Environmental drivers of temporal and spatial variability in Southern Ocean NPP and export flux

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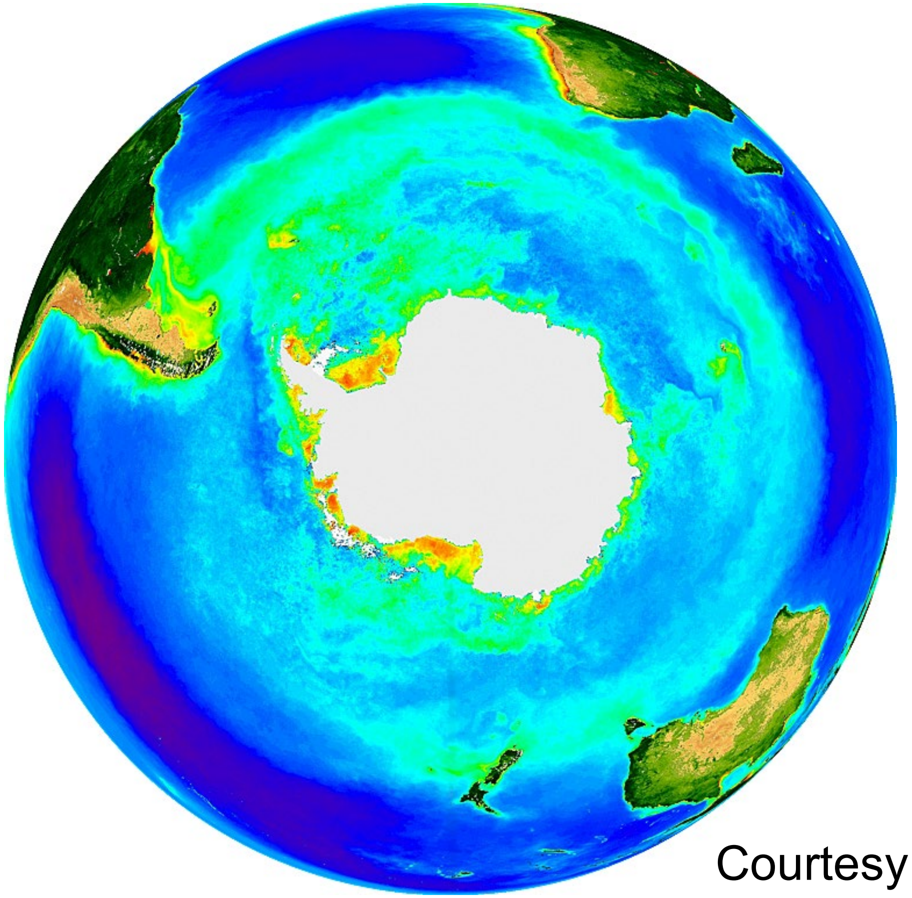
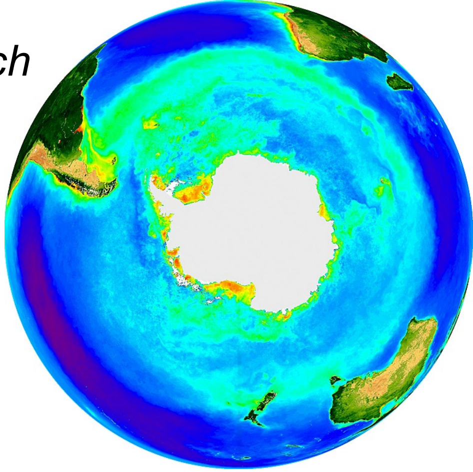


Courtesy NASA

Acknowledgements – Arrigo, Buesseler, Doney, Johnson, Matear, Nodder, Rintoul, Schofield, Trull



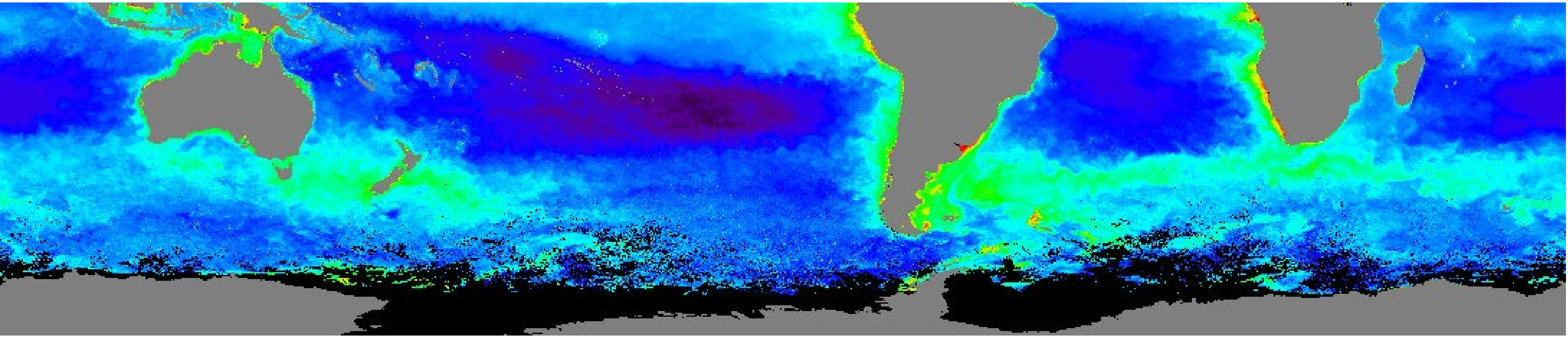
Outline

- Issues
- The variegated Southern Ocean
- Climate variability – NPP
- Climate variability – export
- Coupling NPP & export
- Climate variability – controls on NPP
- Environmental controls on phytoplankton
- Wish-list slides

