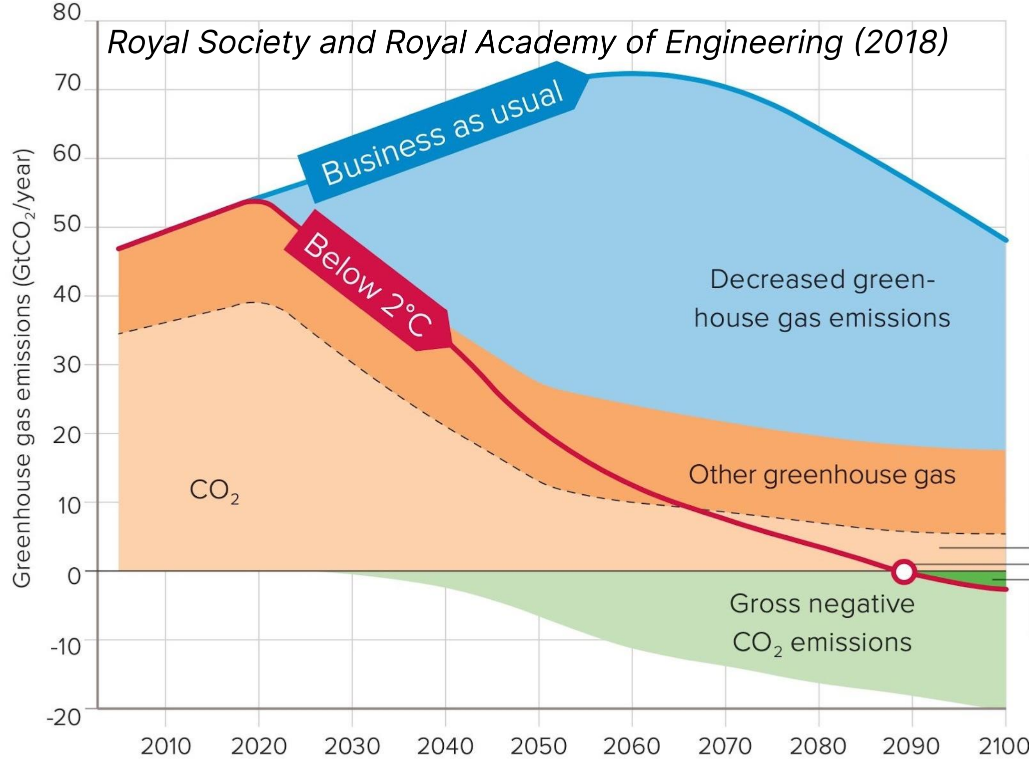
Impulse Response Functions:

A statistical tool for marine CO_2 removal quantification

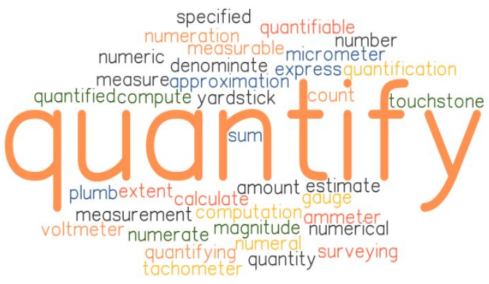
Elizabeth Yankovsky

Carbon dioxide removal is required to achieve net zero



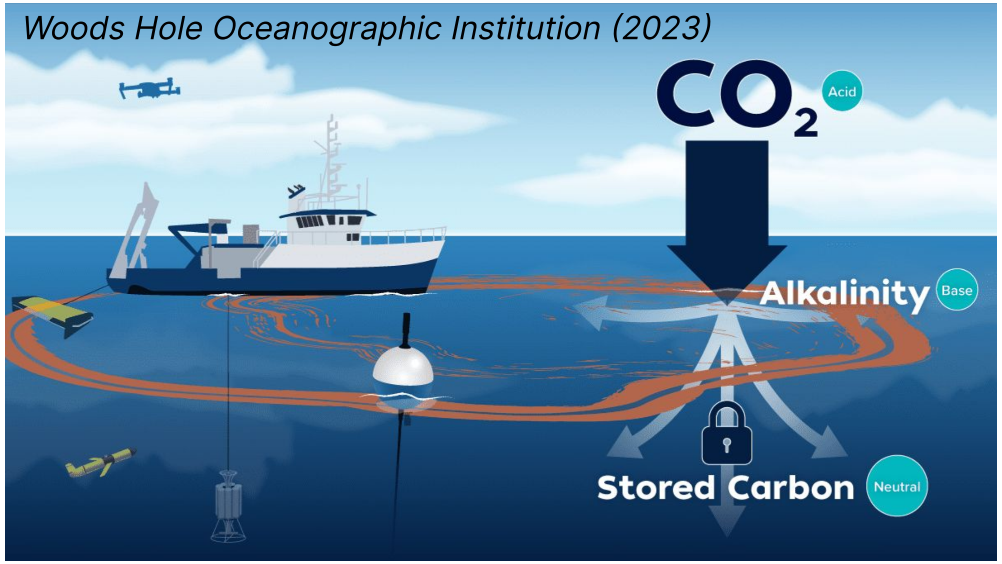
THE CHALLENGE: Reaching net-zero
Meeting the 1.5°C - 2°C climate target requires billions of tons of active Carbon Dioxide Removal (CDR) annually by mid-century.

THE PROMISE: Ocean CDR technologies
Ocean-based CDR technologies have the potential to scale to meaningful levels – as such, they are forecast to experience rapid development in the next decade.



THE CRITICAL GAP: Quantification
There are no accepted frameworks for **quantifying ocean-CDR.** Robust quantification requires both observations and numerical models.

Carbon dioxide removal is required to achieve net zero



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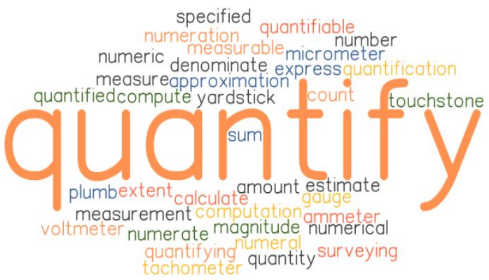

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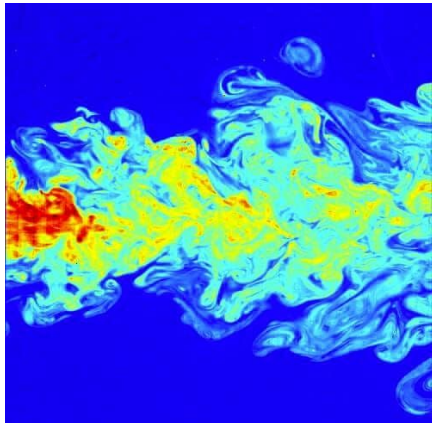
mCDR: A Multiscale Problem

Microscale



- 3D turbulence
- Spatial scale: $\mathcal{O}(10^{-3}-10^{0})$m
- “Fundamental” fluid dynamics

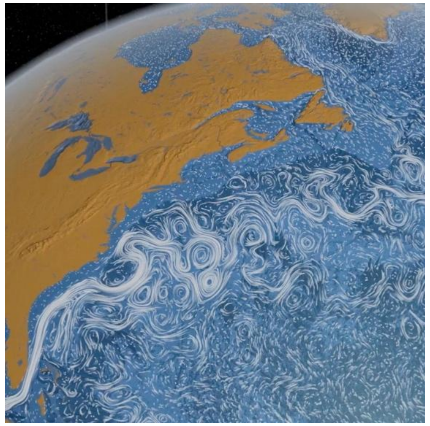
Near Field

- **mCDR intervention**
- Spatial scale: $\mathcal{O}(10^{0}-10^{2})$m
- Project-specific dynamics

Local Region

- **Initial dispersion**
- Spatial scale: $\mathcal{O}(10^{2}-10^{3})$m
- Region-specific dynamics

Regional to Basin



- **Air-to-sea CO_2 transfer**
- Spatial scale: $\mathcal{O}(10^{3}-10^{6})$ m
- Basin to global-scale model

Global

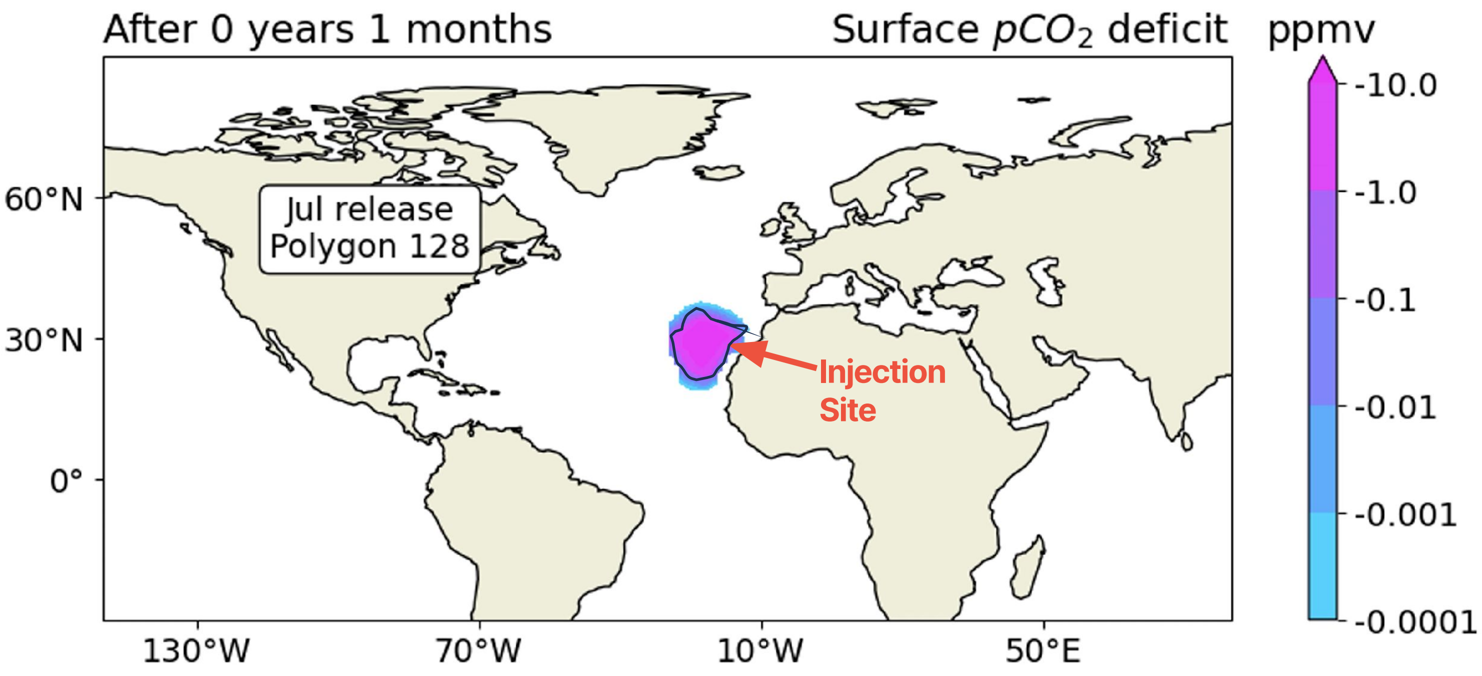
- Earth system model
- Spatial scale: $\mathcal{O}(10^{6}-10^{7})$m
- Deep overturning dynamics

