Multiscale observing system simulation experiments for iron fertilization in the Southern Ocean, Equatorial Pacific, and Northeast Pacific

Dennis McGillicuddy, Ken Buesseler, Gordon Zhang, and Zihua Liu WHOI
Keith Lindsay, Riyanka Choudhury, and Kristen Krumhardt, NCAR
Matt Long, [C]Worthy
Charles Stock, John Dunne, Xiao Liu, Kyung-Min Noh, NOAA GFDL
Daniele Bianchi, Dou Li, Jerome Guiet, UCLA
Fei Chai, Peng Xiu, Xiamen University

EXOIS
EXPLORING OCEAN IRON SOLUTIONS

OCEAN RESILIENCE + CLIMATE ALLIANCE

OCEAN VISIONS

NOPP

NOAA

NSF

Overall approach

Multiple models

- NCAR CESM / MARBL
- GFDL MOM6 / COBALT
- More welcome!

Multiple scales

- Global earth system models O(1°, 100 yrs)
- Global eddying ocean-only models O(1/10°, 30 yrs)
- High resolution nested models O(1km, 5 yrs)

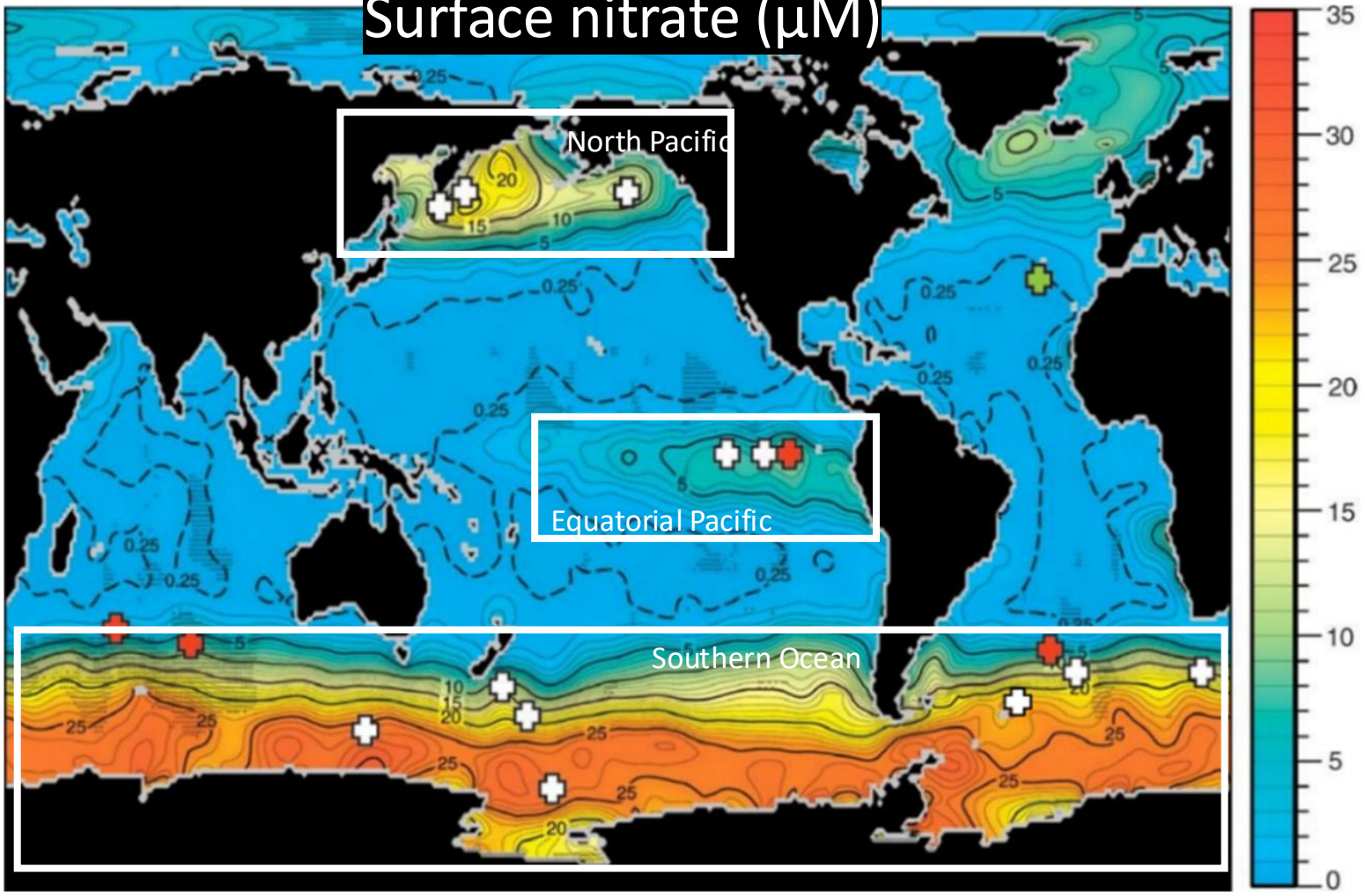
Fertilization strategies

- Regional
- Field trials

Evaluation

- Quantification of intended and unintended consequences of OIF
- OSSEs

Surface nitrate (µM)

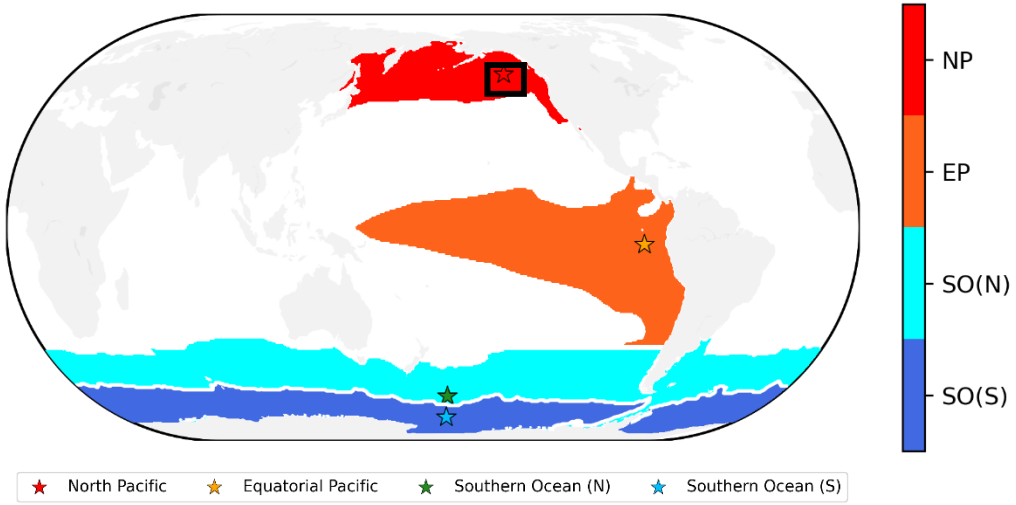


NASEM, 2021

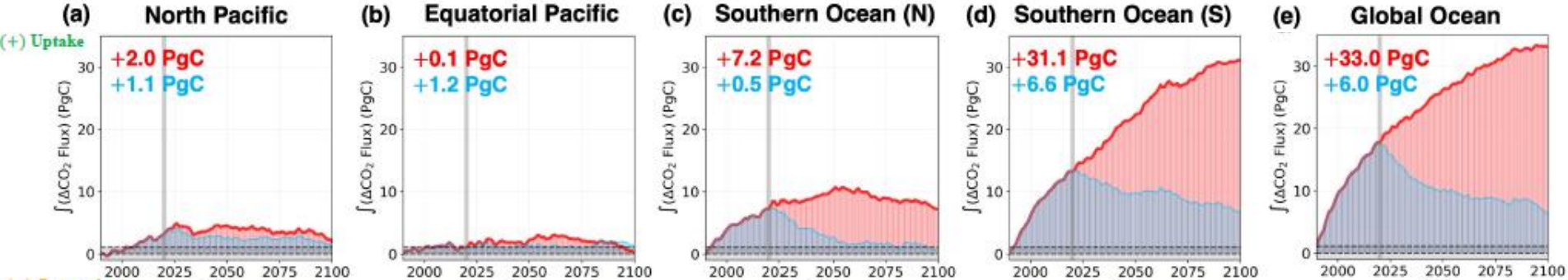
Re-Assessing the Additionality and Durability of Carbon Uptake in Large-Scale Ocean Iron Fertilization

Kyung-Min Noh[1], Xiao Liu[2], Charles Stock[2],Dennis McGlicuddy[3], and John Dunne[2]
[1]Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA
[2]National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA
[3]Woods Hole Oceanographic Institution (WHOI), Falmouth, MA, USA

Noh et al., submitted

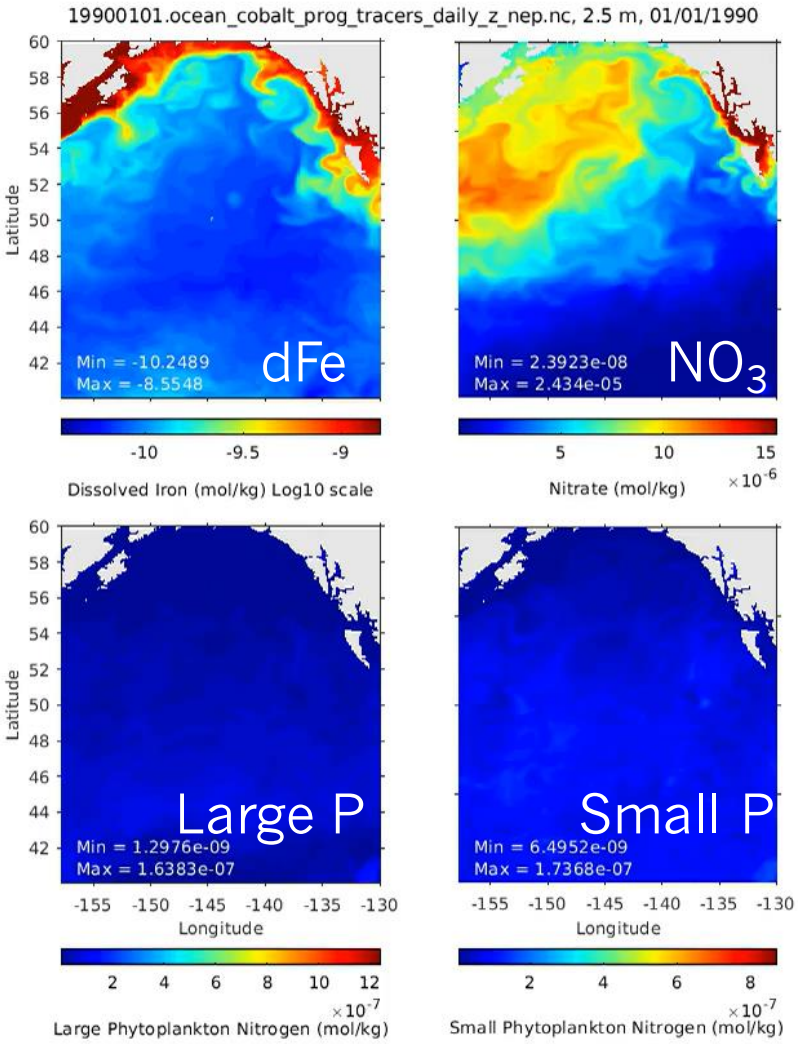


References	Effect of Fertilization : ΔCO_2 (ppm, ATM)	Effect of Fertilization : ΔCO_2 (PgC, OCN)	Method
Peng & Broecker 1991	96 ppm	204 PgC	Advection-Diffusion Box-Model : Nutrient Depletion to 75m
Joos et al., 1991	107 ppm	227 PgC	Advection-Diffusion Box-Model : Nutrient Depletion to 75m
Sarmiento & Orr 1991	72 ppm	153 PgC	3D Ocean-BGC Model (GFDL) : Nutrient Depletion to 50m
Kurz & Maier-Reimer 1993	50 ppm	106 PgC	3D Ocean-BGC Model (MPI) : Nutrient Depletion to 50m
Marinov et al. 2006	70 ppm	147 PgC	3D Ocean-BGC Model (GFDL) : Nutrient Depletion to 75m
Aumont & Bopp 2006	33 ppm	70 PgC	3D Ocean-BGC Model (PISCESv1) : Fixing Fe Concentration in MLD
Oschlies et al. 2010 Oschlies et al. 2025	26 ppm	58.6 PgC	3D Fully Coupled Model (UVicESM) : Doubling Phytoplankton Growth
Keller et al., 2014	42 ppm	98 PgC	3D Fully Coupled Model (UVicESM) : Doubling Phytoplankton Growth
Tagliabue et al. 2023	10 ppm	21 PgC	3D Ocean-BGC Model (PISCESv2) : Surface Iron Flux, Concentration
Noh et al. (This work)	12 ppm	31 PgC	3D Fully Coupled Model (GFDL-ESM4.1) : Surface Iron Flux



