The Role of Marine Carbon Dioxide Removal in Addressing Climate Change

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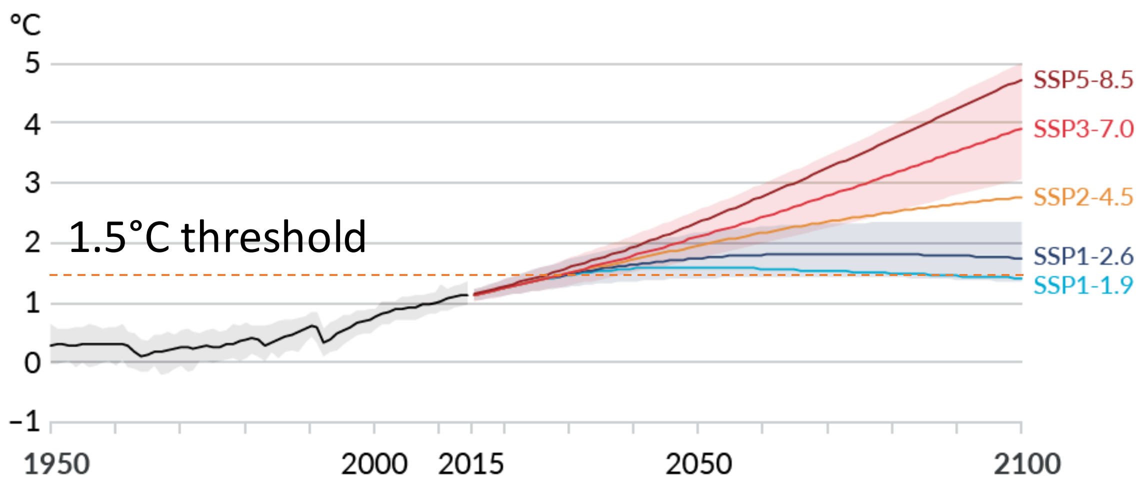
Anthropogenic global temperature rise and ocean acidification

(a) Global surface temperature change relative to 1850–1900



IPCC, 2021

Ocean acidification impact on marine organisms

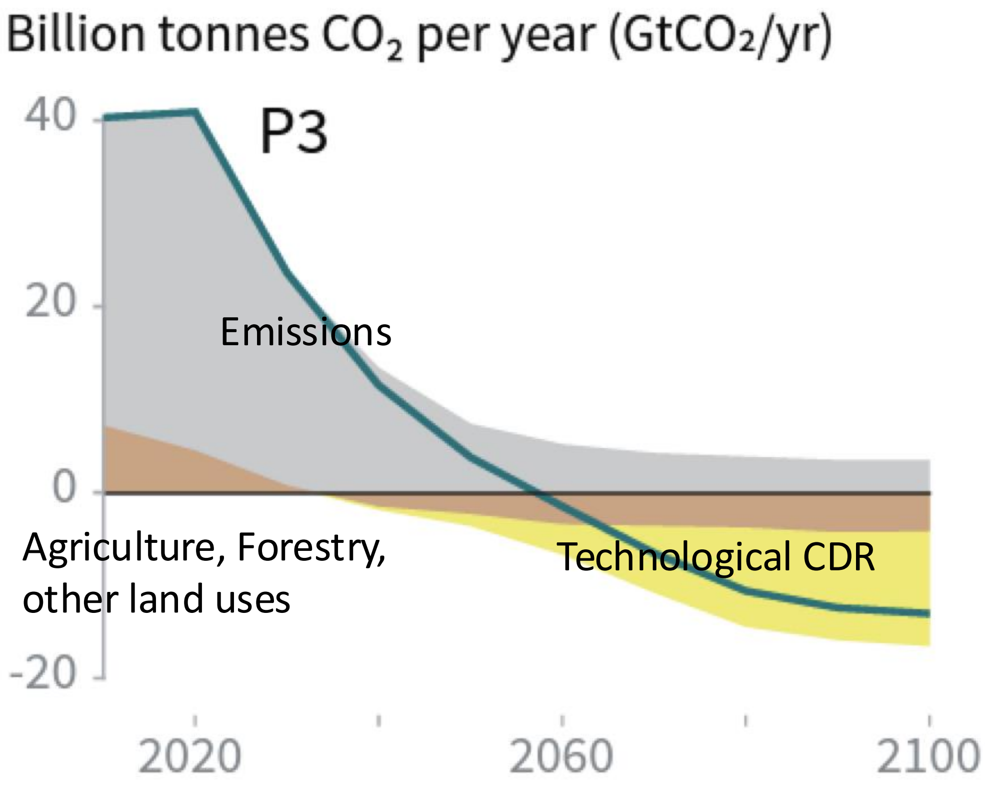
(red = negative impacts)

