Designing an Ocean Iron Fertilization Study System — A Discussion

Mark L. Wells

School of Marine Sciences

University of Maine

Fei Chai

State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Hangzhou, China

Peng Xiu

South China Sea Institute of Oceanology

Designing an OIF Study System

Knowns: Fe addition to HNLC waters stimulates large diatom blooms, resulting in C export (to a large or lesser extent).

Some Known Unknowns:

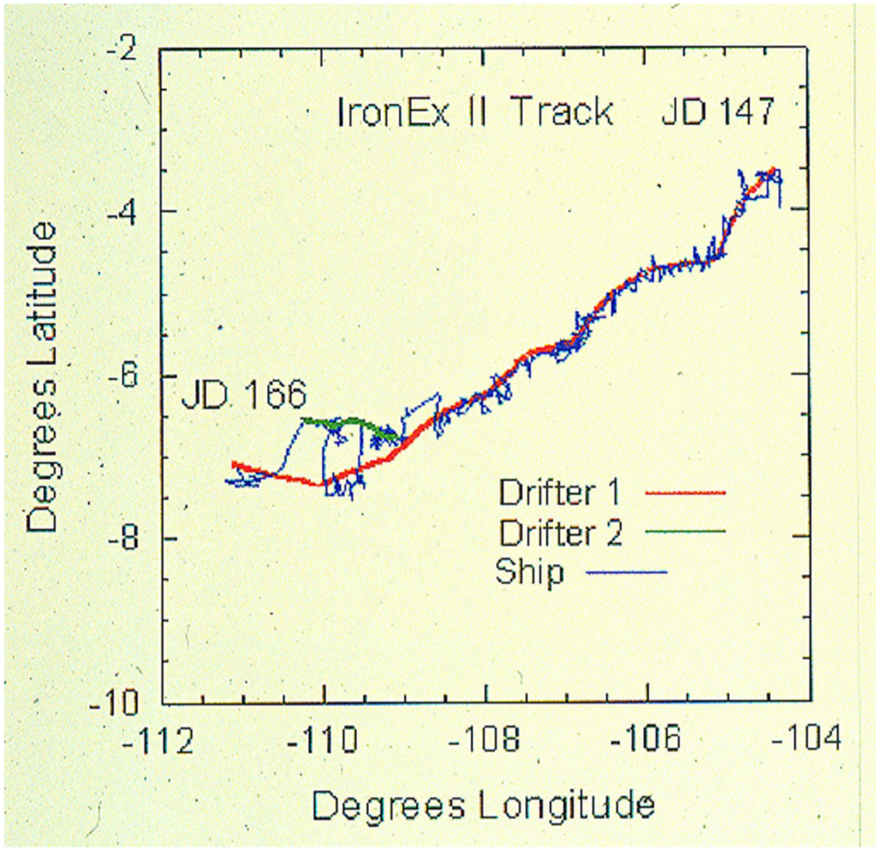
1. What are the Fe forms and rates of addition that maximize *Fe-use efficiency* (C fixed/Fe added)?
2. What are the optimal mechanisms of export (biol. gravit. pump, MLP, subduction, etc.)
3. What is the depth distribution of C remineralization (the sequestration time scale)?
4. What are the resulting biogeochemical effects:
   a) chemical effects (e.g., subsurface oxygen depletion, ocean acidification, etc.)?
   b) Production of other greenhouse gases?
   c) ecosystem effects — at surface and at depth?

The Unknown Unknowns: ????

One Idea; Go back to where it all started—The Eastern Equatorial Pacific

Rationale:

1. Generally low potential for storms
2. Conditions are relatively constant annually (other than El Nino and La Nina years)
3. Warm temperatures, so a rapid plankton response
4. Relatively cohesive surface flows
5. Relatively good access for remote sensing

