MESOSCALE AND SUBMESOSCALE DYNAMICS AND THEIR CONTROL OF OCEAN ALKALINITY ENHANCEMENT EFFICIENCY

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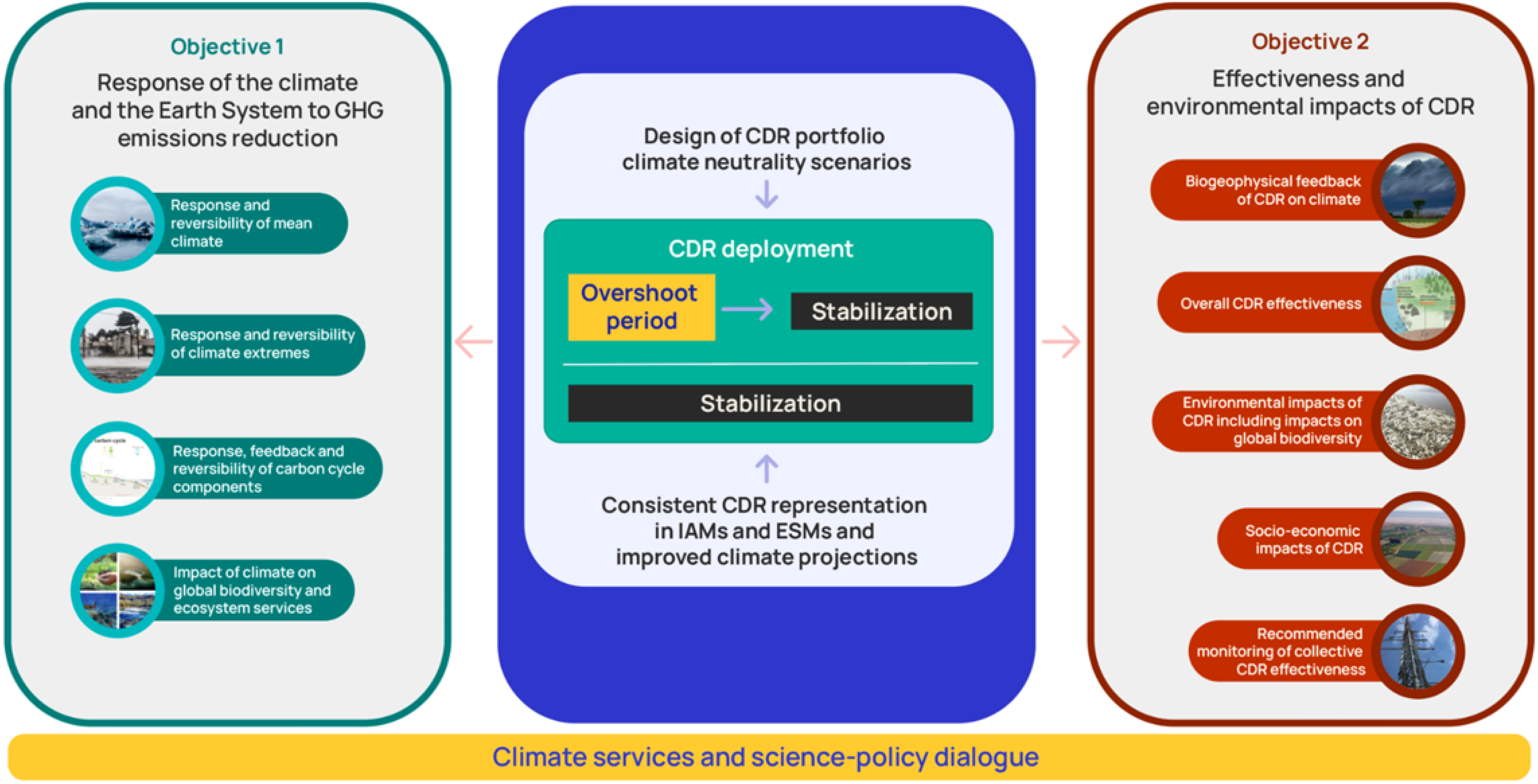
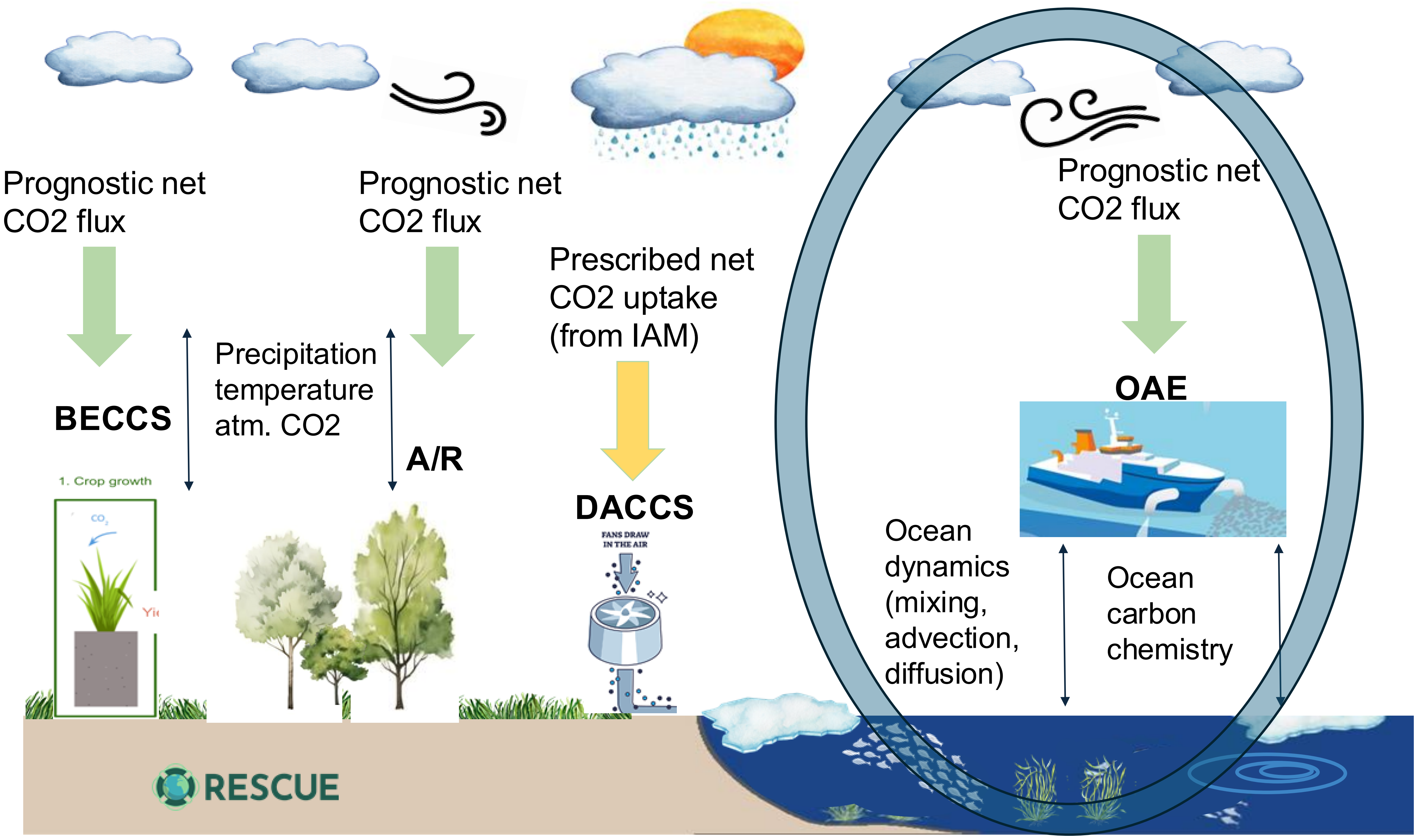
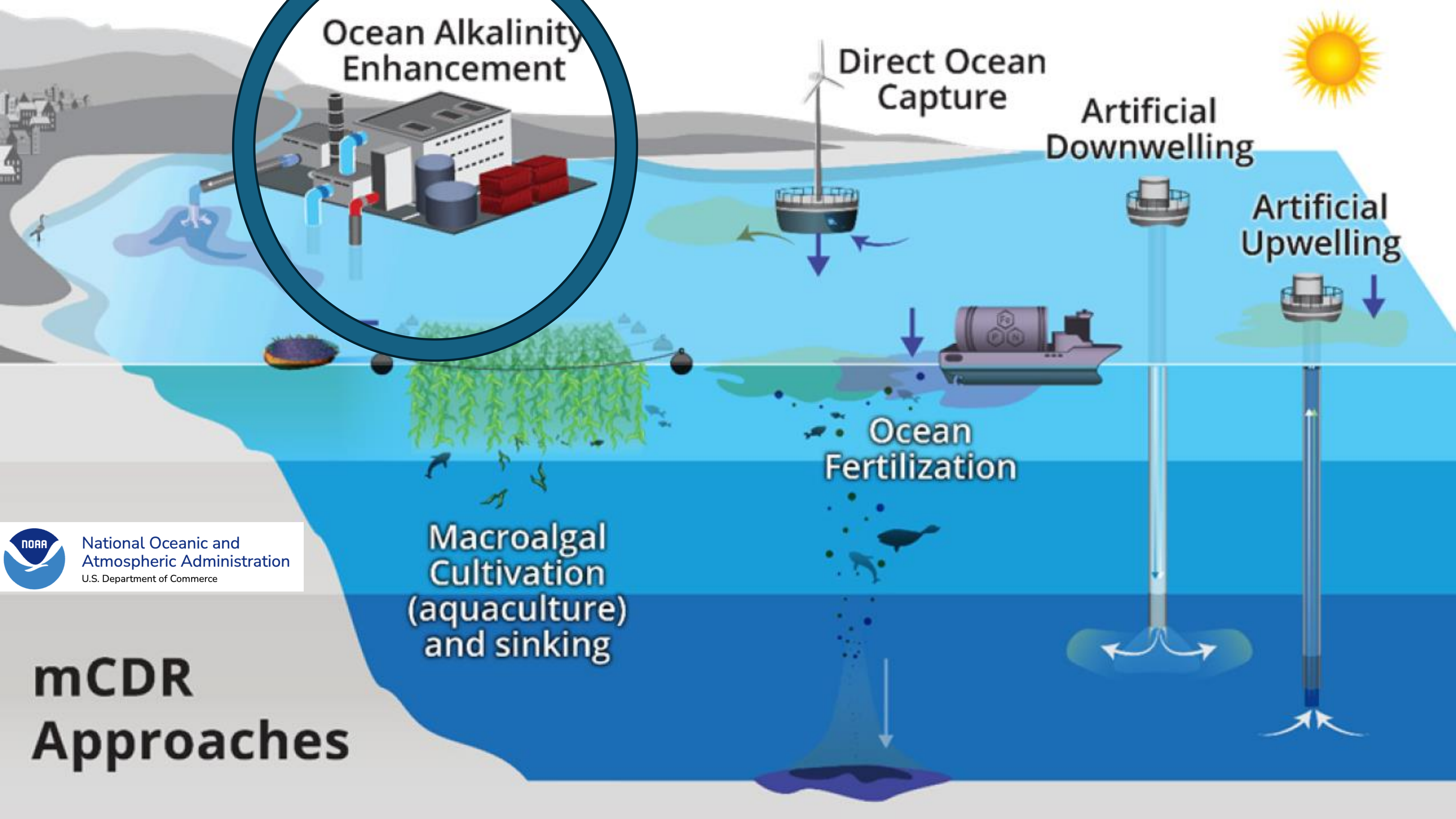
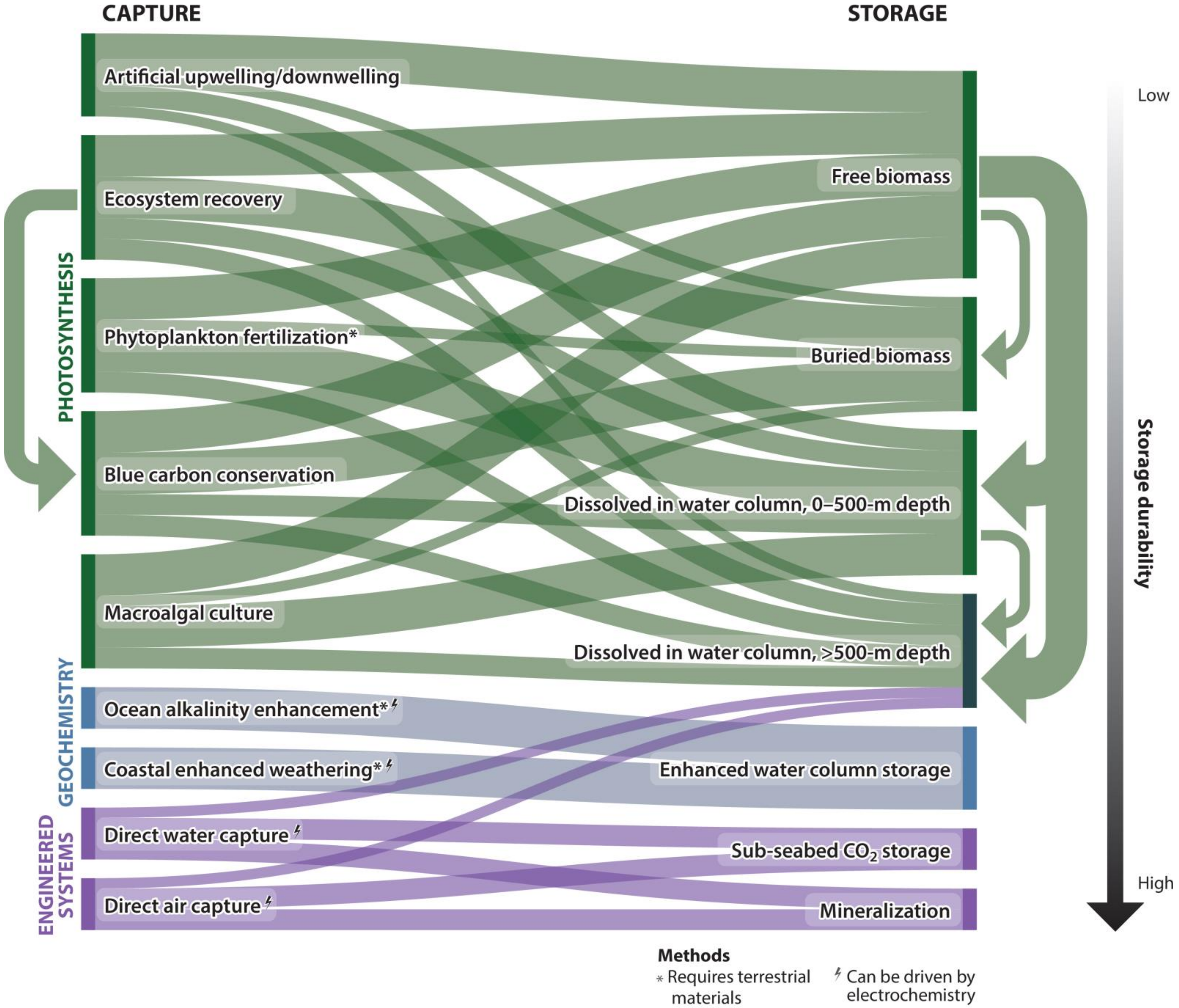
RESCUE

