Basin-scale multi-year OIF deployments require a different planning approach – a plea for reverse-engineering

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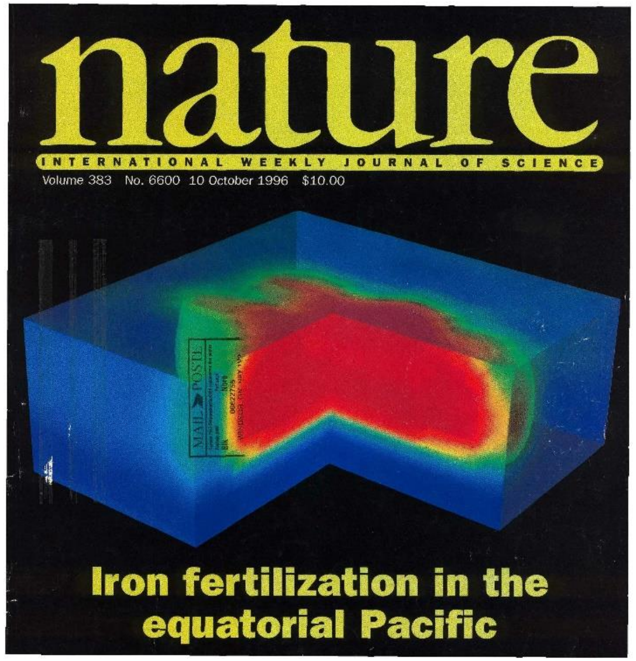
ExOIS July Meeting - Southern Ocean Experiments - 18 July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Iron fertilization in the
equatorial Pacific

Designing the next generation of ocean iron fertilization experiments

Andrew J. Watson[1,*], Philip W. Boyd[2], Suzanne M. Turner[1], Timothy D. Jickells[1], Peter S. Liss[1]

doi: 10.3354/meps07552

Developing a test-bed for robust research governance of geoengineering: the contribution of ocean iron biogeochemistry

Philip W. Boyd[1,2] and Matthieu Bressac[1]

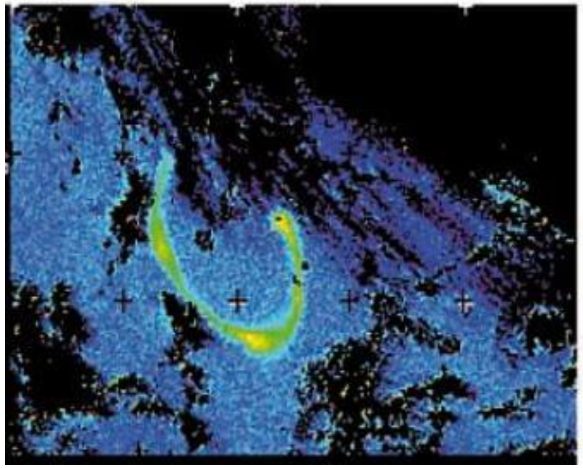
http://dx.doi.org/10.1098/rsta.2015.0299

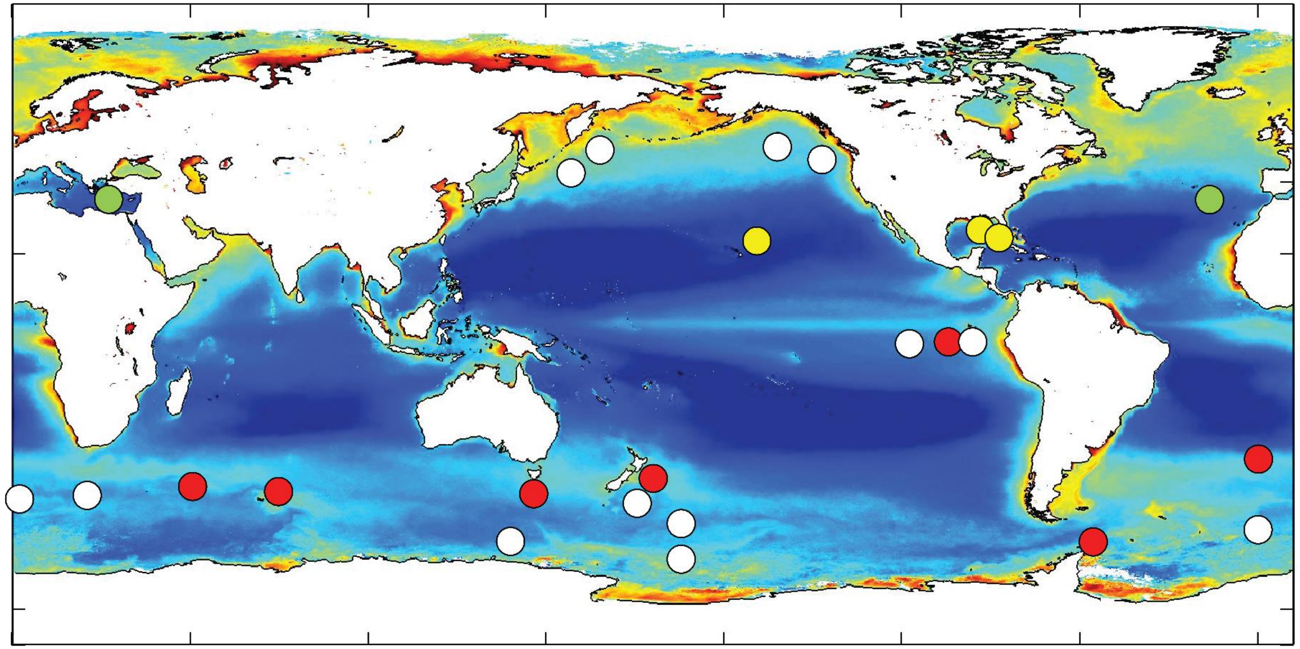
correspondence

NATURE CLIMATE CHANGE | VOL 9 | MAY 2019 | 342 | www.nature.com/natureclimatechange

Foresight must guide geoengineering research and development

Andrew Lenton[1,2*],
Philip W. Boyd[2,3], Marcus Thatcher[4] and
Kathryn M. Emmerson[4]





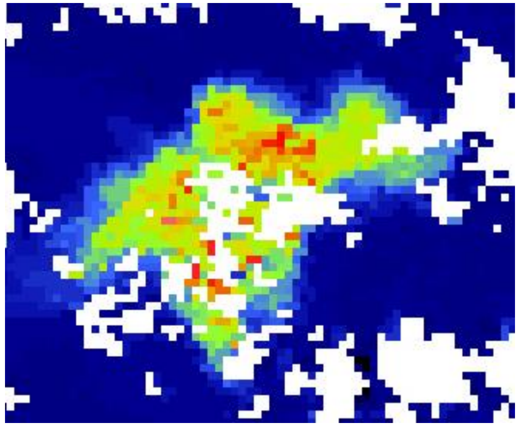
Deliberate iron fertilisation experiments

Deliberate phosphorous

Natural iron fertilisation studies

Oceanic geoengineering trials or pilot studies (including iron fertilisation & nutrient upwelling using ocean pipes)

Boyd & Bressac (2016)