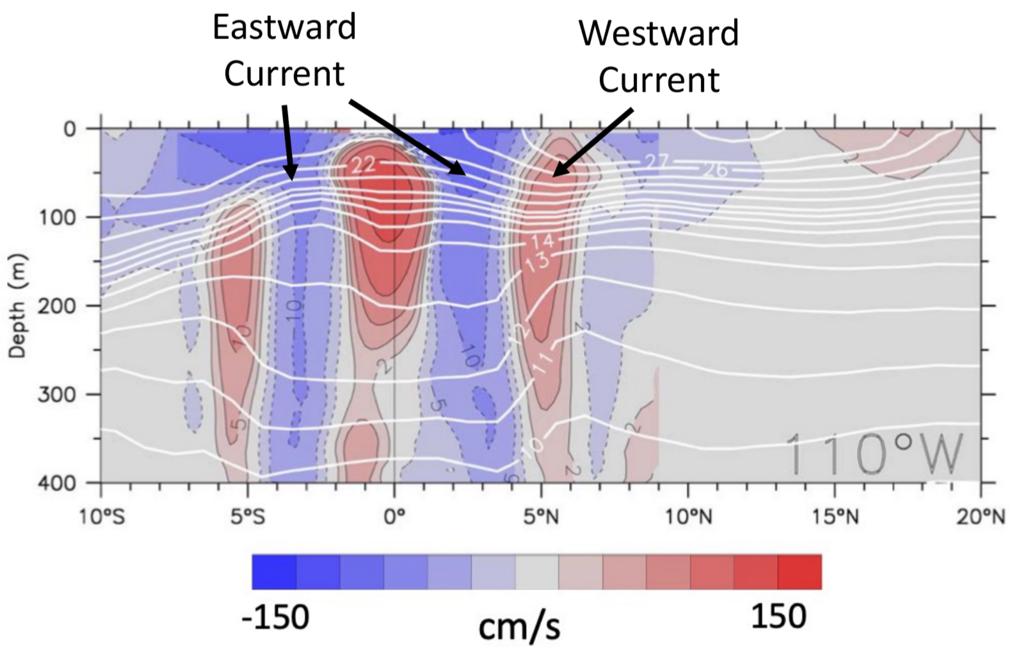


~1200 km in 18 days

Straw Plan Experimental Design

Draft design:

1. Mimic the island effect: Use a line of *moored barges* to introduce Fe continuously across the zone of equatorial upwelling.



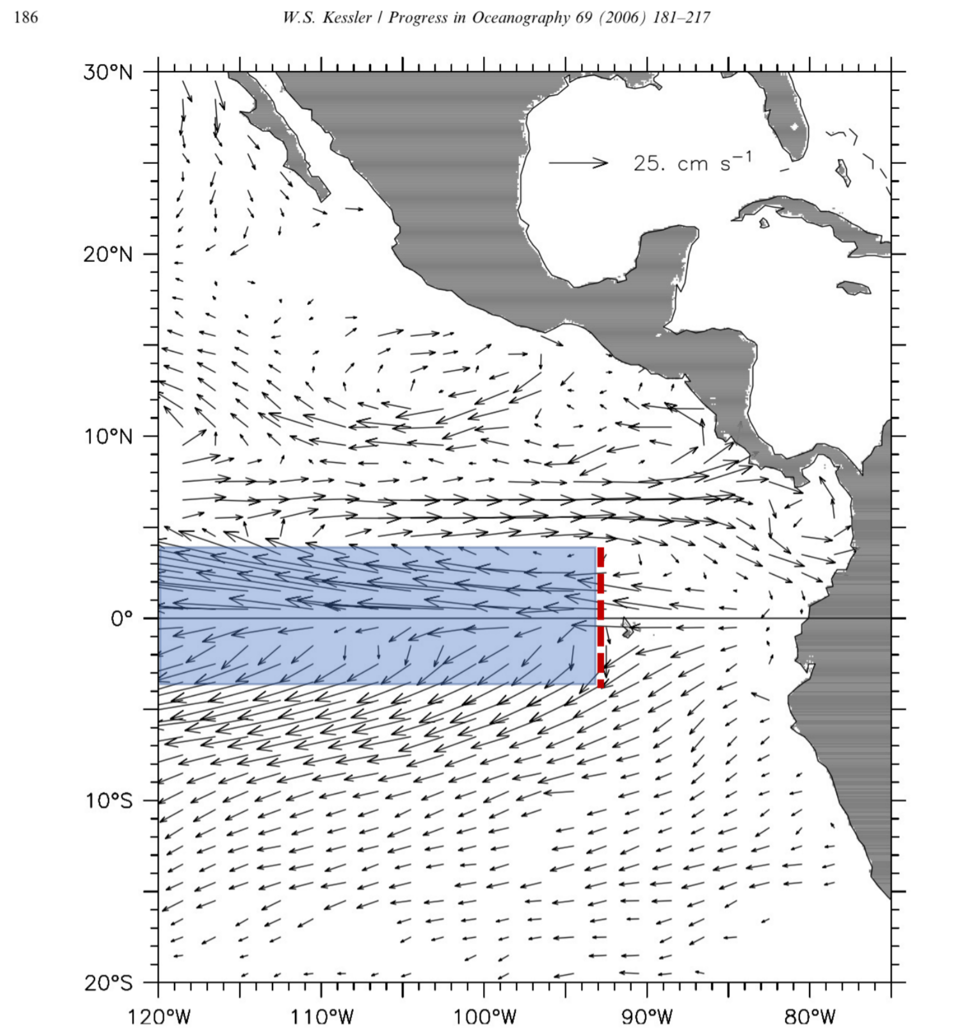
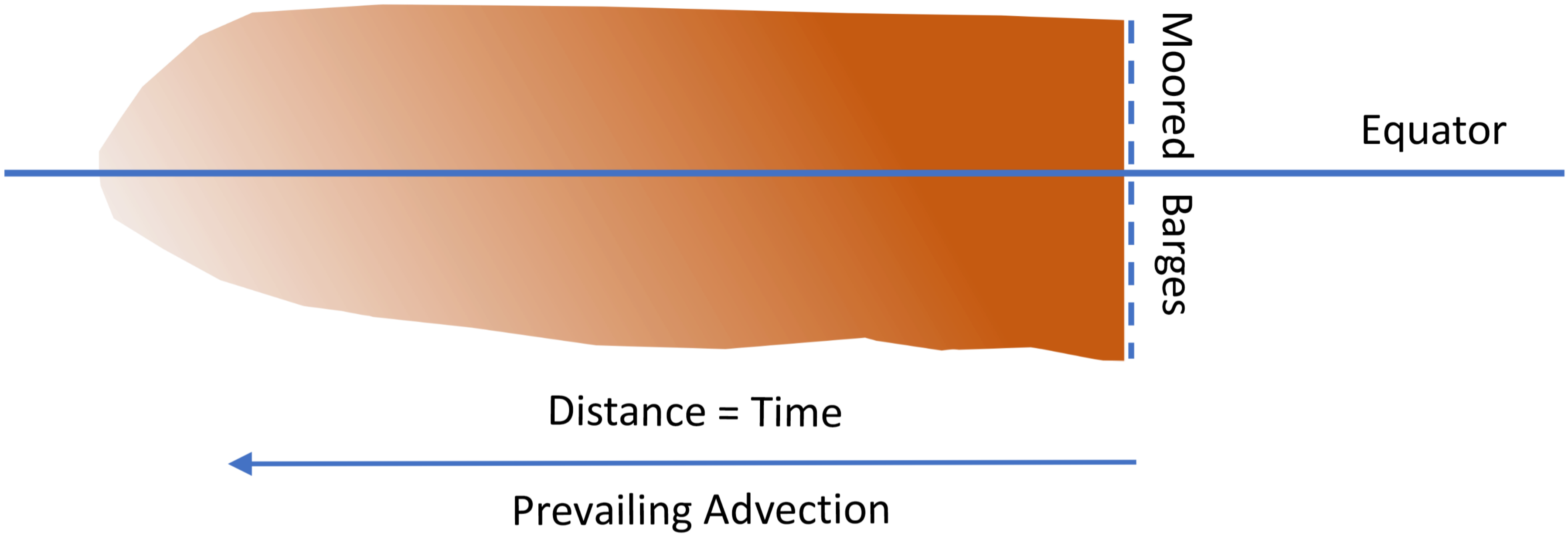