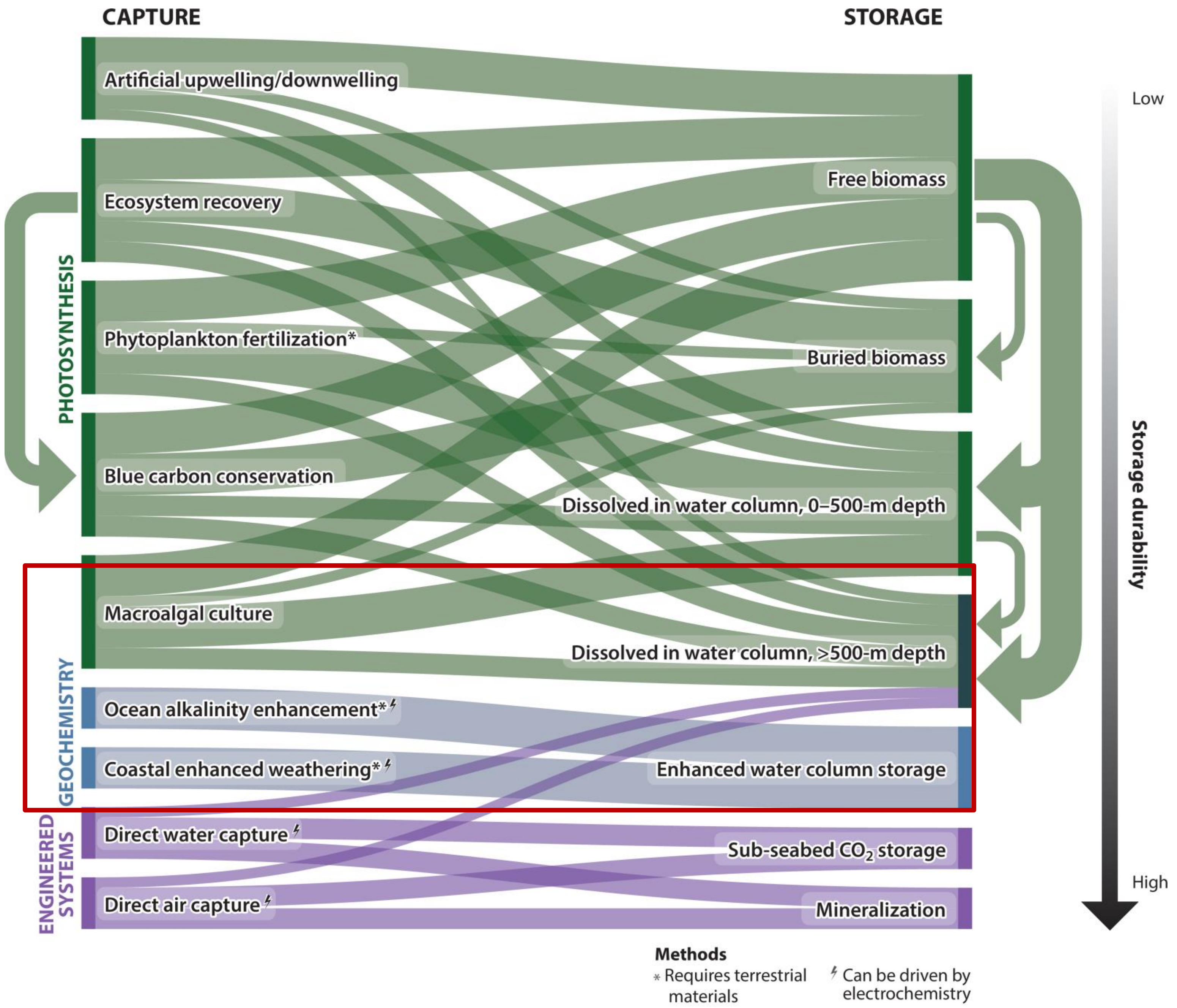

Objective 1
Response of the climate and the Earth System to GHG emissions reduction
Response and reversibility of mean climate
Response and reversibility of climate extremes
Response, feedback and reversibility of carbon cycle components
Impact of climate on global biodiversity and ecosystem services
Design of CDR portfolio climate neutrality scenarios
CDR deployment
Overshoot period
Stabilization
Stabilization
Consistent CDR representation in IAMs and ESMs and improved climate projections
Objective 2
Effectiveness and environmental impacts of CDR
Biogeophysical feedback of CDR on climate
Overall CDR effectiveness
Environmental impacts of CDR including impacts on global biodiversity
Socio-economic impacts of CDR
Recommended monitoring of collective CDR effectiveness
Climate services and science-policy dialogue


Prognostic net CO2 flux
Prognostic net CO2 flux
Prescribed net CO2 uptake (from IAM)
Prognostic net CO2 flux
BECCS
Precipitation temperature atm. CO2
A/R
DACCS
OAE
1. Crop growth
CO2
FANS DRAW IN THE AIR
Ocean dynamics (mixing, advection, diffusion)
Ocean carbon chemistry
RESCUE


Ocean Alkalinity Enhancement
Direct Ocean Capture
Artificial Downwelling
Artificial Upwelling
Ocean Fertilization
Macroalgal Cultivation (aquaculture) and sinking
National Oceanic and Atmospheric Administration
U.S. Department of Commerce
mCDR Approaches



