Buffered *vs.* non-buffered ocean carbon reservoir variations: Application to atmospheric pCO$_2$ sensitivity to ocean circulation

Marc d'Orgeville[1,2], Matthew England[1] and Willem Sijp[1]
[1]Climate Change Research Centre, University of New South Wales, Sydney, Australia
[2]currently working from Ottawa, Canada.

Introduction

Changes in the ocean circulation on millenial timescales can impact the atmospheric CO$_2$ concentration by two distinct mechanisms: either by modifying the non-buffered ocean carbon storage (through changes in the physical and biological oceanic pumps) or by directly varying the surface mean oceanic partial pressure of pCO$_2$ (through changes in mean surface alkalinity, temperature or salinity). This second mecanism was not taken into account in a previous study [*Marinov et al.* 2008]. The equal importance of the two mechanisms is illustrated here by **introducing a new diagnostic buffered carbon budget** on the results of simulations performed with the University of Victoria Earth System Climate Model.

Experimental design

The climate boundary conditions of the control simulation correspond to a warm interglacial climate with a 300 ppm atmospheric CO$_2$ concentration (7000 years spinup). The first perturbation experiment consists of a **permanent shutdown of NADW formation** obtained by a fresh water hosing of the Atlantic ocean (0.2 Sv for 2000 years and 4000 years of new equilibrium). The second and third perturbation experiments consist of changes in the Southern Hemisphere Westerlies (SHW) with a **permanent doubling of the amplitude of the SHW** and a **permanent poleward shift of the SHW** respectively. These wind experiments are integrated for 3000 years [*d'Orgeville et al*. 2010 – **Thursday – C37 – Poster TH85A**]

Illustrations of the new buffered carbon budget below compare the 100 year averages of each perturbation experiment and of the control simulation.

