

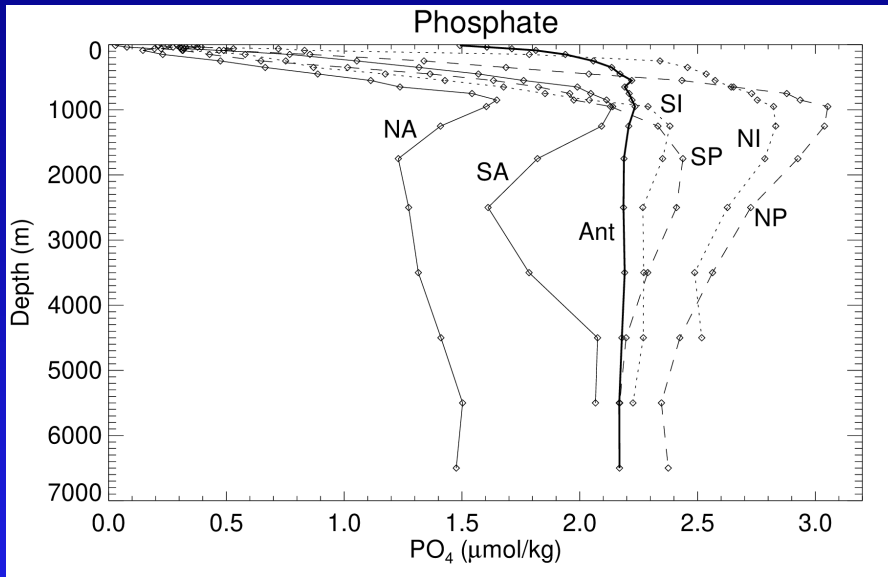
THE OCEAN CARBON CYCLE

21st February 2024

- 1 Box-model of the global ocean
phosphorus, alkalinity, carbon
- 2 Pre-industrial model
- 3 Evolution during the industrial period
- 4 ^{13}C isotopic evolution

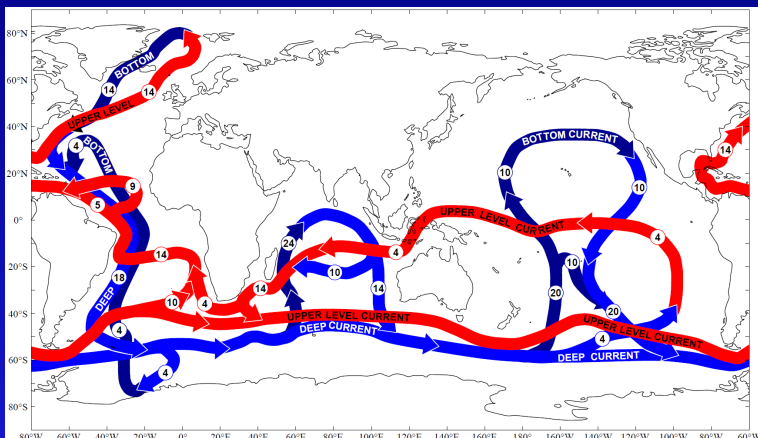
**BOX-MODEL OF
THE GLOBAL OCEAN
Phosphorus, Alkalinity, Carbon**

PHOSPHATE DISTRIBUTION IN THE OCEAN

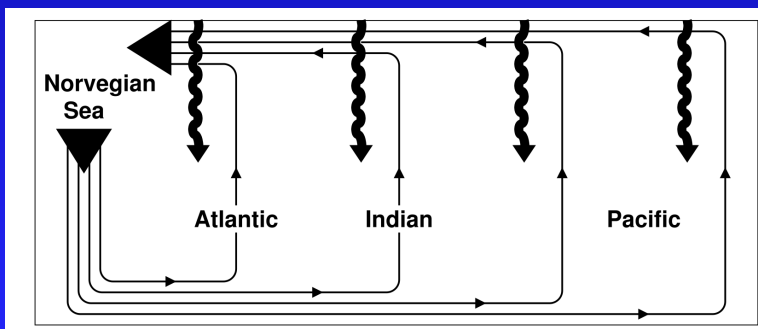


Ant – Antarctic; •A – Atlantic; •I – Indian; •P – Pacific;
N• and S• – Northern and Southern parts of •, resp.

