Introduction to Coupled Earth System Modeling

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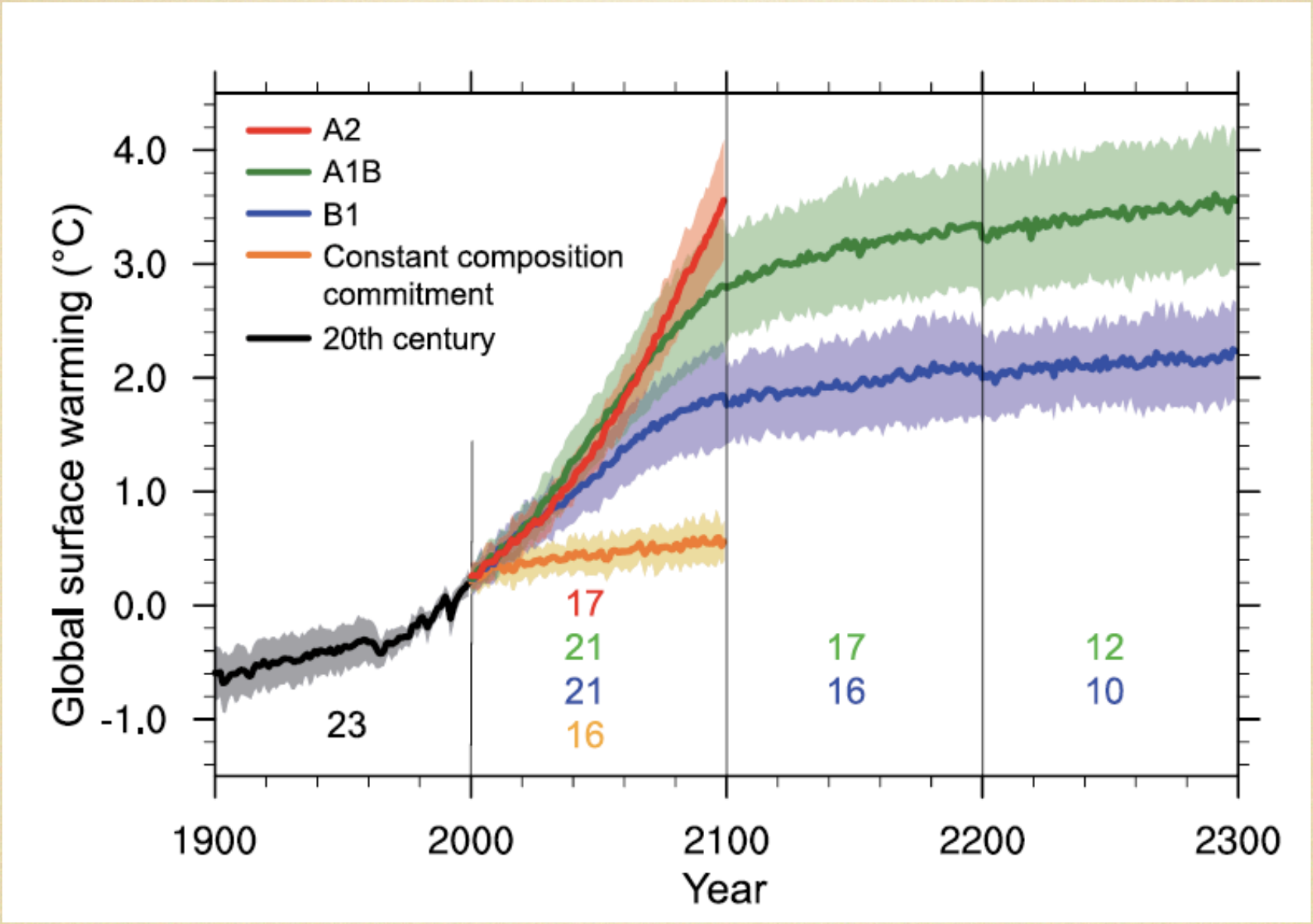
Why Couple?

The more we study the major problems over time, the more we come to realize that they cannot be understood in isolation. They are systemic problems, which means that they are interconnected and interdependent.

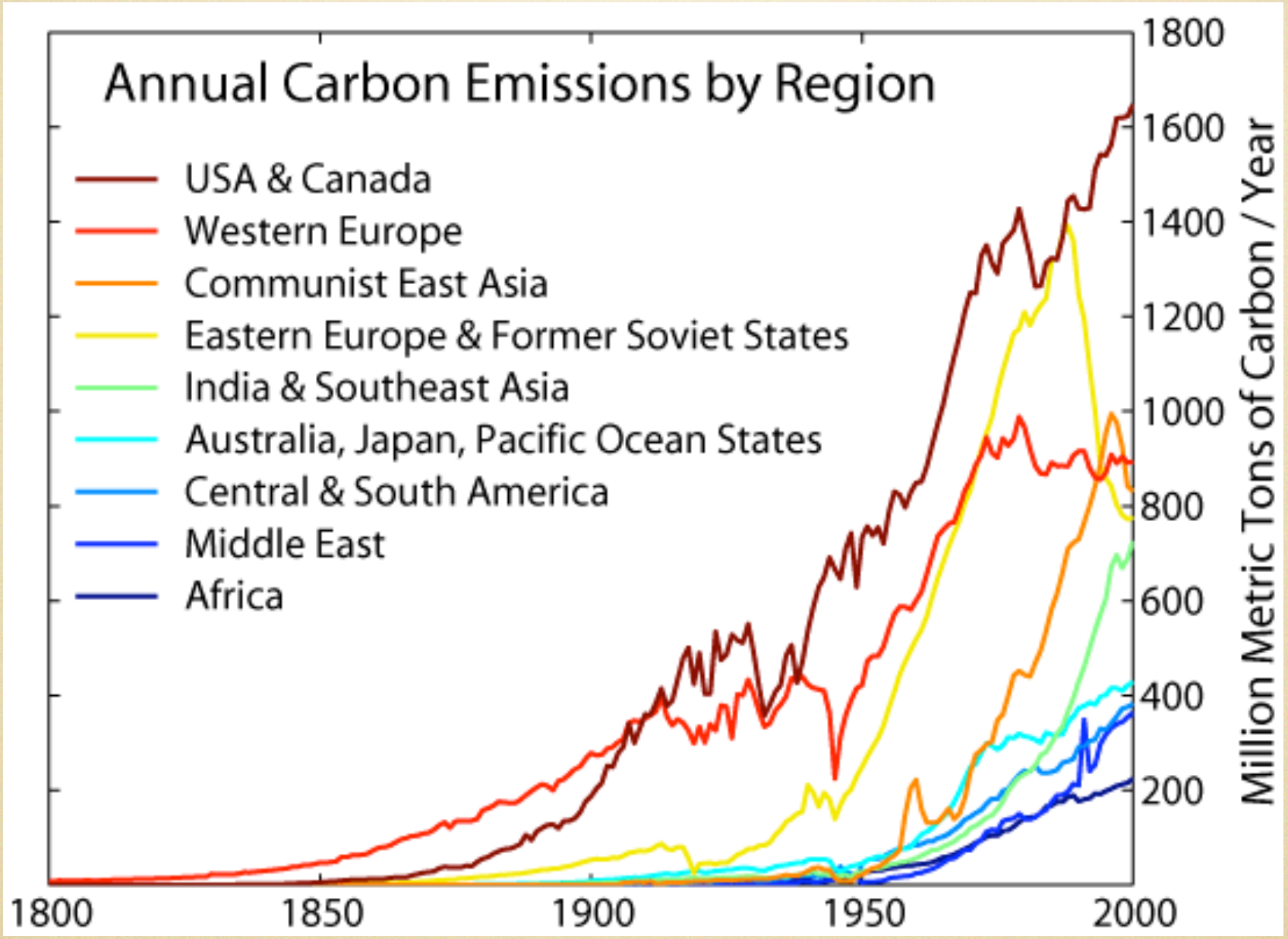
F. Capra (1996)

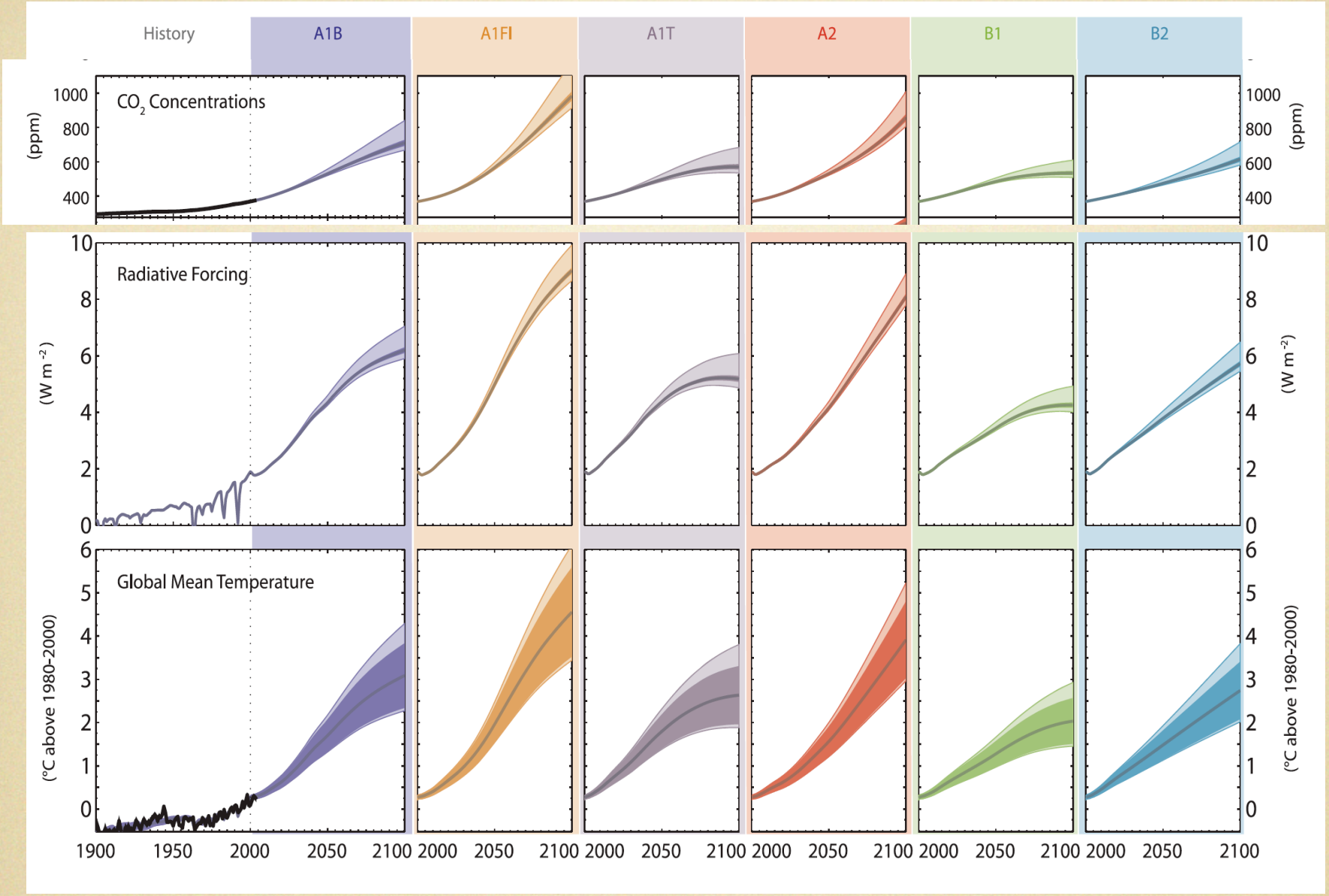
Outline

- Why coupled models?
- Motivation for Coupling Models
- Coupling Requirements
- What coupling creates
- Sensitivity & Feedbacks
- The Human Interaction

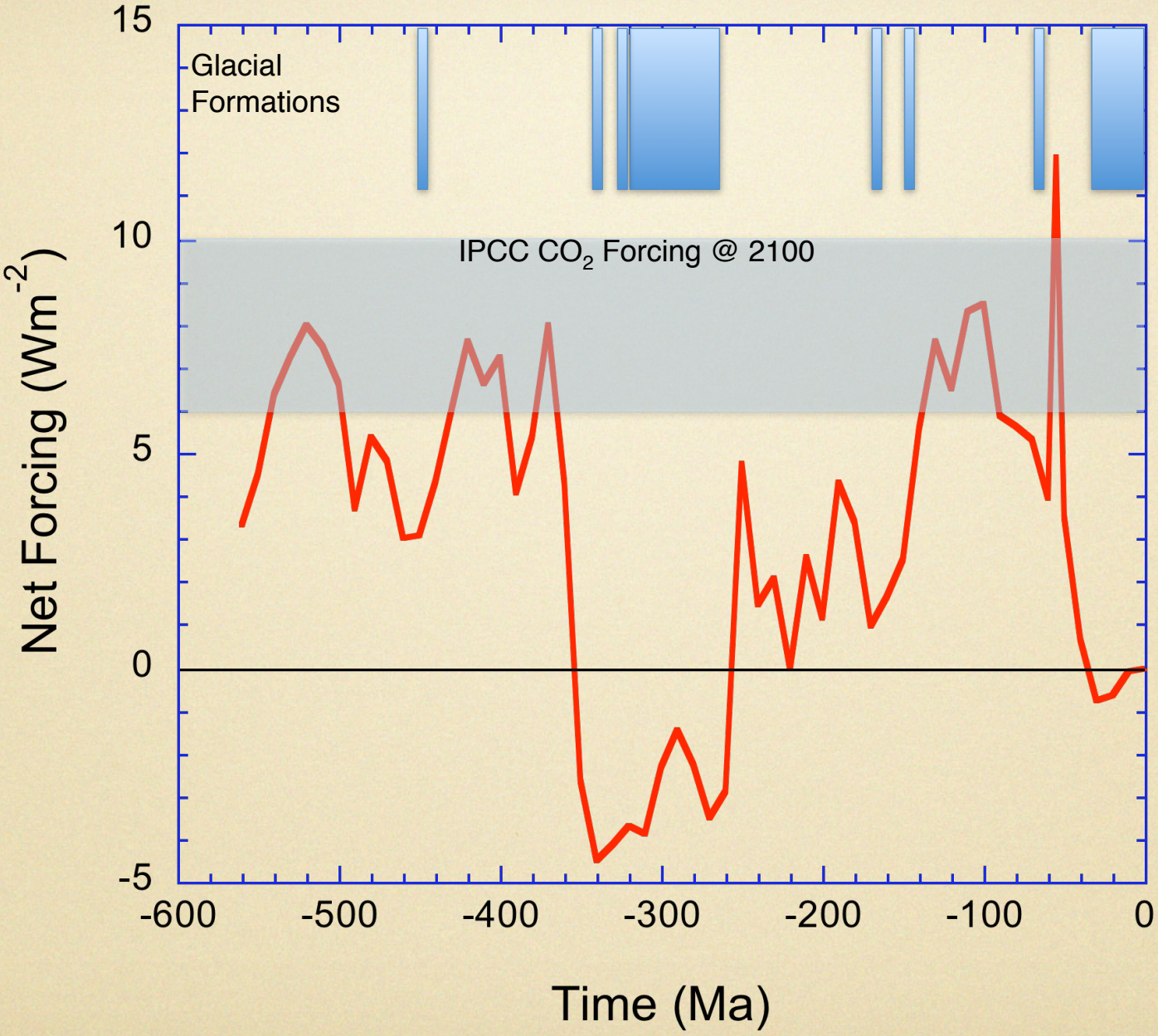

A2
A1B
B1
Constant composition commitment
20th century
Global surface warming (°C)
4.0
3.0
2.0
1.0
0.0
-1.0
1900
2000
2100
2200
2300
Year
23
17
21
21
16
17
16
12
10