Equations and illustrations

Climate perturbation with conservation of the total quantity of C

$$\delta\Sigma C = \delta C_{lnd} + \delta C_{atm} + \delta C_{ocn} = 0$$

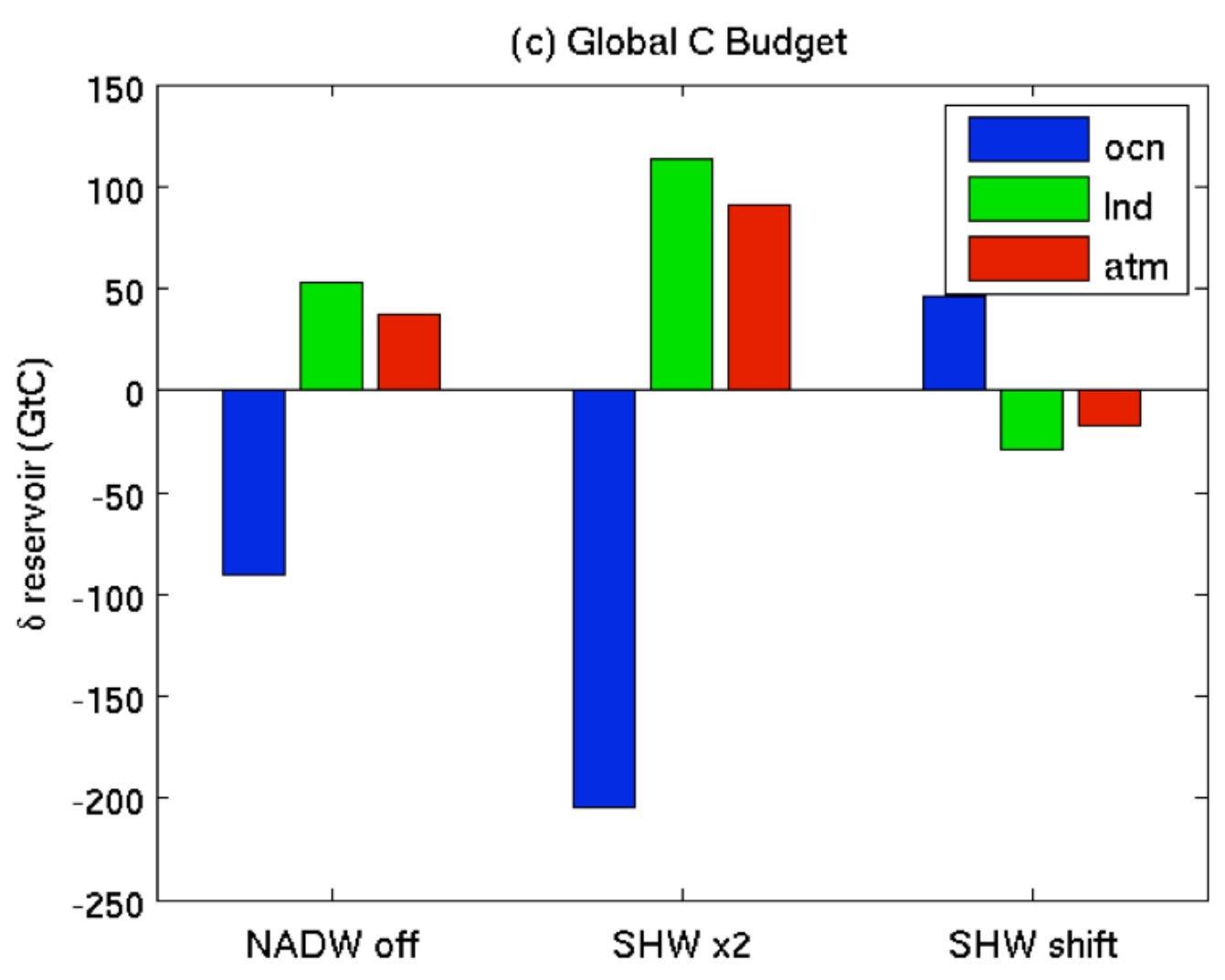

Figure 1. Variation of carbon content (in GtC) of the ocean, land and atmosphere reservoirs for each pertubation experiment compared to the control simulation.

With $$C_{atm} = M_a pCO_2^a$$

and separation of buffered and non-buffered ocean C reservoirs

$$C_{ocn} = V_o\overline{D} + C_{pumps}$$

the **buffering effect** of the ocean becomes apparent in

$$\delta C_{lnd} + M_a \delta pCO_2^a + V_o\delta\overline{D} + \delta C_{pumps} = 0$$

because **global $\delta\underline{D}$ varies together with global δpCO_2** (i.e. mean surface DIC with atm. partial pressure of CO$_2$).

However, $\boldsymbol{\delta pCO_2}$ **also varies with $\delta\underline{A}$, $\delta\underline{T}$ and $\delta\underline{S}$** (mean surface alkalinity, temperature and salinity changes)

$$\delta pCO_2^a = \gamma_D\delta\overline{D} + \gamma_A\delta\overline{A} + \gamma_T\delta\overline{T} + \gamma_S\delta\overline{S}$$

(with $\gamma_X = \partial pCO_2^o/\partial X$)

