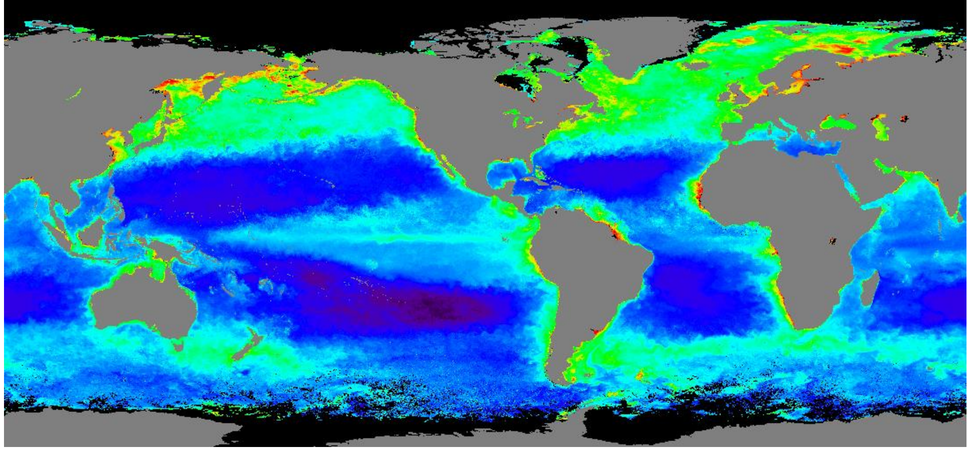
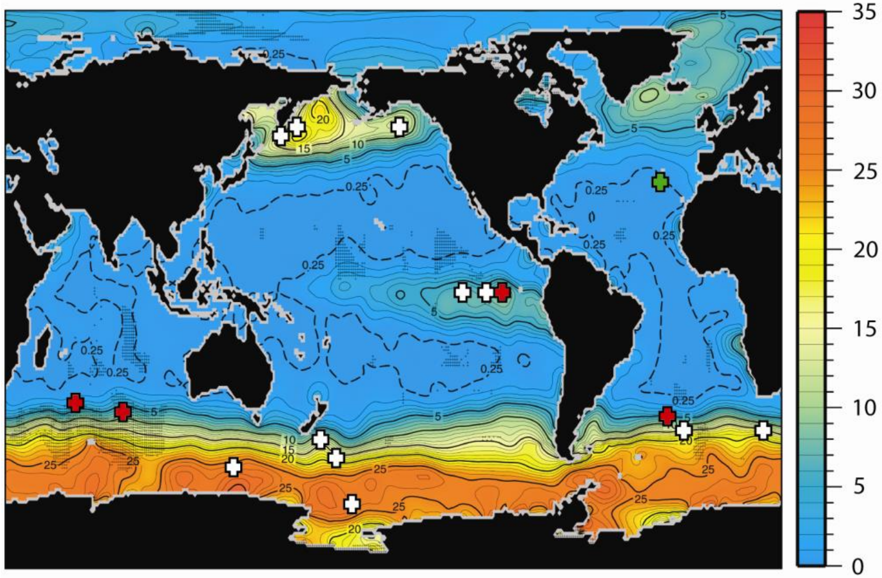
Iron biogeochemistry & the HNLC condition



Philip Boyd
Institute for Marine & Antarctic Studies

2014



Outline

HNLC waters – definition and implications
What causes the HNLC condition?
Everyday life in HNLC waters
A closer look at the Southern Ocean
Ready for iron – opportunism by HNLC biota
Iron biogeochemistry

HNLC waters – definition and implications

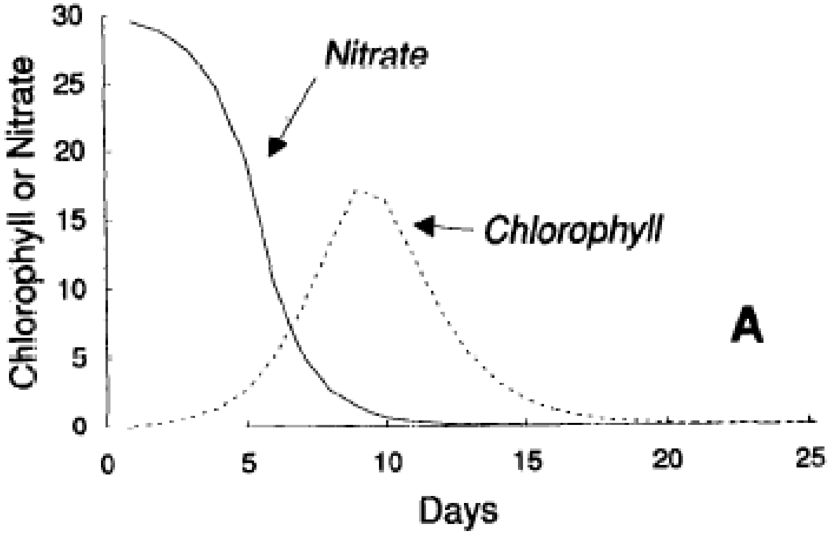
The existence of HNLC waters has long been known…

Ruud (1930) on a voyage to the whaling grounds
at the ice edge of the Weddell Sea

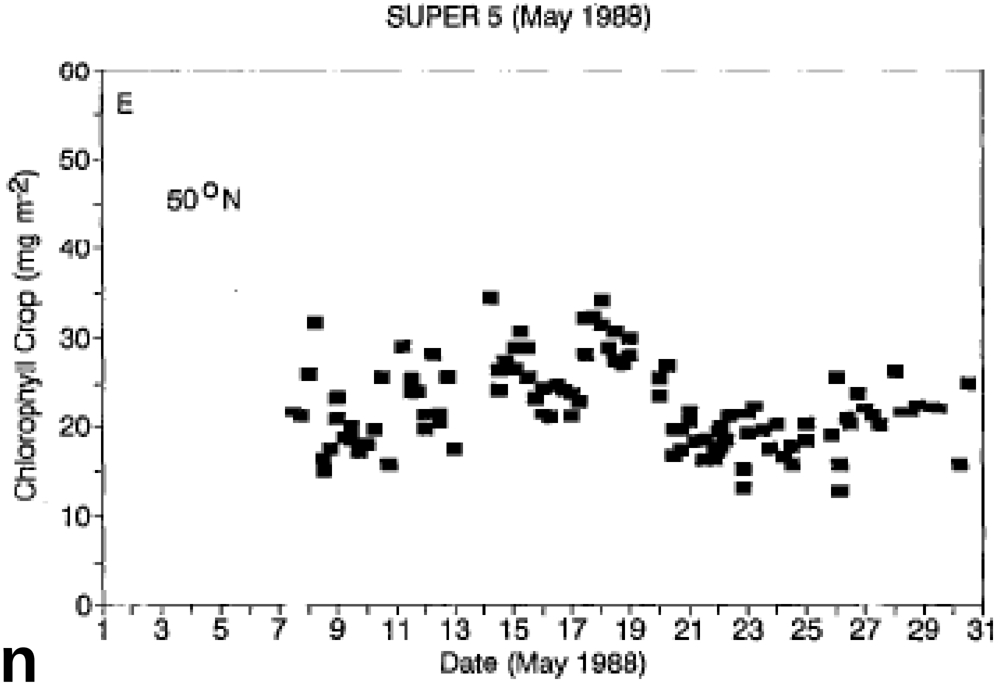
"In contrast to elsewhere, the concentrations of phosphate and nitrate
Proved to be very high….yet throughout the summer the phytoplankton
Was hardly blooming……"

The so-called Antarctic Paradox

Gran (1931) **"Another study seemed to indicate that the growth of diatoms**
Is determined by other factors than the concentration of phosphates and nitrates
Besides light and temperature…….."

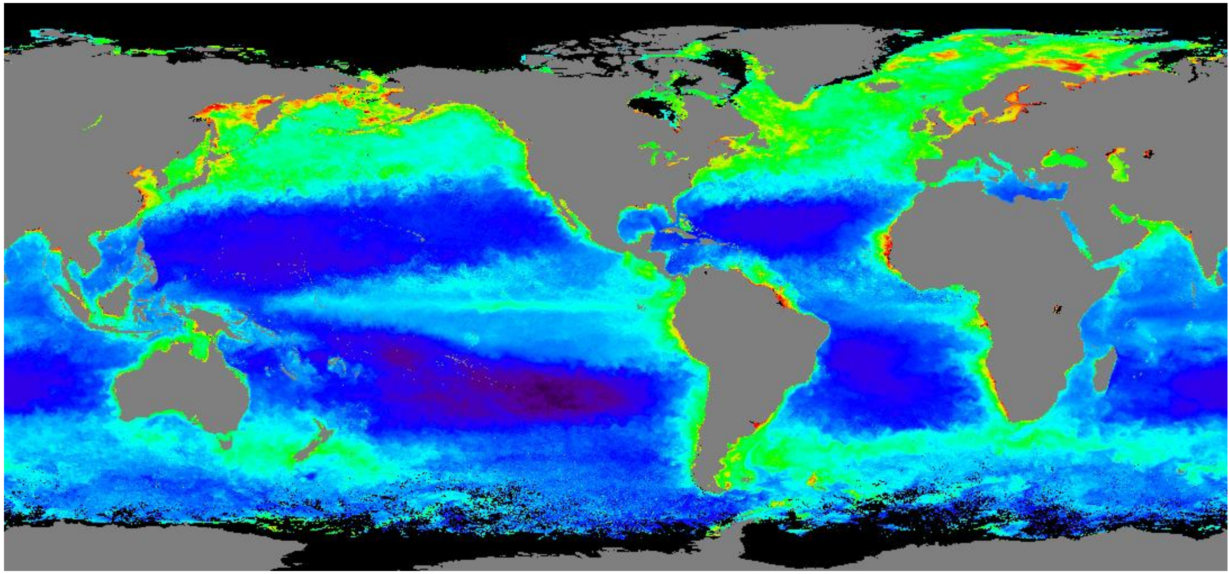


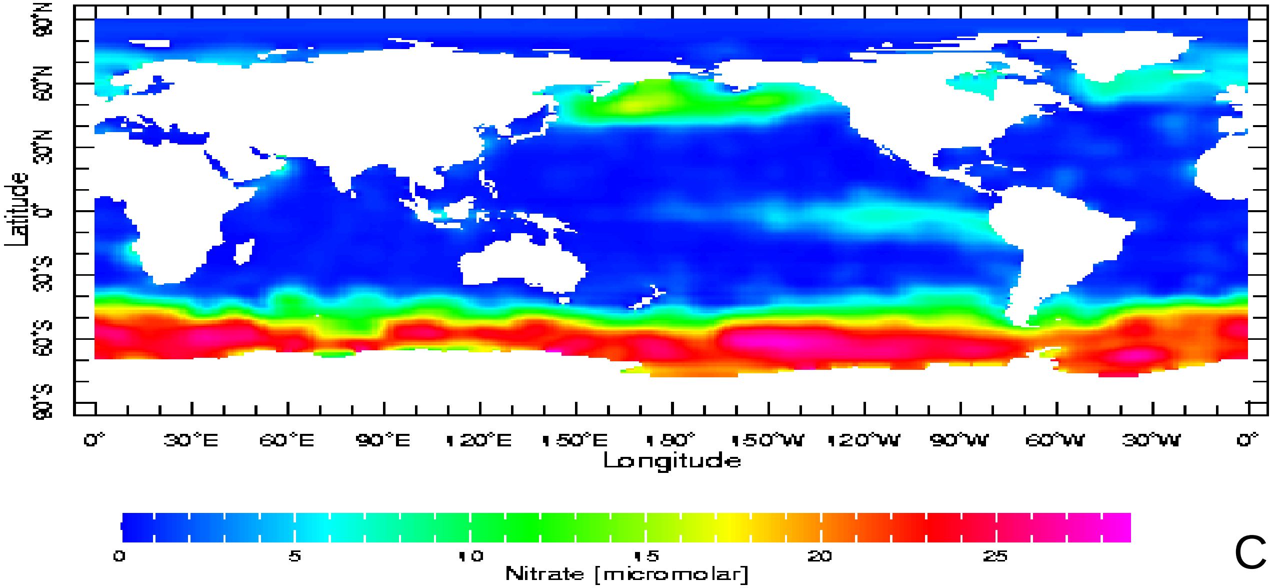
Conventional NO_3 and chlorophyll relationship



HNLC ocean

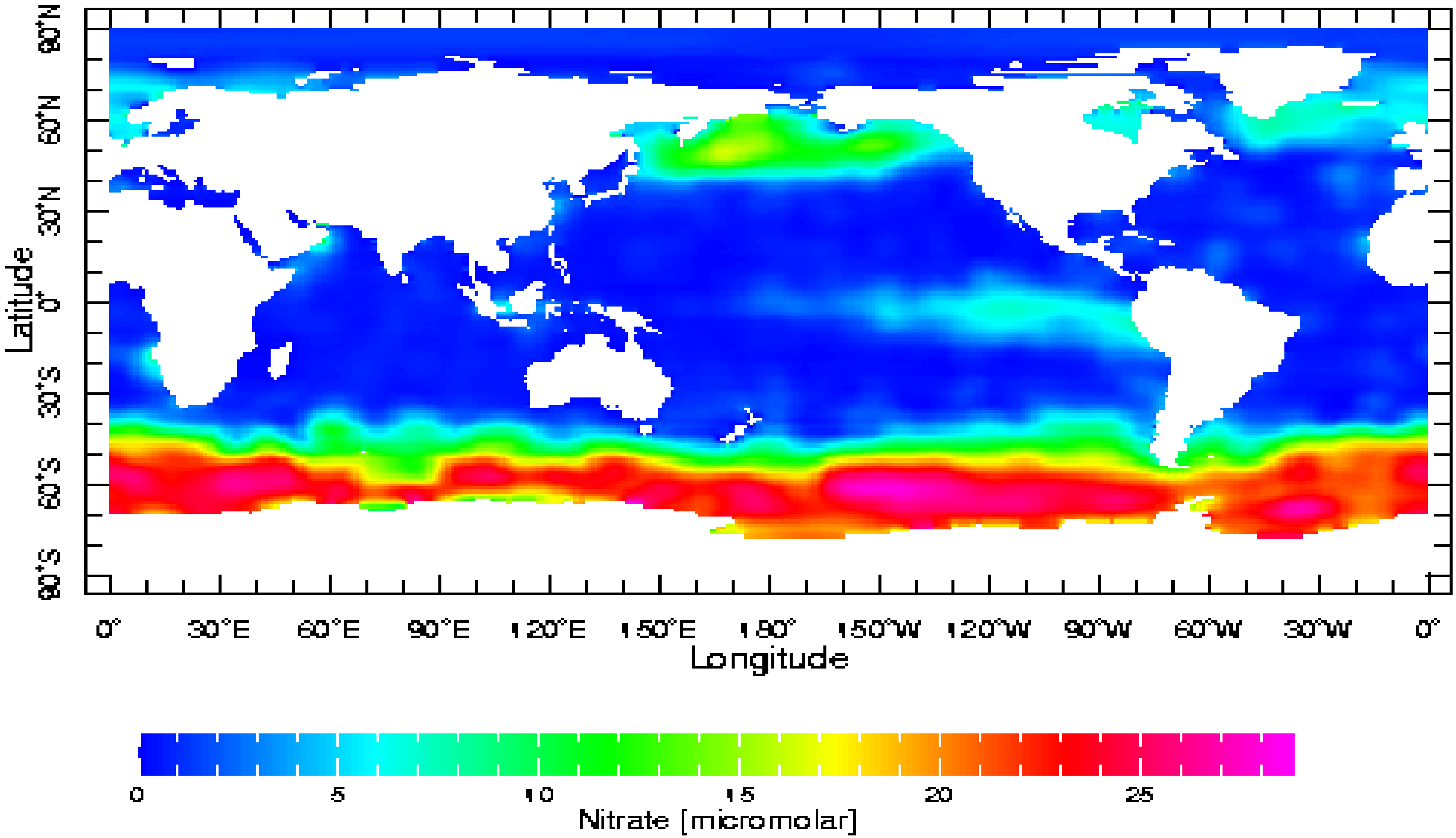
Miller et al. 1993





Courtesy NASA

Courtesy NODC

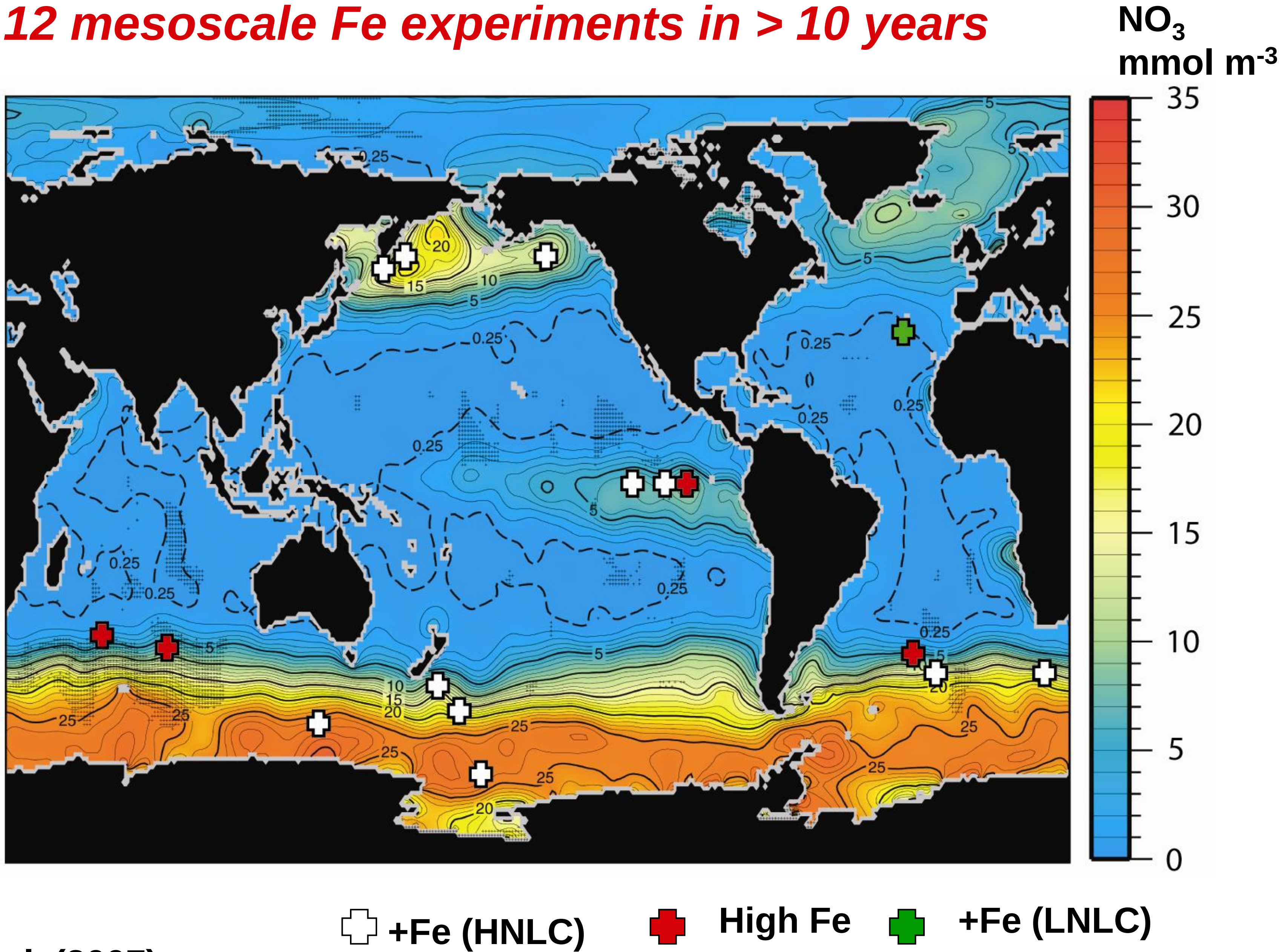


In 1/3 of the ocean, excess plant nutrients are present perennially, yet paradoxically phytoplankton stocks are at low levels

High Nitrate Low Chlorophyll waters

Courtesy NODC

12 mesoscale Fe experiments in > 10 years

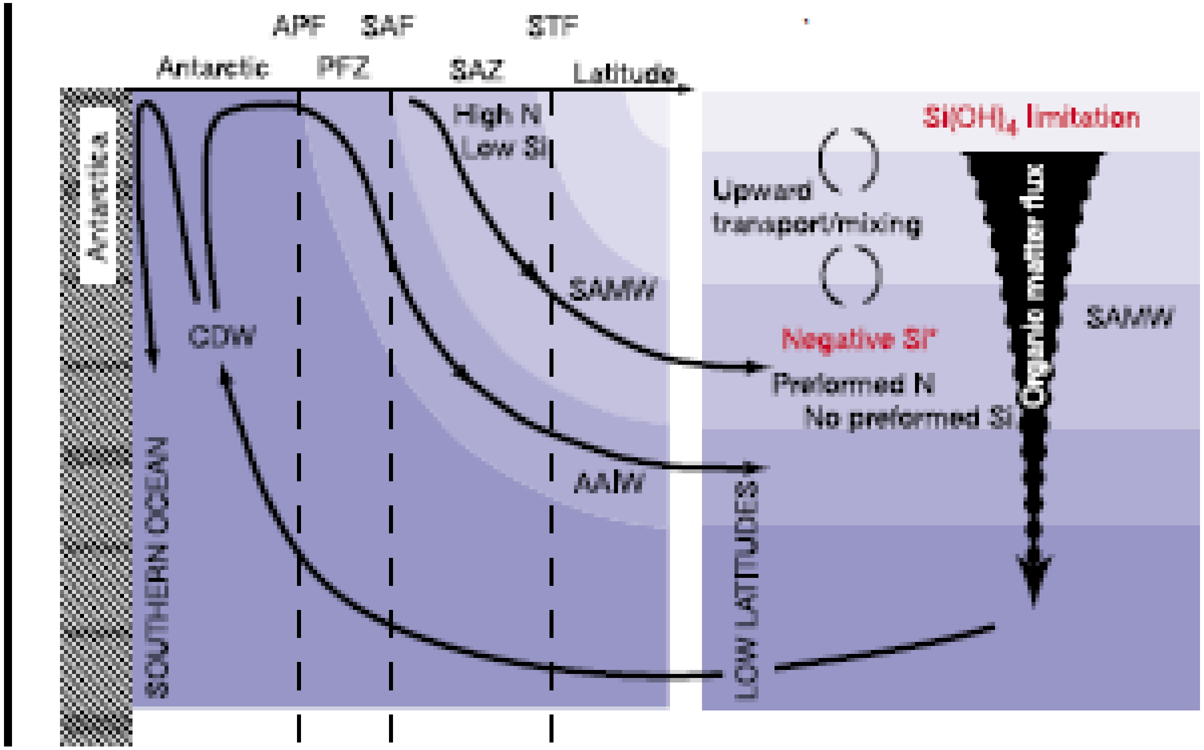


Boyd et al. (2007)

High-latitude controls of thermocline nutrients and low latitude biological productivity

J. L. Sarmiento[1], N. Gruber[2], M. A. Brzezinski[3] & J. P. Dunne[4]

HNLC



S. Ocean control on thermocline nutrient concentrations

Widespread influence of S. Ocean nutrient supply

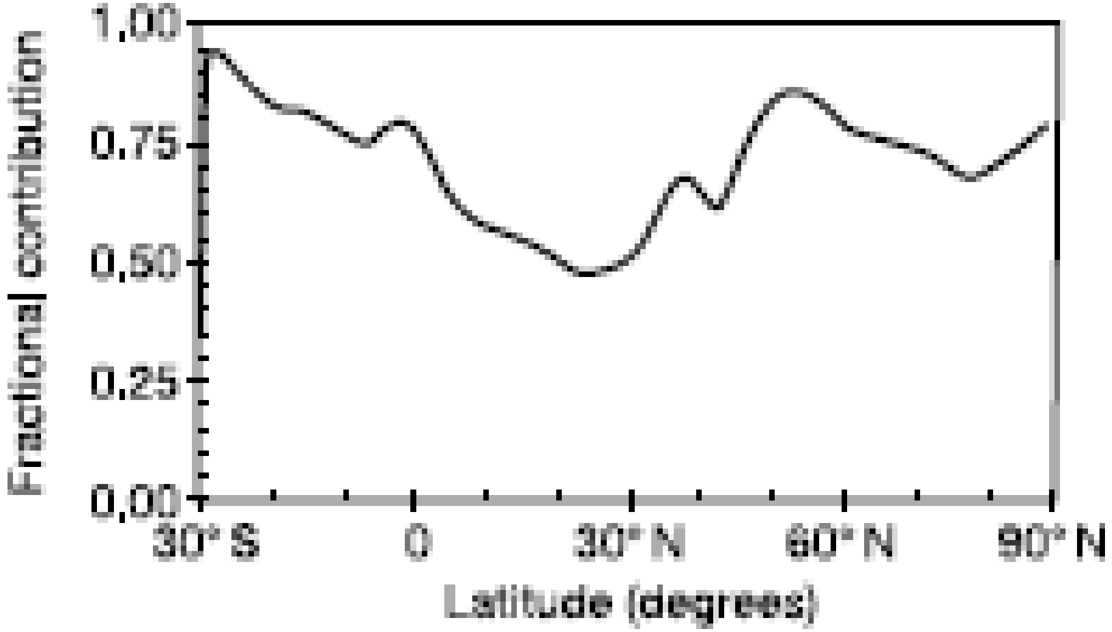
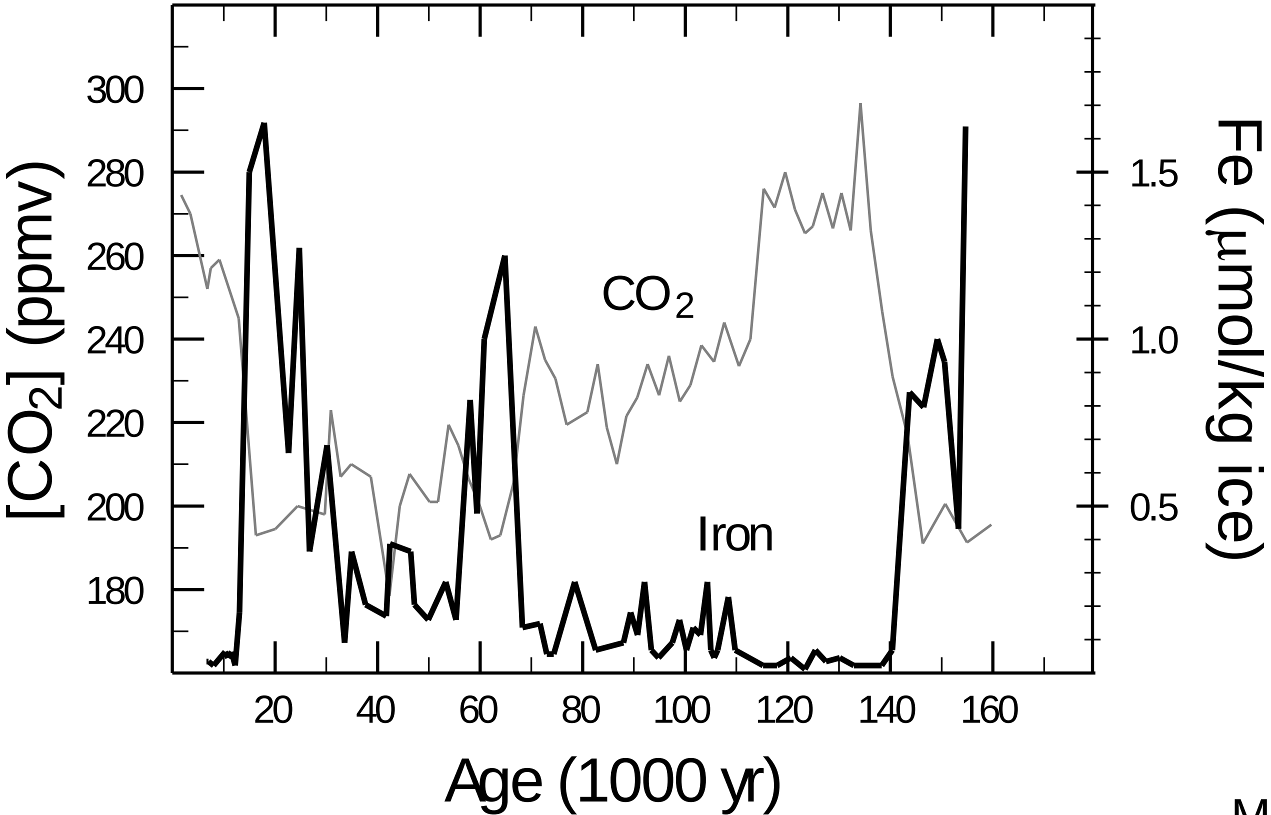


