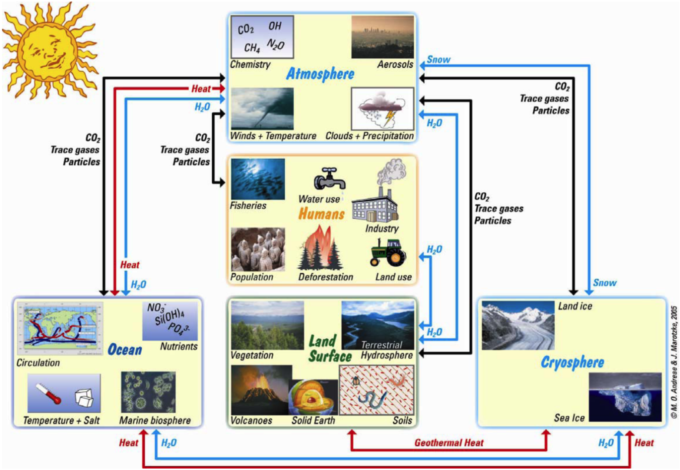
Earth system models (ESM)



Courtesy: M.O. Andreae and J. Marotze

Definitions (from the IPCC AR5 glossary)

GCM: General Circulation Model: A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes.

AOGCM: Coupled Atmosphere-Ocean GCM: They provide a representation of the climate system (atmosphere, ocean, land, sea ice) that is near or at the most comprehensive end of the spectrum currently available

ESM: A coupled AOGCM in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions. May include additional components, e.g. aerosols, atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, urban or crop models

ESM development (IPCC AR5, Flato et al., 2013)

3 steps:

1. Express the system's physical laws in mathematical terms
2. Implement these expressions on a computer
3. Build and implement parameterizations for those processes that cannot be represented explicitly

Because of limited supercomputer resources, compromises are made in 3 areas:

1. Model resolution
2. Include only those processes that matter on the time scale of interest
3. Number of ensemble simulations

Main features of ESMs and AOGCMs in AR5

CMIP5

Model name		AOGCM				ESM				
		Atmos	Land Surface	Ocean	Sea-Ice	FC	Aerosol	Atmos Chem	Land Carbon	Ocean BGC
ACCESS1.0, ACCESS1.3	Australia									
BCC-CSM1.1, BCC-CSM1.1(m)	China									
BNU-ESM	China									
CanCM4	Canada									
CanESM2										
CCSM4	USA									
CESM1 (BGC)										
CESM1 (WACCM)		HT								
CESM1 (FASTCHEM)										
CESM1 (CAM5)										
CESM1 (CAM5.1-FV2)	USA									
CMCC-CM, CMCC-CMS	Italy	HT								
CMCC-CESM		HT								
CNRM-CM5	France									
CSIRO-Mk3.6.0	Australia									
EC-EARTH	Europe									
FGOALS-g2	China									
FGOALS-s2										
FIO-ESM v1.0	China									
GFDL-ESM2M, GFDL-ESM2G	USA									
GFDL-CM2.1										
GFDL-CM3		HT								
GISS-E2-R, GISS-E2-H	USA	HT					p2,p3*	p2, p3*		
GISS-E2-R-CC, GISS-E2-H-CC		HT					p2,p3*	p2, p3*		
HadGEM2-ES	UK									
HadGEM2-CC		HT								
HadCM3										
HadGEM2-AO	Korea									
INM-CM4	Russia									
IPSL-CM5A-LR / -CM5A-MR / -CM5B-LR	France	HT								
MIROC4h, MIROC5	Japan	HT								
MIROC-ESM		HT								
MIROC-ESM-CHEM		HT								
MPI-ESM-LR / -ESM-MR / -ESM-P	Germany	HT								
MRI-ESM1	Japan	HT								
MRI-CGCM3		HT								
NCEP-CFSv2	USA									
NorESM1-M	Norway									
NorESM1-ME										

Increasing complexity

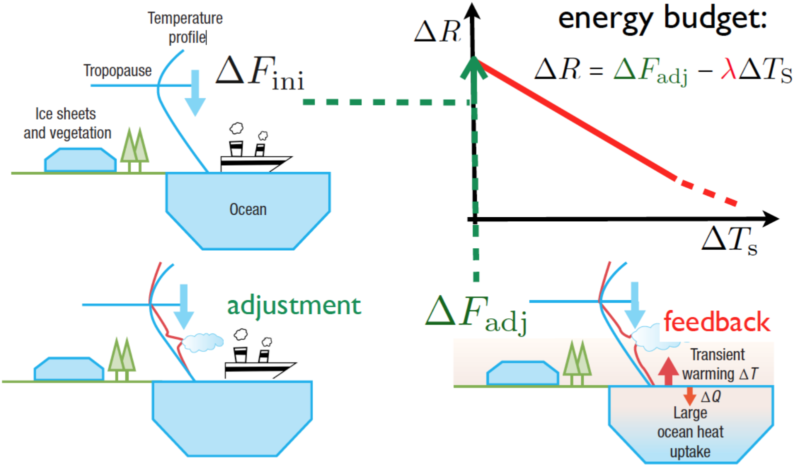
Increasing resolution Atmosphere / Ocean
(total number of horizonal grid points)