Cooley SR, et al. 2023
Annu. Rev. Mar. Sci. 15:41–66



Cooley SR, et al. 2023
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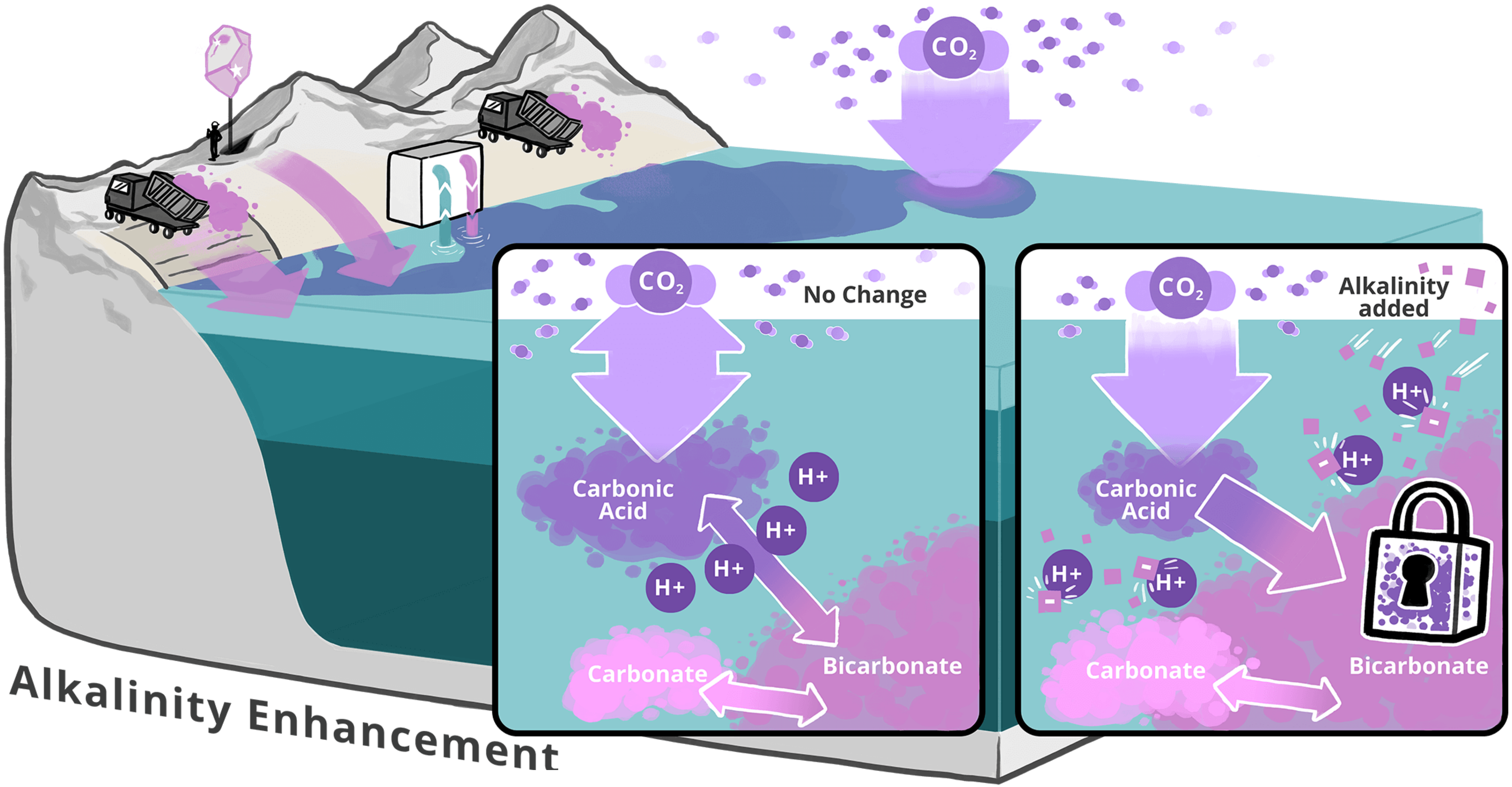


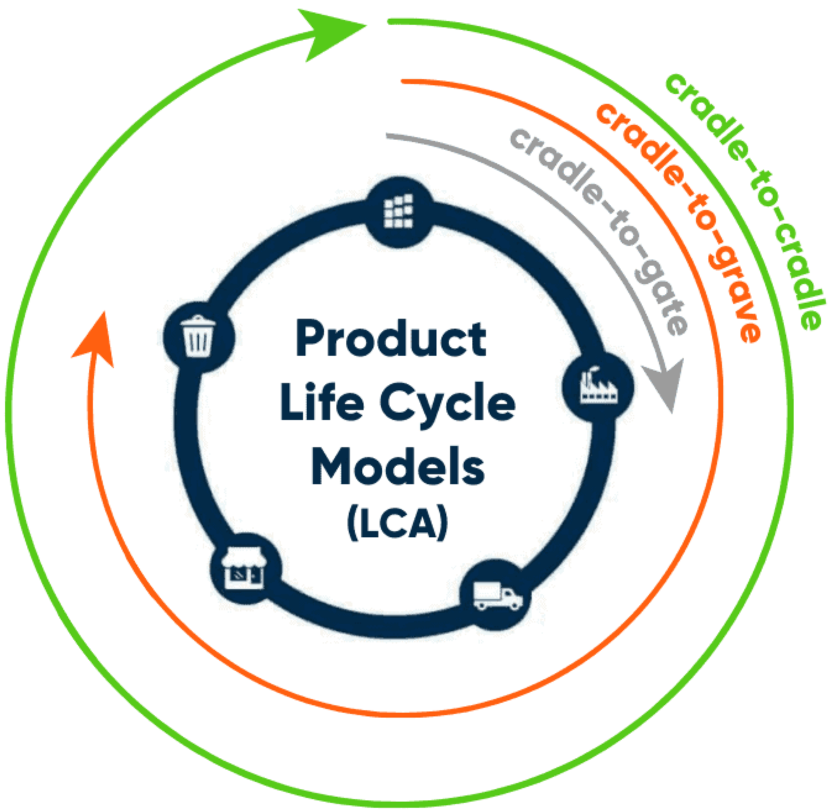
$$CO_{2(atm)} \rightleftharpoons CO_{2(aq)} + H_2O \rightleftharpoons H^+ + HCO_3^-$$
$$\rightleftharpoons 2H^+ + CO_3^{2-}.$$

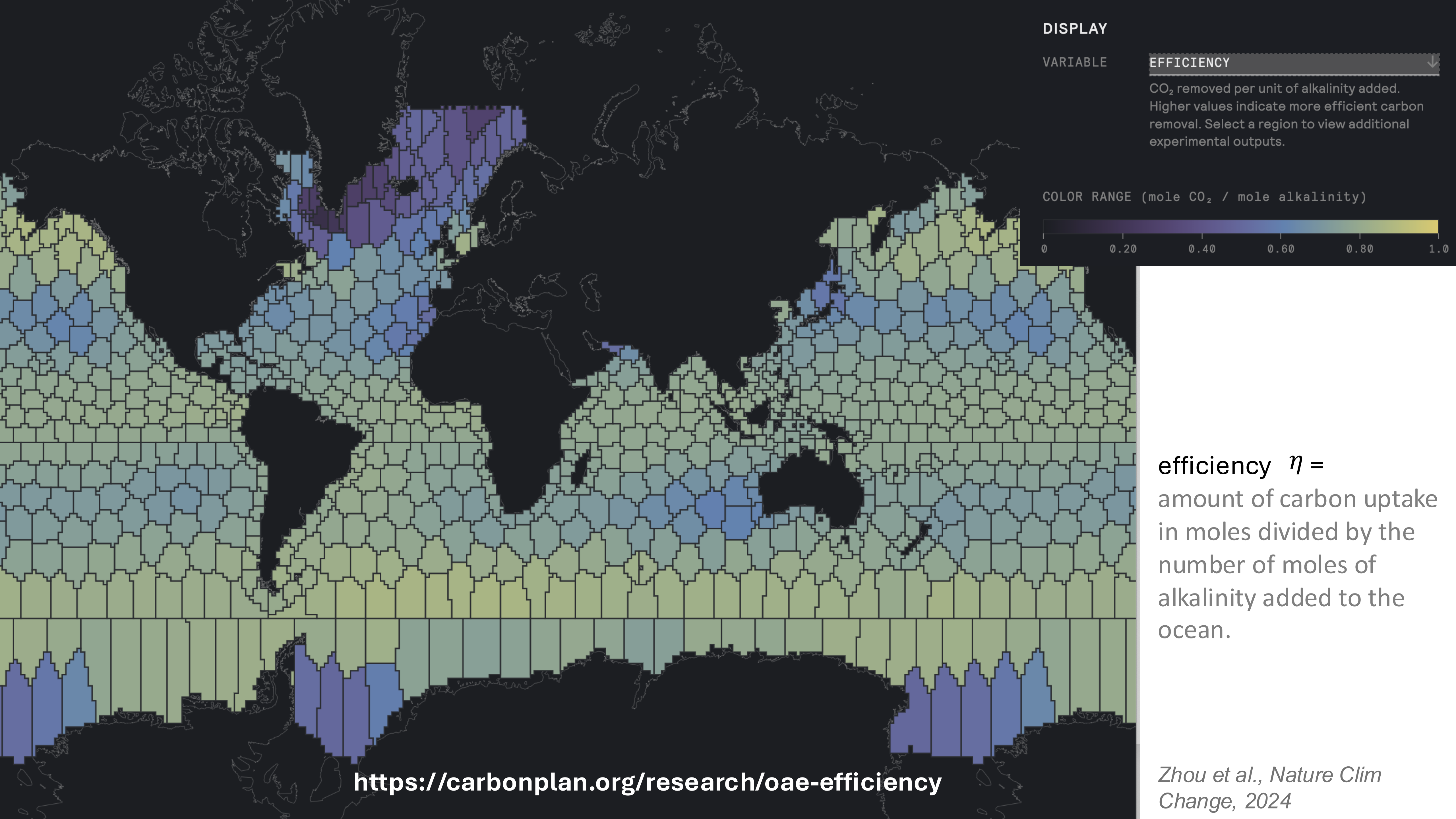
Monitoring, Reporting, and Verification (MRV)

robust and precise attribution/MRV is critical for scaling CDR

1. understanding mechanisms/impacts
2. building public/stakeholder confidence
3. fungibility on voluntary/compliance markets