Taxa	Response	Mean Effect
Calcifying algae	Survival	
	Calcification	
	Growth	
	Photosynthesis	−28%
	Abundance	−80%
Corals	Survival	
	Calcification	−32%
	Growth	
	Photosynthesis	
	Abundance	−47%
Coccolithophores	Survival	
	Calcification	−23%
	Growth	
	Photosynthesis	
	Abundance	
Mollusks	Survival	−34%
	Calcification	−40%
	Growth	−17%
	Development	−25%
	Abundance	

- Not tested or too few studies
- Enhanced <25%
- 95% CI overlaps 0
- Reduced <25%
- Reduced >25%

Kroeker et al., 2013

Aggressive carbon emission reduction alone won't prevent dangerous climate change effects!

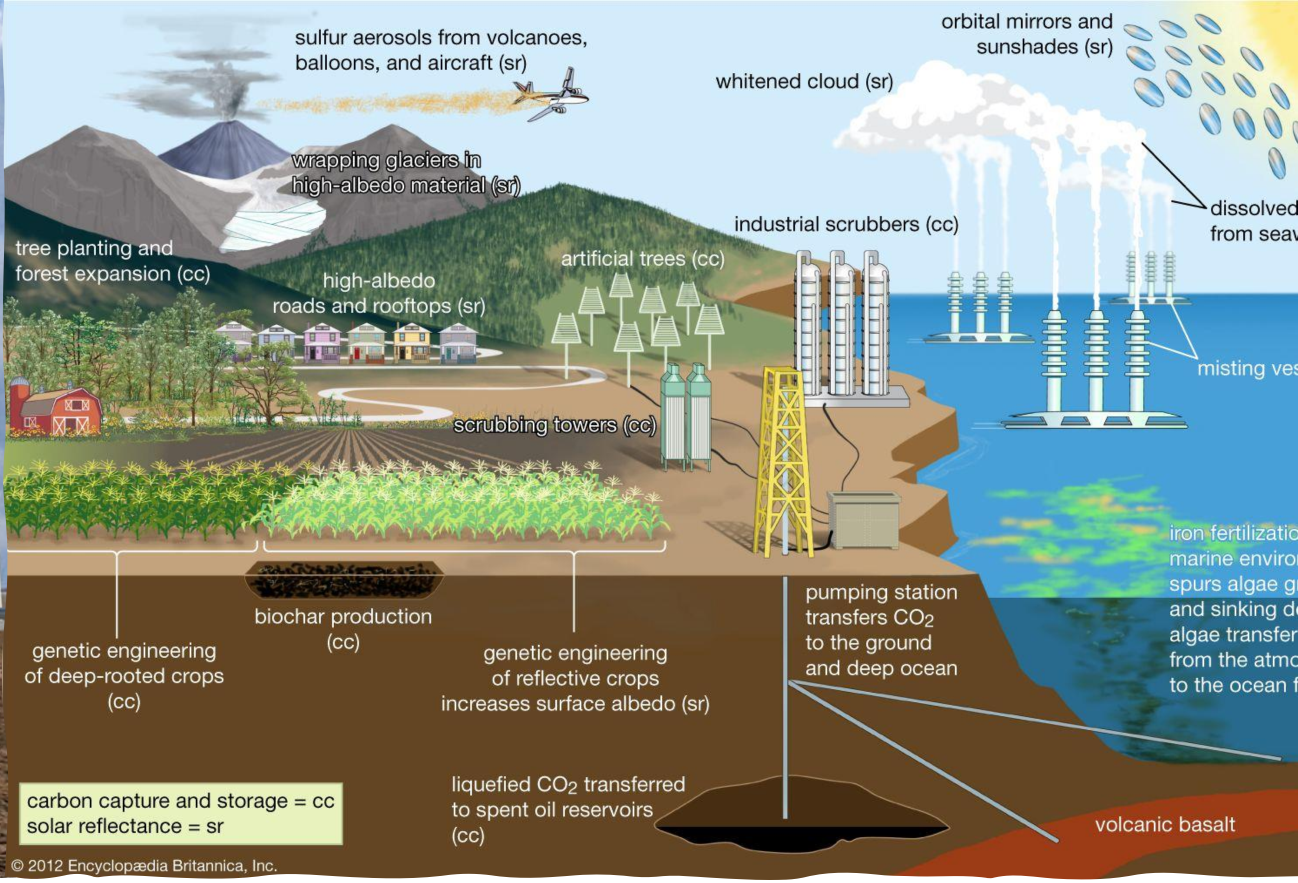


IPCC, 2021: Negative emissions to keep temperature below 1.5C for SP3 scenario

1. There is no reasonable scenario where the emission reductions will be enough to keep global temperature below dangerous levels (e.g. 1.5°C warming with respect to pre-industrial levels)