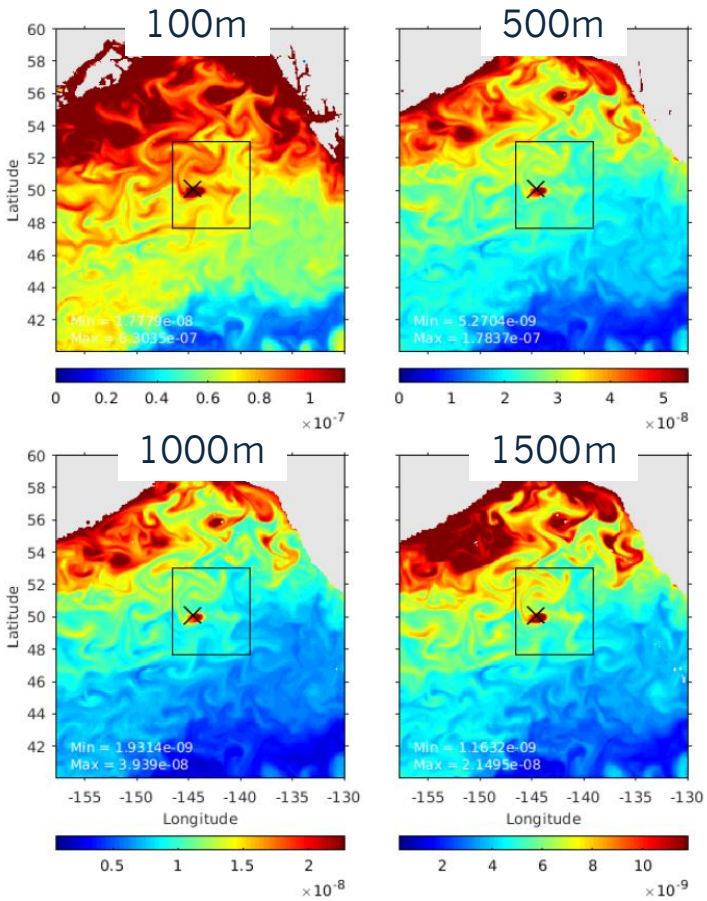
A continuous release of dFe
from a fixed location (14 km)^2
GFDL MOM6 / COBALT
Global 1/8° model
January 1 – December 31