Fig. 4. Mean surface circulation from surface drifters. Vectors were left blank if either the total count of samples in that 1° × 1° box was less than 10, or if fewer than 4 months of the year were represented. The scale vector is located in the Gulf of Mexico.

Straw Plan Experimental Design



1. Use the surface current to distribute the Fe rather than ships
2. Logistically simplified, and would move the experiment towards carbon-neutrality

Straw Plan Experimental Design

Draft design:

1. Mimic the island effect: Use a line of *moored barges* to introduce Fe continuously across the zone of equatorial upwelling.

2. Sampling along the plume track would enable steady state, time-based sampling (surface and deep)—capture C export across all stages of the bloom

3. The effects of Fe introduction dynamics on Fe-use efficiencies could be studied by altering the pumping strategies.

4. Barges could contain multiple tanks to test different Fe forms (or mixtures), resupplied when needed

5. Cycling the pumps on and off would reset the system to the control conditions along the plume track, and enable easy replication of the experiment.

6. The plume could provide a predictable, large spatial patch distribution to better enable ancillary studies.

Role of **modeling** in assessing CDR by OIF

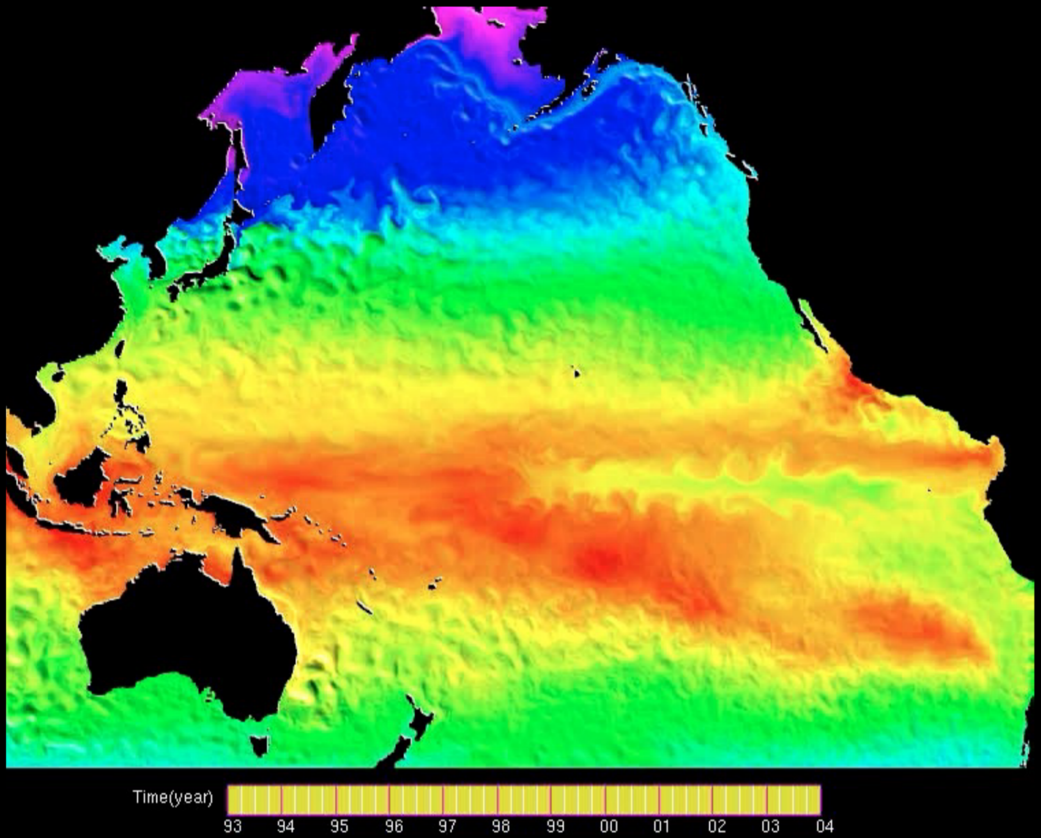
- Some issues for considering OIF using global low-resolution models
- Need to use regional high-resolution physical-biogeochemical models (including detailed iron components)
- Local and regional physical and biogeochemical conditions, timing and duration, and OIF experiment designs for the equatorial Pacific Ocean

