# Earth Systems Science

Jason Beringer
Monash University

# Outline

- Climate/Earth system
- Spheres and cycles
- Feedbacks, interactions and couplings
- Global Change

# The Earth System

The earth behaves as a system in which the components are all connected. Differs from climate system in the inclusion of *Anthroposphere and Biogeochemical cycling*

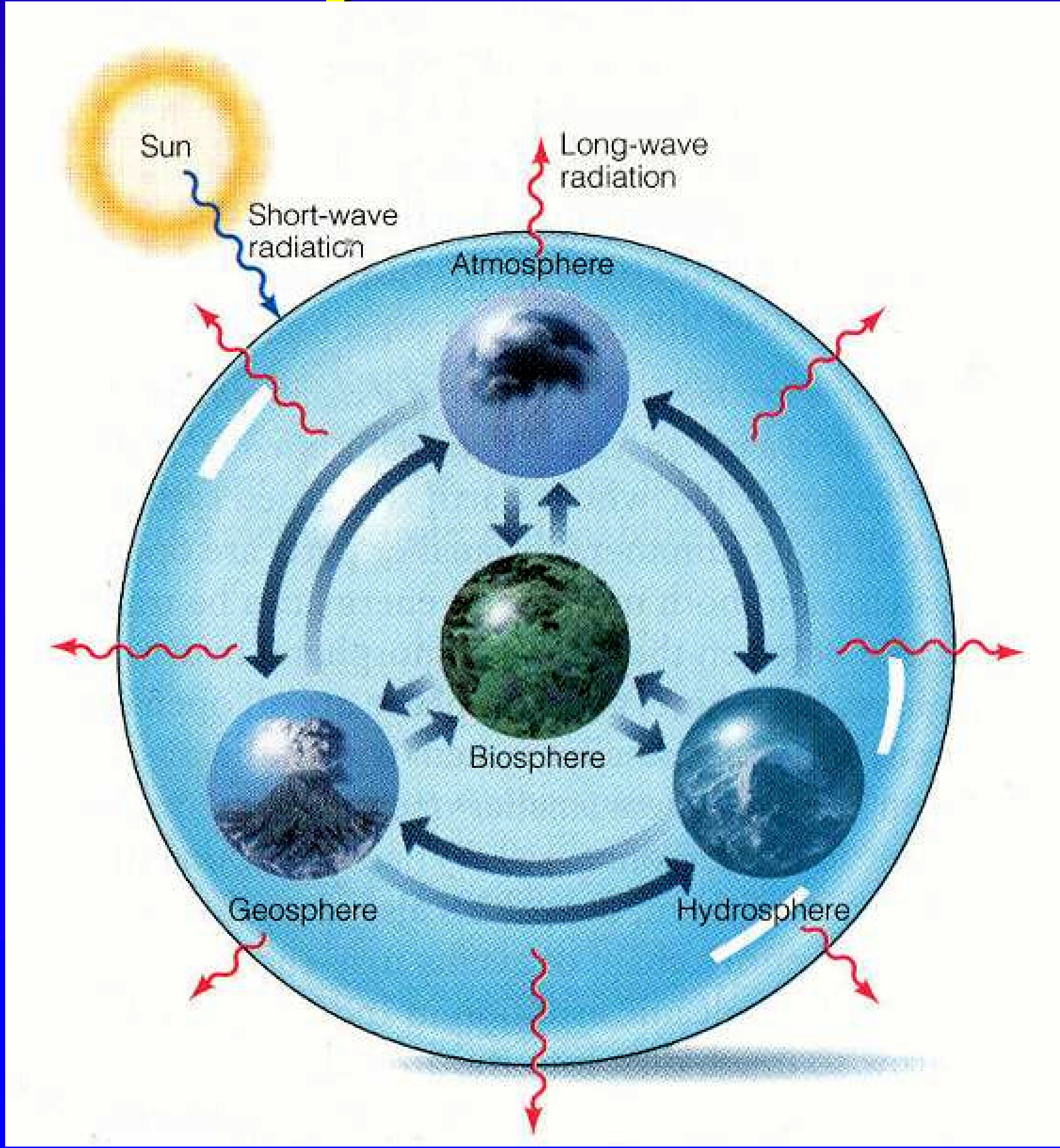

http://epod.usra.edu/archive/images/theearthsystem.jpg

# Gaia hypothesis - planetary self-regulation

- Gaia concept introduced by Lovelock and Margulis in 1970's. Treats the earth as a living entity.
- States that *life* on earth controls the physical and chemical conditions of the environment
- Challenge to a Darwinian idea of organism evolving / responding to environment
- Points to stable conditions, such as oxygen levels and climate, as evidence that living organisms maintain a life-sustaining environment
- Little understanding of processes, feedbacks and dynamics
- Earth System Science similar in interdisciplinary approach
  - seeks to understand the mass and energy transfers among interacting components of the Earth System

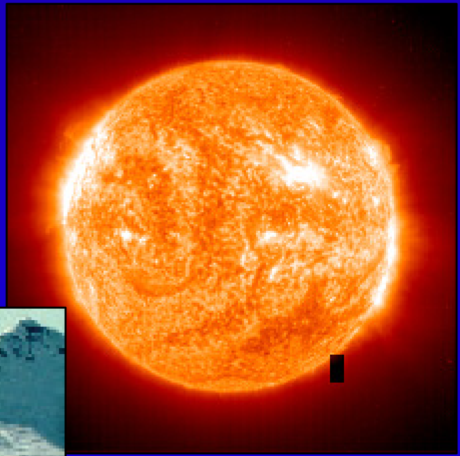
# The Earth System

- The Earth is a system
- Energy is the driver
- Atmosphere, Biosphere, Hydrosphere, Geosphere, Cryosphere,
- Components are closely linked
- Human modification (Anthroposphere)



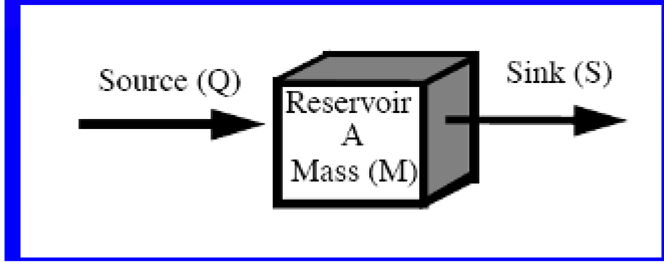
# The Earth System

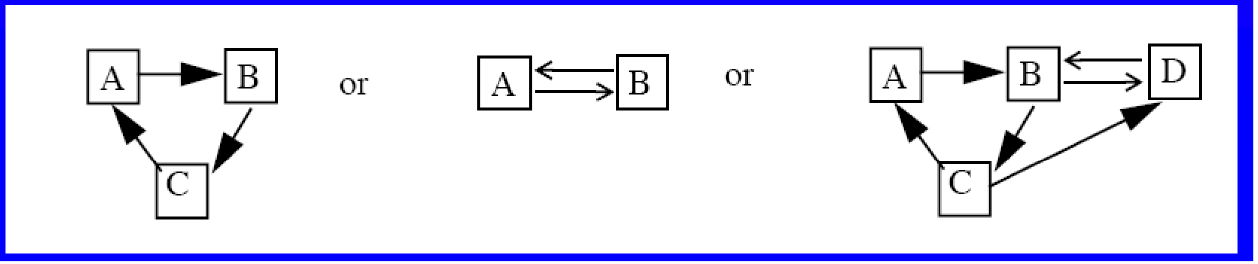
- The Earth system is linked through several major coupled cycles:
  - Energy cycle
  - Water cycle
  - Carbon cycle
  - Nitrogen
  - Rock cycle
- Influences climate
- Budgets of fluxes into and out of various reservoirs



# Definitions

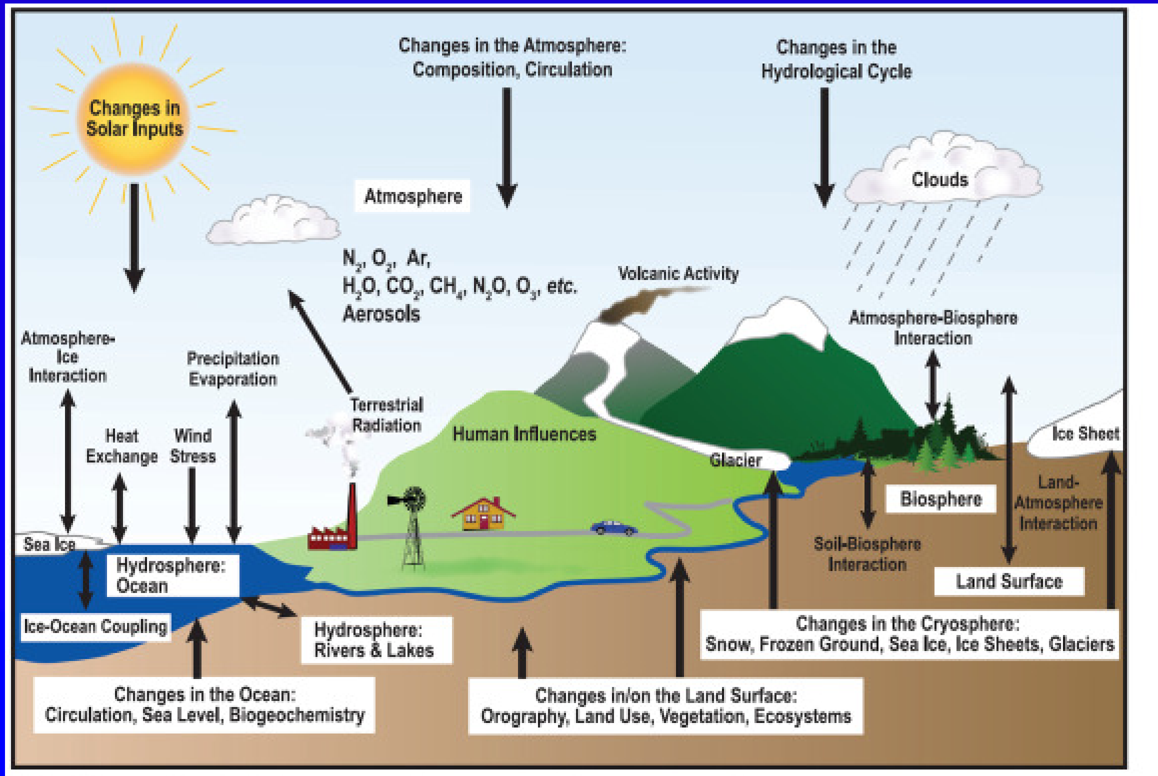
- Reservoir – Given amount of material
- Flux – Amount of material transferred from one reservoir to another
- Turnover time – Average time spent by an element in a reservoir
- Source/sink – Flux of material into/out of a reservoir
- Budget – Balance of sinks and sources
- Cycle – System of two or more connected reservoirs. (Physical cycles (Supercontinent cycle, rock cycle, energy) or Biogeochemical cycles ($H_2O$, carbon, nitrogen, phosphorus) ).



# Recent definition Climate system (IPCC 4AR)

"**<u>Climate system</u>:** The climate system is the highly complex system consisting of five major components: the *atmosphere*, the *hydrosphere*, the *cryosphere*, the land surface and the *biosphere*, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of *external forcings* such as volcanic eruptions, solar variations and *anthropogenic* forcings such as the changing composition of the atmosphere and *land use change*."




**FAQ 1.2, Figure 1.** *Schematic view of the components of the climate system, their processes and interactions.*

*www.ipcc.ch*

# Last decade of research

1. Biological processes interact with physical ones. Biology is important.
2. Interacting human effects
3. Thresholds and abrupt change
4. Earth is operating in a non-analogue state

