Earth system models

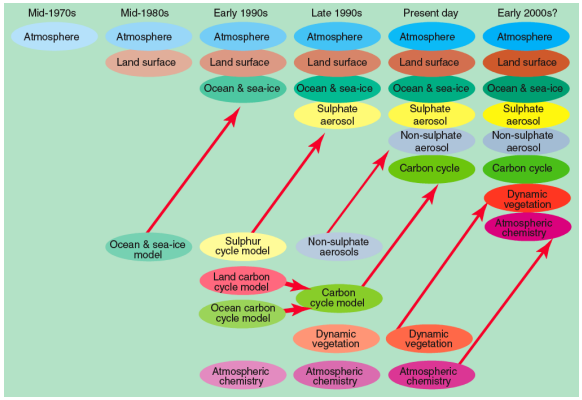


Figure: IPCC, 2001

Energy balance (courtesy Sonia Seneviratne)

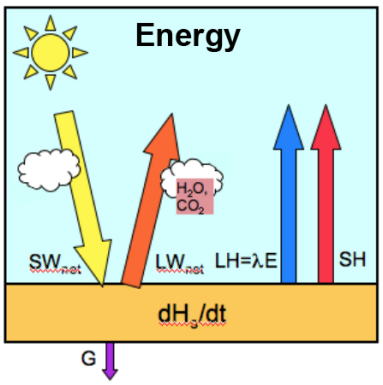


Figure: Role of land-surface: Partitioning of energy into latent (LH) and sensible (SH) heat flux

Water balance (courtesy Sonia Seneviratne)

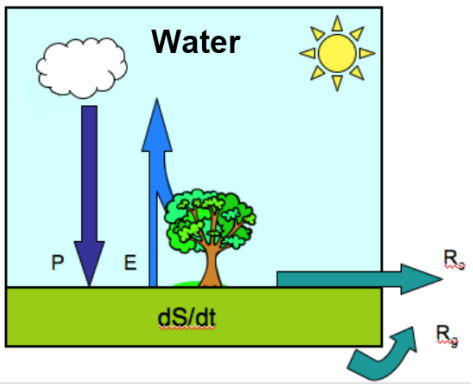


Figure: Role of land-surface: Partitioning of water into evaporation and runoff.

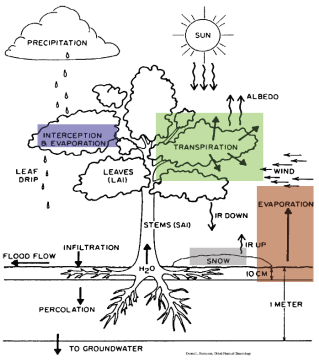
Total evapotranspiration (S. Seneviratne)

Total Evapotranspiration ET:

$$ET = E_b + E_i + E_s + TR$$

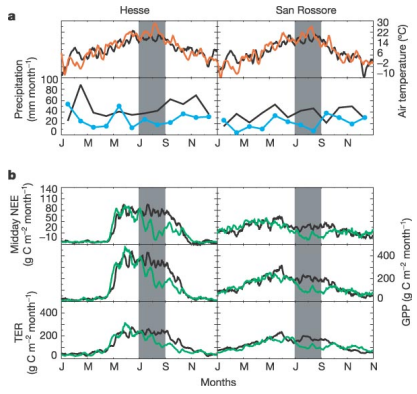
With:

E_b:	Bare soil evaporation
E_i:	Evaporation from interception storage (on soil and vegetation surface)
E_s:	Snow sublimation
TR:	Plant transpiration



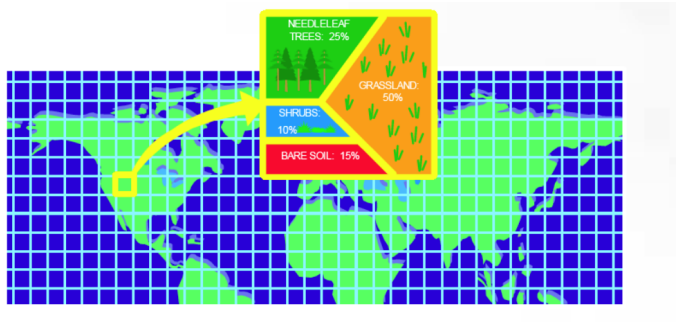
(Dickinson 1984)

Land is important for carbon cycle: source instead of sink in 2003 (Ciais et al., 2005)



- Hesse: deciduous beech forest (France)
- San Rossore: southern evergreen pine forest (Italy)
- black lines: 2002; color: 2003
- NEE: net carbon uptake
- GPP: gross primary productivity
- TER: total ecosystem respiration

