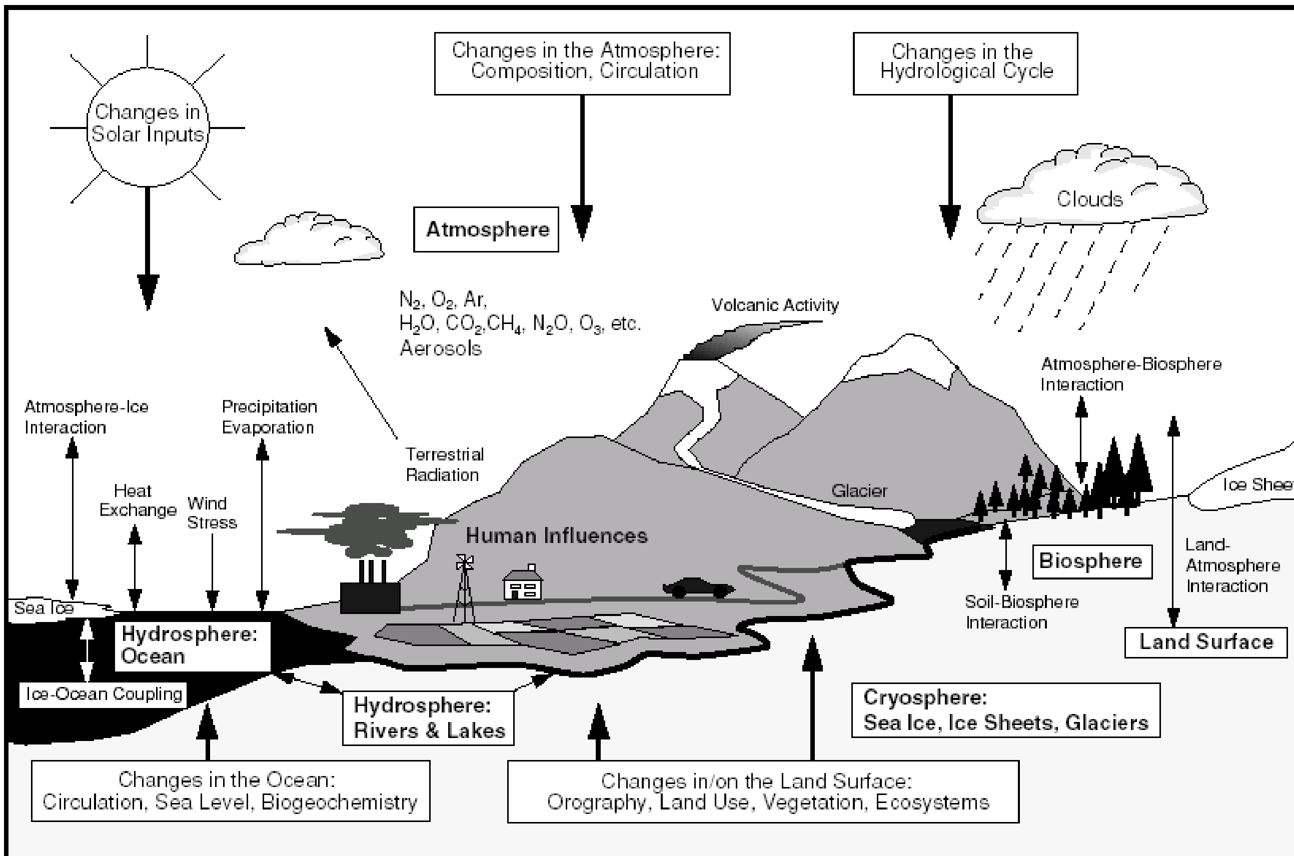
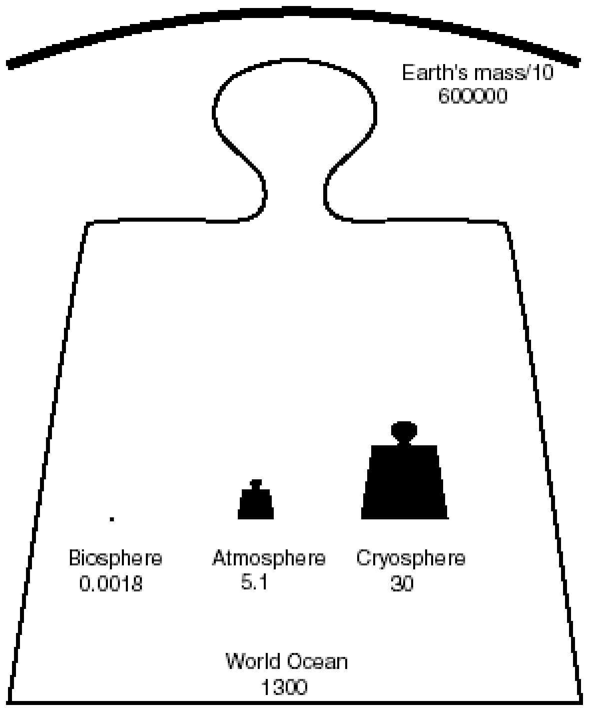
The climate system