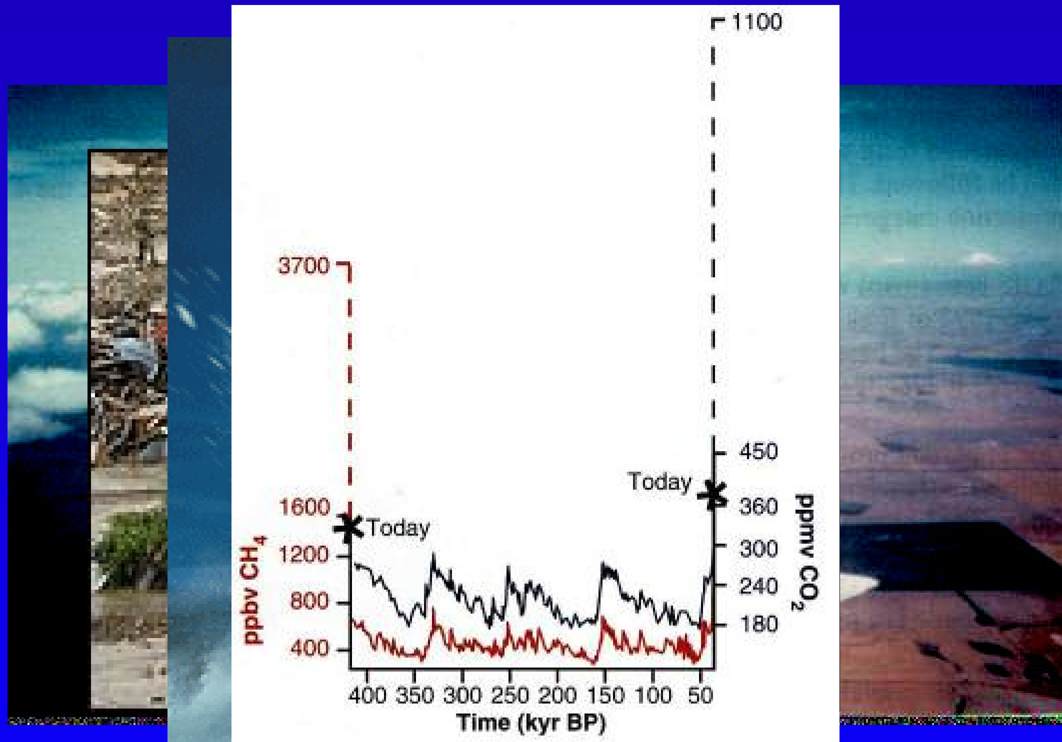
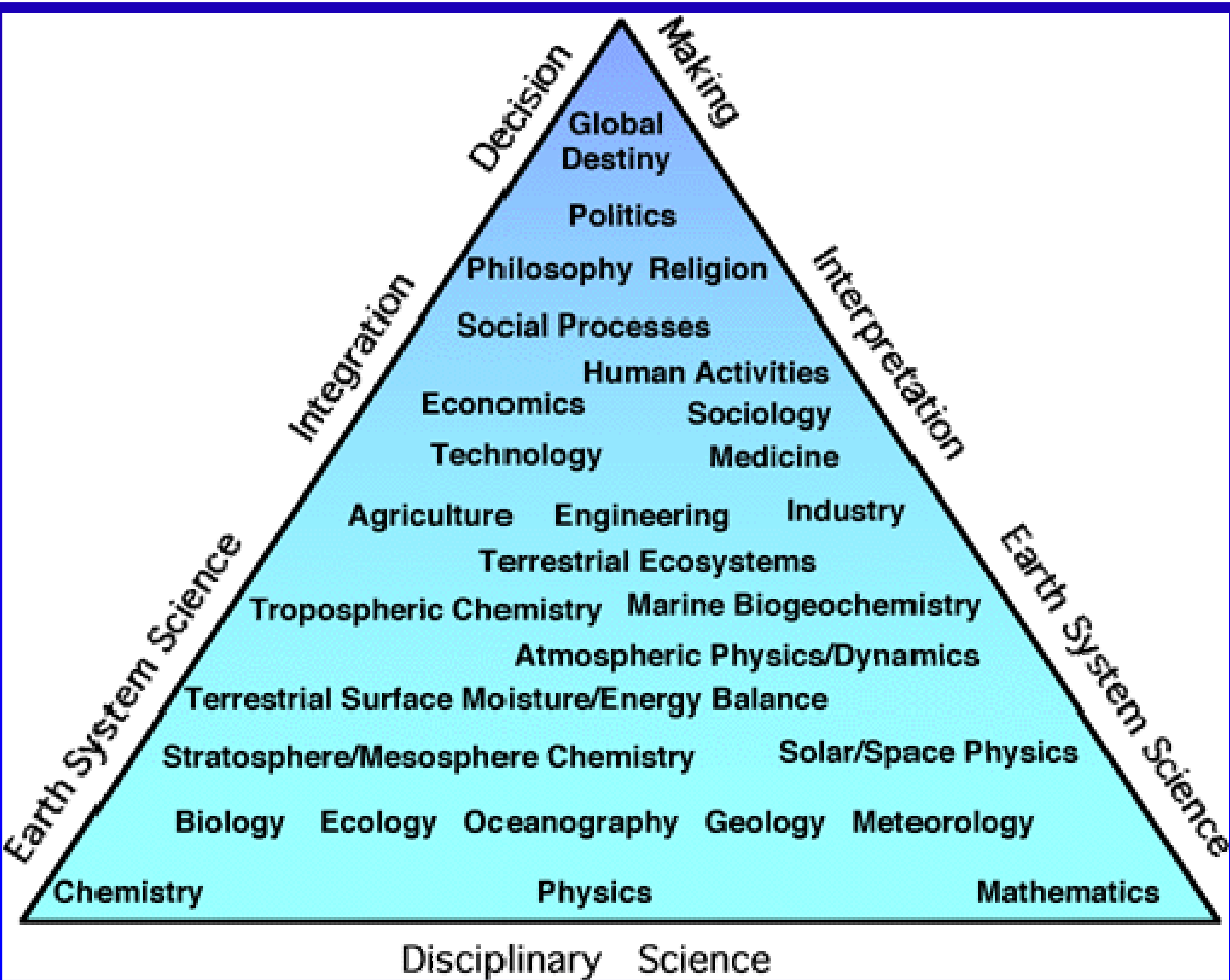



Fig. 1.1. Measurements of the atmospheric concentrations of the greenhouse gases $CO_2$ and $CH_4$ over the last four glacial-interglacial cycles from the Vostok ice core record, combined with current measurements and projections of future $CO_2$ and $CH_4$ levels based on IPCC 2000 scenarios (Petit et al. 1999; IPCC 2001). *Dashed lines* along the *y*-axis indicate the IPCC range of projections for $CO_2$ and $CH_4$ concentrations in 2100

# Evolution of Earth System Science

There is a need to understand our planet's physical and biological phenomena and how they interact, and to determine human contributions to global change

- Growing concern for environment
- Science of processes has matured
- Biological and physicochemical Earth processes and activities often are mutually interlocked or influential
- Key processes act on a regional, and often global, scale
- Technology advancing (global monitoring, modelling)
- Disciplines are interrelated


Decision
Making
Global
Destiny
Politics
Philosophy Religion
Social Processes
Integration
Interpretation
Human Activities
Economics
Sociology
Technology
Medicine
Agriculture
Engineering
Industry
Terrestrial Ecosystems
Earth System Science
Earth System Science
Tropospheric Chemistry
Marine Biogeochemistry
Atmospheric Physics/Dynamics
Terrestrial Surface Moisture/Energy Balance
Stratosphere/Mesosphere Chemistry
Solar/Space Physics
Biology
Ecology
Oceanography
Geology
Meteorology
Chemistry
Physics
Mathematics
Disciplinary Science

# Earth System Science toolkit

Challenge to manage global change demands an earth systems approach

- Still need for focused disciplinary research
- Challenge to integrate information to understand dynamics as a whole
- Complex systems analysis
- Paleo data and understanding
- Global observations
- Place based studies (hotspots)
- Integrated studies using multiple techniques
- Coupled 3D earth system models

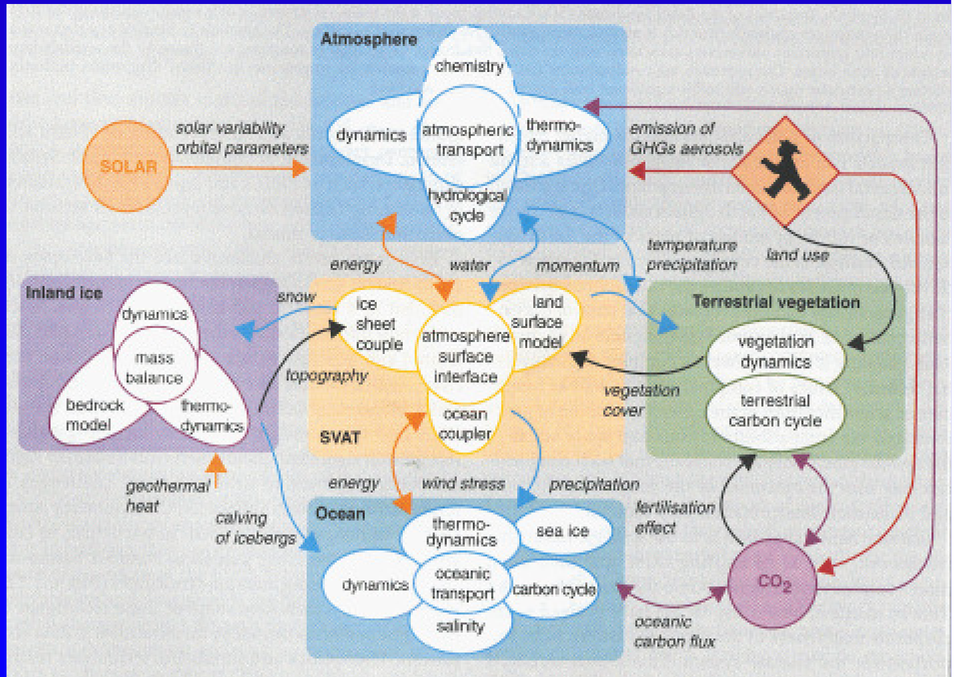
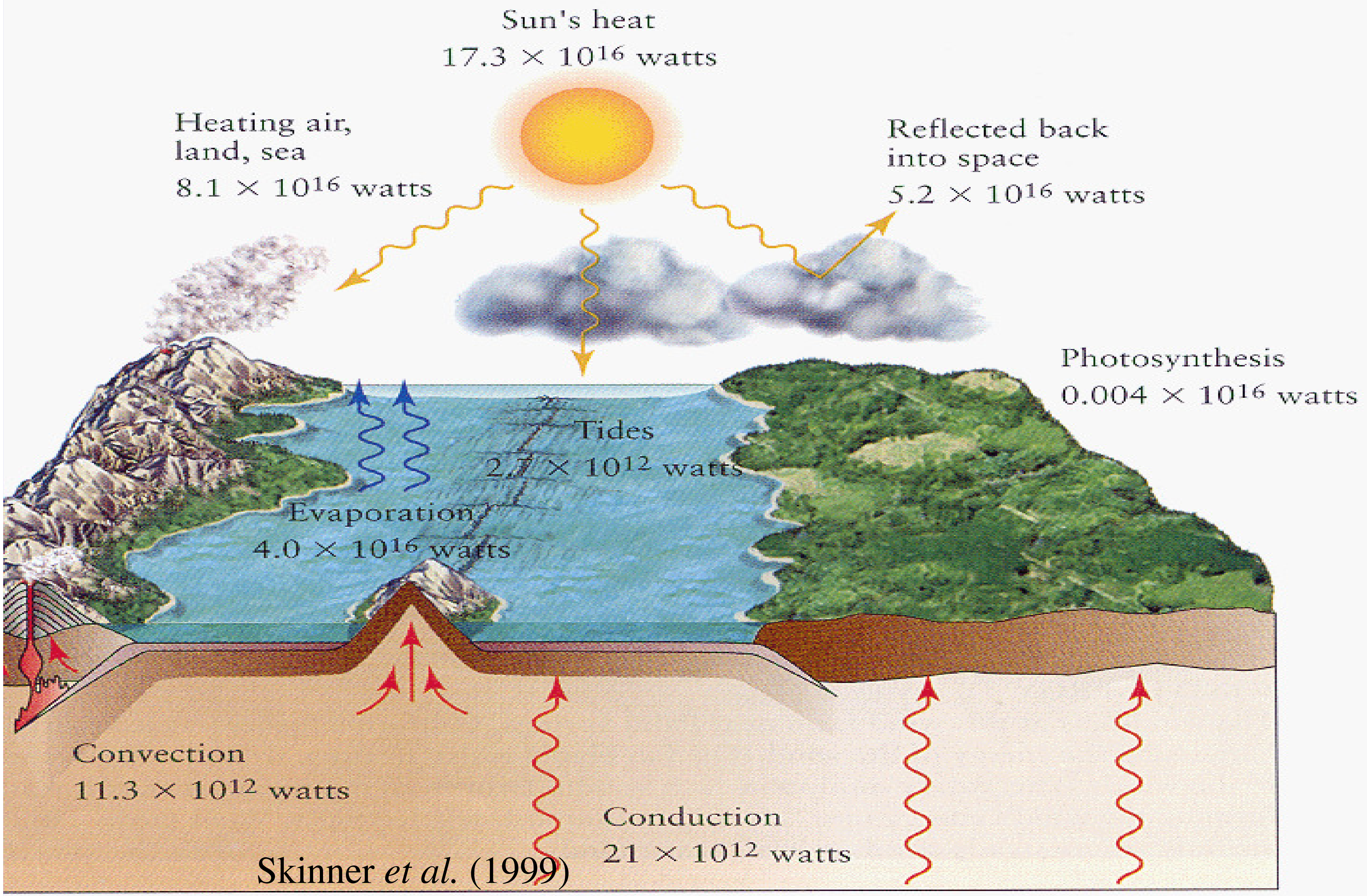


Fig. 6.20. Structural diagram of CLIMBER, an example of an Earth System Model of Intermediate Complexity

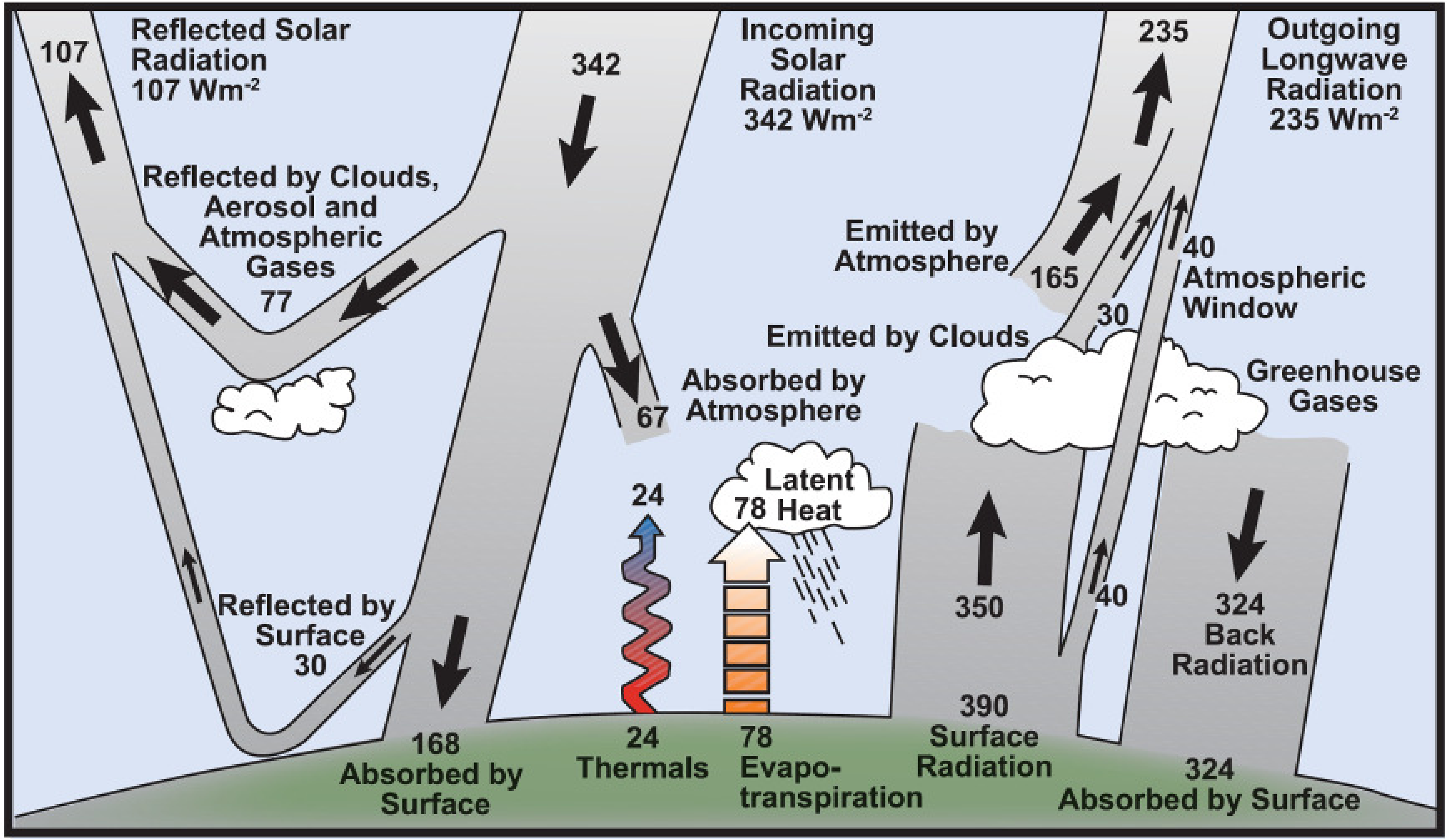
# Spheres and cycles

# The energy cycle




Skinner *et al.* (1999)