Issues

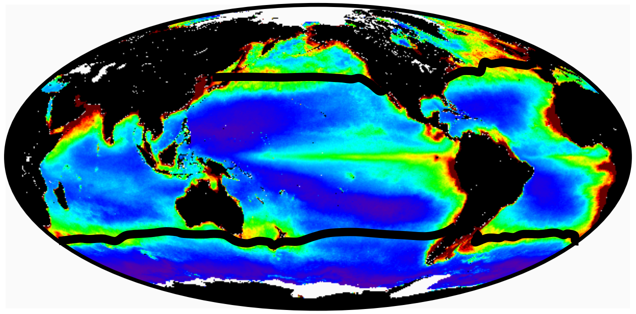
- **NPP (4.8 Gt C a^{-1} Arrigo, unpubl.); export (>0.2 <0.4 Gt C a^{-1}, Lutz et al., 2007) play pivotal roles in supporting ecosystems and C sequestration**
- **NPP and export are sub-maximal in much of the S. Ocean – HNLC waters**
- **Climate variability – impact of SAM – stronger and poleward shift in winds**
- **Climate change vs. variability- stronger winds (Ekman transport) versus enhanced stratification (slower upwelling)**
- **Data-poor - reliance on satellite data and models**
- **Aspiration to develop a better mechanistic understanding of phytoplankton processes**

The variegated Southern Ocean

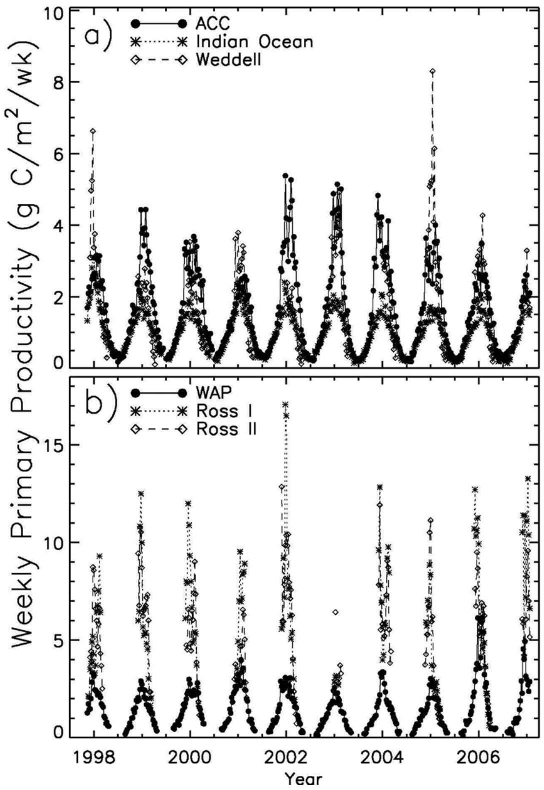


The air–sea balance of CO_2 is controlled mainly by the biological pump & circulation in the Antarctic deep-water formation region, whereas global export production is controlled mainly by the biological pump and circulation in the Subantarctic intermediate and mode water formation region. (Marinov et al. 2006)

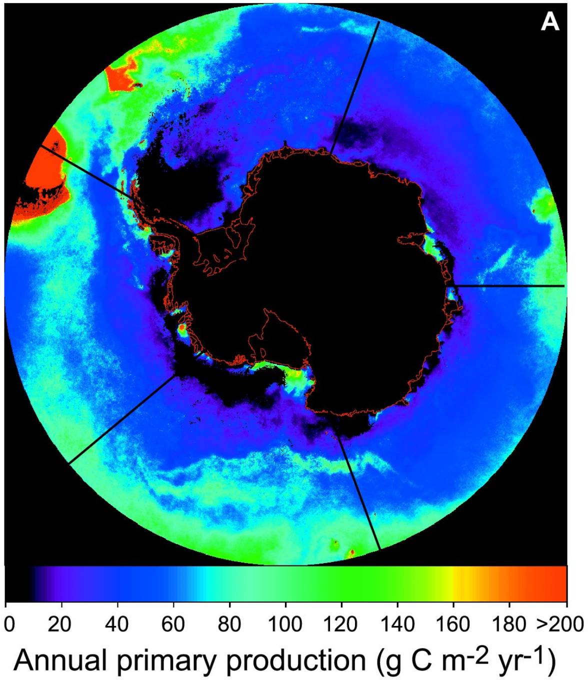
Remote-sensing / algorithms provides basin wide estimates of NPP



