Geogg124
The Terrestrial Carbon Cycle

P. Lewis

Professor of Remote Sensing
UCL Geography
& NERC NCEO

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Aims of lecture

In this lecture, we will:

- consider the importance of understanding the science of climate change
- look at basic principles of energy transfer in the earth system
- examine greenhouse gases and their sources
- look in detail at the terrestrial carbon cycle
- provide an overview of relevant biogeochemical processes
- look in some detail at photosynthesis and factors that limit this

Terrestrial Climate and Climate Change

"(C)limate change is a defining issue of our generation. Our responses to the challenges of climate change - accurate prediction, equitable adaptation, and efficient mitigation - will influence the quality of life for ... the world, for generations to come." (NASA, 2010).

From the IPCC AR4 (synthesis report):

Observed changes in climate and their effects

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.

There is medium confidence that other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers

From the IPCC AR4 (synthesis report):

Causes of change

Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004.

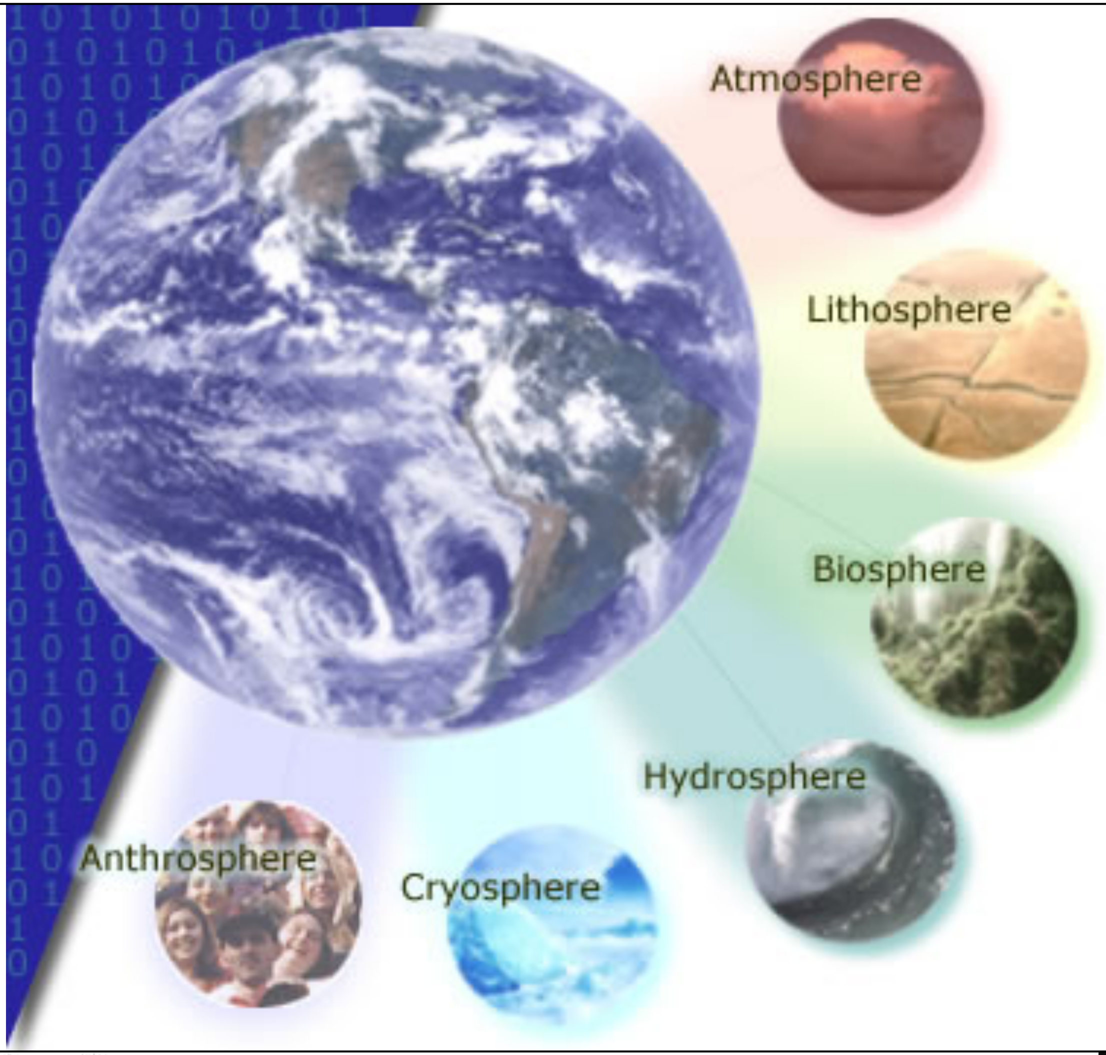
Global atmospheric concentrations of CO2, methane (CH4) and nitrous oxide (N2O) have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. It is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica).

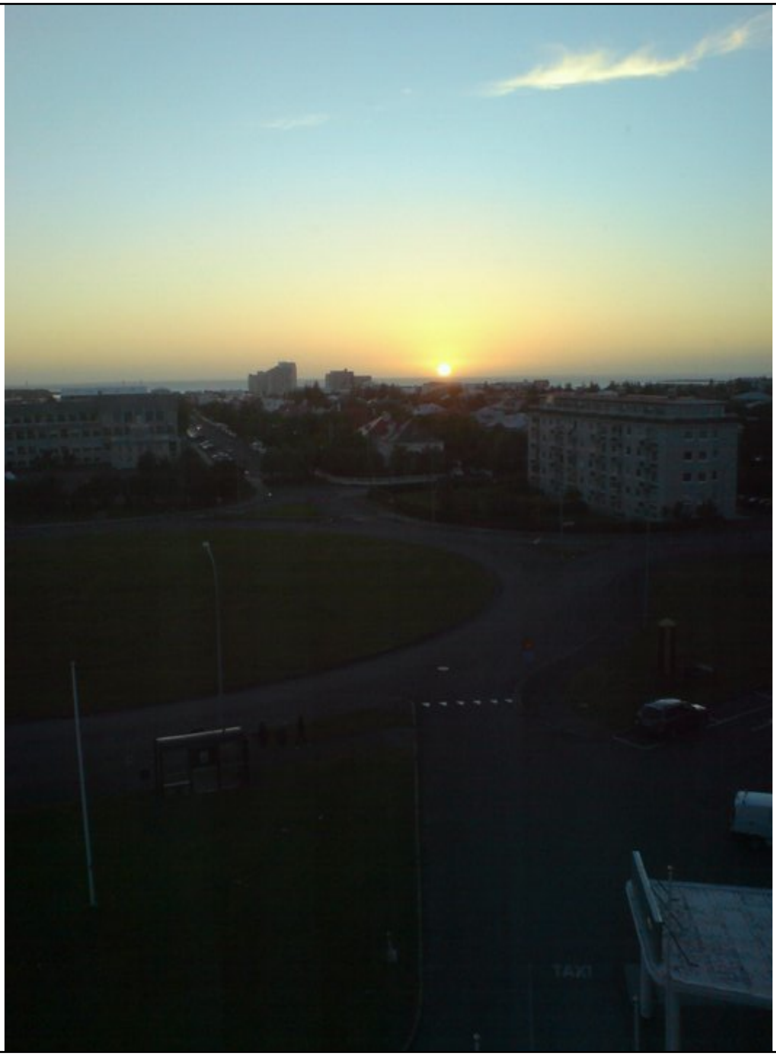
Advances since the TAR show that discernible human influences extend beyond average temperature to other aspects of climate.

Anthropogenic warming over the last three decades has likely had a discernible influence at the global scale on observed changes in many physical and biological systems.

The 'spheres' of influence on the climate system

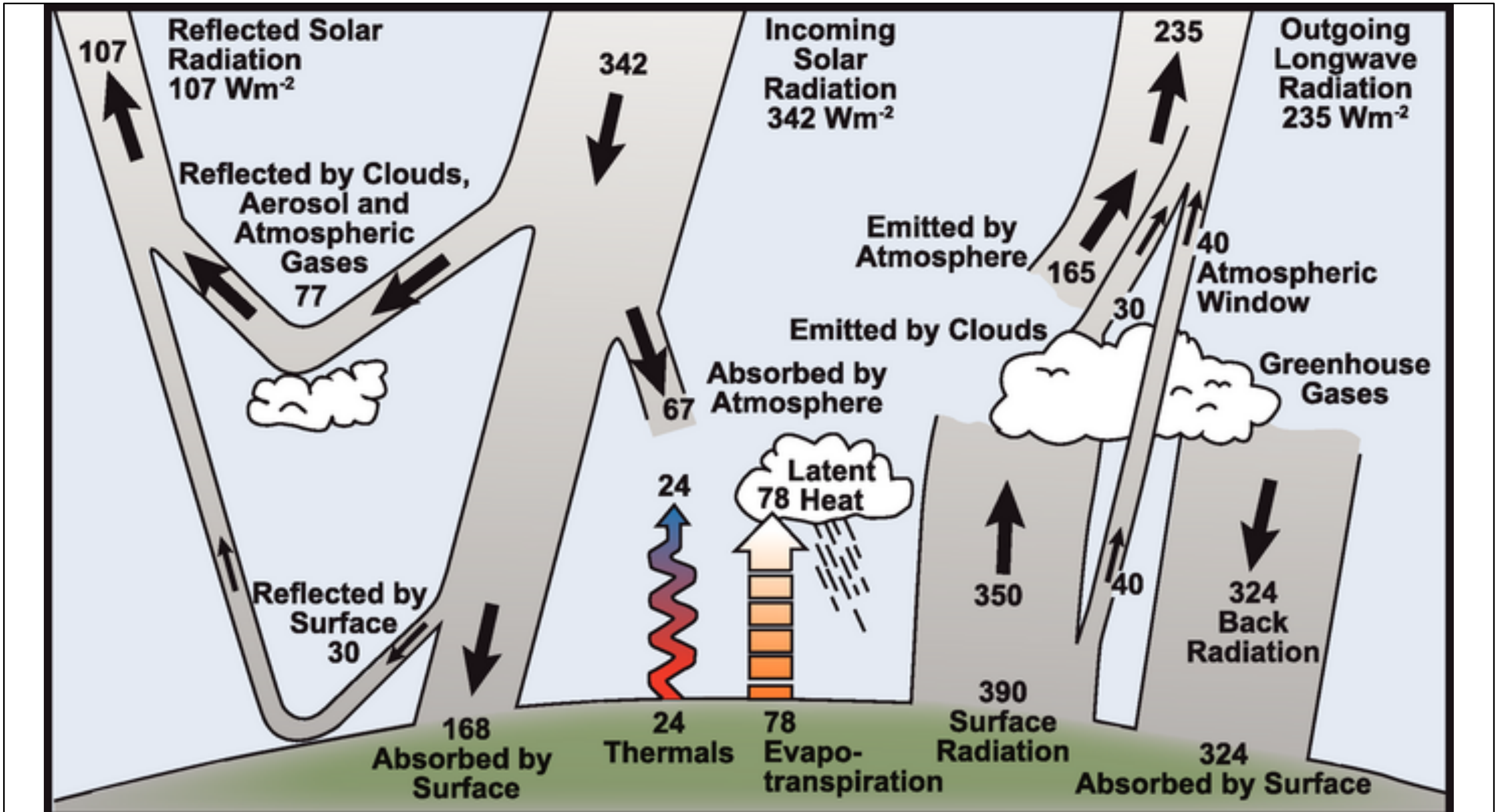


Energy transfer: basics



Driven by solar radiation

Earth's climate is driven by (shortwave) solar radiation



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large proportion of longwave radiation emitted by the surface is re-radiated back to the surface (and absorbed by the surface) by clouds and so-called greenhouse gases

‘trapping’ of longwave radiation naturally maintains temperature on Earth – the ‘natural greenhouse effect’.

Without this, temperature much less that it presently is (-19C)

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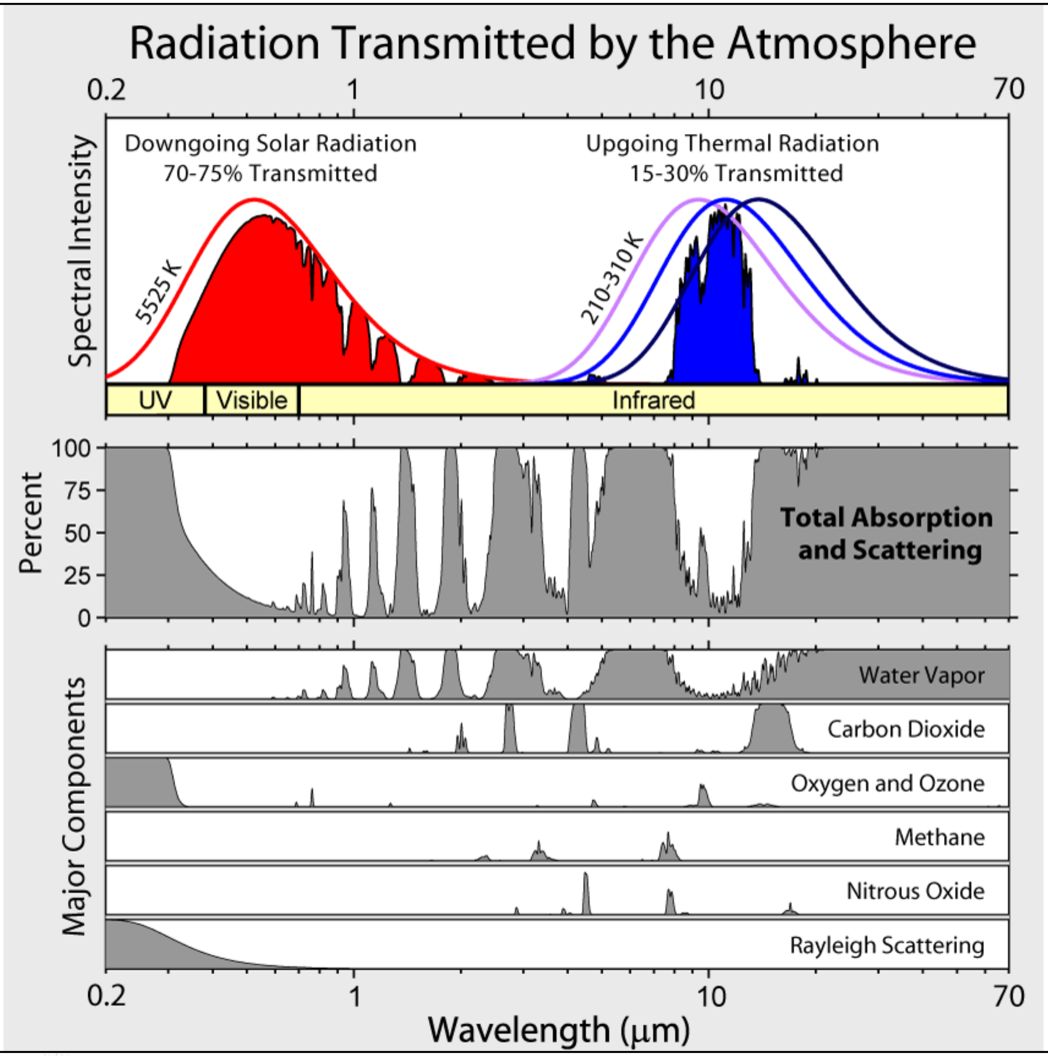
Exercise

‘develop a simple ‘zero-dimensional’ model of the climate system

- Use this model to show what the sensitivity of the temperature is to albedo and the incoming solar radiation.
- what factors would cause variations in these terms?
- Assuming the actual average surface temperature is around 14 C, modify the code above to return the *effective emissivity* of the Earth.
- We assumed above that the effective (broadband) shortwave albedo was 0.31, so the effective (broadband) shortwave absorptance is 1-0.31=0.69. The effective (broadband) longwave absorptance is equal to the effective (broadband) longwave emissivity through Kirchoff’s law (of thermal radiation), assuming thermal equilibrium. What then is the effective (broadband) longwave albedo?
- Why do we use the words *effective* and *broadband* above?
- What impact would increasing the concentrations of greenhouse gases have on the effective (broadband) longwave albedo?

Atmospheric absorption



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Radiative Forcing

measure of the *radiative* impact of components of the climate system

"a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. ... radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in watts per square meter (W/m^2)." IPCC AR4

AR4: most likely value of (net positive) radiative forcing due to anthrogenic sources is about an order of magnitude larger than the estimated radiative forcing from changes in solar irradiance.

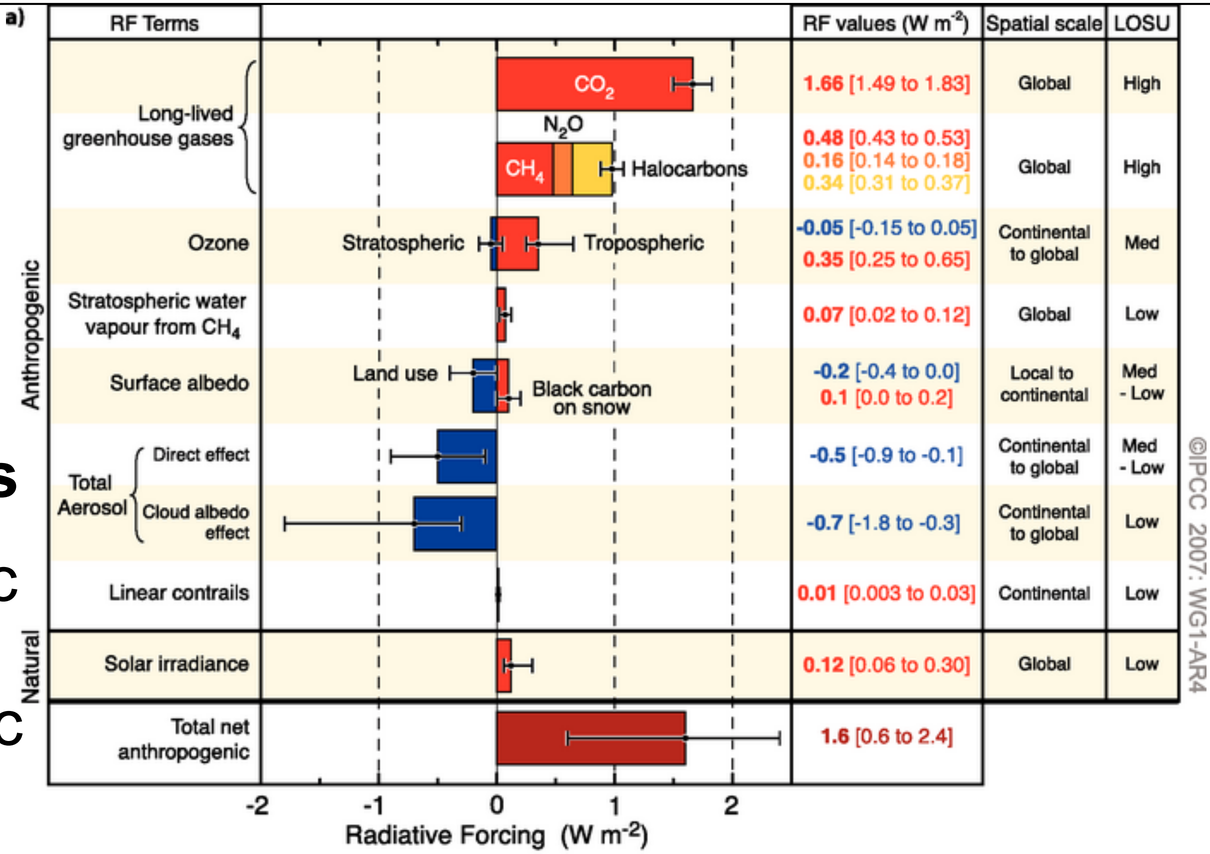
Rockstrom et al. (2009)

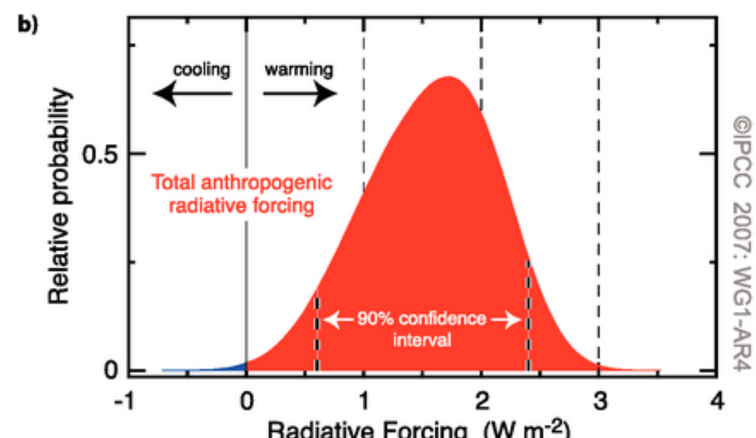
“human changes to atmospheric CO_2 concentrations should not exceed 350 parts per million by volume, and that radiative forcing should not exceed 1 watt per square metre above pre-industrial levels. Transgressing these boundaries will increase the risk of irreversible climate change, such as the loss of major ice sheets, accelerated sea- level rise and abrupt shifts in forest and agri- cultural systems. Current CO_2 concentration stands at 387 p.p.m.v. and the change in radiative forcing is 1.5 W m^{-2}”

Radiative forcings

RF for different mechanisms

most significant anthropogenic positive RF term is CO2 followed by CH4, Tropospheric O3, Halocarbons, NO2, (natural) Solar irradiance variations, and black carbon effects on snow (lowering snow albedo).





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Carbon in the Earth System

- 4th most abundant element in the universe.
- able to bond with itself and many other elements
- forms over 10 million known compounds.
- present
  - in the atmosphere as CO_2, CH_4 etc)
  - in all natural waters as dissolved CO_2
  - in various carbonates in rocks
  - as organic molecules in living and dead organisms in the biosphere .

Carbon in the Earth System

also important in radiative forcing

Directly

- Halocarbons in the atmosphere
- black carbon deposits on snow

indirectly

- elsewhere (e.g. land cover change).