Xiao Liu

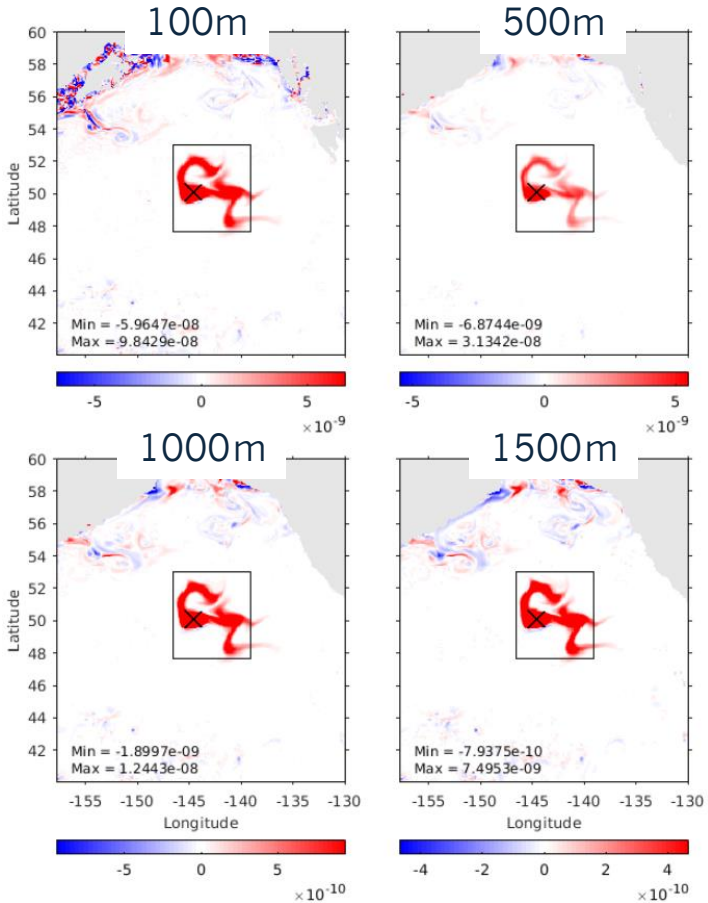


POC flux May 16 – Continuous release using MOM6 / COBALT

Experiment



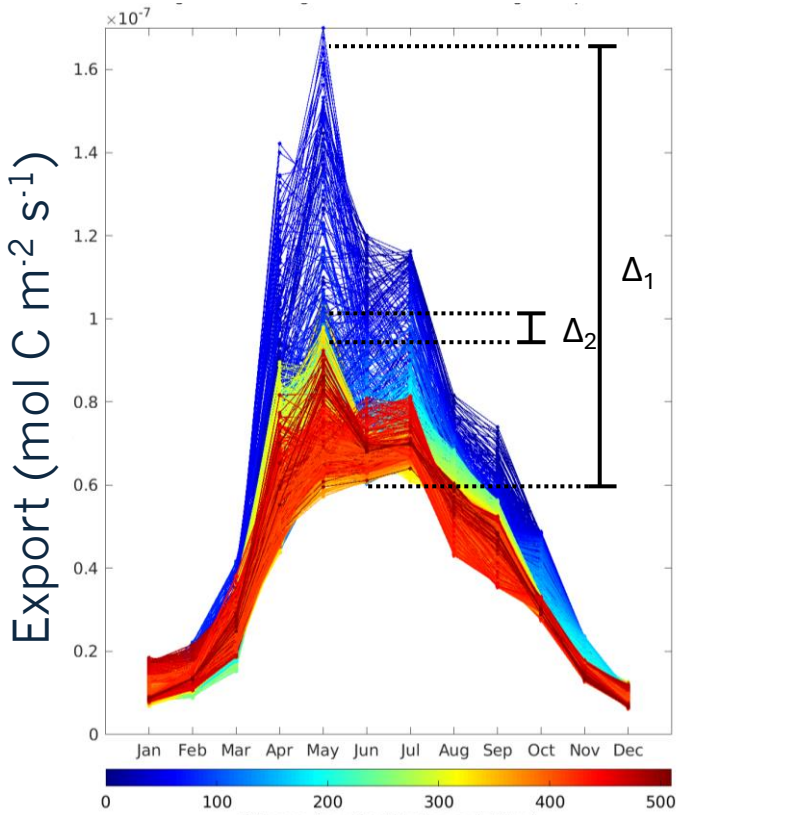
Experiment - control



POC flux at 100m sampled in a 68x61 grid around the release point

Traditional fertilization exp: contrast inside versus outside a patch

Goal for a continuous release experiment: **volume integral of the response**



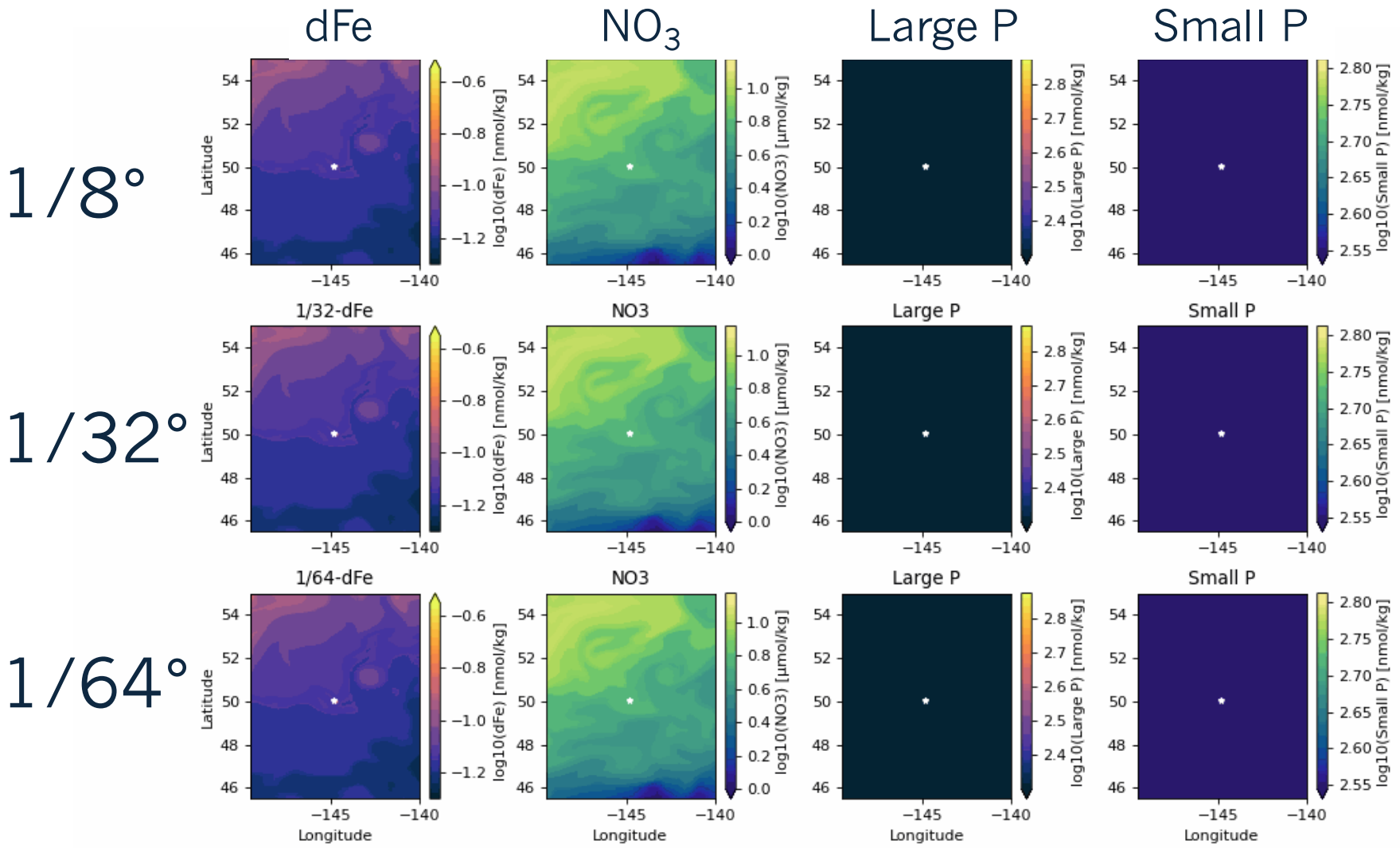
Issues

Resolution of the model

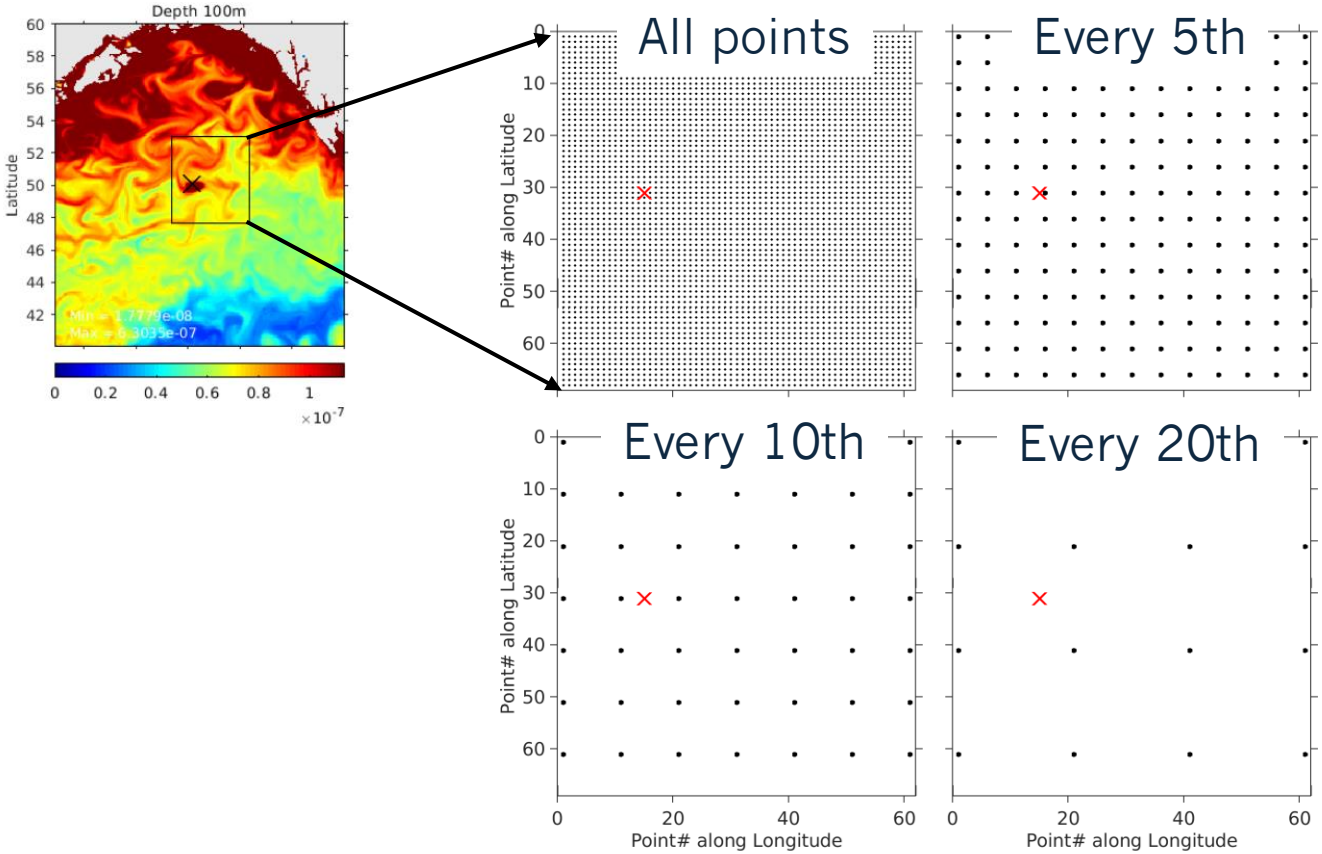
Resolution of the observing system

Sampling error

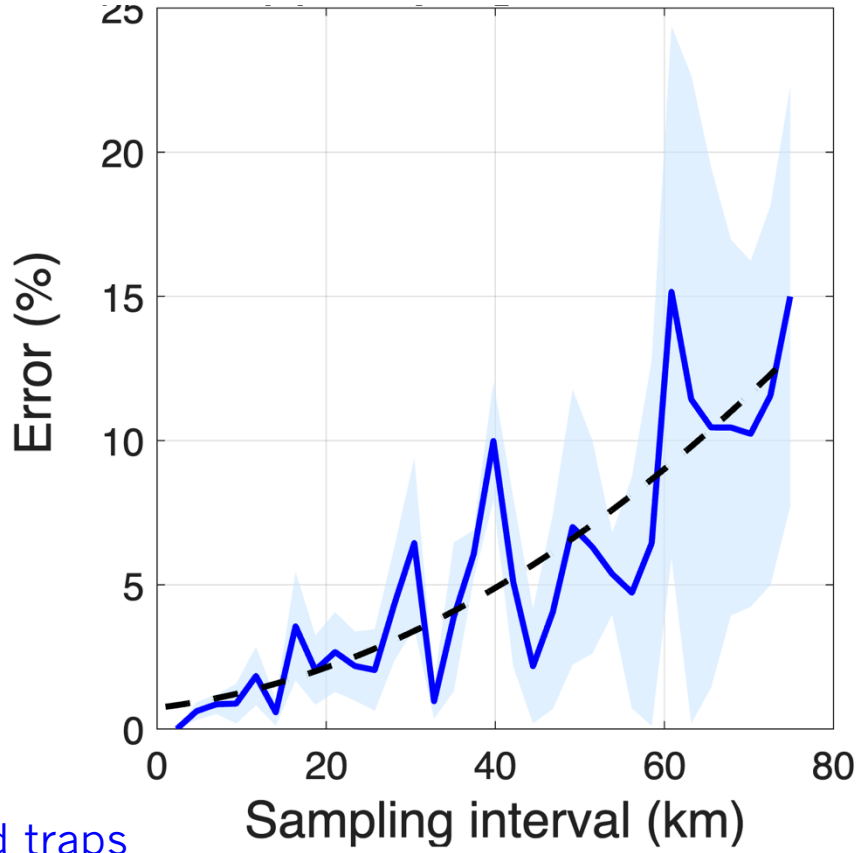
Interannual variability


dFe
NO_3
Large P
Small P
1/8°
1/32°
1/64°
1/32-dFe
NO3
Large P
Small P
1/64-dFe
NO3
Large P
Small P
Latitude
Longitude
log10(dFe) [nmol/kg]
log10(NO3) [µmol/kg]
log10(Large P) [nmol/kg]
log10(Small P) [nmol/kg]

Subsampling the volume



Effect of sampling resolution on error



Sed traps
12,700 252 80 35 20 12

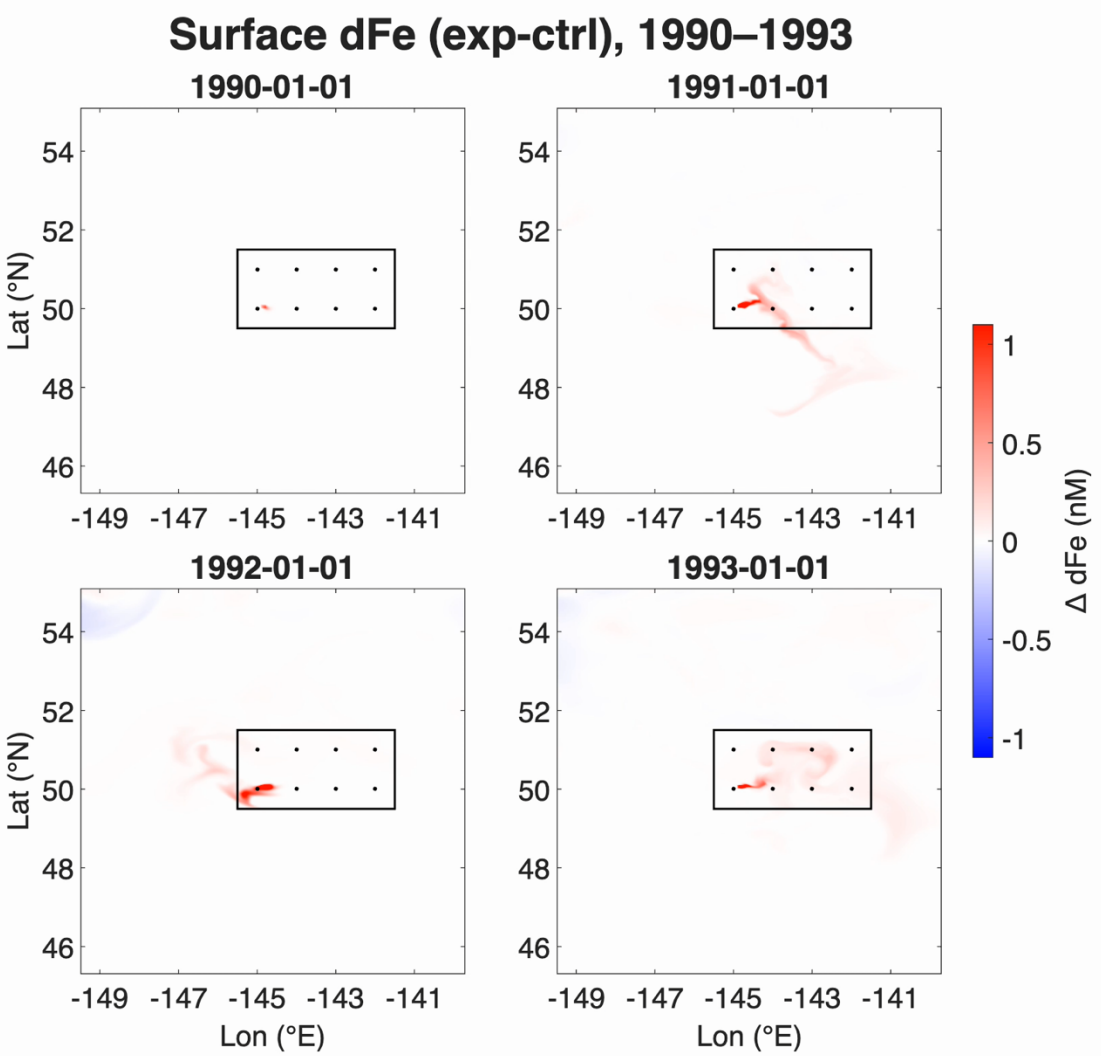
Experiment (subsampled) – control (full res)