VGPM Behrenfeld et al. (2006)
Global algorithm

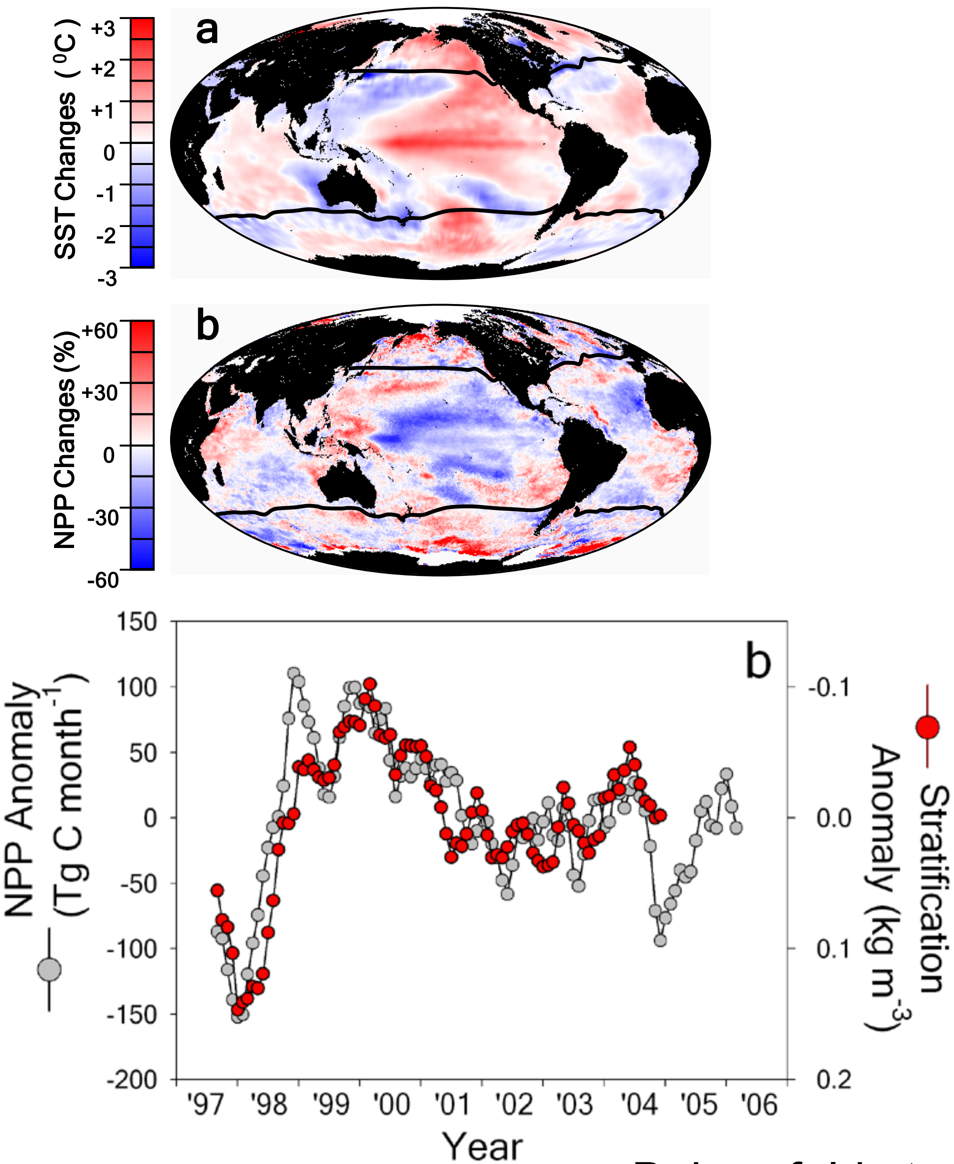


Smith & Comiso (2008)
applied VGPM algorithm
regionally

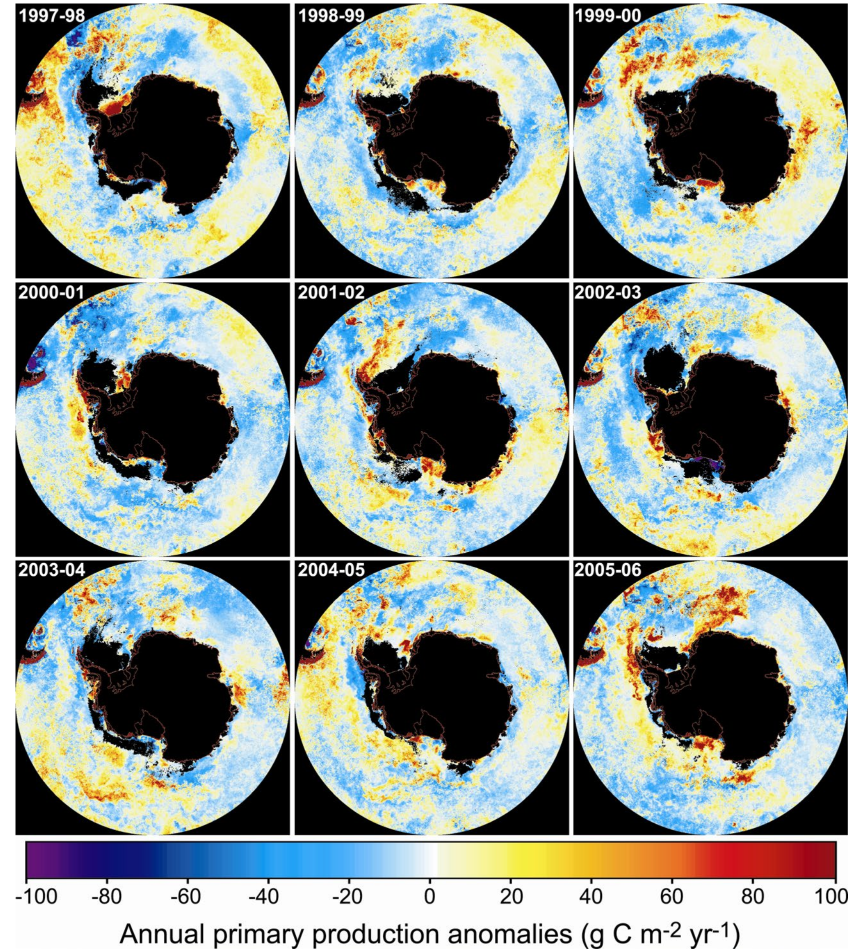


Arrigo et al. (2008)
regional algorithm
development

NPP and climate variability



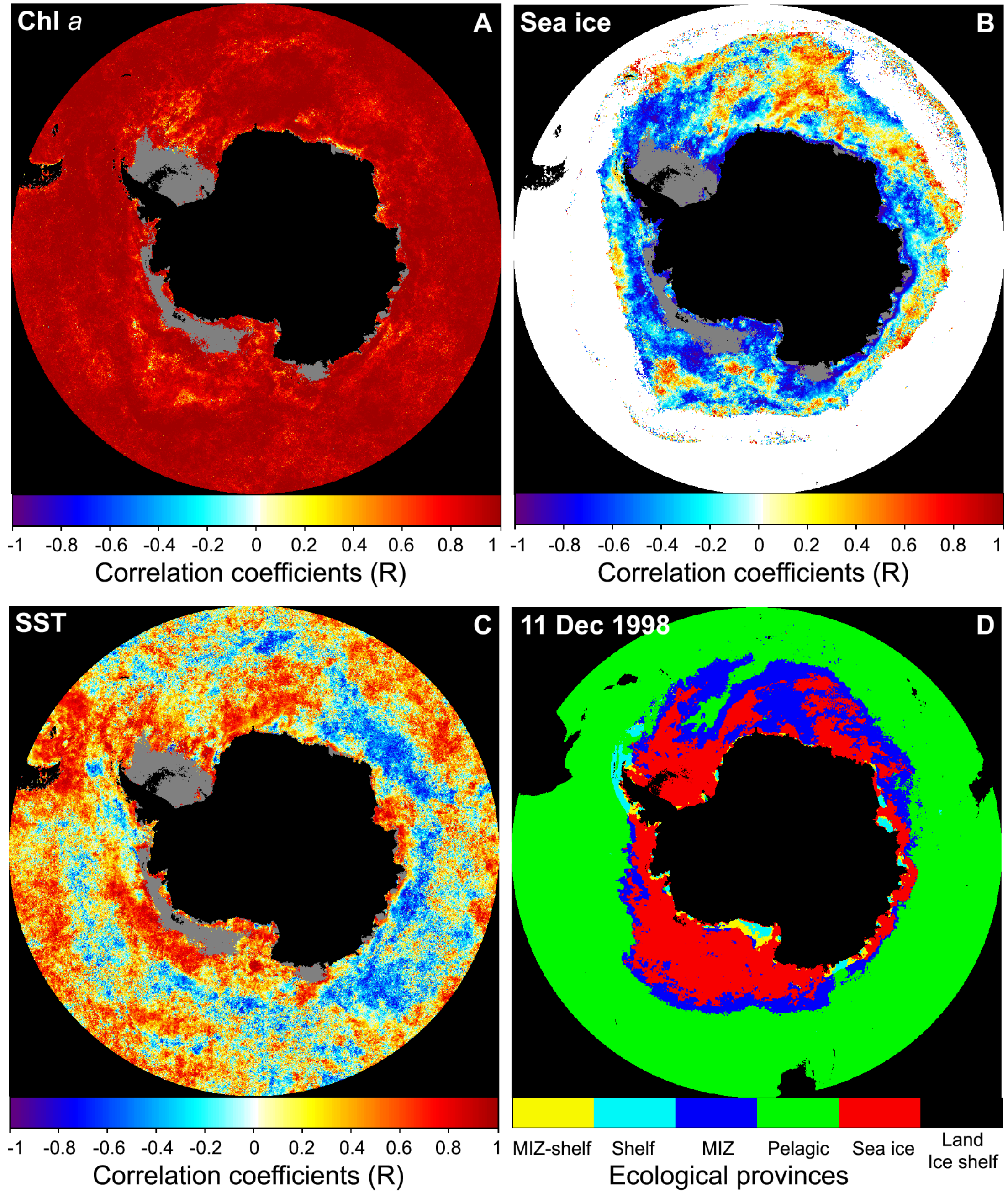
Behrenfeld et al. (2006)



Arrigo et al. (2008)