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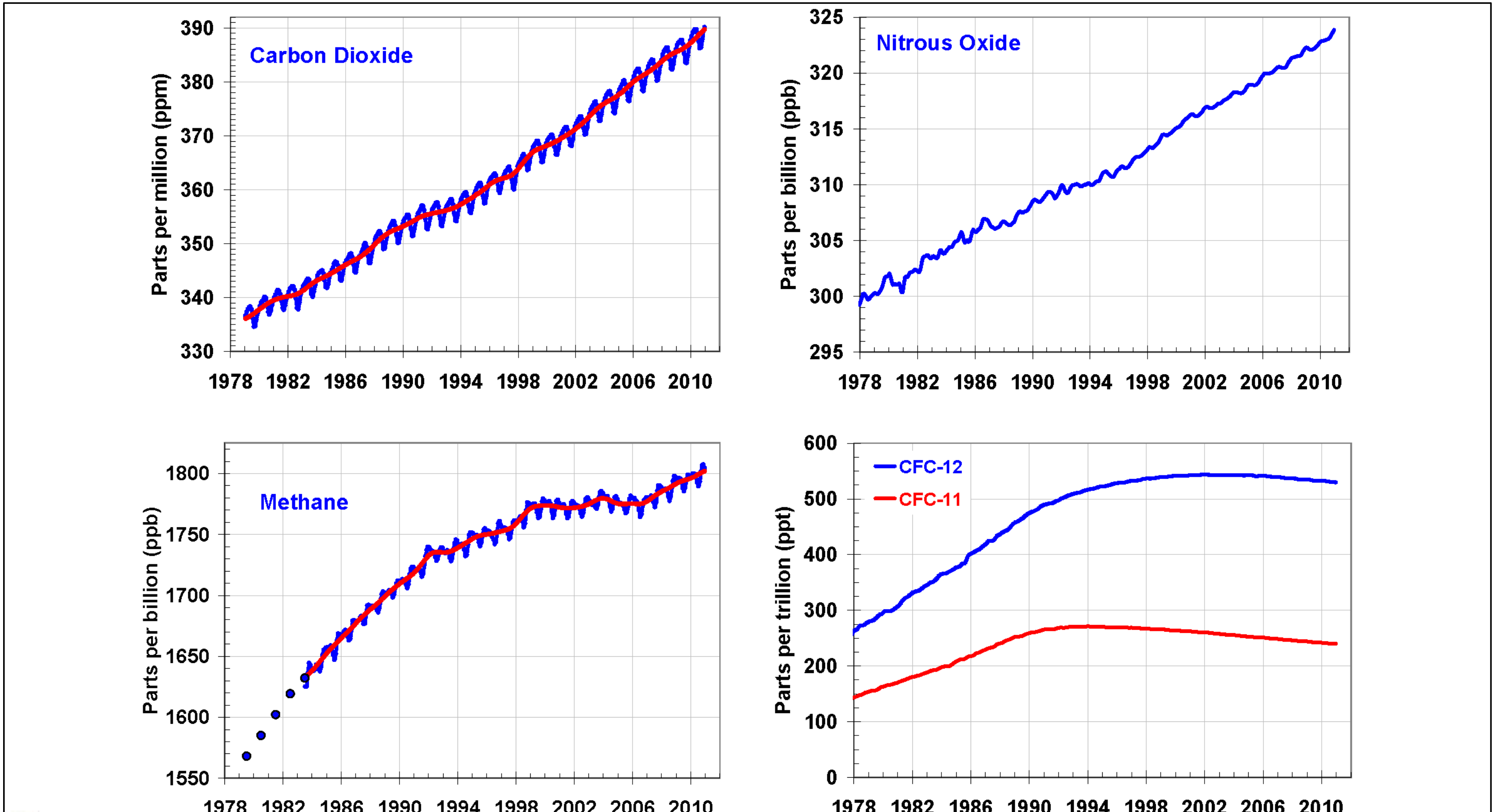
Atmospheric Carbon and Greenhouse Gases



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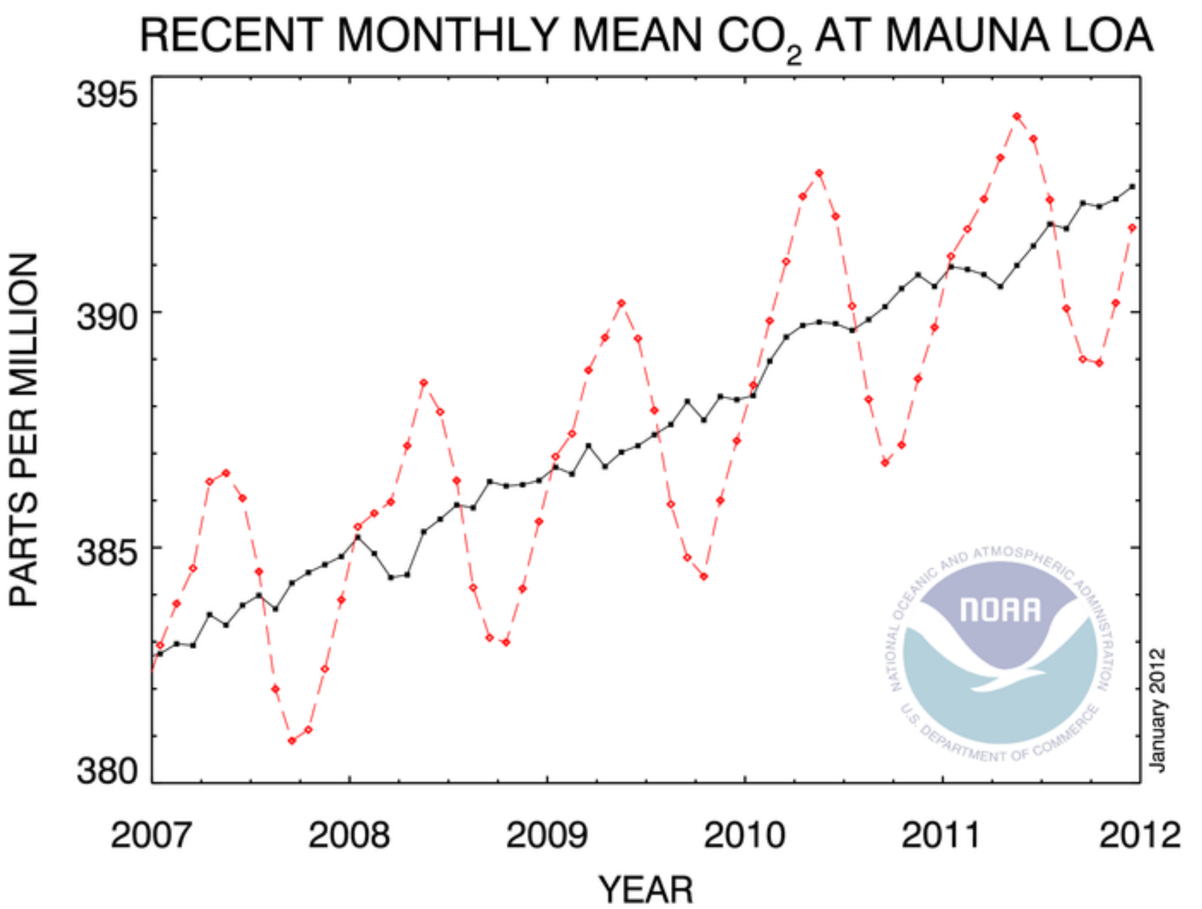
Annual cycles



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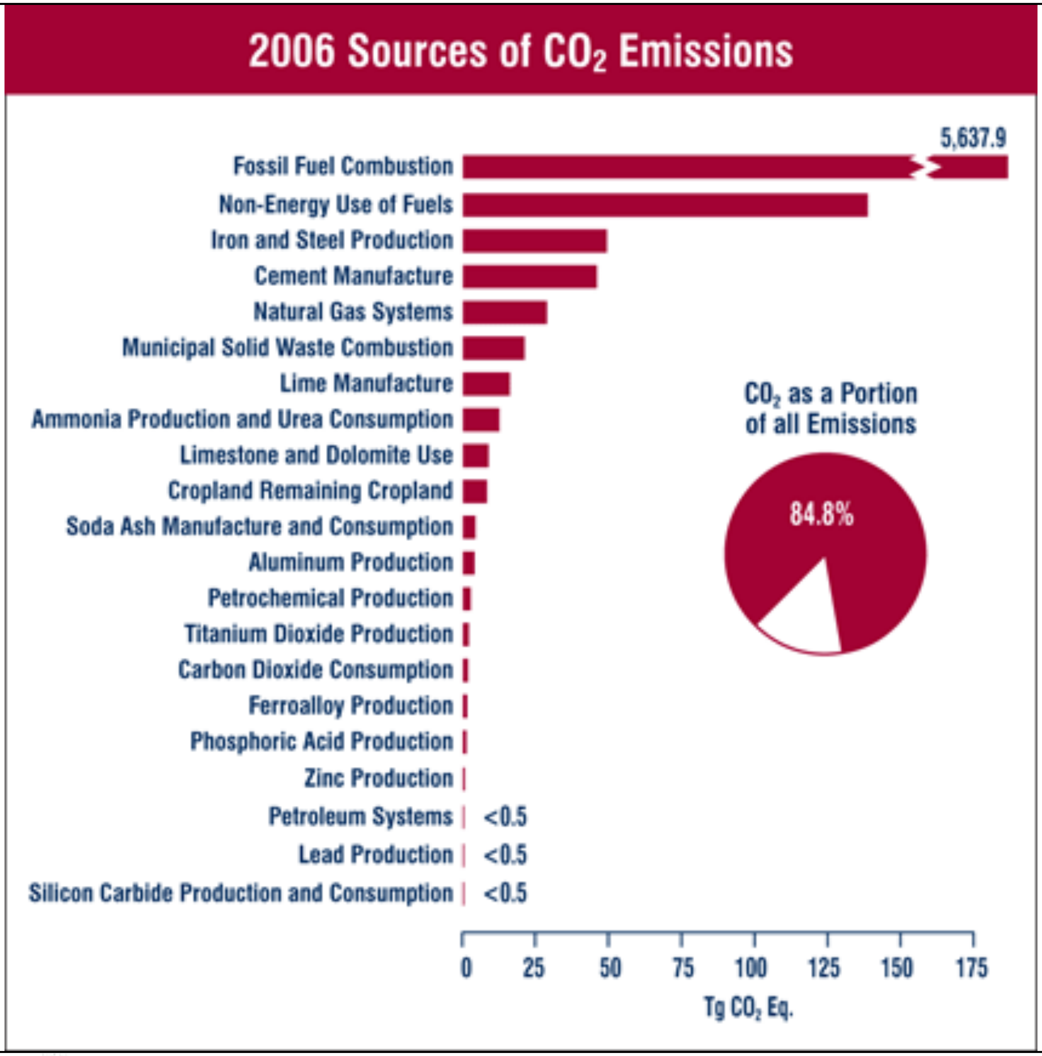
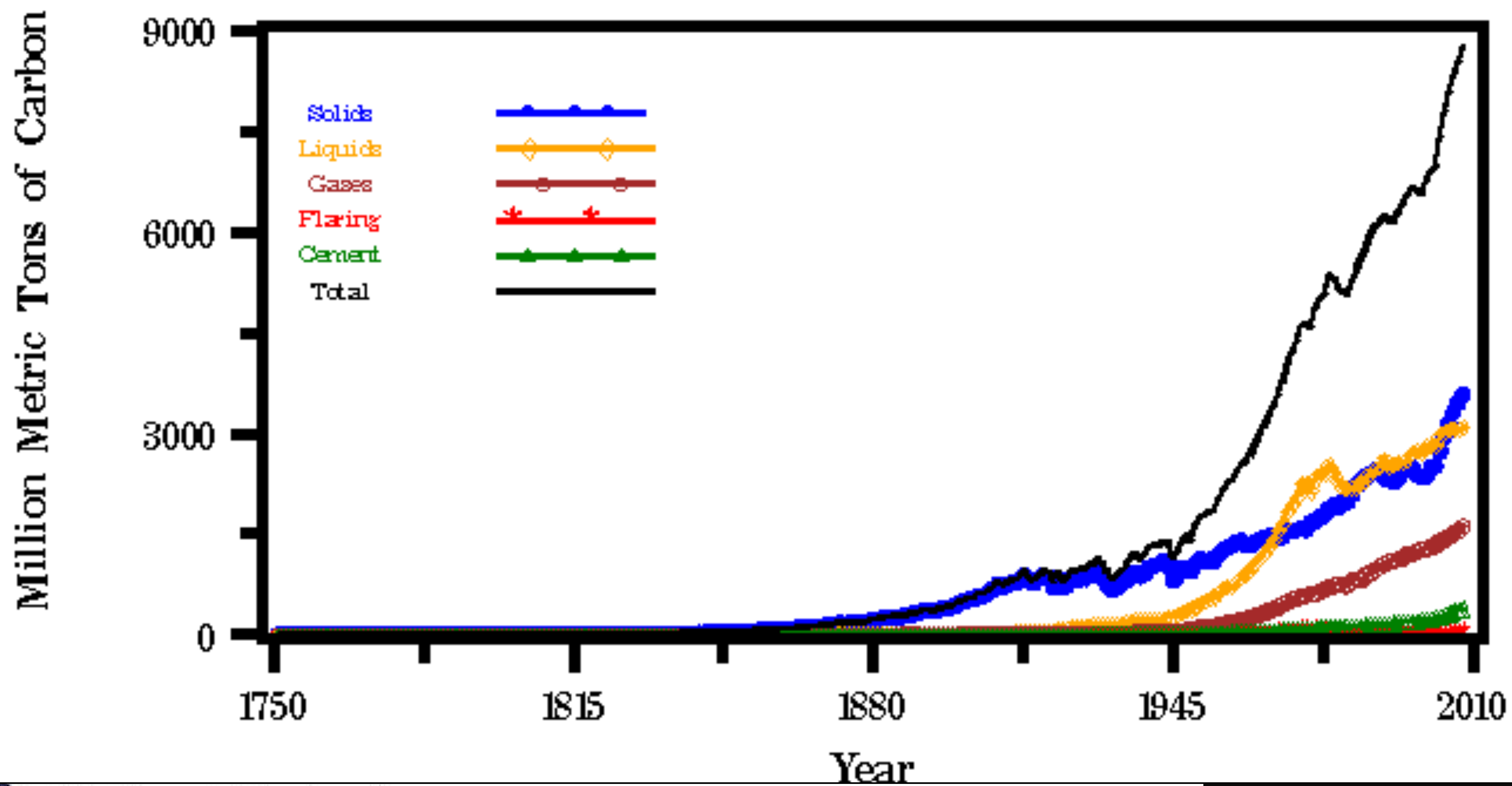
US emissions (2006)



Global trends



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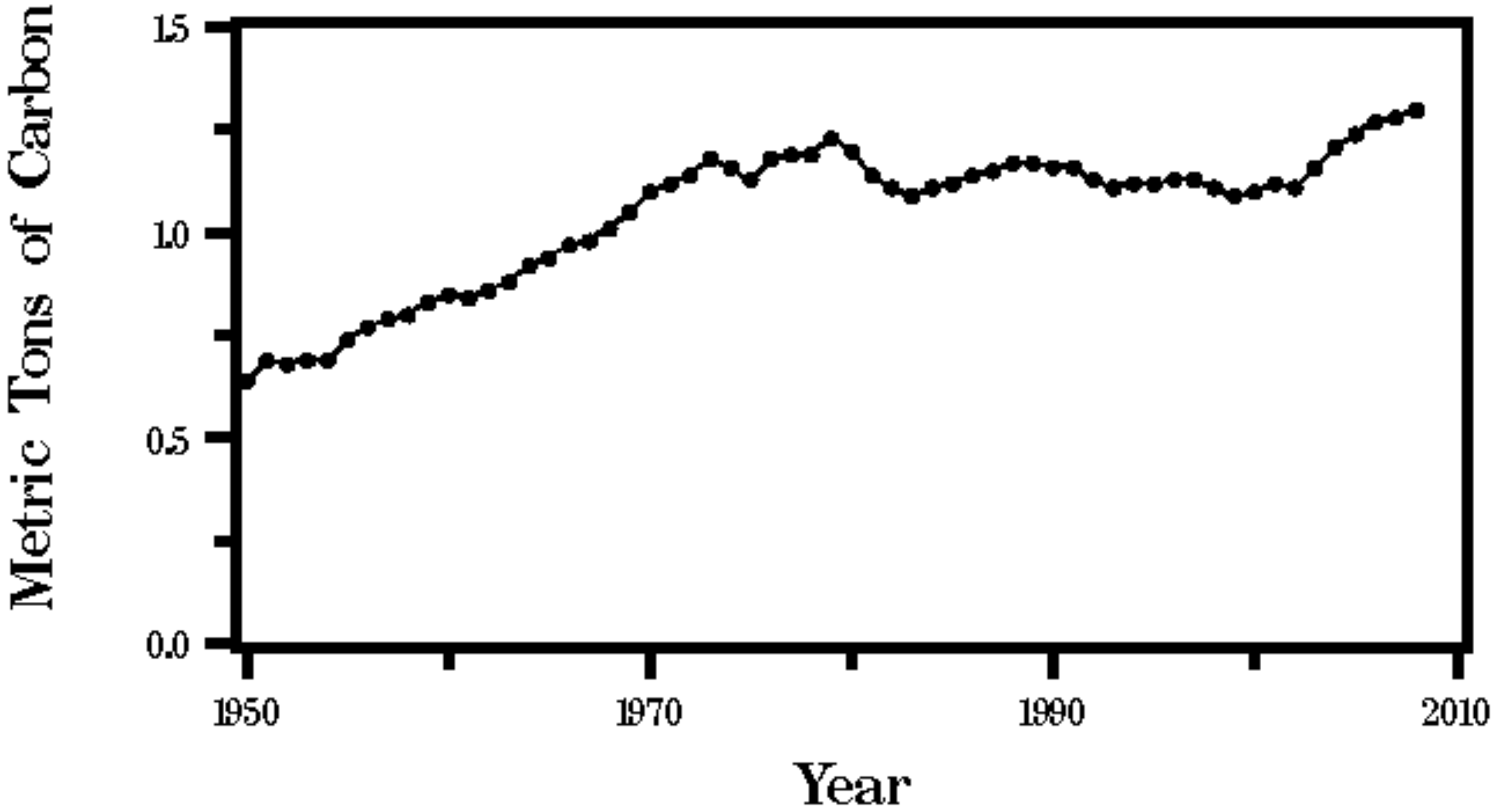
EXERCISE

Data on CO2 emissions and per capita emissions



Global per capita emissions

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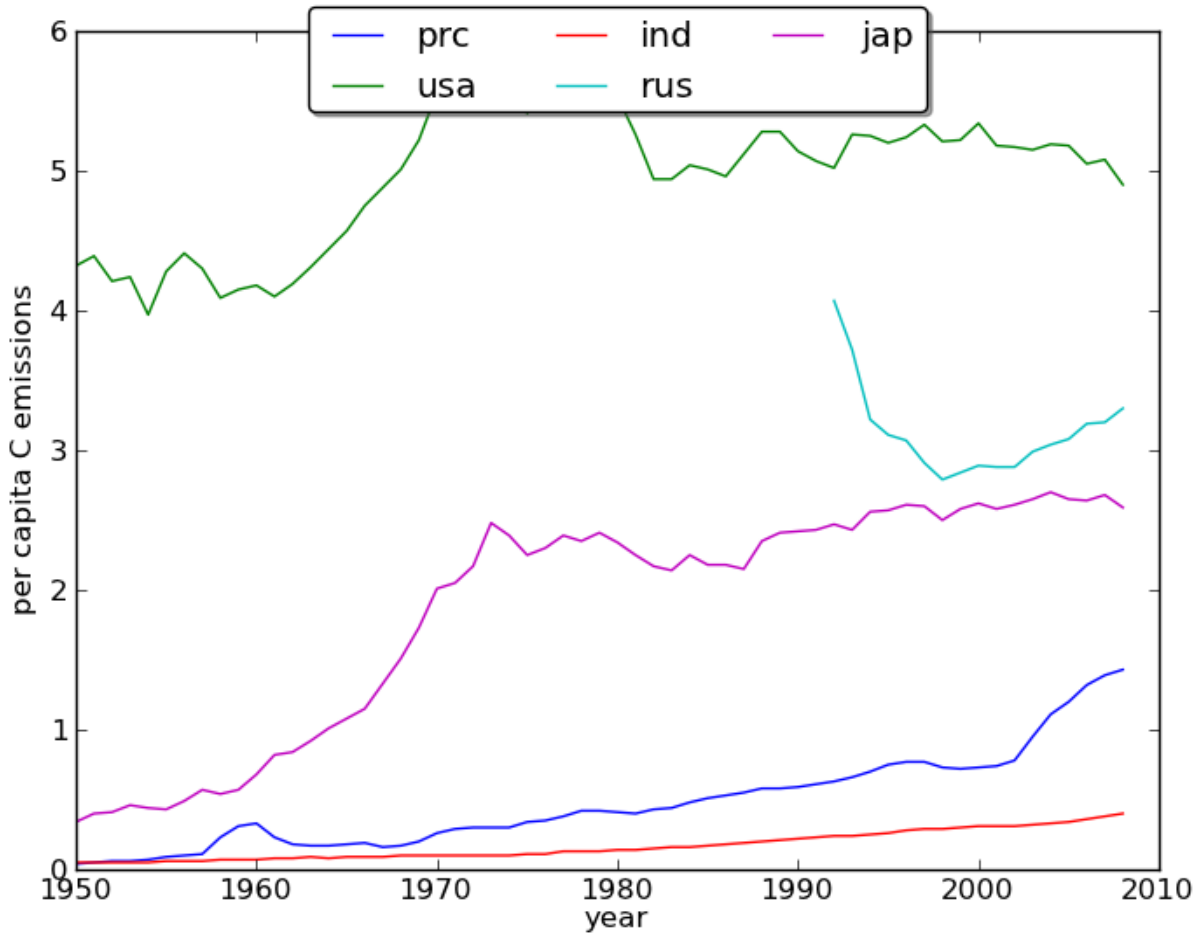
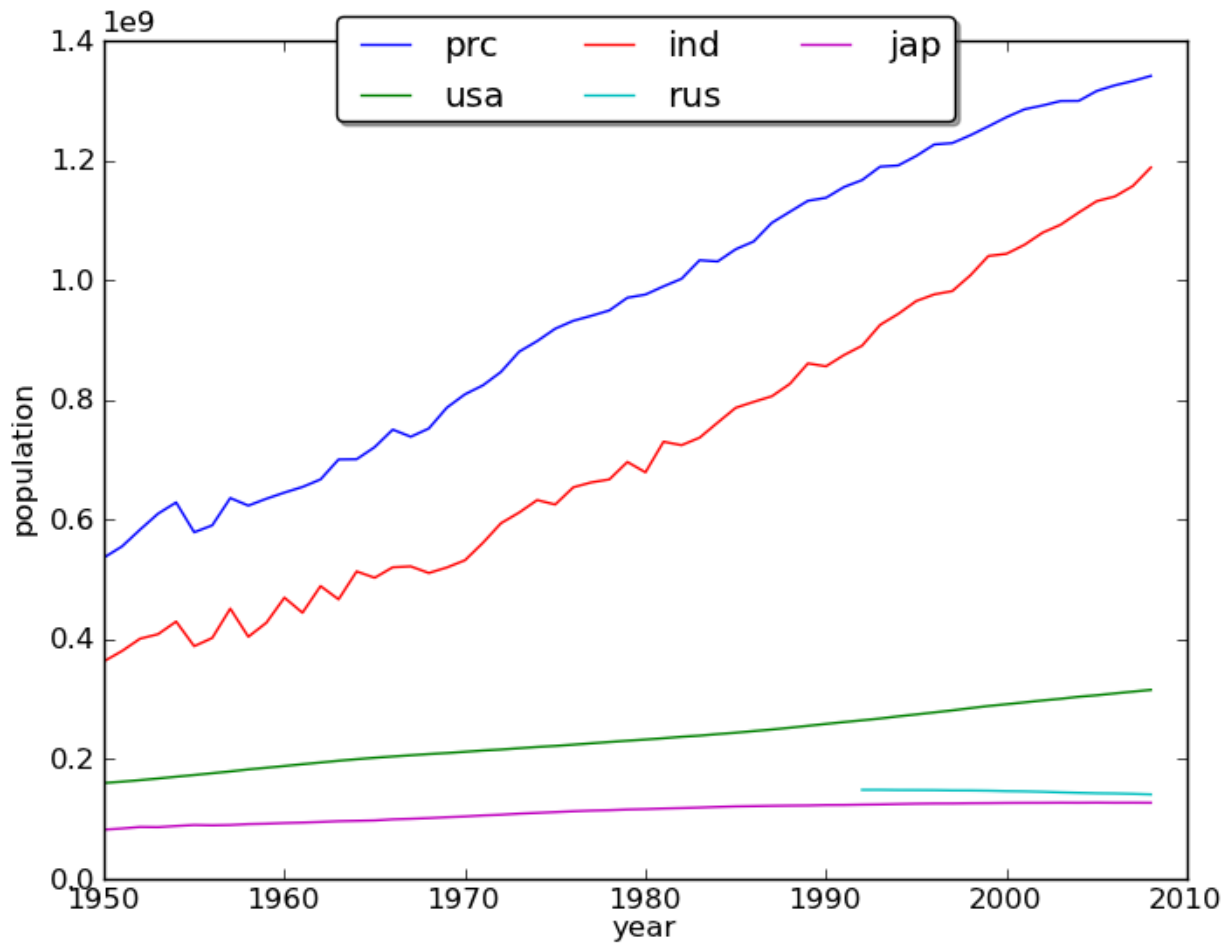
EXERCISE



prc
ind
jap
usa
rus
per capita C emissions
0
1
2
3
4
5
6
1950
1960
1970
1980
1990
2000
2010
year

EXERCISE



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EXERCISE

Identify those countries in the top twenty emitting nations lists which have increasing trends in (a) population and (b) per capita emissions rates. Rank them in order.

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EXERCISE

Given a start at some code …

The code above provides linear extrapolation estimates for per captia emissions for the year 2020 based on data for 1995 to 2008.

Adapt the code so that it provides estimates of Total Fossil-Fuel Emissions for 2020 for the top 20 emitting countries, *assuming population does not increase*.

Adapt the code so that it provides estimates of Total Fossil-Fuel Emissions for 2020 for the top 20 emitting countries, *assuming a linear trend in population*.

