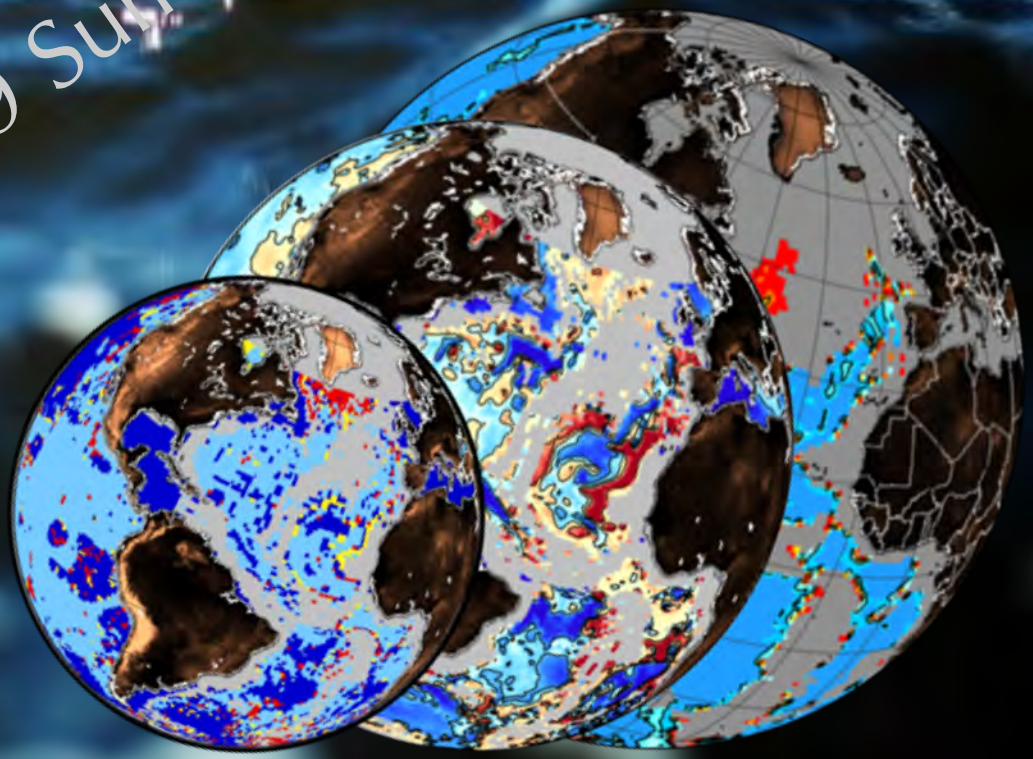
# Current $CaCO_3$ dissolution at the seafloor caused by anthropogenic $CO_2$





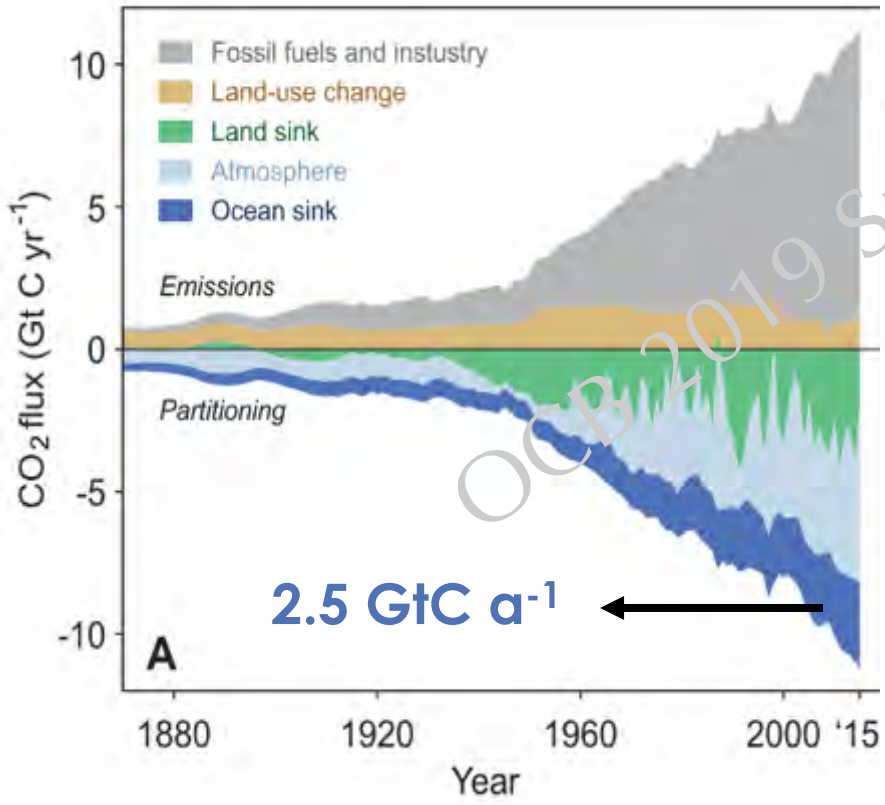
**Olivier Sulpis**
McGill University

**June 26th, 2019**
OCB summer workshop

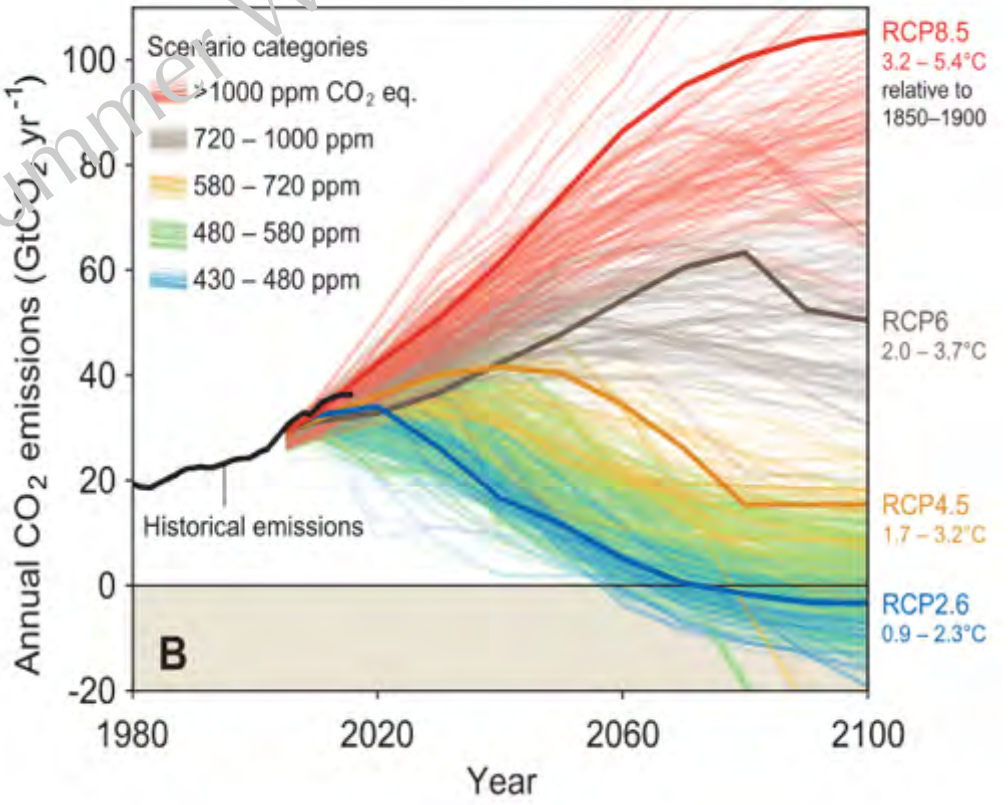
# The ocean carbon sink.

Each year, about 25% of the anthropogenic carbon emitted into the atmosphere is absorbed by the ocean.