NPP anomalies were compared with those for biological & environmental drivers

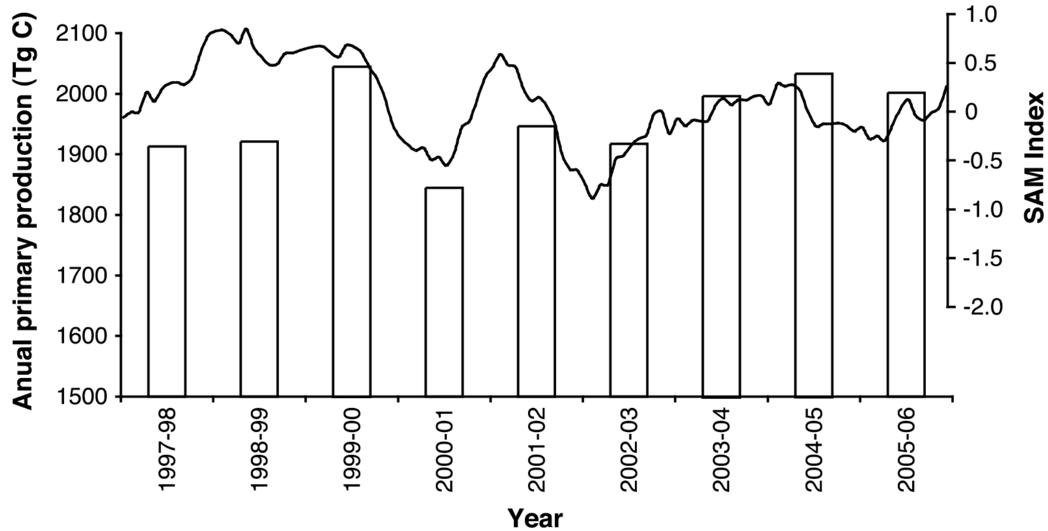
Arrigo et al. (2008)



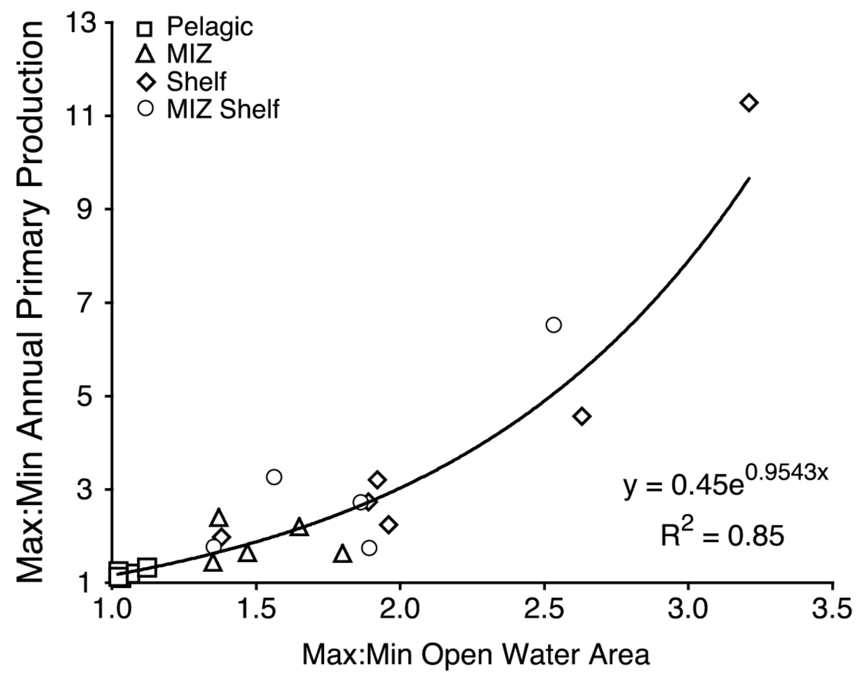
Arrigo et al. (2008) Concluded

Interannual variability in NPP was 17%

Of this, 31% of the variation in NPP was explained by SAM



Interannual variability in NPP was most closely tied to changes in sea ice cover, although changes in SST also played a role.