# The earths radiation balance



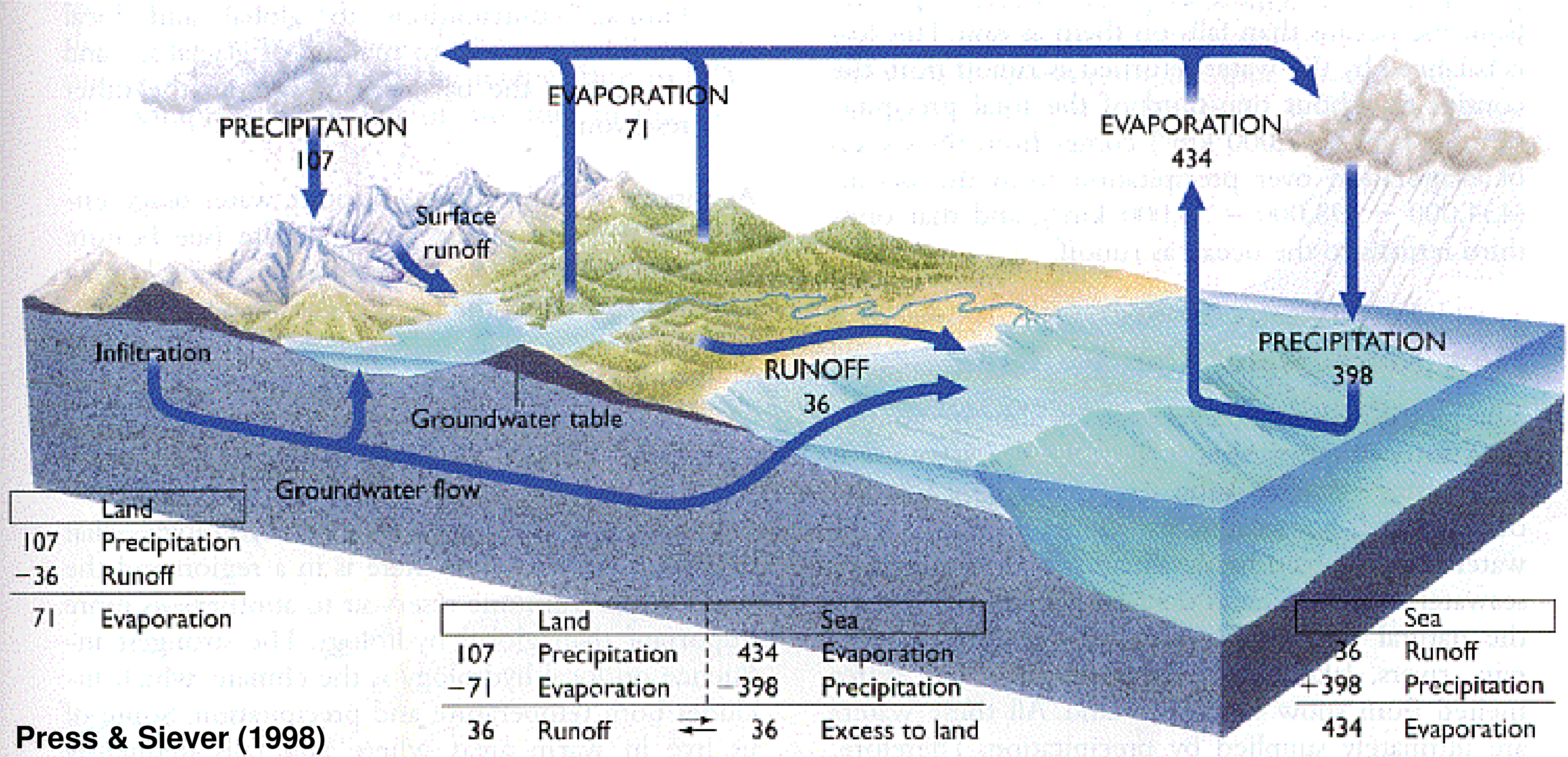

**FAQ 1.1, Figure 1.** *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

IPCC 4AR 2007

# The hydrosphere and the water cycle

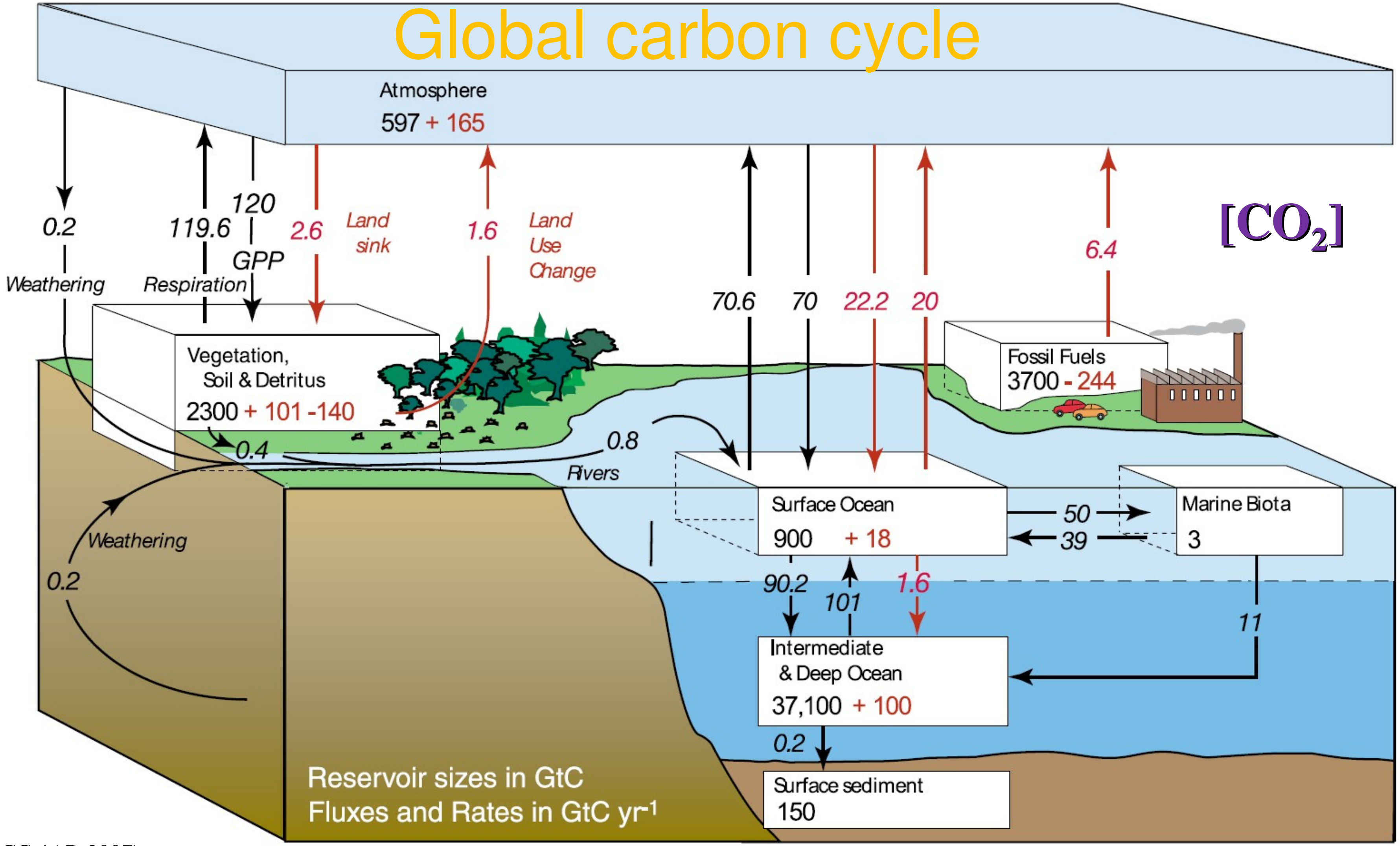
- There are 4 major pathways of cycling in the global water cycle: *precipitation, evaporation, vapour advection*, and *runoff.*
- Note fluxes in the system

*The Global Water Cycle - Pathways and Fluxes. (Values in $10^3$ $km^3/yr$).*




Press & Siever (1998)

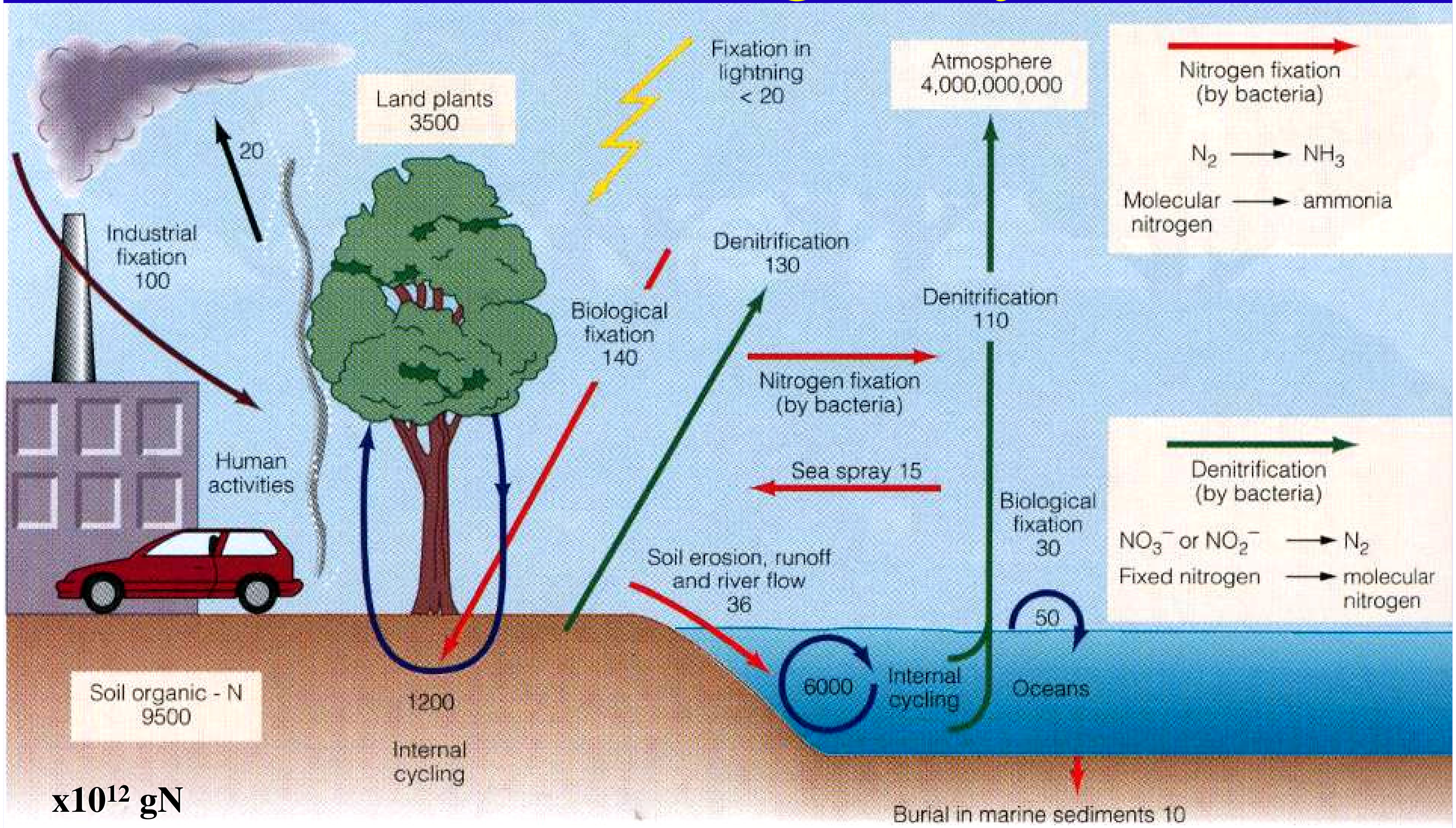
# Global carbon cycle




(IPCC 4AR 2007)

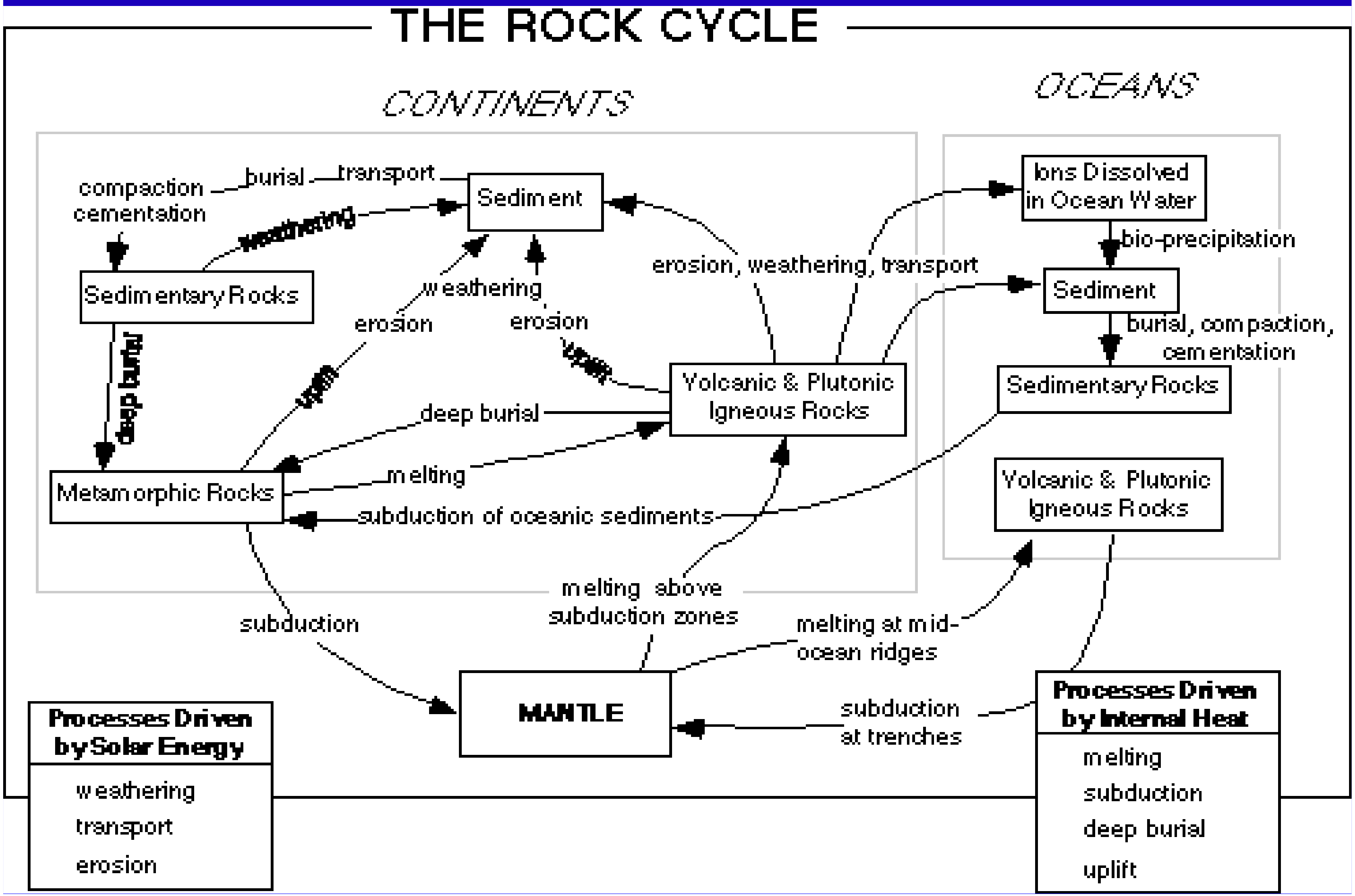
**Figure 7.3.** *The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr$^{-1}$: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004a). The net terrestrial loss of –39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of –140 GtC from the 'vegetation, soil and detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of –140 to –80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are from Column 5 'AR4' in Table 7.1. Gross fluxes generally have uncertainties of more than ±20% but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr$^{-1}$ for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994.*