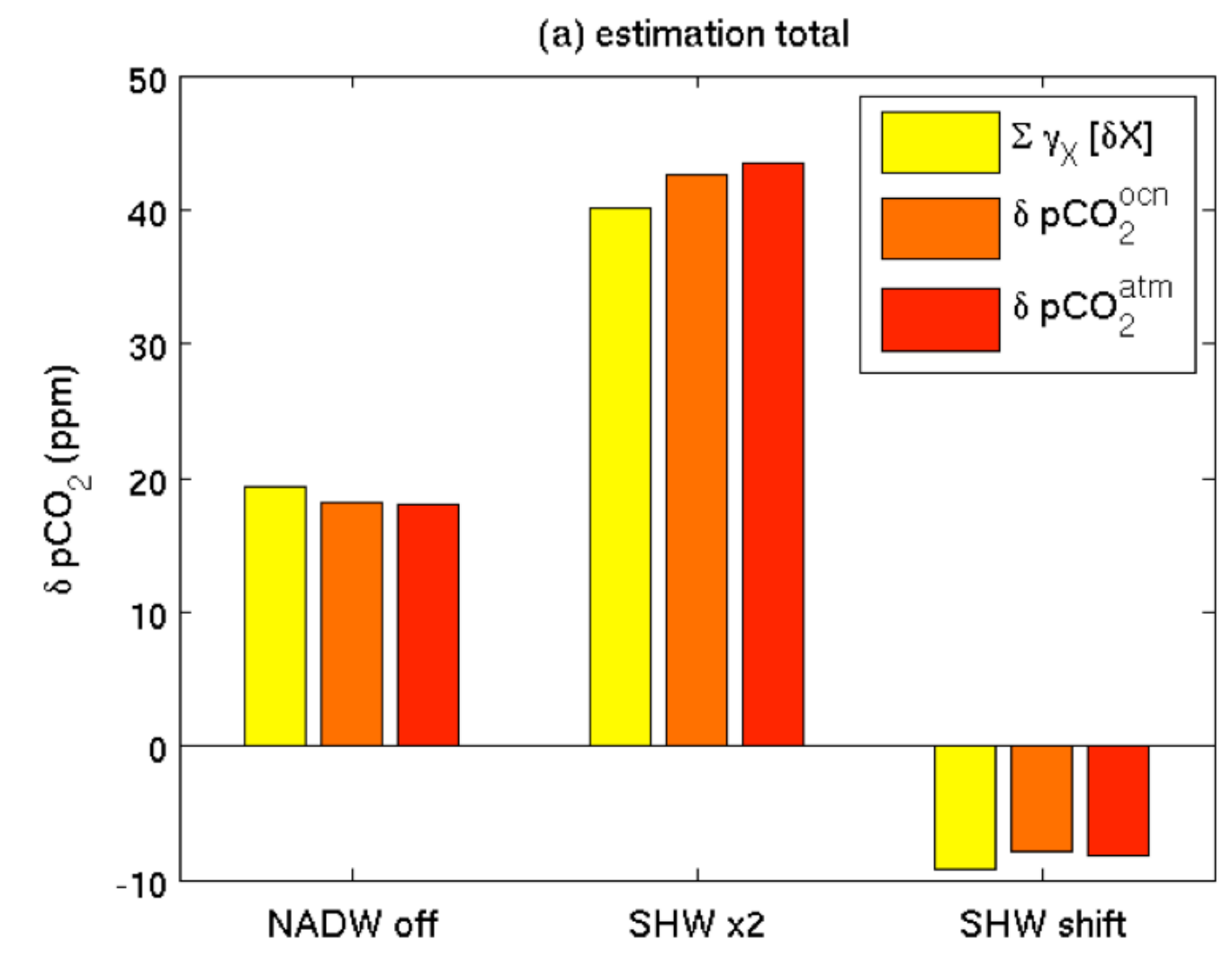

Figure 2a. Comparison in ppm between the RHS of the equation above (yellow), the averaged partial pressure of CO$_2$ of the ocean (orange) and of the atmosphere (red).