Use these two sets of figures to estimate the impact of population growth on total (global) Fossil-Fuel Emissions for 2020 (i.e. what proiortion of the change in estimated emissions can be attributed to population growth?). You can assume that the proportion of emissions from the top 20 countries remains at 63% if you need that information.

What impact does the time period over which you perform the linear regression have (e.g. change it to start at 2000)?

If you have time, you might try to estimate the uncertainty on these estimates.

Criticise the model developed. What factors might come into play that we have not accounted for here (a starter: global economic conditions; also, have we missed any important countries)?

Methane

Natural	*Anthropogenic*
Wetlands	Agricultural livestock
Termite activity	Rice cultivation
Oceans	Waste practices
	Coal mining
	Natural gas distribution
	Biomass burning

NO2

Anthropogenic activity accounts for around 30% of N_2O, with tropical soils and oceanic release account for the majority of the remainder

halocarbons

Refrigerants, aerosols …

Limited by “Montreal Protocol on substances that deplete the Ozone Layer”

Despite control, their continued presence in the atmosphere is of continuing concern for Ozone depletion as well as their role as GHGs.

Terrestrial Carbon

carbon that is stored in the vegetation and soils of the Earth's land surface

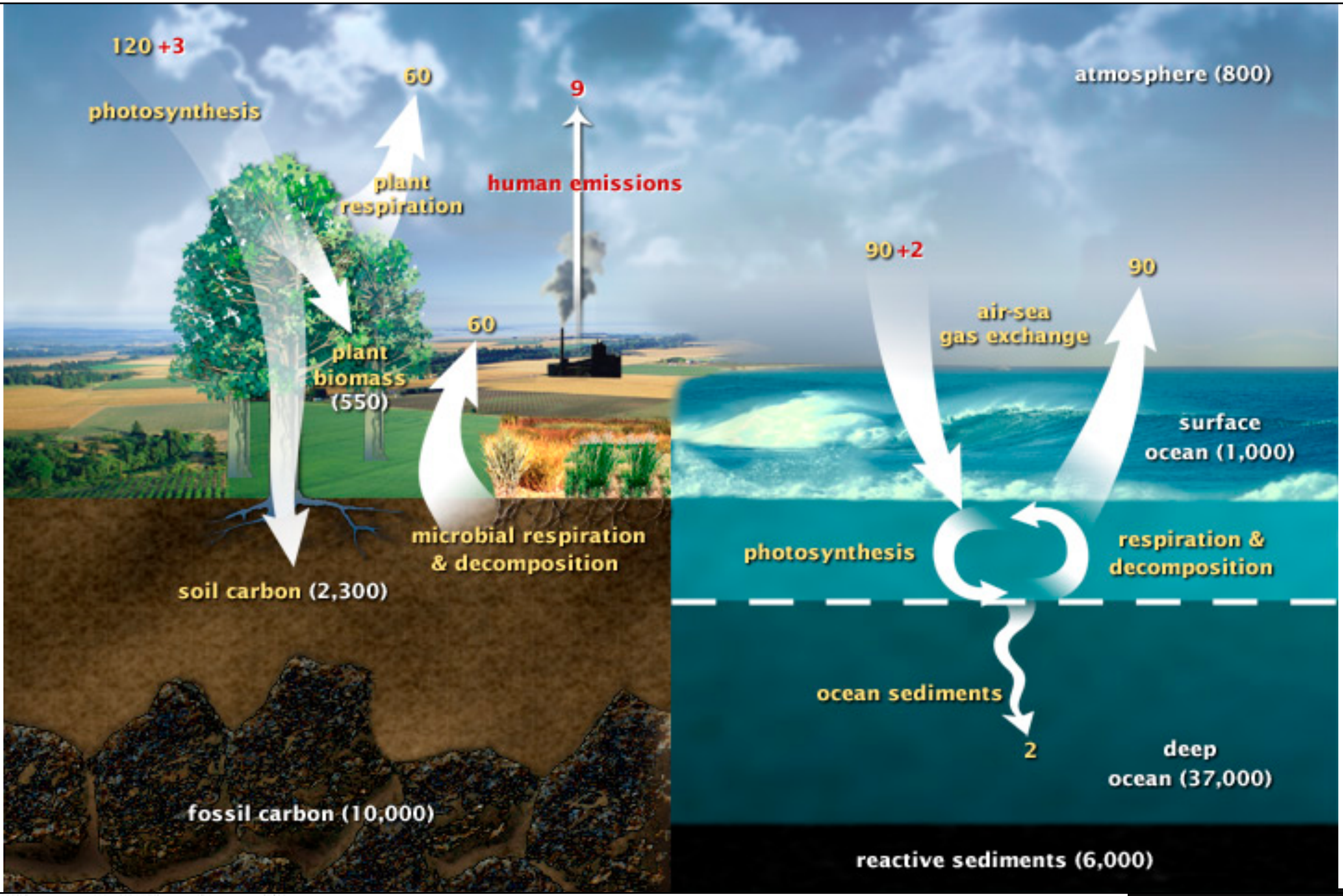
The Earth Systems Science:

Maintain focus on interactions between different spheres, but understand processes and interactions within each sphere.

Terrestrial Carbon

- Justification:
  - major role it plays in anthropogenic climate change.
- Also:
  - the role that terrestrial vegetation plays in biodiversity;
  - role of vegetation in providing food and fuel.

The Carbon Cycle



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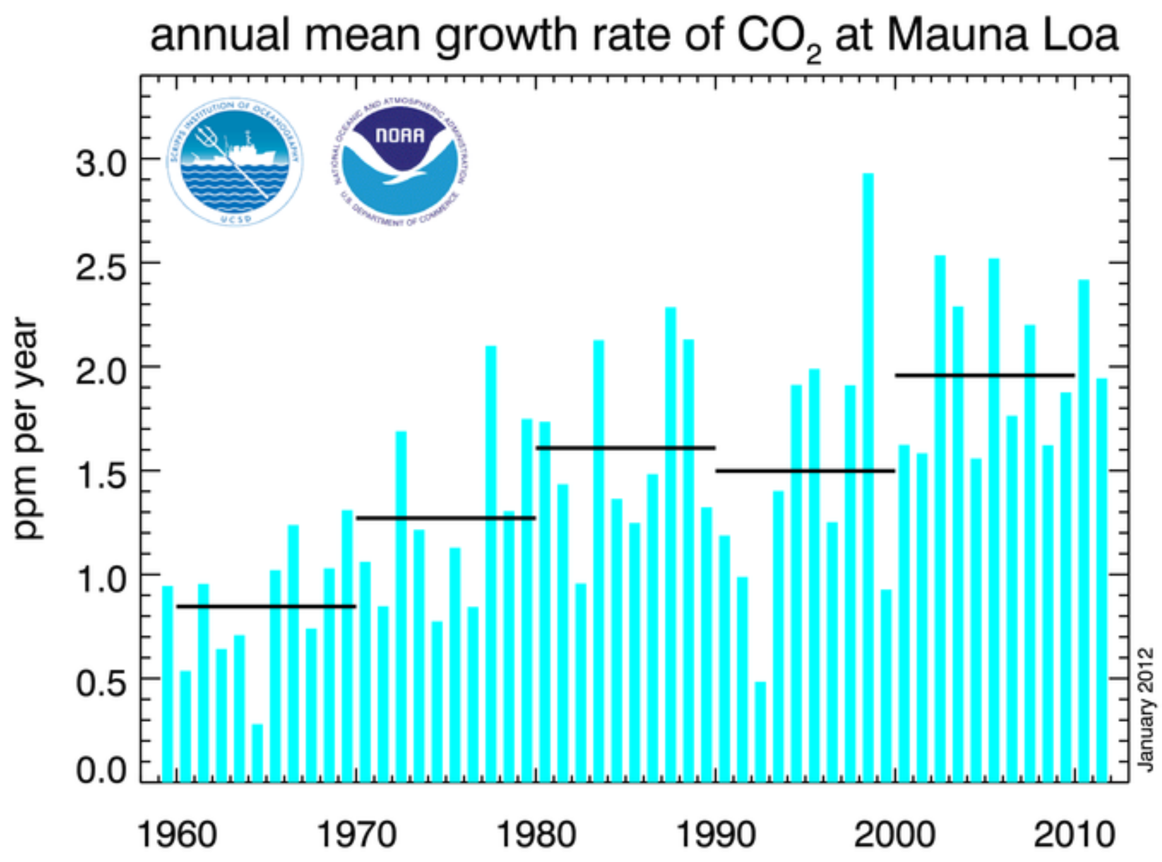
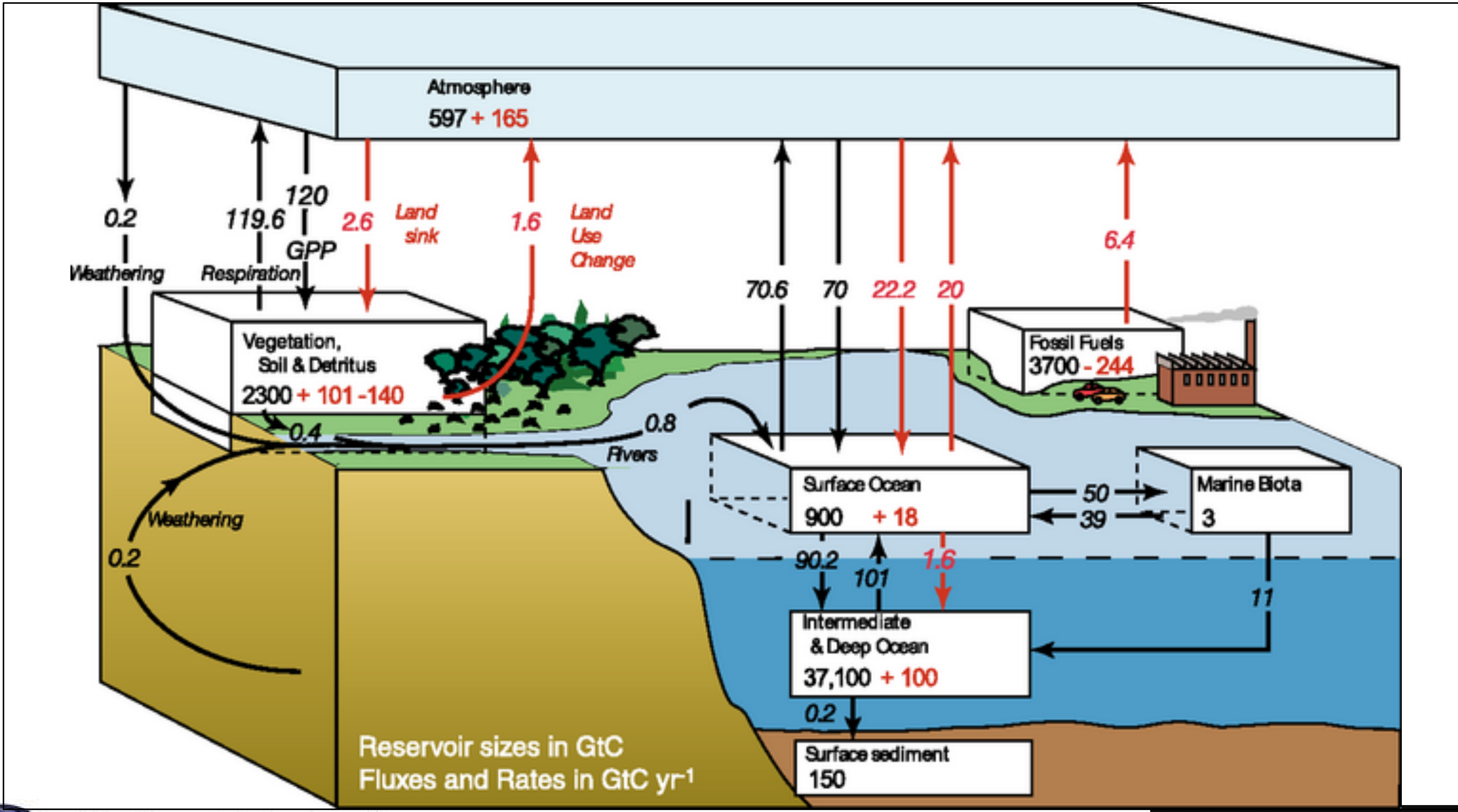
CO2 growth rate



Carbon Cycle



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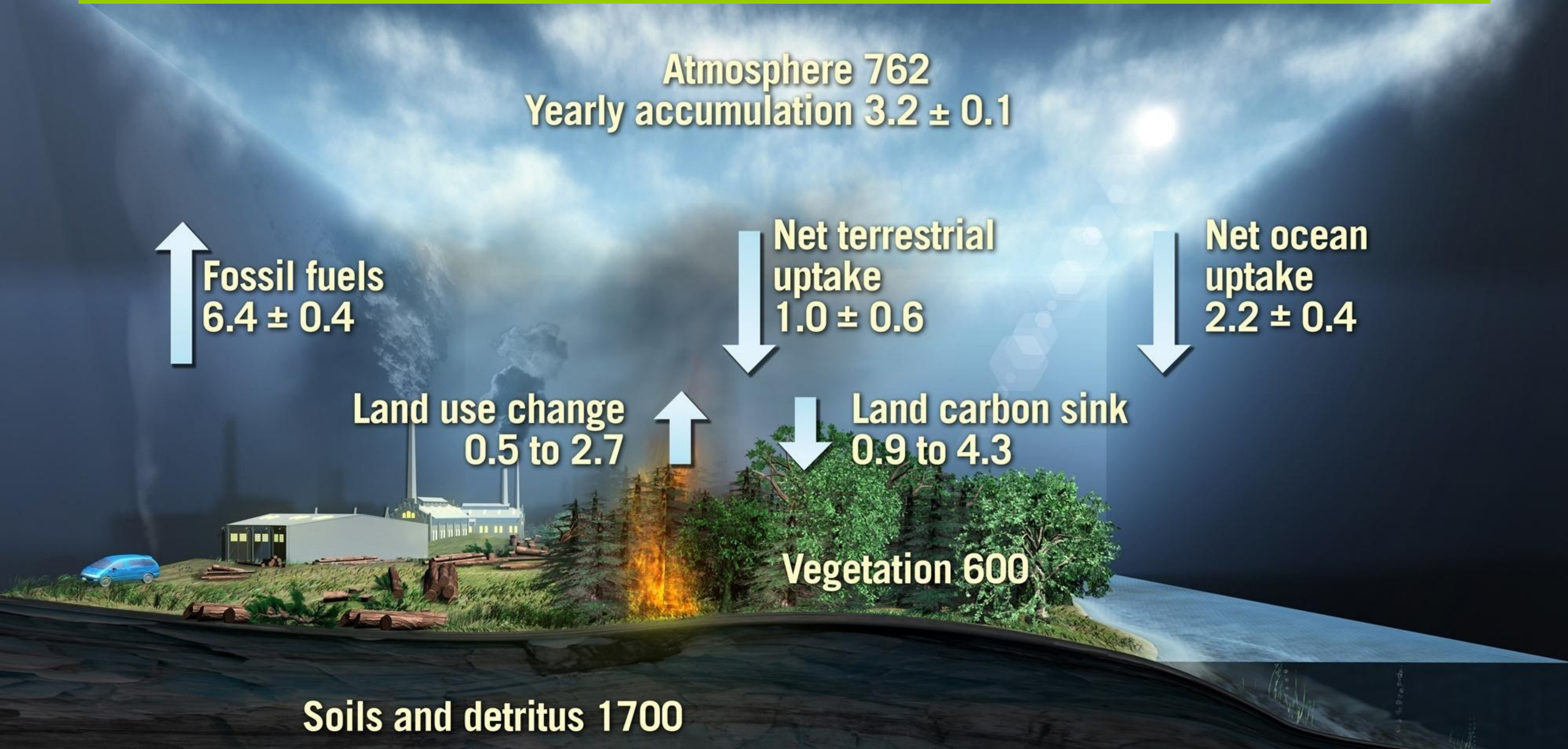
The global carbon cycle for the 1990s



Values from IPCC 2007. Units: Gigatons of carbon/ yr

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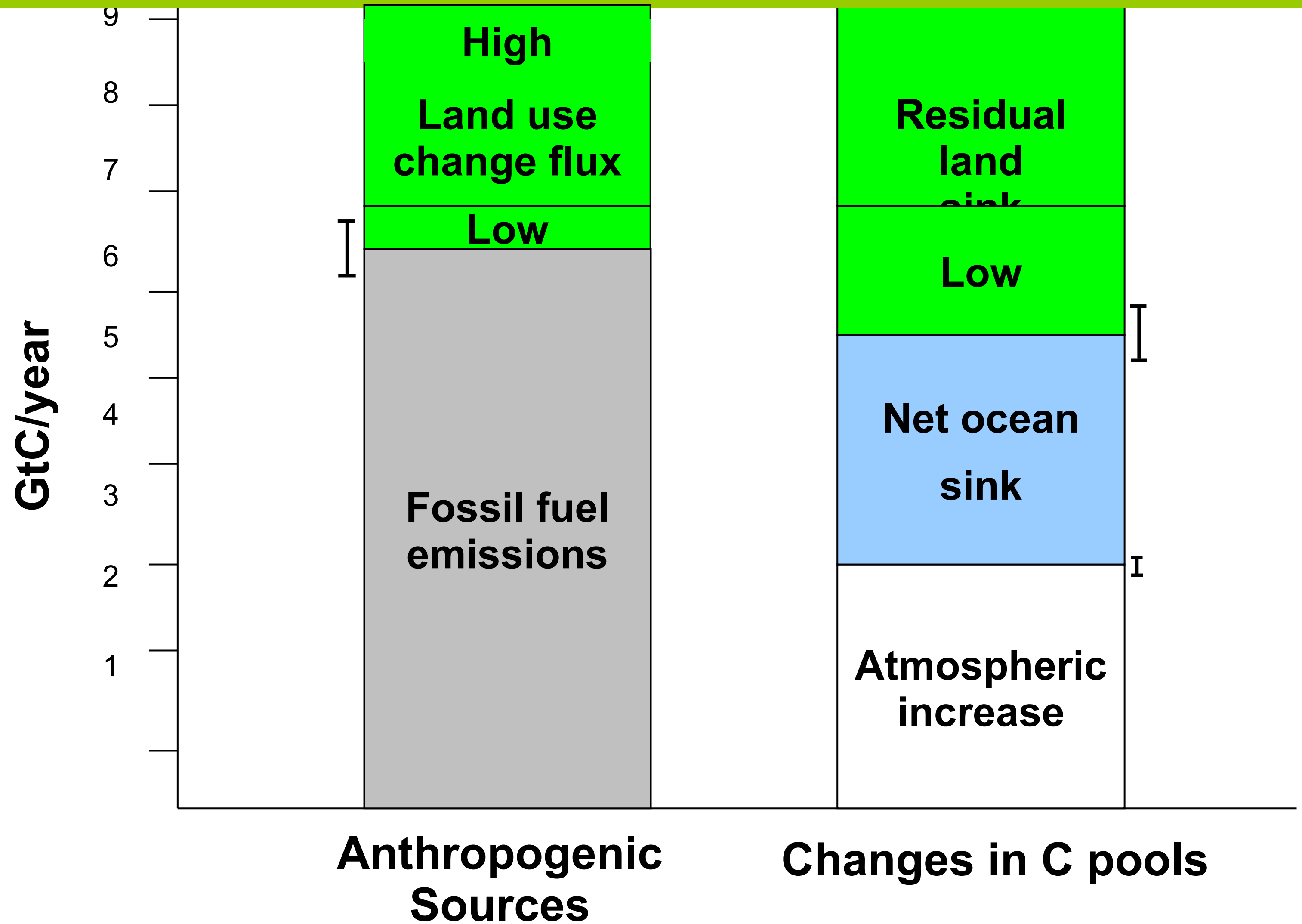
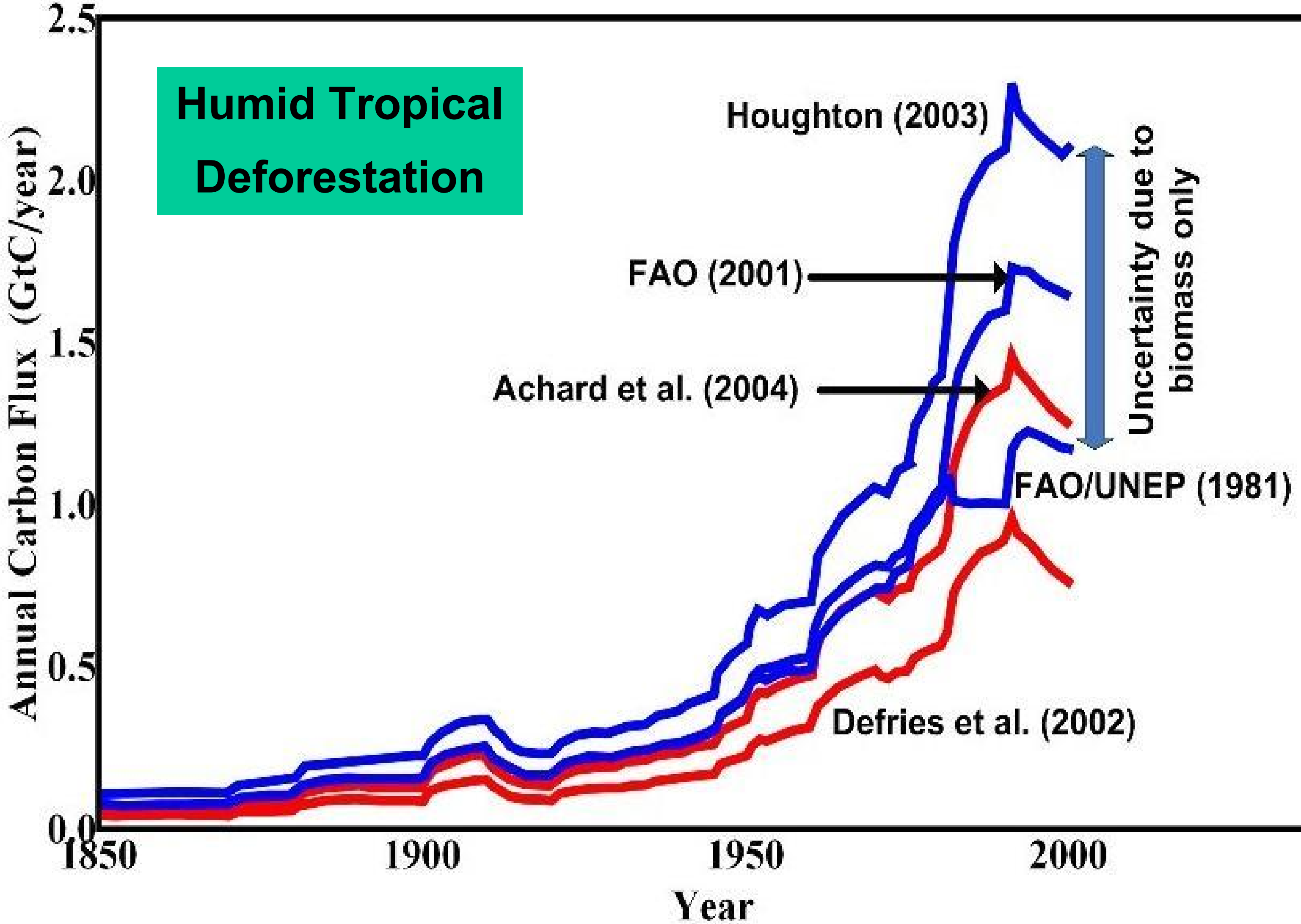
The mean global carbon cycle for the 1990s

