Past & present ocean radiocarbon distributions with NEMO

A. Mouchet[1], Ch. Ethé[2], J.-C. Dutay[2], and J. Orr[2]

[1] ULiege, Liège, Belgium; [2] LSCE, CEA/CNRS/UVSQ/IPSL, Gif-Sur-Yvette, France

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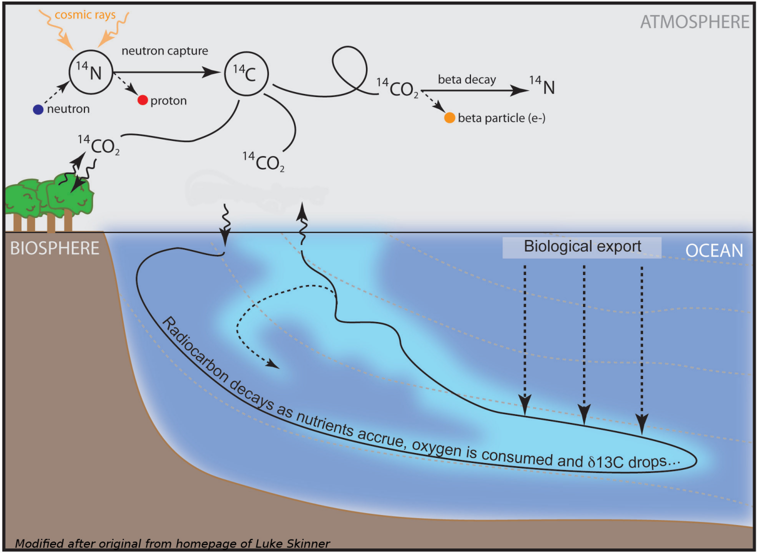
Why radiocarbon?

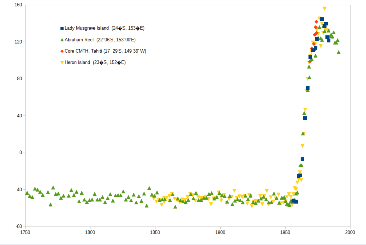


Radiocarbon: half-life 5730 yr; abundancy: ~ 1 every 10^{12} C atom

Why radiocarbon?

OGCM assessment

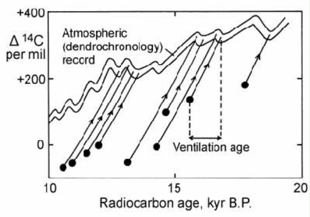
- deep ventilation rate (e.g., Maier-Reimer, 1993)
- air-sea exchange rate (e.g., Wanninkhof, 1992)
- shallow-to-deep ocean exchange (e.g., Graven et al.,2012)



Druffel and Griffin, 2004

Paleo studies: deep ocean ventilation rate

- Coexisting Planktonic & Benthic forams
- Planktonic ⇒ calendar age
- **Ventilation** age:
  - B-P radiocarbon age difference
  - Projection age method



Modeling $\Delta^{14}\mathrm{C}$

$^{14}\mathrm{R}$ = purely physical tracer

$$\frac{\partial}{\partial t}\,{}^{14}\mathrm{R} = -\,\nabla\cdot\left(\mathbf{u}\,{}^{14}\mathrm{R} - \mathbf{K}\cdot\nabla\,{}^{14}\mathrm{R}\right) - \lambda\,{}^{14}\mathrm{R}$$

$$\Delta^{14}\mathrm{C} = \left({}^{14}\mathrm{R}/{}^{14}\mathrm{R}_{\mathrm{STD}} - 1\right) 10^{3} \quad \& \quad {}^{14}\mathrm{R} = {}^{14}\mathrm{C}/\mathrm{C}$$

- biological activity and fractionation factors are ignored
- **Local** air-sea $\mathrm{CO_2}$ equilibrium ($\mathrm{C_T}$ homogeneous and constant)

Air-sea boundary condition:

$$\mathcal{F} = \frac{\kappa_{\mathrm{CO_2}} K_H}{\overline{\mathrm{C_T}}}\, \mathrm{p}^{\mathrm{a}}_{\mathrm{CO_2}} \left({}^{14}\mathrm{R}_{atm} - {}^{14}\mathrm{R}\right)$$