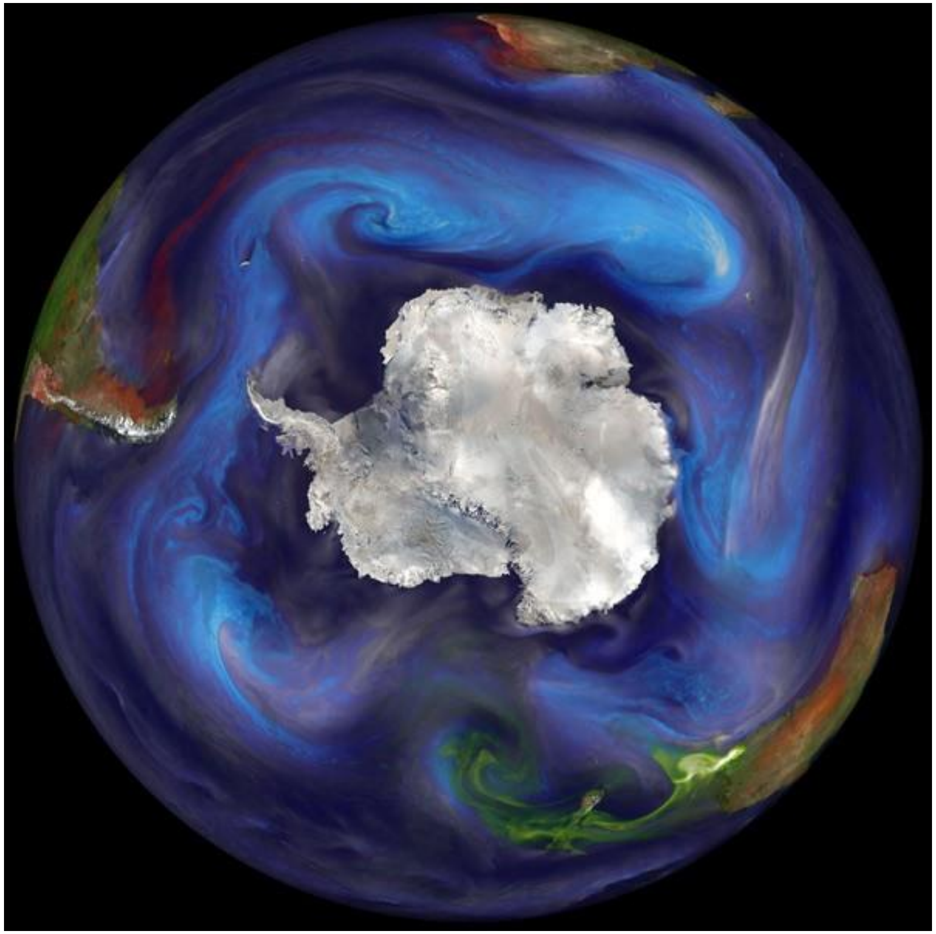
Figure 3 Predicted global zonal mean of the fractional contribution of Southern Ocean nutrient supply to global export production. Data obtained from an ocean biogeochemistry

HNLC waters in the geological past



Martin 1990

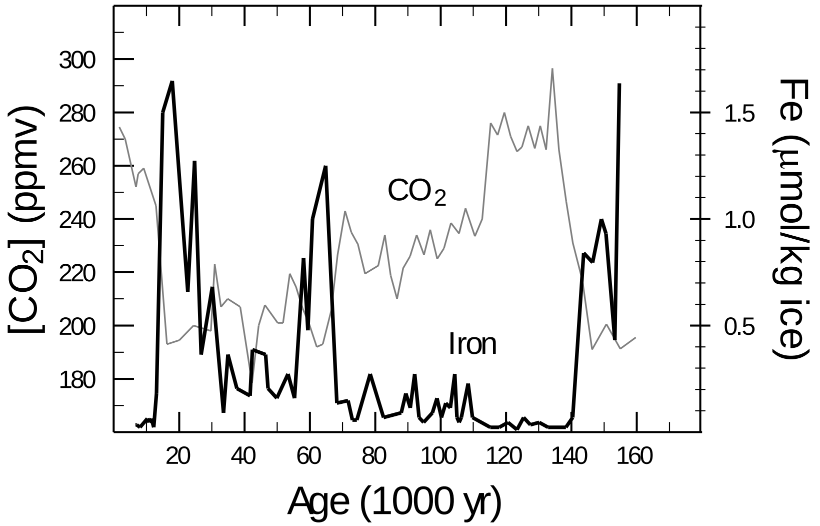
This record has been taken further into the past (4 million years) during recent ODP studies in the Atlantic sector of the Subantarctic S. Ocean (Martínez-Garcia et al. 2011, Nature)



Courtesy Science

Dust supply to the Southern Ocean increases during ice ages, and ‘iron fertilization’ <u>of the subantarctic zone</u> may have contributed up to 40 ppmv of the decrease (80–100 ppmv) in atmospheric carbon dioxide

A more complex picture of the Ice ages is emerging from cores



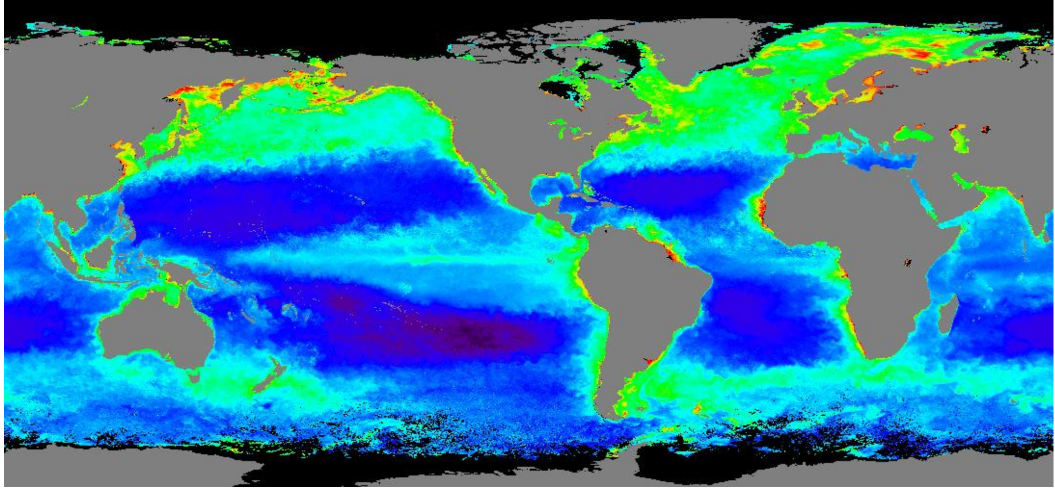
Antarctic Zone - reduced POC export
Subantarctic Zone – increased POC export coincident with rising dust fluxes

In the subantarctic, glacial times are characterized by increases in:
dust flux
productivity
the degree of nitrate consumption

The consequent strengthening of the biological pump can explain
the lowering of CO_2 at the transition from mid-climate states
to full ice age conditions

Jaccard et al. 2013 Science; Martínez-Garcia et al. 2014, Science

What causes
the HNLC condition?

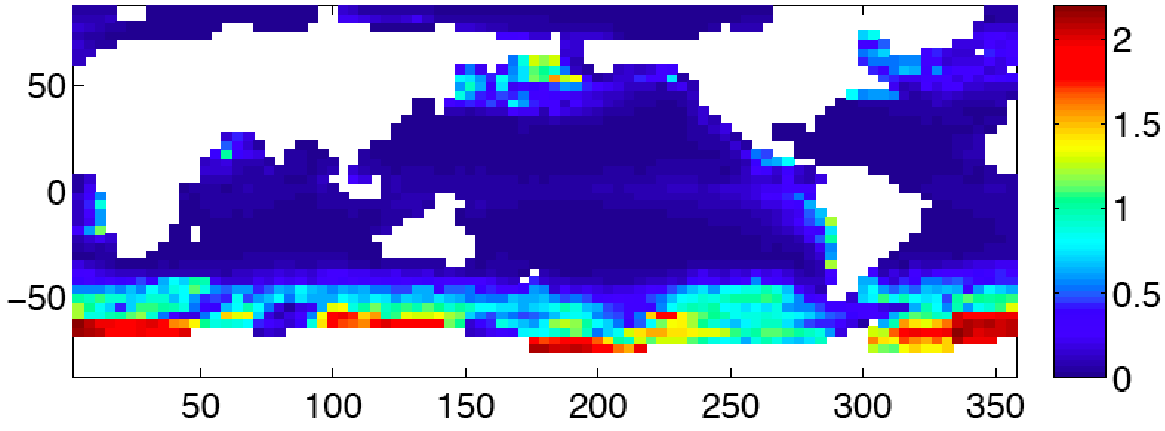


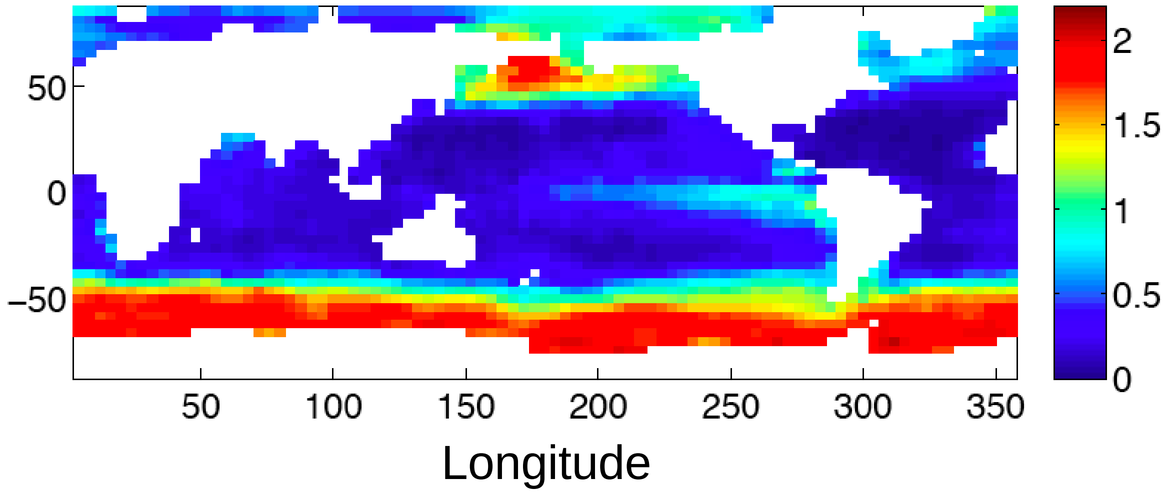
Strength of ocean circulation (Curtis’s lecture on Wednesday)

Geographical isolation – from sources of aerosol iron

Mismatch between the depth of the ferricline and nutricline/thermocline

Circulation-PO_4 model


Surface PO_4: Model


Surface PO_4: Climatology

A model whose phytoplankton have a uniform growth rate, subject only to PO_4 limitation produce the observed features, but not their magnitudes.

HNLC regions are at least partly a direct consequence of ocean circulation.

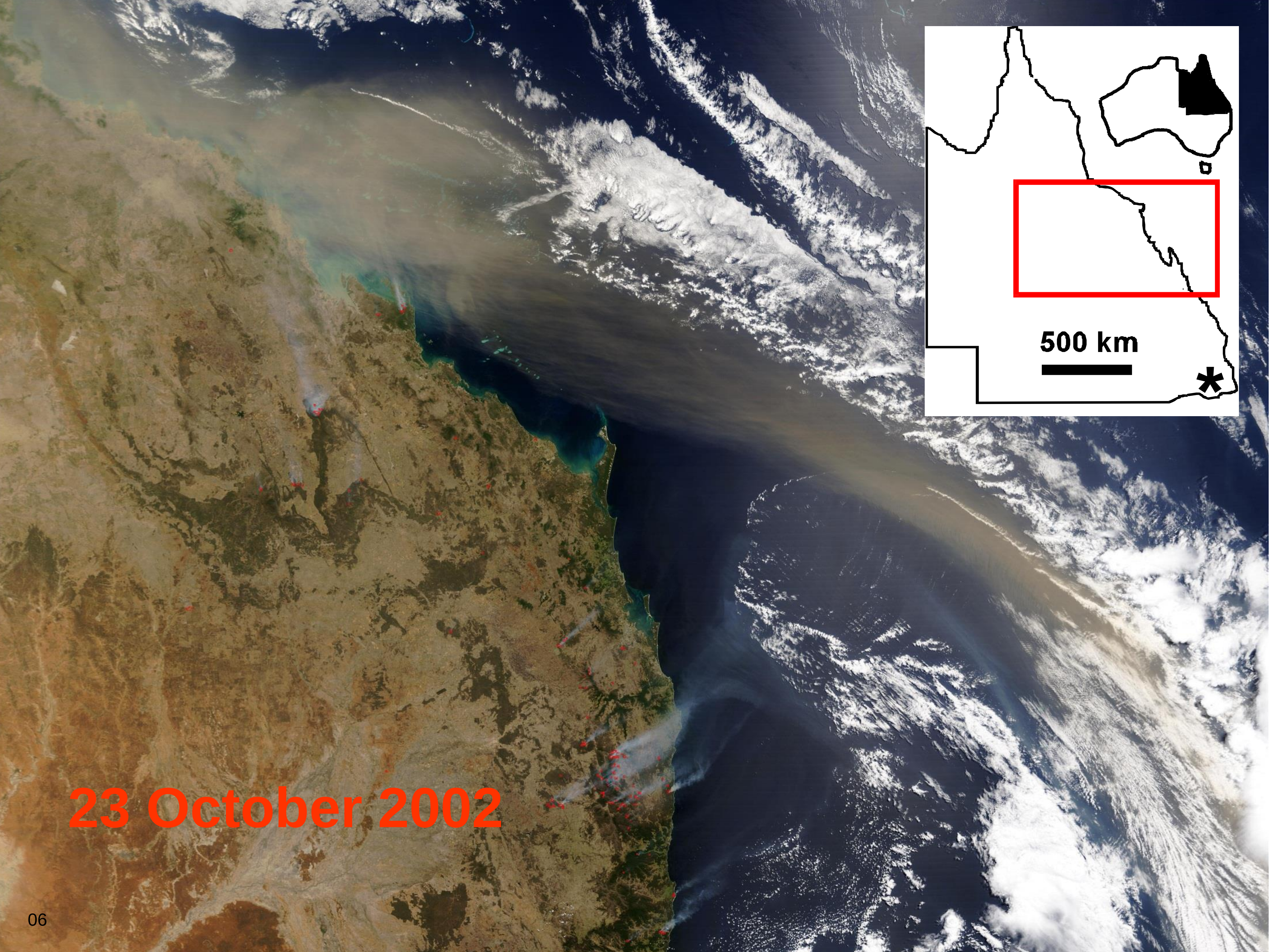
Other limiting factors are important nearly everywhere (all latitudes).

Predominant dust source regions and transport routes

Pye (1987)

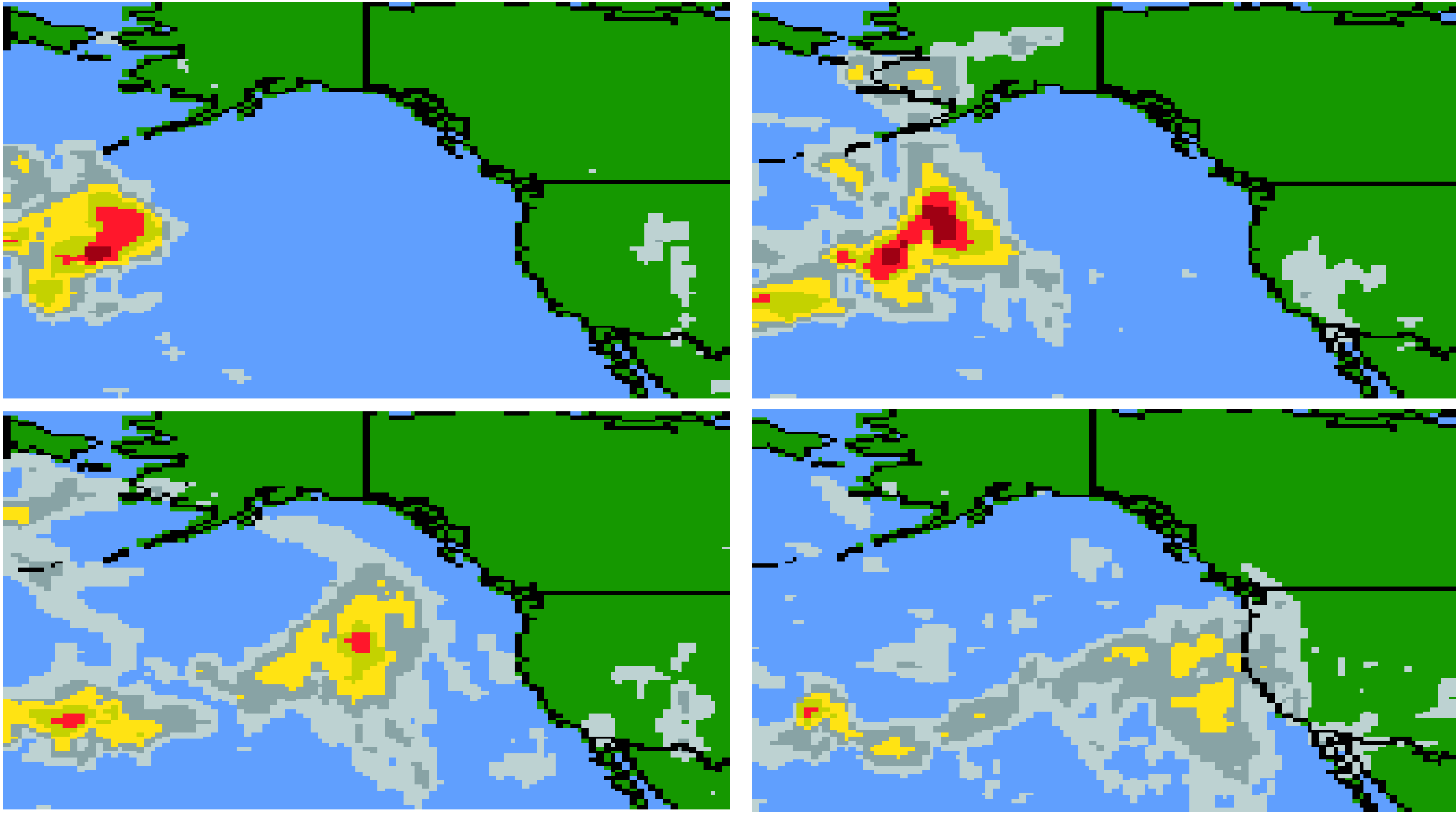
Initial uplift of soil in a dust storm

Courtesy McTainsh Australia



23 October 2002

Evidence of a dust storm from TOMS Aerosol Index, April 22 -25 1998 NE Pacific



Boyd 2009

Geographical isolation – from sources of aerosol iron

1724 *Duce and Tindale* 1991

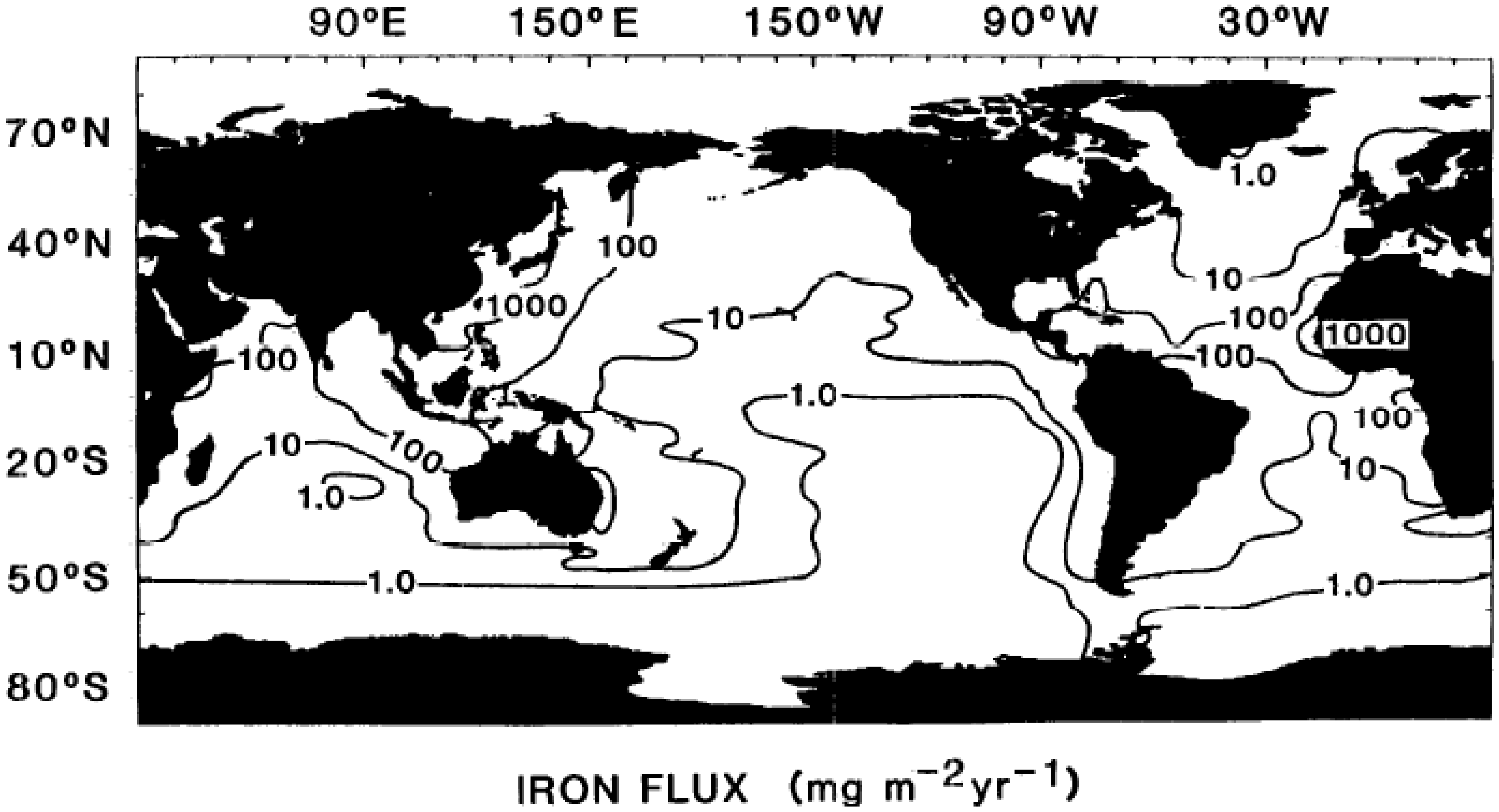
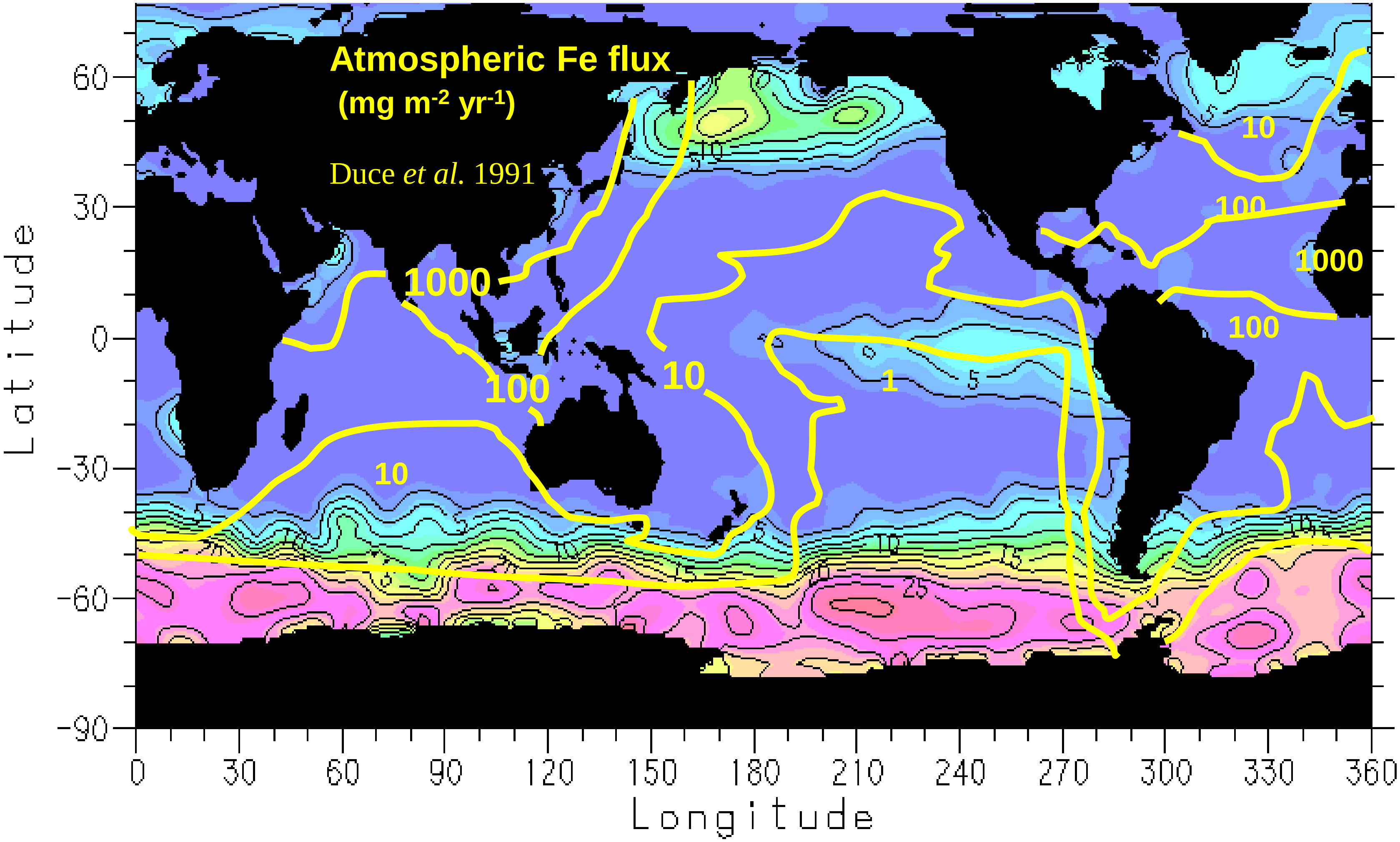


Fig. 8. Calculated flux of total (particulate plus dissolved) Fe from the atmosphere to the ocean (adapted from Donaghay et al. 1991).