THERMOHALINE CIRCULATION

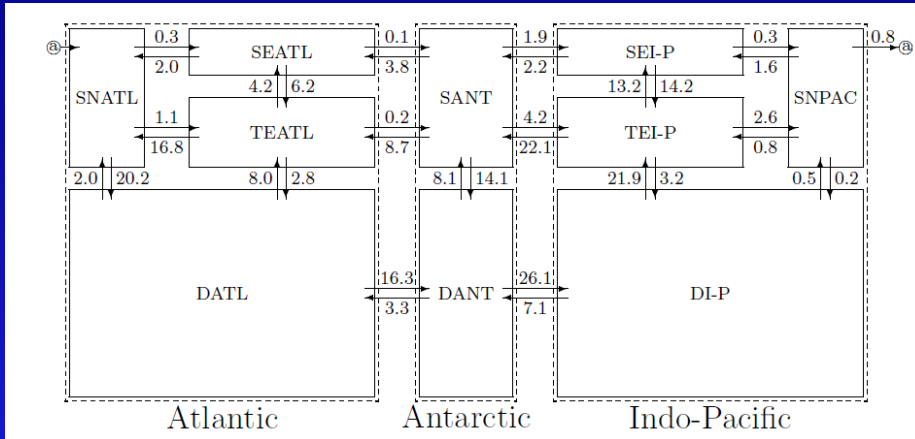


surface-to-deep-sea gradient



inter-basin gradient

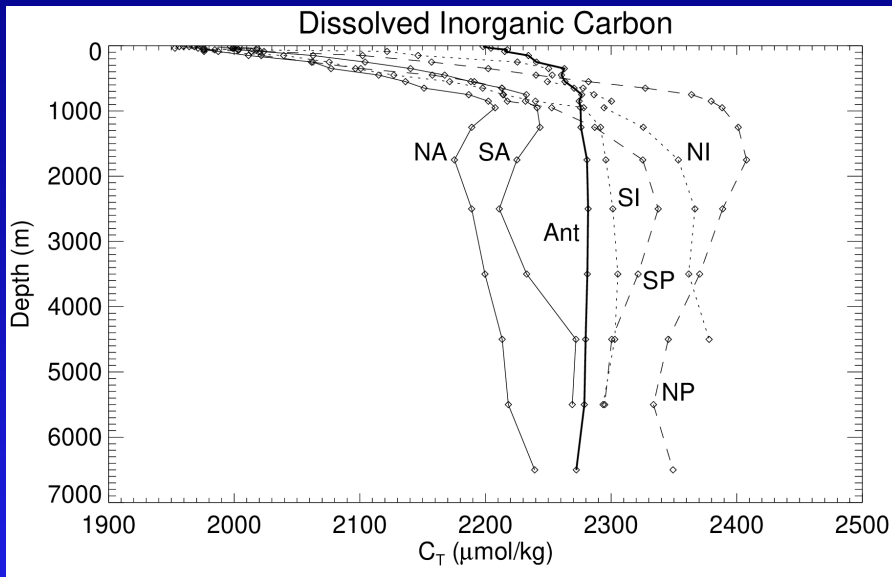
MODEL STRUCTURE



Water fluxes in Sverdrup (Sv):
1 Sv = $10^6 \text{ m}^3 \text{ s}^{-1}$

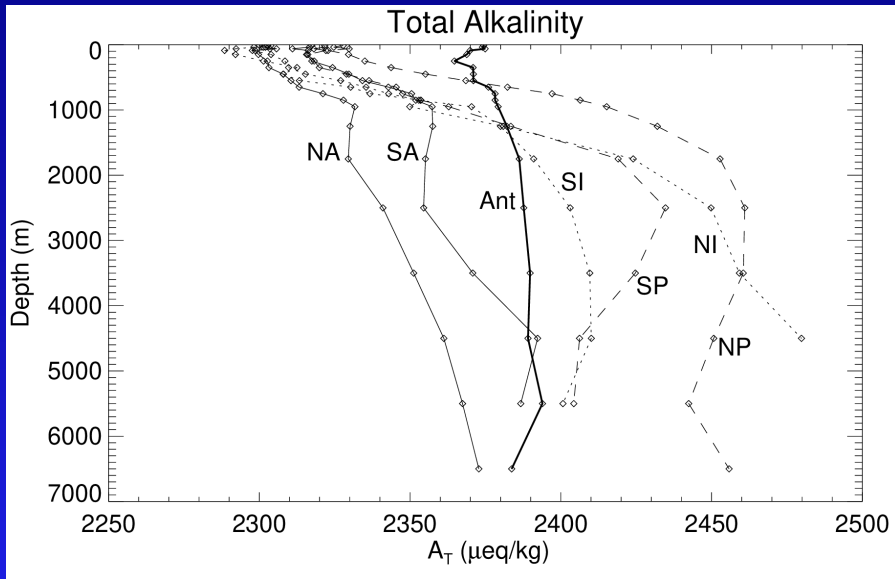
Basin	Input flux (m ³ /yr)	Output flux (m ³ /yr)	Reservoir budget (m ³ /yr)	Turnover Time (yr)
1 SNATL	0.68117760E+15	0.68117760E+15	0.00000000E+00	17.62
2 SEATL	0.26174880E+15	0.26174880E+15	0.00000000E+00	22.92
3 SANT	0.10312272E+16	0.10312272E+16	0.00000000E+00	70.79
4 SEI-P	0.52665120E+15	0.52665120E+15	0.00000000E+00	34.18
5 SNPAC	0.10722240E+15	0.10722240E+15	0.00000000E+00	121.24
6 TEATL	0.75686400E+15	0.75686400E+15	0.00000000E+00	72.67
7 TEI-P	0.12961296E+16	0.12961296E+16	0.00000000E+00	120.36
8 DATL	0.82939680E+15	0.82939680E+15	0.00000000E+00	245.96
9 DANT	0.11826000E+16	0.11826000E+16	0.00000000E+00	184.34
10 DI-P	0.93031200E+15	0.93031200E+15	0.00000000E+00	628.82