Modeling $\Delta^{14}C$: methods

- Equilibrium, long timescales, deep ocean
  - "$\Delta^{14}C$ contours are insensitive to the formulation of the biota model" (Bacastow and Maier-Reimer, 1990)
  - "$\Delta^{14}C$ contours are insensitive to the formulation of the air-sea flux: complete vs simplified" (Mouchet, 2011, 2013)
- Bomb transient
  - Simplified method: underestimates the actual bomb inventory (Mouchet, 2013)
  - Biota:
    Global bomb inventories are insensitive to the formulation of the biota model (Mouchet, 2011)
    Local inventory differences: very productive areas (CO_2 flux sign; Mouchet, 2011) $\Rightarrow$!!! to further investigate !!!
  - **Data**: underestimate actual inventory (Naegler, 2009)

Modeling; NEMO C14 package

Air-sea boundary condition:

$$\mathcal{F} = \frac{\kappa_{CO_2} K_H}{\overline{C_T}} \, p^{a}_{CO_2} \, ({}^{14}R_{atm} - {}^{14}R)$$

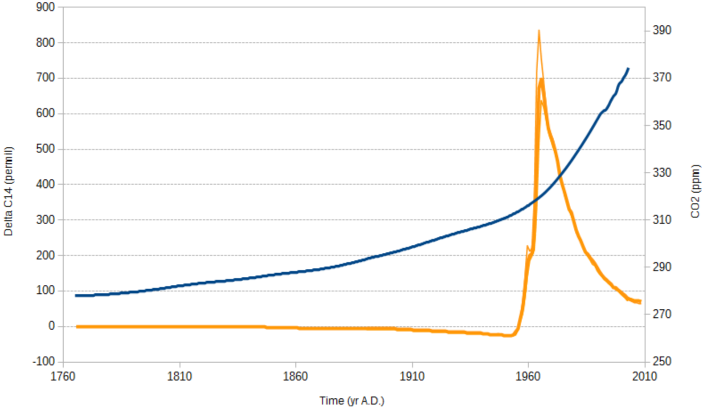
$$\kappa_{CO_2} = \left(K_W \, w^2 + b\right) \, (1 - f_{ice}) \, \sqrt{660/Sc}$$

Sc Schmidt number; coefficients from Wanninkhof (2014).
K_H: CO_2 solubility based on Weiss (1974).
K_H and Sc are computed with the OGCM temperature and salinity fields

Parameters intervening in the air-sea exchange rate are set in *namelist_c14*:

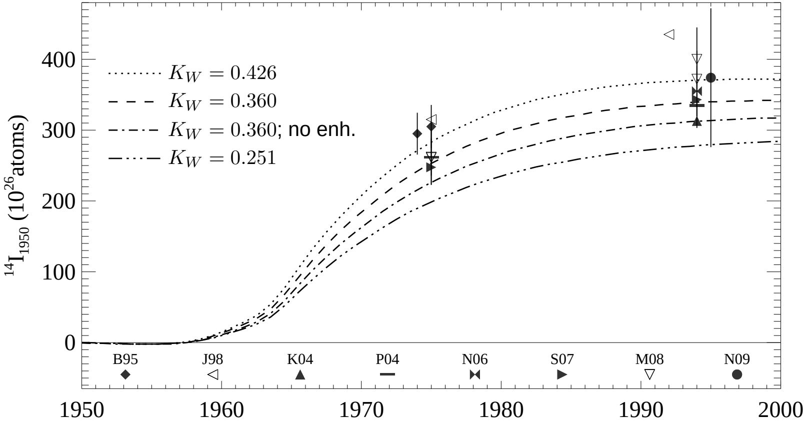
- Empirical coefficient K_W depends on the wind field and on the model upper ocean mixing rate (Toggweiler et al., 1989; Wanninkhof, 1992, 2014; Naegler, 2009). It should be adjusted so that the globally averaged CO_2 piston velocity is $\kappa_{CO_2} = 16.5 \pm 3.2$ cm/h (Naegler, 2009).
- The reference DIC concentration $\overline{C_T}$ is classically set to 2 mol m^{-3} (Toggweiler et al., 1989; Orr et al., 2001; Butzin et al., 2005).
- Chemical enhancement may be set on/off by means of a logical variable.

