A next generation model of carbon isotopes for climate studies

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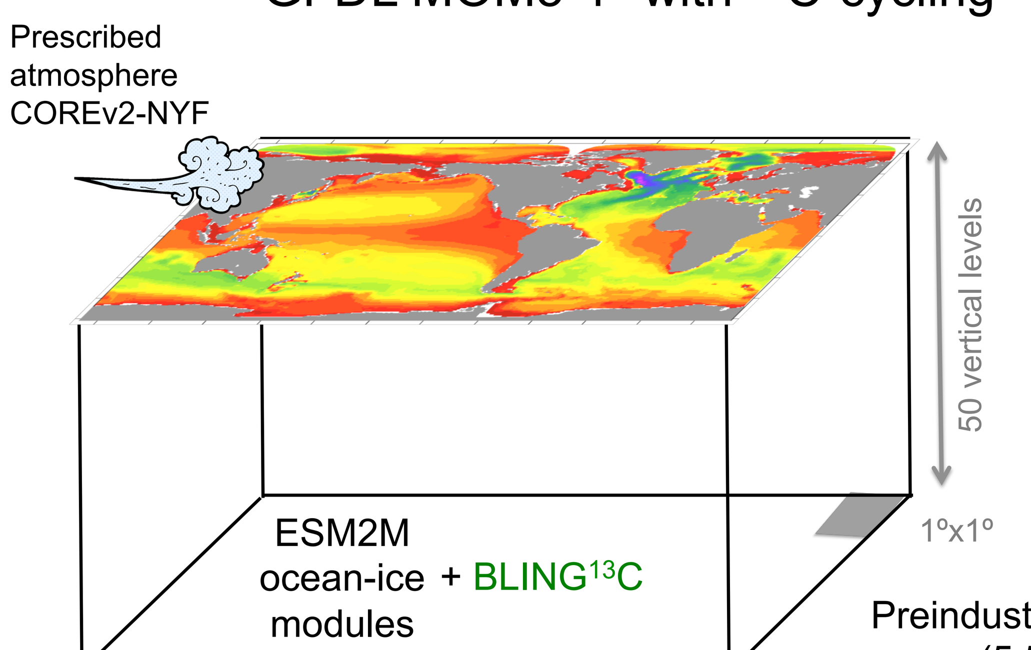
MOTIVATION:
δ^{13}C of DIC for validation of C-cycling in CMIP6 models

Useful characteristics of δ^{13}C for model evaluation:

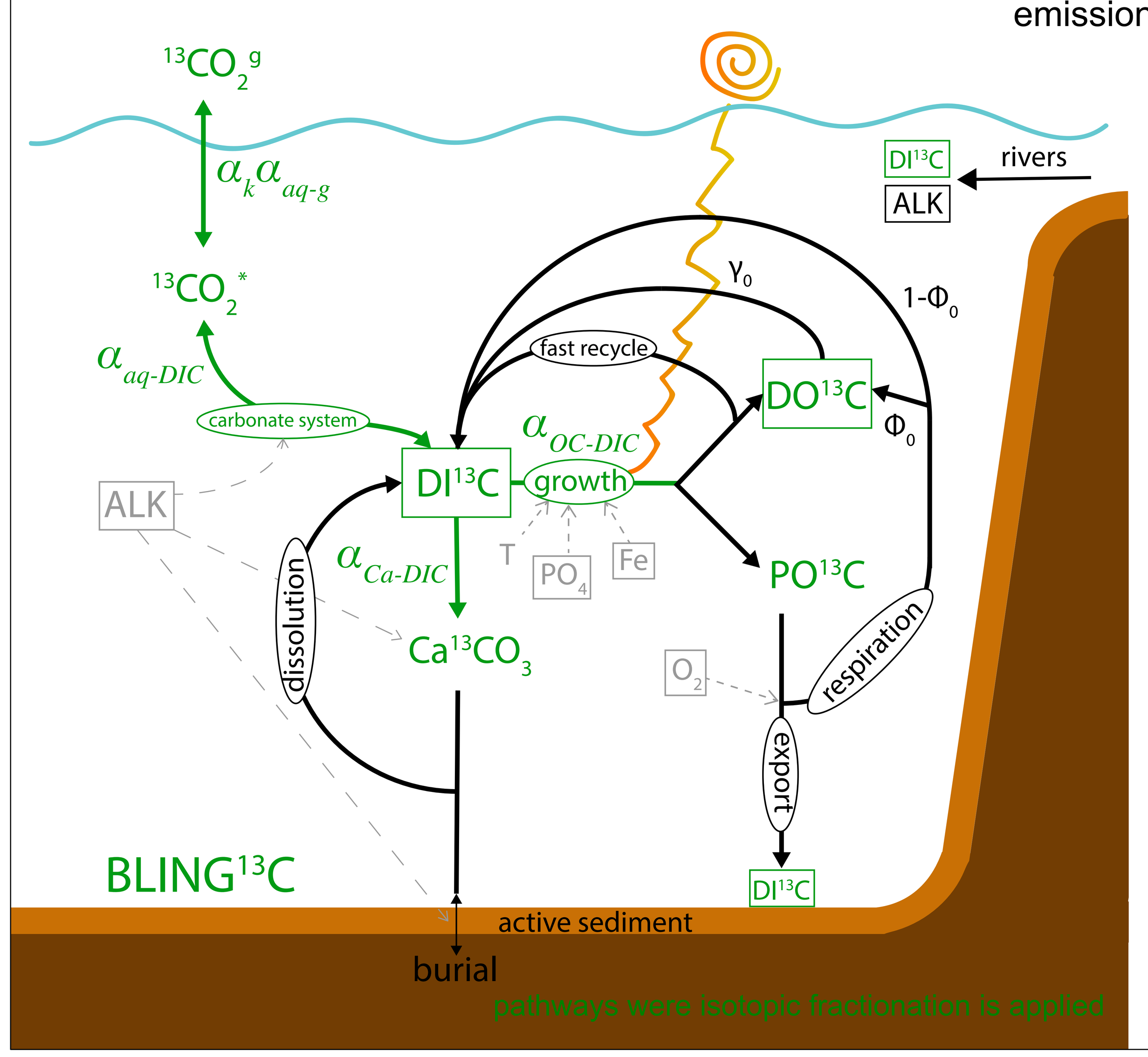
1) Oceanic changes in δ^{13}C are caused by oceanic uptake of anthropogenic carbon. Anthropogenic δ^{13}C changes are measurable to superior signal to noise than changes in DIC.
2) Air/sea δ^{13}C disequilibrium is measurable, providing a means of evaluating modeled air/sea carbon fluxes.
3) Abyssal ocean's δ^{13}C is sensitive to the relative proportions of North Atlantic and Southern Ocean deep waters.
4) Sea surface δ^{13}C is sensitive to the wind-speed dependence of gas exchange, and to biological export rates.

While state-of-the-art carbon-cycle models have been coupled to high-resolution climate models (~1/10º), **^{13}C-cycling models are conventionally coupled to coarse resolution (~2-4º)** models due to the long spinup time needed to equilibrate the oceanic DI^{13}C inventory with the preindustrial atmosphere (~5000 model years). As a result, **uncertainties in coarsely resolved large-scale circulation significantly affect the modeled δ^{13}C fields.**

STATE-OF-THE-ART MODEL:
GFDL MOM5-1º with ^{13}C-cycling



Preindustrial steady state (5,500 years using 360CPUs)
+
transient carbon emissions