DIC DISTRIBUTION IN THE OCEAN



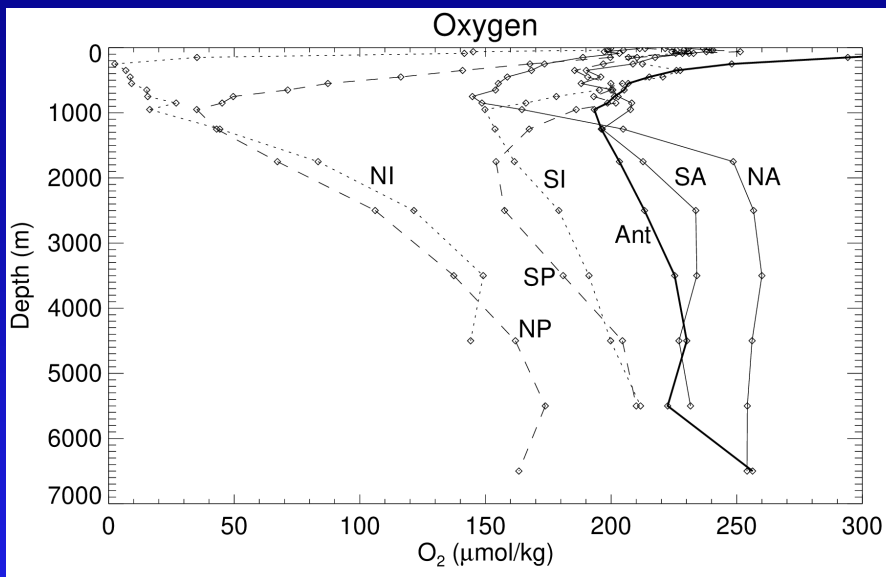
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ALKALINITY DISTRIBUTION IN THE OCEAN



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OXYGEN DISTRIBUTION IN THE OCEAN

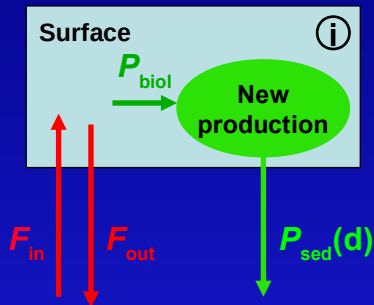


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PRE-INDUSTRIAL MODEL

PHOSPHORUS: PRODUCTIVITY CONTROL

Surface boxes



Input Fluxes:

$$F_{in} = \sum_j w_{ji} c_j \quad (\text{advection}) \quad \text{with } c_i = Q_i/V_i$$

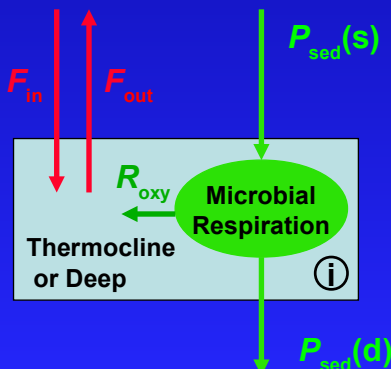
Output Fluxes:

$$F_{out} = \left(\sum_j w_{ij} \right) c_i \quad (\text{advection})$$

$$P_{sed}(d) = P_{biol} = \Phi_{ut} \cdot F_{in} \quad (\text{new production})$$

→ Φ_{ut} lower at high latitudes

Thermocline and deep boxes



Input Fluxes:

$$F_{in} = \sum_j w_{ji} c_j \quad (\text{advection})$$

$$R_{oxy} = k_{oxy} \cdot P_{sed}(s) \quad (\text{microbial respiration})$$

$$P_{sed}(d) = P_{sed}(s) - R_{oxy}$$

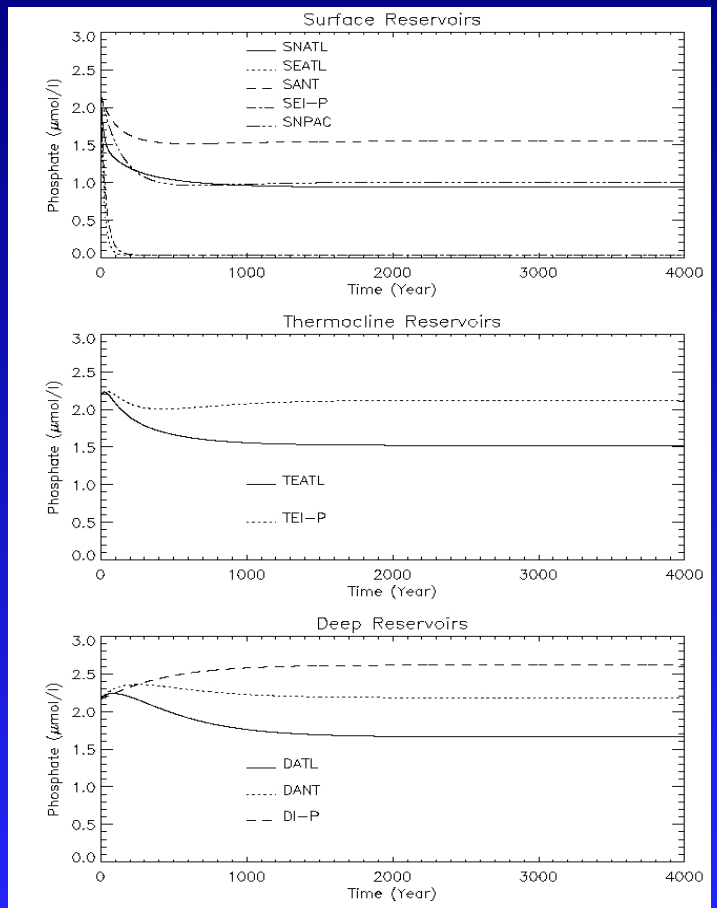
Output Fluxes:

$$F_{out} = \left(\sum_j w_{ij} \right) c_i \quad (\text{advection})$$

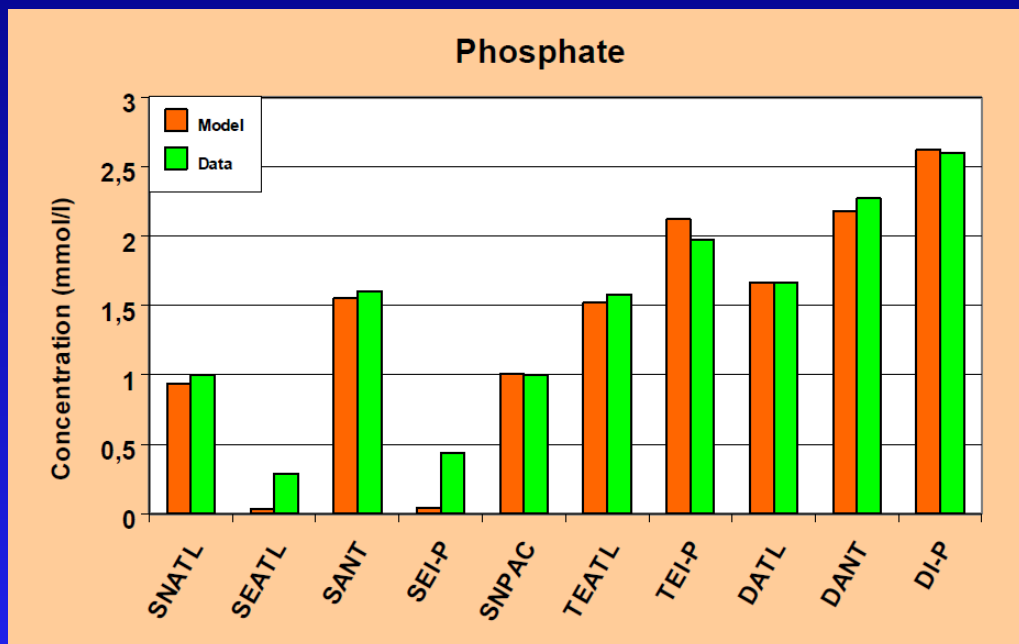
PRE-INDUSTRIAL STEADY-STATE SOLUTION (PHOSPHORUS)

→ Integration: 4000 years

→ Initial conditions:
Homogeneous ocean
($c = 2.164 \mu\text{mol P/litre}$)



COMPARISON WITH DATA: PHOSPHORUS



Data: Geosecs ('70)

CARBON AND ALKALINITY

- Model linked to the phosphorus model through the usage elemental ratios
- At the **surface**: C_{org} and $CaCO_3$ (aragonite/calcite) production
 - C_{org} : $C/P = 106/1$ (Redfield)
 - $CaCO_3$: $r_{carb} = CaCO_3/C_{org}$ (adjustable parameter)
- In the **thermocline**: partial oxidation of C_{org} (→ k_{oxy})
 - $C/P = 106/1$ (Redfield)
- At **depth**:
 - oxidation of the remaining C_{org} (→ $1-k_{oxy}$)
 - dissolution of $CaCO_3$
- In each box: **pH calculation and carbonate speciation**
- **Exchange with the atmosphere** in each surface reservoir i :
 - $F_{ao} = k_{ao} \cdot area(i) \cdot (pCO_2 - pCO_2(i))$

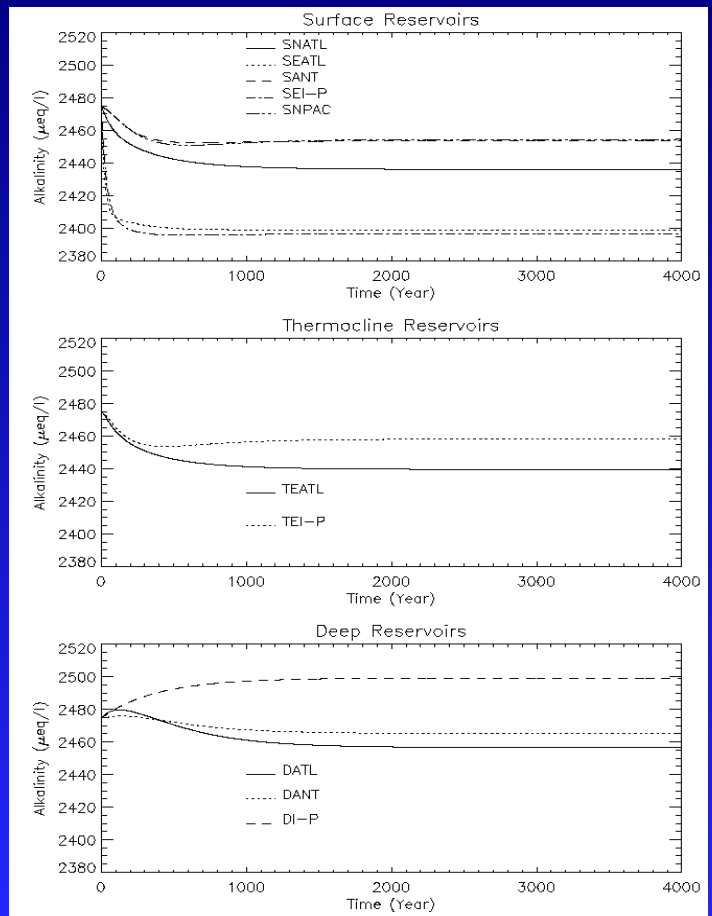
PRE-INDUSTRIAL STEADY-STATE SOLUTION (ALKALINITY)

