Modeling of Radiative Forcing and Climate Change at GFDL: A Perspective

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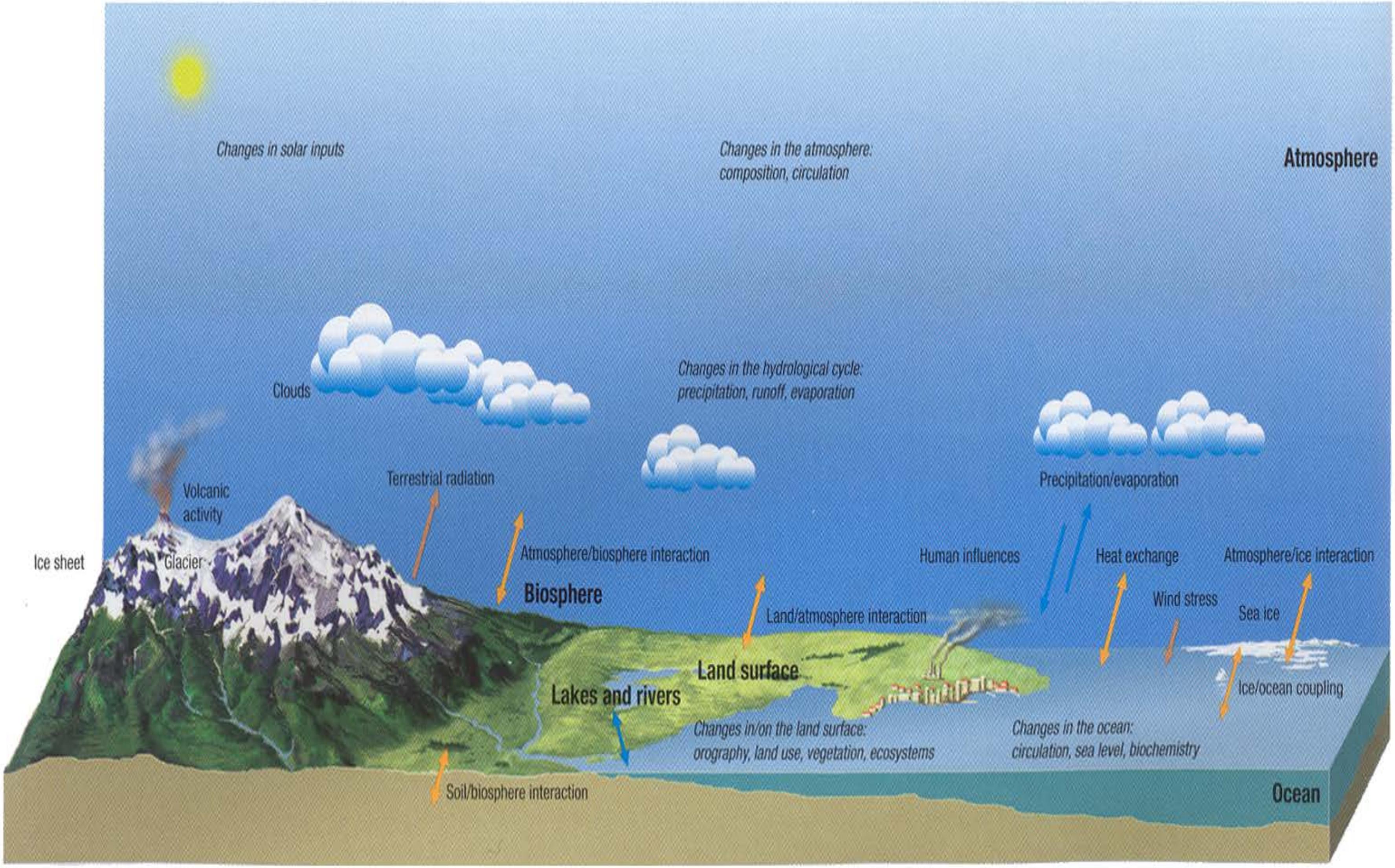


Changes in solar inputs
Changes in the atmosphere:
composition, circulation
Atmosphere
Clouds
Changes in the hydrological cycle:
precipitation, runoff, evaporation
Volcanic
activity
Terrestrial radiation
Precipitation/evaporation
Ice sheet
Glacier
Atmosphere/biosphere interaction
Human influences
Heat exchange
Atmosphere/ice interaction
Biosphere
Wind stress
Land/atmosphere interaction
Sea ice
Land surface
Ice/ocean coupling
Lakes and rivers
Changes in/on the land surface:
orography, land use, vegetation, ecosystems
Changes in the ocean:
circulation, sea level, biochemistry
Soil/biosphere interaction
Ocean

Climate and Climate Change

- Basic curiosity → understanding the climate system
- With the advancement of knowledge, through theory and measurements, an increasing desire to know the properties of all the components of the system and the interactions between them
- Understanding climate variations and change, including those caused by internal and external forcings
- Goal of climate predictions and projections, much like "weather forecasts"
- Societal needs, questions and concerns → as reflected by UNFCCC, IPCC and other international bodies. E.g., extremes and abrupt changes.

Challenges in modeling

- Need to continually inject increased realism → explicit incorporation of more physical and chemical (and biological) processes
- Increasing cross-disciplinariness in climate sciences
- Need to continually study parameterizations; understand causes of biases; question both model and measurements including accounting for variability
- Improving upon the known biases and limitations, and paying attention to the advances in fundamental aspects – theory and measurements
- Models are ‘tuned’; as physical realism increases, ‘knobs’ for tuning may no longer exist or give way to newer ones; linkages across classical boundaries (e.g., aerosols and clouds) demand more stringent consistency checks
- Address the climate-centric questions posed by society with models whose reliability keeps on improving

Modeling "Axioms"

- Early recognition (1950s-1960s) of the need for models and computational infrastructure.
- Realization of the need for adequate, appropriate and relevant physics as the building blocks for the models.
- Recognition that models must be suitably built to address the complex problems, consistent with computational power available.

Hardware-to-Brainware expense ratio has remained approximately steady at 1:1 at GFDL

GFDL Modeling: 1970s to 2000+

By early 1970s, 3 atmospheric models emerged

→ Manabe Climate Model: coupled atmosphere-ocean; simple physics; no climate drift; focus on surface-troposphere long-term changes; multi-century integrations; computationally fast

→ SKYHI model: higher vertical and horizontal resolution; top at mesopause; focus on stratospheric radiation-dynamical-chemical processes; up to decade's worth of simulations possible

→ NWP model: research tool; more physics details than in Climate model, but had drifts; surface and troposphere variations on the intraseasonal to interannual time scales, especially in the tropics.

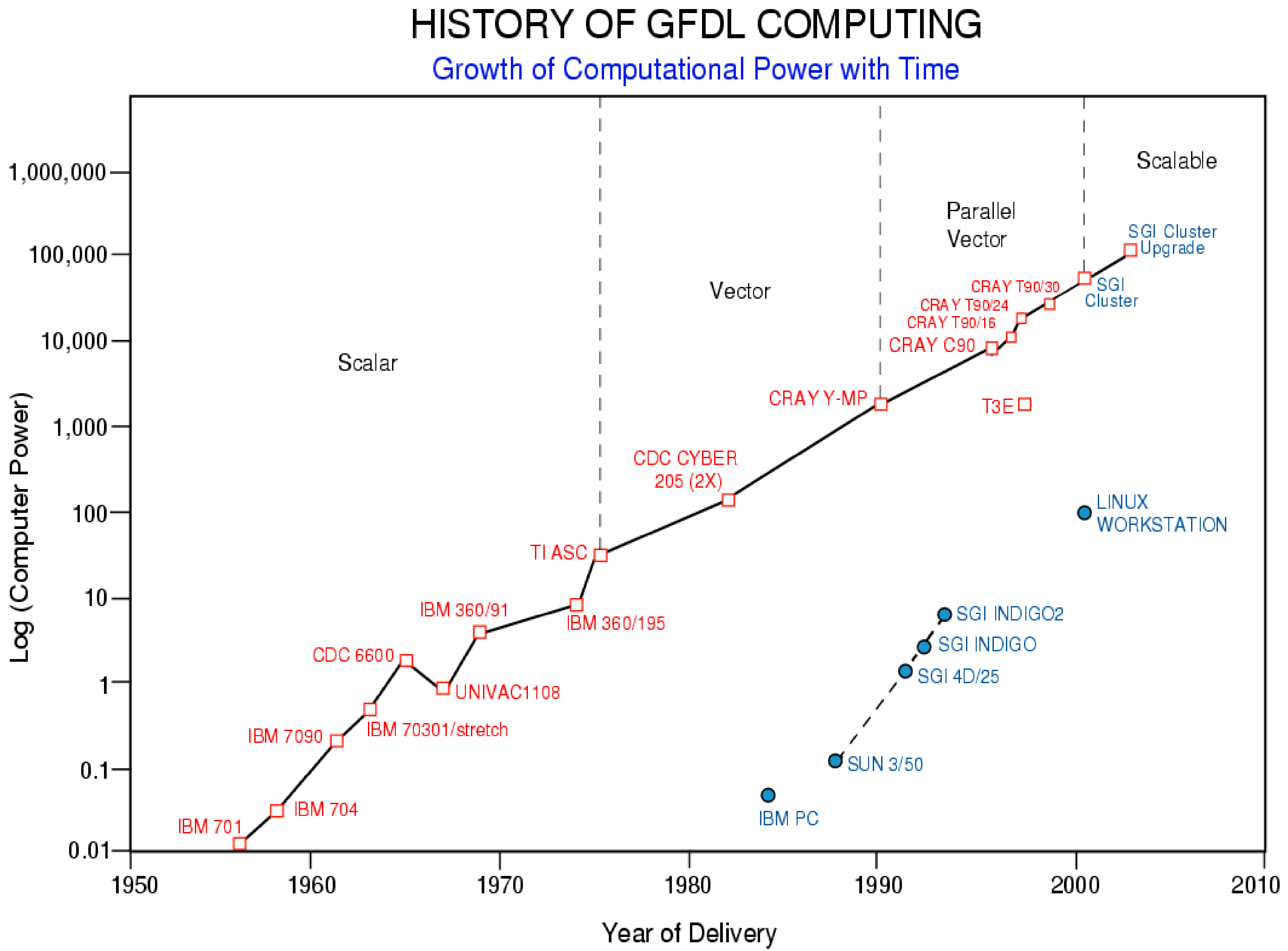
From early 2000 onwards, SINGLE model framework for doing climate science

Essentials…….

