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What have we learned from past iron fertilization experiments?

Mesoscale iron-addition ‘101’
Synthesis of 11 experiments
Case study - Ocean Physics and bloom signatures
Case study - Export and Sequestration
Scaling up – temporal and spatial effects
A SYNTHESIS OF MESOSCALE IRON-ENRICHMENTS

Oct. 30 to Nov. 3 2005 Wellington


Also Fei Chai and Ed Abraham
Fe-addition 101 - Pre-release Oceanographic Survey
Iron is added with $\text{SF}_6$

Why not just add iron alone?
Iron is rapidly transformed into other forms

Croot et al. (2002)
SF$_6$/Iron  Initial Release
(after Watson et al. (1991))
Iron fertilization in the equatorial Pacific

Behrenfeld et al. (1996)
What have we learned from past iron fertilization experiments?

Synthesis of 11 HNLC experiments
Initial conditions
Phytoplankton
Ecological responses
Other elements and biogenic gases
Modelling – a test of our understanding
11 mesoscale Fe experiments in > 10 years
Range of initial conditions for iron experiments

- **Temperature**: -1 to > 24°C
- **Mixed-layer depth**: 13 to 100 m
- **Light climate**: 45 to 250 umol m\(^{-2}\) s\(^{-1}\)
- **Silicic acid**: 2 to 60 umol l\(^{-1}\)
- **Dissolved Fe**: 0.04 to 0.10 nmol l\(^{-1}\)
- **Chlorophyll**: 0.2 to 0.9 µg l\(^{-1}\)
- **Season**: Spring to autumn
- **\(F_v/F_m\)**: 0.2 to 0.3
Common findings in mesoscale iron experiments

Virtually all experiments resulted in blooms

A similar experimental design was used in all studies
A wide range in bloom signatures

De Baar et al. (2005)
Factors controlling bloom signatures

- **Environmental**
  - Initial conditions - optical, chemical, plankton community
  - Underlying physics – dilution rate $0.05$ versus $0.07-0.16 \text{ d}^{-1}$
  - Interplay of conditions

- **Experimental**
  - Fe supply – magnitude and timing
  - Duration
  - Site selection
  - Sampling interval
The development of a mechanistic understanding of what controls bloom longevity

Boyd et al. (2004; 2005)
The wide-ranging influence of iron supply

- **DIRECT**
  - Photosynthesis
  - Growth rate, NPP
  - Nutrient uptake (Si:N)
  - Species composition
  - Exudation - DOC
  - Bacterial processes
  - Biogenic gases
  - Grazer physiology
  - Siderophore production

- **INDIRECT**
  - S, C, N, Si biogeochemistry
  - Export flux
  - Gas efflux and drawdown
  - Foodweb structure
  - Zooplankton growth and reproduction
  - Faunistic shifts
The blooms were mainly dominated by larger phytoplankton - diatoms.
Phytoplankton composition (+Fe, SEEDS II)

Tsuda, unpublished data
The importance of the initial stocks of phyto- & zoo-plankton

Tsuda, unpublished data
Mesoscale Fe-enrichments provide a holistic view of the foodweb
Mesoscale Fe-enrichments provide a holistic view of the foodweb and how it impacts biogeochemical cycles

Boyd and Doney 2002
Iron addition

- Diatom increase
  - Upward shift of Vertical distribution
  - Increase of food availability
  - Enhanced growth
  - Increase of zooplankton biomass
  - Increase of Egg production
  - E. bungii
  - N. cristatus
  - M. pacifica

- Increased Copepod #
- N. cristatus
- Increased survival rate in egg and nauplii
- Lowered predation rate

P1: Change of behaviors
P2: Lowered mortality
P3: Reproduction enhancement

Hints of complex ecological interactions

Tsuda (2006)
Fe supply impacts the biogeochemical cycles of multiple elements

**Graph 1: Nitrate and Silicic Acid Depletion**

- Nitrate depletion
- Silicic acid depletion

**Graph 2: Spatial Distribution**

- Longitude (degree W)
- Latitude (degree N)
- nmol/l

- Contour lines represent concentration levels:
  - 2.0
  - 1.8
  - 1.6
  - 1.4
  - 1.2
  - 1.0
  - 0.8
  - 0.6
  - 0.4
  - 0.2
  - 0.0

- DMS

**Graph 3: Heatmap**

- Latitude (degree N)
- Longitude (degree W)
- nmol/l

- Color scale from 410 to 260
DIFFERENT MICROBES DOMINATE EACH PHASE OF THE BLOOM
Influences other climate-reactive gases?

Comparison of radiative forcing IPCC (1996)

Global mean radiative forcing /W m$^{-2}$

<table>
<thead>
<tr>
<th>Gas Type</th>
<th>Radiative Forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halocarbon</td>
<td>3.2</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>2.0</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1.0</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Law & Ling (2001)
Mesoscale Fe experiments provide the datasets to test new conceptual models – e.g. Le Clainche et al. 2005

The relative importance of physical and biological processes on DMS pool
What have we learned from past iron fertilization experiments?

Case study - Ocean Physics and bloom signatures

Physics modifies bloom biogeochemistry & fate
Location, location, location - Subduction & patch drift
Experimental artefacts even in 200-1000 km² experiments

*The continual stretching by the horizontal currents creates a chemostat – changing the concentrations of properties in and outside the patch by mixing, and regulating phytoplankton growth* - Boyd & Law (2001)
Entrainment of surrounding HNLC waters which modifies the biogeochemical signature of the bloom

- Stretching via horizontal flows
- Mixing of water by horizontal diffusion

[Graph showing Entrainment at patch centre, DIC, DOC (OUT 53), DOC (OUT 49.6), POC]

Law et al. (2006)
The stirring of a square of ink (Welander, 1955)

Growth phytoplankton in an Fe-enriched patch
(joint effects of iron and silicate)

Abraham (2002)
Locale is important - Propagation by Currents - 1500 km of drift in 19 days

IronEx II (Coale et al., 1996)

OR Subduction Capped by less dense waters

IronEx2 SF6 patch evolution (P. Nightingale)
What have we learned from past iron fertilization experiments?