→ integration: 4000 years

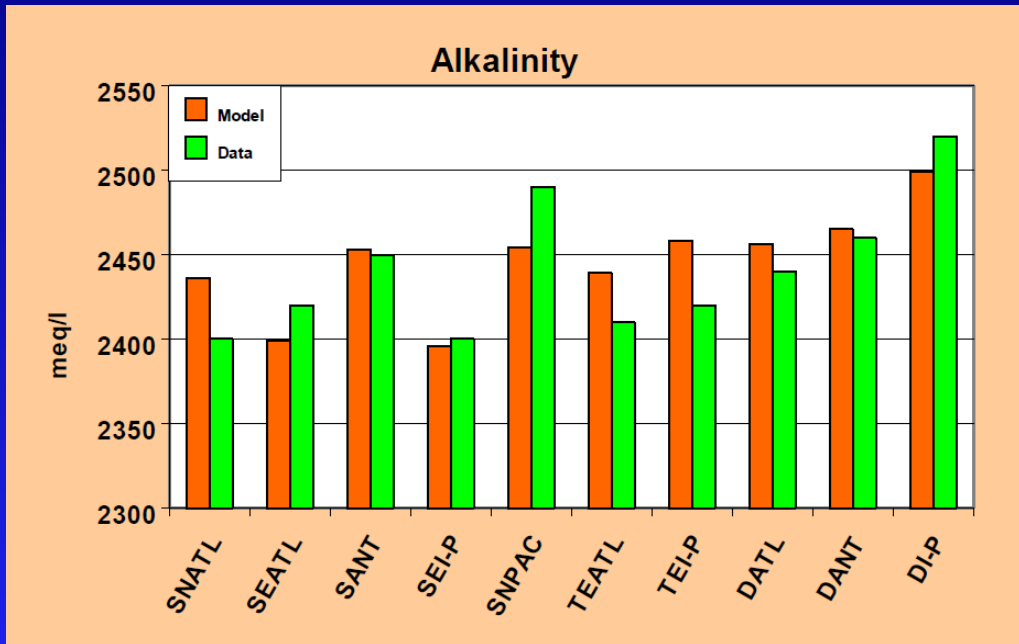
→ initial conditions: homogeneous ocean (Alk = 2474 $\mu eq/litre$)

→ $r_{carb} = CaCO_3/C_{org}$

$$= \begin{cases} 0.15 \text{ (equator. box)} \\ 0.02 \text{ (polar boxes)} \end{cases}$$

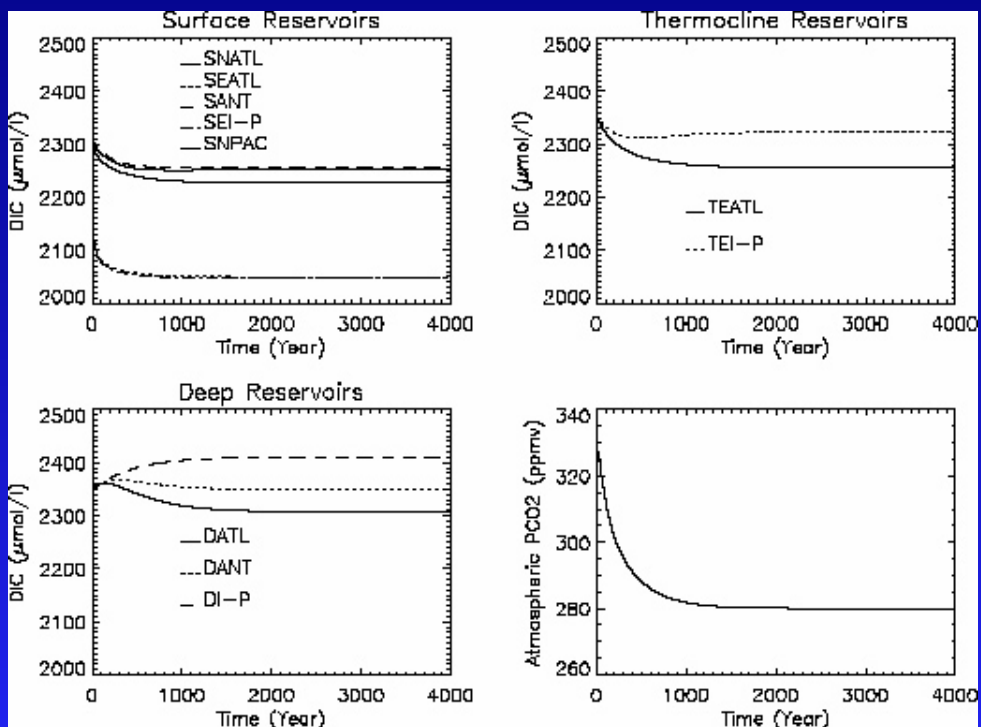


COMPARISON WITH DATA: ALKALINITY



Data: Geosecs ('70)

