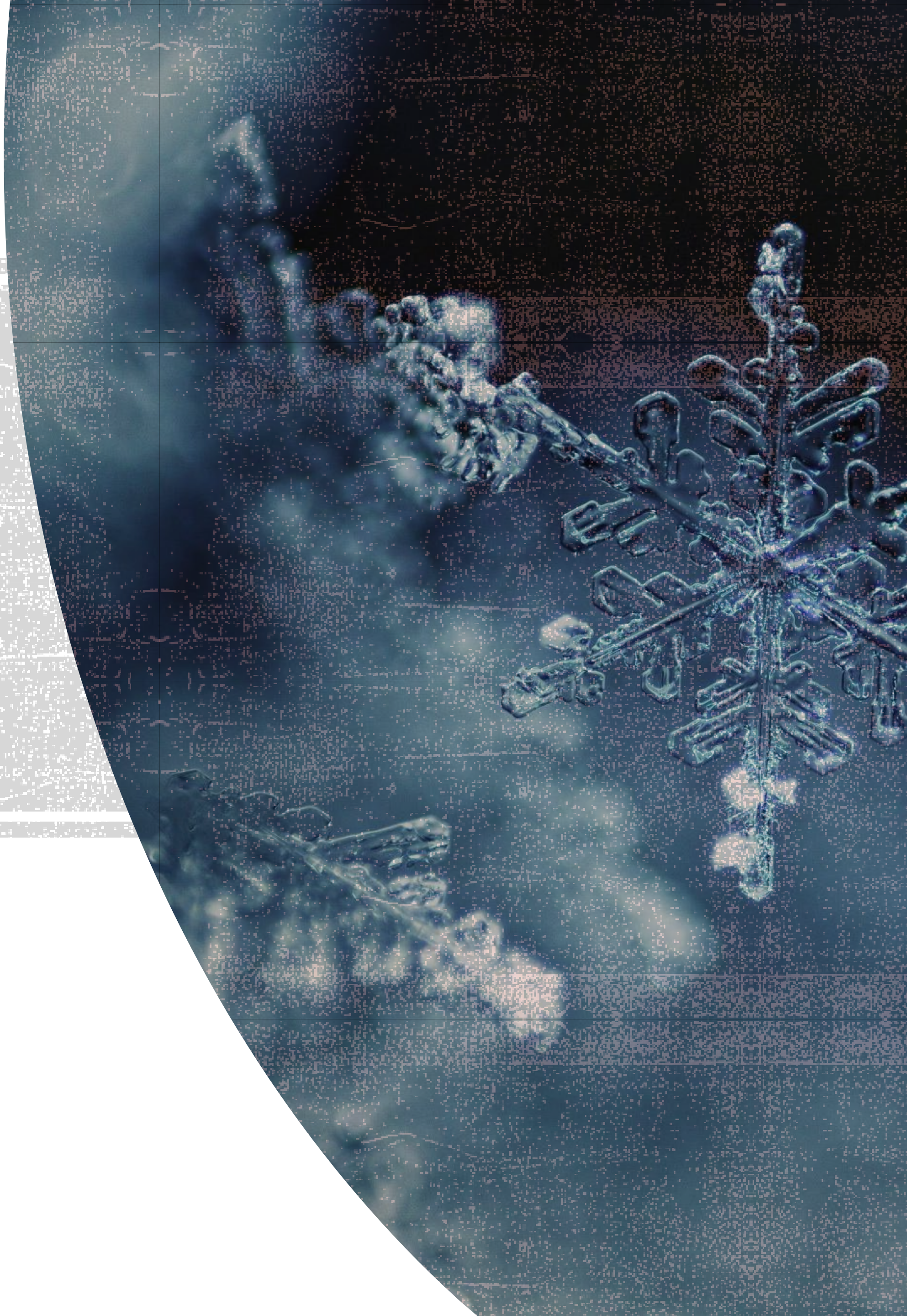
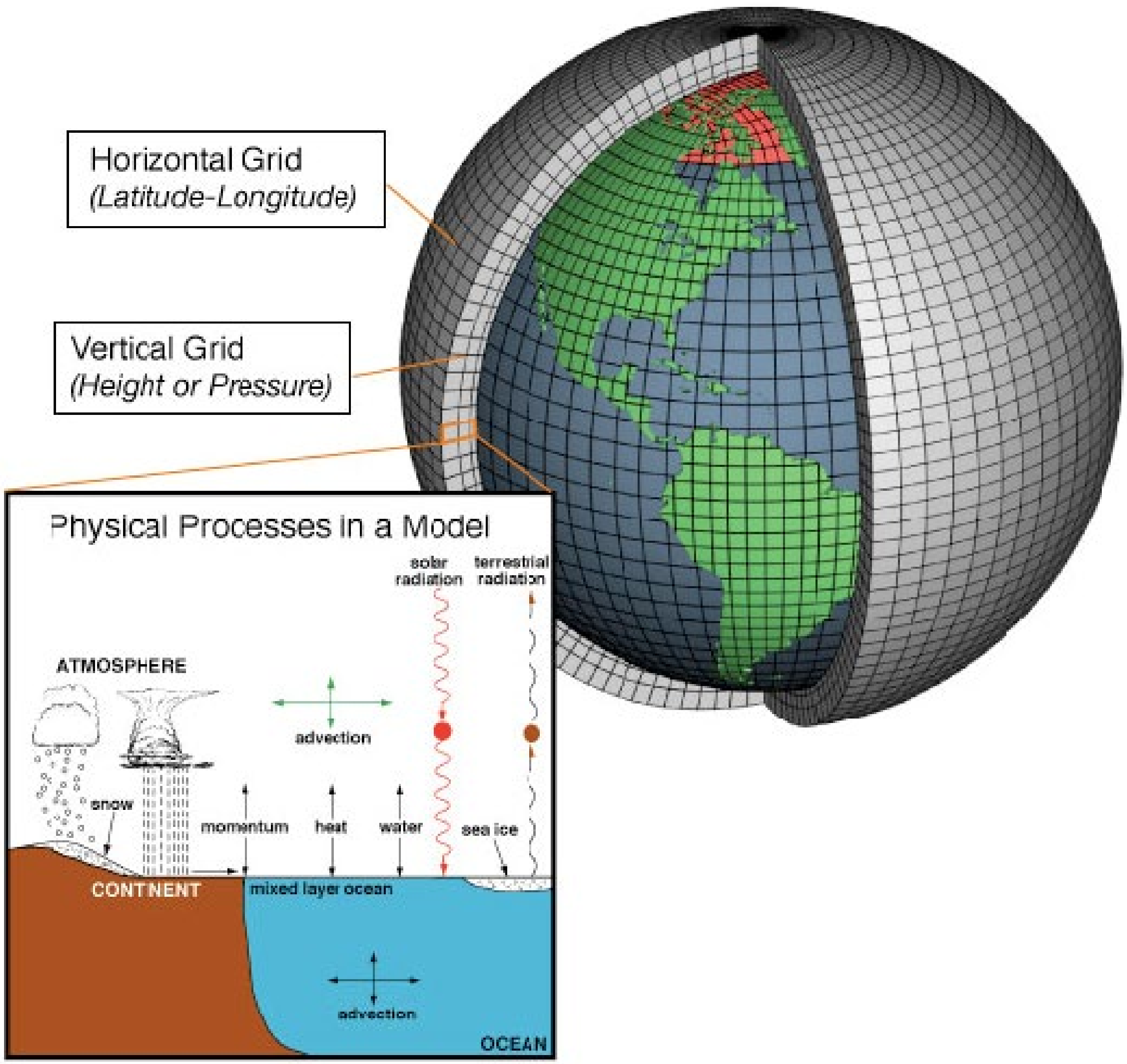
CLIMATE MODELING



COMPUTER MODELING

- Goal: To simulate a system using mathematical expressions / equations and parameterizations.

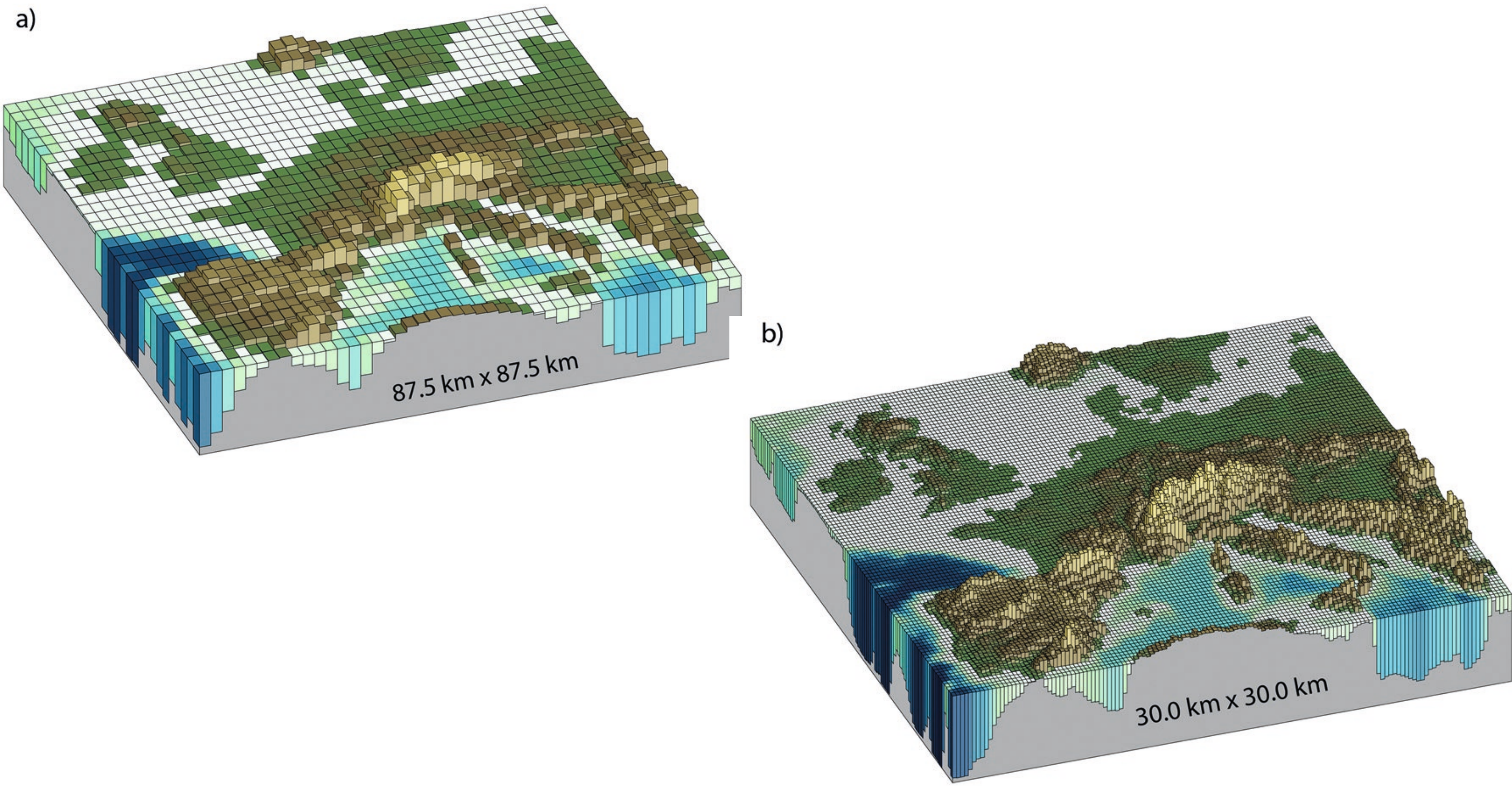
- Steps:
  1) Define domain
  2) Divide the domain into gridpoints (horizontal and vertical)
  3) Assess equations / relationships at each gridpoint
  4) Step forward in time