Anthropogenic perturbation

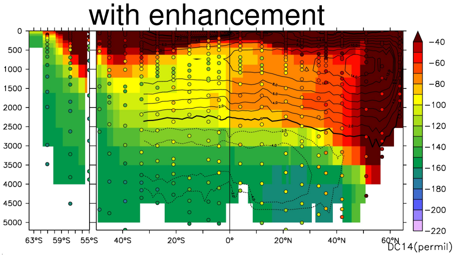


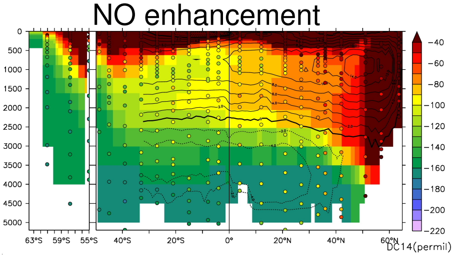
Orr et al., 2017

Bomb radiocarbon inventory



Modern $\Delta^{14}C$ distributions in the Atlantic

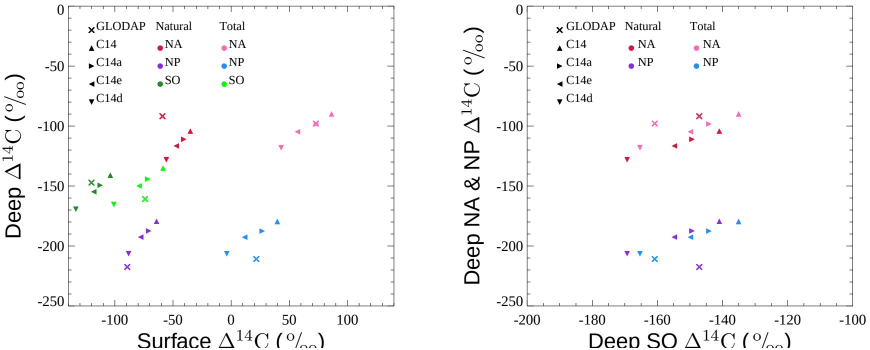




Too weak & shallow NADW

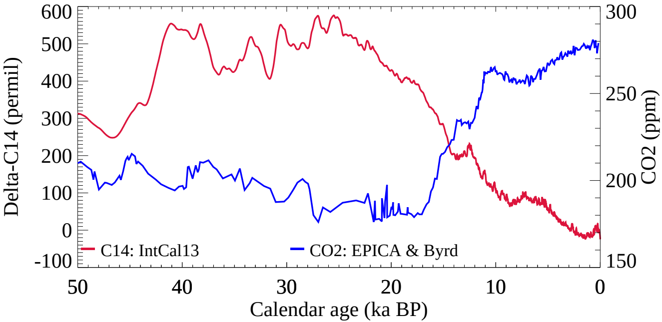
GLODAP data (Key et al., 2004)
standard NEMO v3.6
wind fields: ERA40

Pre-bomb & modern distributions



GLODAP data (Key et al., 2004)
standard NEMO v3.6
wind fields: ERA40

Paleo radiocarbon



$\Delta^{14}C$ IntCal13

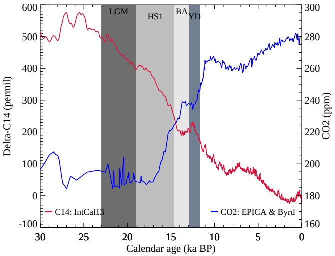
Reimer & al. (2013)

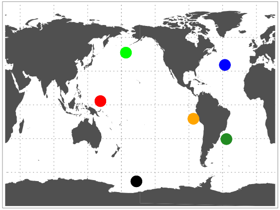
CO_2 EPICA Dome C (Monnin & al. 2004)

Byrd (Ahn & Brook, 2008)

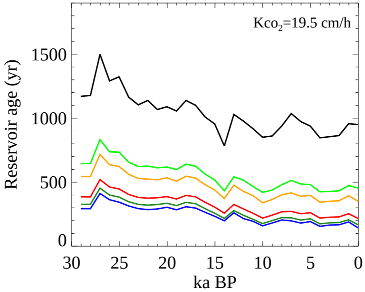
Reservoir age evolution – Steady-state ocean