but — must avoid bottlenecks at scale

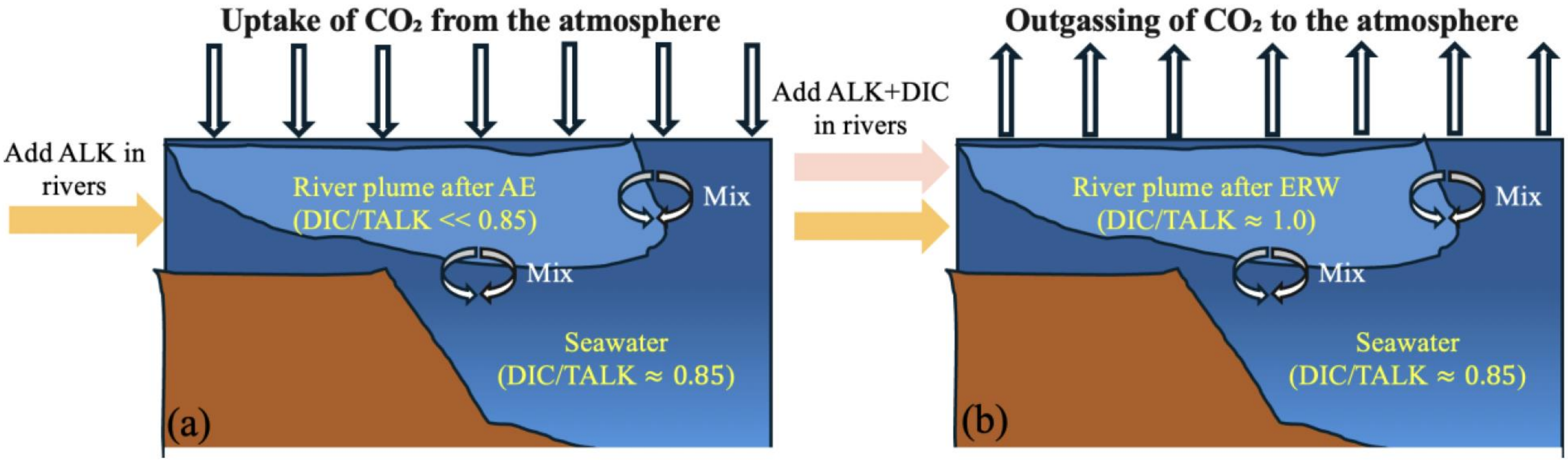




efficiency η =
amount of carbon uptake in moles divided by the number of moles of alkalinity added to the ocean.

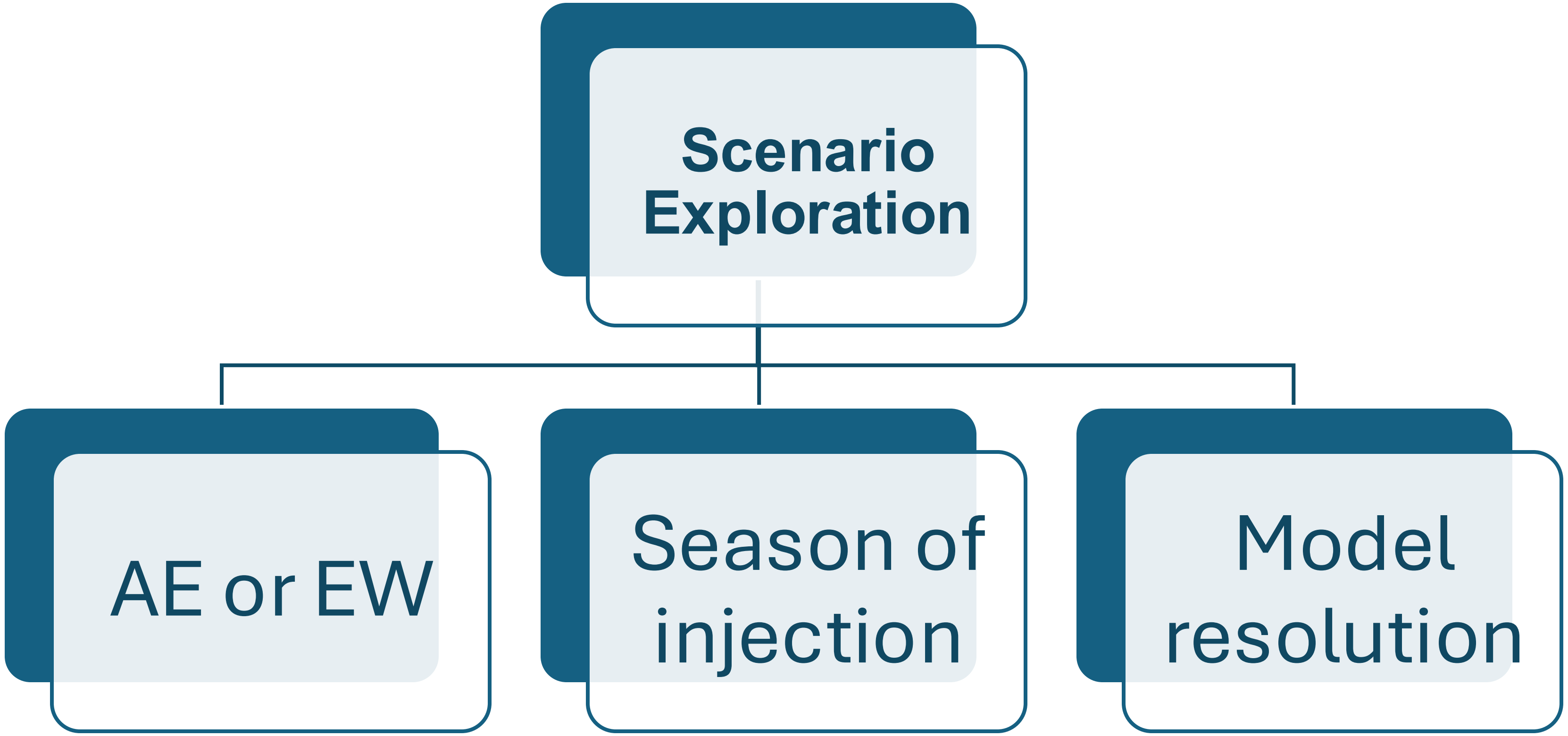
Zhou et al., Nature Clim Change, 2024

- More realistically, enhancement will occur near/at a coastline
- Potentially with a quasi point-source injection
- Rivers are preferred locations also through enhanced weathering



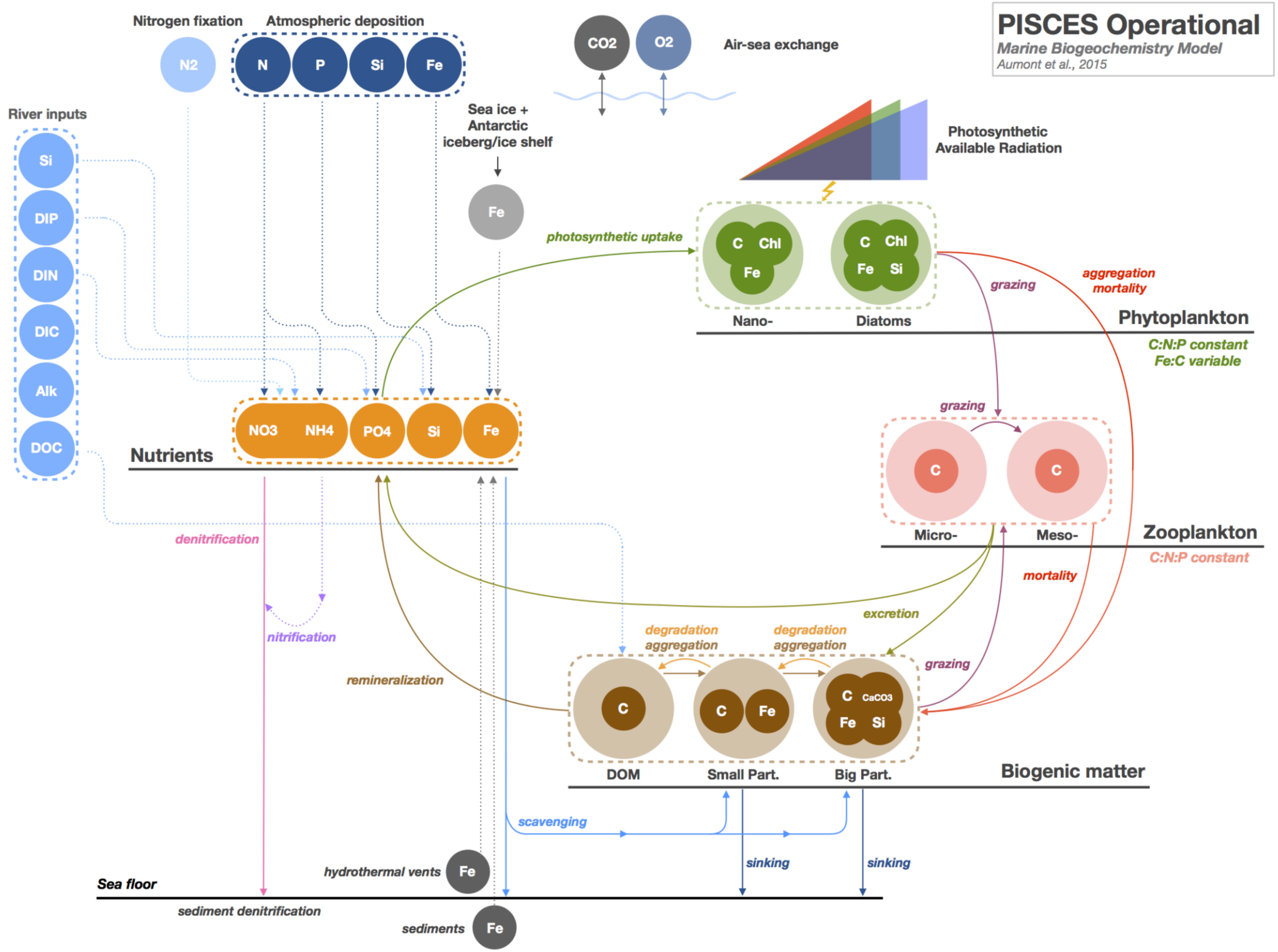
Conceptual diagram showing changes in the ocean carbonate system following river-based AE(a) and EW (b).