Horizontal Grid
(Latitude-Longitude)
Vertical Grid
(Height or Pressure)
Physical Processes in a Model
solar radiation
terrestrial radiation
ATMOSPHERE
advection
snow
momentum
heat
water
sea ice
CONTINENT
mixed layer ocean
advection
OCEAN

MODEL RESOLUTION

- Spatial and temporal resolution can be increased to simulate smaller scale processes.



MODEL VARIABLES

- Deterministic: can be solved in equation

$$\frac{\partial \vec{V}}{\partial t} = -\vec{U} \cdot \nabla \vec{V} - \frac{1}{\rho} \nabla_h p - f\hat{k} \times \vec{V} + \vec{F}_r$$

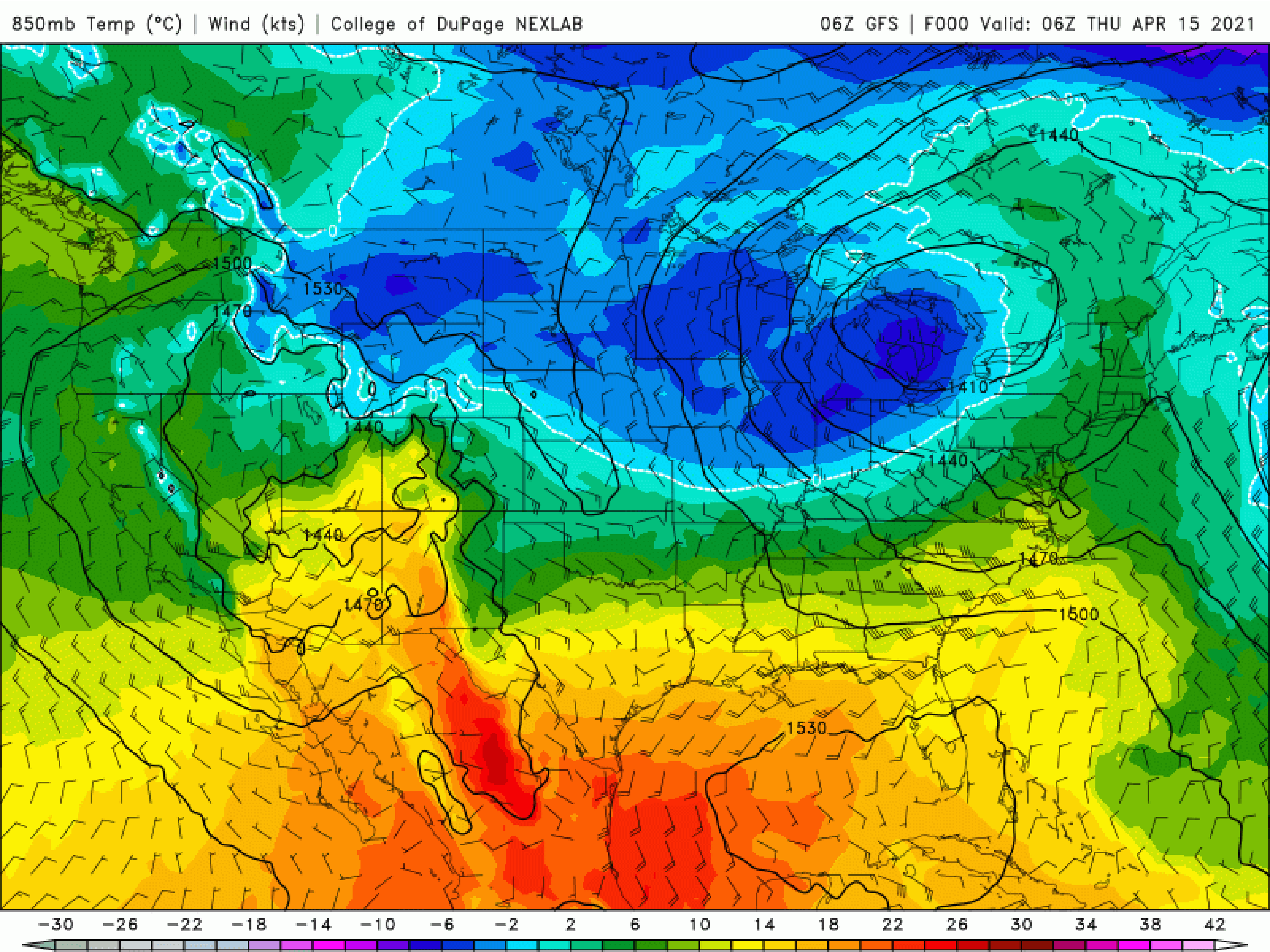
- Parameterized: Estimated or approximated
  - Surface Type
  - Microphysical processes
  - Initial conditions