Why is Measurement, Reporting, and Verification (MRV) so difficult?

Large spatiotemporal scales
Slow CO_2 equilibration timescales leads to basin-scale signals that cannot be monitored in-situ.

Unfavorable signal-to-noise
High intrinsic background variability relative to signal size makes detection of signal beyond the nearfield impossible.

Complex baselines
Counterfactual baselines are needed to assess additionality.



$p\mathrm{CO}_2$ anomaly from simulated ocean alkalinity enhancement

Figure courtesy of **Mengyang Zhou**

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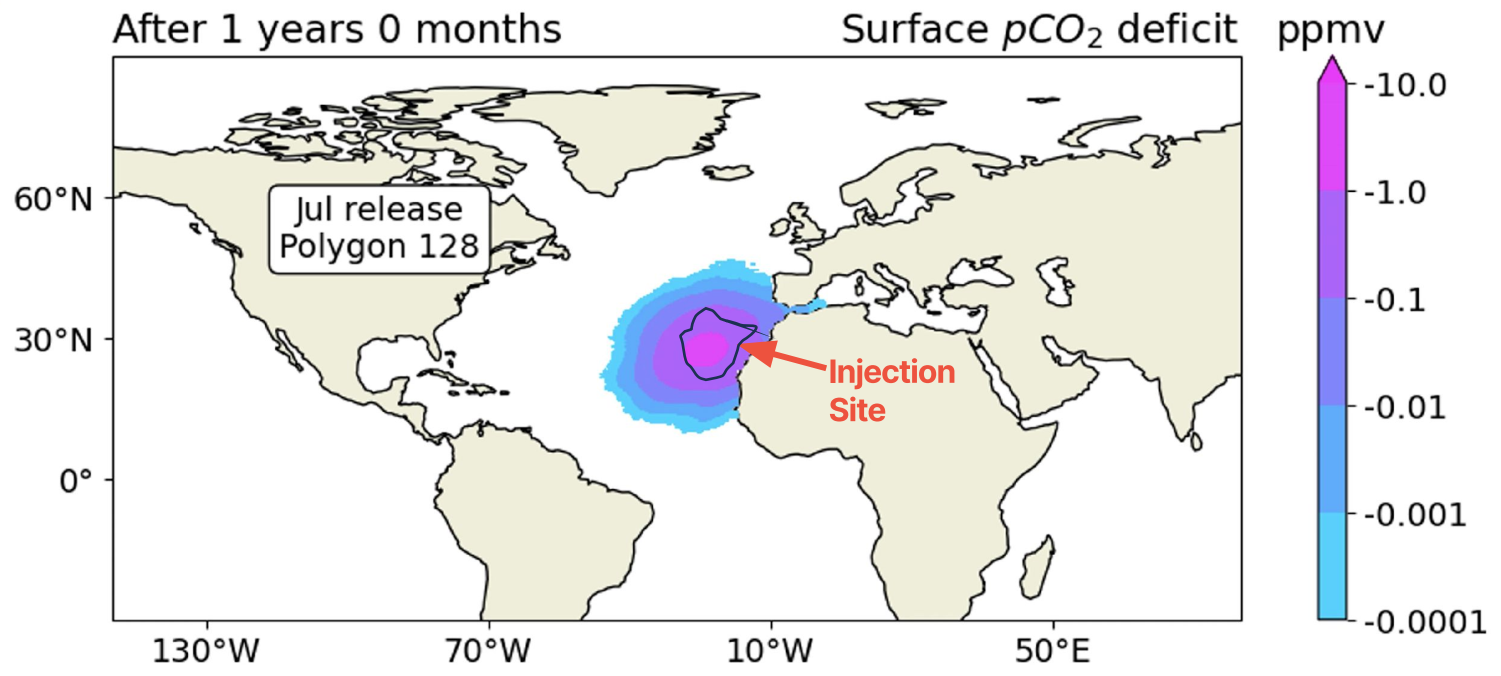

pCO_2 anomaly from simulated ocean alkalinity enhancement

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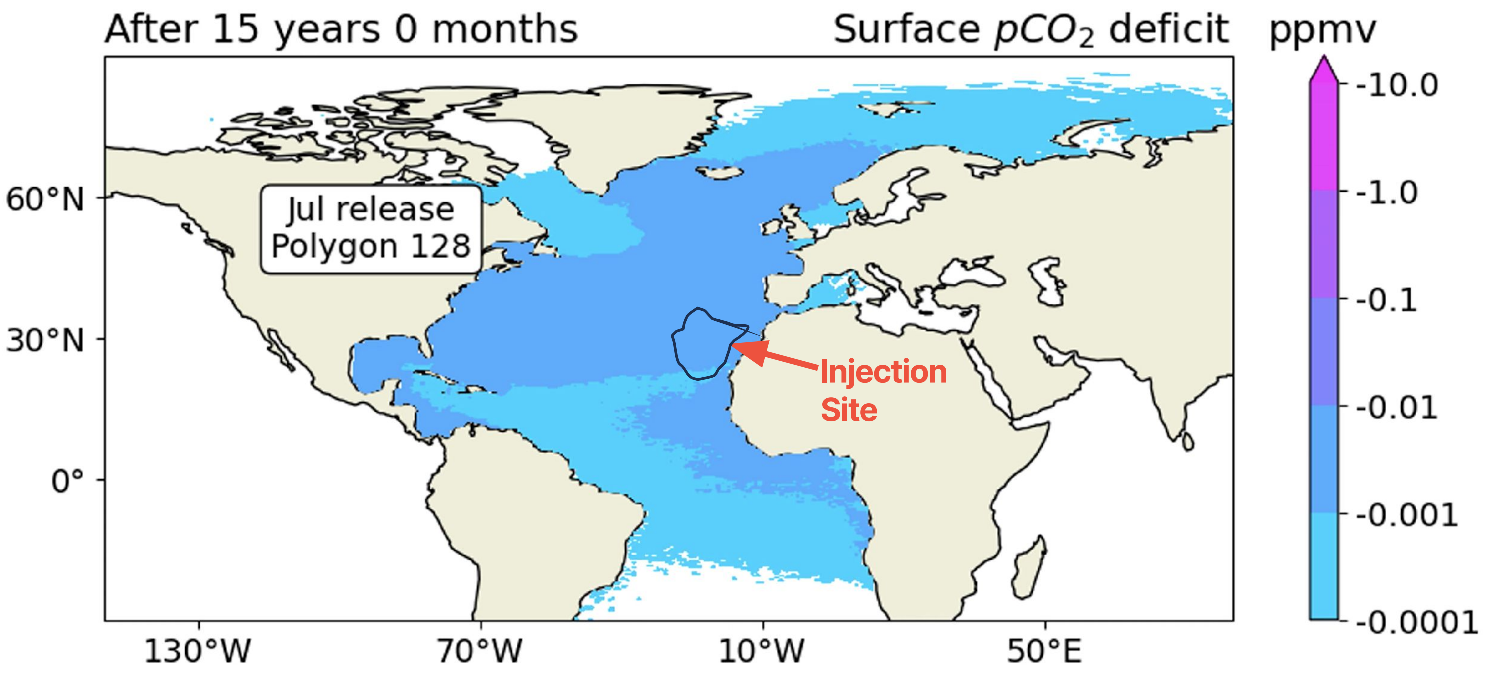

***p*CO_2 anomaly from**
simulated ocean alkalinity enhancement

Figure courtesy of **Mengyang Zhou**

[C]Worthy

Building the modeling tools needed to ensure safe, effective, and market-ready marine carbon dioxide removal (mCDR).

Matt Long, Ph.D.

Co-Founder,

Chief Executive Officer

Alicia Karspeck, Ph.D.

Co-Founder,

Chief Technology Officer

David Ho, Ph.D.