# Global Nitrogen cycle

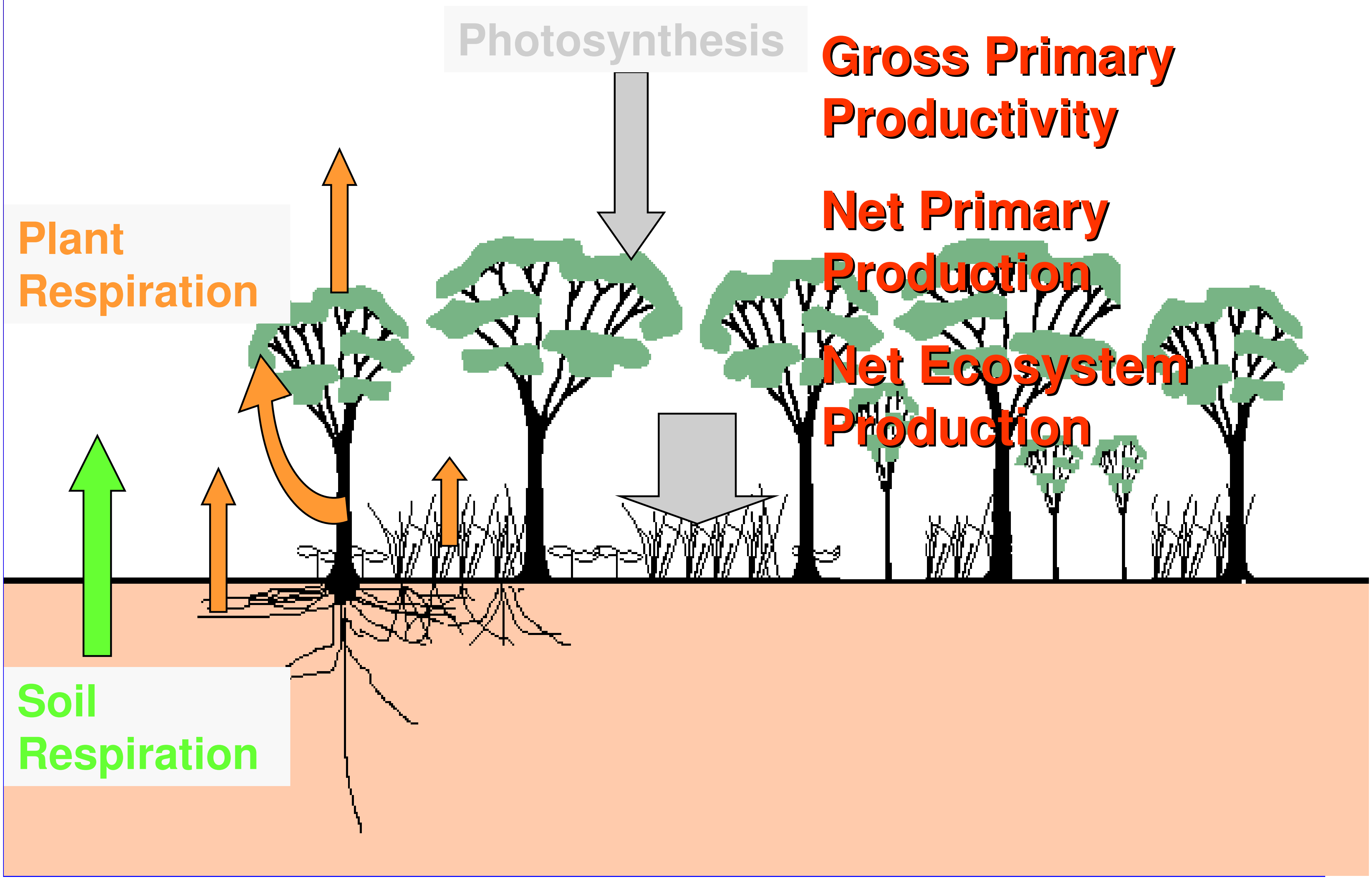



- Note industrial fixation equivalent to total biological fixation
- Most cycling is internal within the reservoir

# The geosphere



# The biosphere



# Interactions, Feedbacks and coupling

# Dynamic system interactions

- Feedback loops - **positive feedback** the system responds in the same direction as the output
  - – Small input change results in a large output change
  - – e.g. respiration loop – changes amplified and system away from equilibrium
- **Negative feedbacks** the system responds in the opposite direction
  - – Change results in moving back towards equilibrium
  - – Maintain equilibrium
- Stability vs instability

Skinner *et al.* (1999)

# Positive/negative cloud feedbacks

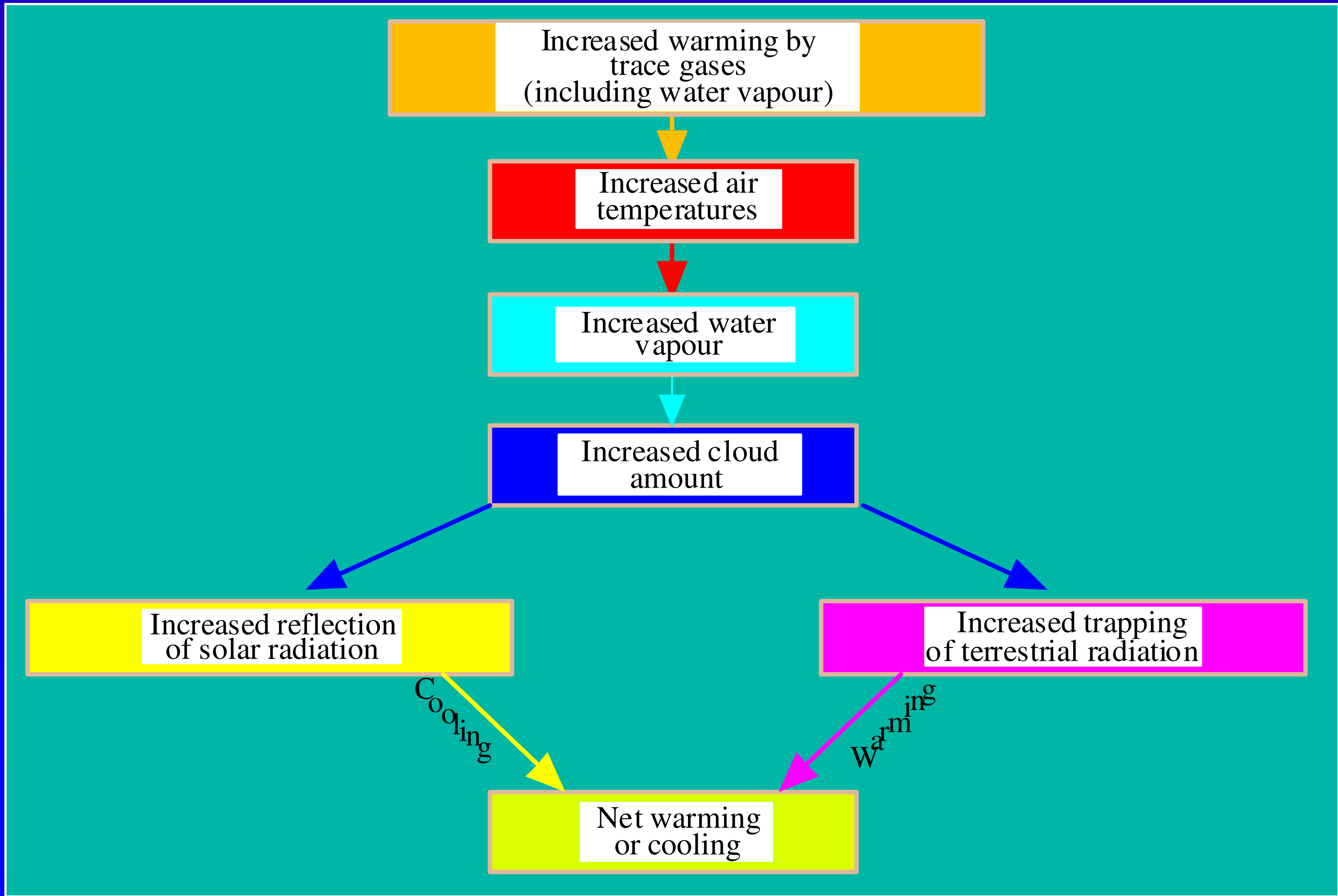
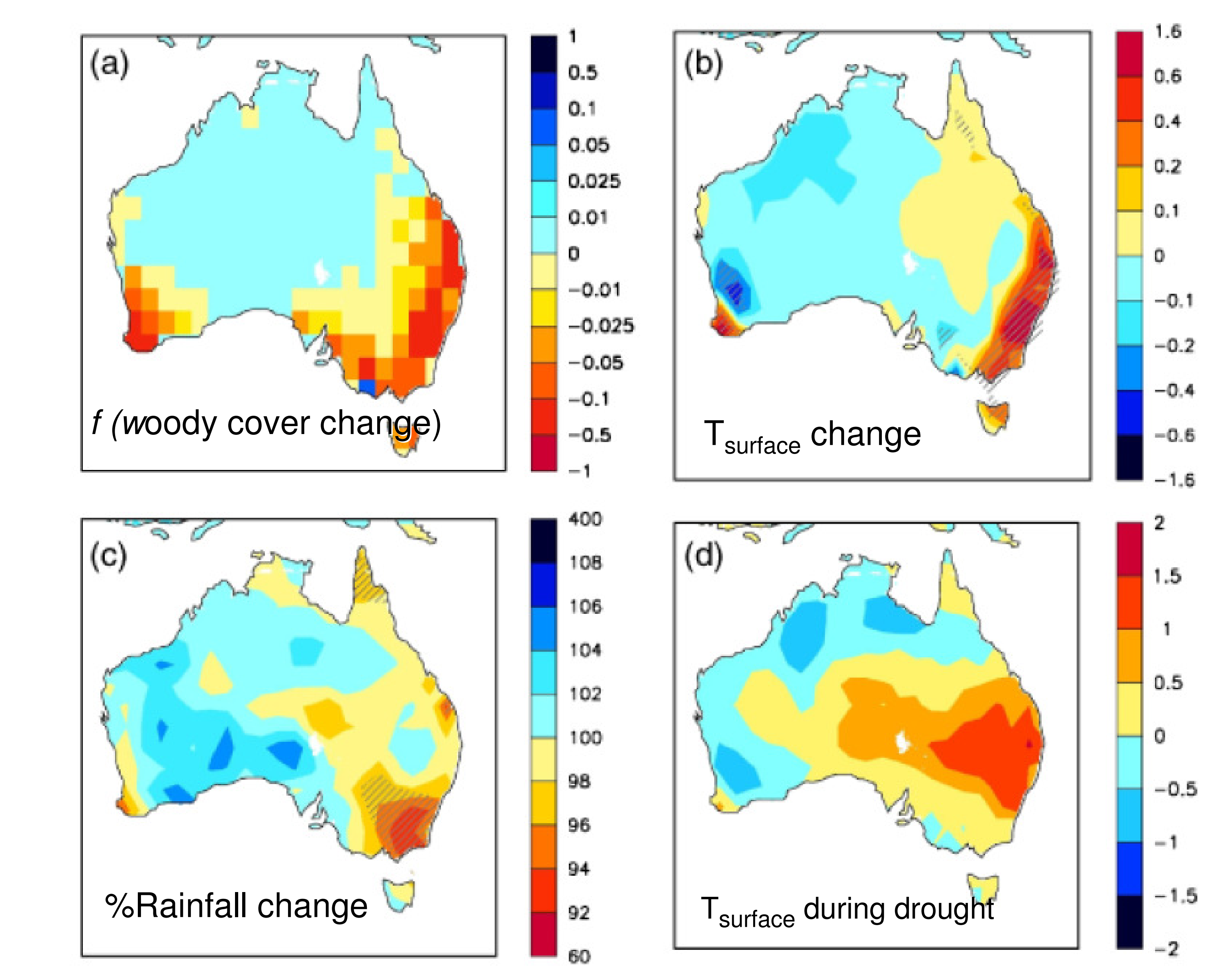



Figure 12.7 Role of cloud in both warming and cooling the atmosphere.