Fundamental Knowledge gaps

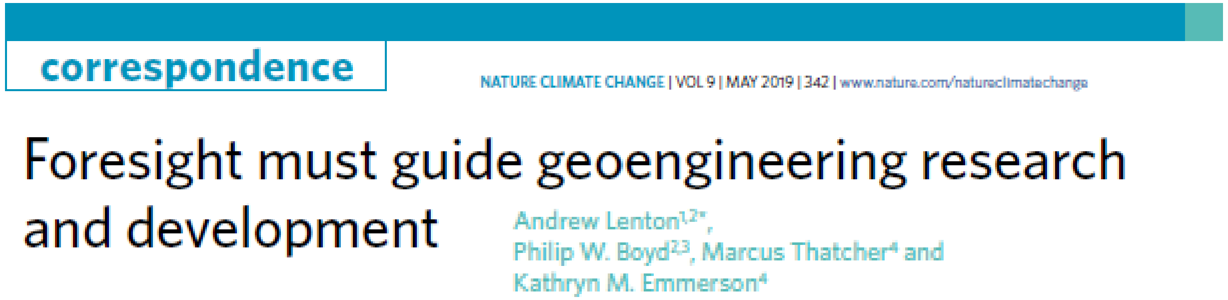
Table 1. Major uncertainties in the effects of deliberate ocean iron fertilization

Process	Issue	Finding	Comments
Carbon sequestration efficiency	Carbon fixation in surface water	Variable[a]	Latitude, mixed layer depths + light co-limitation
	Carbon export	None/little/significant[b]	Limited duration of studies
	Depth of carbon export	Poorly constrained	
	Duration of carbon sequestration	Unknown	Unanswerable by observations alone
	Fraction fixed from atmosphere	Poorly known	Likely unanswerable by observations alone
Influence on dissolved oxygen	Formation of subsurface O_2 minima	Poorly known[c]	Potentially harmful, depth dependent
Production of other climate-active gases	Methane & nitrous oxide	No effect/possible enhancement[d,e,f]	Significant warming potential
	Dimethylsulphide	No change/ increase[b]	Some evidence that enhancement is transient
	Biogenic halocarbons	Reduction/no change/ increase[g]	Pertinent to atmospheric oxidation chemistry & particle formation
	Biogenic hydrocarbons, including alkyl nitrates	No change/increase[e,g]	Pertinent to atmospheric oxidation chemistry & particle formation
Effects on ecosystems and biogeochemistry	Phytoplankton species shifts	Mainly towards diatoms[b]	Are shifts transient?
	Mesozooplankton stocks	No change/increase[b]	Localised increases within Fe patch due to arrested vertical migration: duration of study & longer reproductive cycles
	Higher trophic levels	Unknown	Limited duration of studies. Possibility of enhanced secondary and higher-level production[j]
	Macronutrient uptake	Small to significant[b]	Mixed layer depths + light co-limitation
	Reduction of nutrient transport	Important in upwelling regions[h]	Supply flows to other areas cut off, e.g. sub-tropical gyres
	Nutrient remineralization	May affect global distributions	At present only evident from modelling studies[i]

[a]de Baar et al. (2005); [b]Boyd et al. (2007); [c]Natural O_2 minima: e.g. Arabian Sea & east subtropical Pacific, anthropogenic minima: e.g. Gulf of Mexico eutrophication; [d]Law & Ling (2001); [e]Wingenter et al. (2004); [f]Walter et al. (2005); [g]Liss et al. (2005), [h]Cooper et al. (1996); [i]Gnanadesikan et al. (2003); [j]Tsuda et al. 2006

Watson et al. (2008) MEPS

Development of R&D to progress ocean-based CDR approaches to basin-scale deployment scales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Foresight must guide geoengineering research and development

Andrew Lenton[1,2*],
Philip W. Boyd[2,3], Marcus Thatcher[4] and
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"It is essential to first elucidate the longer-term goals and then identify the trajectory towards a full implementation."

"This trajectory must be formulated around the scientific and engineering questions relevant for any geoengineering technique at each stage of its development."

State-of-the-art → New Research Targets → Nested Pilot studies → Implementation & Deployment

Development of R&D to progress ocean-based CDR approaches to basin-scale deployment scales

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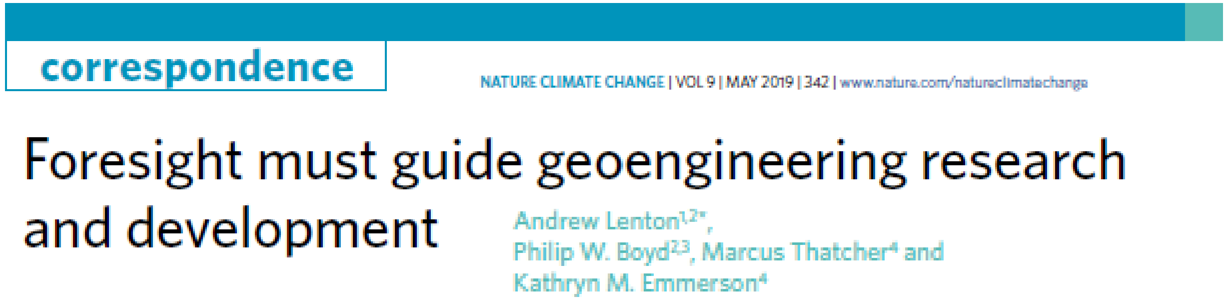
Reverse engineering

State-of-the-art	New Research Targets	Nested Pilot studies	Full Implementation & Deployment
Reveals Knowledge Gaps and challenges		Upscaling Suitable technologies Location(s)	Repeated deployments Where and at what scale Other actors Baseline for D&A

Issues to consider for the development of a R&D agenda to progress ocean-based CDR approaches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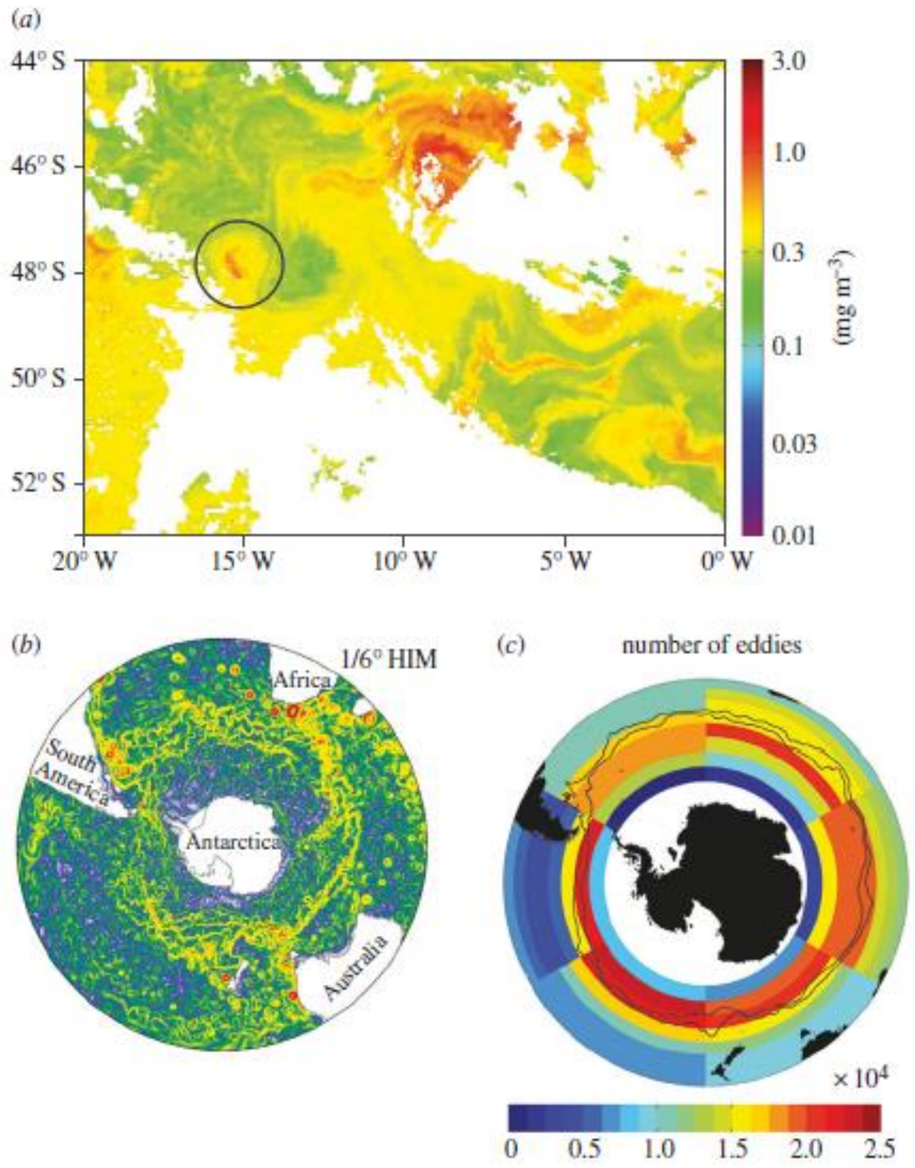
Full Implementation & Deployment