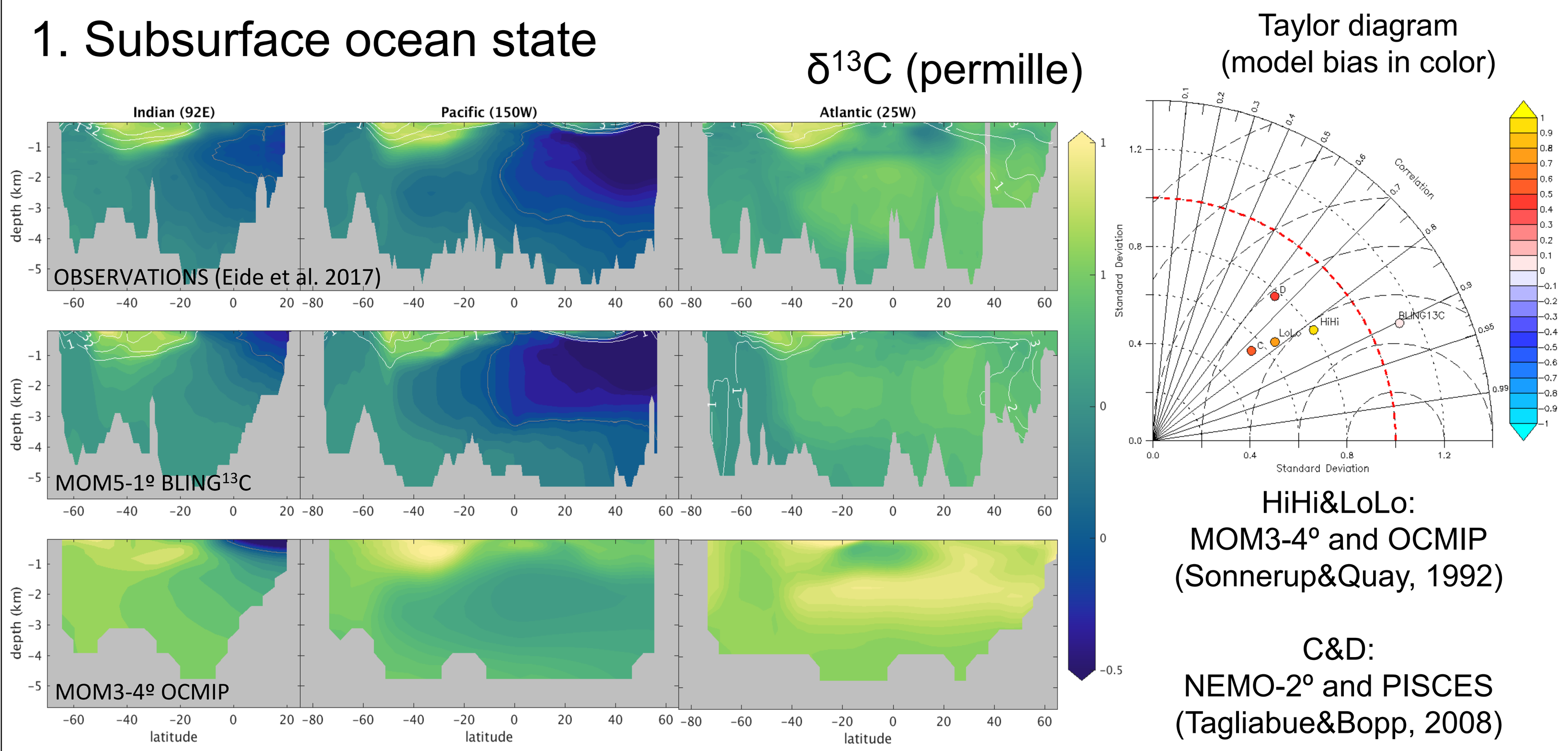


Rivers: 0.45 Gt C yr^{-1} at δ^{13}C of -28 permille

(river input minus carbon burial is 0.25 Gt yr^{-1})

RESULTS: Comparison between 4º (MOM3) and 1º (MOM5) ocean models with ^{13}C-cycling