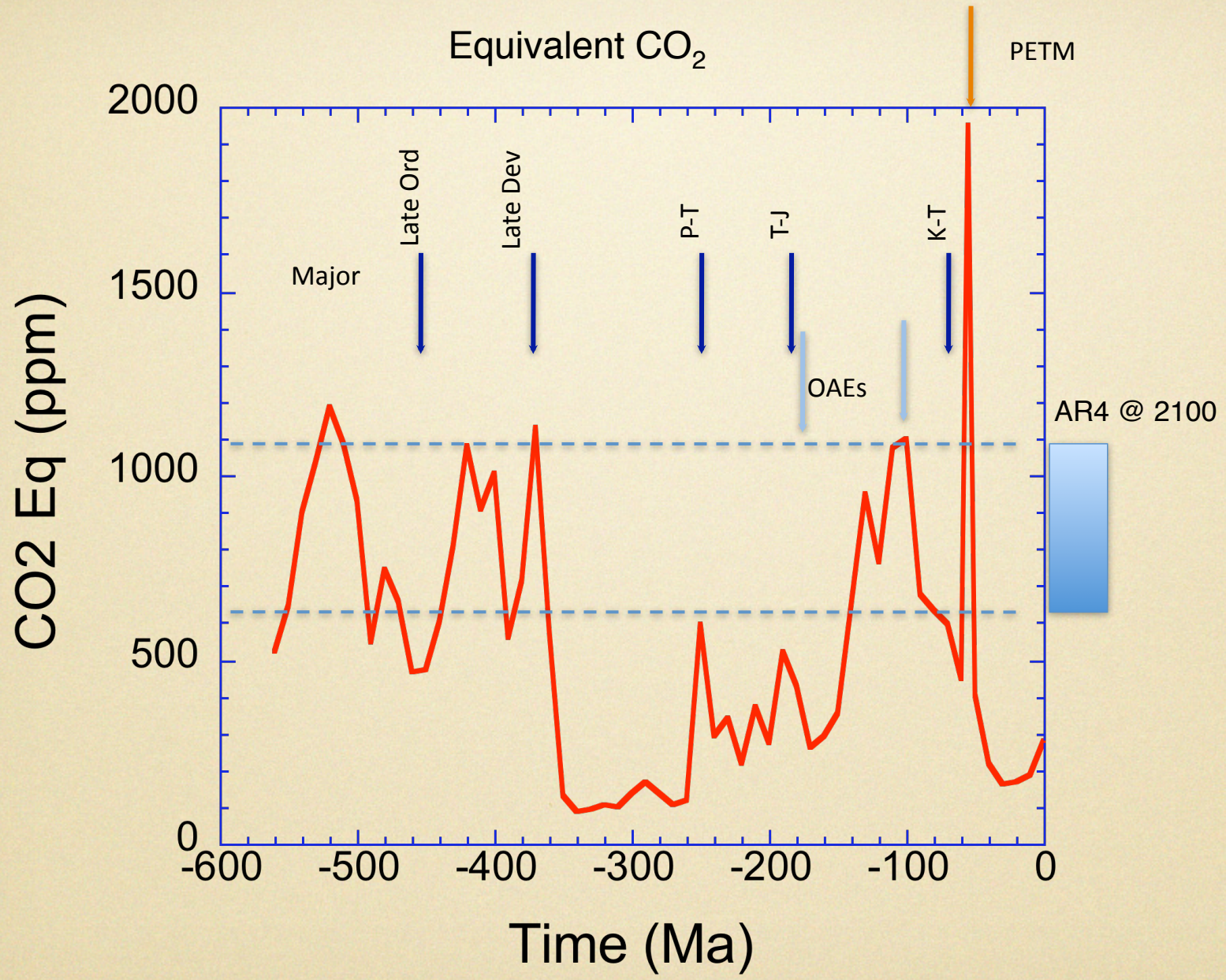
IPCC AR4

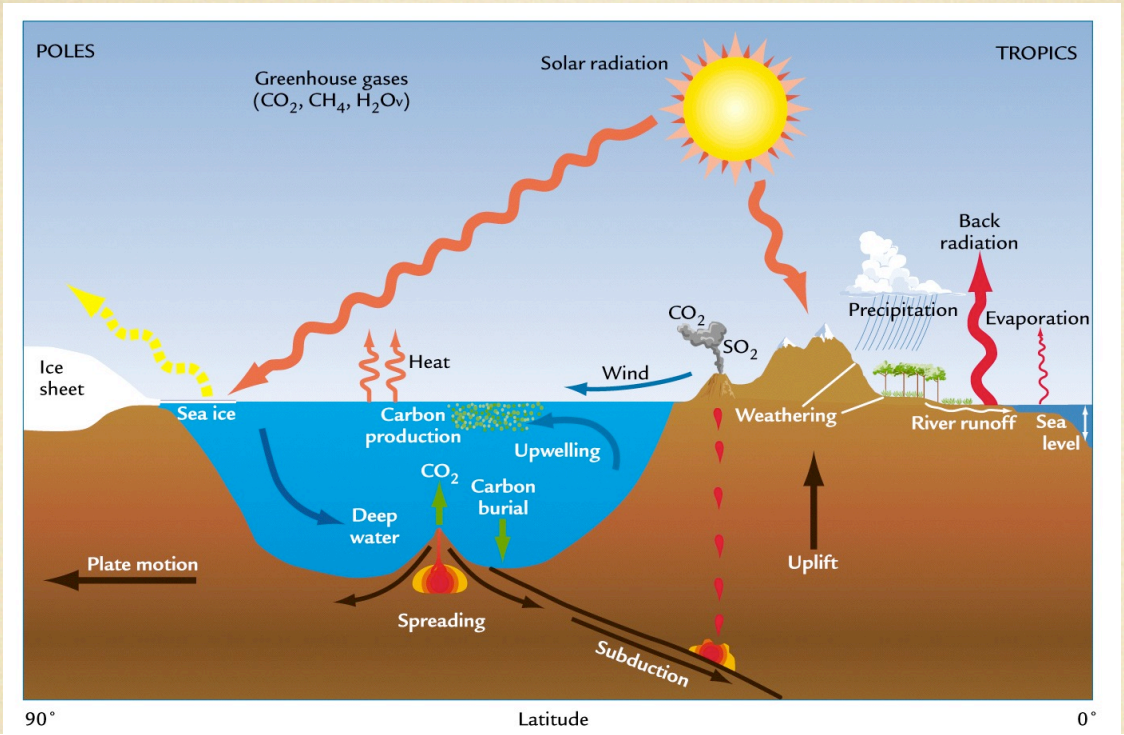

Annual Carbon Emissions by Region
USA & Canada
Western Europe
Communist East Asia
Eastern Europe & Former Soviet States
India & Southeast Asia
Australia, Japan, Pacific Ocean States
Central & South America
Middle East
Africa
1800
1850
1900
1950
2000
200
400
600
800
1000
1200
1400
1600
1800
Million Metric Tons of Carbon / Year

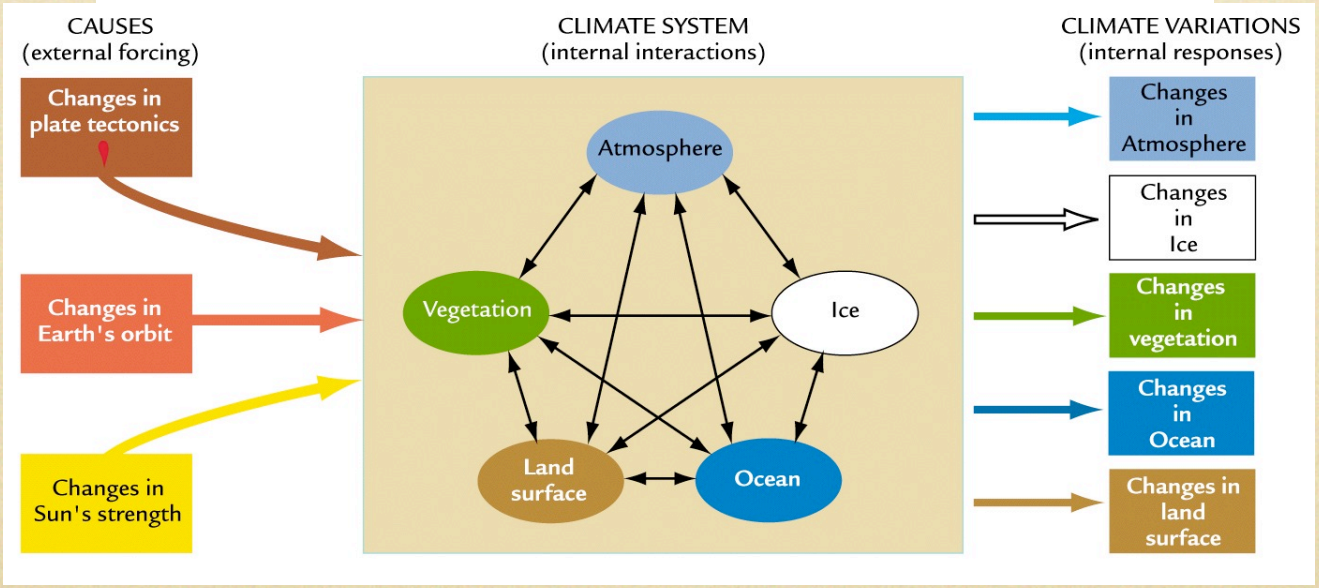

History
A1B
A1FI
A1T
A2
B1
B2
CO2 Concentrations
(ppm)
1000
800
600
400
Radiative Forcing
(W m-2)
10
8
6
4
2
0
Global Mean Temperature
(°C above 1980-2000)
6
5
4
3
2
1
0
1900
1950
2000
2050
2100

IPCC AR4


15
10
5
0
-5
Glacial
Formations
IPCC CO_2 Forcing @ 2100
Net Forcing (Wm^{-2})
-600
-500
-400
-300
-200
-100
0
Time (Ma)

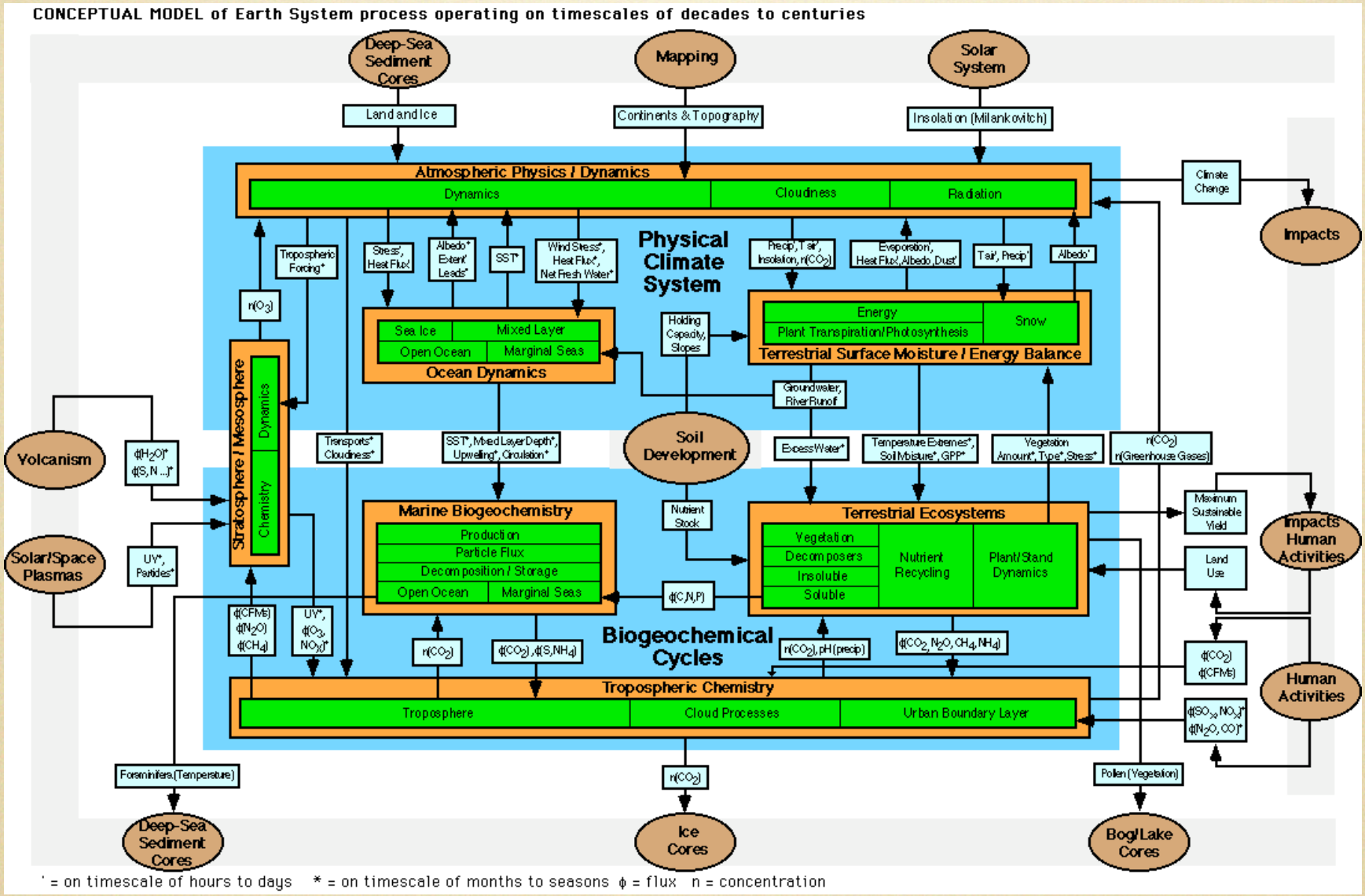

Equivalent CO_2
PETM
2000
1500
1000
500
0
CO2 Eq (ppm)
Late Ord
Late Dev
P-T
T-J
K-T
Major
OAEs
AR4 @ 2100
-600
-500
-400
-300
-200
-100
0
Time (Ma)





Ruddiman (1990)

Let's zoom in!


CONCEPTUAL MODEL of Earth System process operating on timescales of decades to centuries
Deep-Sea Sediment Cores
Mapping
Solar System
Land and Ice
Continents & Topography
Insolation (Milankovitch)
Atmospheric Physics / Dynamics
Dynamics
Cloudiness
Radiation
Climate Change
Impacts
Physical Climate System
Tropospheric Forcing*
Stress', Heat Flux'
Albedo' Extent' Leads'
SST'
Wind Stress', Heat Flux', Net Fresh Water'
Precip', T air', Insolation, n(CO2)
Evaporation', Heat Flux', Albedo, Dust'
T air', Precip'
Albedo'
n(O3)
Sea Ice
Mixed Layer
Open Ocean
Marginal Seas
Ocean Dynamics
Holding Capacity, Slopes
Energy
Plant Transpiration/Photosynthesis
Snow
Terrestrial Surface Moisture / Energy Balance
Groundwater, River Runoff
Stratosphere / Mesosphere
Dynamics
Chemistry
Volcanism
ϕ(H2O)* ϕ(S, N ...)*
Transports* Cloudiness*
SST*, Mixed Layer Depth*, Upwelling*, Circulation*
Soil Development
Excess Water*
Temperature Extremes*, Soil Moisture*, GPP*
Vegetation Amount*, Type*, Stress*
n(CO2) n(Greenhouse Gases)
Marine Biogeochemistry
Production
Particle Flux
Decomposition / Storage
Open Ocean
Marginal Seas
Nutrient Stock
Terrestrial Ecosystems
Vegetation
Decomposers
Insoluble
Soluble
Nutrient Recycling
Plant/Stand Dynamics
Maximum Sustainable Yield
Impacts Human Activities
Land Use
Solar/Space Plasmas
UV*, Particles*
ϕ(CFMs) ϕ(N2O) ϕ(CH4)
UV*, ϕ(O3, NOy)*
n(CO2)
ϕ(CO2), ϕ(S,NH4)
ϕ(C,N,P)
Biogeochemical Cycles
n(CO2), pH (precip)
ϕ(CO2, N2O, CH4, NH4)
ϕ(CO2) ϕ(CFMs)
Human Activities
Tropospheric Chemistry
Troposphere
Cloud Processes
Urban Boundary Layer
ϕ(SOx, NOx)* ϕ(N2O, CO)*
Foraminifera (Temperature)
n(CO2)
Pollen (Vegetation)
Deep-Sea Sediment Cores
Ice Cores
Bog/Lake Cores
' = on timescale of hours to days
* = on timescale of months to seasons
ϕ = flux
n = concentration

Coupling Components

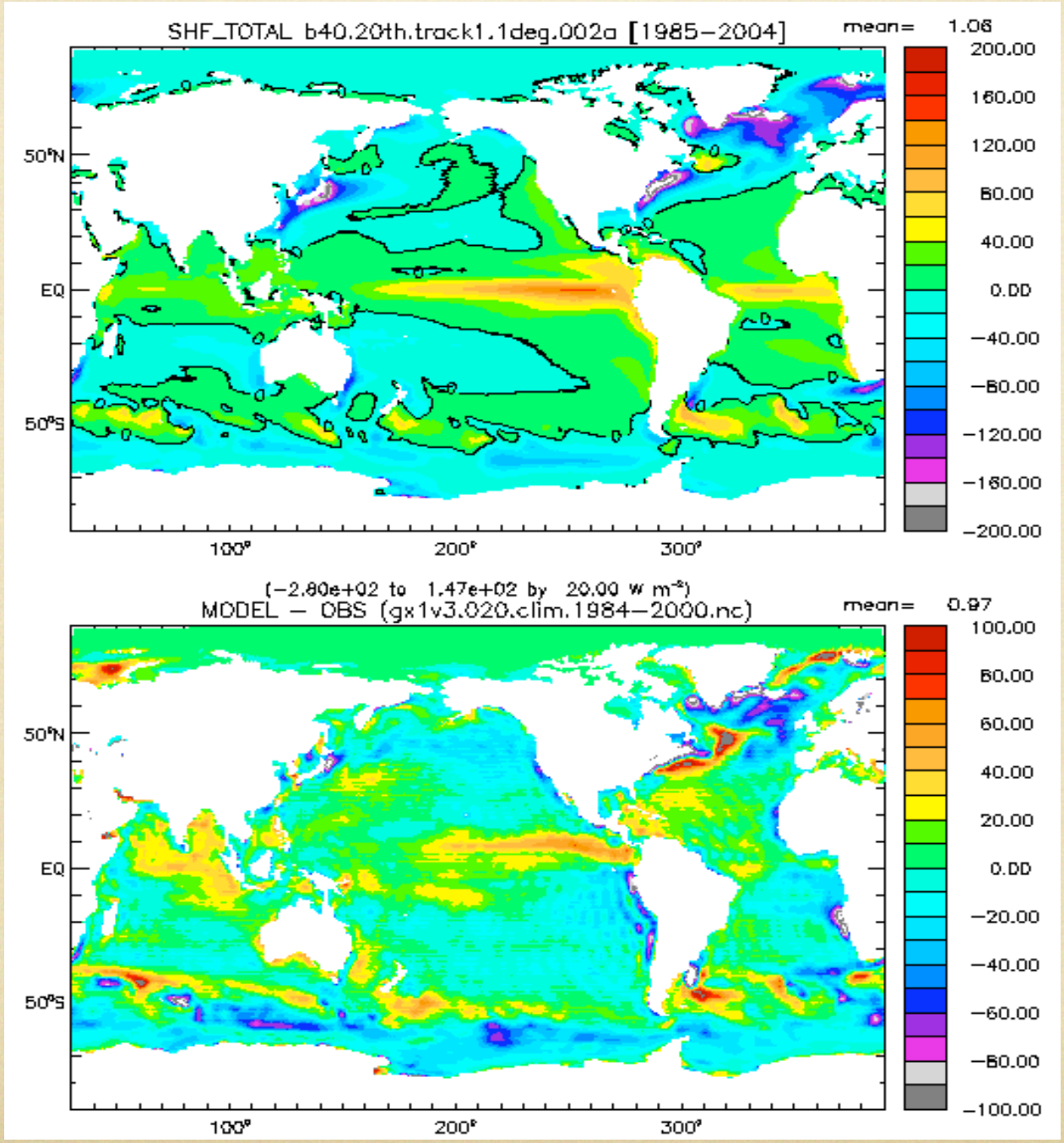
Requires transfer across boundaries of:

- Energy
- Momentum
- Mass

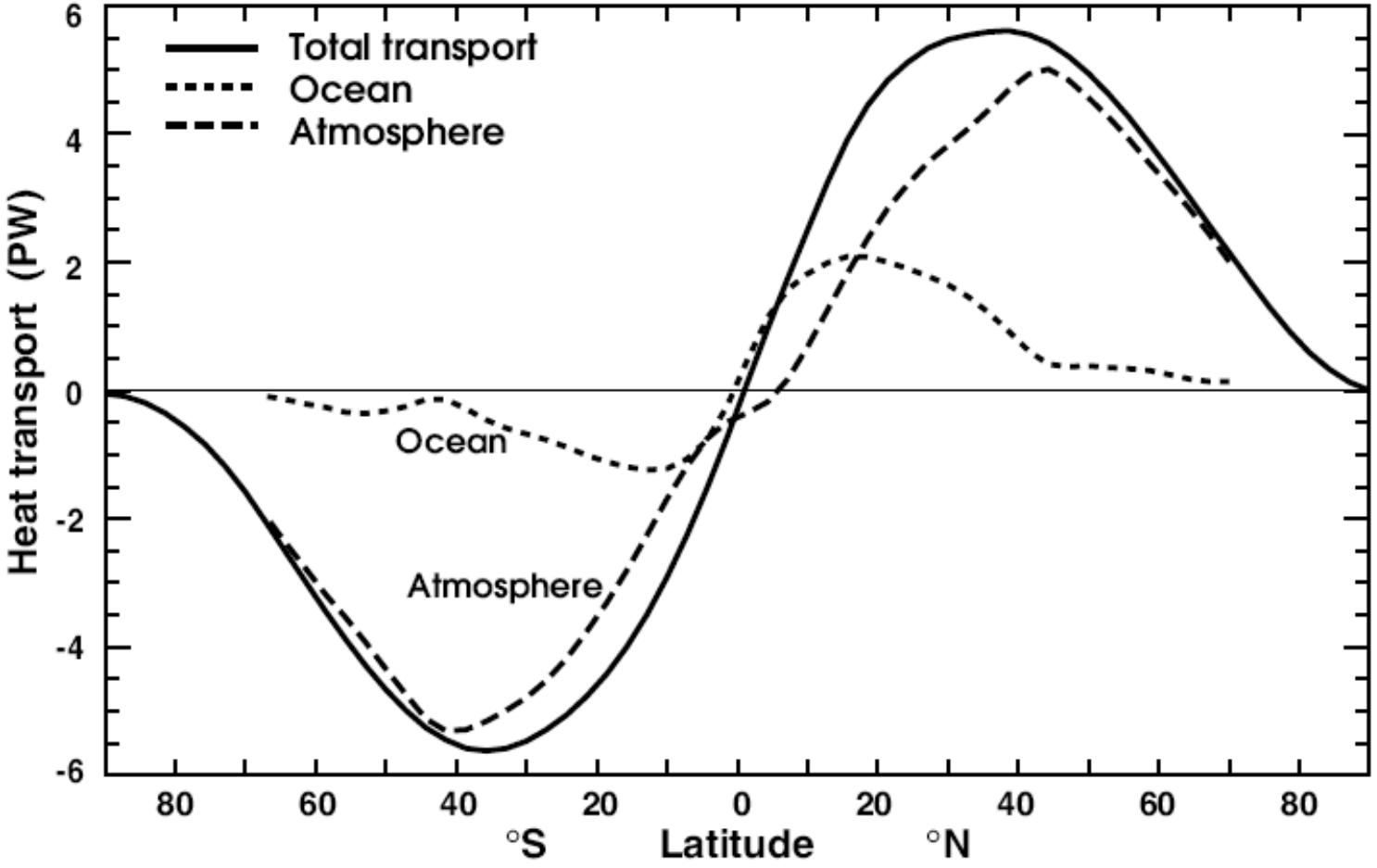
Practical Issues:

- How frequent do components communicate
- Properties must conserve across boundaries
- Must deal with disparate grids

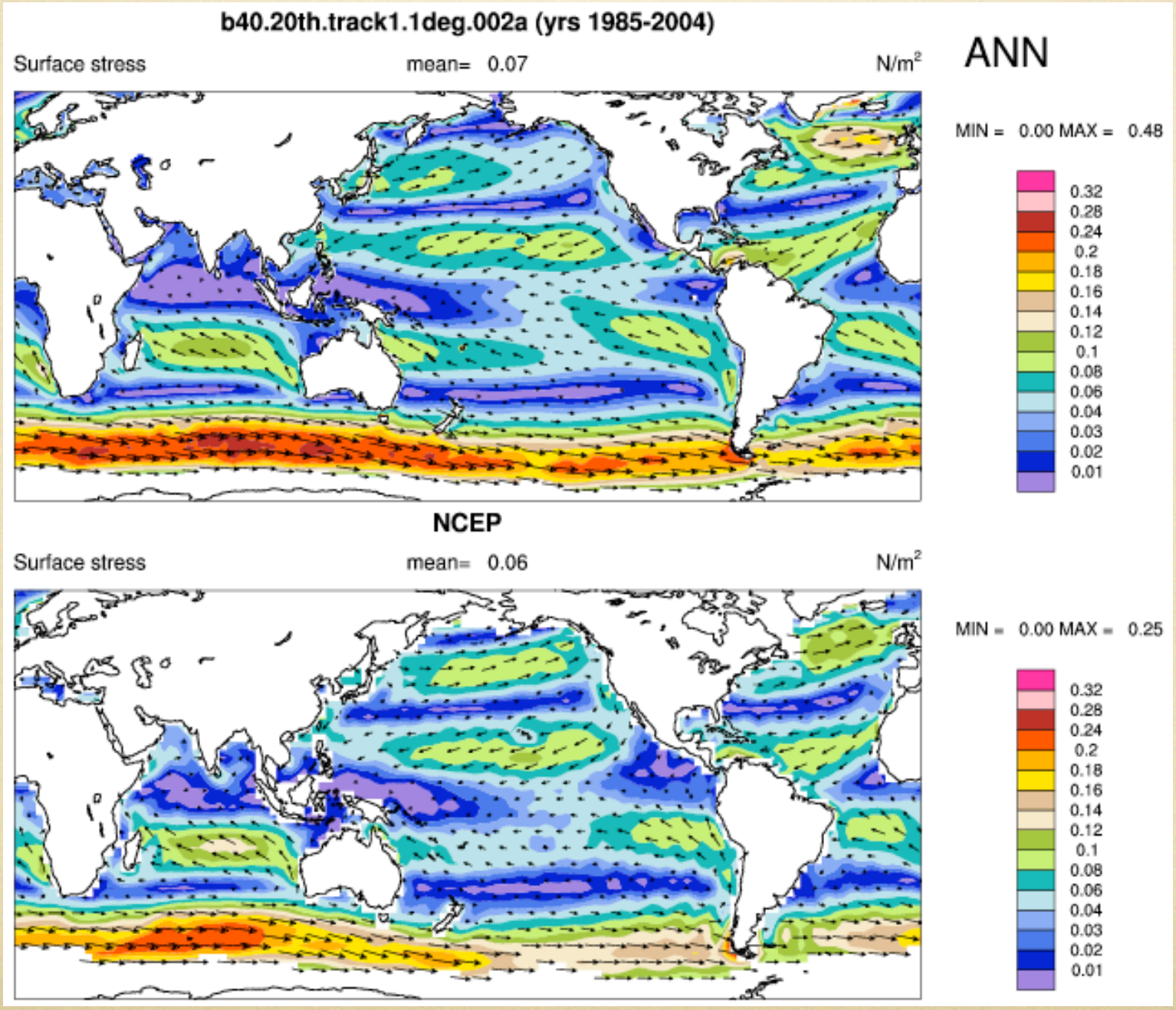
Energy


SHF_TOTAL b40.20th.track1.1deg.002a [1985–2004]
mean= 1.06
200.00
160.00
120.00
80.00
40.00
0.00
−40.00
−80.00
−120.00
−160.00
−200.00
50°N
EQ
50°S
100°
200°
300°
(−2.80e+02 to 1.47e+02 by 20.00 W m⁻²)
MODEL − OBS (gx1v3.020.clim.1984–2000.nc)
mean= 0.97
100.00
80.00
60.00
40.00
20.00
0.00
−20.00
−40.00
−60.00
−80.00
−100.00
50°N
EQ
50°S
100°
200°
300°

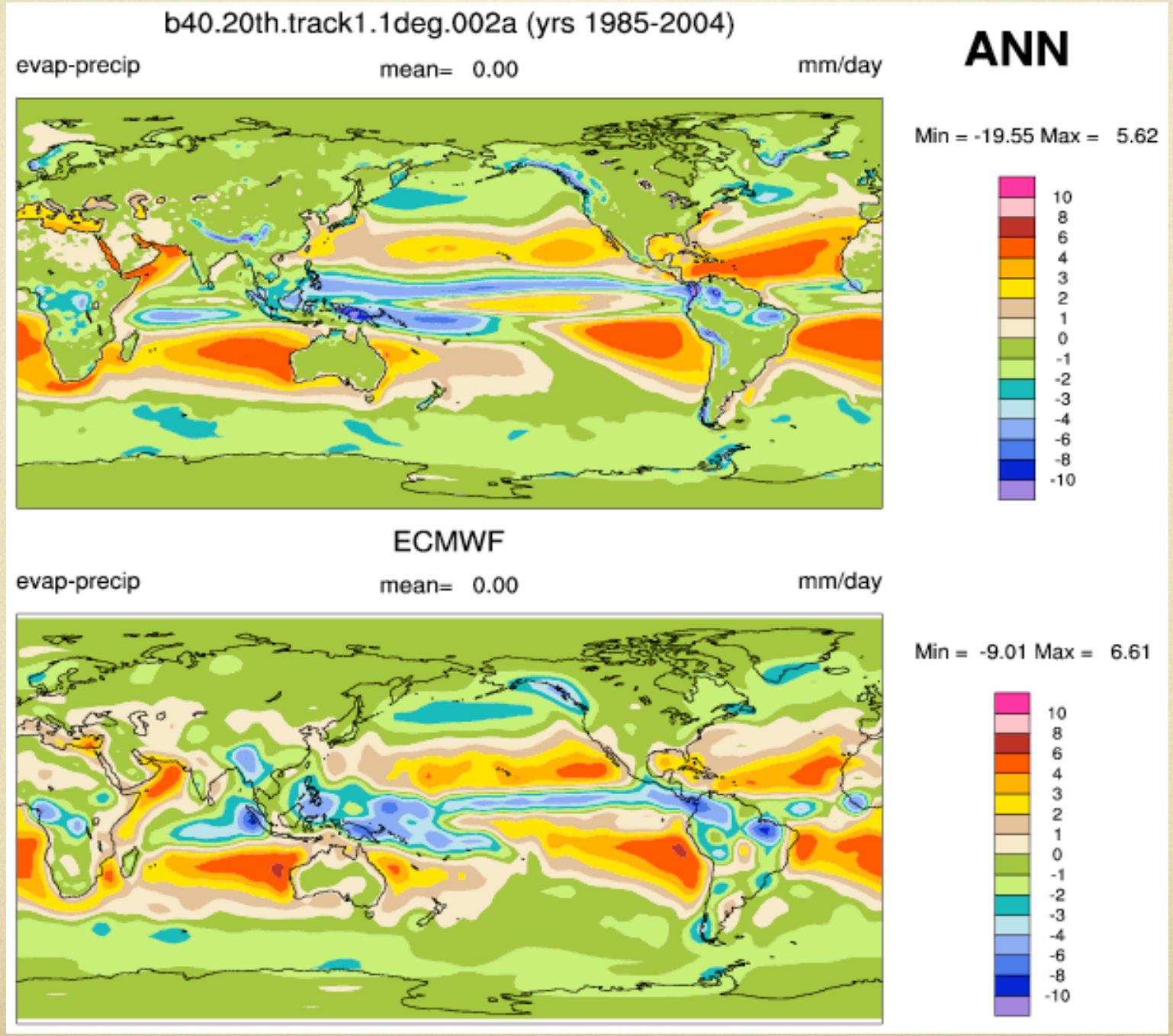
K. E. TRENBERTH and D. P. STEPANIAK



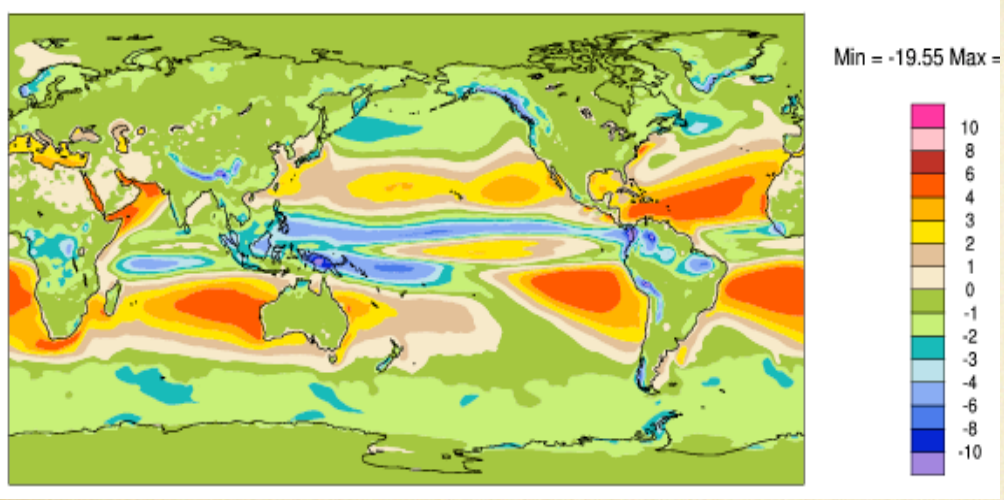
Momentum


b40.20th.track1.1deg.002a (yrs 1985-2004)
Surface stress
mean= 0.07
N/m²
ANN
MIN = 0.00 MAX = 0.48
0.32
0.28
0.24
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.03
0.02
0.01
NCEP
Surface stress
mean= 0.06
N/m²
MIN = 0.00 MAX = 0.25
0.32
0.28
0.24
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.03
0.02
0.01

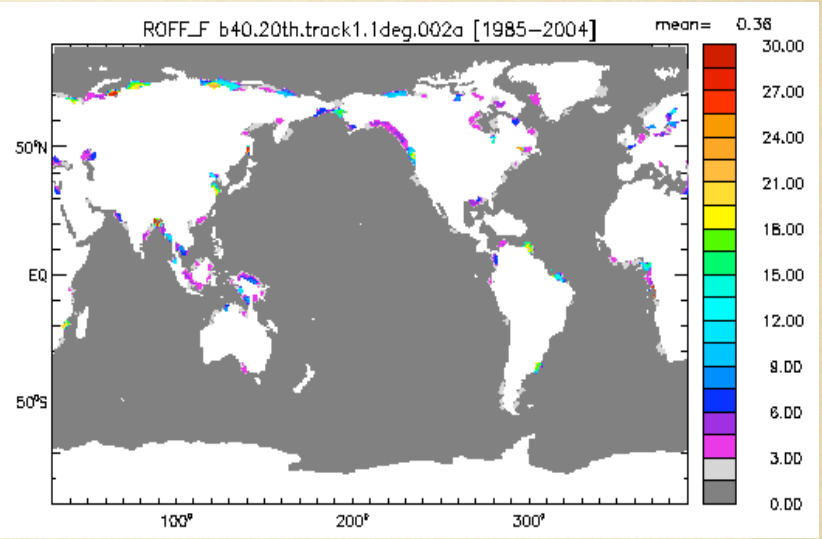
Water Mass


b40.20th.track1.1deg.002a (yrs 1985-2004)
evap-precip
mean= 0.00
mm/day
ANN
Min = -19.55 Max = 5.62
10
8
6
4
3
2
1
0
-1
-2
-3
-4
-6
-8
-10
ECMWF
evap-precip
mean= 0.00
mm/day
Min = -9.01 Max = 6.61
10
8
6
4
3
2
1
0
-1
-2
-3
-4
-6
-8
-10