Repeated deployments
Of OIF over multiple years

Working backwards - Knowledge gaps

Proving “Additionality” *sensu* Kyoto Protocol



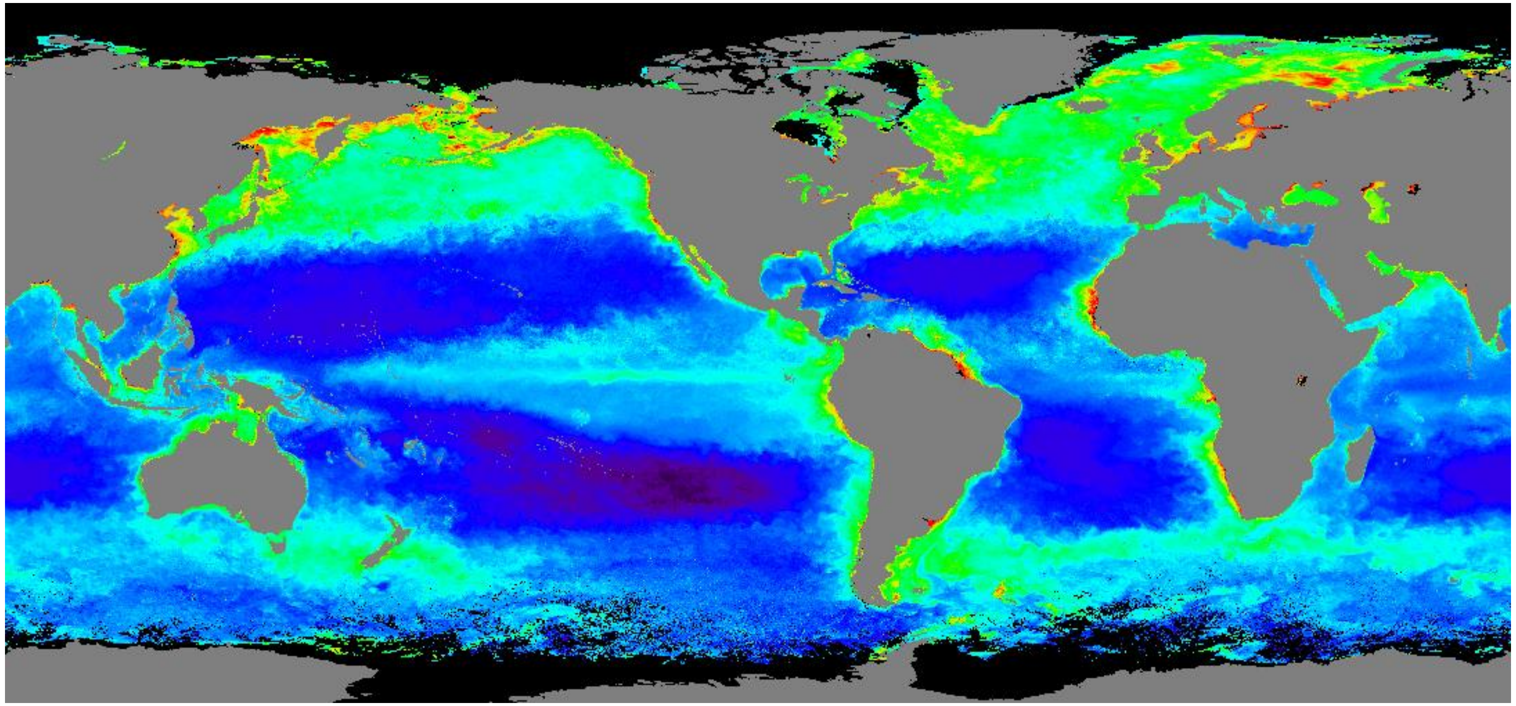
Boyd & Bressac
(2016)

Full Implementation & Deployment

Working backwards - Knowledge gaps

Where and at what scale?

Circulation
Depth of permanent pycnocline
Air/sea equilibration timescales
Resident Fauna
Degree of Anthropogenic change
Ocean temperature
Depth/bathymetry



NASA

Full Implementation & Deployment

Working backwards - Knowledge gaps

Other actors

Its unlikely that only one
Climate intervention will be deployed
In the ocean

There are also likely to be
Concurrent feedbacks, variability, altered emissions (hysteresis, see Aurich Jeltsch-Thön
Res. Lett. 15 124026)

