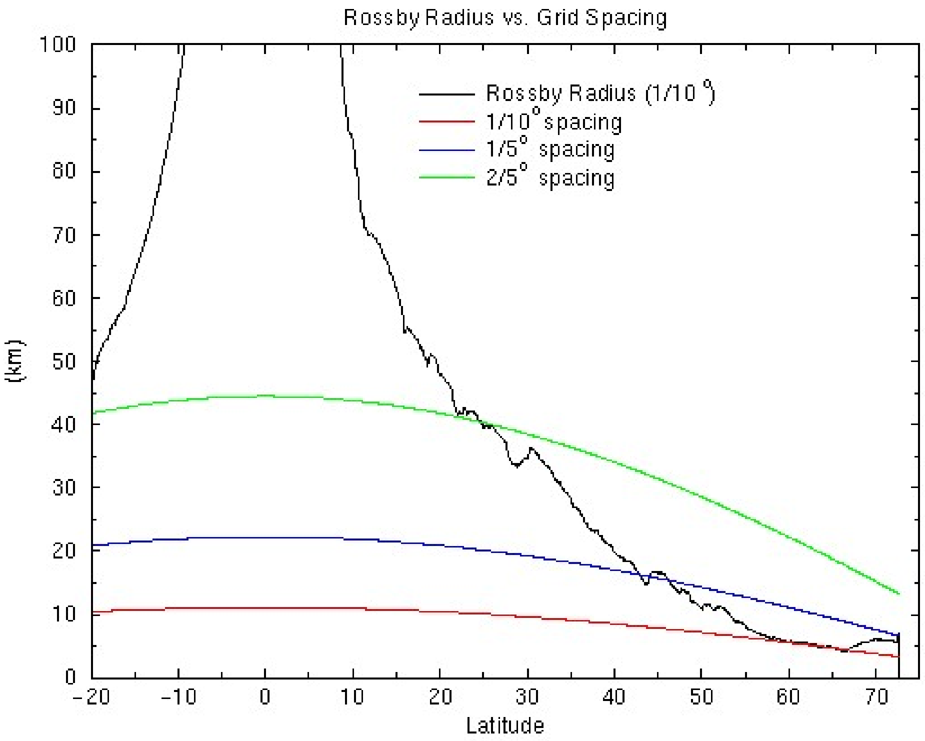
POP Global 1/10° Simulation



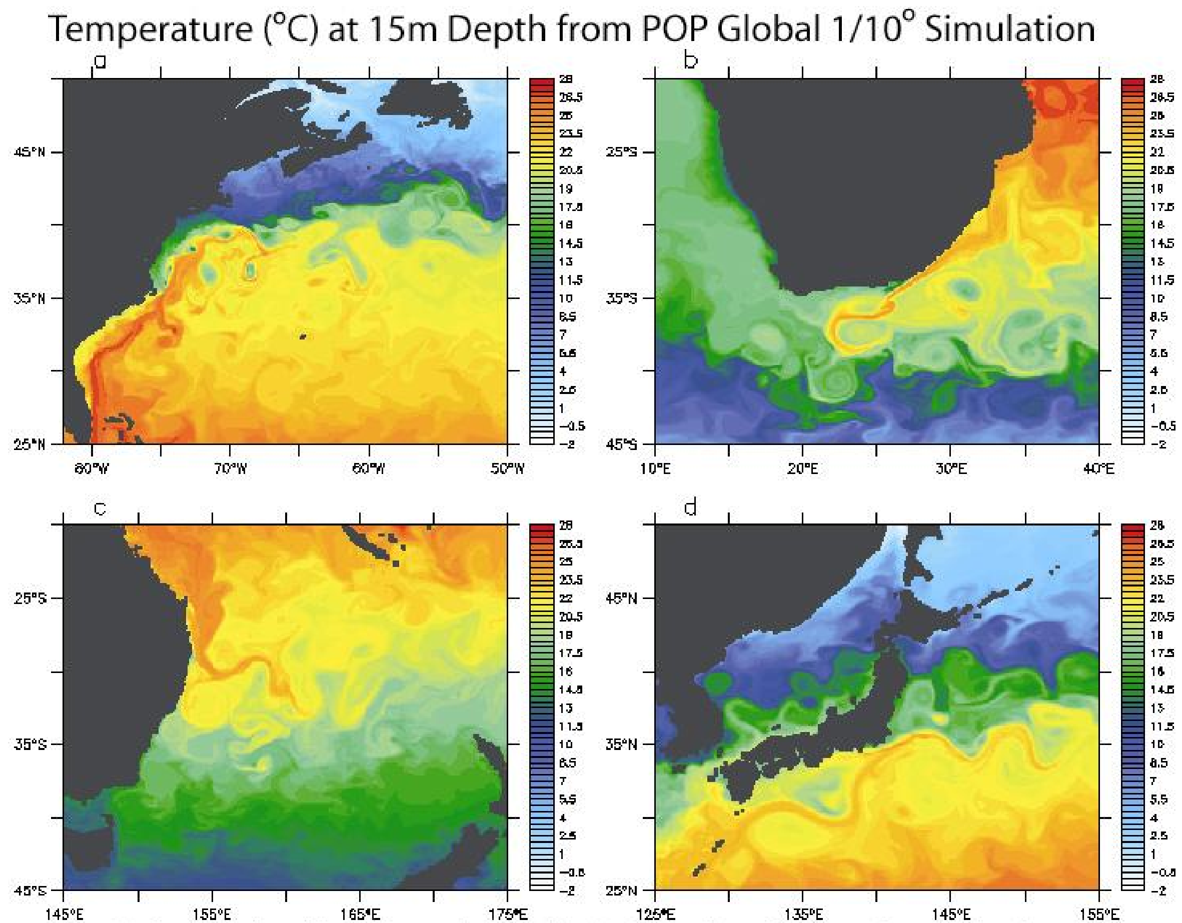
Mathew Maltrud (Los Alamos) and Julie McClean (Naval Postgraduate School)