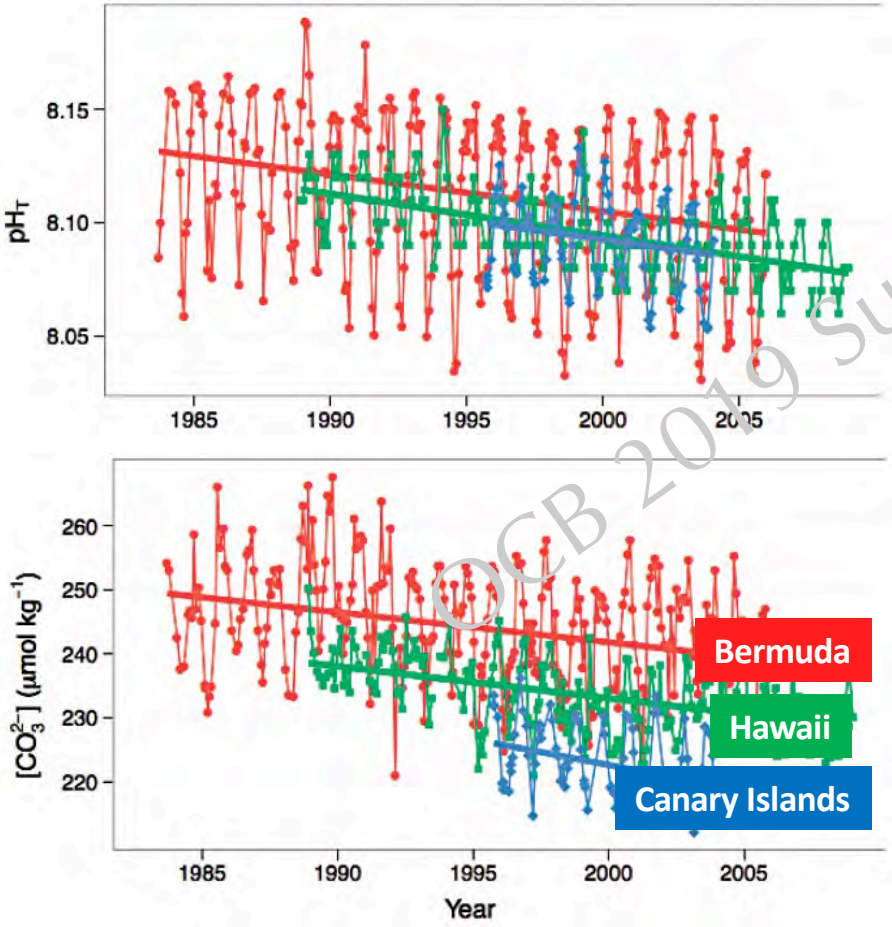

Le Quéré et al. (2013) *Earth Syst. Science Data*

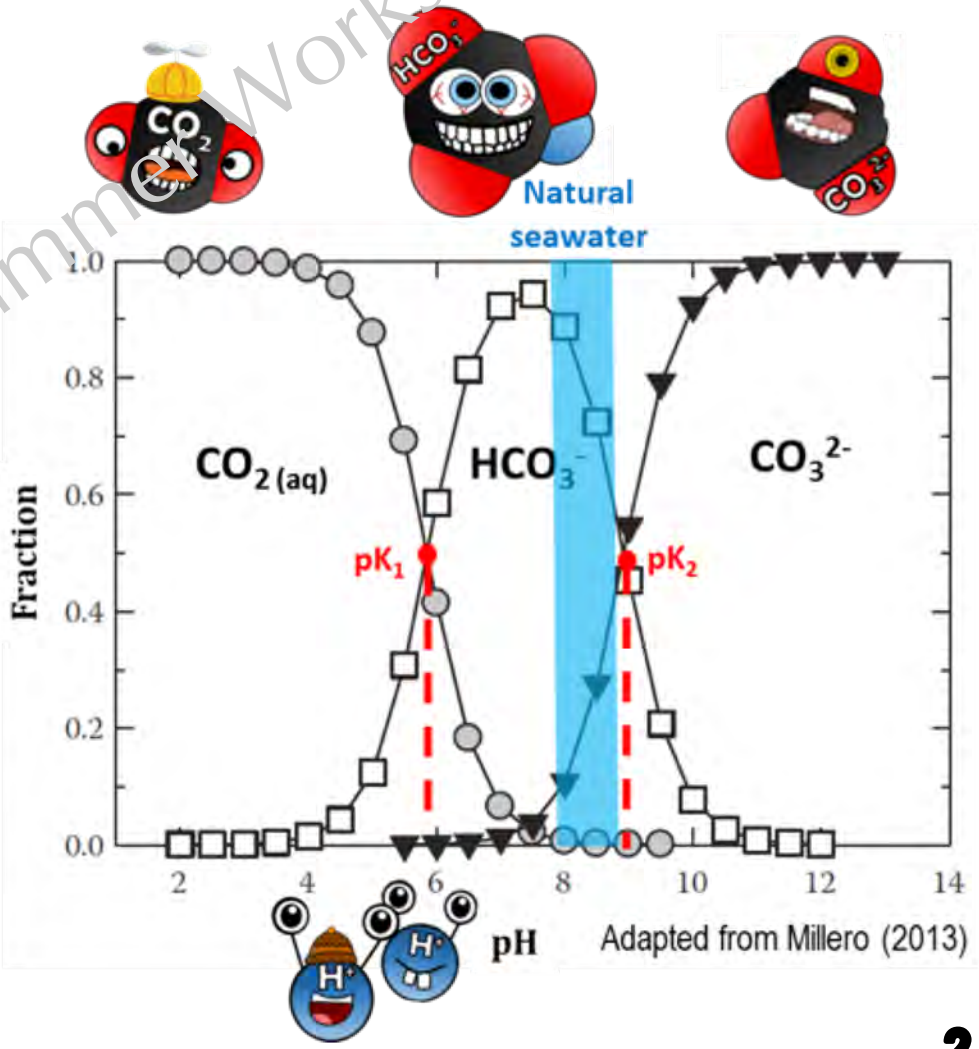



Global Carbon Budget (2016)