That need to be dissected out

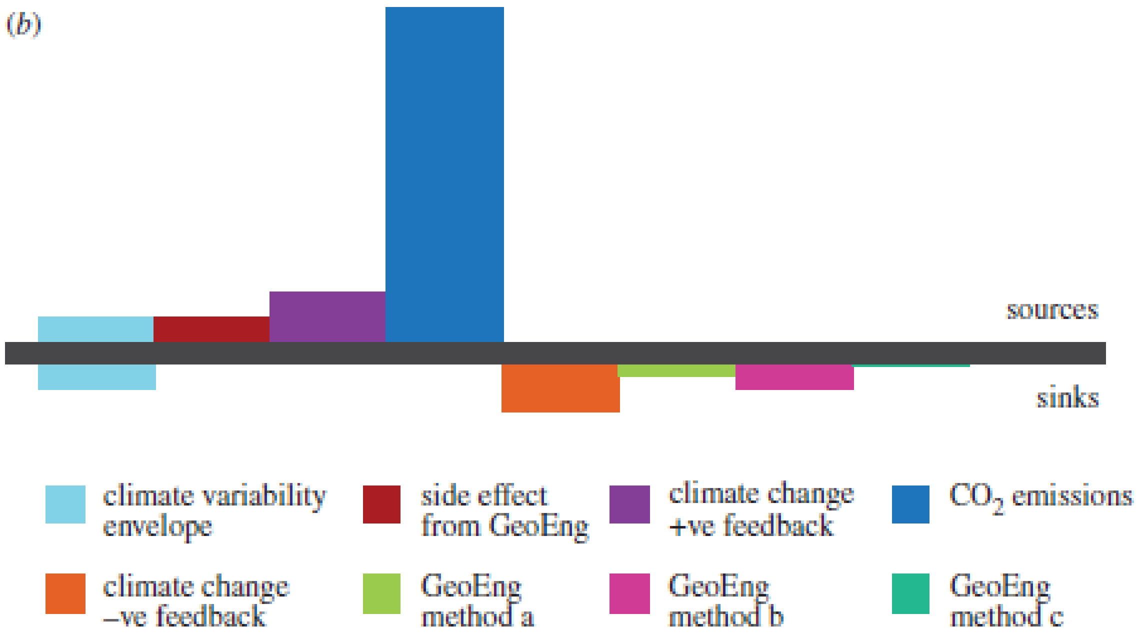


Figure 5. A major challenge for all ocean geoengineering approaches, including iron fertilization, is the detection and attribution of carbon sequestration, and any side-effects on the ocean system. Panel (*a*) illustrates this challenge using hypothetical changes in iron stocks and/or bioavailability that will likely be mediated by natural variability (such as El Nino

Boyd & Bressac (2016)

The reinvigoration of the Southern Ocean carbon sink

Peter Landschützer,[1*] Nicolas Gruber,[1,2] F. Alexander Haumann,[1,2]
Christian Rödenbeck,[3] Dorothee C. E. Bakker,[4] Steven van Heuven,[5†] Mario Hoppema,[5]
Nicolas Metzl,[6] Colm Sweeney,[7,8] Taro Takahashi,[9]
Bronte Tilbrook,[10] Rik Wanninkhof[11]

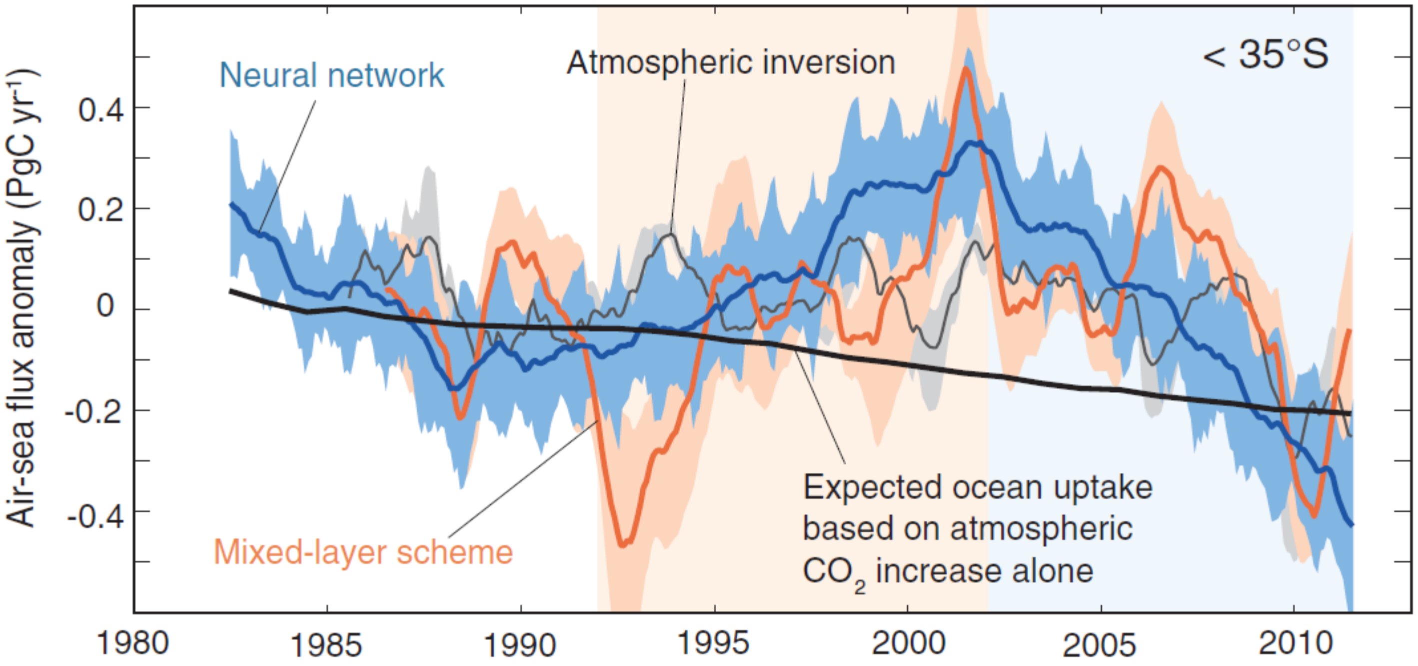


Fig. 1. Evolution of the Southern Ocean carbon sink anomaly south of 35°S. The lines show the integrated air-sea CO_2 flux derived from two complementary surface ocean pCO_2 interpolation methods [a two-step neural network technique (*15*) and a mixed-layer scheme (*17*)] as well as the integrated flux from an atmospheric inversion based on measurements of atmospheric CO_2 (*14*). These estimates are compared with the expected uptake based on the growth of atmospheric CO_2 alone, based on a simulation with the ocean component of the Community Climate System Model (CCSM3) (*18*). All data are plotted as anomalies by subtracting the 1980s mean flux from each method. Negative values indicate anomalous uptake by the ocean.