Components



IPCC (2001)

Absolute and relative mass sizes



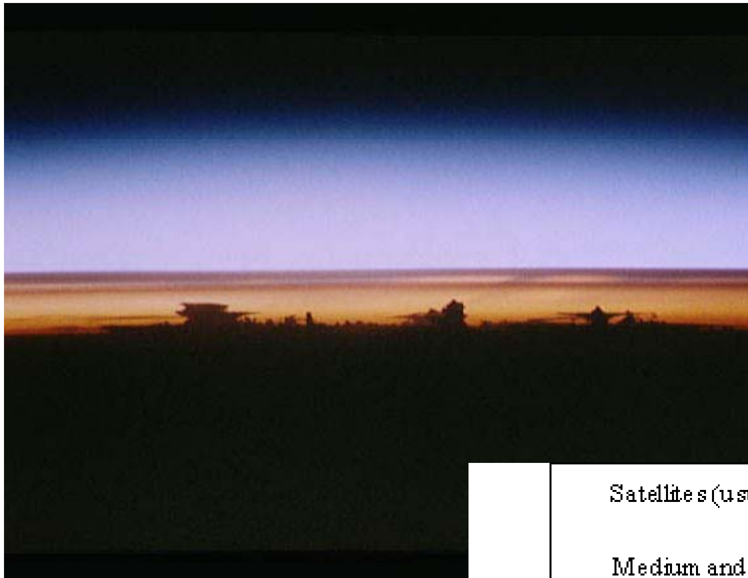
Mass of selected components of the climate systems in 10^{18} kg.

Hantel (2006)

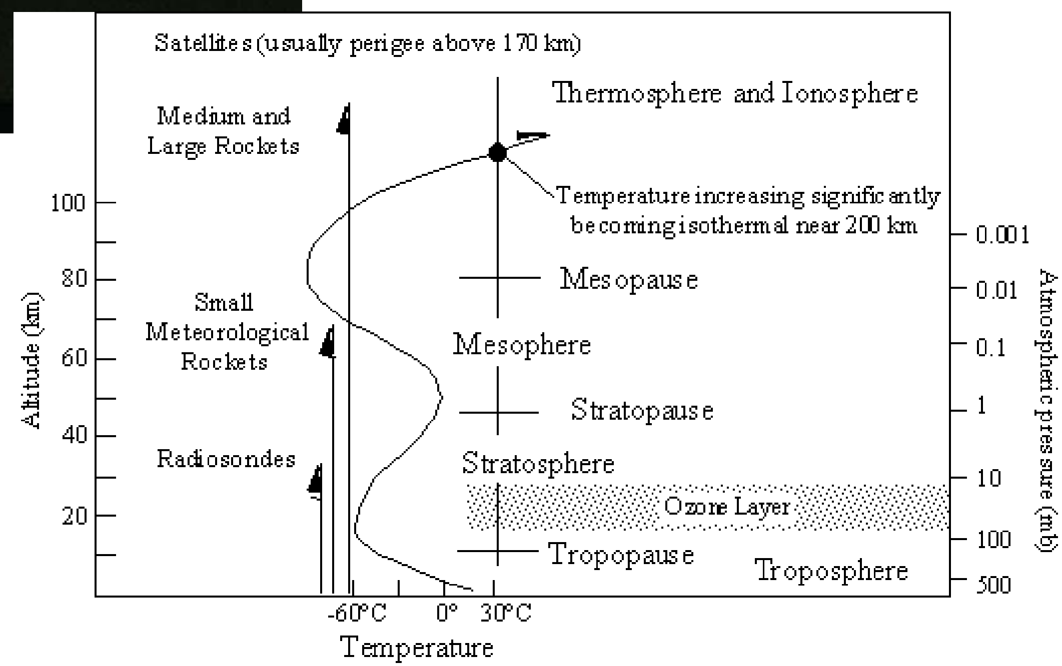
$\Rightarrow$ mass oceans ~ 260 x mass of the atmosphere