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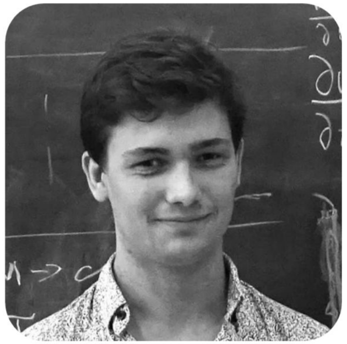
Staff Scientist: Scientific Algorithms



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Head of Security

[C]Worthy is a nonprofit R & D organization

Motivation for using Impulse Response Functions (IRFs)

- Infeasible to numerically simulate the fate of every mole of alkalinity reduce the problem
- Understand physical processes governing carbon uptake: how is carbon uptake influenced by location, seasonal/interannual variability, ocean dynamics, and deployment strategy?
- Develop a statistical tool to simplify mCDR accounting (MRV)

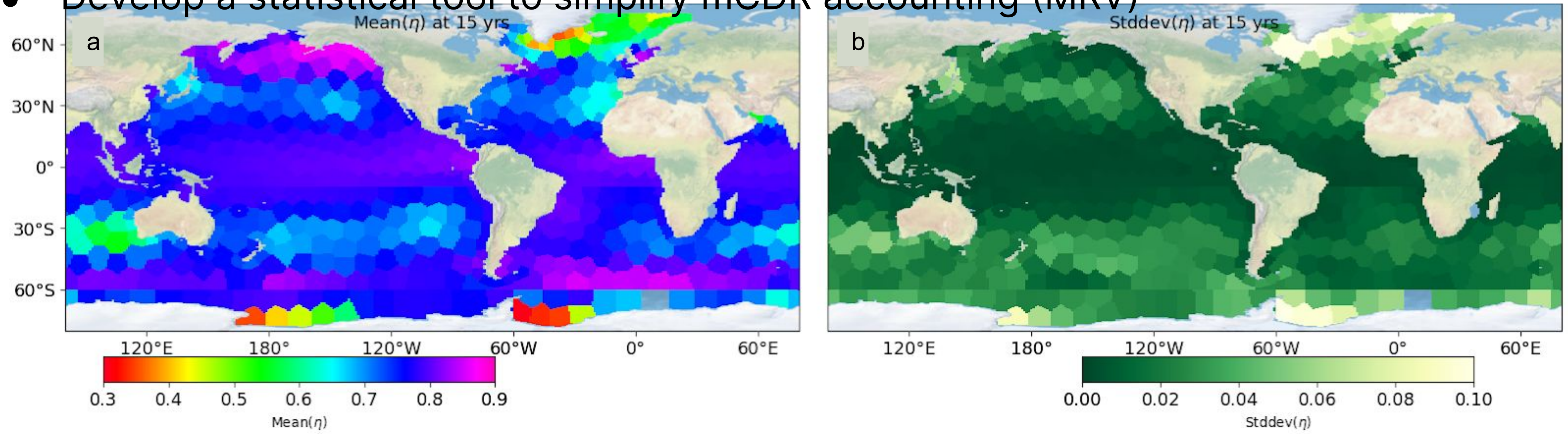
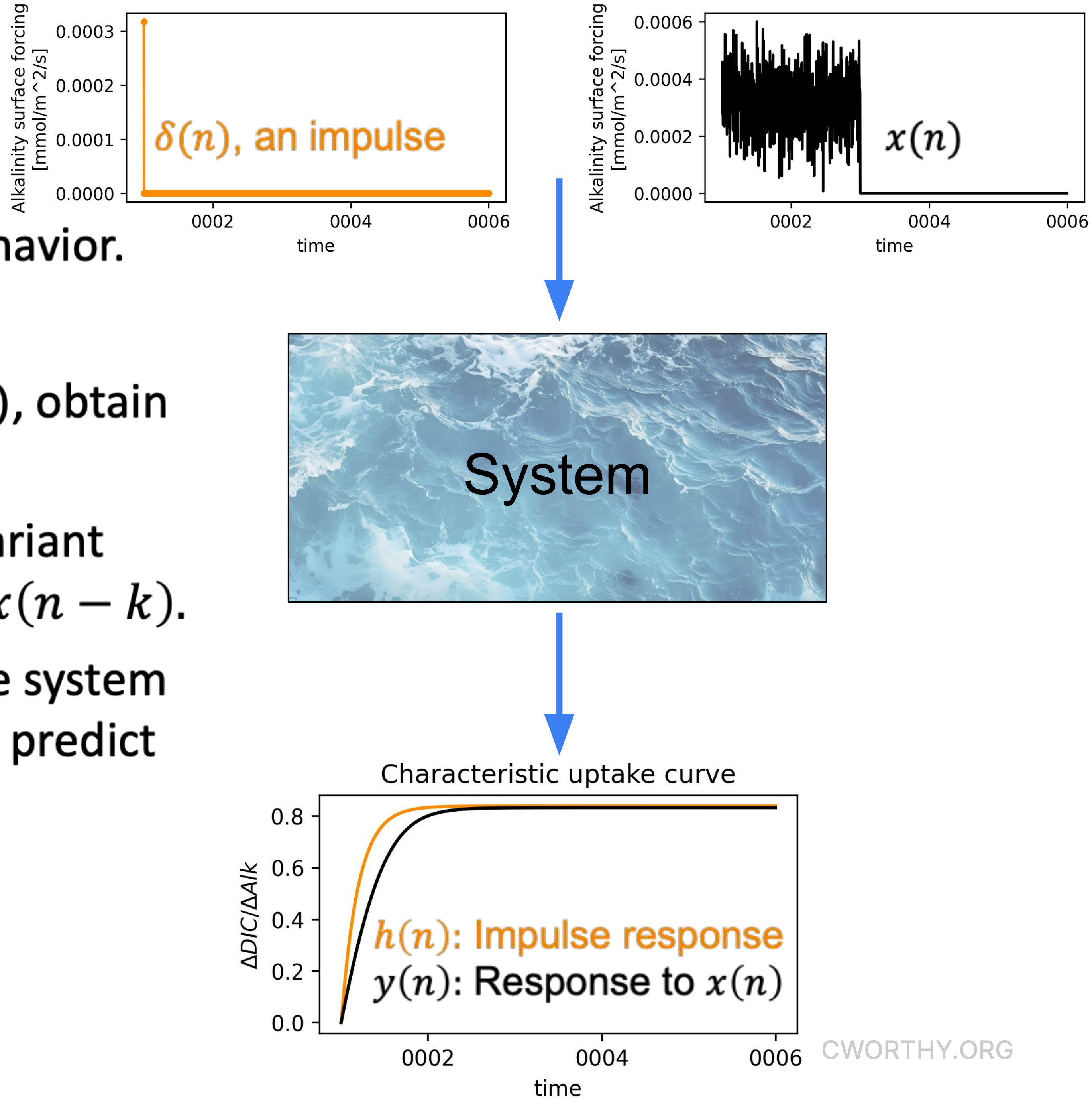


Figure by **Mengyang Zhou**, OAE Global Efficiency Atlas

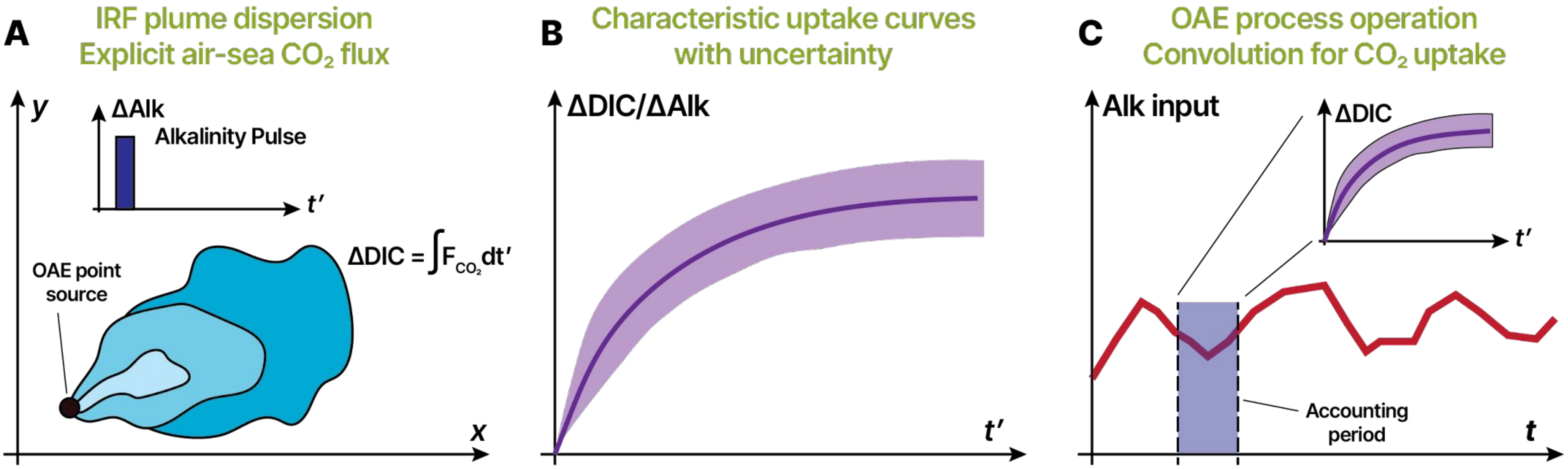
What is an IRF?

- A way to encapsulate a system's behavior.

- Probe the system with impulse $\delta(n)$, obtain IRF $h(n)$.
- Requirement: a linear and time-invariant system. Then: $y(n) = \sum_{k=-\infty}^{\infty} h(k)x(n-k)$.
- Advantage: just by knowing how the system responds to an impulse allows us to predict how the system will respond to *any*

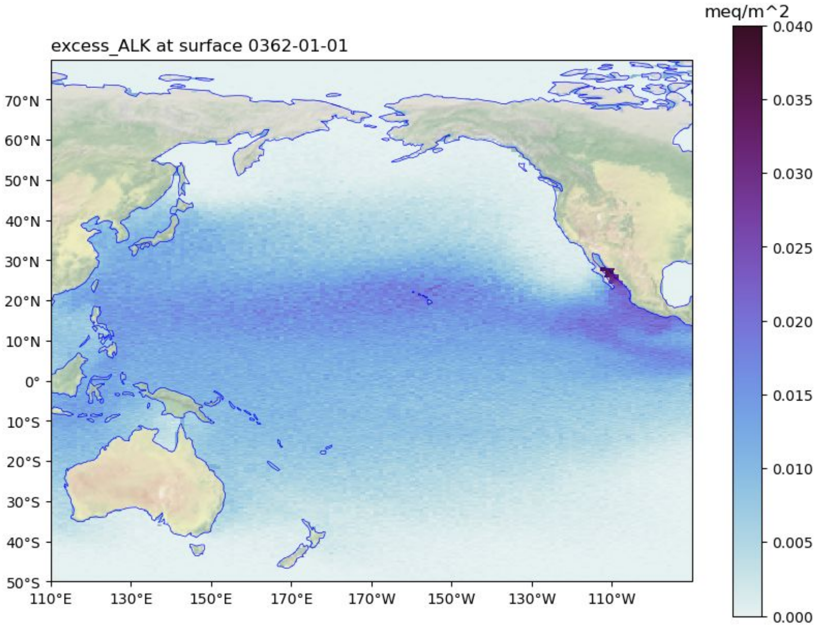


What is an IRF?



