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What have we learned from past iron fertilization experiments?

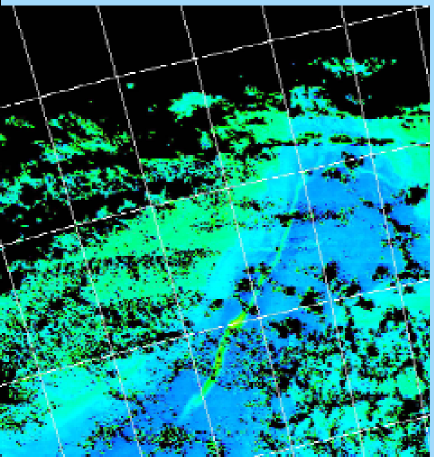
Mesoscale iron-addition ‘101’
Synthesis of 11 experiments
Case study - Ocean Physics and bloom signatures
Case study - Export and Sequestration
Scaling up – temporal and spatial effects

oceanironfertilization
come to listen • learn • debate • explore

solas surface.ocean lower.atmosphere.study

NSF

NIWA Taihoro Nukurangi

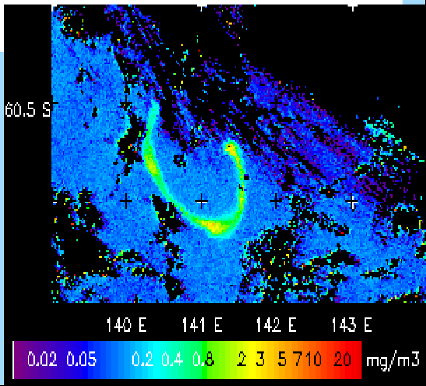


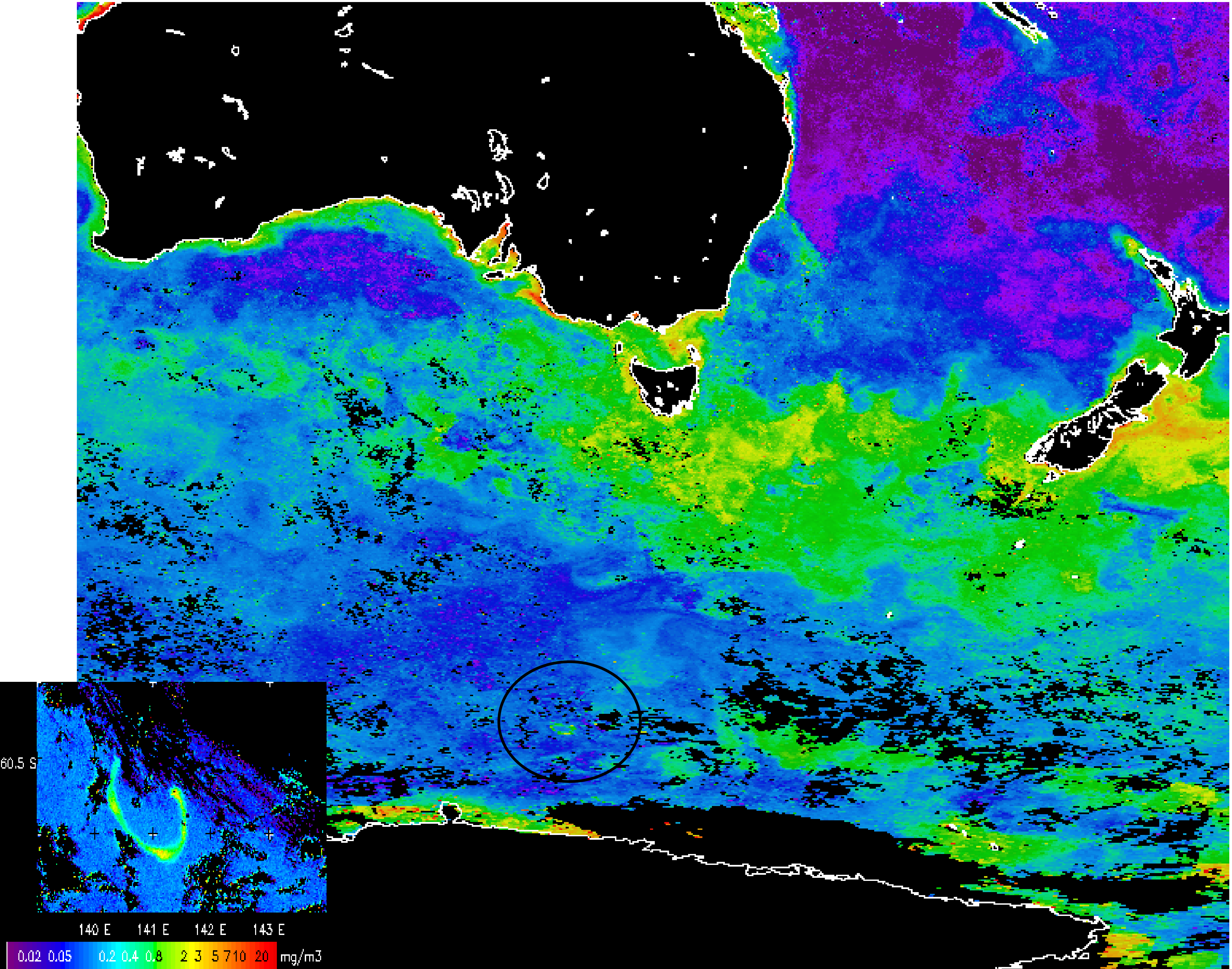
A SYNTHESIS OF MESOSCALE IRON-ENRICHMENTS

Oct. 30 to Nov. 3 2005 Wellington

Participants – S. Blain, P. Boyd, E. Boyle, K. Buesseler, H. de Baar, K. Coale, J. Cullen, M. Follows, M. Harvey, T. Jickells, C. Lancelot, C. Law, M. Levasseur, R. Pollard, J. Sarmiento, V. Schoemann, V. Smetacek, S. Takeda, A. Tsuda, S. Turner, A. Watson

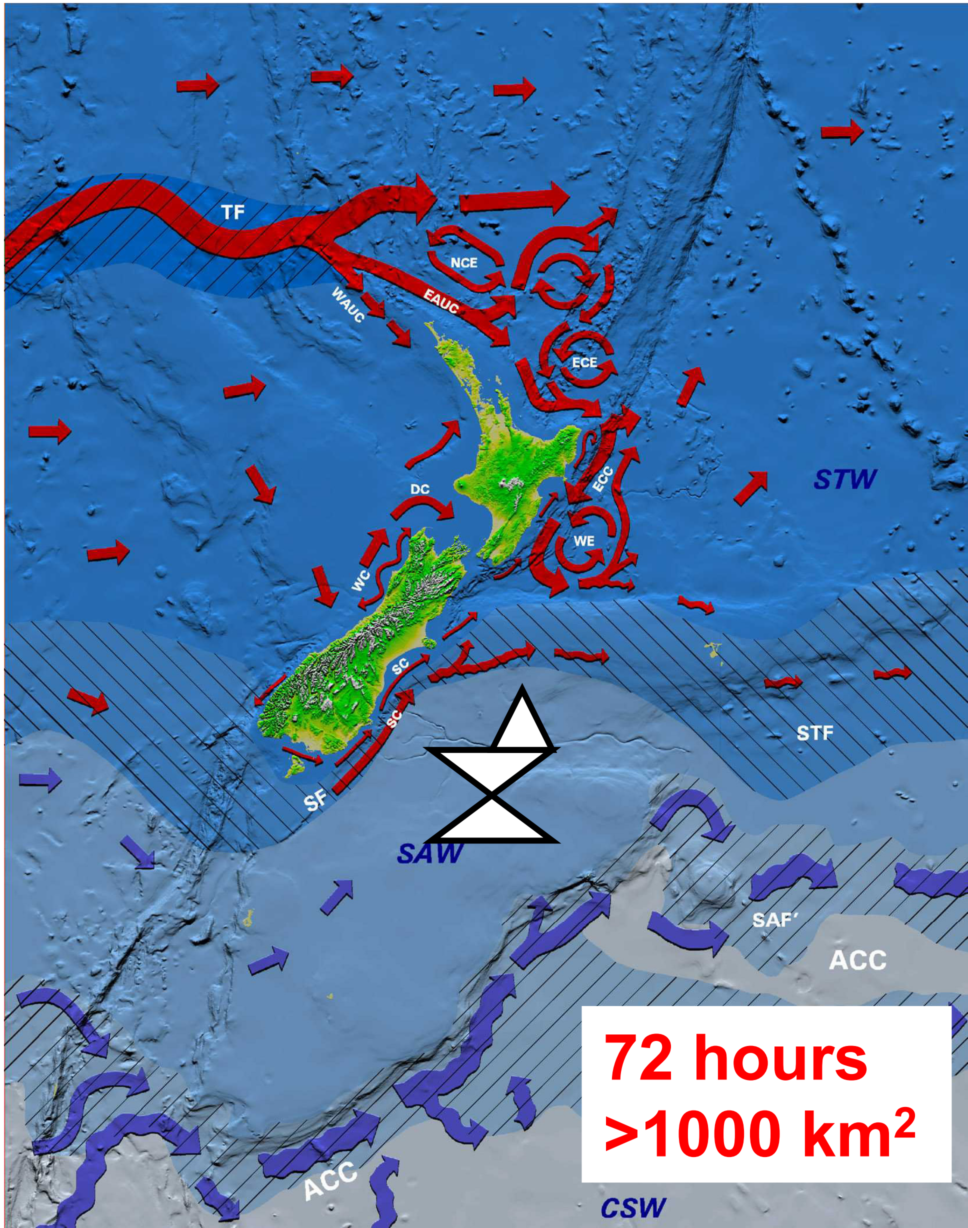
Also Fei Chai and Ed Abraham





60.5 S
140 E
141 E
142 E
143 E
0.02 0.05 0.2 0.4 0.8 2 3 5 7 10 20 mg/m3

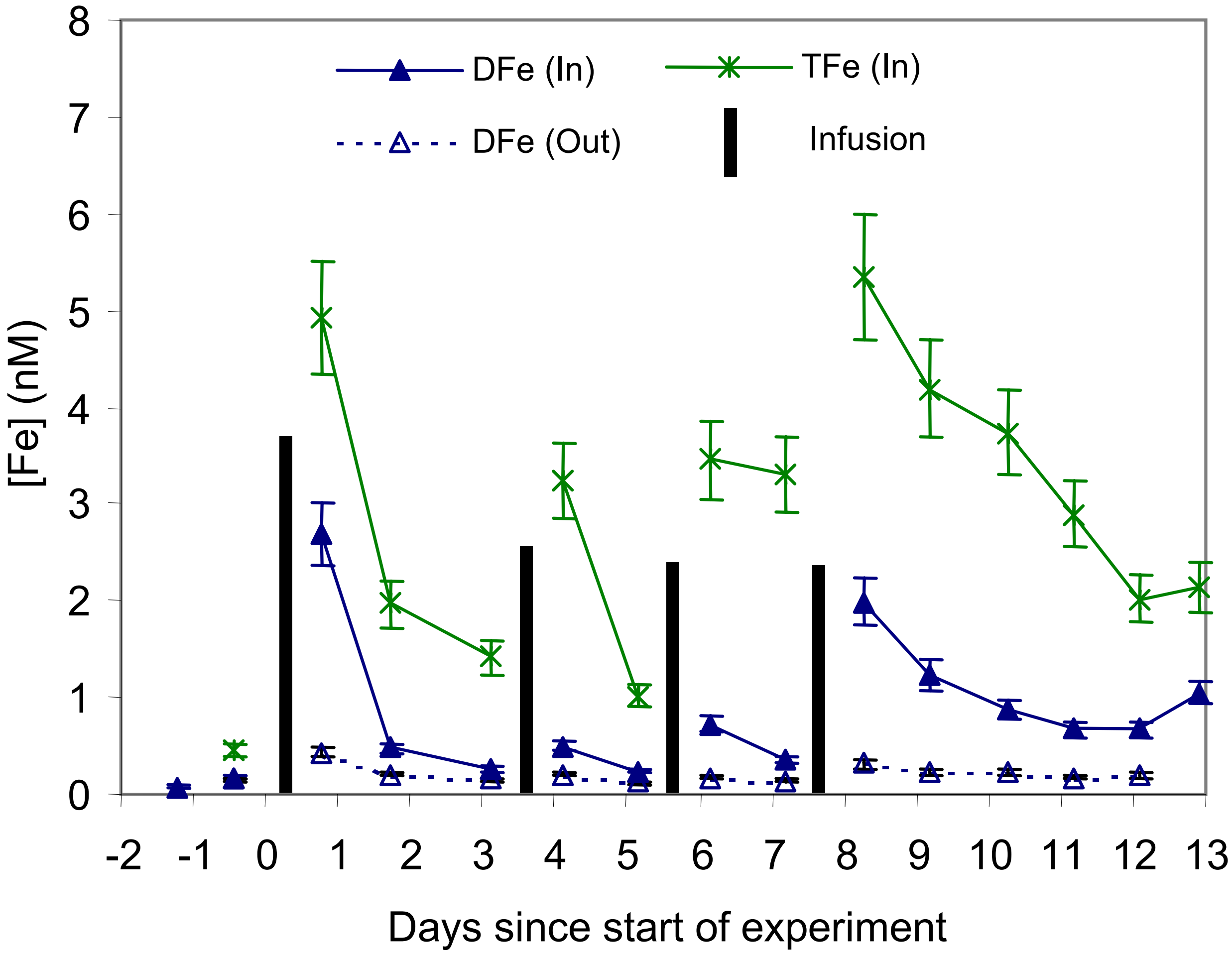
Fe-addition 101 - Pre-release Oceanographic Survey

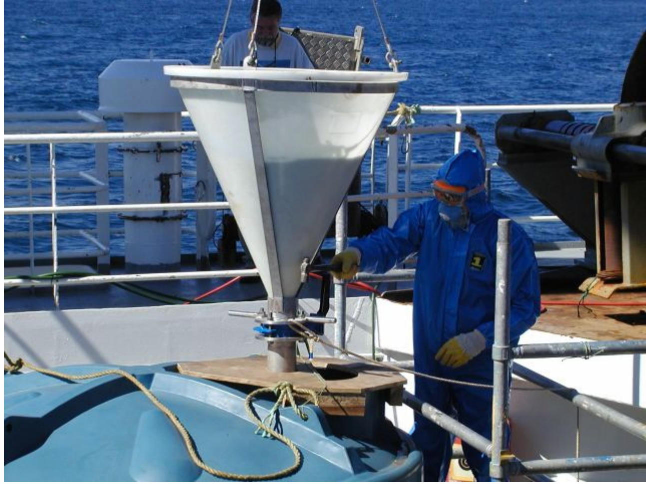


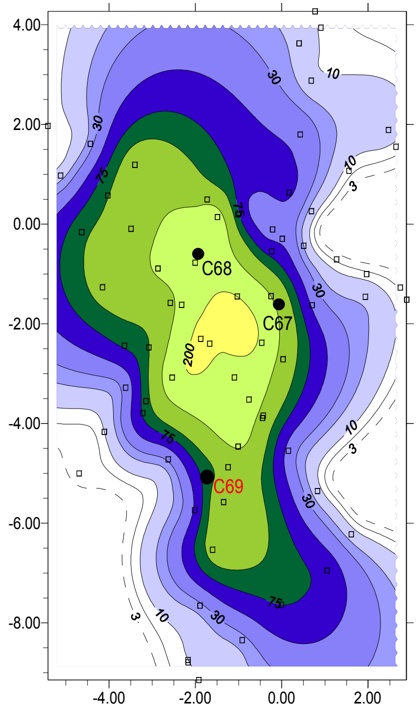
Iron is added with SF_6

Why not just add iron alone?

Iron is rapidly transformed into other forms

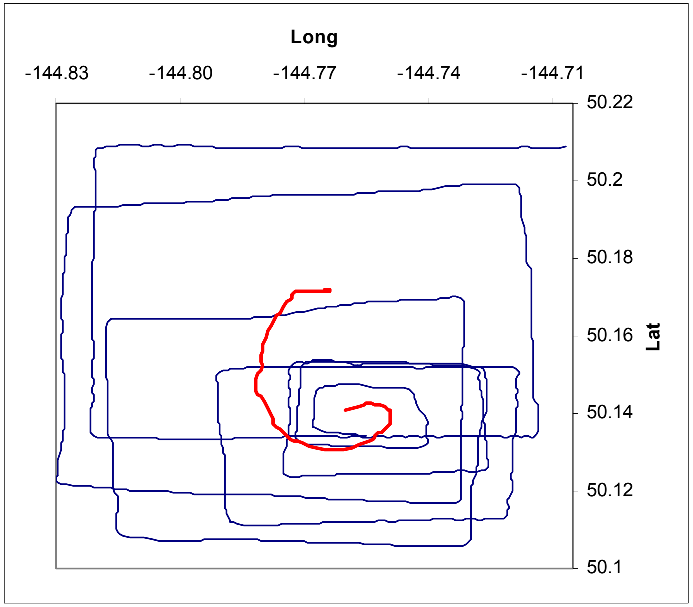


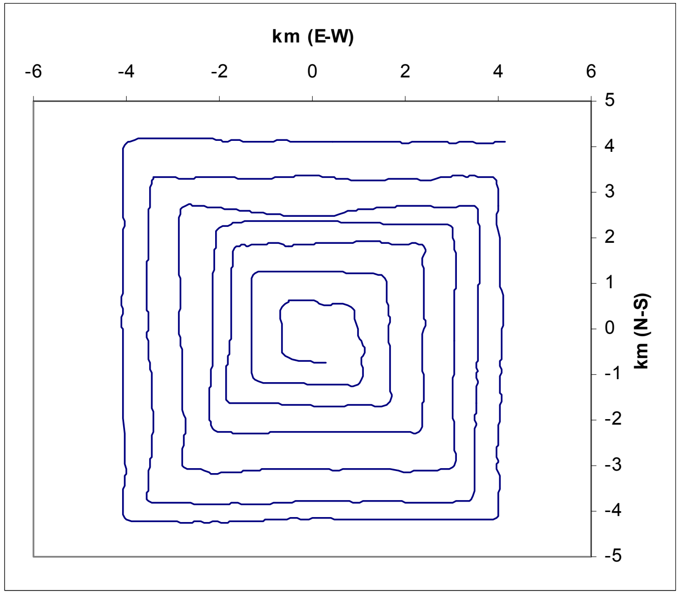


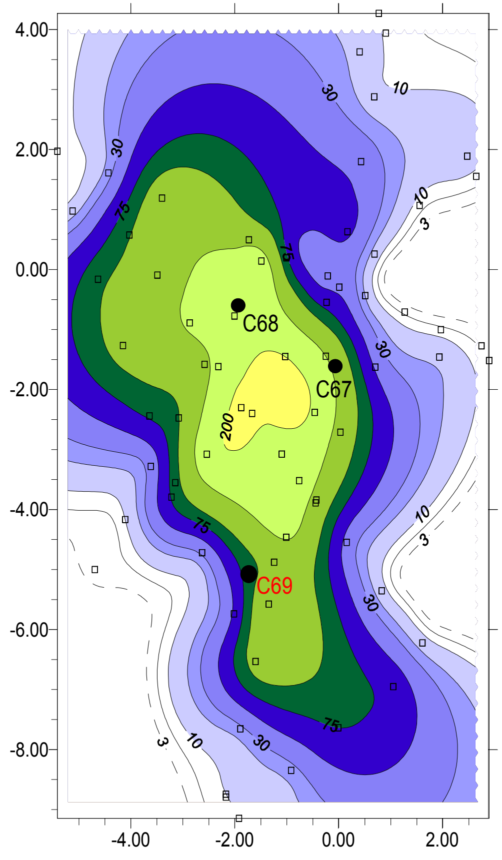


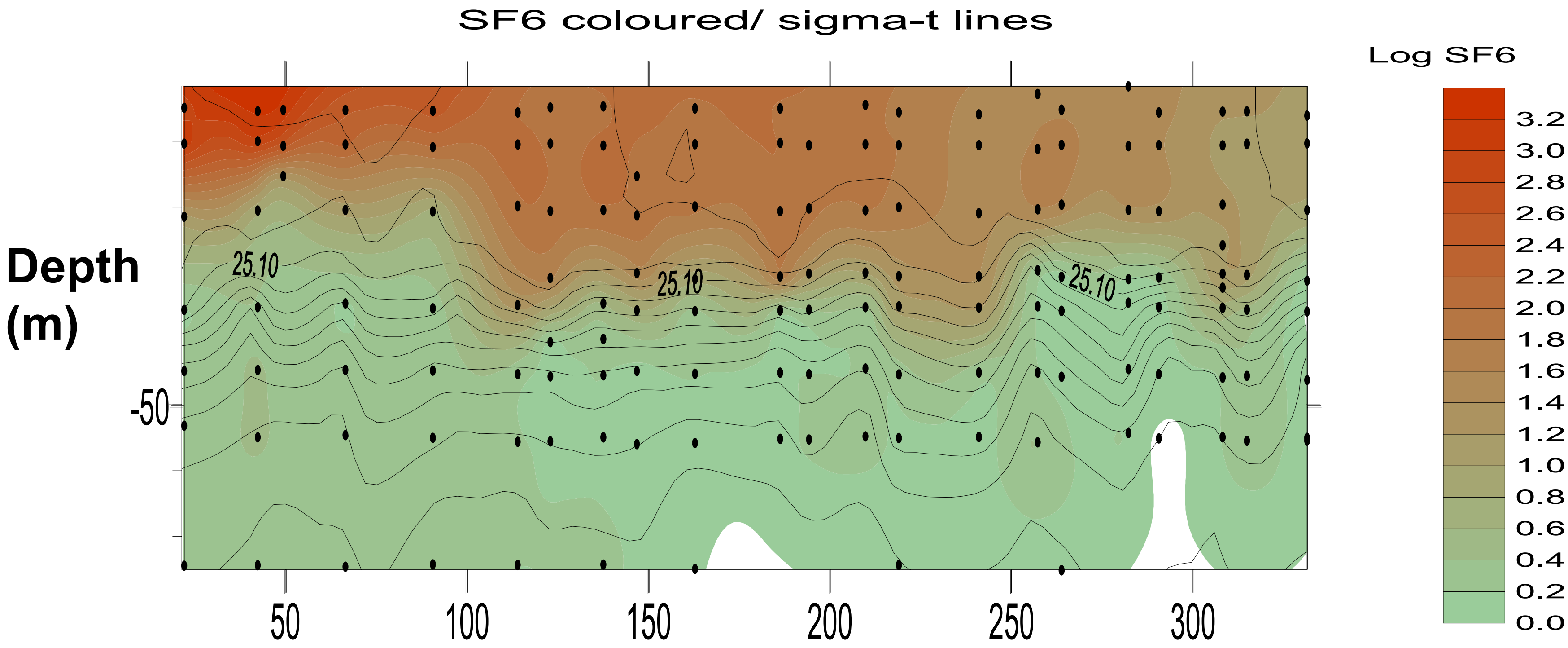
Croot et al. (2002)

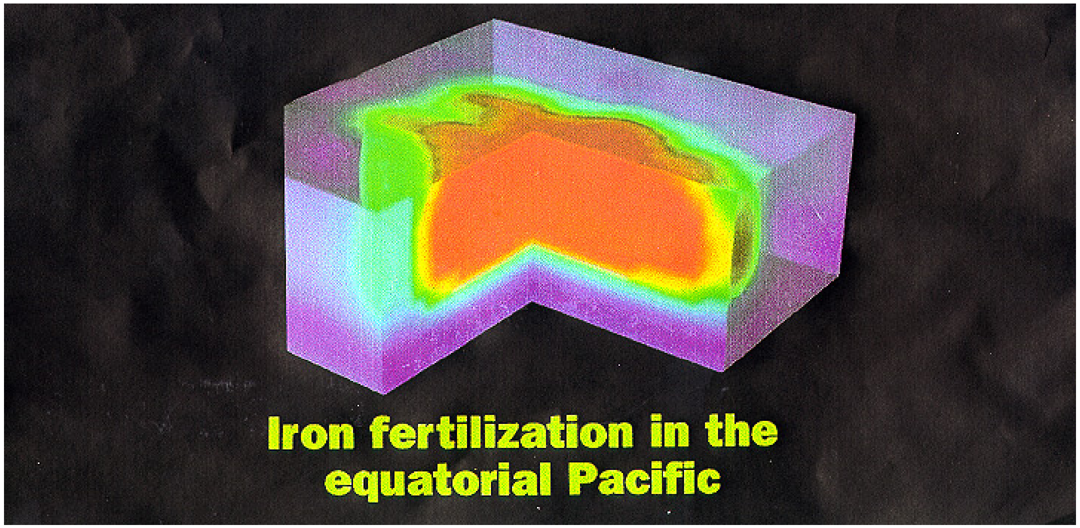
SF$_6$/Iron Initial Release
(after Watson et al. (1991))



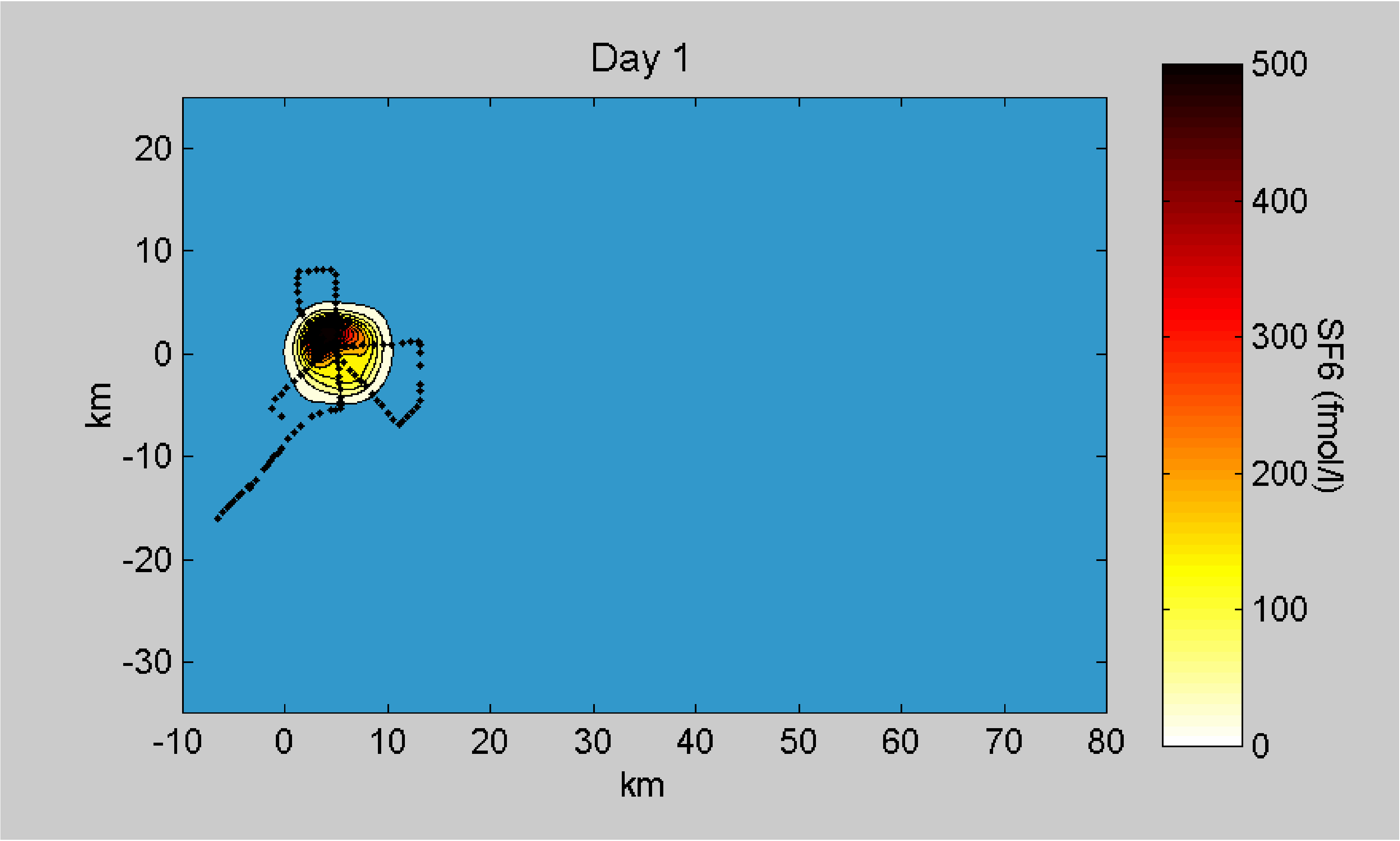


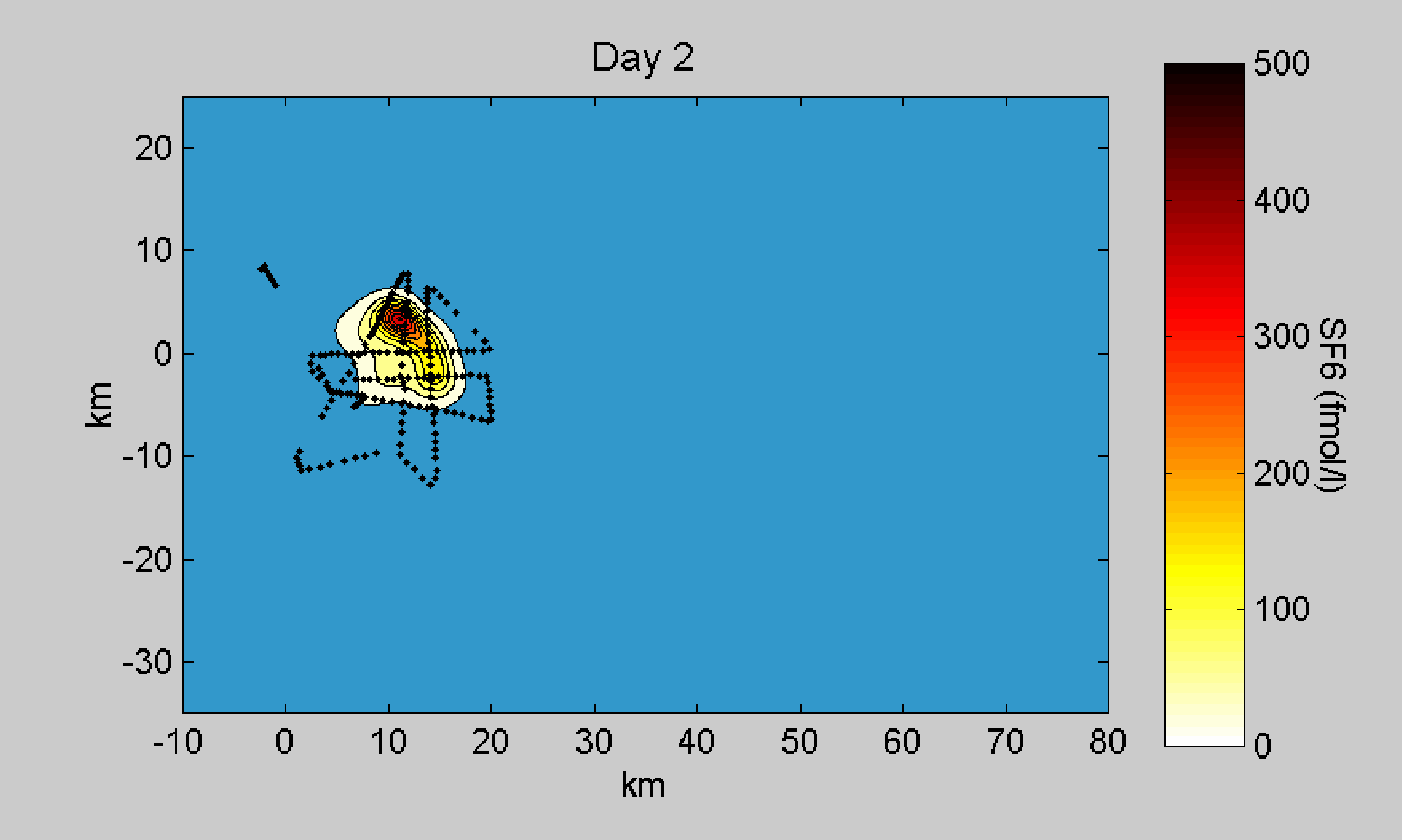






Behrenfeld et al. (1996)