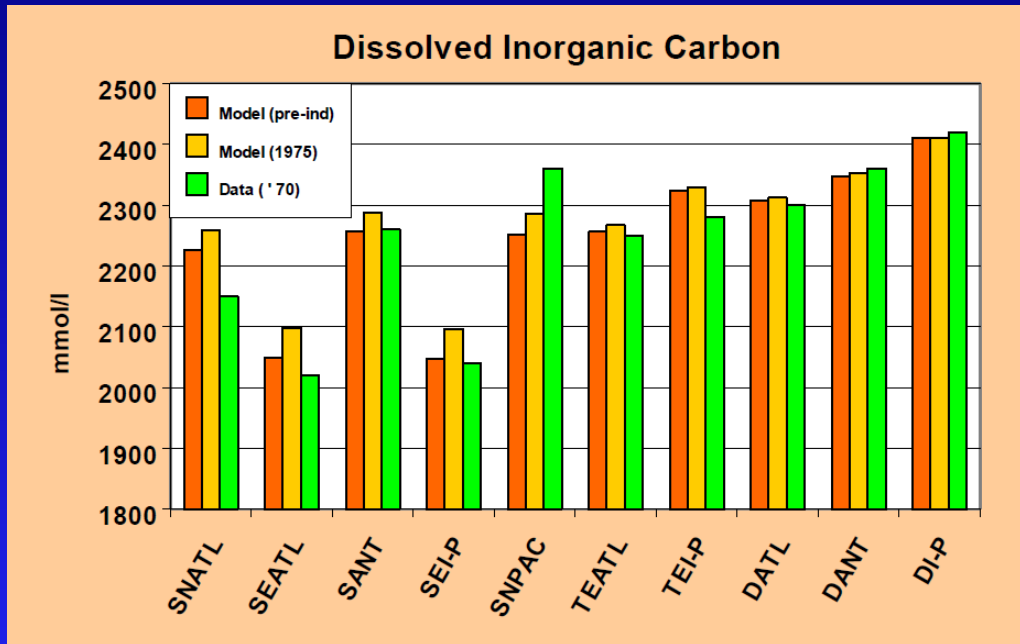
PRE-INDUSTRIAL STEADY STATE (CARBON)



Initial conditions:

Homogeneous ocean (DIC = 2350 µmol/l), pCO₂(atm) = 280 ppmv

COMPARISON WITH DATA: CARBON

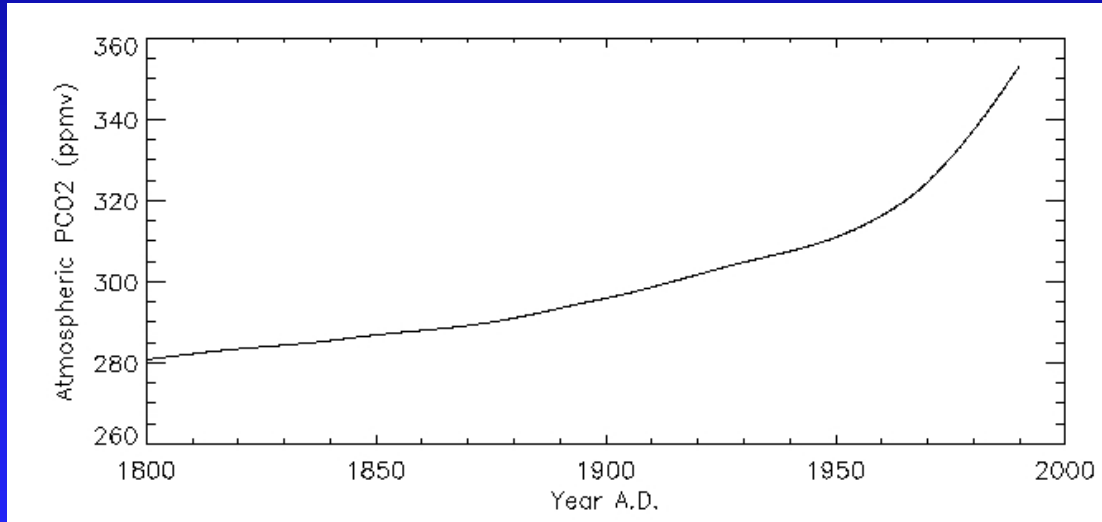


Data: Geosecs ('70)

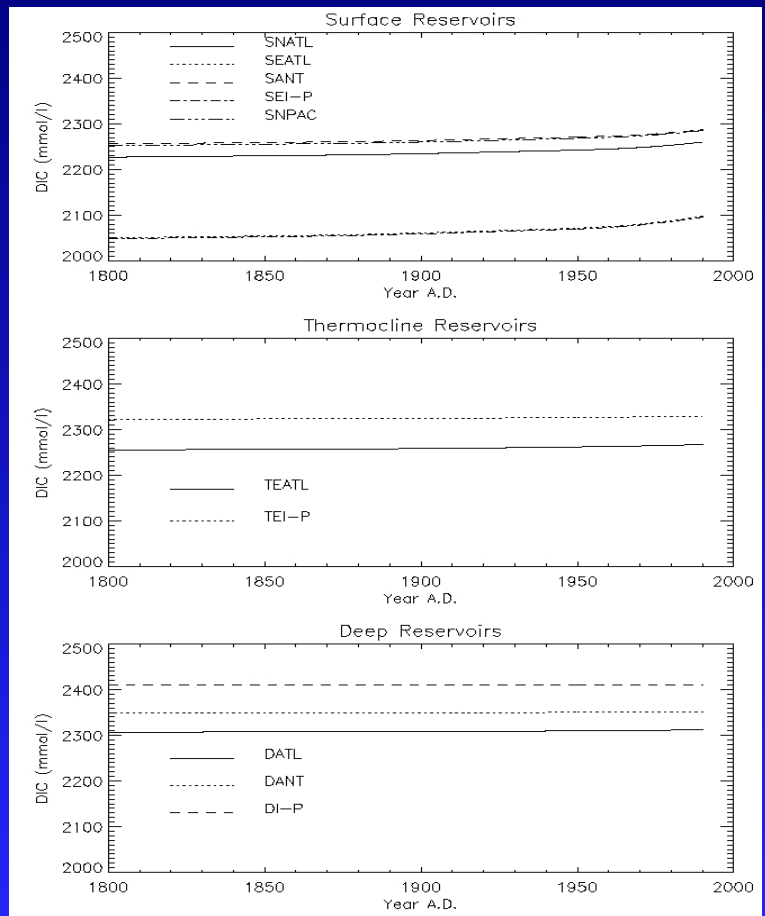
**EVOLUTION DURING
THE INDUSTRIAL PERIOD**