Example: Northern California

1-month release after 15 years



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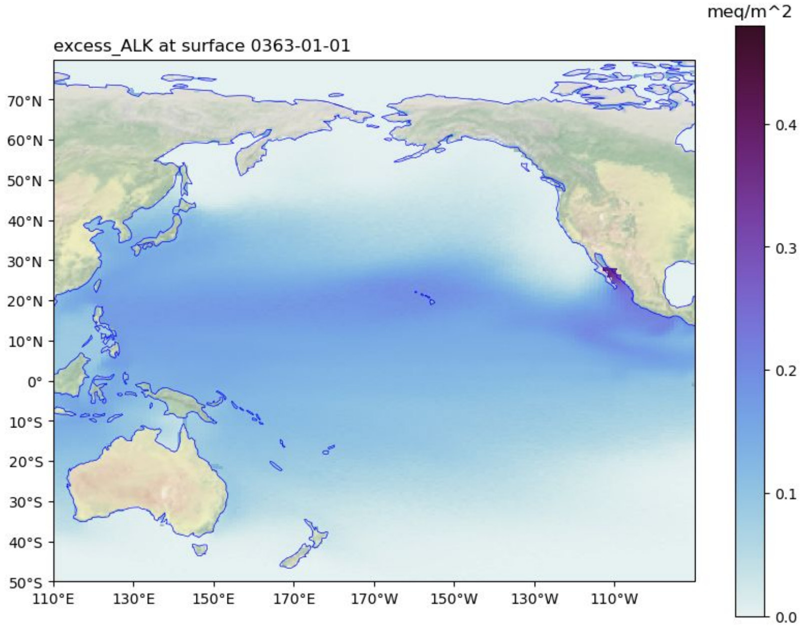
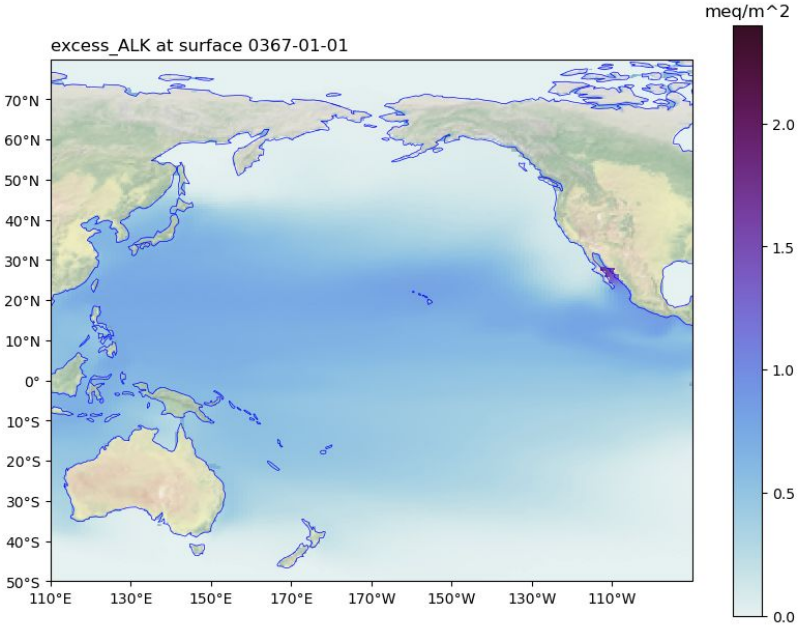
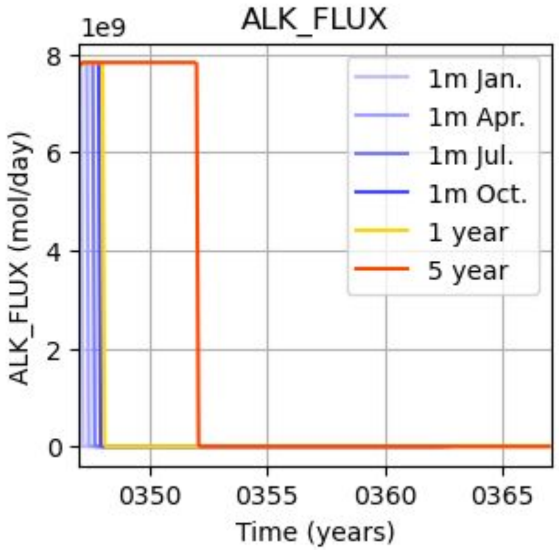
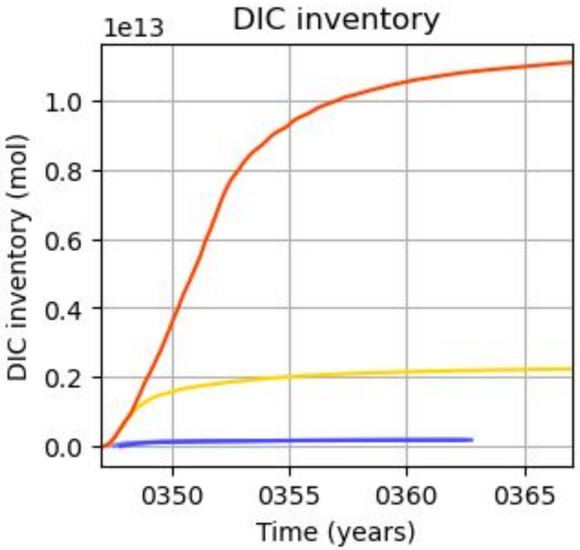
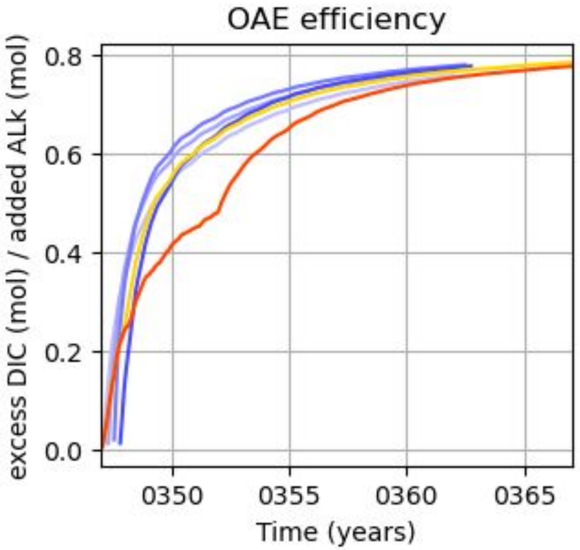