Atmosphere: 8000 30000 52000

Ocean: 12000 50000 110000

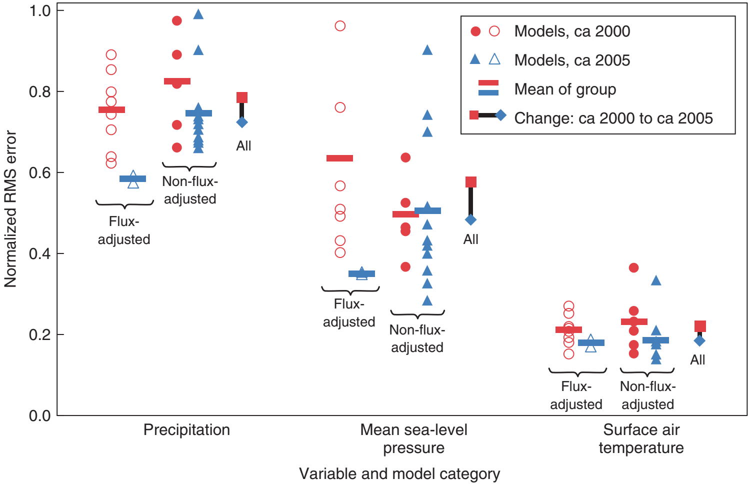
Table 9.1 IPCC AR5 (Flato et al., 2013)

Radiative forcing, adjustments and feedbacks



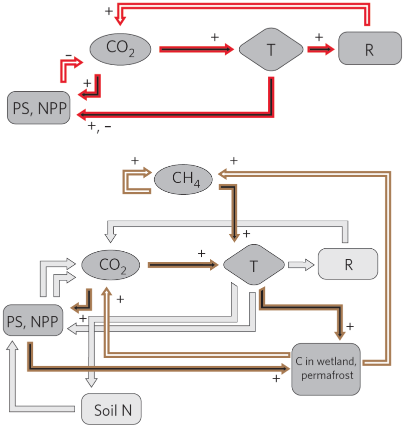
Knutti and Hegerl, NatGeo, 2008; courtesy of Franziska Glassmeier

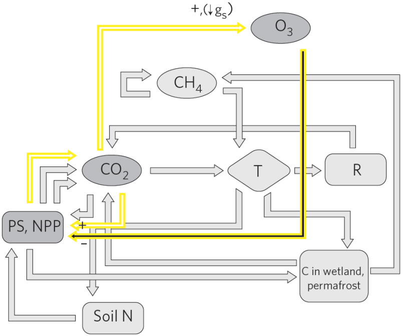
Performance of CMIP2 vs. CMIP3 models



Flato, WIRE Climate Change, 2011

Feedbacks involving biogeochemical cycles





PS: photosynthesis; *NPP*: net primary production; *R*: respiration

g_s: stomatal conductance

forcings: closed arrows

feedbacks: open arrows

Arneth et al., NatGeo, 2010

Coupled ocean-atmosphere models

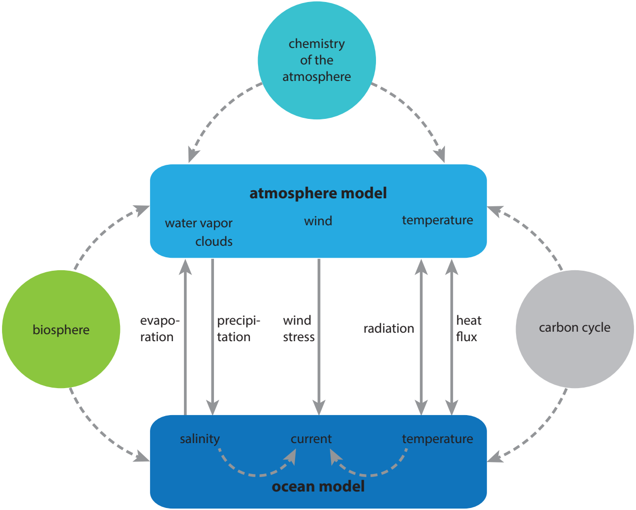


Figure courtesy of Fabian Mahrt

Optics and phase transitions

- 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 meters 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

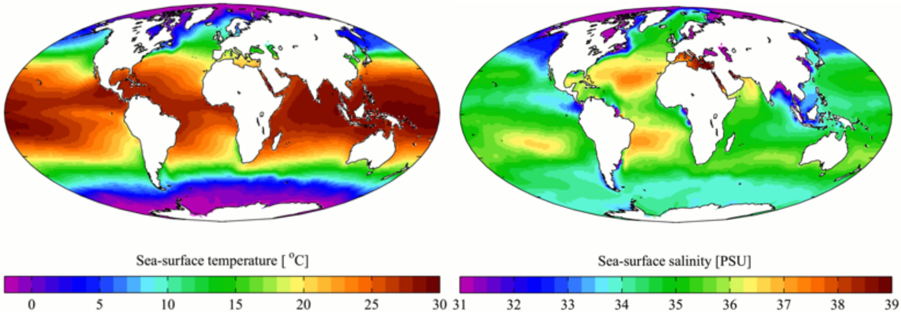
Courtesy J. Marotzke, MPI for Met.

Composition and Dynamics

- 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)

Courtesy J. Marotzke, MPI for Met.

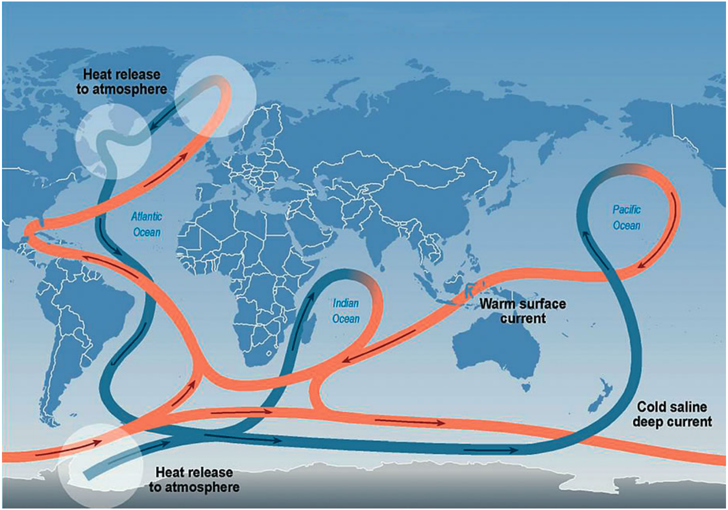
Temperature & salinity in surface waters