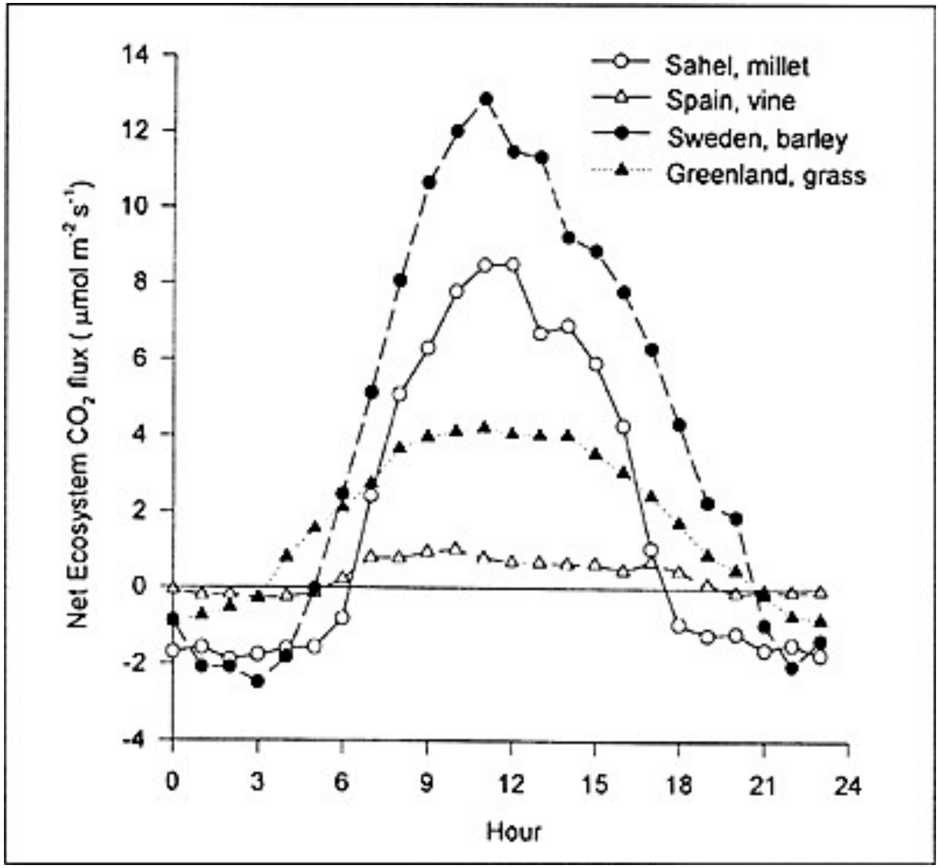


Uncertainty in carbon emissions due to biomass



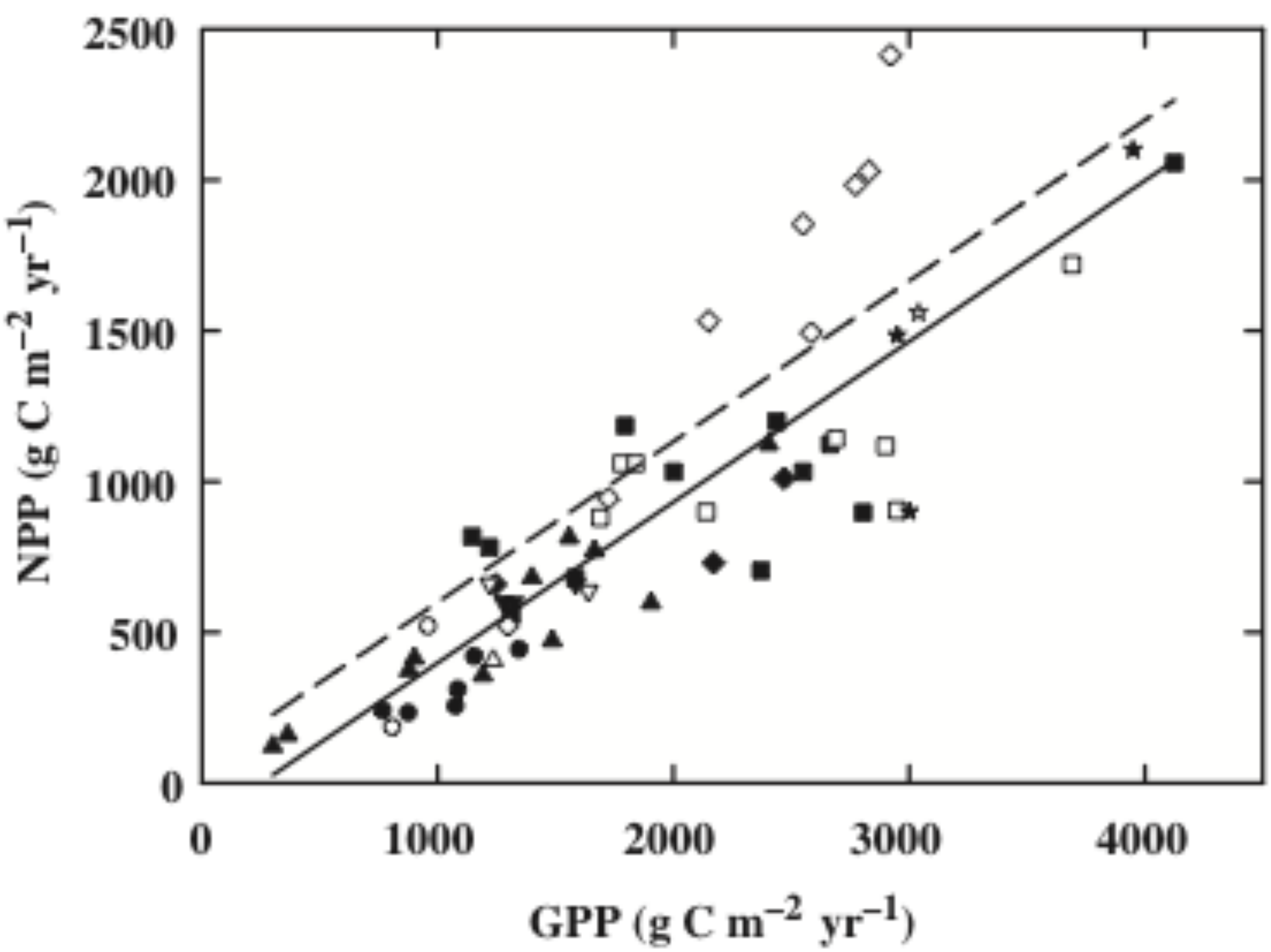
Biogeochemical processes

Net Ecosystem CO2 flux: NEP



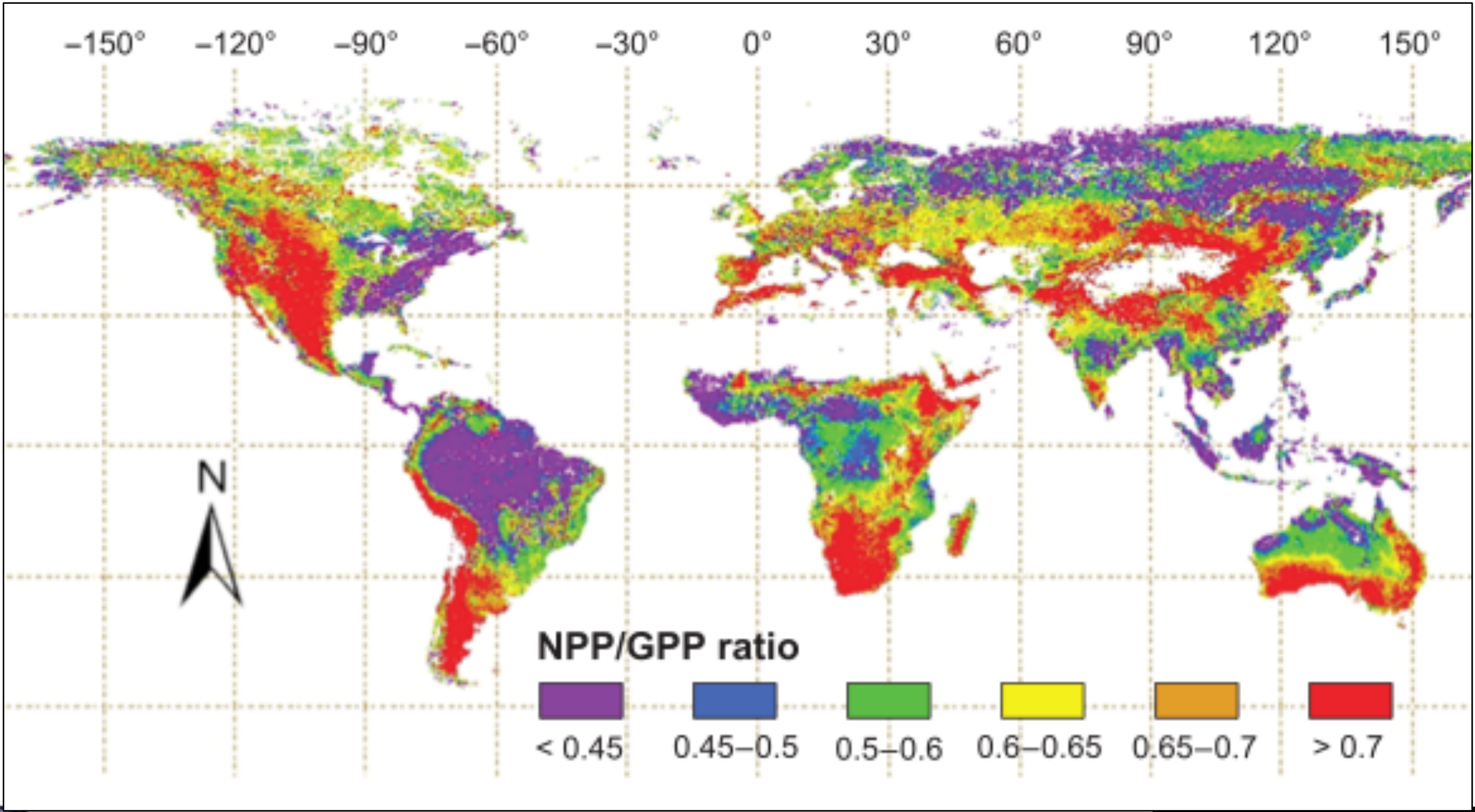
Diurnal variations

NPP/GPP: CUE



2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
NPP (g C m−2 yr−1)
GPP (g C m−2 yr−1)

NPP/GPP



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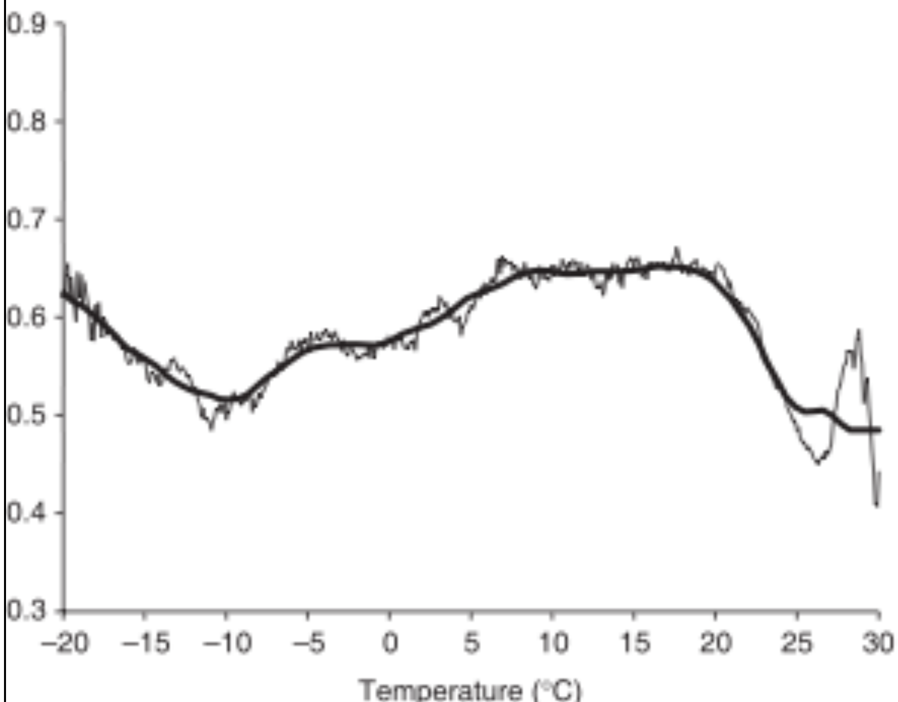
CUE dependencies



ure 4 The NPP/GPP ratio pattern with temperature. The thin behind connects each point representing the average NPP/GPP o over 0.1 °C temperature; the bold line represents the central dency produced by moving average over 1 °C temperature.

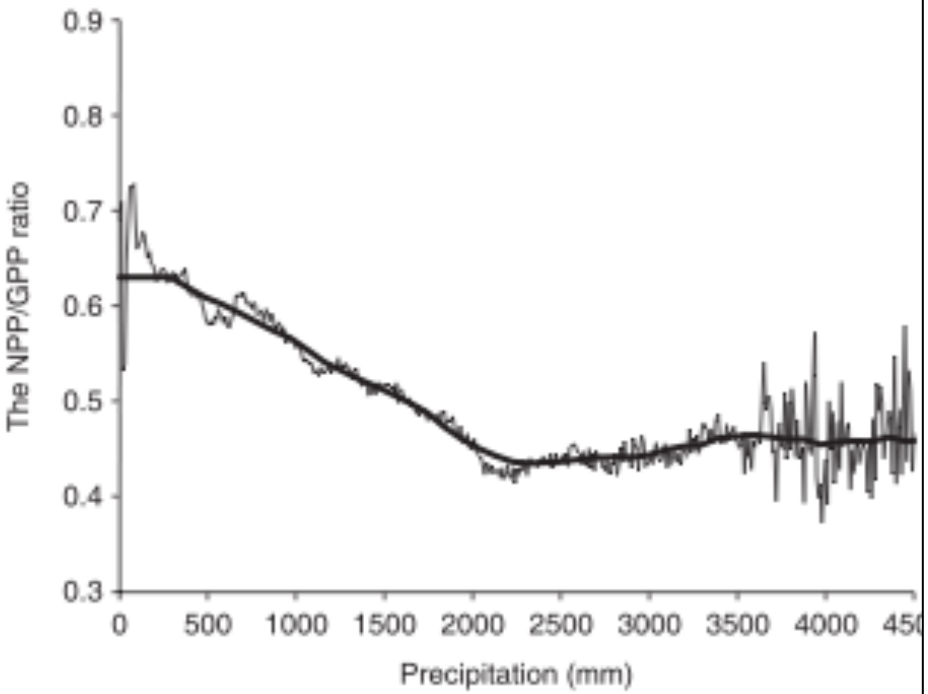
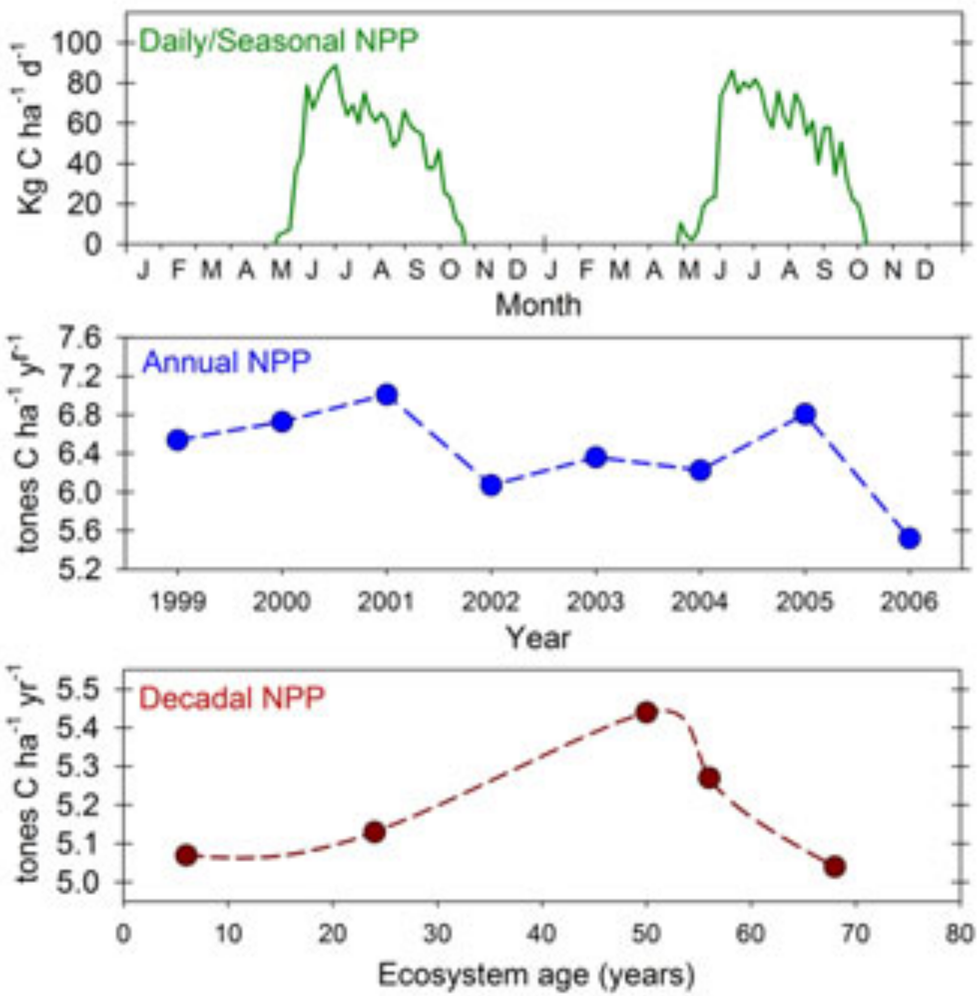


Figure 5 The NPP/GPP ratio pattern with precipitation. The thir line connects each point representing the average NPP/GPP ratio over 10 mm precipitation; the bold line represents the central tendency produced by the moving average over 100 mm precipitation.

NPP temporal scales



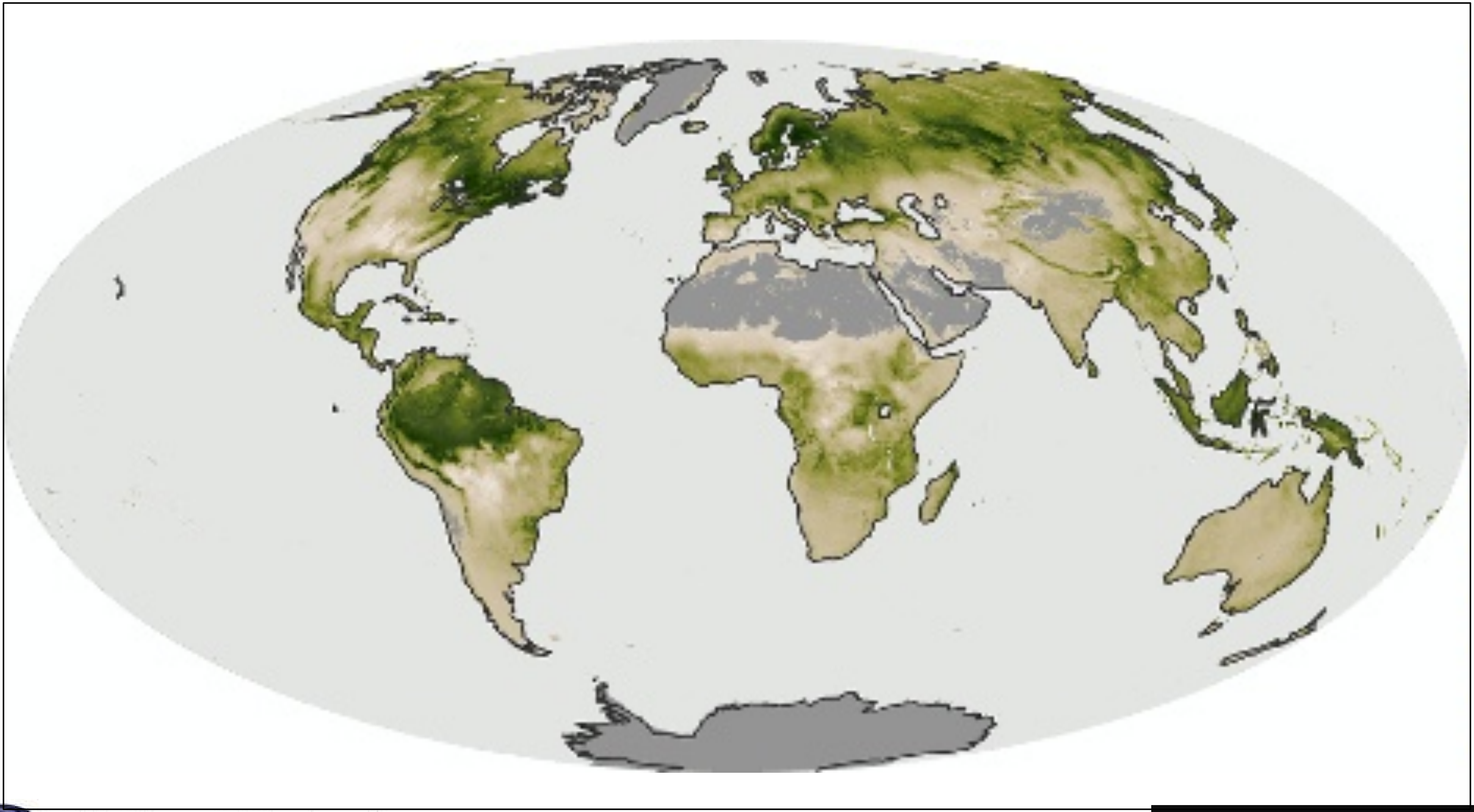
NPP biomes

Biome	Global GPP[1] (Pg C yr $^{-1}$)	Global NPP[2] (PG C yr $^{-1}$)	Ecosystem NPP[3] (g C ha-1 yr
Tropical forest	40.8	16.0-23.1	871-1098
Temperate forest	9.9	4.6-9.1	465-741
Boreal forest	8.3	2.6-4.6	173-238
Tropical savannah and grasslands	31.3	14.9-19.2	343-393
Temperate grasslands and shrublands	8.5	3.4-7.0	129-342
Deserts	6.4	0.5-3.5	28-151
Tundra	1.6	0.5-1.0	80-130
Croplands	14.8	4.1-8.0	288-468
TOTAL	121.7	48.0-69.0	2377-3561

Table 1: Global and ecosystem-scale estimates of mean terrestrial gross and net primary production for the Earth's major biomes from remotely sensed satellite data and modeling students. 1 Petagram (Pg) = 10^{15} grams (g).