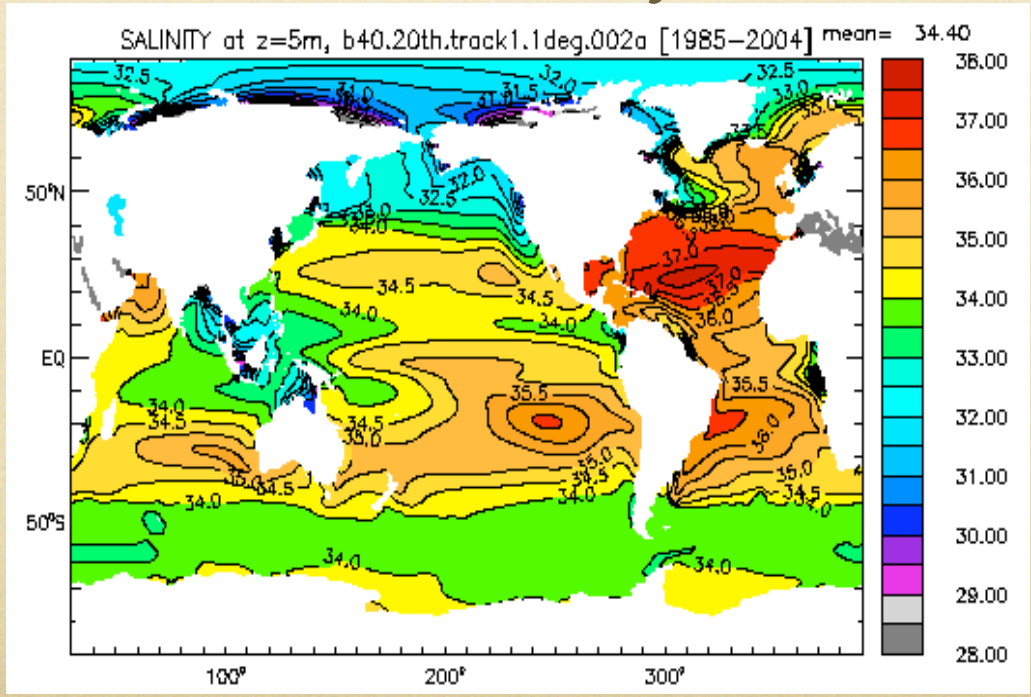
Evap-Precip



Runoff



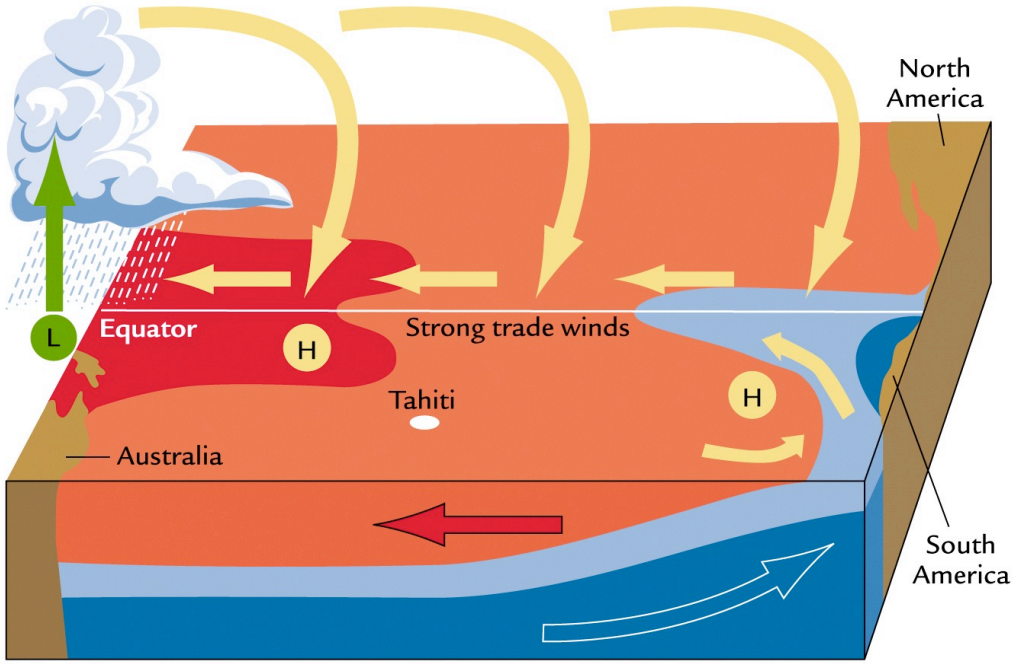
Salinity



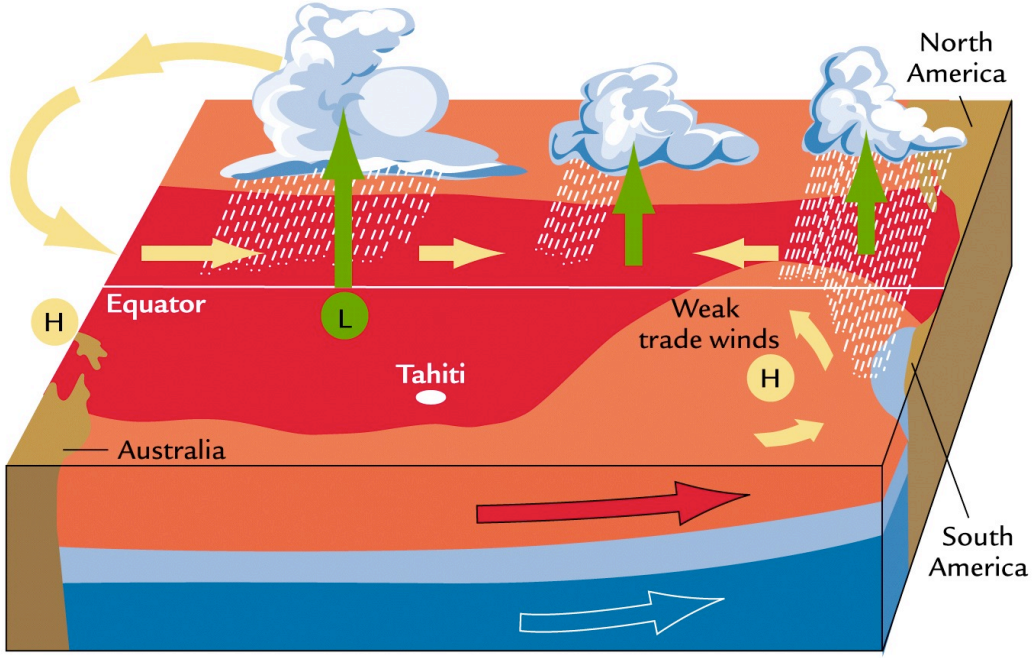
Coupling Affects Modes of Climate Variability

- El Nino Southern Oscillation (ENSO)
- North Atlantic Oscillation
- Pacific Decadal Oscillation
- Heinrch Events
- Others?

But some things don't improve!



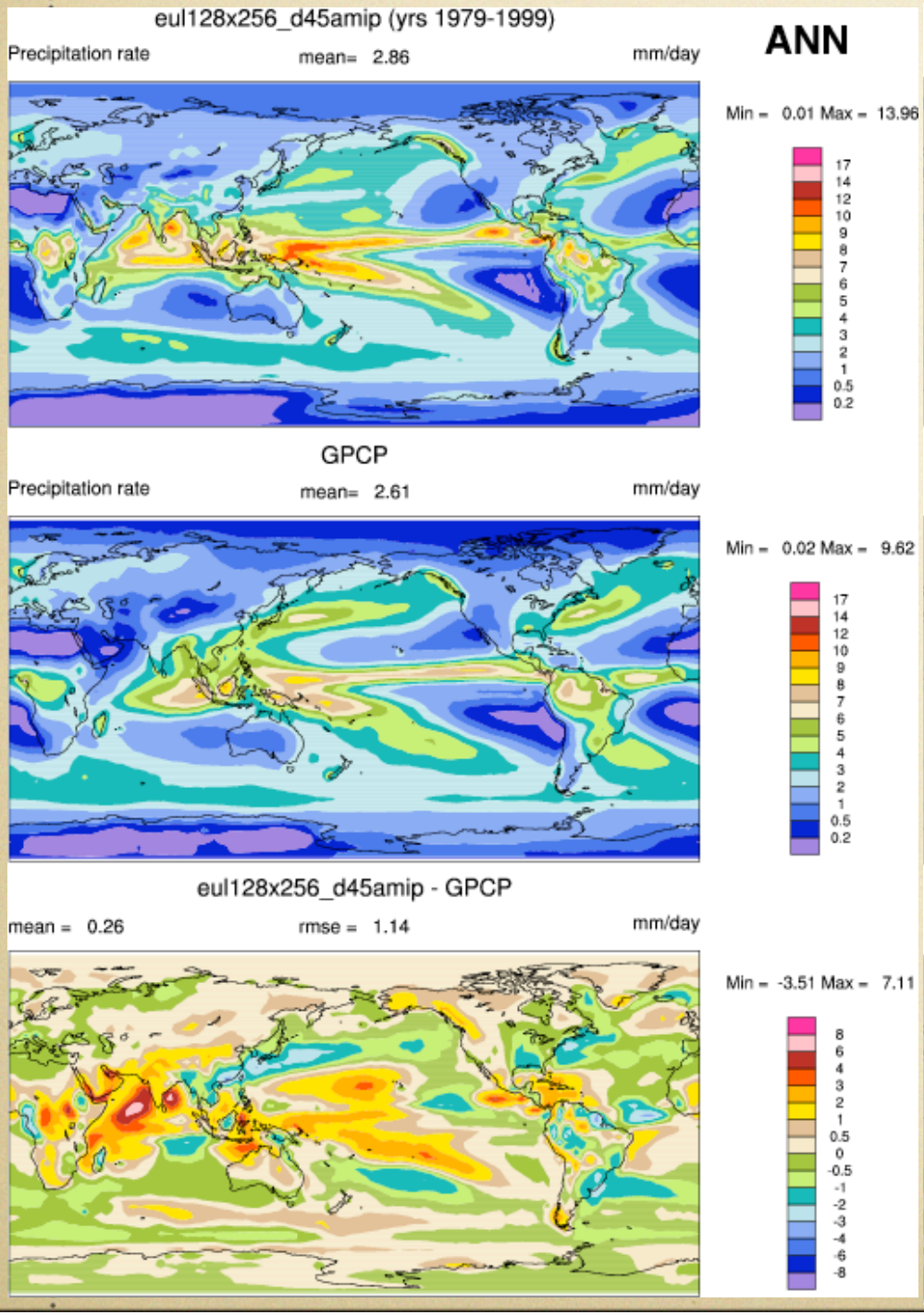
A Non–El Niño year

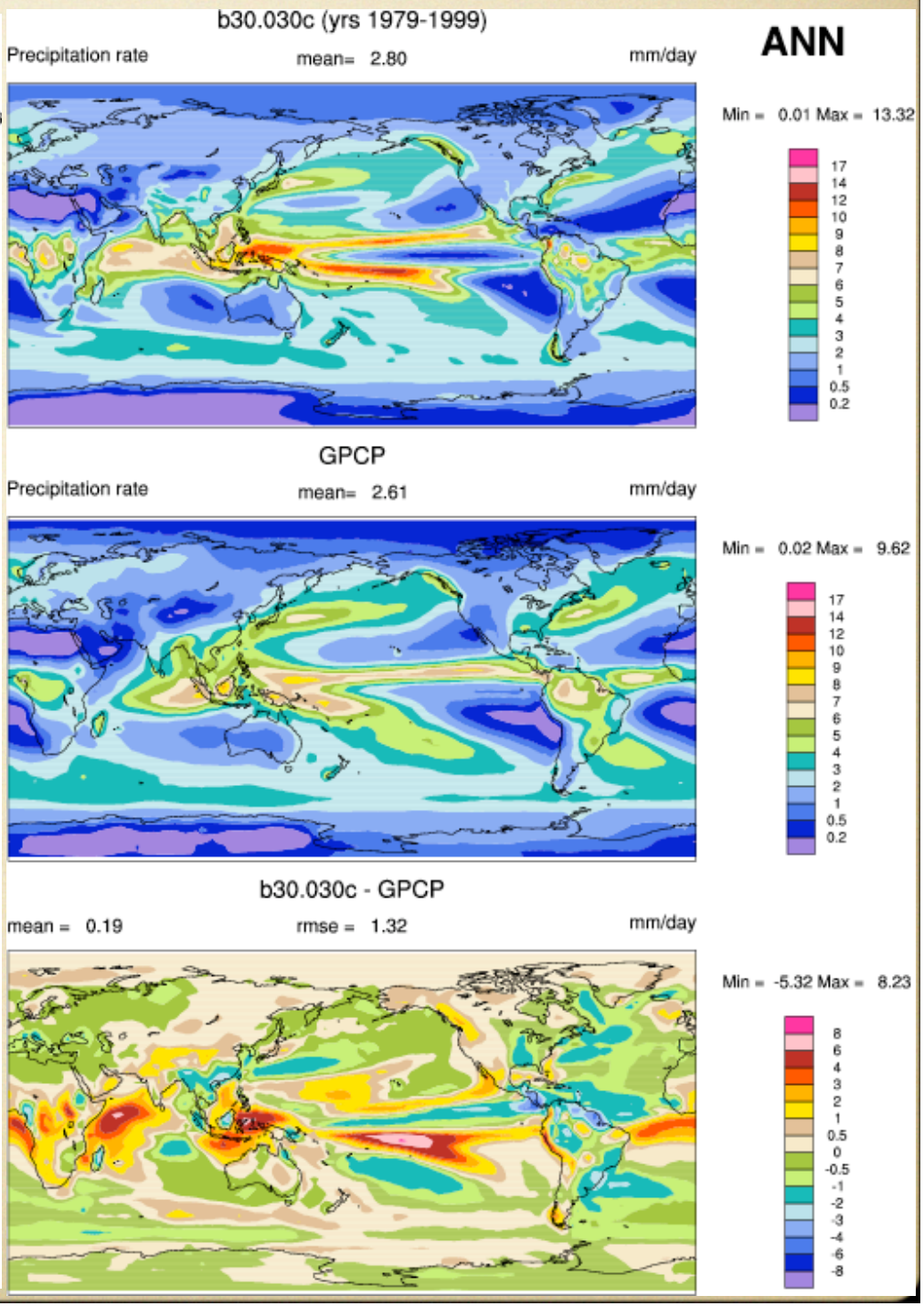


B El Niño year

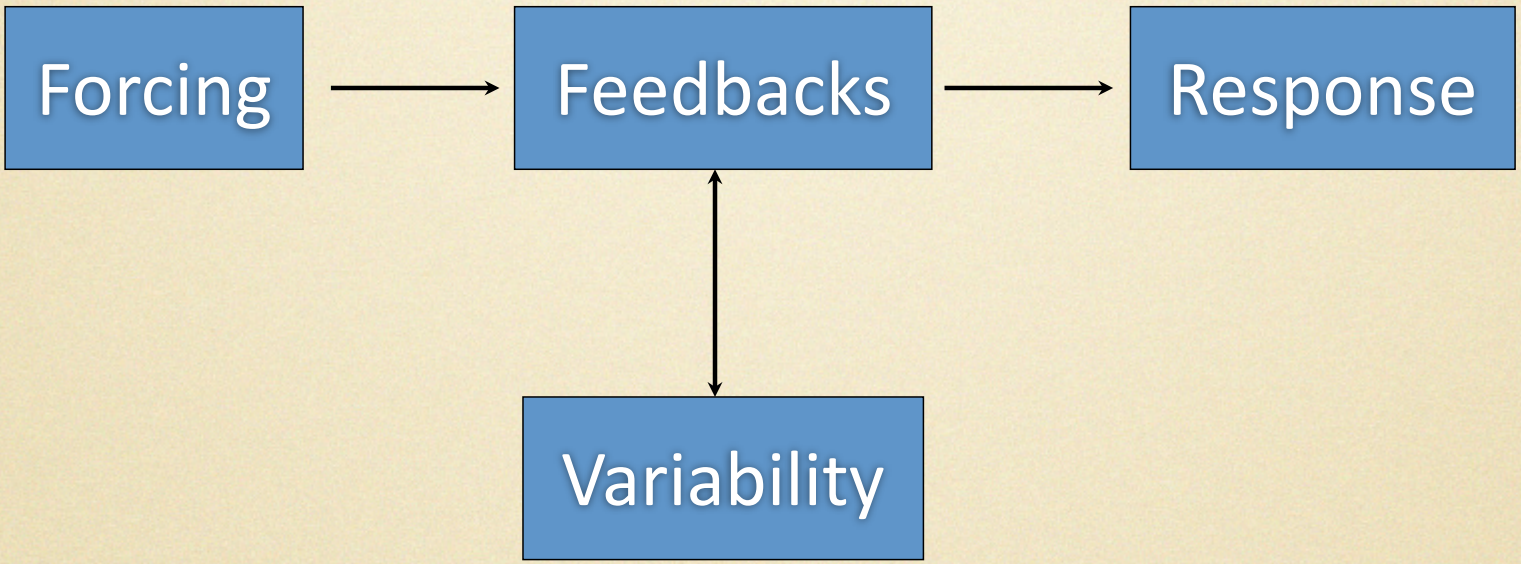
Ruddiman (1990)