Dust flux overlaid on the NO_3 distribution (µM) in the upper ocean

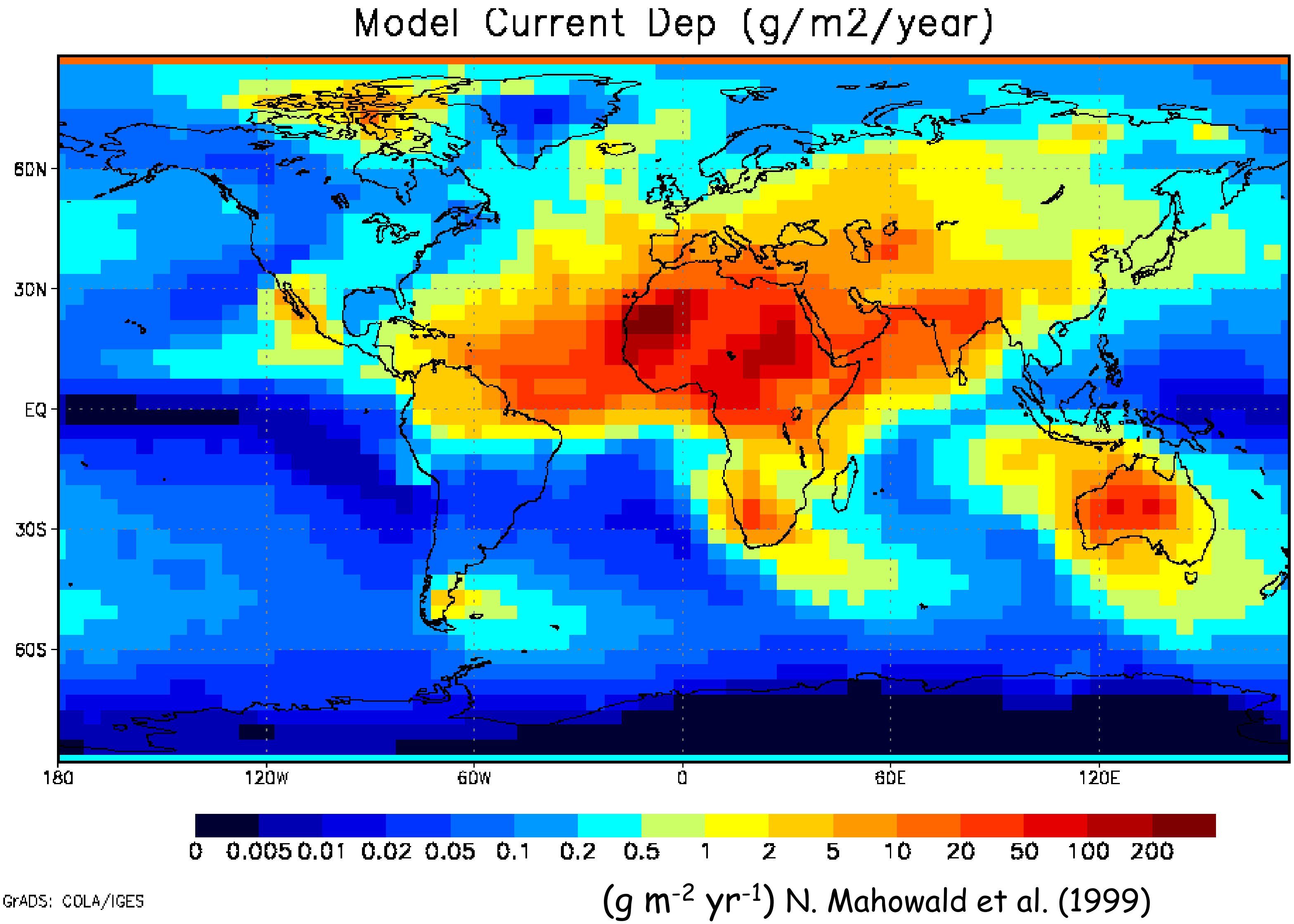
NOAA world ocean atlas, 1994



Atmospheric Fe flux (mg m^{-2} yr^{-1})

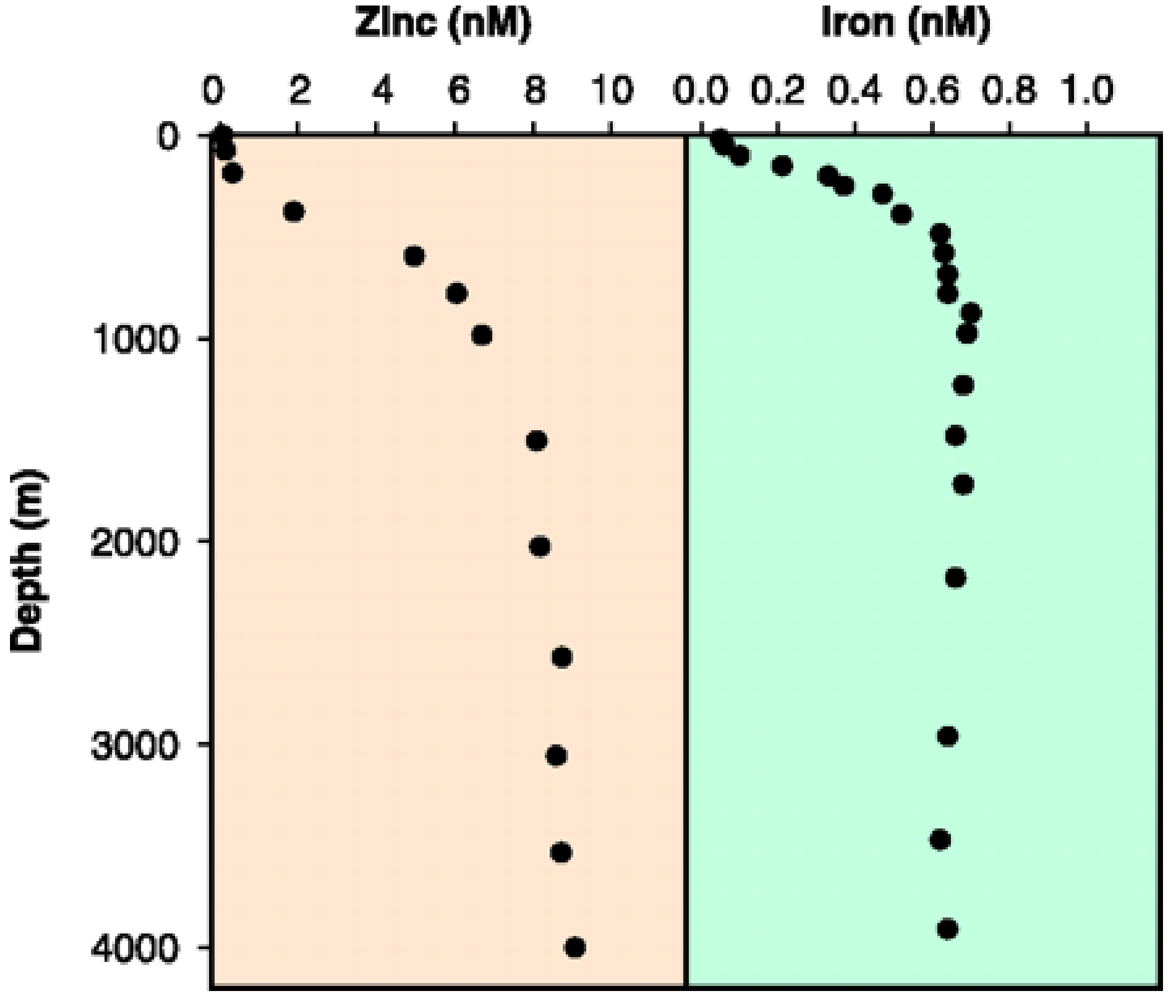
Duce *et al.* 1991

Modelled dust deposition rates



(g m^{-2} yr^{-1}) N. Mahowald et al. (1999)

Mismatch between the depth of the ferricline & nutricline/thermocline



Morel & Price 2003

nature geoscience

ARTICLES

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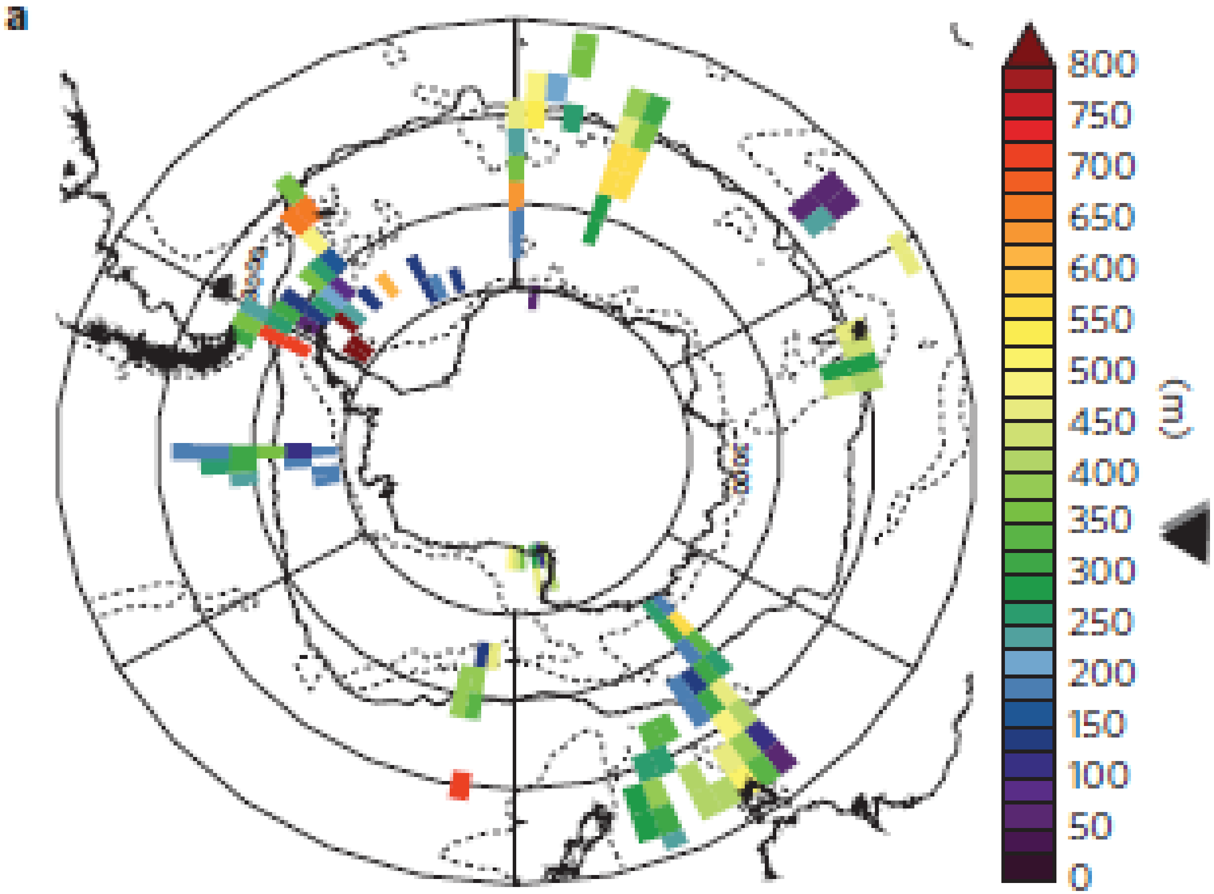
2014

Surface water iron supplies in the Southern Ocean sustained by deep winter mixing

Alessandro Tagliabue[1,2]*, Jean-Baptiste Sallée[3,4,5], Andrew R. Bowie[6], Marina Lévy[3,4], Sebastiaan Swart[2,7] and Philip W. Boyd[8,9]



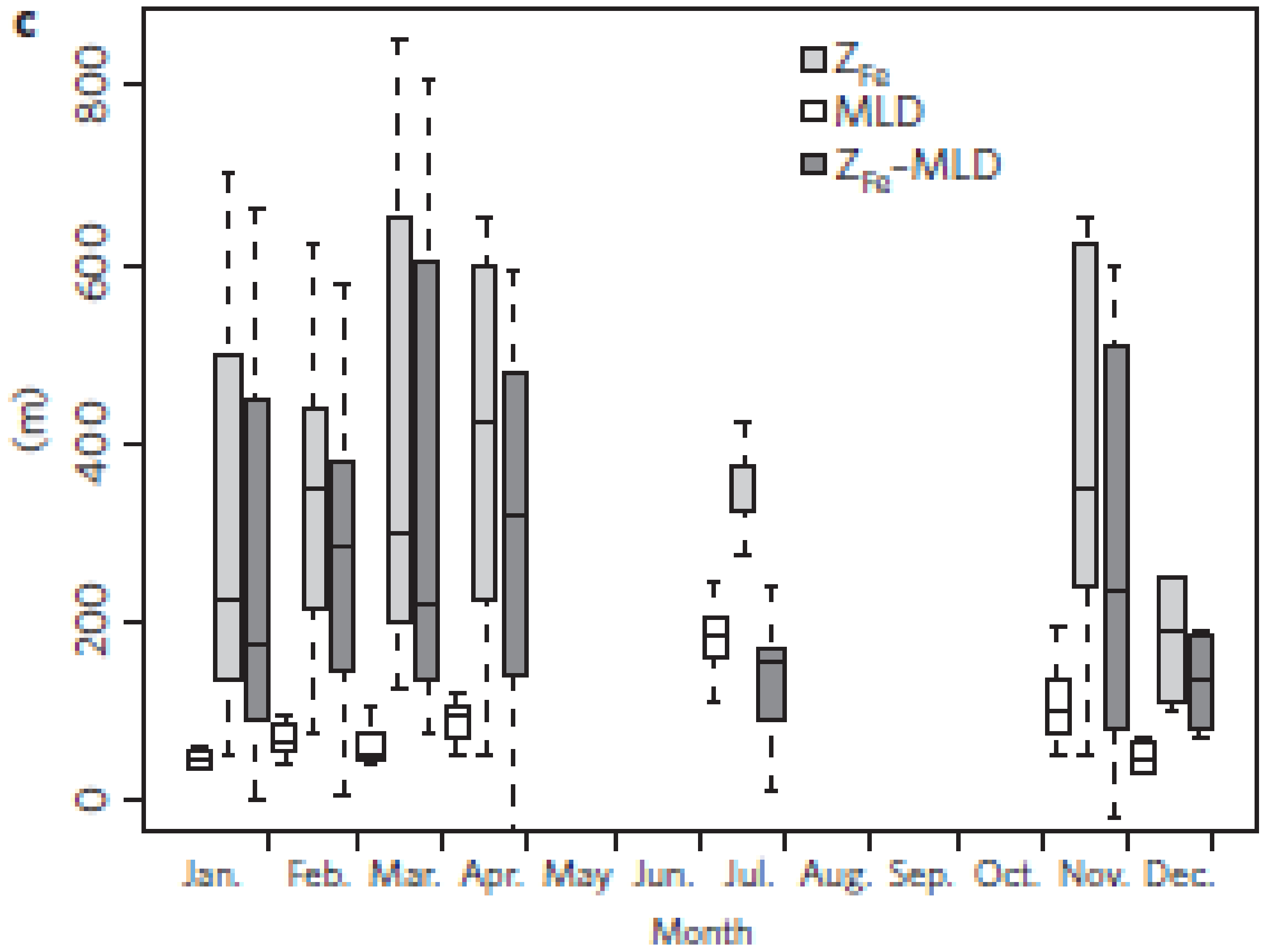
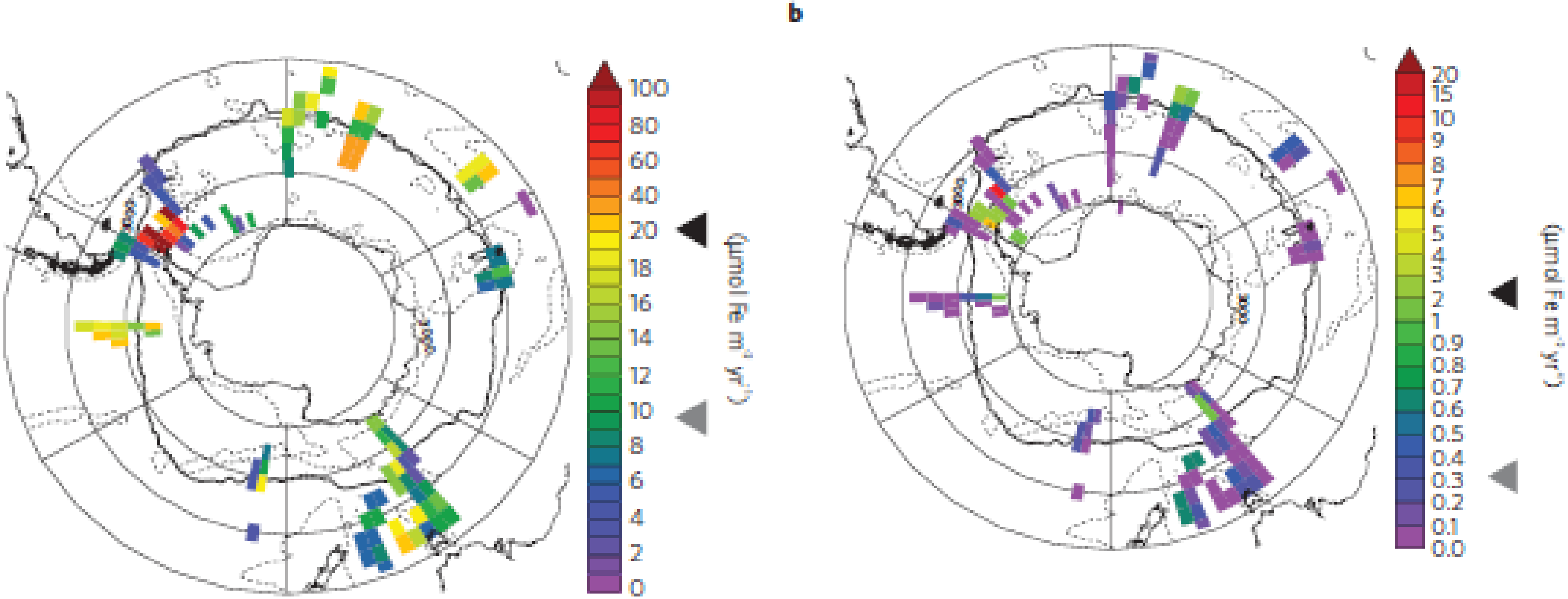


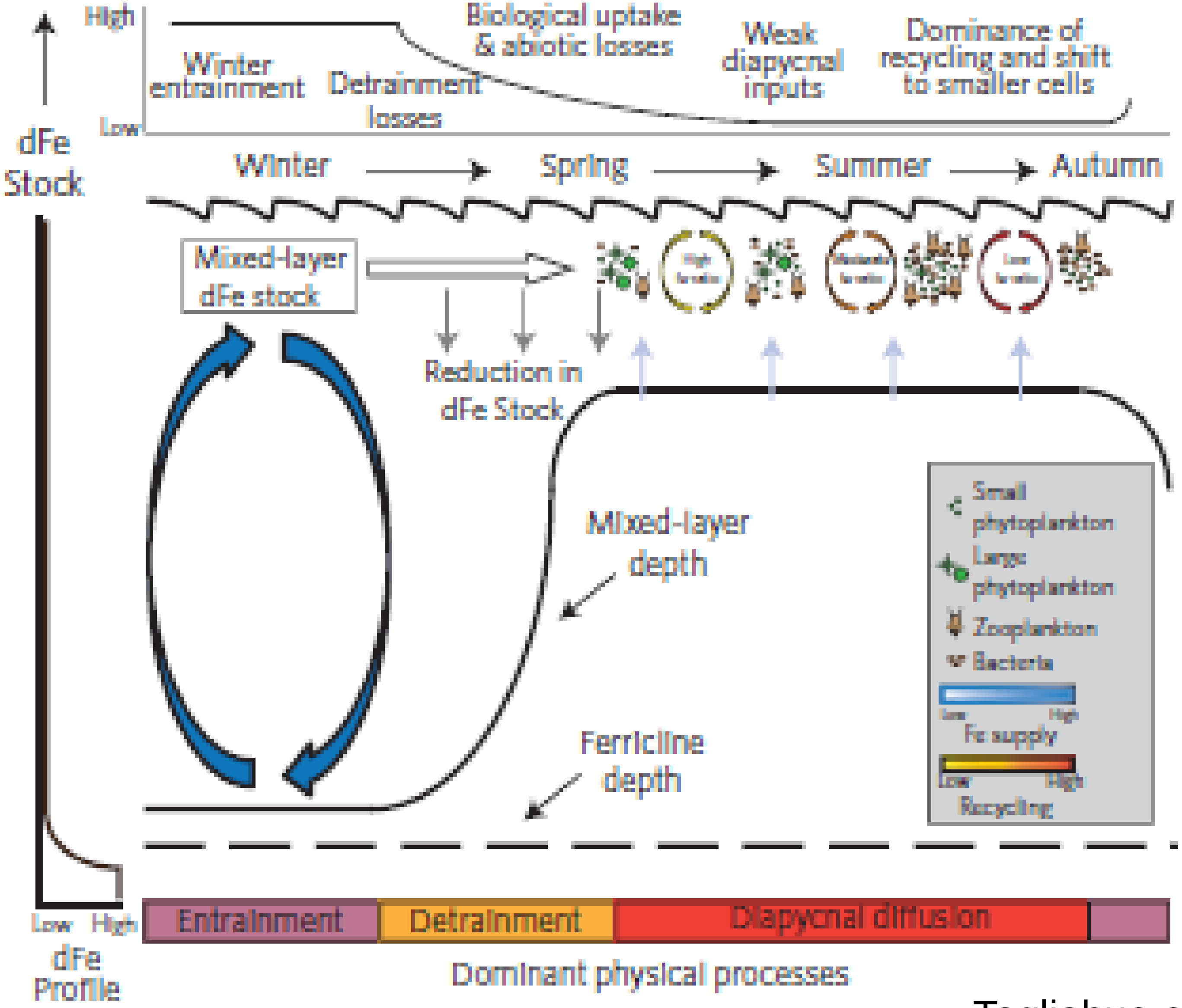
Figure 1 | Depths and potential density of the ferricline and its seasonal