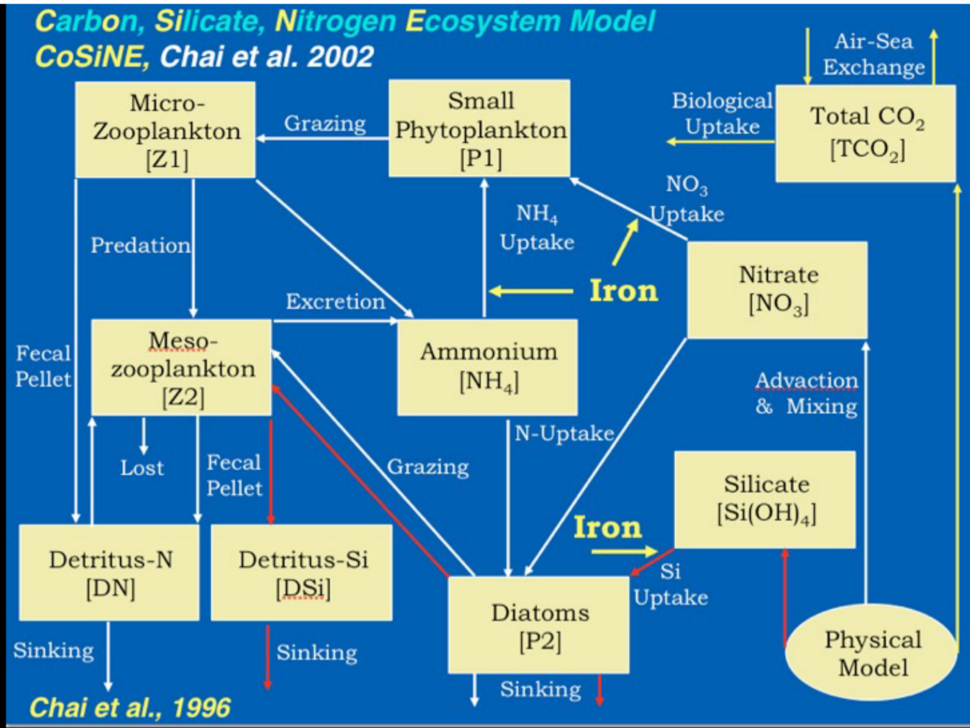
Location, size, timing, and duration

Some issues with previous global modeled OIF estimates

- Early version of global general circulation models (GCM) with coarse resolution (100-200 km)
- Inconsistency among different models and often poor performance
- Very different designs and approaches to conduct model OIF experiments
  - Upper ocean nutrient restoring for different regions and time scale
  - Increase phytoplankton growth rates to reflect iron effect
  - Adding iron to the upper ocean (~20-80m)
  - Different fertilization period and areas: one fertilization per year for the Southern Ocean, continue fertilization for the equatorial Pacific, for 10, 50, and 100 years.
- Responses of non-fertilized areas are very different among the models, mainly due to poorly constrained physics, nutrient and carbon transport processes