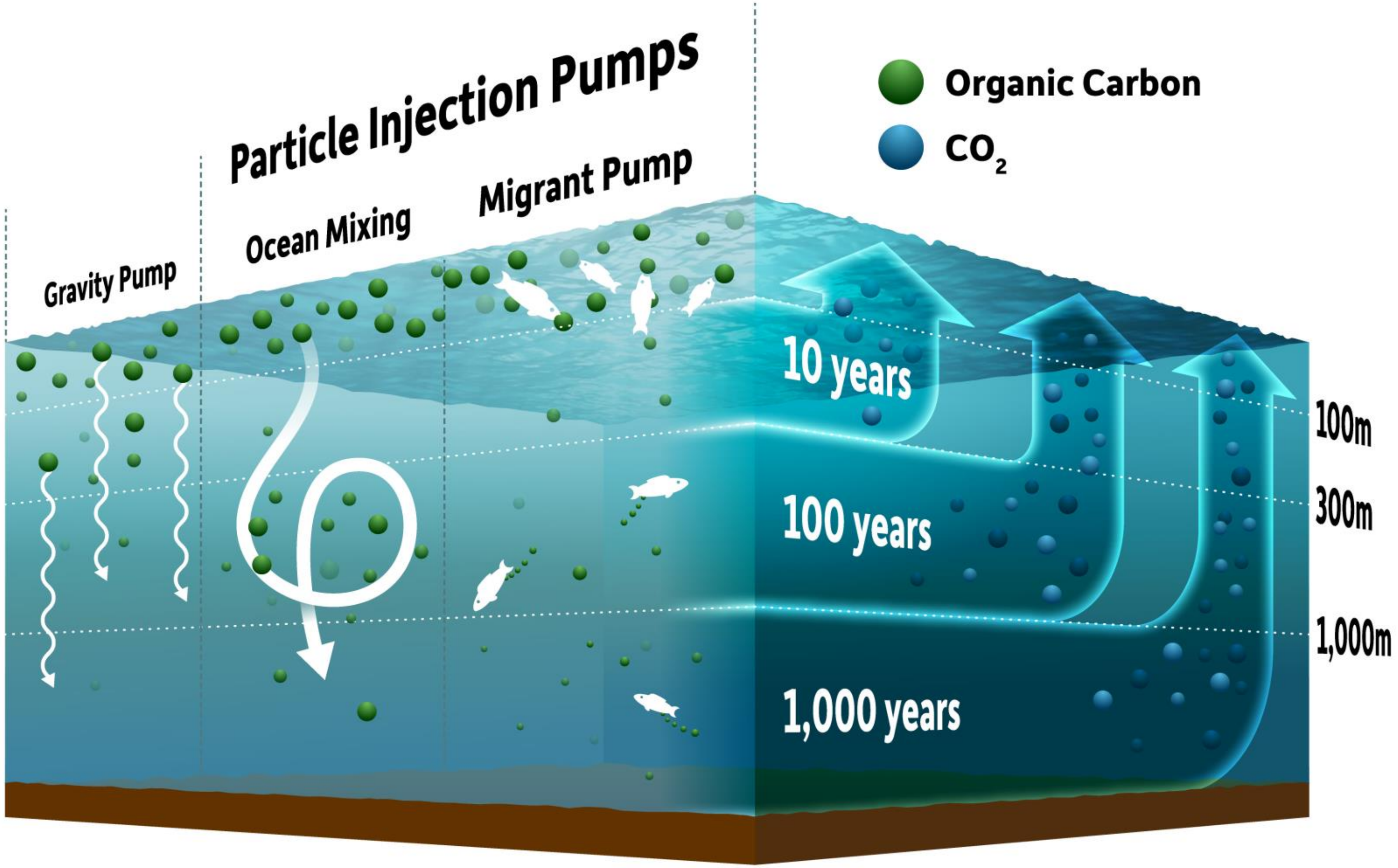
Full Implementation & Deployment

Working backwards - Knowledge gaps

We still do not have a baseline for C sequestration in the modern ocean!!

Baseline for D&A
Conspicuous imbalances between POC downward export and export fluxes derived from geochemical tracers

Multi-faceted ways to
Sequester C in the modern ocean



Multi-faceted particle pumps drive carbon sequestration in the ocean

Philip W. Boyd[1*], Hervé Claustre[2,6], Marina Levy[3,6], David A. Siegel[4,6] & Thomas Weber[5,6]

Boyd et al. (2019)

Figure courtesy of Tom Weber

Nested Pilot studies

Working backwards - Knowledge gaps

Upscaling – what about a 10000 km^2 OIF patch for next gen pilot studies?

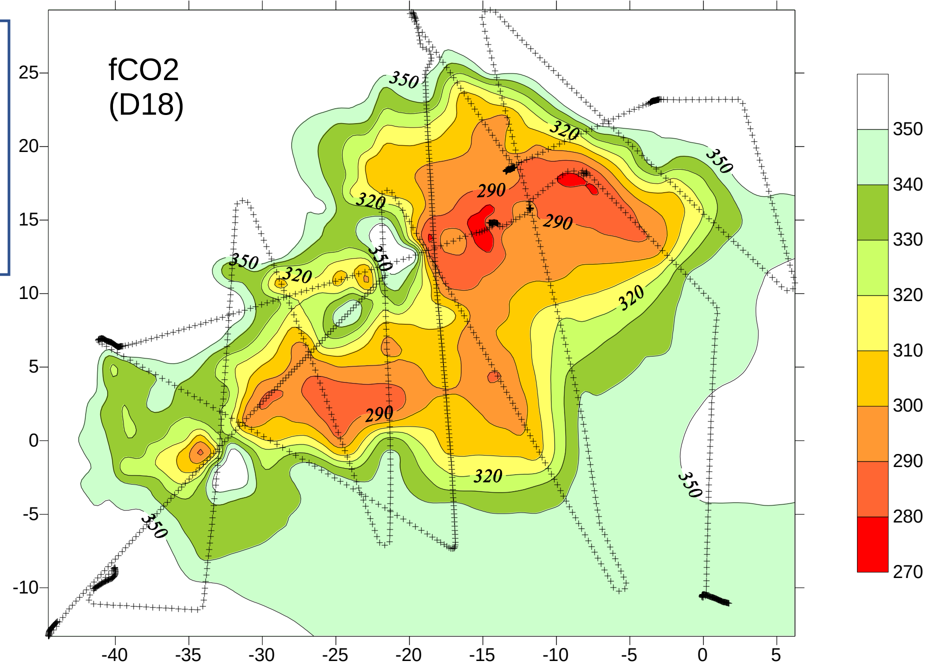
Designing the next generation of ocean iron fertilization experiments

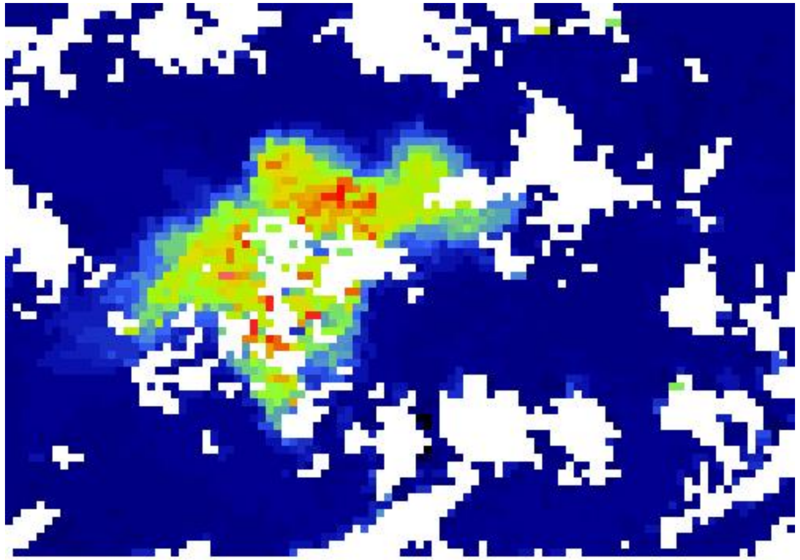
Andrew J. Watson[1,*], Philip W. Boyd[2], Suzanne M. Turner[1], Timothy D. Jickells[1], Peter S. Liss[1]

MEPS 2008

“Our present understanding suggests that any carbon sequestration will occur as the net result of changes in the air–sea flux integrated over millions km$_2$ and many years, and can only realistically be assessed by modelling.”