POC flux at 500m

10°x10° domain

5 yr simulation

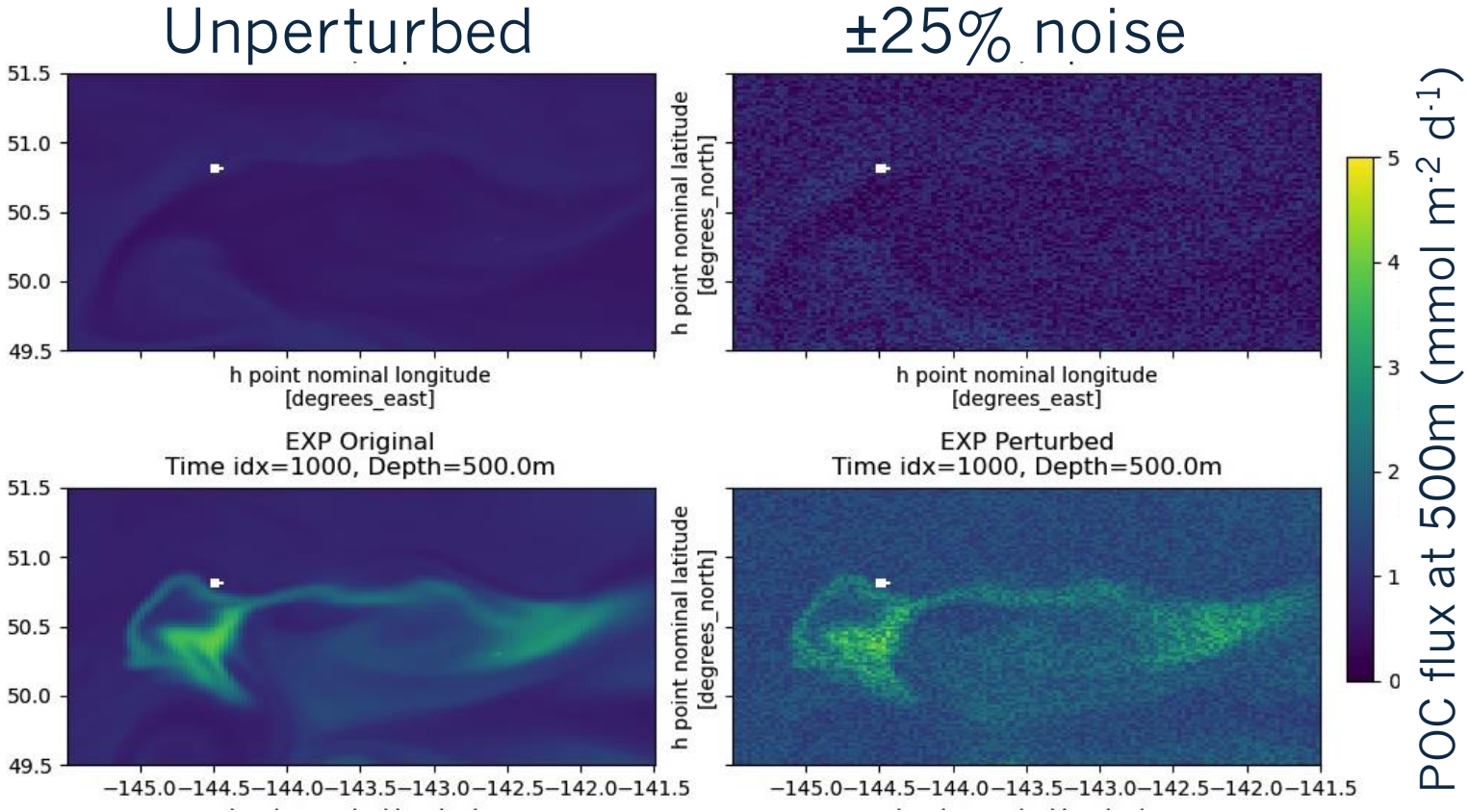
Mean and std dev



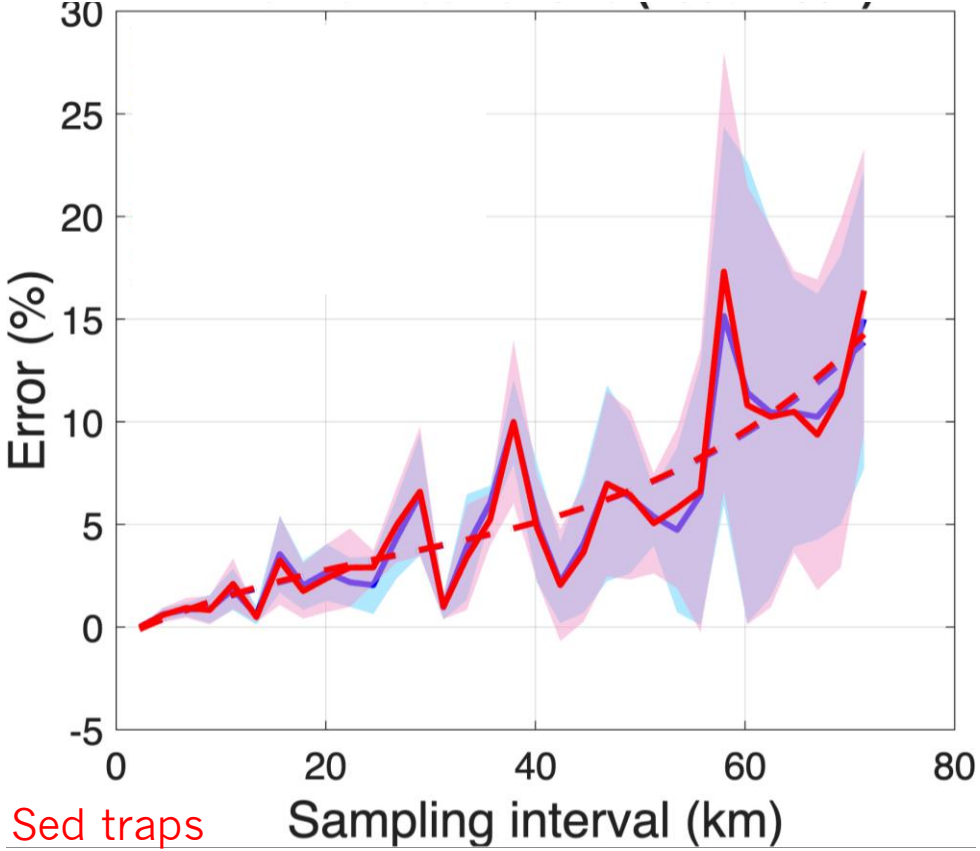
1° spacin
between
numerica
sediment
traps

Simulating observational error

Baker et al. (2020) intra-cup variability 23%



Sampling resolution and observational error



Sed traps
12,700 252 80 35 20 12

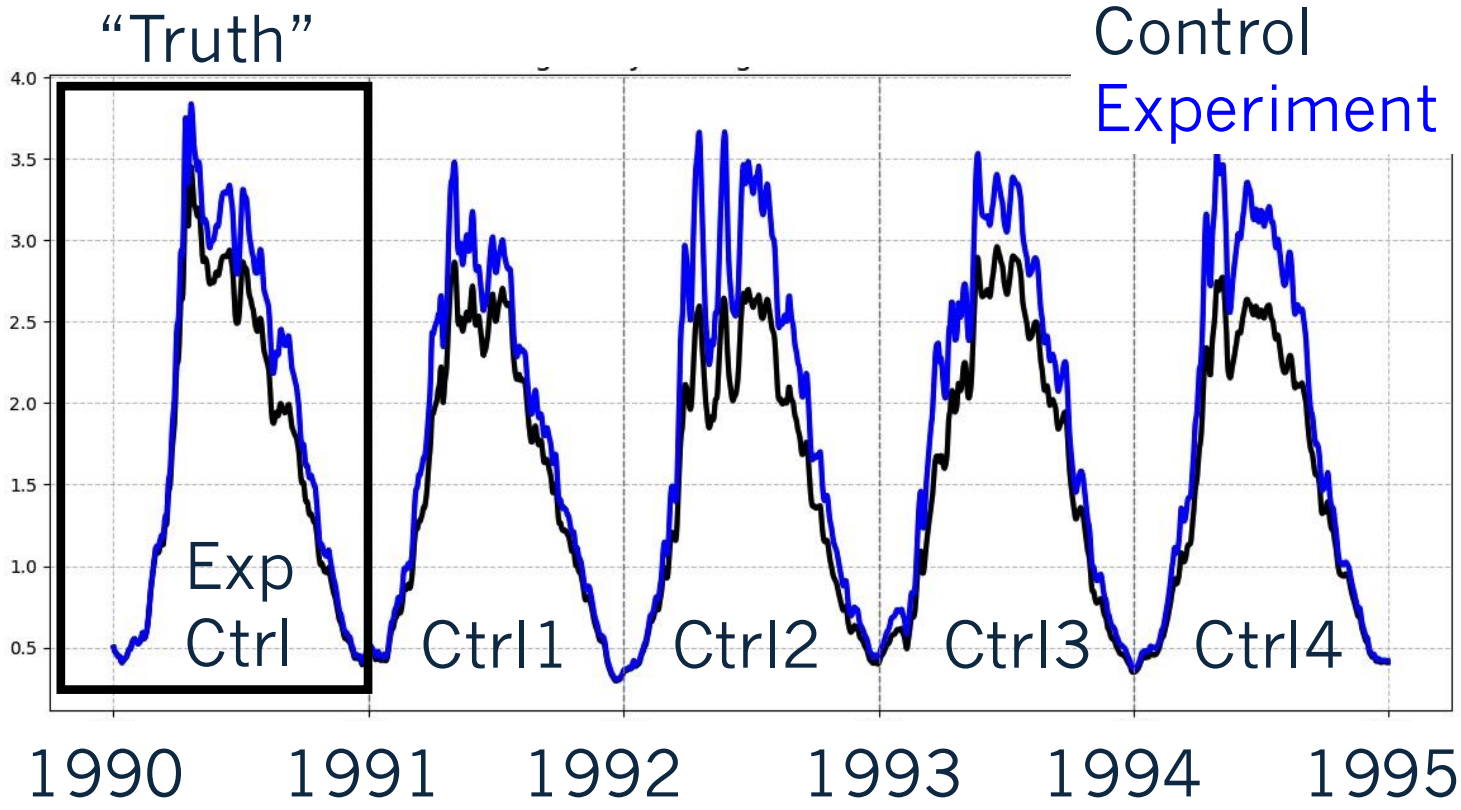
Exp (subsampled) – ctrl (full res)

Exp + noise (subsampled) – ctrl (full res)

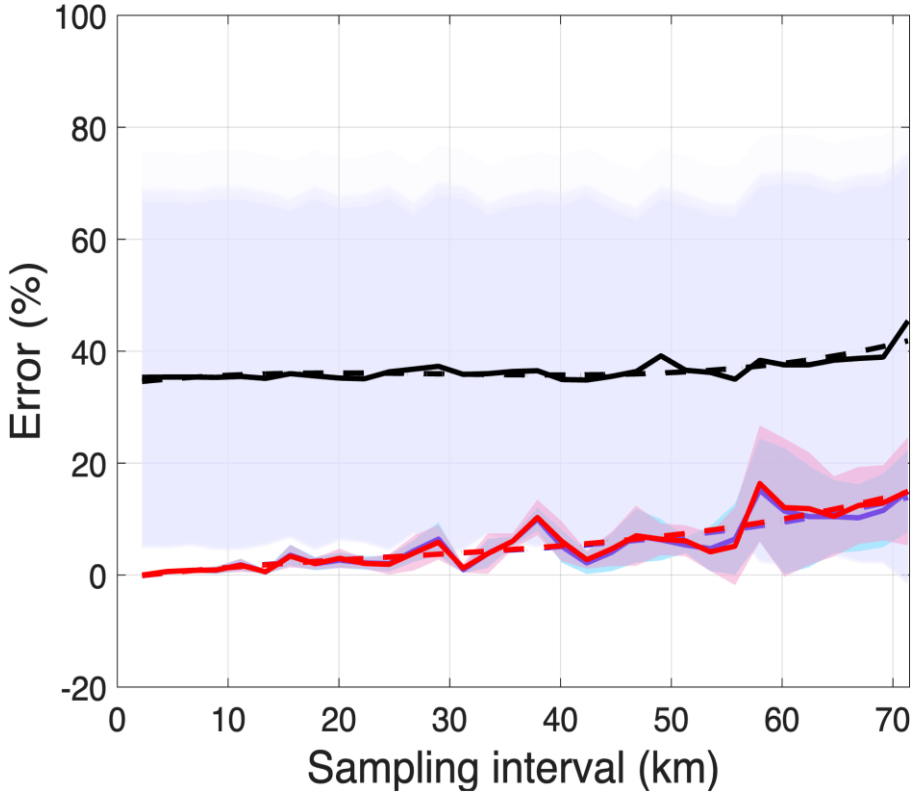
POC flux at 500m
10°x10° domain
5 yr simulation
Mean and std dev

Interannual variability in the 1/32° nested model

POC flux
mmol m^{-2} d^{-1}
500m
10°x10° domain



Putting it all together: resolution, sampling error, interannual variability



Resolution + obs error + interannual variability

Resolution only

Resolution + obs error

Sed traps 12,700 252 80 35 20 12

OSSEs for a continuous release of dFe from a fixed location

- High resolution models needed (at least 1/32°)

- Solutions show strong variations on multiple scales
  - Interannual
  - Seasonal
  - Mesoscale / submesoscale

- OSSE-estimated annual mean POC flux at 500m depends on
  - Sampling resolution
  - Observational error
  - What is used for the control

- One year is not enough, either for the control or the experiment

Design of a patch-release field trial in the NE Pacific using a multi-model ensemble