N.B.: For the oceans we assume an average depth of 3650 m, a surface area of 0.7 x 5.1 $\cdot 10^{14}$ m^2 and a density of ρ = 1000 kg m^{-3}. For the atmosphere the mass is computed assuming an average surface pressure of 1000 hPa.

The atmosphere



NASA



The atmosphere (2)

Specific and absolute mass

$$M_A = \frac{p_S}{g} \equiv \frac{10^5 \ \mathrm{Pa}}{9.8\,\mathrm{m\,s^{-2}}} \approx 10^4 \ \mathrm{kg\,m^{-2}}$$

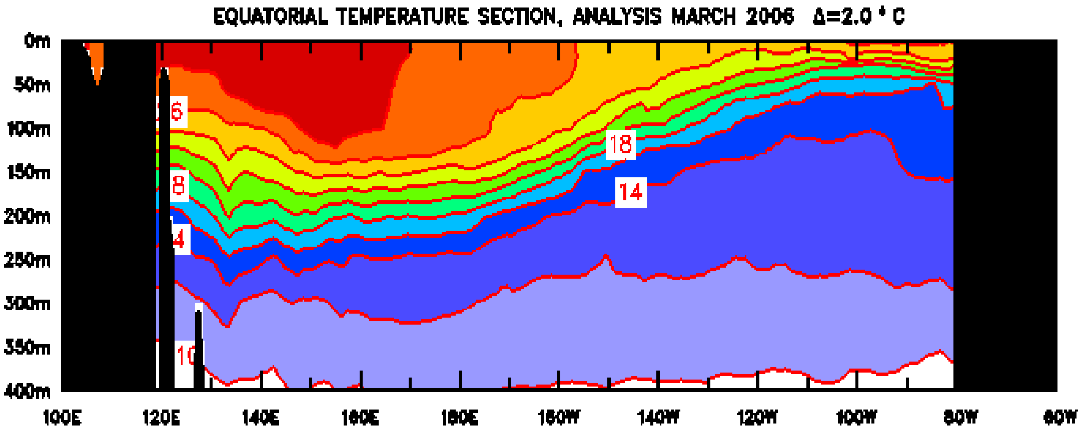
$$m_A = M_A \cdot s_E = 10^4 \ \mathrm{kg\,m^{-2}} \cdot 5.1 \cdot 10^{14} \ \mathrm{m^2} = 5.1 \cdot 10^{18} \ \mathrm{kg}$$

where

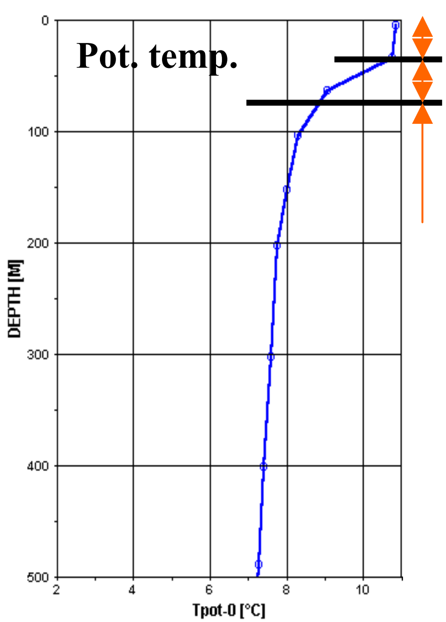
p_S = 1000 hPa, mean sea-level pressure

s_E = $5.1 \cdot 10^{14}$ m^2, Earth's surface

The ocean



Atlantic Ocean, 60 N



mixed layer: $d\theta/dz \sim 0$, $\Delta z \sim 50$ m

thermocline: $d\theta/dz < 0$, $\Delta z \sim 50$ m

deep water

The ocean (2)