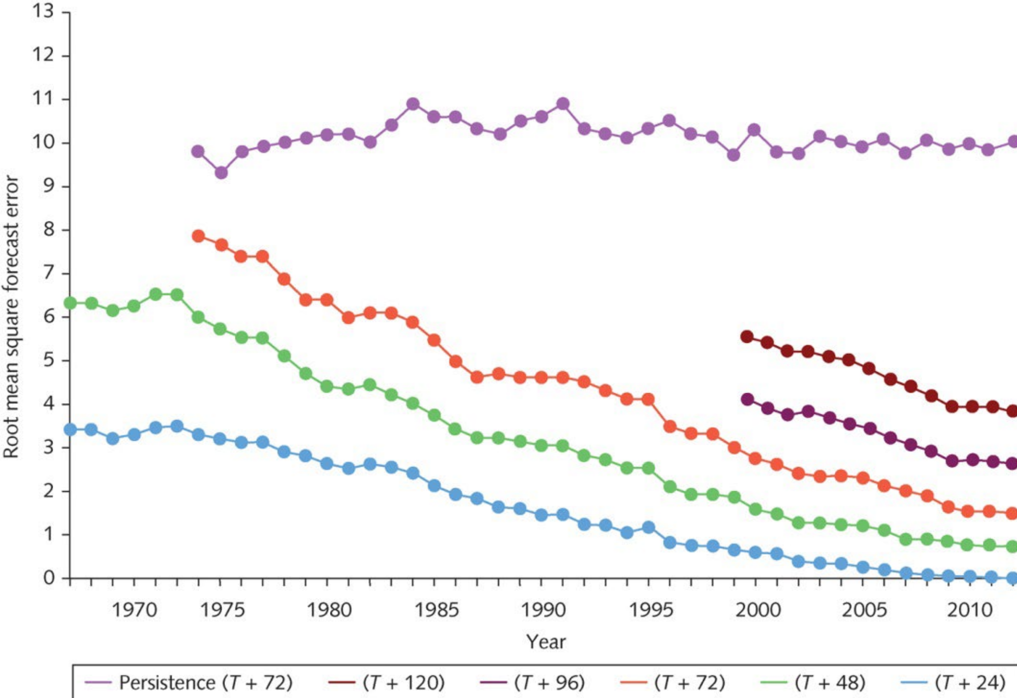
WEATHER MODELS VS. CLIMATE MODELS

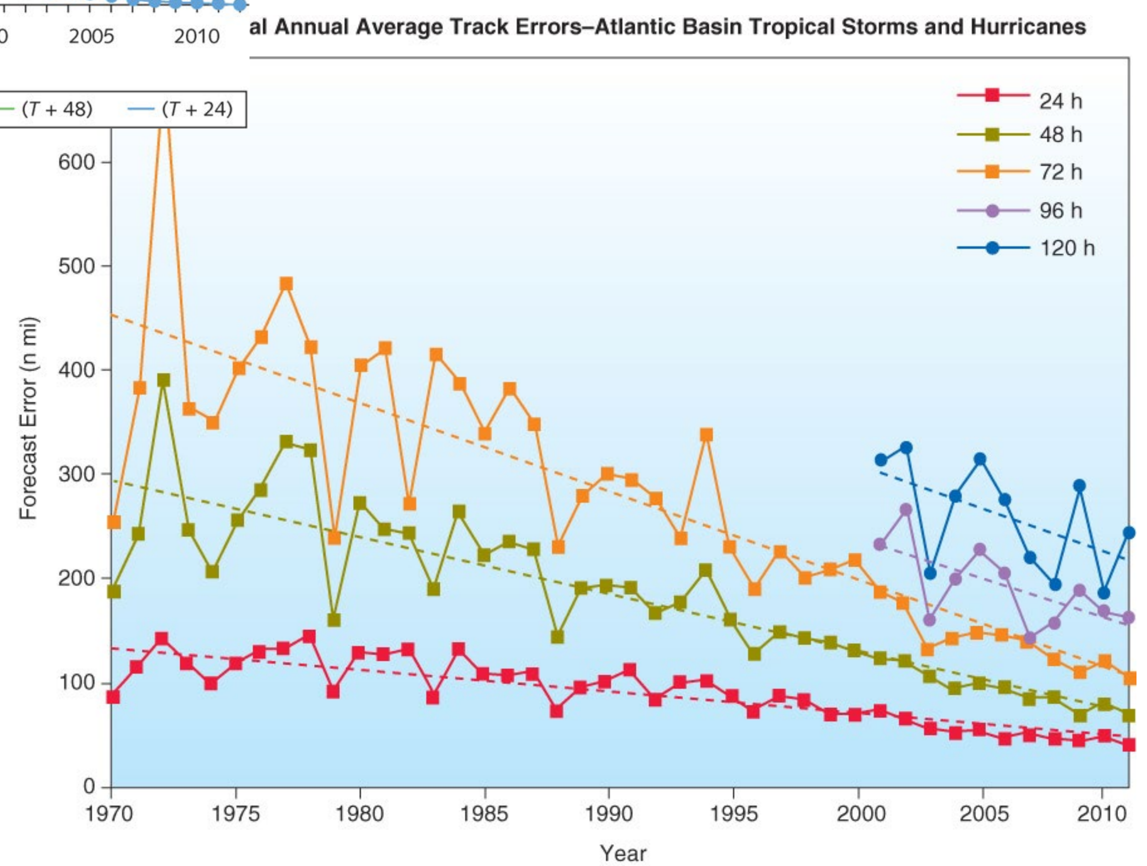
- Numerical weather prediction (NWP) is different from global climate modeling (GCMs).
- "How can they predict global warming if they can't predict the weather correctly for tomorrow!"

NWP

- Goal: Specific value, specific place, specific time.
- Based on initial conditions, equations, and parameterizations
- Accuracy greatly improved over the years


850mb Temp (°C) | Wind (kts) | College of DuPage NEXLAB
06Z GFS | F000 Valid: 06Z THU APR 15 2021
1440
1500
1530
1470
0
1410
1440
1440
1470
1470
1500
1530
-30 -26 -22 -18 -14 -10 -6 -2 2 6 10 14 18 22 26 30 34 38 42


Root mean square forecast error
Year
Persistence (T + 72)
(T + 120)
(T + 96)
(T + 72)
(T + 48)
(T + 24)


al Annual Average Track Errors–Atlantic Basin Tropical Storms and Hurricanes
24 h
48 h
72 h
96 h
120 h
Forecast Error (n mi)
Year

GCM

- Concerned with longer time scales and different goals compared to NWP.

- Driven by feedbacks / parameterizations
  - Ex. GHG concentration

- Rely heavily on statistics
  - Averages
  - Anomalies
  - Variance
  - Probability Distributions

MODEL VALIDATION

- Need to make sure model isn't "Out to Lunch". Several ways to validate climate model:

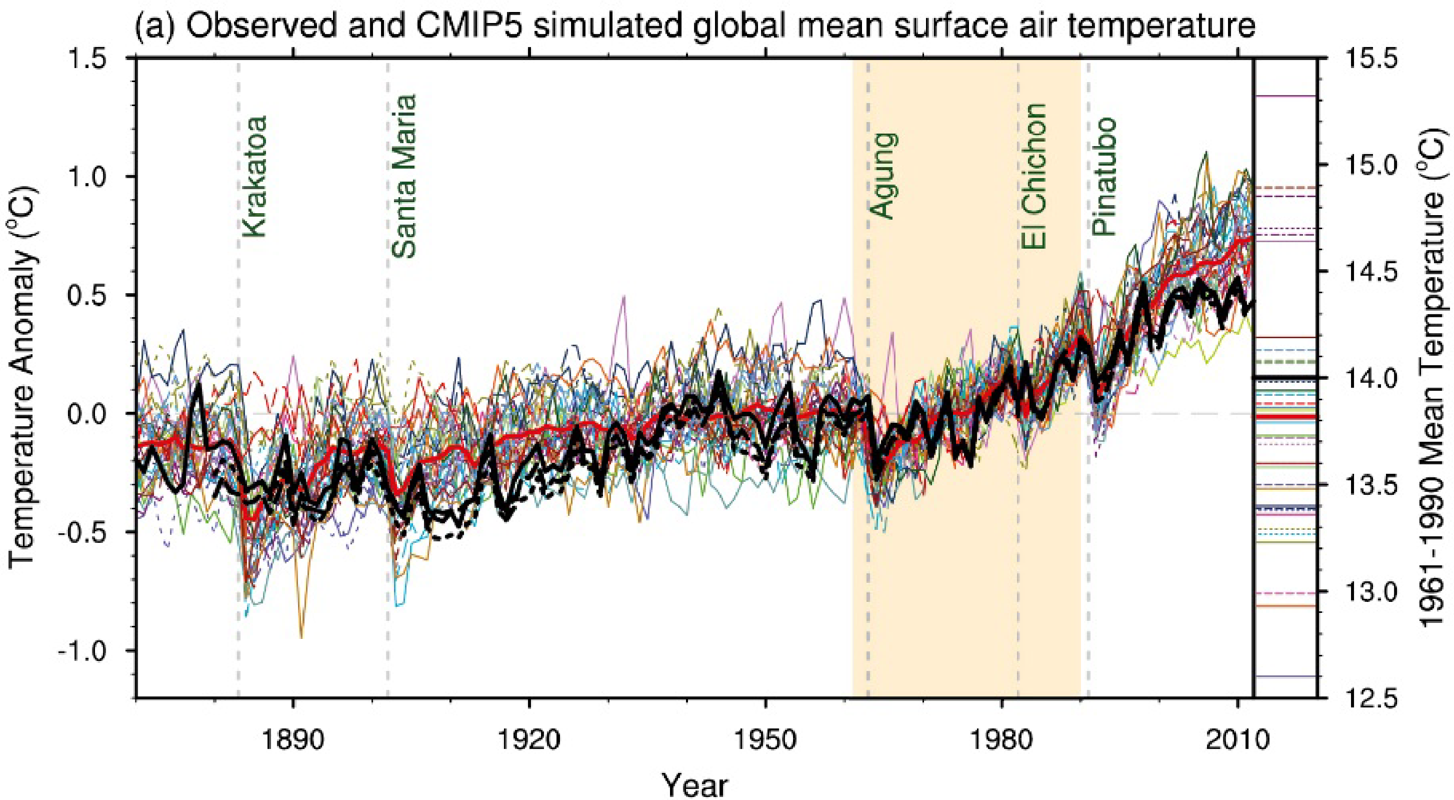
1) Compare with recent past (150 year instrument record).

2) Compare with paleoclimate data

3) Compare large climatic perturbations

COMPARE WITH INSTRUMENT RECORD

- Coupled Model Intercomparison Project (CMIP) 4 and 5 (and 6)
  - Compare models with observations and each other



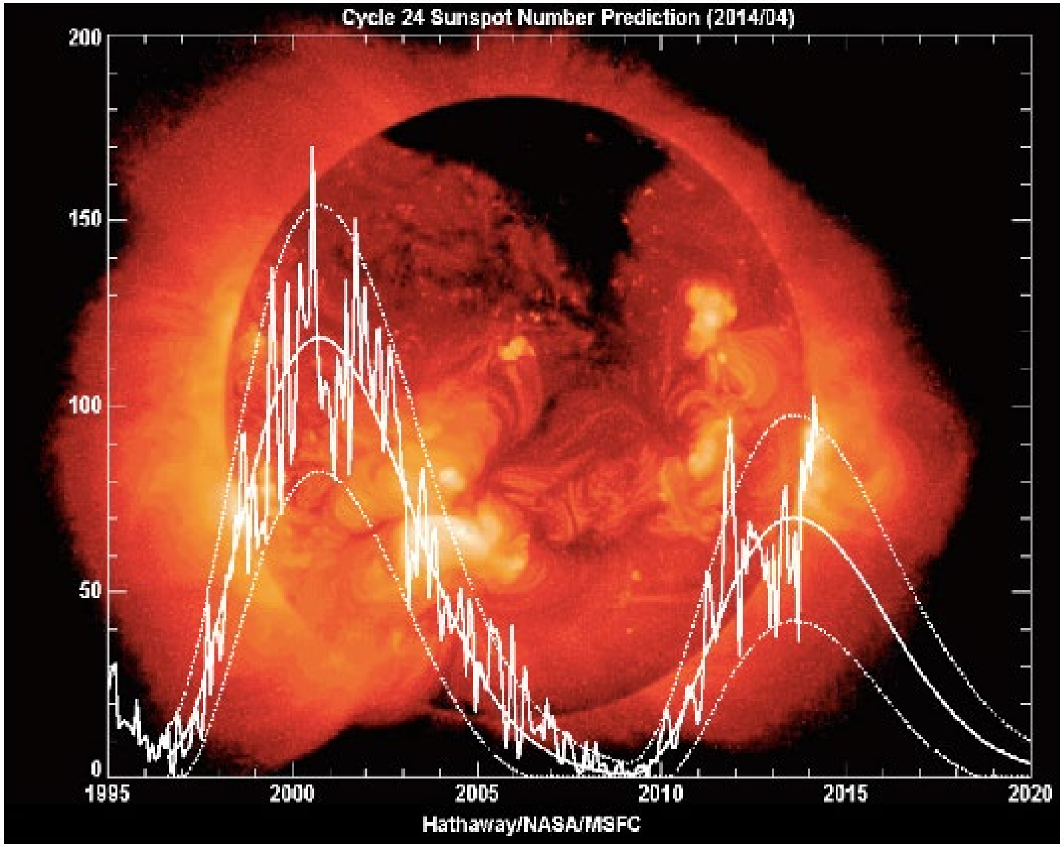
CMIP 4

- Goal: Separate anthropogenic and natural influences in 20th century climate.
- Natural:
  - Solar output variations (sunspots, etc)
  - Internal Forcings (El Nino)
  - Orbital Variations
  - Plate Tectonics
  - Volcanic Eruptions
- Anthropogenic
  - GHG emissions
  - Aerosols

SOLAR OUTPUT VARIATIONS

- Recall solar "constant" is 1360 W/m^2.