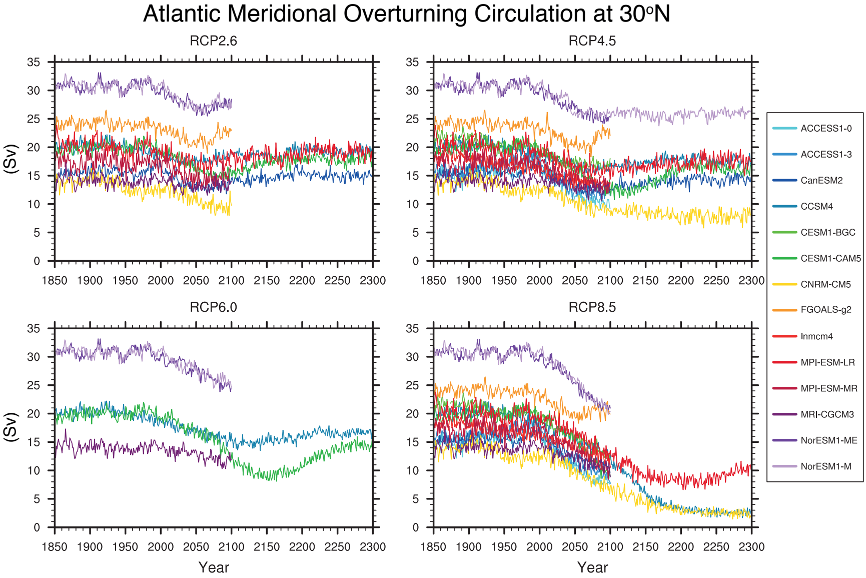
PSU = practical salinity units (conductivity ratio); divide by 1000 to obtain salinity

Courtesy Nicolas Gruber

Oceanic conveyor belt



http://planetearth.nerc.ac.uk/images/uploaded/custom/sea-circulation-920x644.jpg



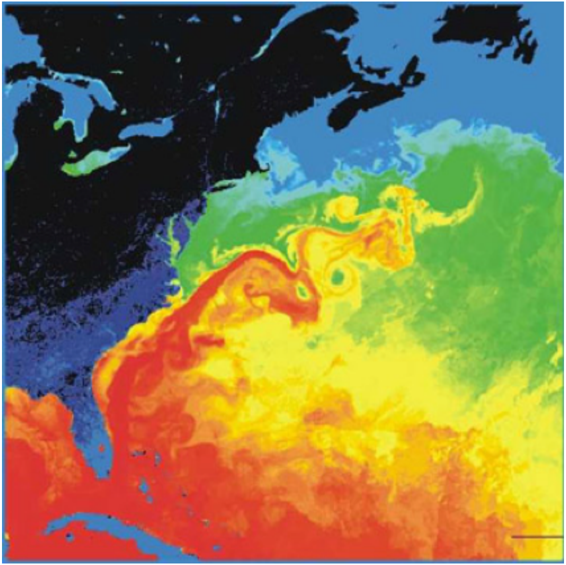
IPCC, AR5, 2013, Fig. 12.35

Heat capacity

- Heat capacities ocean (O), atmosphere (A): $\rho_O = 1000\rho_A$; $c_{p,O}$ (4180 J kg^{-1} K^{-1}) $= 4 \times c_{p,A}$ (1007 J kg^{-1} K^{-1})
- $\sim$ 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

Courtesy J. Marotzke, MPI for Met.

Small oceanic deformation radius



- Wintertime SST
- See cold-core eddies
- Ocean eddies much smaller than in atmosphere

Courtesy J. Marotzke, MPI for Met.

Stratification

- The ocean is only weakly stratified
- Even after subtracting compressibility effects, relative density difference greater in atmosphere (A) than in ocean (O): $(\rho_{A,sfc} - \rho_{A,top})/\rho_{A,mean} \gg (\rho_{O,upper} - \rho_{O,lower})/\rho_{O,mean}$
- (Internal) gravity waves are much slower in the ocean (c_g = 2-3 m/s) than in the 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
- 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

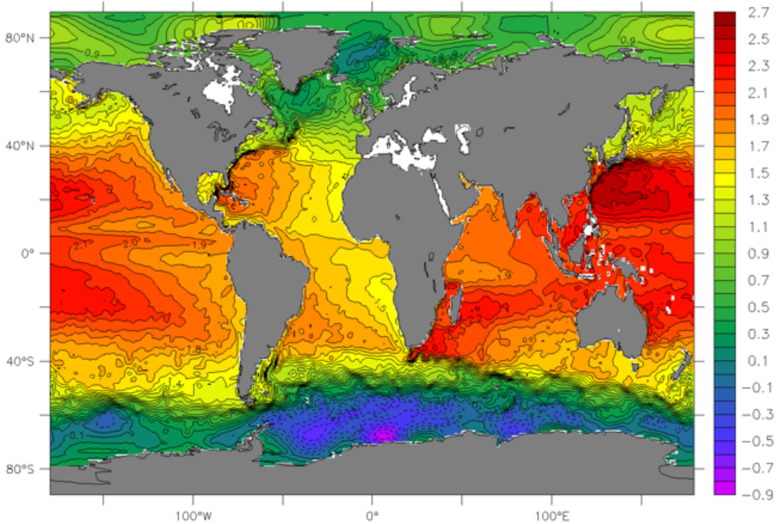
Courtesy J. Marotzke, MPI for Met.

Mechanical energy budget

- 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

Courtesy J. Marotzke, MPI for Met.