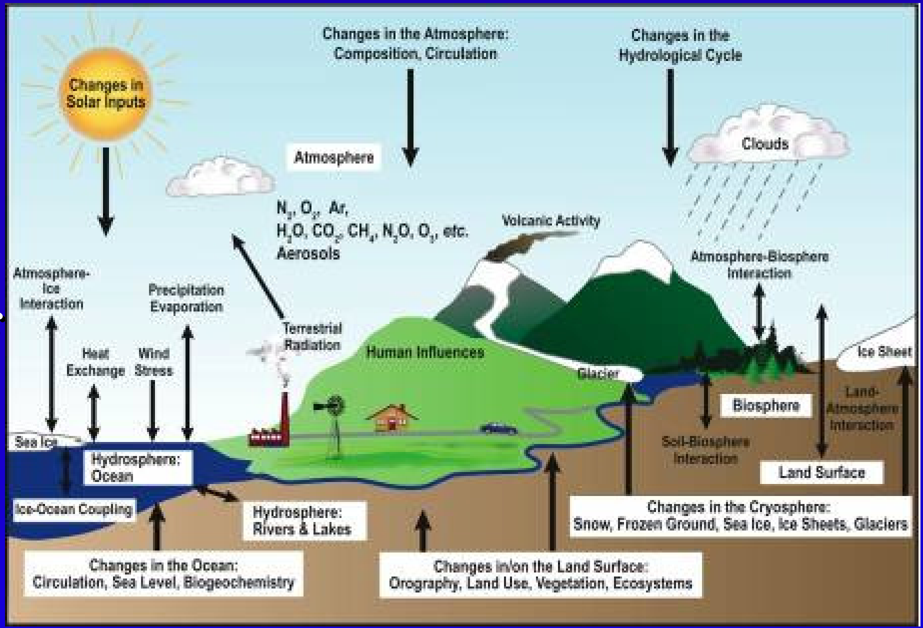
# LUCC and climate feedbacks

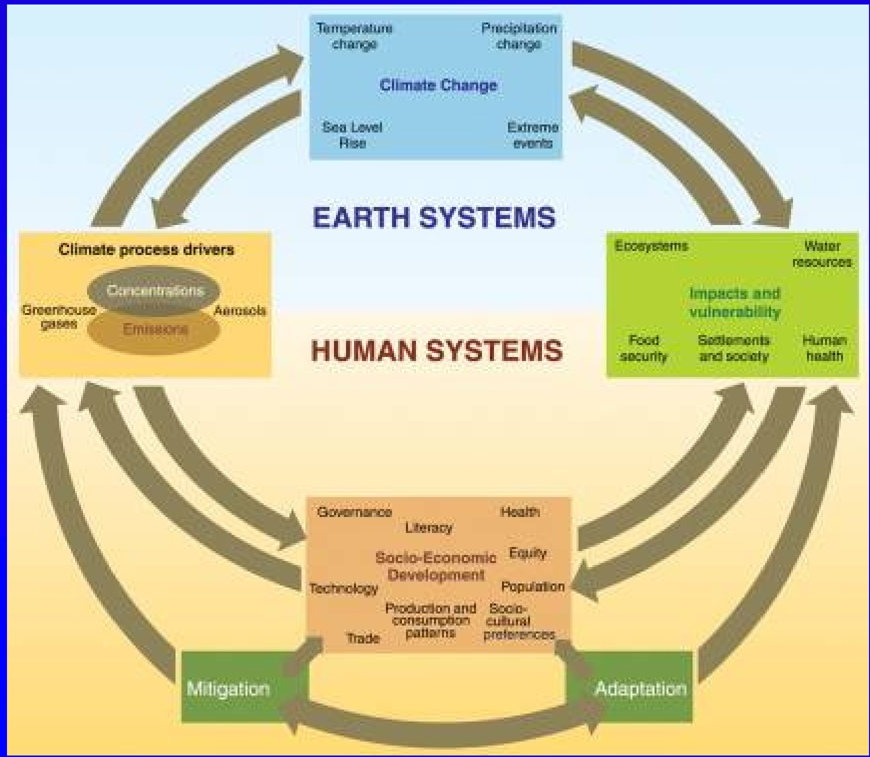


# Modelling tools

# Earth System models

- A numerical representation of the earth system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties.
- **Includes human interactions to be true ES model**



# Numerical models

- Models can be represented diagrammatically (Forrester)
- Variables that represent states of parts of the system (reservoirs)
- Variables that drive the system
- Sources and sinks
- Flows from one variable to another via rates (fluxes)

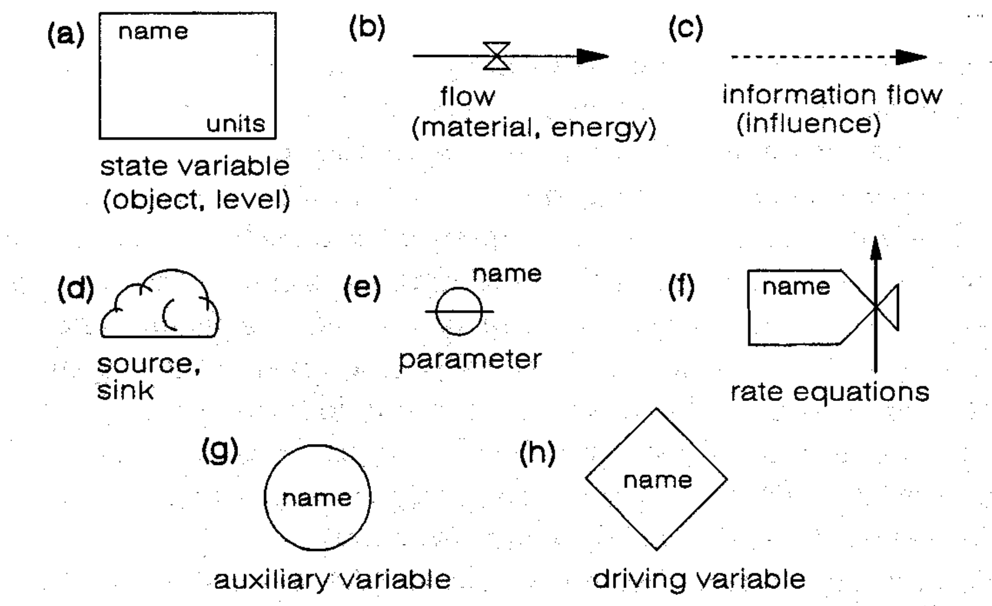



**Figure 3.2:** The basic components of a Forrester diagram.

Haefner (1996)

# Example - Terrestrial carbon cycle

- Land, ATM and soil reservoirs
- Fluxes between reservoirs are prescribed (pre-industrial)
- But altered by other parameters (i.e. fertilisation effect or soil respiration and temperature).

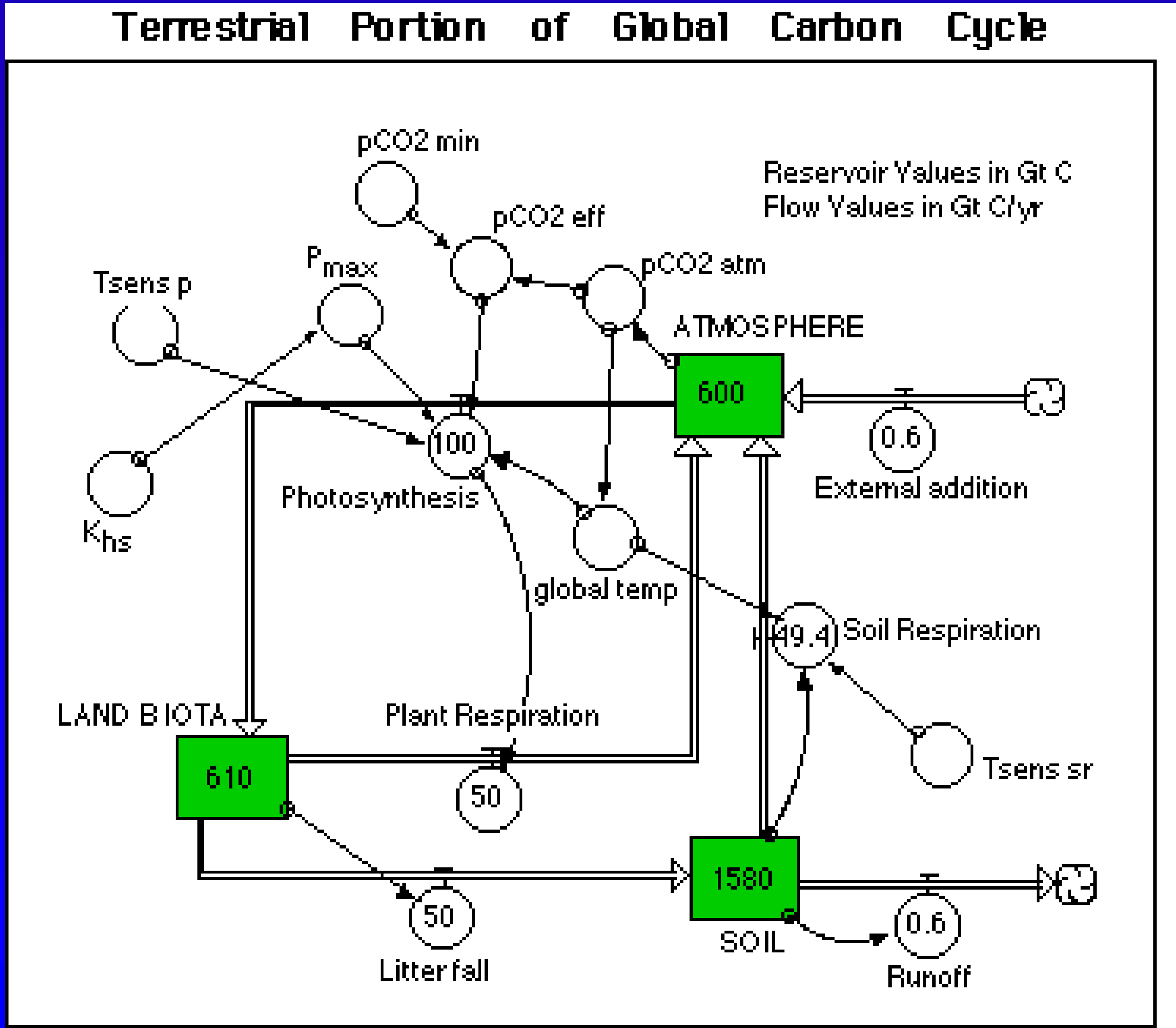
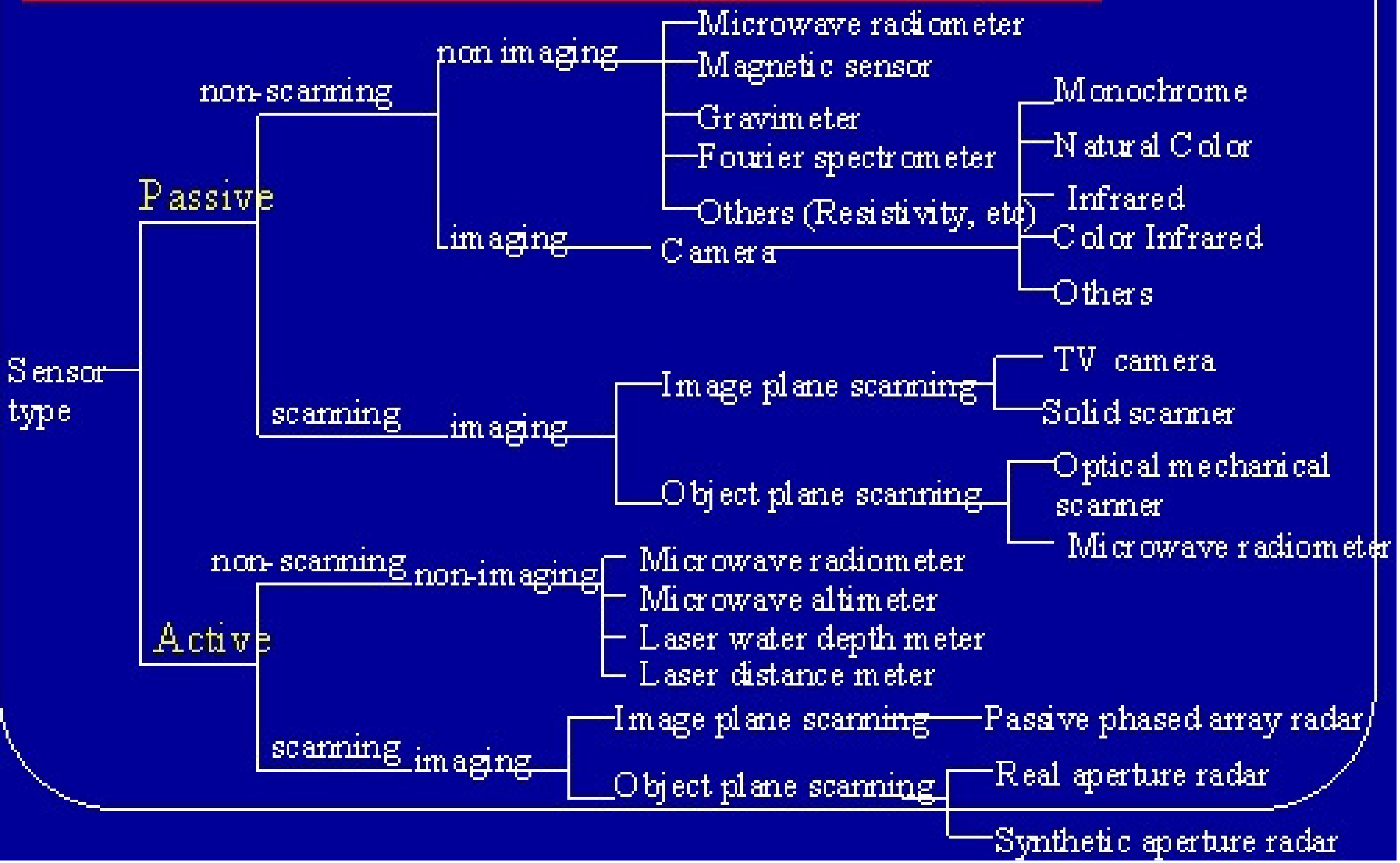



Figure 7.11. Simple model of the terrestrial portion of the carbon cycle, with reservoirs set to reflect the pre-industrial condition of the global carbon cycle. The initial values of the flows, in Gt C/yr are shown; these are not constants — they will vary as other components of the system change.