Nested Pilot studies

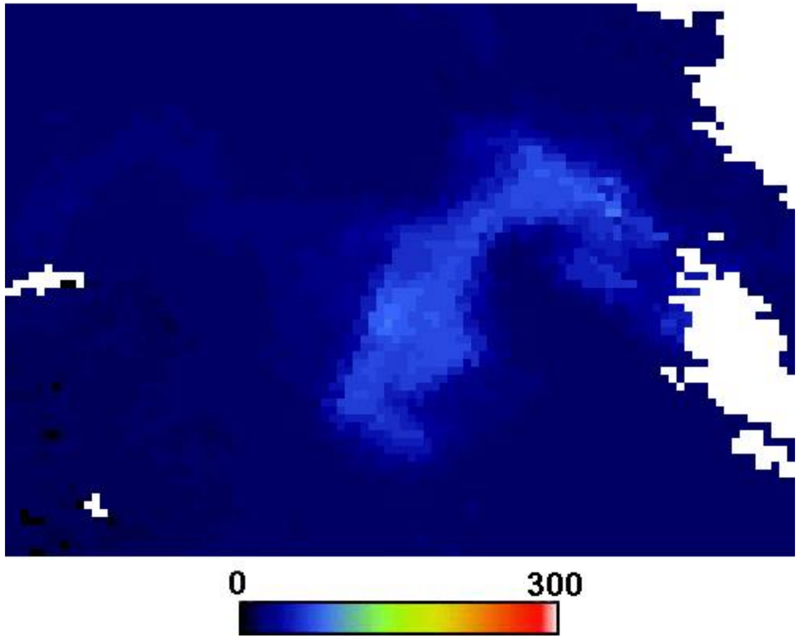




SERIES experiment (NE subarctic Pacific)

Concurrent ship survey maps of CO_2 drawdown by the Blooming phytoplankton, which match the shape of the bloom as observed from SeaWiFS satellite images

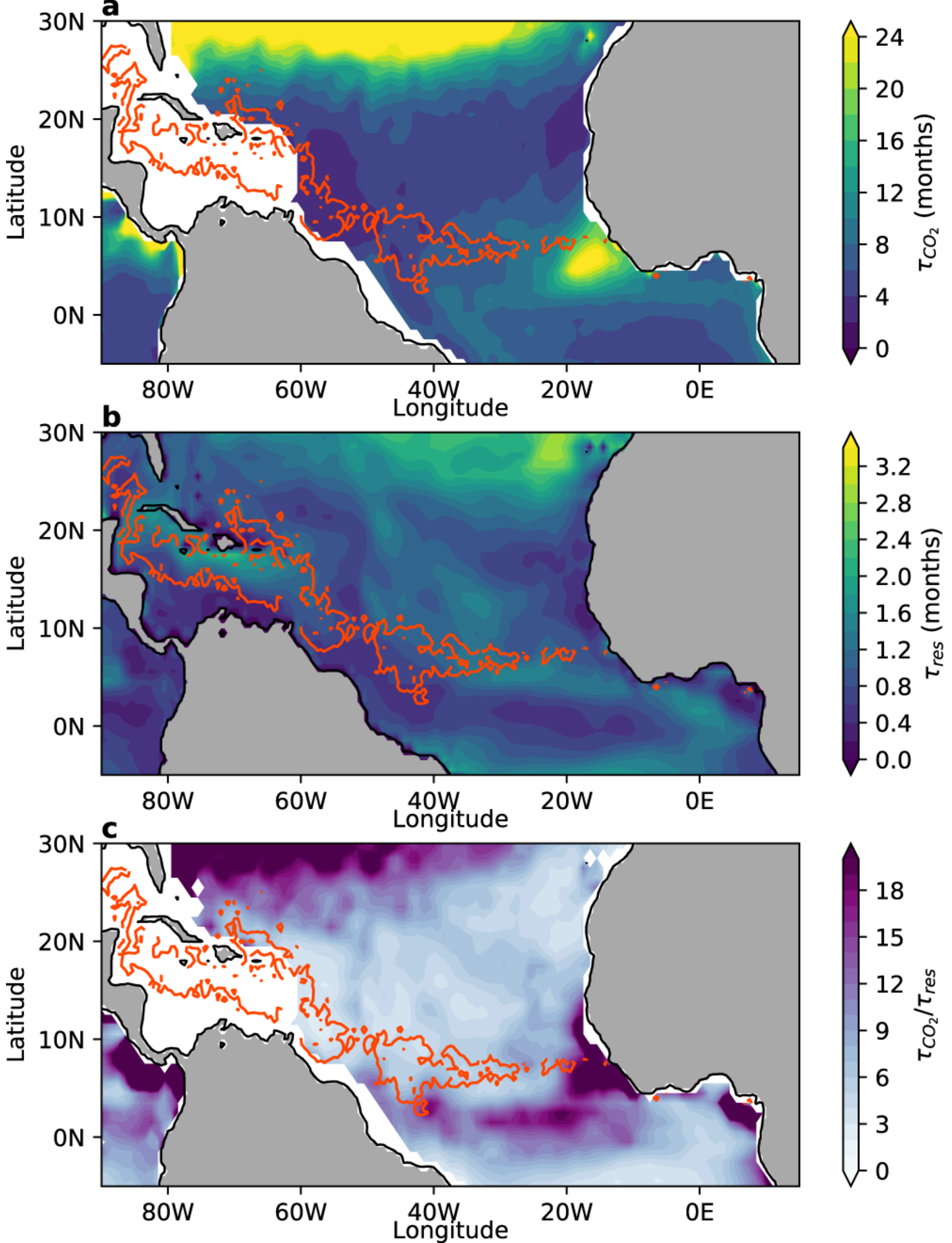
No ships were present for re-equilibration of the upper ocean
The often neglected key step in C sequestration



Algal carbon (mg)

Boyd et al. (2004) Nature

Modelling Timescales of CO_2 equilibration in the Great Atlantic Sargassum Belt



Annual mean timescales of CO_2 equilibration between the ocean and atmosphere.

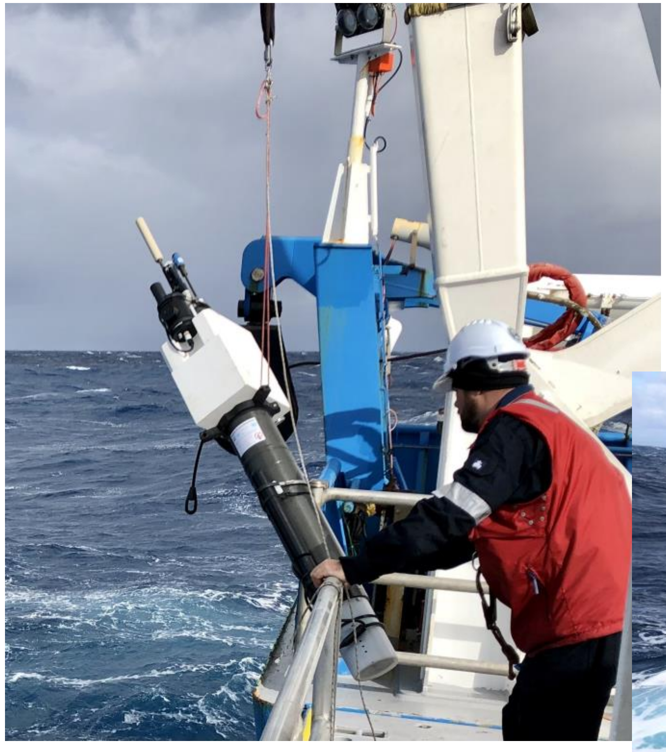
Residence time of seawater in the surface mixed layer

From:
Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt (2021).
Bach, L.T., V. Tamsitt, J. Gower, C.L. Hurd, J.A. Raven & P. W. Boyd.
Nature Communications,12, 2556.