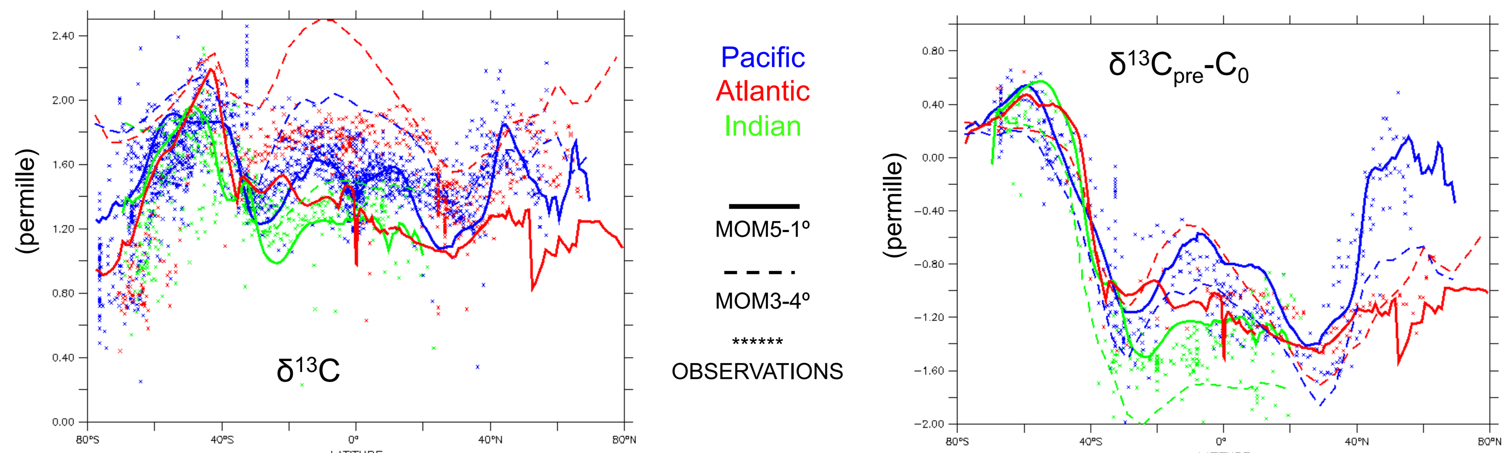
1. Subsurface ocean state



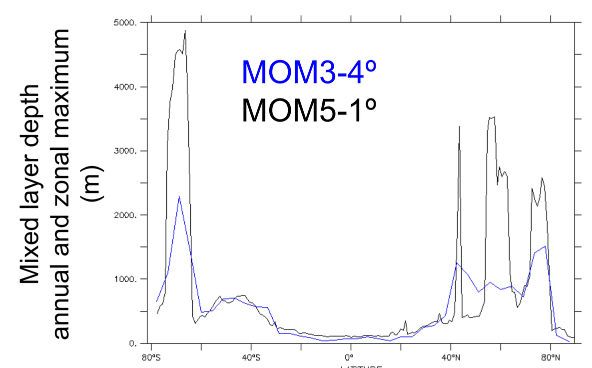
MOM5-1º with BLING^{13}C has a model bias within instrumental accuracy. Coarse resolution models are biased high. All models reproduce meridional subsurface δ^{13}C patterns, reflecting the large-scale circulation patterns. BLING^{13}C reproduces better upwelling and deep convection regions (see surface meridional values below).

3. On preformed δ^{13}C endmember values

Meridional δ^{13}C trends at the sea surface allow us to understand model biases in the end-member δ^{13}C values, and thus in the deep sea. Because δ^{13}C equilibrates with the atmosphere about ten times slower than CO_2, its preformed value reflects the relative impacts of air/sea gas exchange, temperature, deep convection, and lateral transport.



MOM5-1º captures the signature of isotopically light δ^{13}C due to upwelling and deep convection as opposed to MOM3-4º (LEFT). Differences in the overall meridional pattern are reduced when biological effects are removed (RIGHT), but discrepancies at high latitudes and in the magnitude of C_0 are still large among models.



Possible causes of sea surface model discrepancies?

Deep convection is stronger with increased model resolution. Deeper mixed layers lower surface δ^{13}C as the deep ocean δ^{13}C is isotopically light compared to the upper ocean.