Day 1
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)


Day 2
20
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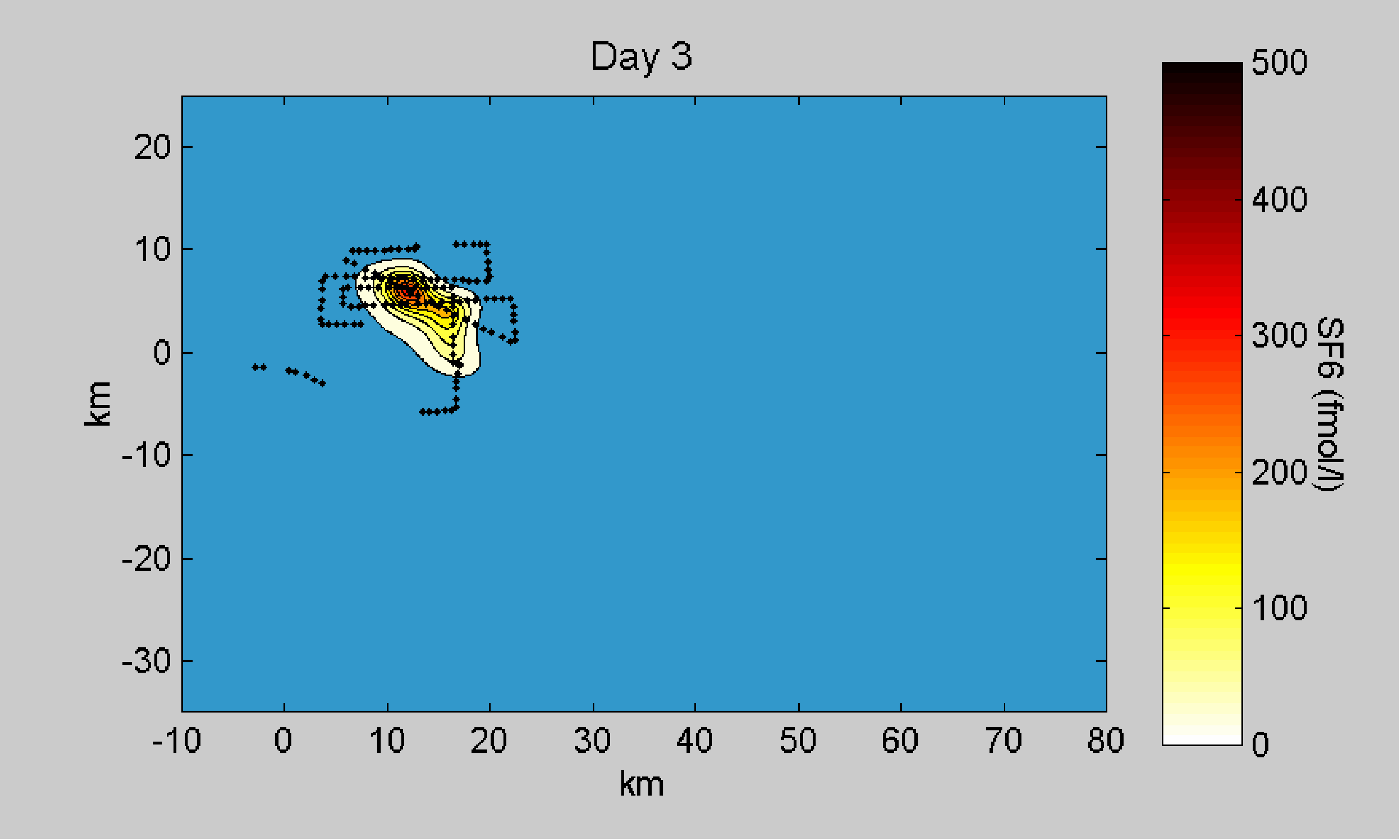
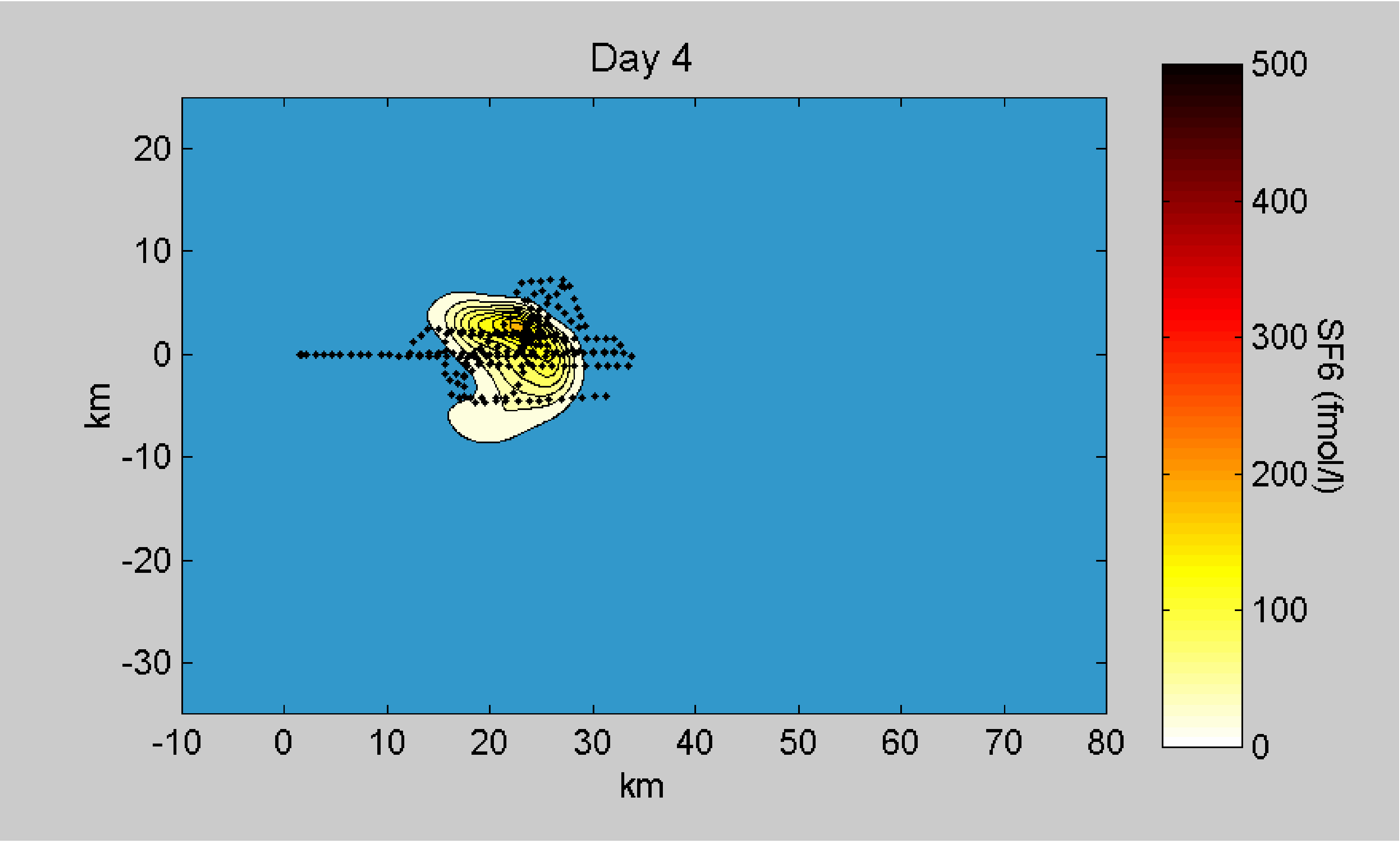
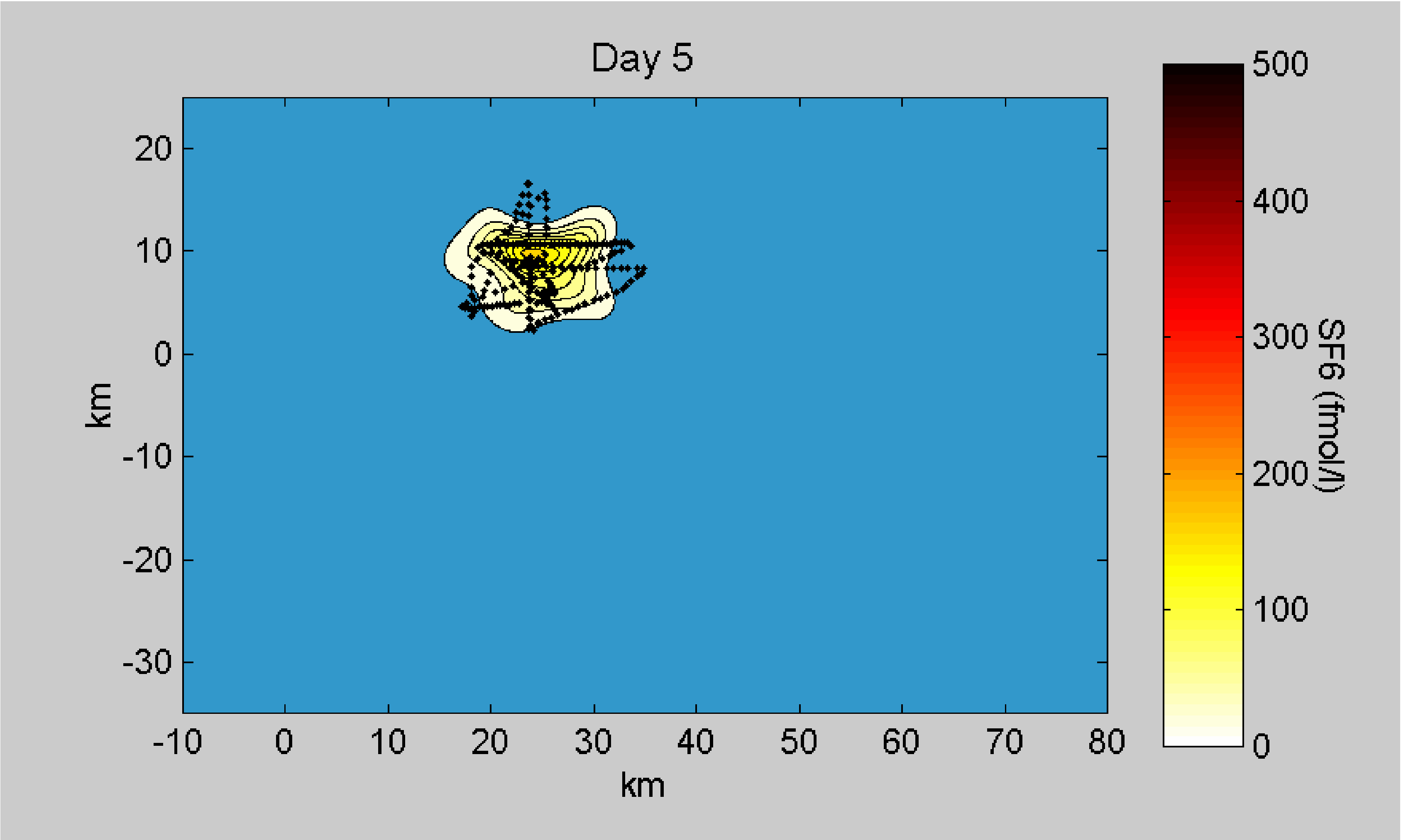
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)



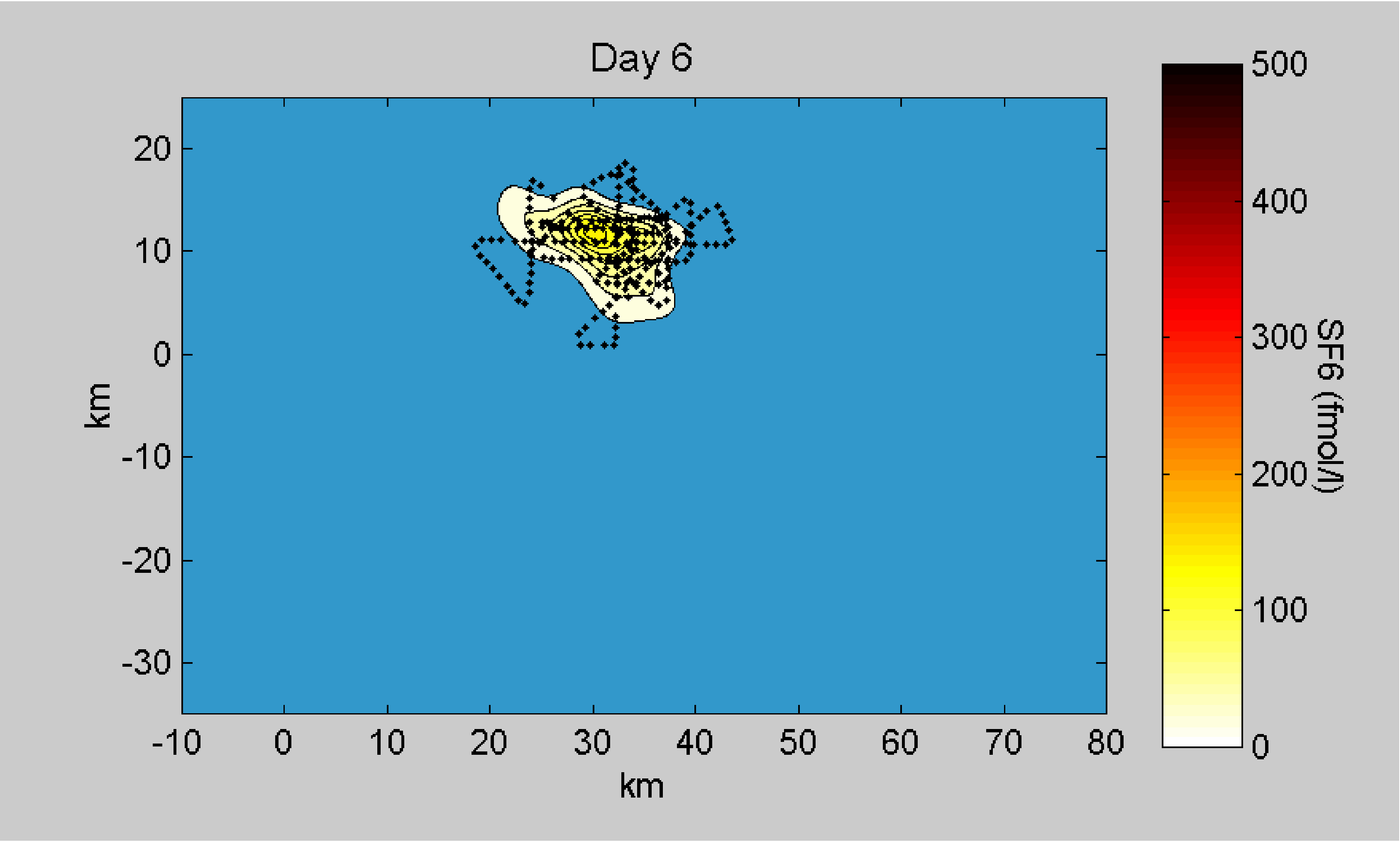
Day 3
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)



Day 4
km
km
SF6 (fmol/l)
-10
0
10
20
30
40
50
60
70
80
20
10
0
-10
-20
-30
500
400
300
200
100
0



Day 5
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)


Day 6
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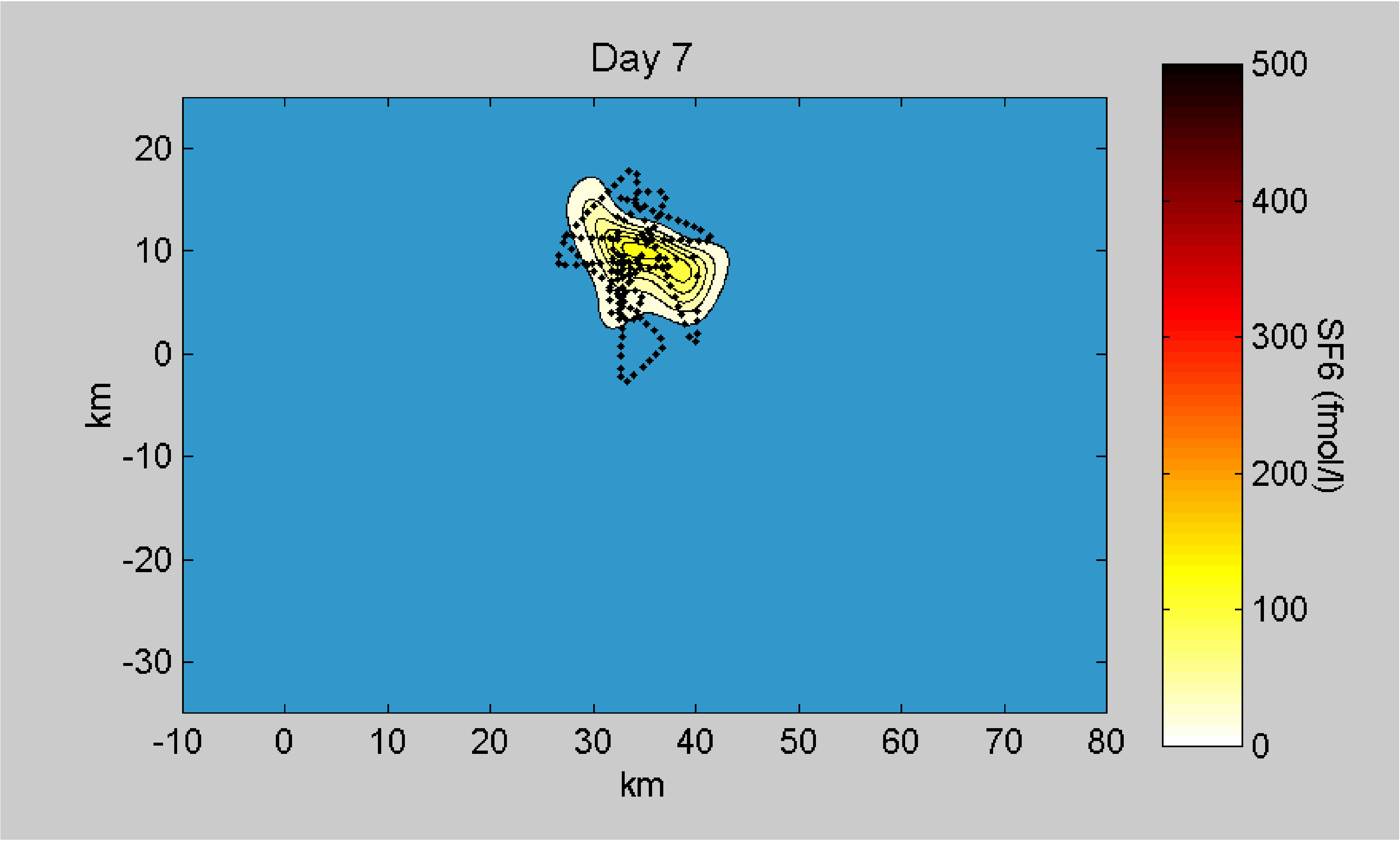
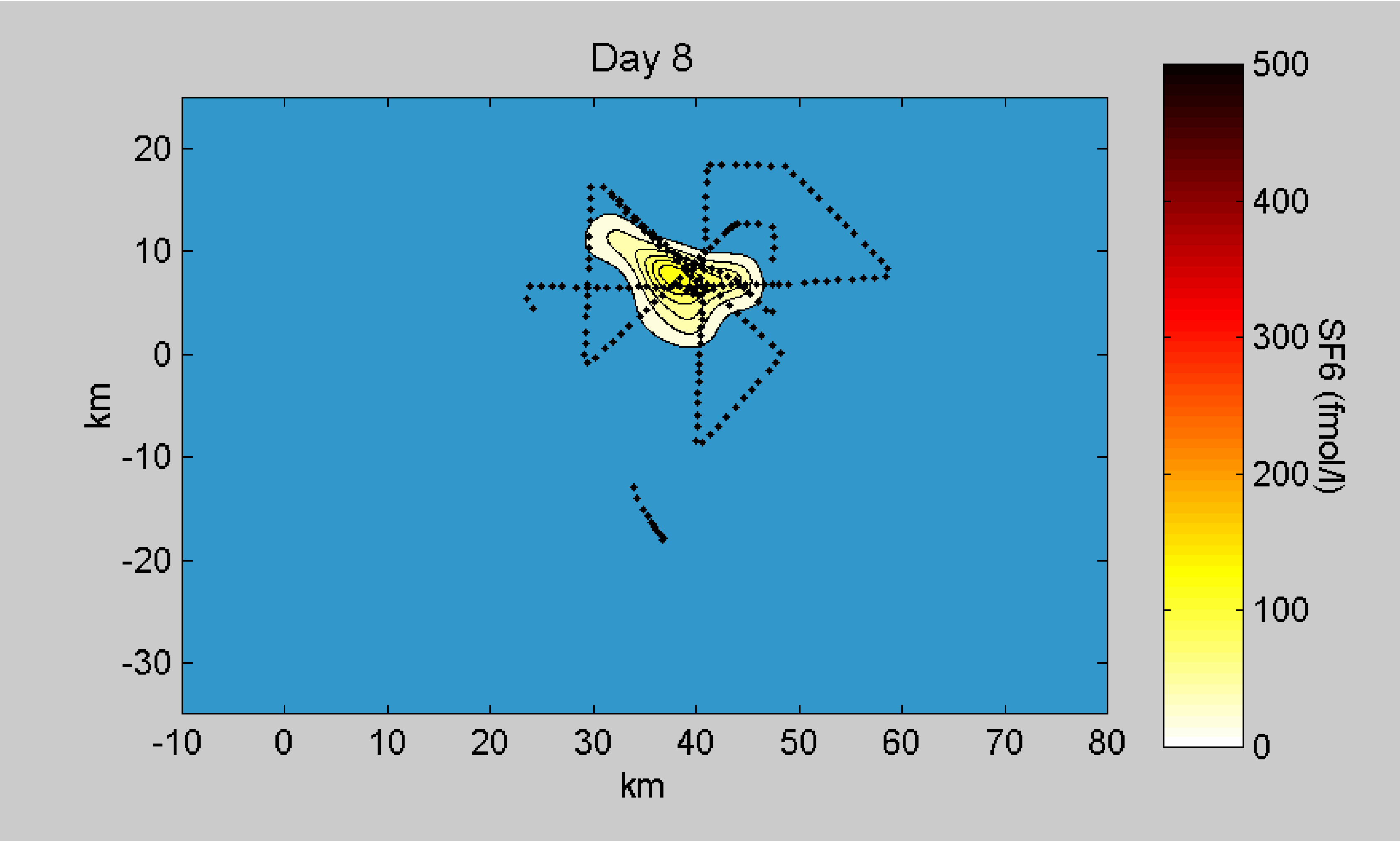
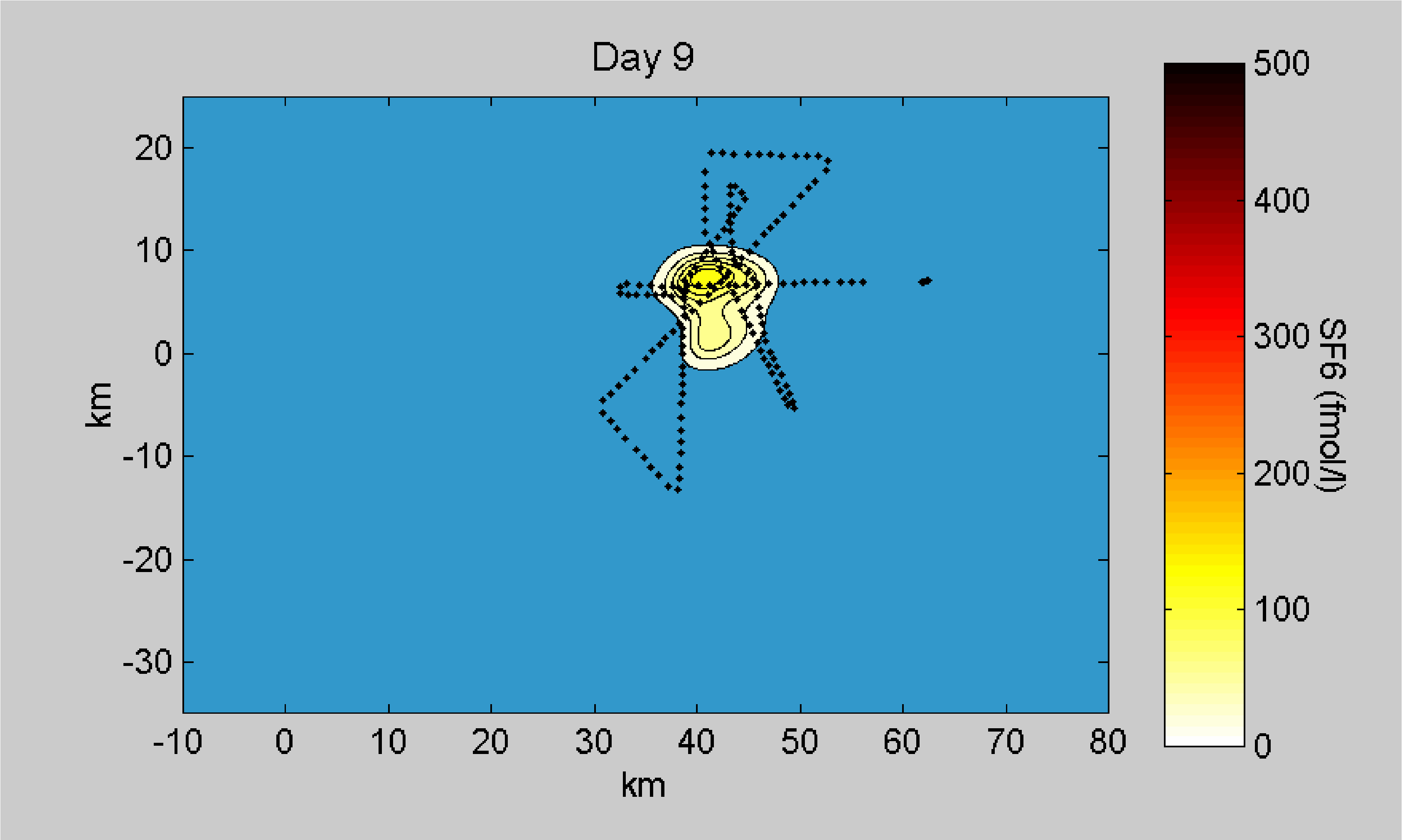
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)