Tagliabue et al. 2014

Fe supply from
Winter entrainment
Diapycnal diffusion



Tagliabue et al. 2014

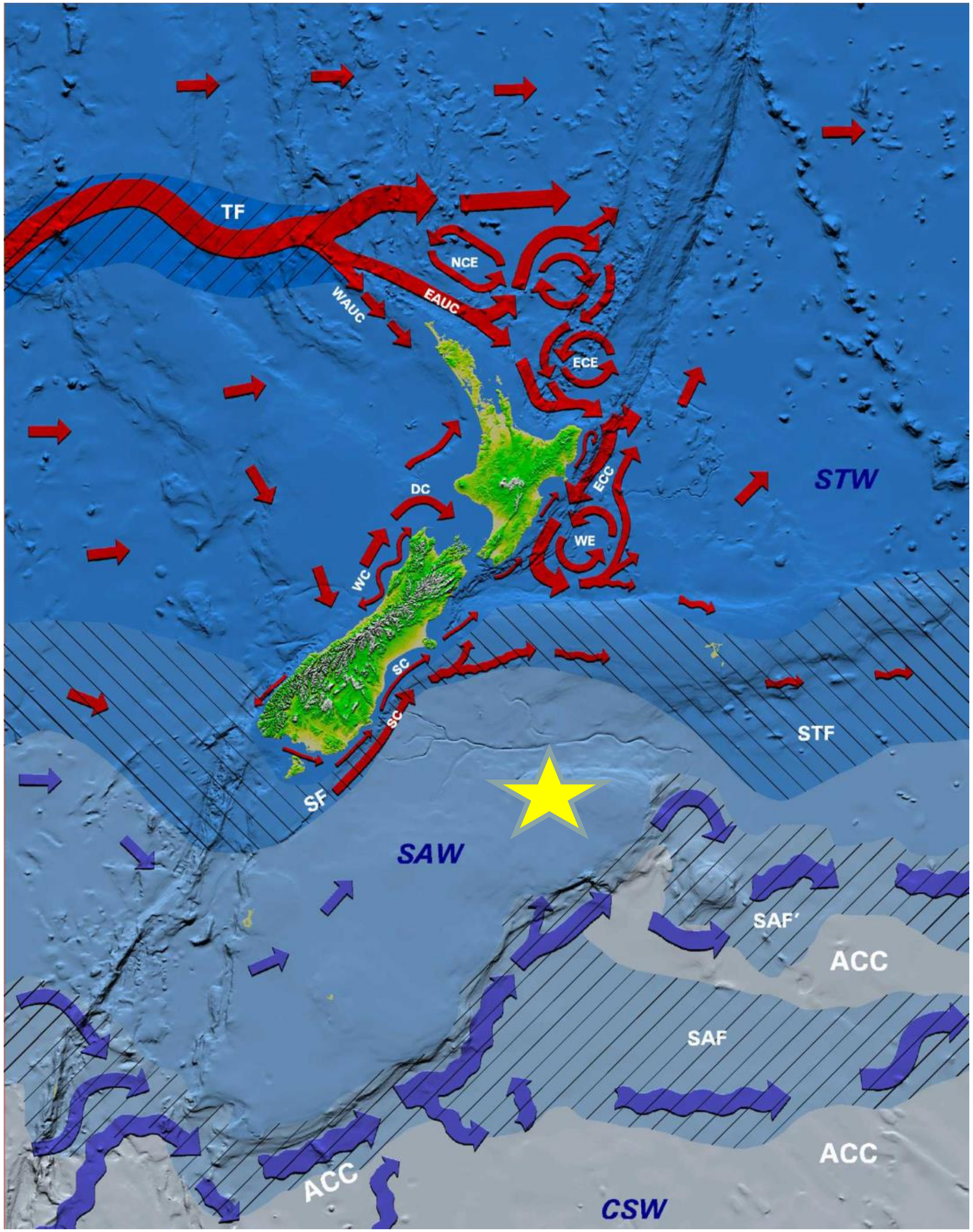


Tagliabue et al. 2014

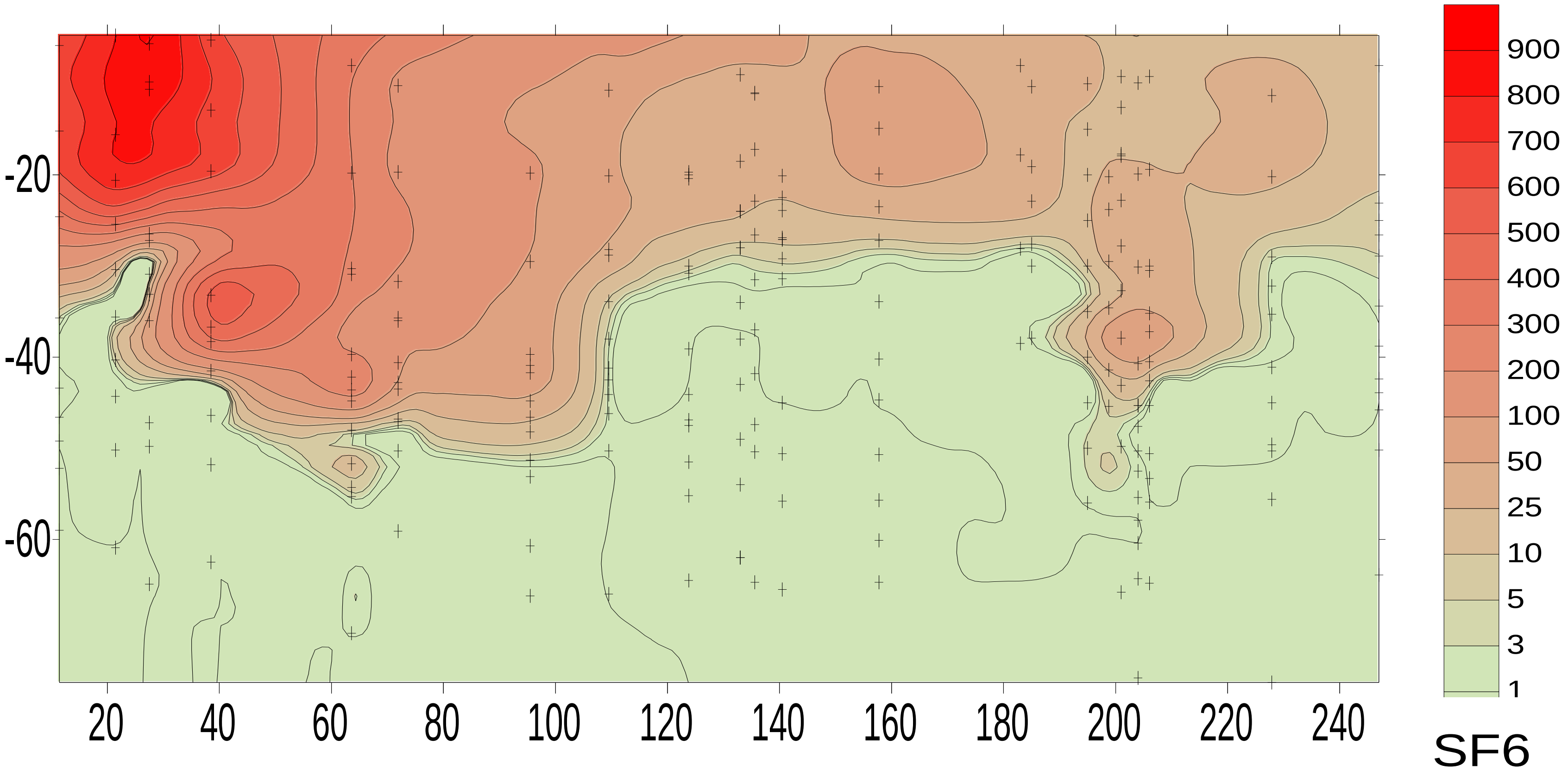
Figure 4 | A schematic representation of the seasonal variability in Southern Ocean Fe cycling. We emphasize seasonal changes in the

Everyday life in HNLC waters

A case study
FeCycle

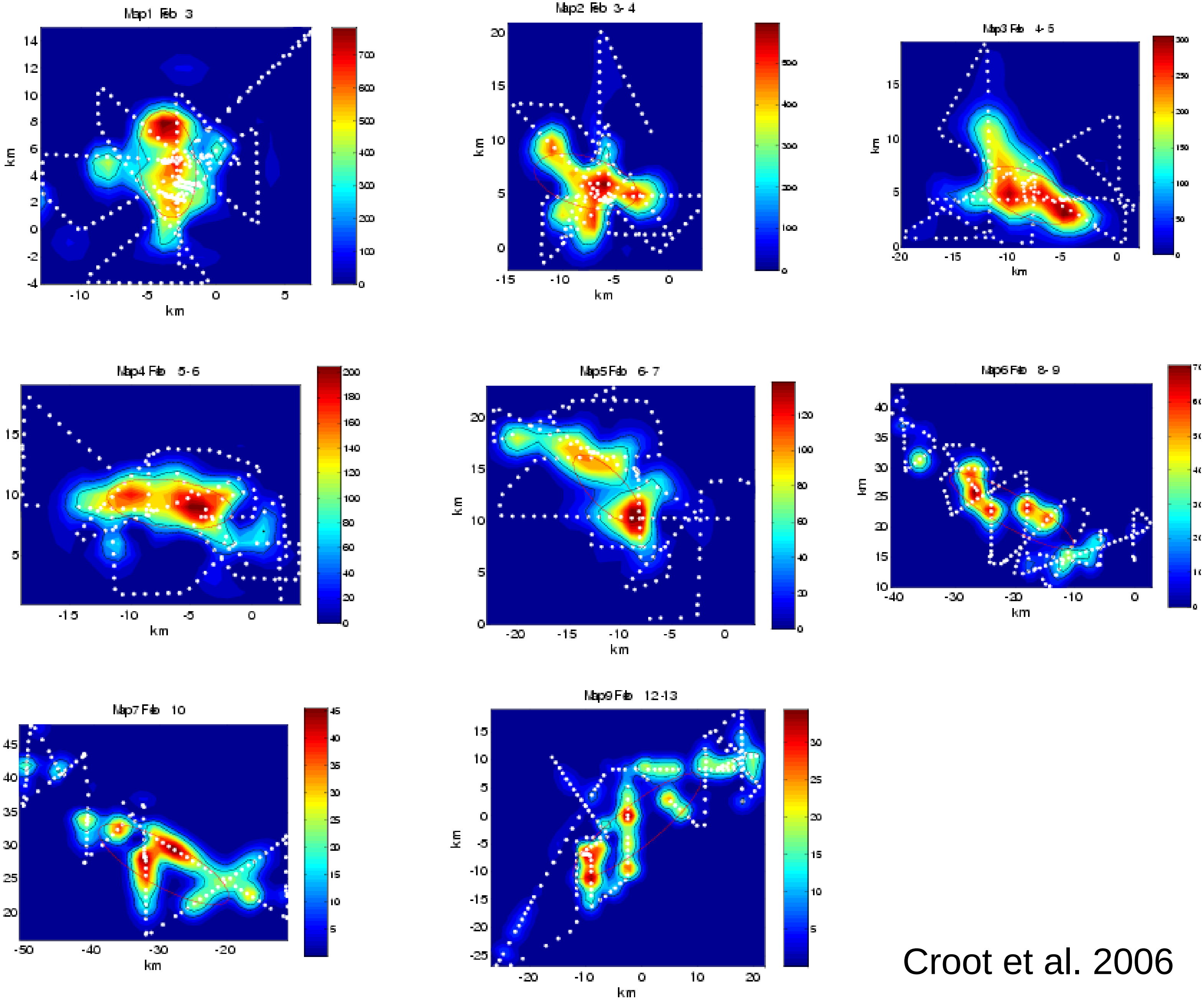


FeCycle - a mesoscale SF_6 tracer study of iron cycling in unperturbed HNLC waters



Boyd et al. 2005

Time (h) versus depth (m)