Uncoupled PRECIP Coupled



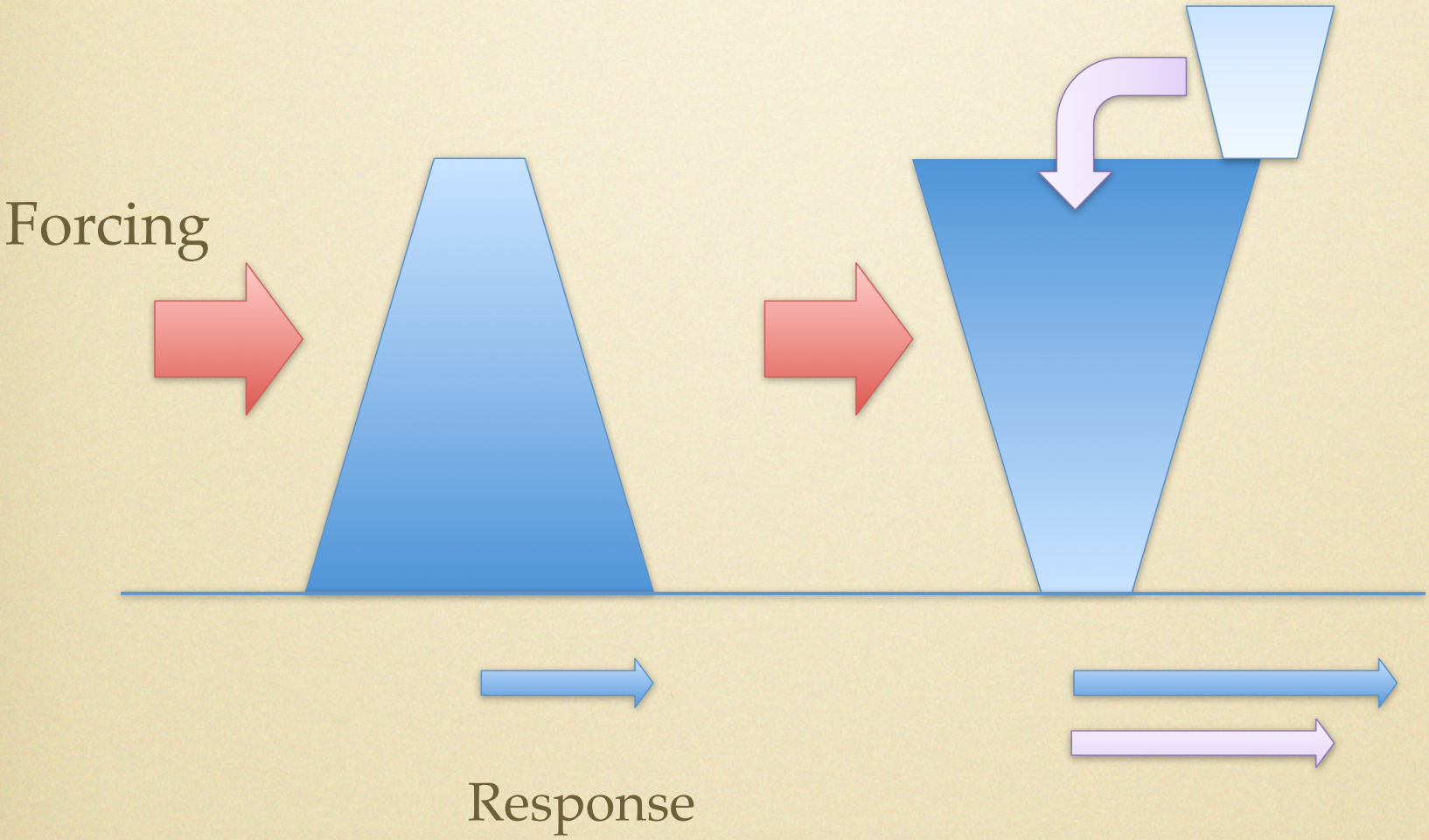


Climate Science

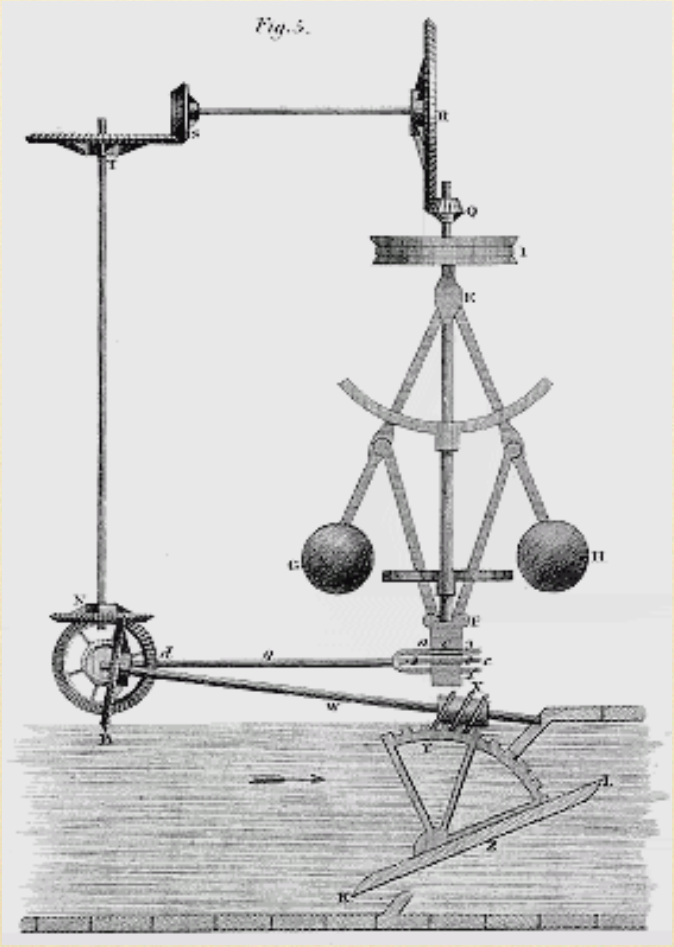


We all fit in here somewhere!

Sensitivity

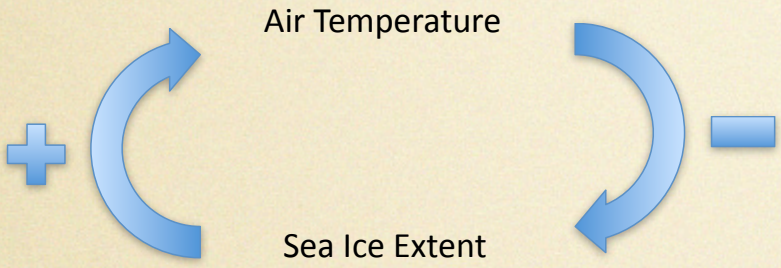


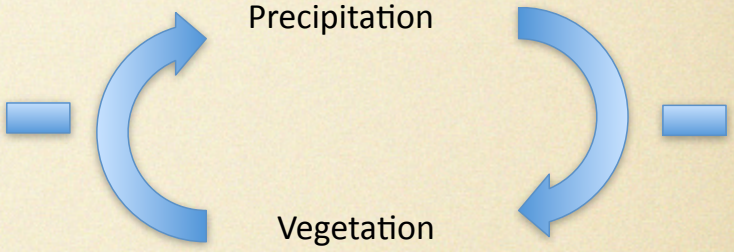
Feedbacks

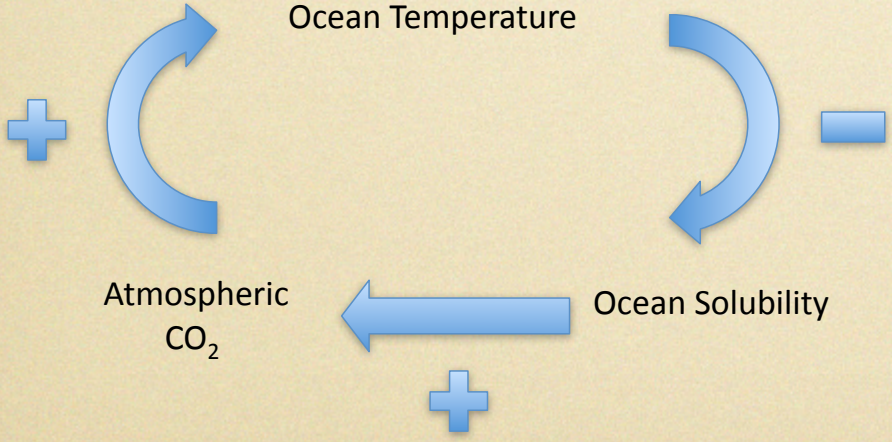


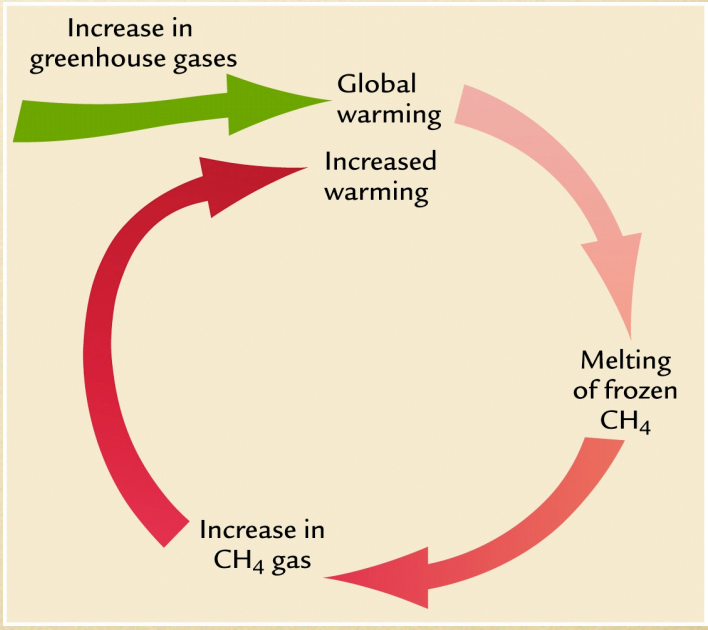
I. "On Governors." By J. Clerk Maxwell, M.A., F.R.SS.L. & E.
Received Feb. 20, 1868.

Coupled Feedbacks









Climate Timescales

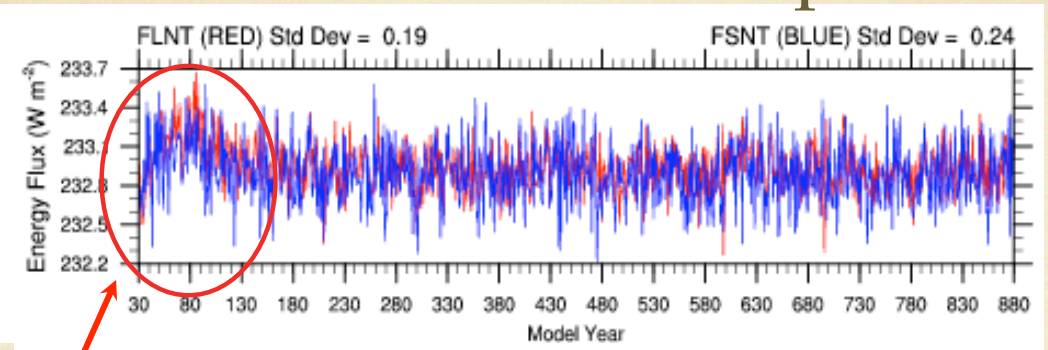
TABLE 1.1 Response Times of Various Climate System Components

Component	Response time (range)	Example
	Fast responses	
Atmosphere	Hours to weeks	Daily heating and cooling Gradual buildup of heat wave
Land surface	Hours to months	Daily heating of upper ground surface Midwinter freezing and thawing
Ocean surface	Days to months	Afternoon heating of upper few feet Warmest beach temperatures late in summer
Vegetation	Hours to decades/centuries	Sudden leaf kill by frost Slow growth of trees to maturity
Sea ice	Weeks to years	Late-winter maximum extent Historical changes near Iceland
	Slow responses	
Mountain glaciers	10–100 years	Widespread glacier retreat in 20th century
Deep ocean	100–1500 years	Time to replace world's deep water
Ice sheets	100–10,000 years	Advances/retreats of ice sheet margins Growth/decay of entire ice sheet

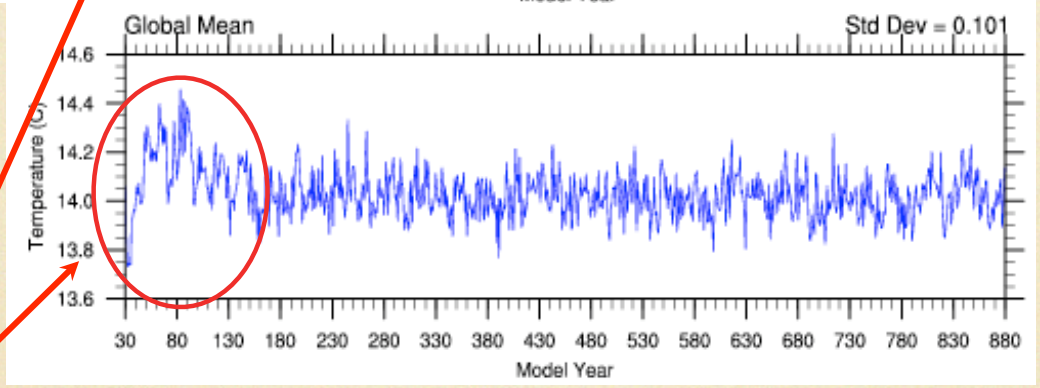
Ruddiman (1990)