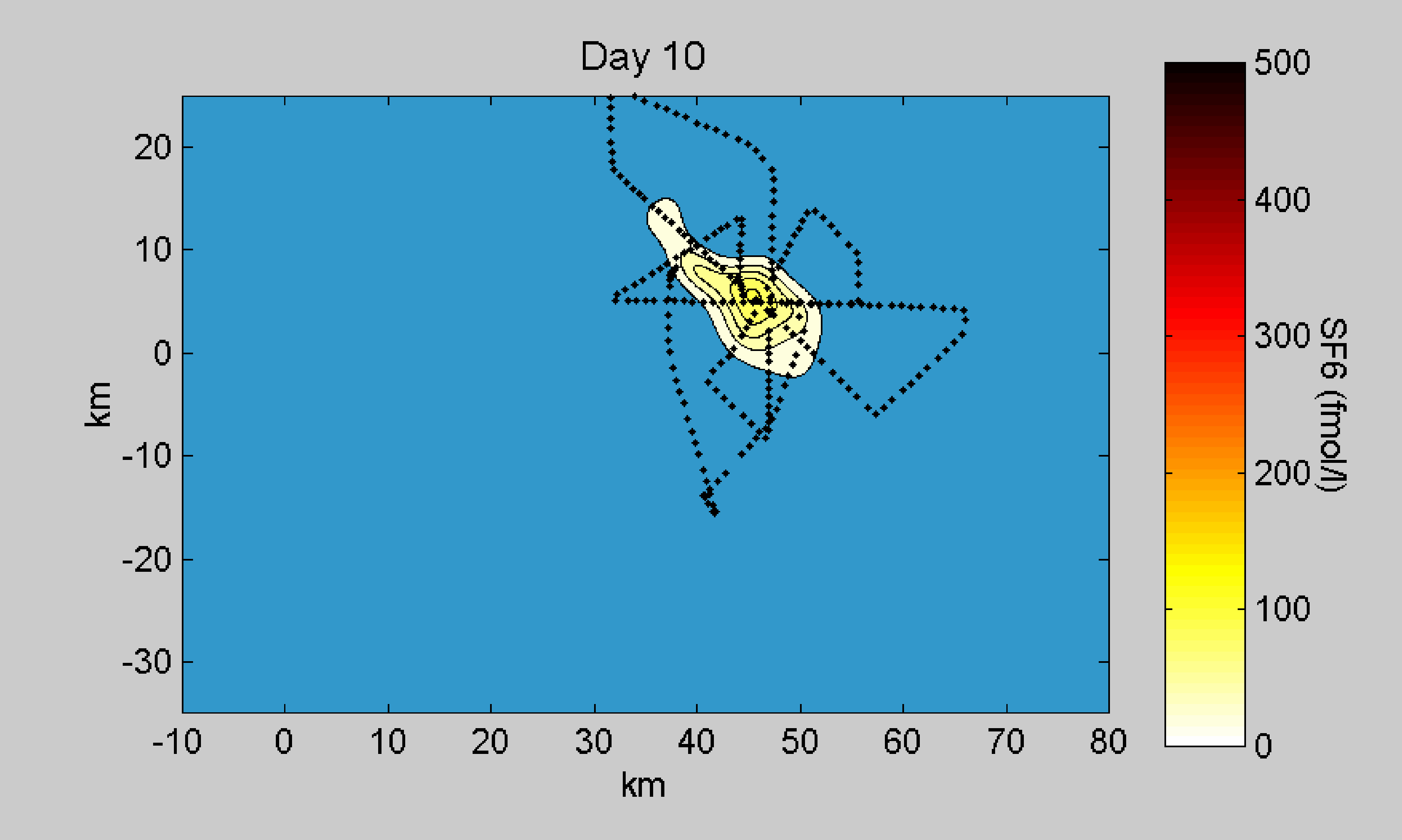


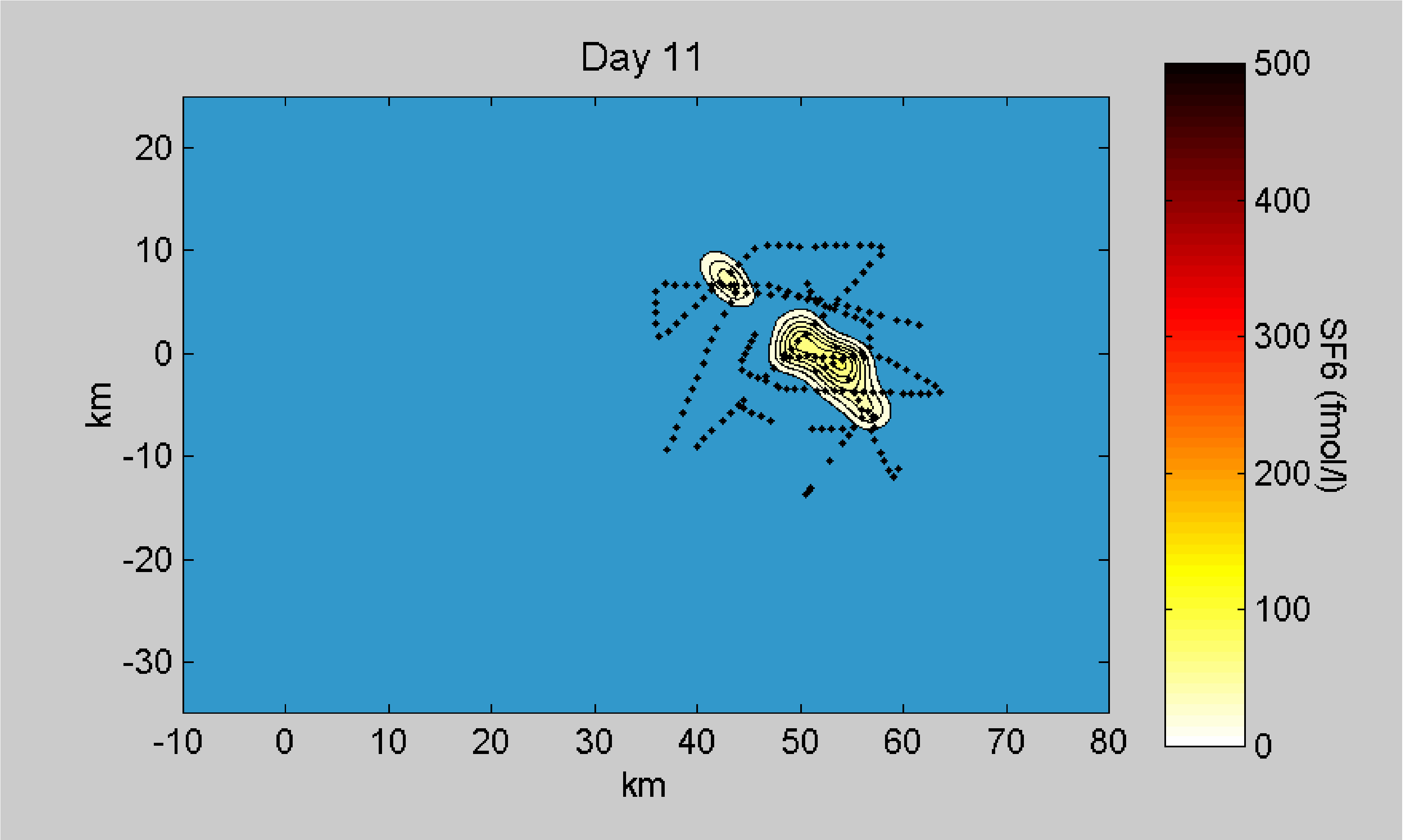
Day 7
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)

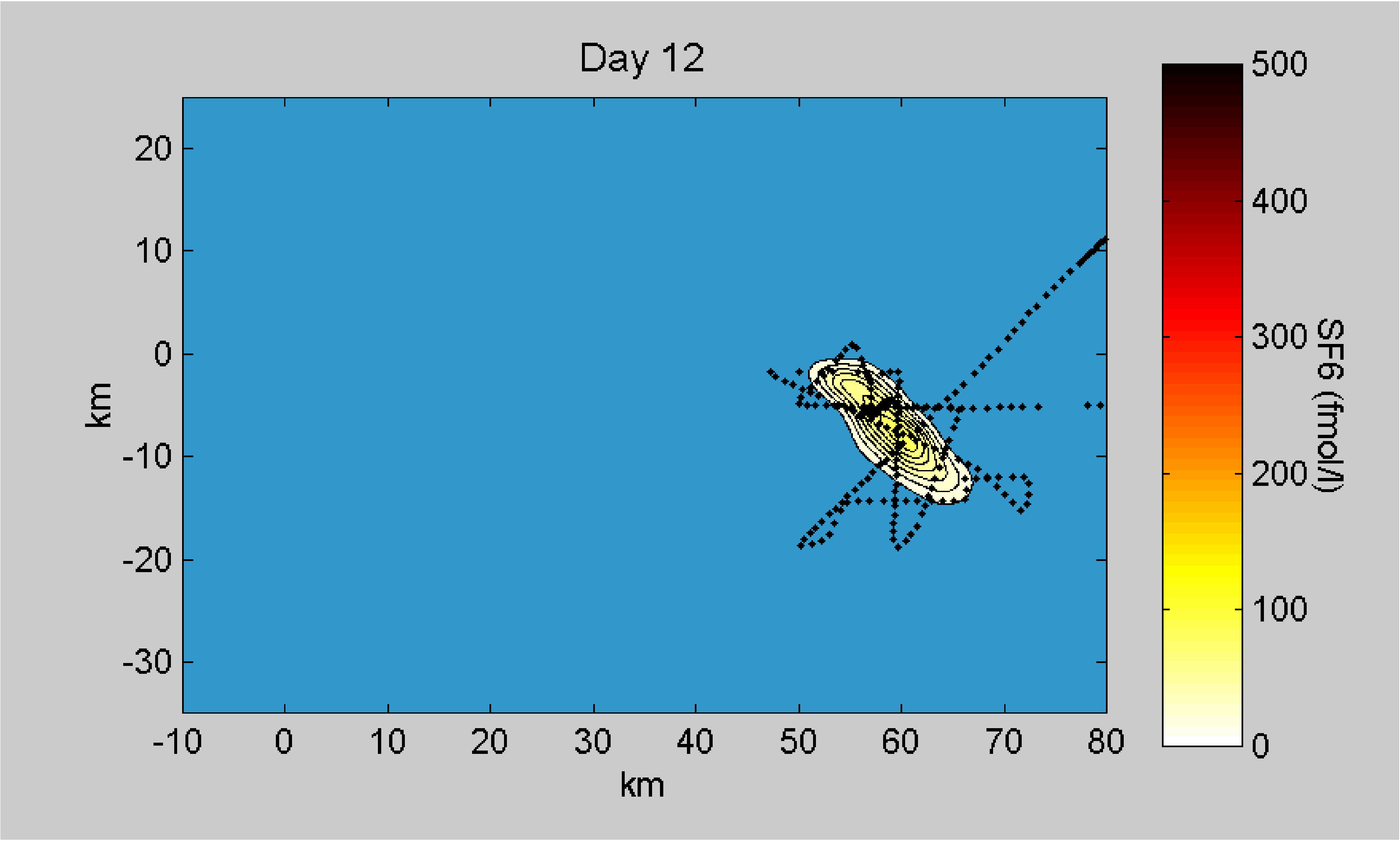

Day 8
km
km
SF6 (fmol/l)
20
10
0
-10
-20
-30
-10
0
10
20
30
40
50
60
70
80
500
400
300
200
100
0

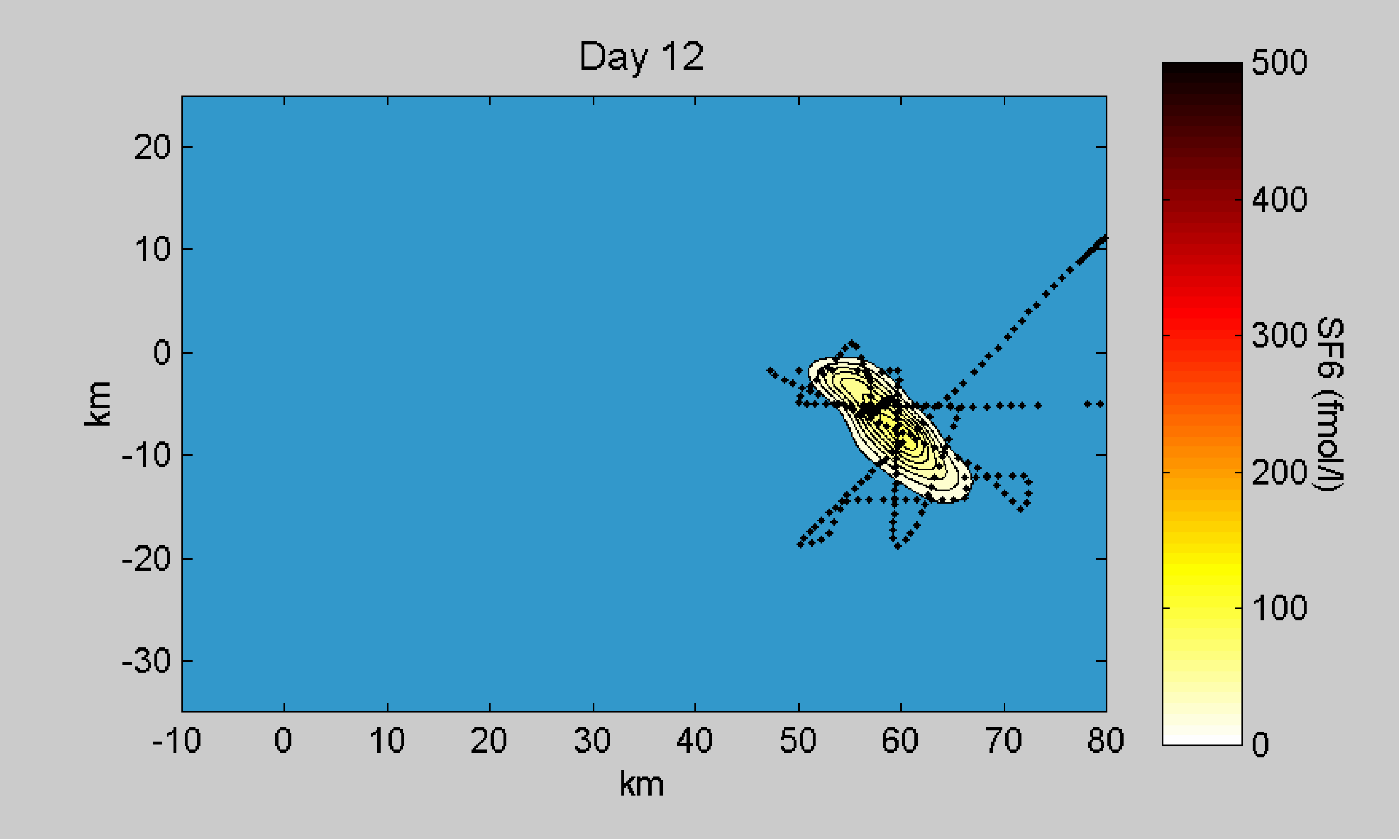


Day 9
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)


Day 10
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)


Day 11
km
km
SF6 (fmol/l)
20
10
0
-10
-20
-30
-10
0
10
20
30
40
50
60
70
80
500
400
300
200
100
0


Day 12
km
km
SF6 (fmol/l)
20
10
0
-10
-20
-30
-10
0
10
20
30
40
50
60
70
80
500
400
300
200
100
0

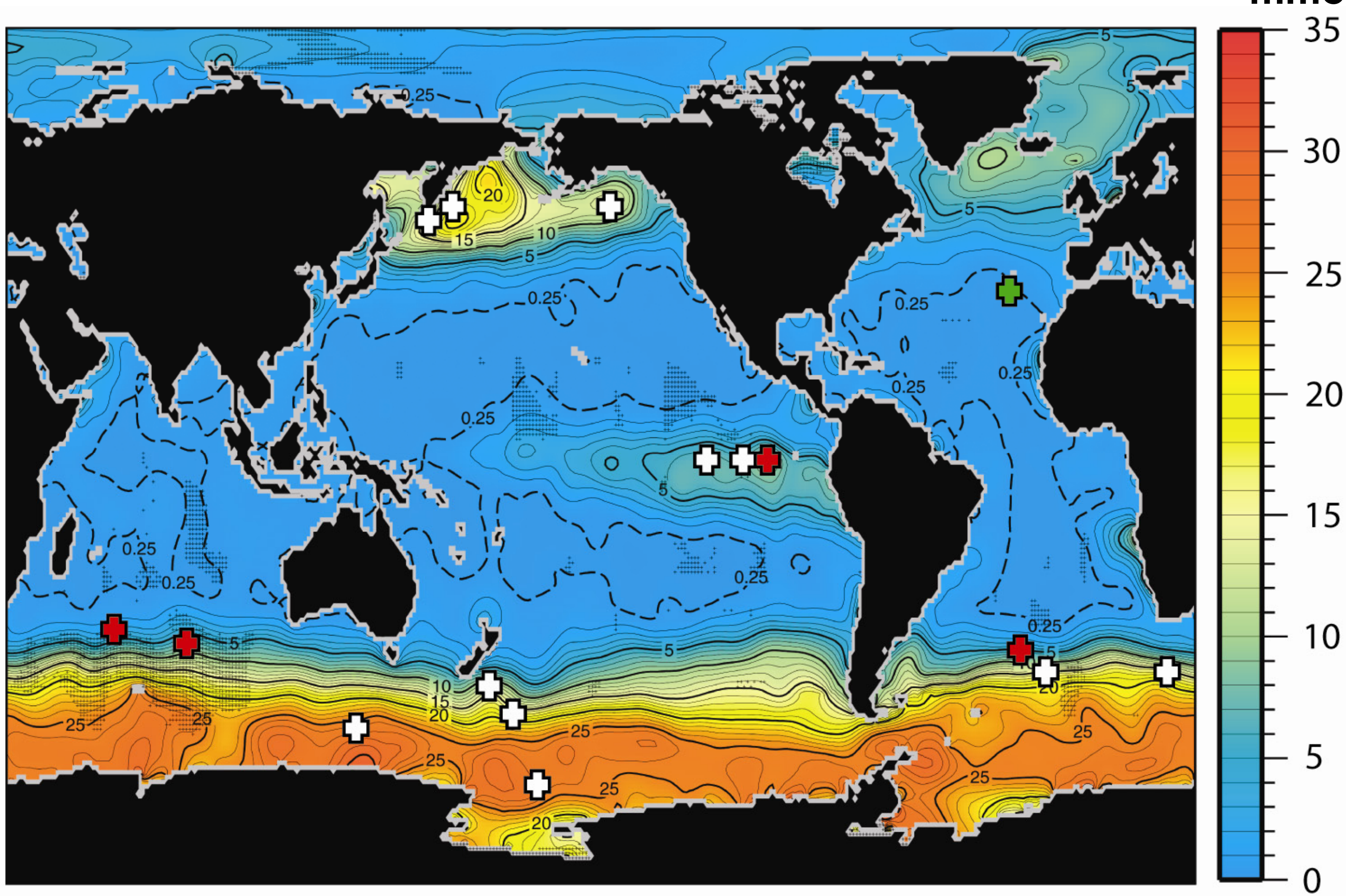


Day 12
20
10
0
-10
-20
-30
km
-10
0
10
20
30
40
50
60
70
80
km
500
400
300
200
100
0
SF6 (fmol/l)

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

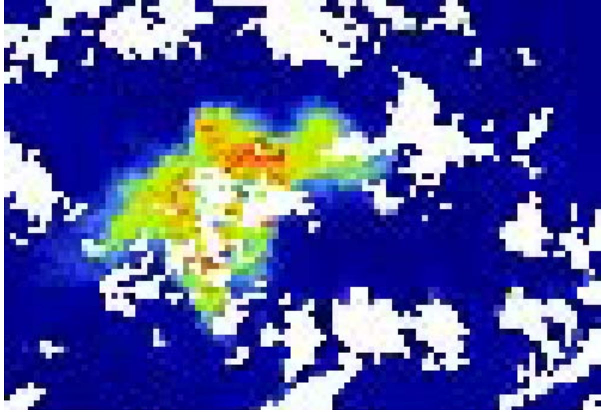
11 mesoscale Fe experiments in > 10 years



+Fe (HNLC)   High Fe   +Fe (LNLC)

Boyd et al. (2007)

Range of initial conditions for iron experiments

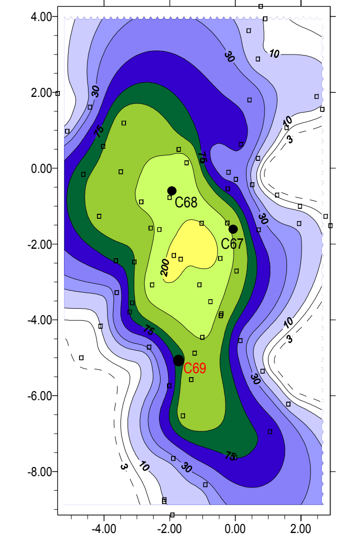


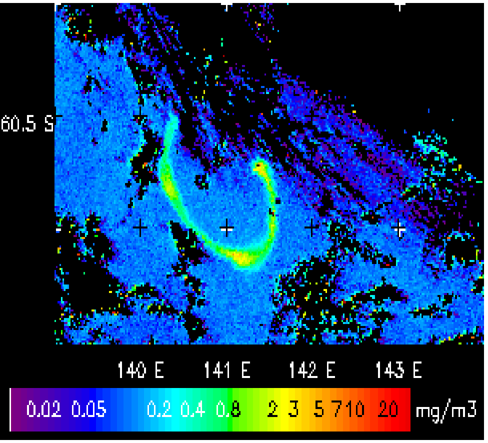
- *Temperature*
- *Mixed-layer depth*
- *Light climate*
- *Silicic acid*
- *Dissolved Fe*
- *Chlorophyll*
- *Season*
- F_v/F_m

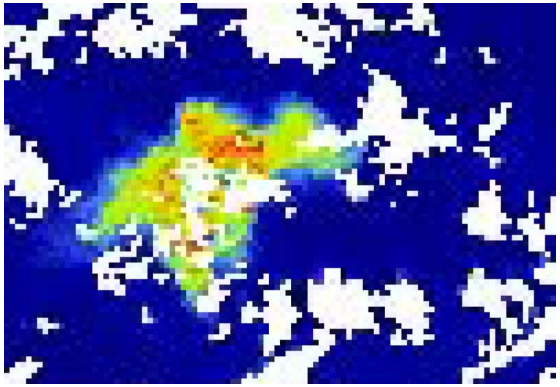
- -1 to > 24 C
- 13 to 100 m
- 45 to 250 umol m^{-2} s^{-1}
- 2 to 60 umol l^{-1}
- 0.04 to 0.10 nmol l^{-1}
- 0.2 to 0.9 ug l^{-1}
- Spring to autumn
- 0.2 to 0.3

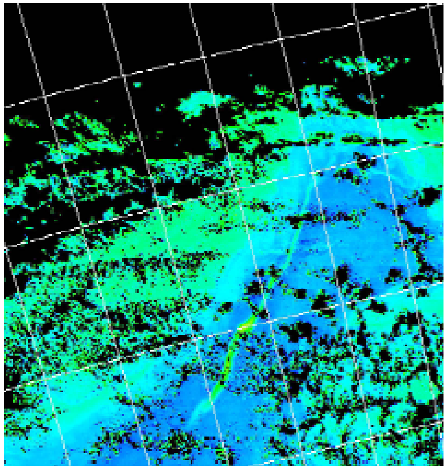
Common findings in mesoscale iron experiments

A similar experimental design was used in all studies



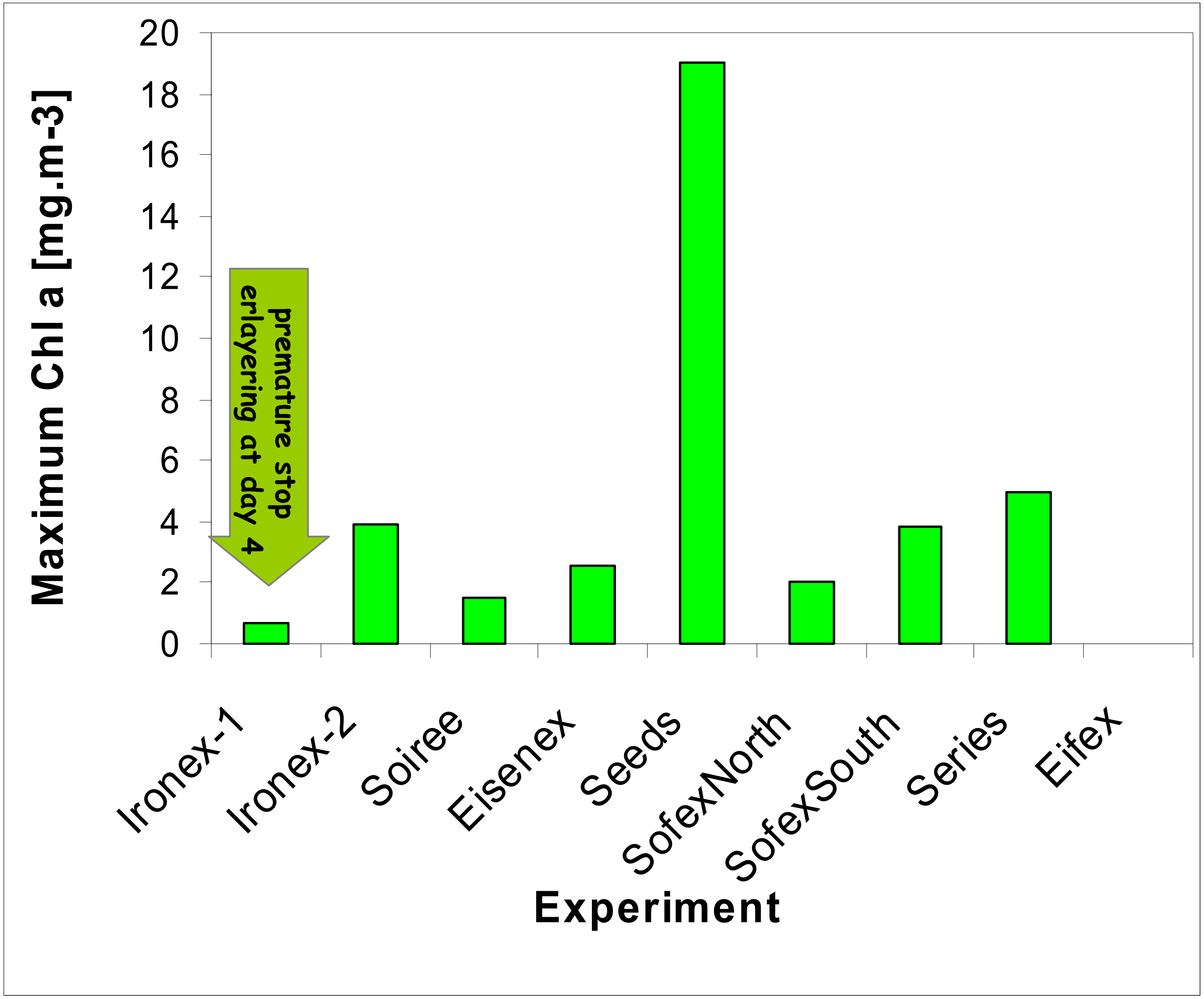






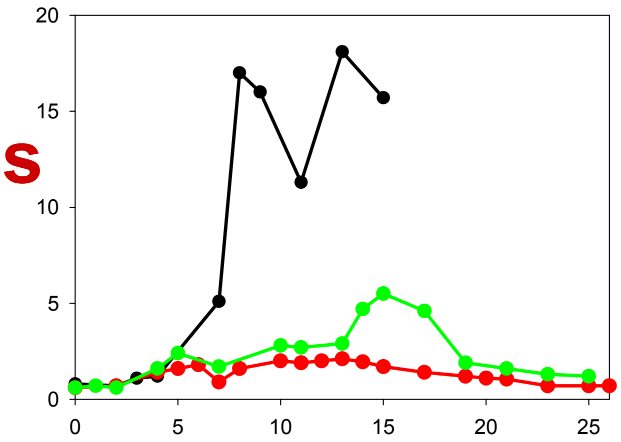
Virtually all experiments resulted in blooms

A wide range in bloom signatures



De Baar et al. (2005)

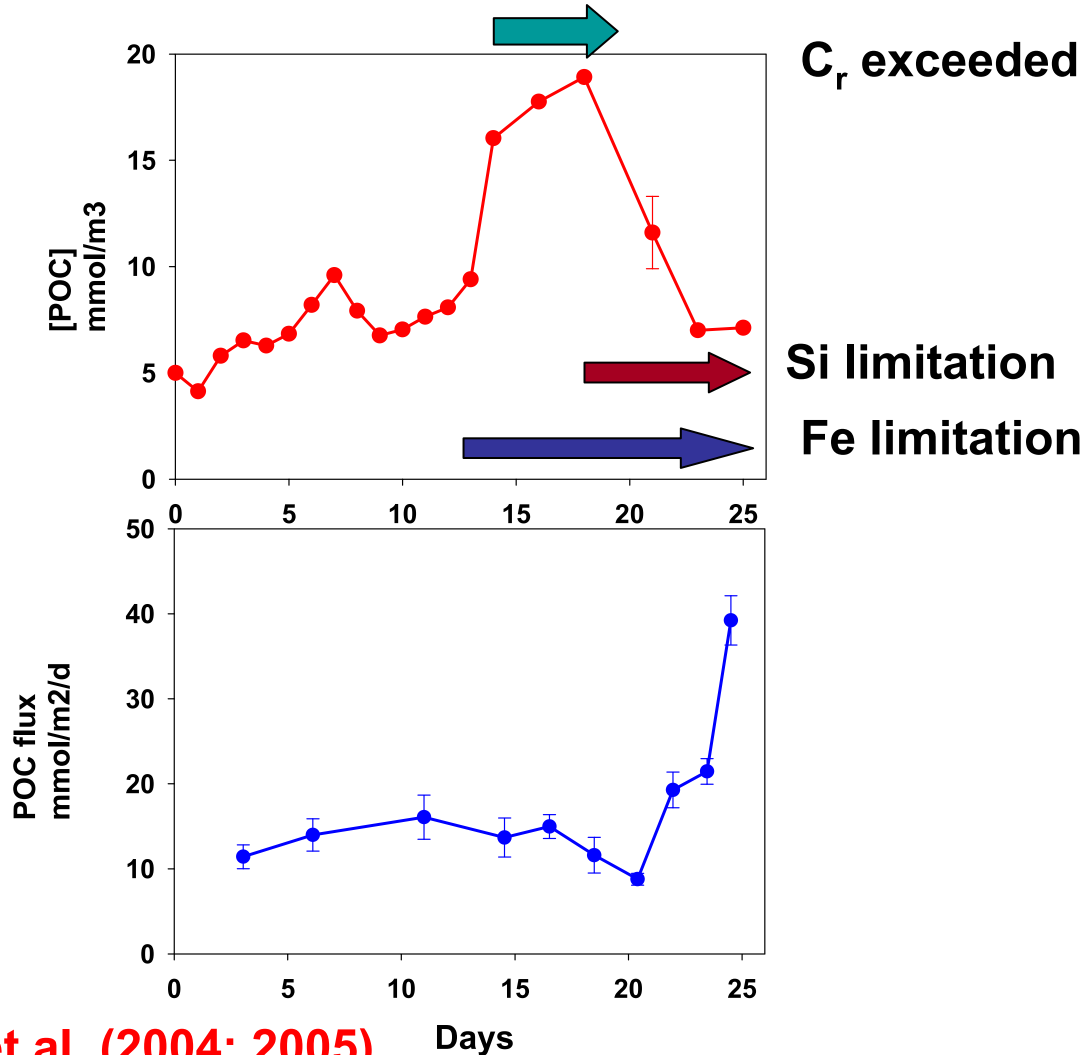
Factors controlling bloom signatures

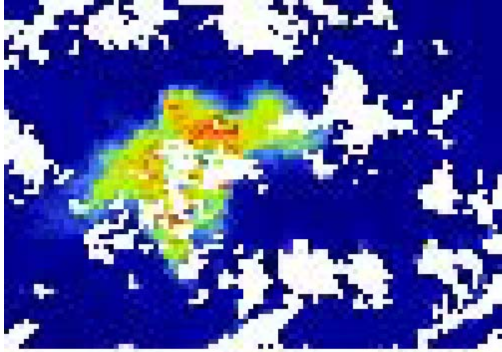


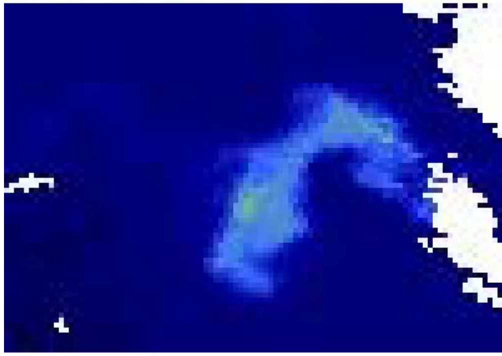
- *Environmental*
- Initial conditions - optical, chemical, plankton community
- Underlying physics – dilution rate 0.05 versus 0.07-0.16 d^{-1}
- Interplay of conditions