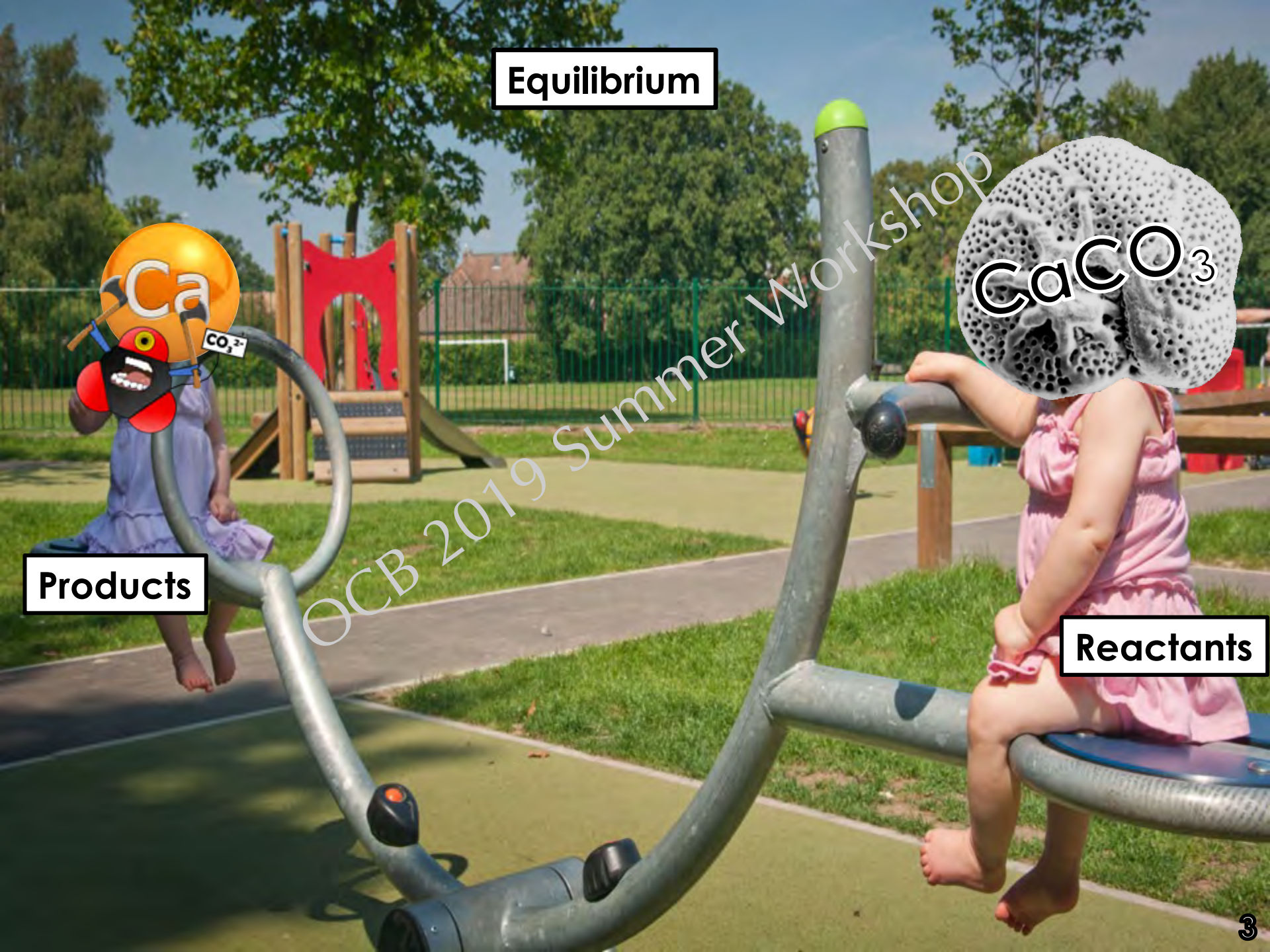
# Ocean acidification

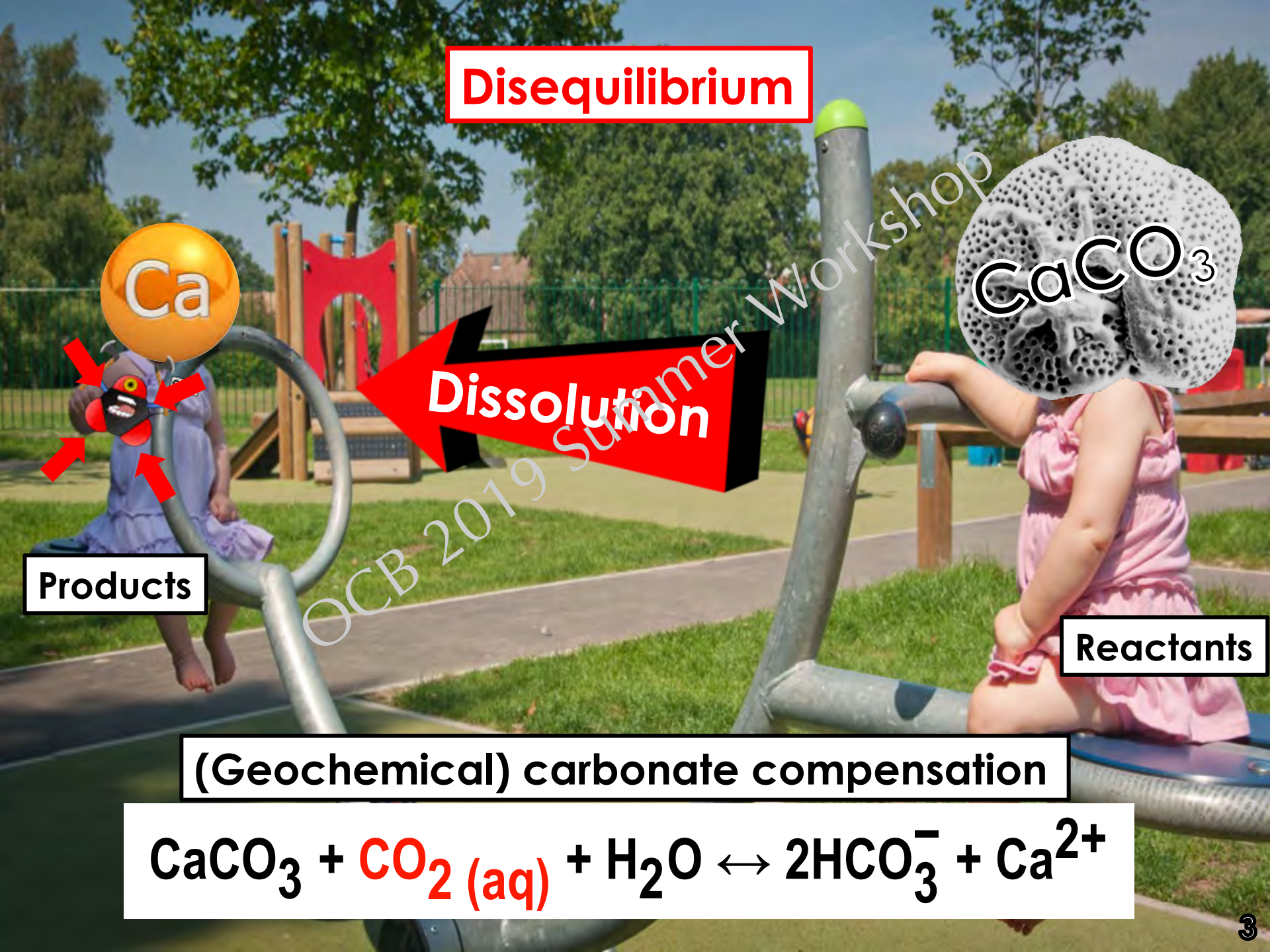
The absorption of $CO_2$ in seawater leads to a pH decrease, which reduces the $CO_3^{2-}$ concentration of seawater.




Mackenzie and Andersson (2013)
*Geochemical Perspectives*

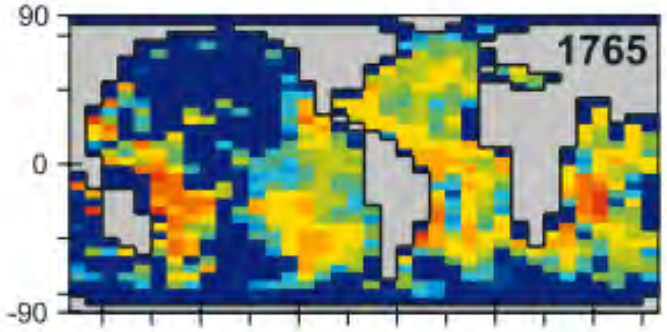

Equilibrium
Ca
$CO_3^{2-}$
$CaCO_3$
Products
Reactants
OCB 2019 Summer Workshop

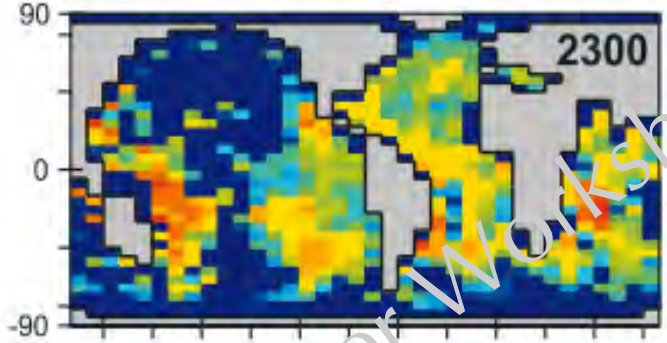



(Geochemical) carbonate compensation

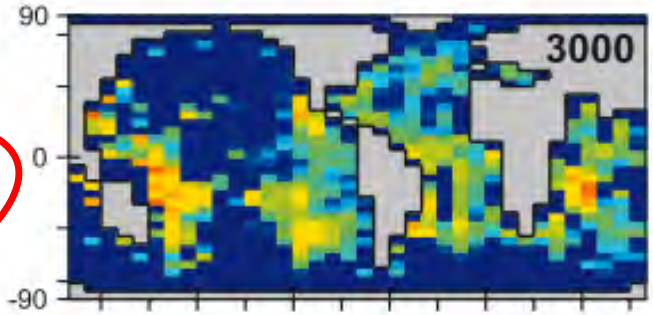
$$CaCO_3 + CO_{2\,(aq)} + H_2O \leftrightarrow 2HCO_3^- + Ca^{2+}$$

# The ultimate sink for anthropogenic $CO_2$




**$CaCO_3$ surface content in response to the burning of all fossil fuel reserves by 2400** (Ridgwell and Hargreaves, 2007, *GBC*)