- Ask questions of models that can be answered on the present system using the current model.
  - CPU time – Can it be run on this system?
  - Code – Can it be simulated?
  - Simulation – Is simulation good enough?

Other Important Issues

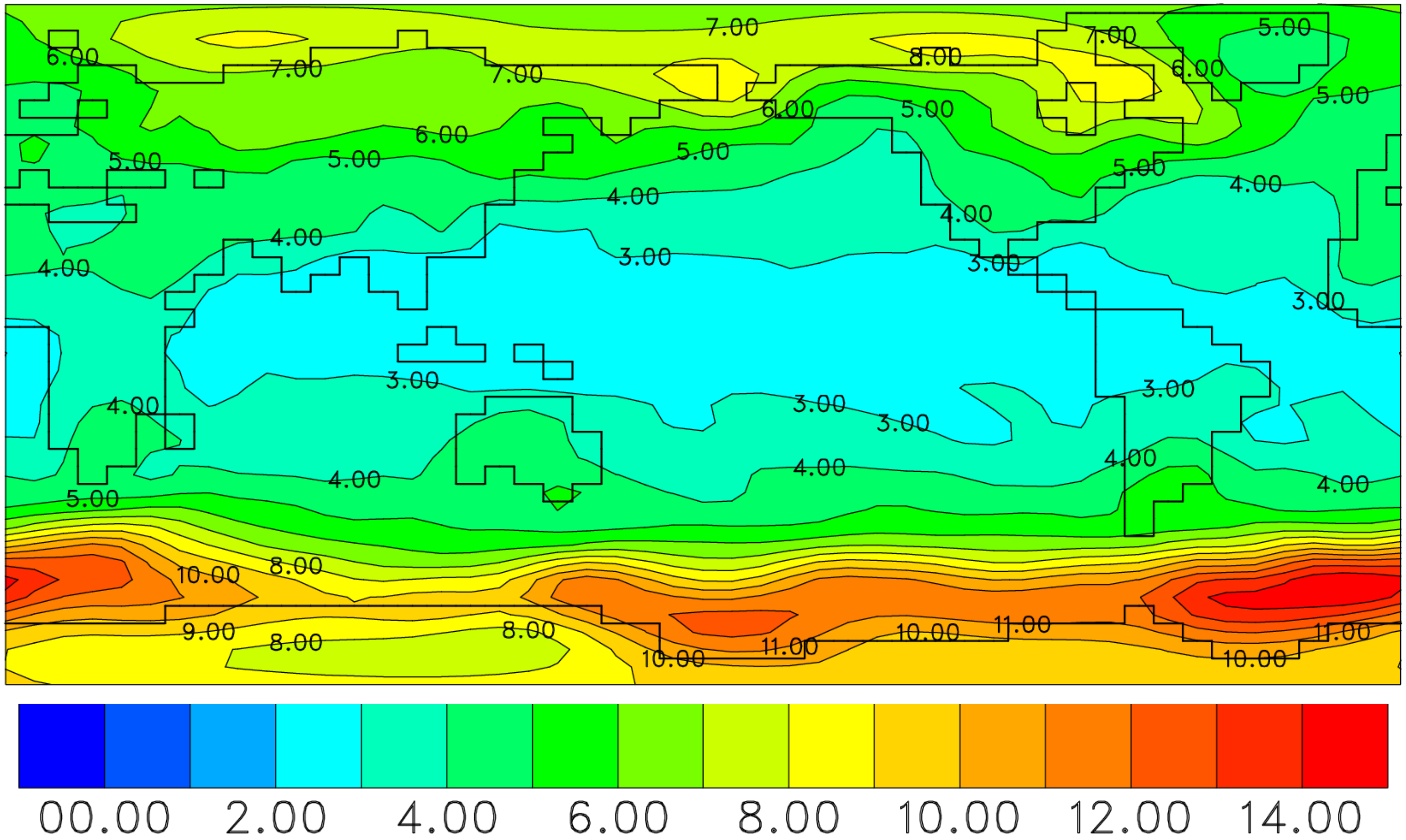
- Data storage
- Ease of analysis
- Stability of hardware and software
- Model code and script environment
- Visualization convenience


HISTORY OF GFDL COMPUTING
Growth of Computational Power with Time
Scalar
Vector
Parallel Vector
Scalable
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.01
Log (Computer Power)
1950
1960
1970
1980
1990
2000
2010
Year of Delivery
IBM 701
IBM 704
IBM 7090
IBM 70301/stretch
CDC 6600
UNIVAC1108
IBM 360/91
IBM 360/195
TI ASC
CDC CYBER 205 (2X)
CRAY Y-MP
CRAY C90
CRAY T90/16
CRAY T90/24
CRAY T90/30
T3E
SGI Cluster
SGI Cluster Upgrade
LINUX WORKSTATION
SGI INDIGO2
SGI INDIGO
SGI 4D/25
SUN 3/50
IBM PC

TI ASC Findings

Annual Mean Surface Air Temperature ($2XCO_2$ – $1XCO_2$)

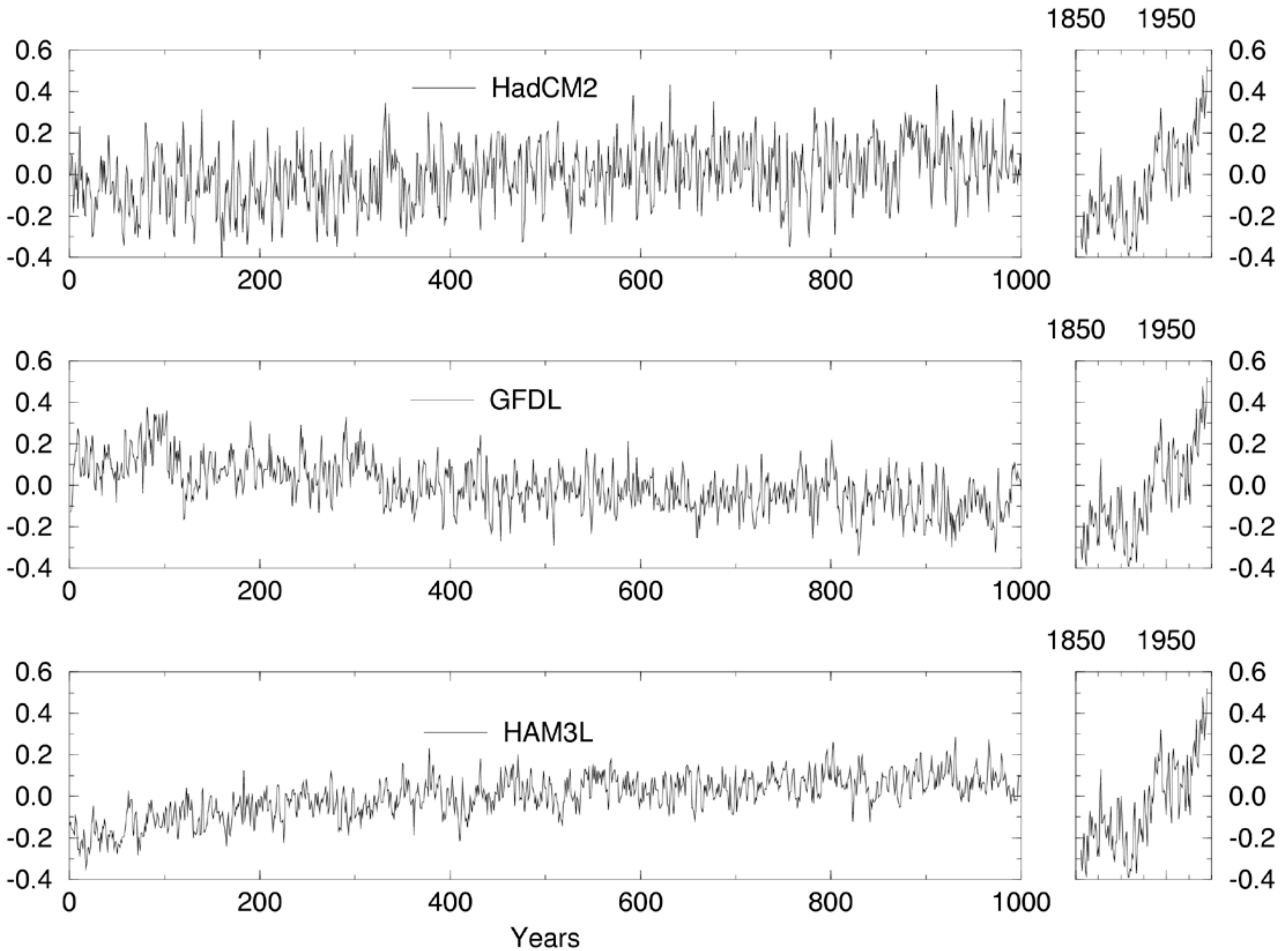
1. Polar amplification
2. Land warms more than adj. Ocean
3. Warming max in spring near snow edge
4. Warming max in fall near sea ice edge