# Remote sensing tools

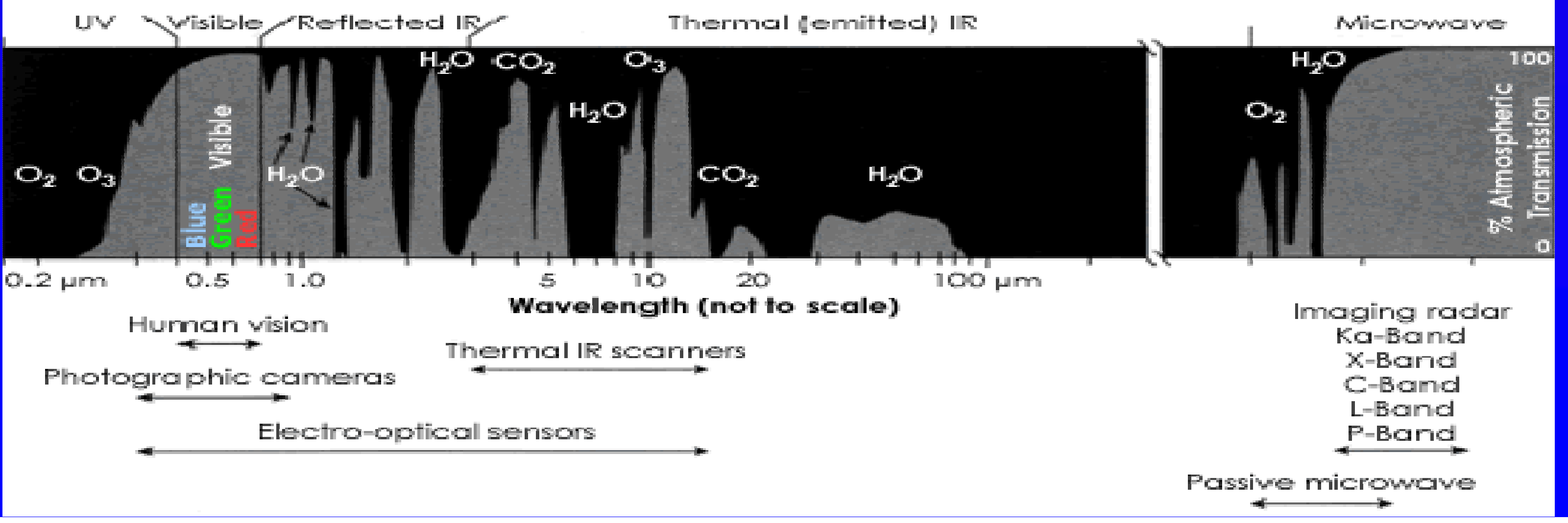
# *There are many remote sensors*



# "Science of obtaining information about an object/area through data analysis whilst not in contact with it."

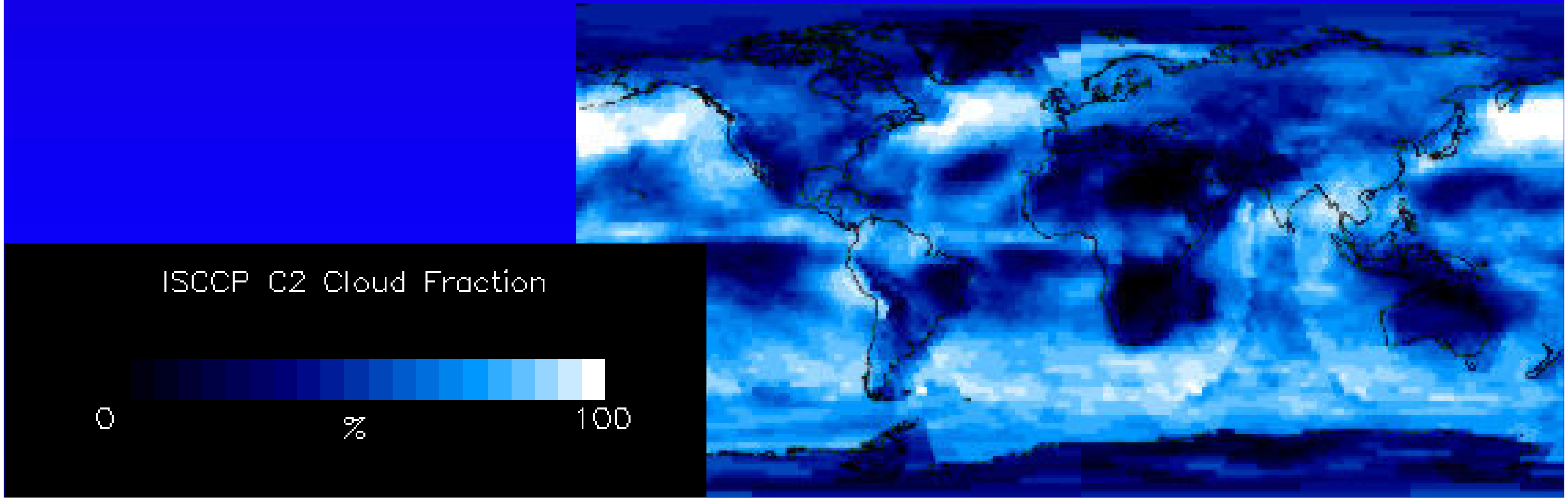
Important for:

- Monitoring over space and time – change detection
  - Land use / soils / geological / agriculture / forestry / water resources/ urban / environmental applications
- Assessment of human impact
- Data used to understand spatial patterns and processes within spheres and cycles
- Quantify aspects of the earth system (i.e. carbon uptake)
- Data input to models – climate/ecological/SVAT



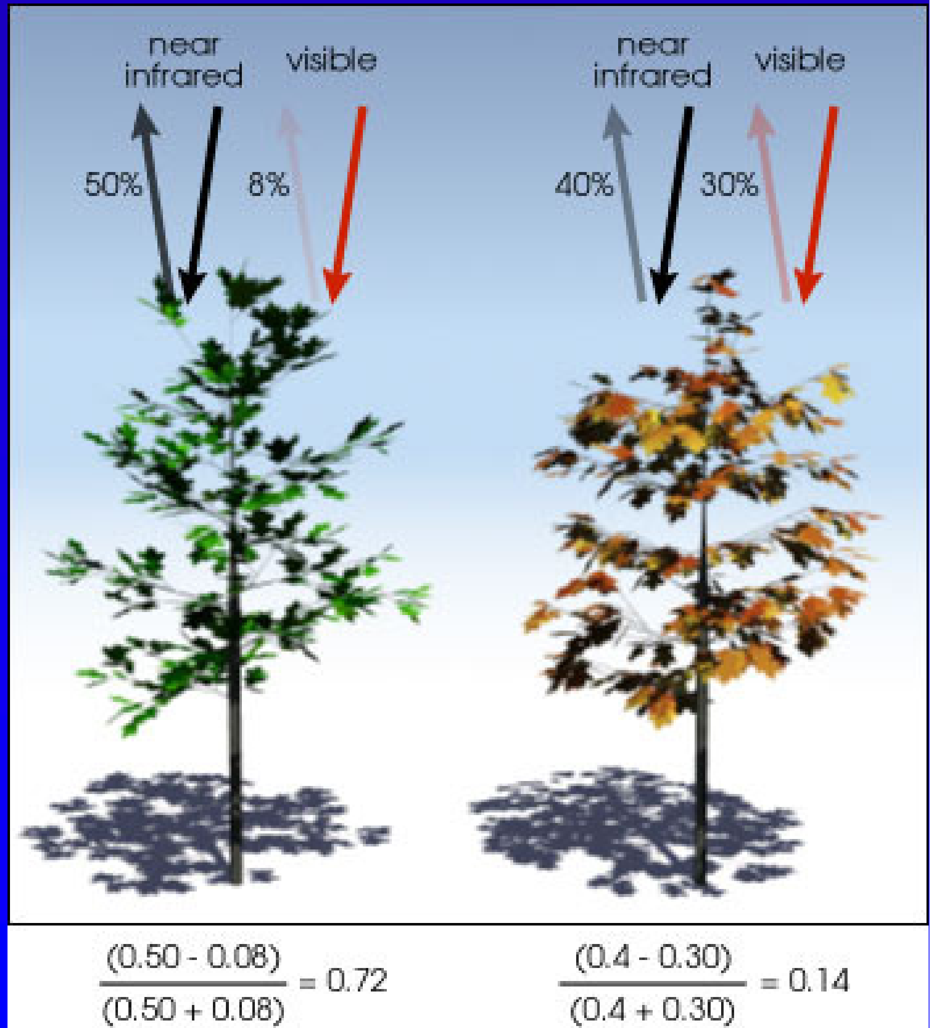
# Hydrosphere – Example clouds

- Satellites can measure cloud fraction over the entire atmosphere and for all types of clouds.
- Since most clouds reflect incoming sunlight very well and trap heat escaping from the Earth's surface, cloud fraction is an important parameter in studies of our planet's radiant energy budget.



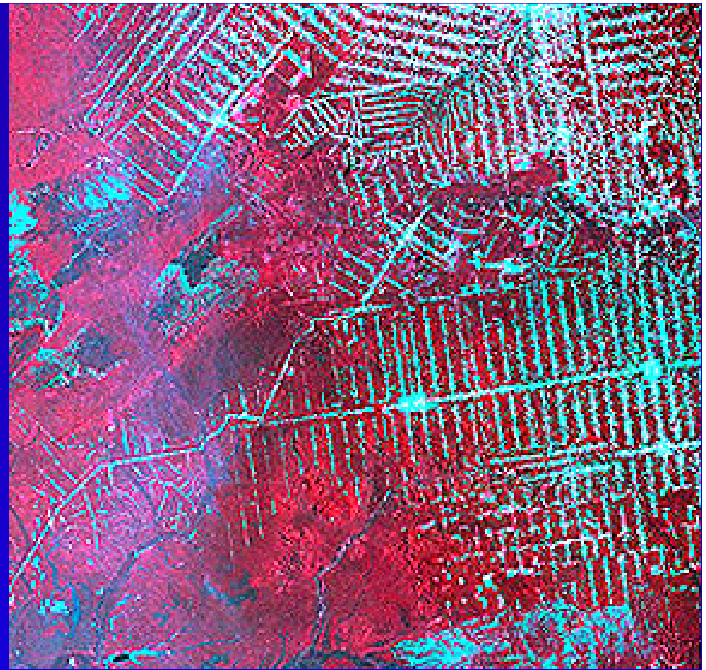
# Biosphere - NDVI

- Normalised Difference Vegetation Index is calculated from the visible and near-infrared light reflected by vegetation.
- Healthy vegetation (left) absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light.
- Unhealthy or sparse vegetation (right) reflects more visible light and less near-infrared light.



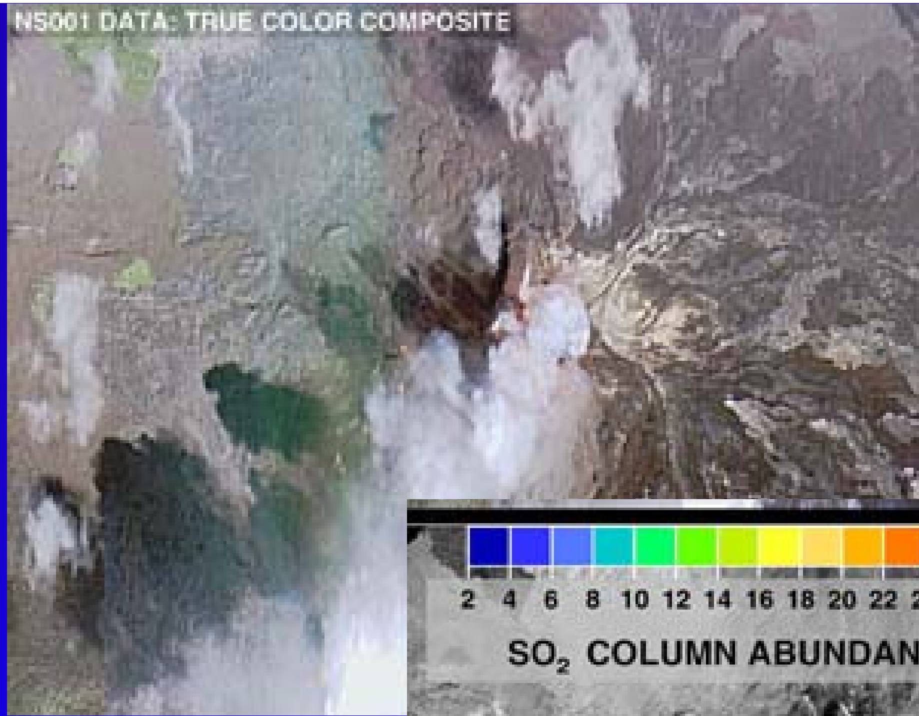
# Biosphere – Land use change Deforestation

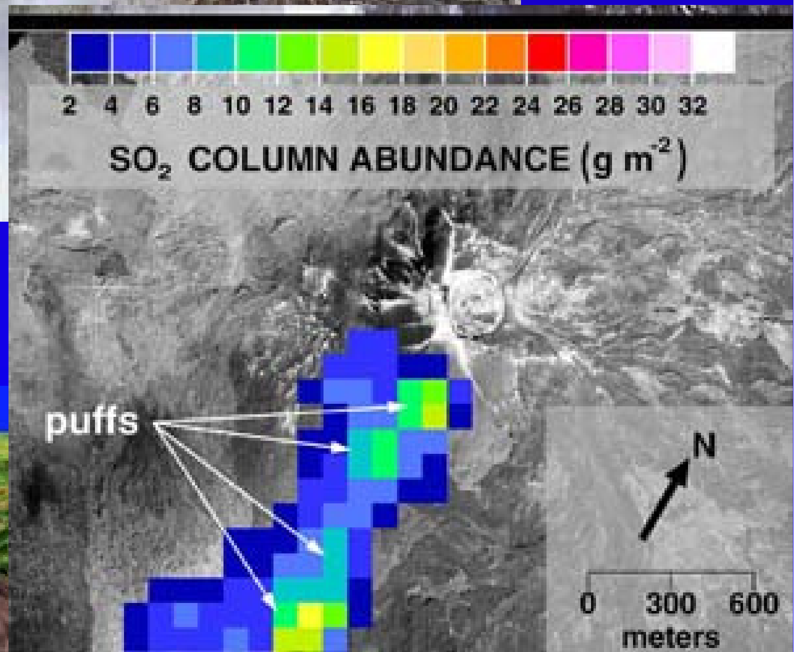
- Conversion of rain forests to cultivated land in Amazon.
- Deforestation outward from a common center, as shown in the astronaut photo of an area in eastern Bolivia

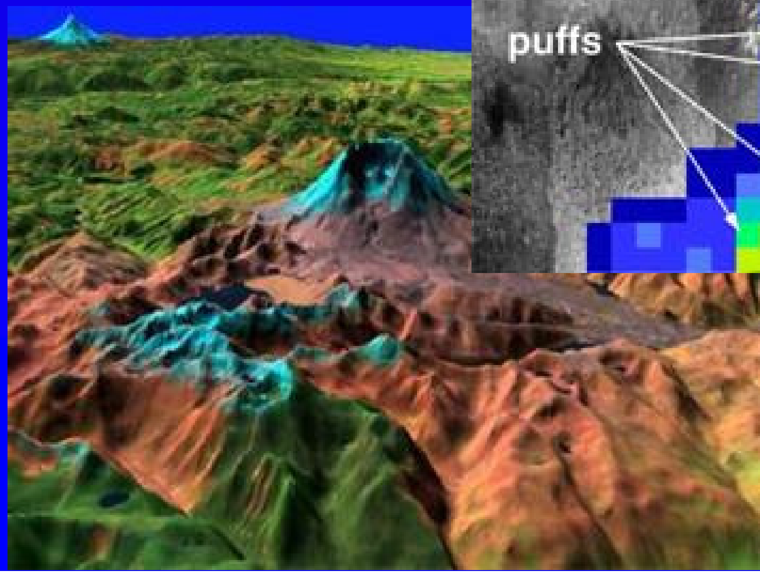


# Geosphere – example Volcanoes

- Monitor volcanic eruptions and their impact. Pu’u O’o crater part of Kilauea volcano on Hawaii.
- Vegetation monitoring in the ash deposits
- DEMs provide an additional tool. Mt. St. Helens, in Washington State