Specific mass

$$M_O = \rho Z_O \approx 1000 \;\; \mathrm{kg\,m^{-3}} \cdot 3600 \;\; \mathrm{m} \approx 3.6 \cdot 10^6 \;\; \mathrm{kg\,m^{-2}}$$

$$M_{ML} = \rho Z_{ML} \sim 1000 \;\; \mathrm{kg\,m^{-3}} \cdot 100 \;\; \mathrm{m} \approx 1.0 \cdot 10^5 \;\; \mathrm{kg\,m^{-2}}$$

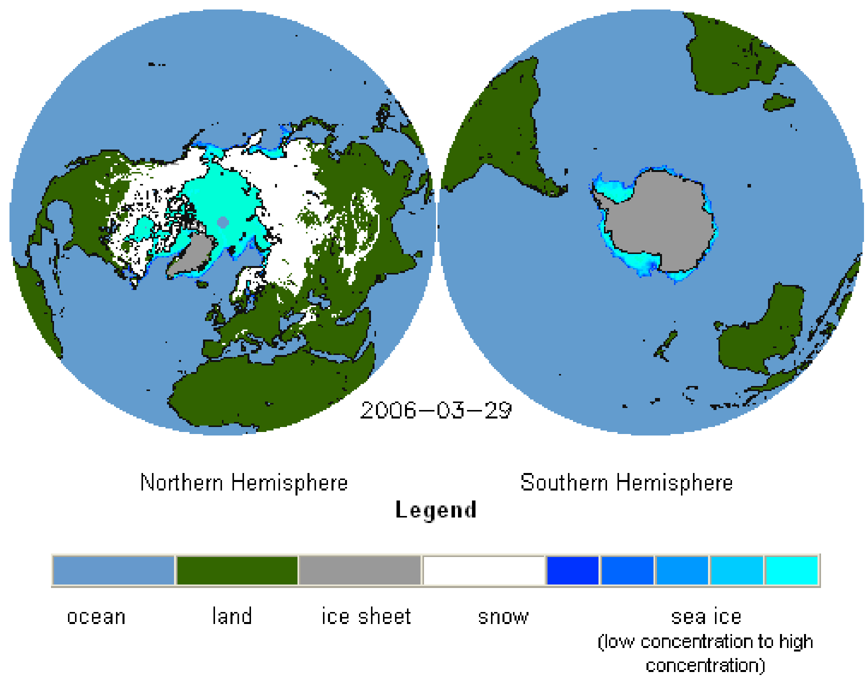
where

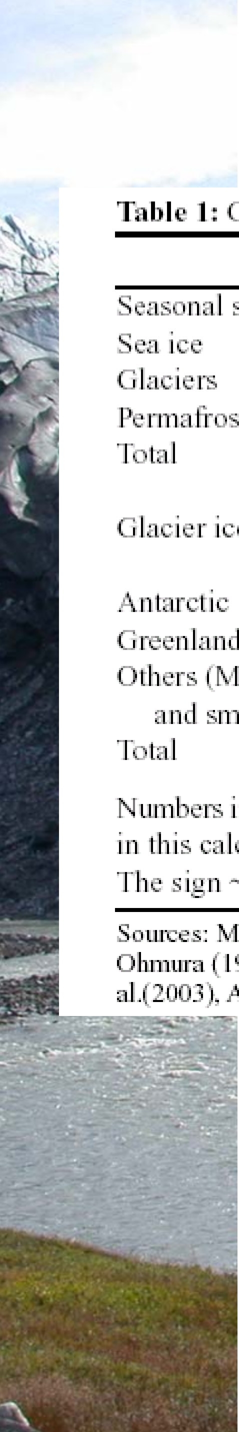
Z_O = mean depth of the oceans

Z_{ML} = depth scale of the mixed layer

The cryosphere

NSIDC





The cryosphere (2)

Table 1: Global Cryosphere Area and Volume

	Area in [10^6 km^2]	Volume
Seasonal snow cover	4 (19) ~ 46 (58)	0.5 (1) ~ 5 (6) x 10^3 km^3
Sea ice	15.0 ~ 21.5	19 ~ 25 x 10^3 km^3
Glaciers	15.9	33.1 x 10^6 km^3
Permafrost	23	0.4 x 10^6 km^3 (11-35x10^3 km^3 segregated ice)
Total	59 ~ 78 x 10^6 km^2	33.2 x 10^6 km^3
Glacier ice distribution		
	[10^6 km^2]	[10^6 km^3]
Antarctic	13.59 (86 %)	30.11 (91.0 %)
Greenland	1.75 (11 %)	2.93 (8.9%)
Others (Mountain glaciers and small ice caps)	0.51 (3%)	0.05 (0.2%)
Total	15.85 x 10^6 km^2	33.09 x 10^6 km^3

Numbers in ( ) for seasonal snow cover are areas and volumes when the snow cover on sea ice is considered. The snow cover on glaciers is excluded in this calculation.
The sign ~ indicates the range of the seasonal fluctuation., while - means the range of uncertainty.