Map1 Feb 3

Map2 Feb 3- 4

Map3 Feb 4- 5

Map4 Feb 5- 6

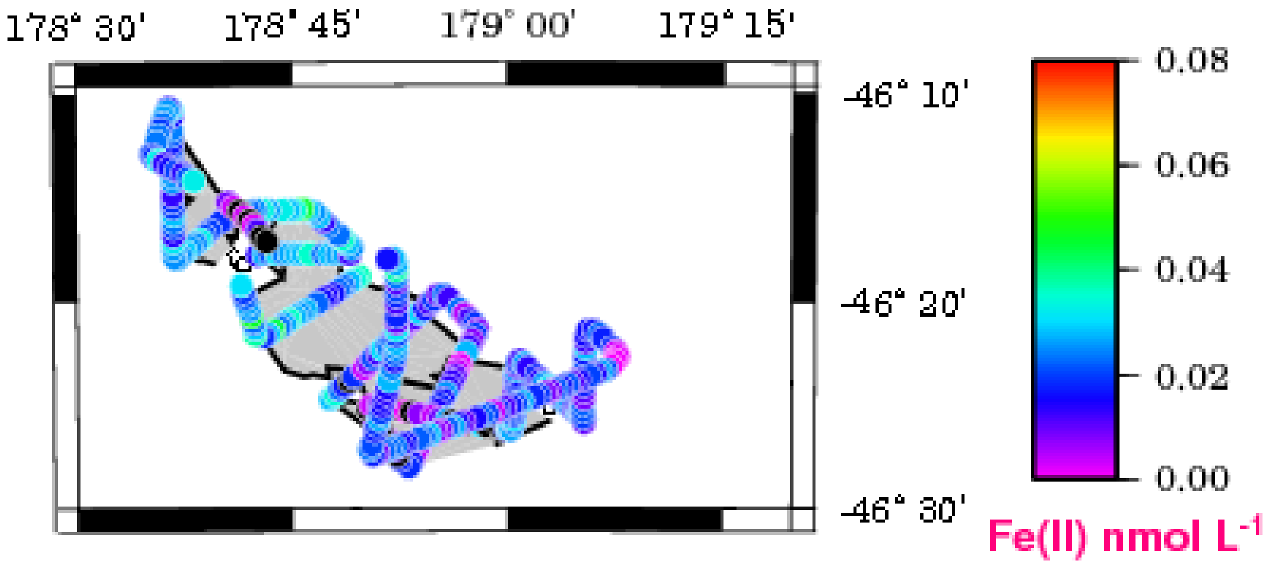
Map5 Feb 6- 7

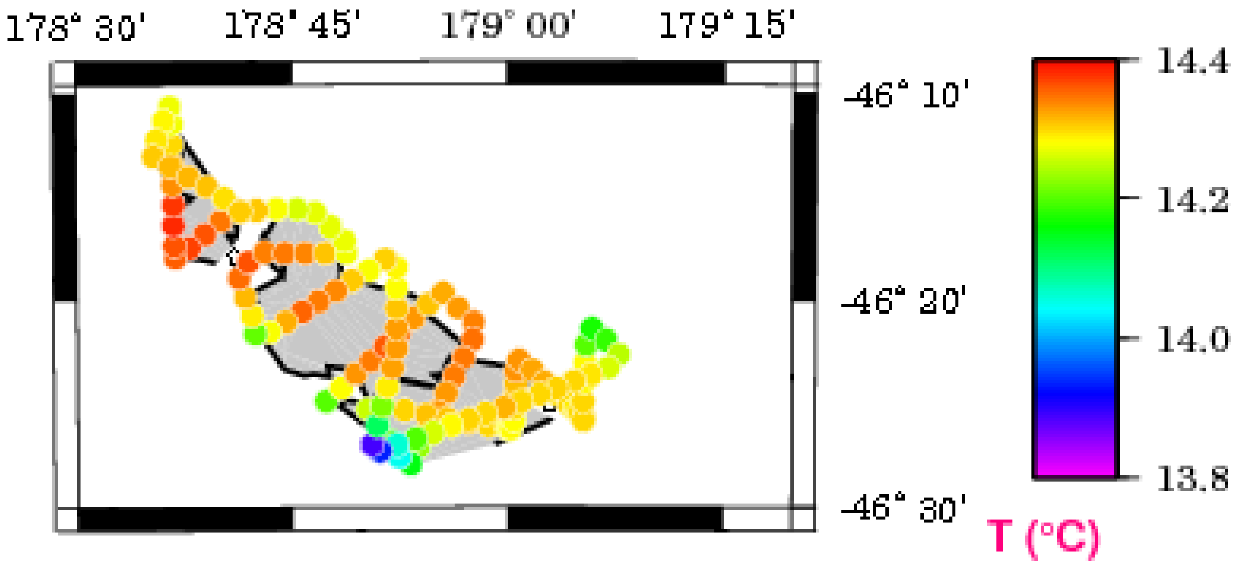
Map6 Feb 8- 9

Map7 Feb 10

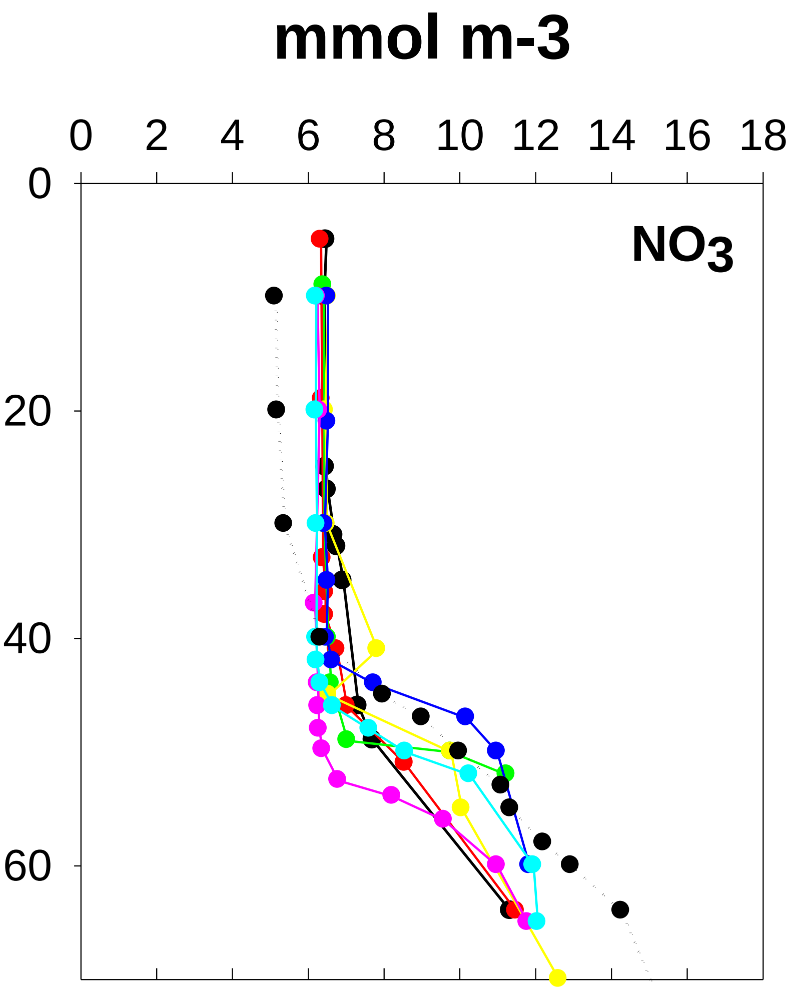
Map9 Feb 12-13

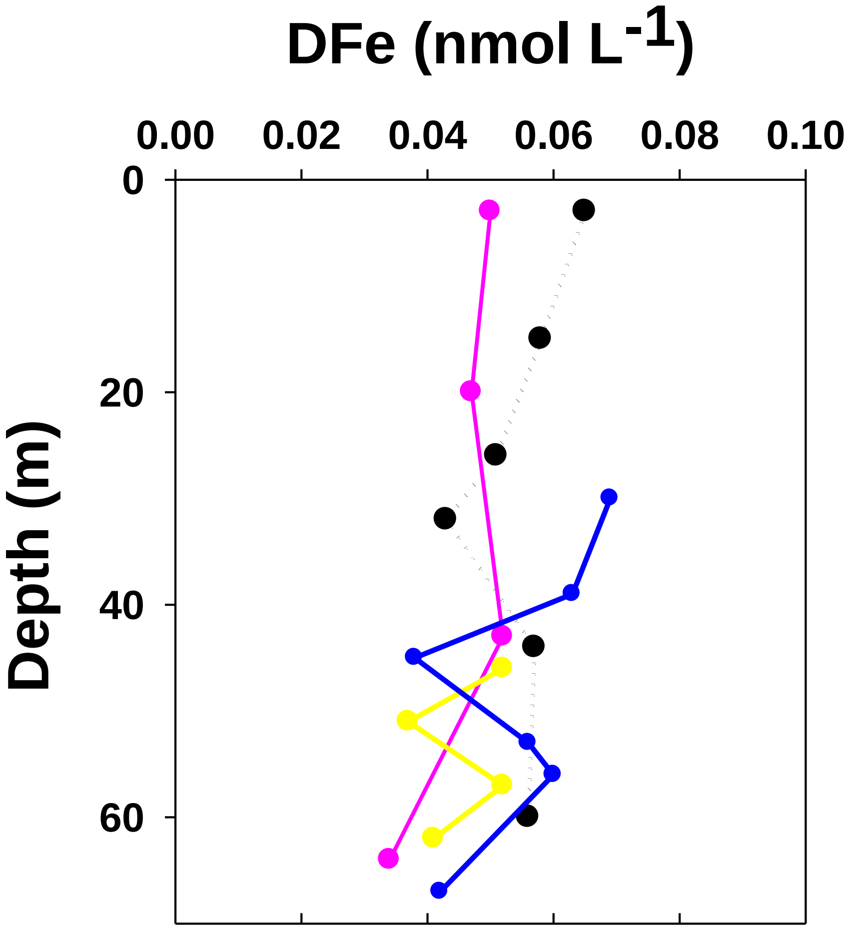
Croot et al. 2006





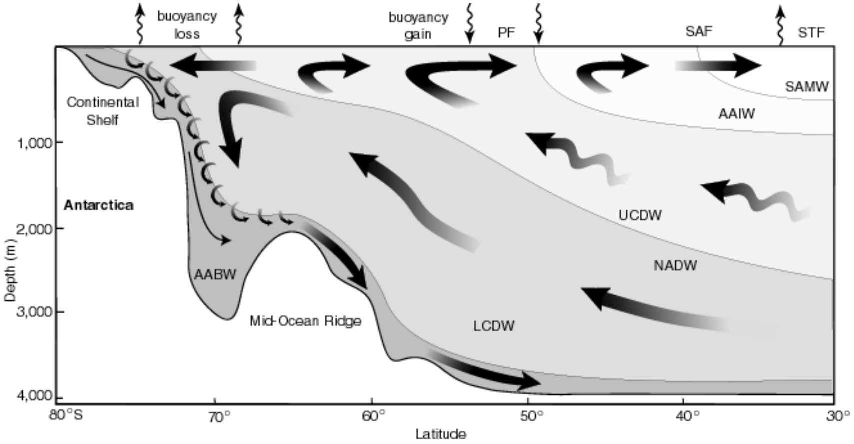
Croot et al. 2006



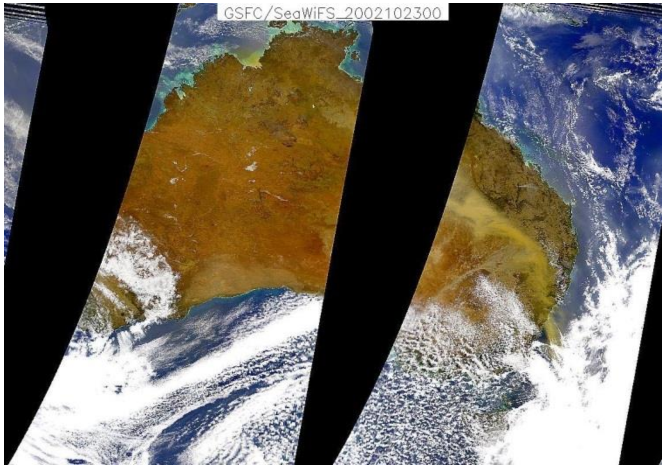


Boyd et al. 2005

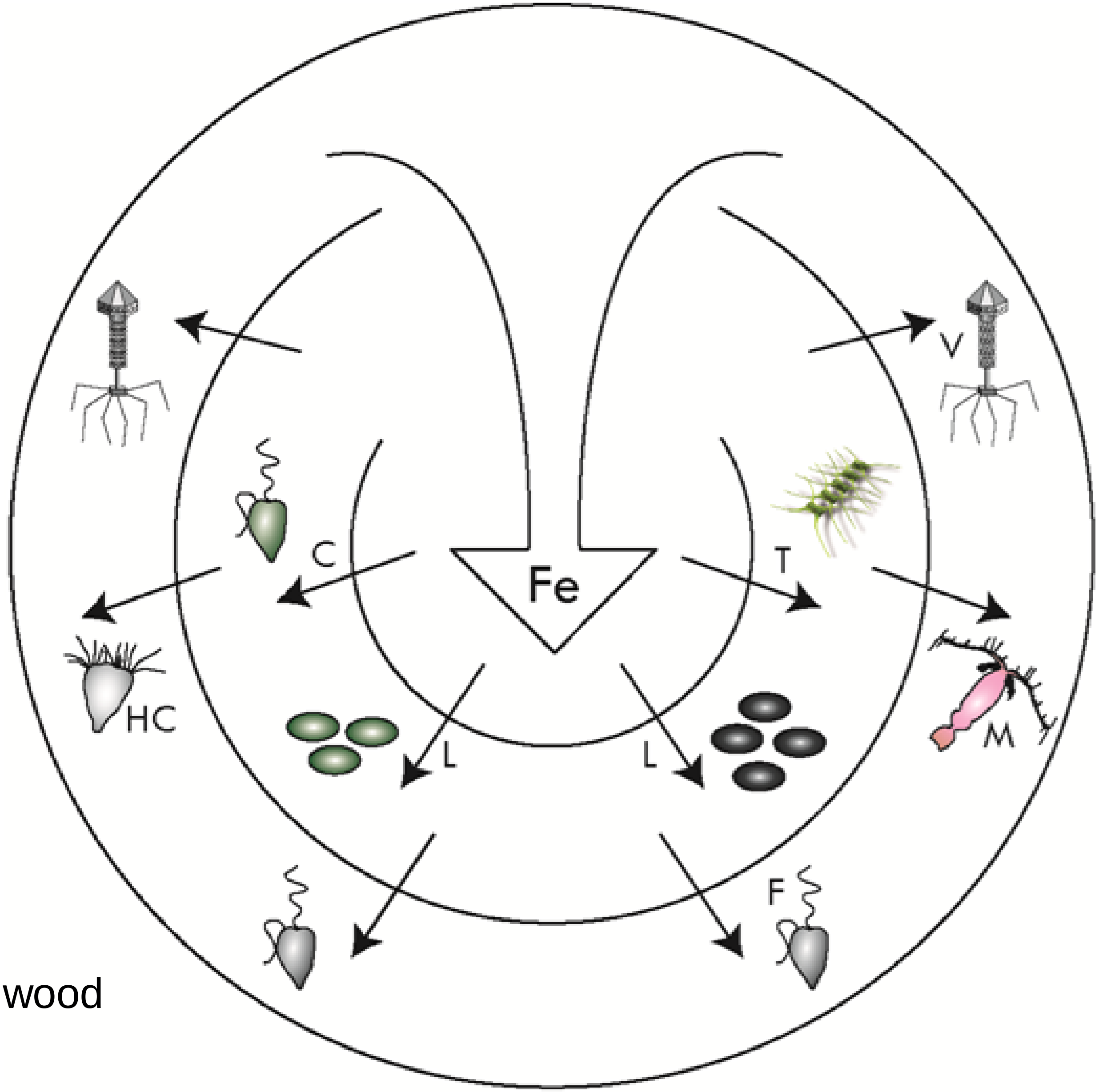
New versus regenerated iron



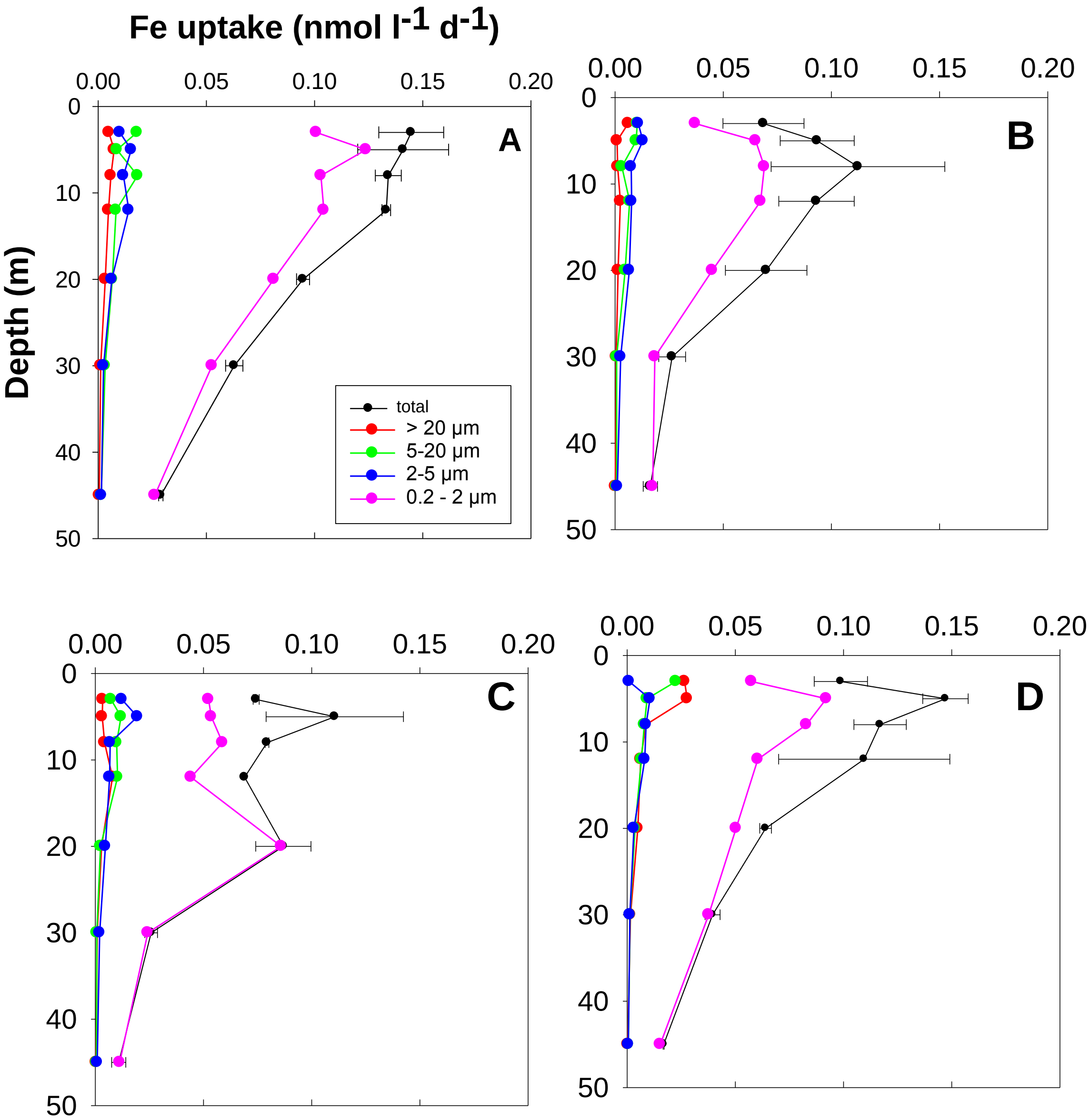
***fe* ratio = new Fe / (new + regen Fe)**



Microbes drive the oceanic ferrous wheel

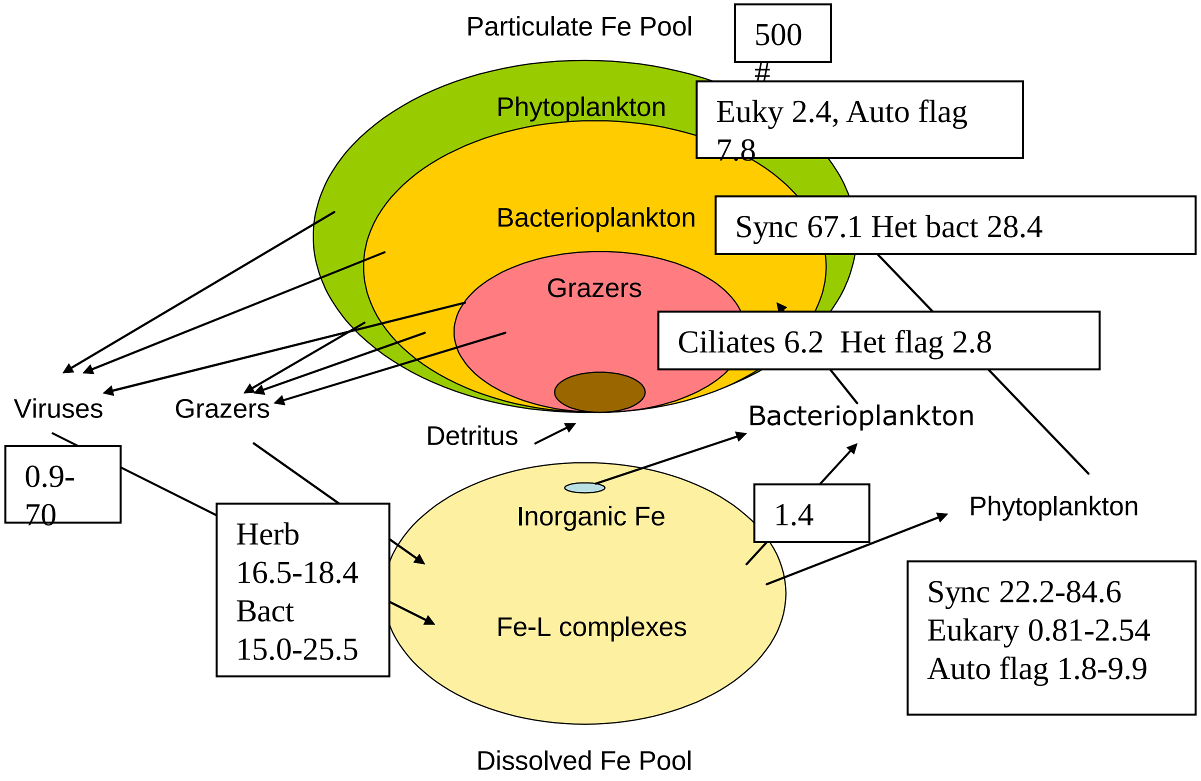


Boyd & Ellwood
2010



McKay et al. 2005

WHO HAS THE IRON?



Particulate Fe Pool

500 #

Phytoplankton

Euky 2.4, Auto flag 7.8

Bacterioplankton

Sync 67.1 Het bact 28.4

Grazers

Ciliates 6.2 Het flag 2.8

Viruses

Grazers

Detritus

Bacterioplankton

0.9-70

Herb 16.5-18.4 Bact 15.0-25.5

Inorganic Fe

1.4

Phytoplankton

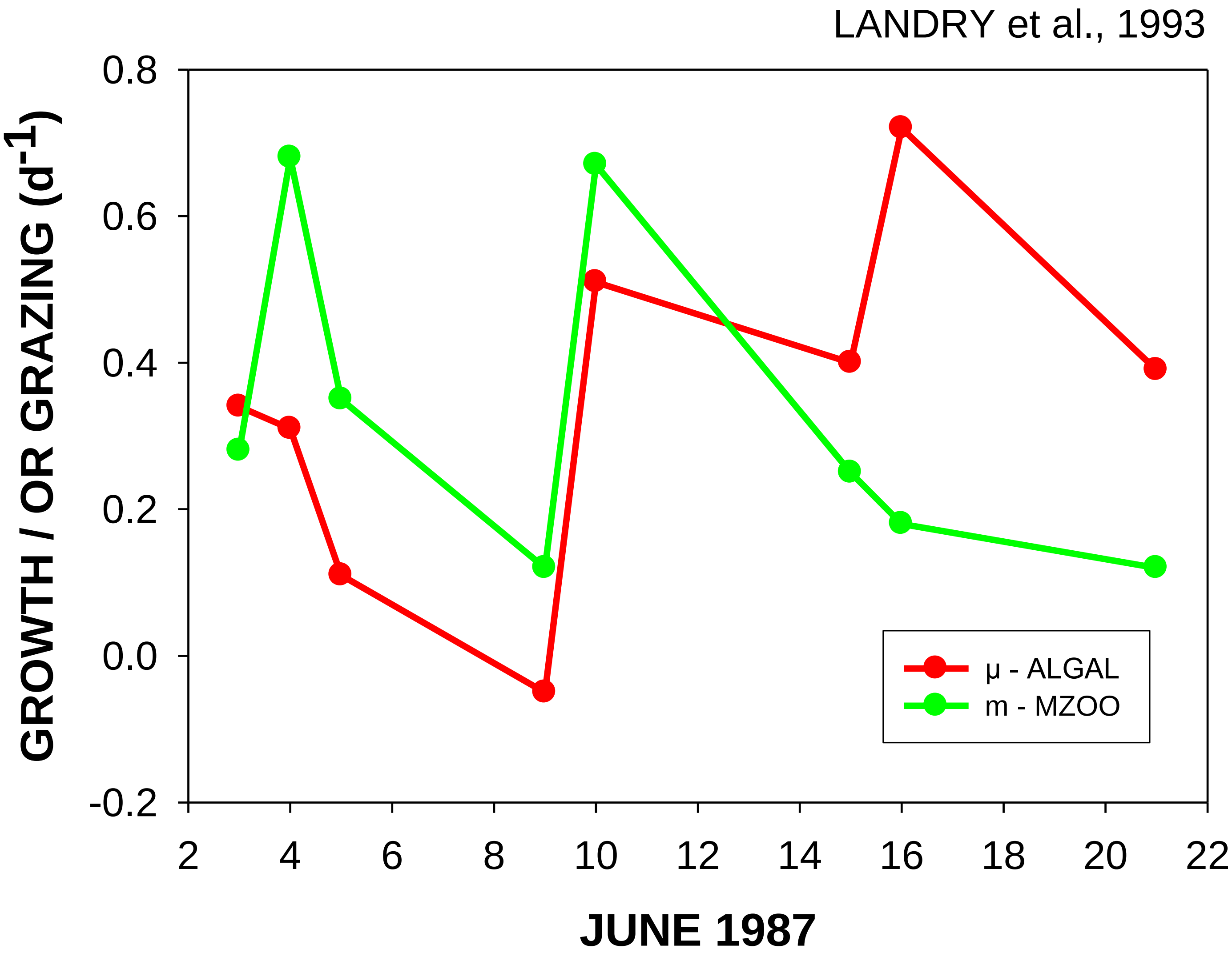
Fe-L complexes

Sync 22.2-84.6
Eukary 0.81-2.54
Auto flag 1.8-9.9

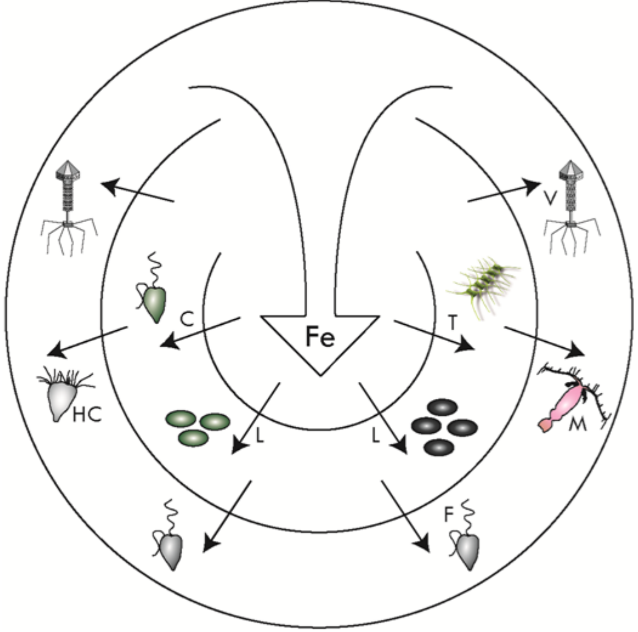
Dissolved Fe Pool

Strzepek et al. 2005

GROWTH RATE versus GRAZING MORTALITY



Internal cycling of IRON



UPTAKE

2453 to 4055 (e)

Biological

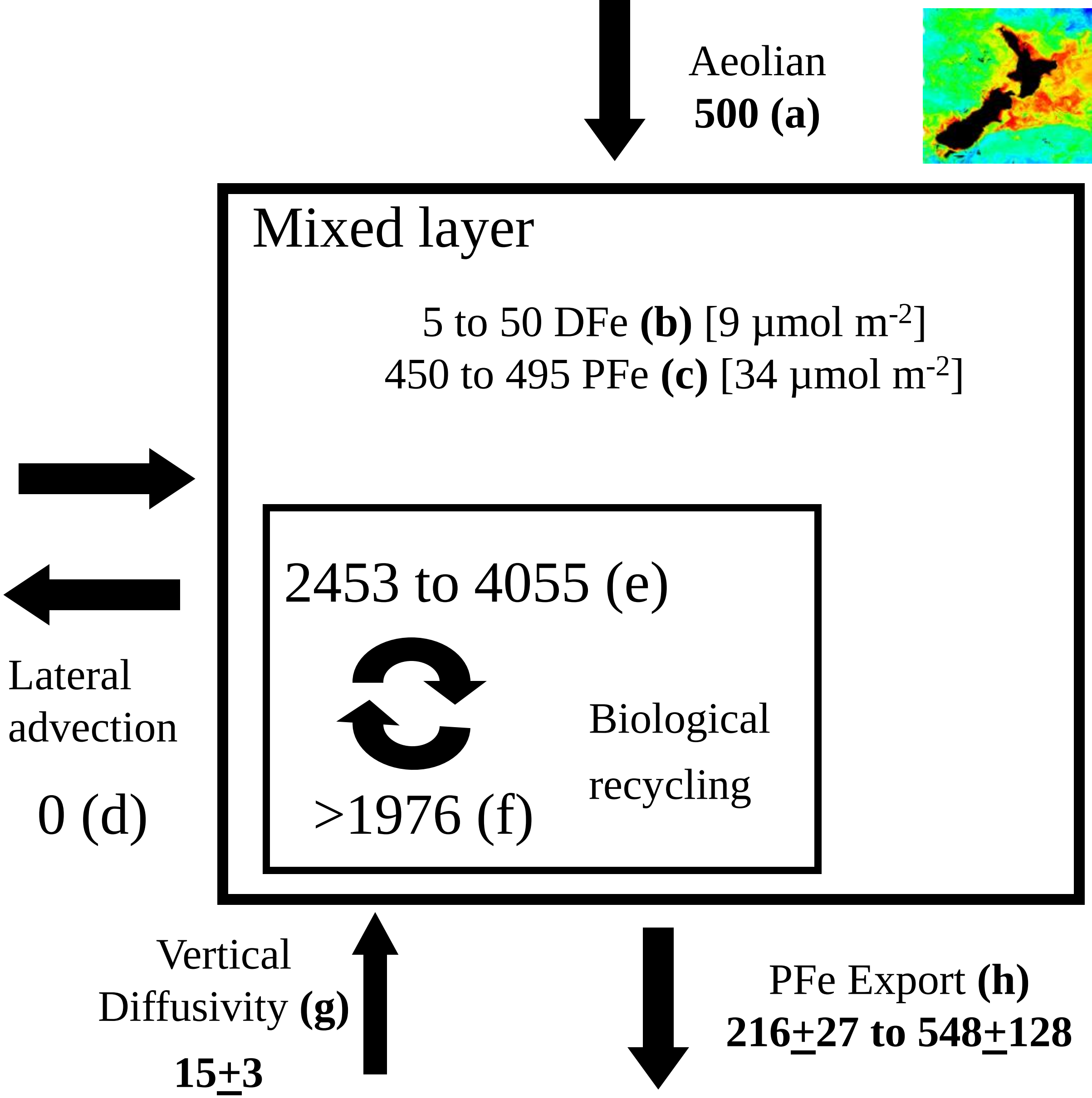
recycling

>1976 (f)

GRAZING AND VIRAL LYSIS

Boyd et al. 2005

Fe Cycle
Voyage, January/February, 2003



Aeolian
500 (a)

Mixed layer

5 to 50 DFe **(b)** [9 µmol m^{-2}]
450 to 495 PFe **(c)** [34 µmol m^{-2}]

2453 to 4055 (e)

>1976 (f)

Biological
recycling

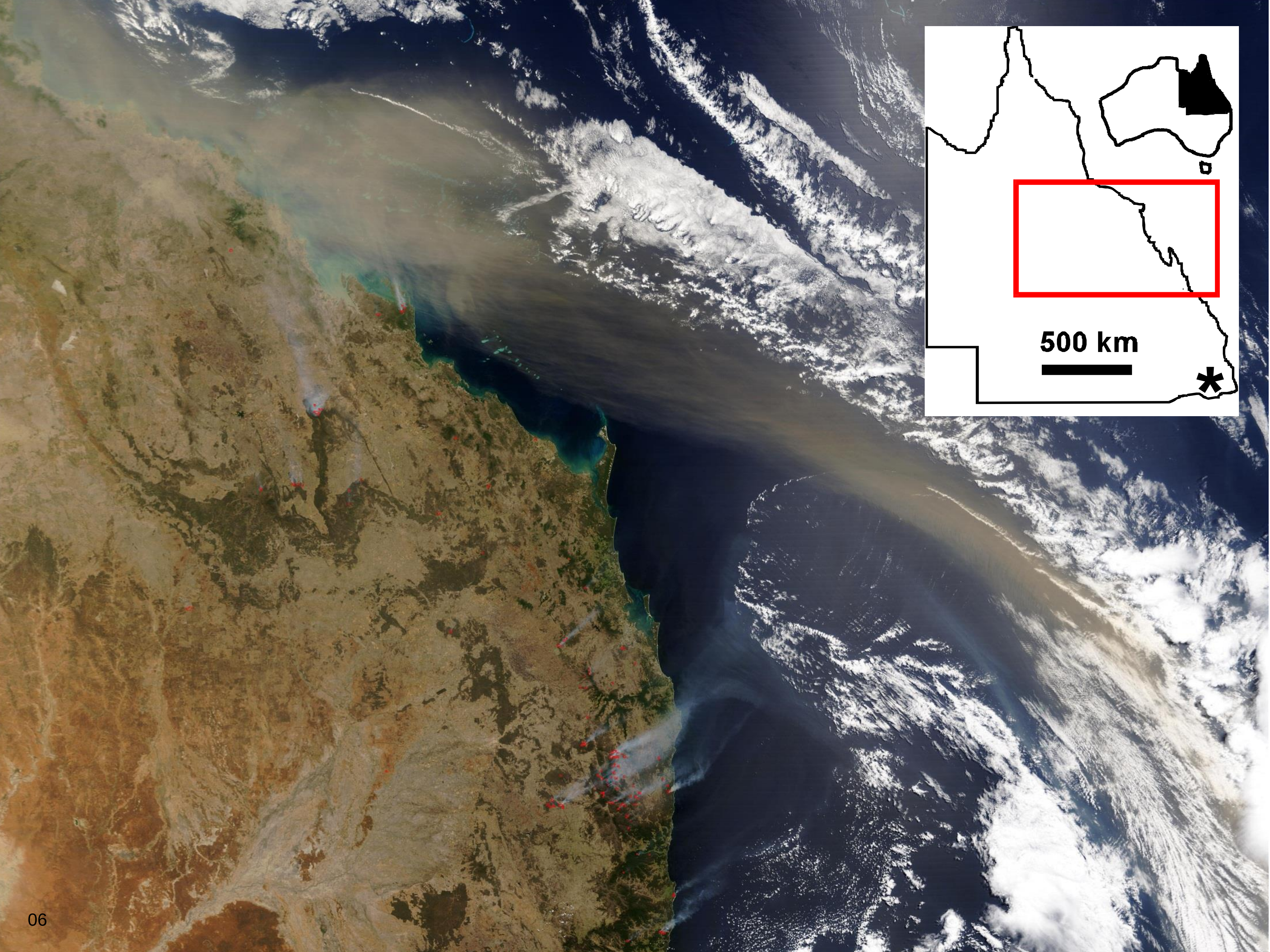
Lateral
advection

0 (d)

Vertical
Diffusivity **(g)**
15±3

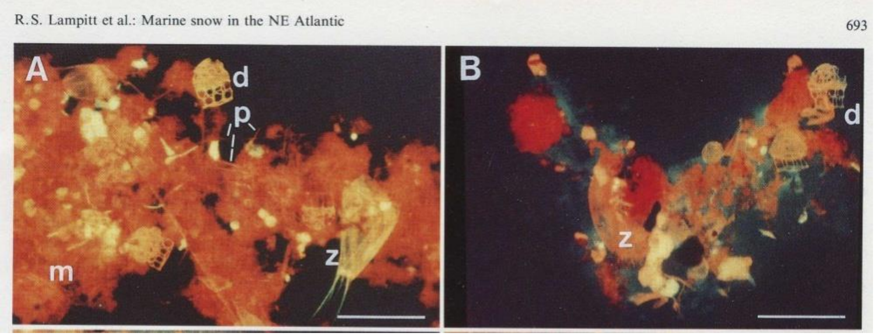
PFe Export **(h)**
216±27 to 548±128

Boyd et al. 2005

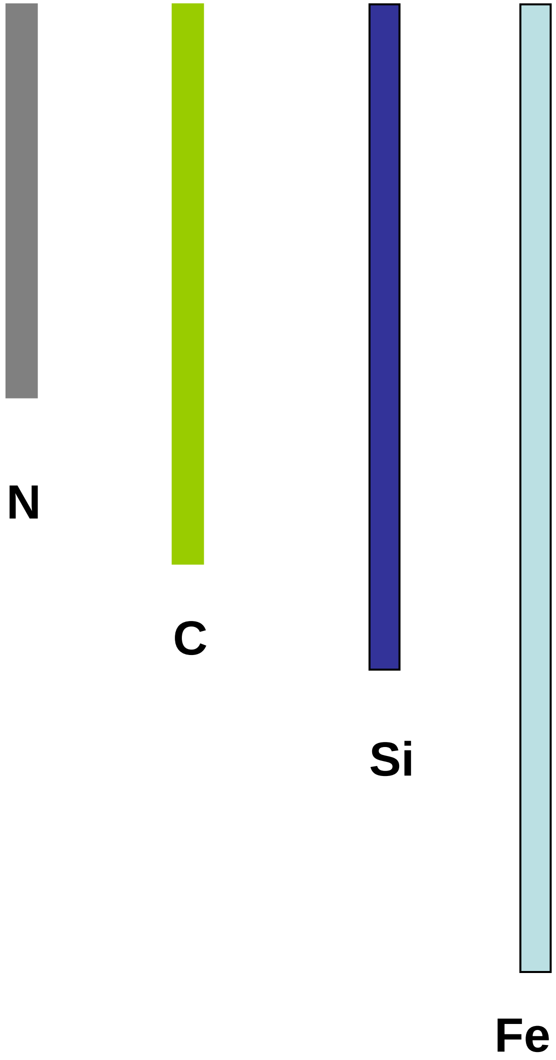


06

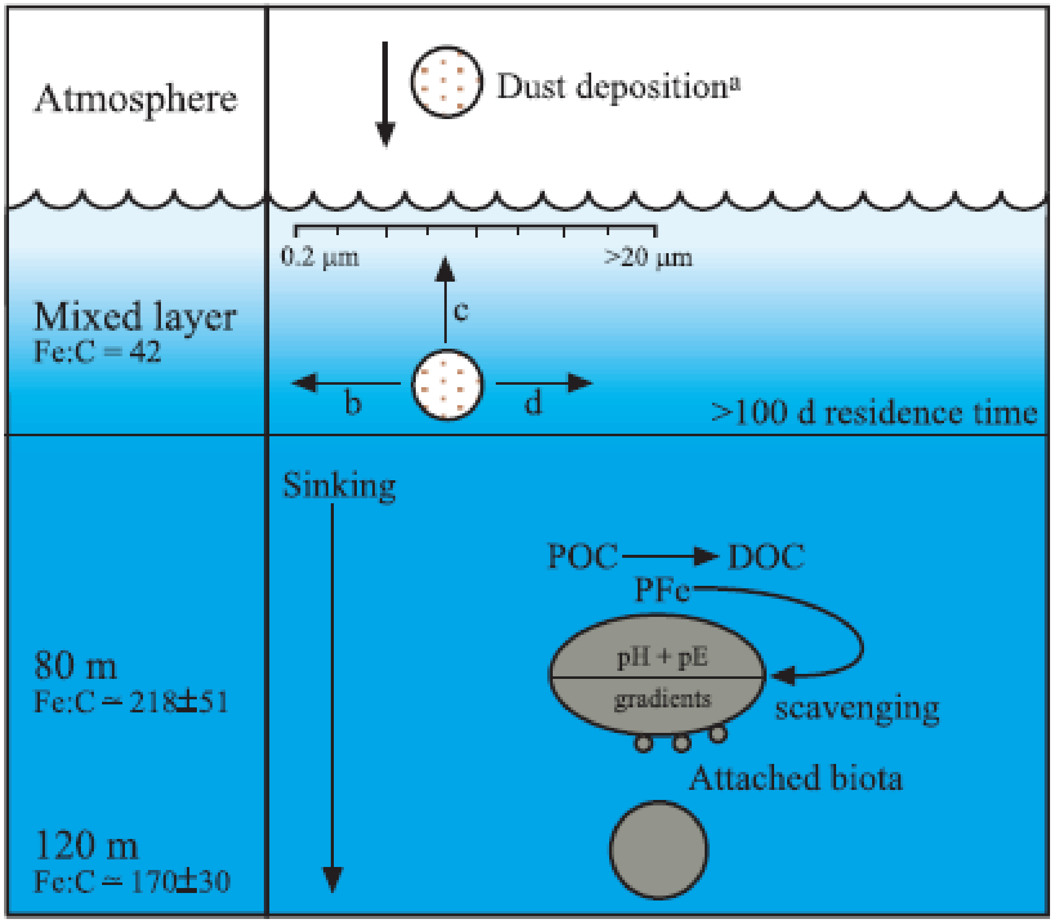
Remineralization length scales
Why is Fe > Si, C, N , P?