1. Beer *et al.* 2000; 2. Melillo *et al.* 1993; Potter *et al.* 1993; Prince & Goward 1995; Field *et al.* 1998; Beer *et al.* 2010 3. Melillo *et al.* 1993; Potter *et al.* 1993; Prince & Goward 1995

NPP: July 2006



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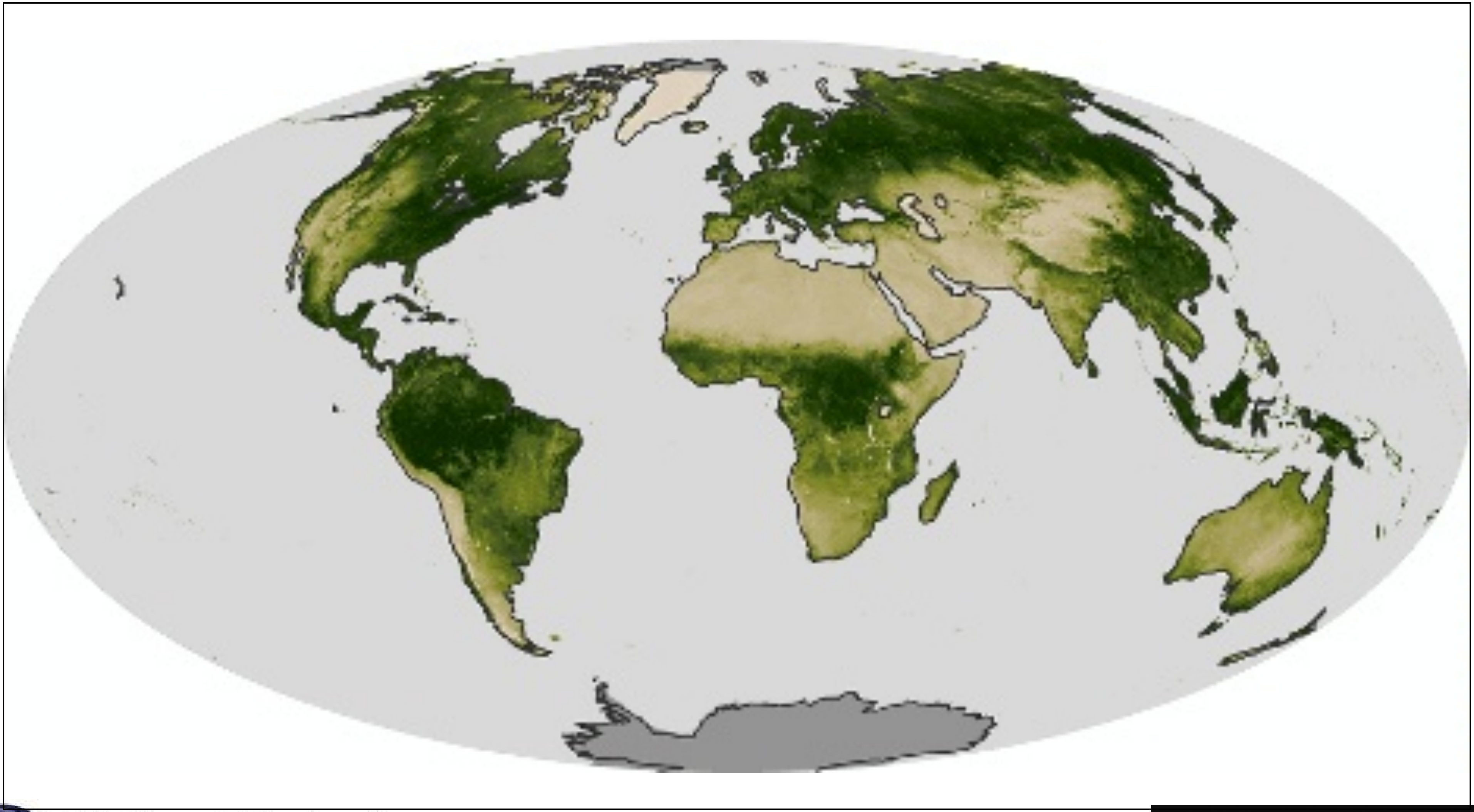
NDVI: July 2006



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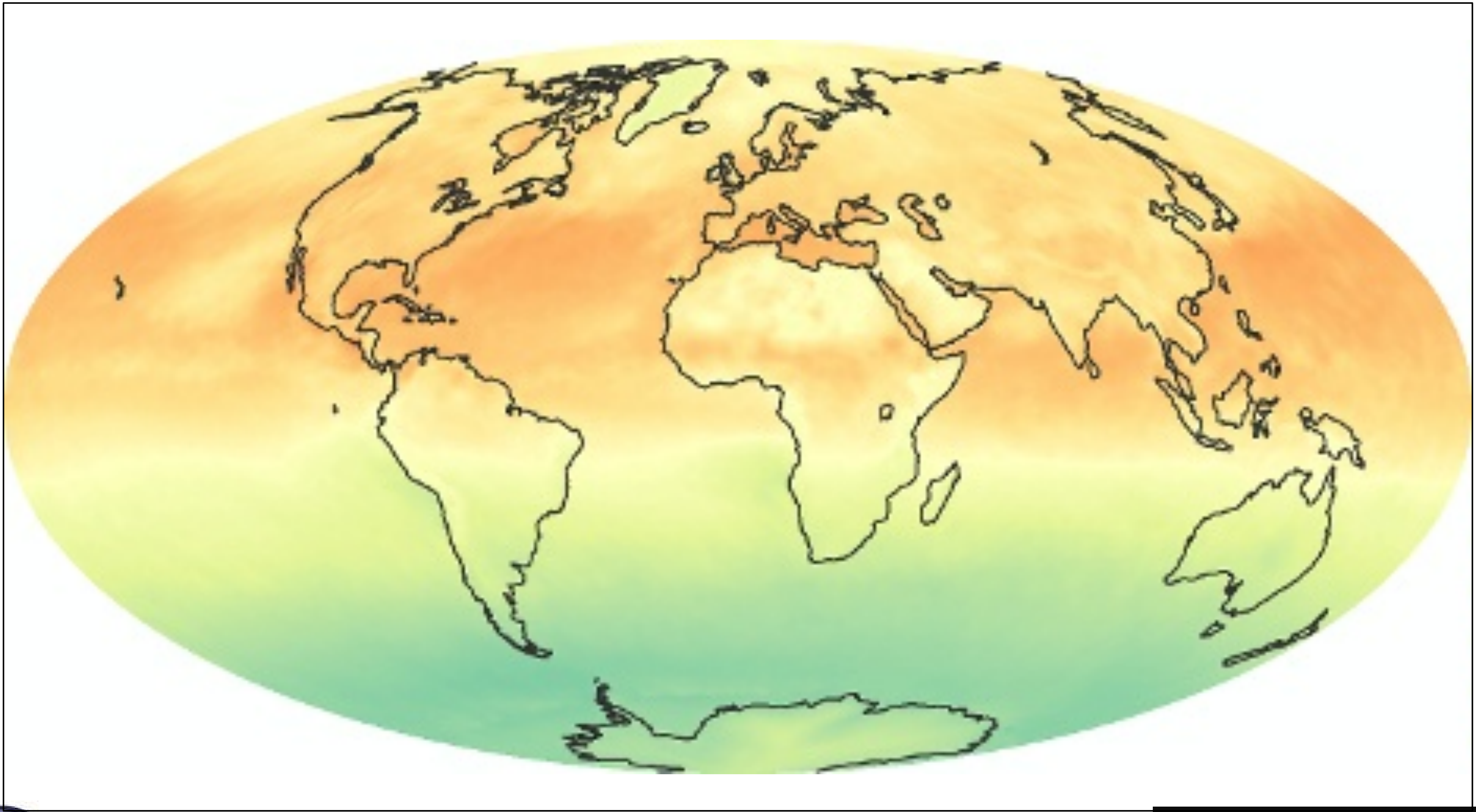
Net radiation: July 2006



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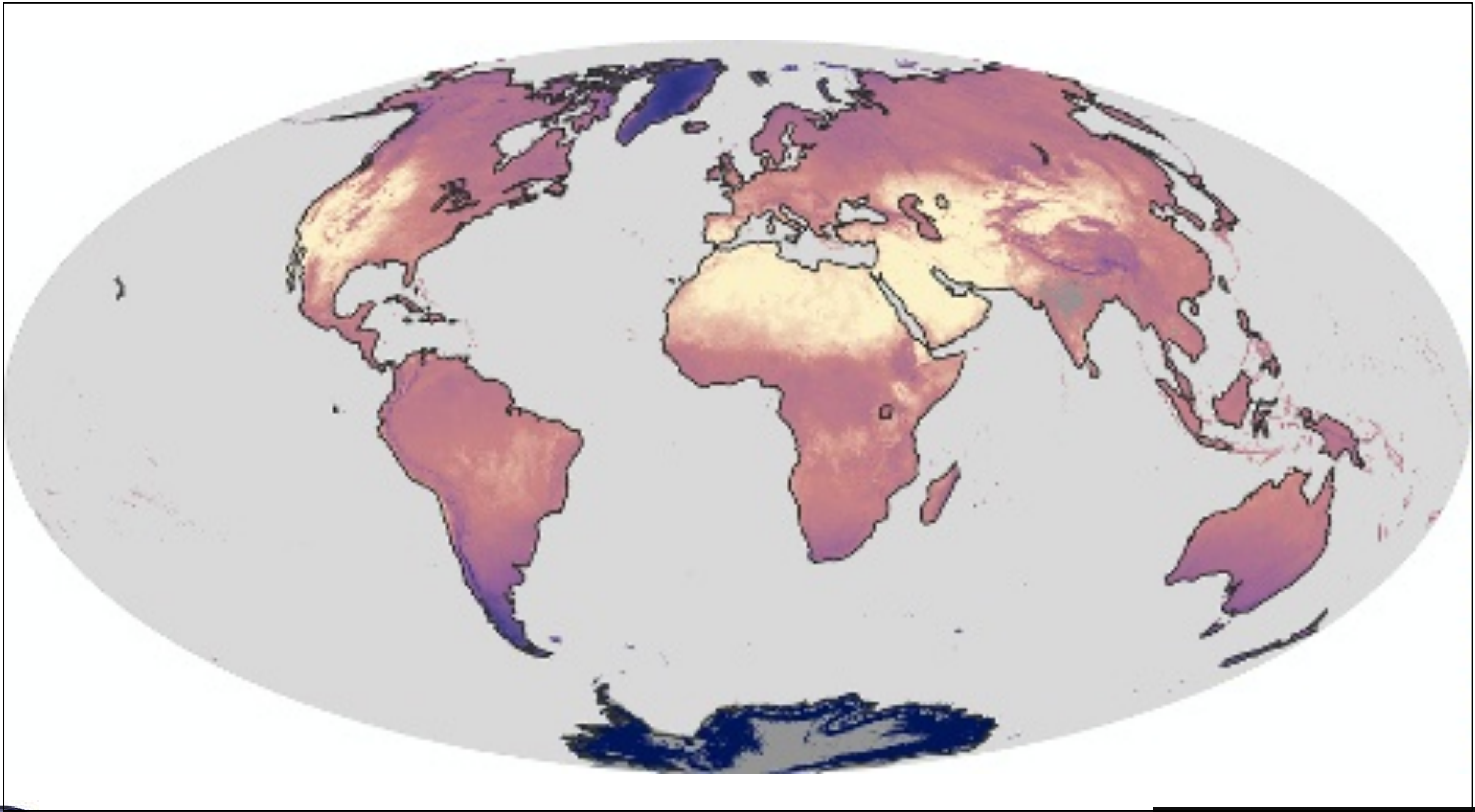
LST: July 2006



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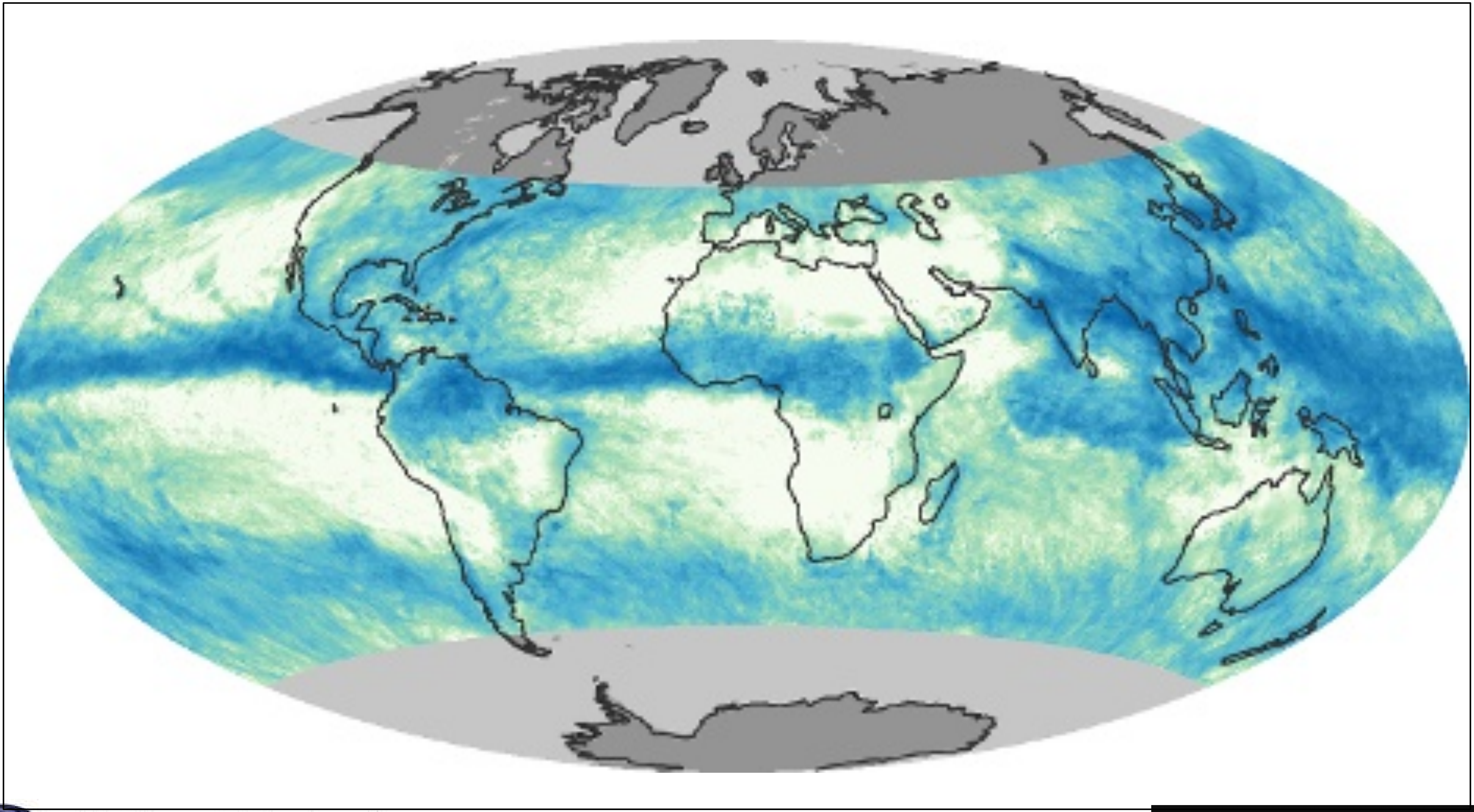
Precip: July 2006



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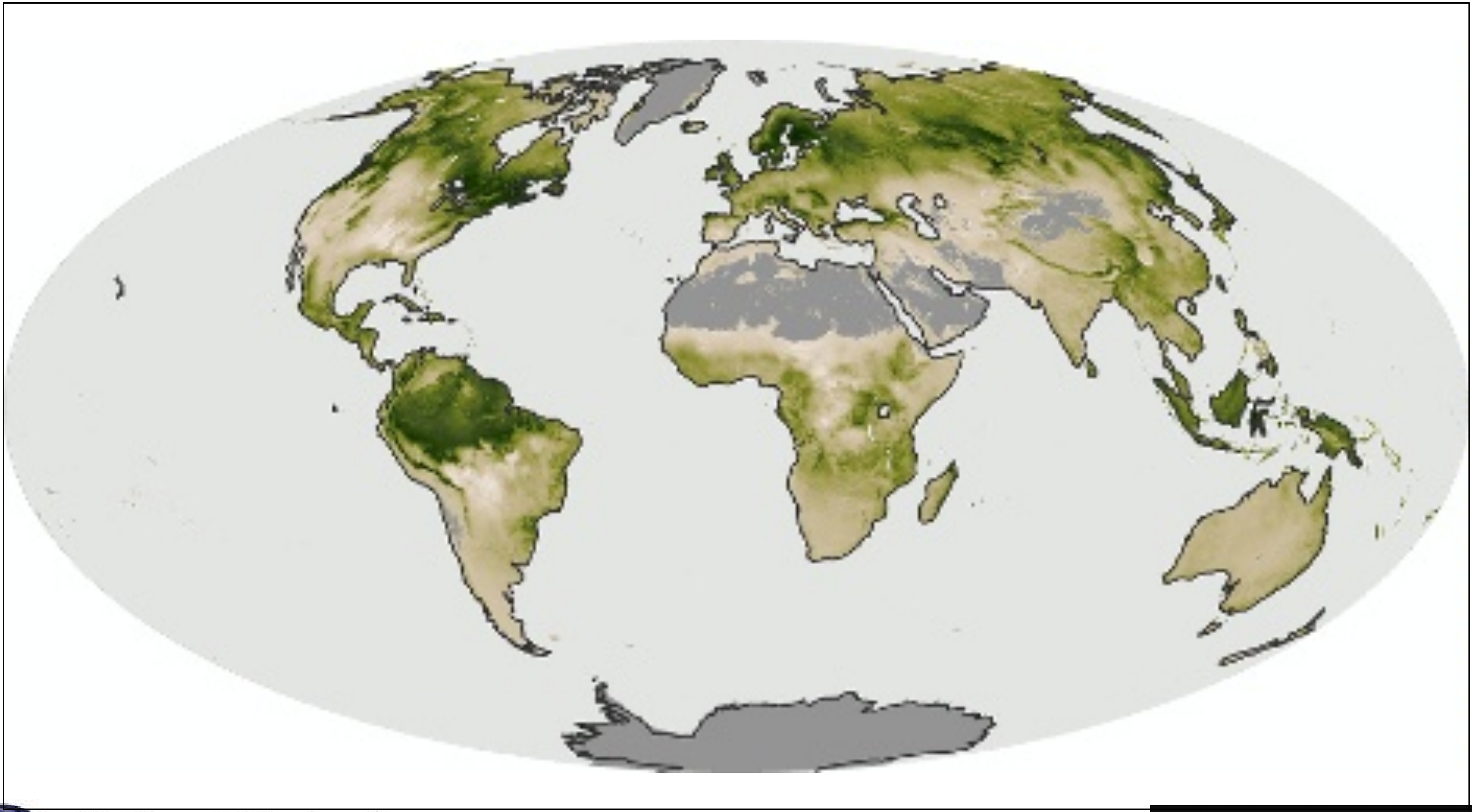
NPP: July 2006



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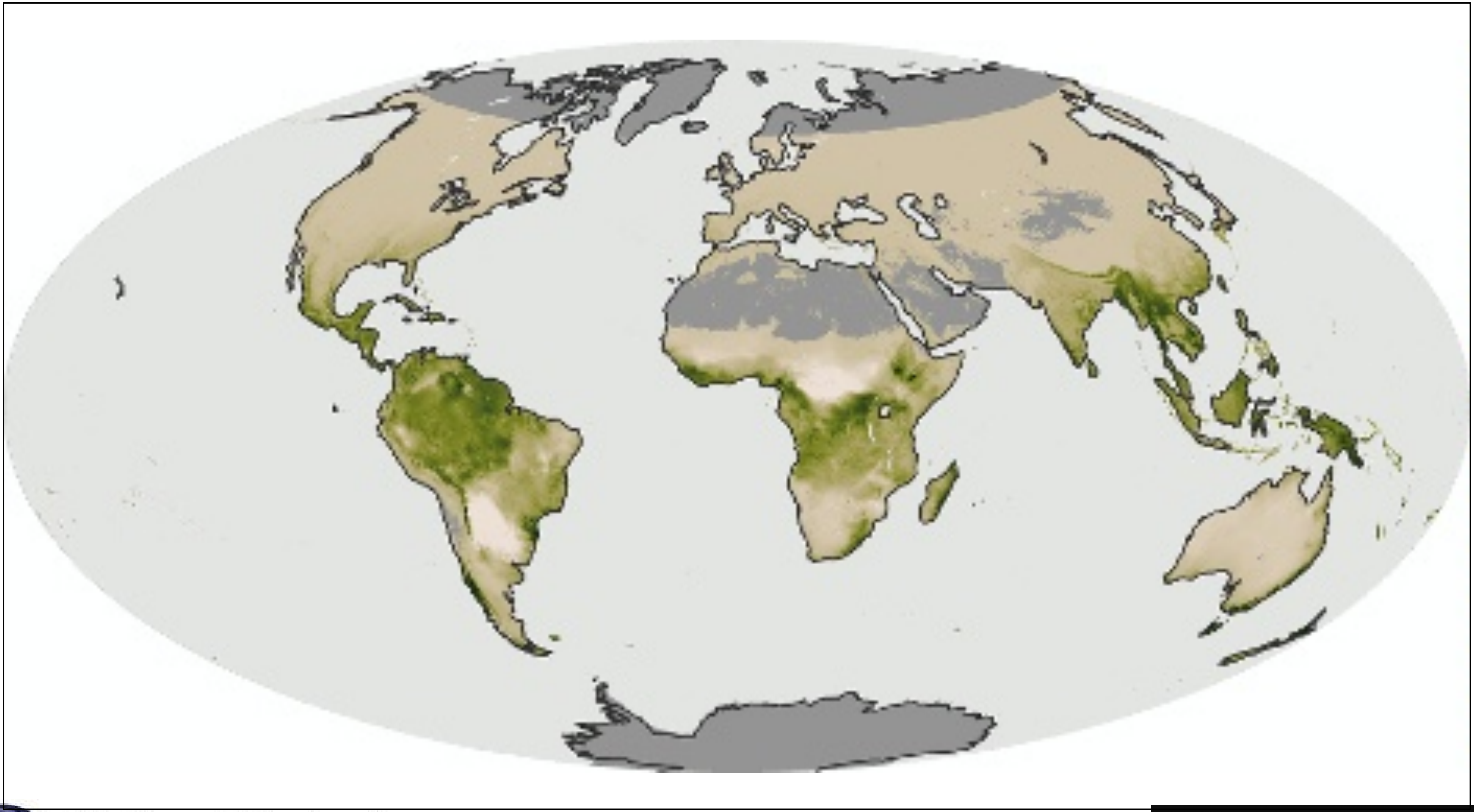
NPP: Dec 2006



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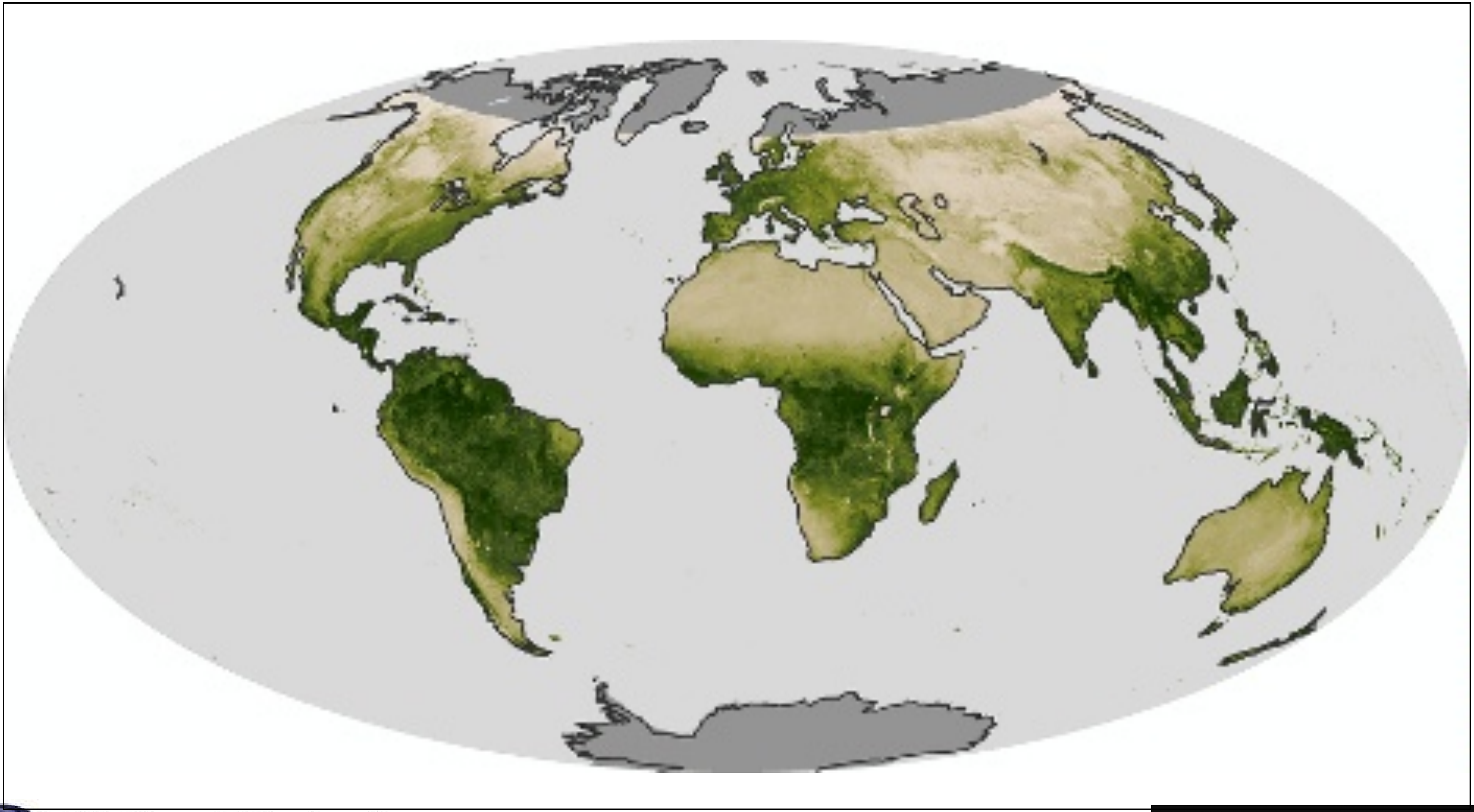
NDVI: Dec 2006