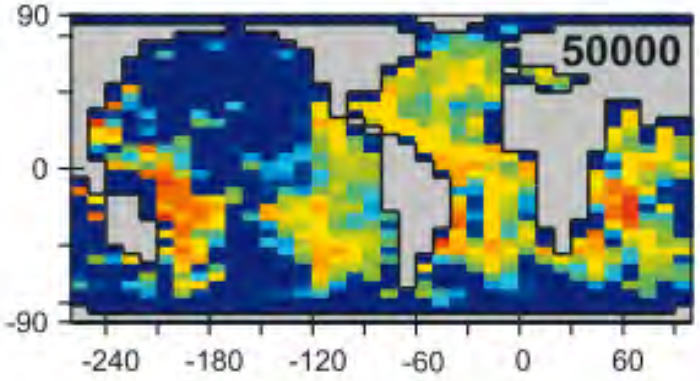


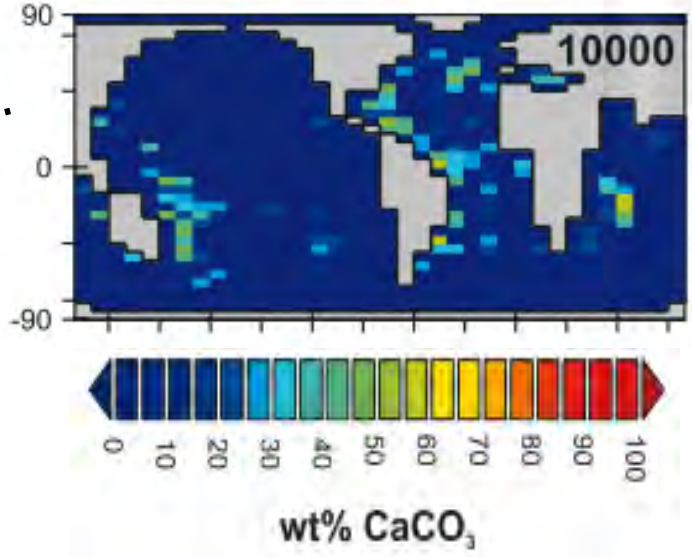

More $CO_2$…

**Negative feedback loop**

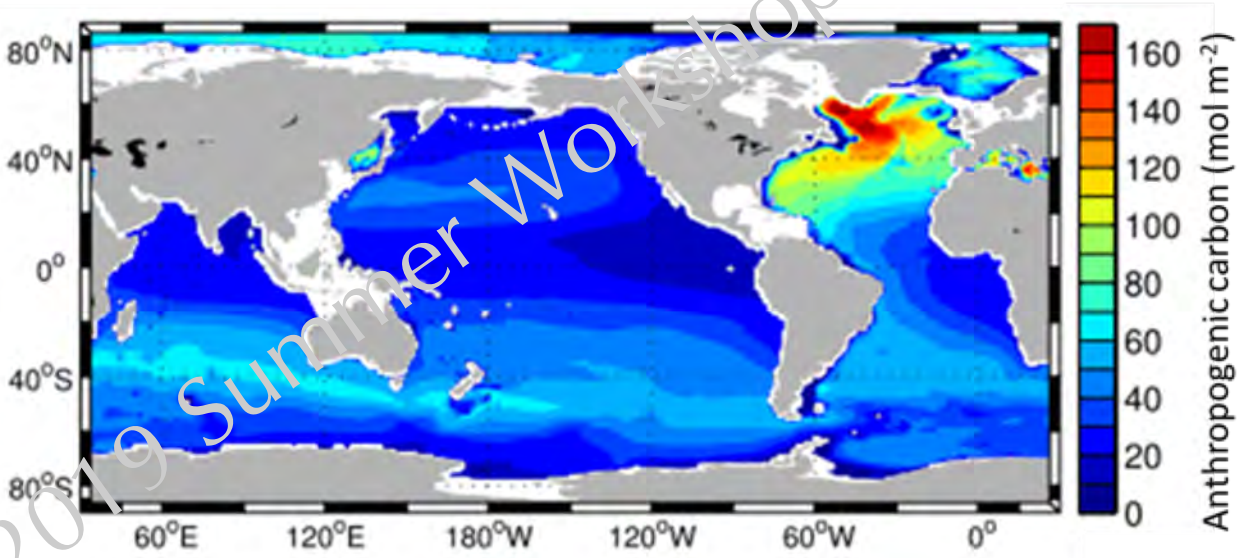
Less $CO_2$

More $CaCO_3$ dissolution…



# Anthropogenic $CO_2$ marine inventory




Khatiwala et al., 2013, *Biogeosciences*



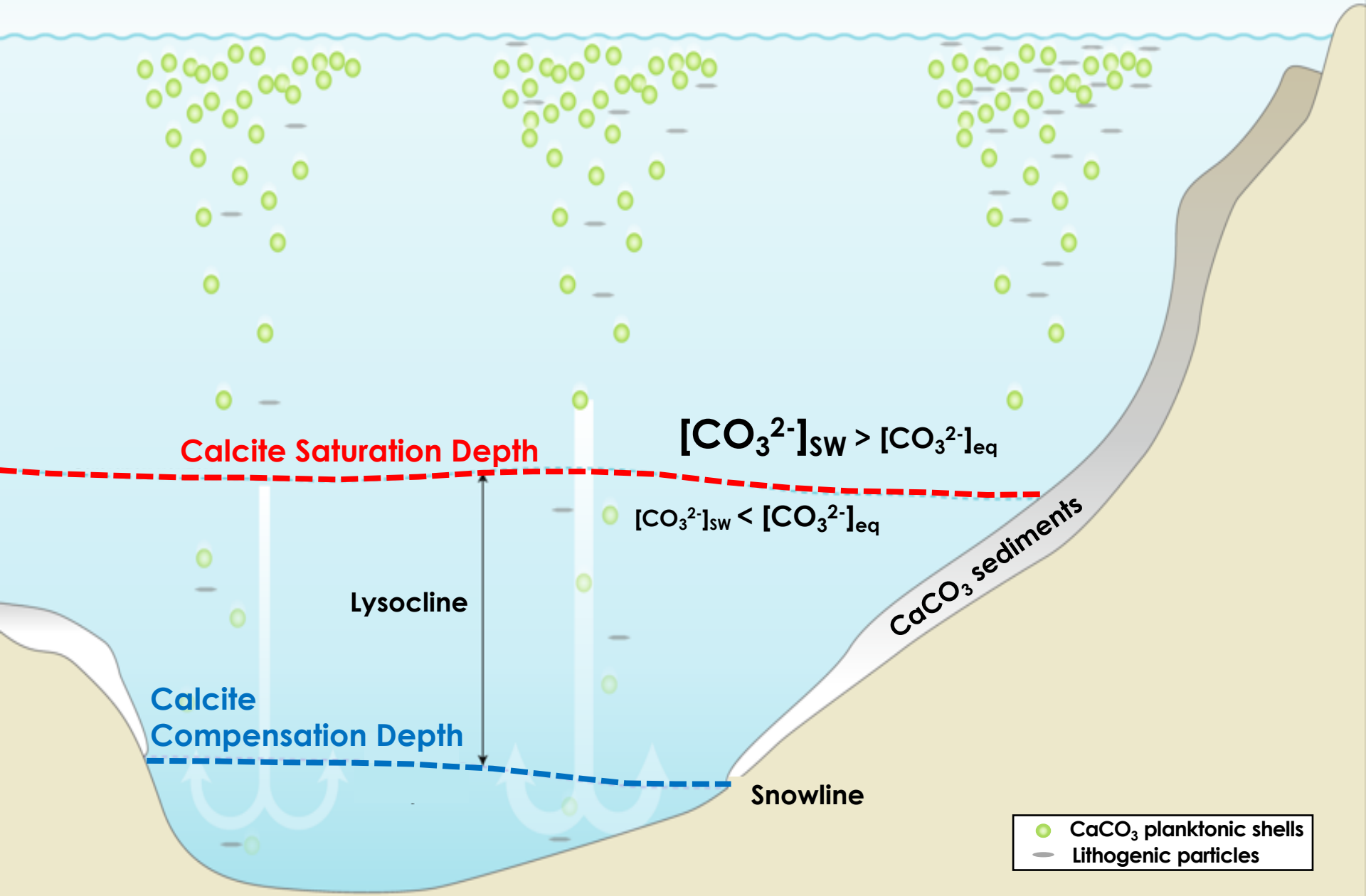
**CFC content in the Atlantic Ocean below 2000m between 1945 and 2065**
(Sen Gupta and England, 2004, *JPO*)

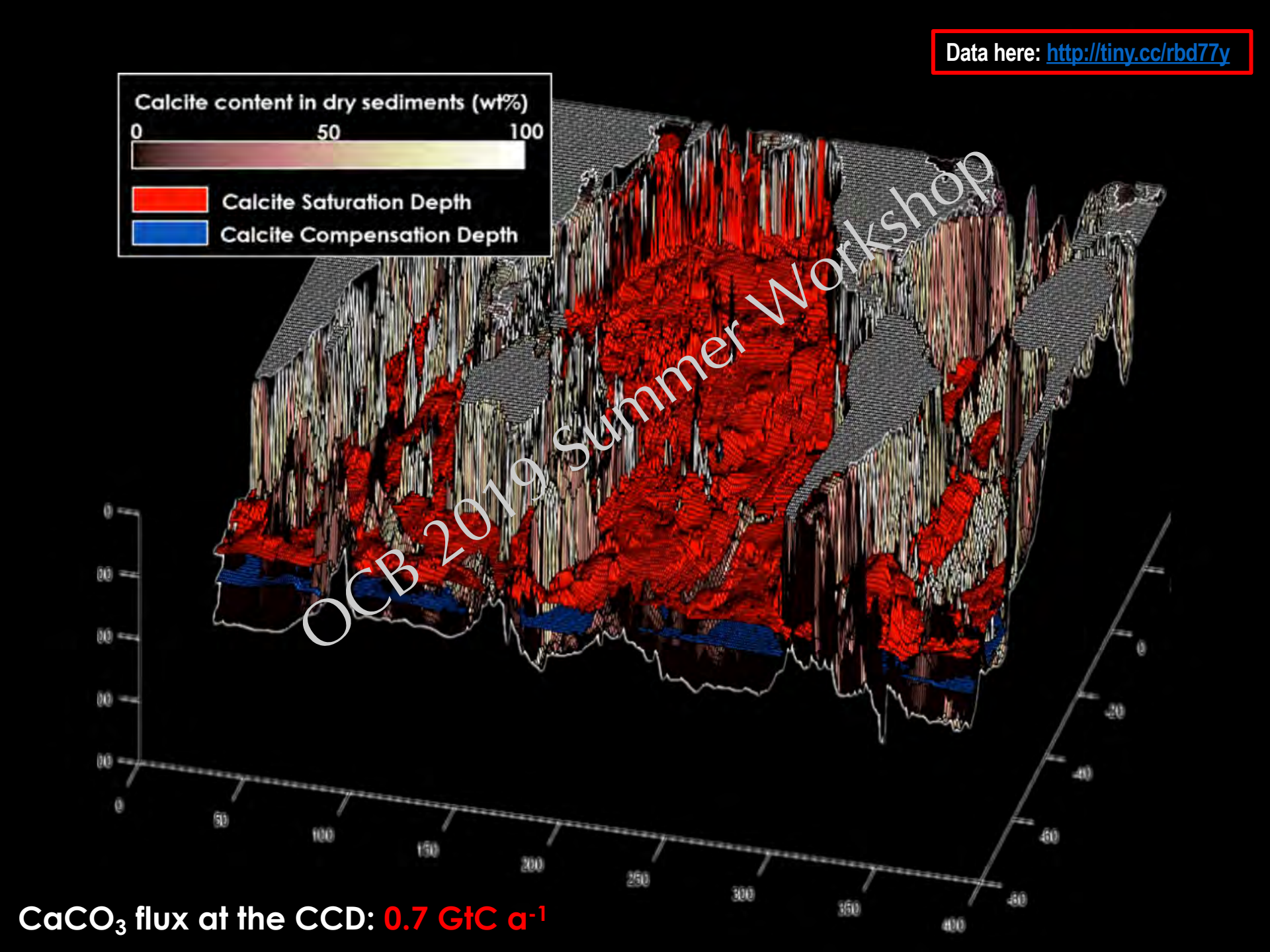
Where is the anthropogenic $CO_2$?