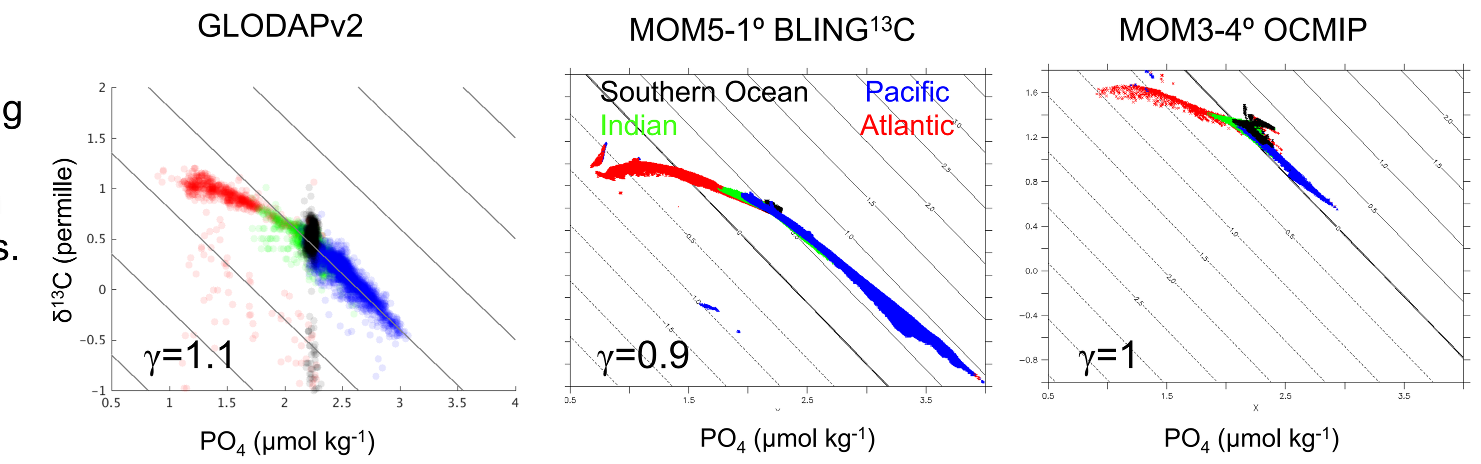
Other possibilities?
+ Wind speed dependence of CO_2 gas exchange, likely overestimated in all ^{13}C-cycling ocean models.
+ Organic matter fractionation, likely too large at high latitudes in all models.

2. Deep ocean (z > 2000 m)

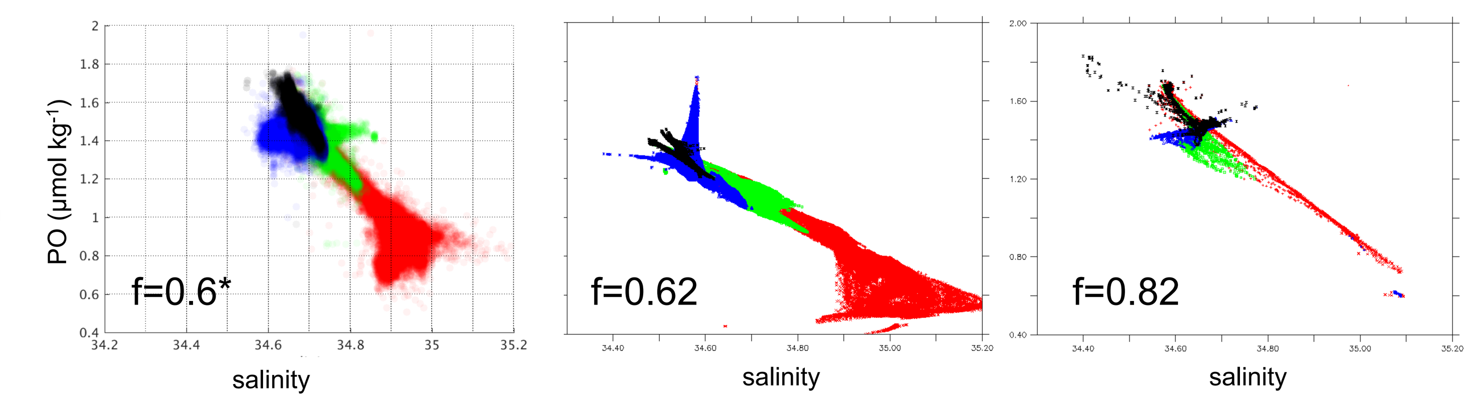
The δ^{13}C averaged value at depth can be estimated by linear mixing of preformed δ^{13}C (δ$^{13}C_{pre}$) between two endmembers, North Atlantic Deep Water (NADW) and Southern Ocean Deep Water (SODW), plus remineralization of organic matter:

$$\delta^{13}C^{MIX} = \underbrace{f\,\delta^{13}C_{pre}(SODW) + (1-f)\,\delta^{13}C_{pre}(NADW)}_{\delta^{13}C_{pre}} - \gamma PO_4 \approx \delta^{13}C$$