Case study - POC Export and Sequestration
Not all blooms resulted in more export
Decoupling of bloom development and export
Attenuance of export signal – sequestration
C exported per unit iron added
Marked differences in bloom status attained in Fe enrichments

Boyd (2004) Due to the range of experimental (duration) and/or environmental (MLD) conditions
Concurrent mapping of CO₂ drawdown, POC accumulation and export

Boyd et al. (2005); Tsuda unpublished
POC (mg m$^{-3}$)

SERIES bloom

POC (ug L$^{-1}$) Boyd et al. (2005)
HOW MUCH POC WAS EXPORTED TO DEPTH?

POC intercepted at 50 m  18%

Boyd et al. (2005)
VERTICAL ATTENUATION OF EXPORTED PARTICLE SIGNAL

Boyd et al. (2004)

POC export

50 m trap
125 m trap

18% @ 50 m
7% @ 125 m

mmol C m\(^{-2}\) d\(^{-1}\)

Days
FATE of the bloom carbon

EVIDENCE OF DIFFERENTIAL REMINERALISATION
Microbial utilization of diatom POC and Si protectants – followed by BSi dissolution (Bidle and Azam, 2002)

Boyd et al. 2005
FATE of the bloom carbon

POC intercepted at 50 m 18%

WHAT IS THE FATE OF THE POC DEFICIT (258 MMOL m⁻²) ?

EXPORT  47
MESOZOO  29
UNDERTRAPPING  11
DIFF. REMIN  41
or
NH₄ ACCUM  100

TOTAL 127 to 215 MMOL M⁻²

Boyd et al. 2004
C exported per tonne of iron added

31428 to 110000

265

1571

6285  2095  105
What have we learned from past iron fertilization experiments?

Scaling up – temporal and spatial effects
Seasonal – towards nutrient depletion and export
Basin – pro’s and con’s of physics
Multiple enrichments
C sequestration, issues of depth and decoupling
Interannual – tools for tracking?
Seasonal scales

Boyd et al. 2004

A longer experiment?
Thanks Dr. Jim Gower of IOS and NASA

Boyd et al. (2005)

A bigger experiment?

Detection and attribution

Bloom biogeochemical signal in the context of the annual cycle

Boyd et al. (2005)
Upscaling – issues

At scales of 100km and above the mixing will be inefficient. Mixing at patch edges, but bloom may exhaust other nutrients such as silicate before the added iron has been used.
Disjoint between surface source for particles and their trajectory to depth

0-200 m

depth

20-30 km

0-2000 m

100-300 km
State of knowledge

Iron causes blooms, and does many other things
Biogenic gases, export, ecological shifts – cumulative effects

Location, location, location – same biogeochemistry
but different manifestations due to physics

Initial conditions are important \( (n=2) \) SEEDS I & II

Some blooms lead to export \( (n=3) \)

Rapid attenuation of export signal \( (n=1) \)

Evidence of other biogenic gas production – but either rarely sampled or little consensus
Remaining uncertainties

Small and large scale experiments

Do different initial conditions result in different algal communities?

Biogenic gas production – $\text{N}_2\text{O}$ rarely studied

C exported per unit of iron added ($n=2$)

Fate of added iron / siderophores

Moving experimental design from 1D biogeochemical slices to 3D animated biogeochemistry on appropriate timescales
Stirring of a tracer patch in the East Australian Current

$t = 1$ day start:

100 km
Stirring of a tracer patch in the East Australian Current

t = 2 day

100 km
Stirring of a tracer patch in the East Australian Current

$t = 3$ day

100 km
Stirring of a tracer patch in the East Australian Current

t = 4 day
Stirring of a tracer patch in the East Australian Current

$t = 5$ day

100 km
Stirring of a tracer patch in the East Australian Current

t = 6 day

100 km
Stirring of a tracer patch in the East Australian Current

\[ t = 7 \text{ day} \]
Stirring of a tracer patch in the East Australian Current

$t = 8$ day

100 km
Stirring of a tracer patch in the East Australian Current

\[ t = 9 \text{ day} \]

100 km
Stirring of a tracer patch in the East Australian Current

$t = 10$ day
Stirring of a tracer patch in the East Australian Current

$t = 11$ day

100 km
Stirring of a tracer patch in the East Australian Current

\[ t = 12 \text{ day} \]
Stirring of a tracer patch in the East Australian Current

\[ t = 13 \text{ day} \]
Stirring of a tracer patch in the East Australian Current

$t = 14$ day
Stirring of a tracer patch in the East Australian Current

t = 15 day finish:
Fe:C uptake ratios (mol:mol)

2 to $7 \times 10^{-6}$

$8.3 \times 10^{-4}$

$1.4 \times 10^{-4}$

$3.5 \times 10^{-5}$

$1.05 \times 10^{-4}$

$2.1 \times 10^{-3}$
C:Fe uptake ratios – ‘Pick a lucky number’

Geo-engineers – ‘ two buck Chuck’

142857 to 500,000

12558 to 38461

1204.8

7142

28571 9523 476

Environmentalists