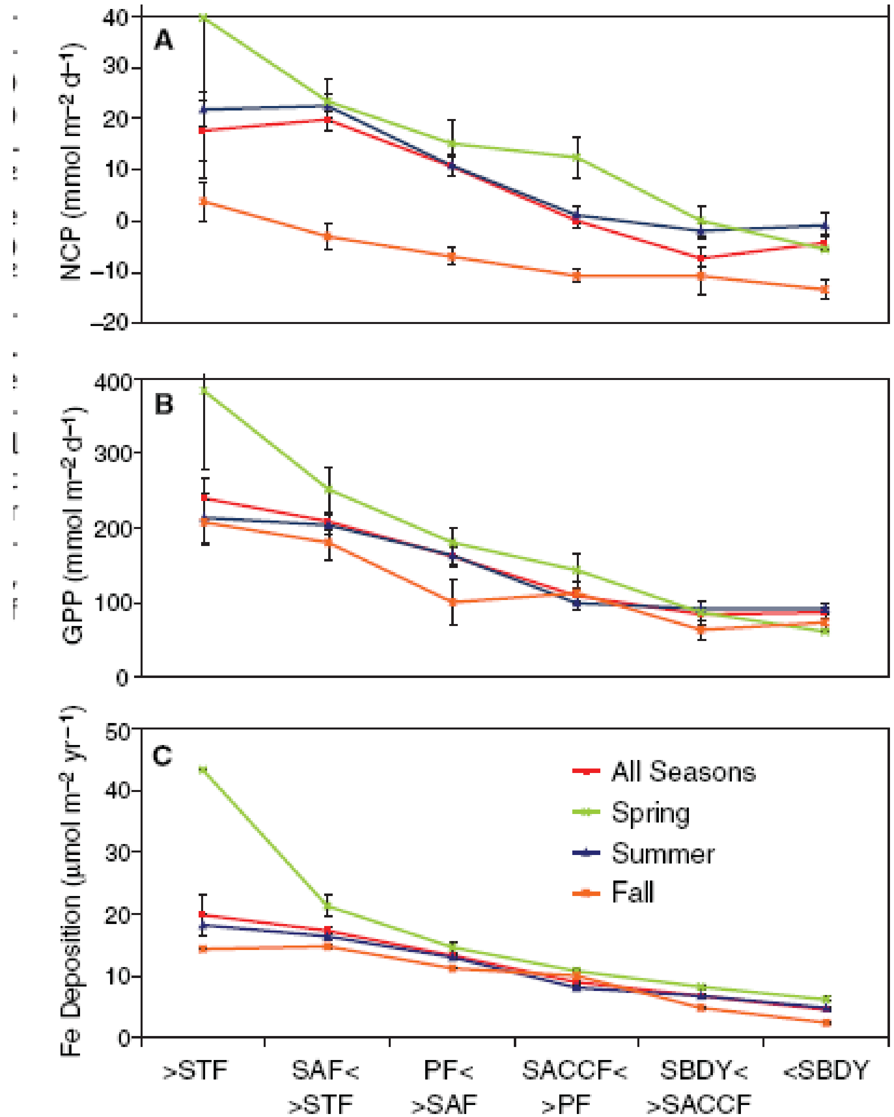


Annual NPP could increase in the future as stronger winds increase nutrient upwelling.

Other studies provided alternative explanations

The Southern Ocean Biological Response to Aeolian Iron Deposition

Nicolas Cassar,[1]* Michael L. Bender,[1] Bruce A. Barnett,[1] Songmiao Fan,[2]
Walter J. Moxim,[2] Hiram Levy II,[2] Bronte Tilbrook[3]