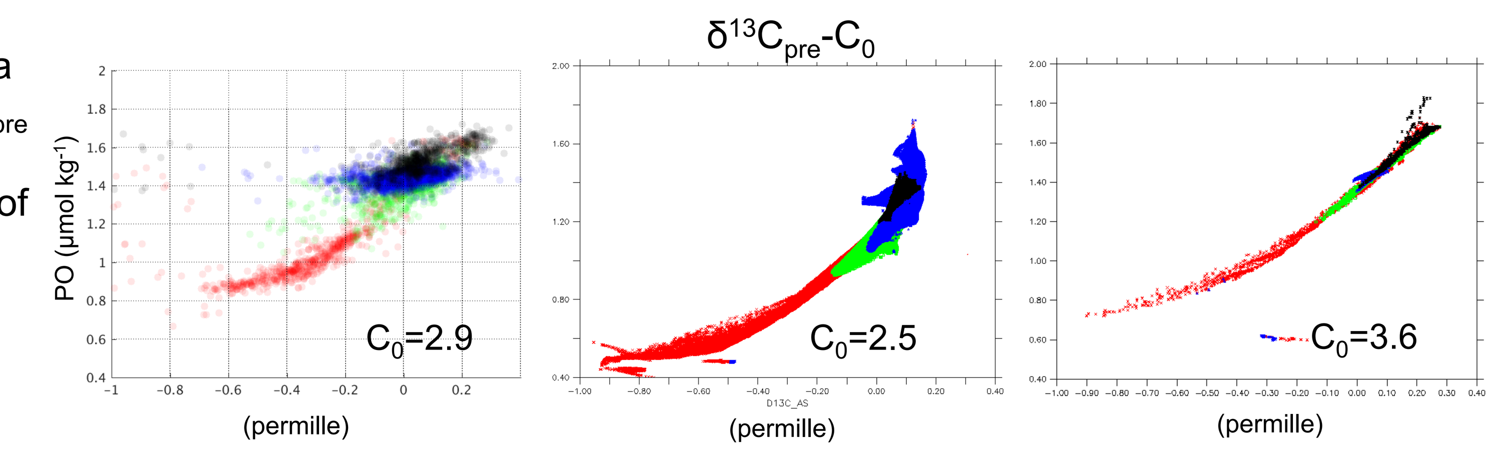
The biological effect on δ^{13}C is found using the empirical δ^{13}C to PO_4 ratio (γ) at depth in Indo-Pacific waters. Anthropogenic δ^{13}C obscures this ratio in the Atlantic.



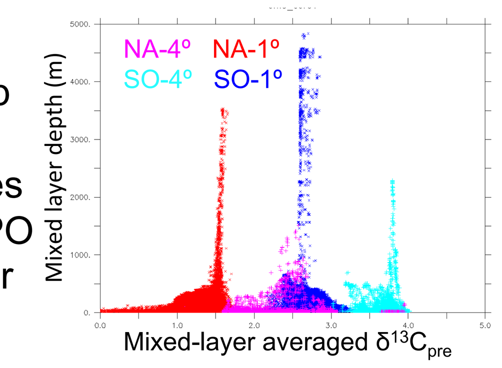
The water mass fraction of SODW (f) is found solving two-endmember mixing models for salinity (S) and preformed phosphate PO (Broecker et al.1998).