**55 % in the top 100 m**

**4 % below 1000 m**

**Critical horizons of open-ocean carbonate compensation**, adapted from Boudreau et al. (2018) *Nature Geoscience*

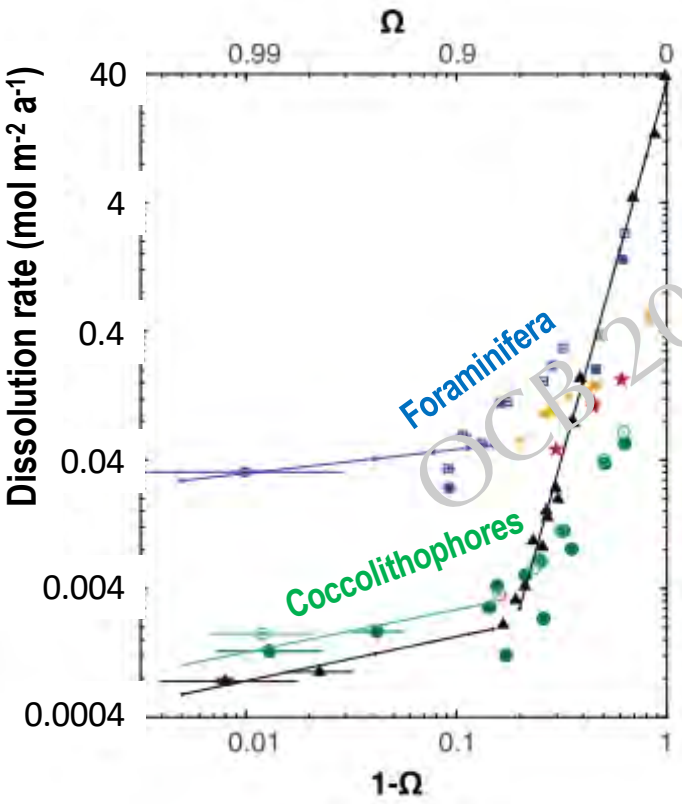





$CaCO_3$ flux at the CCD: 0.7 GtC $a^{-1}$

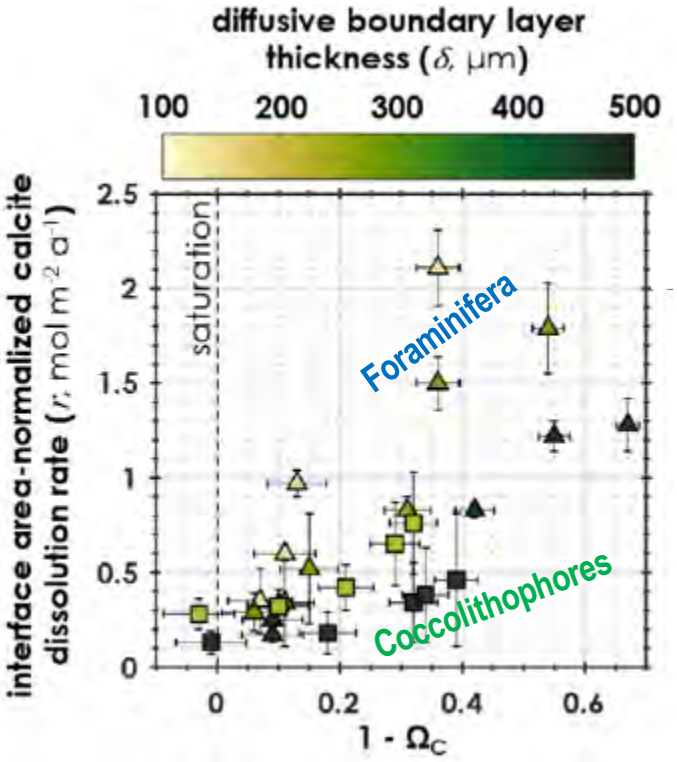
# From the water-column to the seafloor

Dissolution rate normalized by the surface area of the grains.



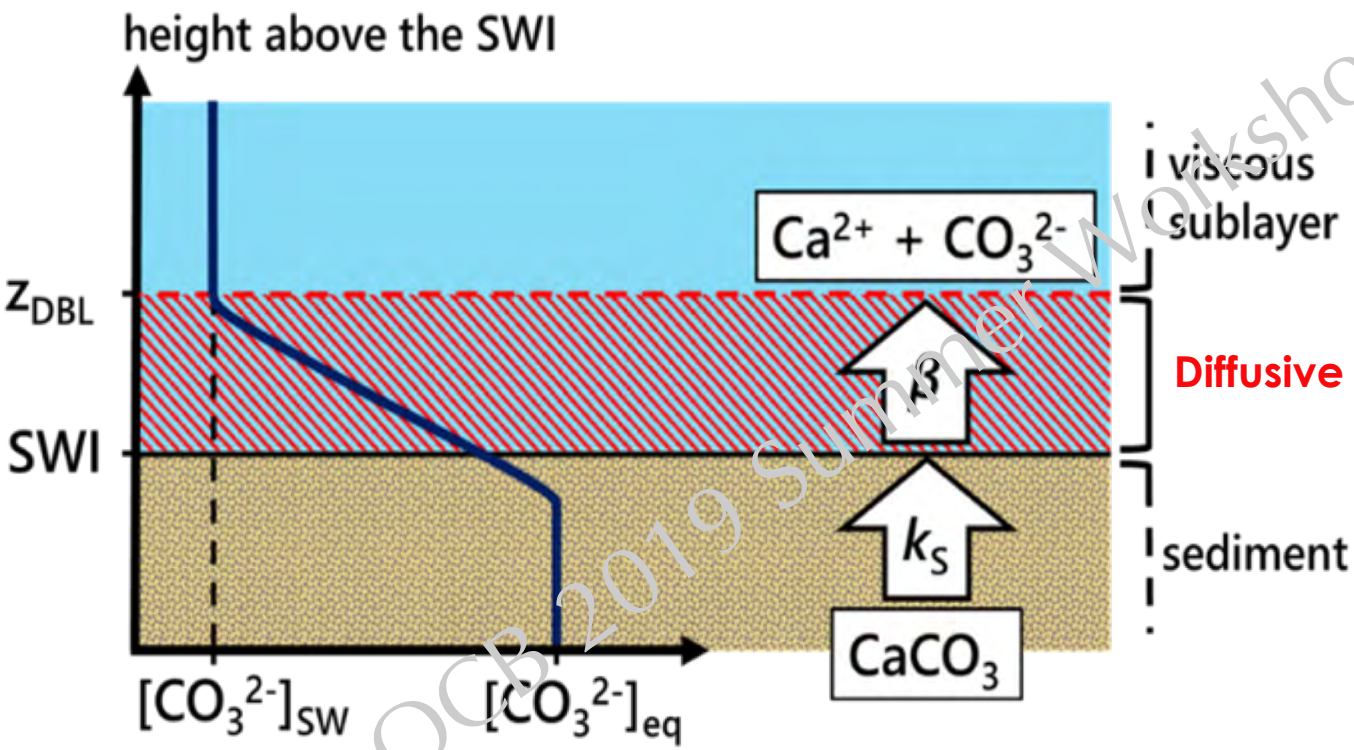

Subhas et al., 2018, *Mar. Chem.*


Dissolution rate normalized by the sediment-water interface surface area.