Subgrid-scale heterogeneity (S. Seneviratne)



(P. Houser 2006)

Figure: Mosaic approach

Coupled ocean-atmosphere models

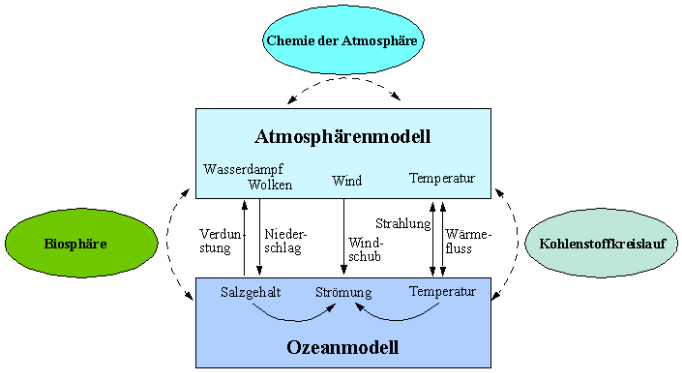


Figure: *lbs.hh.schule.de/welcome.phtml?unten = /klima/infothek.htm*

Optics and phase transitions (courtesy J. Marotzke, MPI Met.)

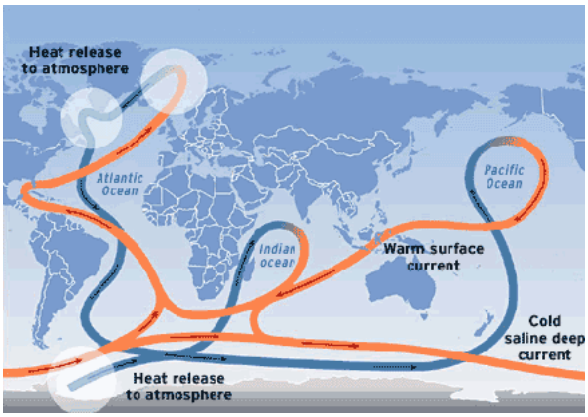
- Water is electric conductor (dielectric), impenetrable to electromagnetic radiation, in contrast to air
- Ocean opaque, atmosphere transparent
- All sunlight absorbed within at most tens of metres from surface
- Cannot perform optical remote sensing of ocean water column
- Modelling: Radiative transfer much simpler in ocean
- Ocean: Phase transitions only at surface (evaporation, sea ice formation)
- No effects comparable to cloud formation & interaction with radiation
- Modelling: This aspect much simpler in the ocean

Composition and Dynamics (Marotzke)

- Seawater is a "two-component fluid" (freshwater, salt)
- Density is significantly influenced by both temperature, T, and salinity, S
- Temperature dominates (deep ocean is dense because it is cold), but salinity has first-order influence
- Atmosphere: Water vapour has negligible influence on density except in near-surface tropics; small also there
- Modelling: Extremely interesting salinity effects in ocean circulation (e.g., multiple equilibria in thermohaline circulation)

IACETH Institute for Atmospheric and Climate Science

Oceanic conveyor belt



www.ucsusa.org/assets/images/global_warming/conveyor-belt.gif

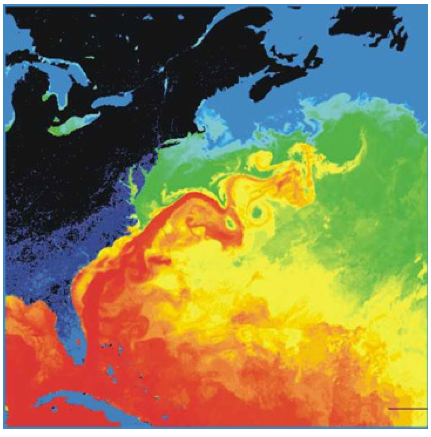
IACETH Institute for Atmospheric and Climate Science

Heat capacity (Marotzke)

- Heat capacities ocean (O), atmosphere (A): $\rho_O = 1000\rho_A$; $c_{p,O} = 4 \times c_{p,A}$
- $\sim$ 2.5m of water have same heat content as entire atmosphere
- Atmosphere equilibrates over about 1 year
- Thermal timescale of ocean very long (1000 years)
- Ocean "stiff" system (vastly different timescales - from wind forcing over a few hours, to millennia)
- Modelling: Timesteps need to be short enough to resolve fast processes; very many timesteps needed to reach long integration times
- Modelling: Long timescales and role of salinity make exact conservation of mass and partial masses crucial