Scenario Exploration



CROCO

Coastal and Regional Ocean COmmunity model



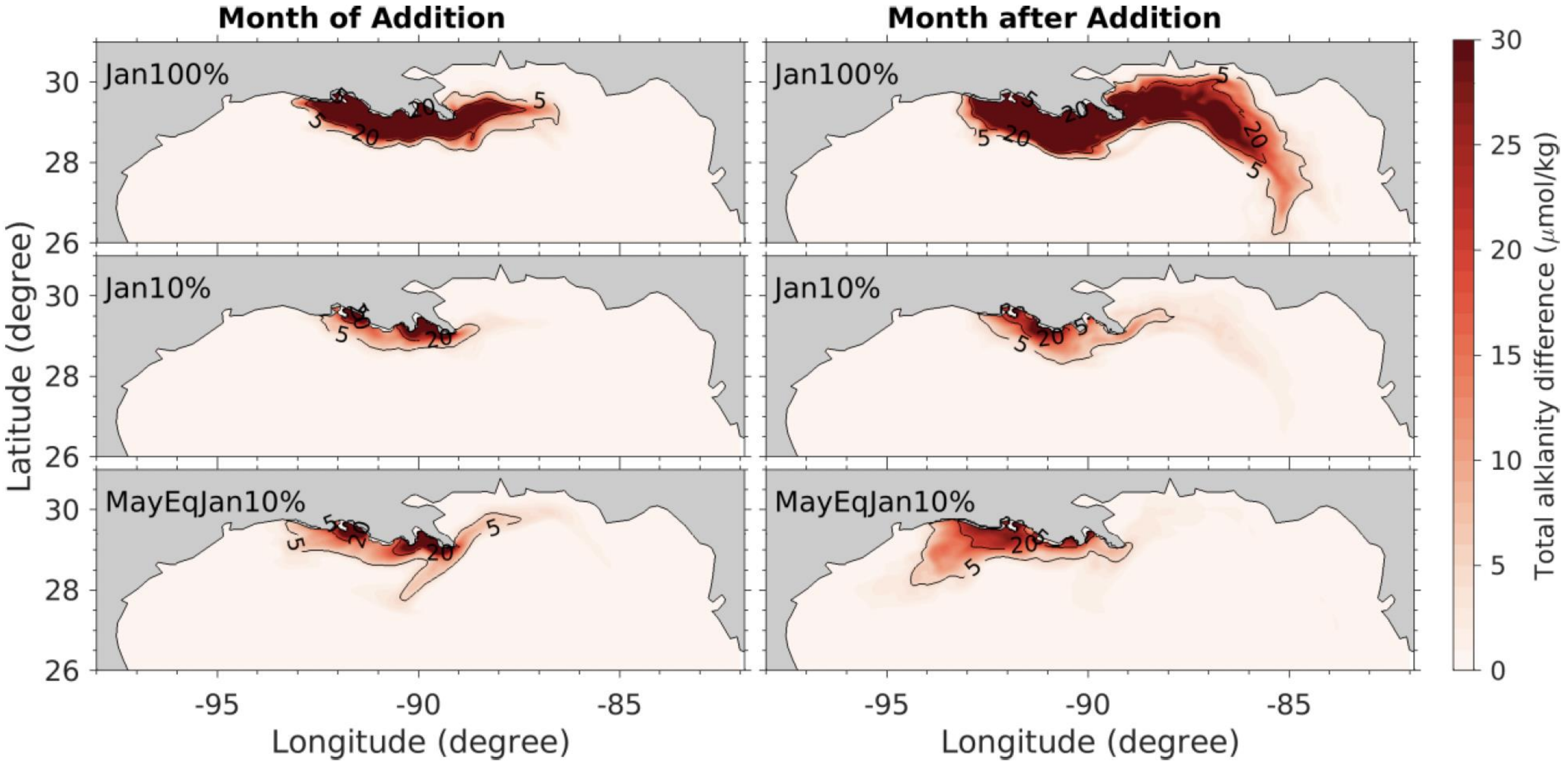
ALK only or ALK + DIC

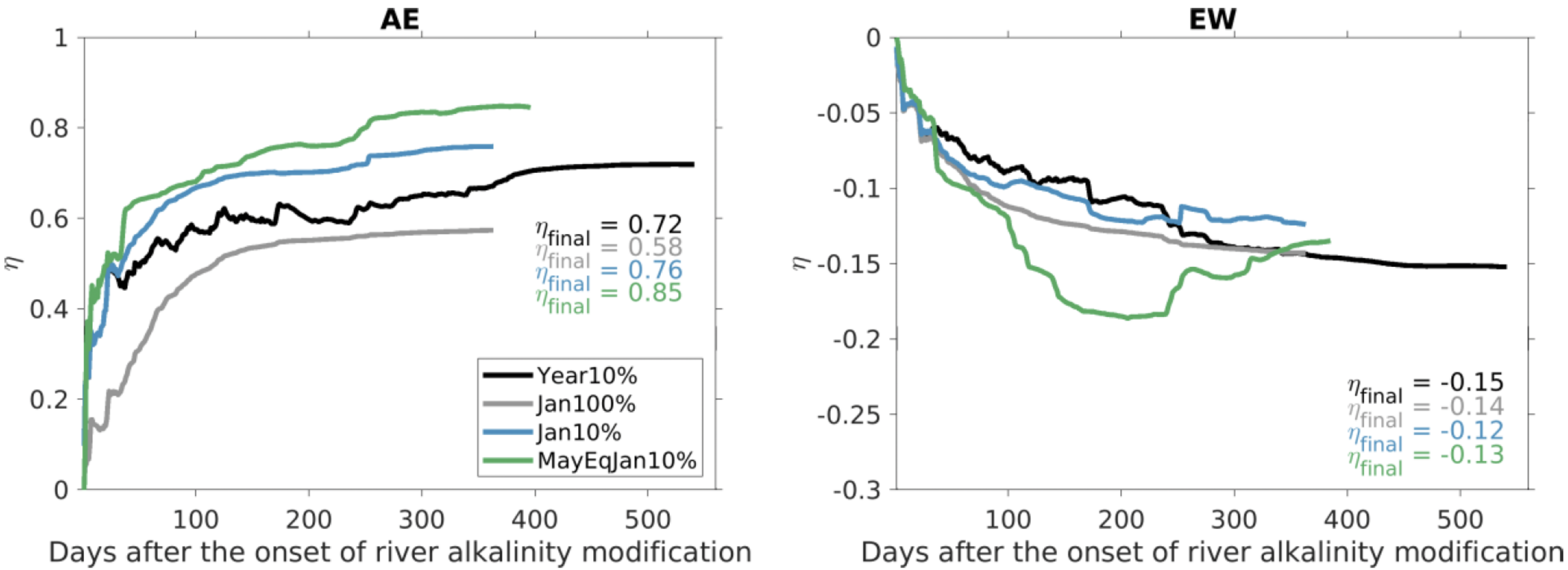
River modifications
Control run
10% increase in 2017 (Year10%)
100% increase in Jan (Jan100%)
10% increase in Jan (Jan10%)
10% increase (of Jan) in mid-May (MayEqJan10%)

Efficiency $$\eta = \frac{A \int_0^t \Delta F(t)}{\Delta ALK_{river}(t)}$$

All at 5km horizontal resolution
+ Jan100% and MayEqJan10%
at 1km horizontal resolution

Seasonality + Scenario exploration





- Efficiency is higher for Spring than Winter, and for smaller than large additions
- Significant differences in the AE scenarios: $0.5 < \eta < 0.85$
- Small differences across EW scenarios (loss is comparable and max is 15.6%)

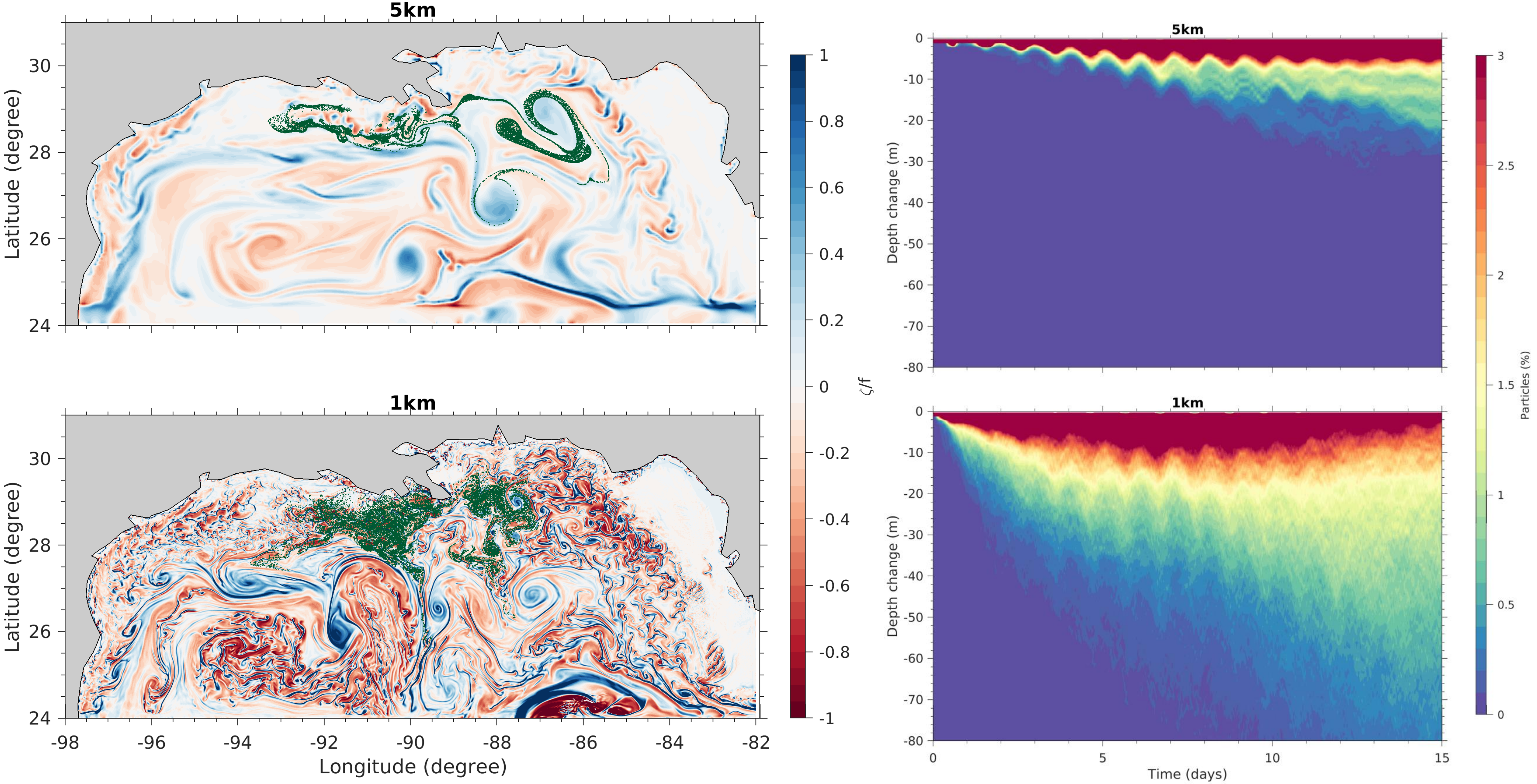
- Small additions of alkalinity to riverine discharge yield higher efficiency
  Caveat: smaller perturbations maximize efficiency but may not achieve the total CO_2 uptake needed for large-scale mitigation

- In the Northern Gulf AE is more effective in summer than in winter
  Stronger stratification + shallower mixed layer promote a longer surface retention

- EW cases reveal only minor differences in ocean-side leakage: better for strategy design. EW approaches should focus on land-based factors (mineral feedstock, weathering kinetics, cost, and signal resolvability...)