Sulpis et al., *in preparation*

# Mixed control of $CaCO_3$ dissolution






$$r = k^*([CO_3^{2-}]_{eq} - [CO_3^{2-}]_{SW})$$

$$k^* = \frac{\beta k_S}{\beta + k_S}$$

Current speed

$CaCO_3$ content in sediments

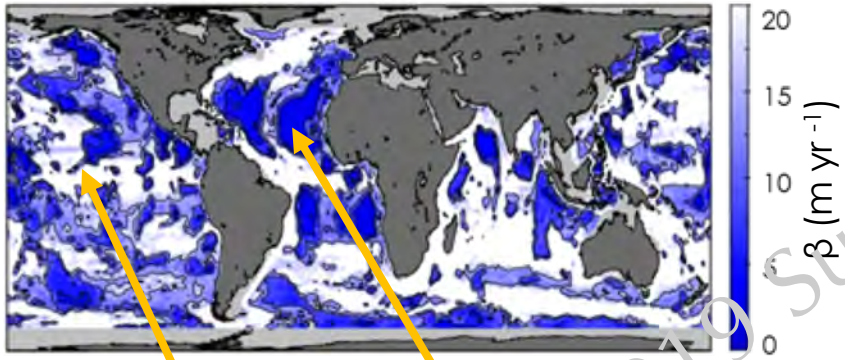
# The reactivity of the seafloor

Data here: http://tiny.cc/rbd77y

$$r = k^*([CO_3^{2-}]_{eq} - [CO_3^{2-}]_{sw})$$

$$k^* = \frac{k_s \beta}{k_s + \beta}$$

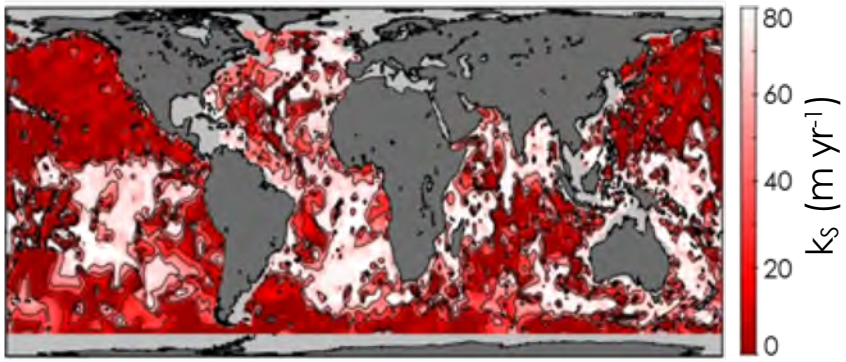
Sulpis et al., 2018, *PNAS*




water-side

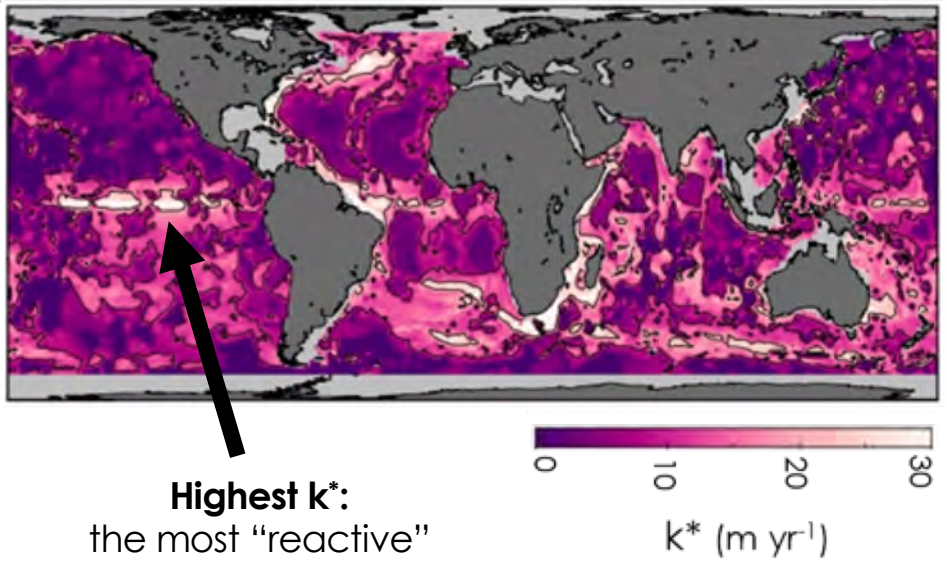
**Thinnest DBL:** ~ 200 µm

**Thickest DBL:** ~ 3 mm



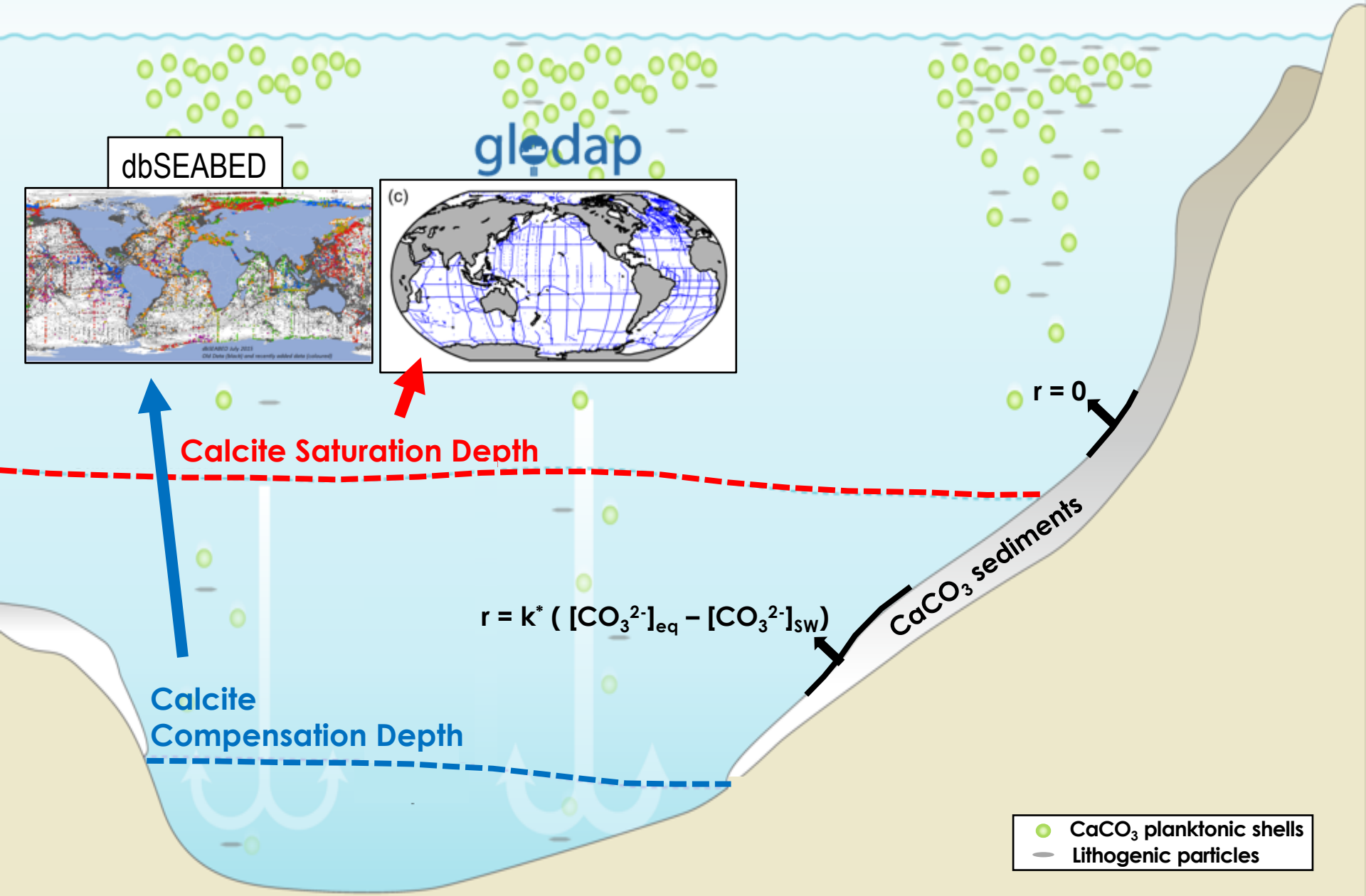

sediment-side

**Overall $CO_3^{2-}$ mass-transfer coefficient**




**Highest k*:** the most "reactive" $CaCO_3$ sediments

**Critical horizons of open-ocean carbonate compensation**, adapted from Boudreau et al. (2018) *Nature Geoscience*



# Bottom-water calcite saturation state

**Data here:** http://tiny.cc/rbd77y

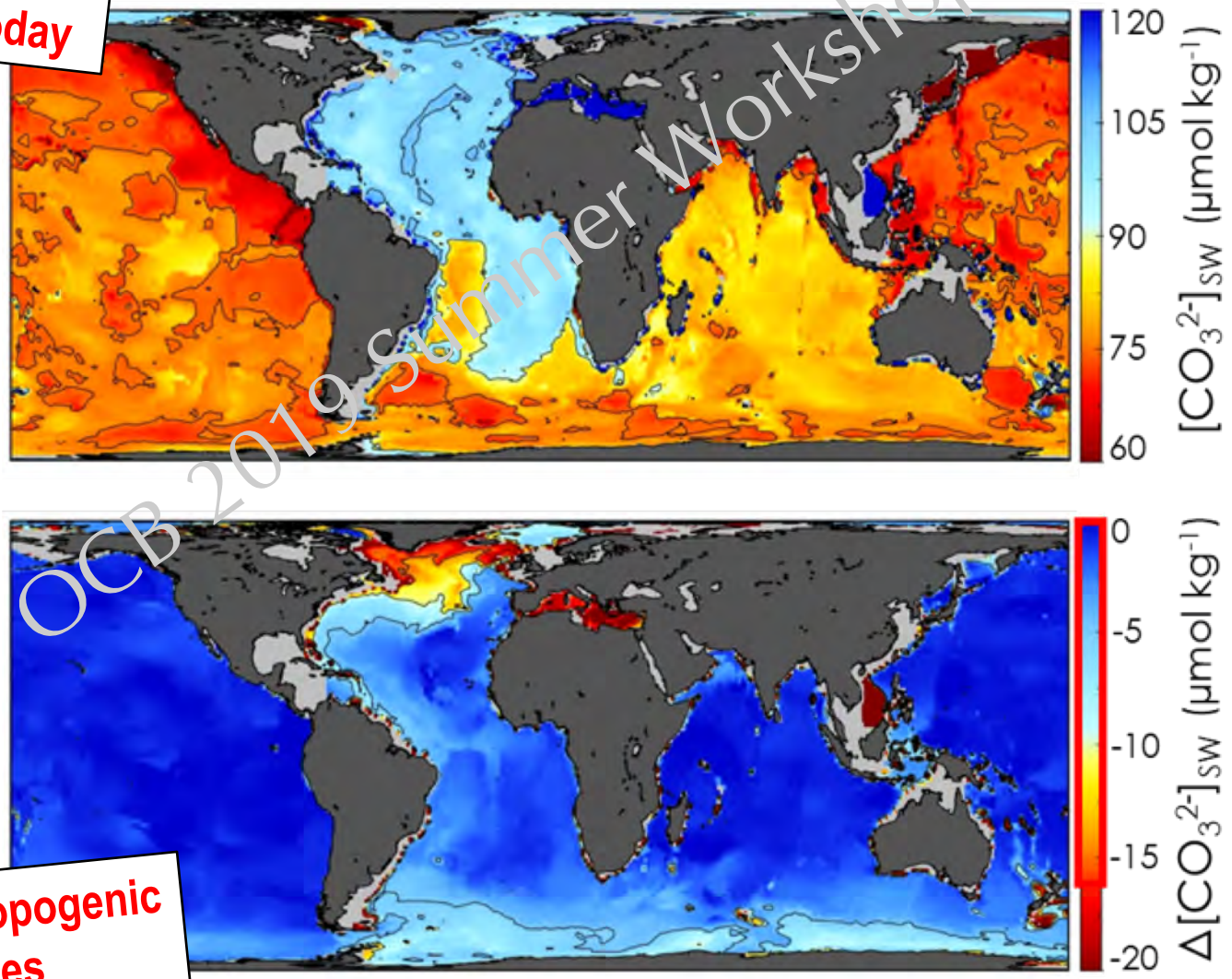
Sulpis et al., 2018, *PNAS*

**GLODAPv2**

~1 million samples

Lauvset et al. (2016)
*Earth Syst. Sci. Data*