IACETH Institute for Atmospheric and Climate Science

Small oceanic deformation radius (Marotzke)



- Wintertime SST
- See cold-core eddies
- Much smaller than in the atmosphere

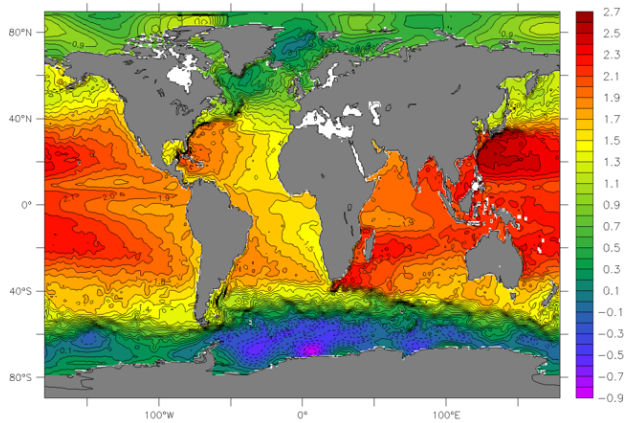
Stratification (Marotzke)

- Ocean weakly stratified
- Even after subtracting compressibility effects, relative density difference greater in atmosphere (A) than in ocean (O): $(\rho_{A,sfc} - \rho_{A,top})/\rho_{A,mean} >> (\rho_{O,upper} - \rho_{O,lower})/\rho_{O,mean}$
- (Internal) gravity waves much slower in ocean (c_g = 2-3 m/s) than in atmosphere (c_g = 20-80 m/s)
- Characteristic length scale: Deformation (Rossby) radius, R_d:
- $R_d = c/f$, 30 km ocean; 500-1000 km atmosphere
- Ocean eddies much smaller than in atmosphere
- Can fit many more eddies in ocean than in atmosphere
- Modelling: High demands on spatial resolution just for fluid motion and wave propagation
- No standard climate model resolves these features
- Requirement for very many short timesteps

Mechanical energy budget (Marotzke)

- Atmosphere moves more vigorously, per unit of heat deposited
- Mechanical (potential) energy ca. 30% of internal energy $(c_p - c_v)/c_p$ (ideal gas)
- Ocean: Internal energy = 1000. $\times$ mechanical energy.
- Atmosphere: largely heated from below (air transparent)
- Atmosphere: efficient heat engine
- Ocean: is not a heat engine - heated and cooled at surface
- External mechanical energy source (tides, winds) needed to support mixing, which in turn is needed to maintain density differences and thermohaline circulation
- Modelling: Oceanic mechanical energy budget subtle in reality but still extremely crude in models

Sea level ↔ Ocean circulation



Rio and Hernandez, 2004

Summary: Ocean vs. atmosphere modelling (courtesy Marotzke)

- Phase transitions are simpler in ocean; optics simpler in ocean
- The second component of seawater (salt) is dynamically very important (density)
- Ocean dynamics are very stiff numerically
- The deformation (Rossby) radius is much smaller in the ocean
- Very long thermal equilibration timescale
- Ocean is not a heat engine
- Ocean geometry - fundamentally different dynamics (force balance) of mean meridional circulation
- Ocean general circulation modelling has become widespread only quite recently

Aerosol cycle

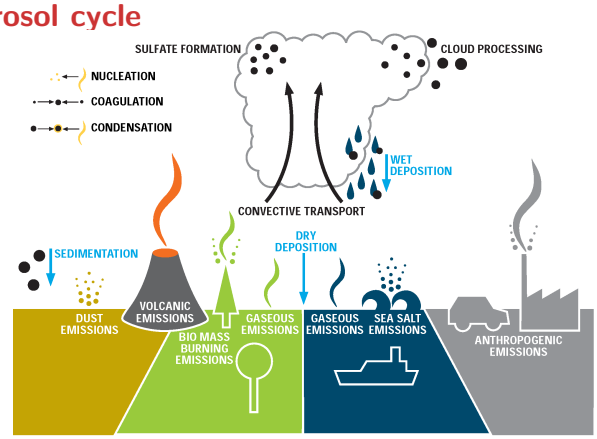
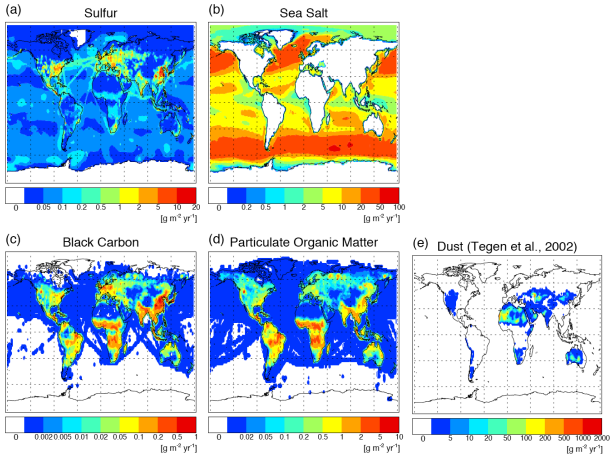