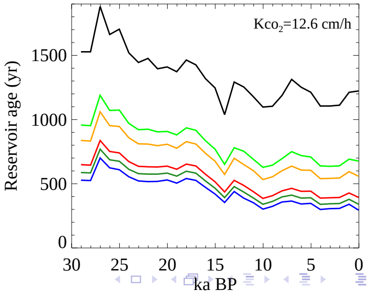
$$\mathcal{F} = \frac{\kappa_{CO_2} K_H}{\overline{C_T}} \, p^{a}_{CO_2} \left({}^{14}R_{atm} - {}^{14}R \right)$$



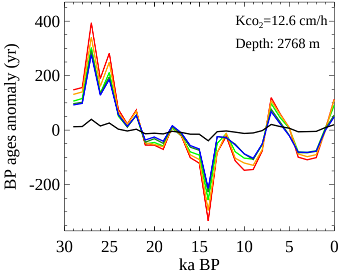


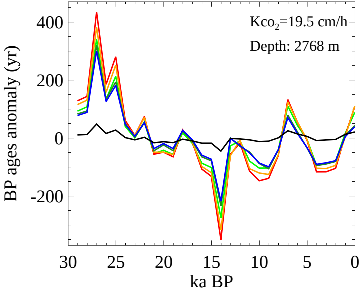
Off-line NEMO-OGCM, present-day circulation

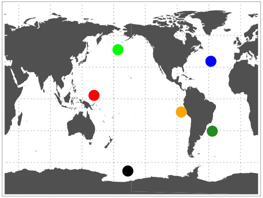




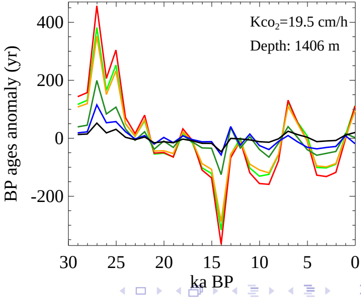
B-P ages evolution – ‘Steady-state’ ocean





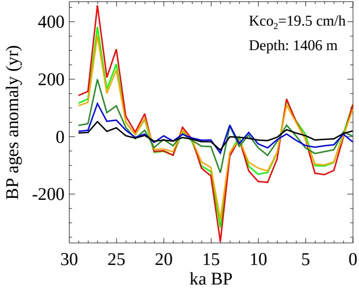


Off-line NEMO-OGCM, present-day circulation



Mouchet et al. (in prep.)

B-P ages evolution – 'Steady-state' ocean



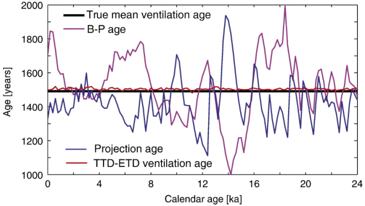
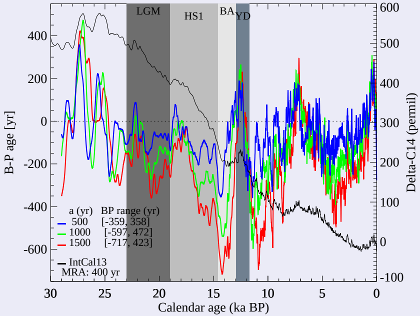


Fig. 3 from DeVries & Primeau (2010)

$$\boldsymbol{\theta}_{BP} = -8267. \log\left({}^{14}\mathrm{R}_B(t-a)/{}^{14}\mathrm{R}_P(t)\right)$$



Actual correction $\neq$ 'projection' age

Air-sea exchange rate (CO_2) changes & multiplicity of pathways

Mouchet et al. (in prep.)

NEMO C14 package

Modeling

- Simplified Radiocarbon formulation (Fiadeiro, 1982)
- Schmidt , solubility, air-sea exchange rates computed with model physics
- Flexibility:
  parameters, dates, atmospheric scenarios set in namelist
- Complete description in NEMO-v4 guide

Applications

- Equilibrium $\Delta^{14}\mathrm{C}$
- Transient $\Delta^{14}\mathrm{C}$ (atmospheric $\Delta^{14}\mathrm{C}$ & $\mathrm{CO_2}$ scenarios)
  - Bomb (initial state from Eq.)
  - Perturbation (from C14b)
  - Future scenarios
  - Paleo-studies (!! dates)