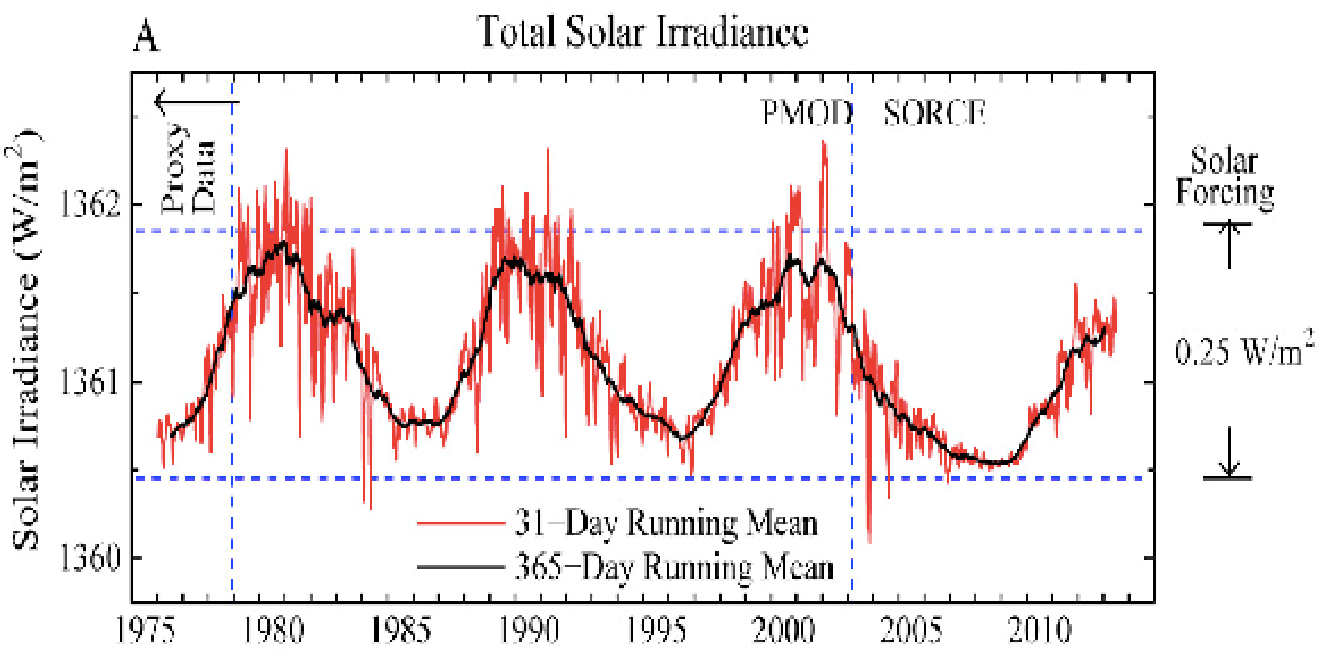
- Variations due to 11 year sunspot cycle
  - Sunspot: Cool, dark areas on solar surface.



SOLAR OUTPUT VARIATIONS

- Recall solar "constant" is ~1360 W/m^2.

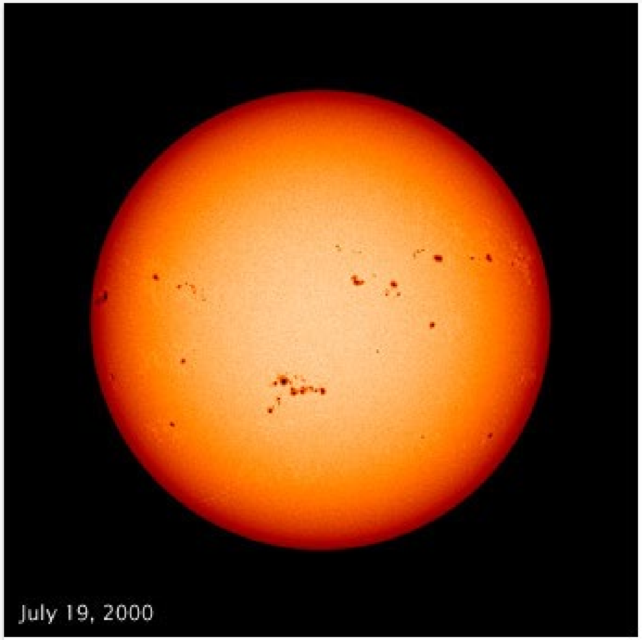
- Variations due to 11-year sunspot cycle
  - Sunspot: Cool, dark areas on solar surface.
  - Fewer sunspots = smaller solar constant = cooler temps

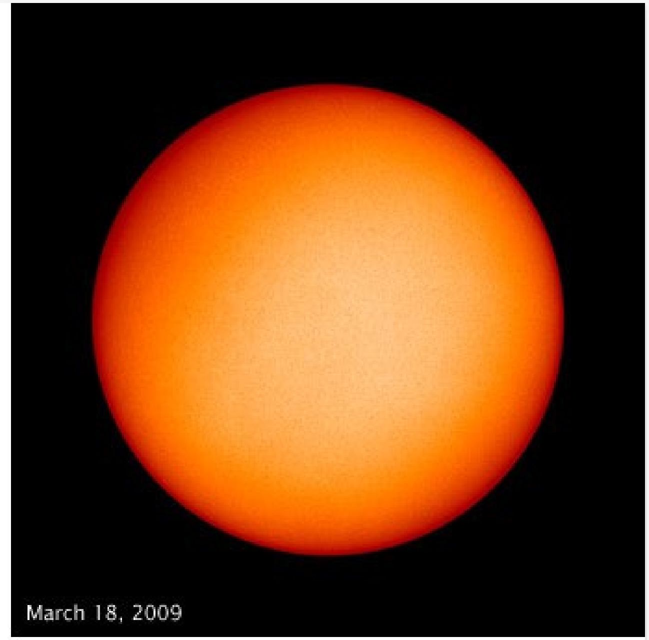


SOLAR OUTPUT VARIATIONS

- Recall solar "constant" is 1360 W/m^2.

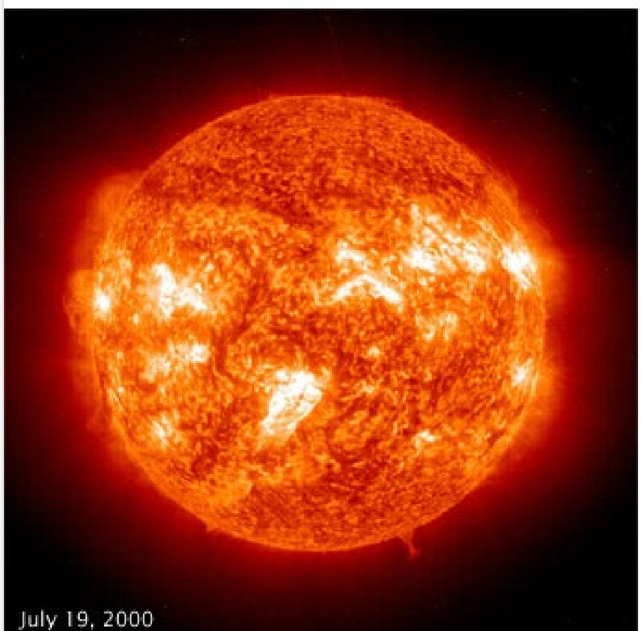
- Variations due to 11 year sunspot cycle
  - Sunspot: Cool, dark areas on solar surface.
  - Fewer sunspots = smaller solar constant = cooler temps
  - Accompanied by faculae
  - Change of 1.4 W/m^2 over the cycle.





Sunspots

acquired July 19, 2000 - March 18, 2009



Ultraviolet

SOLAR OUTPUT VARIATIONS

- Recall solar "constant" is 1360 W/m^2.

- Variations due to 11 year sunspot cycle
  - Sunspot: Cool, dark areas on solar surface.
  - Fewer sunspots = smaller solar constant = cooler temps
  - Accompanied by faculae
  - Change of 1.4 W/m^2 over the cycle.

- "Maunder Minimum" thought to have contributed to the Little Ice Age

- Existence of longer cycles uncertain
  - Bigger solar minimum between 2020 – 2030?

INTERNAL VARIABILITY

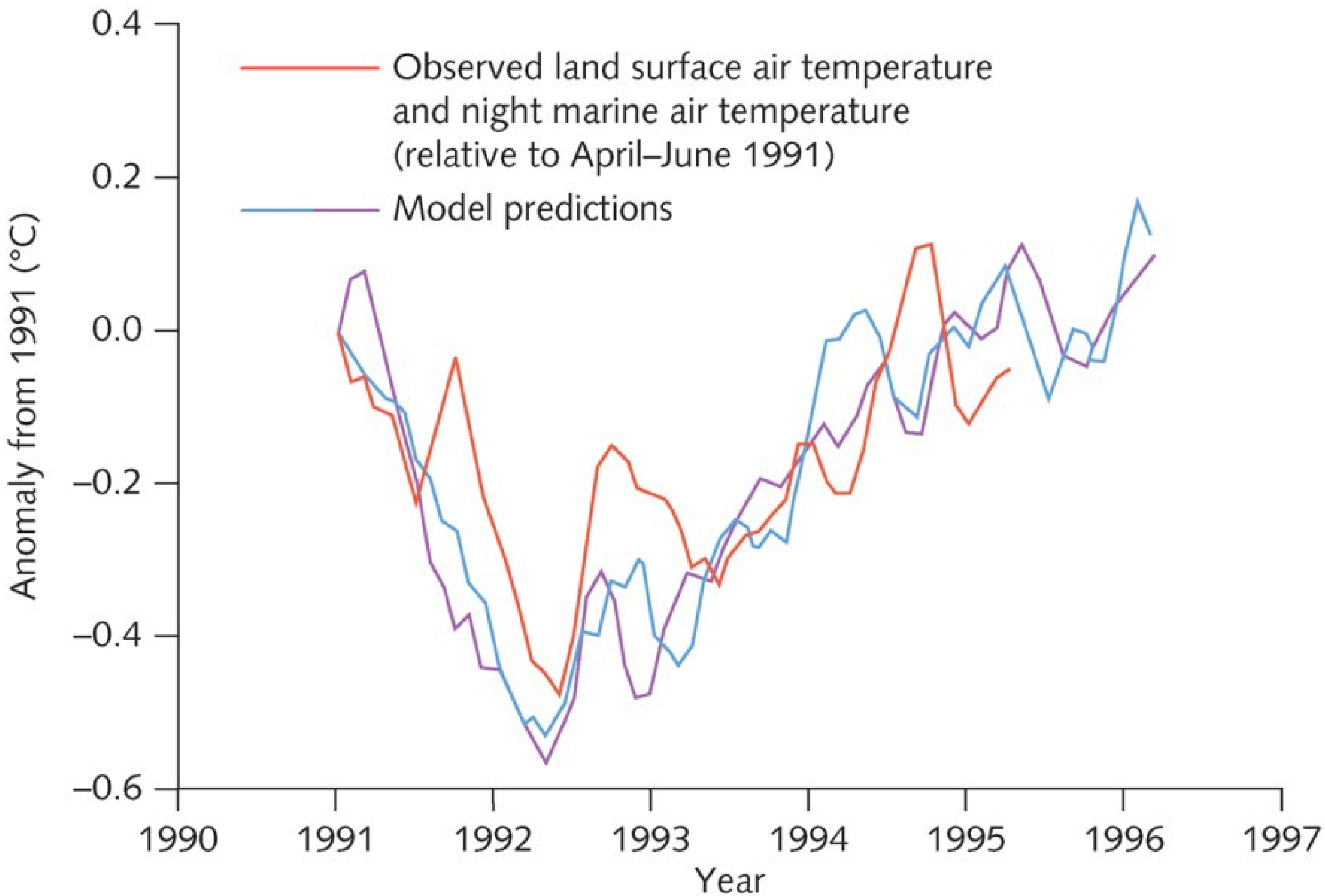
- Changes of the internal physics of planet rather than external changes to the energy budget.