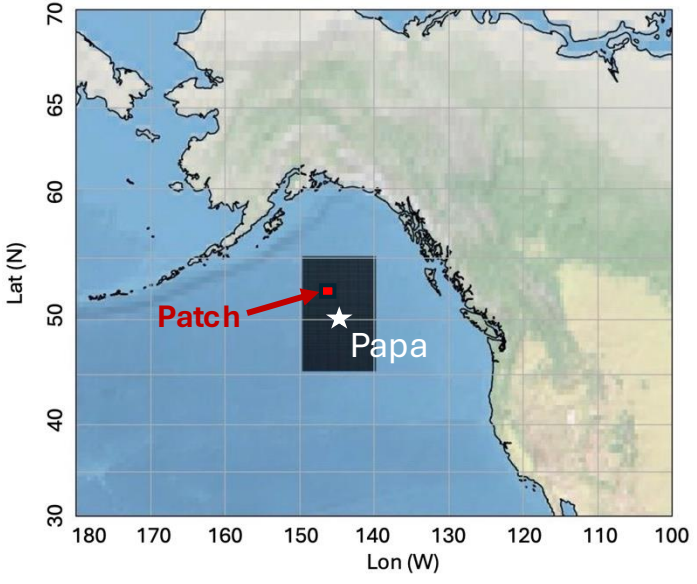
ROMS - COSINE (Chai et al. Xiamen)
ROMS - MARBL (Bianchi et al., UCLA)
MOM6 - COBALT (McGillicuddy et al., WHOI)

Monthly releases April – August

Patch size: 30x30km & 50x50km

Site choice

Assessment of potential impacts on Station P



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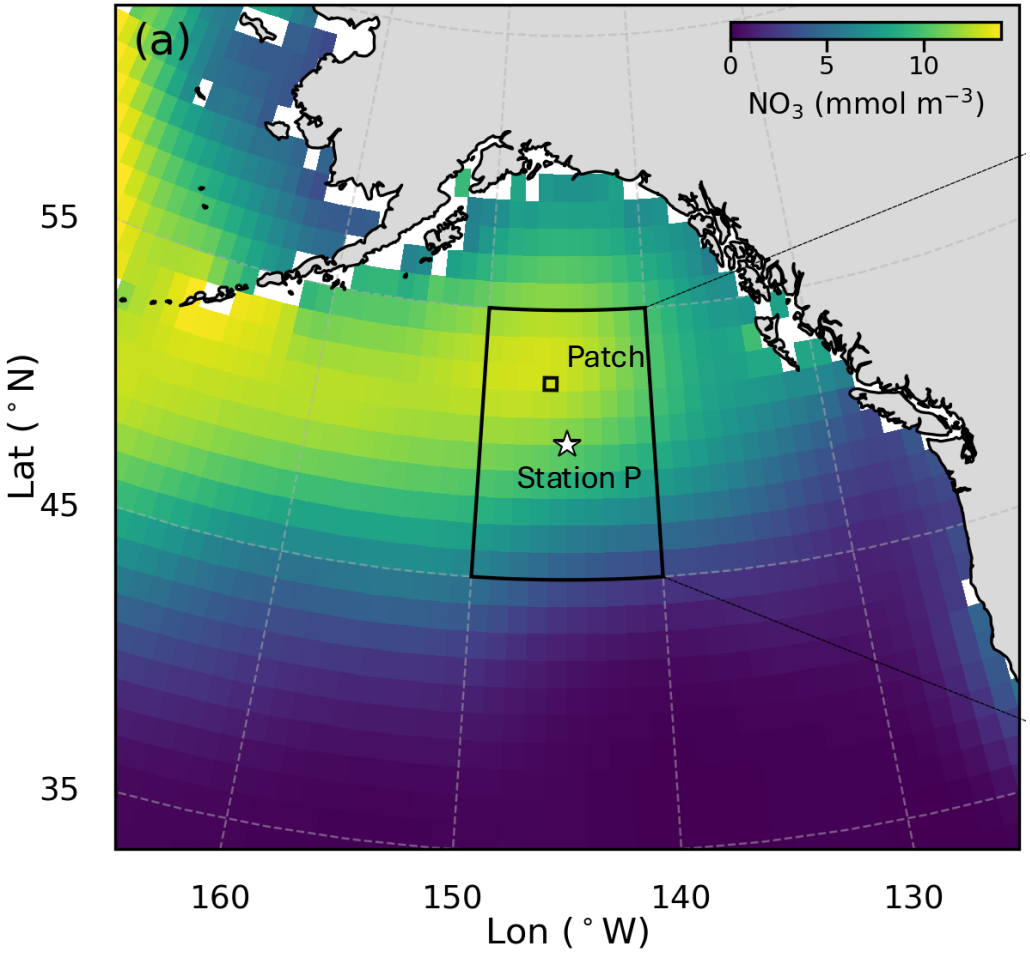
OCEAN VISIONS

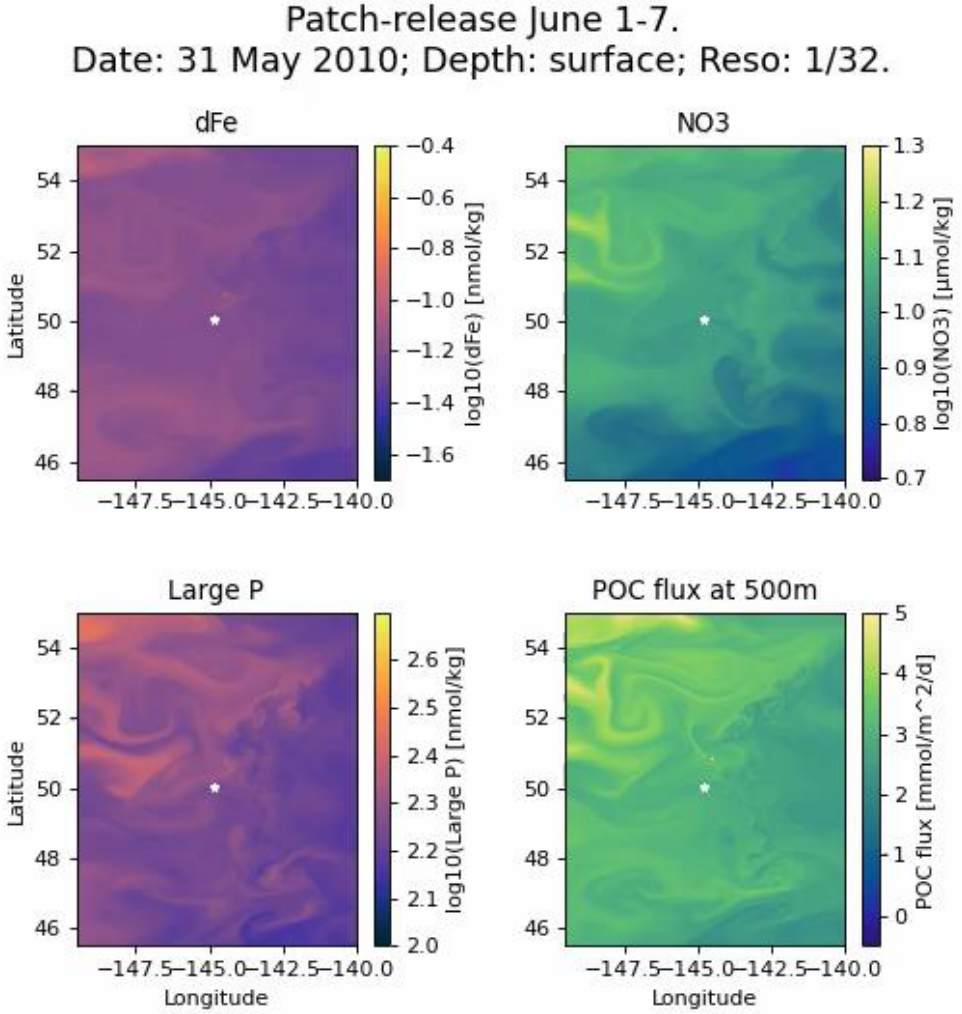
OCEAN RESILIENCE+ CLIMATE ALLIANCE

Nitrate climatology – WOA 1965-2022

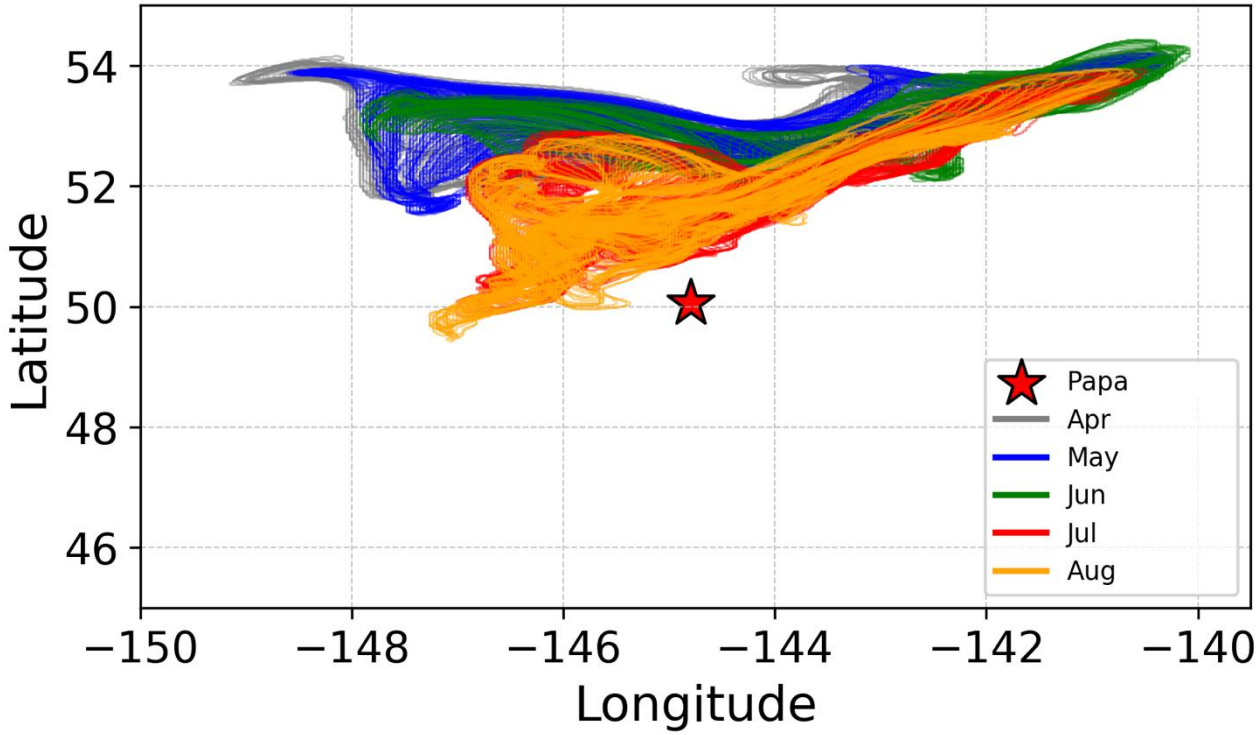


MOM6/COBALT 1/32°

Zihua Liu



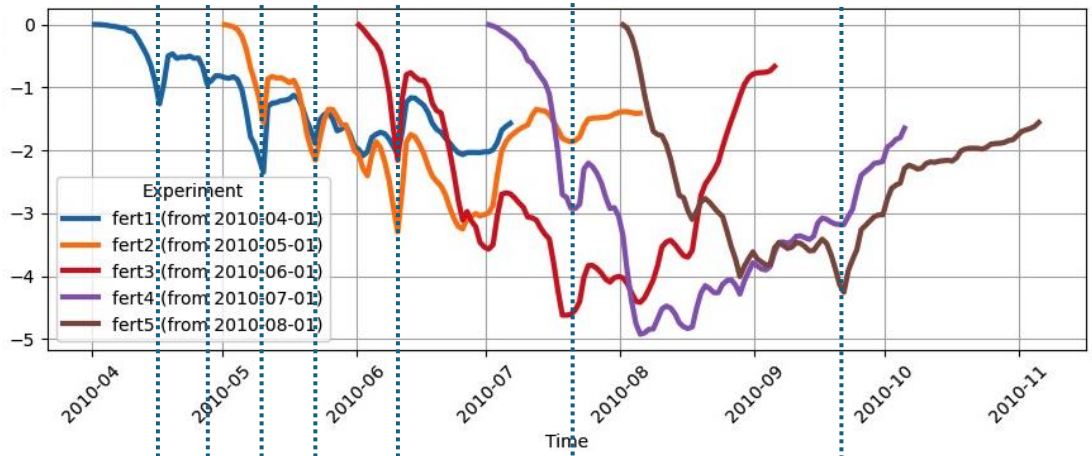
Outer contours of phytoplankton response (small plus large)