R.S. Lampitt et al.: Marine snow in the NE Atlantic 693



Iron's particle reactivity is the main cause



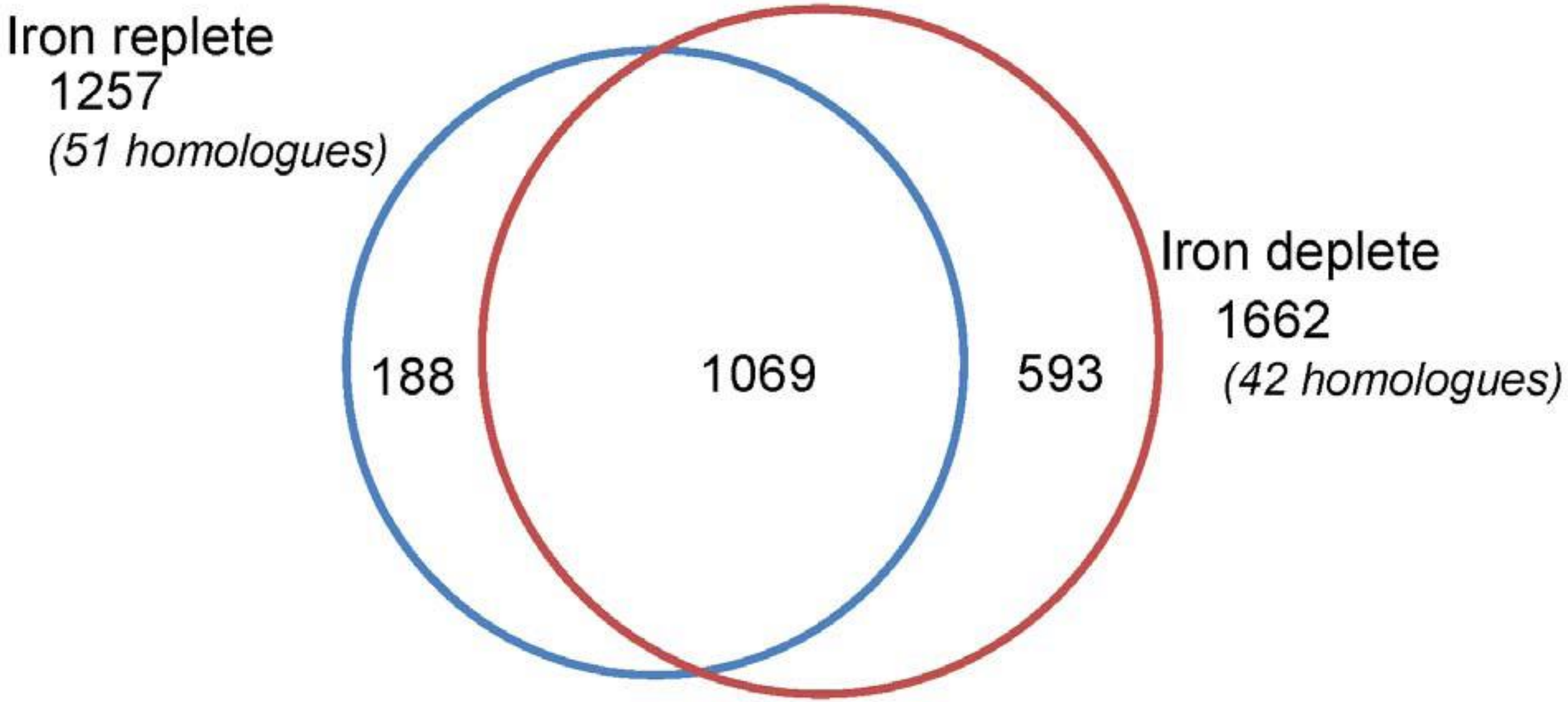
Frew et al. 2006

How do phytoplankton cope with perennially low iron conditions?

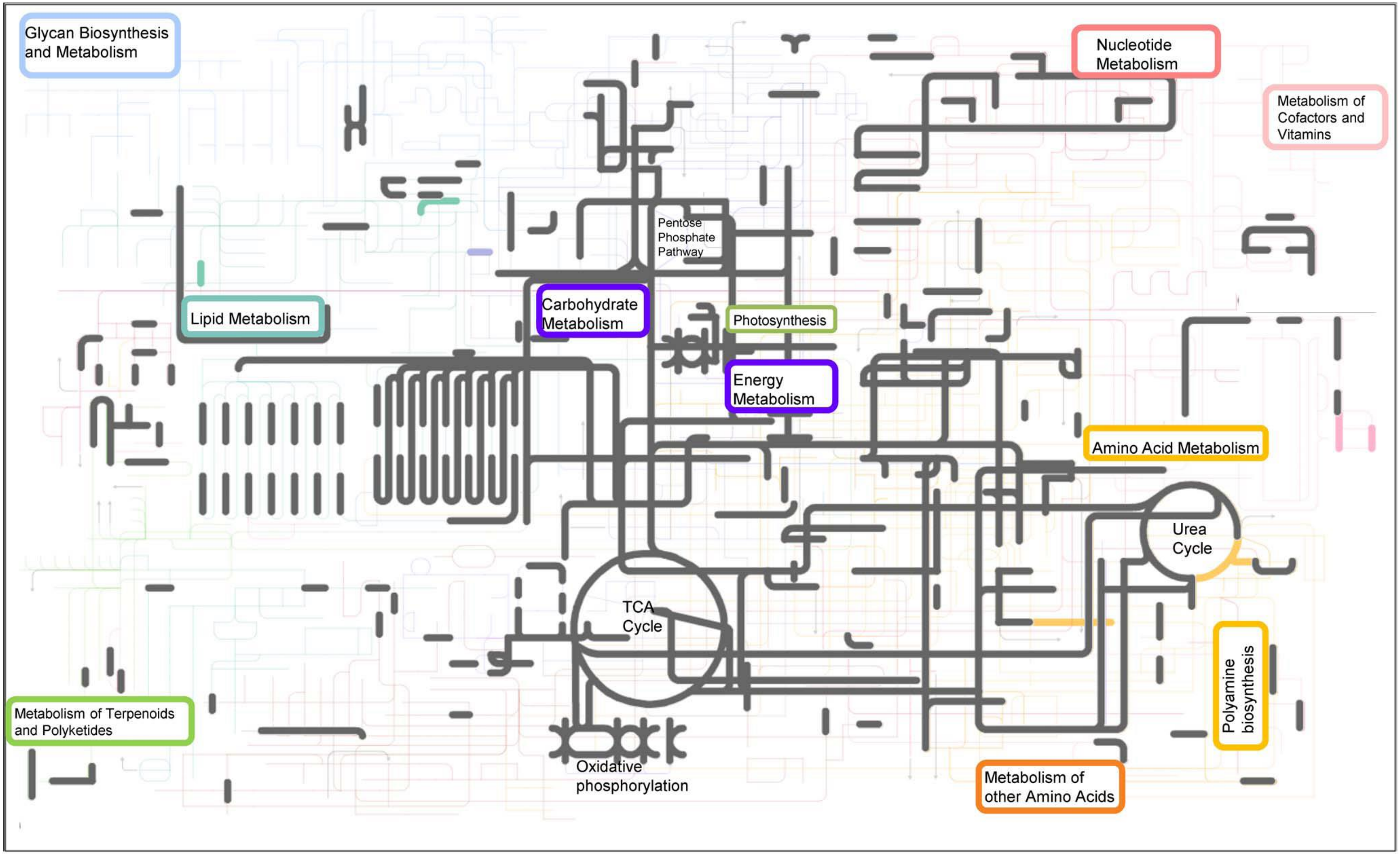
Diatom Proteomics Reveals Unique Acclimation Strategies to Mitigate Fe Limitation

Brook L. Nunn[1,2*], Jessica F. Faux[3], Anna A. Hippmann[4], Maria T. Maldonado[4], H. Rodger Harvey[5], David R. Goodlett[1], Philip W. Boyd[6], Robert F. Strzepek[7]

2014 PLoS ONE

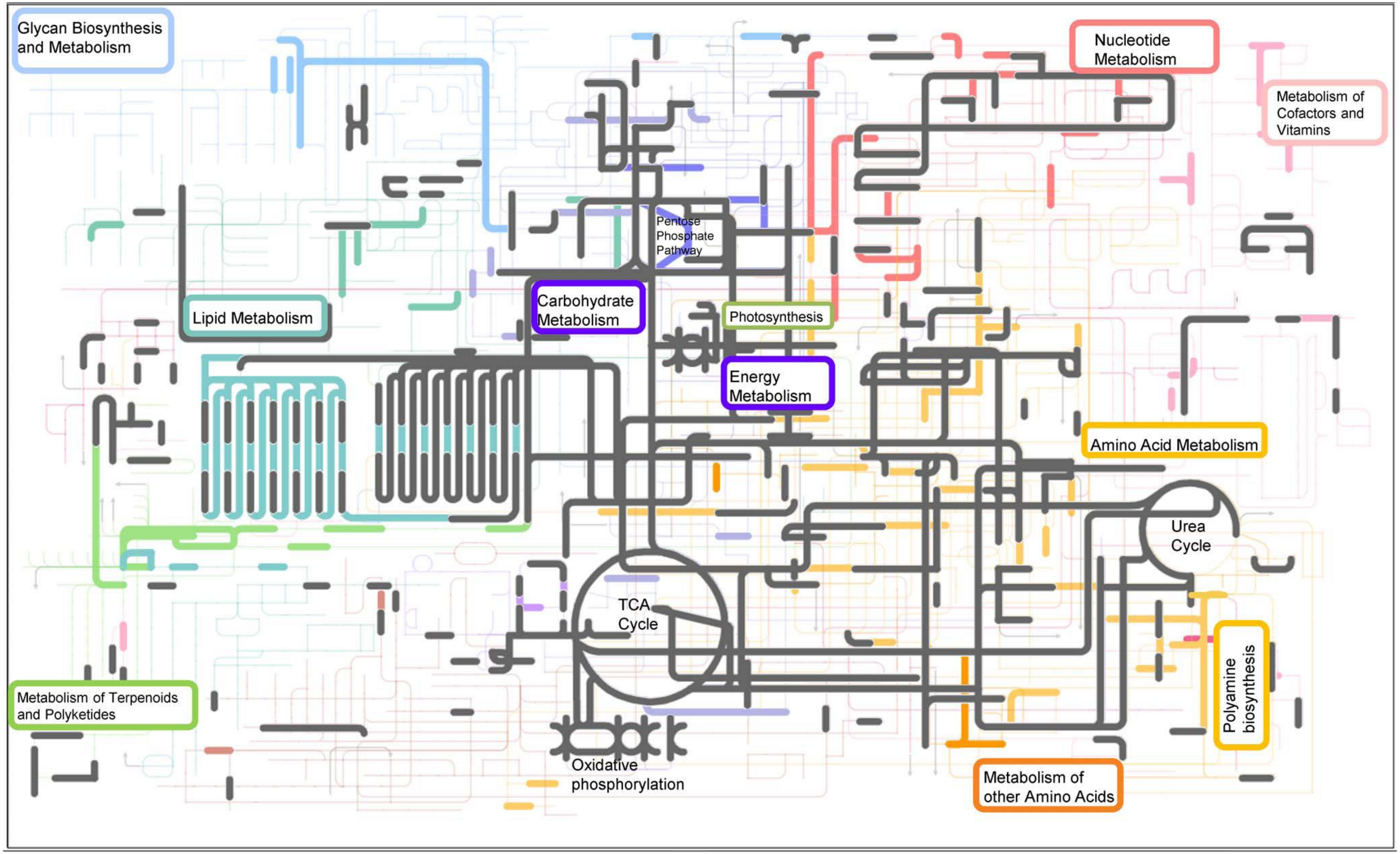


Nunn et al. 2014



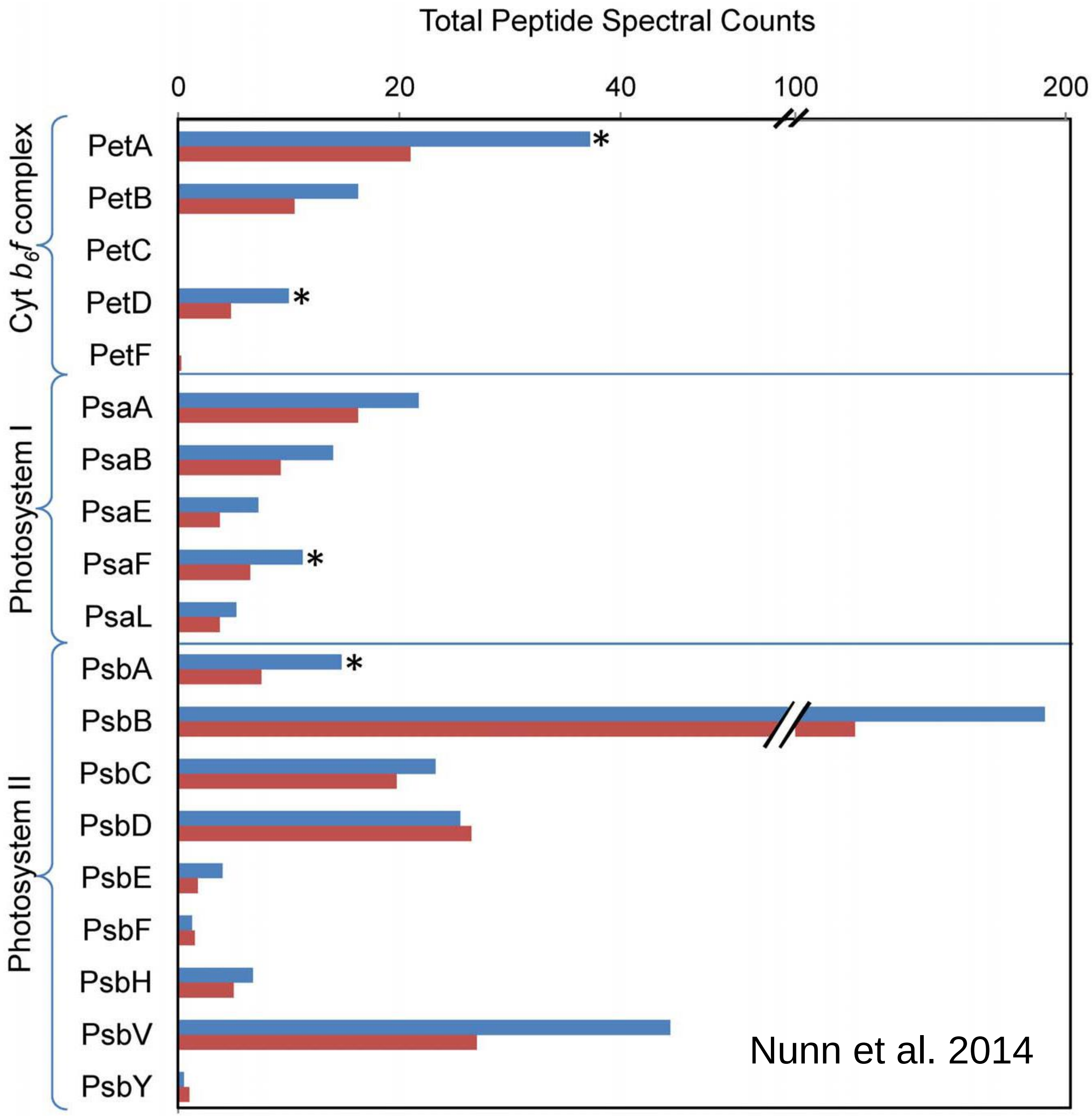
+Fe

Nunn et al. 2014



-Fe

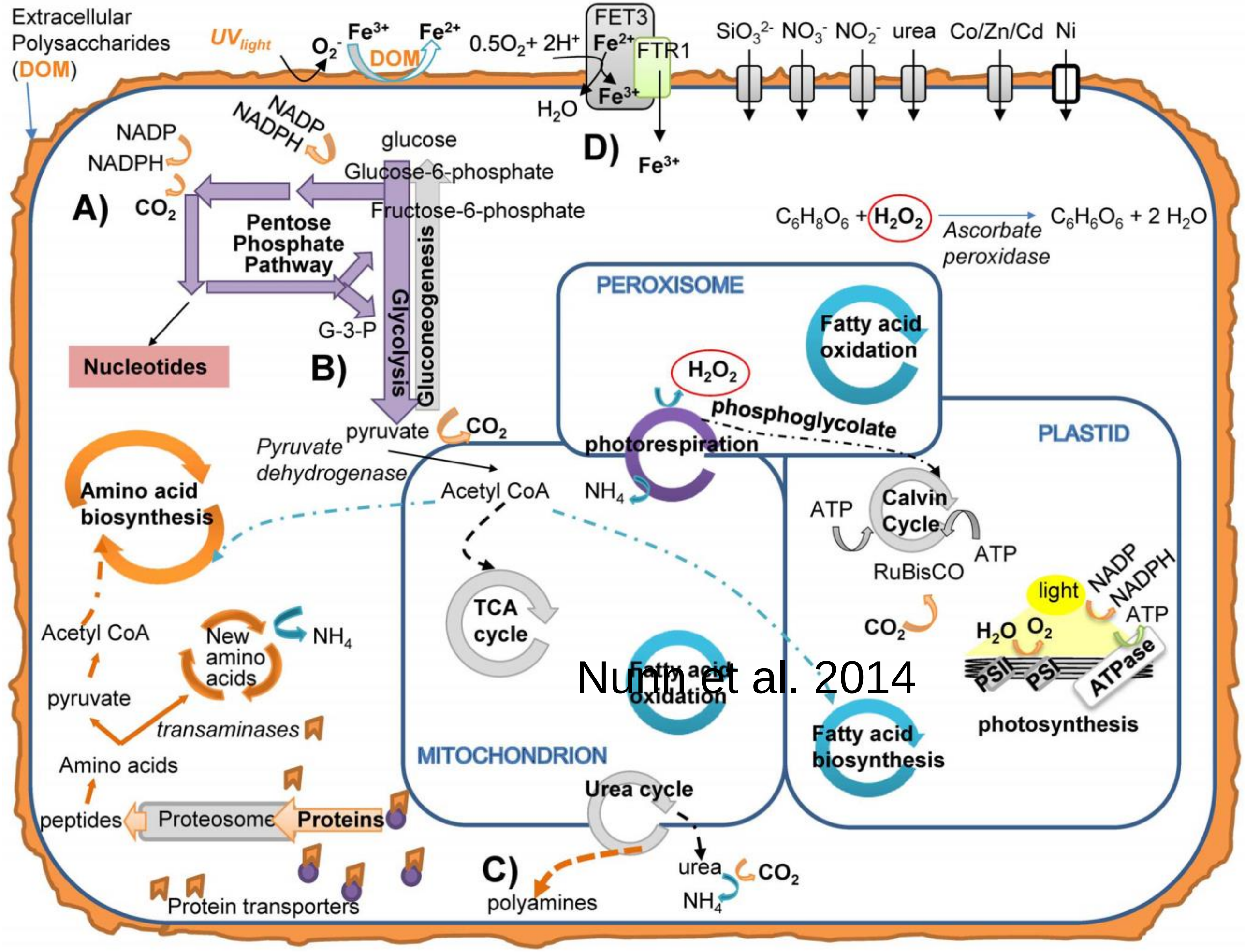
Nunn et al. 2014



Nunn et al. 2014

+Fe

* up-reg



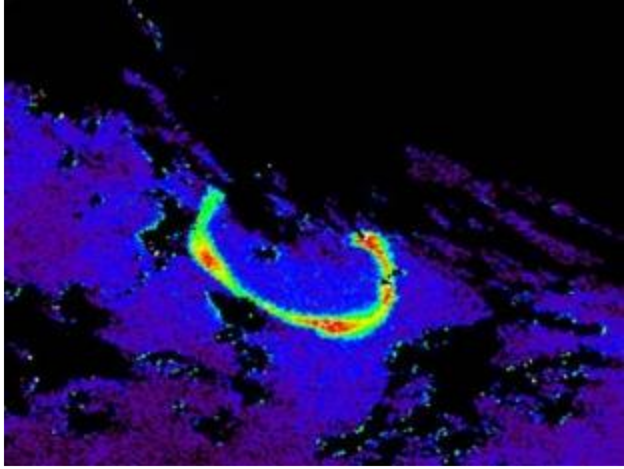
Nunn et al. 2014

Nunn et al. 2014

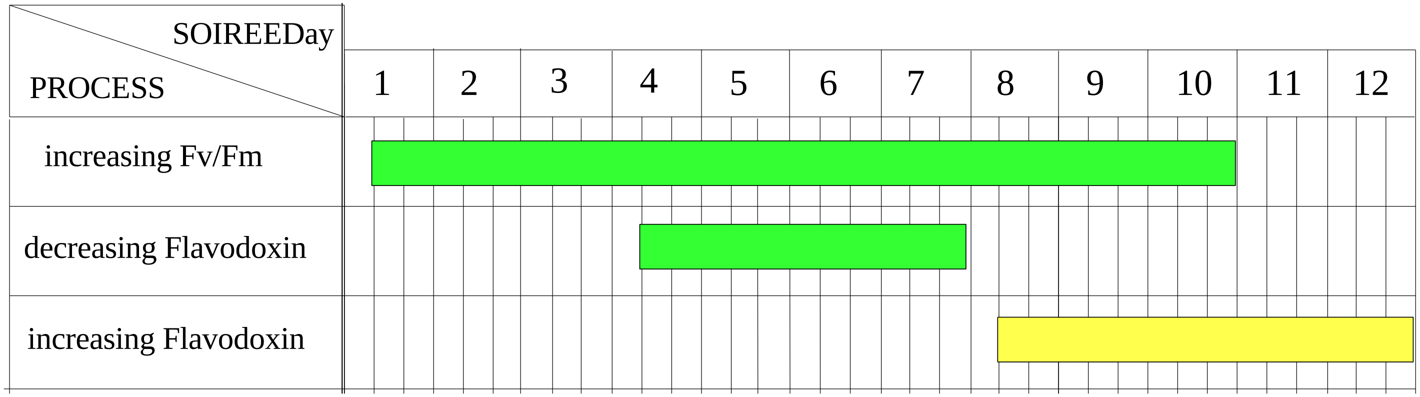
In summary – when diatoms are acclimated to Fe limitation
Proteomics suggest that intracellular N and Fe recycling are used
To conserve essential resources during mid-exponential growth

For example – up-regulation of transaminases and proteolytic enzymes
Allows cells to harvest N from amino-acids