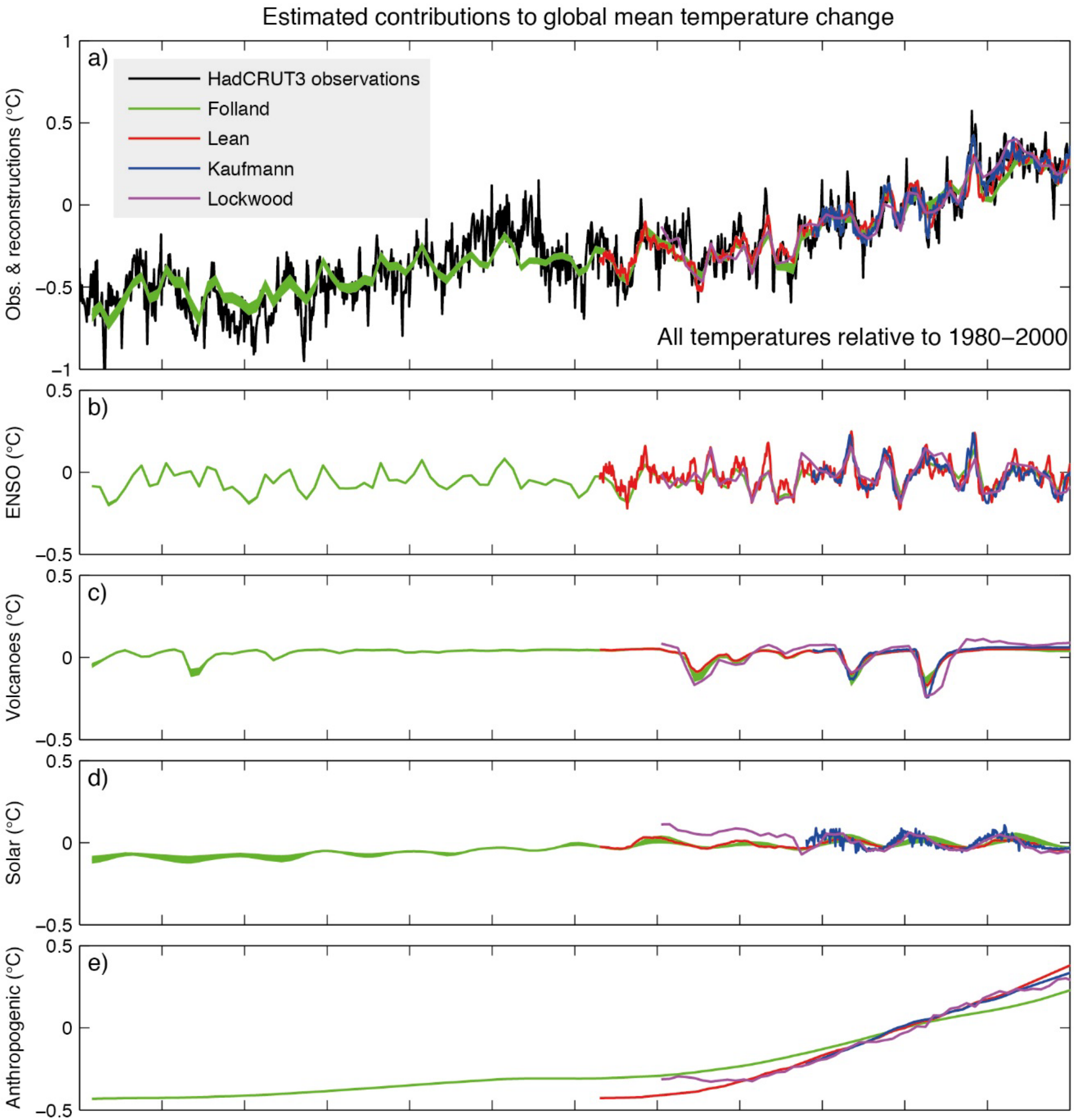
- Teleconnections:
  - El Nino / La Nina (ENSO)
  - Pacific Decadal Oscillation (PDO)
  - Atlantic Multi-Decadal Oscillation (AMO)

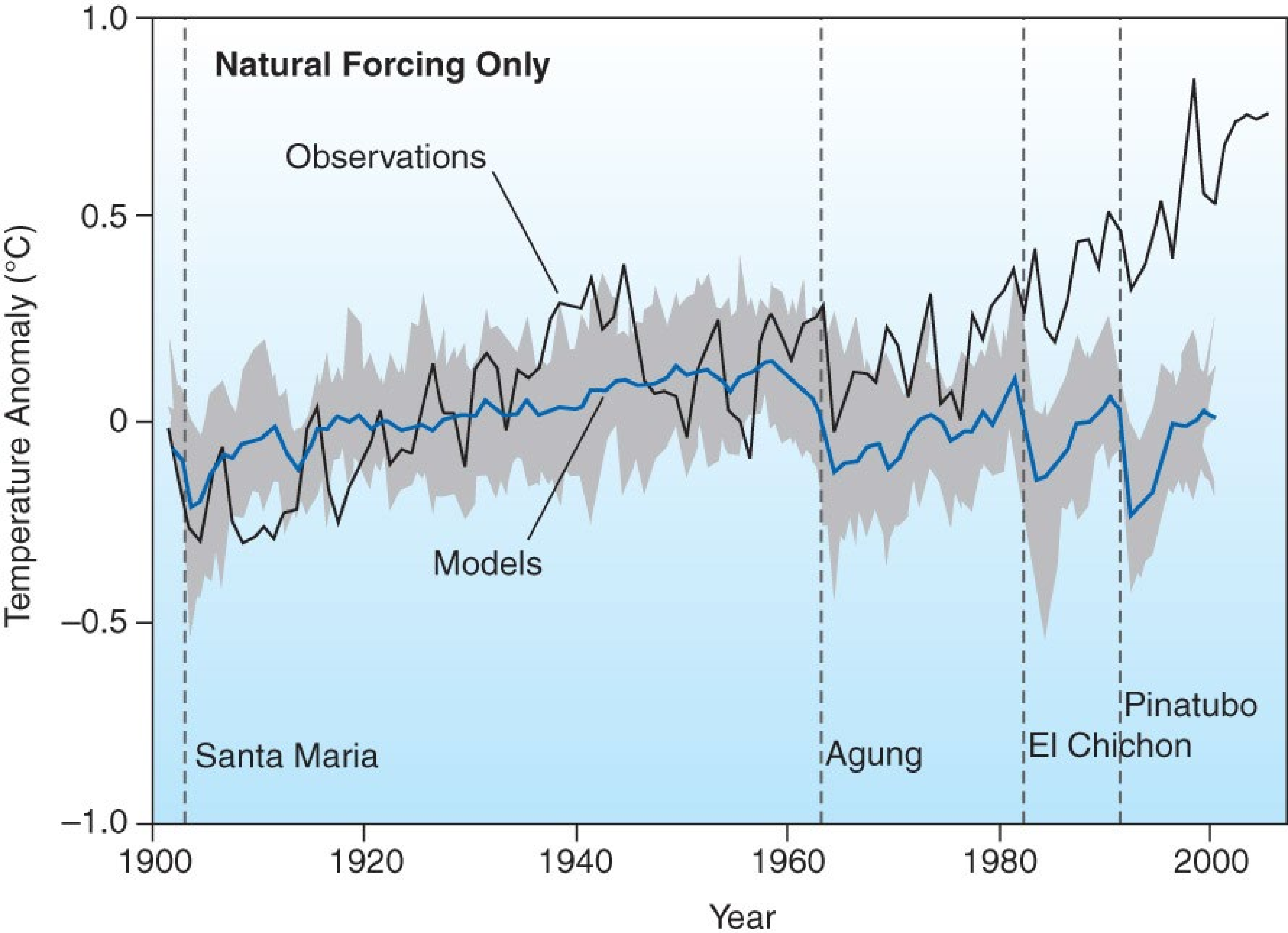
- ENSO:
  - Warm Phase (El Nino) increases global temp.
  - Cool Phase (La Nina) decreases global temp.