Sources: Mercer (1967), Ommanney (1972), Field (1975), Drewry (1983), Zwally et al. (1983), Hastenrath (1984), Björnsson (1986), Parkinson et al. (1987), Ohmura (1987), Østrem et al. (1988), Chen and Ohmura (1990), Haeberli et al. (1989), Weidick (1995), Zhang et al. (2000), Bamber et al. (2001), Rikiishi et al.(2003), A. Blochkov, M. Fukuda, A. Roesch (personal communication)

Absolute and specific mass

$$m_C = \rho_{ice} \cdot V_C \approx 917 \text{ kg m}^{-3} \cdot 33 \cdot 10^6 \text{ km}^3 \cdot 10^9 \text{ m}^3 \text{ km}^{-3} = 30 \cdot 10^{18} \text{ kg}$$

$$M_C = m_C/A_C \approx 30 \cdot 10^{18} \text{ kg} \; / \; 15.9 \cdot 10^{12} \text{ m}^2 \approx 1.9 \cdot 10^6 \text{ kg m}^{-2}$$

The biosphere

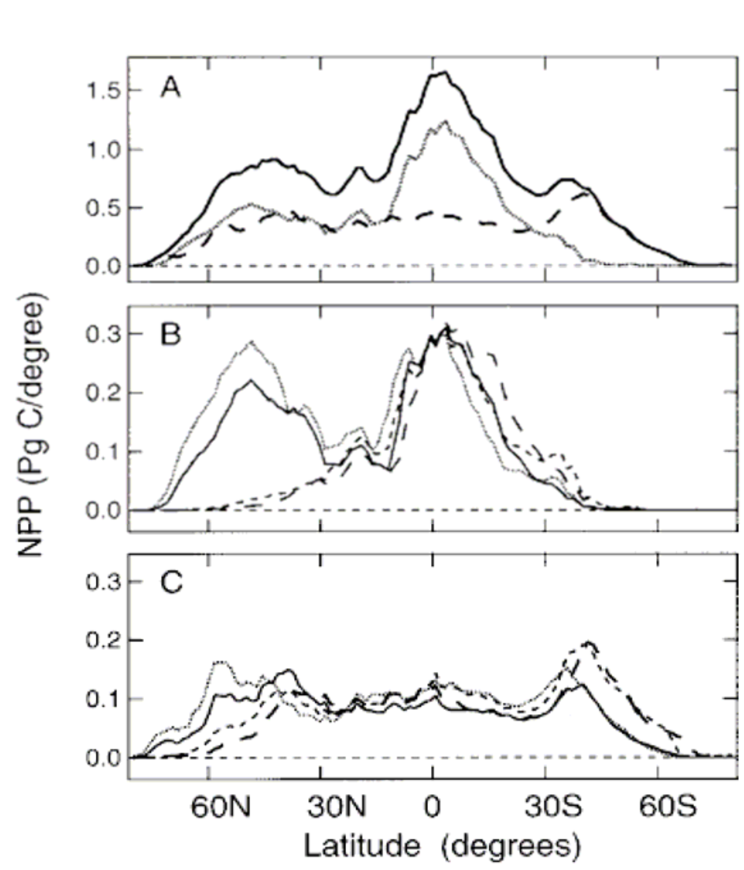
Absolute mass

$m_B \approx 2 \cdot 10^{15}$ kg

The biosphere (2)