5-year release after 15 years

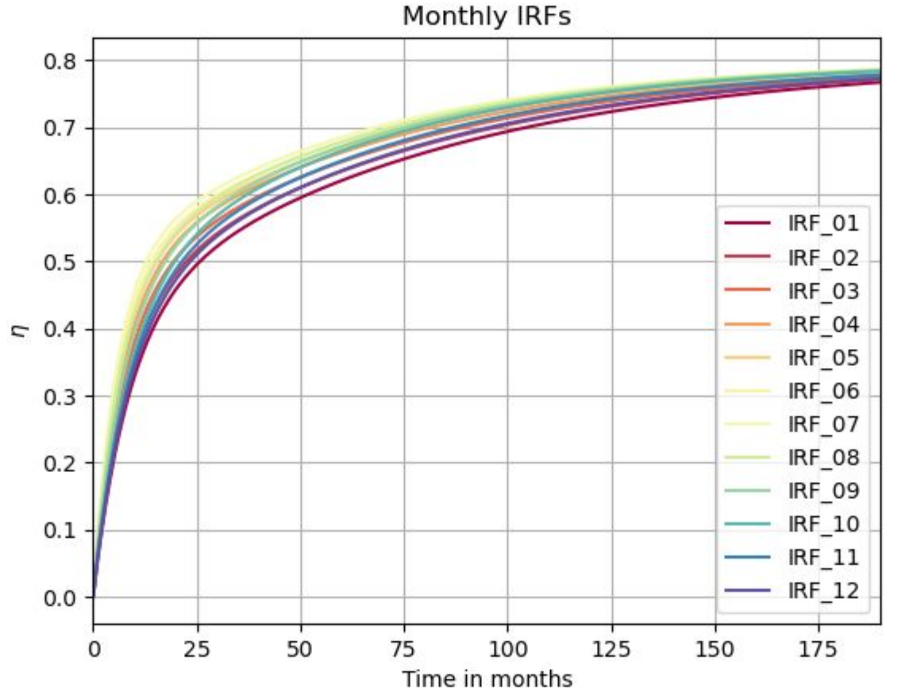


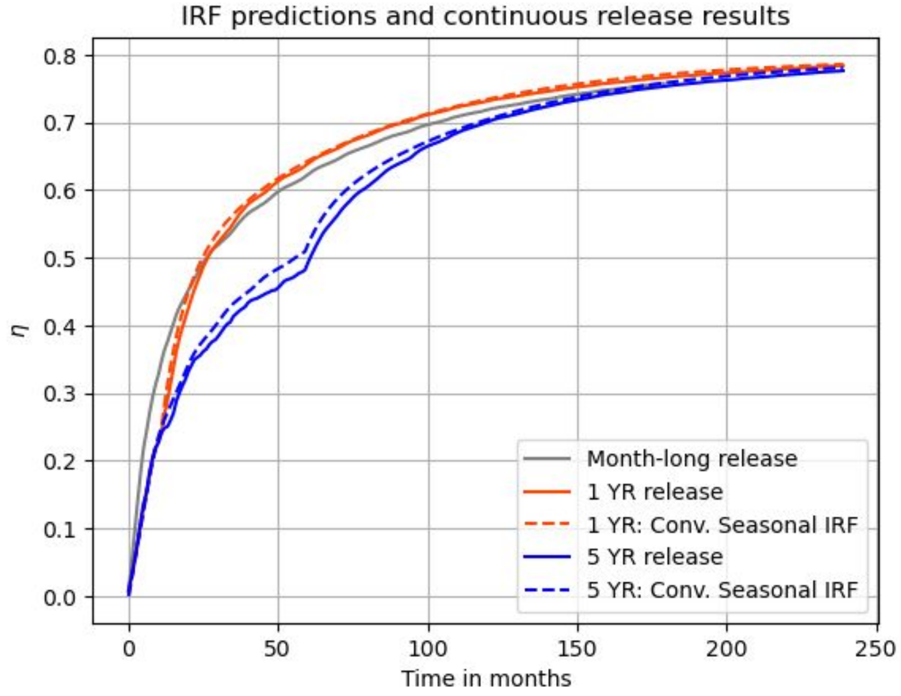






Applying the IRF Approach





I. Obtain IRFs

Use Global Efficiency Atlas monthly pulse experiments, interpolate over months.

II. Convolve IRFs with 1-year and 5-year alkalinity forcing.

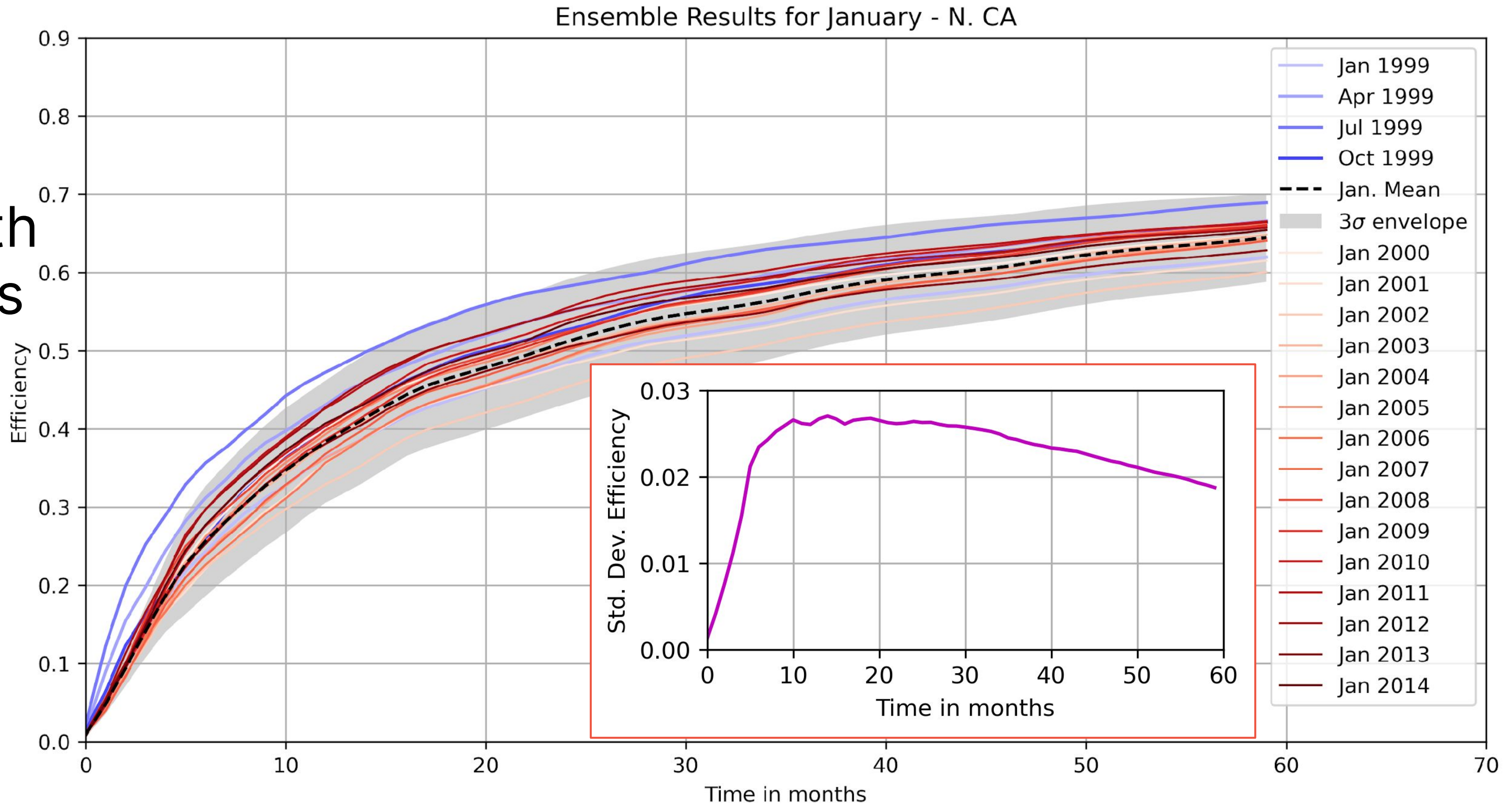
$$y(n) = \sum_{k=-\infty}^{\infty} h(k)x(n-k)$$

III. Compare the IRF result to the corresponding model simulation.

Observe excellent matchup!

Caveats

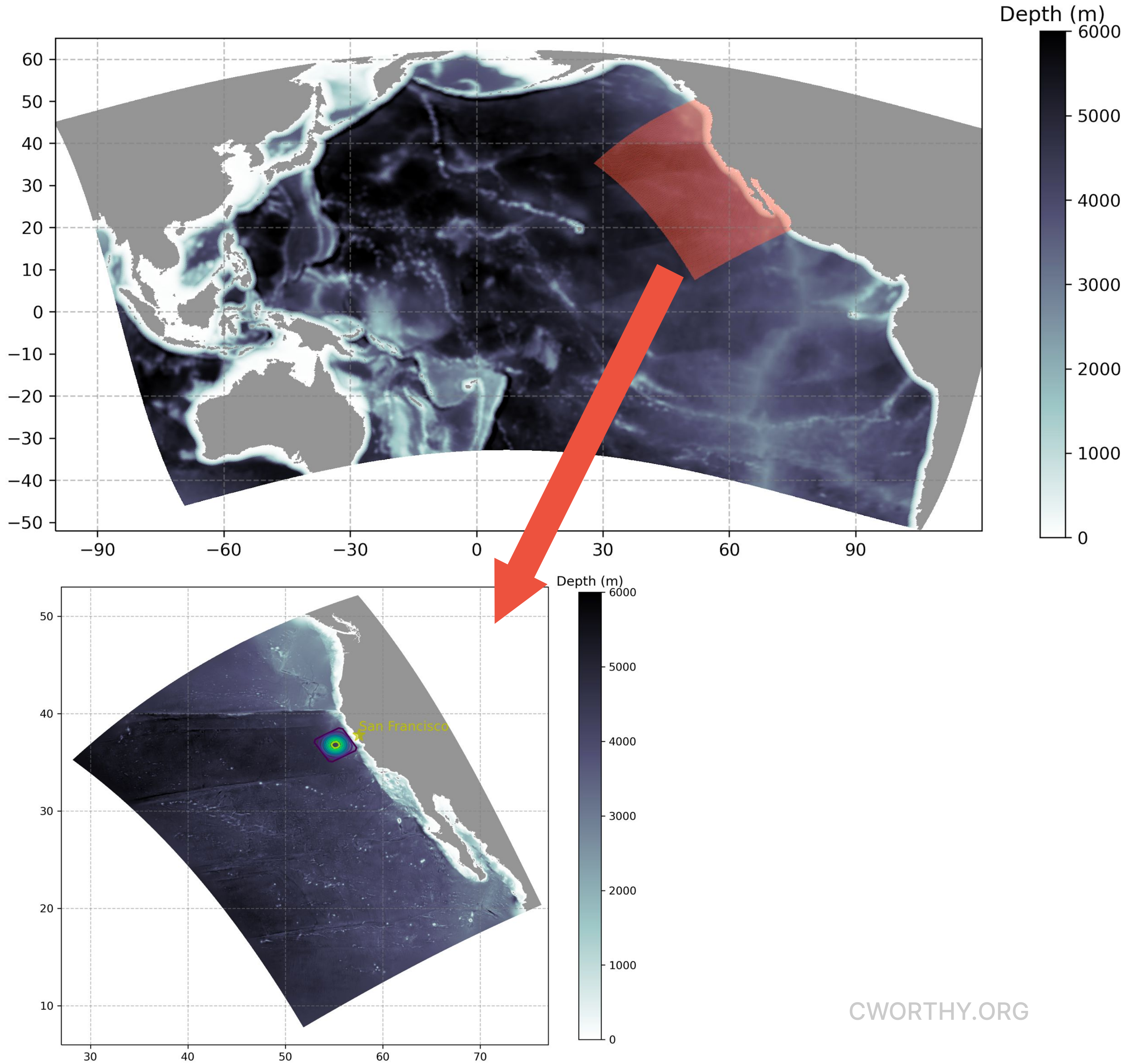
- Uncertainty associated with variability poses challenges
- Sources:
  - Seasonal (handled)
  - Inter-annual
  - Initial conditions
  - Ocean turbulence



Next Steps

Test IRFs in a high-resolution regional model (UCLA-ROMS). Examine role of grid resolution & ocean turbulence.