Annual mean sea level [m] ↔ Ocean circulation



Rio and Hernandez, JGR, 2004

Summary: Ocean vs. atmosphere modelling

- 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

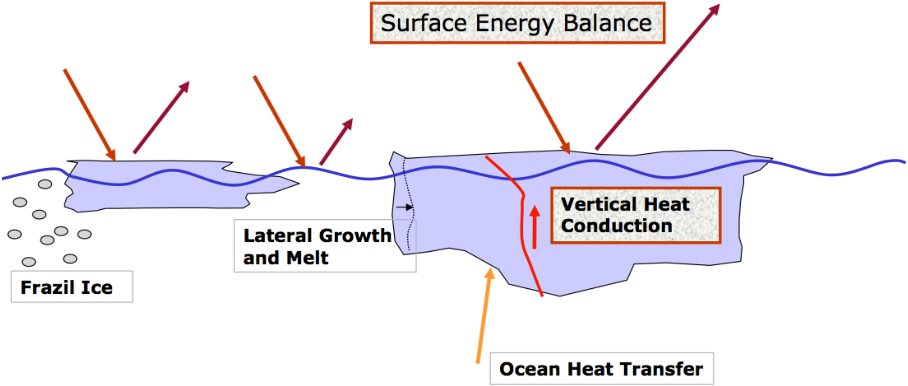
Courtesy J. Marotzke, MPI for Met.

Sea-ice models

- A sea-ice submodel needs to provide surface temperature and albedo
- A full sea-ice model consists of at least 3 components (Hunke et al., 2010):
  - Vertical thermodynamics: calculation of growth and melt
  - Horizontal dynamics: calculation of ice velocity field
  - Conservation: description of ice state including advection and deformation
- A sea-ice model used in climate models needs to:
  - Simulate the climatological mean annual cycle of ice and snow
  - Represent the sensitivity to perturbations - must have the key feedbacks
  - Include physics appropriate to the model's spatial scale and parameterizations for sub-scale behaviors
- Normally ice cover is represented in terms of mean thickness and concentration (fraction of local area covered by ice)

Sea-ice models: Thermodynamics

Courtesy: Greg Flato, CCCma



- Ice grows by accretion on its underside
- Inside the ice, heat is stored and conducted as in any solid
- LW cooling and sensible heat flux dominate during ice growth
- SW heating dominates during melting; surface albedo is important

Sea-ice models: Dynamics

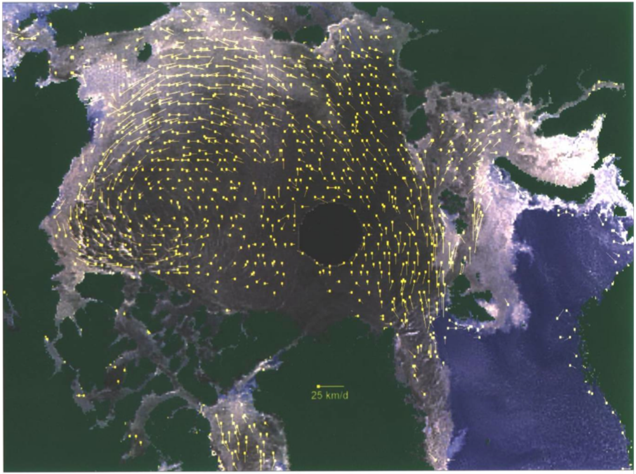


Fig. 8. Estimated 4-day ice motion vectors with SSM/I 85.5 GHz image for January 13, 1994 as background.

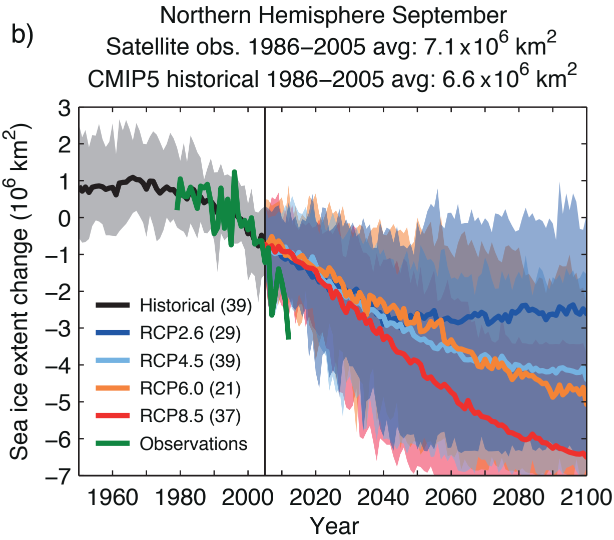
Courtesy: Greg Flato, CCCma

Sea-ice models: Parameterizations

- Fractional albedo that at least includes 4 values: cold snow; warm, melting snow; cold, bare ice; warm, melting ice.
- More advanced albedo parameterizations account for melt ponds, ice and snow thickness, spectral bands
- Snow model development typically lags behind terrestrial snow models
- Salinity needs to be prescribed or predicted
- Account for ice microstructure evolution and anisotropy:
  - Subgrid-scale thickness variations
  - Conversion of thinner ice to thicker ice under deformation