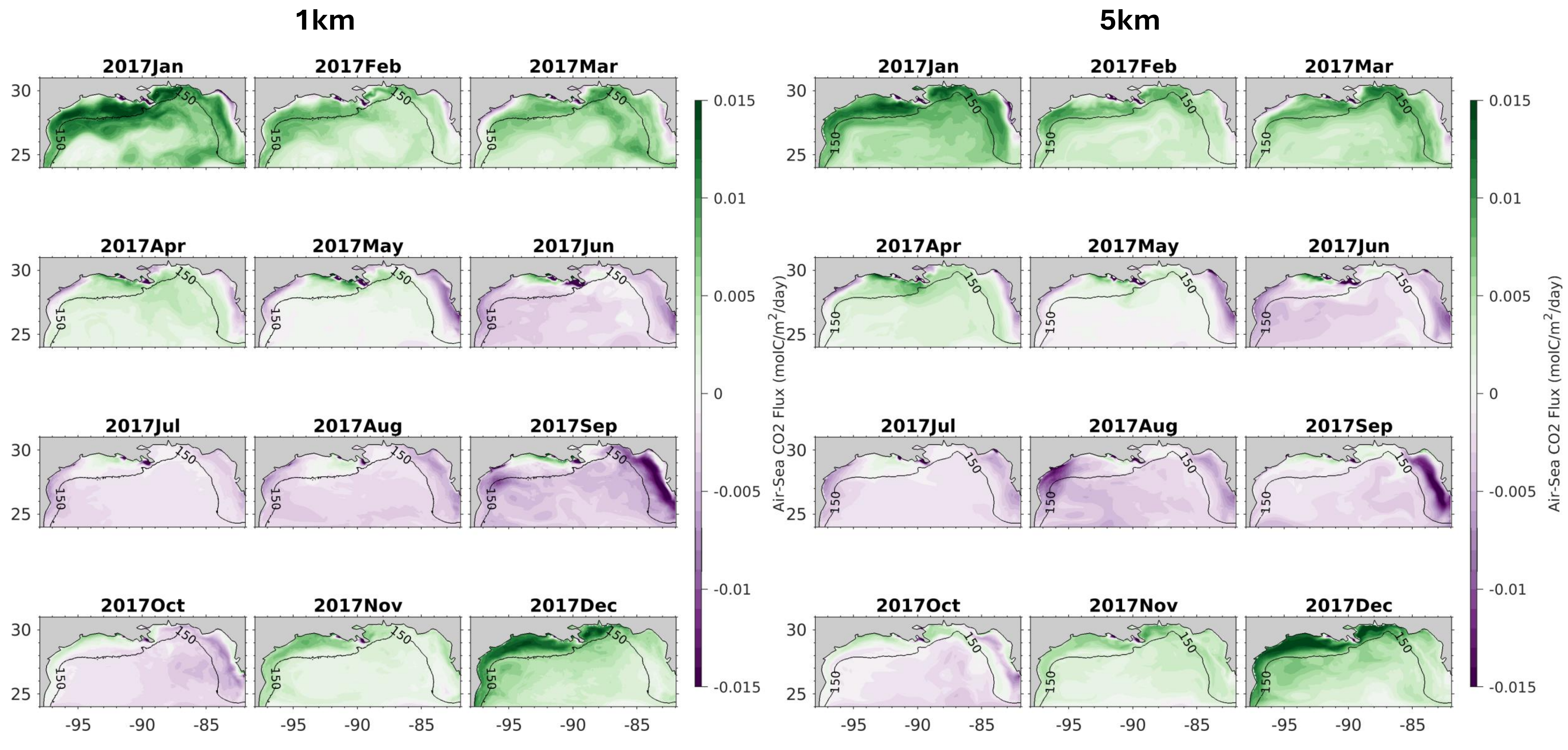
- For a given amount of ALK modification, EW approaches will result in more effective ocean carbon storage because they will deviate less strongly from the background ALK/DIC field during transient ALK modification.

RESOLUTION

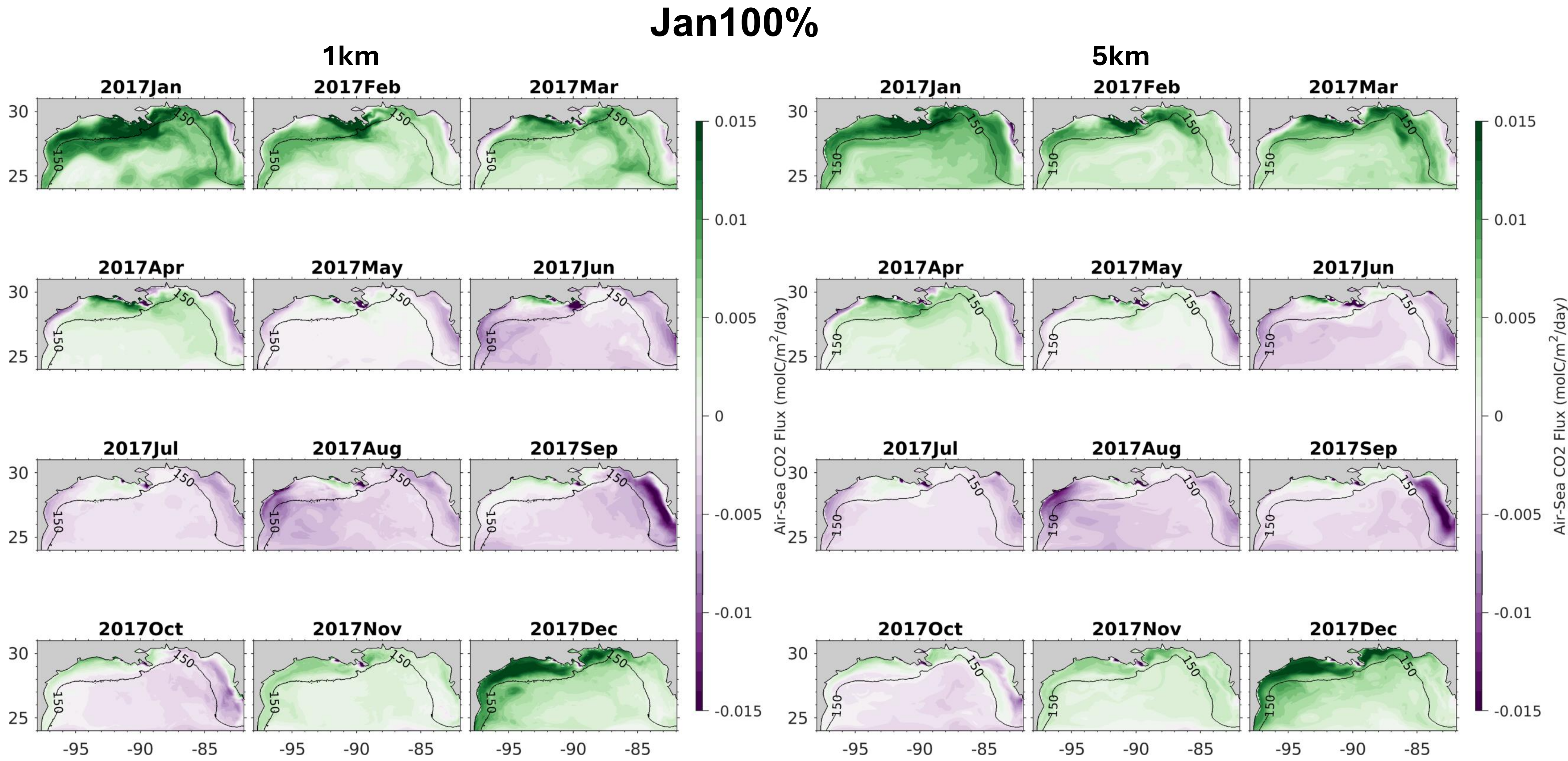


Zhou, Reinhard, Ito, Bracco, et al, In Prep

Control runs - CO^2 fluxes



ALK modification run - CO^2 fluxes



$$\frac{dF}{dt} = -\frac{G\alpha_C}{h}F + \{f_{\text{trans}} + f_{\text{bio}} + f_T + f_{\text{atm}}\}$$