FORCING OF THE MODEL FOR THE INDUSTRIAL PERIOD

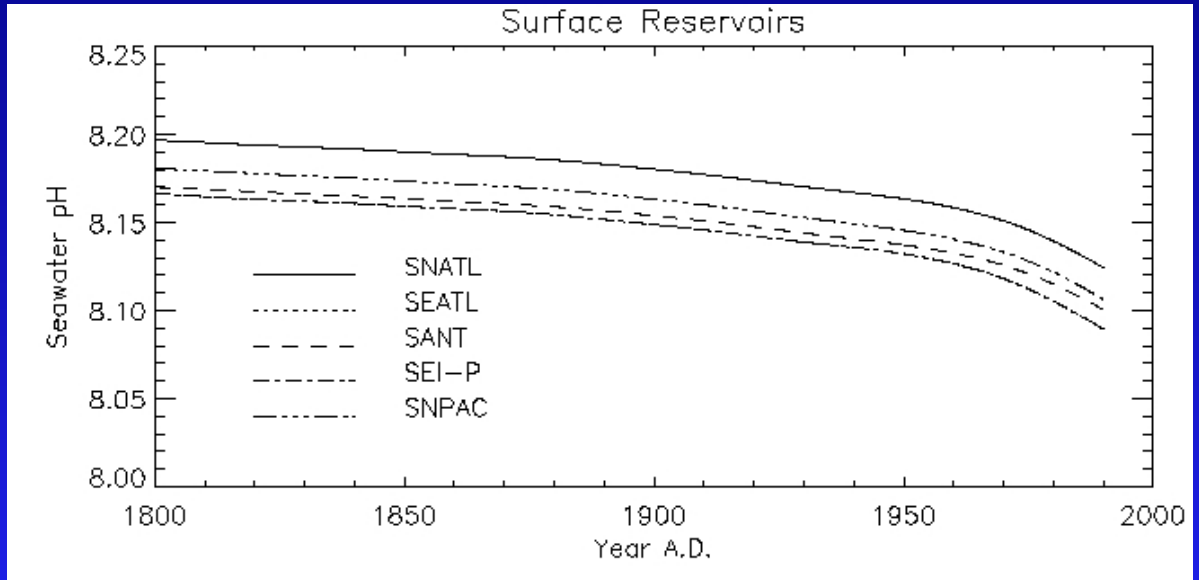
- Initial conditions in 1800 provided by the previously calculated pre-industrial steady state
- Evolution of atmospheric CO₂ prescribed from 1800 to 1990



EVOLUTION OF DISSOLVED INORGANIC CARBON

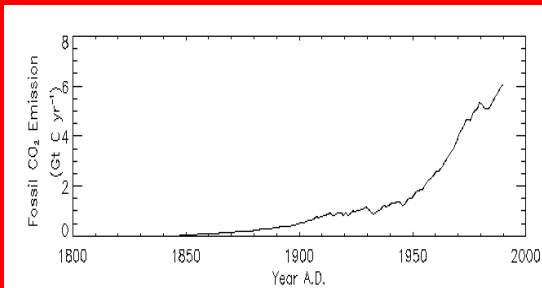


EVOLUTION OF pH IN THE SURFACE RESERVOIRS

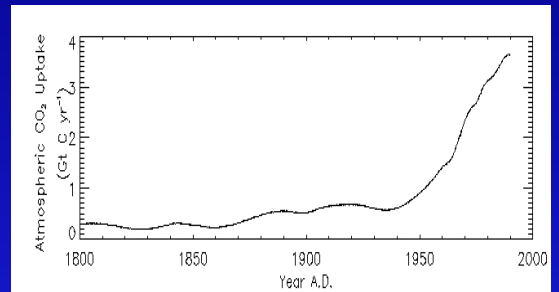


FLUX BALANCE OF ATMOSPHERIC CO₂ FOR THE INDUSTRIAL PERIOD

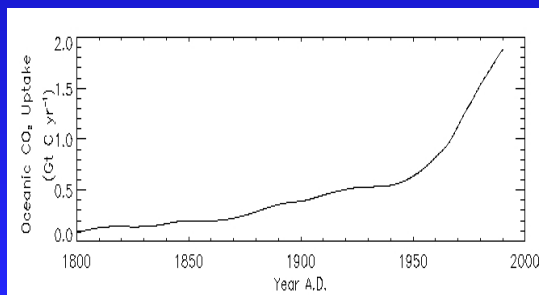
Fossil fuel CO₂ emissions



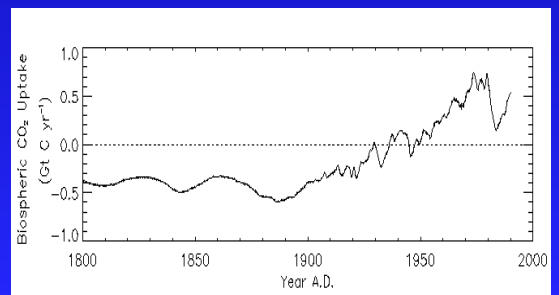
Rate of change in the atmosphere (dpCO₂/dt)