R15 atmosphere-mixed layer ocean result

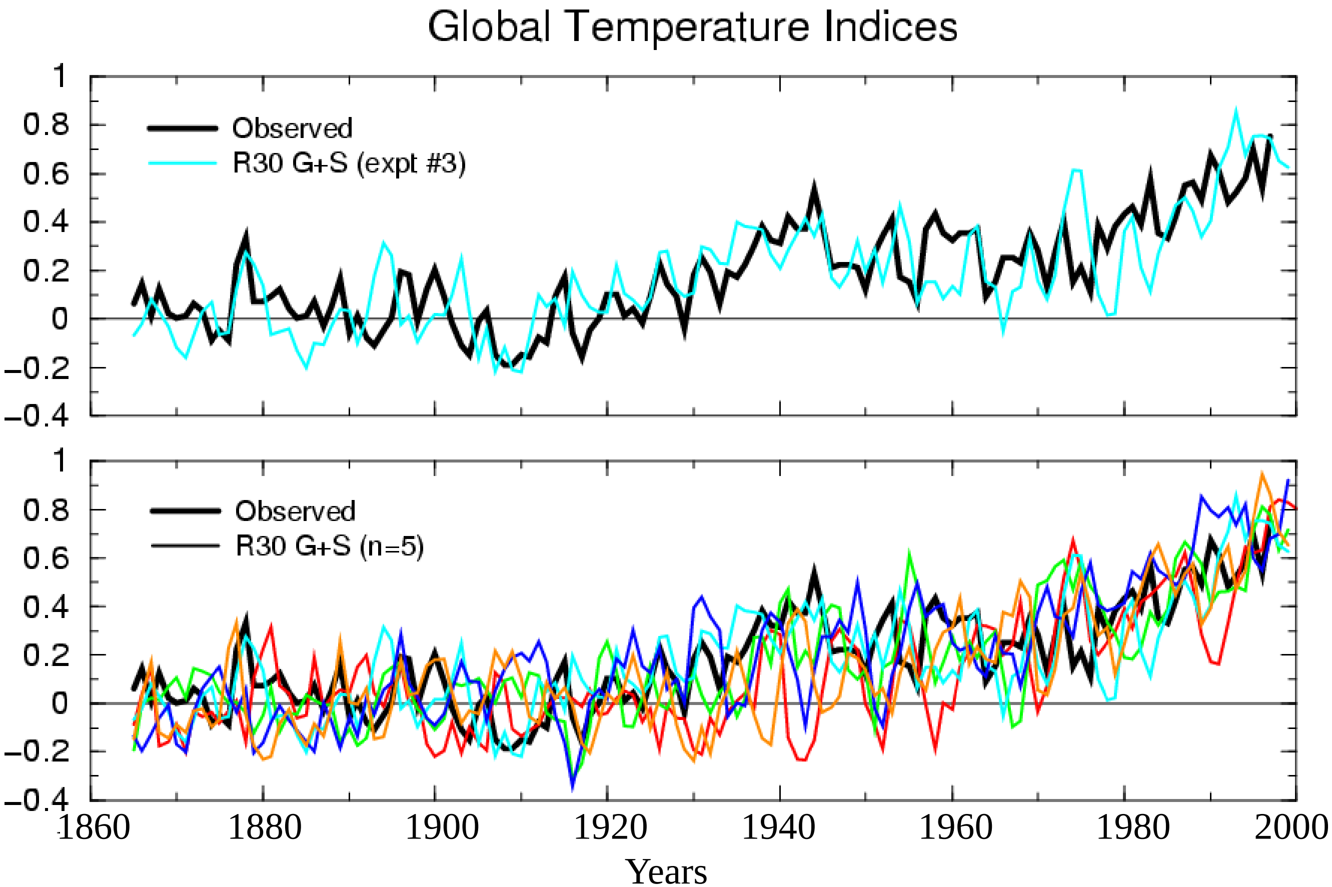
YMP Findings

1. Variability on short time scales (less than 10 years) assessed
2. Variability on longer time scales leads to detection of changed climate



C90 New Findings

1. Detection and attribution of climate change
2. Part of early 20th century warming may be due to natural variability

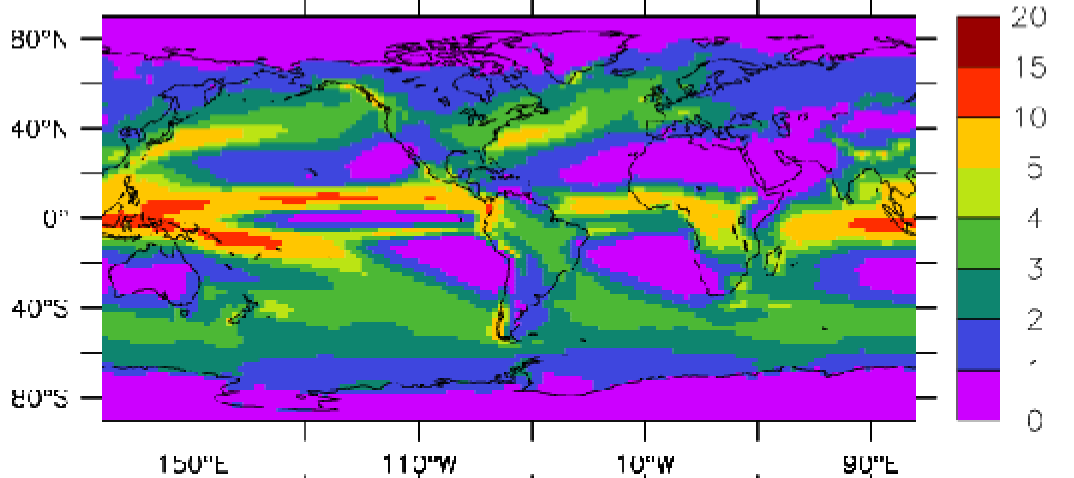


R30 coupled model results

GFDL Coupled Model: CM 2.1

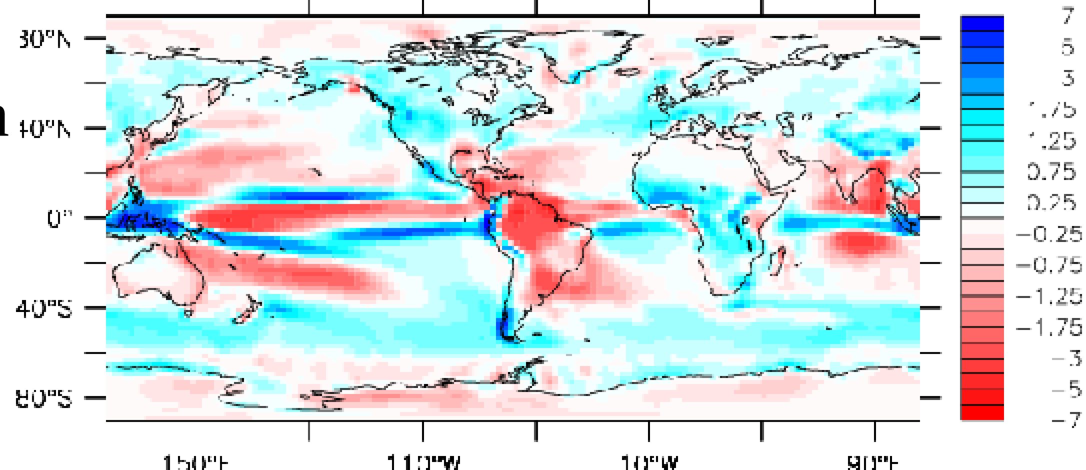
- Grid-point model using finite volume method for atmosphere and ocean dynamics.
- Horizontal resolution of atmosphere and land components is 2x2.5 degrees. Ocean component is 1x1 degrees (finer in tropics).
- Vertical resolution of atmosphere is 24 layers. 8 layers in planetary boundary layer. 4 layers in the stratosphere with highest layer at ~3 hPa or ~40 km.
- Coupled model description and performance - Delworth et al (*J. Clim., 2005*); atmospheric component description - Anderson et al (*J. Clim., 2004*)

Coupled

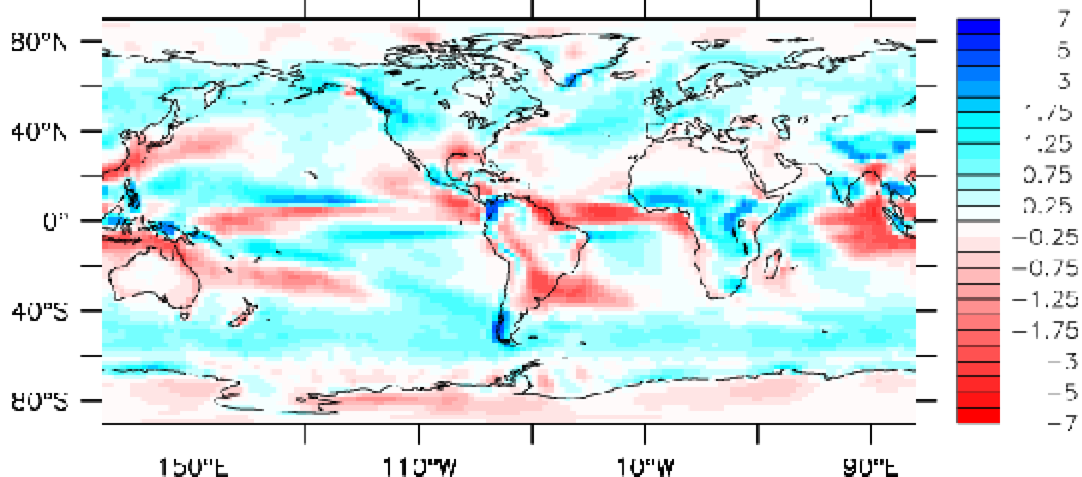


Precipitation (mm/day)