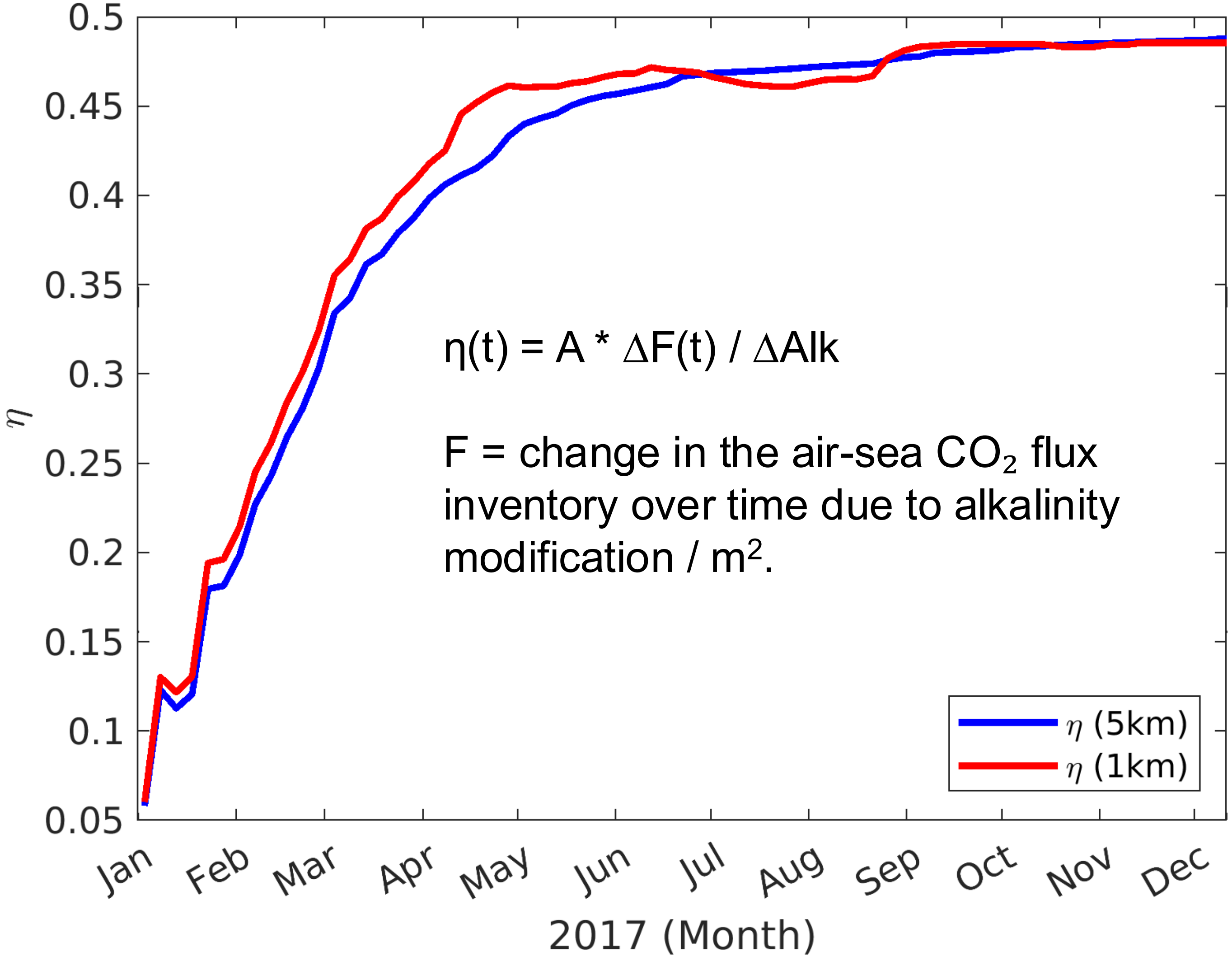
Attribution framework

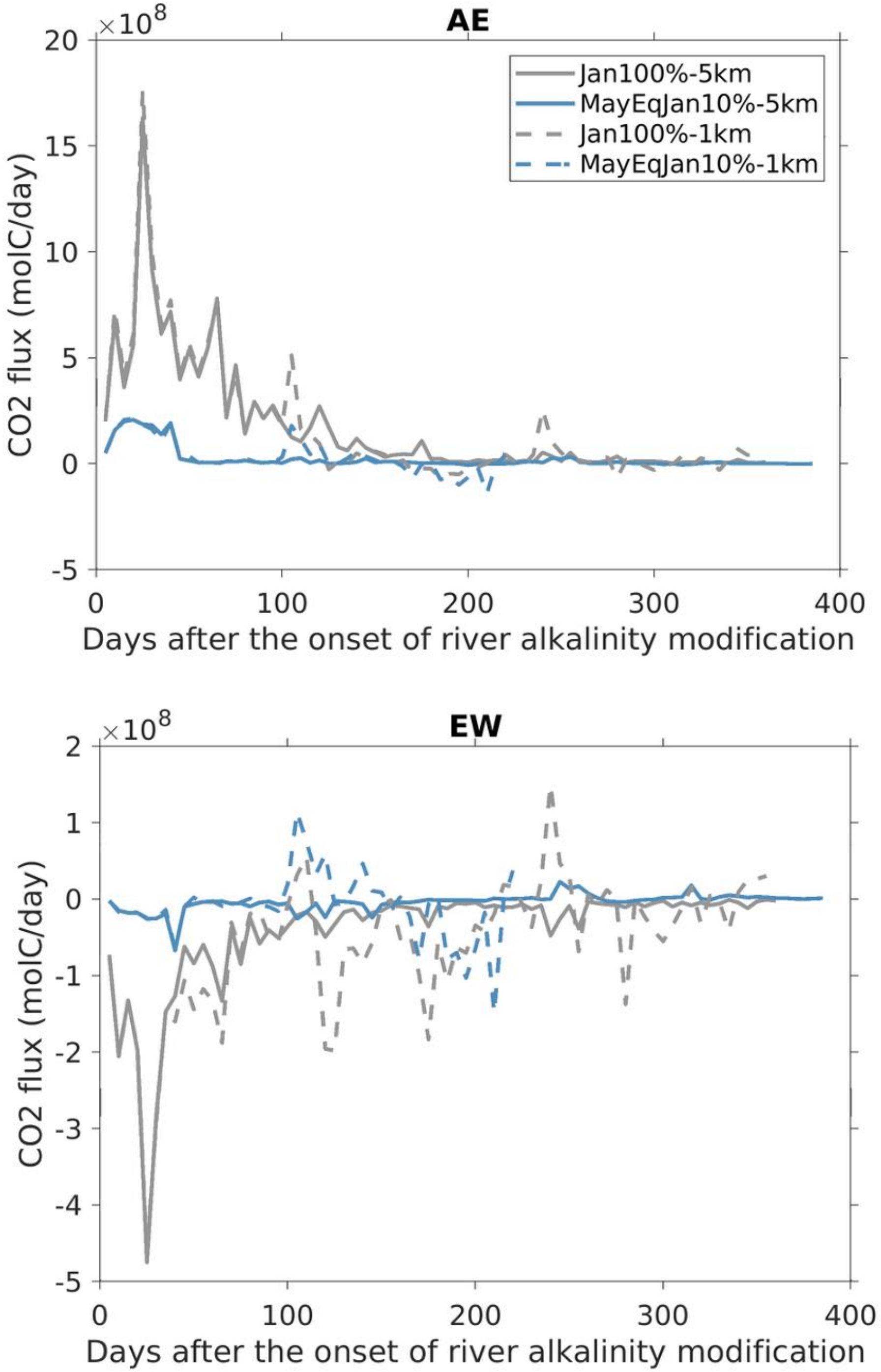
Ito and Reinhard, GBC 2025

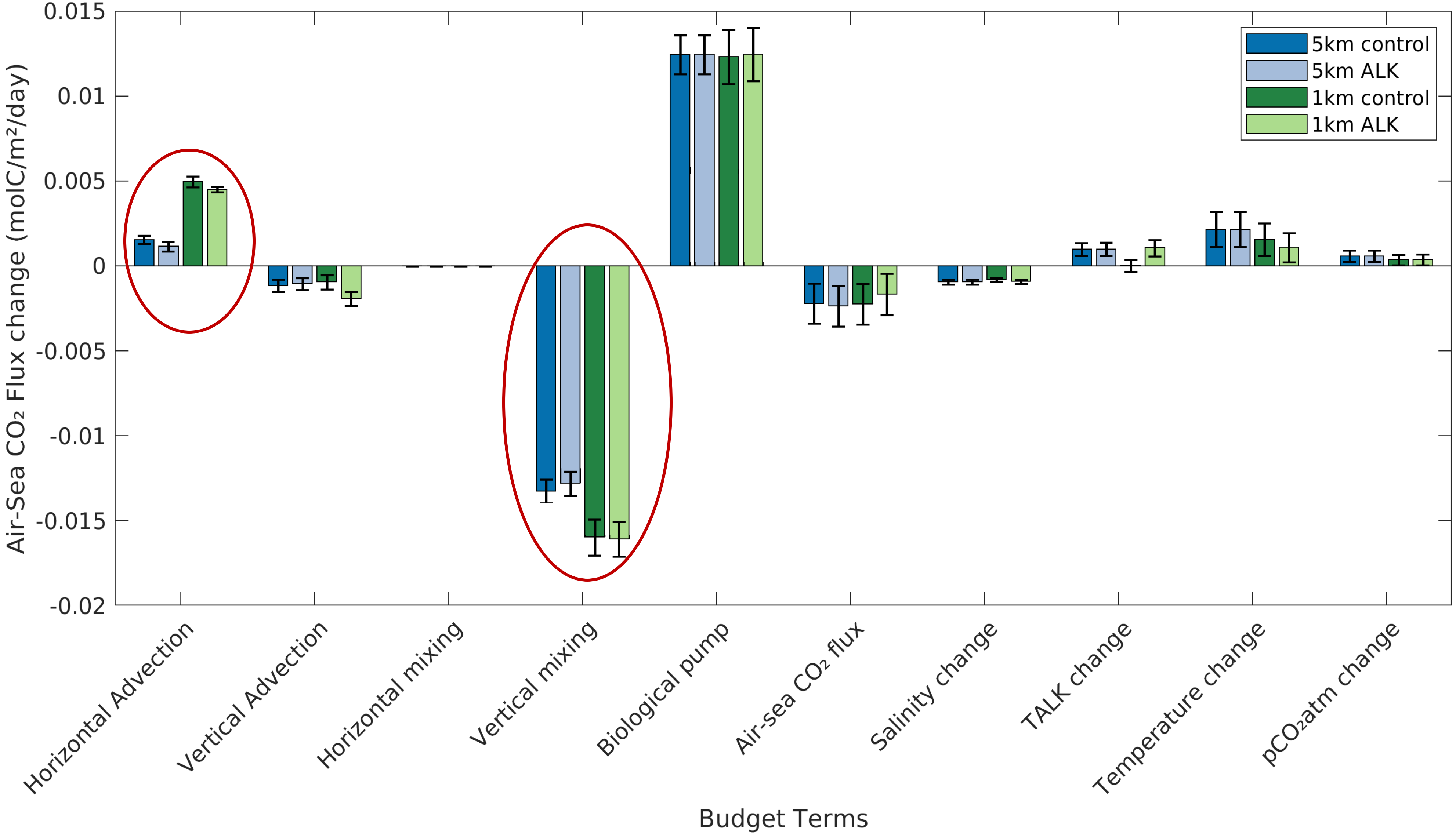
$$\begin{aligned}\frac{\partial F}{\partial t} = -\frac{G^*\alpha_C}{h}F + \Big[& G^*\alpha_C\nabla\cdot(\boldsymbol{u}C) \\ & - G^*\alpha_C\nabla\cdot(\boldsymbol{K}\nabla C) \\ & + G^*\alpha_C B \\ & - G^*\alpha_A\dot{A} \\ & - G^*\left\{\frac{\alpha_C C}{h}(E-P) + \alpha_S\dot{S}\right\}, \\ & + G^*\{\dot{K}_H pCO_2^{atm} - \alpha_T\dot{T}\} \\ & + G^*K_H p\dot{CO}_2^{atm} \\ & + \dot{G}^*\{K_H pCO_2^{atm} - [CO_2]\}\Big]\end{aligned}$$