2. A "middle of the road" scenario for keeping global warming below 1.5°C requires **capture of >400 Gt CO_2 by 2100**.

1 gigaton is >100 million African elephants



Carbon Removal Approaches & Geo-engineering

1. **Direct carbon capture:**
   - Large industrial investments
   - Nearly impossible to scale to Gton C/yr
2. **Geo-engineering, e.g. cloud whitening, aerosol injection:**
   - Most approaches do not address CO_2 increase (and ocean acidification).
   - Unwanted/unexpected weather feedbacks.
3. **Nature-based approaches – enhancing natural carbon cycle.**
   - "Speed-up" natural carbon sequestration feedbacks.

Marine CO_2 removal (mCDR): nature-based approach

Advantages:

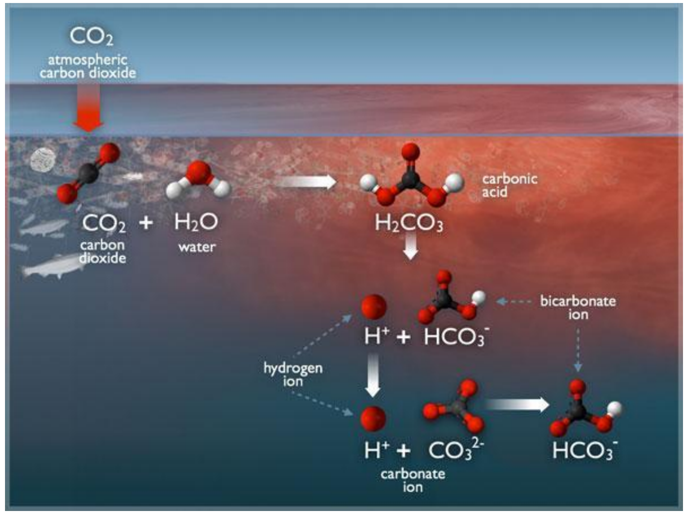
1. The ocean has a virtually unlimited potential for CO_2 storage
2. mCDR does not compete for space with other land uses
3. mCDR targets and accelerates natural sequestration processes
4. Some approaches mitigate local ocean acidification