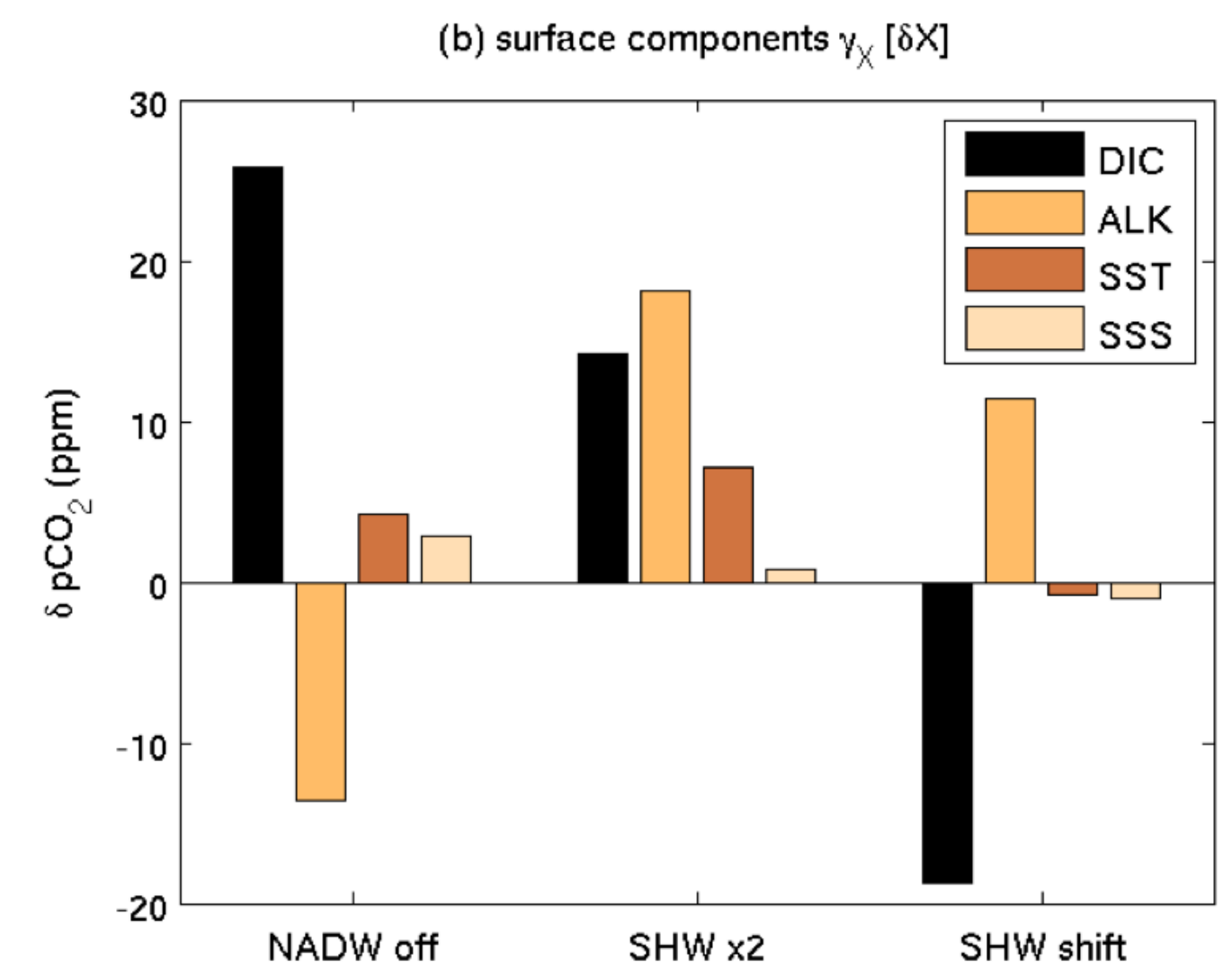

Figure 2b. The four components of the RHS of the above equation, i.e. change in atmospheric partial pressure of CO$_2$ in ppm due to changes in surface DIC, alkalinity, temperature and salinity. The sum of the four equals the yellow bar of Figure 2a.

The buffered carbon budget can then be written as

$$\boxed{\delta C_{buff} + \delta C_{lnd} + \delta C_{surf} + \delta C_{pumps} = 0}$$

where

- $\delta C_{buff} = (M_a + V_o / \gamma_D)\, \delta pCO_2^a$ groups together the change in the atmosphere and the associated buffering effect of the ocean. With the buffered Carbon inventory I_b as in *Goodwin et al.* (2007)
$$\delta C_{buff} = I_b \frac{\delta pCO_2^a}{pCO_2^a}$$
- δC_{surf} is the change to the buffered ocean carbon reservoir due to $\underline{\text{A}}$, $\underline{\text{T}}$ and $\underline{\text{S}}$ alone, i.e. before taking into account the buffering effect of the ocean as if pCO_2^a seen by the ocean was artificially kept constant.
$$\delta C_{surf} = -\frac{V_o}{\gamma_D}\sum_{X=A,T,S}\gamma_X\delta\bar{X}$$