Inherent Time Scales of Coupled Model

CCSM3
T31X3 Control

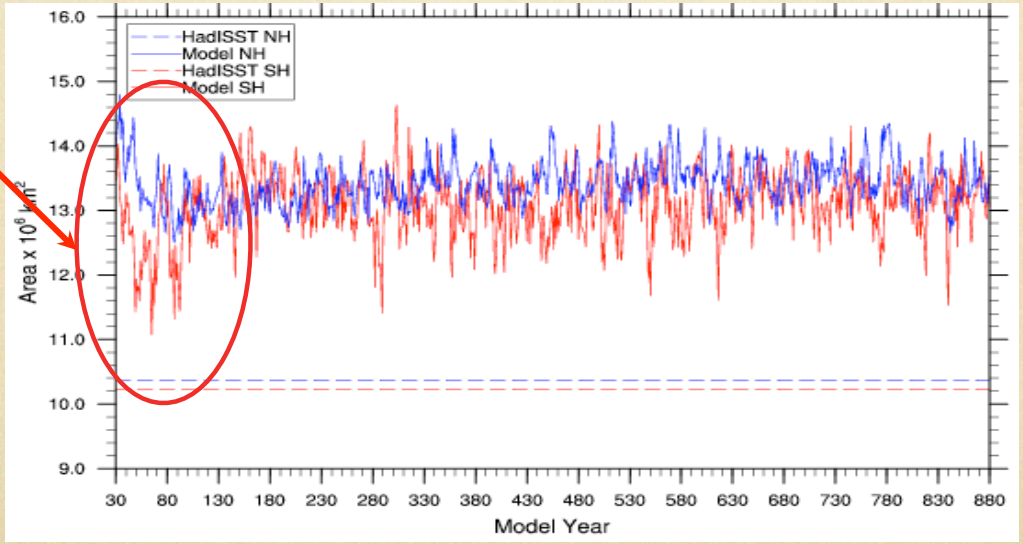


Energy Balance



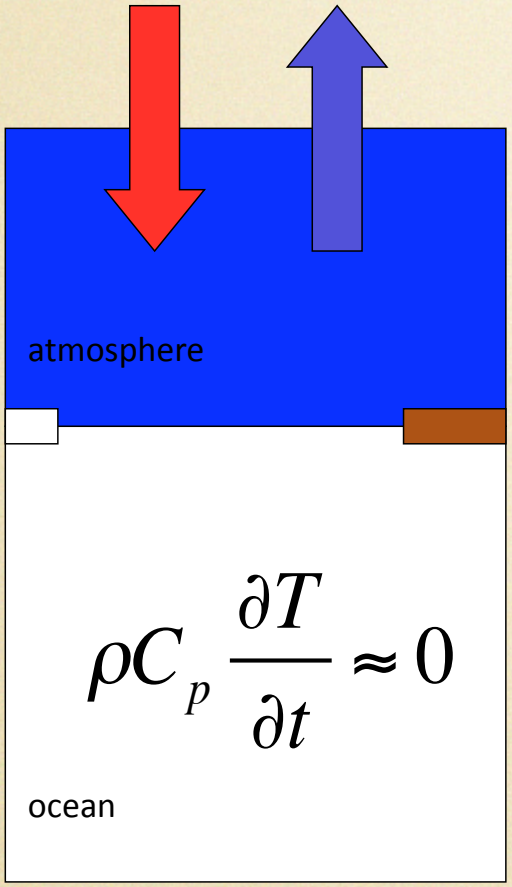
Surface Temperature

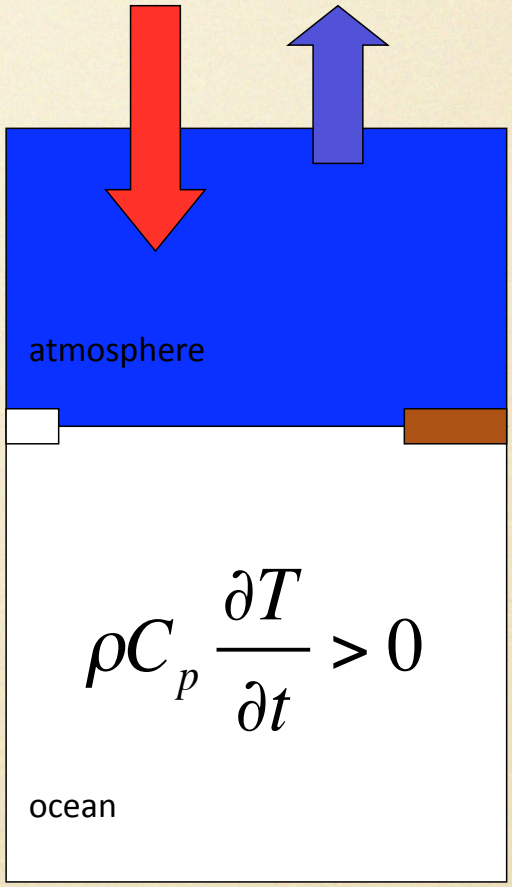
Spin-up
~100 yr



Sea Ice Area

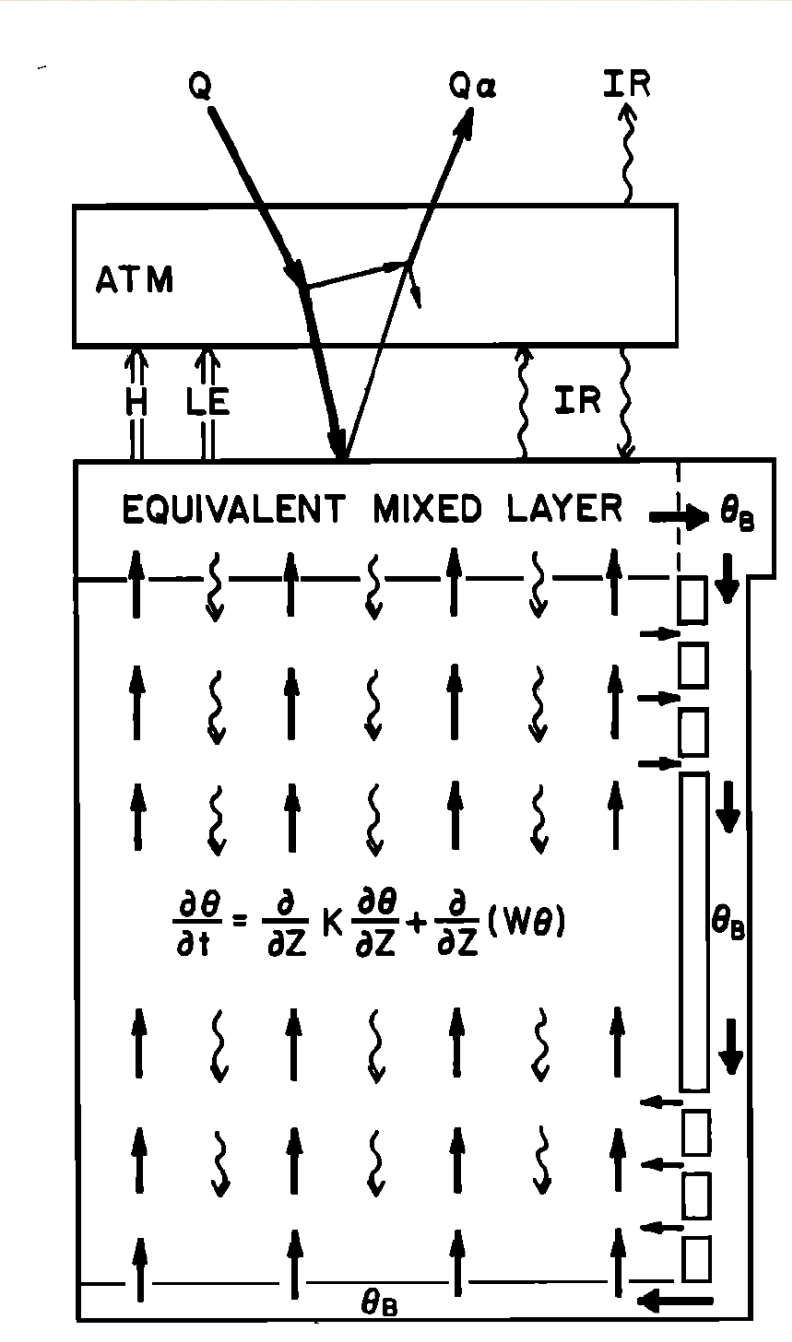
Adjustment Timescale



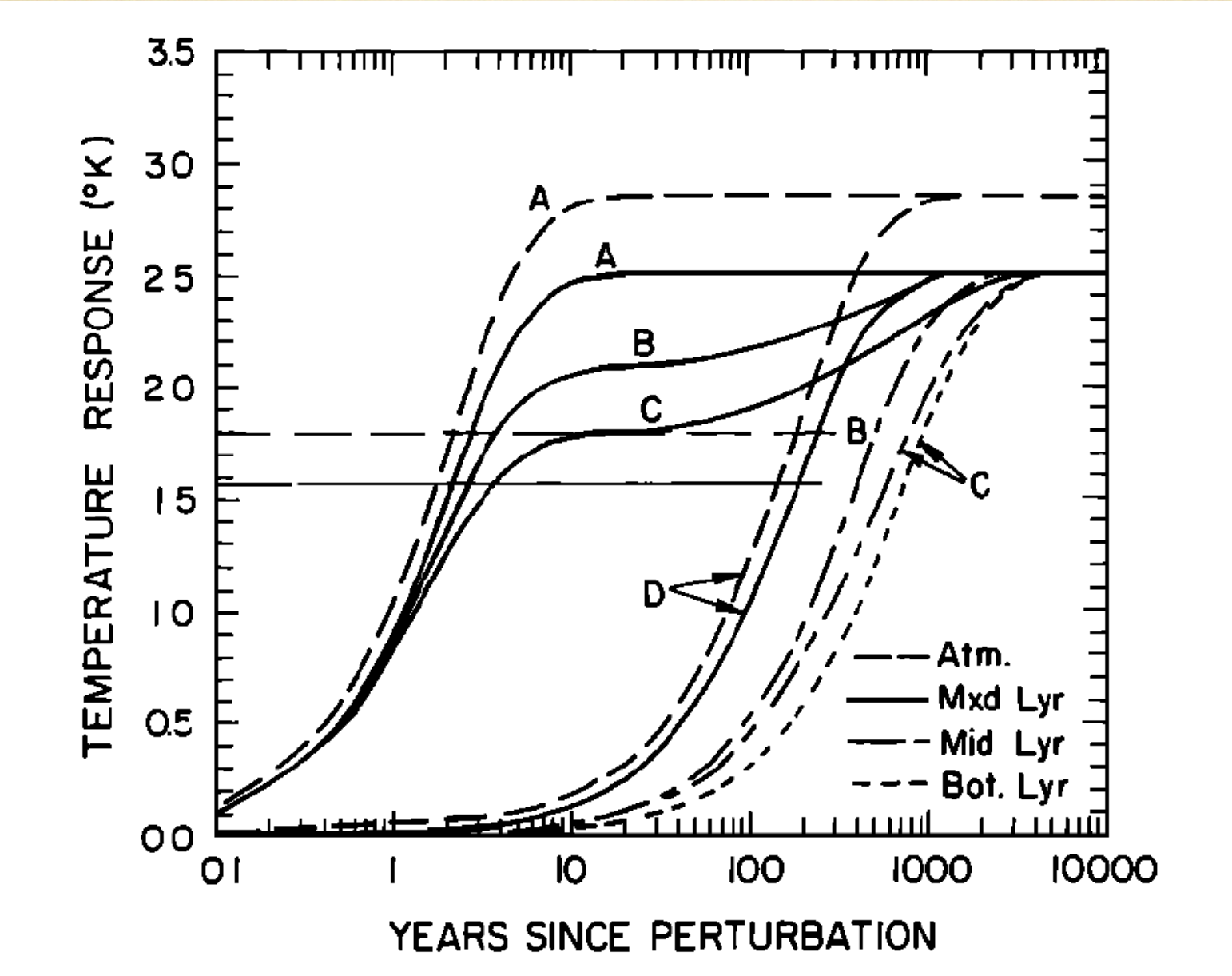


Be aware when things are out of balance.
Tao Te Ching 53

Box Advective Diffusion Model

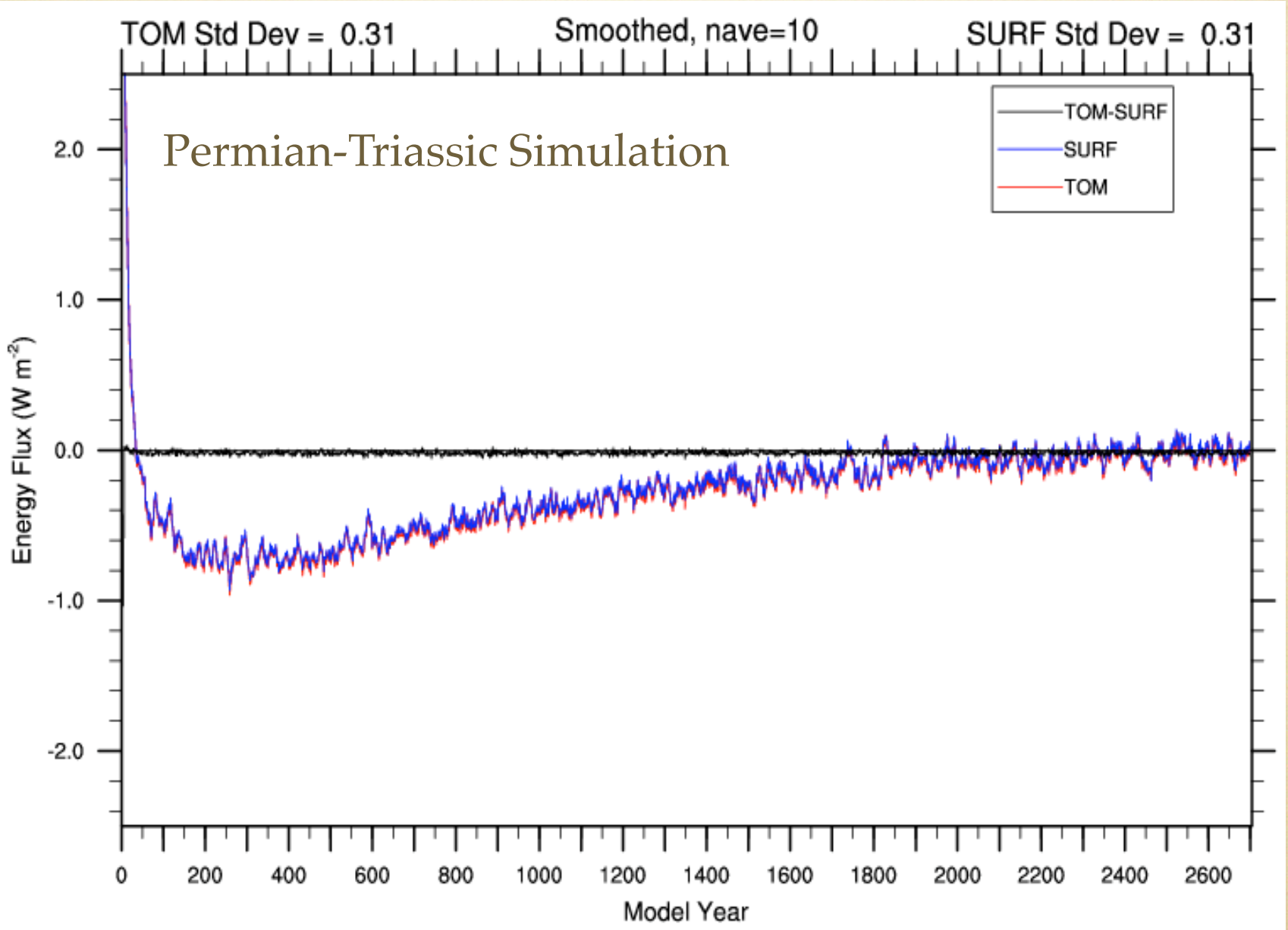


Harvey and Schneider (1985)