Today



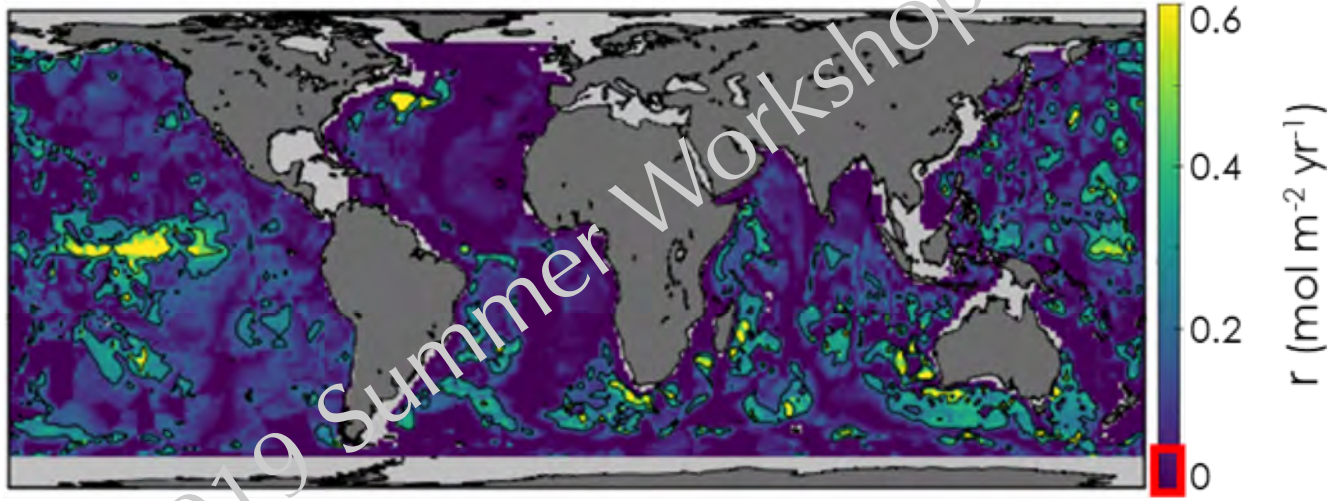

Anthropogenic changes

# Anthropogenic $CaCO_3$ dissolution

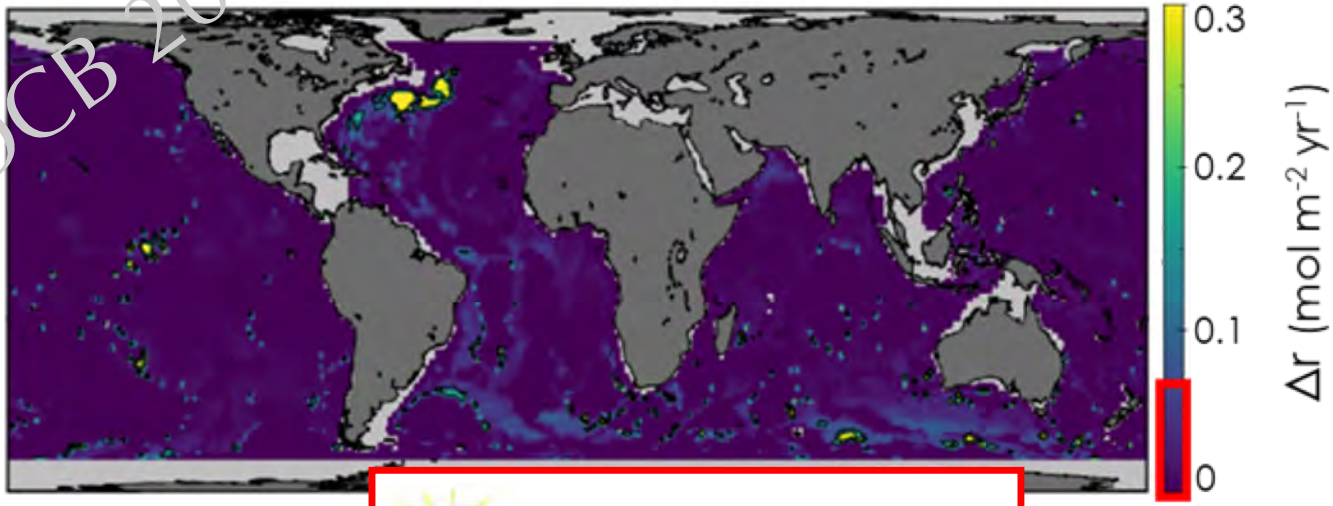
Data here: http://tiny.cc/rbd77y

**Current $CaCO_3$ dissolution**

→ **0.4 GtC** of $CaCO_3$ dissolved at the sediment-water interface each year




**Anthropogenically -driven $CaCO_3$ dissolution rate** (i.e., since ca 1800 A.D.)



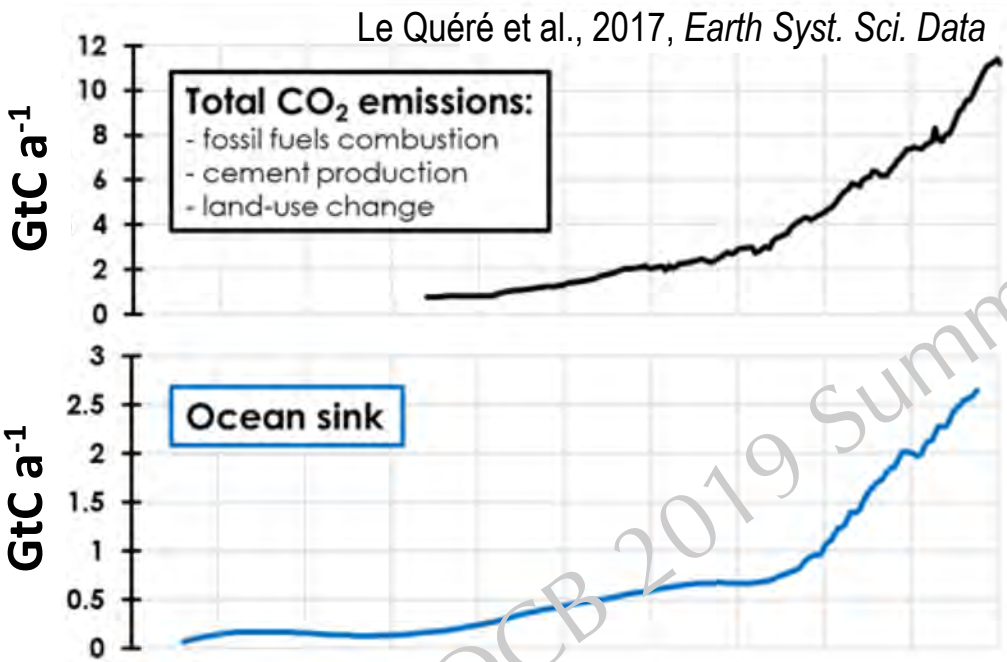



**Discussion idea**

**Why are uncertainties so high in the deep-sea?**

Sulpis et al., 2018, *PNAS*

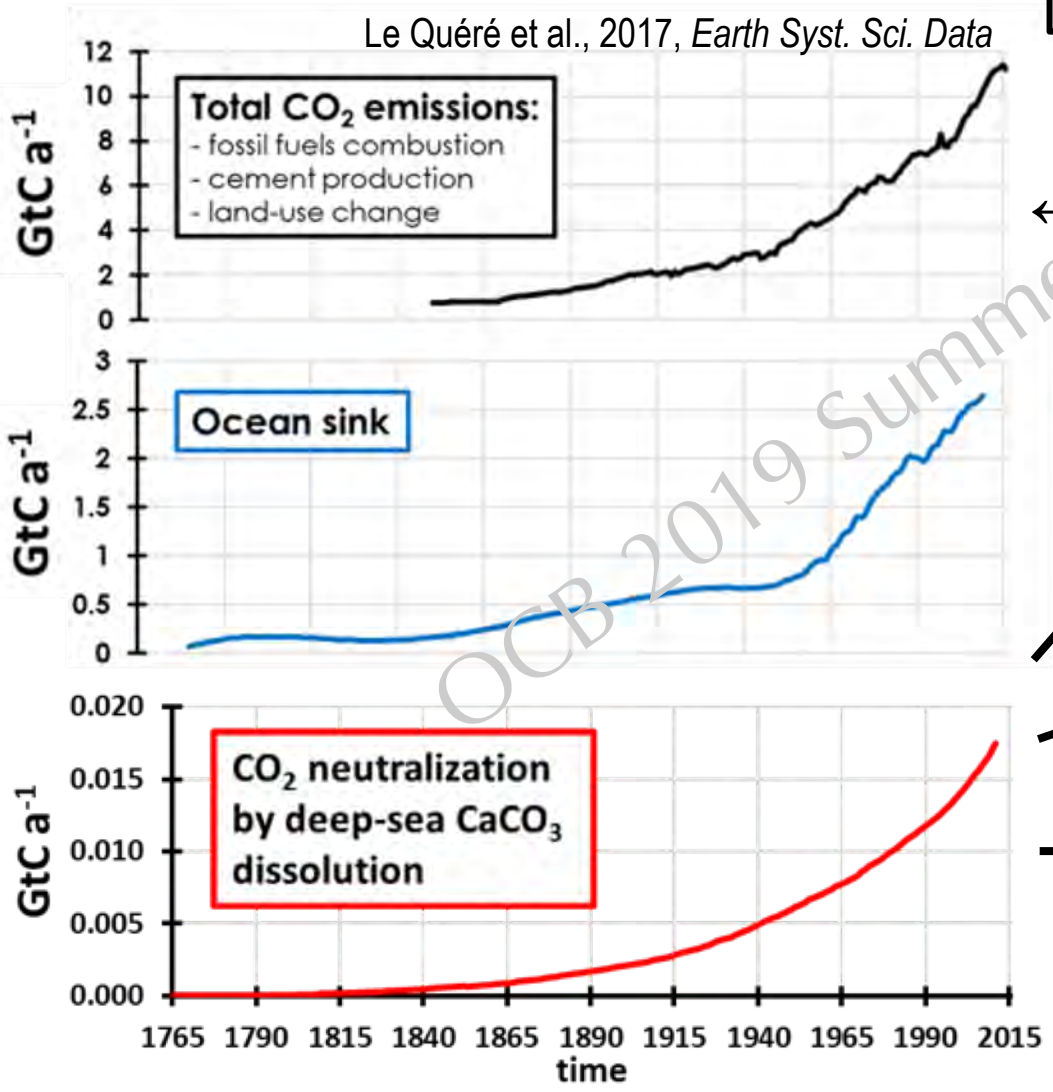
# Negligible $CO_2$ neutralization




**Geochemical carbonate compensation**

$$CaCO_3 + CO_{2\,(aq)} + H_2O \leftrightarrow 2HCO_3^- + Ca^{2+}$$

# Negligible $CO_2$ neutralization




From the data of Khatiwala et al., 2013, *Biogeosciences*

**Geochemical carbonate compensation**

$$CaCO_3 + \psi CO_{2\,(aq)} + H_2O \leftrightarrow (1+\psi)HCO_3^- + (1-\psi)OH^- + Ca^{2+}$$

Smith and Gattuso, 2011, *Aquat. Geochem.*

At the deep seafloor, ~0.8 mole of $CO_2$ neutralized for each mole of $CaCO_3$ dissolved.