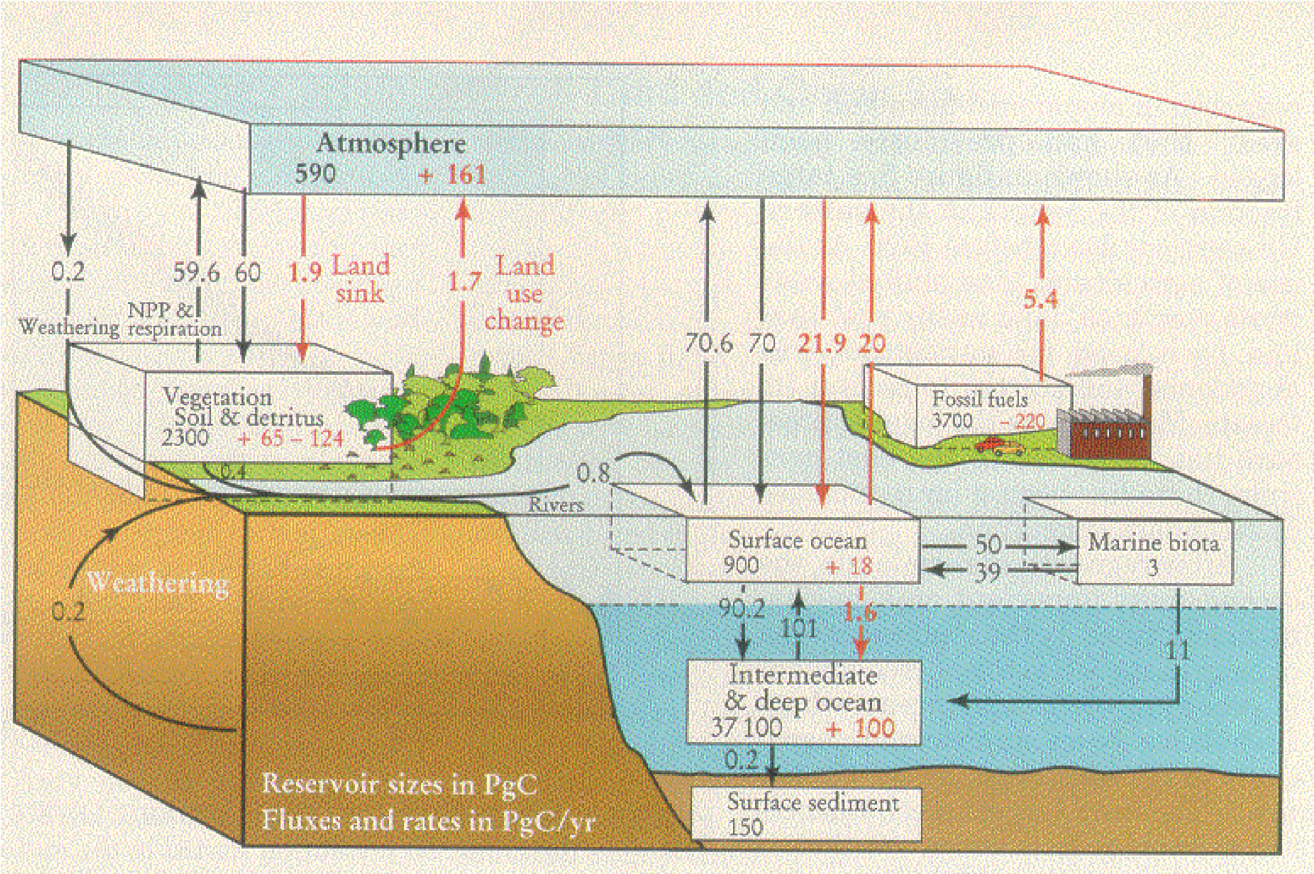
Latitudinal and seasonal variations

Fig. 2. Latitudinal distribution of the global NPP in Fig. 1. (**A**) The global total (land plus ocean) NPP (solid line), land total NPP (dotted line), and ocean total NPP (dashed line). (**B**) Land NPP: April to June (solid line), July to September (dotted line), October to December (short dashed line), and January to March (long dashed line). (**C**) Ocean NPP: The four seasonal periods are as in (B). The seasonal information is available as maps at www.sciencemag.org/feature/data/982246.shl



Field et al. (1998)

The global carbon cycle



Sarmiento and Gruber (2002)

1 Pg (petagram) ≡ 10^{15} g ≡ 10^{12} kg

Time scales (Golytsin, 1983)

We first look at the time constants for **thermal inertia** of the atmosphere and ocean. Recall:

$$\frac{dQ}{dt} = c_p M \frac{dT}{dt}$$

where

dQ/dt	=	heat added or subtracted per unit area and time
c_p	=	specific heat
M	=	mass per unit area (i.e. specific mass)
dT/dt	=	change in temperature per unit time