VOLCANIC ERUPTIONS

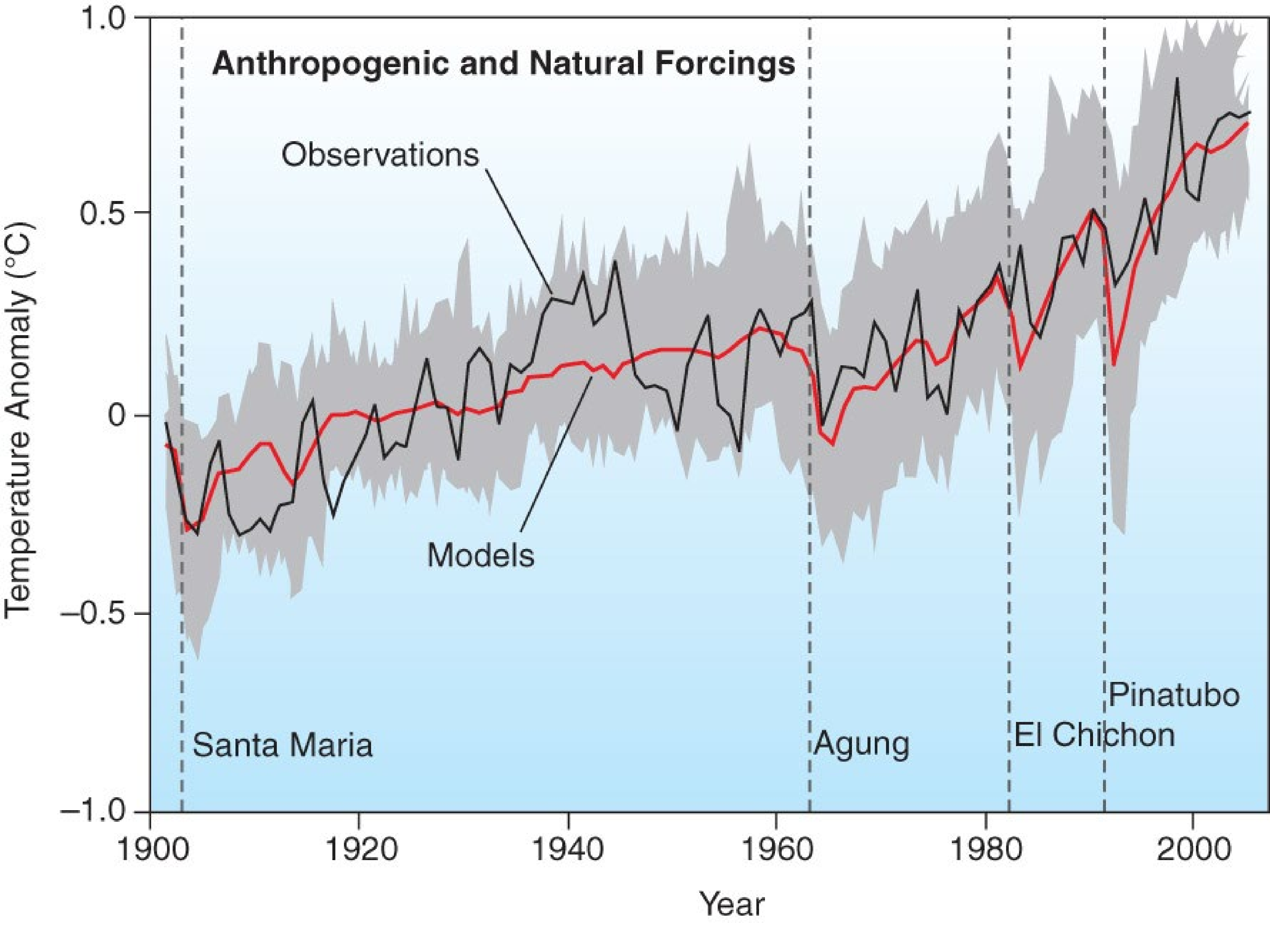
- Large negative temporary radiative forcing




Estimated contributions to global mean temperature change
a)
HadCRUT3 observations
Folland
Lean
Kaufmann
Lockwood
Obs. & reconstructions (°C)
All temperatures relative to 1980–2000
b)
ENSO (°C)
c)
Volcanoes (°C)
d)
Solar (°C)
e)
Anthropogenic (°C)
1
0.5
0
−0.5
−1



Natural Forcing Only
Observations
Models
Santa Maria
Agung
El Chichon
Pinatubo
Temperature Anomaly (°C)
1.0
0.5
0
−0.5
−1.0
1900
1920
1940
1960
1980
2000
Year



Anthropogenic and Natural Forcings
Observations
Models
Santa Maria
Agung
El Chichon
Pinatubo
Temperature Anomaly (°C)
Year
1.0
0.5
0
−0.5
−1.0
1900
1920
1940
1960
1980
2000

MODELING THE FUTURE

- Goal: develop and validate climate models so we can estimate future climate change.

- Model simulations depend on assumptions regarding future emissions of GHGs.
  - Not just one *prediction*, but many *projections*
  - These account for range of assumptions

- Need consistency – one group to organize the research and provide guidelines for assumptions.

IPCC

- Intergovernmental Panel on Climate Change

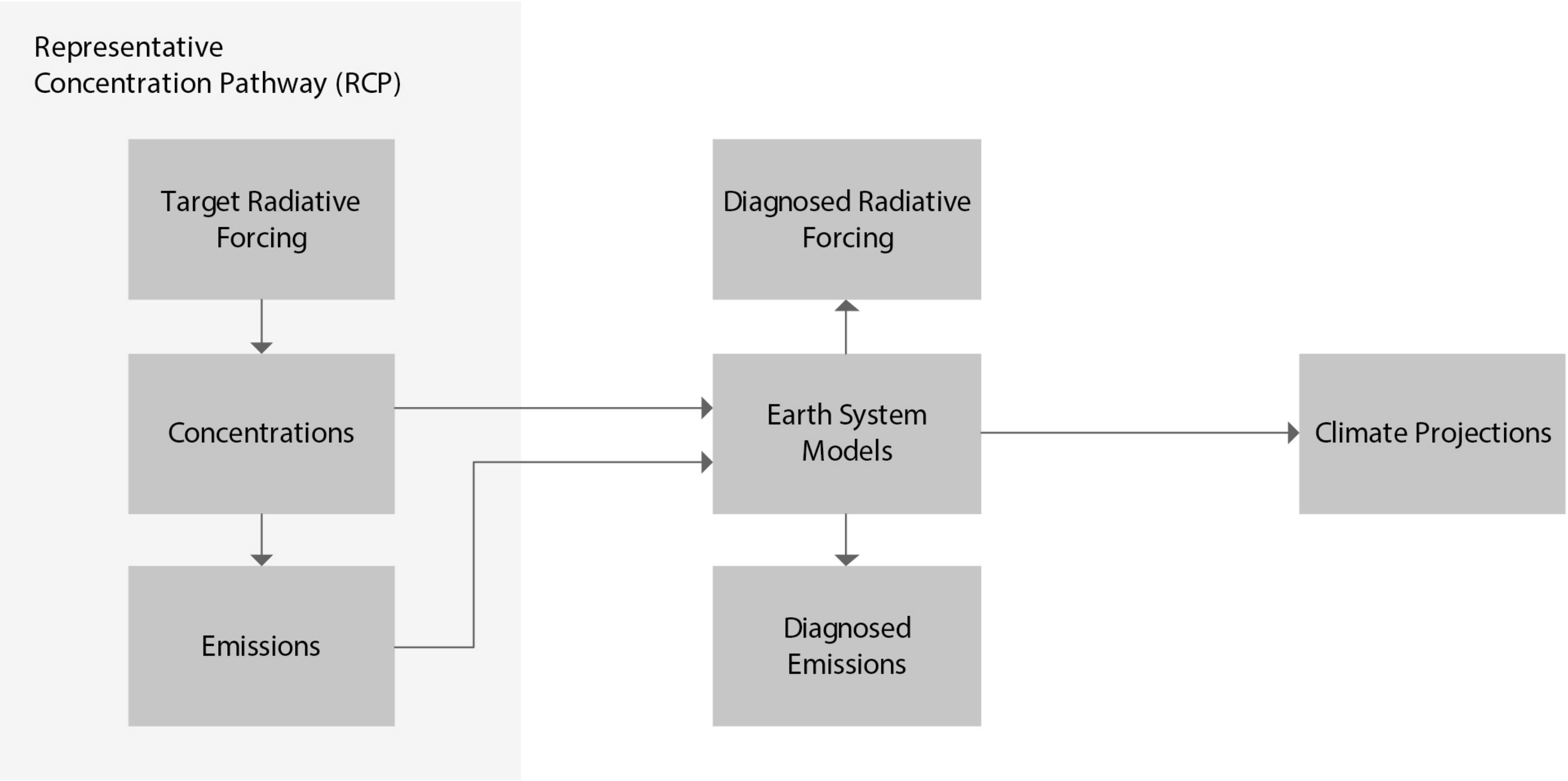
- United Nations based committee that produces comprehensive reviews on the physical science, impacts / adaptation, and mitigation of climate change.