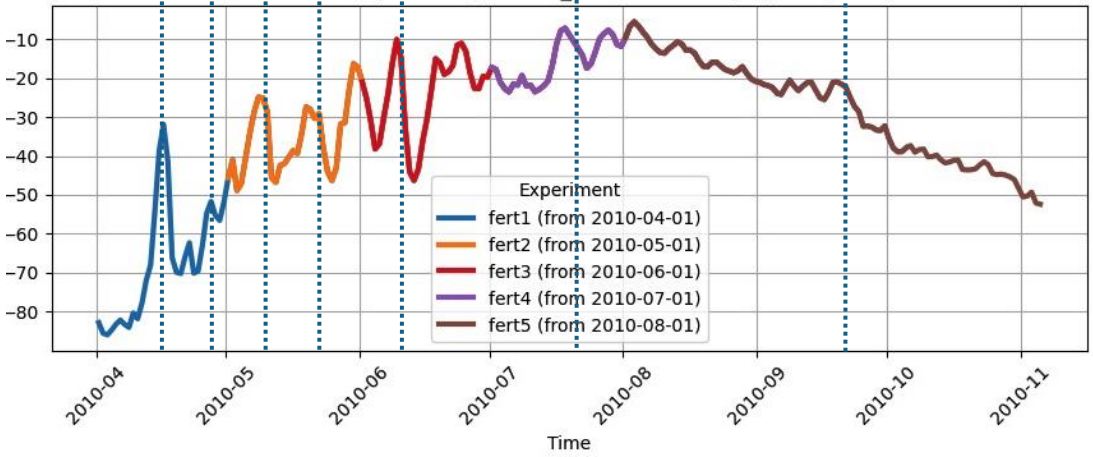
max $\Delta(P_L + P_s) * 1/e$

Variations in nitrate drawdown

ΔNO_3 Inside (μM)



MLD (m)



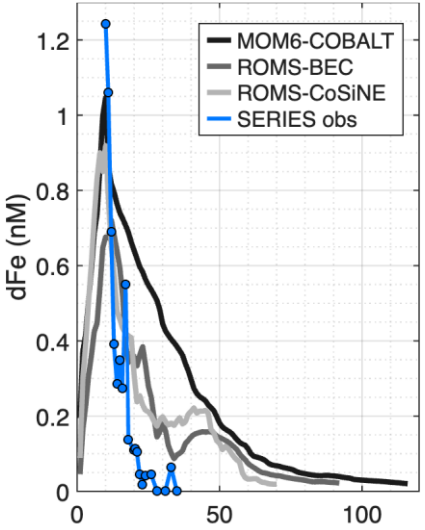
dFe: 0.02mol/m2/yr

Comparison with SERIES observations

(inside – outside) and (experiment – control)

Surface iron

nM



Time (days)

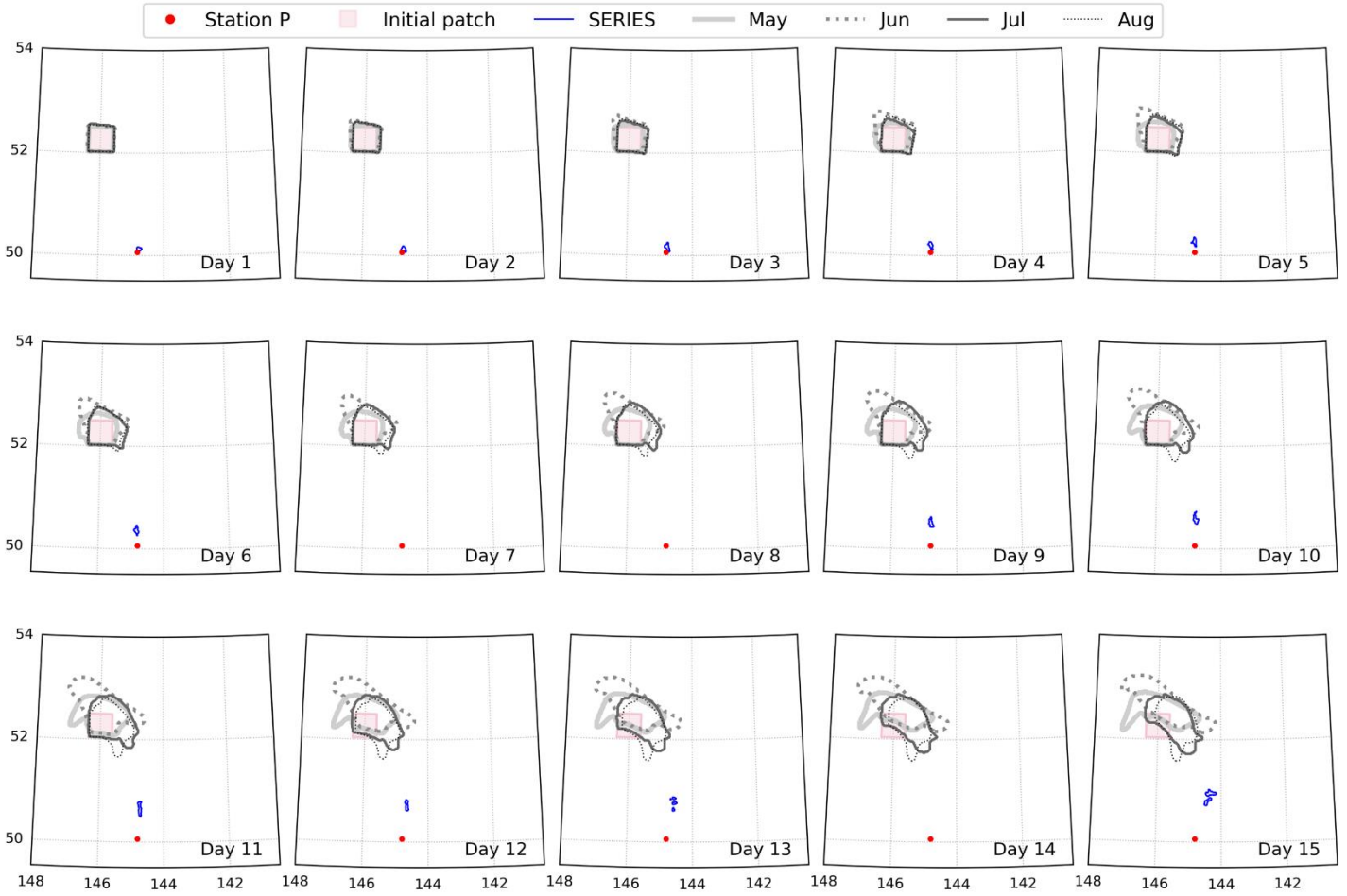
Simulated patch evolution

MOM6-COBALT

May-Aug

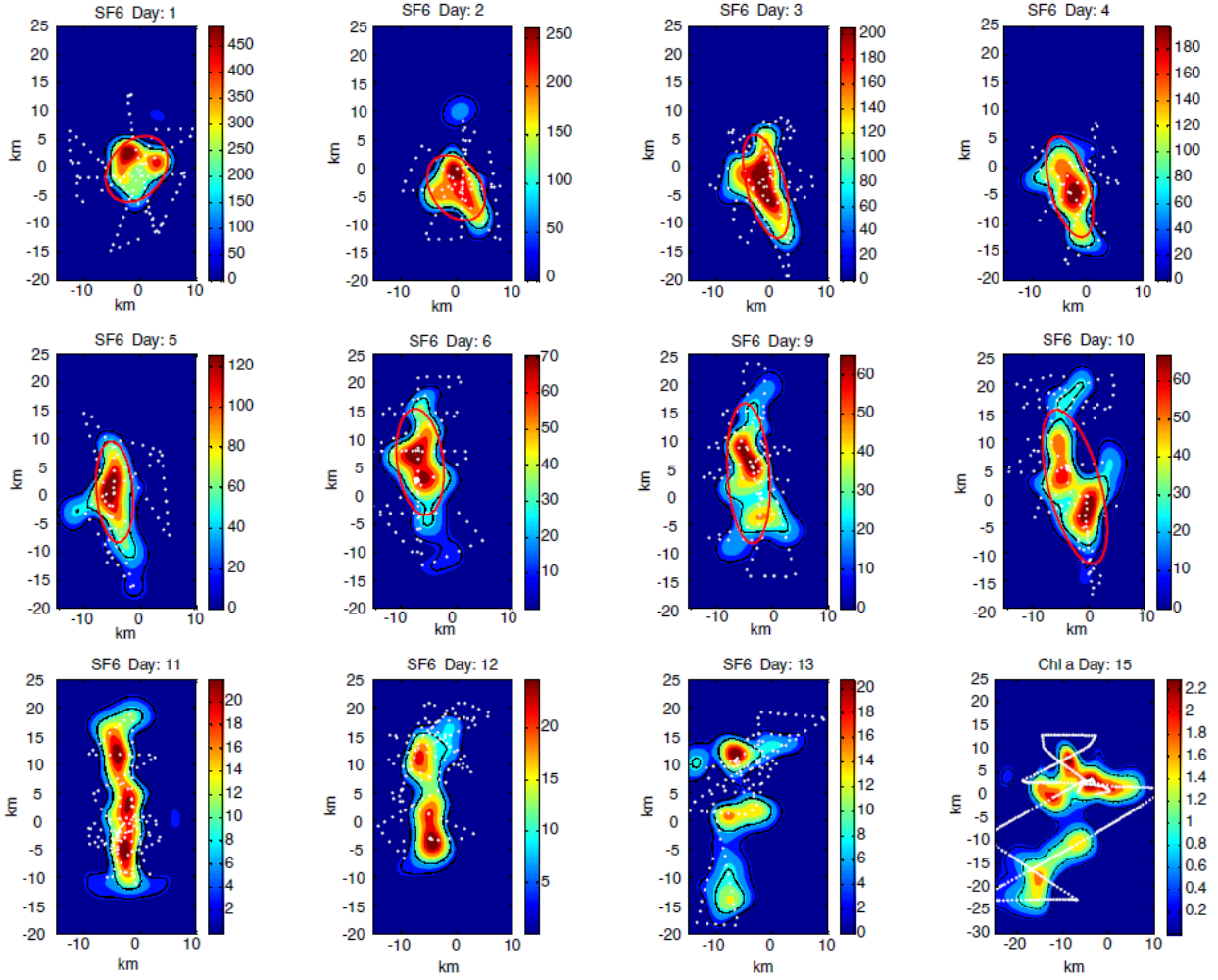
SERIES tracer

Station P



SERIES exp

Time evolution of the tracer



Next Steps

Continued planning for field trials in the NE Pacific

OSSES on multi-model ensemble

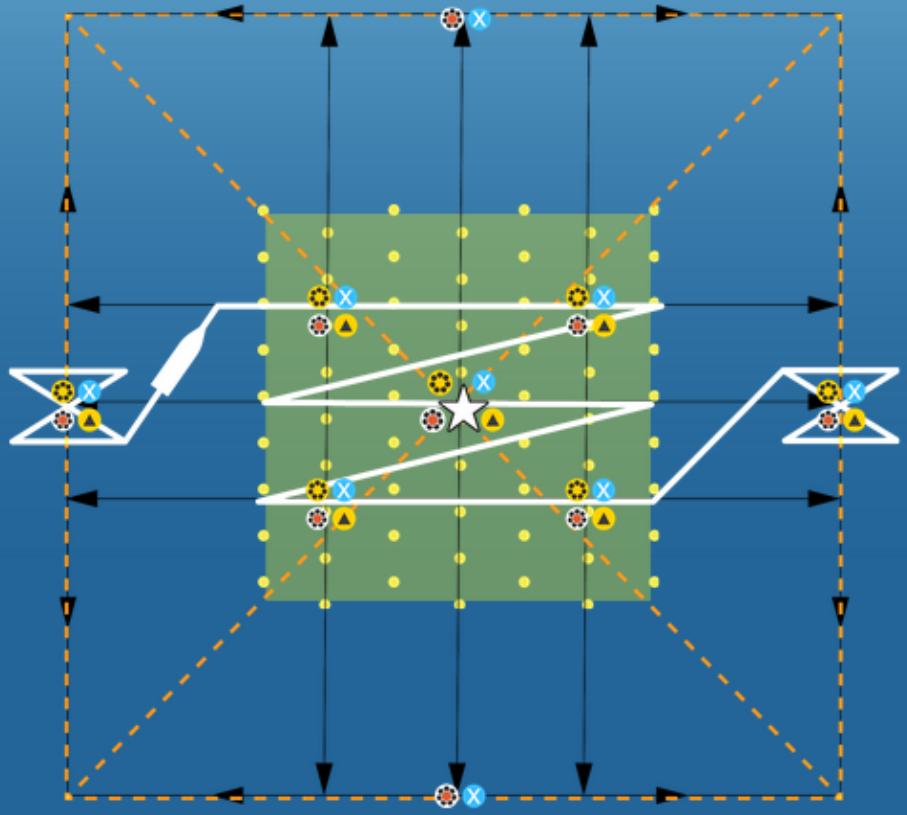
Simulation and design of dFe and tracer release with ultra high resolution models

Continued evaluation of OIF in other HNLC areas

Equatorial Pacific

Southern Ocean

How will we do this?