ocean contributions

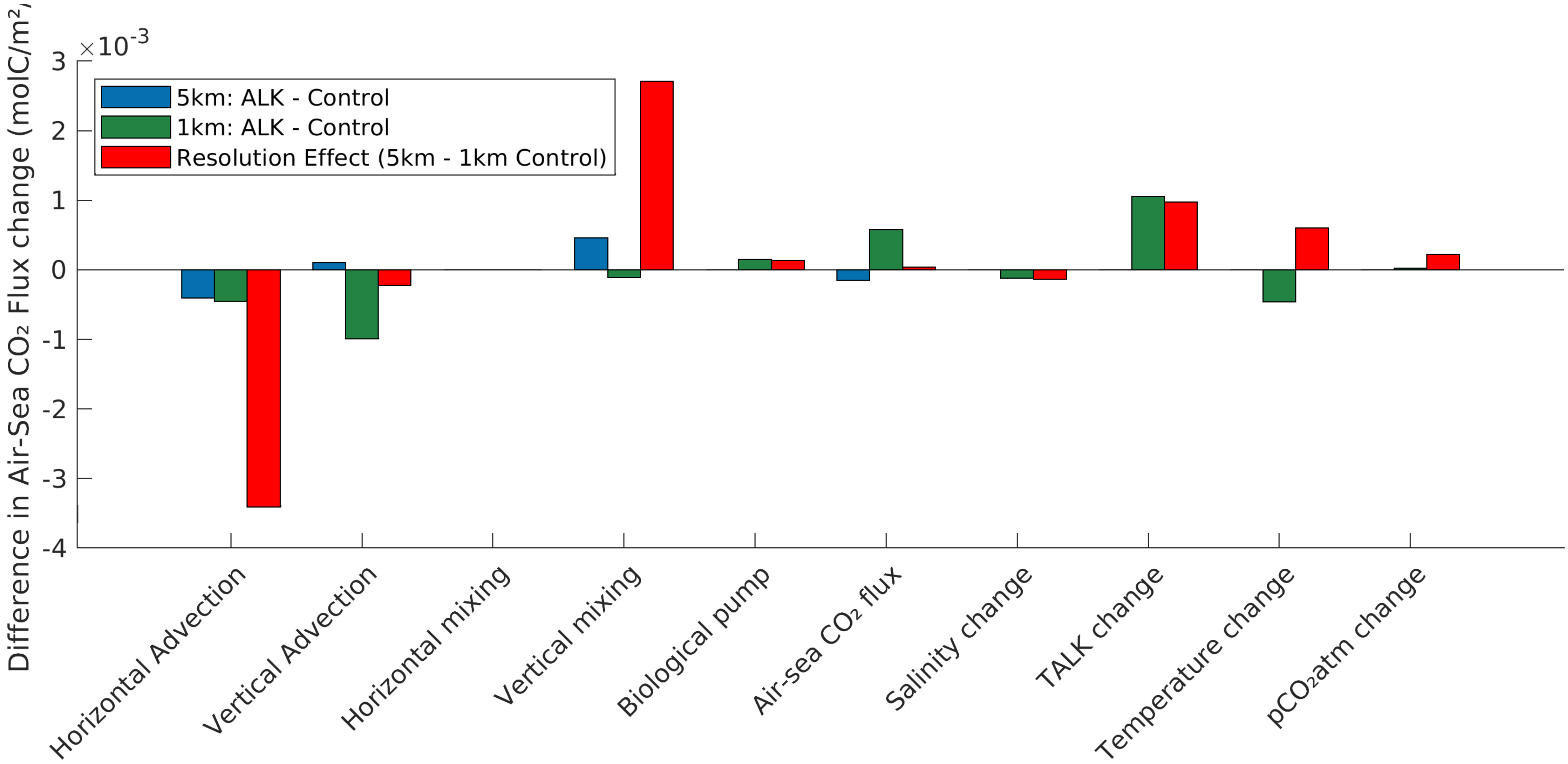
wind


$\eta(t) = A * \Delta F(t) / \Delta Alk$
F = change in the air-sea CO_2 flux inventory over time due to alkalinity modification / m^2.
η (5km)
η (1km)
η
2017 (Month)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

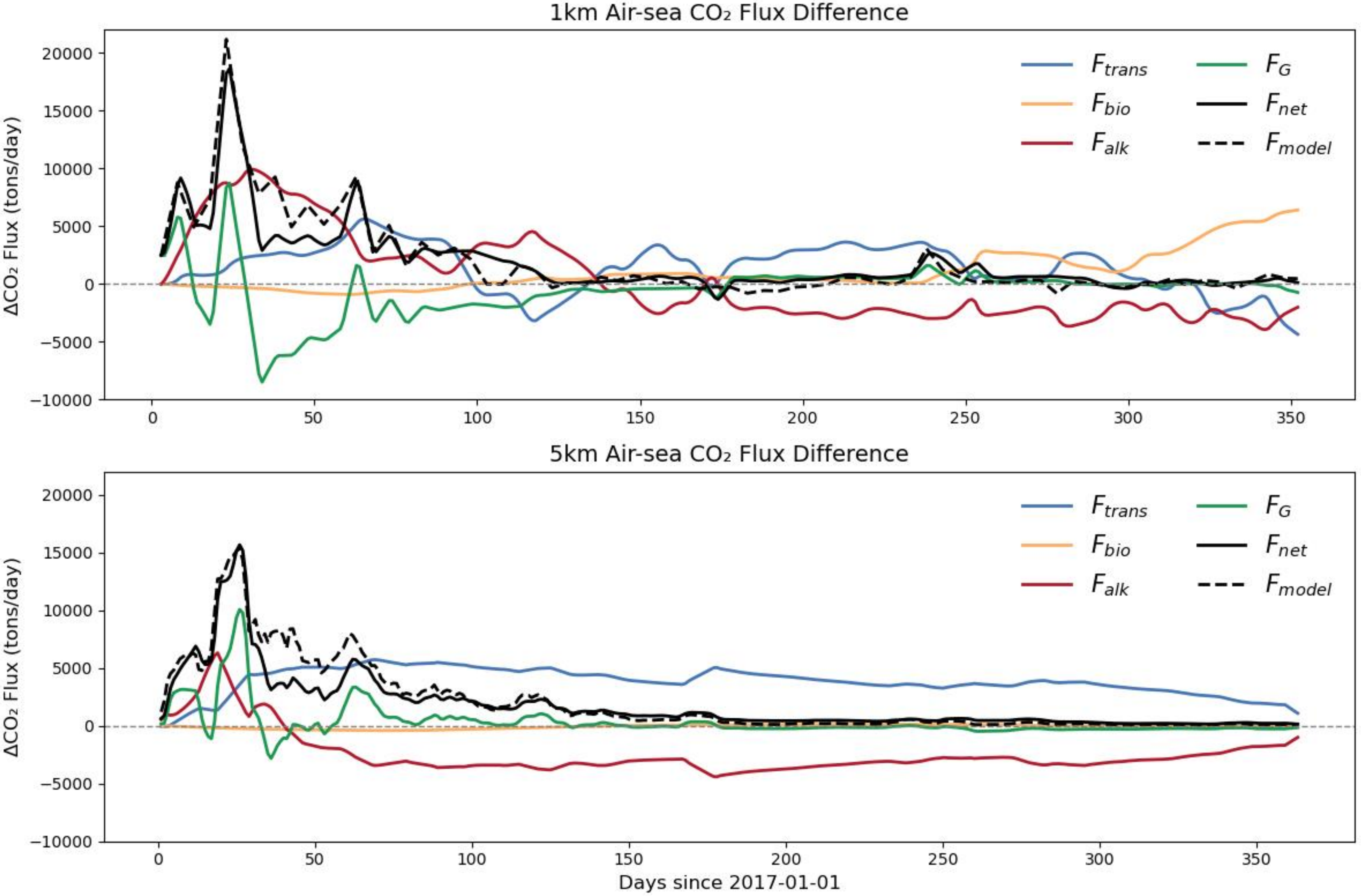

AE
EW
Jan100%-5km
MayEqJan10%-5km
Jan100%-1km
MayEqJan10%-1km
CO2 flux (molC/day)
$\times 10^8$
Days after the onset of river alkalinity modification


5km control
5km ALK
1km control
1km ALK
Air-Sea CO₂ Flux change (molC/m²/day)
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Horizontal Advection
Vertical Advection
Horizontal mixing
Vertical mixing
Biological pump
Air-sea CO₂ flux
Salinity change
TALK change
Temperature change
pCO₂atm change
Budget Terms

cmcc



Zhou, Bracco, Ito & Reinhard, In prep


1km Air-sea CO₂ Flux Difference
5km Air-sea CO₂ Flux Difference
ΔCO₂ Flux (tons/day)
Days since 2017-01-01
F_{trans}
F_{bio}
F_{alk}
F_G
F_{net}
F_{model}

Challenges

- Removing carbon from the atmosphere is, by and large, a multiscale problem for which a reliable representation of main physical processes is essential

- Missing physics remains potentially more important that actual carbon cycle perturbations. These simulations (2 years worth of CPU time on a DOE supercomputer!) remain uncoupled

- Long-time scales associated with climate-carbon perturbations from large-scale CDR deployments. We are not sampling those yet

- The multiscale problem is only getting more complicated.... Emulators may be the way forward