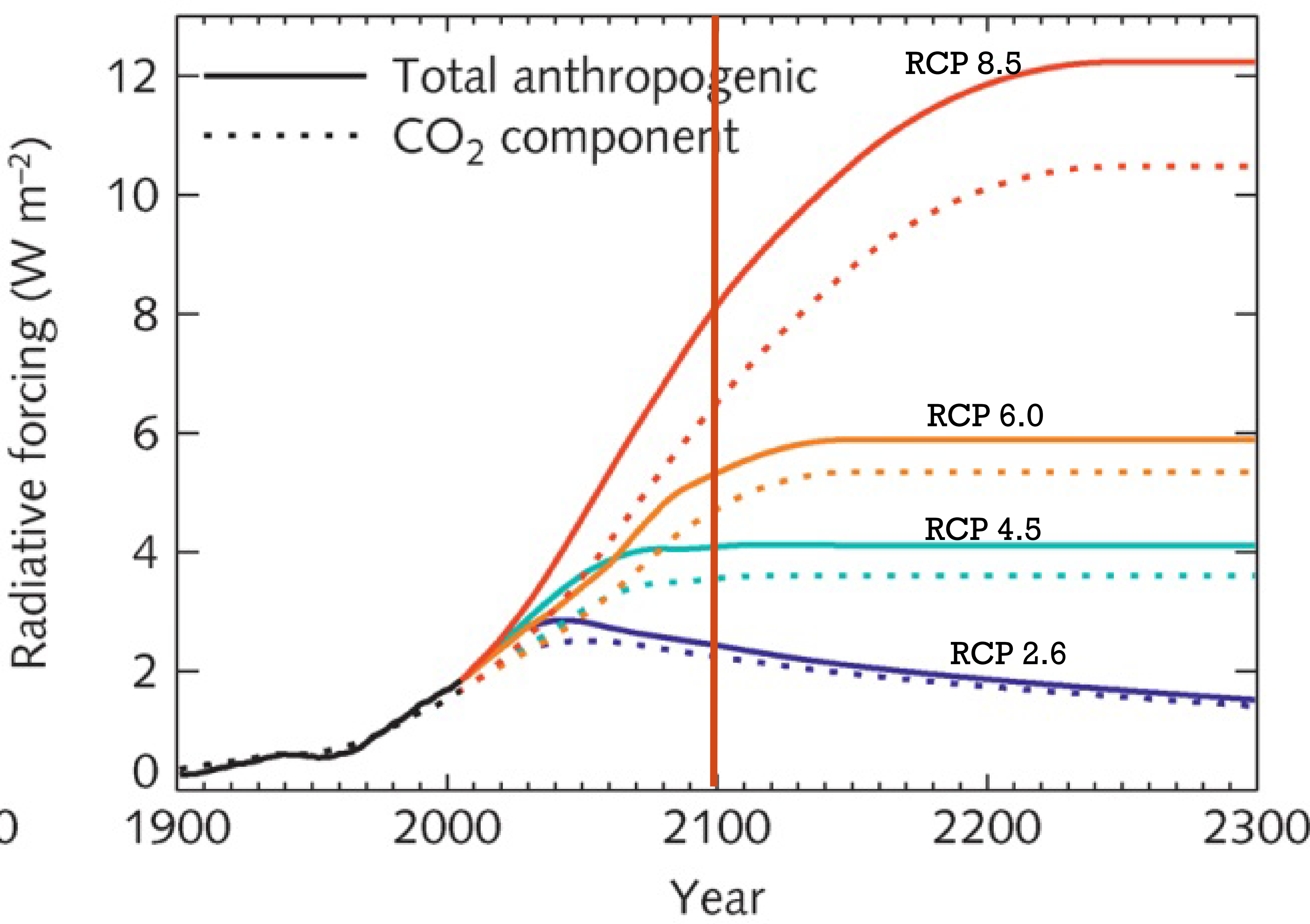
- An assessment report is produced every few years. Most recent is AR 5 (2013-2014). AR 6 is expected in 2022.

IPCC GUIDELINES

- Researchers have determined 4 viable "scenarios" or descriptions of future emissions.
- Described as "Pathways". Each pathway is defined by the increase in radiative forcing:
  - RCP 2.6 (PD3)
  - RCP 4.5 (Stabilize)
  - RCP 6 (Stabilize)
  - RCP 8.5 (Increases)

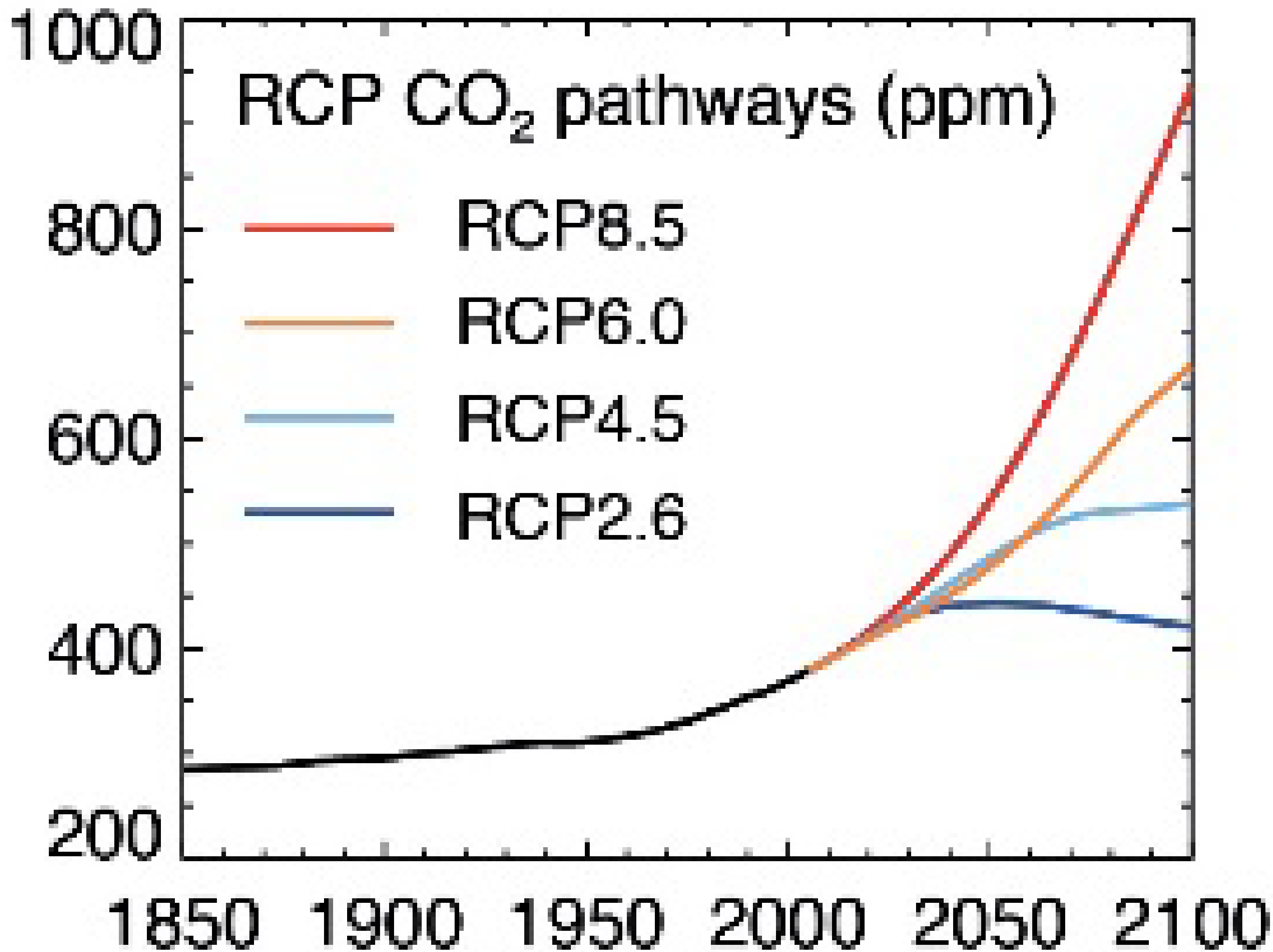
RCP PROCESS

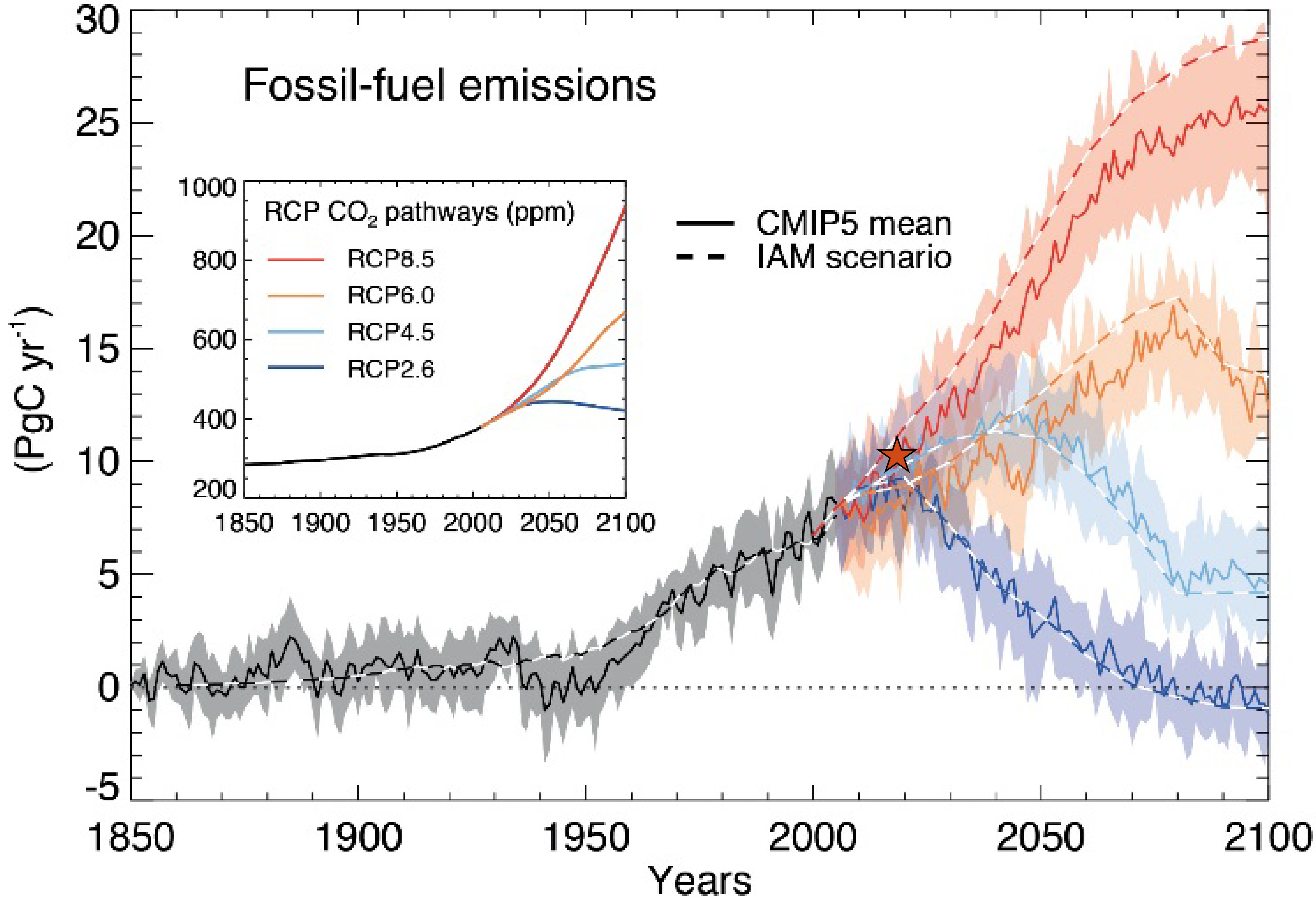

Representative
Concentration Pathway (RCP)
Target Radiative Forcing
Concentrations
Emissions
Diagnosed Radiative Forcing
Earth System Models
Diagnosed Emissions
Climate Projections