Regional Ocean Model System (ROMS) for Pacific Ocean 10-km, 1991 to 2021

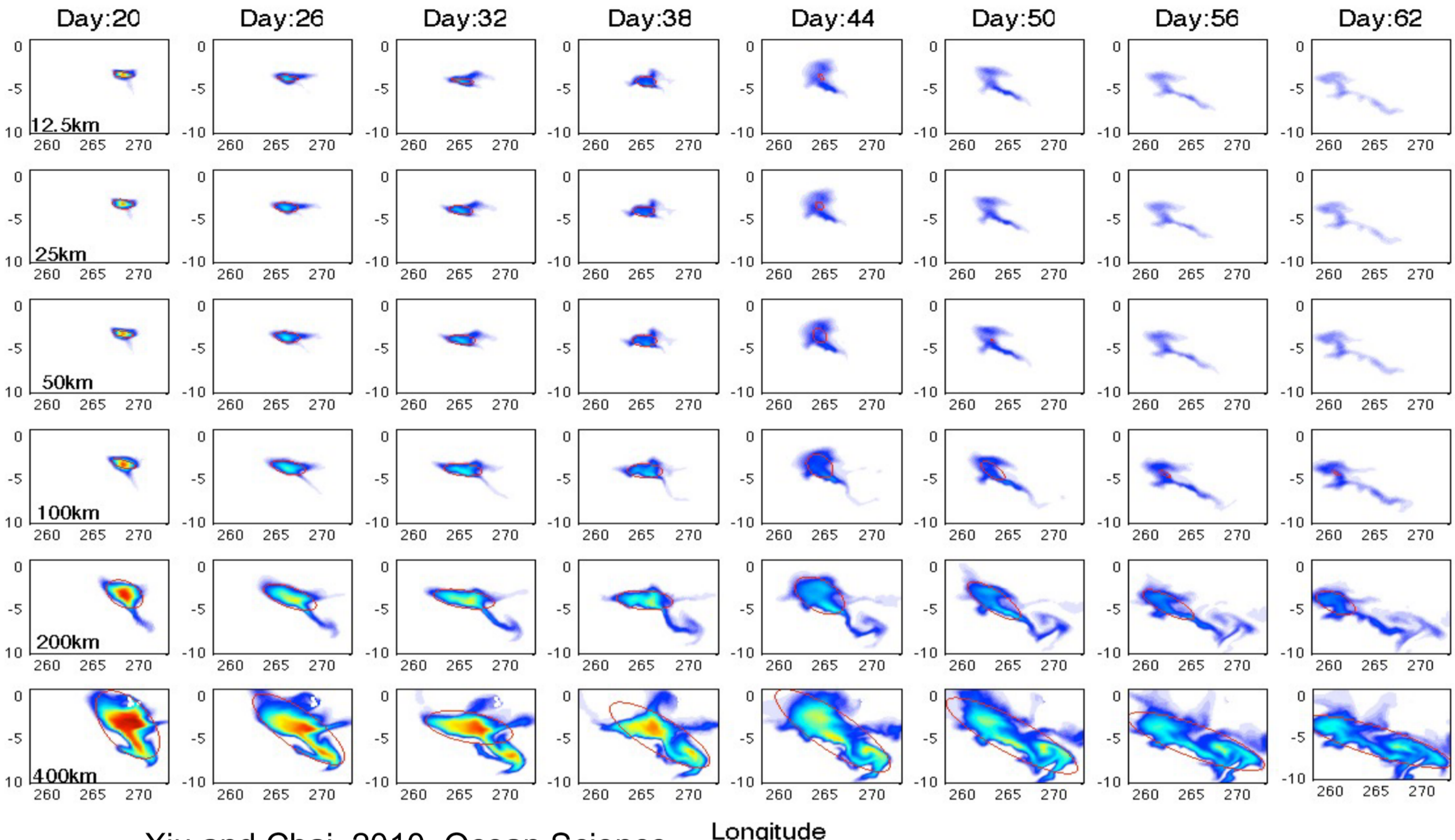




Carbon, Silicate, Nitrogen Ecosystem Model (CoSiNE)

(Chai et al., 2002, 2003, 2007, 2009; Fujii and Chai, 2007; Liu and Chai, 2009; Xiu and Chai, 2011, Palacz et al., 2011, Xu et al., 2013, Xiu and Chai, 2013, 2014, Guo et al., 2014; 2015; Zhou et al., 2017; Liu et al, 2018; Xiu and Chai et al., 2018, 2021; Zhou et al., 2018; 2020; Lin et al., 2020; Guo et al., 2020; Ma at al., 2021;)