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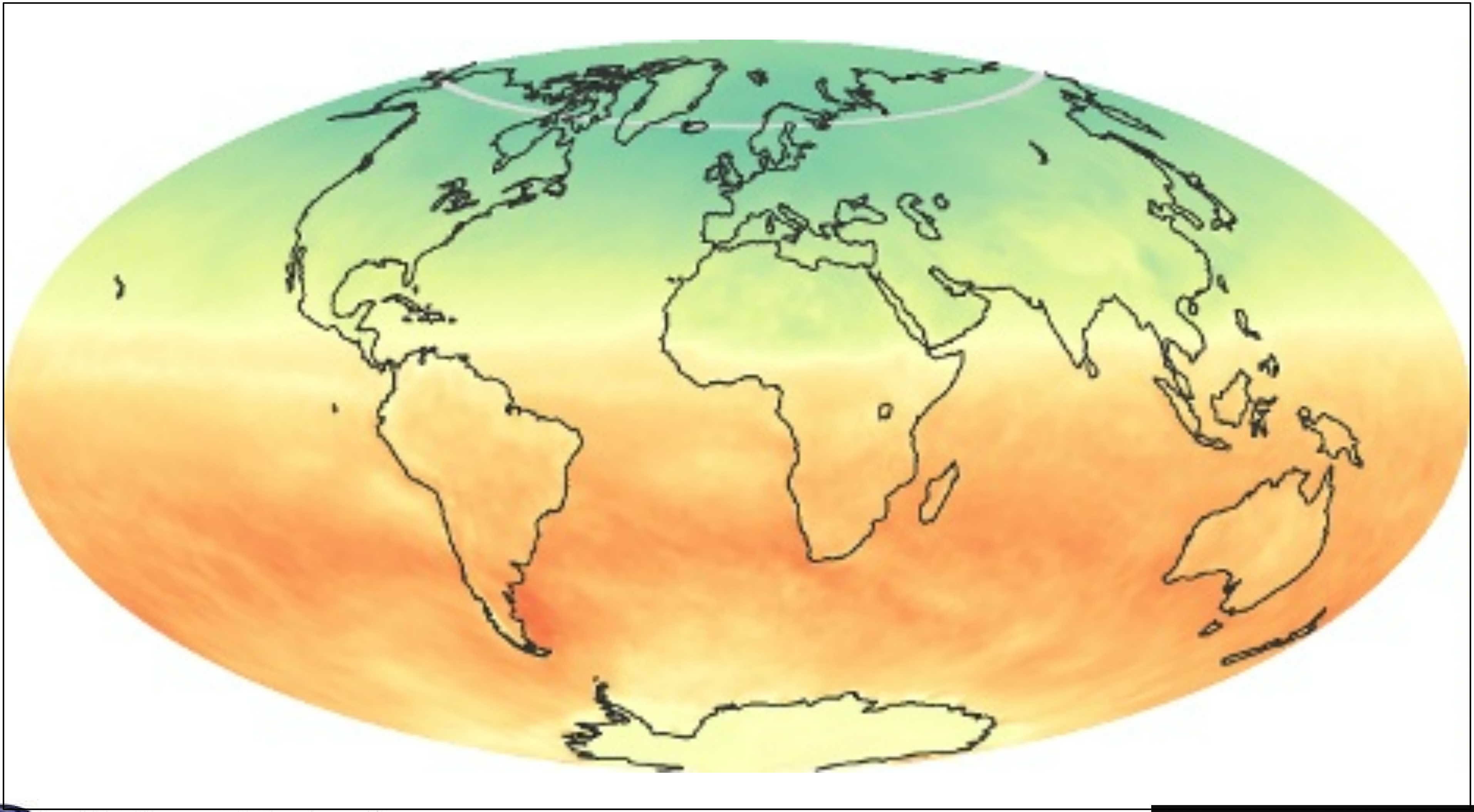
Net radiation: Dec 2006



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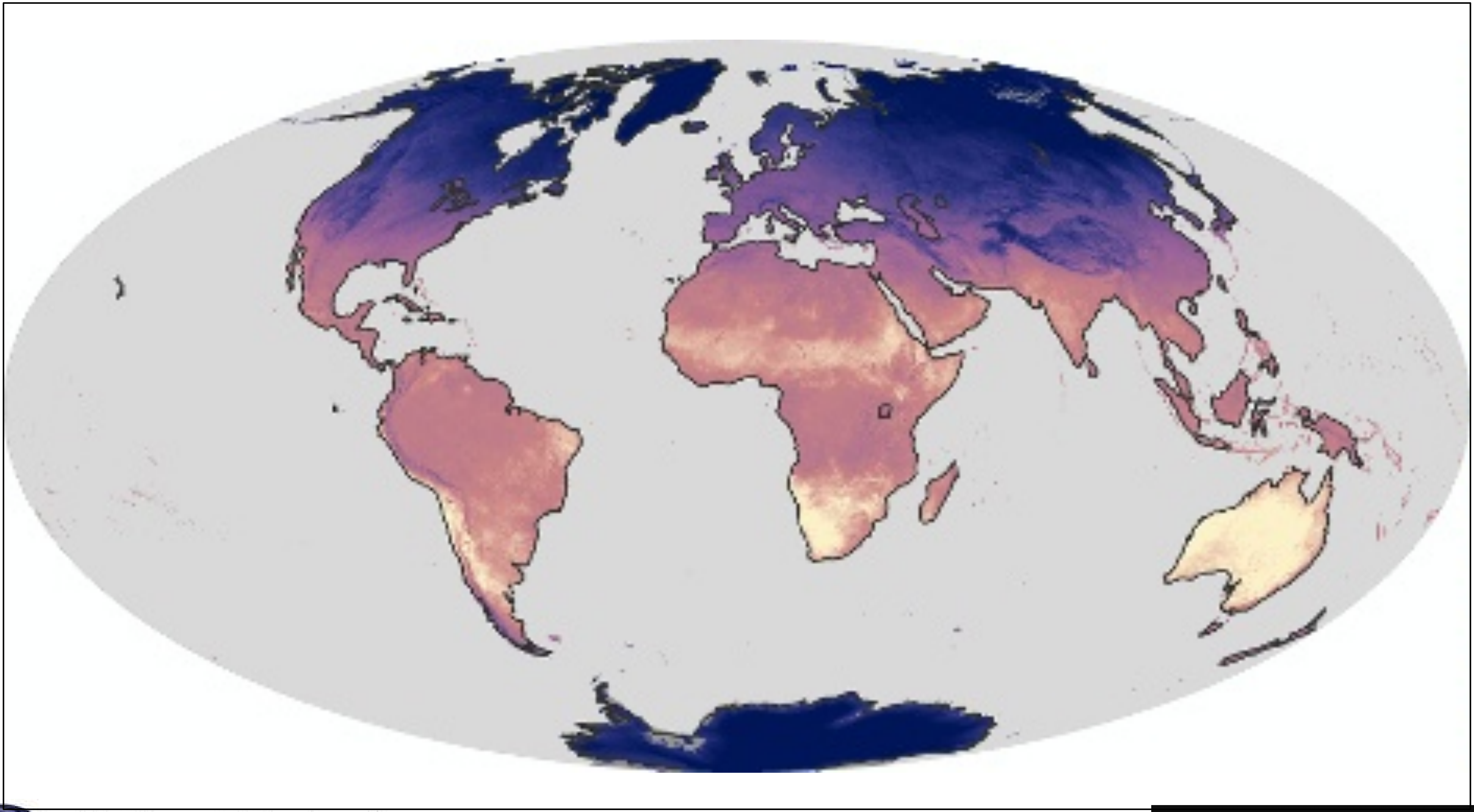
LST: Dec 2006



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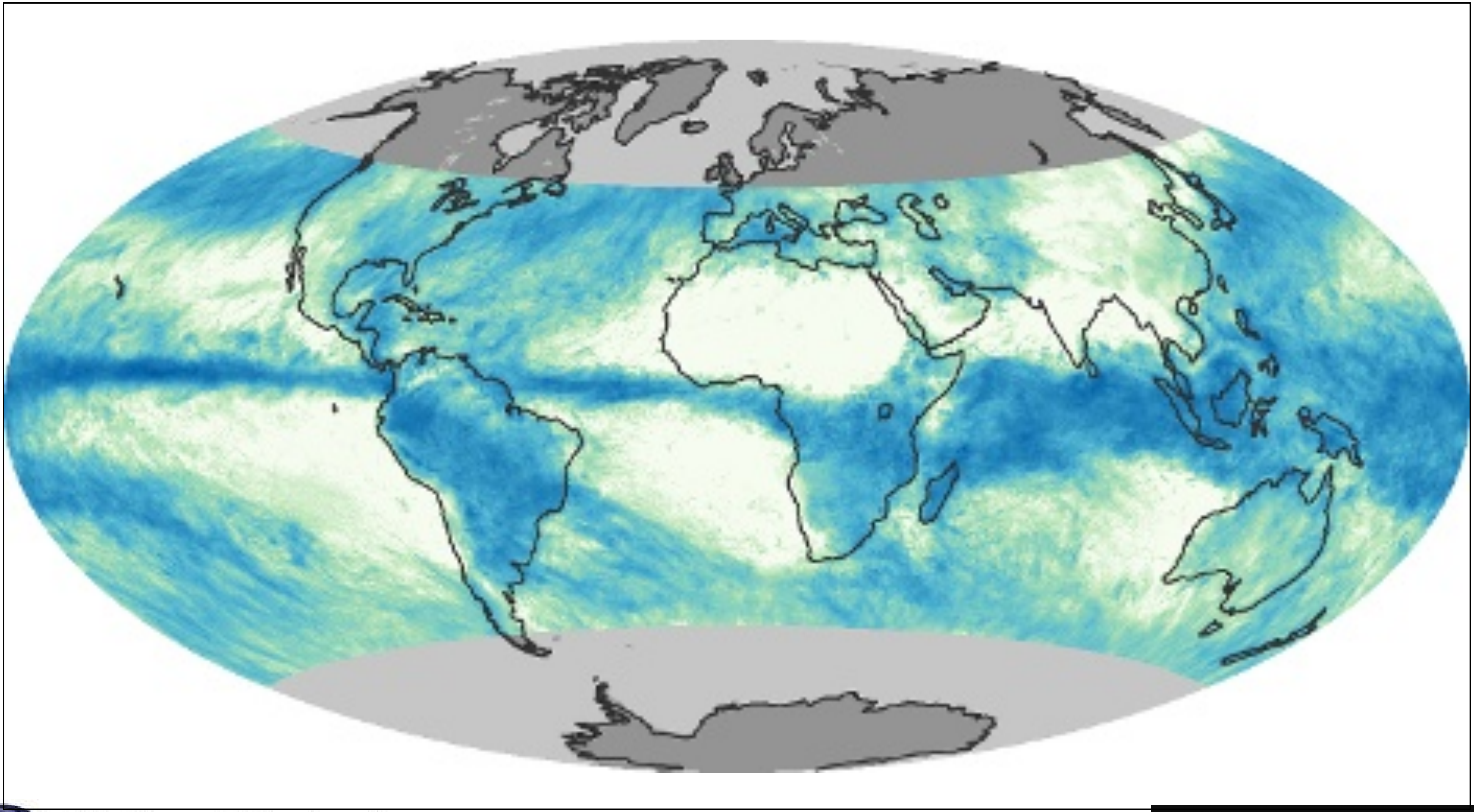
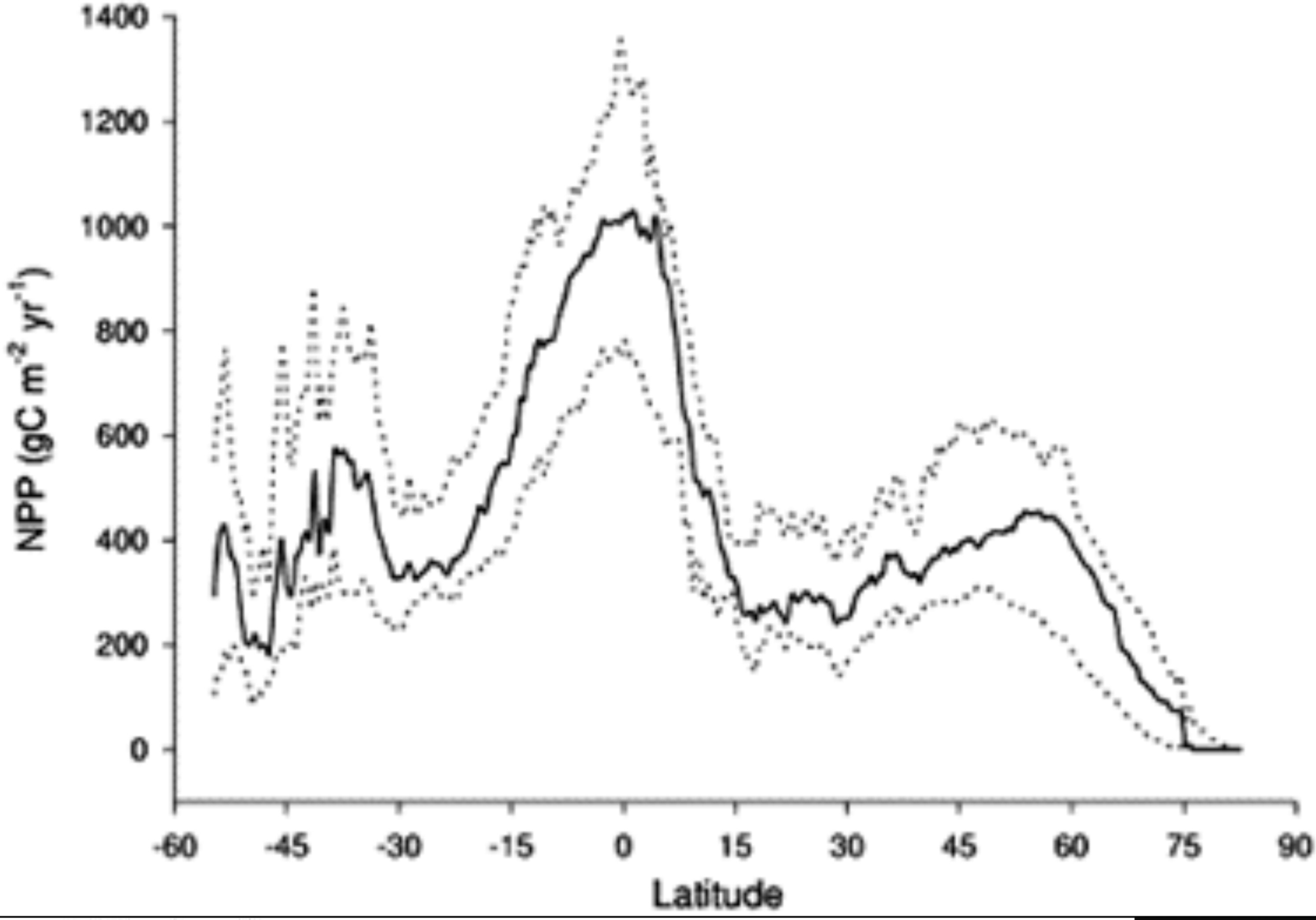
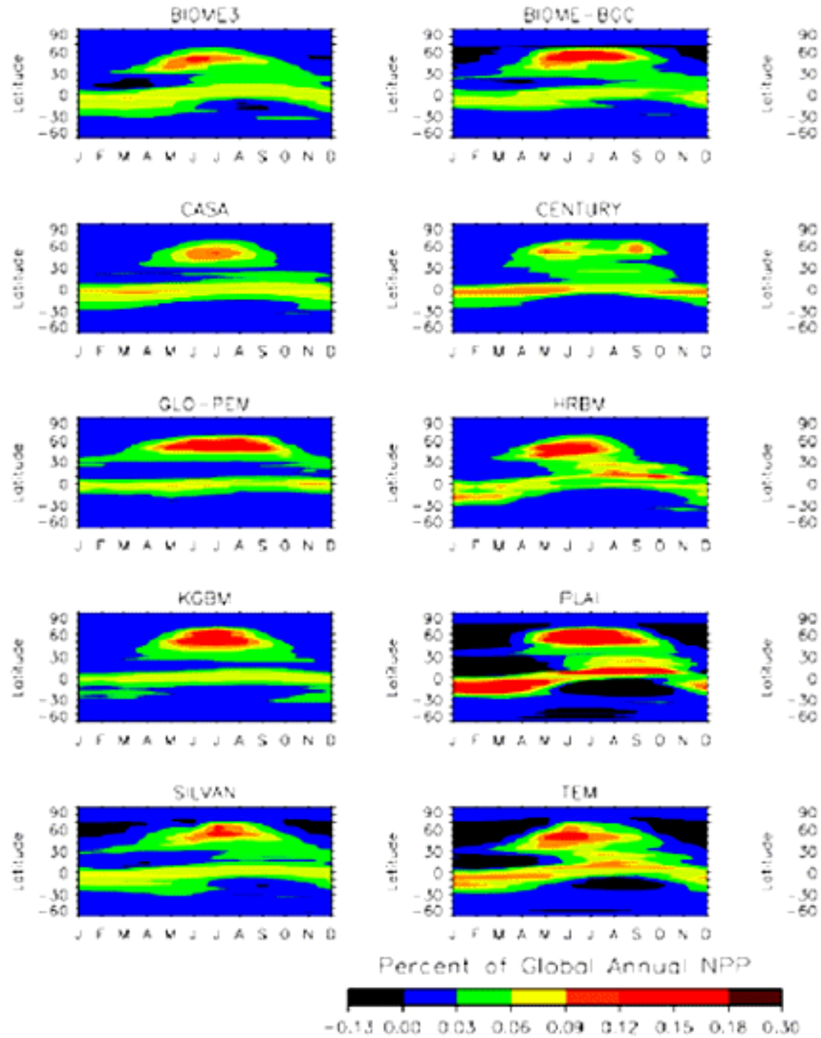
Precip: Dec 2006



Latitudinal distribution of NPP



Latitudinal and time distribution NPP



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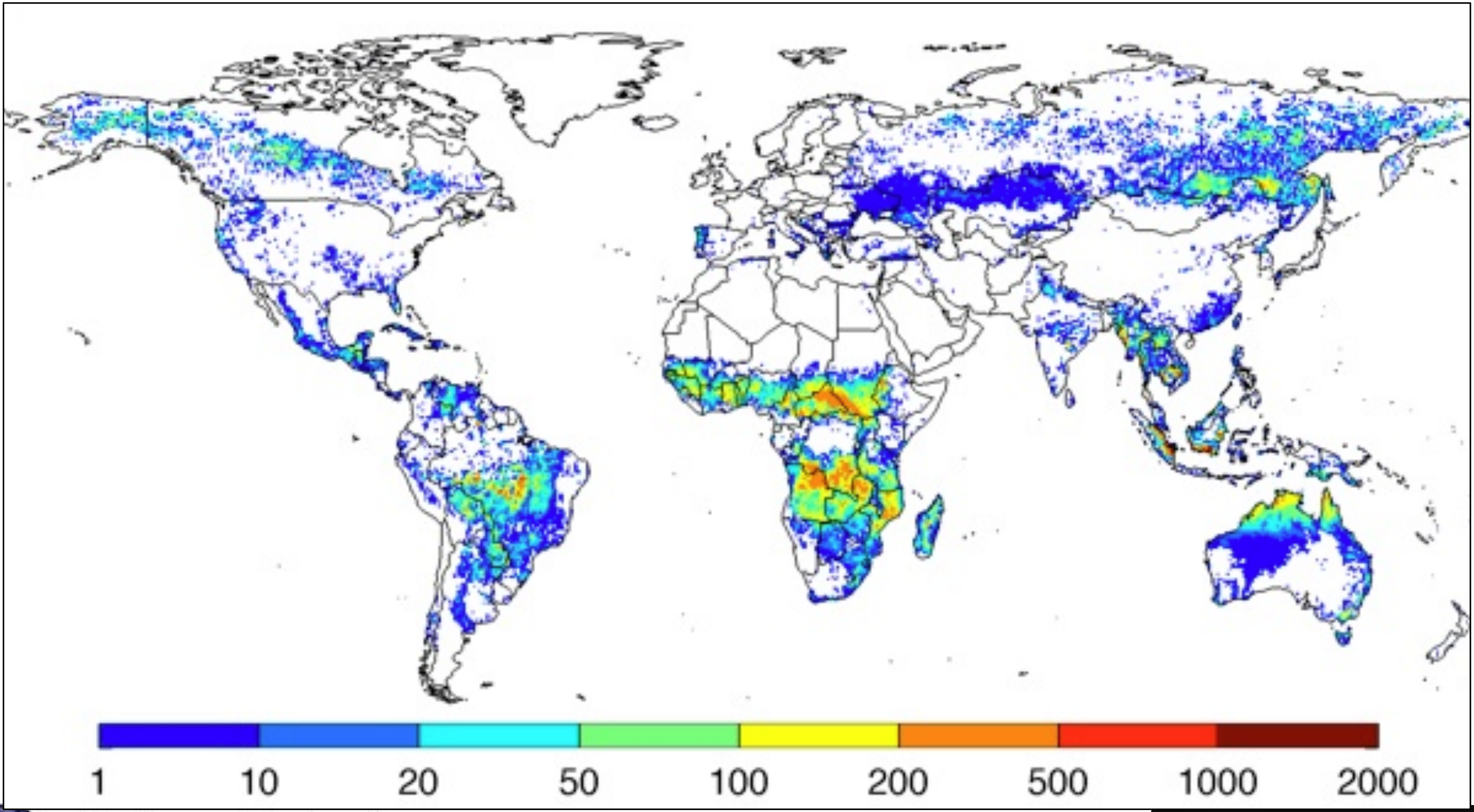
Net Ecosystem Productivity

NEP = NPP minus other losses

- respiration by heterotrophs (organisms – fungi, animals and bacteria in the soil),
- other losses to the ecosystem such as through harvesting or fire.

fire



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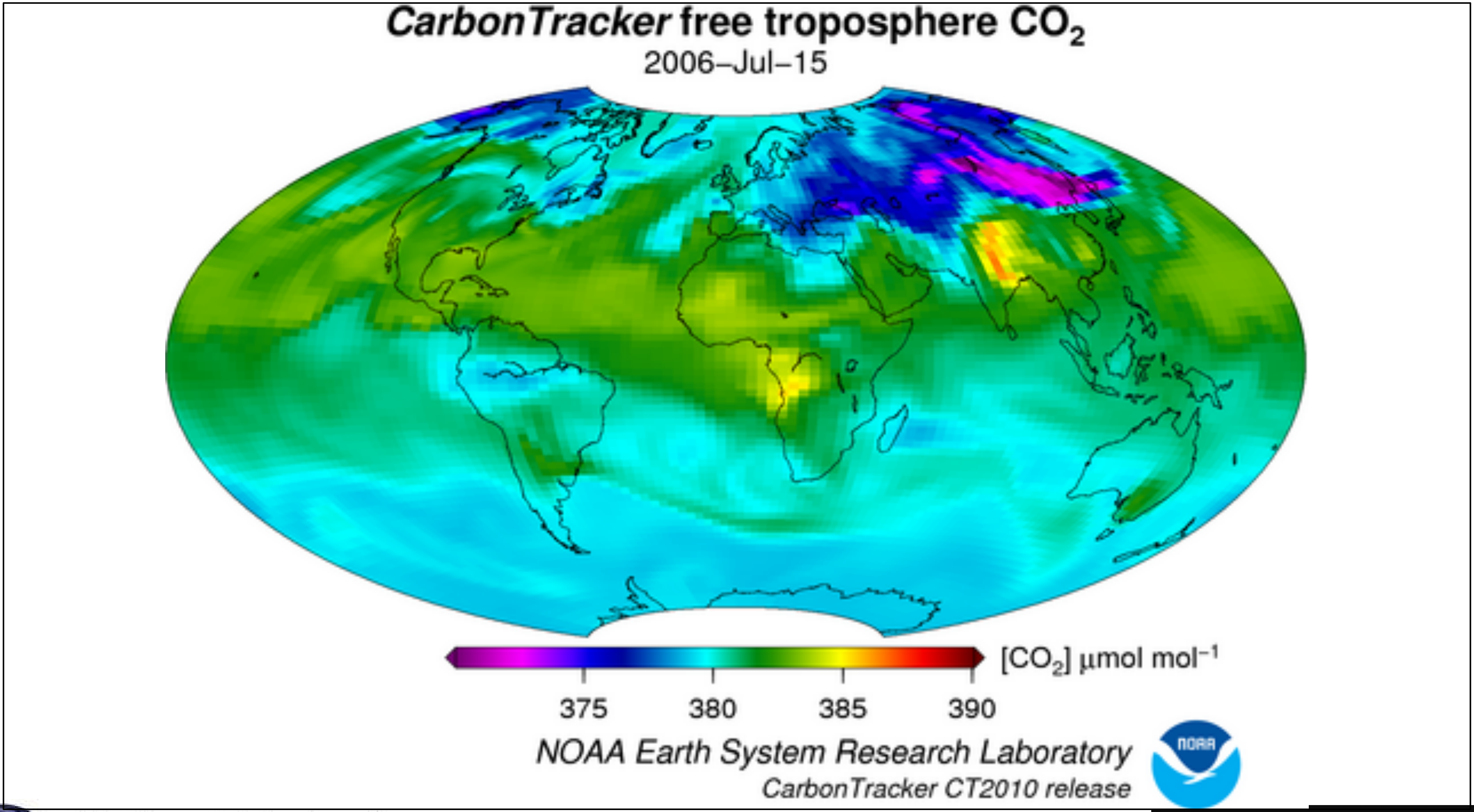
Atmos CO2