Gain new physical insights into mesoscale and submesoscale turbulence influences on carbon uptake.



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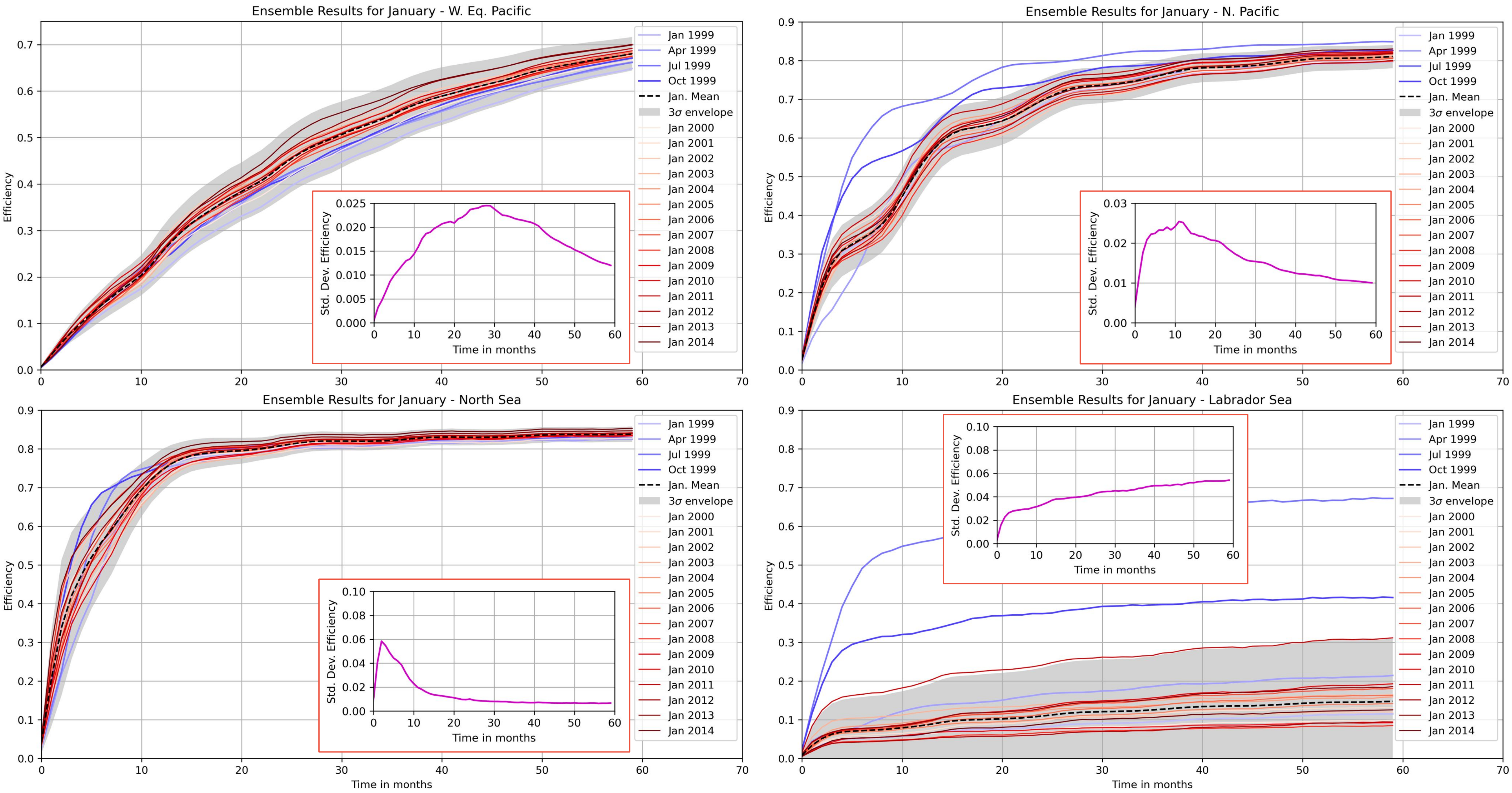
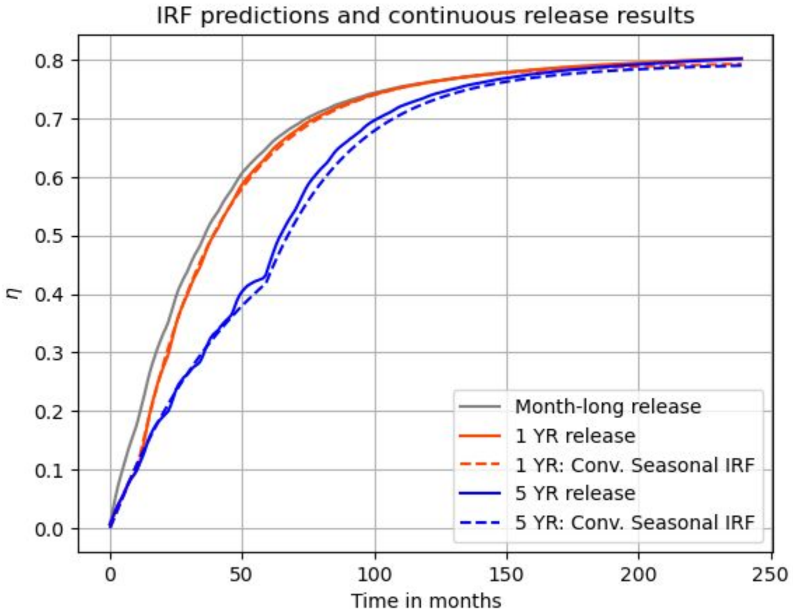
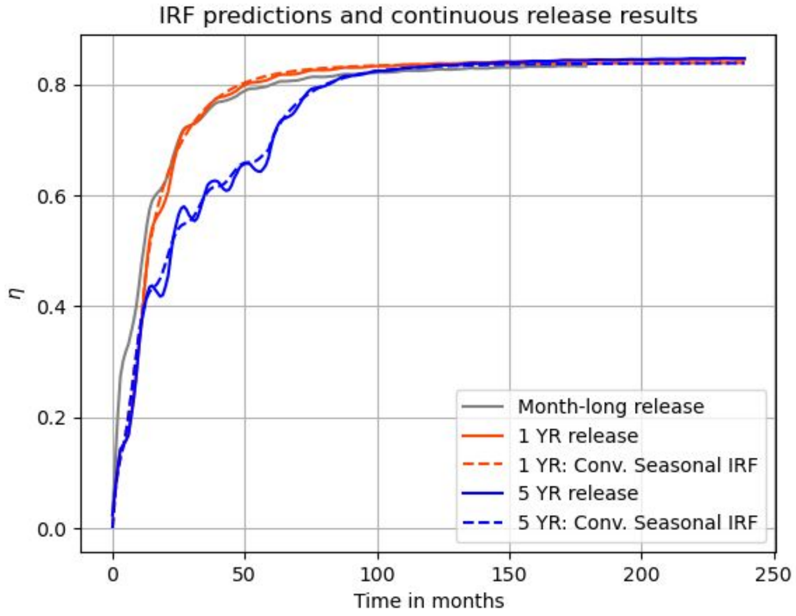

Ensemble Results for January - W. Eq. Pacific
Ensemble Results for January - N. Pacific
Ensemble Results for January - North Sea
Ensemble Results for January - Labrador Sea
Efficiency
Time in months
Std. Dev. Efficiency
Jan 1999
Apr 1999
Jul 1999
Oct 1999
Jan. Mean
3σ envelope
Jan 2000
Jan 2001
Jan 2002
Jan 2003
Jan 2004
Jan 2005
Jan 2006
Jan 2007
Jan 2008
Jan 2009
Jan 2010
Jan 2011
Jan 2012
Jan 2013
Jan 2014