Coupled-
Xie and Arkin

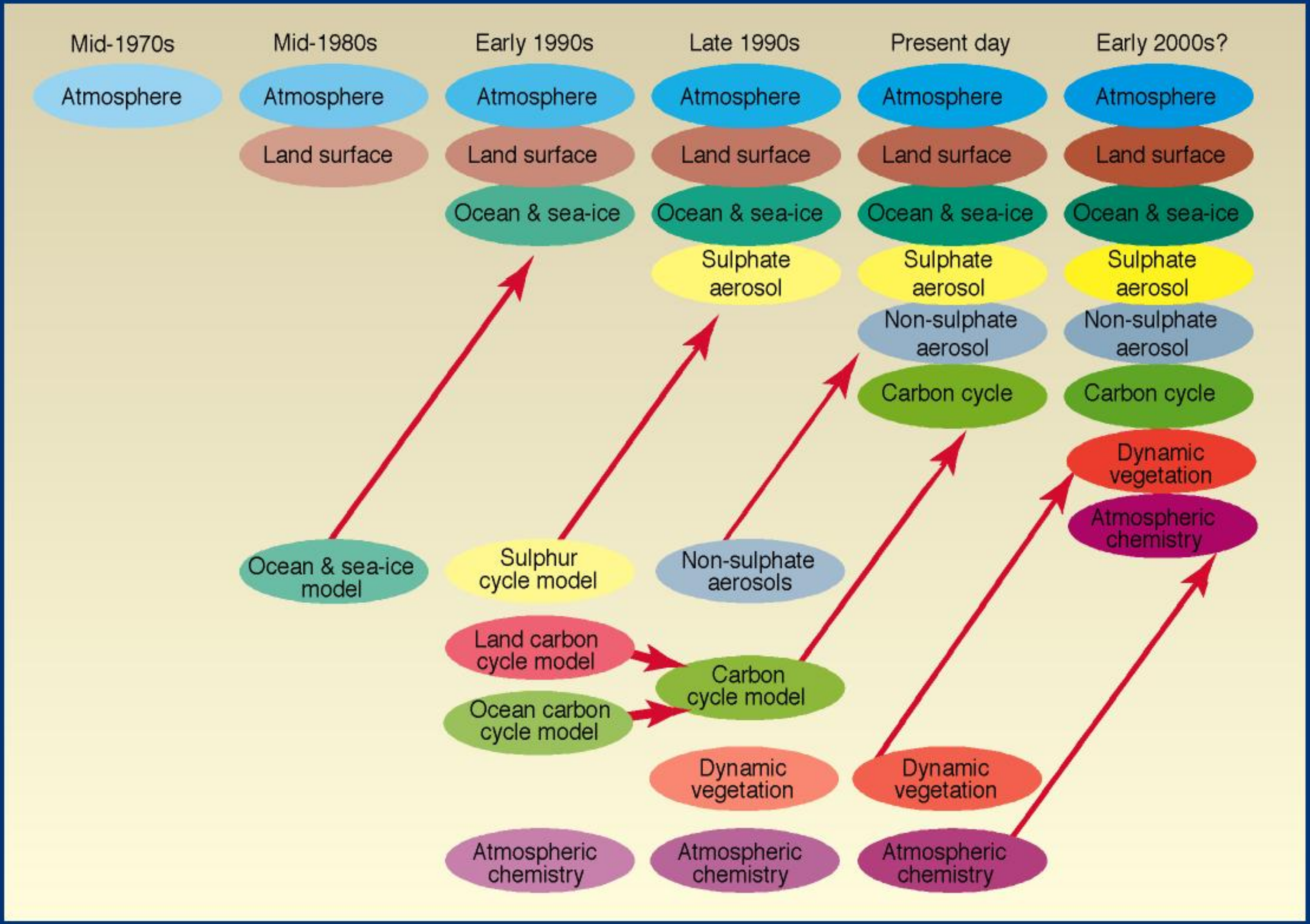


Atmosphere-
Xie and Arkin



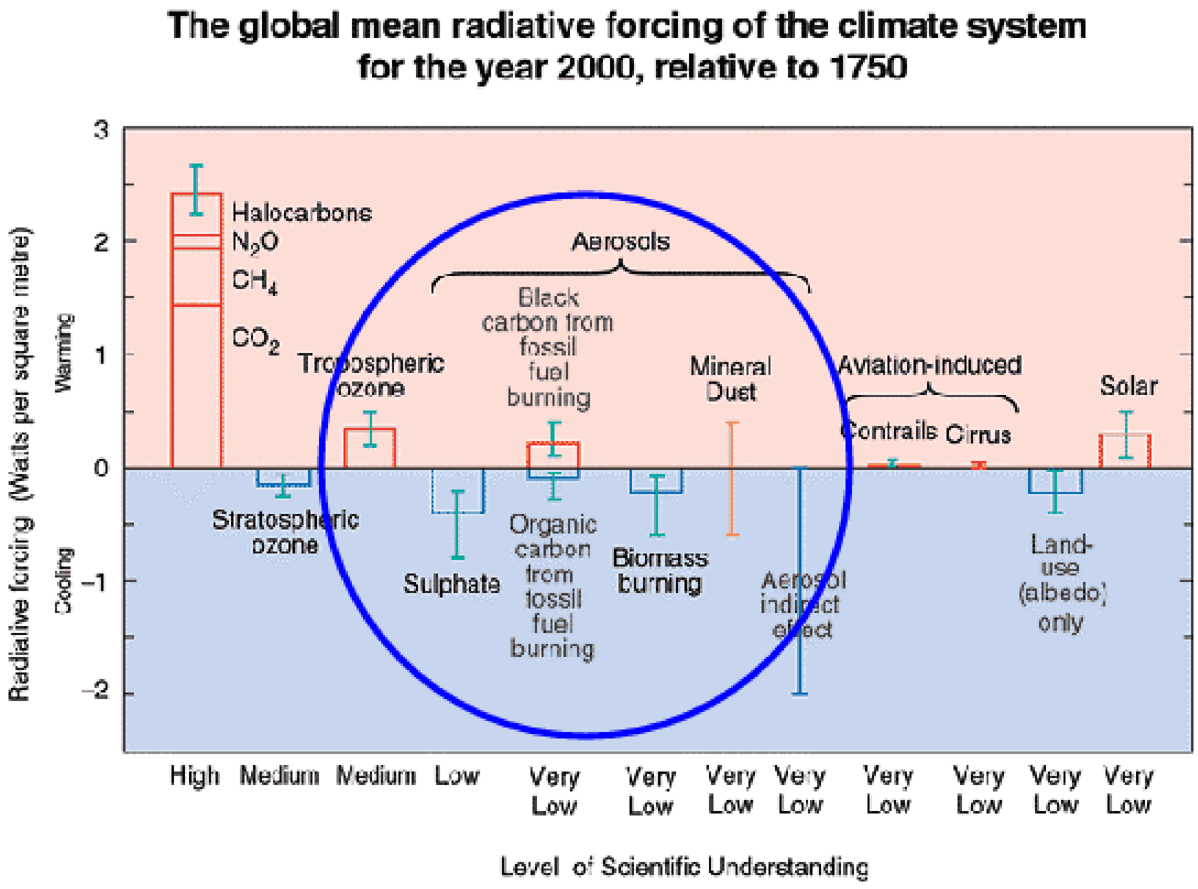
Delworth *et al.* (2005, *J. Clim.*)