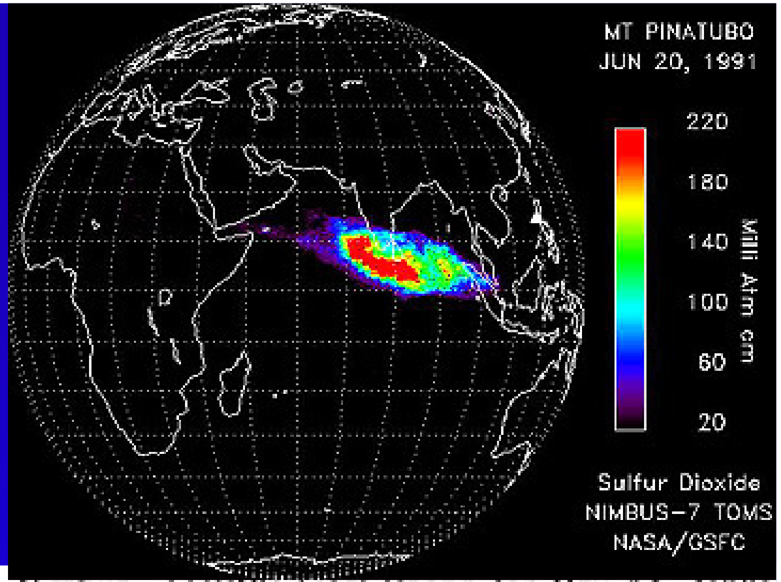


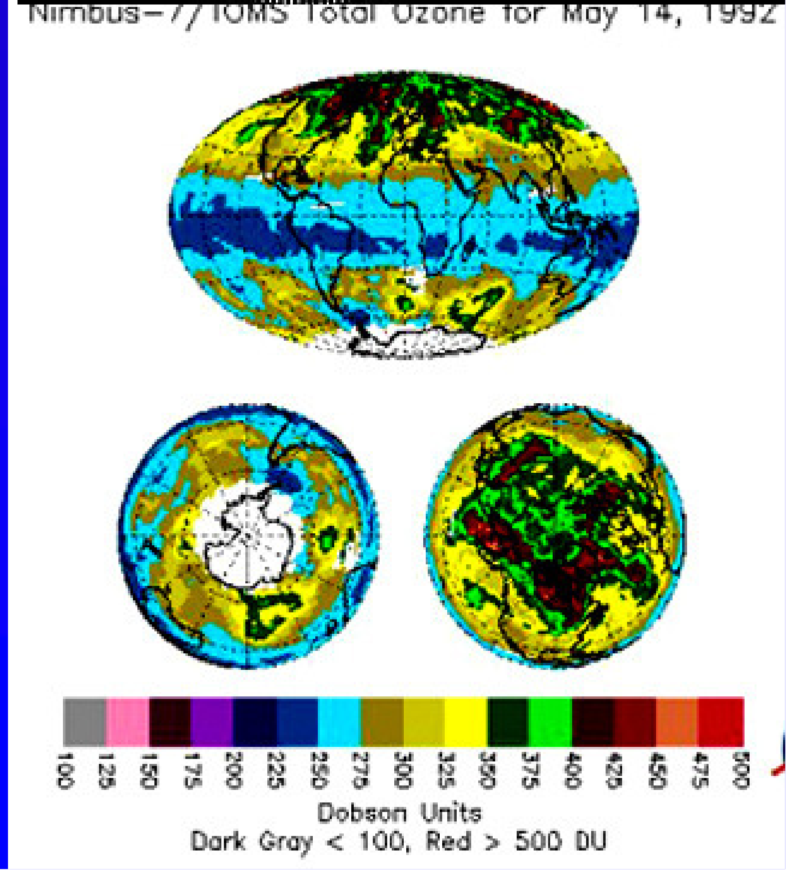



# Atmosphere – example Chemistry

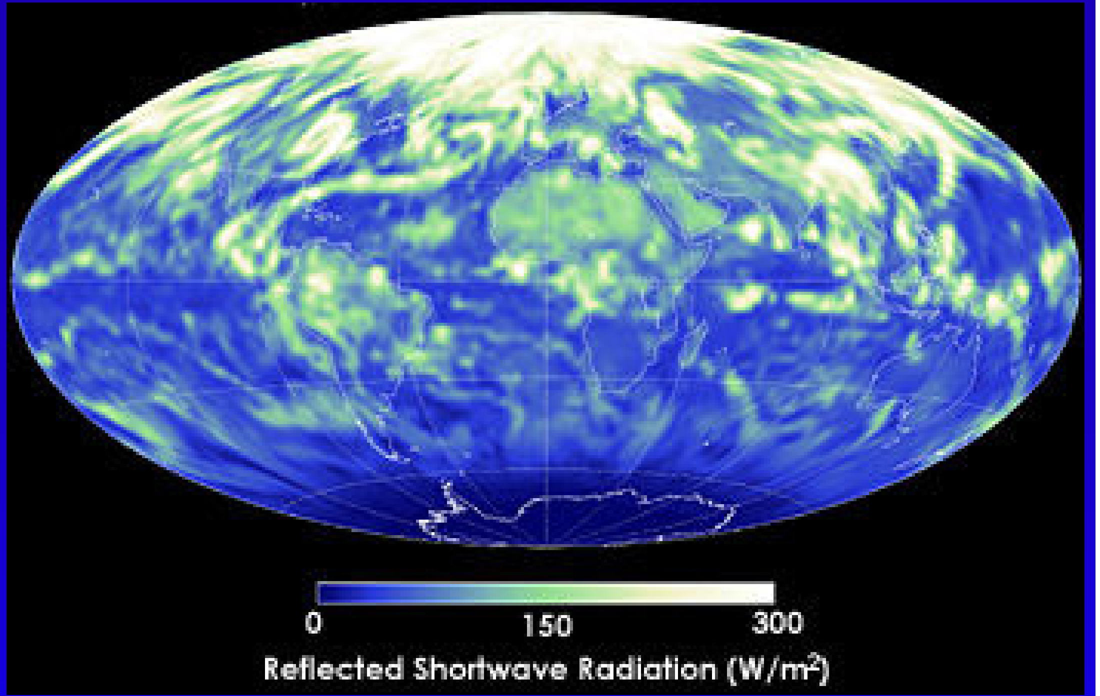
- Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7, measures UV reflectivities
- It calculates ozone quantities from the ratio of the returns in the 0.312/0.331 μm wavelengths.
- TOMS monitors $SO_2$ in the atmosphere. After major volcanic eruptions extensive clouds of $SO_2$ -enriched ash and gases injected into the upper atmosphere.

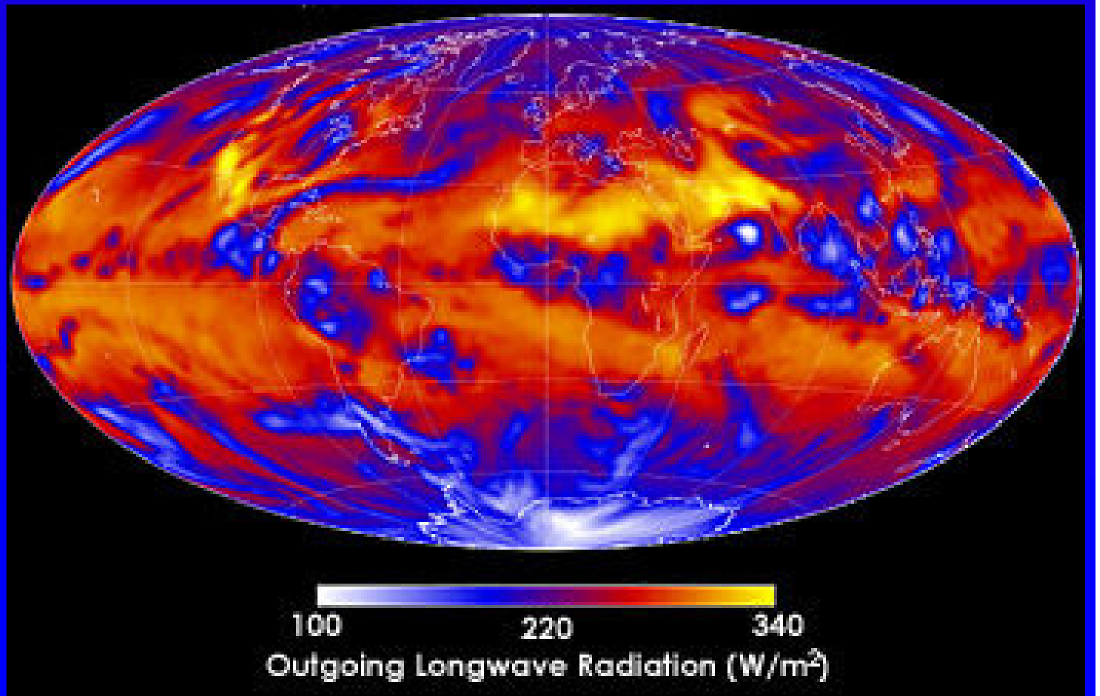


# Energy cycle – Example radiative Energy

- Clouds and the Earth's Radiant Energy System (CERES) on Terra monitor the Earth's energy balance, giving new insights into climate change.
- Earth's energy balance represents the sum total of all the interactions of radiant energy
- Useful for clouds, aerosol particles, surface reflectivity and their impact.

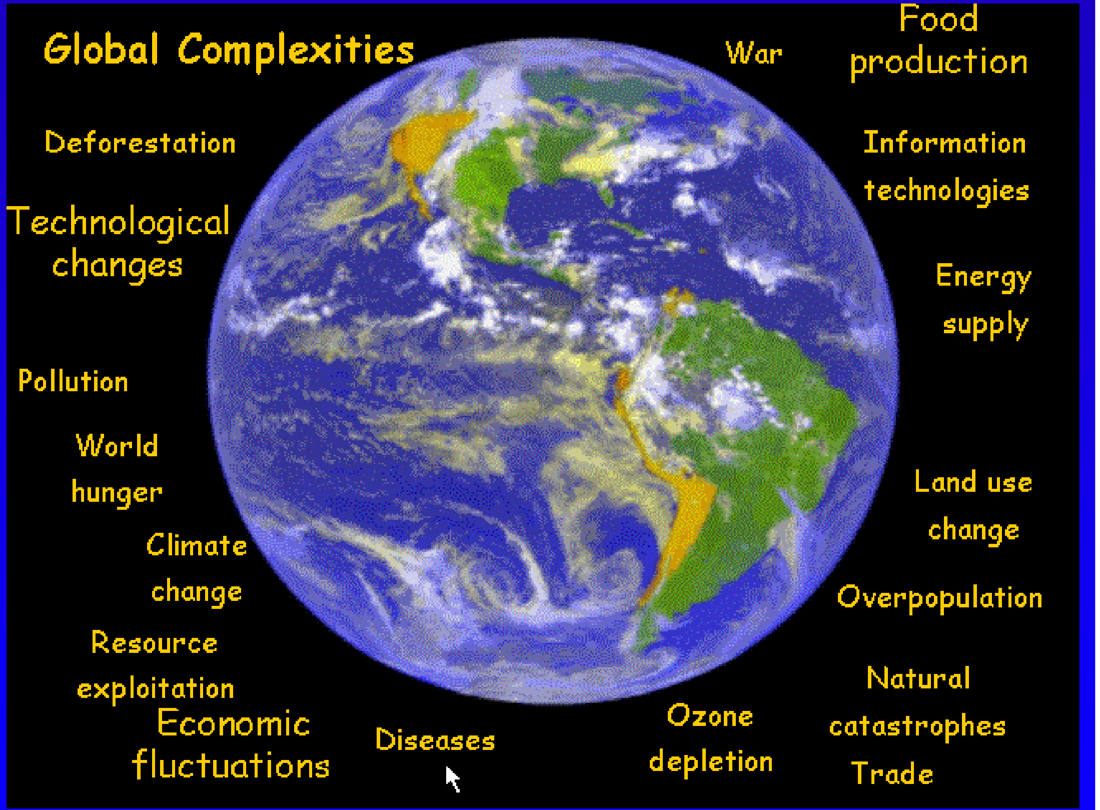


# Global change

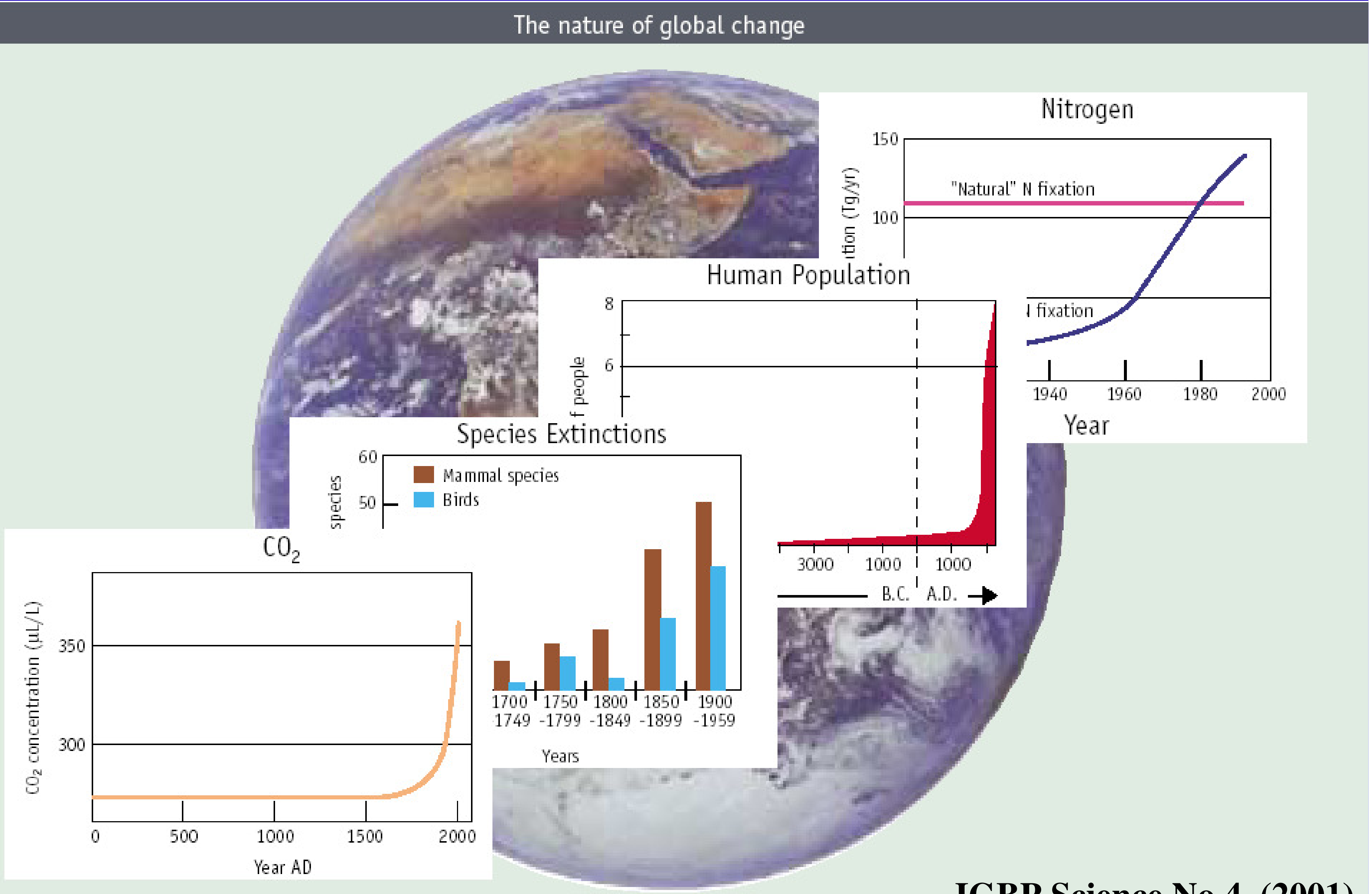
# Global change

- Planetary scale changes occurring rapidly driven by human impacts
- Changes patterns of forcings and feedbacks
- Not the same as climate change – much more inclusive. Many linked issues.
- Change can be unidirectional or bidirectional .