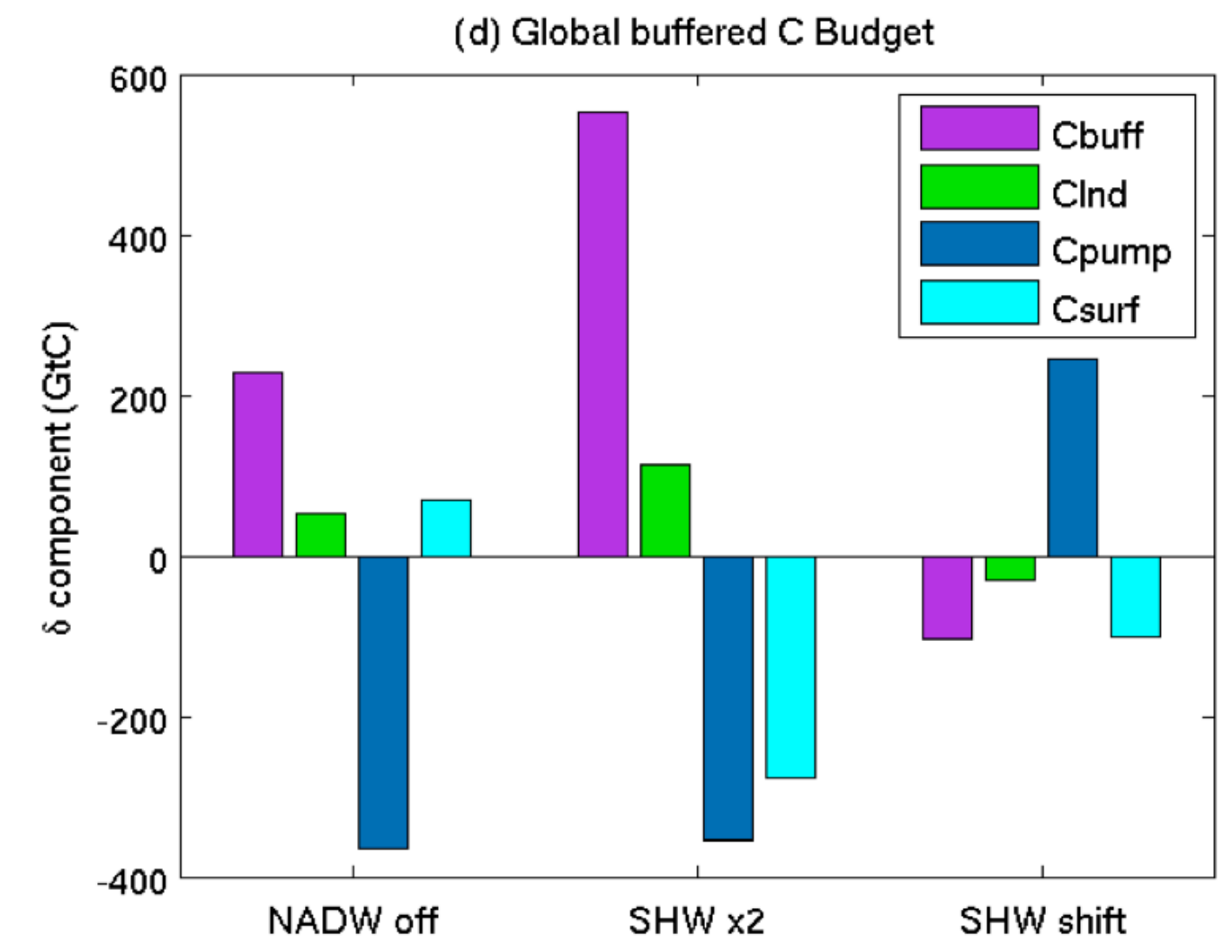

Figure 3. Buffered carbon budget with the ocean-atmosphere buffered component (purple), the land component (green), the oceanic pump component (dark blue) and the surface component (cyan). The sum of the four is zero.