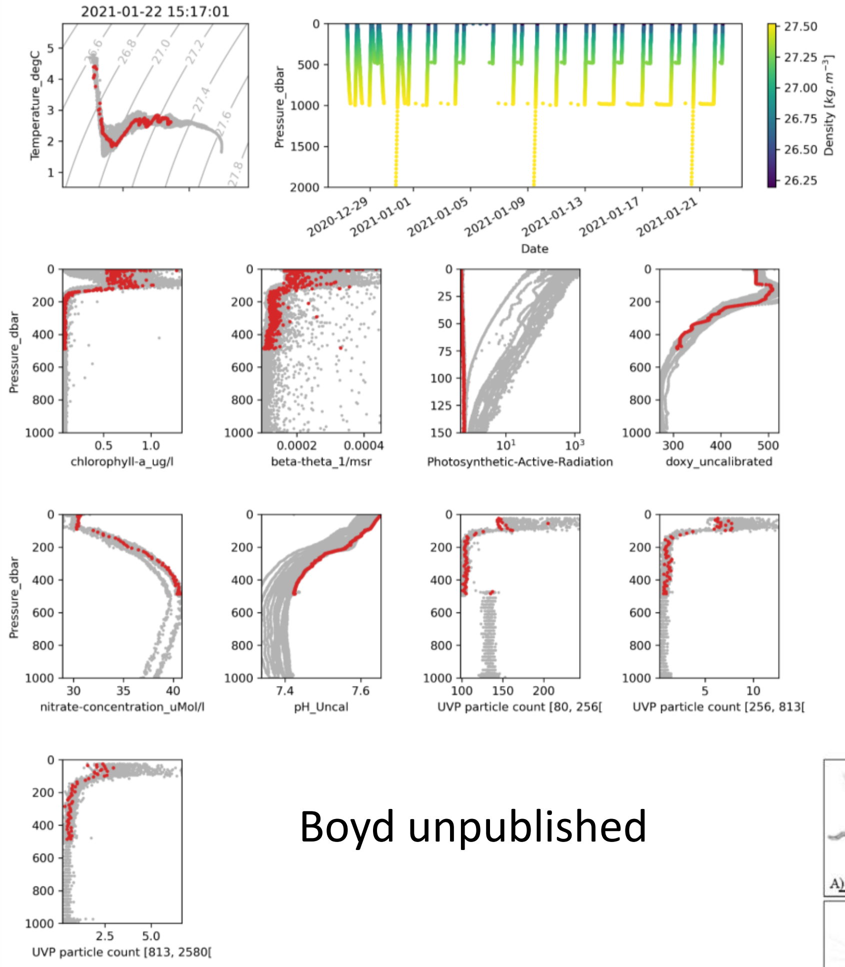
Nested Pilot studies

Working backwards - Knowledge gaps

Suitable technologies for BGC and Ecology

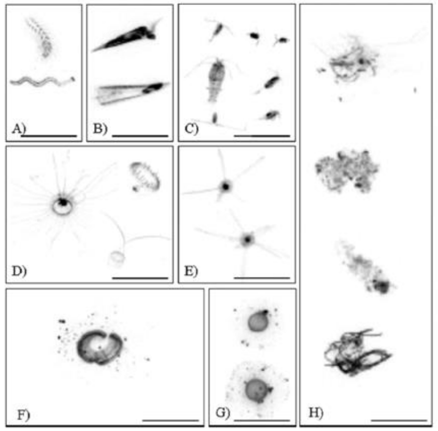


New BGC-ARGO floats
With UVP6 deployed
Jan 2021
In S. Ocean



Boyd unpublished

Claustre unpublished



Constraining Southern Ocean CO_2 Flux Uncertai
Using Uncrewed Surface Vehicle Observations

A. J. Sutton[1], N. L. Williams[2], and B. Tilbrook[3,4]

10.1029/2020GL0

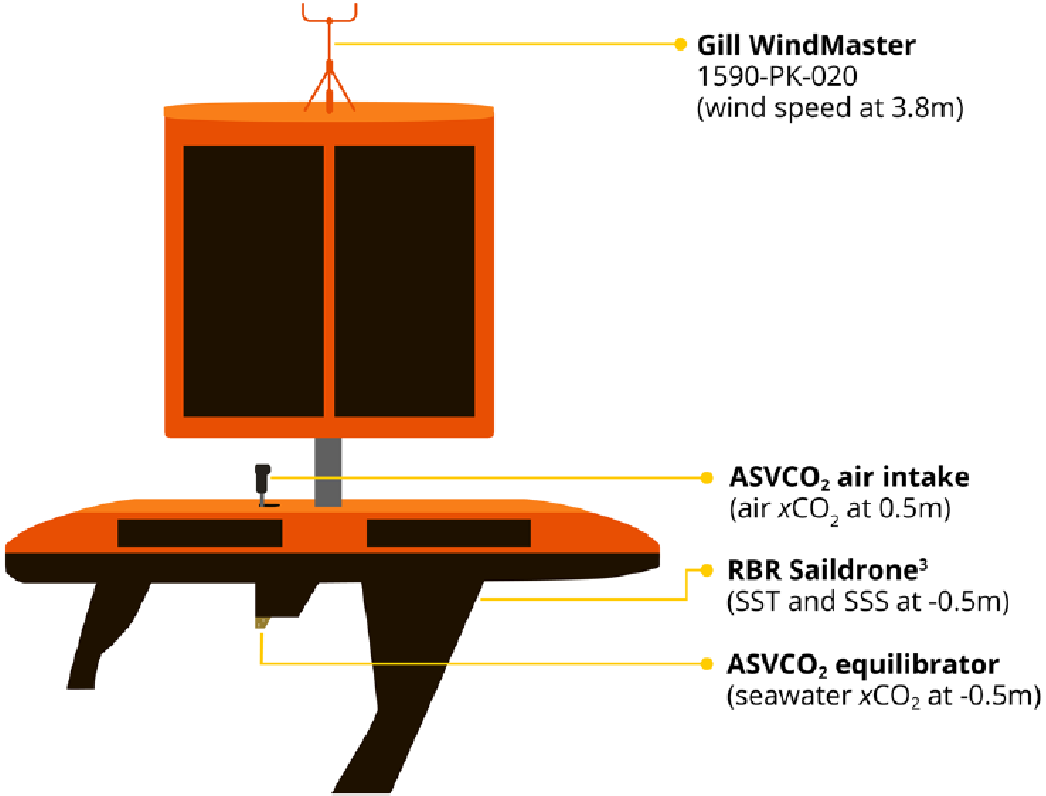


Figure 1. Schematic diagram of the 2019 Southern Ocean Saildrone Uncrewed Surface Vehicle (USV) and location of the sensors used in this study. Schematic is not to scale.