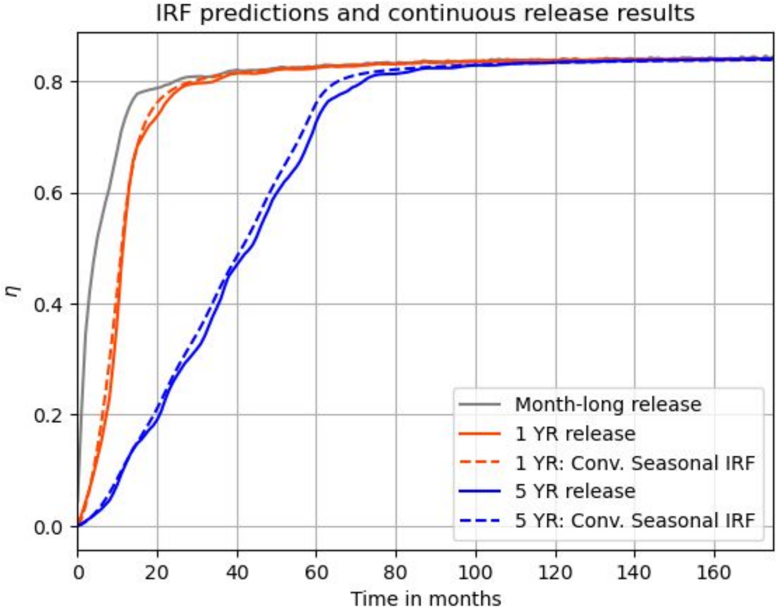
Western Eq. Pacific



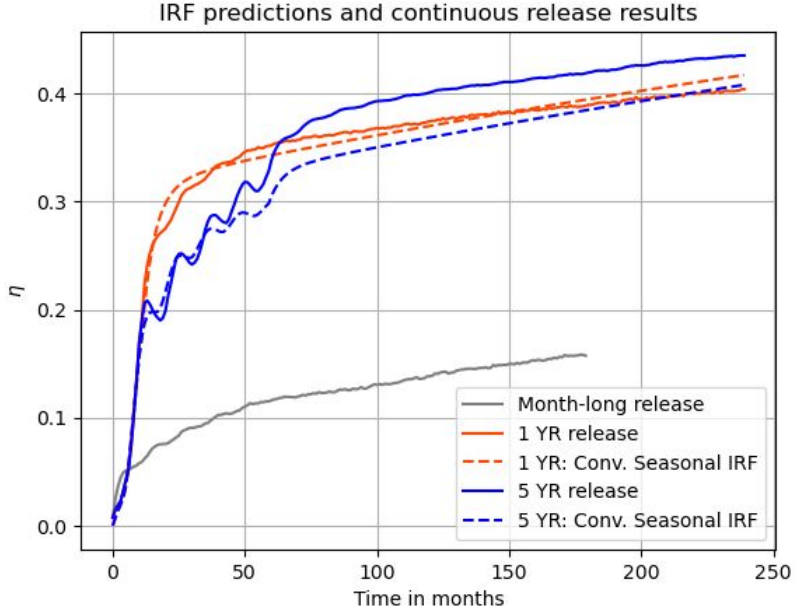
North Pacific

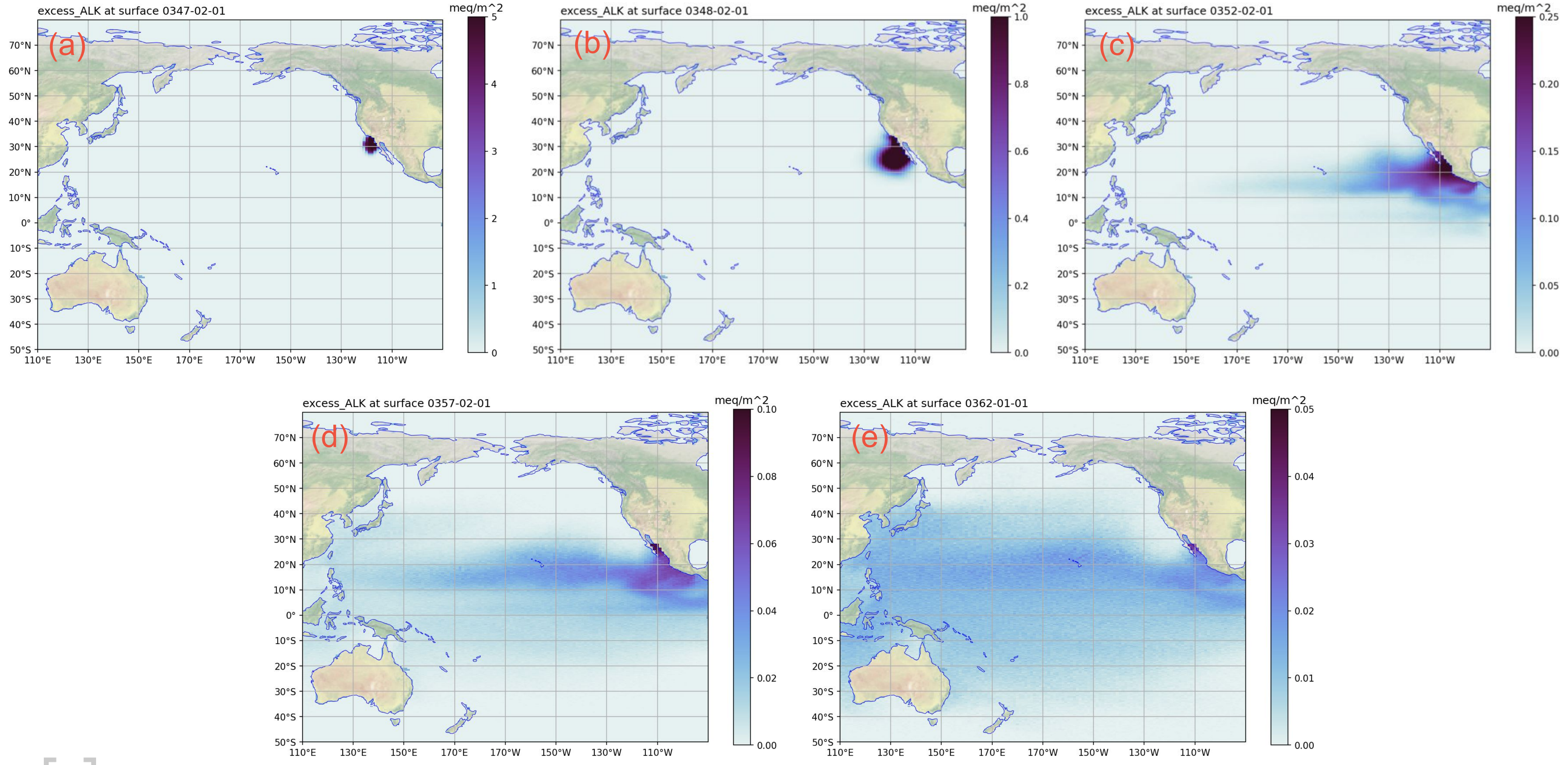


North Sea



Labrador Sea




excess_ALK at surface 0347-02-01
(a)
meq/m^2
excess_ALK at surface 0348-02-01
(b)
excess_ALK at surface 0352-02-01
(c)
excess_ALK at surface 0357-02-01
(d)
excess_ALK at surface 0362-01-01
(e)
70°N
60°N
50°N
40°N
30°N
20°N
10°N
0°
10°S
20°S
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40°S
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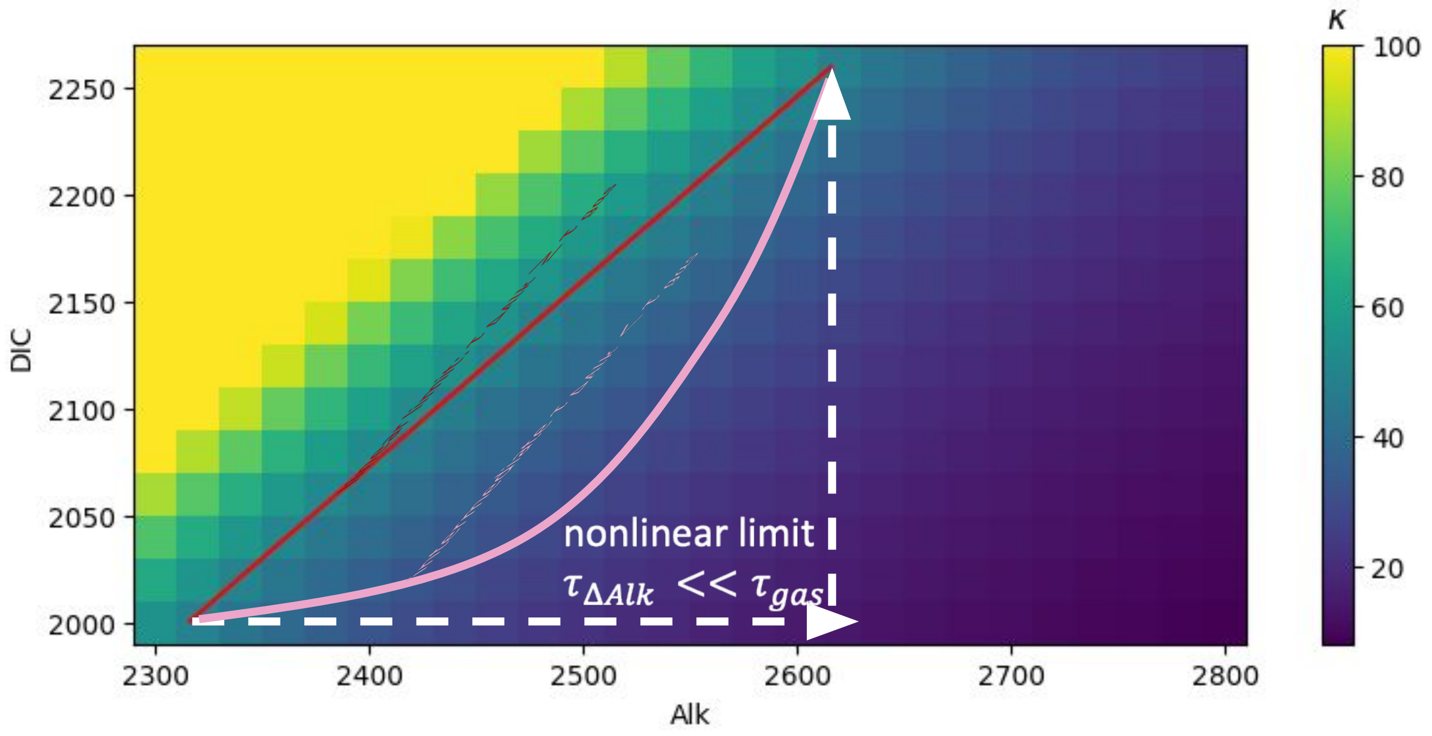
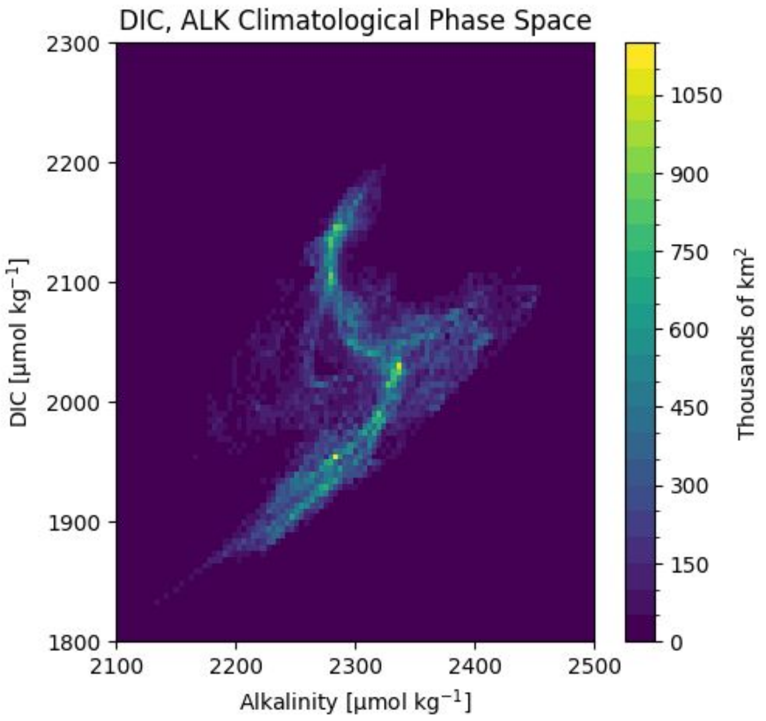
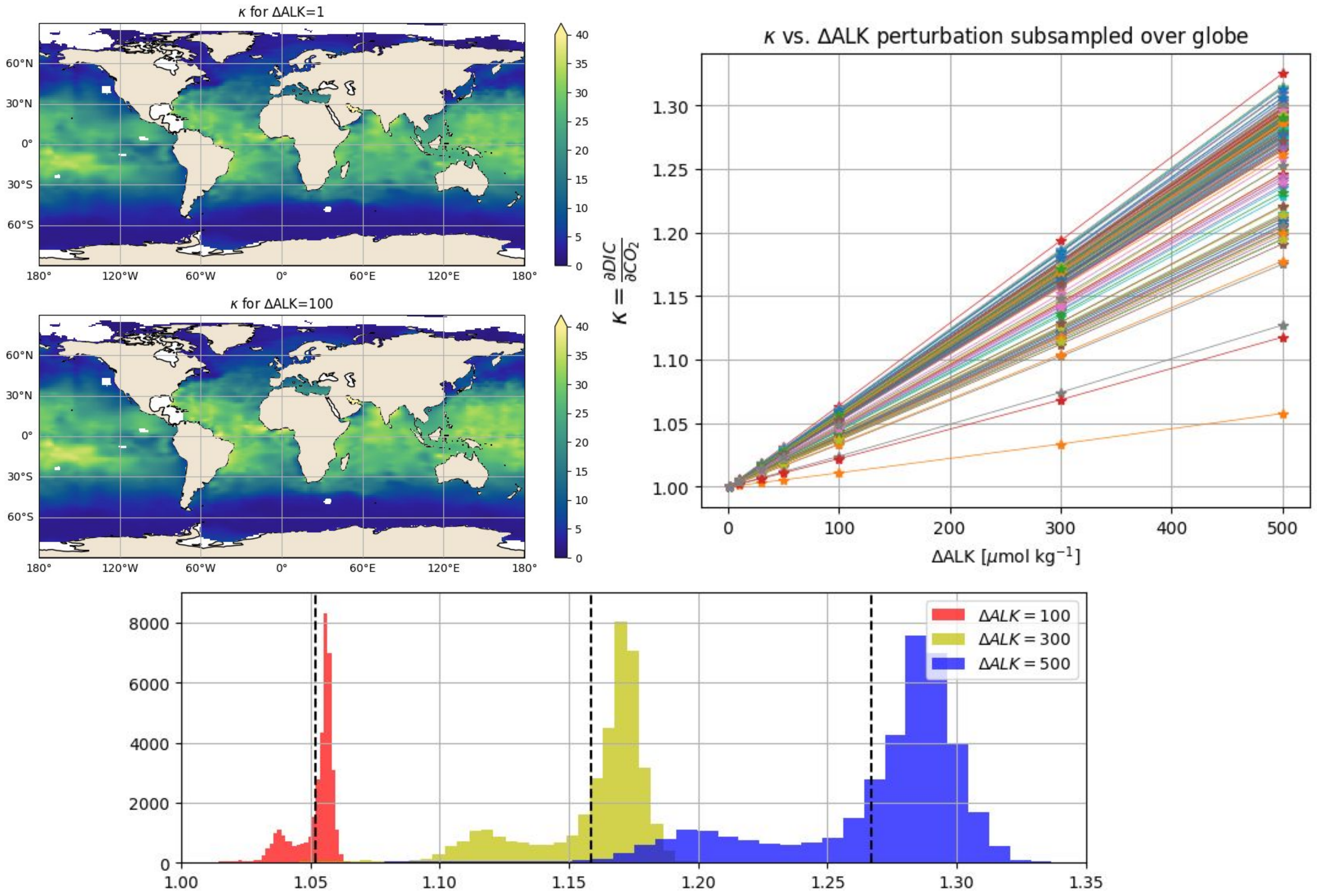
170°W
150°W
130°W
110°W