Results

In our experiments, circulation changes lead to exchanges of tens to hundreds of GtC (Fig. 1) from the ocean towards the two other reservoirs (atmosphere and land) which always have the same sign of change, i.e. **the land has a buffering effect on the atmospheric changes** here.

The surface alkalinity contribution is of the same order of magnitude on δpCO_2^a as surface DIC in all experiments (Fig. 2b). In the hosing and shifted SHW experiments exhibit a large change in surface DIC, yet changes in surface alkalinity mitigate a significant atmospheric pCO$_2$ response. In contrast, the experiment with increased SHW shows a very large pCO$_2$ change because surface alkalinity and DIC work in the same sense. **The effect of surface alkalinity changes cannot be neglected in a subsequent buffered carbon budget**.

➢The decreased mean surface alkalinity in both wind experiments is due to the increased ventilation of the deep ocean without significant change of the carbonate pump [*d'Orgeville et al*., 2010] while the increased mean surface alkalinity in the hosing experiment ensues from the massive reorganization of the ocean water masses triggered by the disappearance of the NADW (not shown).

The changes in the non-buffered carbon reservoir are of the same order of magnitude in both experiments (δC_{pump}: close to 350 GtC). But by comparing these two experiments (Fig. 3) it is evident that **the amplitude of $\boldsymbol{\delta pCO_2^a}$ (proportional to $\boldsymbol{\delta C_{buff}}$) is ultimately determined by the effect of the change in surface ATS ($\boldsymbol{\delta C_{surf}}$).**

➢In the hosing experiment, δC_{pump} is negative due to decreases in the strength of the biological carbon pumps and in the residence time of the deep ocean waters (not shown). In the strengthened SHW experiments, the increase in ventilation leads to a negative value of δC_{pump} [*d'Orgeville et al*., 2010].

Conclusions

On the ocean circulation change impact:

- For all the circulation changes considered in this study, the **change in atmospheric CO$_2$ is driven by the change in the oceanic carbon pump**: the sign of the atmospheric CO$_2$ response is opposite to the sign of the non-buffered ocean carbon storage change, indicating a transfer of carbon between ocean and atmosphere reservoirs.
- However the **concomitant changes in the buffered ocean carbon reservoir** (independent of the buffering effect) **can either greatly enhance or almost inhibit the atmospheric response** depending on its sign.

On the new diagnostic buffered carbon budget

- This budget allows for a **direct comparison of buffered and non-buffered oceanic carbon sources**, independently of the buffering effect.
- Possibility of a **transient budget** (Fig. 4)