- *Experimental*
- Fe supply – magnitude and timing
- Duration
- Site selection
- Sampling interval

The development of a mechanistic understanding of what controls bloom longevity







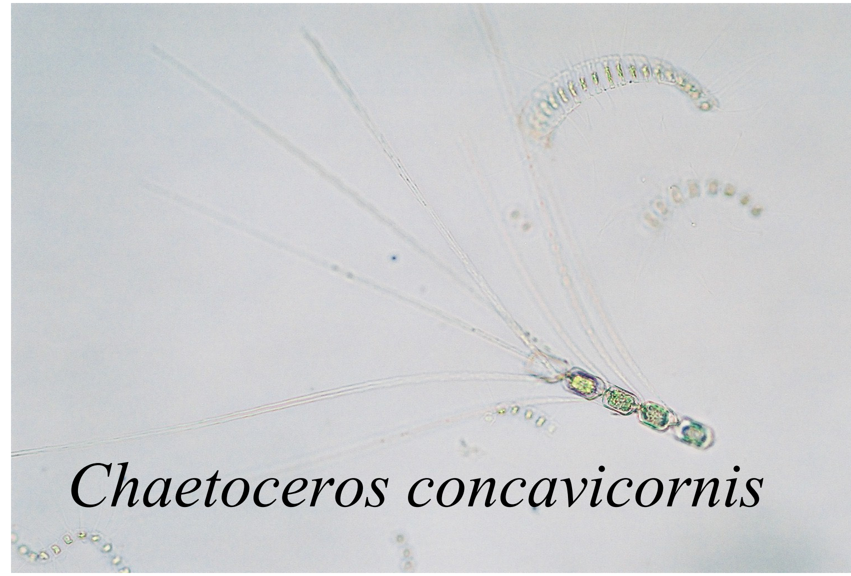
Boyd et al. (2004; 2005)

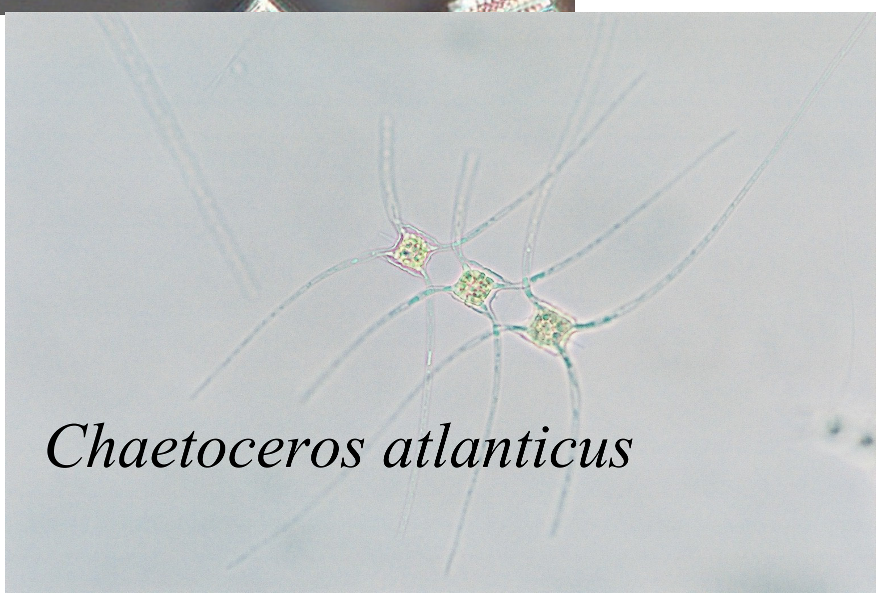
The wide-ranging influence of iron supply

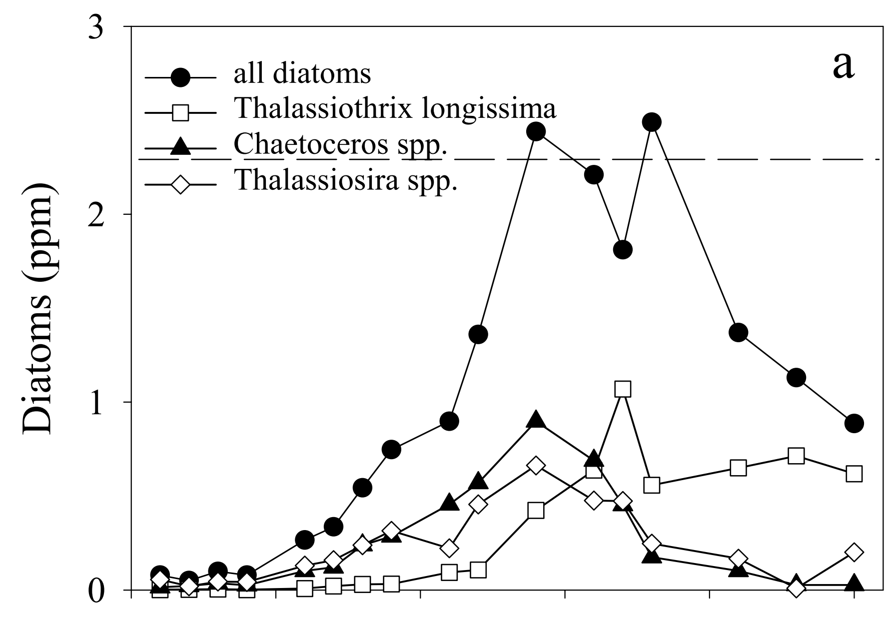
- DIRECT
- Photosynthesis
- Growth rate, NPP
- Nutrient uptake (Si:N)
- Species composition
- Exudation - DOC
- Bacterial processes
- Biogenic gases
- Grazer physiology
- Siderophore production

- *INDIRECT*
- *S, C, N, Si biogeochemistry*
- *Export flux*
- *Gas efflux and drawdown*
- *Foodweb structure*
- *Zooplankton growth and reproduction*
- *Faunistic shifts*

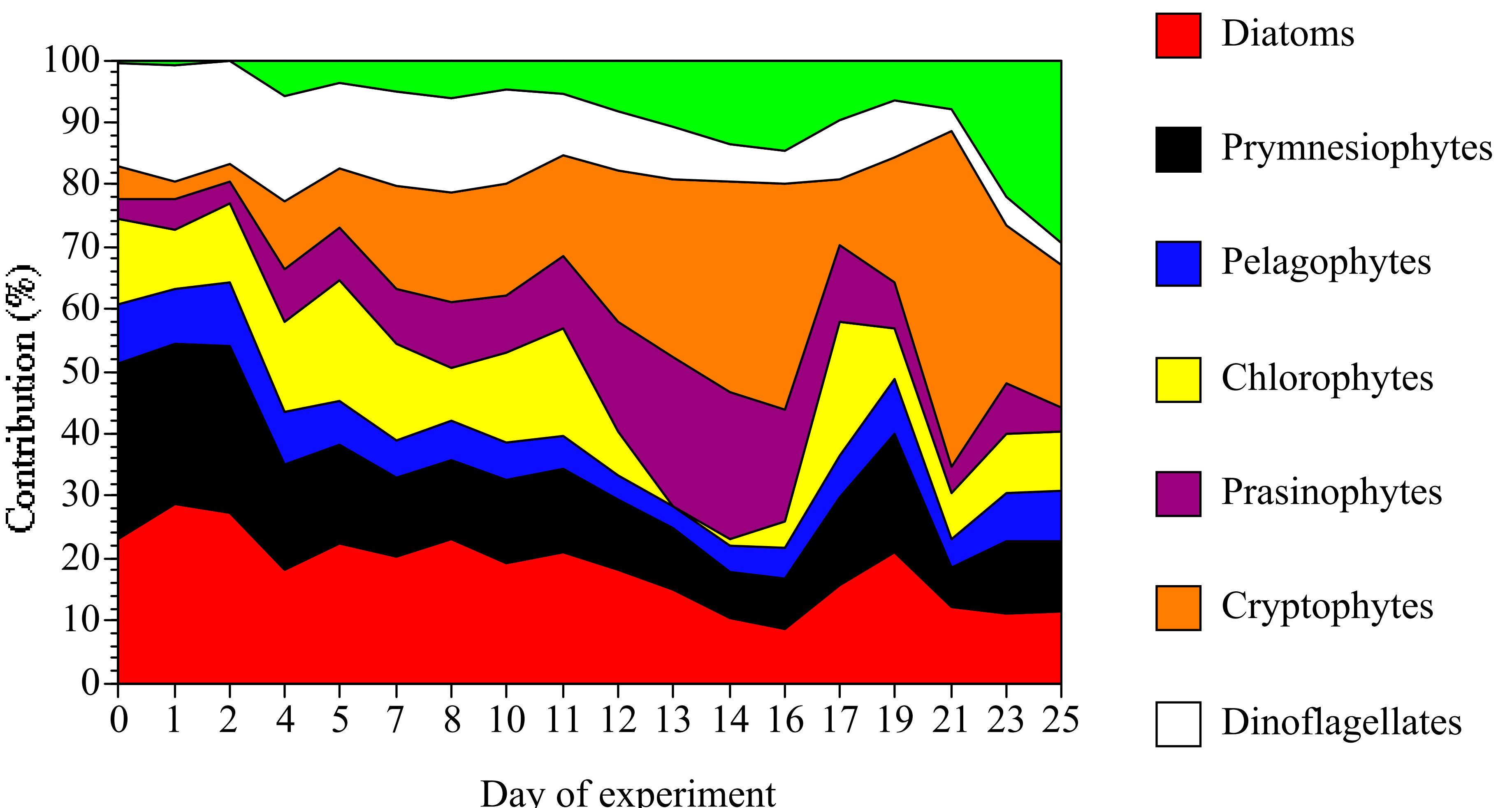
The blooms were mainly dominated by larger phytoplankton - diatoms





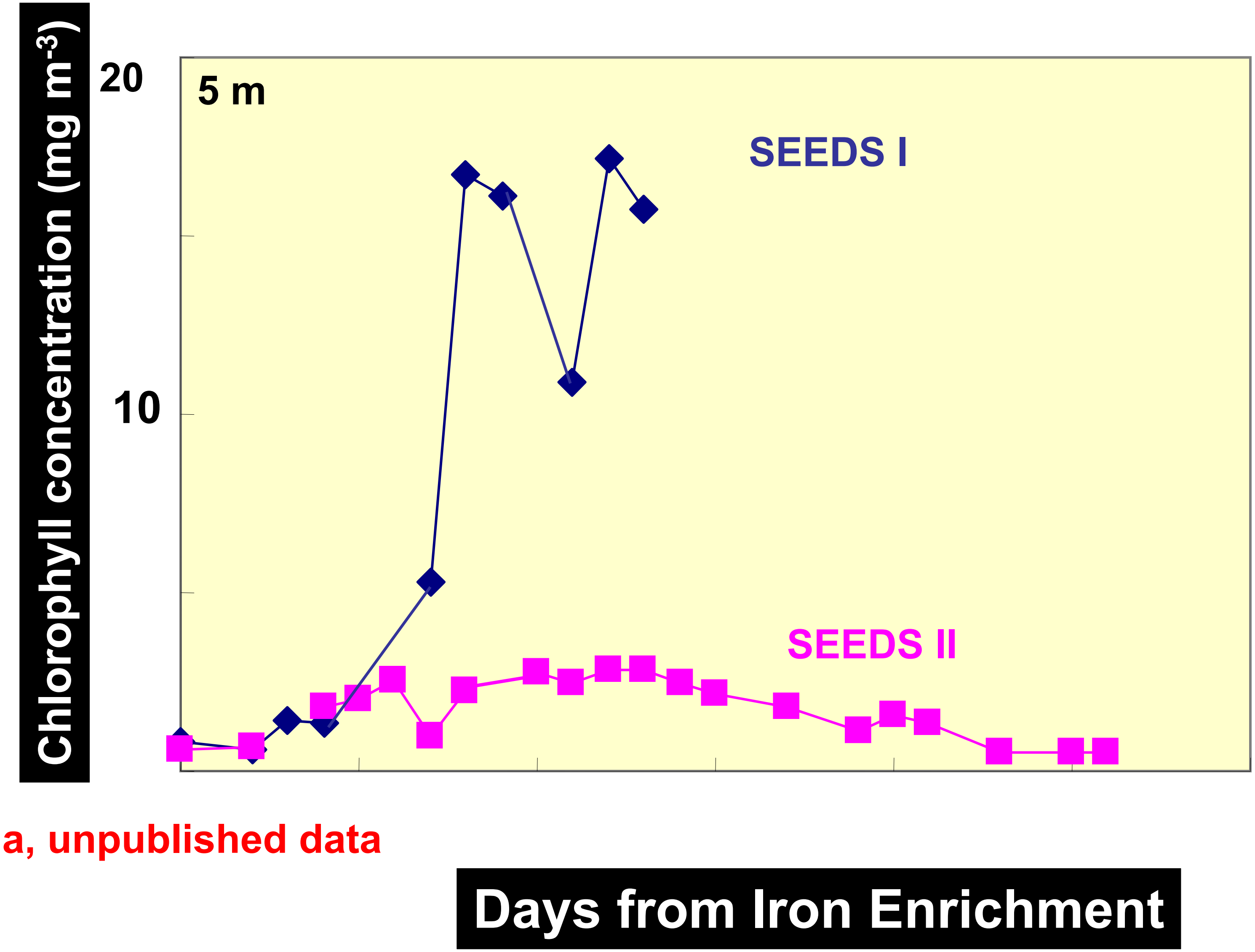


Phytoplankton composition (+Fe, SEEDS II)



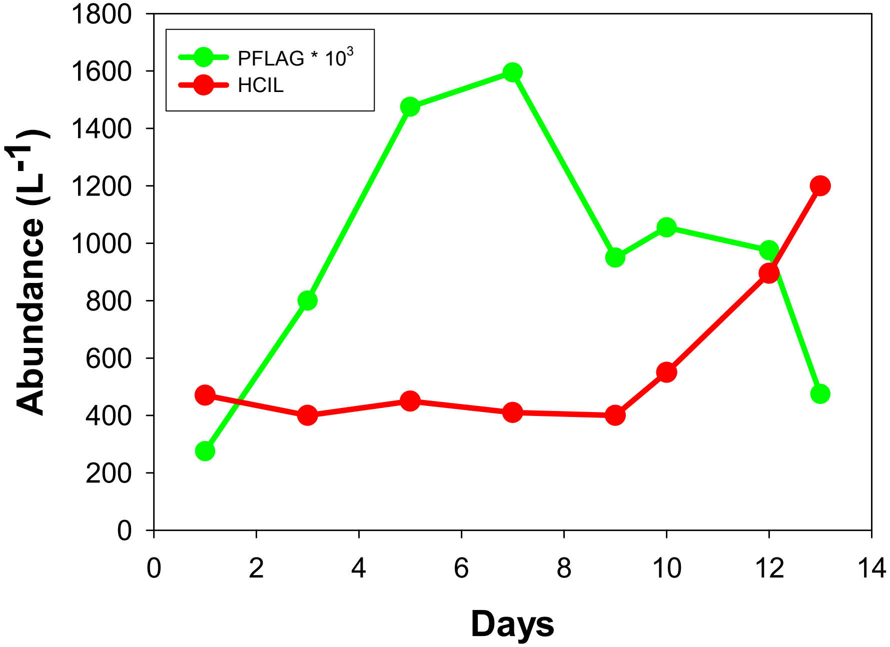
Tsuda, unpublished data

The importance of the initial stocks of phyto- & zoo-plankton

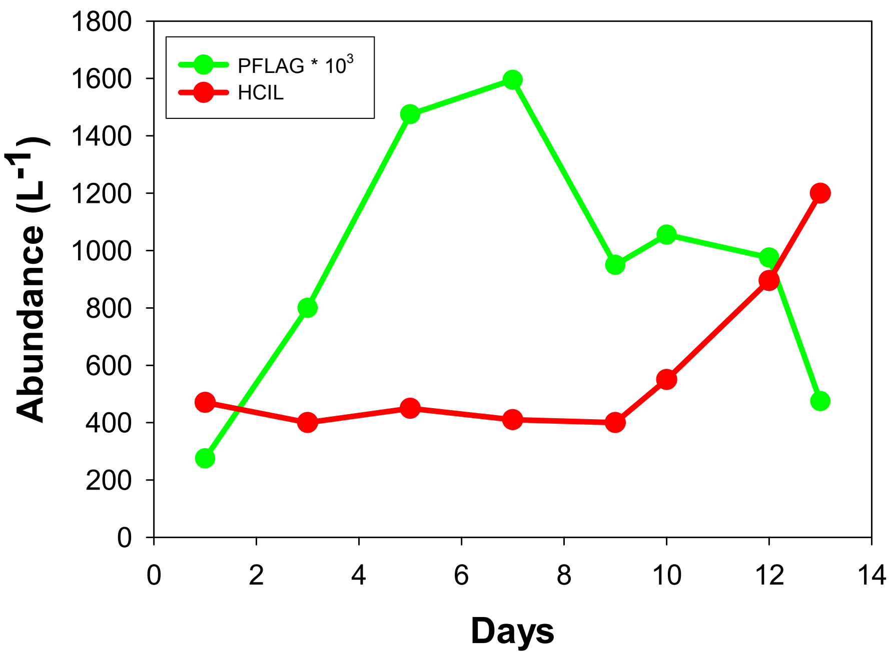


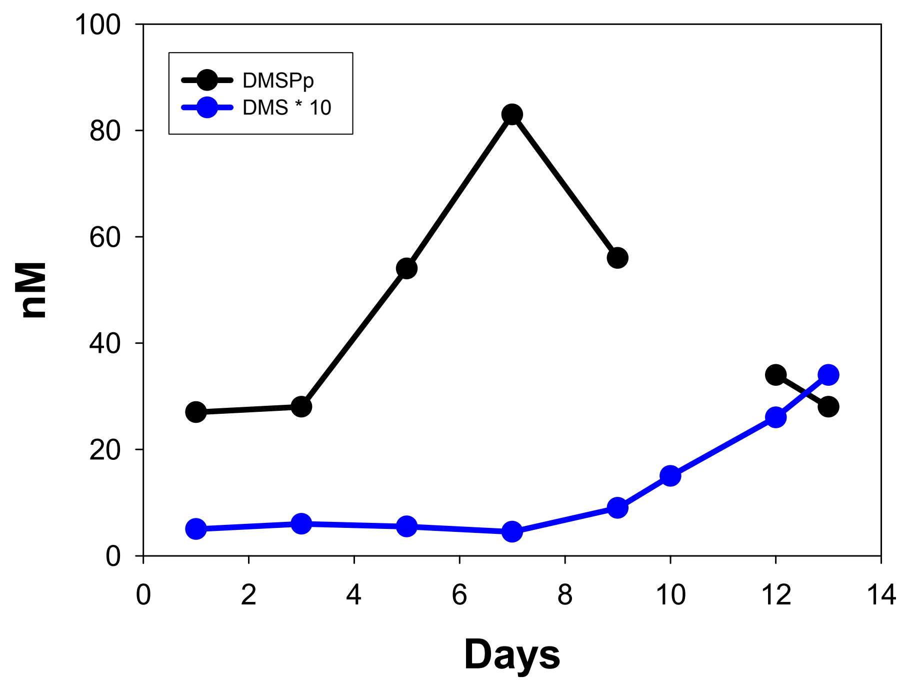
Tsuda, unpublished data

Mesoscale Fe-enrichments provide a holistic view of the foodweb



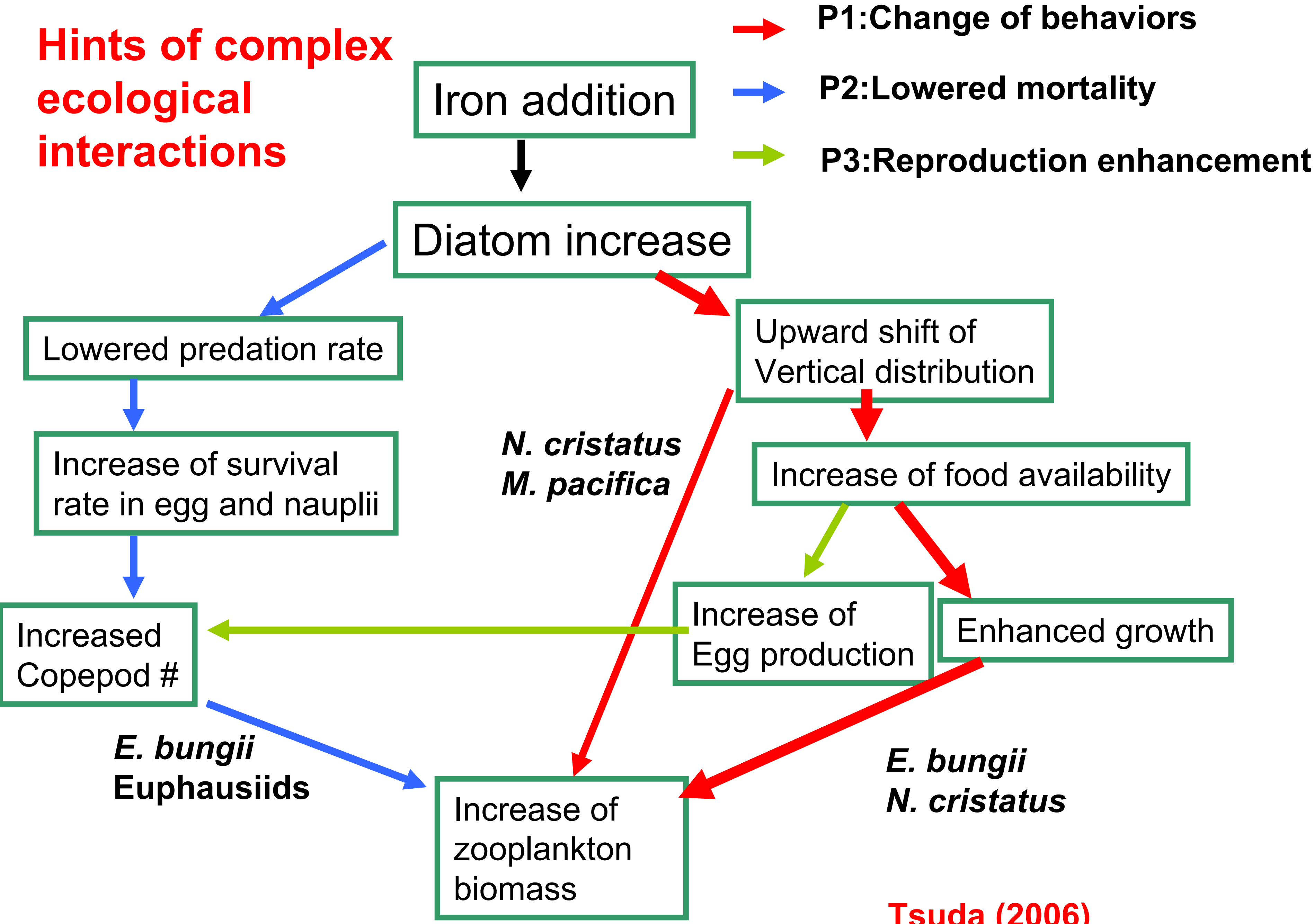
Mesoscale Fe-enrichments provide a holistic view of the foodweb and how it impacts biogeochemical cycles





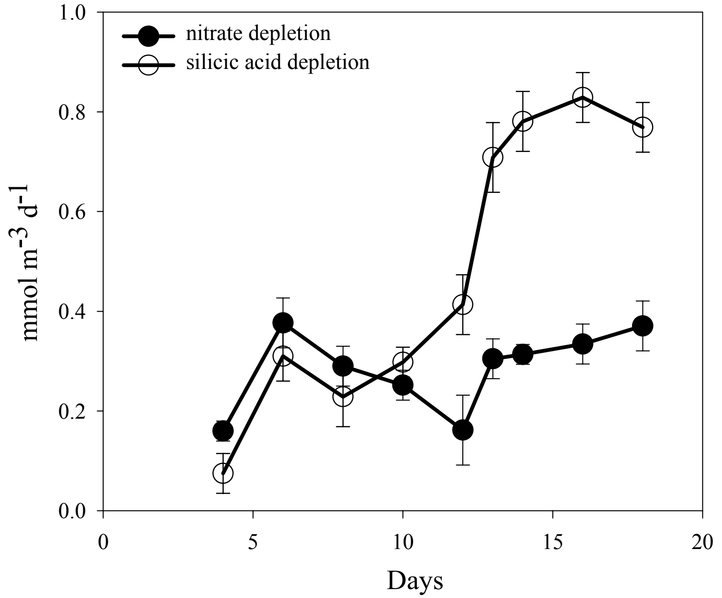
Boyd and Doney 2002

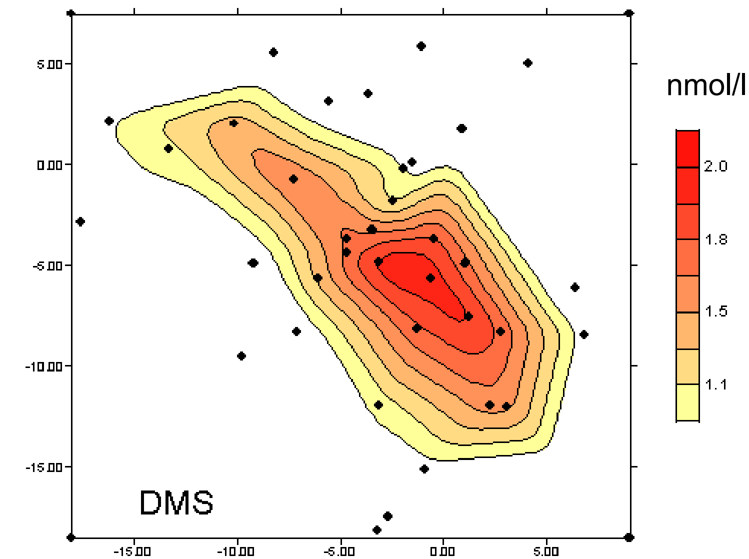
Hints of complex ecological interactions

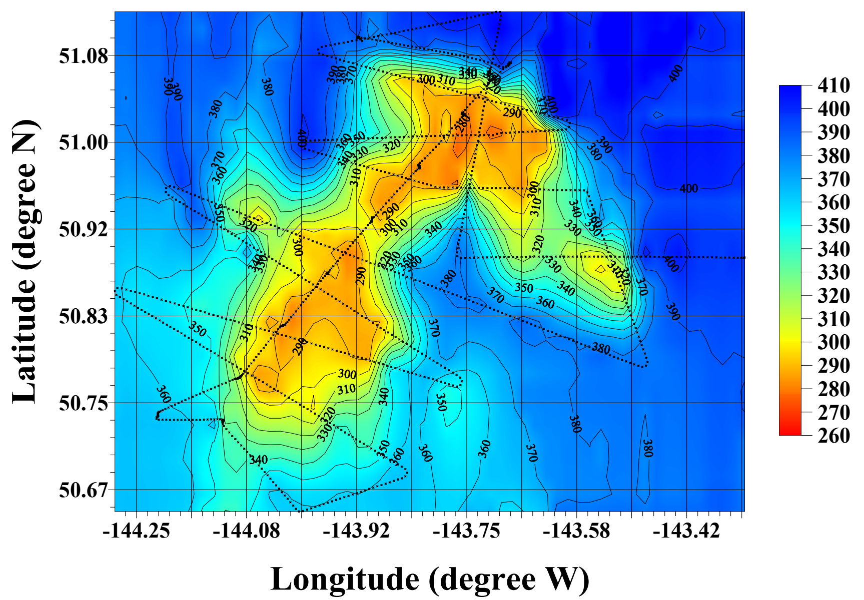


Tsuda (2006)

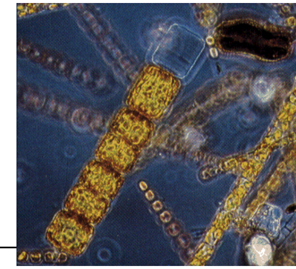
Fe supply impacts the biogeochemical cycles of multiple elements