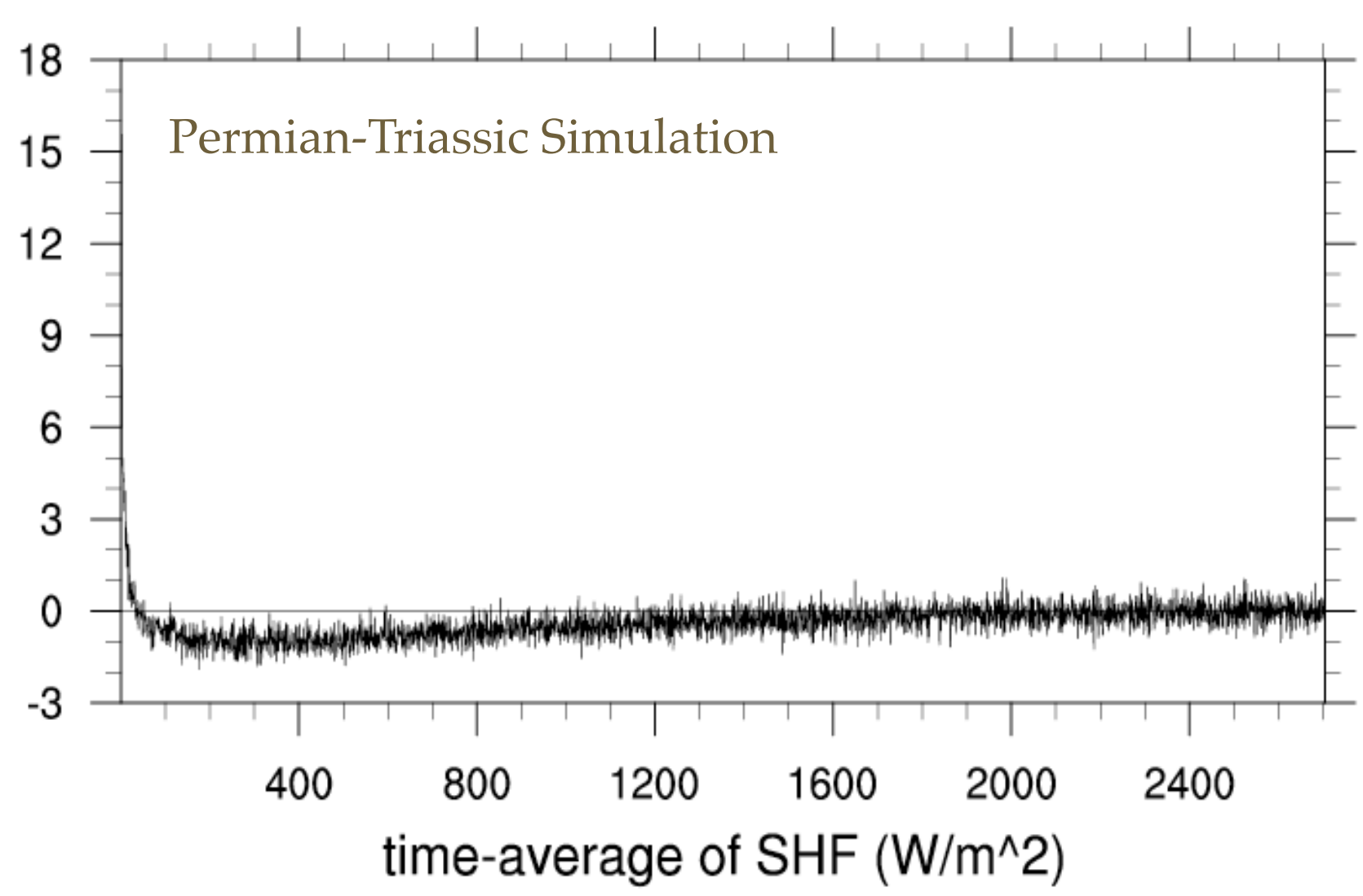


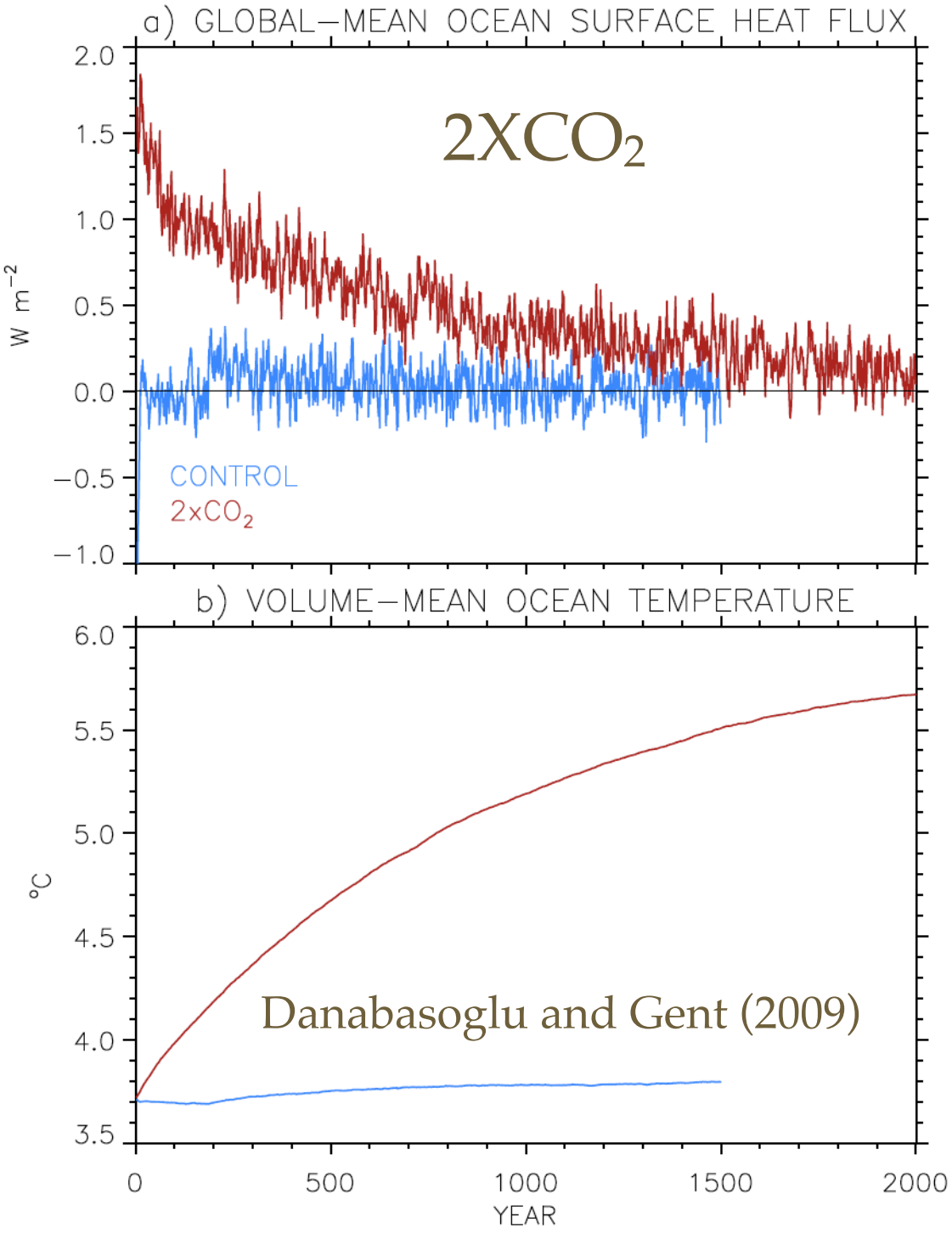
Harvey and Schneider (1985)

Global Surface Energy Balance

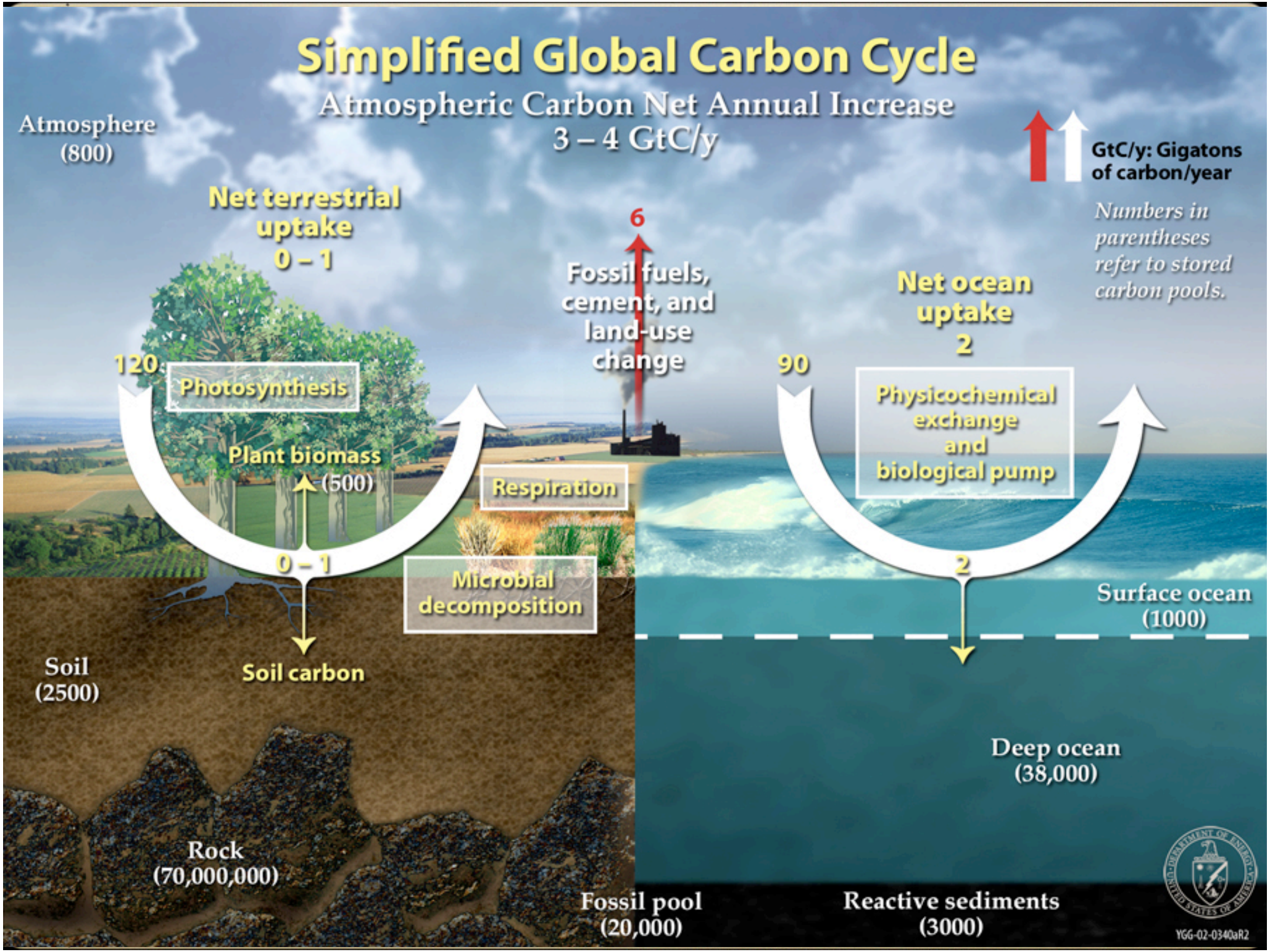


Ocean Surface Energy Balance

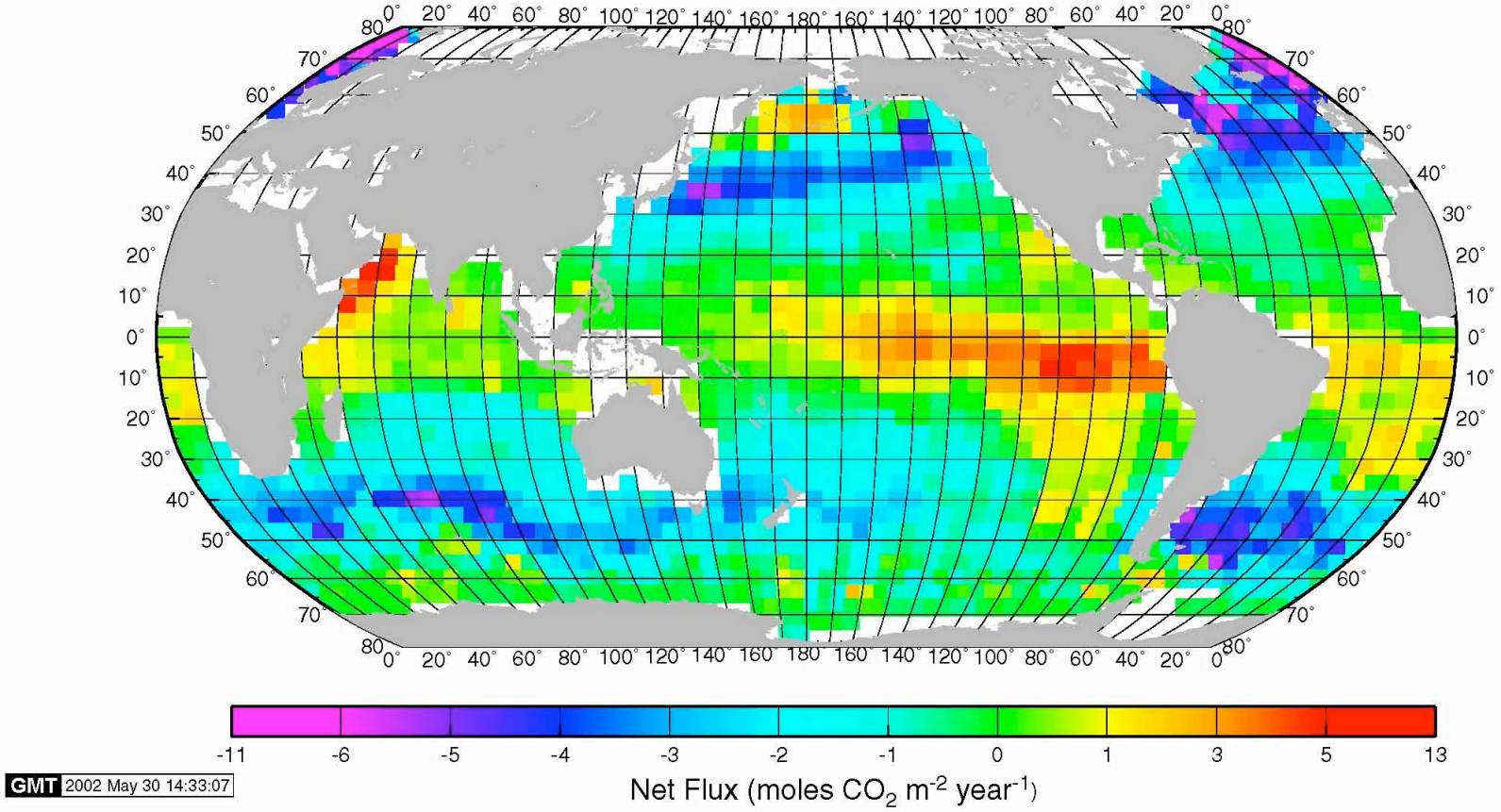



a) GLOBAL–MEAN OCEAN SURFACE HEAT FLUX
2XCO2
W m−2
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
CONTROL
2×CO2
b) VOLUME–MEAN OCEAN TEMPERATURE
°C
6.0
5.5
5.0
4.5
4.0
3.5
0
500
1000
1500
2000
YEAR
Danabasoglu and Gent (2009)

Earth's Carbon Cycle
(on century time scales)

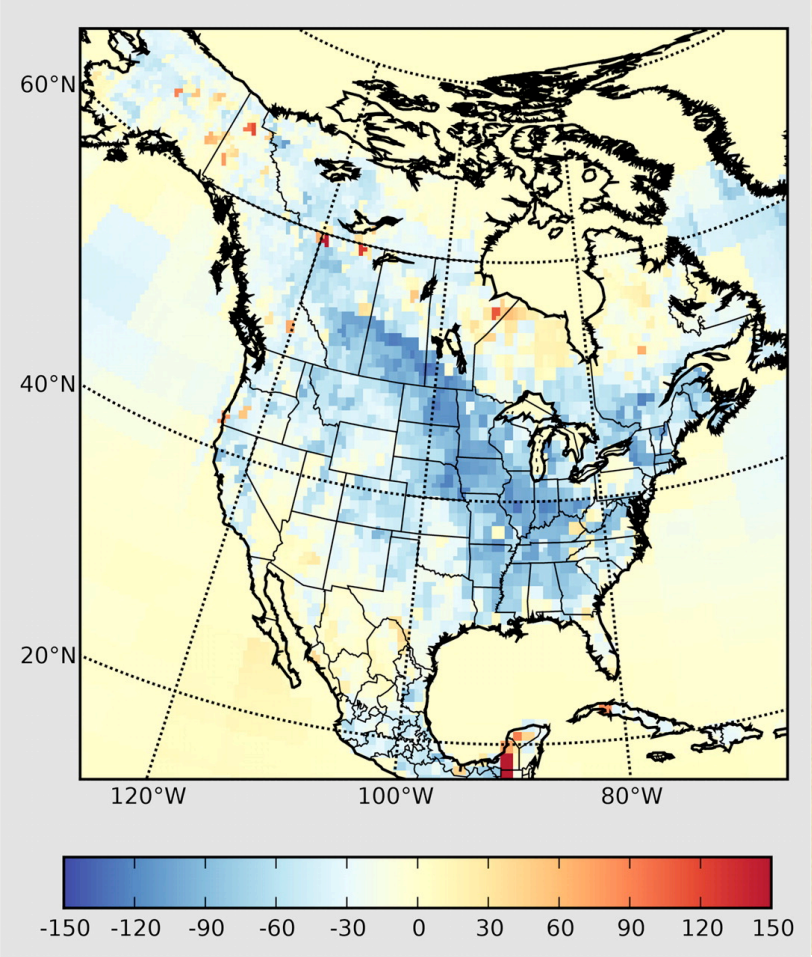

Simplified Global Carbon Cycle
Atmospheric Carbon Net Annual Increase
3 – 4 GtC/y
Atmosphere
(800)
GtC/y: Gigatons of carbon/year
Numbers in parentheses refer to stored carbon pools.
Net terrestrial uptake
0 – 1
6
Fossil fuels, cement, and land-use change
Net ocean uptake
2
120
Photosynthesis
90
Physicochemical exchange and biological pump
Plant biomass
(500)
Respiration
0 – 1
Microbial decomposition
2
Surface ocean
(1000)
Soil
(2500)
Soil carbon
Deep ocean
(38,000)
Rock
(70,000,000)
Fossil pool
(20,000)
Reactive sediments
(3000)
YGG-02-0340aR2

Flux of CO_2 into/out of ocean



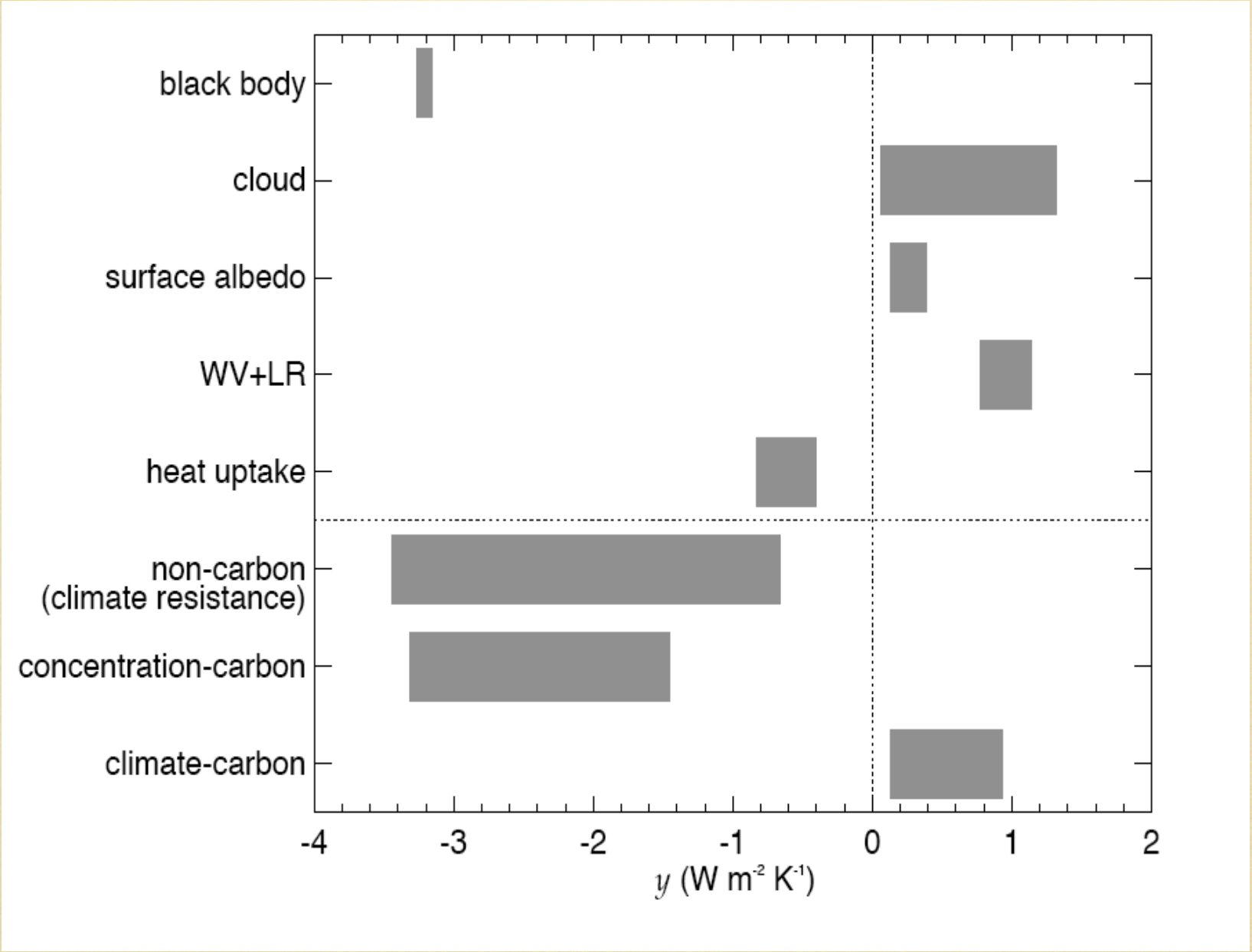
Takahashi et al (2000)