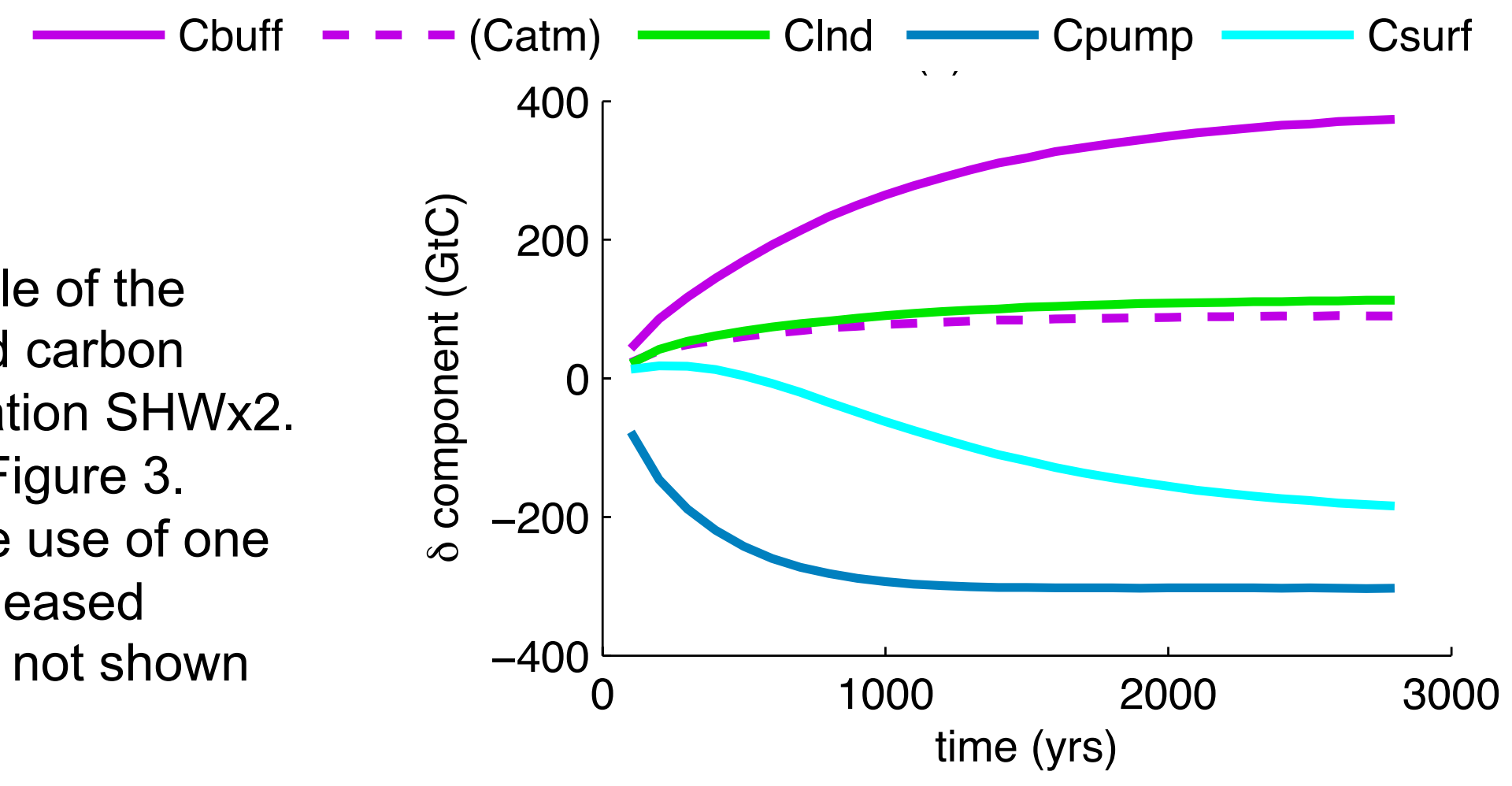

Figure 4. Example of the transient buffered carbon budget for simulation SHWx2. Same colors as Figure 3. Obtained with the use of one passive tracer released globally (detailed not shown here).

References

d'Orgeville et al. (2010), On the control of glacial-interglacial atmospheric CO2 variations by the Southern Hemisphere westerlies, *Geophys. Res. Lett.*, 37, L21703. **Thursday – C37 – Poster TH85A**

d'Orgeville et al. (2011), Buffered *vs*. non-buffered ocean carbon reservoir variations: Application to the atmospheric pCO$_2$ sensitivity to the ocean circulation, *GRL*, (in Revision).

Goodwin et al. (2007), Ocean-atmosphere partitioning of anthropogenic carbon dioxide on centennial timescales, *Global Biogeochem. Cycles*, 21, GB1014.

Marinov et al. (2008), Impact of oceanic circulation on biological carbon storage in the ocean and atmospheric pCO2, *Global Biogeochem. Cycles*, 22, GB3007.

Contact

Email: marcdo@unsw.edu.au

Acknowledgements

This project was supported by the Australian Research Council.

Australian Government
Australian Research Council

UNSW
THE UNIVERSITY OF NEW SOUTH WALES
SYDNEY · CANBERRA · AUSTRALIA

Climate Change Research Centre