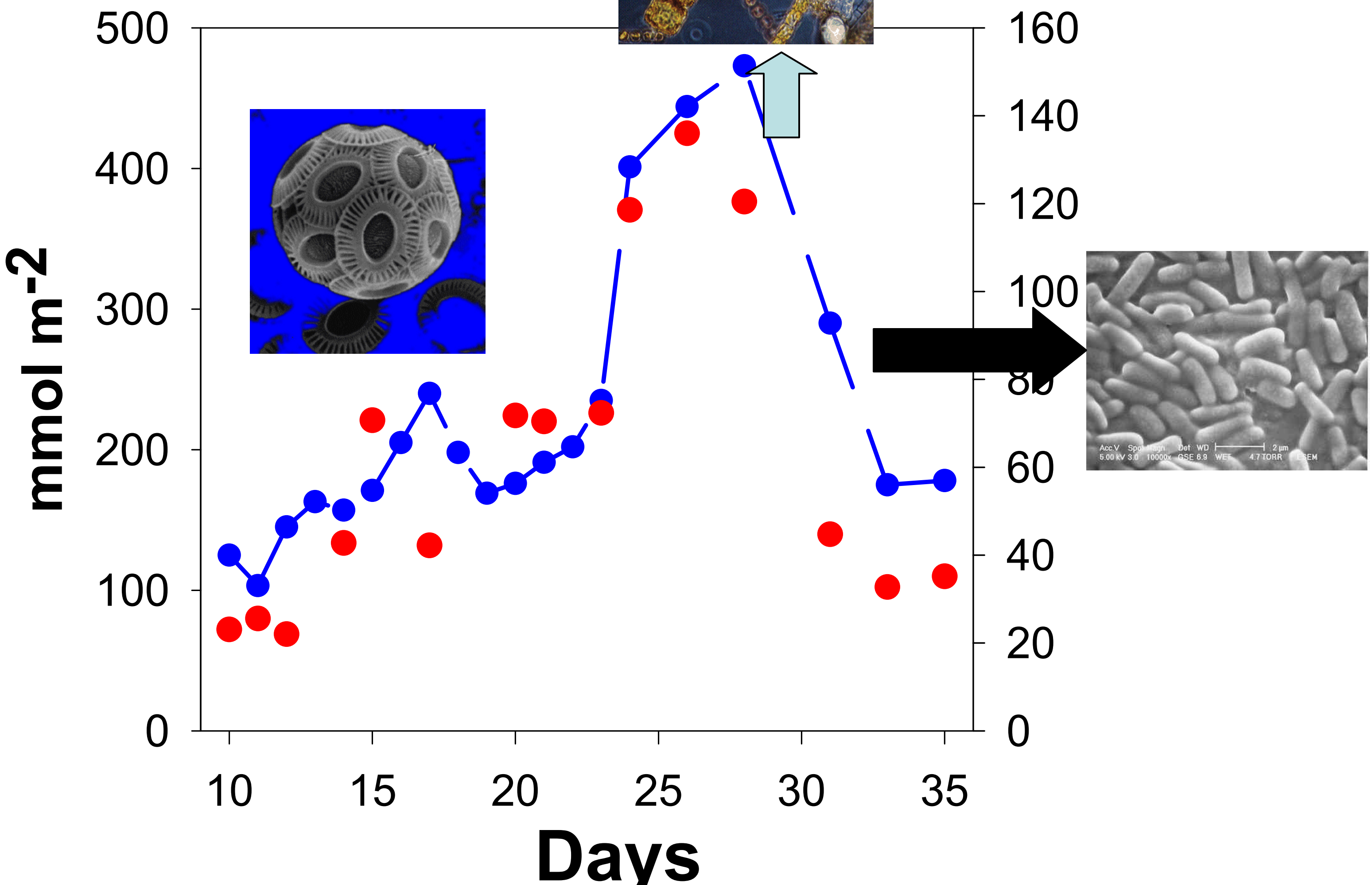




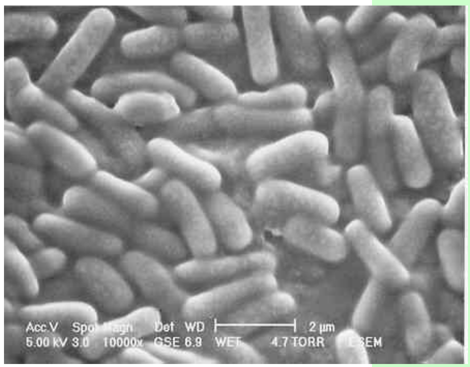
DIFFERENT MICROBES DOMINATE EACH PHASE OF THE BLOOM

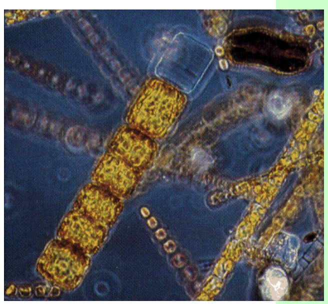


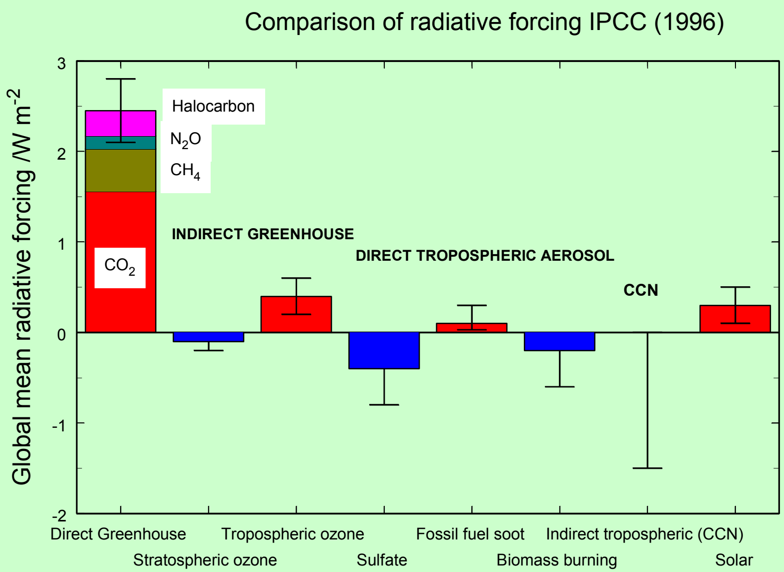
POC

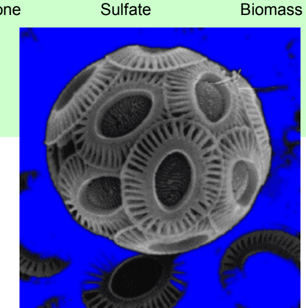


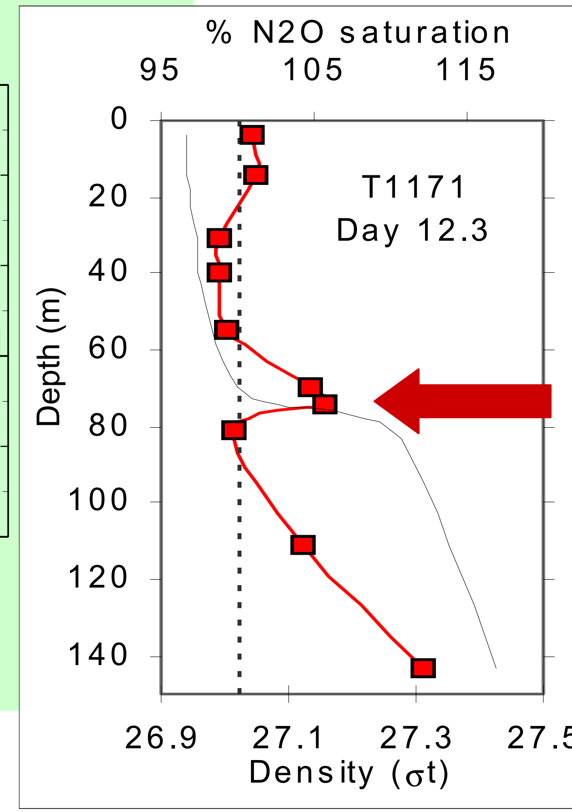
Influences other climate-reactive gases?







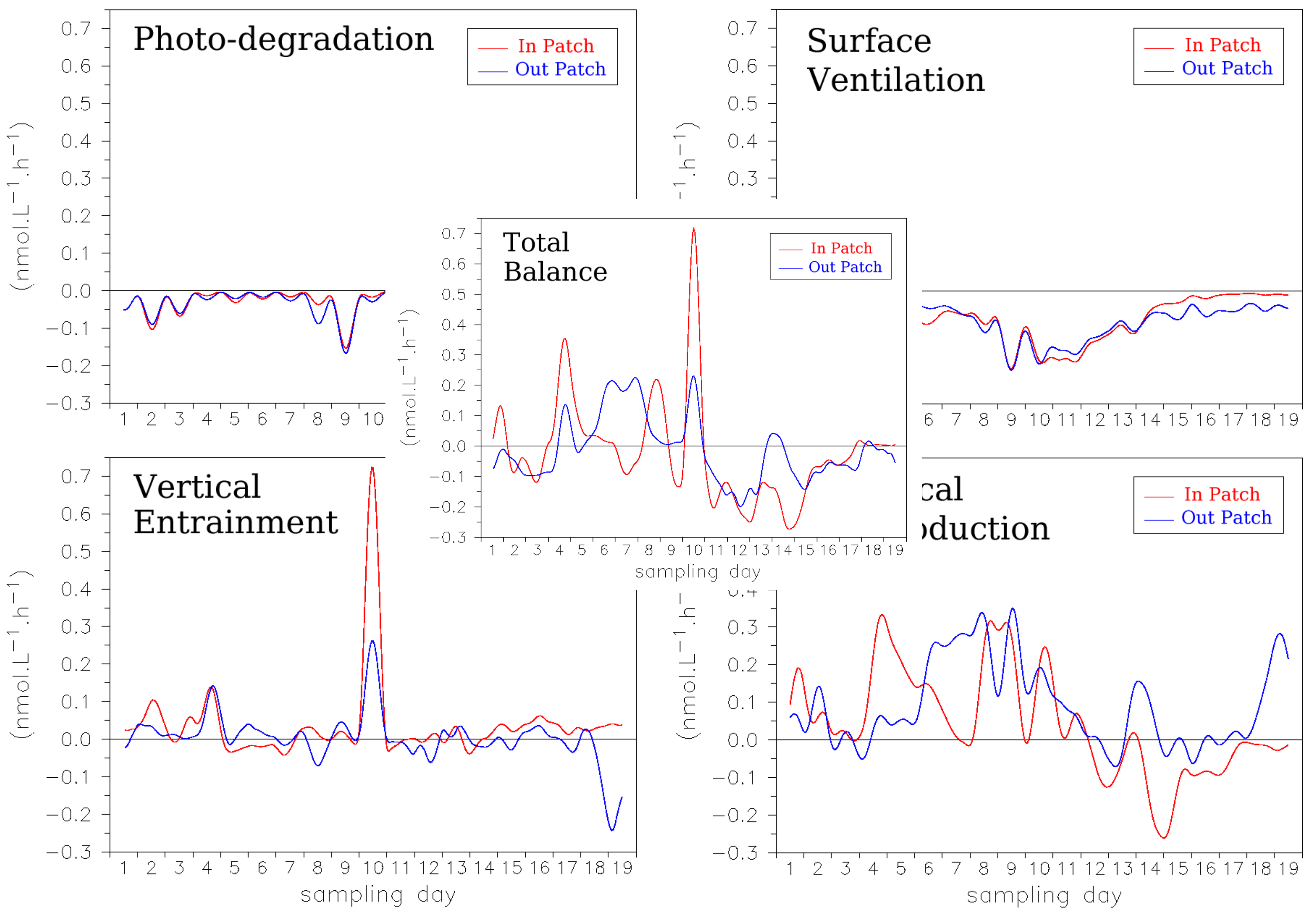




Law & Ling (2001)

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



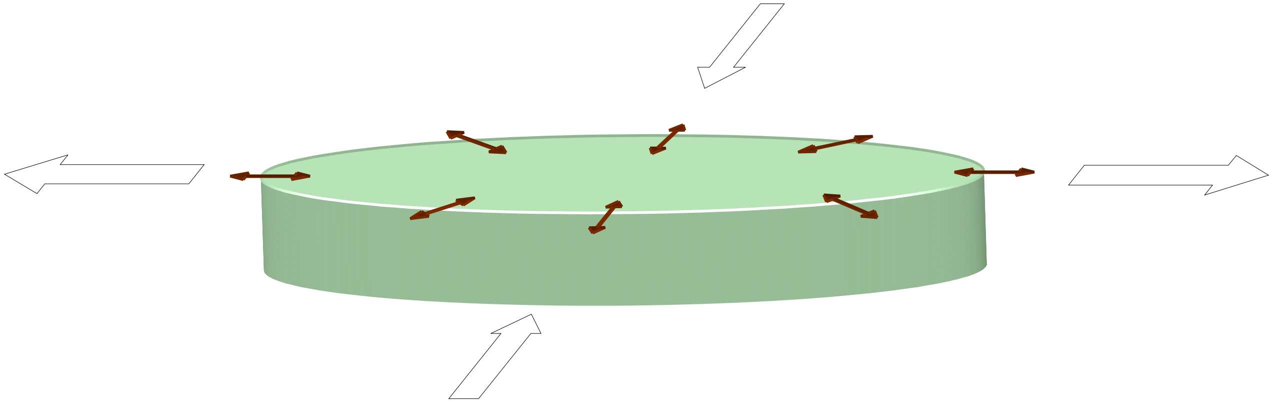
What have we learned from past iron fertilization experiments?

Case study - Ocean Physics and bloom signatures

Physics modifies bloom biogeochemistry & fate
Location, location, location -Subduction & patch drift

oceanironfertilization
come to listen • learn • debate • explore

Experimental artefacts even in 200-1000 km^2 experiments

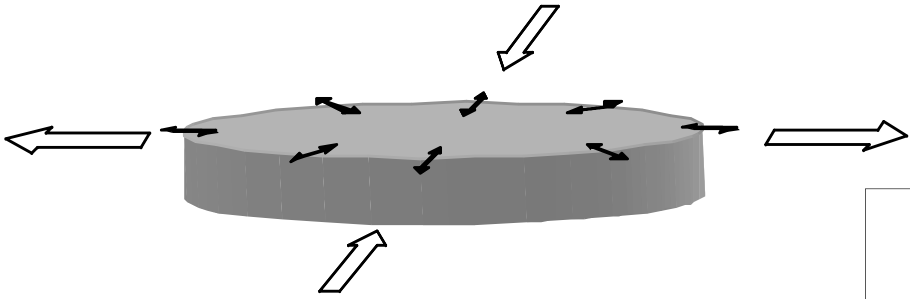


The continual stretching by the horizontal currents creates a chemostat – changing the concentrations of properties in and outside the patch by mixing, and regulating phytoplankton growth - Boyd & Law (2001)

OUT
Phytoplankton
Iron

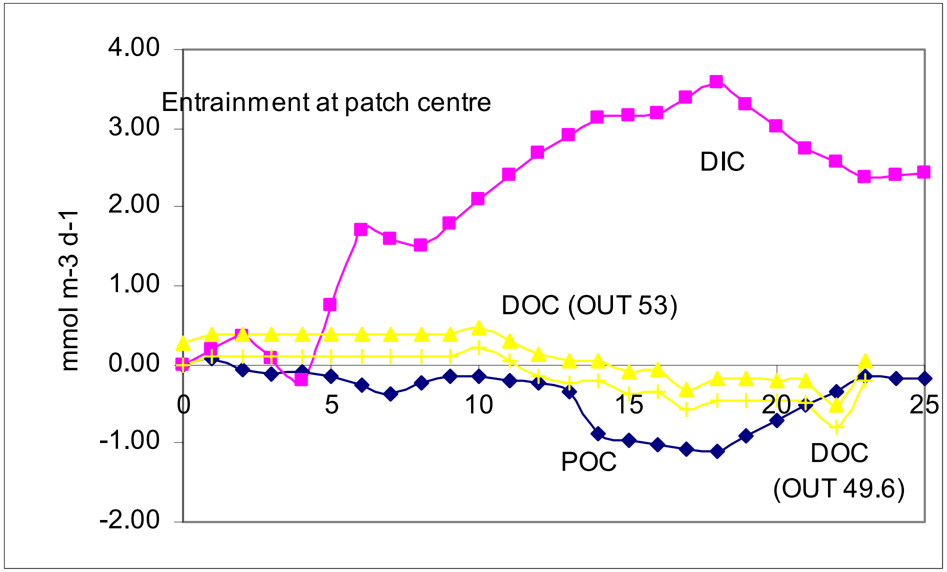
IN
Nutrients
DIC

Entrainment of surrounding HNLC waters which modifies the biogeochemical signature of the bloom



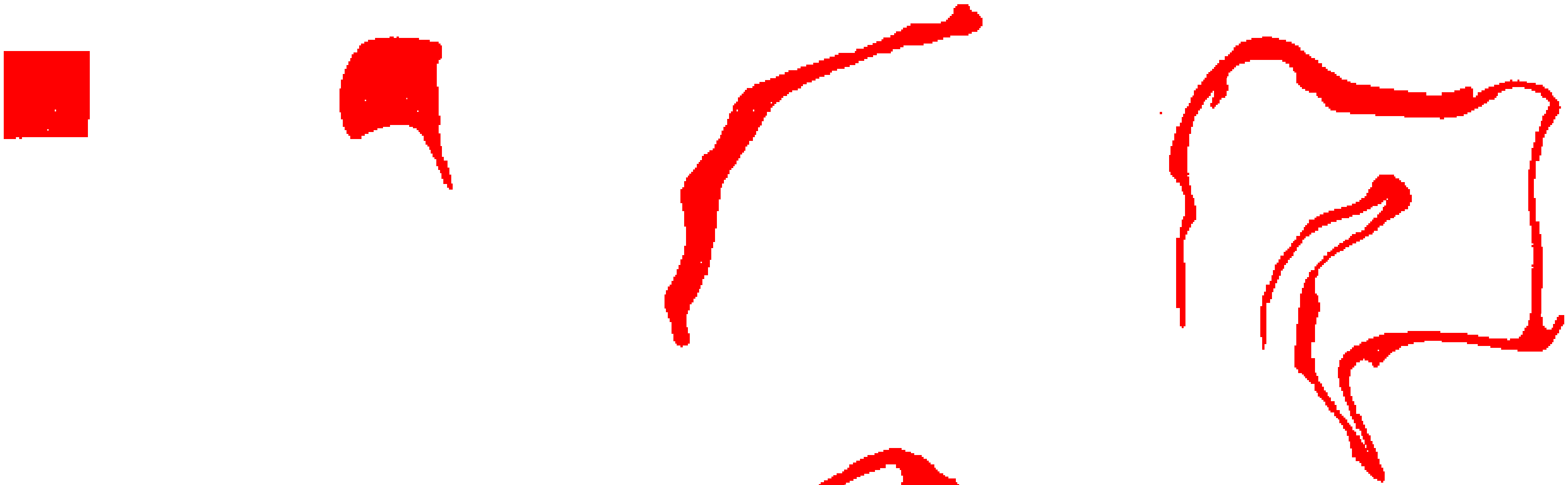
Stretching via horizontal flows

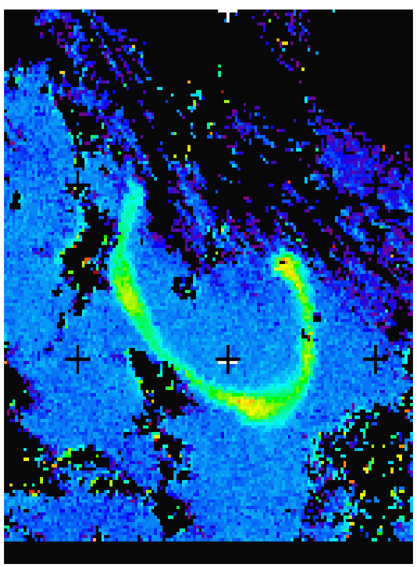
Mixing of water by horizontal diffusion

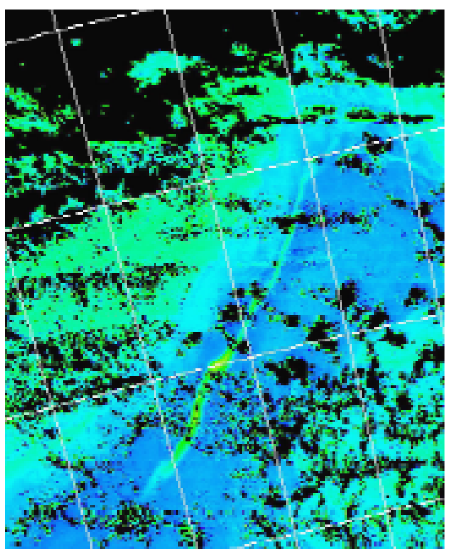


Law et al. (2006)

The stirring of a square of ink (Welander, 1955)





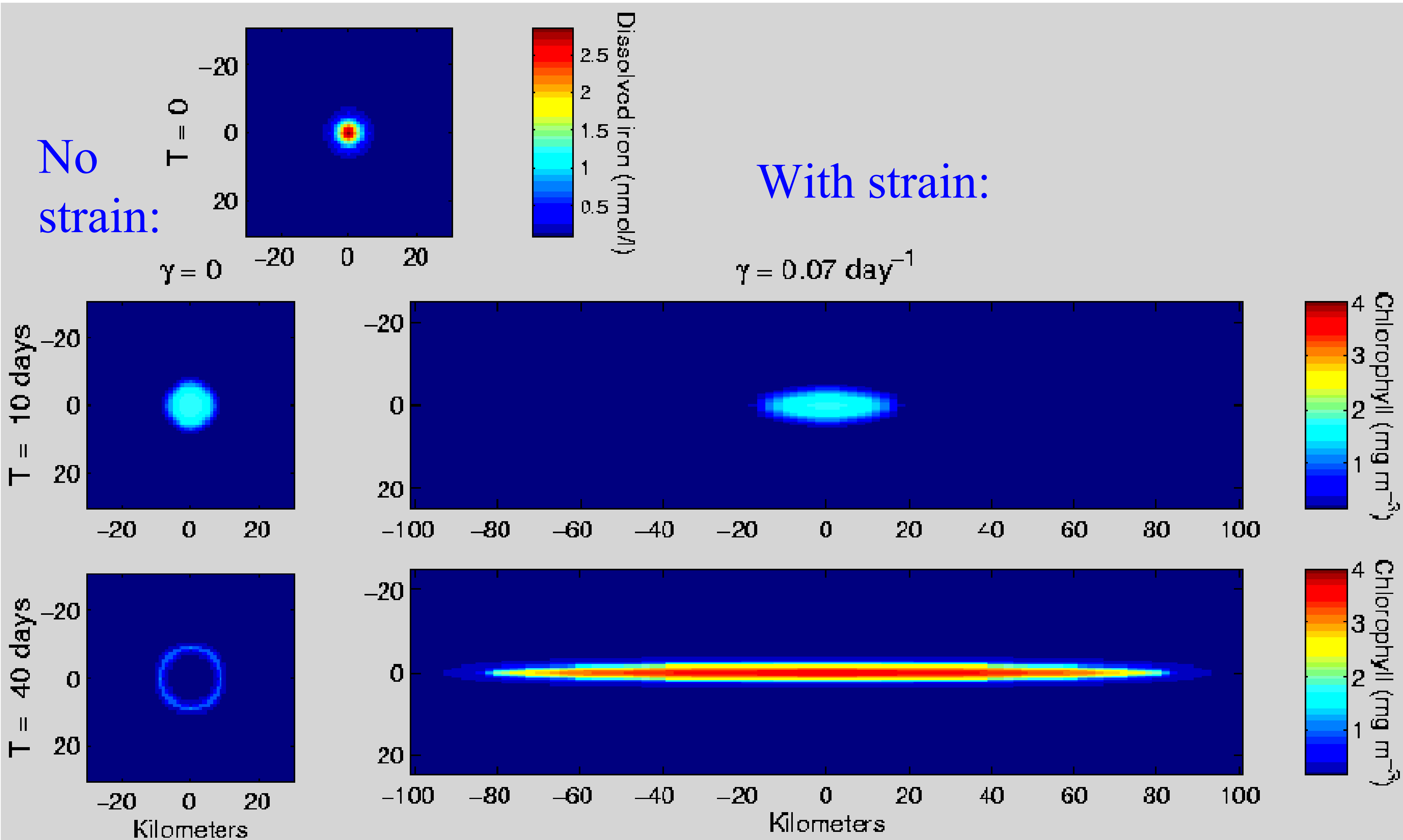


Abraham (1998, 2000)

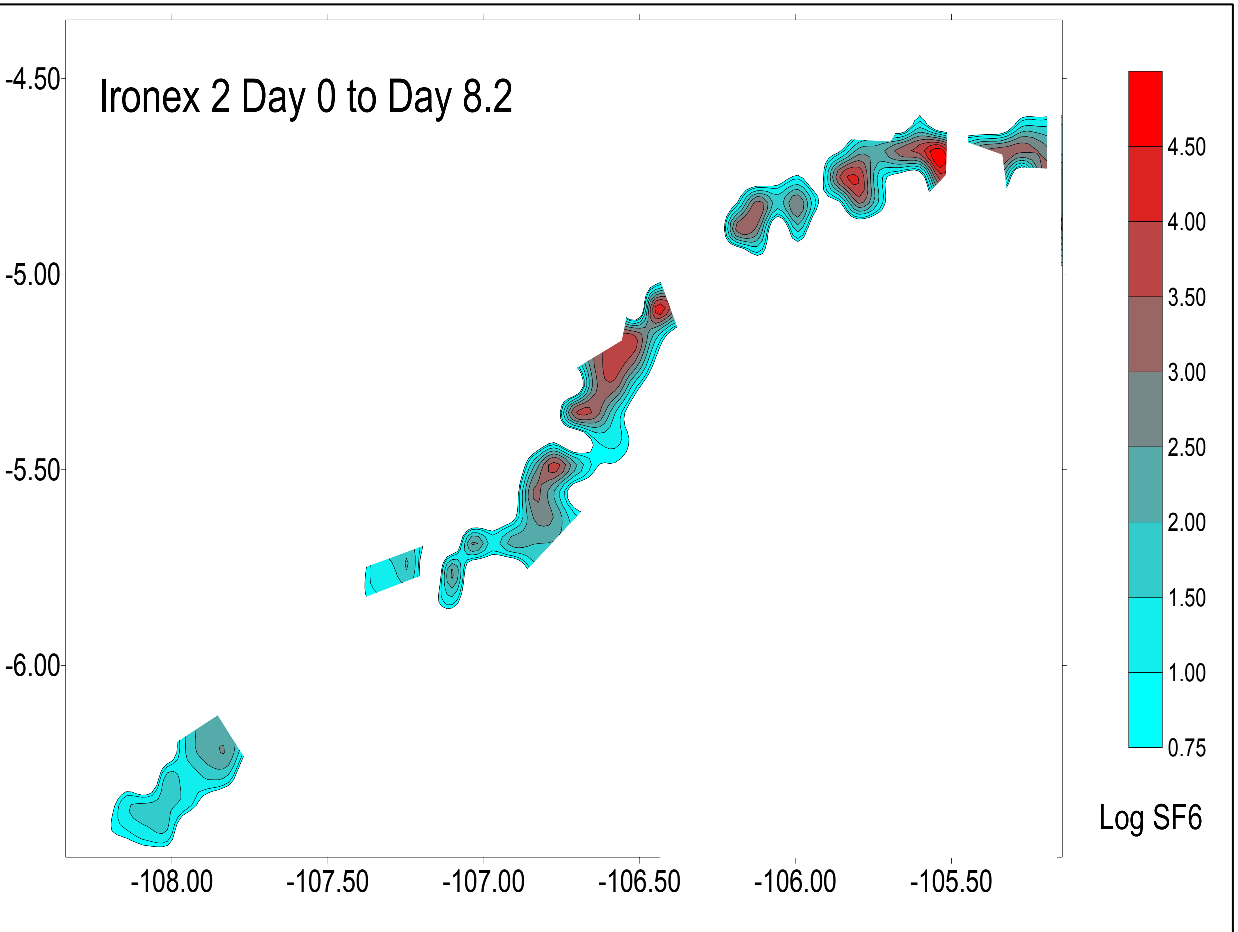
Growth phytoplankton in an Fe-enriched patch

(joint effects of iron and silicate)

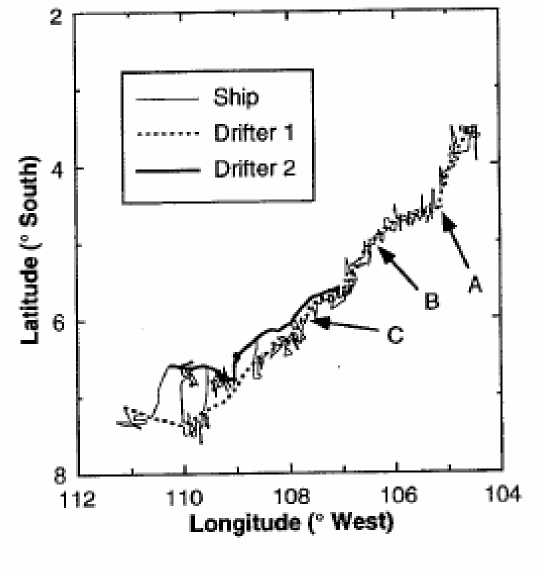
Abraham (2002)



Locale is important - Propagation by Currents - 1500 km of drift in 19 days

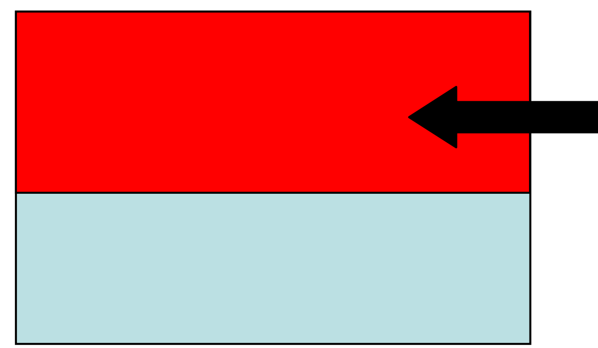


IronEx2 SF6 patch evolution
(P. Nightingale)



IronEx II (Coale et al., 1996)

OR Subduction
Capped by less dense waters



What have we learned from past iron fertilization experiments?