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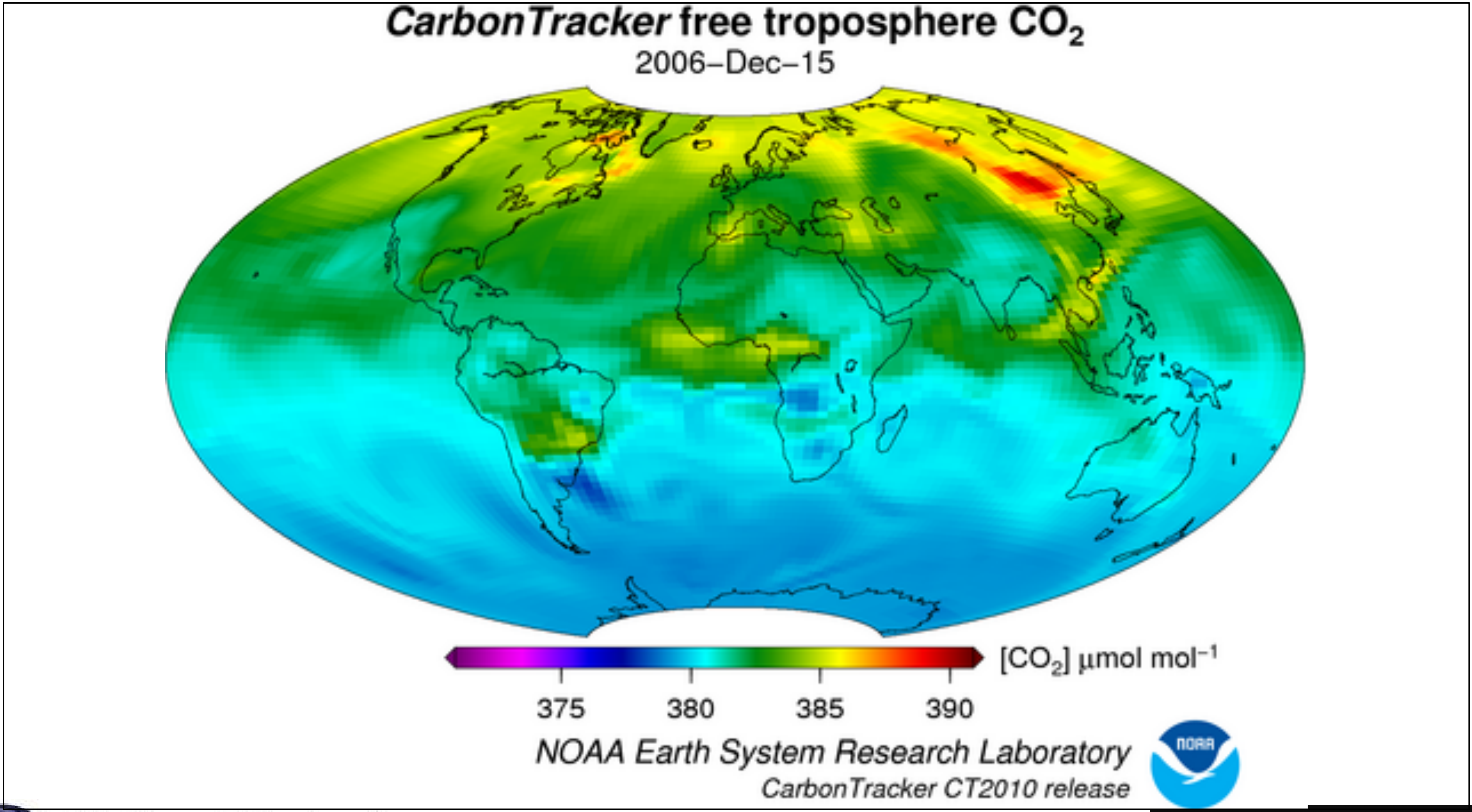
Atmos CO2



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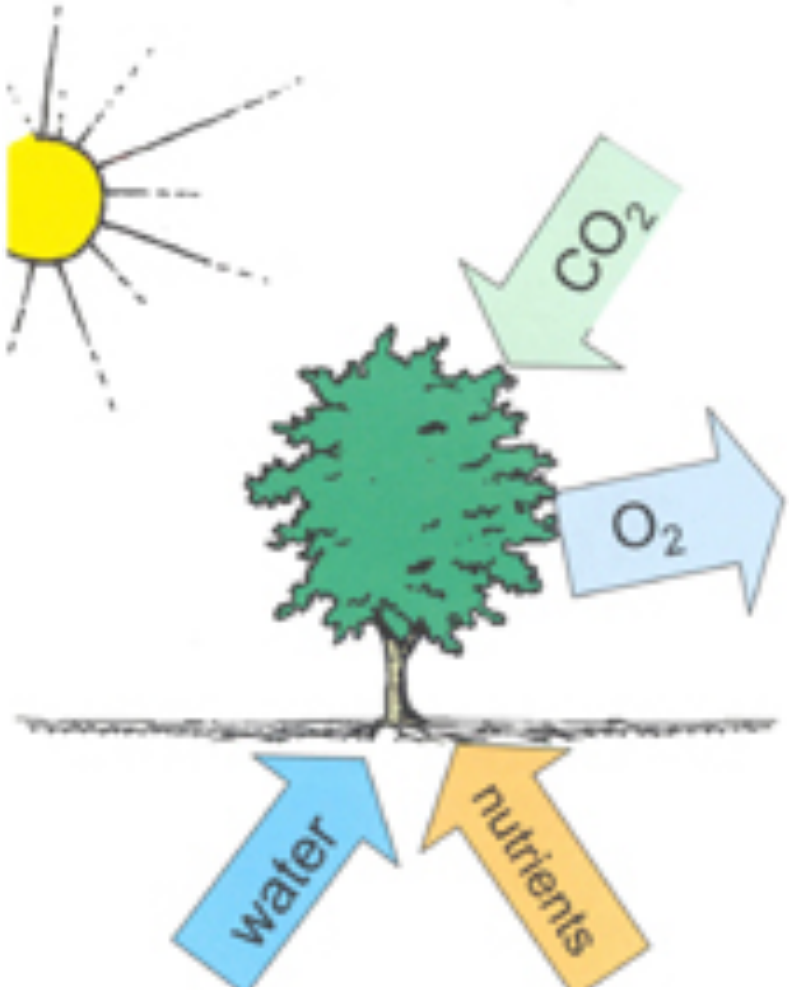
Photosynthesis



Photosynthesis

carbon dioxide + water + light energy = glucose + oxygen

$6CO_2 + 6H_2O +$ light energy $= C_6H_{12}O_6 + 6O_2$

Transpiration

- Provides 10% of moisture found in atmosphere.
- uses around 90% of water that enters plant
  - (the rest being used in cell growth and photosynthesis).
- Most transpiration water in stomata of the leaves.
  - guard cells of the stomata open to allow CO2 diffusion from the air for photosynthesis.
  - can be thought of as the “cost” for opening stomata to allow the diffusion of carbon dioxide gas from the air.

Stomatal conductance

Stomatal conductance, (e.g. in mmol m-2 s-2)

- measure of the rate of passage of carbon dioxide (CO_2) exiting, or water vapor entering through the stomata of a leaf.
- controlled by guard cells leaf stomata and controls transpiration rates and CO_2 diffusion rates (along with gradients of water vapour and CO_2).

Transpiration serves three main roles:

- **movement of minerals**
  - (from roots: xylem) and sugars (from photosynthesis: phloem) throughout the plant.
- **cooling**
  - (loss of heat energy through transpiration)
- **maintenance of turgor pressure**
  - in plant cells for plant structure and the functioning of guard cells in the stomata to regulate water loss and CO2 uptake.

stomata

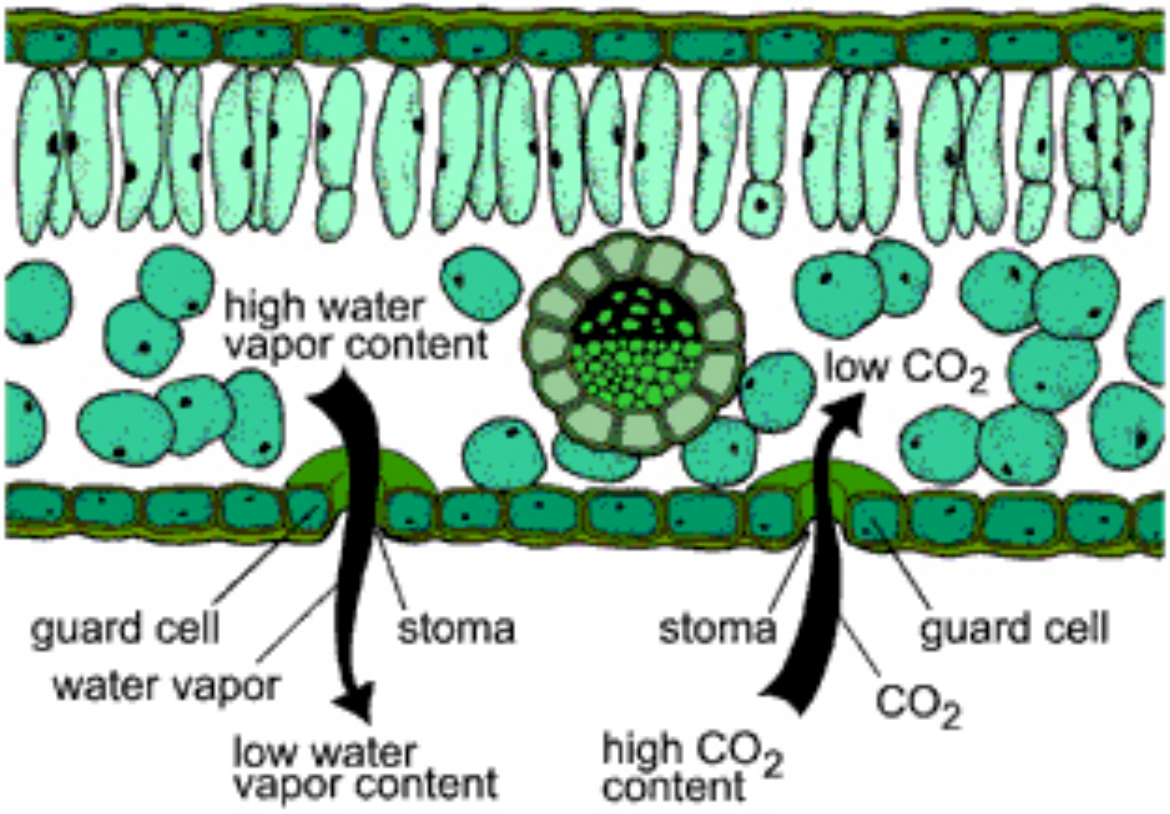
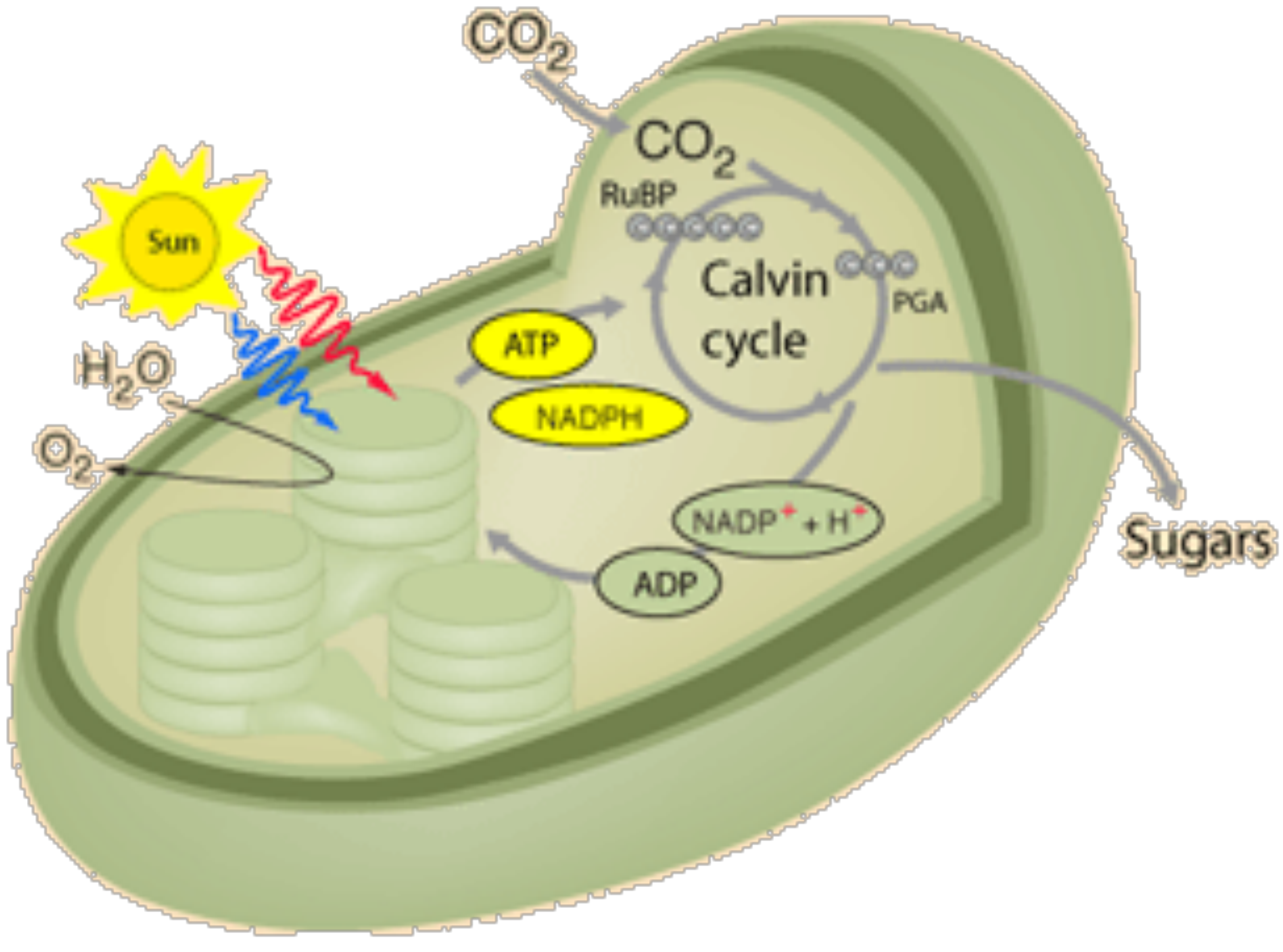


Figure 25. Stomata open to allow carbon dioxide (CO_2) to enter a leaf and water vapor to leave.

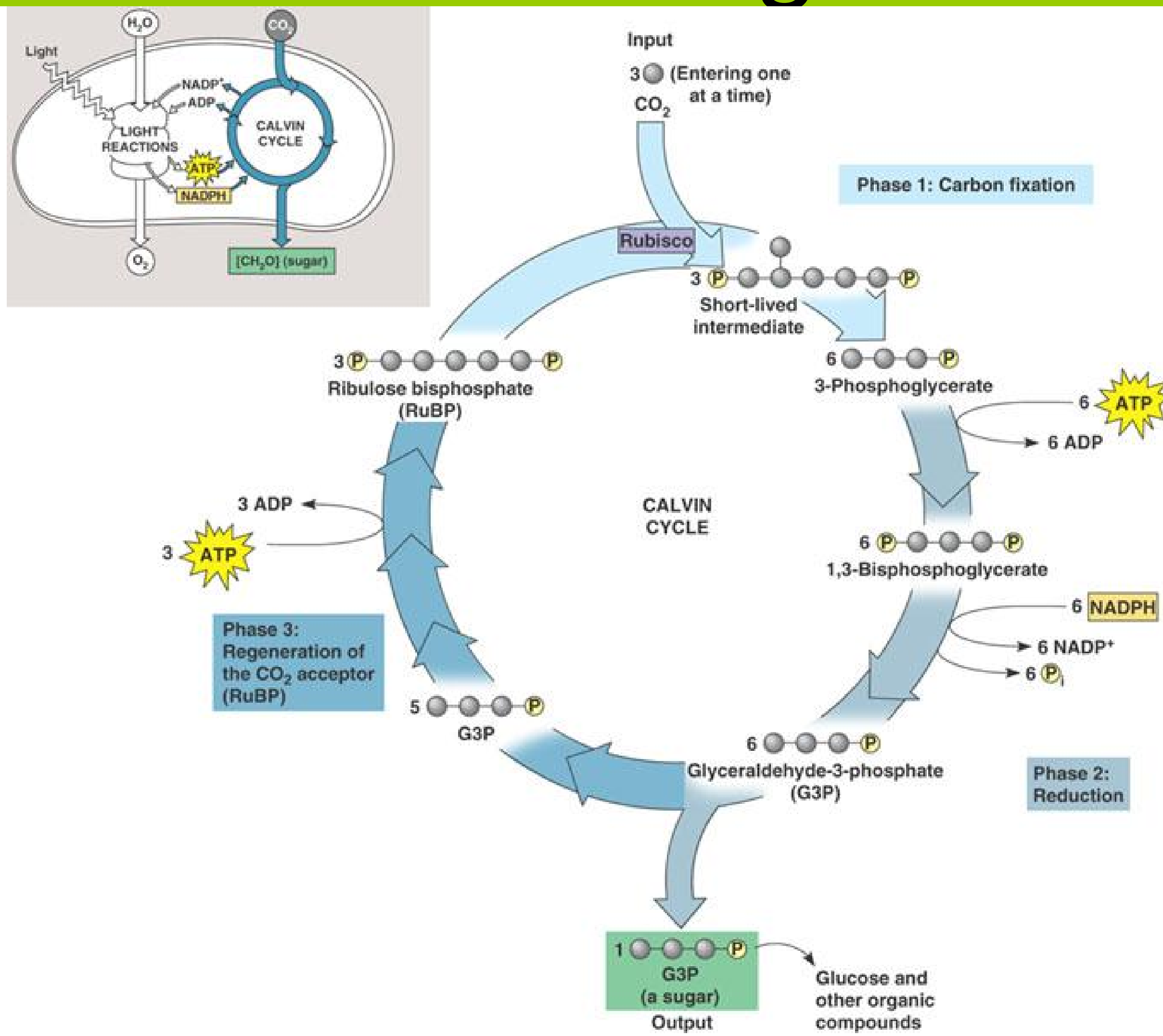
three types of photosynthesis mechanisms

- **C3, C4, CAM**
- **C3:**
  - 85% of plants
  - wheat, barley, potatoes and sugar beet and most trees.
  - cannot grow in hot climates because RuBisCO incorporates more oxygen into RuBP as temperatures increase
    - photorespiration and a net loss of carbon (and nitrogen) that can act as a limit to growth.
  - C3 plants are also sensitive to water availability.

C3 plants use the Calvin cycle for fixing CO2.



C3 plants use the Calvin cycle for fixing CO2.



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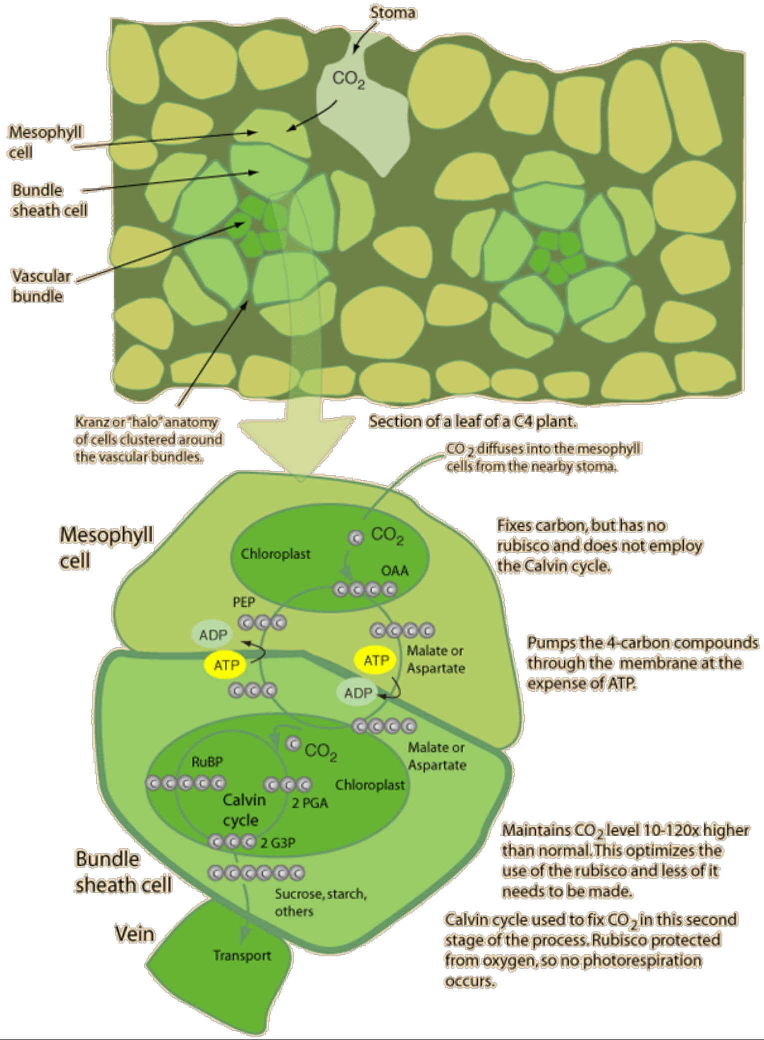
C4 Plants

- C4 plants (and CAM plants)
  - more efficient than C3 plants under conditions of drought, high temperatures, and nitrogen or CO2 limitation.
  - bypassing the photorespiration pathway and efficiently delivering CO2 to the RuBisCO enzyme

C4



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Respiration

- (autotrophic) respiration
  - plants convert sugars back into CO2 and water, and release energy in the process.