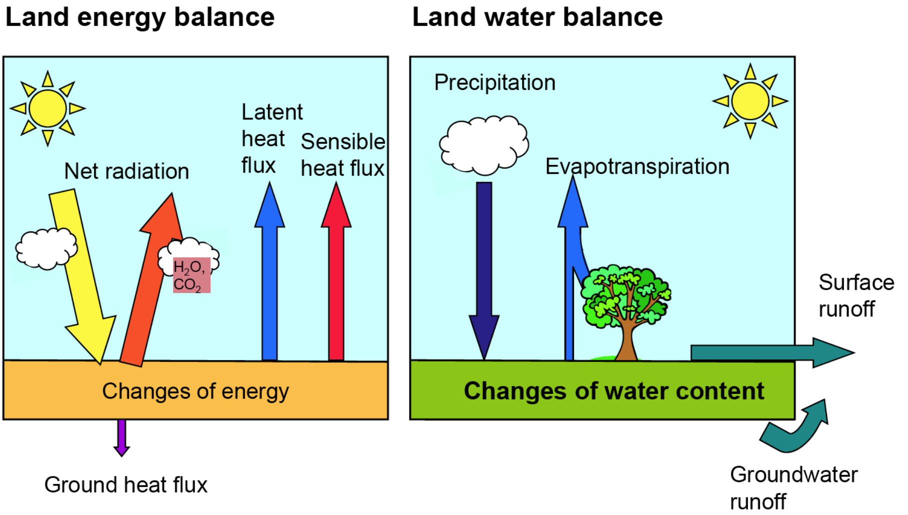
IPCC AR5, Flato et al., 2013

Evolution of Arctic sea ice



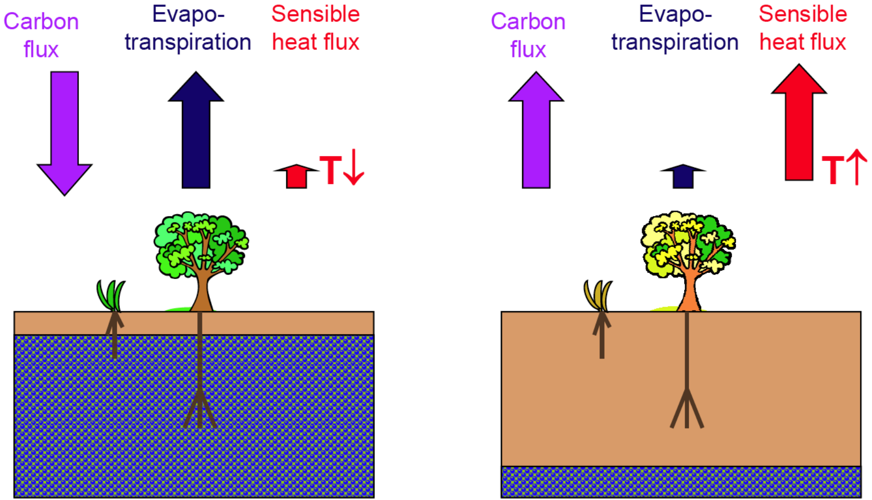
IPCC, AR5, Fig. 12.28

Land energy and water balance



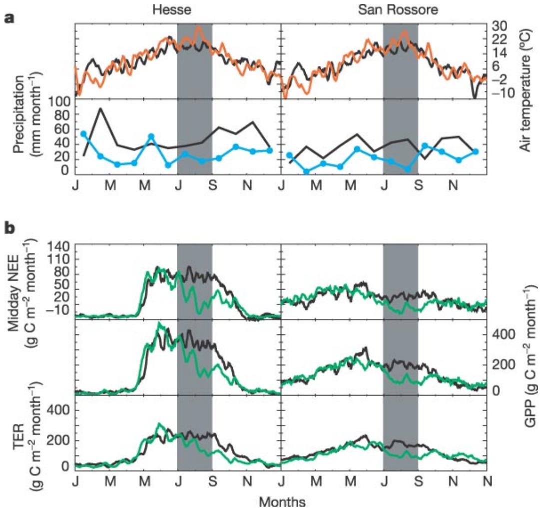
Courtesy Sonia Seneviratne, IAC

Role of soil moisture



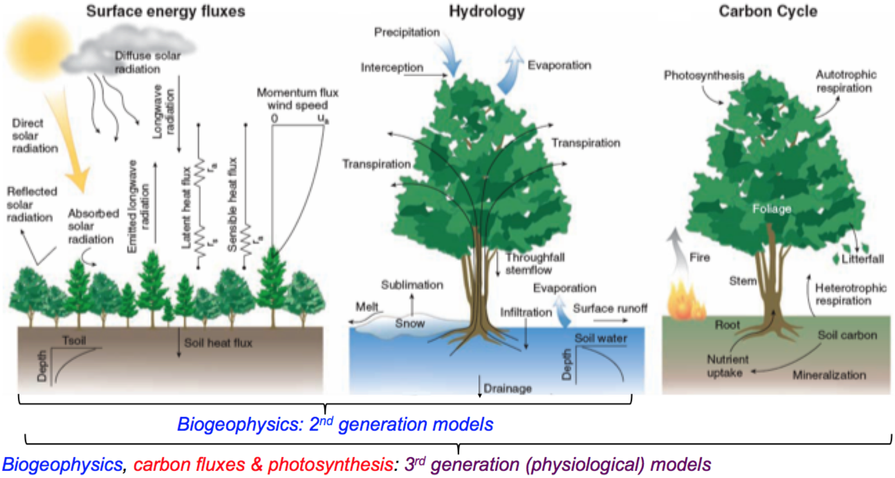
Courtesy Sonia Seneviratne, IAC

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



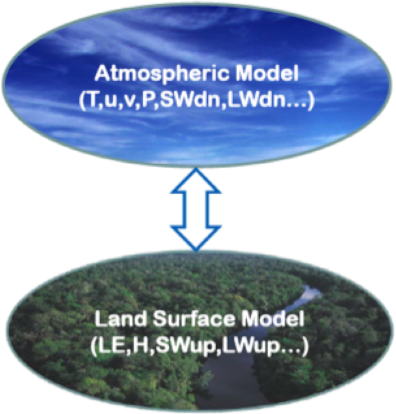
- Hesse: deciduous beech forest (France)
- San Rossore: southern evergreen pine forest (Italy)
- black lines: 2002; color: 2003
- NEE: net carbon uptake
- GPP: gross primary productivity
- TER: total ecosystem respiration