The development of climate models, past, present and future

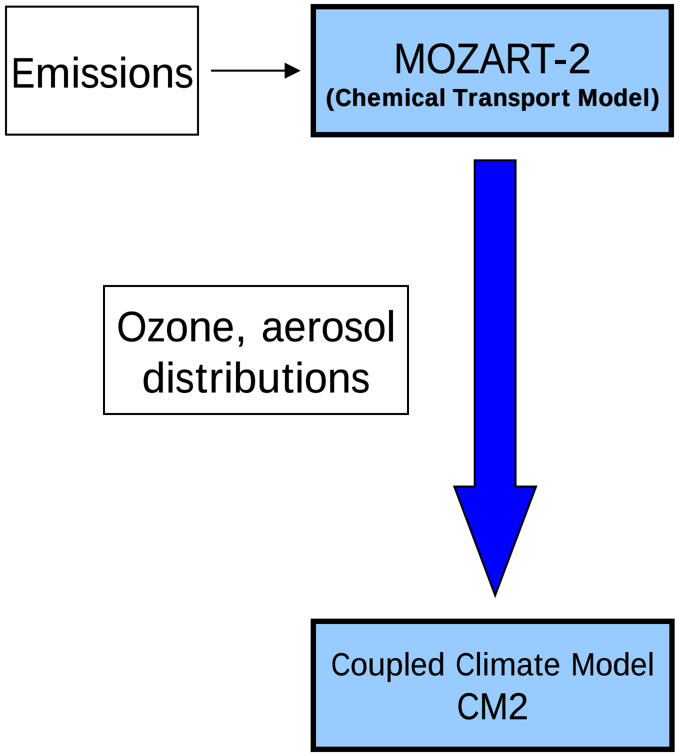


WG1 - TS BOX 3
FIGURE 1

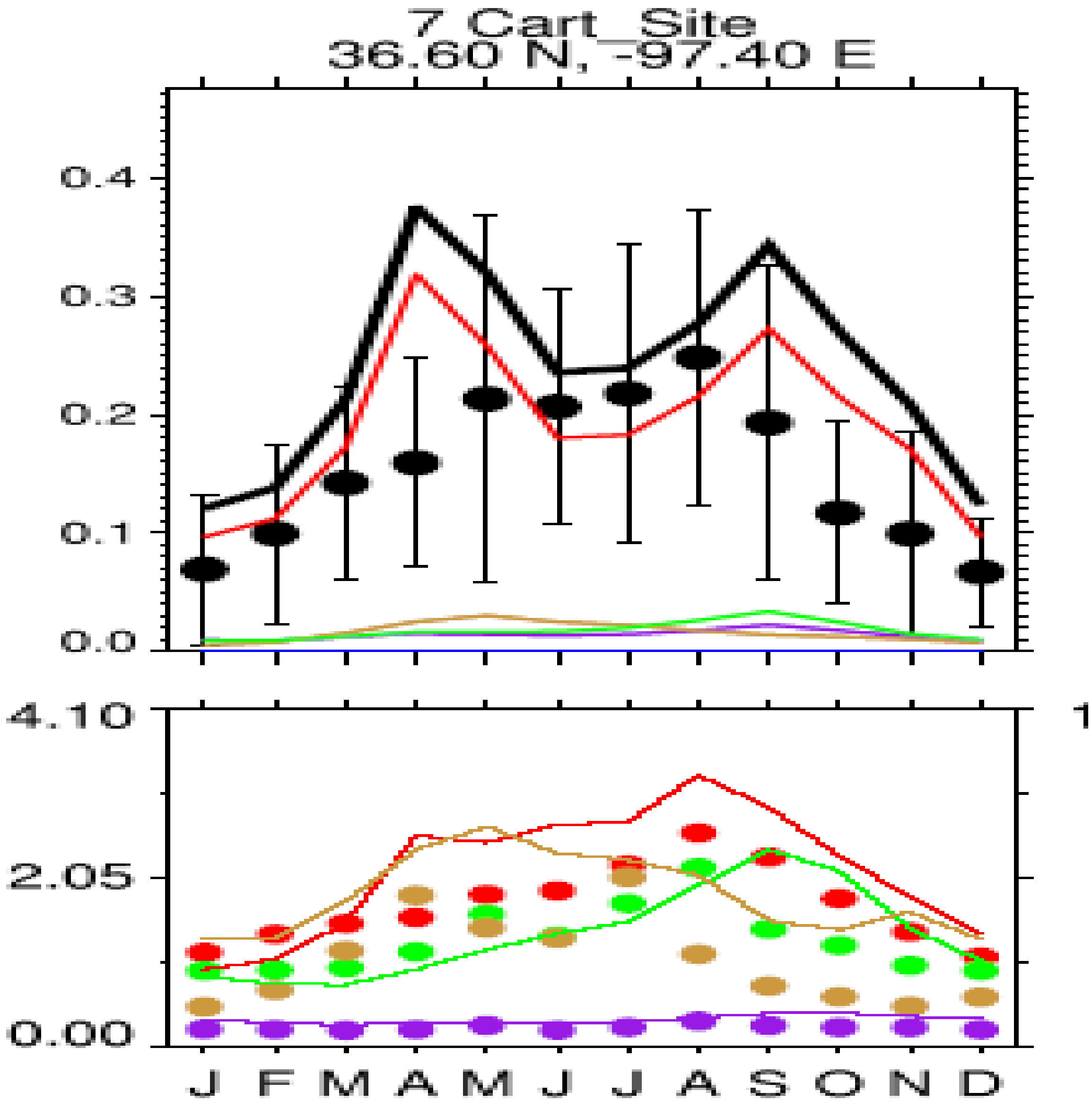
Climate Forcing (IPCC, 2001)



One-way Coupling (completed)

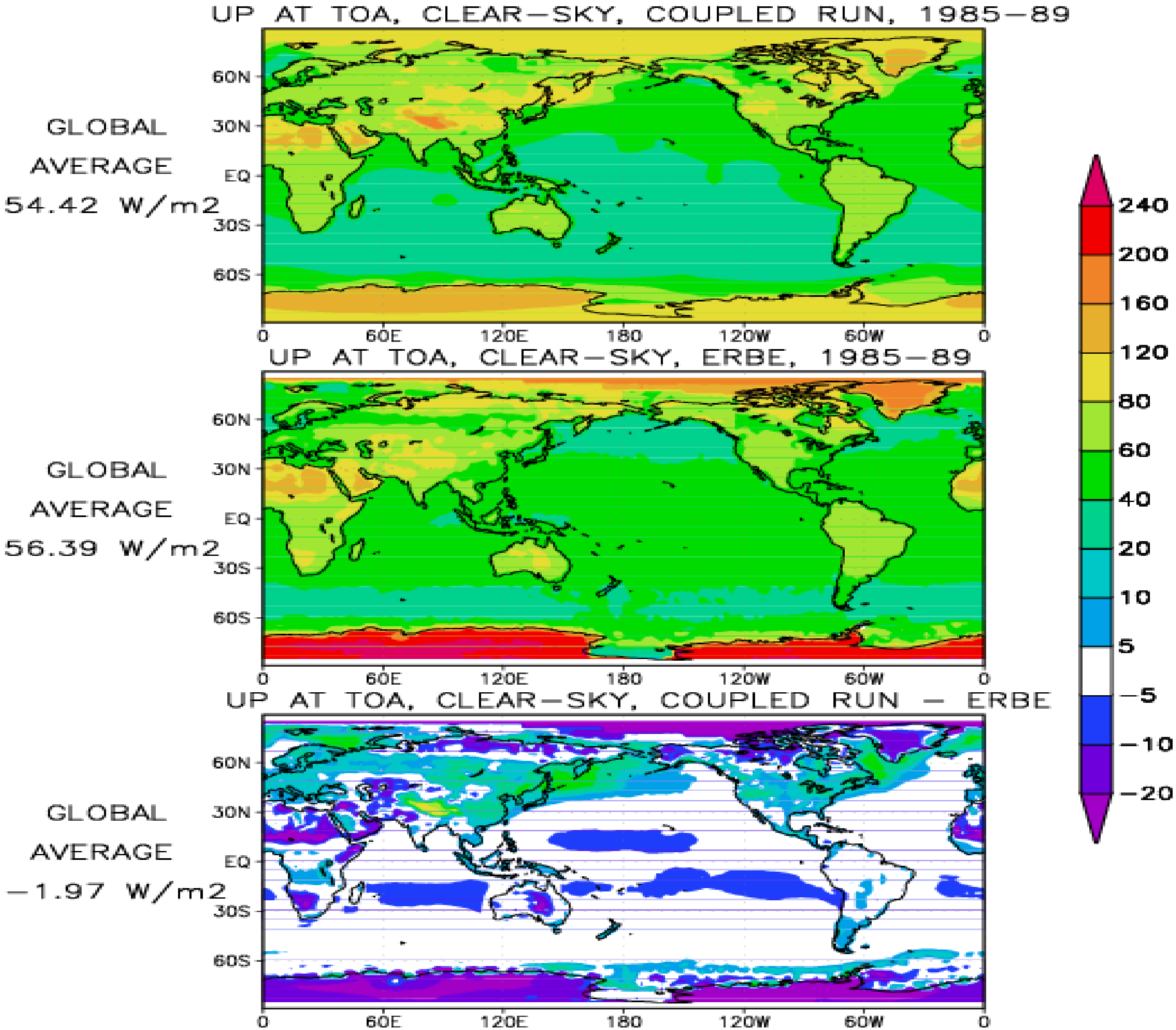


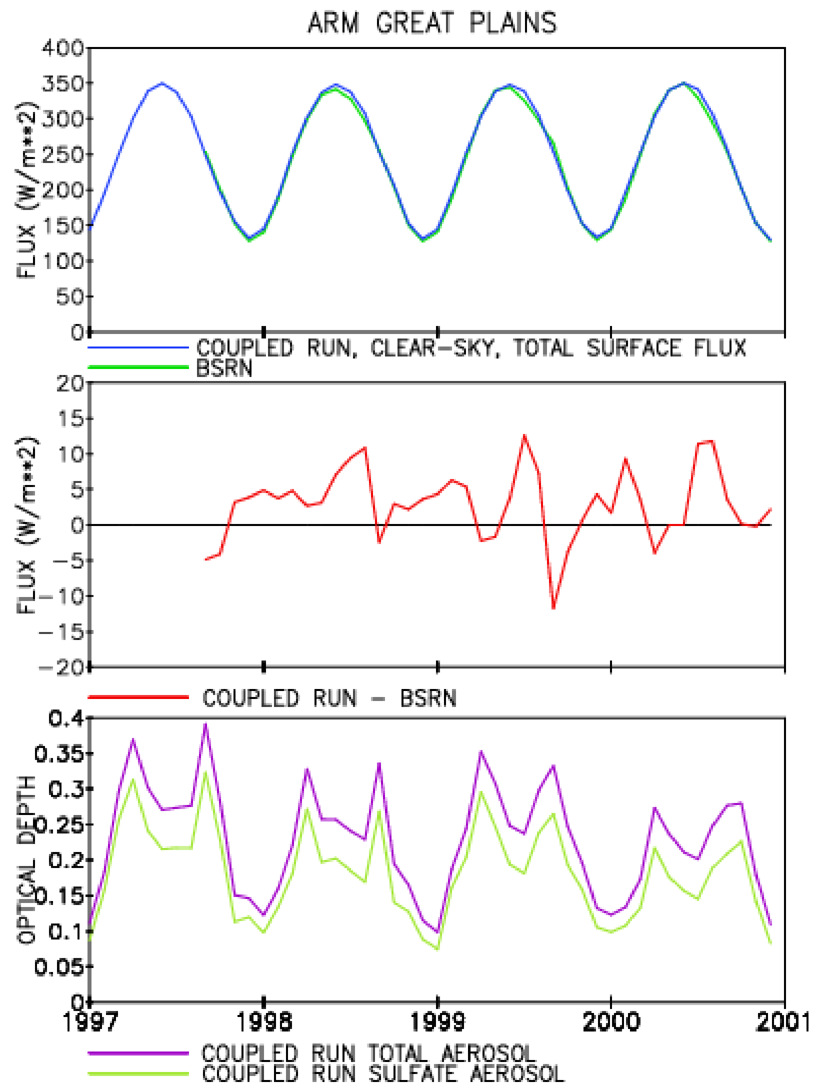
- **Used in GFDL simulations for IPCC/AR4, CCSP, AEROCOM**
- **Impact of changing emissions on climate**
- **Historical runs (1860-present, decadal)**
- **Future runs (present-2100, decadal) for A2, A1B, B1 scenarios**