Buesseler et al.
workshop report

** note green is iron fertilized area*
- sampling in and out of "patch"

Sampling strategy

Autonomous vehicles and ships

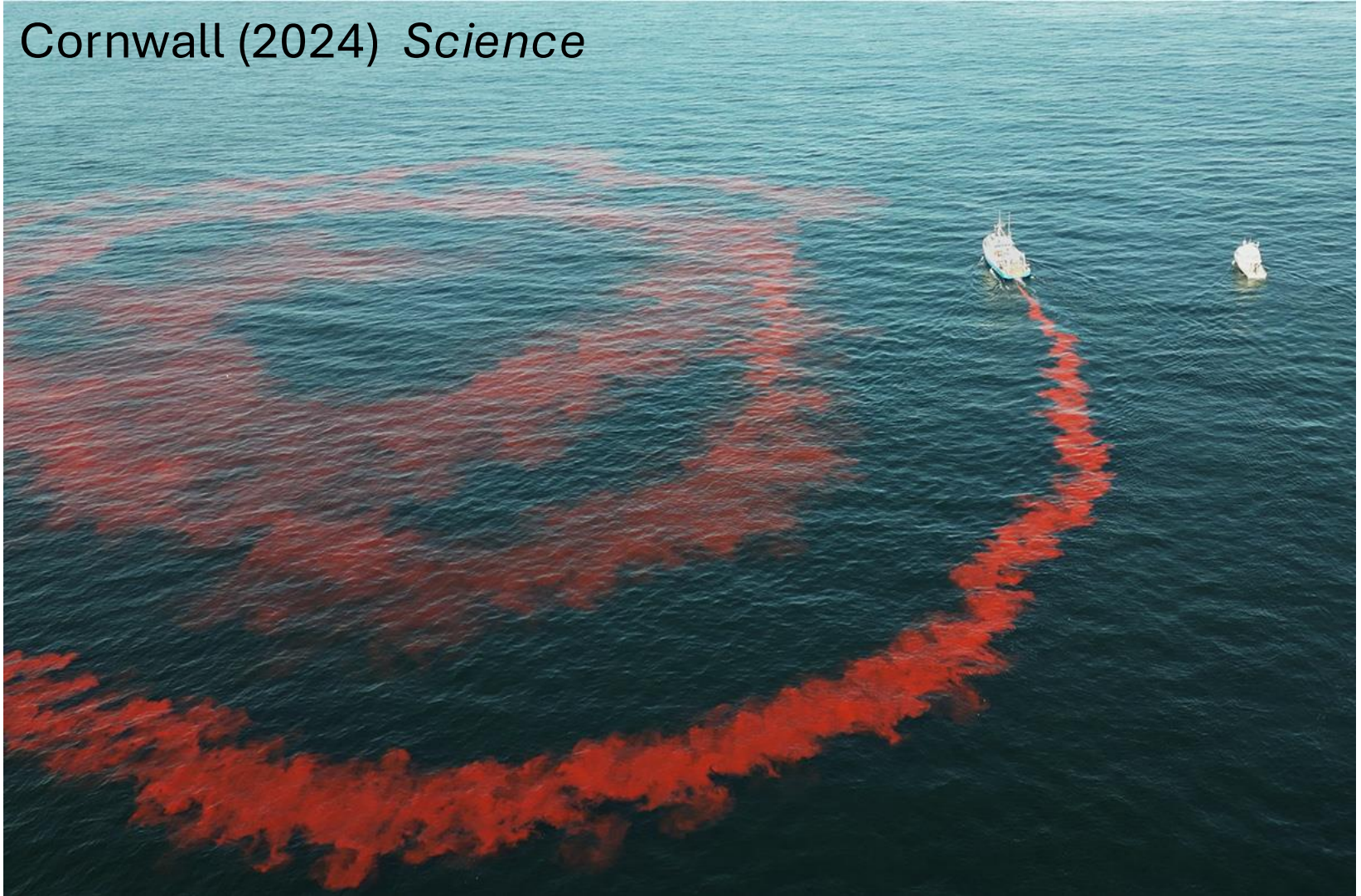
Next Steps

Continued planning for field trials in the NE Pacific

- OSSES on multi-model ensemble
- **Simulation and design of dFe and tracer release with ultra high-resolution models**

Continued evaluation of OIF in other HNLC areas

- Equatorial Pacific
- Southern Ocean


Cornwall (2024) *Science*

Next Steps

Continued planning for field trials in the NE Pacific

- OSSES on multi-model ensemble
- Simulation and design of dFe and tracer release with ultra high-resolution models

Continued evaluation of OIF in other HNLC areas

- **Equatorial Pacific**
- **Southern Ocean**

We want your input and participation!

Feedback on array design, sensors, etc.

Inclusion of other models for

Intercomparison

OSSEs

EXOIS
EXPLORING OCEAN IRON SOLUTIONS

Access to all ExOIS publications

OceanIron.org

The case for ocean iron fertilization field trials

February 2026

Sage Journals

Dialogues on Climate Change

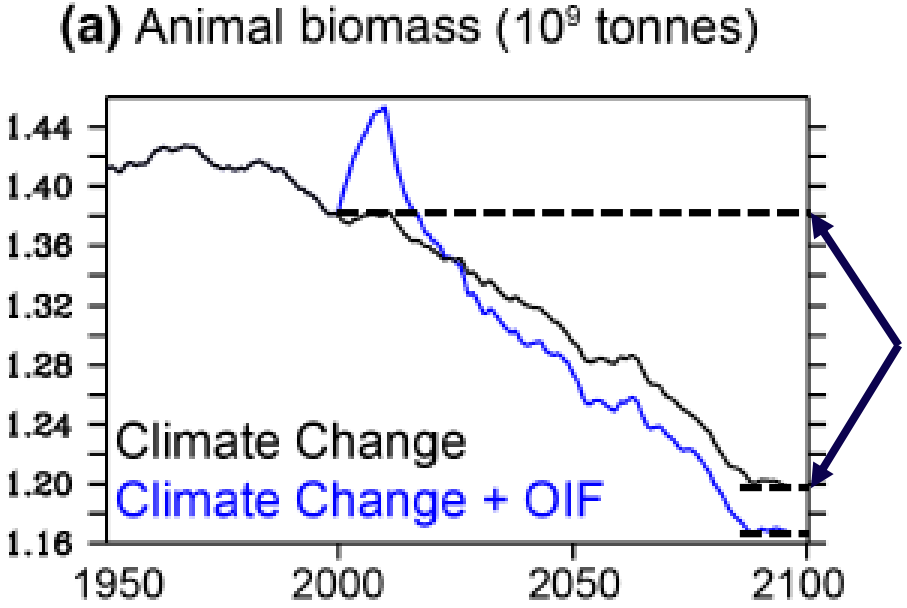
Extras

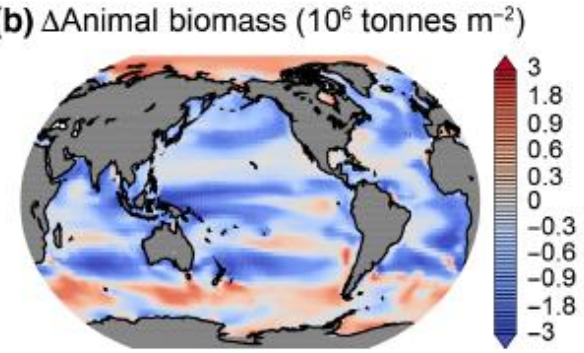
What about unintended consequences?

Ocean iron fertilization may amplify climate change pressures on marine animal biomass for limited climate benefit

Global Change Biology, 2023

Alessandro Tagliabue[1] | Benjamin S. Twining[2] | Nicolas Barrier[3] | Olivier Maury[3] | Manon Berger[4] | Laurent Bopp[4]





13% decline due to climate change

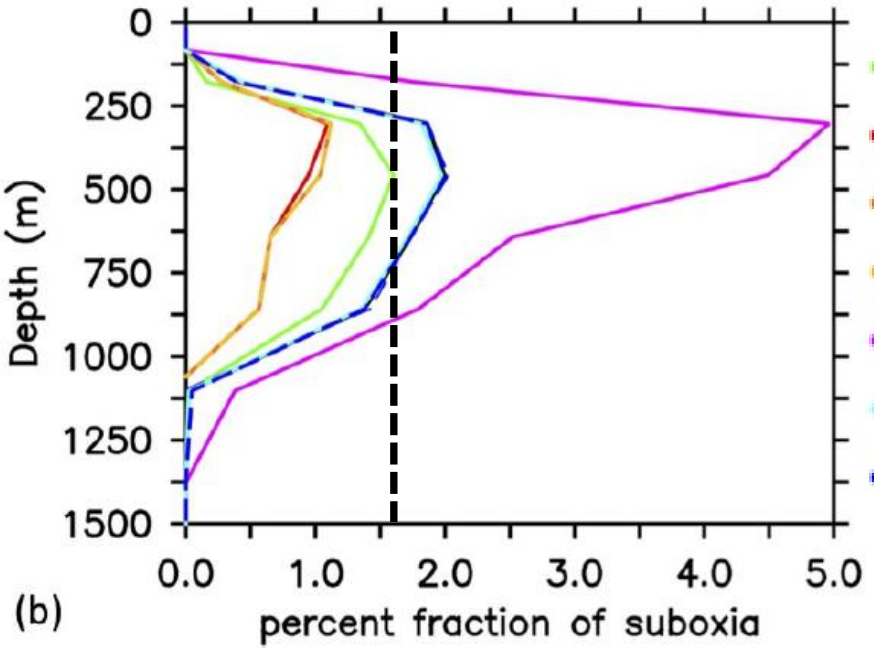
Additional 3% caused by OIF

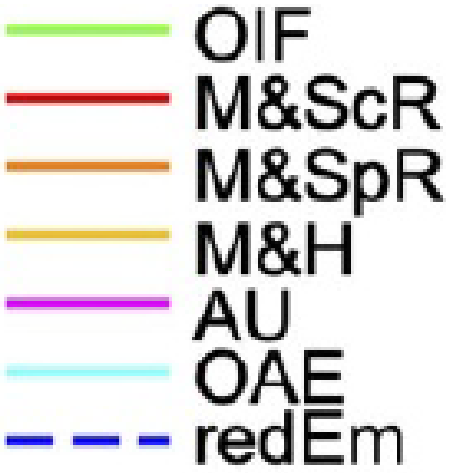
What about unintended consequences?