Processes represented by land surface models



(after Bonan, Science 2008)

Exchange of variables between atmospheric and land models



Courtesy Sonia Seneviratne, IAC

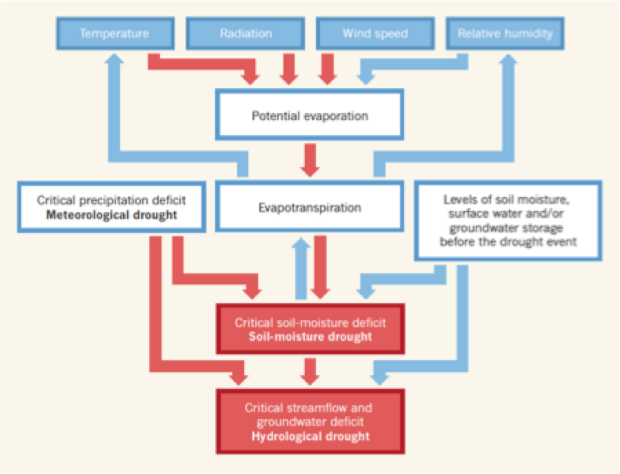
Need to calculate the total evapo-transpiration ET:

$$ET = E_b + E_i + E_s + TR \quad (1)$$

where

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

Drought modelling



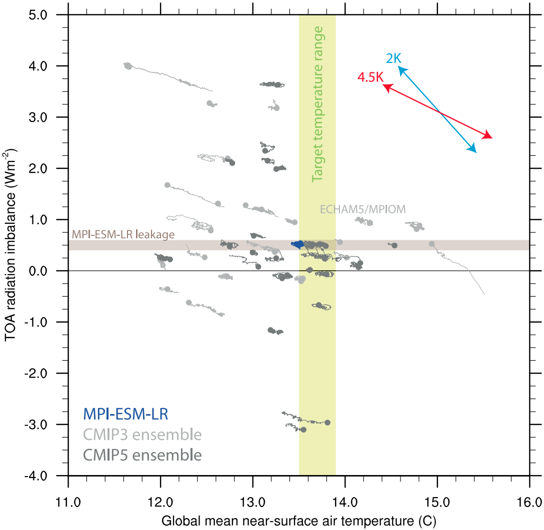
The representation of soil moisture (agricultural) and streamflow (hydrological) drought requires substantial land surface modelling (not only a function of precipitation!)

(Seneviratne et al 2012, Nature)

Model tuning

- Basic criterion: Net radiation balance at the top of the atmosphere has to be slightly positive (0-1 $\mathrm{W\ m^{-2}}$) in the present-day to reproduce observations
- Targets: SW $\approx$ LW $\approx$ 238-241 $\mathrm{W\ m^{-2}}$
- Criteria for the choice of tuning parameters:
  - Uncertainty
  - Sensitivity
  - Variation within "justifiable" limits
  - Minimize the number of parameters
- For example tune α's in the autoconversion and aggregation rate in the prognostic equations for N_l and N_i (see lecture on clouds)

Evaluation of CMIP3 vs. CMIP5 models



Mauritsen et al., JAMES, 2012

Evaluating the parameter space

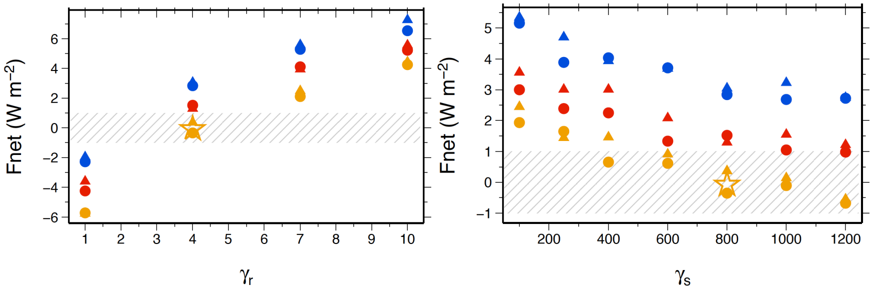
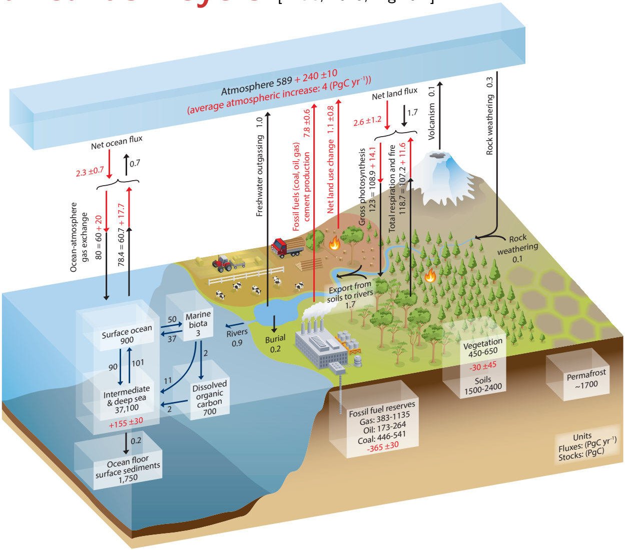


Figure : Net radiation at the top-of-the-atmosphere as a function of the rate of rain formation (γ_r) and rate of snow formation (γ_s) for different values of the entrainment rate in deep convective clouds and the inhomogeneity of ice clouds