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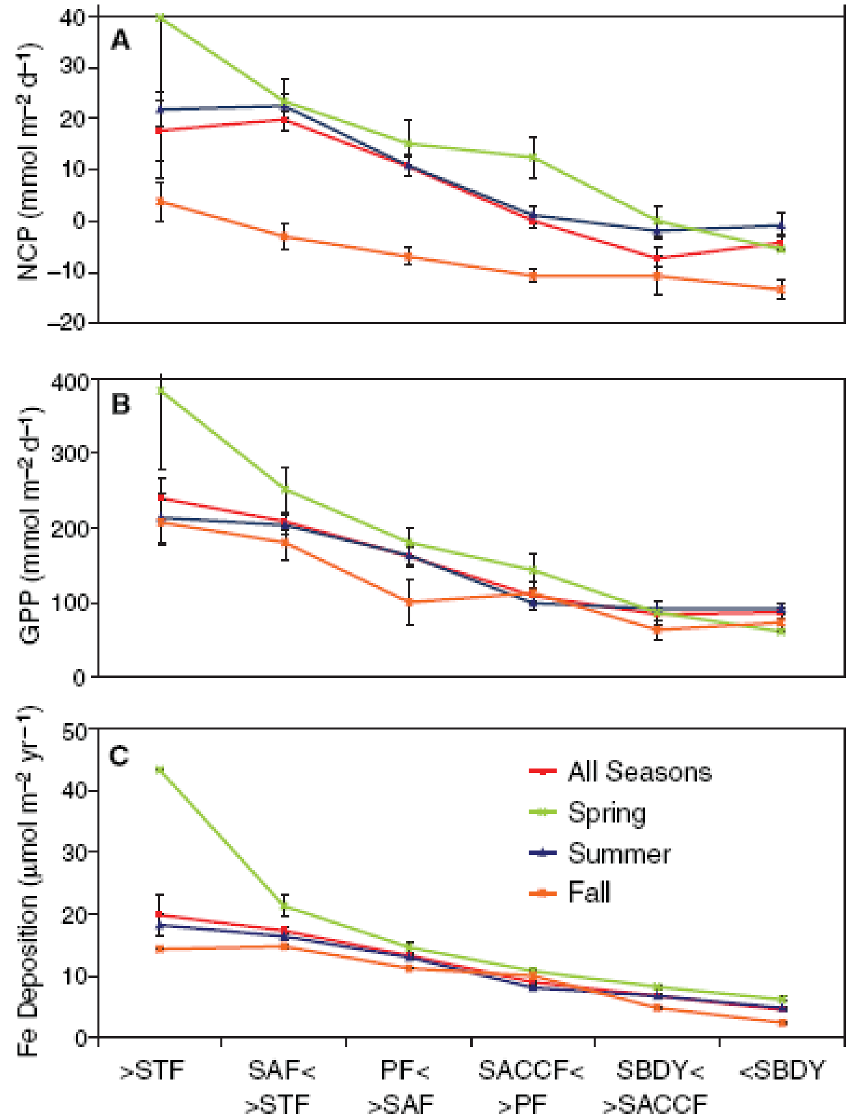
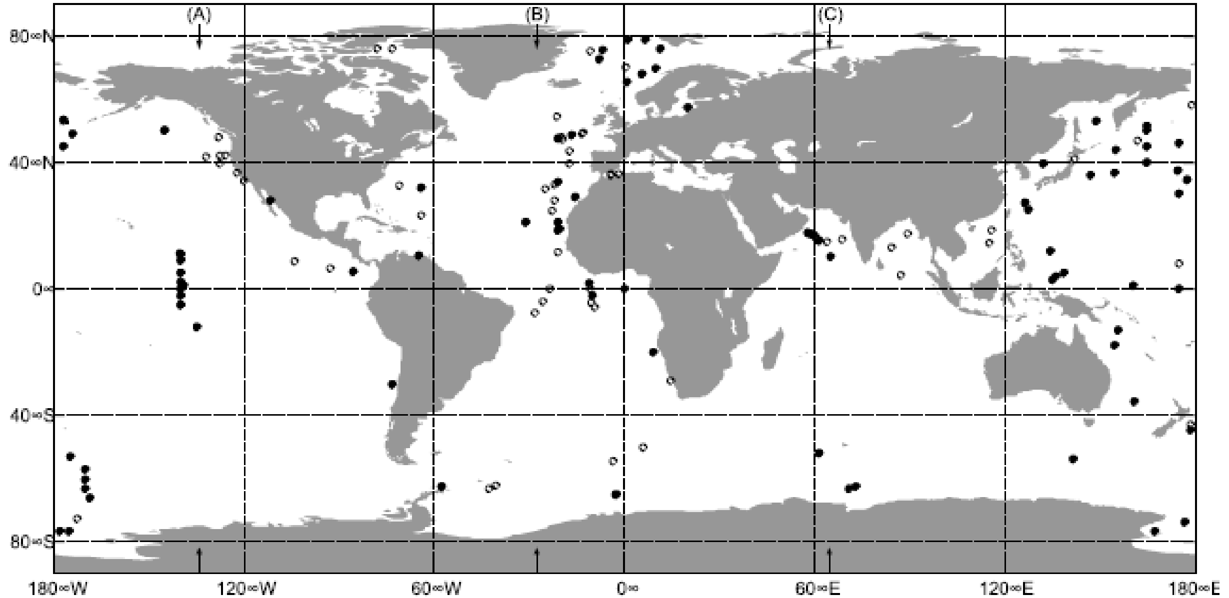
But also left the door ajar



"Some of the variability in NCP versus Fe deposition can be explained by other sources of Fe (such as meltwater, sedimentary, and upwelling sources), variable phytoplankton Fe:C quotas, light and silicate limitations, parameterization of the atmospheric Fe dissolution kinetics, aeolian transport model errors, and wind parameterization of the piston velocity." Cassar et al. 2007

Export flux and climate variability



Lutz et al. 2007

Relatively poorly sampled; few sites sampled in Twilight Zone
Again heavy reliance on satellite data/NPP algorithm/NPP attenuation

Laws et al. (1999) relatively simple global model (temperature/export)
Moore et al. (20002) multi-element foodweb model
Moore et al. (2002) reports large differences in export flux from these models
Lutz et al. (2007) NPP model with tested algorithm (empirical fit between regional NPP and export data)