Size of fertilization patch matters — Inert Tracer



Xiu and Chai, 2010, Ocean Science

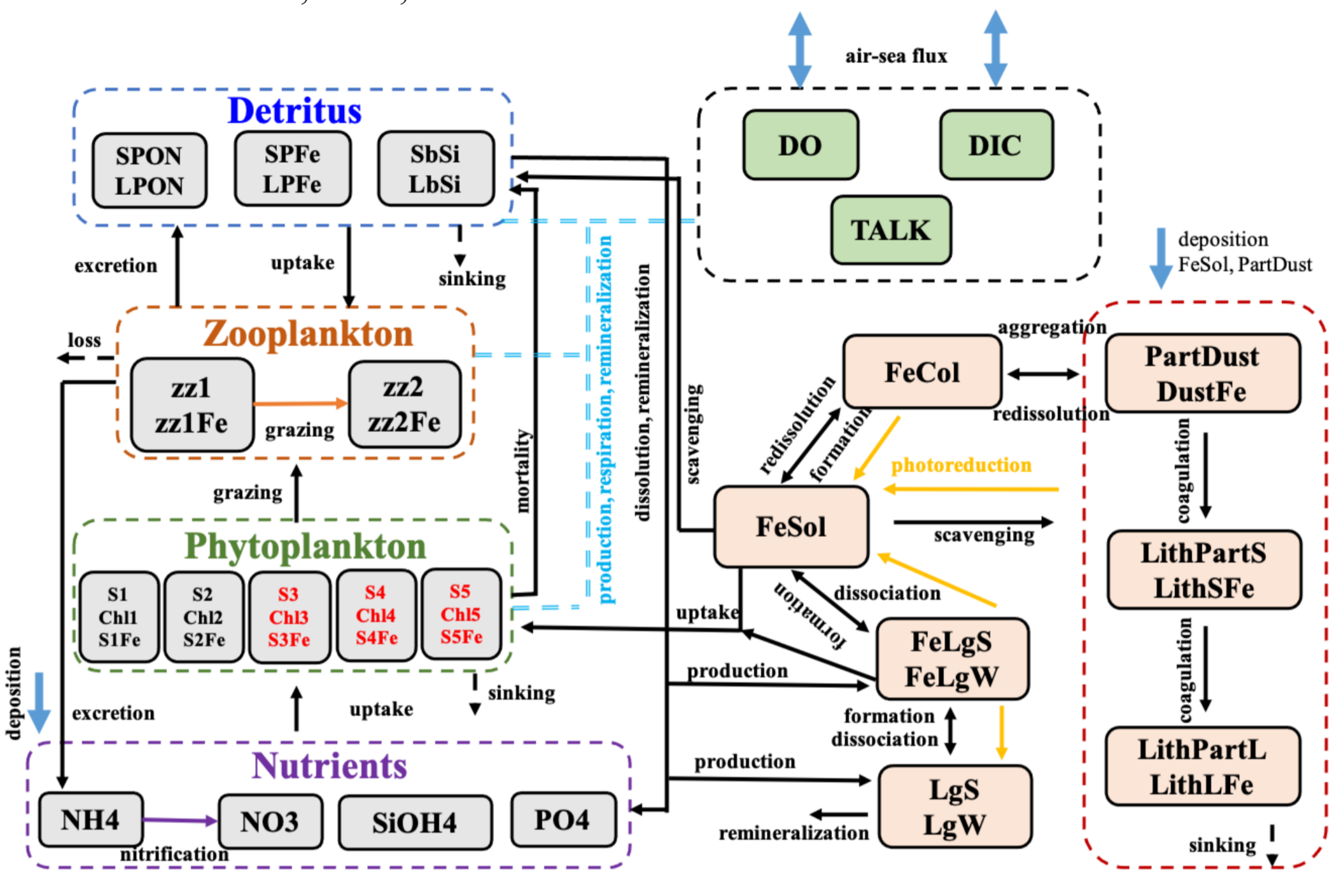
25km X 25km

100km X 100km

400km X 400km

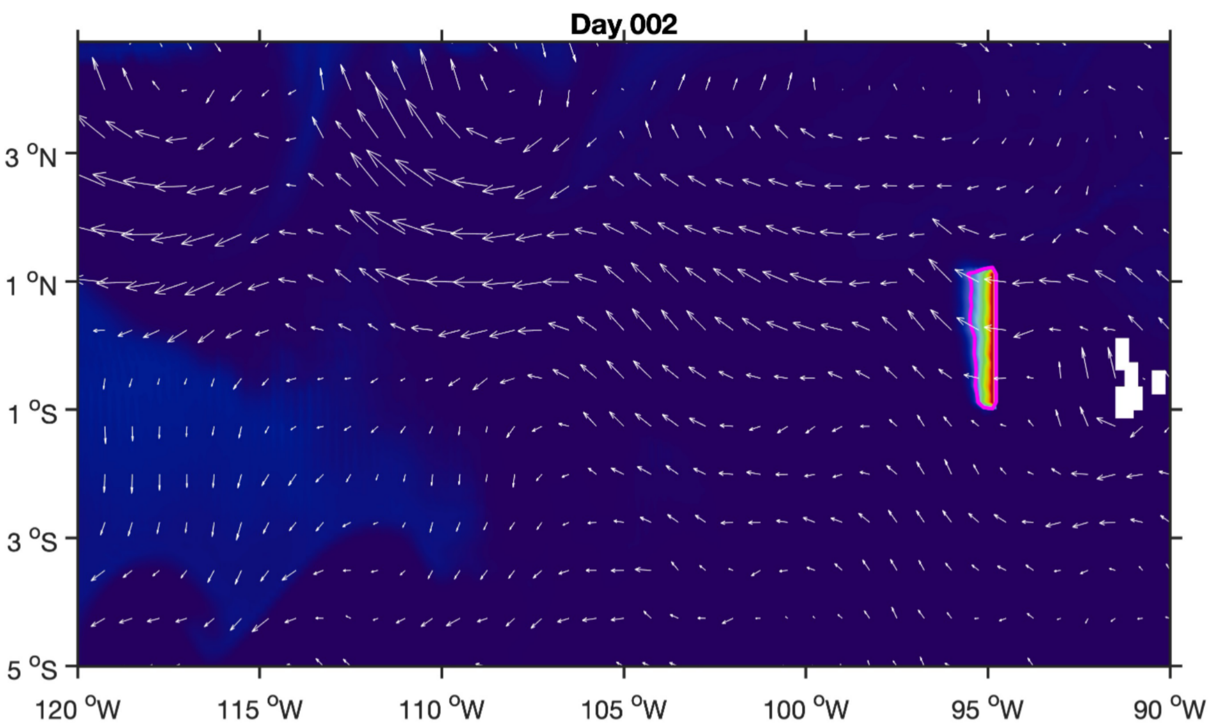
ROMS-CoSiNE-Fe Model

Xiu and Chai, 2021, *GRL*



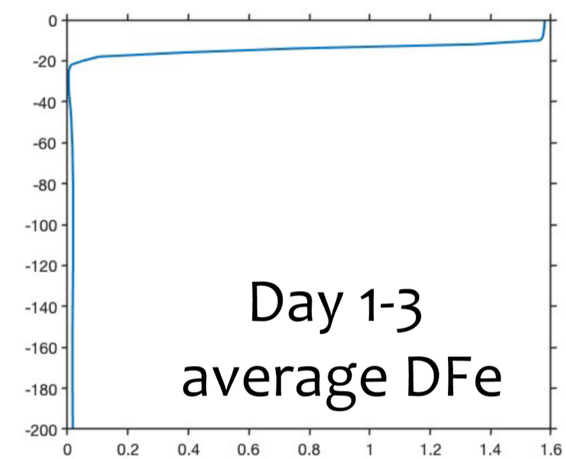
Model	BGC model	diatoms	N-fixers	iron	P-cycle
CANESM2	CMOC	×	×	×	×
CESM1BGC	BEC	✓	×	✓	✓
CMCC-CESM	PELAGOS	✓	×	✓	✓
CNRM-CM5	PISCES	✓	×	✓	×
GFDL_ESM2G	TOPAZ2	✓	✓	×	✓
GISS-E2-H-CC	NOBM	✓	✓	✓	×
HadGEM2-CC	Diat-HadOCC	×	×	×	×