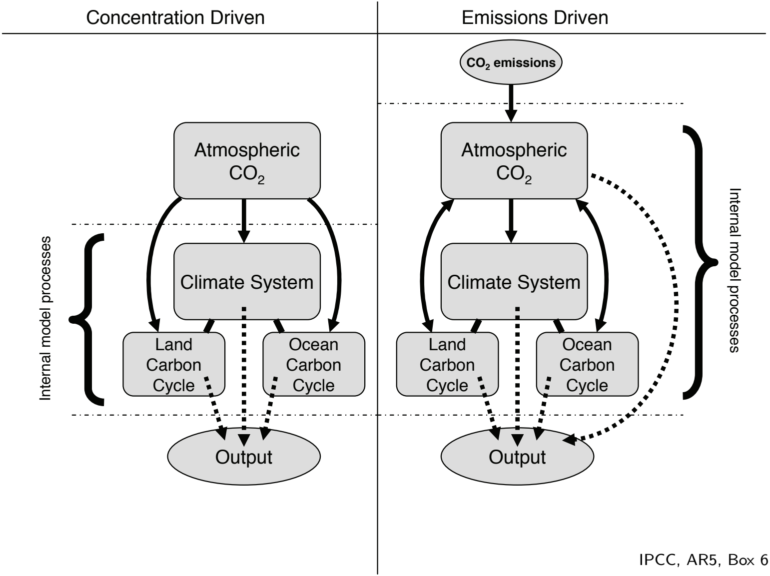
Lohmann and Ferrachat, ACP, 2010

The global carbon cycle [IPCC, 2013, Fig. 6.1]



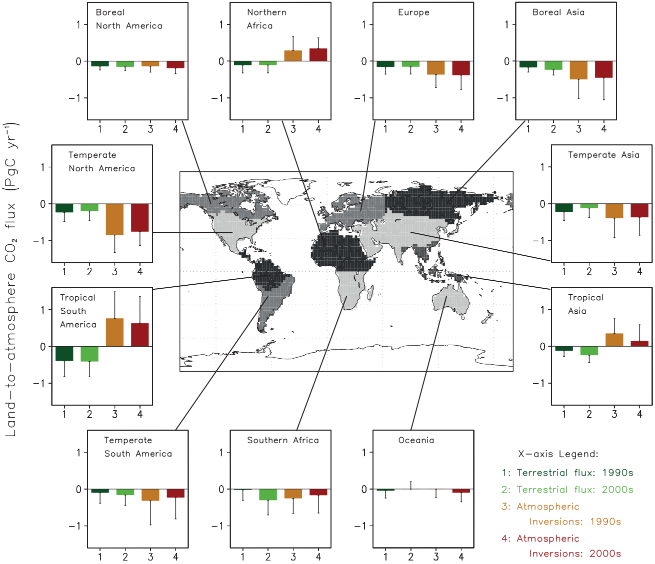
natural fluxes in 1750 (black); anthropogenic fluxes averaged over 2000-2009 (red)

Climate-carbon cycle models

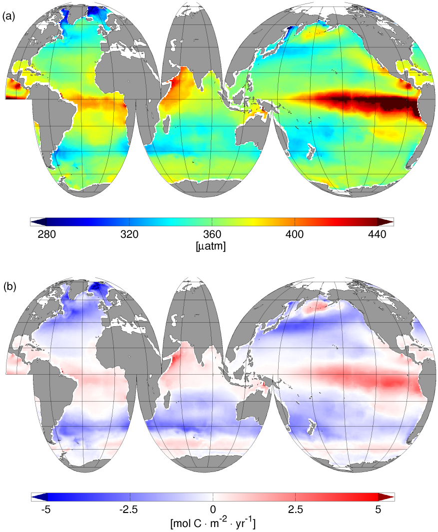


IPCC, AR5, Box 6.4, Fig. 1

Land-to-atmosphere CO_2 flux [IPCC, 2013, Fig. 6.15]

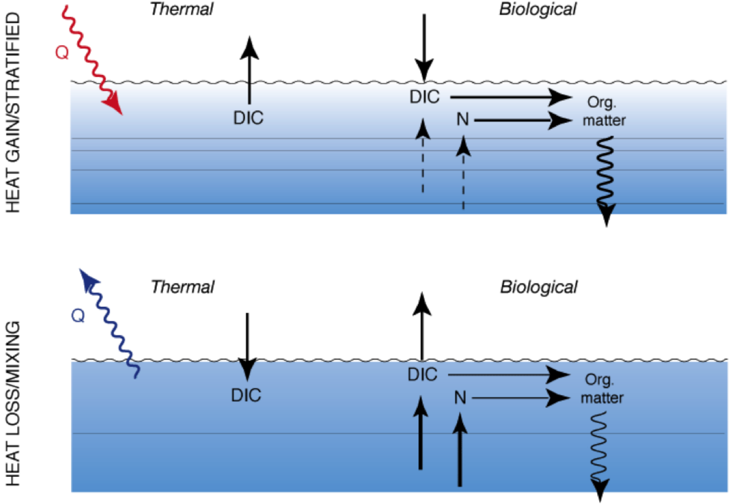


Oceanic CO_2 conc. & sea-air CO_2 flux (1998-2011)