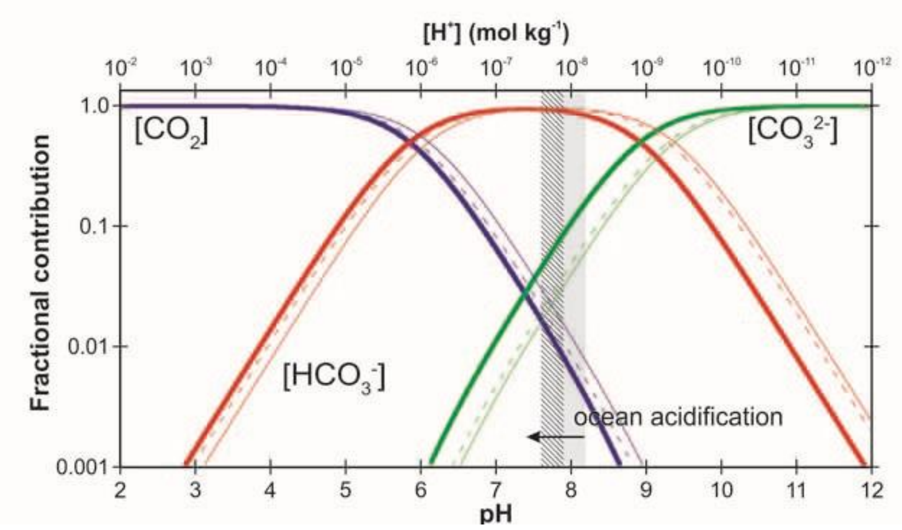
Challenges:

1. Incomplete science understanding of proposed mCDR approaches.
2. Quantification of efficiency (models & observations)
3. Feedbacks and environmental impacts (predicting & monitoring)
4. Large investments – possibly leveraging (voluntary) CO_2 markets
5. Public acceptance, policy and governance

Multiple (m)CDR approaches are likely needed in addition to rapid decarbonization of our economy to keep the worse effects of climate change.

Ocean Alkalinity Enhancement (OAE) mimics Chemical Rock Weathering





Balance between C species as a function of pH

Ocean Alkalinity Enhancement Approach:

1. Increases ocean Alkalinity by adding dissolved minerals (e.g. calcite) increase of surface ocean pH

2. The carbon in ocean water dissolves to form bicarbonate and carbonate ions:

$$CO_{2\,(aq)} + H_20 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2\,H^+$$

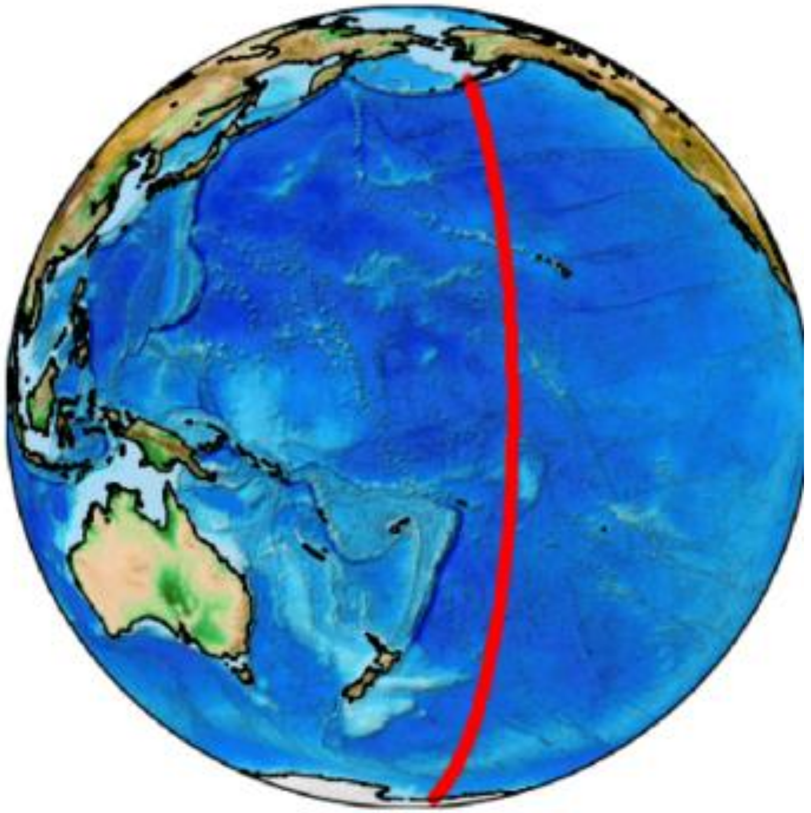
OAE moves the carbon balance to the “right” i.e. decrease partial pressure of CO_2 (pCO_2) … fast process (seconds to hour)