MPI-ESM-LR	HAMOCC5.2	×	×	✓	✓
MRI-ESM1	NPZD	×	×	×	×
ROMS-NPZD	Fennel	×	✓	×	×
ROMS	NEMURO	✓	×	×	×
ROMS-CoSiNE	CoSiNE-Fe	✓	✓	✓	✓

Adding iron in the eastern equatorial Pacific

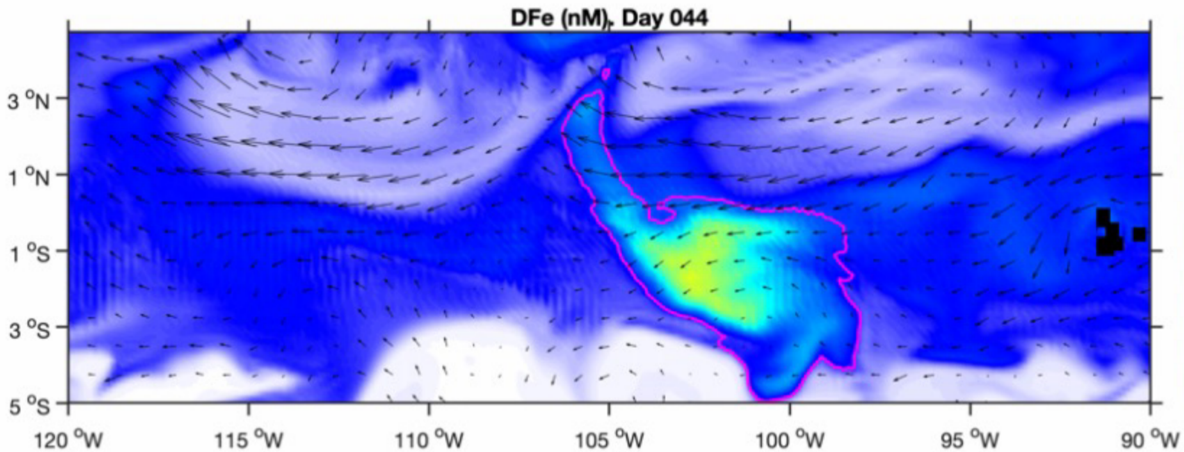


- At 95°W from 1°S to 1°N to mimic the barges
- Total 16 grid points, each grid is 1/8 degrees
- Keep adding DFe in the upper 10 m
- For 15 days from July 1 to July 15, 2016
- Three case runs:

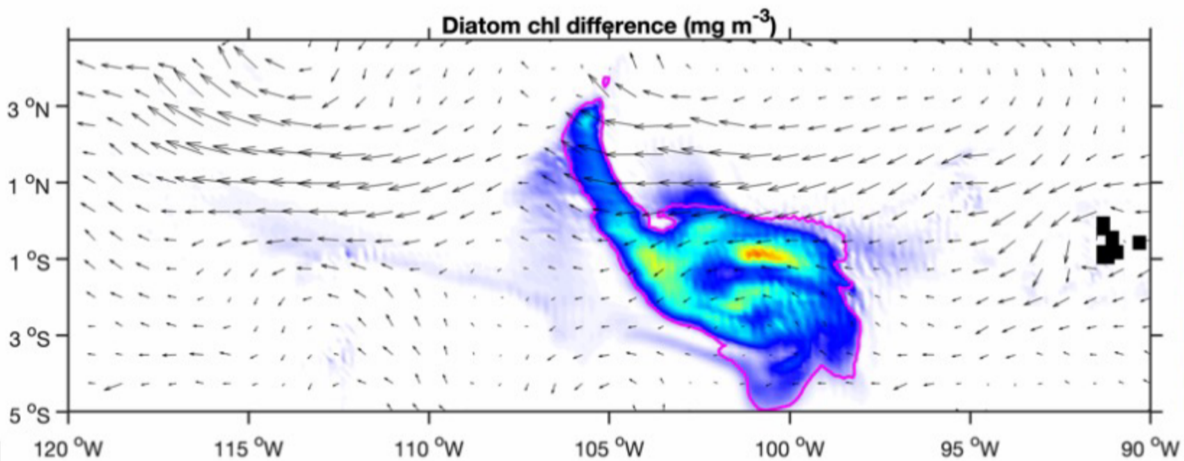
  Control; Case 1 (2 nM); Case 2 (0.5 nM)
- Running the model for three months