Mean net terrestrial and oceanic flux (NEP plus fires; no fossil fuel emissions included) for the period 2001–2005 estimated from our system



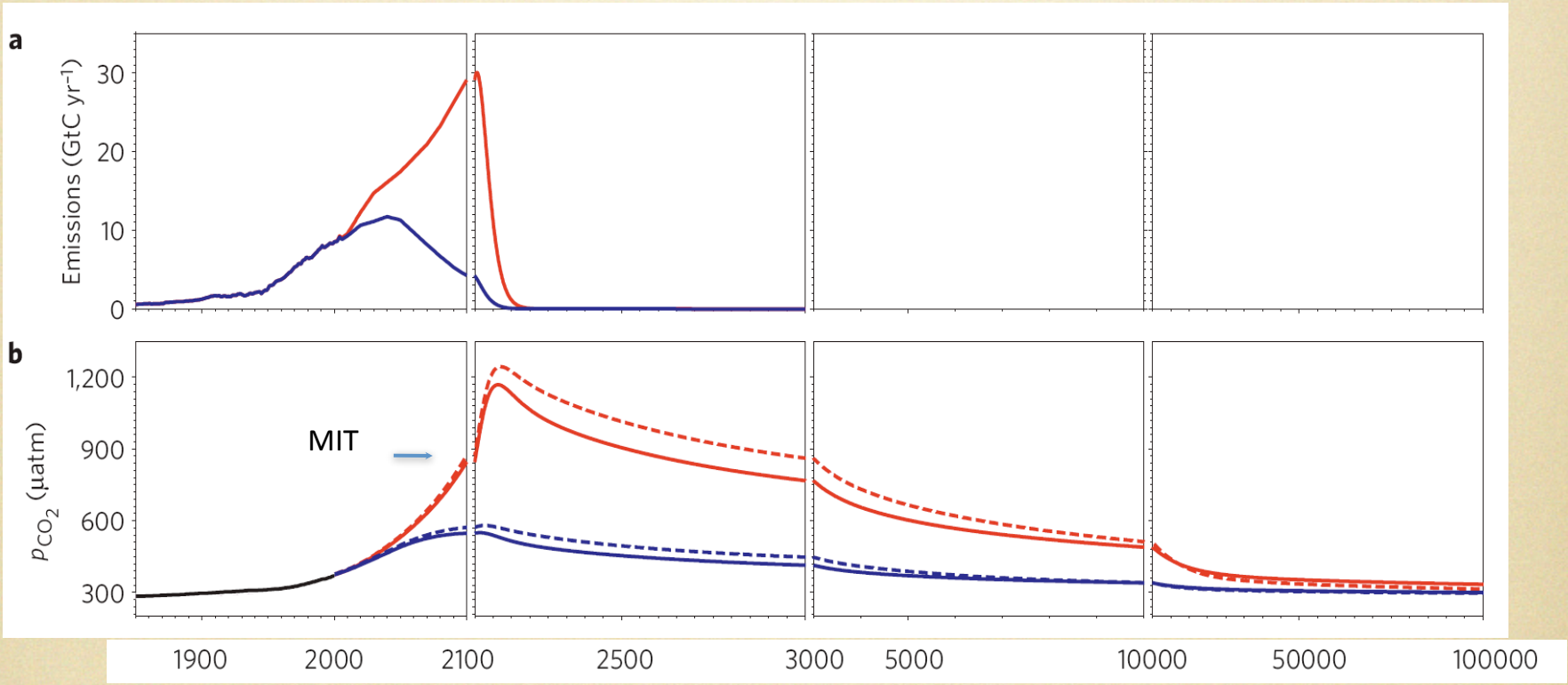
Peters W. et.al. PNAS;2007;104:18925-18930

Feedback Strengths



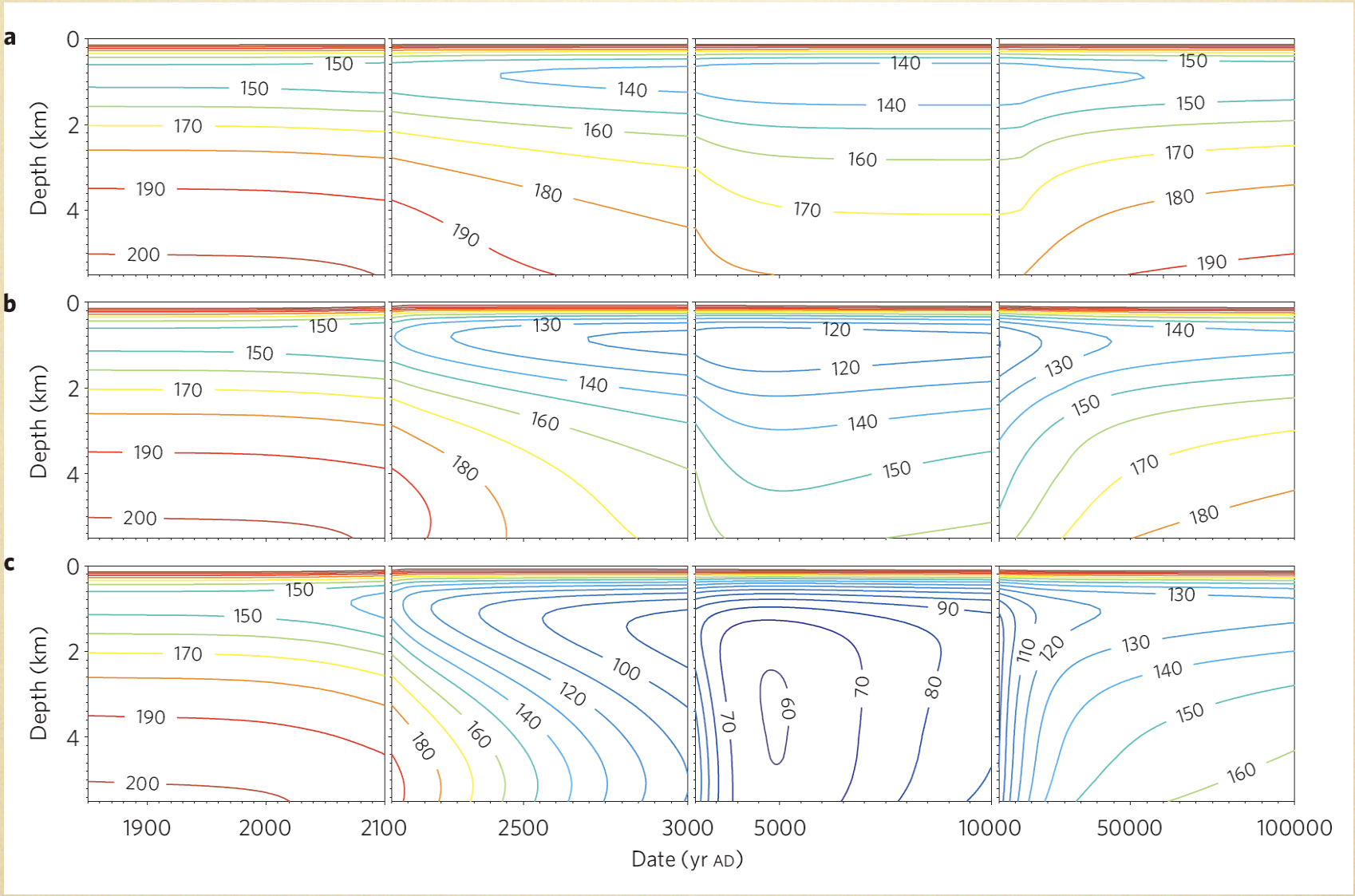
Gregory et al. (2009)

Emissions and Resulting Atmospheric CO_2 Concentration for A2 and B1 Scenarios



Shaffer et al. (2009)

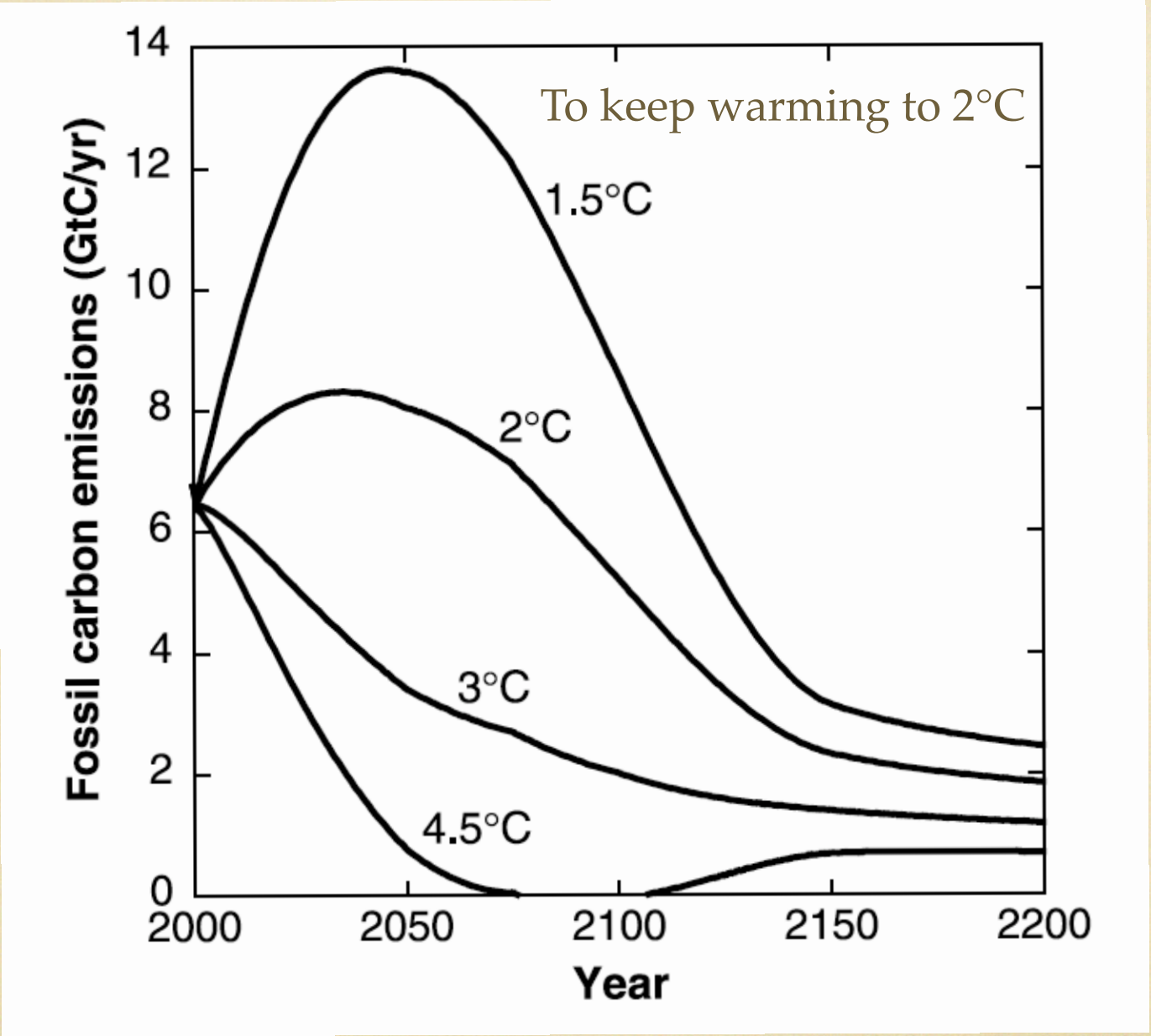
Ocean Dissolved-oxygen (μmol kg^{-1}) for A2 IPCC scenario



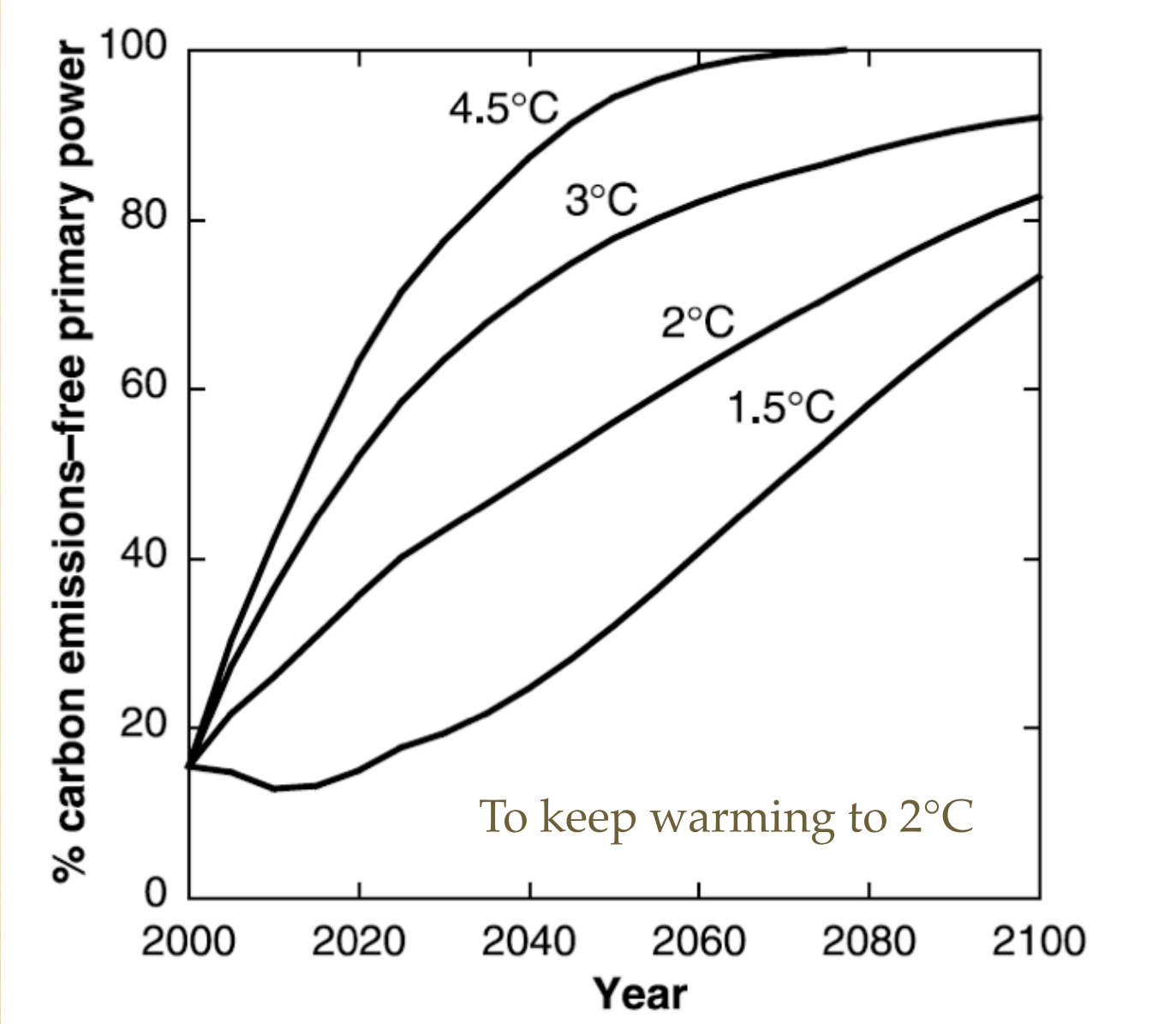
Shaffer et al. (2009)

Human Interactions

Why Does Climate Sensitivity Matter?



Caldeira et al. (2003)



Caldeira et al. (2003)

Don't get involved in partial problems, but always take flight to where there is a free view over the whole single great problem, even if the view is still not a clear one.

Ludwig Wittgenstein

THE END