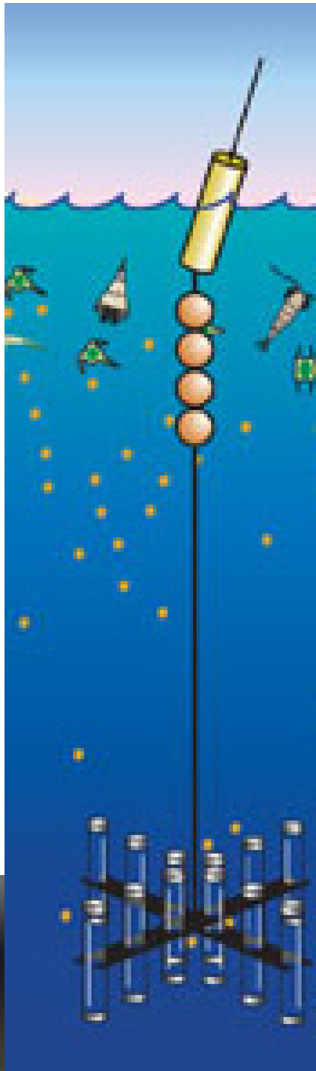
Case study - POC Export and Sequestration

Not all blooms resulted in more export

Decoupling of bloom development and export

Attenuance of export signal – sequestration

C exported per unit iron added



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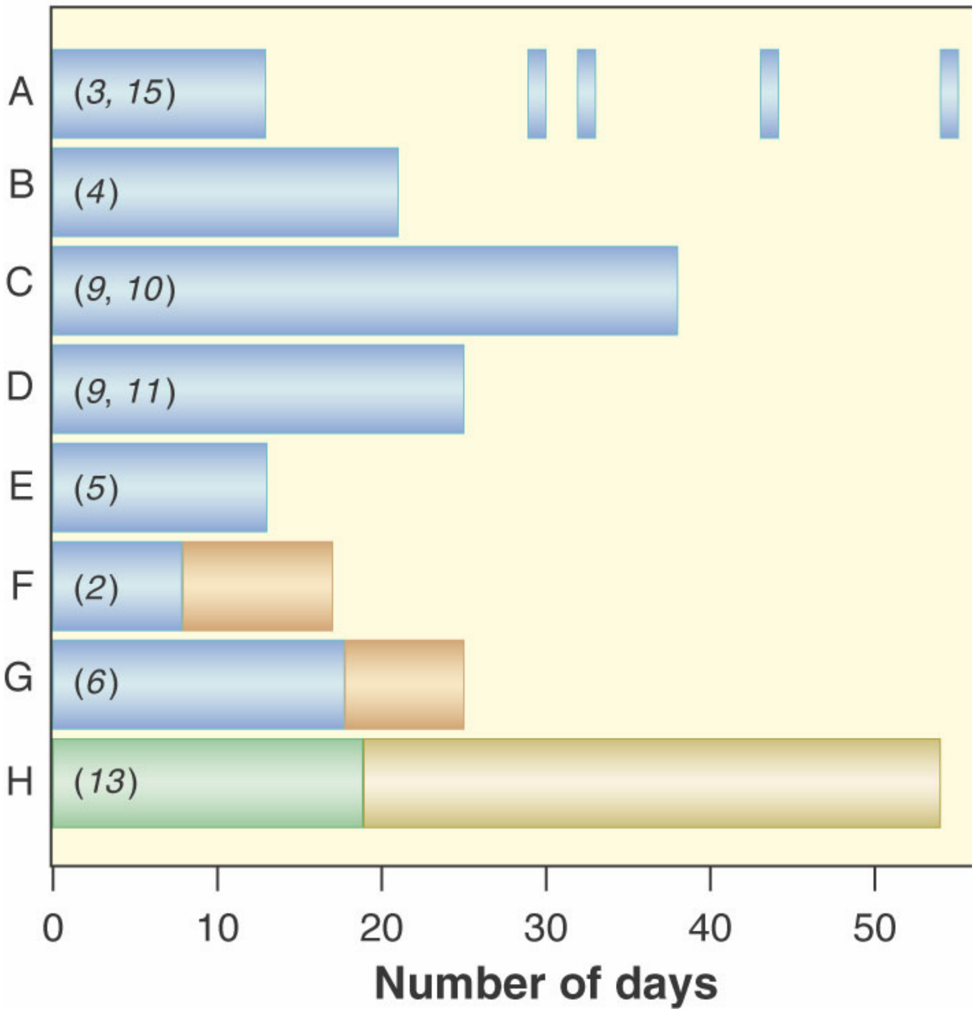
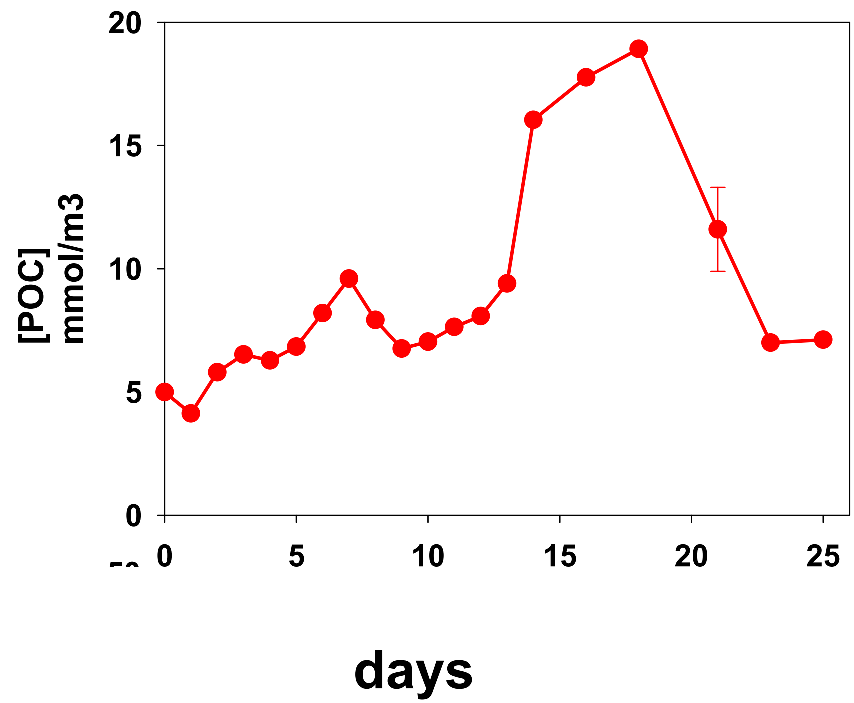
Marked differences in bloom status attained in Fe enrichments

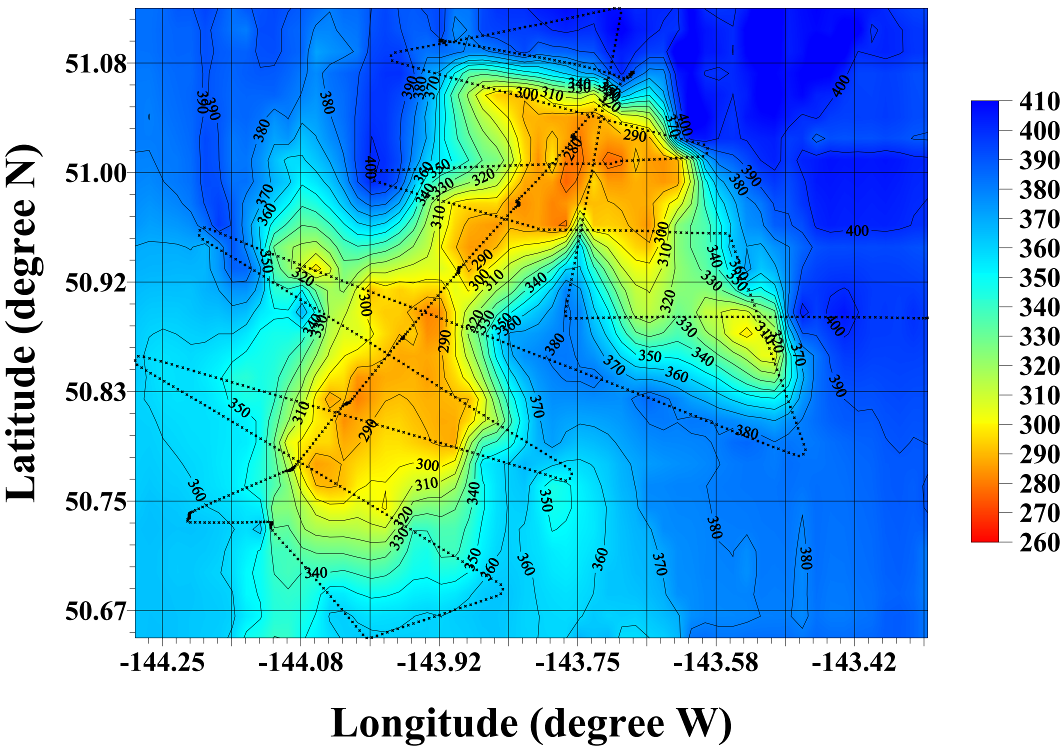


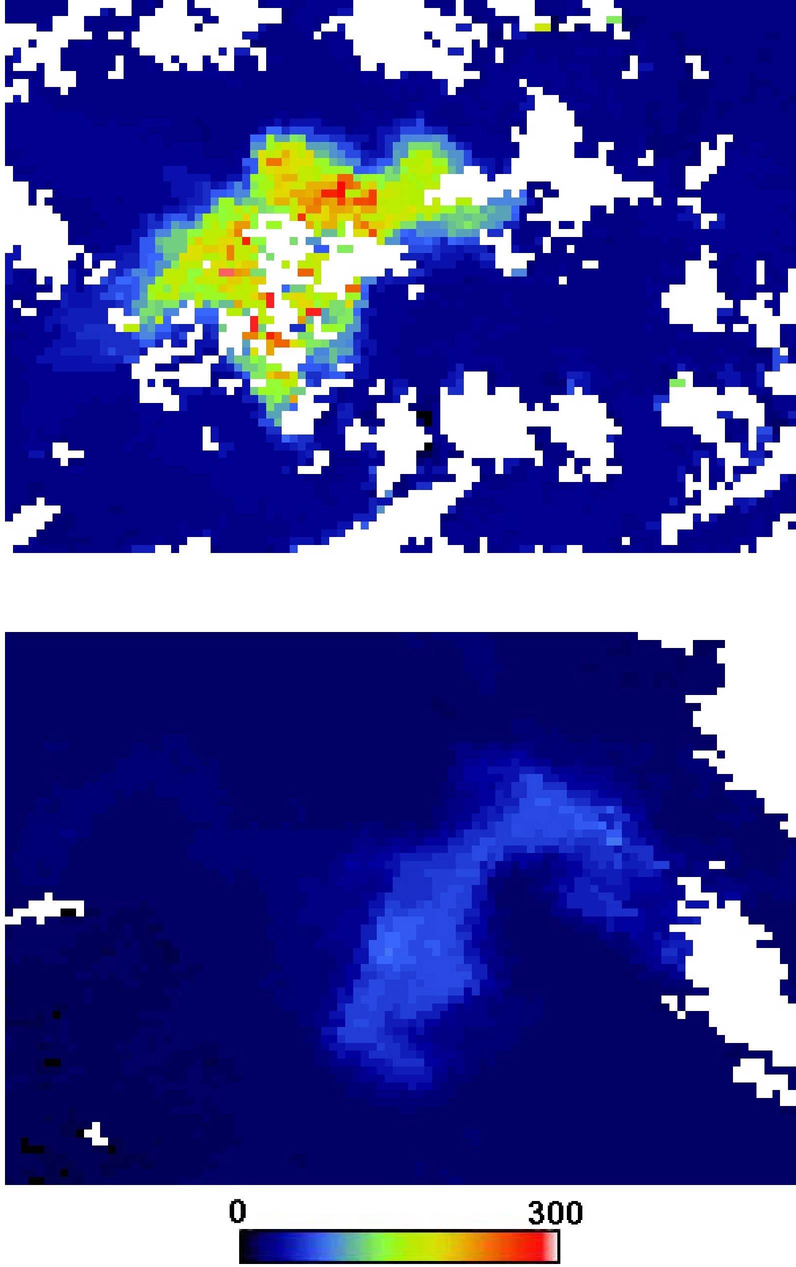


Boyd (2004)

Due to the range of experimental (duration) and/or environmental (MLD) conditions

Concurrent mapping of CO_2 drawdown, POC accumulation and export

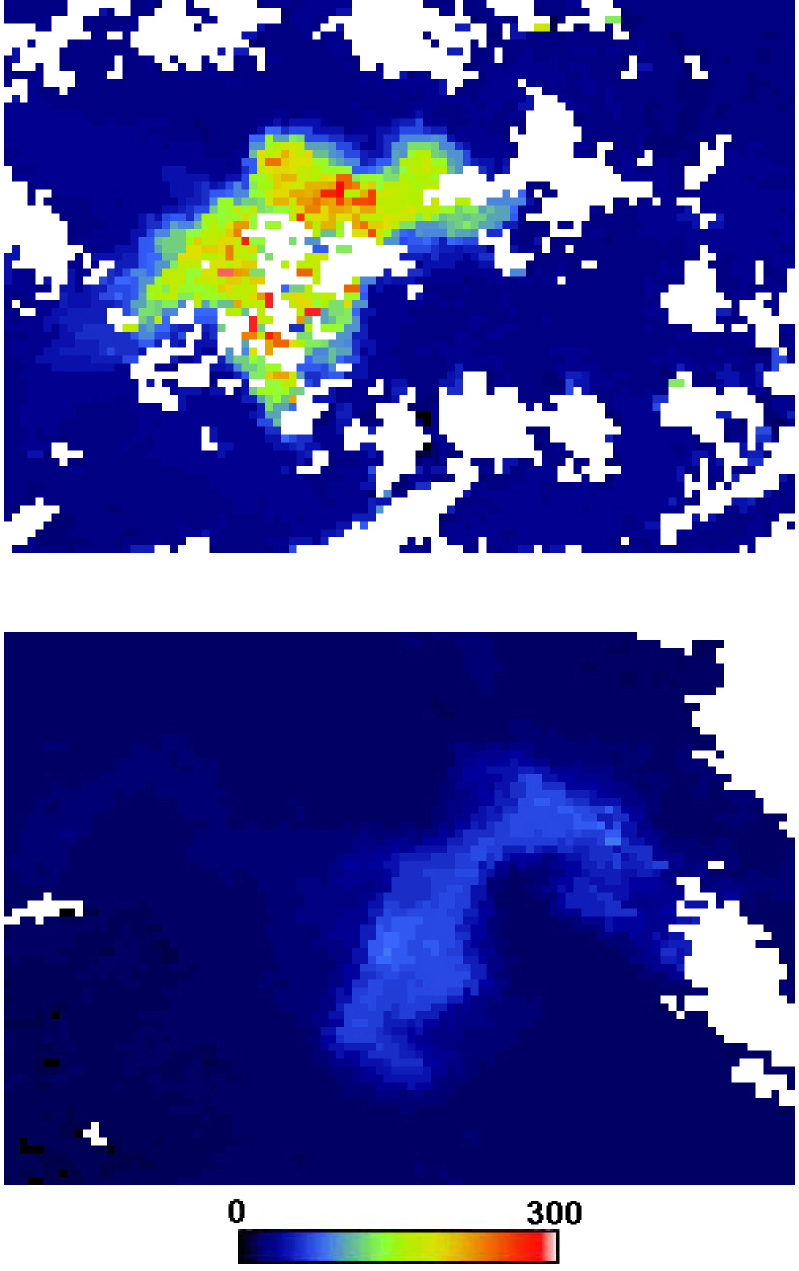


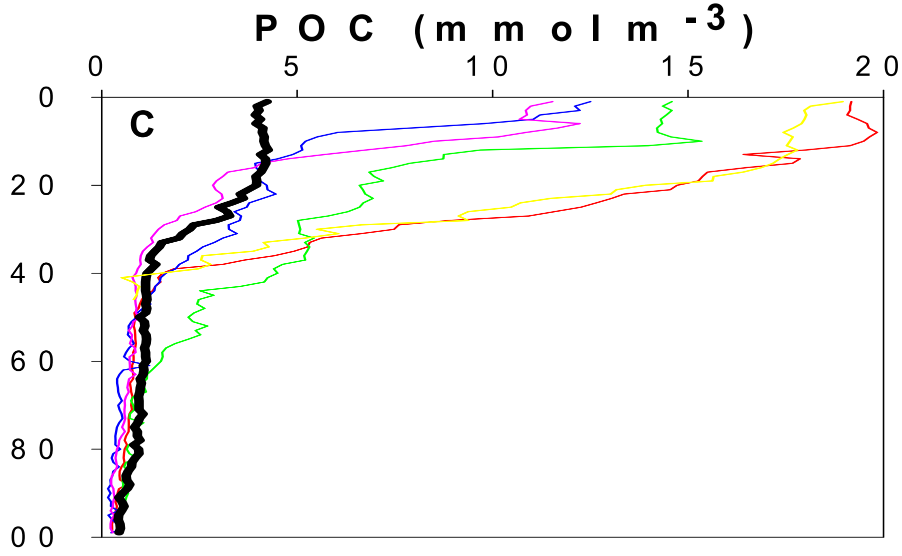


POC (ug L^{-1})

Boyd et al. (2005); Tsuda unpublished

SERIES bloom

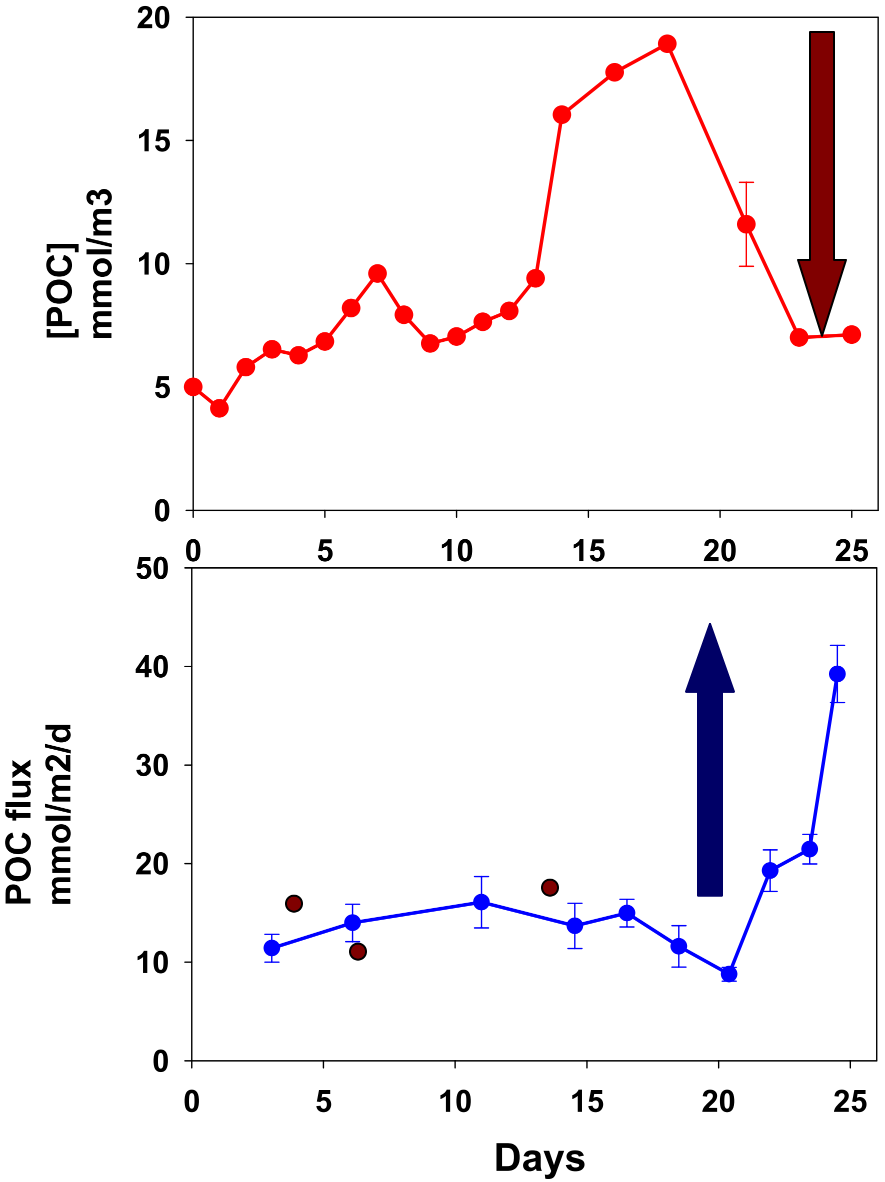


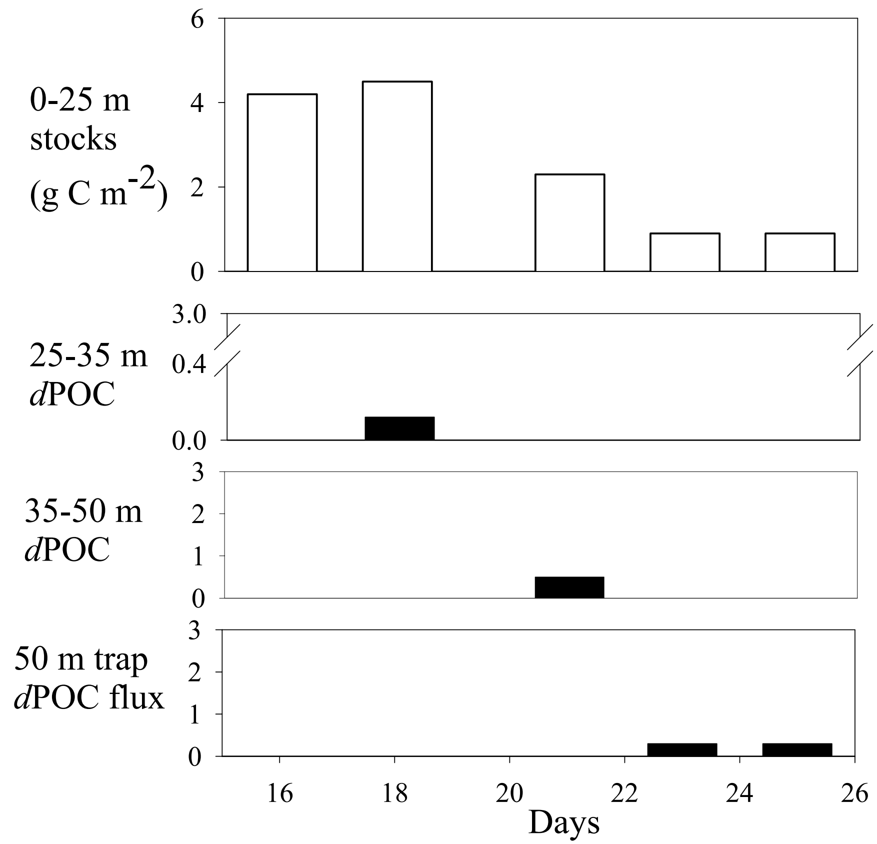


POC (ug L^{-1})

Boyd et al. (2005)

HOW MUCH POC WAS EXPORTED TO DEPTH?



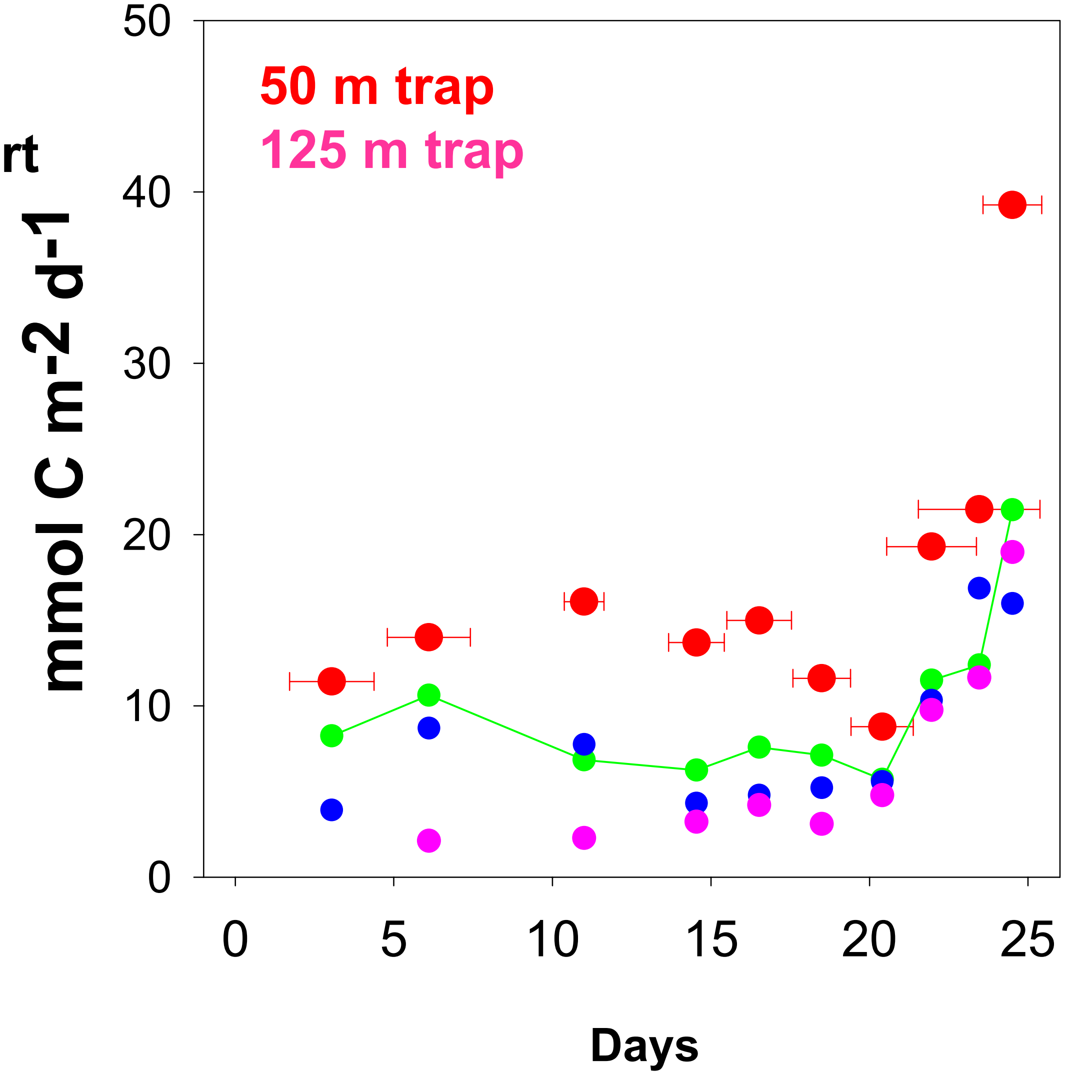


POC intercepted at 50 m 18%

Boyd et al. (2005)

VERTICAL ATTENUATION OF EXPORTED PARTICLE SIGNAL

POC export



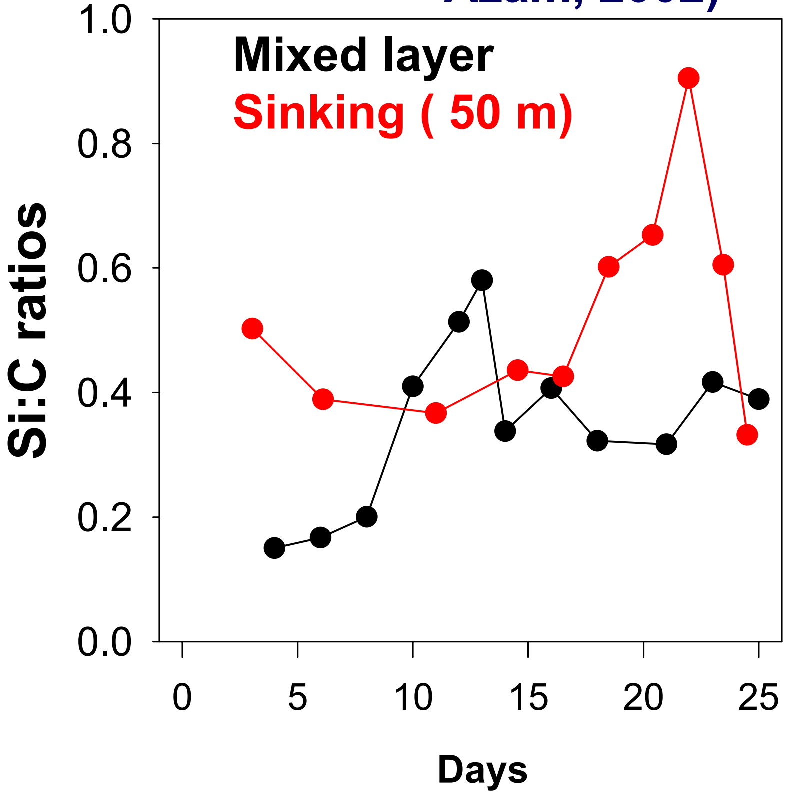
18% @ 50 m

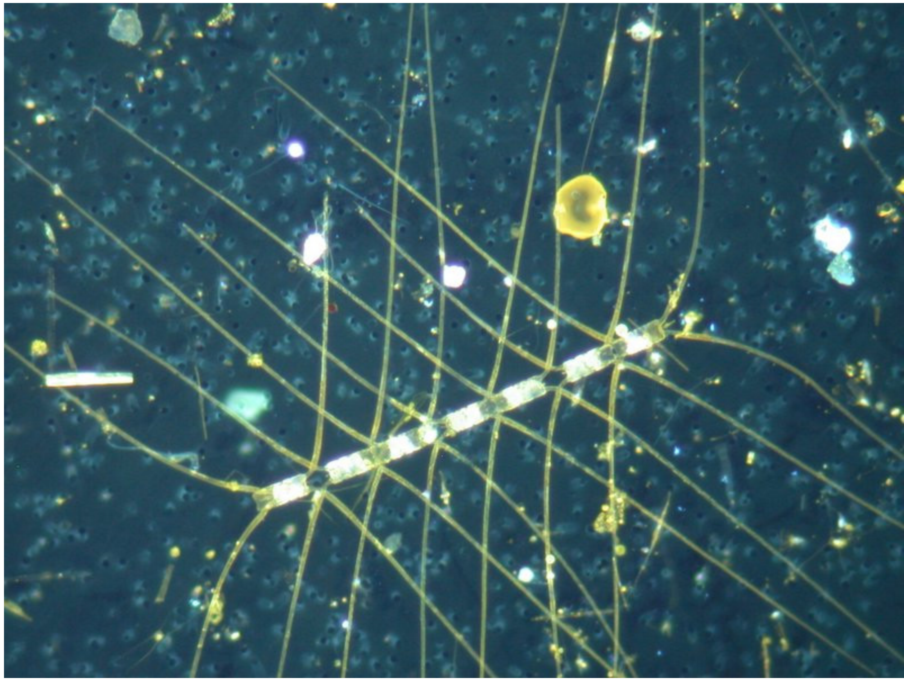
7% @ 125 m

Boyd et al. (2004)

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)





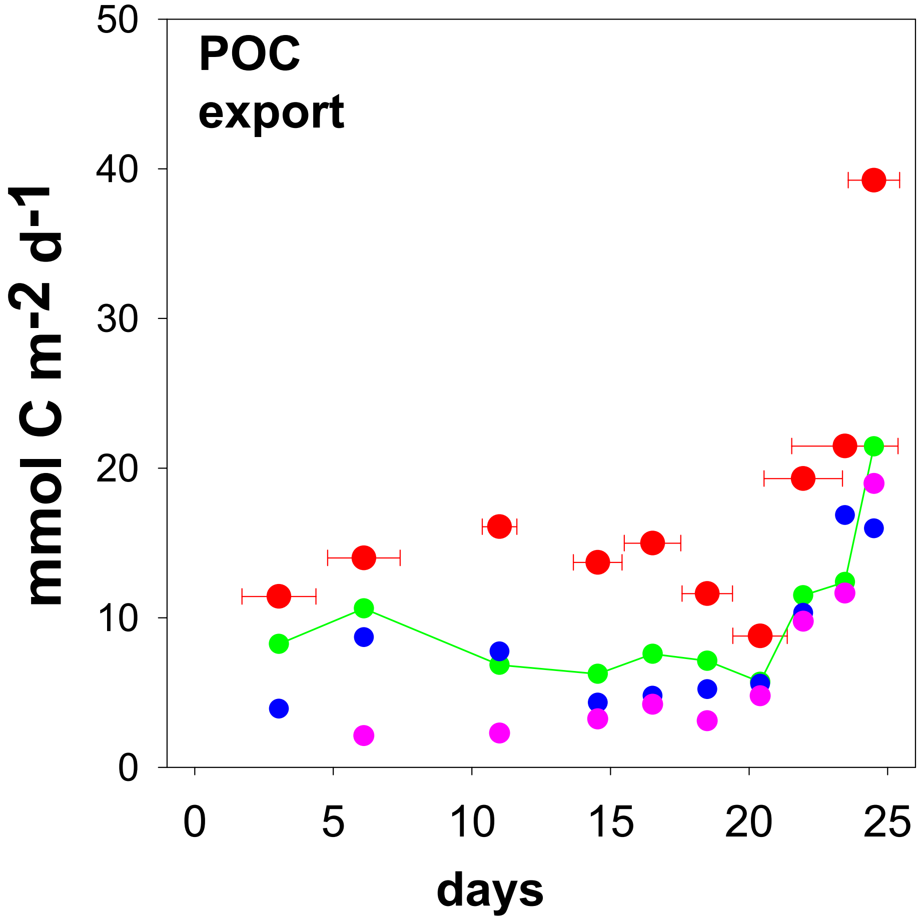
POC intercepted at 50 m 18%

PSi intercepted at 50 m   34%

Boyd et al. 2005

FATE of the bloom carbon

POC intercepted at 50 m 18%



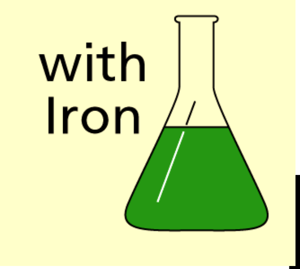
WHAT IS THE FATE OF THE POC DEFICIT (258 MMOL m^{-2}) ?