Difference between Case-1 and Control run at day 44

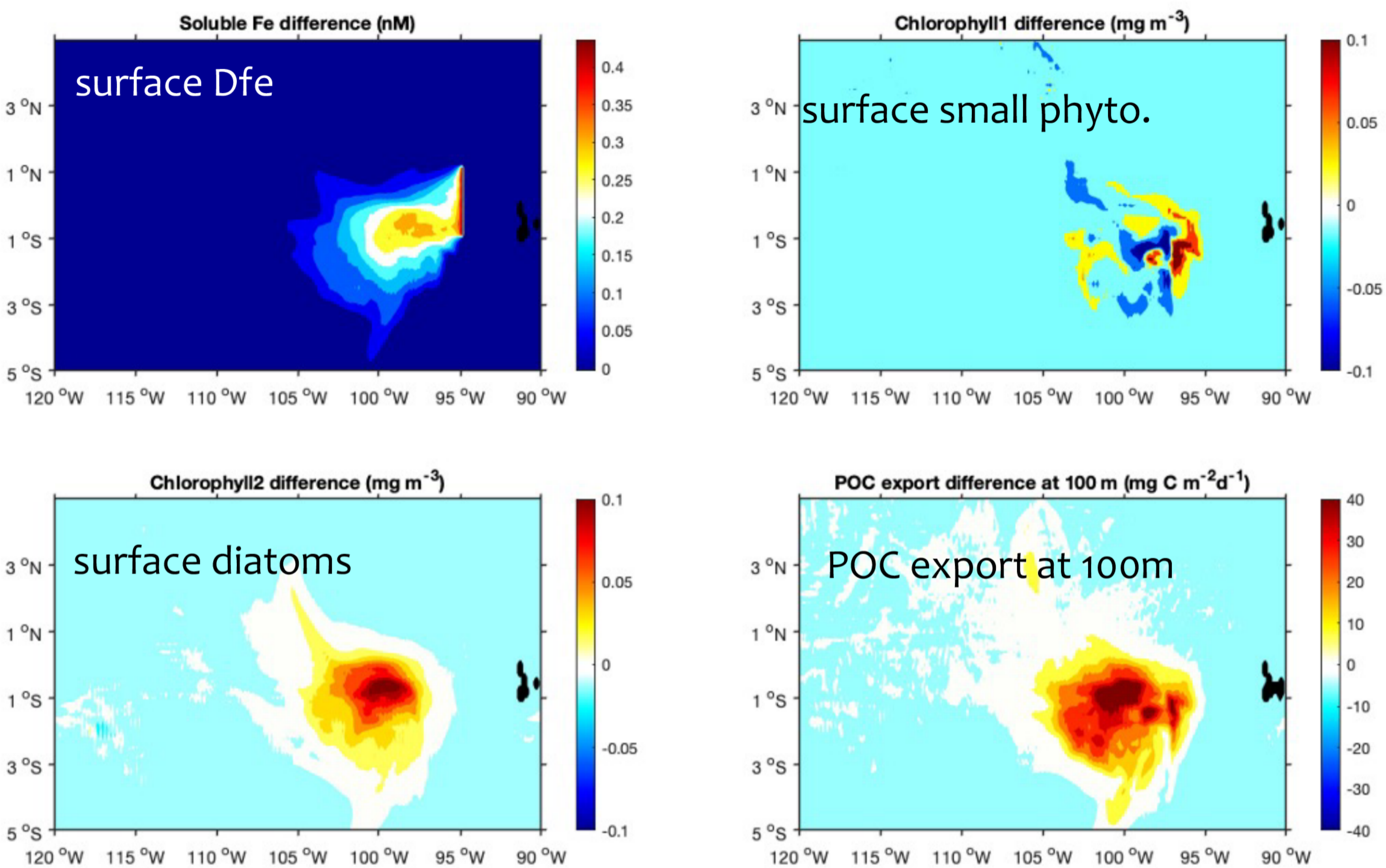


Difference of surface Dfe
(magenta contour is 0.05nM)



Difference of surface diatoms
(magenta contour is 0.05nM)

Difference between day 60 and day 1 for Case-1



Role of modeling in designing and assessing OIF

- Use high-resolution (~10km) physical-biogeochemical-iron model to design and evaluate OIF for the equatorial Pacific Ocean
- At 95°W from 1°S to 1°N released iron in the top 10m for 15 days (July 1-15) to mimic the barge operations, with two releases: 2 nm and 0.5 nm of Dfe
- The equatorial currents transport the released iron westward along the equator, the dissipation rate of iron is relatively low, and difference between these two releases (2 vs. 0.5 nm) is small
- Along the iron patch, the model stimulates both diatom and small phytoplankton growth, and enhances carbon export at 100m
- More detailed analyses are needed in order to refine OIF designs and placement of different observing assets.

Location, size, timing, and duration, high-resolution models