Water masses have a distinct PO and δ$^{13}C_{pre}$ content. Values of δ$^{13}C_{pre}$ as a function of PO unveil a close-to-linear mixing for δ$^{13}C_{pre}$ between endmembers



Modeled endmember δ$^{13}C_{pre}$ values are well-defined in regions of deep convection. From observations, these values are estimated using the PO versus δ13C$_{pre}$ relation for PO of NADW (0.73 µmol kg^{-1}) and SODW (1.95 µmol kg^{-1}*).



	f	δ$^{13}C_{pre}$(SODW)	δ$^{13}C_{pre}$(NADW)	γPO_4	δ$^{13}C^{MIX}$	δ^{13}C
GLODAPv2	0.6*	3.3	2.3	2.5	0.4	0.38
MOM5-1º	0.62	2.65	1.55	1.98	0.25	0.41
MOM3-4º	0.82	3.7	2.5	2.2	1.28	1.12

All units are in permille, except f which is unitless

*Broecker et al. 1998

CONCLUSIONS

MOM5-1º with BLING^{13}C significantly improves the modeled δ^{13}C oceanic mean state relative to coarse resolution models.

Subsurface δ^{13}C can be estimated with a linear mixing model between North Atlantic and Southern Ocean deep waters substracting biological effects.

Endmember δ^{13}C values are strongly biased high in coarse resolution models, which may explain their high global ocean averaged δ^{13}C. The bias may be due to poor resolution of deep convection, but uncertainties due to organic matter fractionation and wind-speed dependence of gas exchange need to be tested.

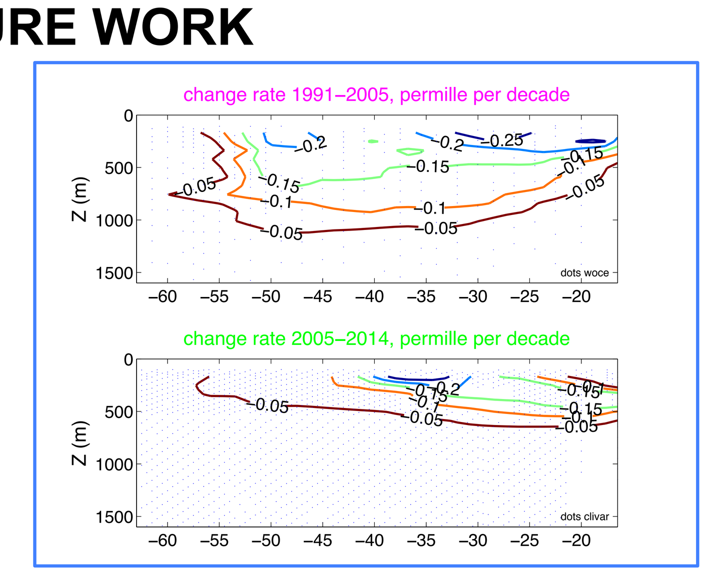
ONGOING AND FUTURE WORK

Test the δ^{13}C budgeting approach to infer transports of anthropogenic carbon using the Suess effect

Use interdecadal changes in δ^{13}C to detect and understand changes in oceanic carbon uptake

Use δ^{13}C to evaluate ocean circulation and carbon cycling in the next generation of GFDL climate models

Implement BLING^{13}C in Earth System Models



Decadal changes in the oceanic uptake of anthropogenic CO_2 along 152W in the South Pacific are visible in the measured ^{13}C changes

Broecker, W. S., et al. (1998), How much deep water is formed in the Southern Ocean?, *J. Geophys. Res.*, 103(C8), 15833–15843, doi: 10.1029/98JC00248.
Eide, M., A. Olsen, U. S. Ninnemann, and T. Johannessen (2017), A global ocean climatology of preindustrial and modern ocean δ13C, Global Biogeochem. Cycles, 31, 515–534, doi:10.1002/ 2016GB005473.
Sonnerup, R. E., and P. D. Quay (2012), 13C constraints on ocean carbon cycle models, Global Biogeochem. Cycles, 26, GB2014, doi:10.1029/2010GB003980.
Tagliabue, A., and L. Bopp (2008), Towards understanding global variability in ocean carbon-13, Global Biogeochem. Cycles, 22, GB1025, doi:10.1029/2007GB003037