Opportunism of HNLC organisms

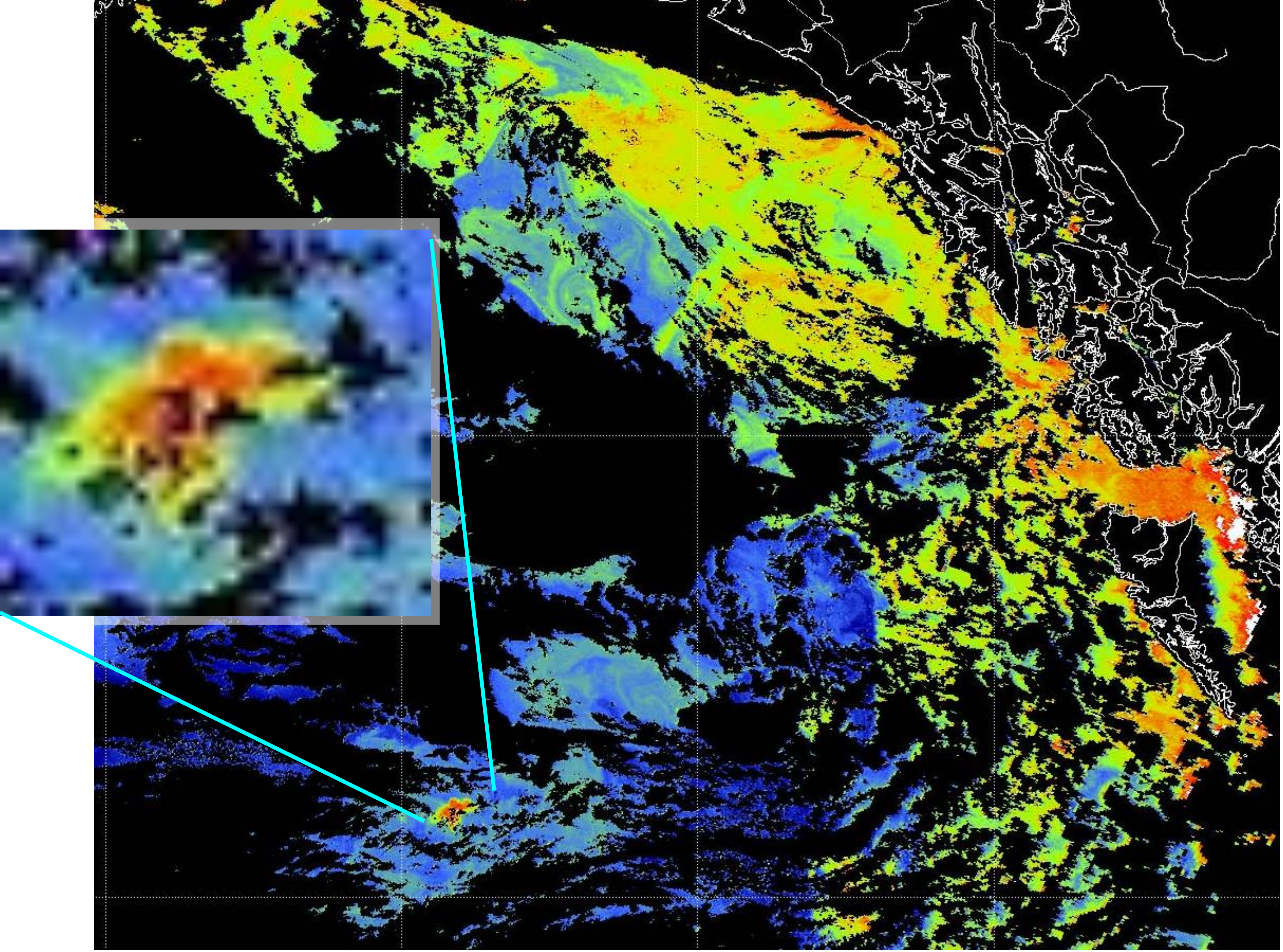


Timescales of responses to iron-enrichment

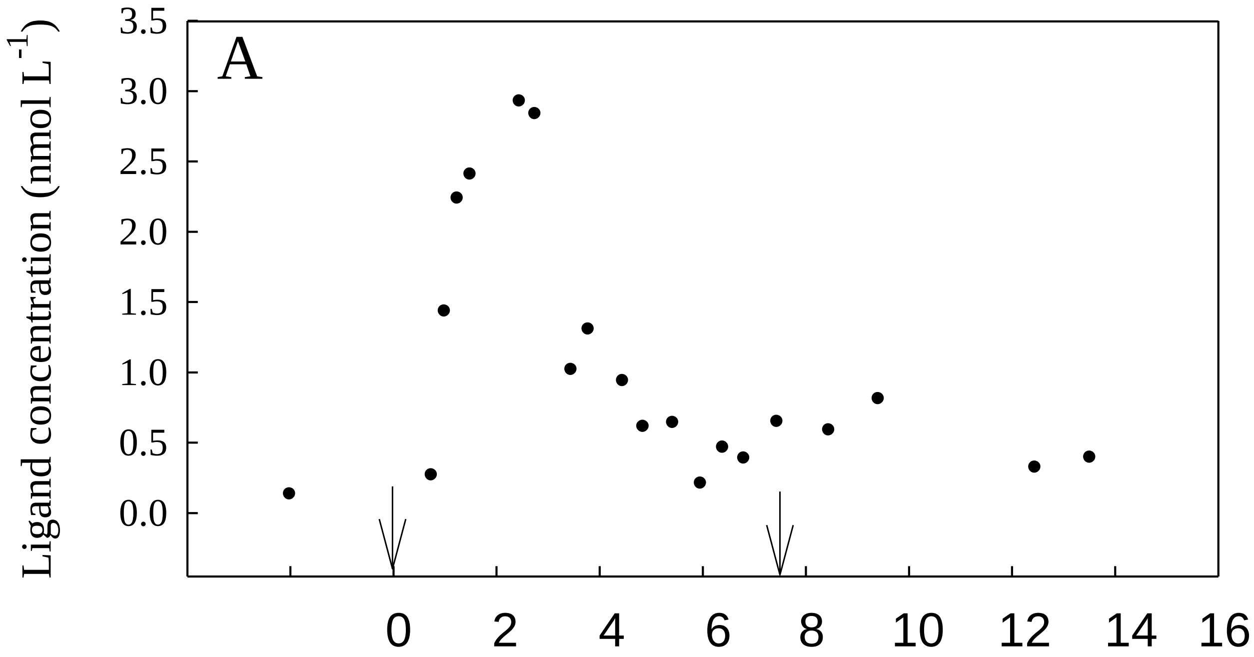


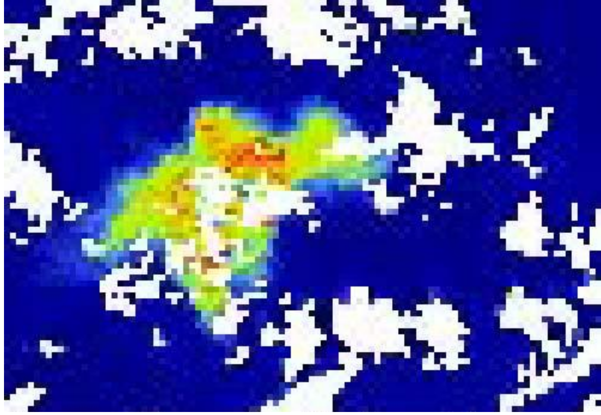
SOIREEDay PROCESS	1	2	3	4	5	6	7	8	9	10	11	12
increasing Fv/Fm	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
decreasing Flavodoxin				🟩	🟩	🟩	🟩					
increasing Flavodoxin								🟨	🟨	🟨	🟨	🟨

Croot et al. 2001



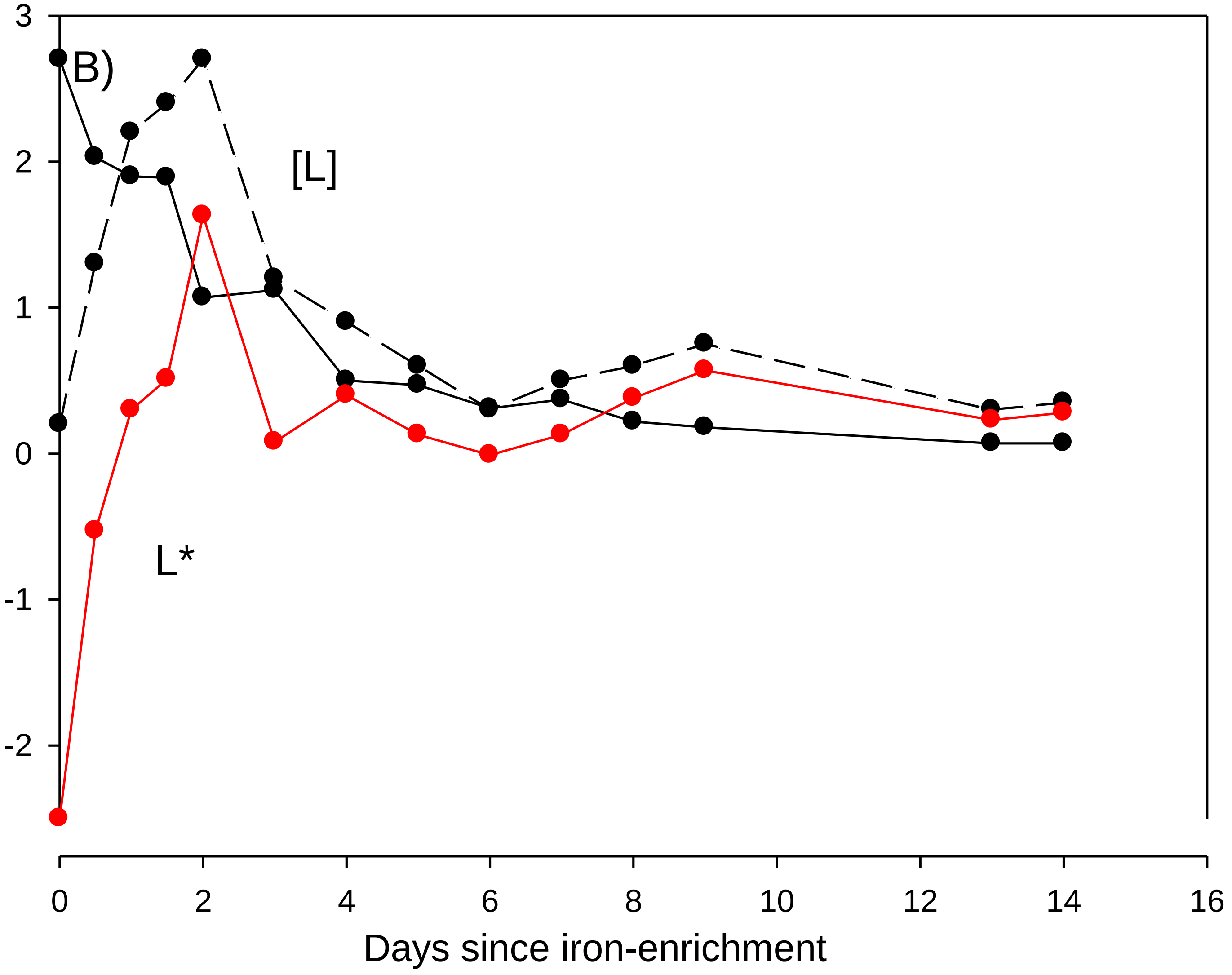
Timescales of responses to iron-enrichment





Adly 2002

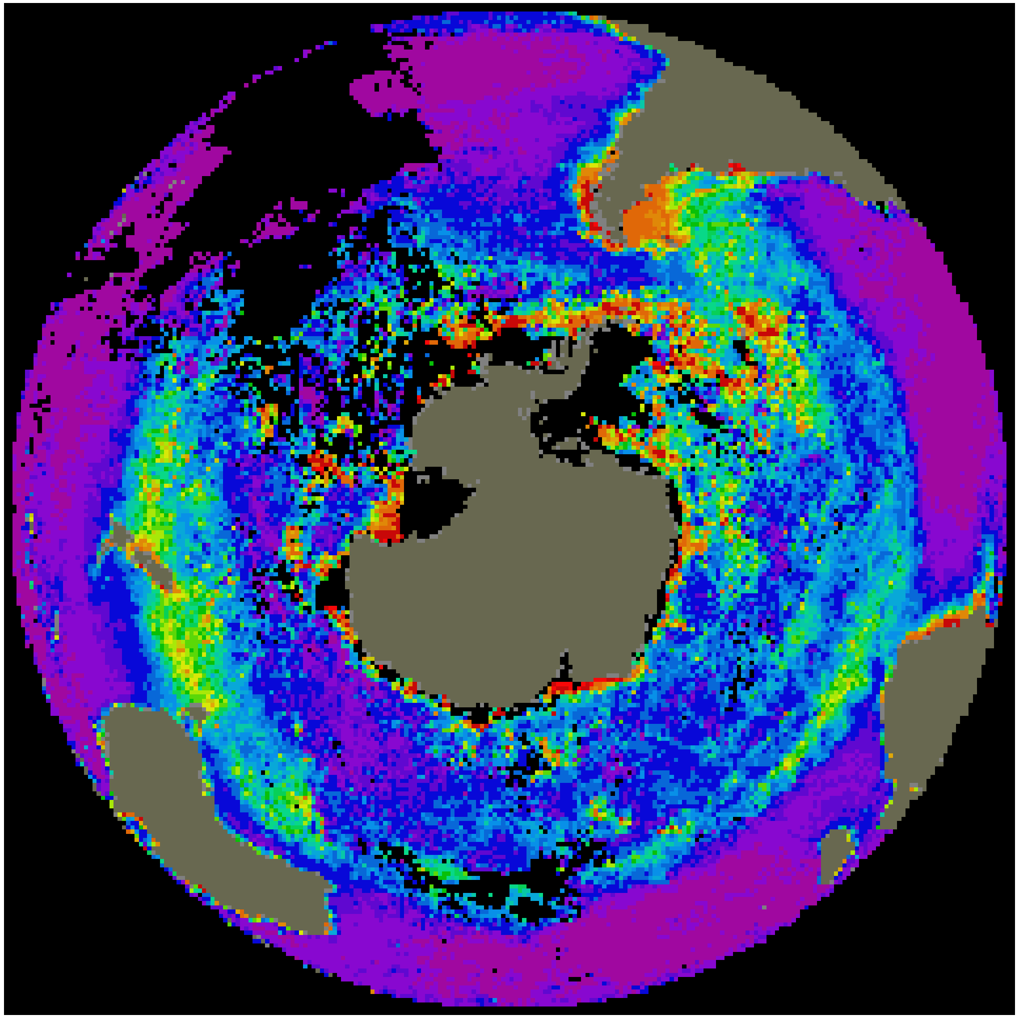
Opportunism is evident in HNLC waters



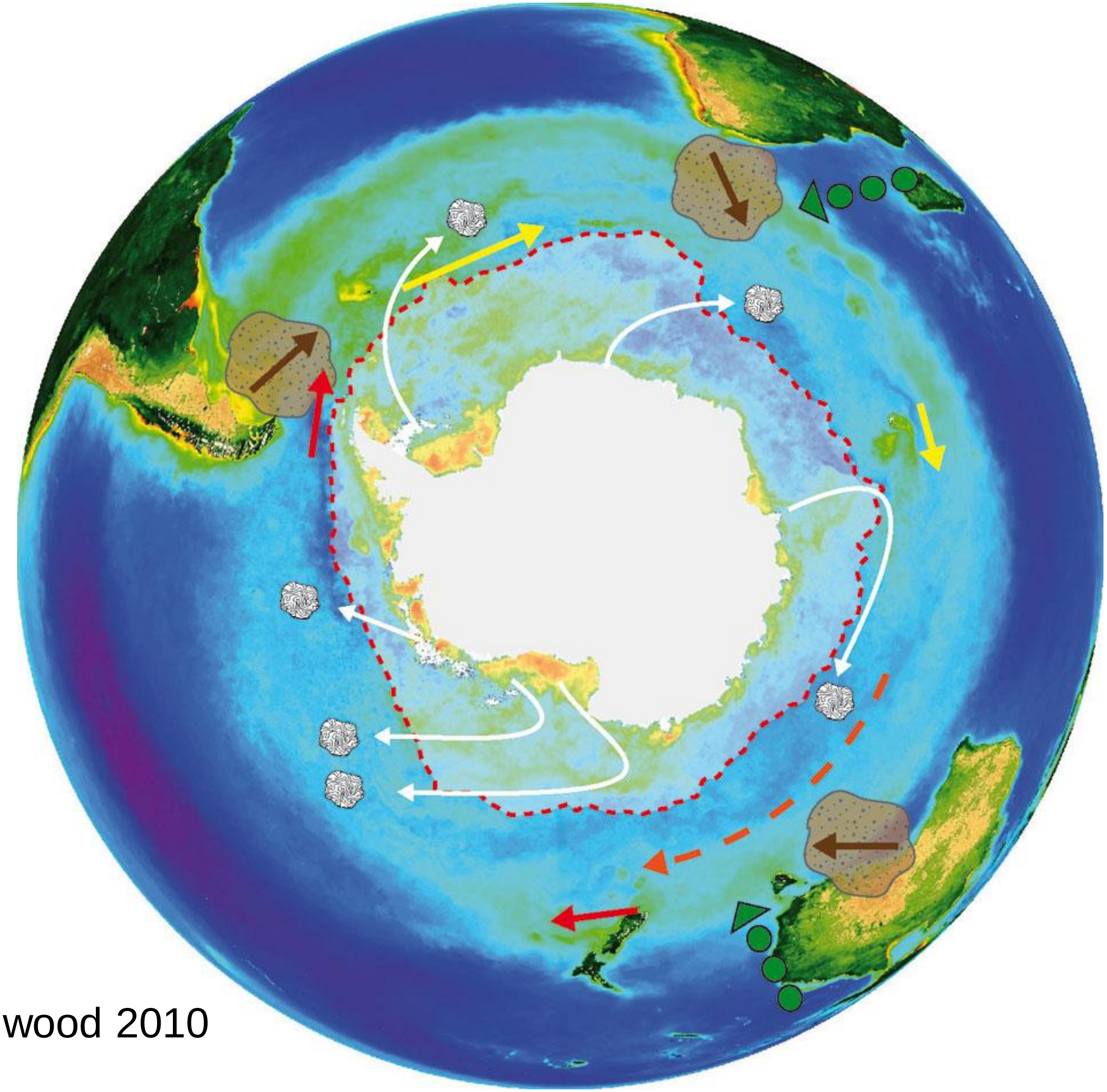
L* = [L1] minus [Dfe]

Boyd and Tagliabue (submitted)

A closer look at Southern Ocean HNLC ‘waters’



> 10 iron supply terms



Boyd & Ellwood 2010

Iron biogeochemistry

C,N,P and
TM stoichiometry

Fe chemistry
& stable isotopes

GEOTRACES

Fe sources
& sinks

Fe
Biogeochemistry

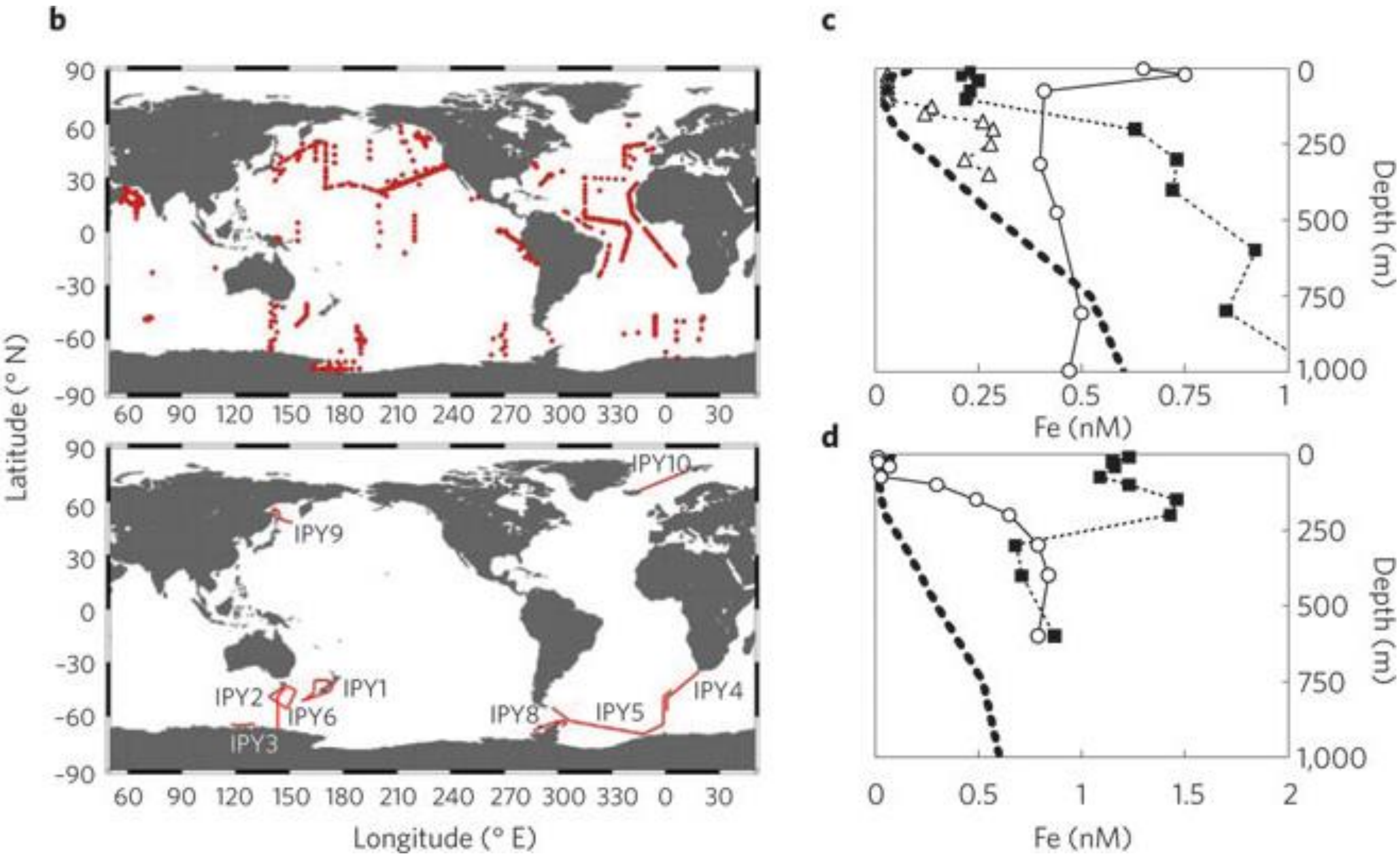
SOLAS
Dust deposition

Ecology

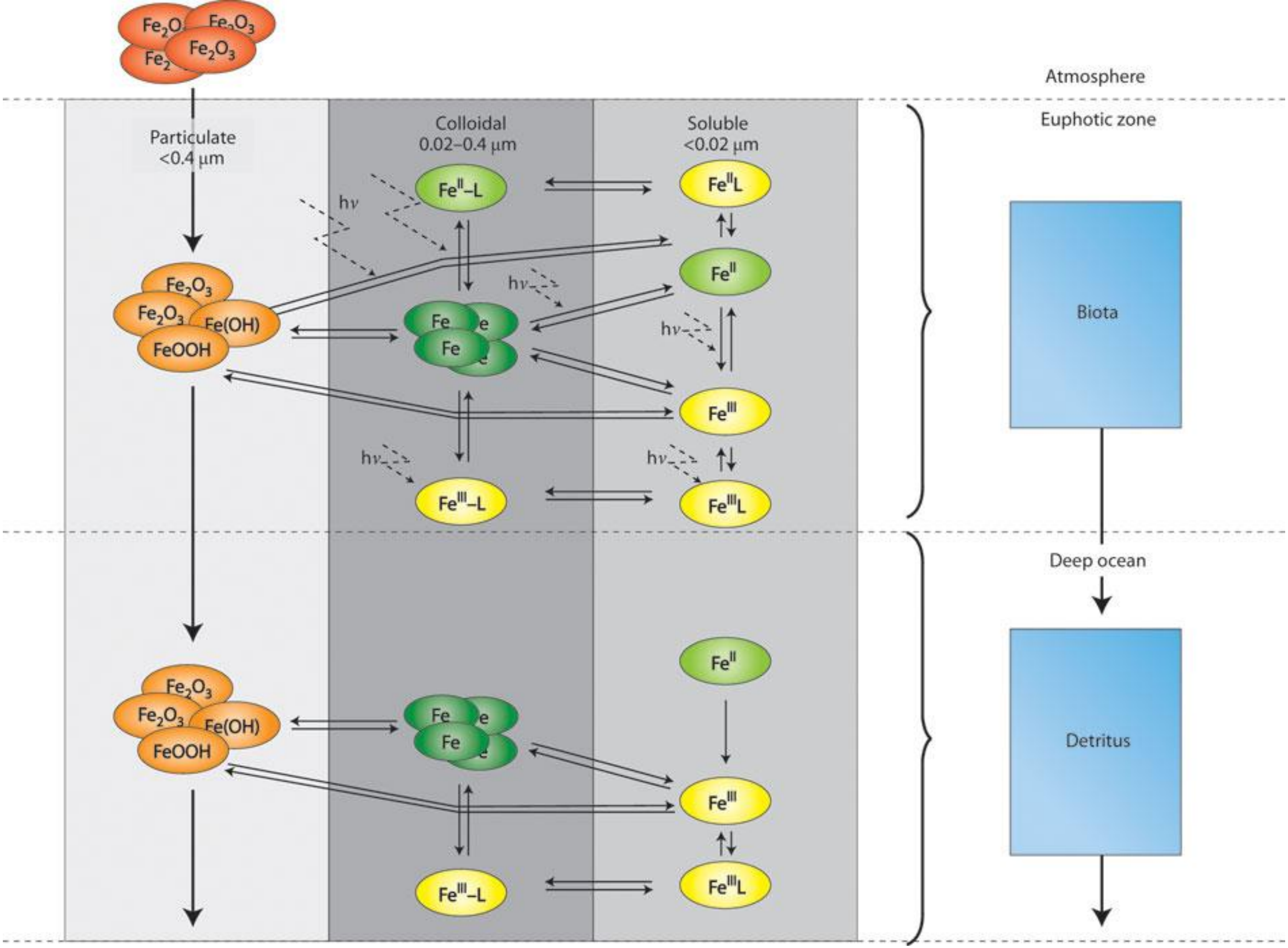
Ligands

Omics
‘Geomics’