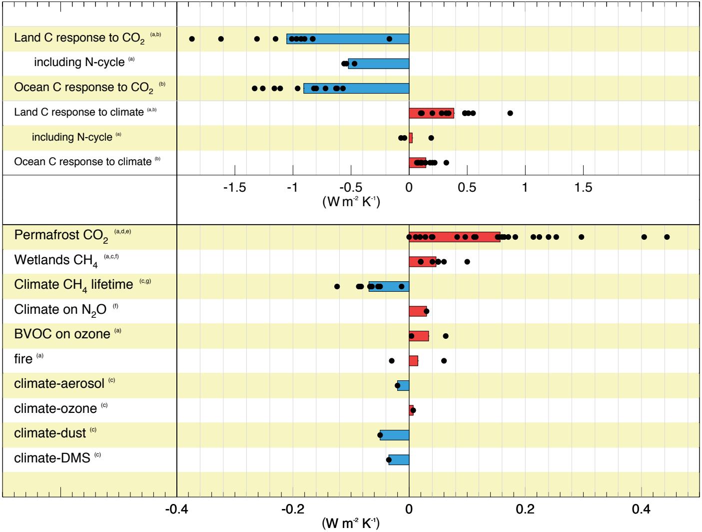
Landschützer, Gruber et al., GBC, 2014

Thermal vs. biological control on air-sea CO_2 fluxes



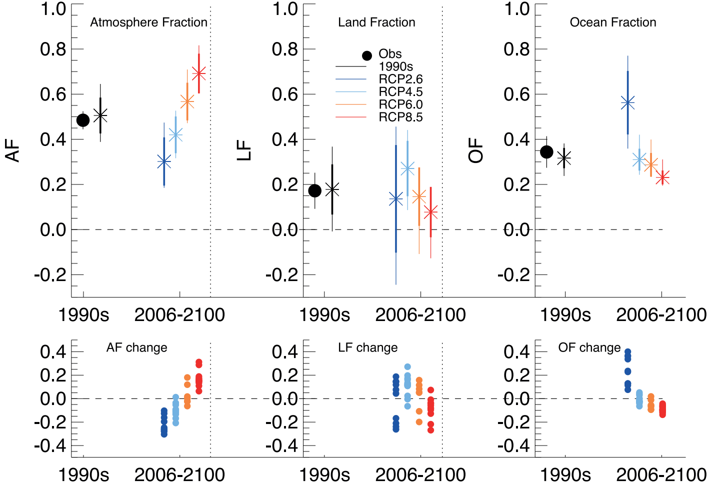
Courtesy Nicolas Gruber

Biogeochemical feedbacks on climate



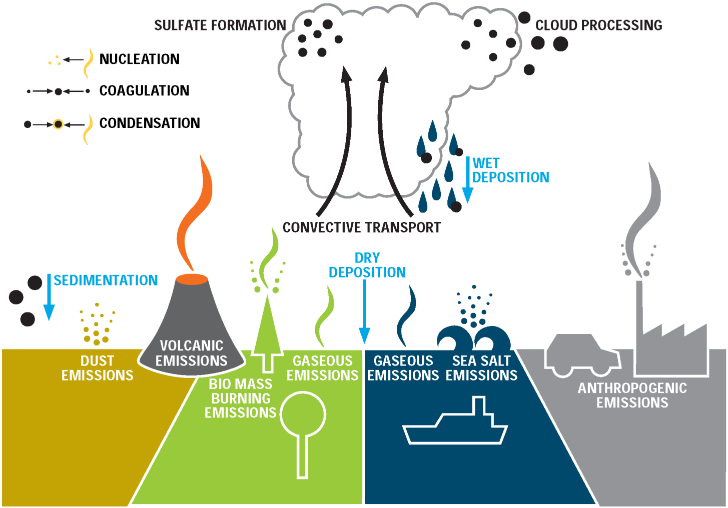
IPCC, AR5, Fig. 6.20

End point of fossil fuel carbon emis.



IPCC, AR5, Fig. 6.26

Aerosol cycle



Courtesy: Philip Stier, Oxford Univ.

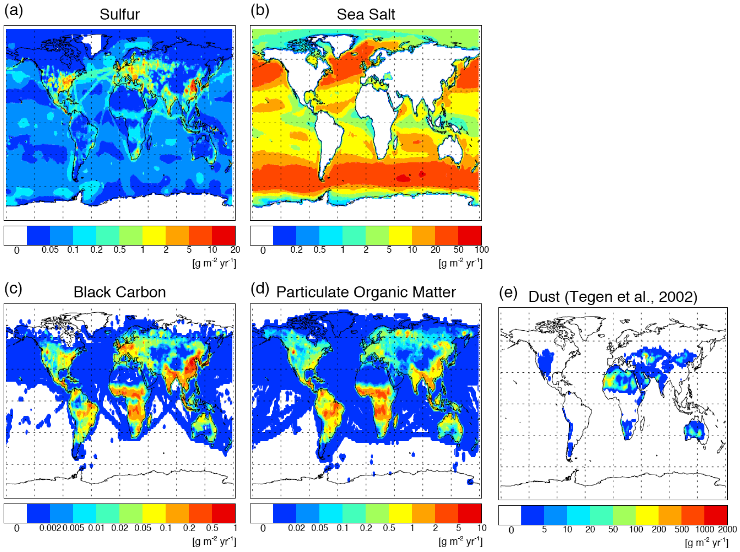
Hamburg Aerosol Module (HAM)

MODES IN M7	SOLUBLE/MIXED	INSOLUBLE
NUCLEATION (r < 0.005 µm)	1 N_1, M^1_{SO4}	
AITKEN (0.005 µm < r < 0.05 µm)	2 N_2, M^2_{SO4}, M^5_{BC}, M^9_{OC}	5 N_5, M^8_{BC}, M^{12}_{OC}
ACCUMULATION (0.05 µm < r < 0.5 µm)	3 N_3, M^3_{SO4}, M^6_{BC}, M^{10}_{OC}, M^{13}_{SS}, M^{15}_{DU}	6 N_6, M^{17}_{DU}
COARSE (0.5 µm < r)	4 N_4, M^4_{SO4}, M^7_{BC}, M^{11}_{OC}, M^{14}_{SS}, M^{16}_{DU}	7 N_7, M^{18}_{DU}

- Two-moment aerosol scheme that predicts mass and number concentrations of sulfate (SO4), black carbon (BC), particulate organic matter (OC), mineral dust (DU) and sea salt (SS)
- $\rightarrow$ Total of 27 prognostic equations

Stier et al., ACP, 2005

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



Vertically integrated aerosol burden [Stier et al., ACP, 2005]