**Each day, each human add ~ 4 kg of $CO_2$ in the ocean, and dissolve ~ 70 g of $CaCO_3$ at the seafloor**

**10 billion tons of $CaCO_3$ dissolved by anthropogenic $CO_2$ (~30 Empire State Buildings)**

**40% of the total $CO_2$ emission rate of Montreal**

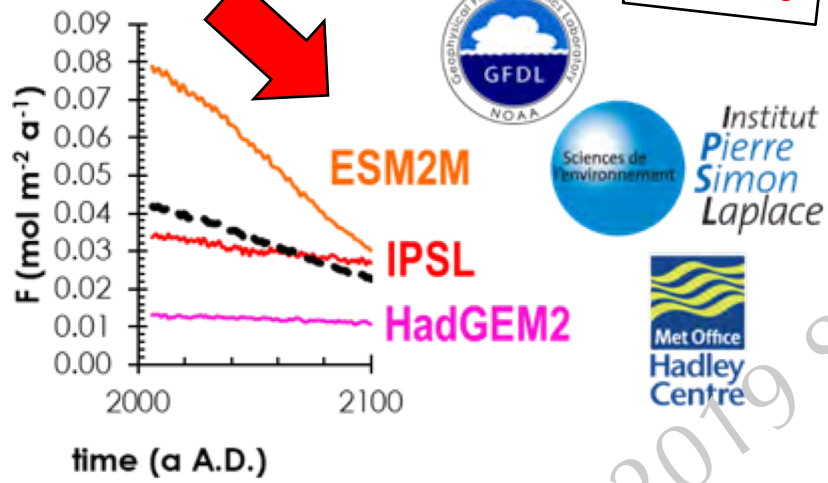
CDP, 2016
Data here:
http://tiny.cc/g8c77y

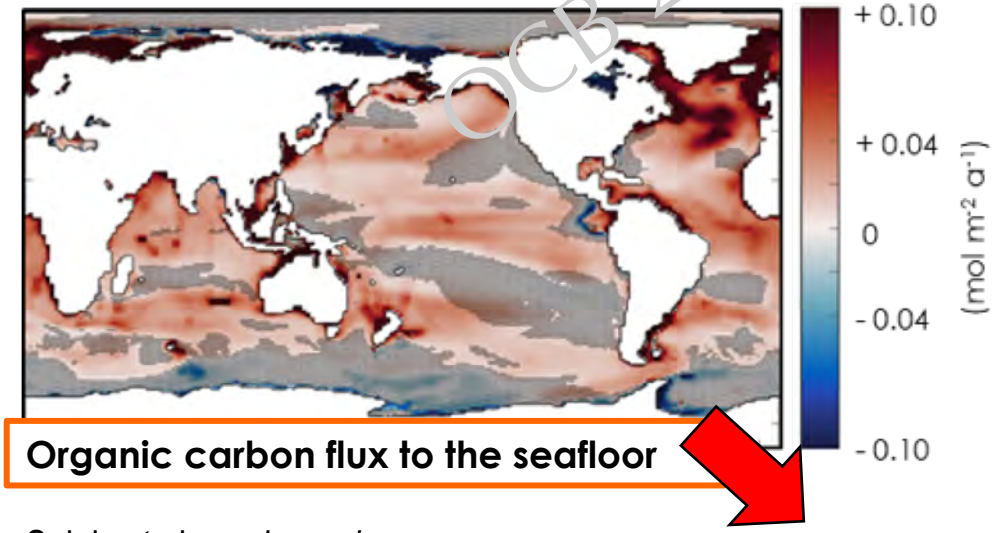
# Predictions for the future

Changes between the first 30 years and the last 30 years of the 21st century

**$CaCO_3$ flux to the seafloor**

RCP8.5

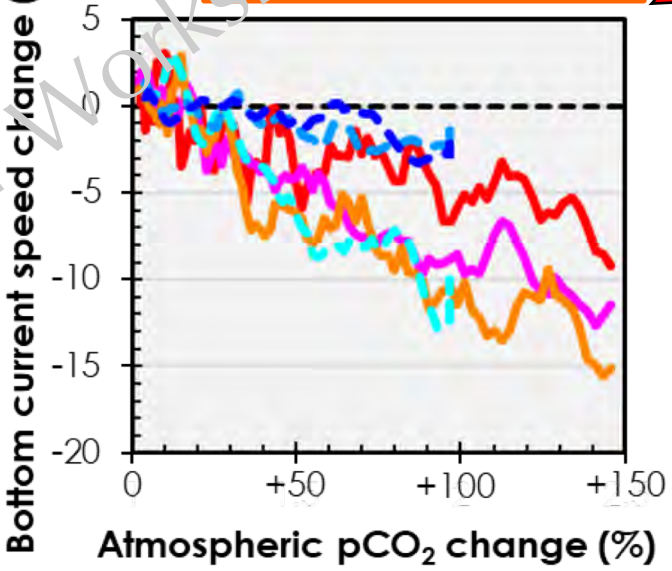



**Organic carbon flux to the seafloor**

Sulpis et al., *under review*

**Bottom current speed**




**CMIP5 models:**
- HadGEM2-CC
- GFDL-ESM2M
- IPSL-CM5A-MR

**GFDL CM suite:**
- CM2-1deg
- CM2.5
- CM2.6

**Discussion idea**

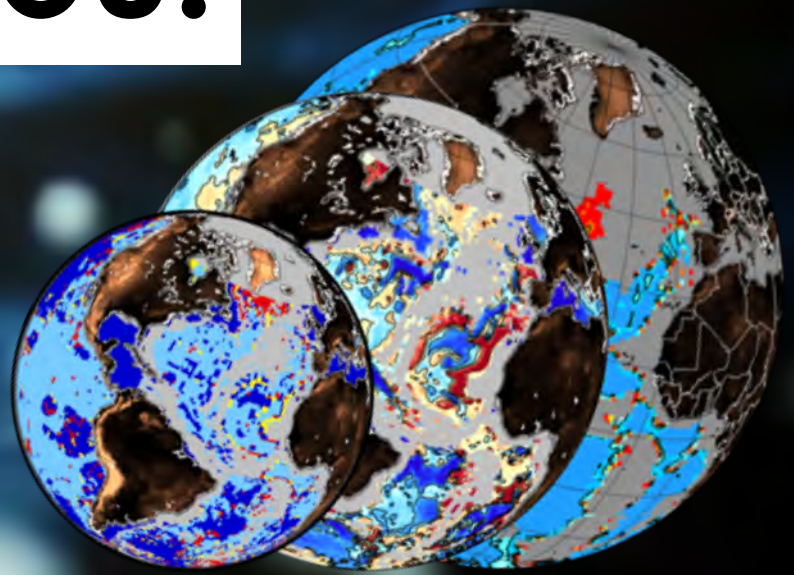
**What could be the impacts of a higher organic matter delivery to the seafloor?**

# Collaborators:

**Alfonso Mucci, Carolina Dufour, Claire Lix, Pascale Daoust, Deneyn White (McGill), Bernard Boudreau (Dalhousie), David Trossman (U Texas - Austin), Andrea Fassbender (MBARI), Brian Arbic (U Michigan), John Dunne (GFDL), Chris Jenkins (INSTAAR), Robert Key (Princeton)**



# Thank you!



**Olivier Sulpis**
McGill University

**June 26th, 2019**
OCB summer workshop

# References:


Boudreau, B.P. and Guinasso, N.L., Jr. (1982) The influence of a diffusive boundary layer on accretion, dissolution, and diagenesis at the sea floor, in: Fanning, K.A., Manheim, F.T. (Eds.), The Dynamic Environment of the Ocean Floor. Lexington Books, Lexington, pp. 115-145.Boudreau et al. (2018) Nature Geoscience

Global Carbon Budget (2016) More info, data sources and data files at http://www.globalcarbonproject.org/

Khatiwala, S., T. Tanhua, S. Mikaloff Fletcher, M., et al. (2013). Global ocean storage of anthropogenic carbon. Biogeosciences 10(4): 2169-2191.

Lauvset, S. K., R. M. Key, A. Olsen, S. v. Heuven, A. Velo, X. Lin, C. Schirnick, A. Kozyr, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, M. Ishii, F. F. Perez, T. Suzuki and S. Watelet (2016). A new global interior ocean mapped climatology: the 1° × 1° GLODAP version 2. Earth System Science Data 8: 325-340.

Le Quéré, C., Andrew, R.M., Friedlingstein, P., et al. (2018) Global Carbon Budget 2017. Earth System Science Data 10, 405-448.

Mackenzie, F. and Andersson, A. (2013) The Marine Carbon System and Ocean Acidification during Phanerozoic Time. Geochemical Perspectives, 1-227.

Millero, F. J. (2013) Chemical Oceanography, Fourth Edition, Boca Raton, CRC Press - Taylor & Francis Group, 591 pp.

Ridgwell, A. and Hargreaves, J.C. (2007) Regulation of atmospheric $CO_2$ by deep-sea sediments in an Earth system model. Global Biogeochemical Cycles 21.

Sen Gupta, A. and M. H. England (2004). Evaluation of Interior Circulation in a High-Resolution Global Ocean Model. Part I: Deep and Bottom Waters. Journal of Physical Oceanography 34: 2592-2614.

Smith, S. V. and J.-P. Gattuso (2011). Balancing the Oceanic Calcium Carbonate Cycle: Consequences of Variable Water Column Ψ. Aquatic Geochemistry 17(4): 327-337.

Subhas, A.V., Rollins, N.E., Berelson, W.M., et al. (2018) The dissolution behavior of biogenic calcites in seawater and a possible role for magnesium and organic carbon. Marine Chemistry 205, 100-112.

Sulpis, O., Boudreau, B.P., Mucci, A., et al. (2018) Current $CaCO_3$ dissolution at the seafloor caused by anthropogenic $CO_2$. PNAS 115, 11700-11705 **Data here:** http://tiny.cc/rbd77y

Sulpis, O., Mucci, A., Daoust, P., et al. Impact of environmental conditions and sediment properties on the dissolution kinetics of natural and synthetic calcites. In preparation

Sulpis, O., Dufour, C.O., Trossman, D.S., et al. Decreasing bottom-current speeds and seafloor CaCO3 dissolution under a business-as-usual scenario. Under review





**Olivier Sulpis**
McGill University


**June 26th, 2019**
OCB summer workshop