Transfer to the ocean (model)



Transfer to the biosphere (by difference)



ATMOSPHERIC CO₂ BALANCE (1980-1990) (Gt C yr⁻¹)

SOURCES

	This work	IPCC 1995
Fossil fuels & cements	5.44	5.5 ± 0.5
Land-use change	1.57	1.6 ± 1.0
<i>Total</i>	<i>7.01</i>	<i>7.1 ± 1.0</i>

SINKS

Atmosphere	3.40	3.3 ± 0.2
Ocean (Model)	1.71	2.0 ± 0.8
<i>Difference (→ terrestrial biosphere)</i>	<i>1.90</i>	<i>1.8 ± 1.5</i>

¹³C ISOTOPIC EVOLUTION

CARBON ISOTOPES

Three naturally occurring carbon isotopes:

$^{12}\text{C} \sim 98.94 \pm 0.10\%$

$^{13}\text{C} \sim 1.06 \pm 0.10\%$

^{14}C (radiogenic, radioactive) trace amounts

where:

C_i = carbon content of reservoir i

F_{ji} = flux entering reservoir i (from reservoir j)

F_{ij} = flux leaving reservoir i (for reservoir j)

δ_i = $\delta^{13}\text{C}$ of the carbon in reservoir i

δ_{ji} = $\delta^{13}\text{C}$ of flux F_{ji} (into reservoir i)

δ_{ij} = $\delta^{13}\text{C}$ of flux F_{ij} (out of reservoir i)

Notice: output fluxes only have to be considered if they are subject to fractionation, i. e., if $\Delta = \delta_{ij} - \delta_i \neq 0$

ISOTOPIC EVOLUTION EQUATION

The equation describing the evolution of the isotopic composition of a reservoir i in time can be written (approximation):

$$d\delta_i / dt = [\sum_{j \neq i} F_{ji} (\delta_{ji} - \delta_i) - \sum_{j \neq i} F_{ij} (\delta_{ij} - \delta_i)] / C_i$$

where:

C_i = carbon content of reservoir i

F_{ji} = flux entering reservoir i (from reservoir j)

F_{ij} = flux leaving reservoir i (for reservoir j)

δ_i = $\delta^{13}\text{C}$ of the carbon in reservoir i

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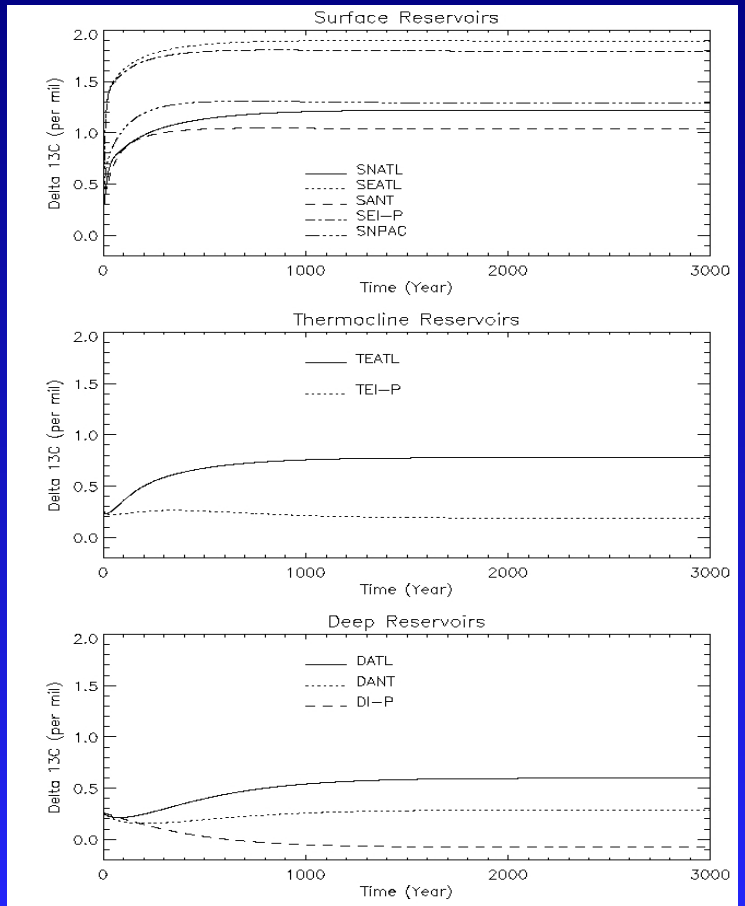
δ_{ij} = $\delta^{13}\text{C}$ of flux F_{ij} (out of reservoir i)

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PRE-INDUSTRIAL STEADY-STATE SOLUTION ($\delta^{13}\text{C}$)

→ integration: 3000 years

→ initial conditions:
homogeneous ocean
($\delta^{13}\text{C} = 0.259 \text{ ‰}$)



EVOLUTION OF $\delta^{13}\text{C}$ DURING THE INDUSTRIAL PERIOD (coupled ocean-atmosphere-biosphere model)