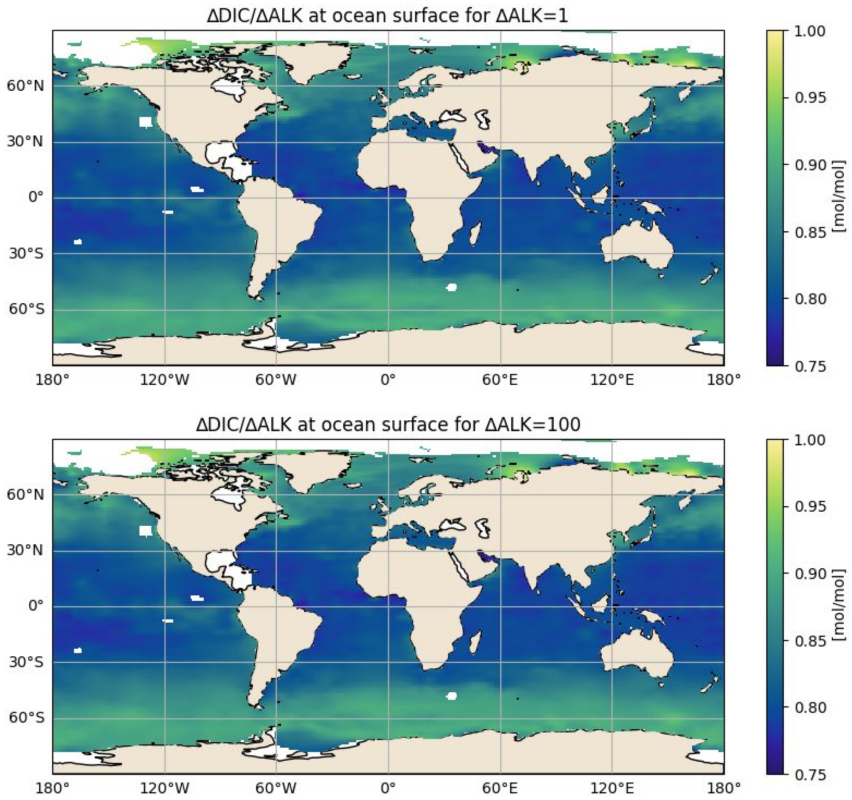


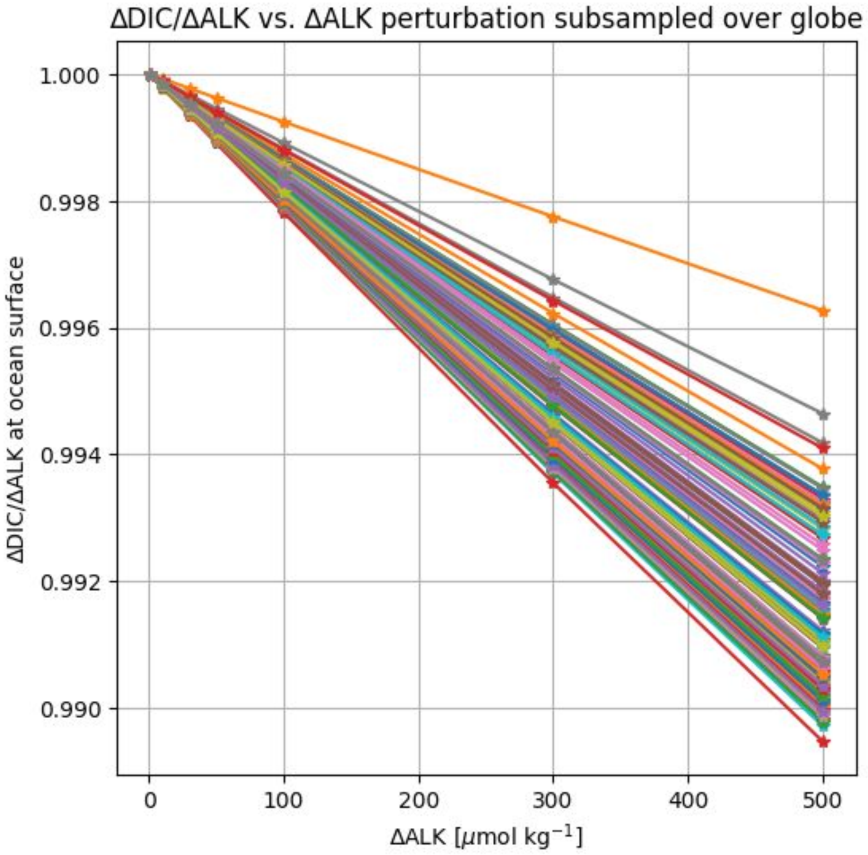
$$\frac{\partial pCO_2}{\partial DIC} = \frac{K_2}{K_0K_1}\frac{(3 \cdot Alk - 2 \cdot DIC)(2 \cdot DIC - Alk)}{(Alk - DIC)^2} = \frac{K_2}{K_0K_1}\kappa$$

κ encapsulates the nonlinearity due to carbonate chemistry, refers to the change in how CO_2 will be taken up as a function of DIC for a given atmospheric CO_2 concentration. If we compute the IRF for a given alkalinity injection, as long as our release's κ remains close in value, the system remains



Depending on the magnitude of the alkalinity pulse, we may violate the linearity.





Goal is to show that η_{max} does not depend significantly on $|\Delta Alk|$. This means linearity with respect to the magnitude of the alkalinity pulse.