Ocean climate models

- **Non-Eddy-Resolving Models (dx > 100 km)**
  - —*All turbulence must be paramete*
  - —*Most ocean-atmosphere models*
- **Eddy-Permitting Models (10 km < dx < 100 km)**
  - —*Only largest eddies resolved*
  - —*Few coupled ocean-atmosphere*
- **Eddy-Resolving Models (dx < 10 km)**
  - —*Dominant eddies well resolved*
  - —*Coupled systems expected soon*



Realistic simulations of coastal zones



Mathew Maltrud (Los Alamos) and Julie McClean (Naval Postgraduate School)

- Higher resolution enables realistic simulation of coastal currents.
- Computational cost is approximately 100 times current models.

Grand challenges in ocean biogeochemistry

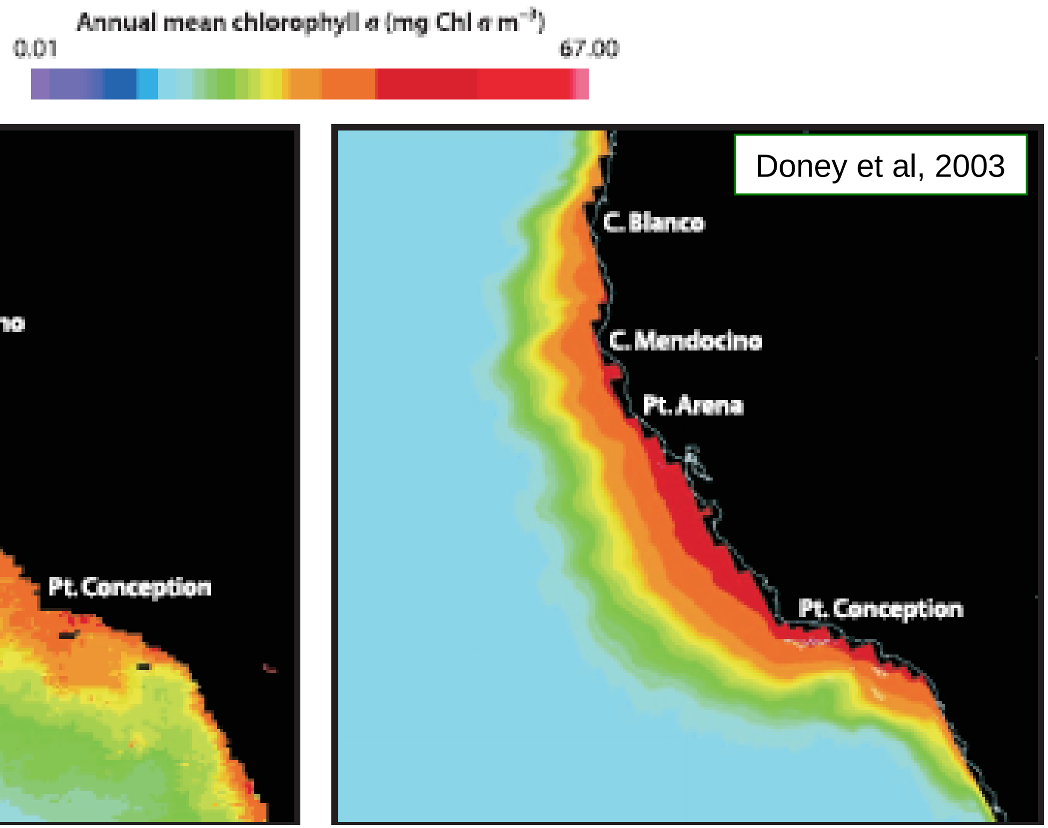


Fig. 9.16. Annual mean chlorophyll for the California Current coastal region from SeaWiFs and the UCLA regional coastal ecosystem model ROMS (James McWilliams, pers. comm.)

- Biogeochemistry in coastal zones.
- Interactions of ocean fronts and eddies with ocean ecosystems.
- Treatment of the ocean carbon cycle at the organism level.

Key climate questions for transformative computer capabilities

- How do natural and anthropogenic factors influence past, present, and future climate?
- How will natural systems amplify or reduce human influences on climate?
- How will the hydrological and ecological cycles respond to these influences?
- What are optimal methods for adapting to and mitigating climate change?