Respiration

glucose + oxygen = energy + carbon dioxide + water

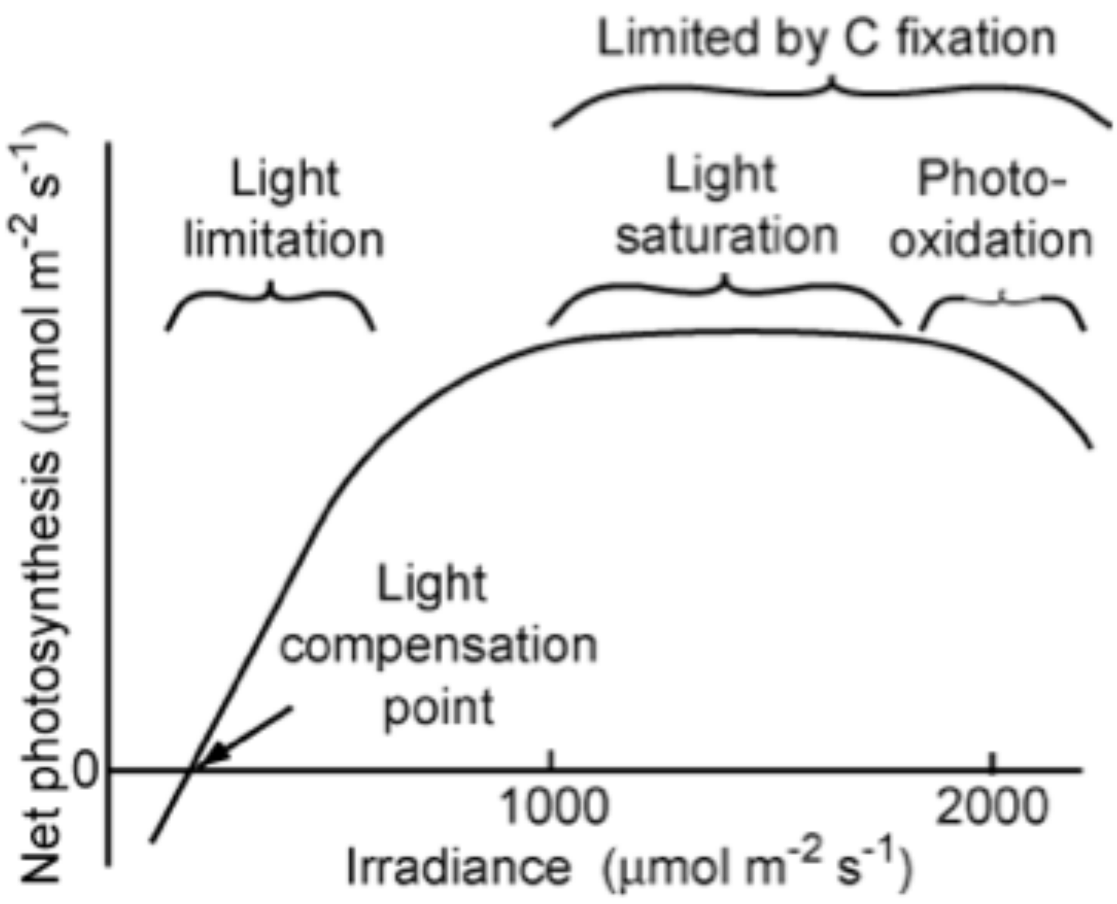
$C_6H_{12}O_6 + 6O_2 = \text{energy} + 6CO_2 + 6H_2O$

  - energy released used for growth and maintenance of existing material.
  - Consumes 25% to75% of all of the carbohydrates generated in photosynthesis.

Limitations to photosynthesis at the leaf level

- light limitation;
- CO_2 limitation;
- nitrogen limitation and photosynthetic capacity;
- water limitation;
- temperature effects;
- pollutants

light limitation



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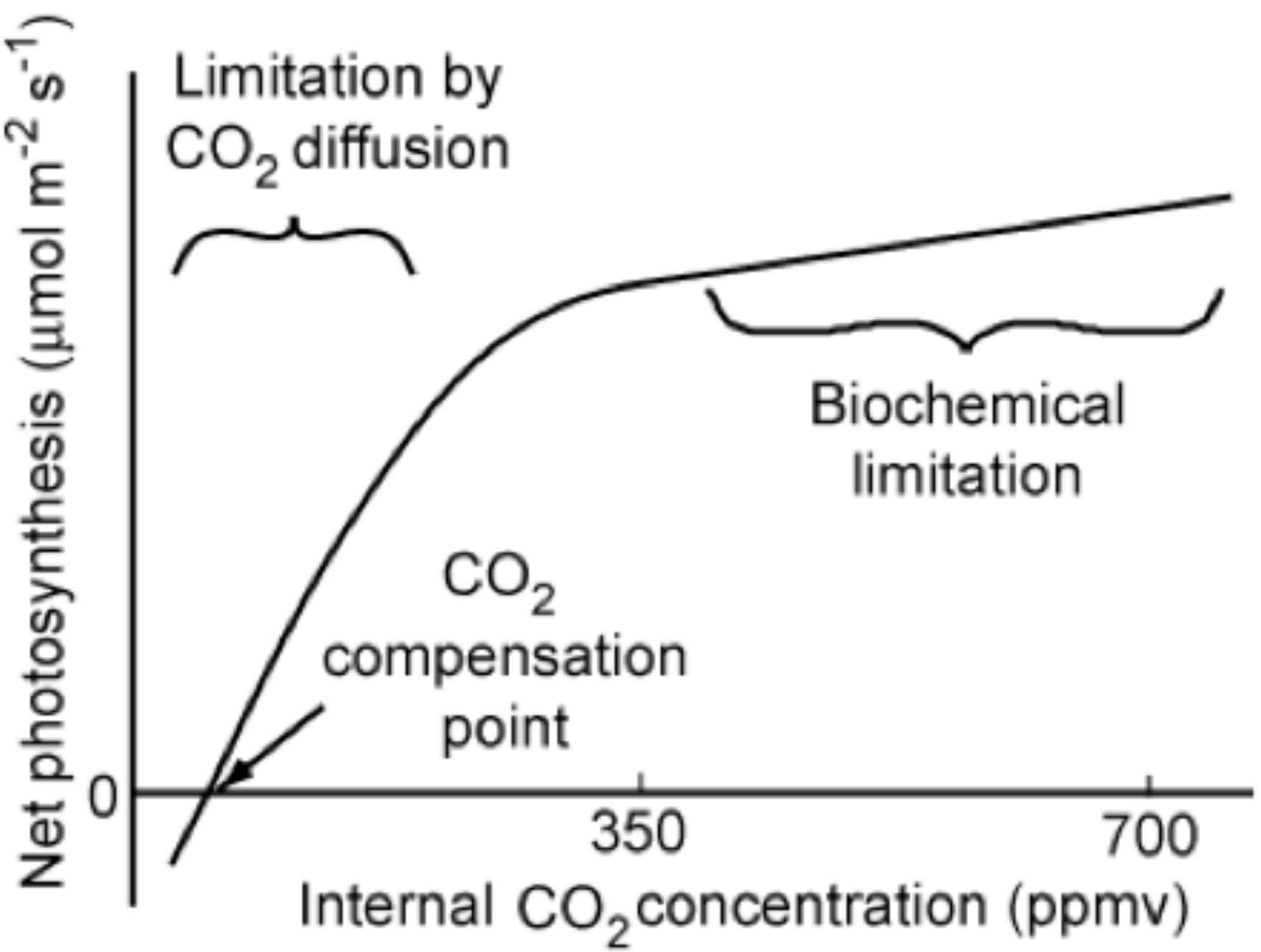
Light limitation

- rate of change of net photosynthesis in low-moderate region: quantum yield of photosynthesis.
- Similar for all C3 (non stress) at ~6%
- Saturation at higher levels: reduced efficiency
- Acclimation responses
  - Sun leaves
    - More cell layers and higher photosynthetic capacity
  - Respiration rate depends on tissue protein content
    - So shade leaves lower protein content to minimise respiration losses

CO2 limitation



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CO2 limitation

- Over long term, *indirect* effects of elevated CO_2 concentrations may be more important than increased net photosynthesis rates
  - E.g. changes to water cycle

- C4 relatively unresponsive
  - Less competitive in higher CO_2 environment?
  - Probably indirect effects important

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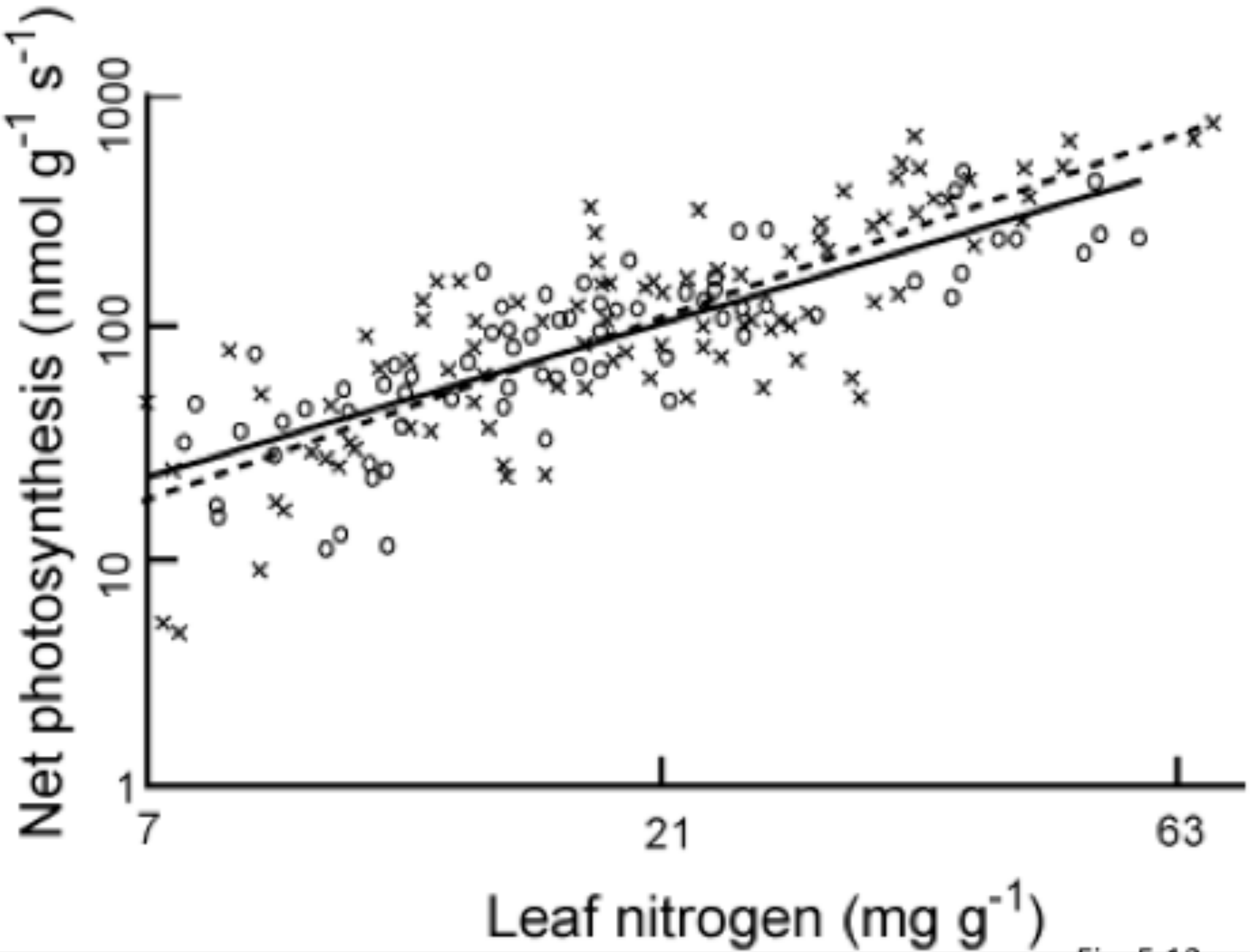
Nitrogen limitation and photosynthetic capacity



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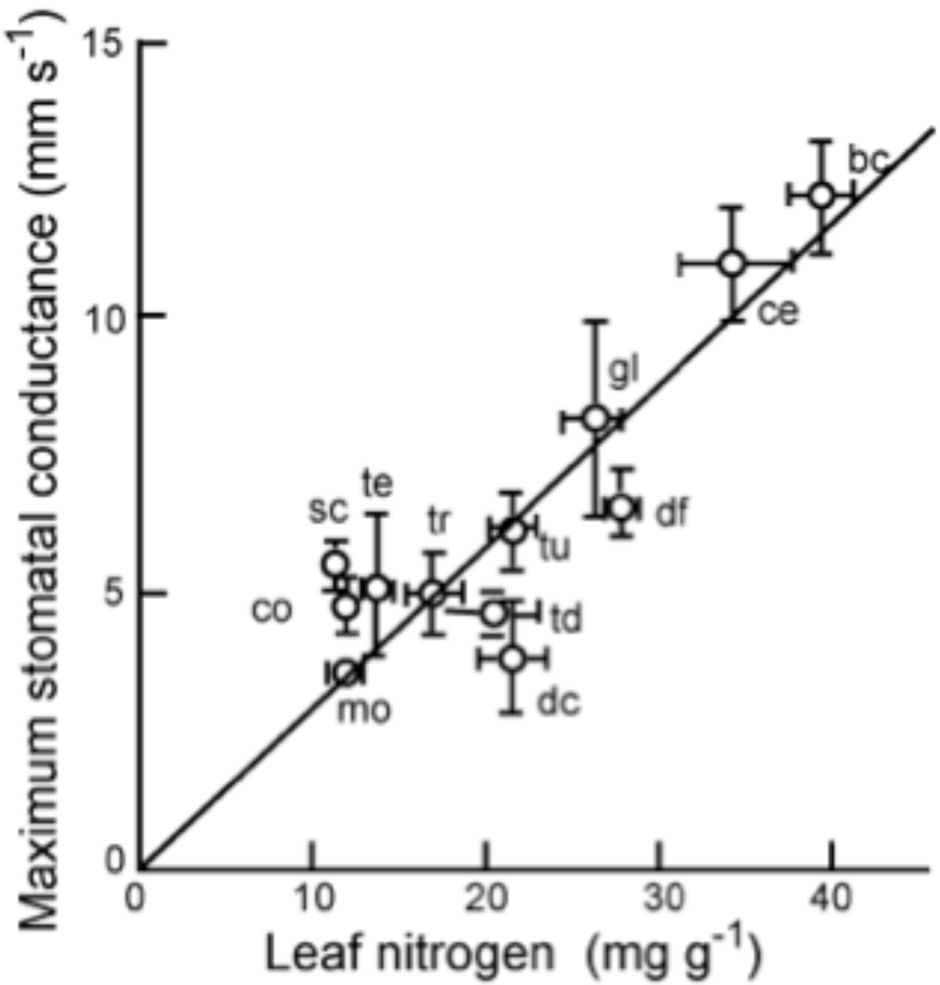
Nitrogen



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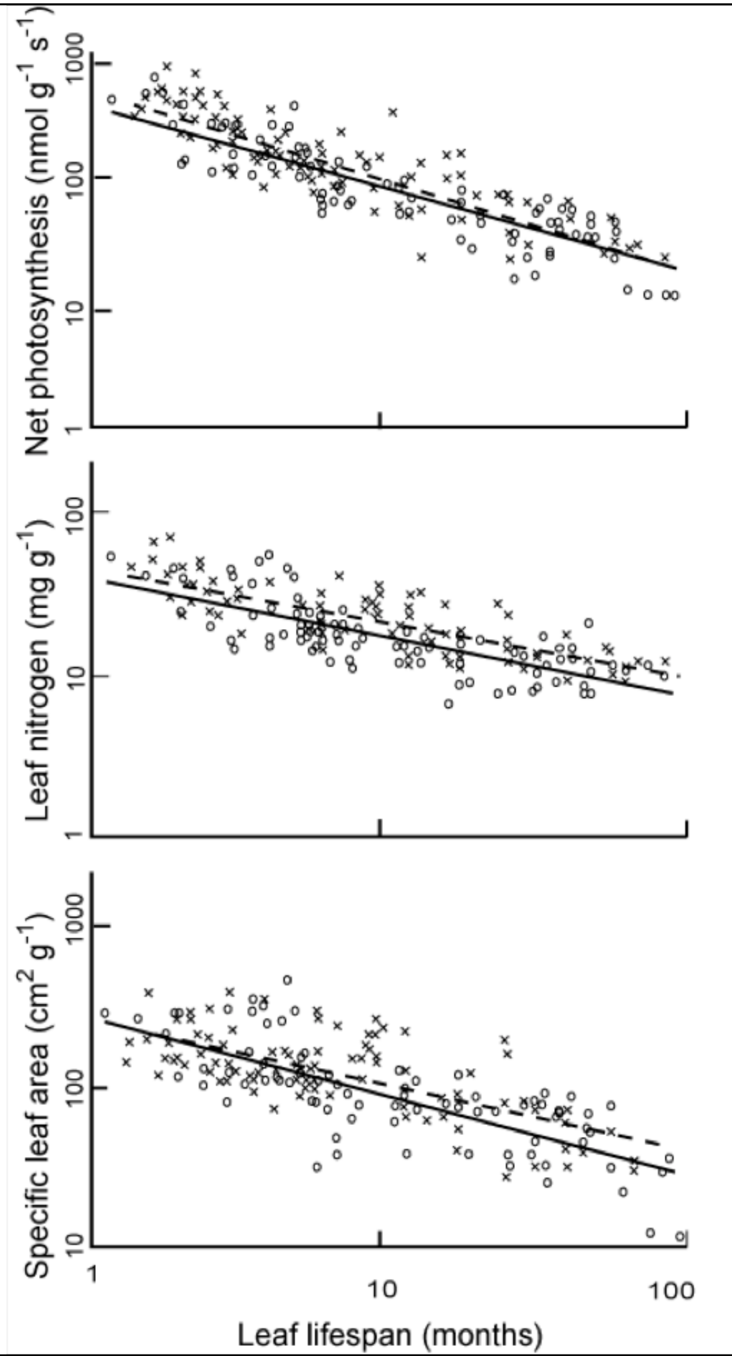
Nitrogen

Relationships between N, leaf lifespan, SLA and net photosynthesis

higher the leaf N concentration, the shorter the leaf lifespan.

Leaves with shorter lifspans tend to have lower specific leaf area (SLA, the leaf surface area per unit of biomass) (i.e. long-lived leaves are more dense), so higher leaf N concentration correlates with higher SLA.



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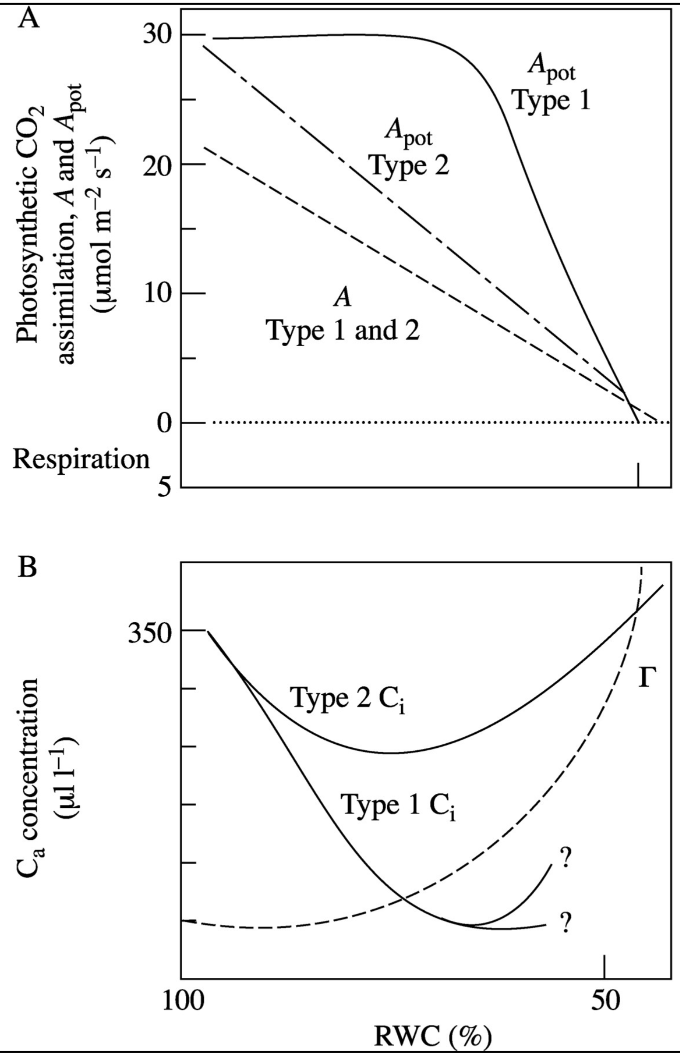
Water limitation

- reduces the capacity of leaves to match CO_2 supply with light availability
- manifested as a decrease in leaf relative water content (RWC).
- Decreasing RWC progressively decreases stomatal conductance which slows CO_2 assimilation (lower photosynthetic capacity) although different studies show different responses for RWC between 100% and 70%

Water limitation



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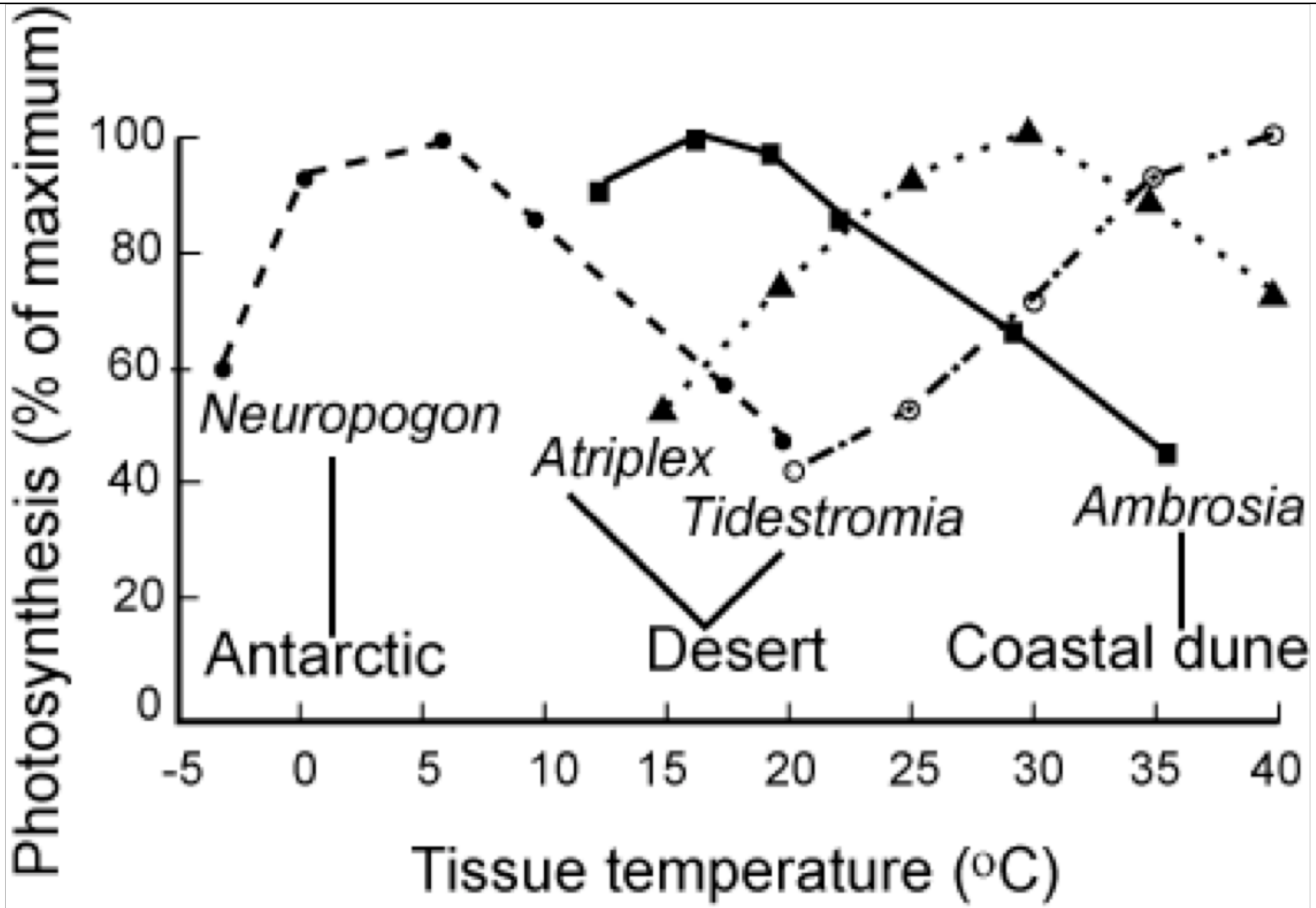
Water limitation

Plants acclimated and adapted to dry conditions

- reduce photosynthetic capacity and leaf N concentrations
  - low stomatal conductance that conserves water
- minimse leaf area (shedding or lower leaf production rates) to minimise water loss.
- Some minimise radiation absorption by higher leaf reflectance more vertically-inclined (erectophile) leaves.

Temperature effects



summary

- *considered the importance of understanding the science of climate change*
- *looked at basic principles of energy transfer in the earth system*
- *examined greenhouse gases and their sources*
- *looked in detail at the terrestrial carbon cycle*
- *provided an overview of relevant biogeochemical processes*
- *looked in some detail at photosynthesis and factors that limit this*