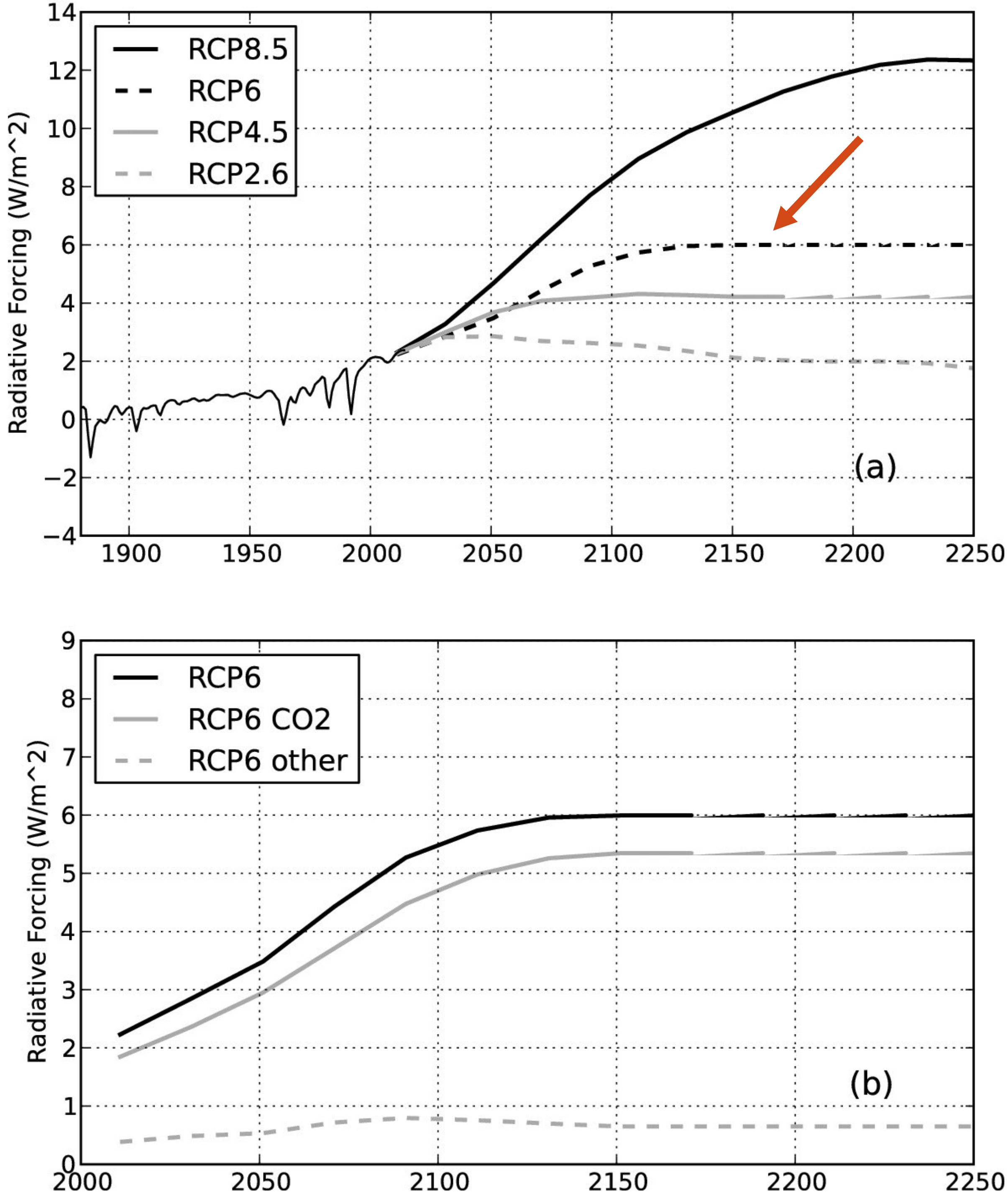

Total anthropogenic
CO2 component
RCP 8.5
RCP 6.0
RCP 4.5
RCP 2.6
Radiative forcing (W m−2)
0
2
4
6
8
10
12
1900
2000
2100
2200
2300
Year

RCP NUMBERS

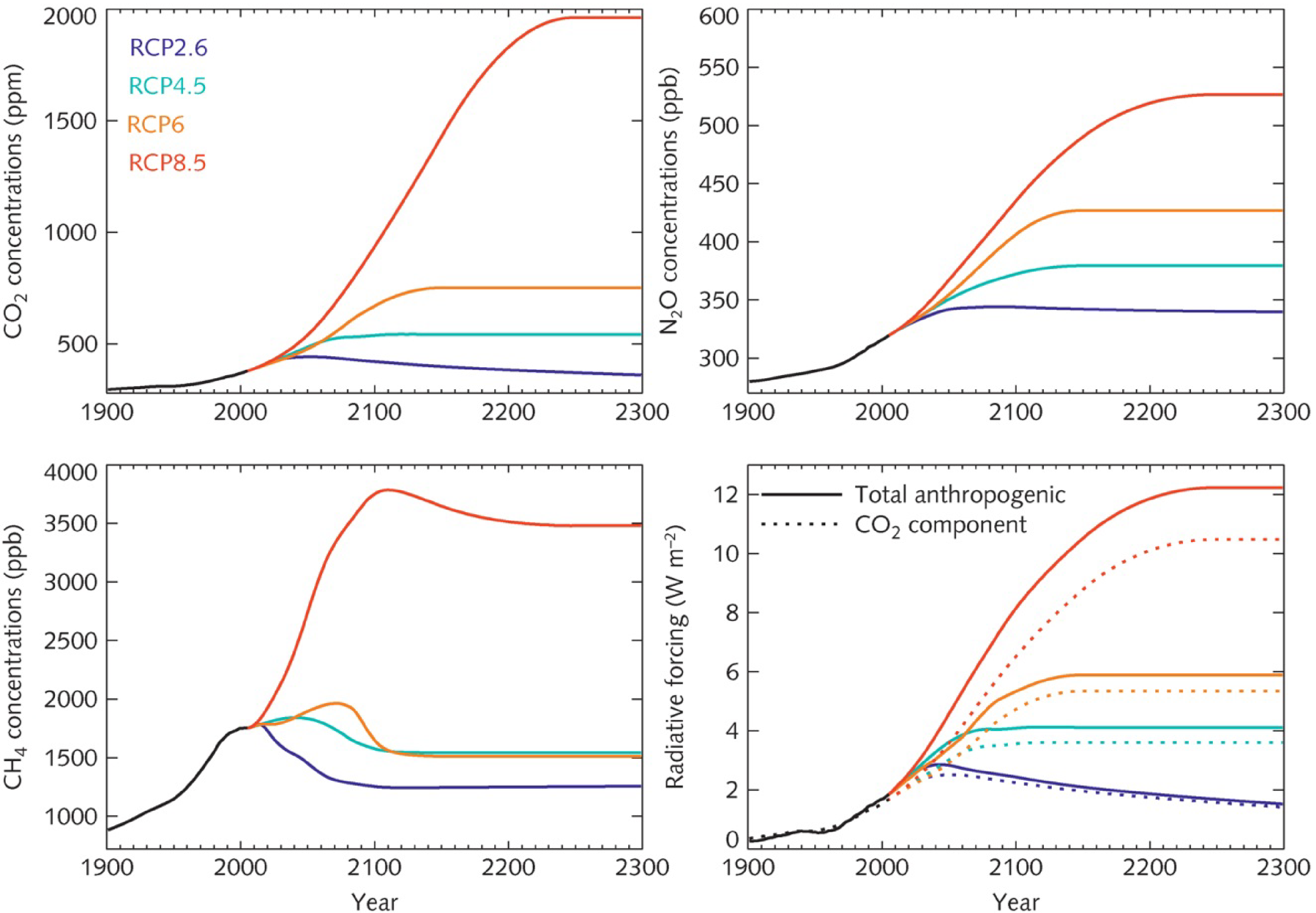
- Concentrations – driven by emissions.
  - RCP 2.6 – 421 ppm (peak of 442 in 2050)
  - RCP 4.5 – 538 ppm (stabilize @ 543 ppm)
  - RCP 6.0 – 669 ppm (stabilize @ 752 ppm)
  - RCP 8.5 – 936 ppm (over 1800 ppm by 2200)


RCP CO_2 pathways (ppm)
RCP8.5
RCP6.0
RCP4.5
RCP2.6
1000
800
600
400
200
1850
1900
1950
2000
2050
2100


Fossil-fuel emissions
(PgC yr-1)
30
25
20
15
10
5
0
-5
1850
1900
1950
2000
2050
2100
Years
CMIP5 mean
IAM scenario
RCP CO2 pathways (ppm)
RCP8.5
RCP6.0
RCP4.5
RCP2.6
1000
800
600
400
200
1850
1900
1950
2000
2050
2100



RCP8.5
RCP6
RCP4.5
RCP2.6
Radiative Forcing (W/m^2)
(a)
RCP6
RCP6 CO2
RCP6 other
Radiative Forcing (W/m^2)
(b)



RCP2.6
RCP4.5
RCP6
RCP8.5
CO2 concentrations (ppm)
2000
1500
1000
500
N2O concentrations (ppb)
600
550
500
450
400
350
300
CH4 concentrations (ppb)
4000
3500
3000
2500
2000
1500
1000
Total anthropogenic
CO2 component
Radiative forcing (W m−2)
12
10
8
6
4
2
0
1900
2000
2100
2200
2300
Year

RCP NUMBERS

- Most future climate forcing is due to carbon dioxide

- Due to long residence time in the atmosphere.
  - 40% of a given value removed in decades
  - 75% in a few centuries
  - Last 25 % takes 10s of thousands of years

- This is why carbon dioxide is such a big focus for policy and regulation