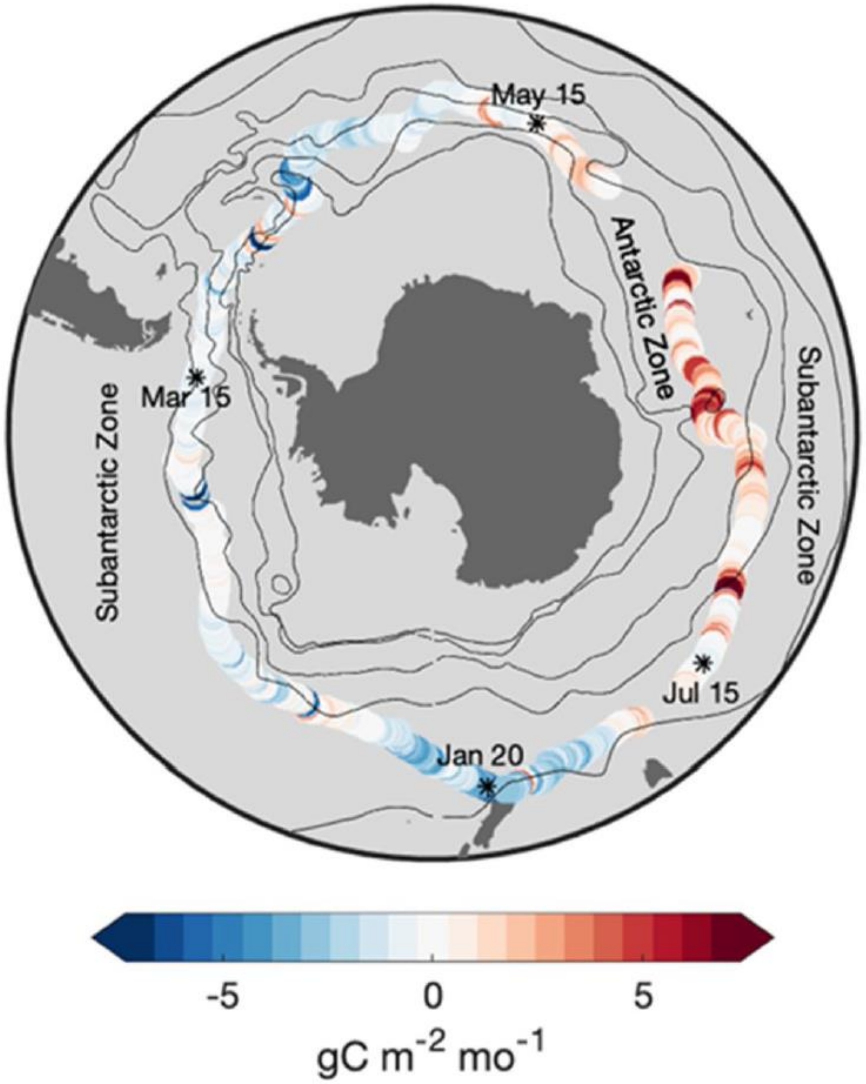


Figure 2. CO_2 flux calculated from Uncrewed Surface Vehicle (USV)-measured ΔpCO_2, sea surface temperature (SST), and salinity (SSS) and CCMP V2 wind speed. Dates and * show the location of the USV with time. Black lines indicate climatological locations of the major fronts from Orsi et al. (1995) as in Figure S1.

Nested Pilot studies

Working backwards - Knowledge gaps

Location(s)
Different Iron supply rates
In a natural setting

Have we optimised the iron supply rate?

Is simply adding more Fe better?

Highest POC export
In region with modest
But sustained Fe supply

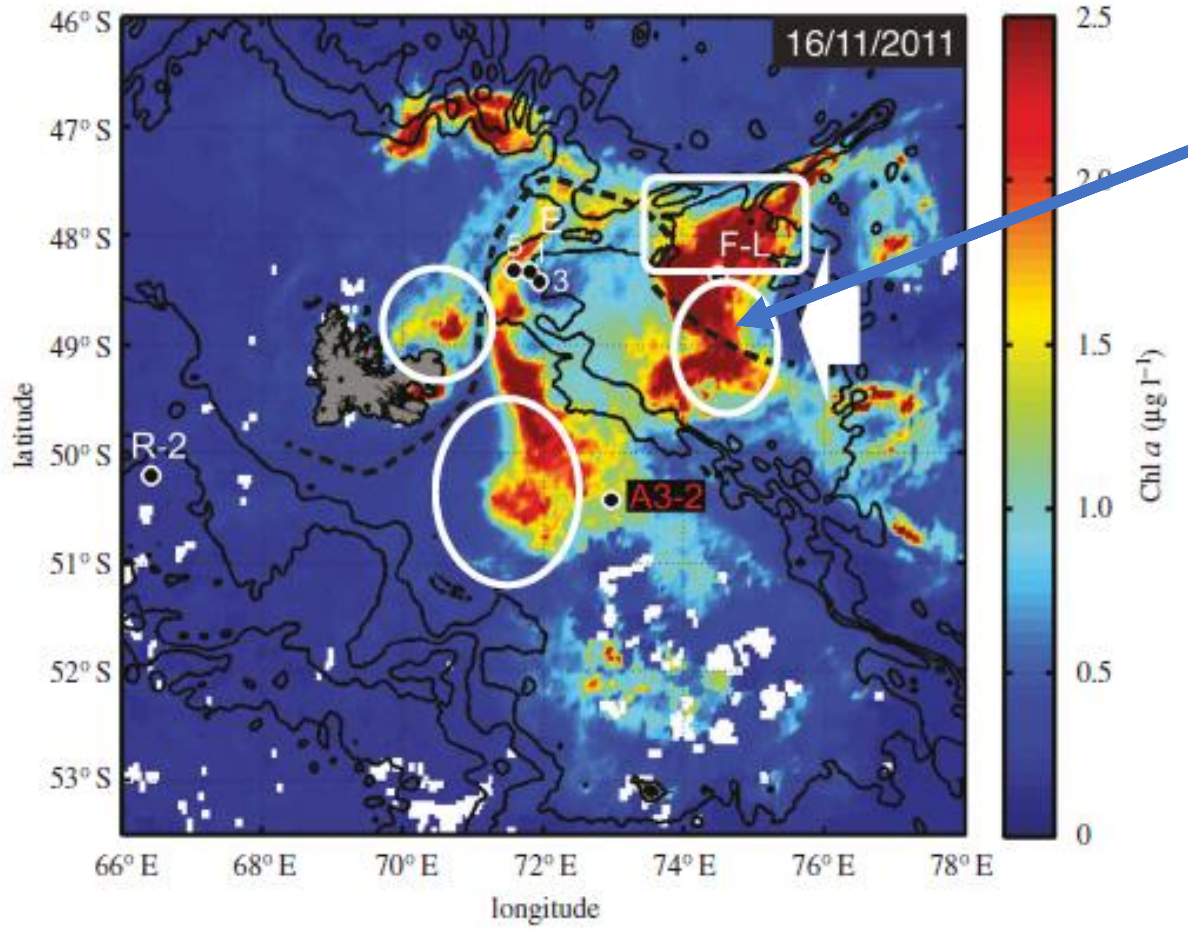


Figure 3. An ocean colour image from MODIS from mid-November 2011 highlights four distinct iron-fuelled surface chlorophyll features (vertical coloured scale bar in mg chlorophyll m^{-3}) that were sampled during the KEOPS II GEOTRACES process study [82]. The highest measured downward POC export was in a region with sustained but moderate iron supply (open circle to the left of horizontal arrow). Other regions sampled, clockwise (open symbols) from top left are Kerguelen coastal waters; Polar Front plume; recirculating feature and the plateau (redrawn from [84]).

Boyd & Bressac (2016)
From Trull et al. (2014)

New Research Targets

R&D agenda set by Foresighting not by incremental increases in knowledge

The importance of line-of-sight from modelling

“As part of this foresighting, there is a strong requirement for (scale- and process appropriate) modelling studies to develop these trajectories from research towards implementation.”

“Critically, this development must precede field experimentation to enable exploration of the wide array of issues around what a pilot study might reveal.”

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Foresight must guide geoengineering research and development

Lenton et al. (2019)

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“To inform the development of realistic trajectories, fit-for-purpose modelling simulations must also look well beyond a pilot study, so as to uncover the characteristics of the subsequent suite of more advanced and upscaled experiments with respect to efficacy, side-effects, and detection and attribution.”

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Lenton et al. (2019)