GEOTRACES

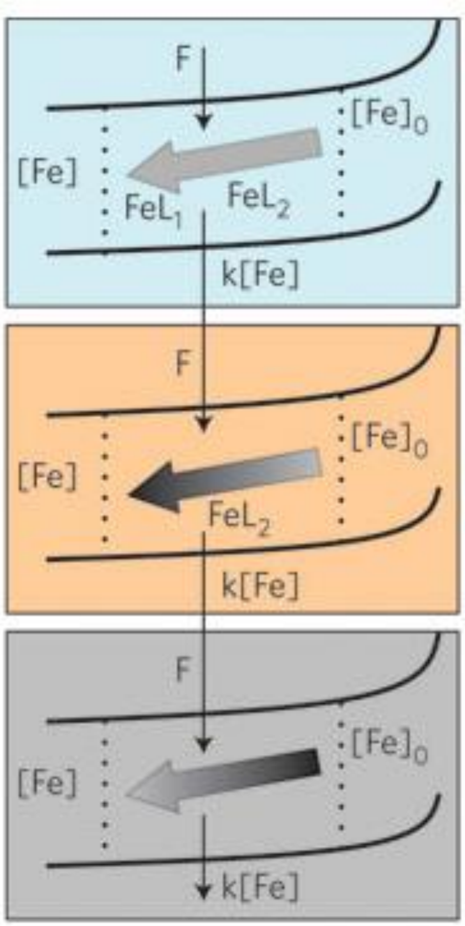


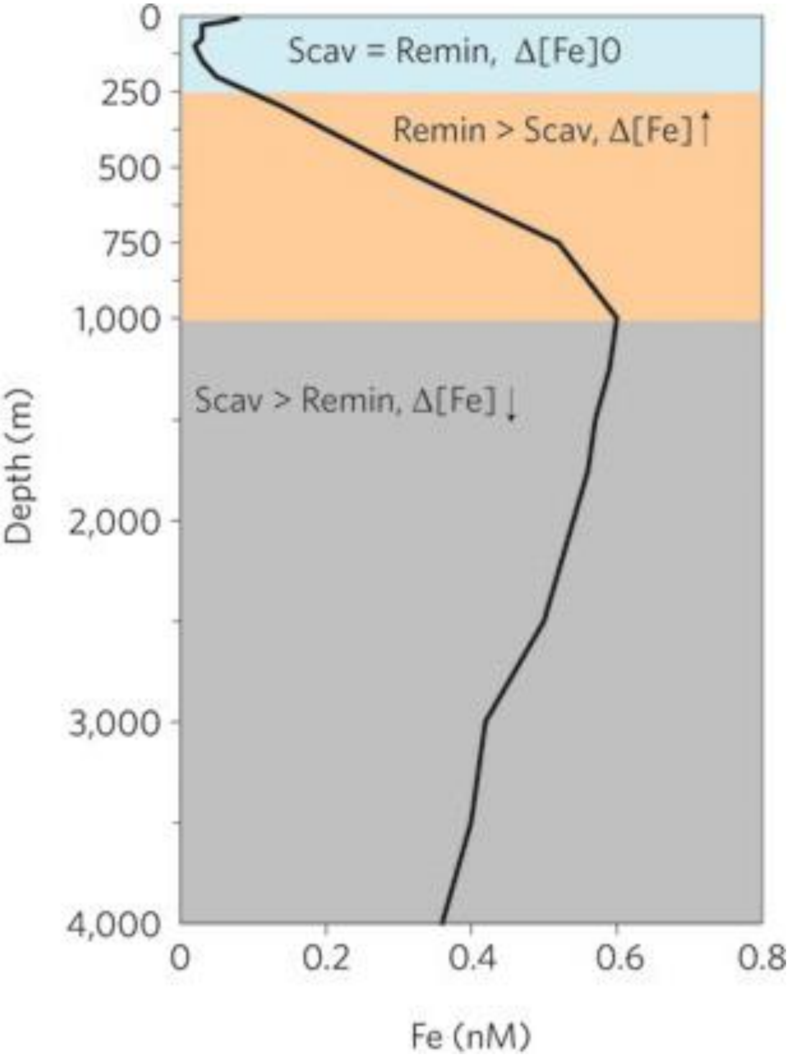
Boyd & Ellwood 2010



Boyd & Ellwood 2010

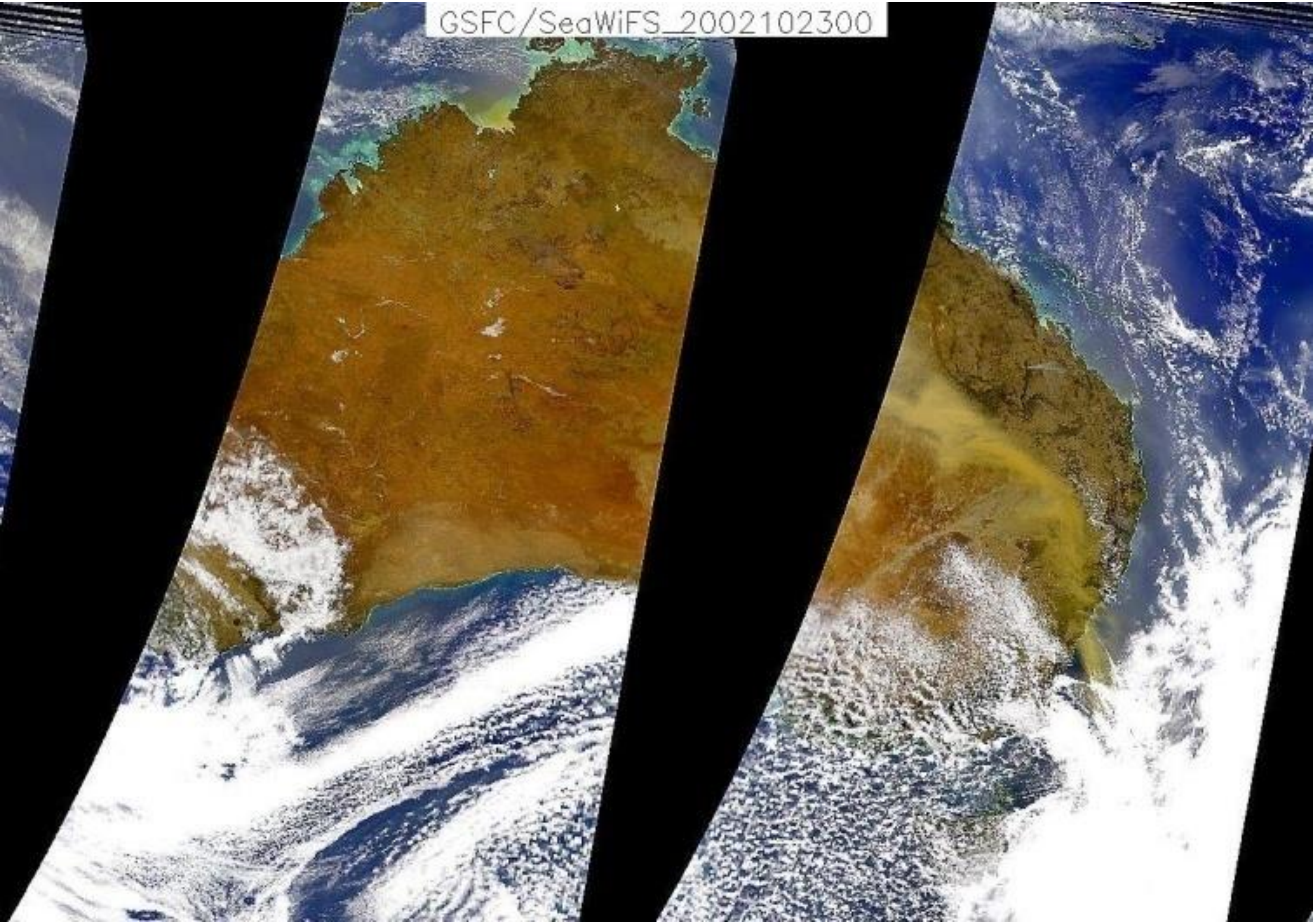
What sets the depth of the ferricline?



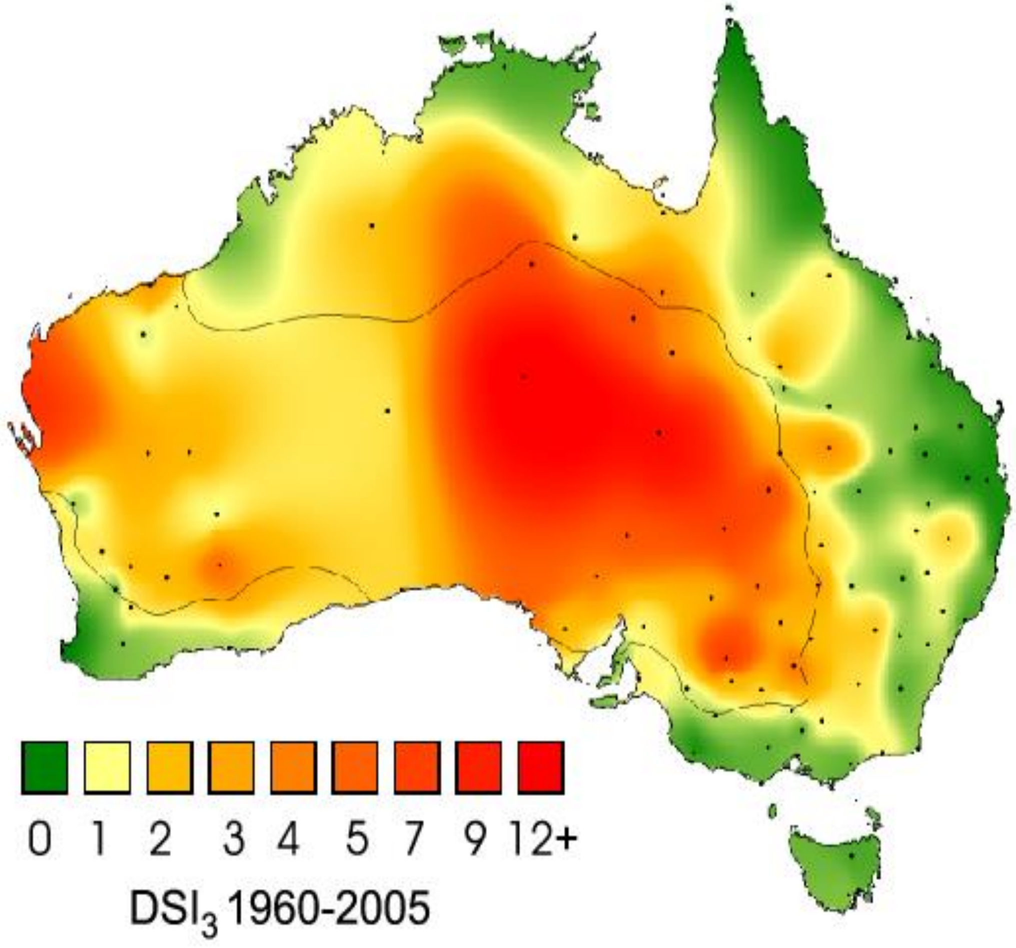


Boyd & Ellwood 2010

Regional Fe biogeochemistry

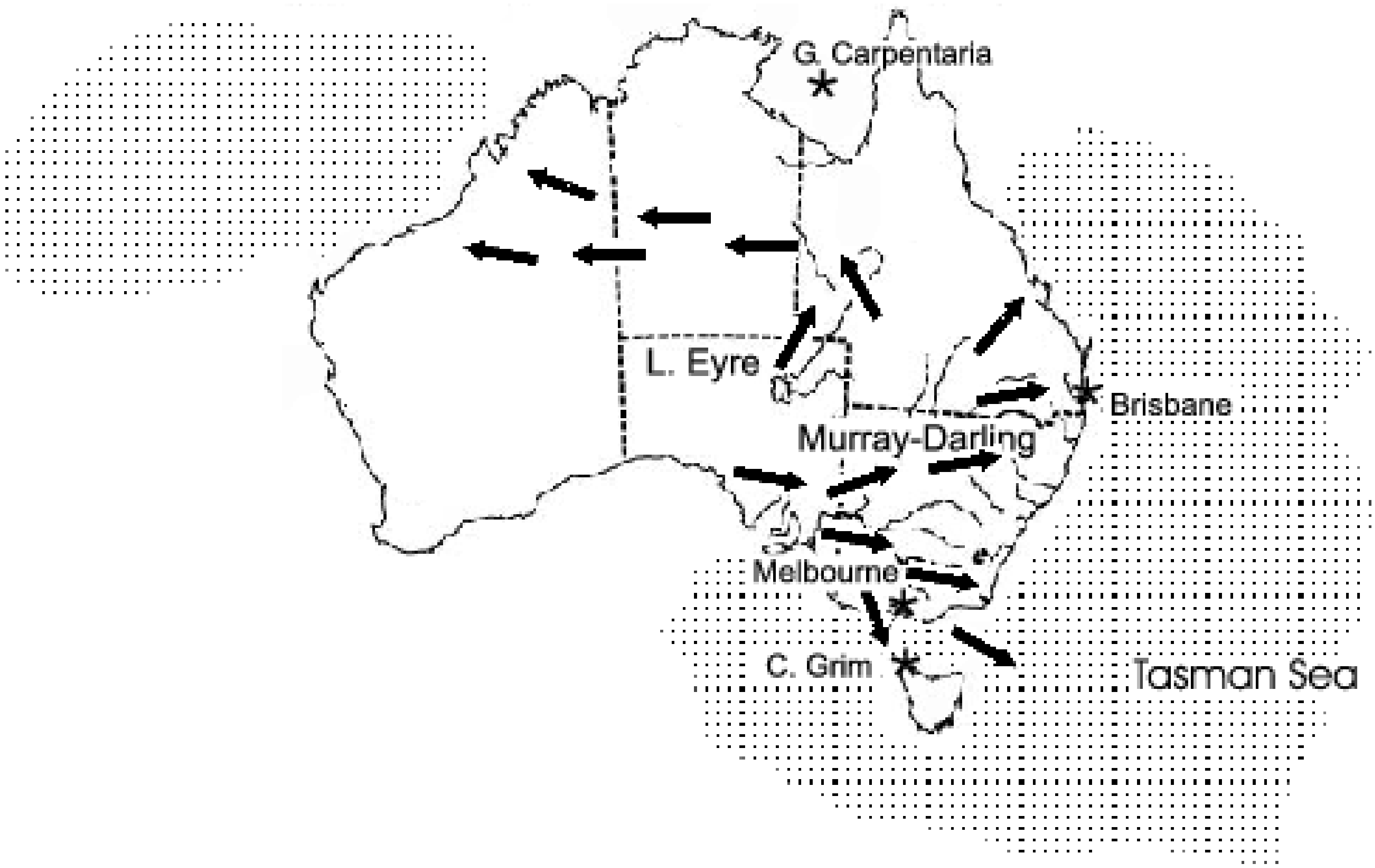


Dust distributions over Australia



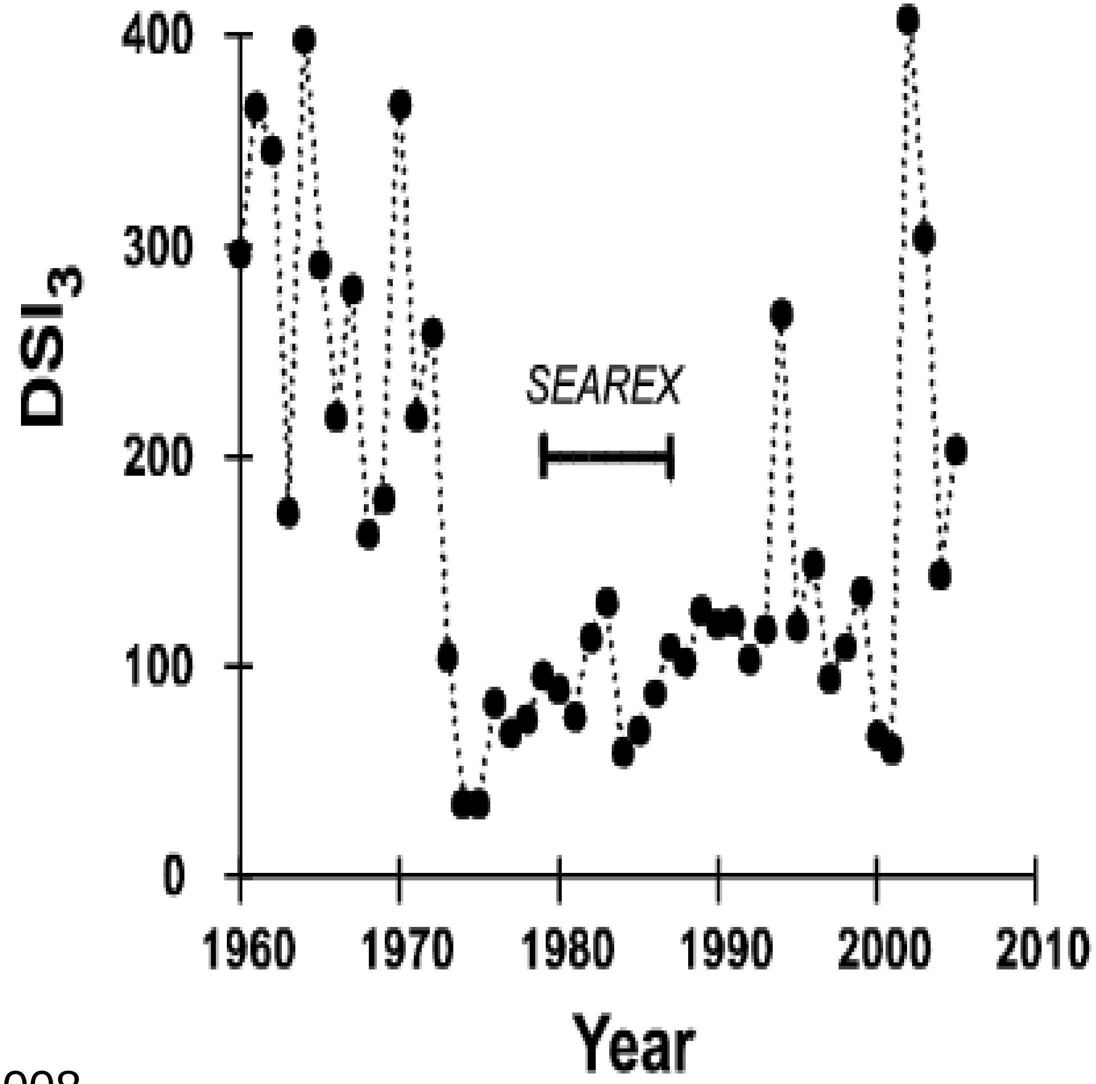
Mackie et al. 2008

2 distinct dust outflow patterns from Australia



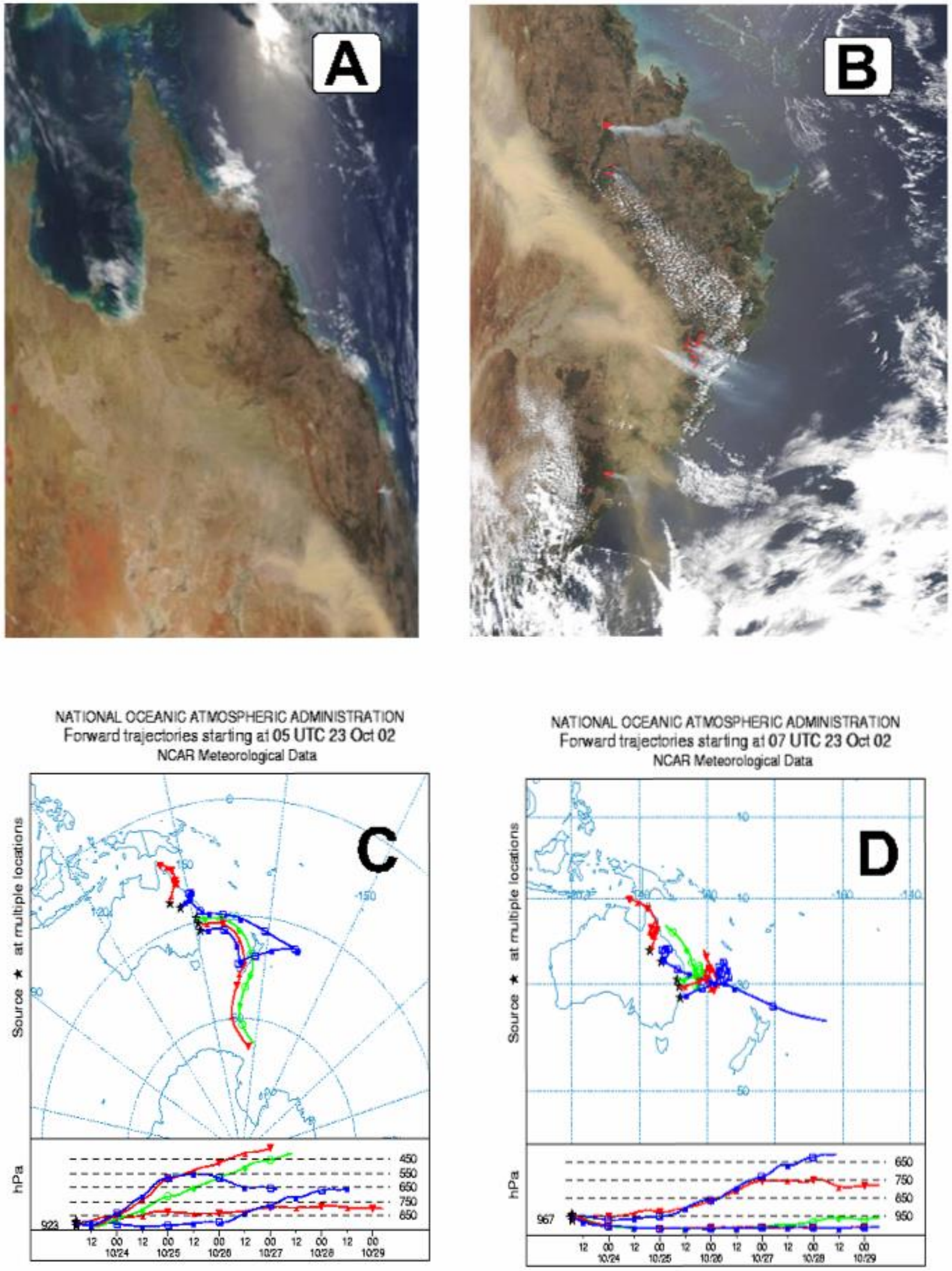
Mackie et al. 2008

Time-series of dust distributions over Australia



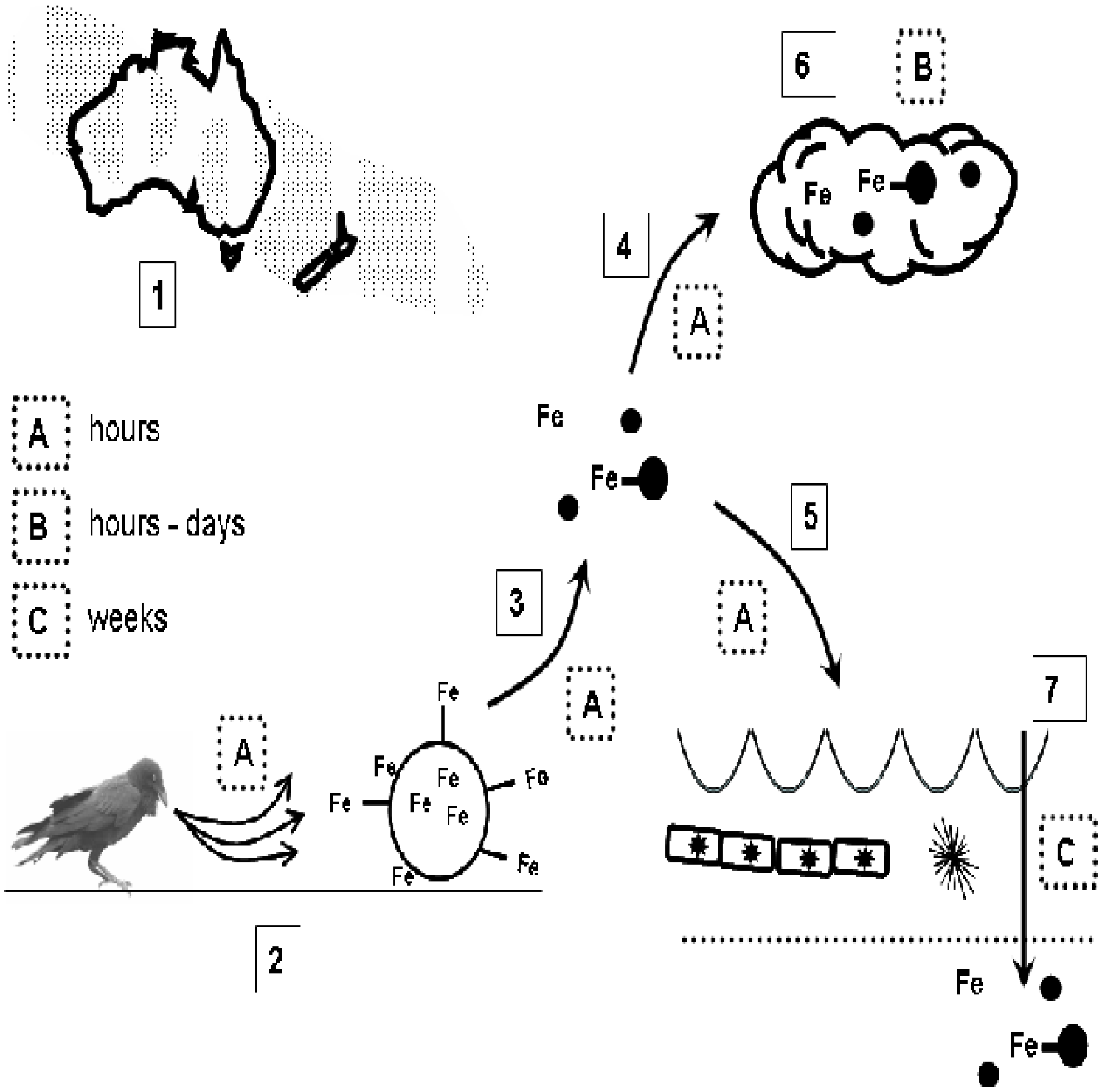
Mackie et al. 2008

Air mass trajectories
To follow dust storms



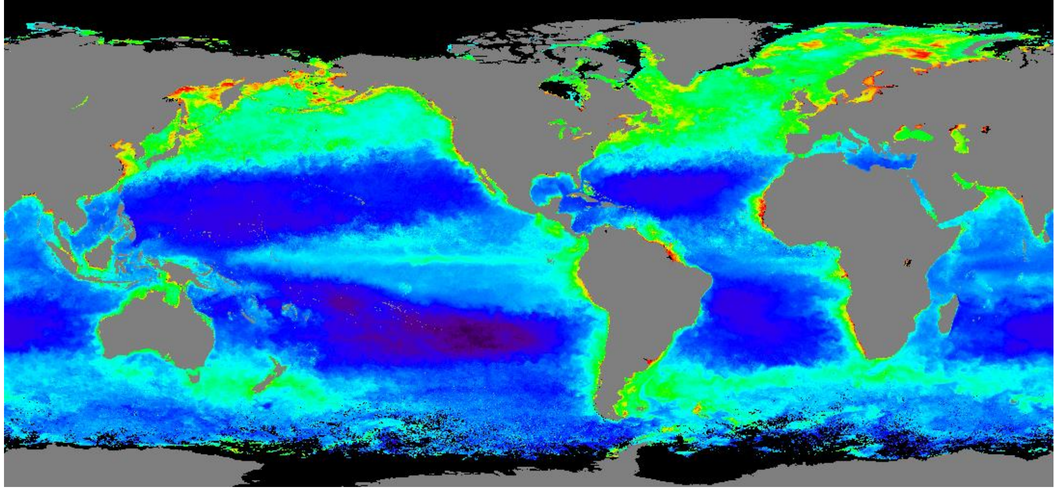
Mackie et al. 2008

Biogeochemistry of iron in Australian dust



Mackie et al. 2008

HNLC Regions of the Ocean



SUMMARY

HNLC waters – 30% OF OPEN OCEAN

Fe SUPPLY largely causes the HNLC condition

Biomass levels in HNLC waters are set by grazing pressure – which in turn resupplies iron

Recycled iron drives most of