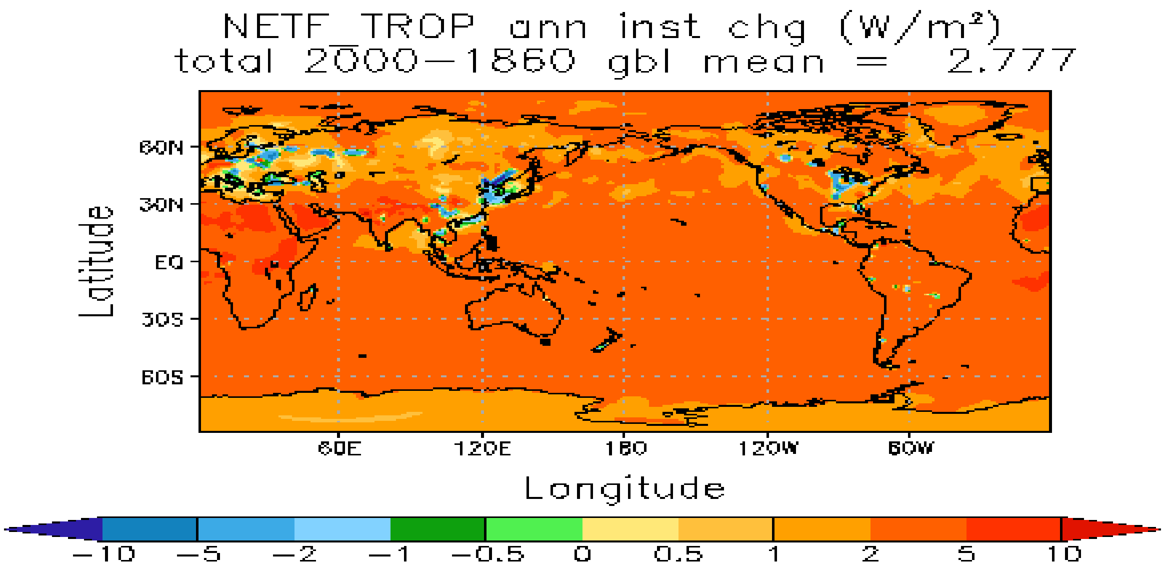
7 Cart_Site
36.60 N, -97.40 E
0.4
0.3
0.2
0.1
0.0
4.10
2.05
0.00
1
J F M A M J J A S O N D

Comparison of Clear-Sky SW @ TOA

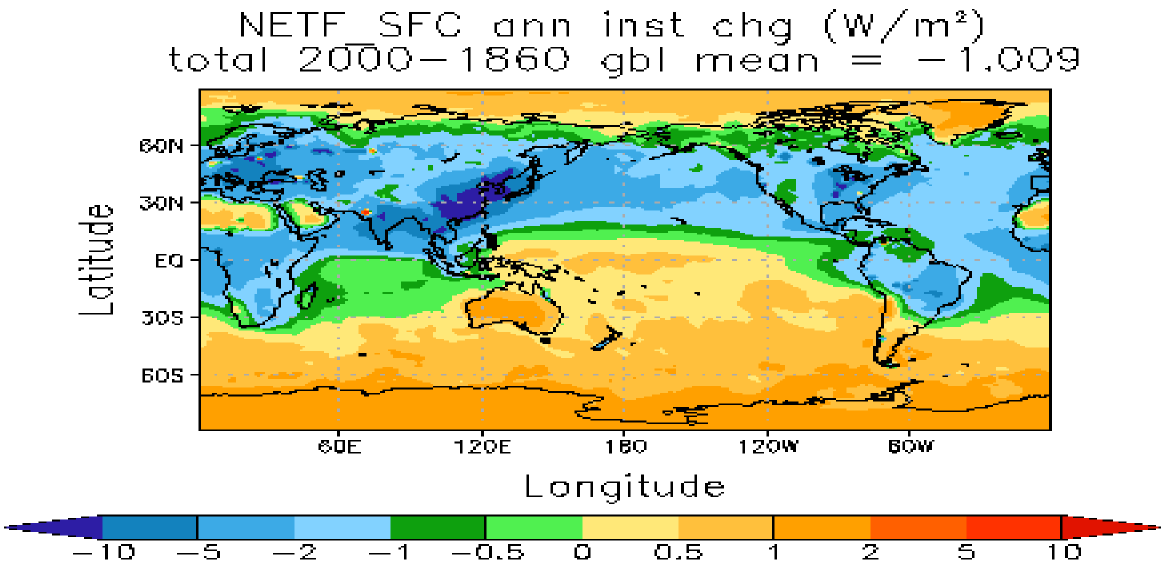




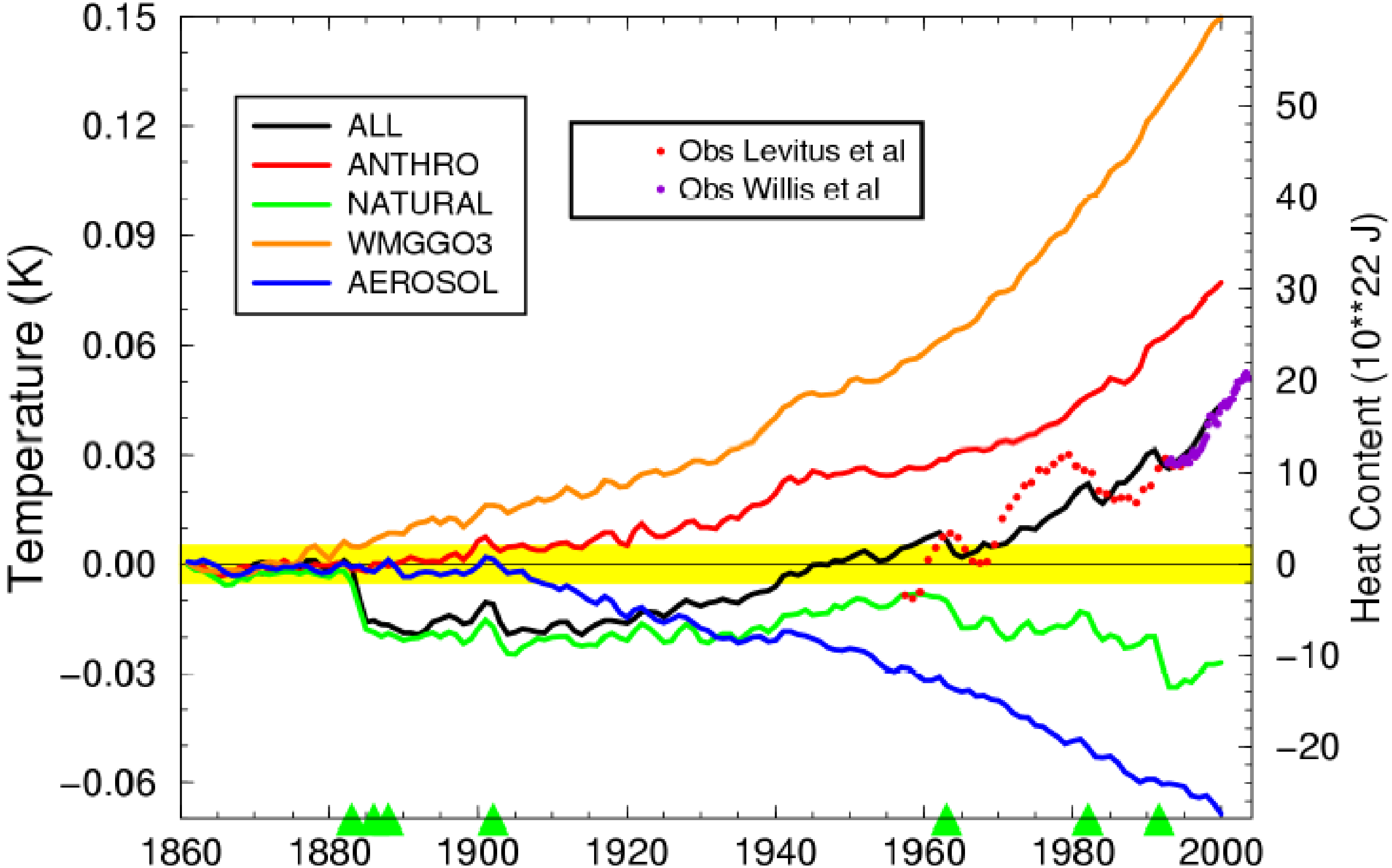
ARM GREAT PLAINS
FLUX (W/m**2)
400
350
300
250
200
150
100
50
0
COUPLED RUN, CLEAR-SKY, TOTAL SURFACE FLUX
BSRN
FLUX (W/m**2)
20
15
10
5
0
−5
−10
−15
−20
COUPLED RUN − BSRN
OPTICAL DEPTH
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1997
1998
1999
2000
2001
COUPLED RUN TOTAL AEROSOL
COUPLED RUN SULFATE AEROSOL