Potential impacts of marine carbon dioxide removal on ocean oxygen

Environmental Research Letters, 2025

Andreas Oschlies[1,2,*], Caroline P Slomp[3], Andrew H Altieri[4], Natalya D Gallo[5,6], Marilaure Gregoire[7], Kirsten Isensee[8], Lisa A Levin[9] and Jiajun Wu[10]





Iron Fertilization

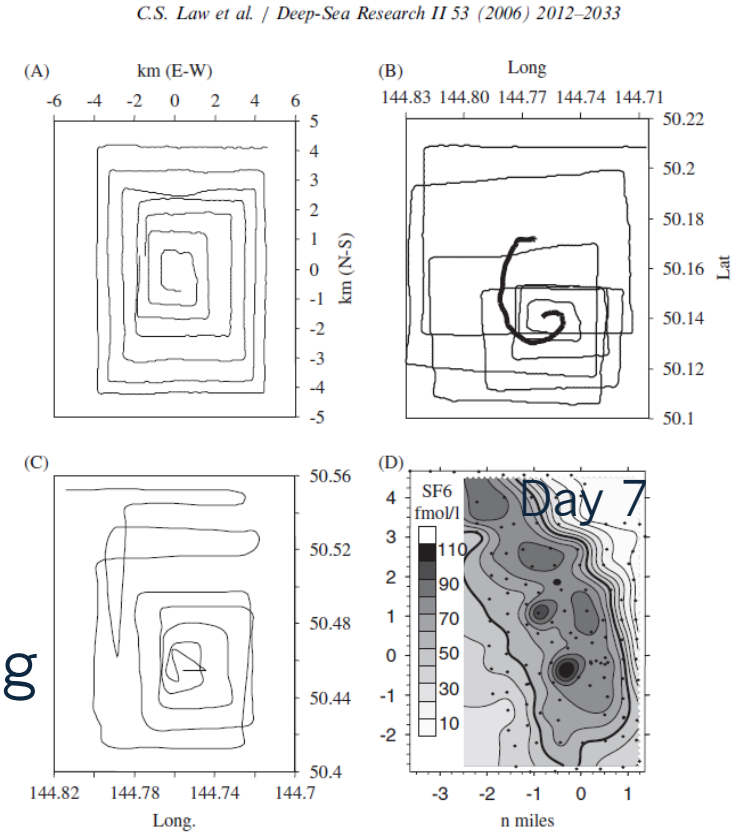
Macro algae farming

Artificial upwelling
Ocean alk enh
Reduced emissions

Toward the goal of a 30x30 km patch fertilization

Spacing between lines
Time required to complete
Tracking
- Drifters
- Tracer

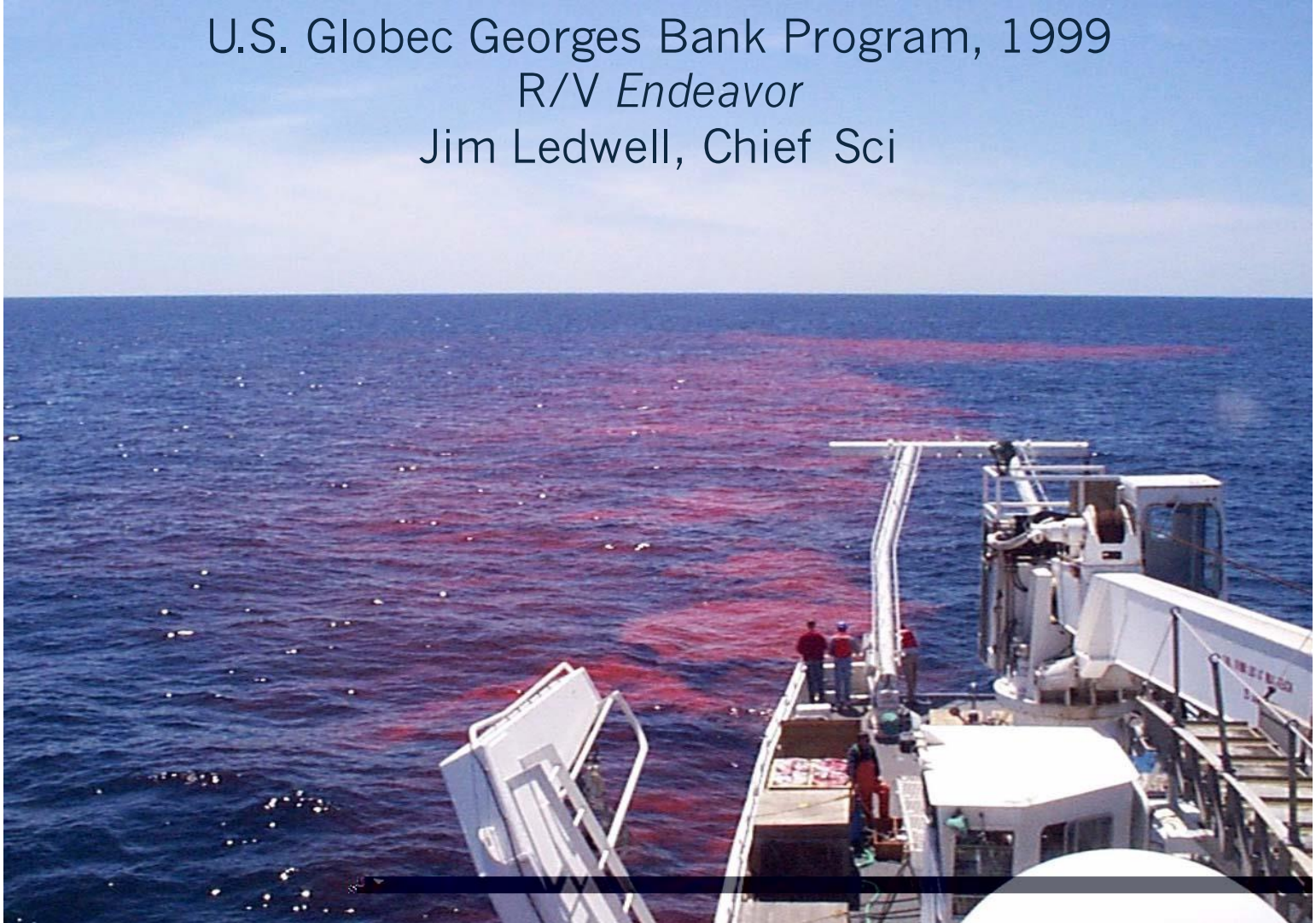
SERIES:
8.5 x 8.5 km
700 m spacing
17.5 hrs



U.S. Globec Georges Bank Program, 1999

R/V *Endeavor*

Jim Ledwell, Chief Sci



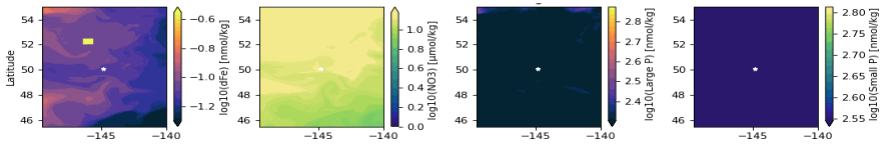
MOM6/COBALT 1/32°

Zihua Liu

0.02 mol/m2/yr

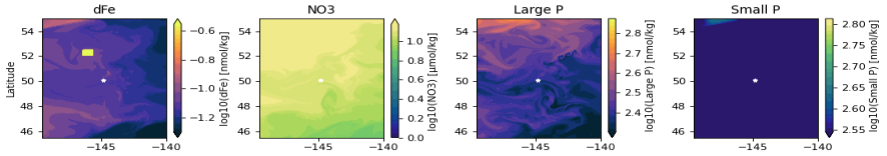
dFe NO_3 Large P Small P

April



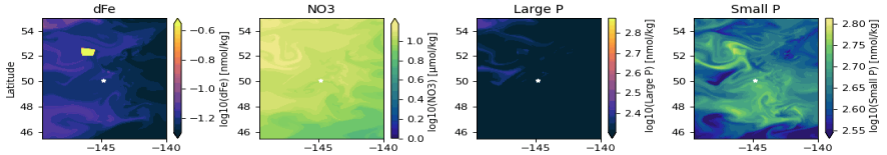
Patch-release dfe002 May 1-7.
Date: 01 May 2010; Depth: 9.0 m; Reso: 1/32.

May



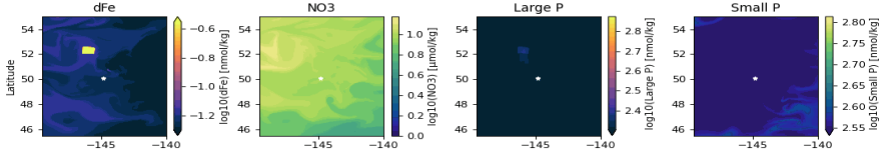
Patch-release dfe002 Jun 1-7.
Date: 02 Jun 2010; Depth: 9.0 m; Reso: 1/32.

June



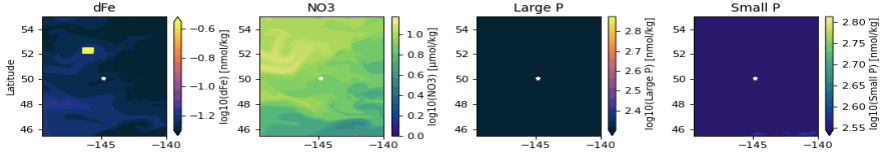
Patch-release dfe002 Jul 1-7.
Date: 02 Jul 2010; Depth: 9.0 m; Reso: 1/32.

July

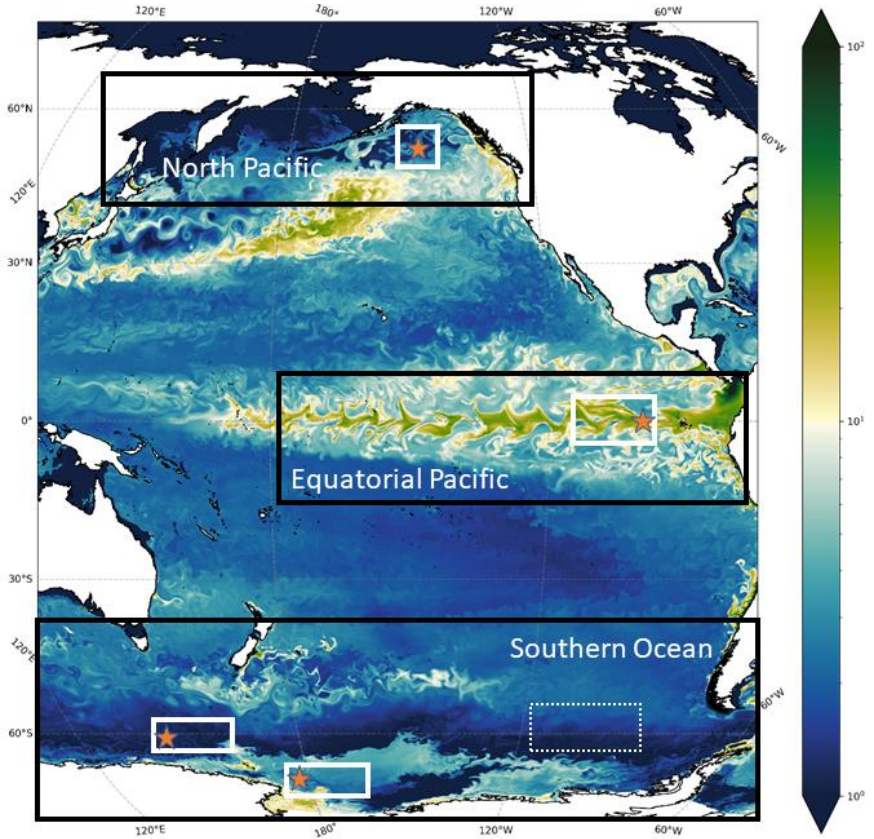


Patch-release dfe002 Aug 1-7.
Date: 01 Aug 2010; Depth: 9.0 m; Reso: 1/32.

Aug



Observing System Simulation Experiments



Snapshot of CESM2-MARBL POC export at 100m

1. Model-based “truth”
2. Subsample in space and time
3. Use simulated data to make field estimates
4. Compare reconstruction with “truth”
5. Evaluate error with quantitative metrics

Caveat: models are an imperfect representation of the natural system