3. The ΔpCO_2 between the ocean and atmosphere can increase CO_2 flux into the ocean … slow process (months to years)

Project goals – sample questions to be answered

Simulate Efficiency of Ocean Alkalinity Enhancement (OAE) along a transect in the Pacific Ocean.

- Which regions are associated with the highest OAE efficiency (most CO_2 removed from the atmosphere per unit of Alk added to the surface ocean)?
- How fast is CO_2 removed from the atmosphere after OAE deployment?
- How does the OAE efficiency change with the season of OAE deployment?
- How do different ocean processes impact OAE efficiency?



Approach

A one-dimensional model for Ocean Alkalinity Enhancement (OAE) - *rapid-mCDR model:*

- For details, please see Suselj et al., 2024 (`https://zenodo.org/records/10632054`)
- Understanding OAE impact requires simulation of the evolution of OAE perturbed Dissolved Inorganic Carbon (DIC) and Alkalinity (Alk) in the ocean, and additional CO_2 uptake
- rapid-mCDR solves partial differential equations governing vertical evolution of OAE-attributed DIC and Alk perturbation, and CO_2 uptake from the atmosphere
- The background ocean state and ocean dynamics (needed to drive rapid-mCDR) taken from ECCO-Darwin ocean data synthesis, representing the best knowledge of ocean state.

Approach

Data and scripts provided on Jupyter-github server (https://hub.jpl-cmda.org/):

- Location with data and scripts: '/home/jovyan/shared/NASA_Summer_School_2024/marine_co2/'
- **Scripts – copy scripts to your work directory:**
  - **`model_v1.py`** … rapid-mCDR model
  - **`run_rapid_mcdr_transect.ipynb`** … reads the forcing files, design OAE experiments and run rapid-mCDR; results are saved as netcdf files. **If you decide to run additional, experiments please consult me and/or Alex – there is a danger that you will run out of storage space.**
  - **`plot_rapid_mcdr_transect.ipynb`** … reads the results of rapid-mCDR and do sample plots.
- **Data – please do not copy the data (you will run out of storage space!):**
  - Forcing data for rapid-mCDR in 'data/rapid_mcdr_inputs'
  - Results of rapid-mCDR for 3 different OAE deployment approaches in 'data/rapid_mcdr_outputs' (see the Jupyter scripts for their description)

Your task

Your tasks:

1. Familiarize yourself with the rapid-mCDR (see Suselj et al., 2024)
2. Design additional diagnostics of the rapid-mCDR results. Some ideas:
   - How does mCDR efficiency change with the time after OAE deployment?
   - How different are efficiencies for summer and winter deployments?
   - *Implement additional diagnostics within `plot_rapid_mcdr_transect.ipynb`,*
3. Design and analyze different deployment strategies. Some ideas:
   - Deployment at different base years to understand intra-annual variability of efficiencies? Does OAE efficiency in for El-Nino and La-Nina years differ?
   - How does OAE efficiency change with the year of deployment?
   - Run additional simulations with modified *`run_rapid_mcdr_transect.ipynb` script and analyze results.* ***Please consult us on where/how to save simulation data.***

- **Have Fun!**