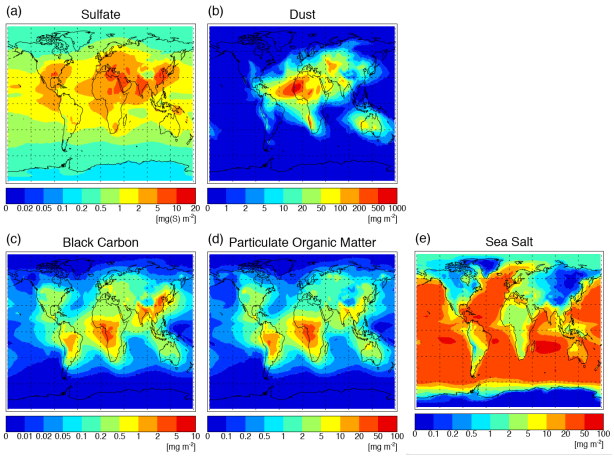
Figure: Courtesy: Philip Stier

Global aerosol sources [Stier et al., ACP, 2005]



IACETH Institute for Atmospheric and Climate Science

Vertically integrated aerosol burden [Stier, ACP, 2005]



IACETH Institute for Atmospheric and Climate Science

Biogeochemical cycles

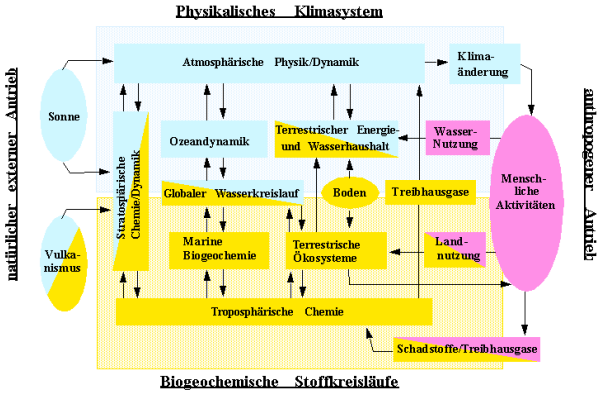
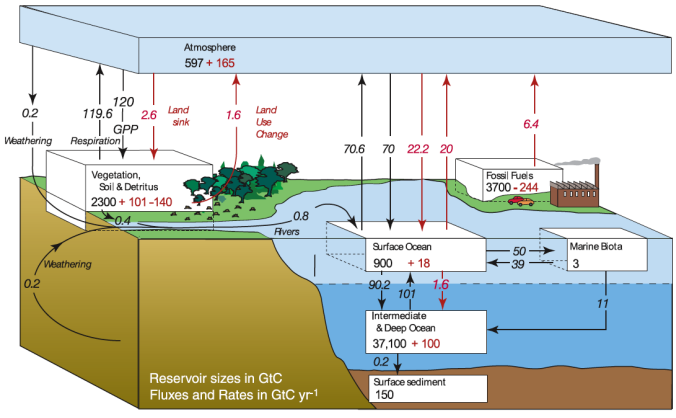


Figure: *lbs.hh.schule.de/welcome.phtml?unten = /klima/infothek.htm*

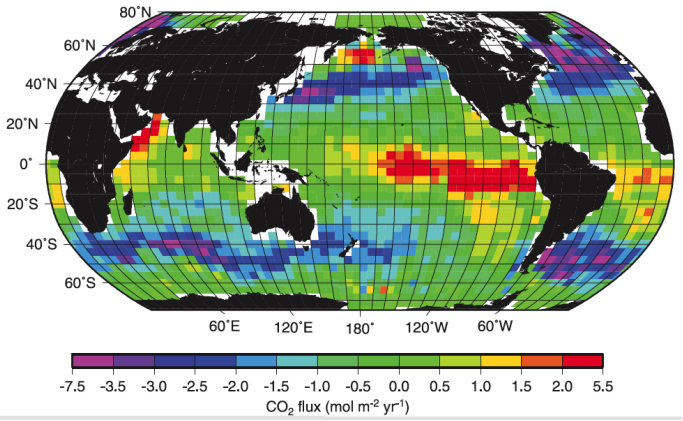
IACETH Institute for Atmospheric and Climate Science