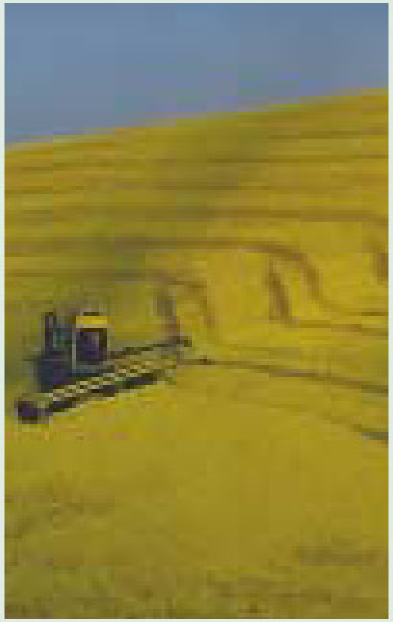
# Global change

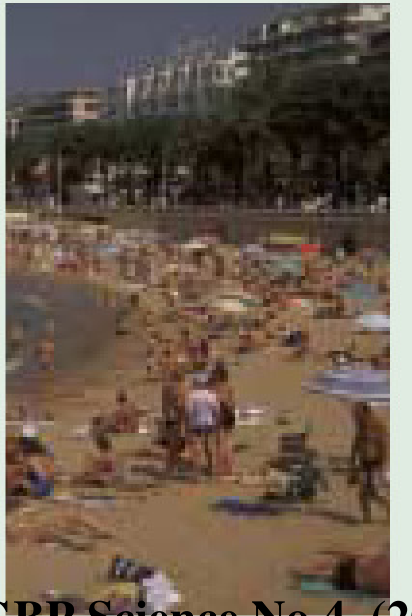
The nature of global change



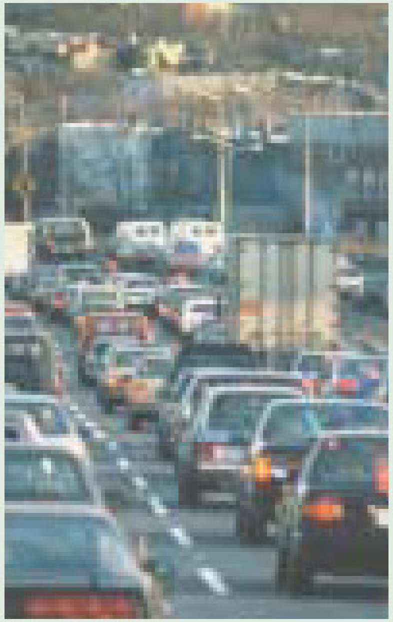

IGBP Science No 4. (2001)

Table 1: Proximate and underlying drivers of human transformation of Earth



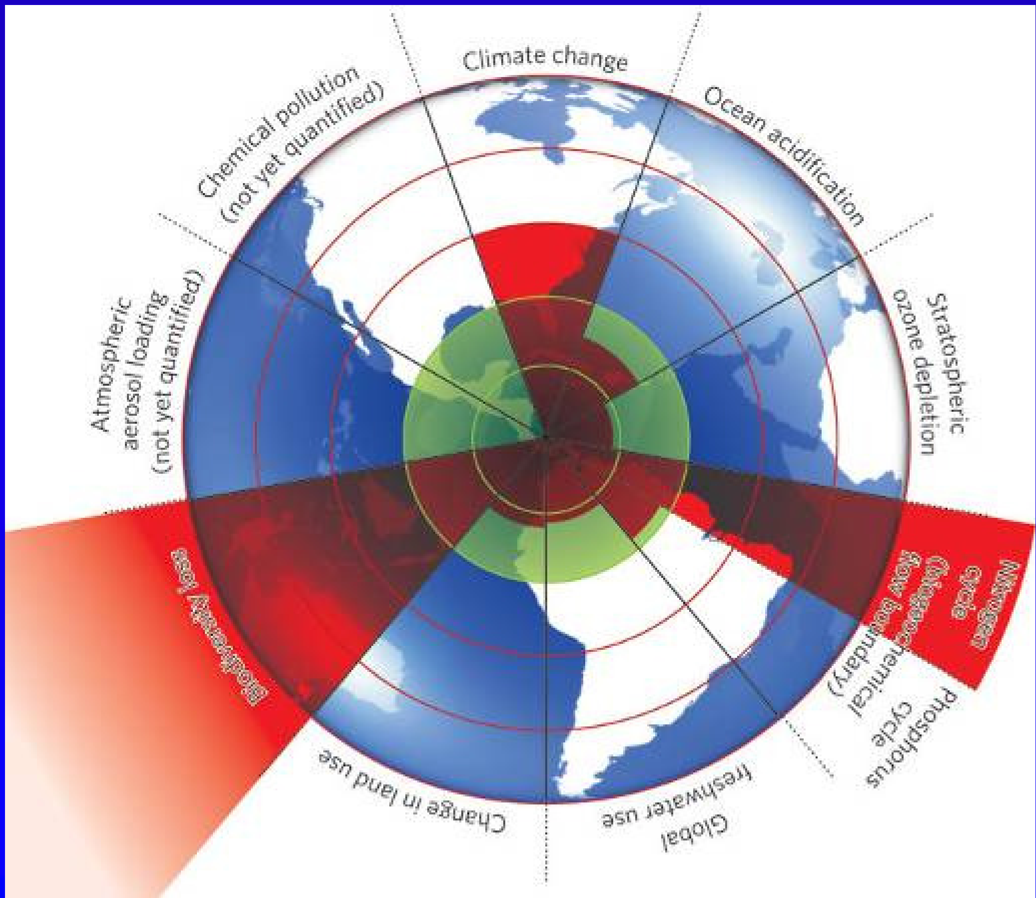


| Compartment/ Cycle Transformed | Proximate Driver | Underlying Driver |
|---|---|---|
| Land | Clearing (cutting forest, + burning), agricultural practices (e.g. tillage, fertilisation, irrigation, pest control, highyielding crops etc.), abandonment | Demand for food (+dietary preferences), recreation, other ecosystem goods and services |
| Atmosphere | Fossil fuel burning, land-use change (e.g., agricultural practices), biomass burning, industrial technology | Demand for mobility, consumer products, food |
| Water | Dams, impoundments, reticulation systems, waste disposal techniques, management practices | Demand for water (direct human use), food (irrigation), consumer products (water usage in industrial processes) |
| Coastal/Marine | Land-cover conversion, groundwater removal, fishing intensity & technique, coastal building patterns, sewage treatment technology, urbanisation | Demand for recreation, lifestyle, food, employment |
| Biodiversity | Clearing of forest/natural ecosystems; introduction of alien species | Demand for food, safety, comfort, landscape amenity |



IGBP Science No 4. (2001)

- Crossing certain biophysical thresholds could be disastrous
- Three of nine interlinked planetary boundaries already overstepped
- Framework based on 'planetary boundaries' has been proposed




The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.

A safe operating space for humanity Johan Rockström, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, III, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, Björn Nykvist, Cynthia A. de Wit, Terry Hughes, Sander van der Leeuw, Henning Rodhe, Sverker Sörlin, Peter K. Snyder, Robert Costanza, Uno Svedin, Malin Falkenmark, Louise Karlberg, Robert W. Corell, Victoria J. Fabry, James Hansen, Brian Walker, Diana Liverman, Katherine Richardson, Paul Crutzen & Jonathan A. Foley Nature 461, 472-475(24 September 2009) doi:10.1038/461472a

## PLANETARY BOUNDARIES

| Earth-system process | Parameters | Proposed boundary | Current status | Pre-industrial value |
|---|---|---|---|---|
| Climate change | (i) Atmospheric carbon dioxide concentration (parts per million by volume) | 350 | 387 | 280 |
| | (ii) Change in radiative forcing (watts per metre squared) | 1 | 1.5 | 0 |
| Rate of biodiversity loss | Extinction rate (number of species per million species per year) | 10 | >100 | 0.1–1 |
| Nitrogen cycle (part of a boundary with the phosphorus cycle) | Amount of $N_2$ removed from the atmosphere for human use (millions of tonnes per year) | 35 | 121 | 0 |
| Phosphorus cycle (part of a boundary with the nitrogen cycle) | Quantity of P flowing into the oceans (millions of tonnes per year) | 11 | 8.5–9.5 | ~1 |
| Stratospheric ozone depletion | Concentration of ozone (Dobson unit) | 276 | 283 | 290 |
| Ocean acidification | Global mean saturation state of aragonite in surface sea water | 2.75 | 2.90 | 3.44 |
| Global freshwater use | Consumption of freshwater by humans ($km^3$ per year) | 4,000 | 2,600 | 415 |
| Change in land use | Percentage of global land cover converted to cropland | 15 | 11.7 | Low |
| Atmospheric aerosol loading | Overall particulate concentration in the atmosphere, on a regional basis | | To be determined | |
| Chemical pollution | For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof | | To be determined | |

Boundaries for processes in red have been crossed. Data sources: ref. 10 and supplementary information

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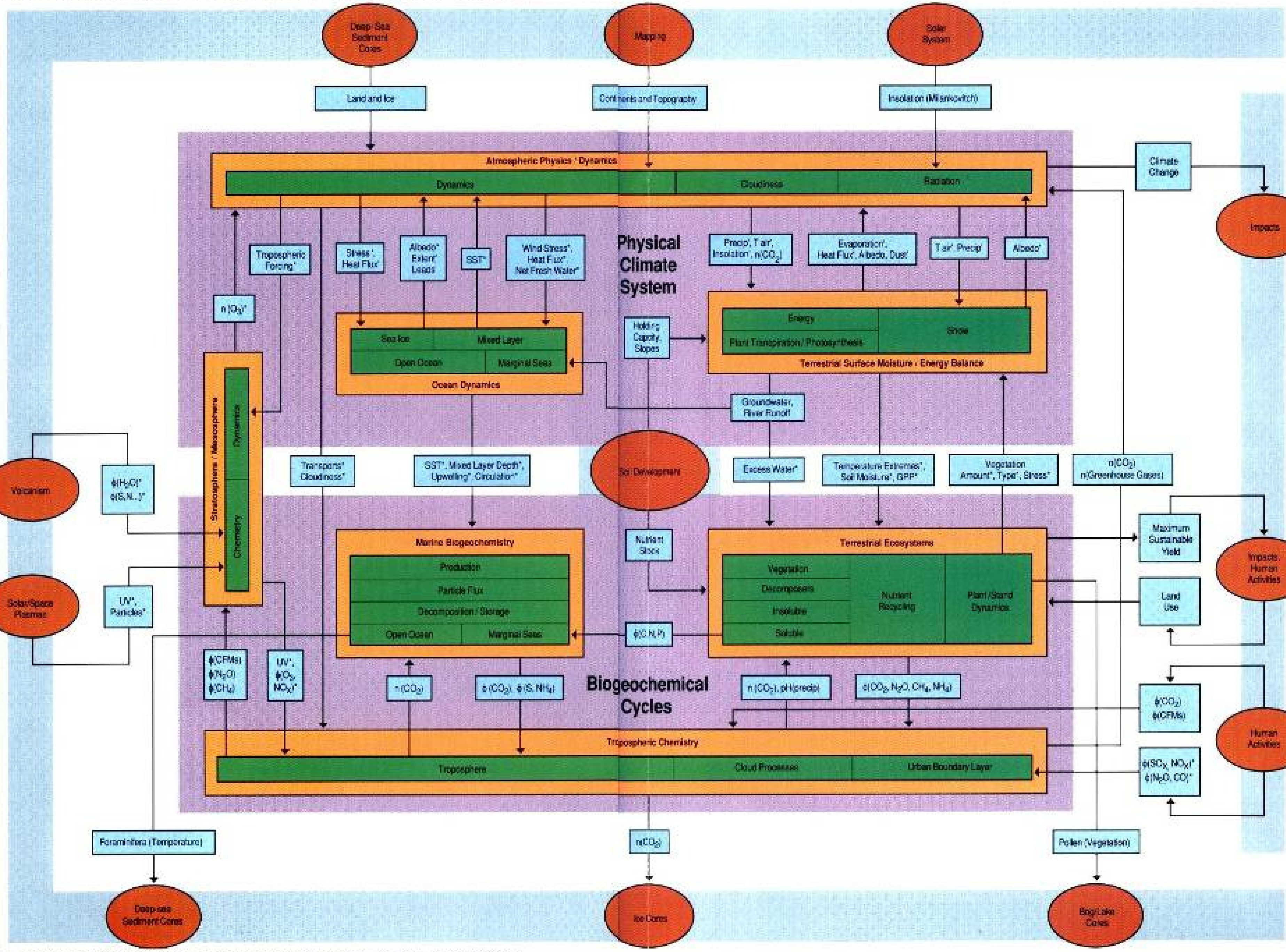
# Summary

Figure 2.4.2 CONCEPTUAL MODEL of Earth system process operating on timescales of decades to centuries.




' = on timescales of hours to days  " = on timescales of months to seasons  φ = flux  n = concentration

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