NETF_TROP ann inst chg (W/m²)
total 2000−1860 gbl mean = 2.777
60N
30N
EQ
30S
60S
Latitude
60E
120E
180
120W
60W
Longitude
−10 −5 −2 −1 −0.5 0 0.5 1 2 5 10



NETF_SFC ann inst chg (W/m²)
total 2000−1860 gbl mean = −1.009
60N
30N
EQ
30S
60S
Latitude
60E
120E
180
120W
60W
Longitude
−10 −5 −2 −1 −0.5 0 0.5 1 2 5 10



0.15
0.12
0.09
0.06
0.03
0.00
−0.03
−0.06
Temperature (K)
ALL
ANTHRO
NATURAL
WMGGO3
AEROSOL
Obs Levitus et al
Obs Willis et al
50
40
30
20
10
0
−10
−20
Heat Content (10**22 J)
1860
1880
1900
1920
1940
1960
1980
2000

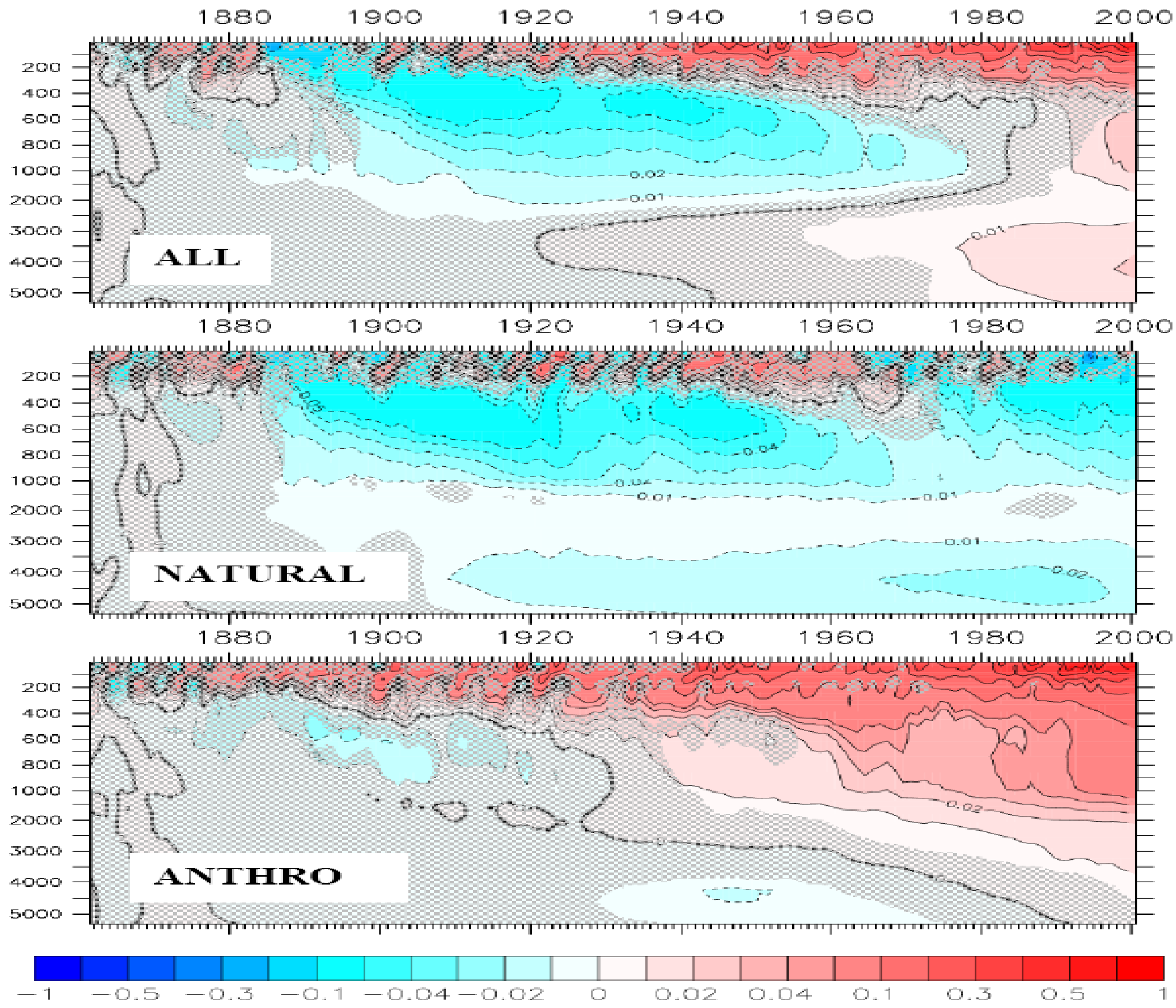
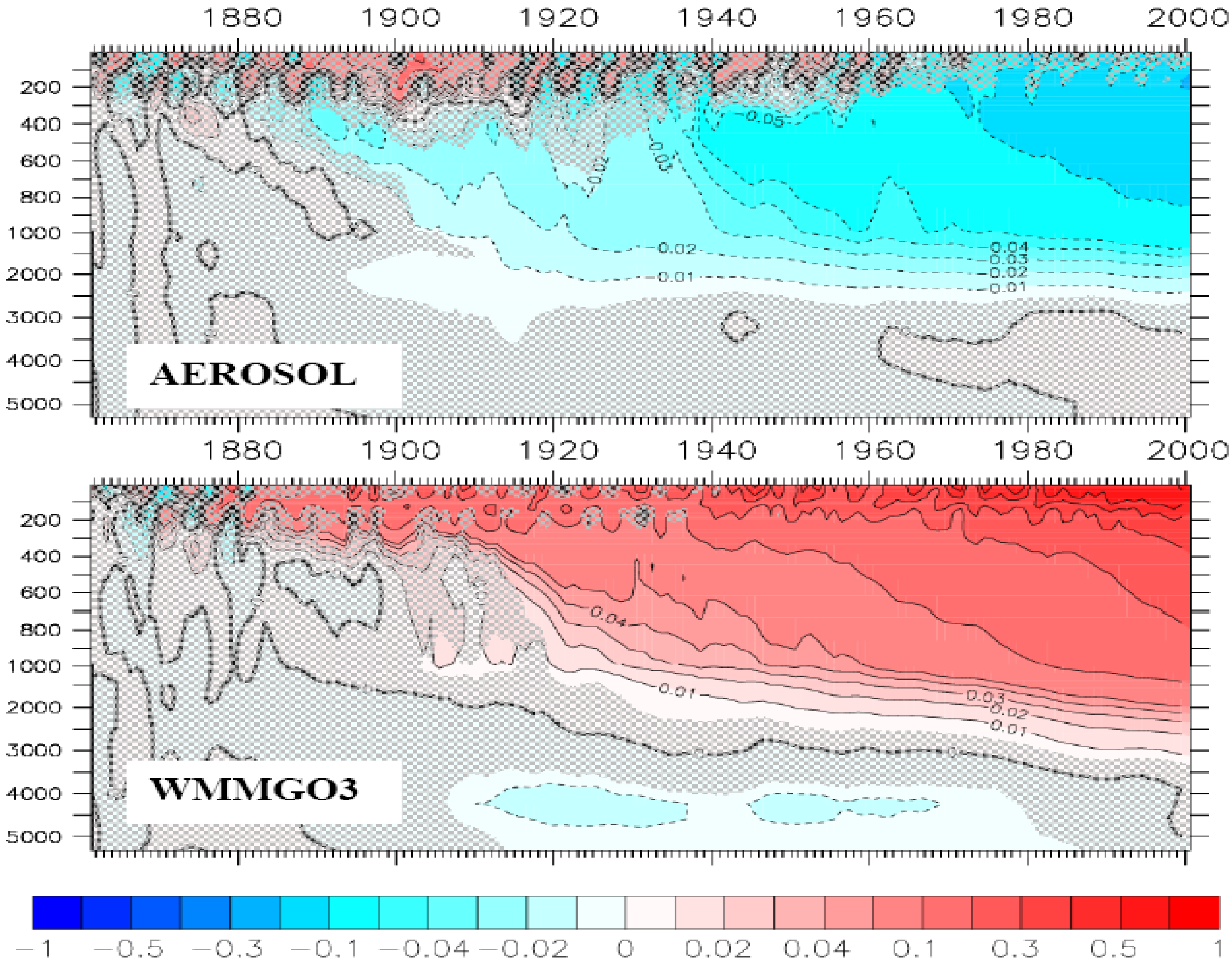
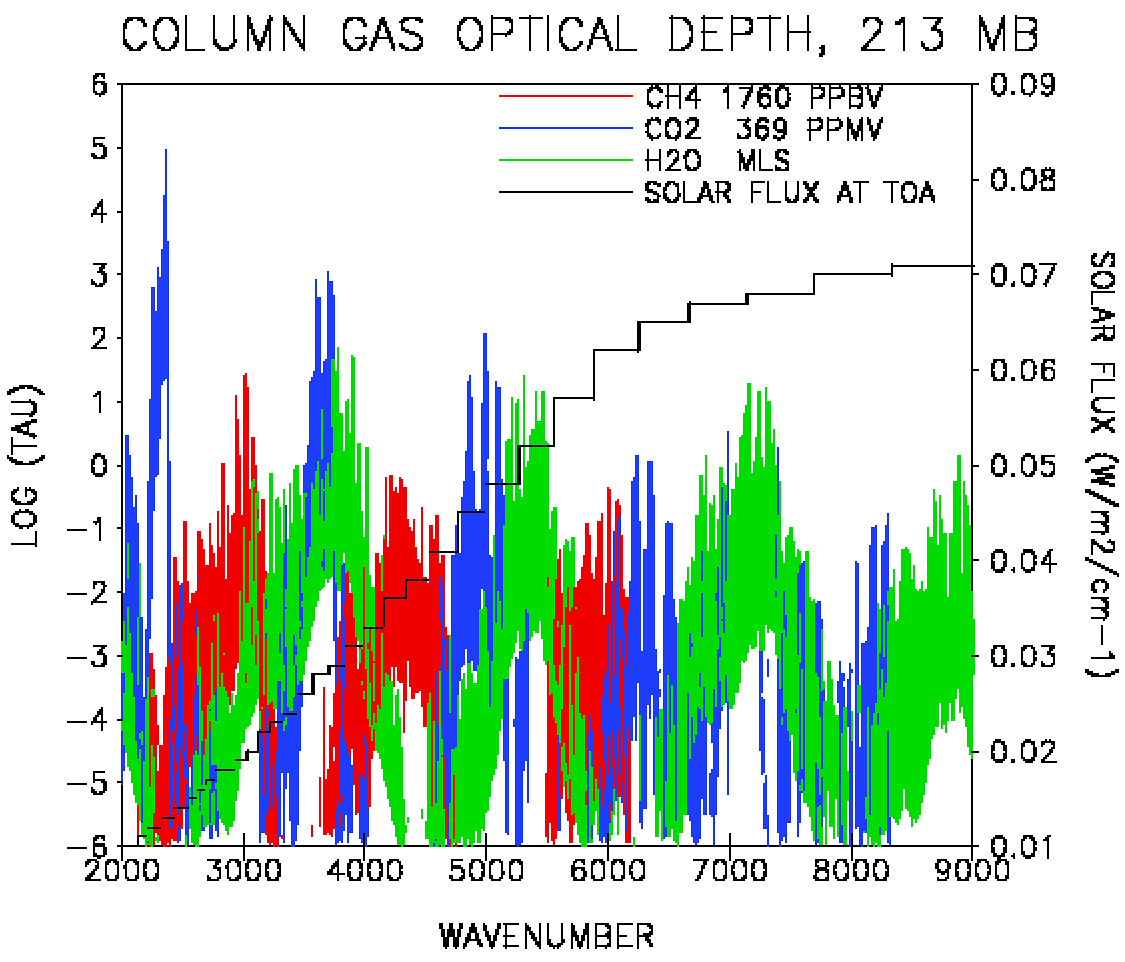