EXPORT	47
MESOZOO	29
UNDERTRAPPING	11
DIFF. REMIN	41
<u>or</u>	
NH_4 ACCUM	100

TOTAL 127 to 215 MMOL M^{-2}

Boyd et al. 2004

C exported per tonne of iron added

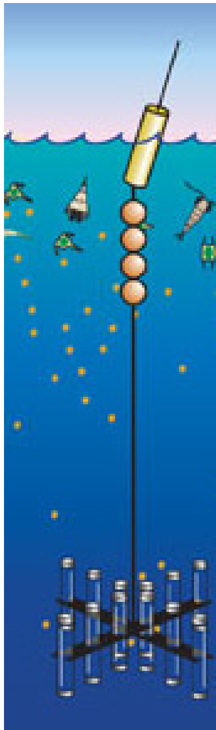


31428 to 110000

265

1571

6285 **2095** **105**

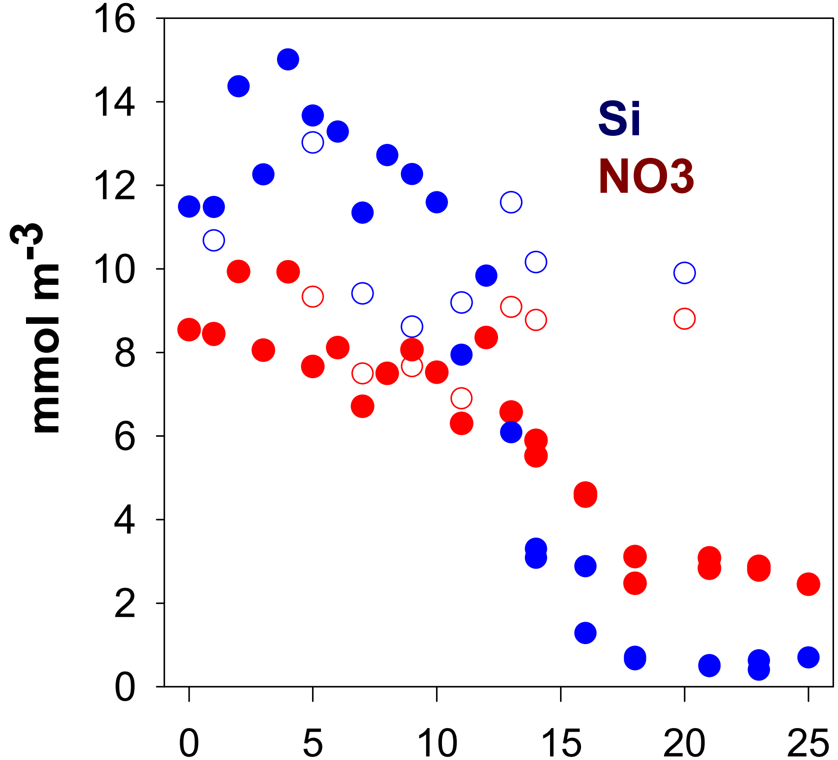


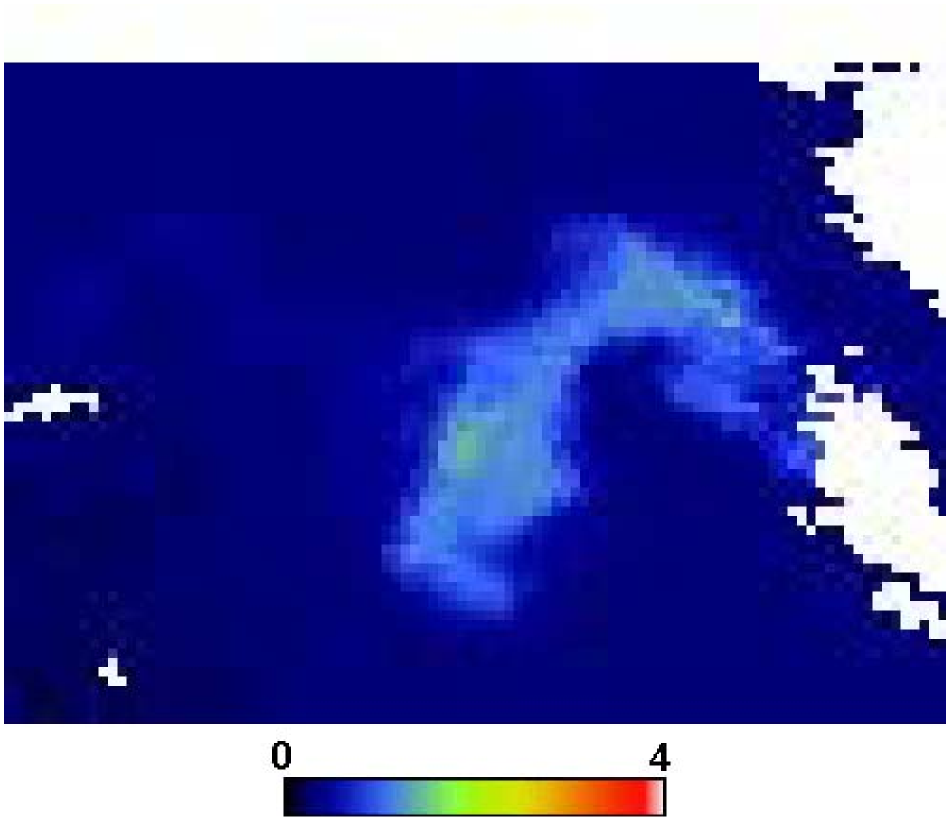
What have we learned from past iron fertilization experiments?

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



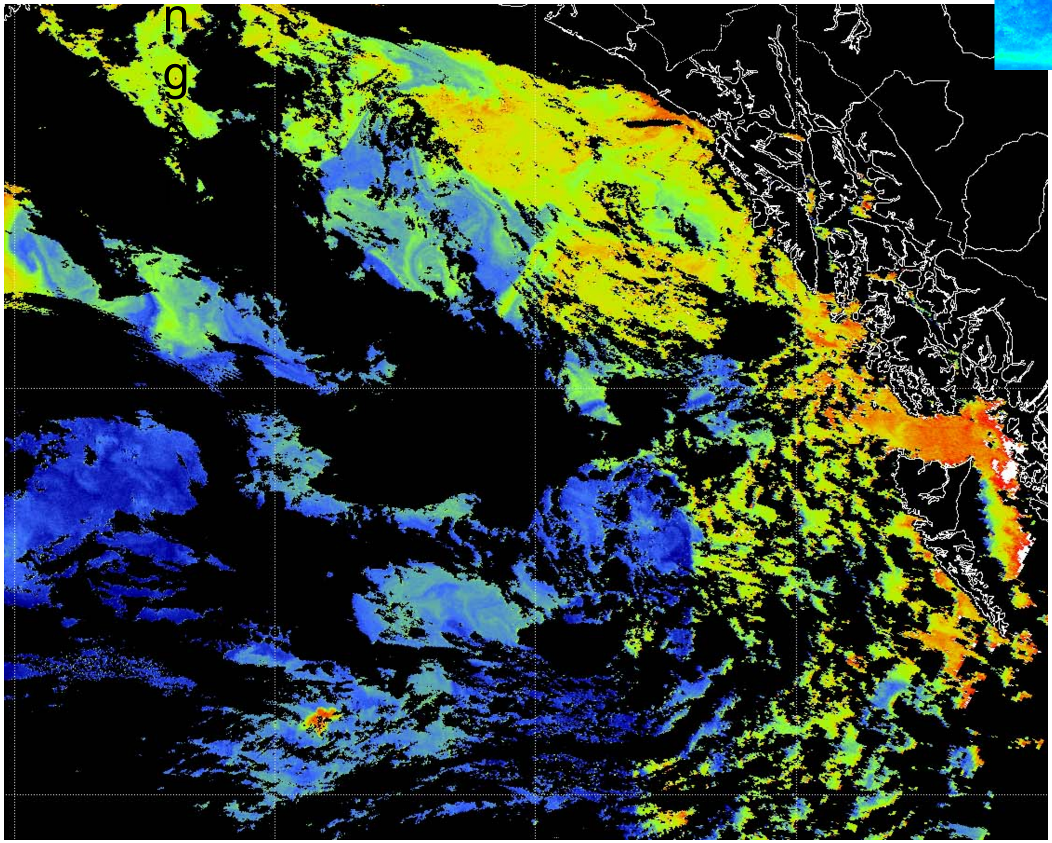


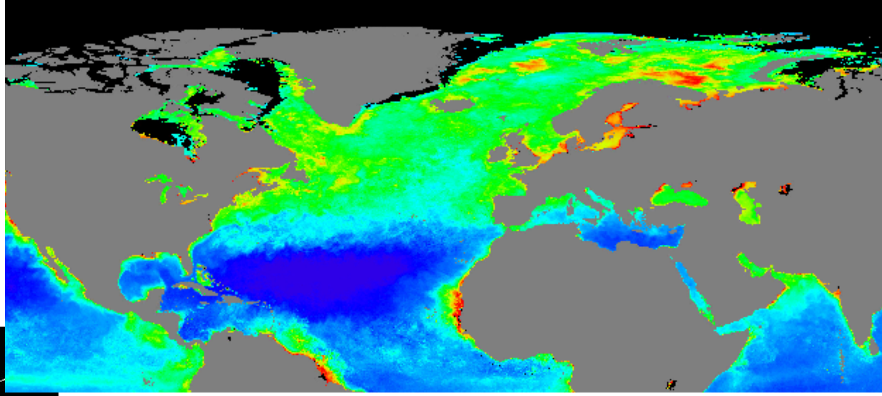
Boyd et al. 2004

A longer experiment?

A bigger experiment?

Along





Detection and attribution

Bloom biogeochemical signal in the context of the annual cycle

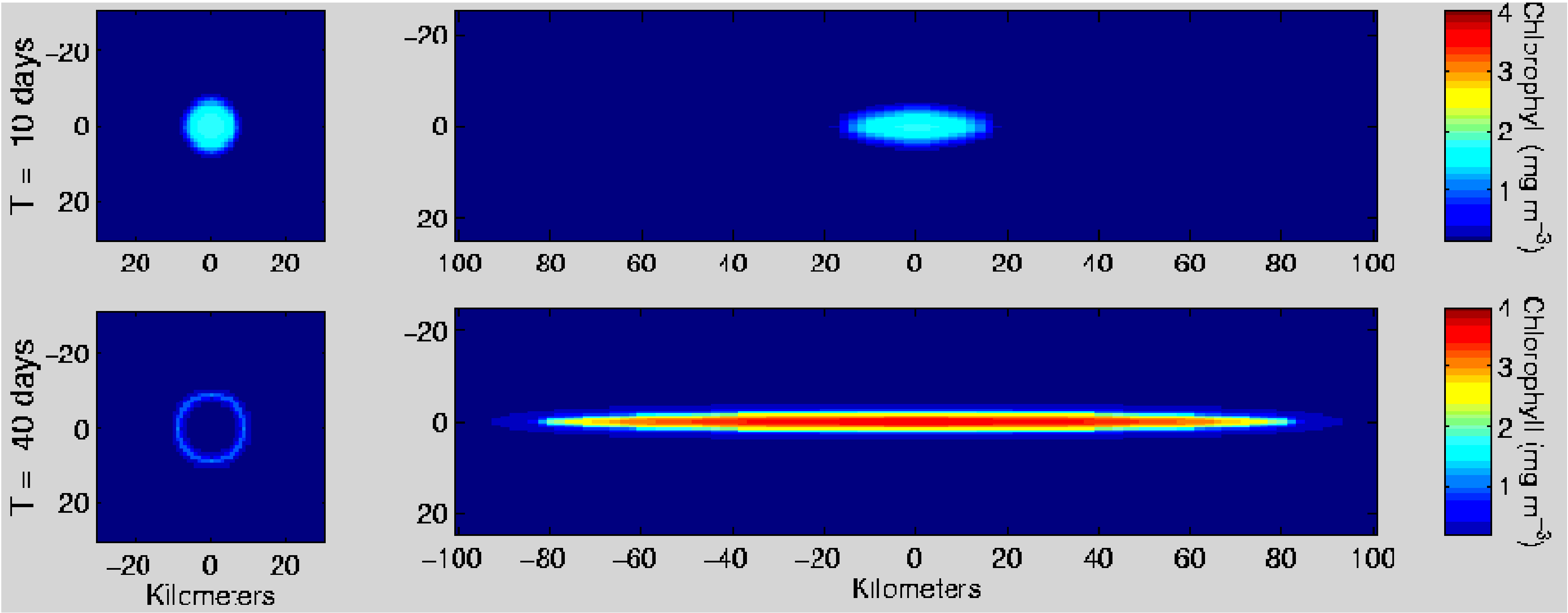
Boyd et al. (2005)

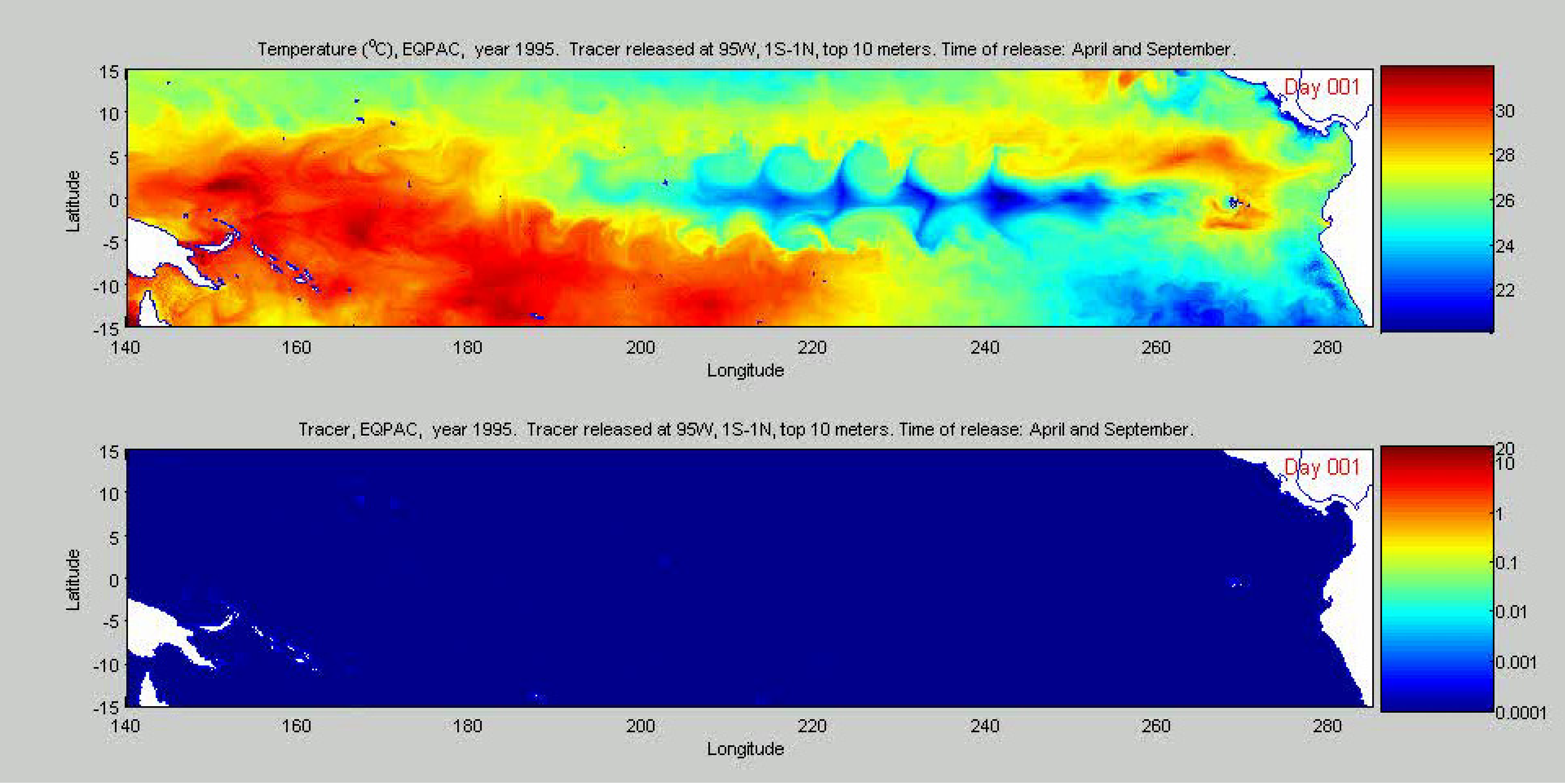
Upscaling – issues

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.

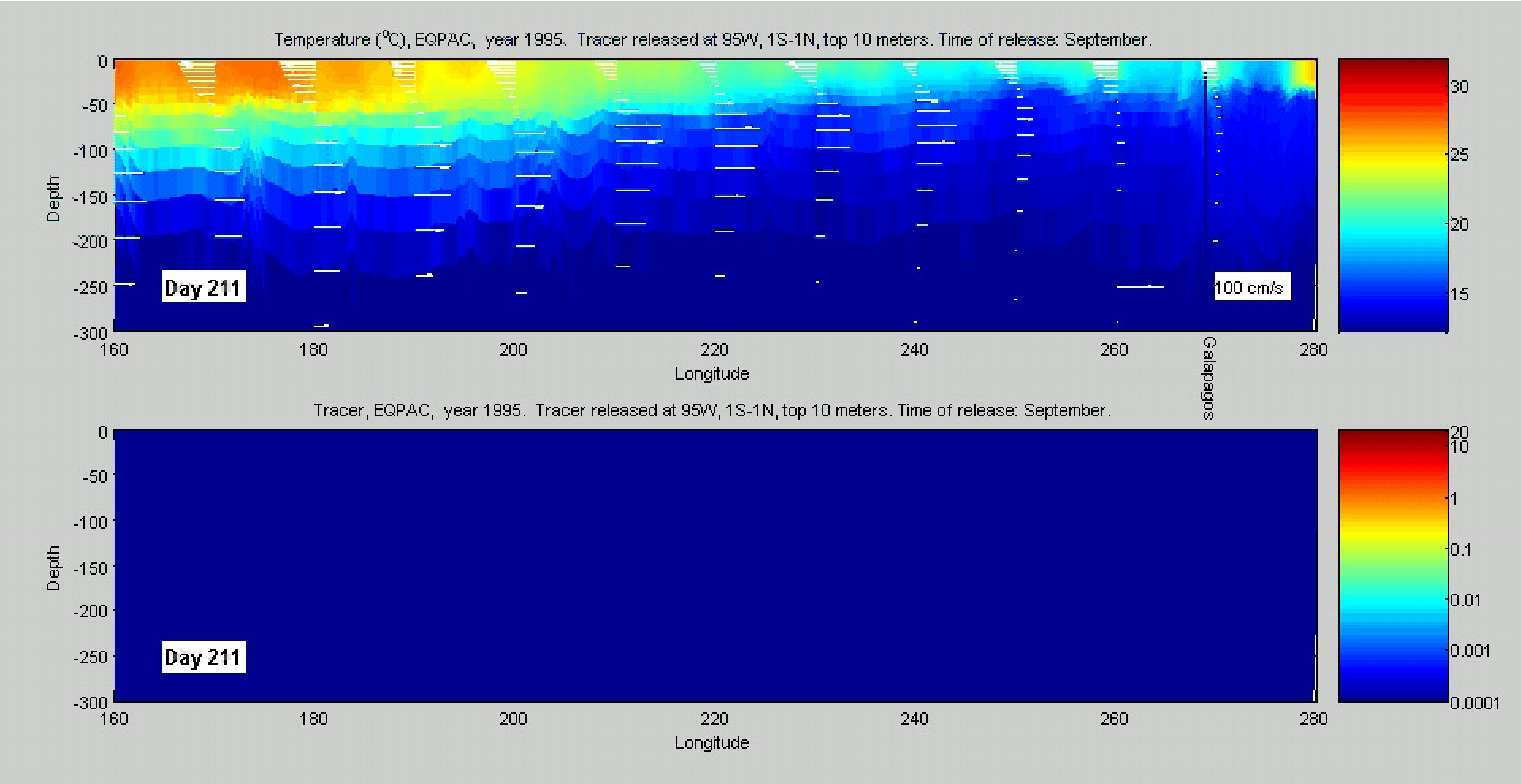
No strain

Strain



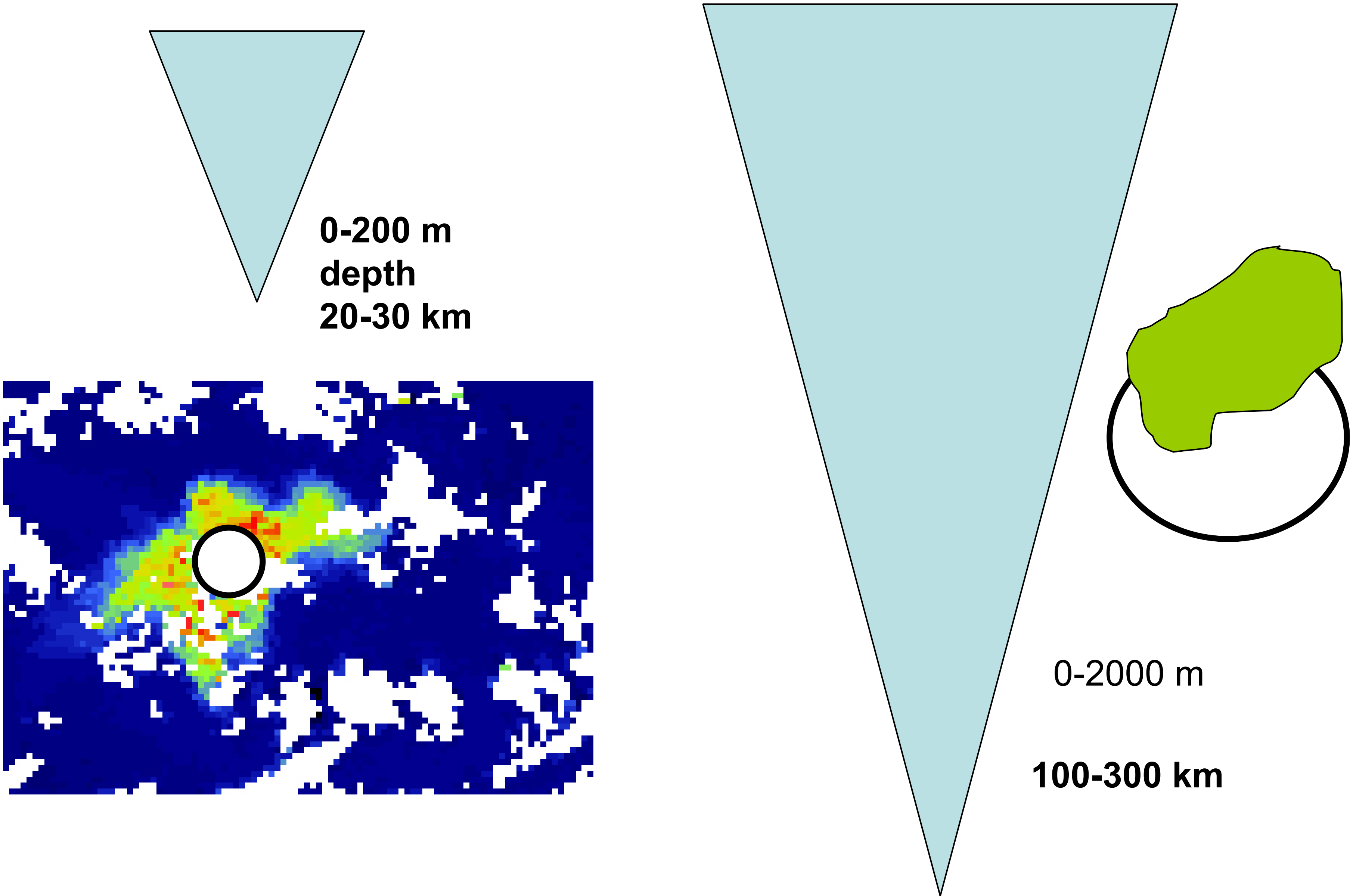


Temperature (°C), EQPAC, year 1995. Tracer released at 95W, 1S-1N, top 10 meters. Time of release: April and September.
Day 001
Latitude
Longitude
15
10
5
0
-5
-10
-15
140
160
180
200
220
240
260
280
30
28
26
24
22
Tracer, EQPAC, year 1995. Tracer released at 95W, 1S-1N, top 10 meters. Time of release: April and September.
Day 001
Latitude
Longitude
20
10
1
0.1
0.01
0.001
0.0001



Temperature (°C), EQPAC, year 1995. Tracer released at 95W, 1S-1N, top 10 meters. Time of release: September.
0
-50
-100
-150
-200
-250
-300
Depth
Day 211
100 cm/s
160
180
200
220
240
260
280
Longitude
Galapagos
30
25
20
15
Tracer, EQPAC, year 1995. Tracer released at 95W, 1S-1N, top 10 meters. Time of release: September.
0
-50
-100
-150
-200
-250
-300
Depth
Day 211
160
180
200
220
240
260
280
Longitude
20
10
1
0.1
0.01
0.001
0.0001

Disjoint between surface source for particles and their trajectory to depth



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 – N_2O 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

oceanironfertilization
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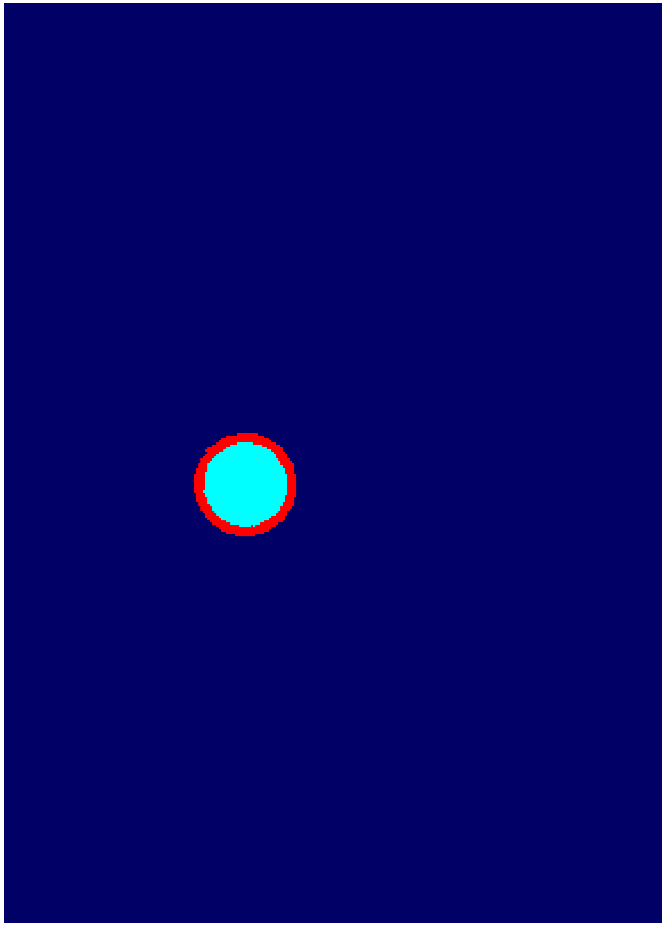
Stirring of a tracer patch in the East Australian Current

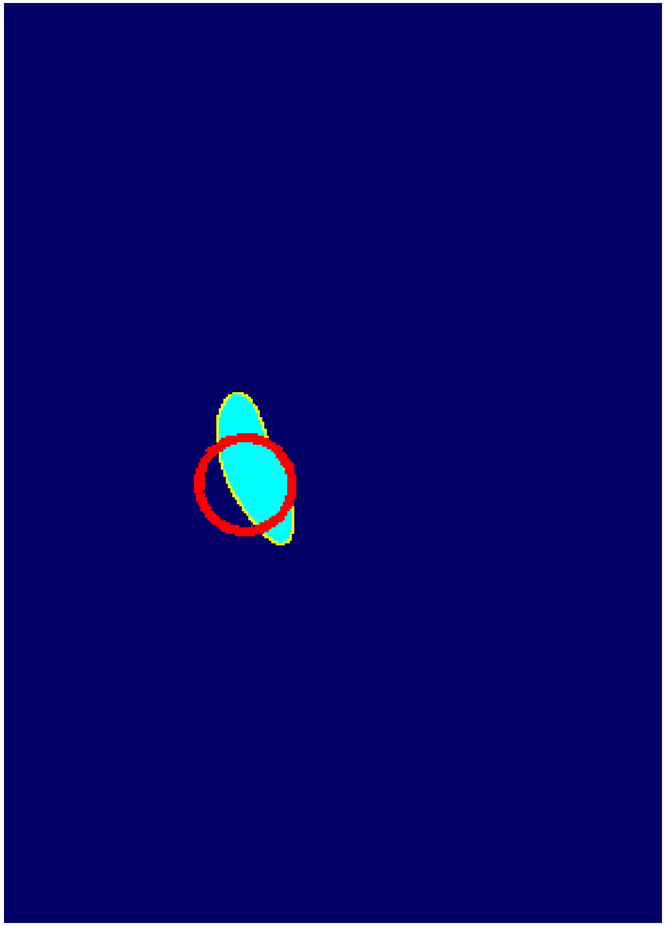
t = 1 day   start:



100 km

Stirring of a tracer patch in the East Australian Current

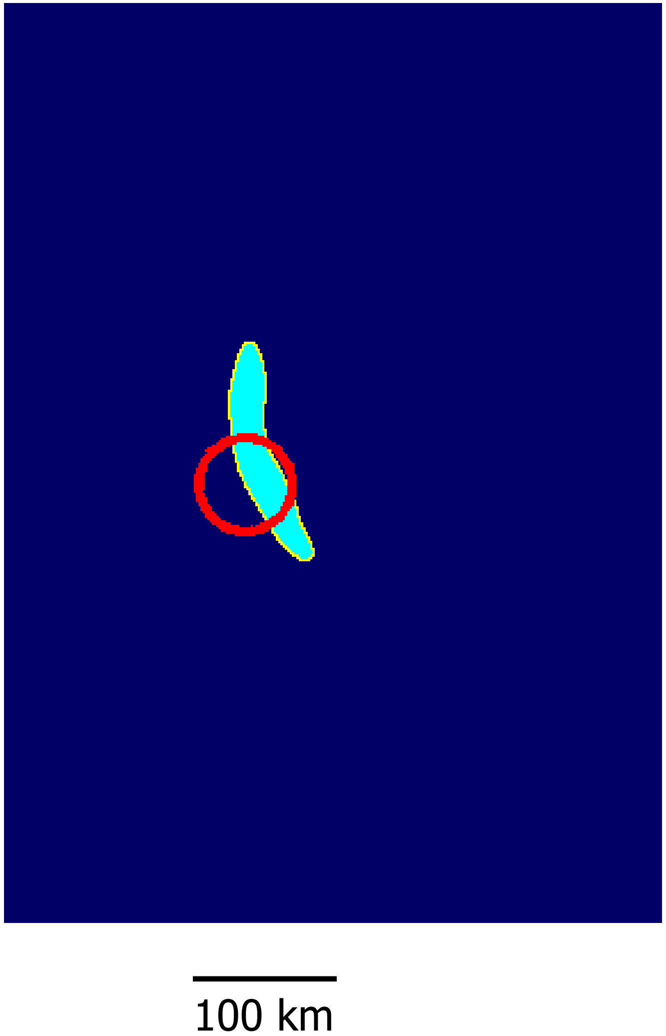
t = 2 day



100 km

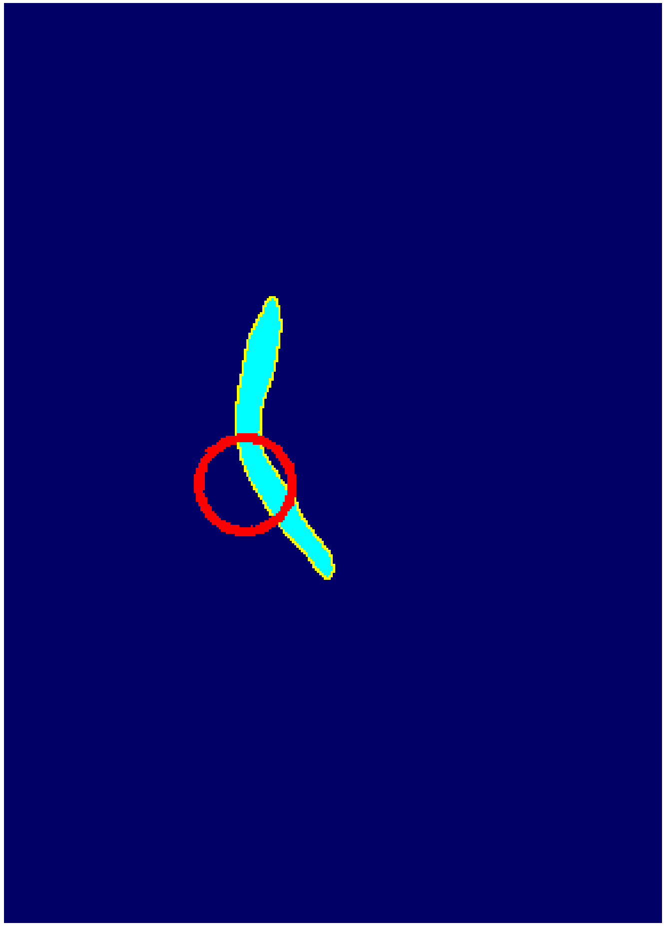
Stirring of a tracer patch in the East Australian Current

t = 3 day



Stirring of a tracer patch in the East Australian Current

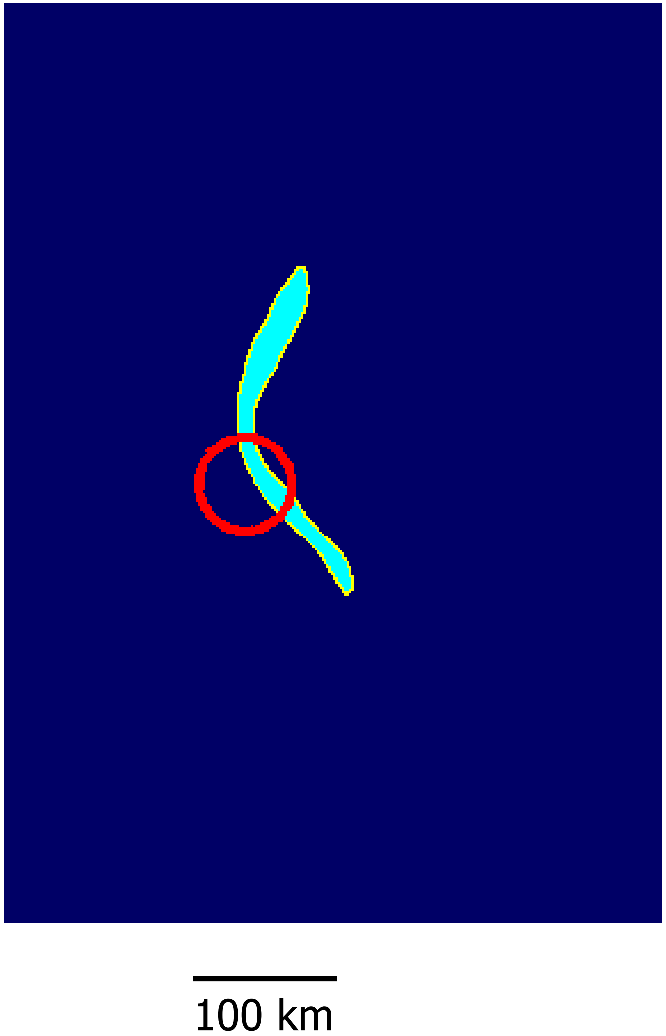
t = 4 day



100 km

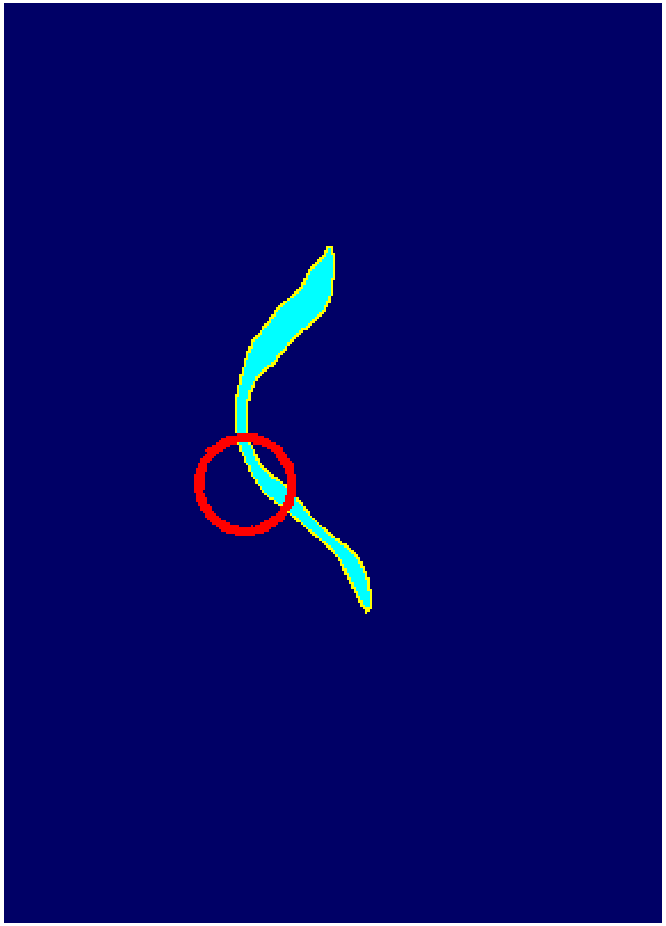
Stirring of a tracer patch in the East Australian Current

t = 5 day



Stirring of a tracer patch in the East Australian Current

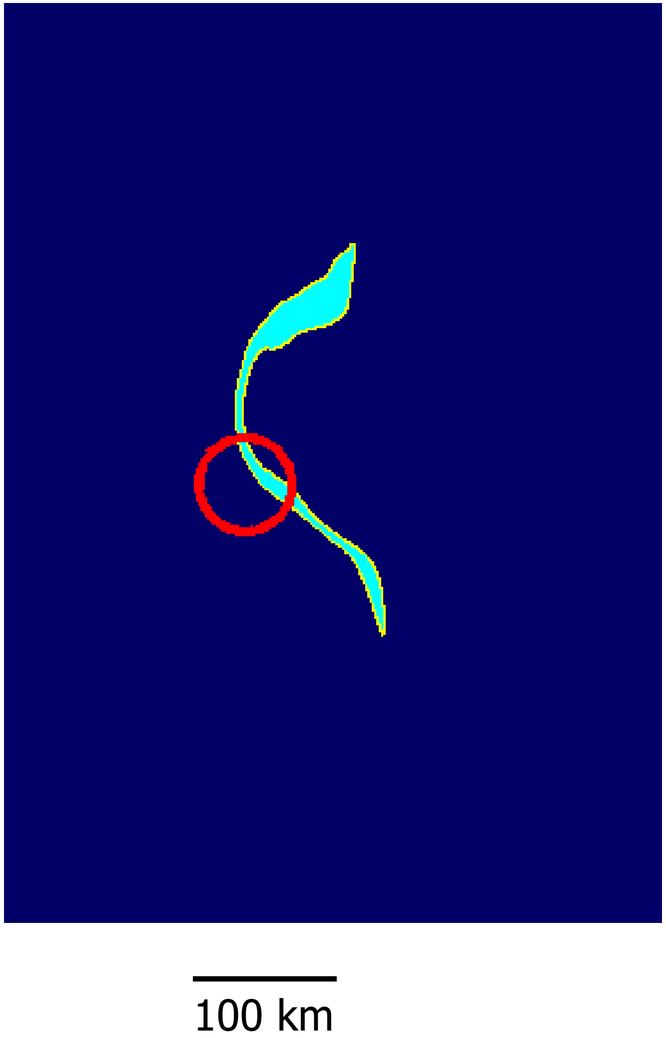
t = 6 day



100 km

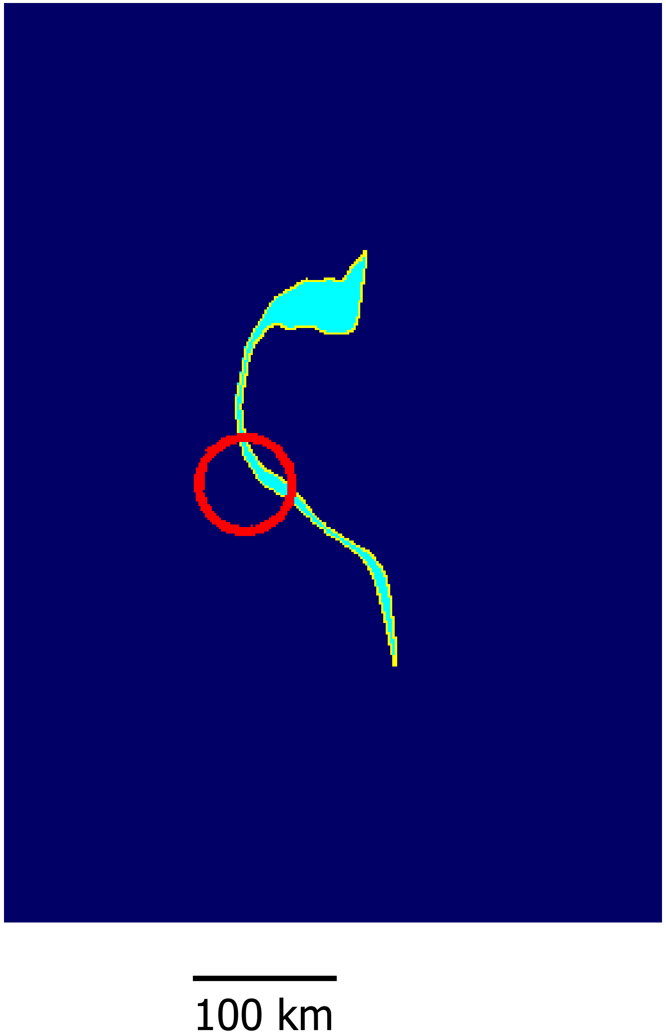
Stirring of a tracer patch in the East Australian Current

t = 7 day



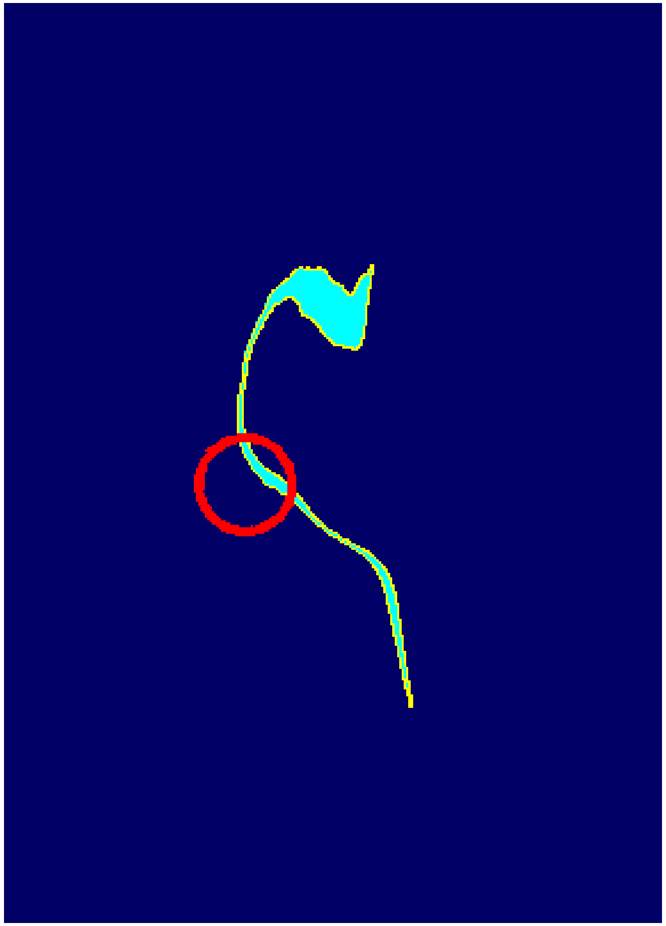
Stirring of a tracer patch in the East Australian Current

t = 8 day



Stirring of a tracer patch in the East Australian Current

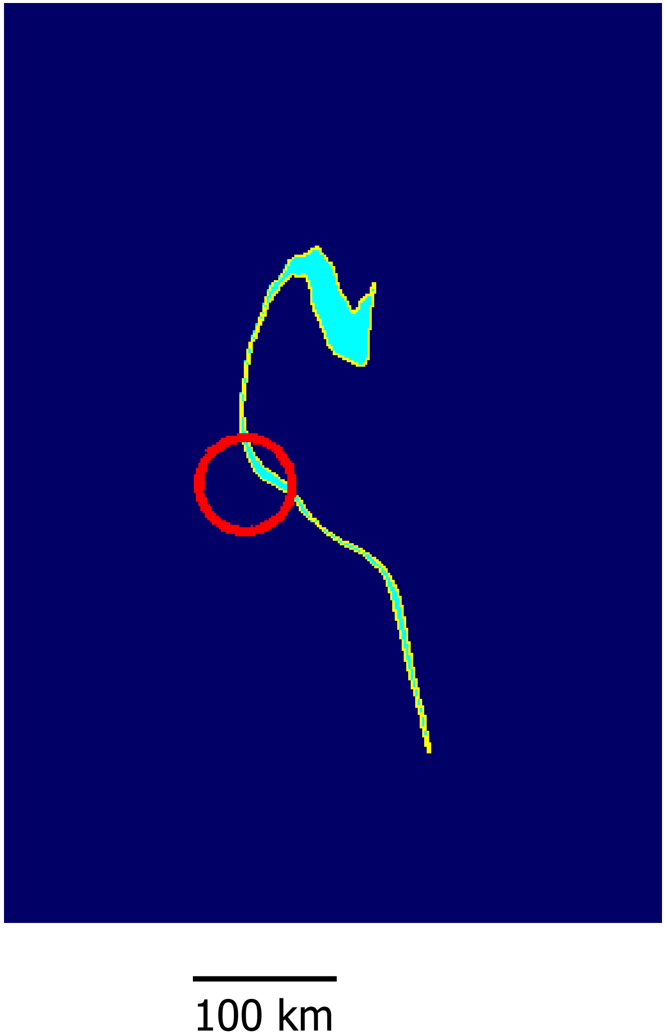
t = 9 day



100 km

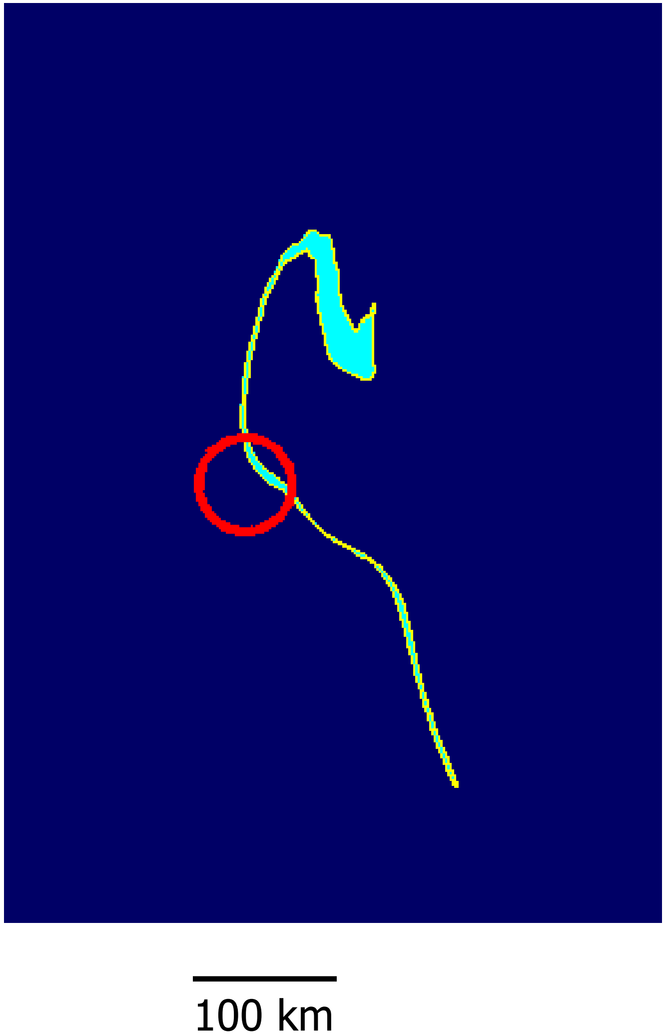
Stirring of a tracer patch in the East Australian Current

t = 10 day



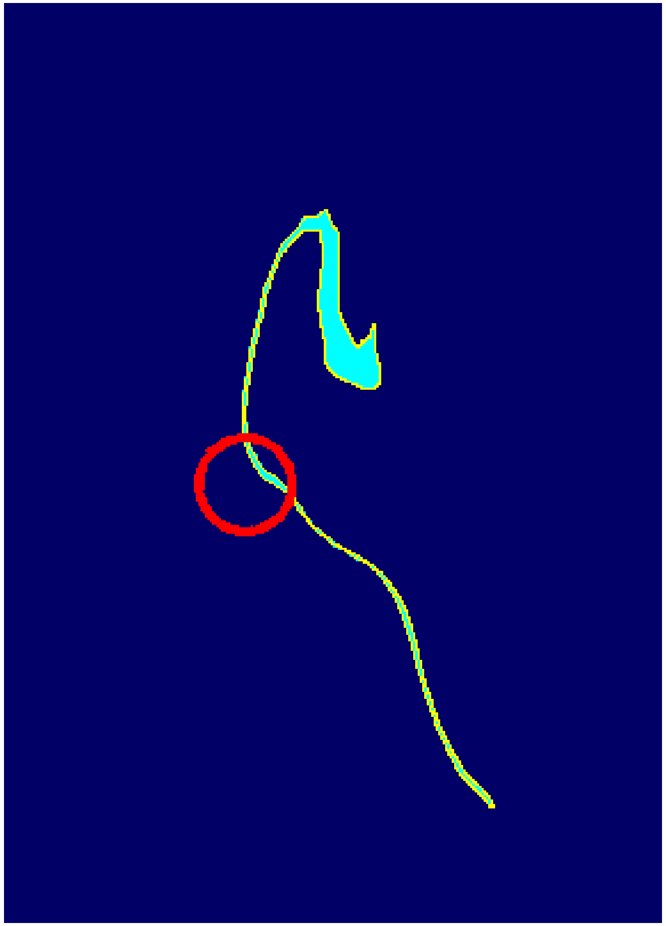
Stirring of a tracer patch in the East Australian Current

t = 11 day



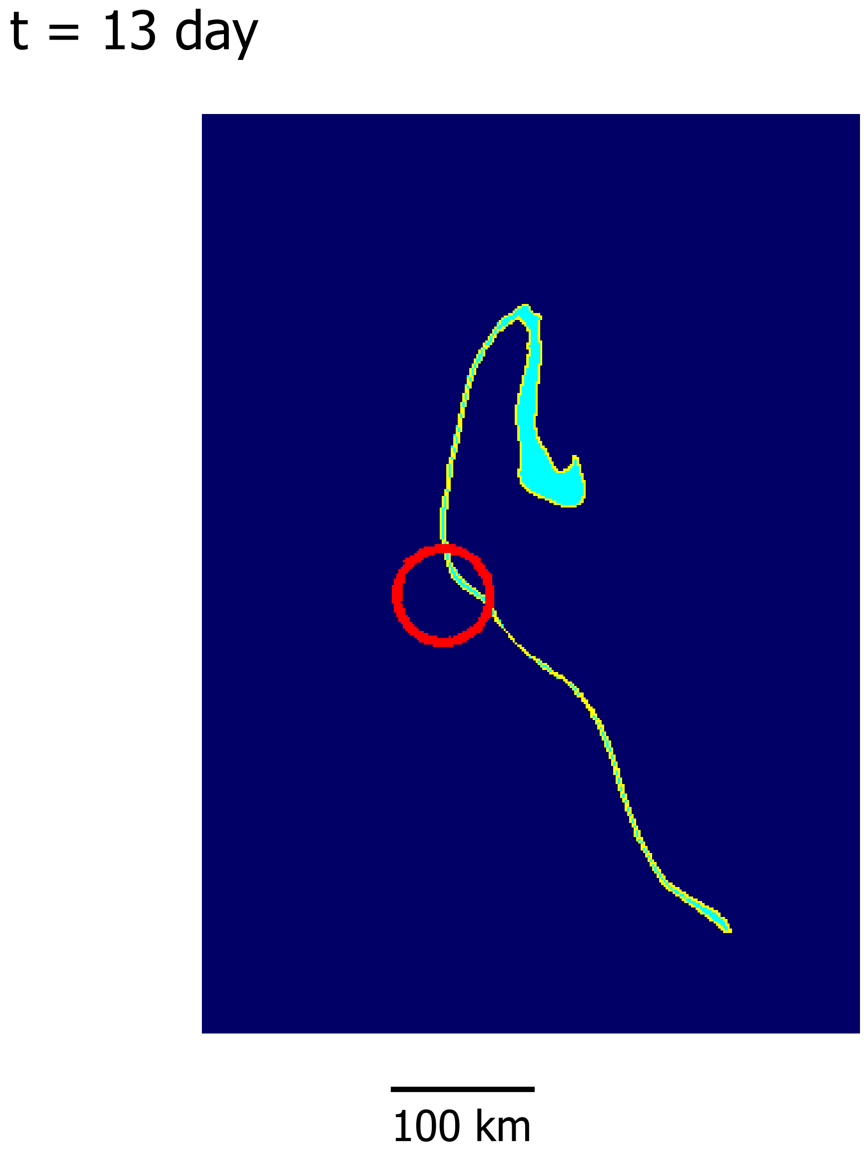
Stirring of a tracer patch in the East Australian Current

t = 12 day



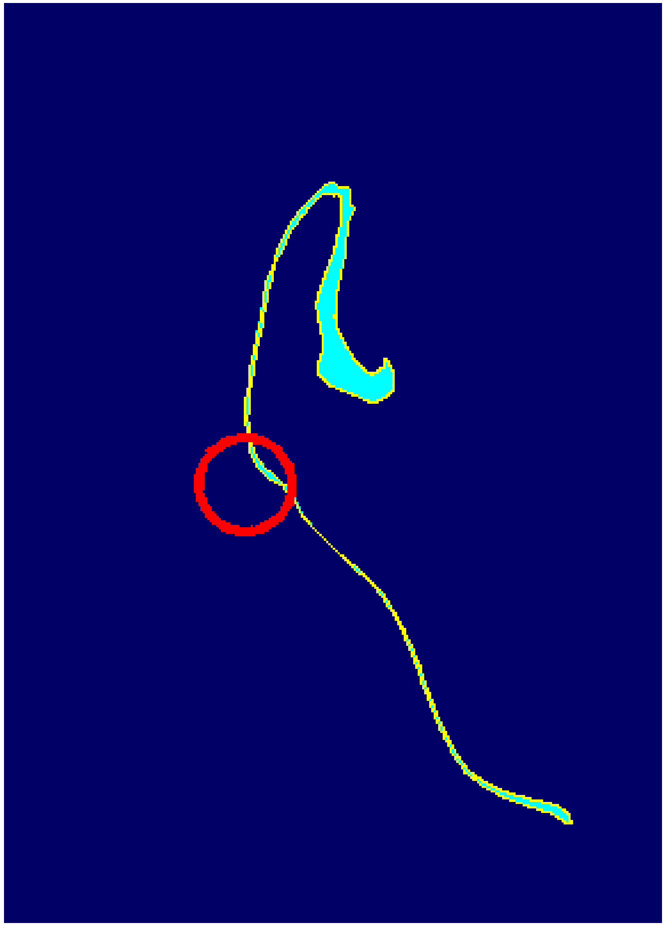
100 km

Stirring of a tracer patch in the East Australian Current



Stirring of a tracer patch in the East Australian Current

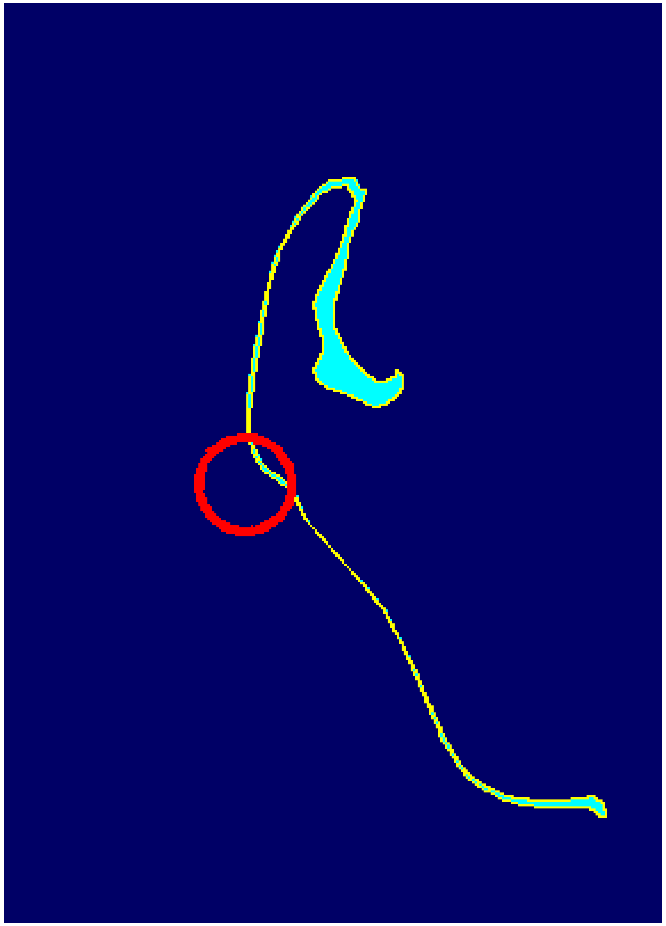
t = 14 day



100 km

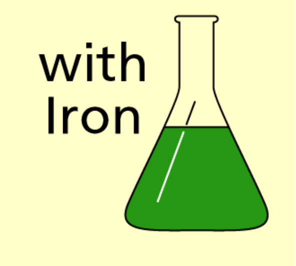
Stirring of a tracer patch in the East Australian Current

t = 15 day   finish:



100 km

Fe:C uptake ratios (mol:mol)

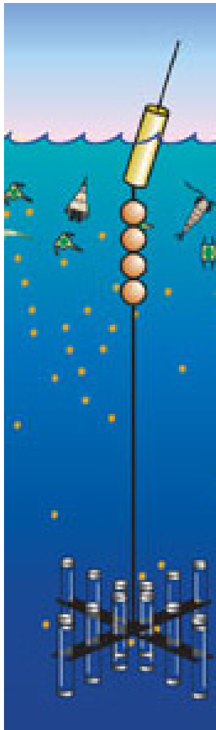


2 to 7 x 10^{-6}

8.3 x 10^{-4}

1.4 x 10^{-4}

3.5 x 10^{-5} 1.05 x 10^{-4} 2.1 x 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