The global carbon cycle [IPCC, 2007, Fig. 7.3]

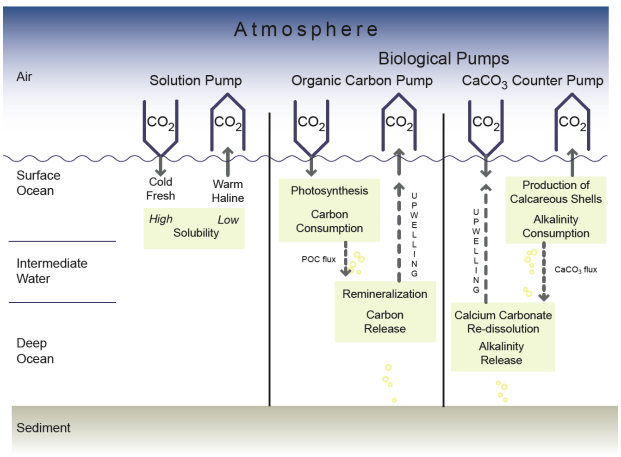


natural fluxes (black); natural ones (red)

Sea-to-air flux of CO_2 for 1995 [IPCC, 2007, Fig. 7.8]



Ocean carbon pumps [IPCC, 2007, Fig. 7.10]

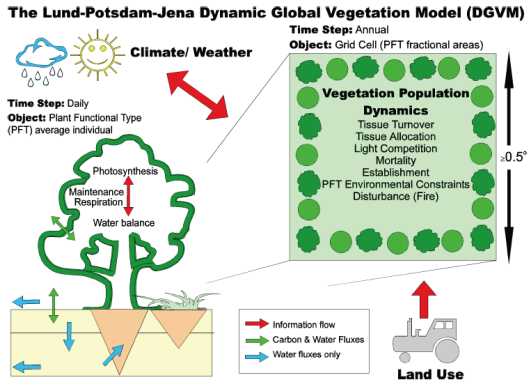


Ocean carbon pumps

The ocean can alter atmospheric CO_2 concentrations through 3 mechanisms:

- Solubility pump: absorption or release of CO_2 due to changes in solubility of gaseous CO_2
- Organic carbon pump: changes in carbon fixation to POC in surface waters by photosynthesis and export of this carbon through sinking of organic particles out of the surface layer - this process is largely limited by availability of light and nutrients (P,N, silicic acid, iron)
- $CaCO_3$ counter pump: changes in the release of CO_2 in surface waters during formation of $CaCO_3$ shell material by plankton

Global vegetation model (S. Seneviratne)



(http://www.pik-potsdam.de/lpj/; Sitch et al. 2003)

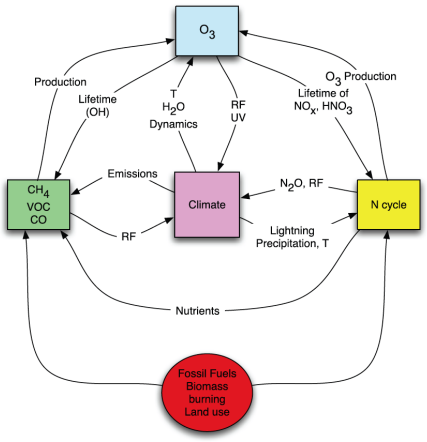
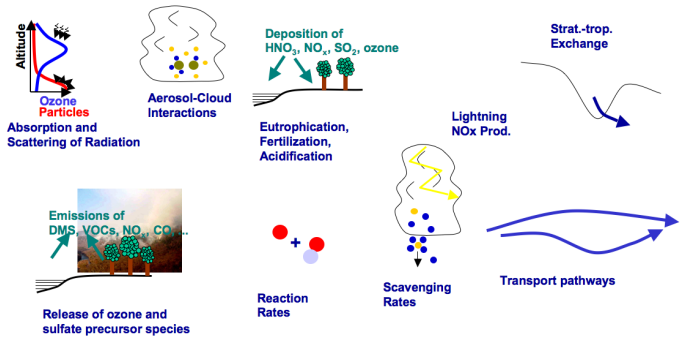


Figure 7.15. *Schematic representation of the multiple interactions between tropospheric chemical processes, biogeochemical cycles and the climate system. RF represents radiative forcing, UV ultraviolet radiation, T temperature and HNO_3 nitric acid.*

Feedbacks Chemistry ↔ Climate



Martin Schultz, MPI Met., pers. comm.