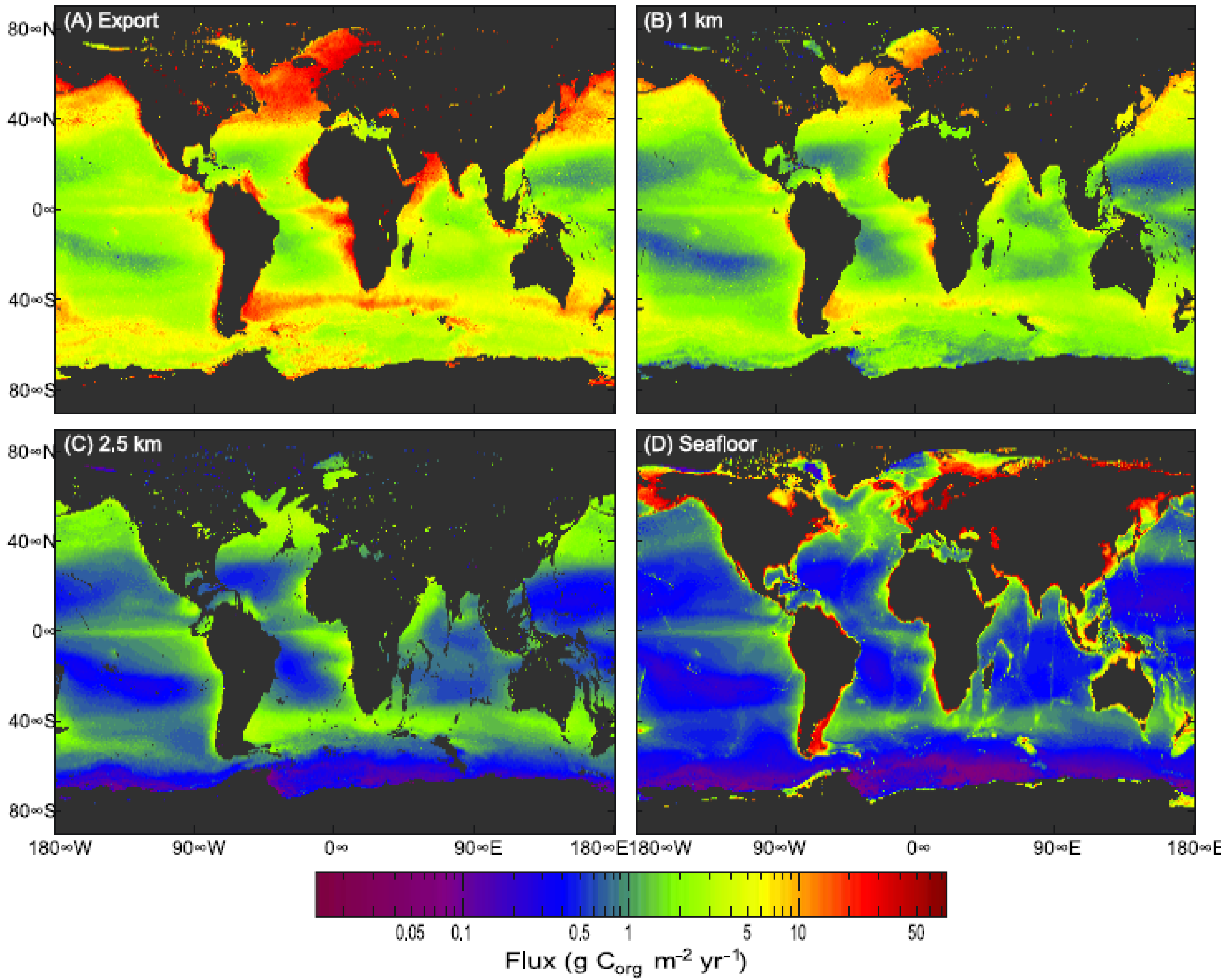
Refractive fast flux

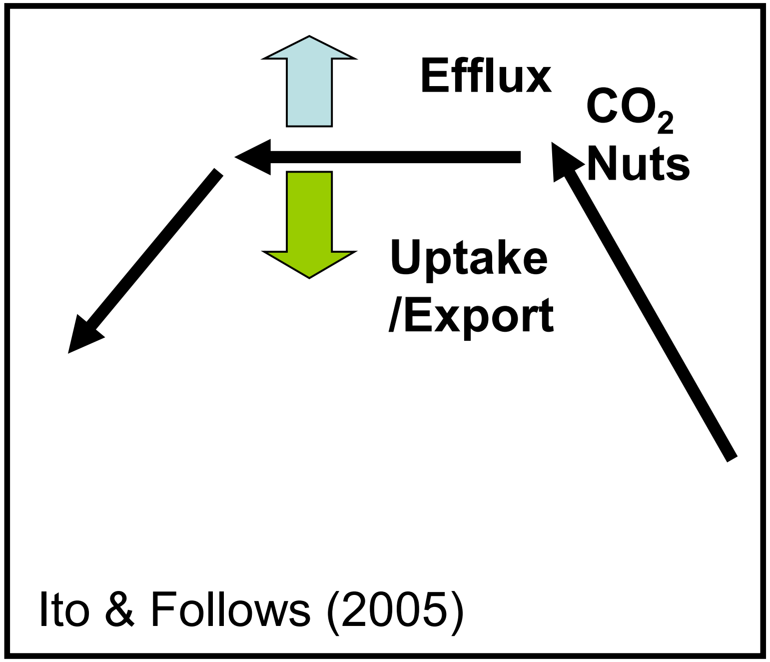
$$p \text{ ratio } (z_e) = pr_d \exp(-z_e/rl_d) + pr_r$$

Slow flux available for decay

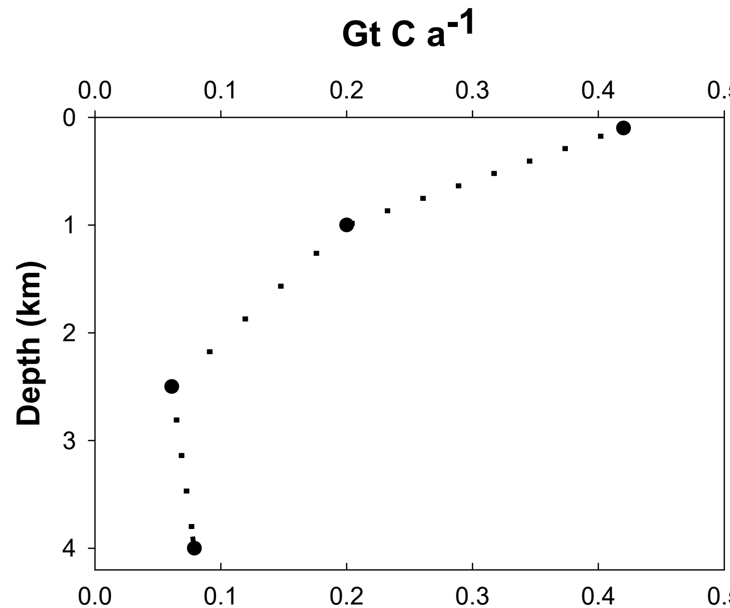
Efolding remin l/scale sinking detritus degradation

Lutz et al. (2007) export maps





Export (S of 40S)



(Lutz et al. 2007)

Three issues

Model performance ??