Assume now that

$$\frac{dT}{dt} \sim \frac{T_{eff}}{\tau}$$

where

T_{eff}	=	effective temperature
τ	=	time constant

Time scales (2)

It follows that

$$\tau \sim \frac{T_{eff}}{dT/dt} = \frac{c_p\, M\, T_{eff}}{dQ/dt}$$

We further assume that

$$\frac{dQ}{dt} = \frac{S_o}{4}\left(1 - \alpha_P\right) = 342 \cdot 0.7 \ \mathrm{W\,m^{-2}} = 240 \ \mathrm{W\,m^{-2}}$$

where

S_o = 1368 W m^{-2} is the solar constant

α_P = 0.3 is the planetary albedo

Time scales (3)

Atmosphere

$M_A \;=\; 10^4 \text{ kg m}^{-2}$

$T_A \;=\; 255 \text{ K}$

$c_{pa} \;=\; 1005 \text{ J kg}^{-1} \text{ K}^{-1}$

$$\Rightarrow \tau_A = \frac{c_{pa} M_A T_A}{dQ/dt} \approx \frac{255 \cdot 10^7}{240} \approx 10^7 \text{ s} \sim \underline{\underline{100 \text{ d}}}$$

Ocean, mixed layer

$M_{ML} = 10^5 \text{ kg m}^{-2}$

$T_{ML} = 288 \text{ K}$

$c_{pw} = 4184 \text{ J kg}^{-1} \text{ K}^{-1}$ (pure water); $3930 \text{ J kg}^{-1} \text{ K}^{-1}$ (salinity of 30 ‰);

$$\Rightarrow \tau_{ML} = \frac{c_{pw} M_{ML} T_{ML}}{dQ/dt} \approx \frac{288 \cdot 4 \cdot 10^8}{240} \approx 5 \cdot 10^8 \text{ s} \sim \underline{\underline{15 \text{ yr}}}$$

Time scales (4)

As pointed out by Golitsyn, the exchange of water between the thermocline and the upper mixed layer takes place at a velocity of the order of 50 m yr^{-1}. The depth of the thermocline varies with latitude and season. Assume that it is of the order of 500 m.

It follows that the time for the mixed layer to reach equilibrium with the thermocline is:

$$\tau_{ML/TC} \sim \frac{500\text{ m}}{50\text{ m yr}^{-1}} \sim \underline{\underline{10\text{ yr}}}$$

This is comparable to the time scale derived before.

Because heated from above, the ocean is almost everywhere stably stratified. The coefficient of turbulent vertical mixing is only of the order of K ~ 1 $cm^2\ s^{-1}$. The mean depth of the ocean is $Z_O \sim 4$ km. Therefore:

$$\tau_O \sim \frac{{Z_O}^2}{K} = \frac{16 \cdot 10^6\text{ m}^2}{10^{-4}\text{ m}^2\text{ s}^{-1}} \sim \underline{\underline{5 \cdot 10^3\text{ yr}}}$$

Time scales (5)

Cryosphere

The heat required to melt 1 kg of ice at 0 °C is $L_f = 0.334 \cdot 10^6$ J kg^{-1} (latent heat of fusion).

The summer radiation balance of the high latitudes is $SW_{net} \sim 60$ W m^{-2}.
The time required to melt 2 km of ice ($33.09 \cdot 10^6$ km^3 / $15.85 \cdot 10^6$ km^2) with a specific mass of $1.9 \cdot 10^6$ kg m^{-2} is:

$$\tau_C \approx \frac{L_f\ M_C}{SW_{net}} \sim \frac{0.334 \cdot 10^6\ \mathrm{J\,kg^{-1}}\ 1.9 \cdot 10^6\ \mathrm{kg\,m^{-2}}}{60\ \mathrm{W\,m^{-2}}} \approx 1 \cdot 10^{10}\ \mathrm{s} \sim \underline{\underline{300\ \mathrm{yr}}}$$

But this only represent a lower bound, because:

- the cryosphere continuously receives new mass during winter (accumulation, i.e. precipitation);
- most of the cryosphere is not at 0 °C;
- dynamical processes (ice flow) are important.

The typical time scale is therefore more like $\tau_C \sim 10^4$ yr.