1880
1900
1920
1940
1960
1980
2000
200
400
600
800
1000
2000
3000
4000
5000
ALL
NATURAL
ANTHRO
0.02
0.01
0.04
−1
−0.5
−0.3
−0.1
−0.04
−0.02
0
0.02
0.04
0.1
0.3
0.5
1

Fig. 2



AEROSOL
WMMGO3
1880
1900
1920
1940
1960
1980
2000
200
400
600
800
1000
2000
3000
4000
5000
-0.05
-0.04
-0.03
-0.02
-0.01
0.04
0.03
0.02
0.01
-1
-0.5
-0.3
-0.1
-0.04
-0.02
0
0.02
0.04
0.1
0.3
0.5
1


COLUMN GAS OPTICAL DEPTH, 213 MB
CH4 1760 PPBV
CO2 369 PPMV
H2O MLS
SOLAR FLUX AT TOA
LOG (TAU)
SOLAR FLUX (W/m2/cm−1)
WAVENUMBER
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
2000
3000
4000
5000
6000
7000
8000
9000
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01

WMGG SW Change in Abs. [2000-1860] {Clear-sky; GFDL LBL}

Gases	Stratos. Abs.	Tropos. Abs.	Sfc.
All	0.55	0.44	-0.86
CH_4+CO_2	0.53	0.43	-0.84
CO_2	0.31	0.04	-0.31
(CH_4)	0.22	0.40	-0.53

Solar CH_4 comparable to Solar CO_2

Future ➔ Computers will continue to get more powerful.

This allows:

- the model grids to become finer,
- model physical parameterizations to become more complex,
- more components to be added.

Future Challenges

More explicit descriptions and understanding of the aerosol, cloud and precipitation problems

➔ Convection-Clouds-Microphysics-Radiation-Precipitation

➔ Emissions-CCN-Aerosols-Clouds

➔ Land surface-atmosphere interactions

➔ Atmosphere-biosphere interactions (e.g., C, N cycles)

*

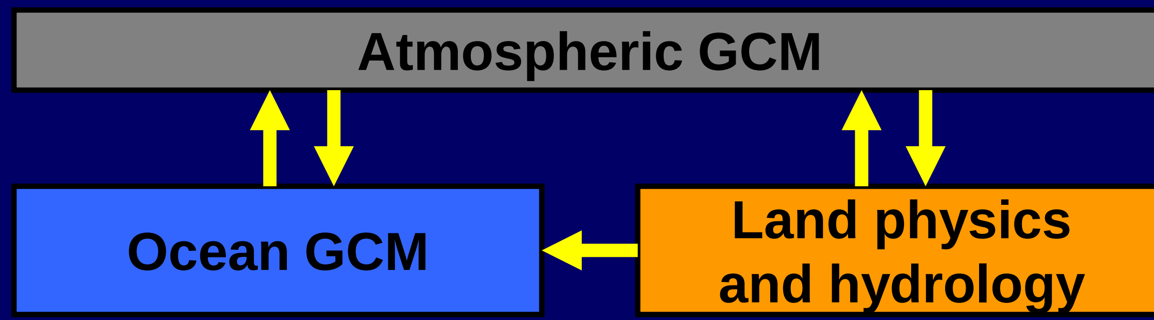
Aerosol effects associated with Clouds [NRC, 2005]

- Twomey effect (cloud albedo effect) ➔ -
- Albrecht effect (cloud lifetime effect) ➔ -
- Semi-direct effect (abs. aerosols) ➔ +
- Glaciation (mixed-phase clouds) ➔ +
- Thermodynamic (mix-phase clds) ➔ ?

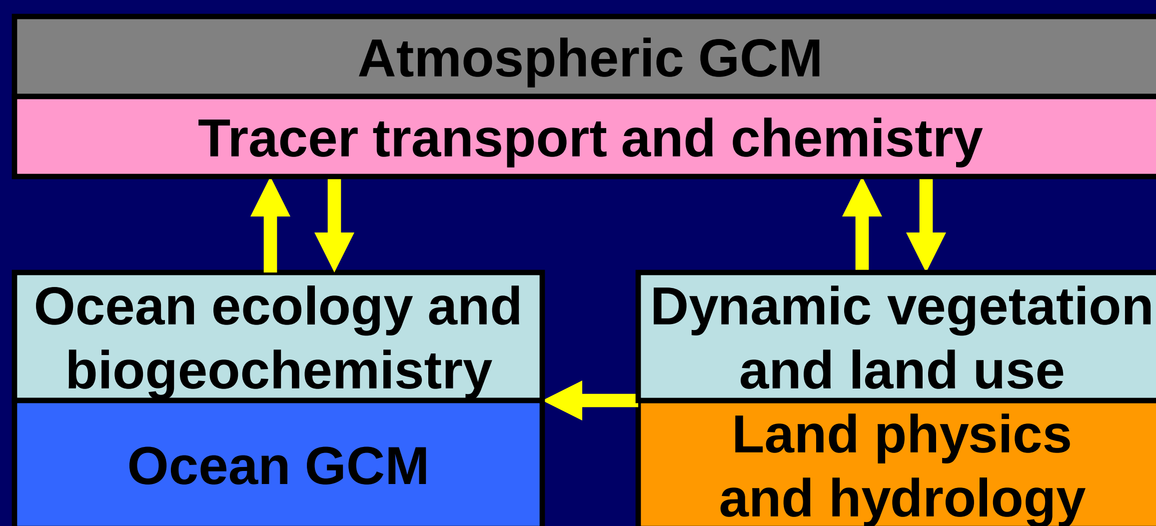
Surface energy (All cloud types) ➔ -

What is an Earth System Model?

Climate Model



Earth System Model



from John Dunne, GFDL

Future Demands on Models

* Understanding the climate system:
  → feedbacks, variations;
  → human-induced, natural, and unforced changes

* Projections and predictions of climate on an “operational” basis

Future:
Likely substantial improvements in Climate Science over the next 10 years?

- Improved knowledge base on clouds, their role in feedbacks and aerosol-(warm) cloud linkages
- Long term climate change (multiple centuries) and stabilization using “realistic” scenarios
- Interactions and feedbacks between physical climate and biogeochemical systems
- Detection/attribution of climate change
  - Better understanding of natural variations (ENSO, NAO, AAO, PDO, etc.)
- Oceanic heat uptake and transport

Acknowledgements

- Global Atmospheric Model Development Team
- Coupled Model Development Team
- Tom Delworth, Paul Ginoux, Steve Klein, Yi Ming, Dan Schwarzkopf, Ron Stouffer