No data on interannual variability

No Twilight zone export data

Very large intermodel differences in Southern Ocean export

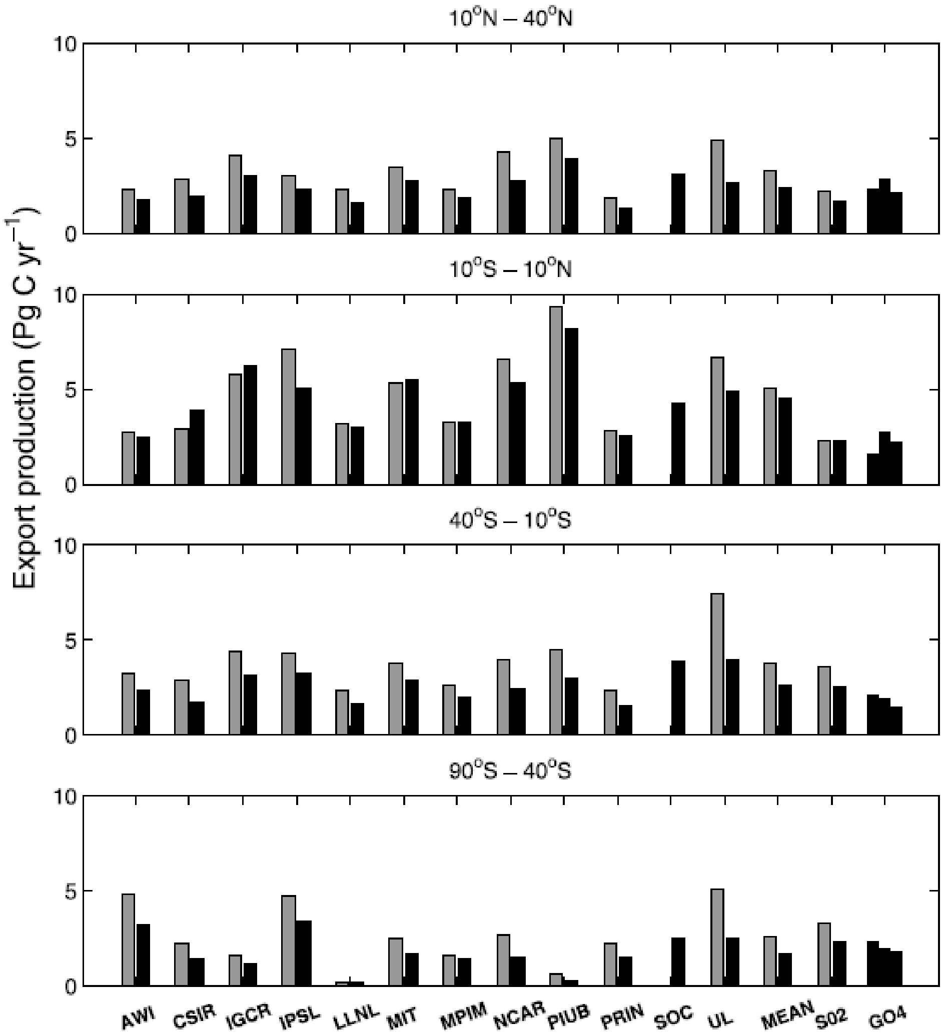
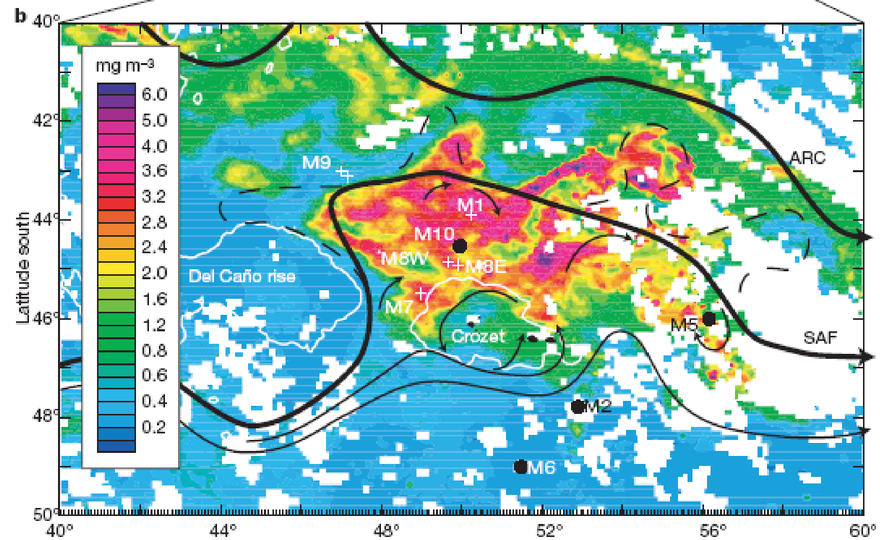


Figure 4. Total (gray) and particle (black) carbon export in five latitude bands for the 12 OCMIP models (Table 1) and their mean, the inverse method of SO2 [*Schlitzer*, 2002], and satellite-based

Najjar et al. (2007) OCMIP

Upper bound on how much export could change due to climate variability or change?



Pollard et al. (2008)

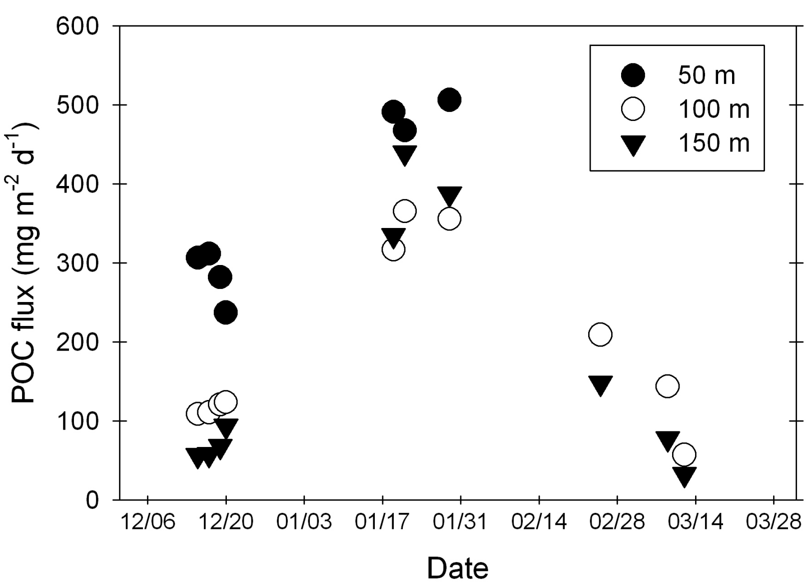
Table 1 | Seasonally integrated carbon fluxes at naturally iron fertilized and HNLC sites and the sequestration efficiency, C/Fe

	Carbon ($mmol\,m^{-2}\,y^{-1}$)		C/Fe‖ ($mol\,mol^{-1}$)
	+Fe (fertilized)	−Fe (HNLC)	
^{234}Th via Si* at 100 m	960	290	17,190
Range	626–1,252	166–415	5,420–60,360
Deep flux† at 3,000 m	25.0	7.1	—
Best estimate‡	28.9	11.6	440
Range‡	25.0–34.2	7.1–17.4	195–1,506
Core top§	9.3 ± 0.5	4.5 ± 0.4	123
Interpolated flux at 150 m¶	642	194	11,487
Interpolated flux at 200 m¶	483	146	8,641

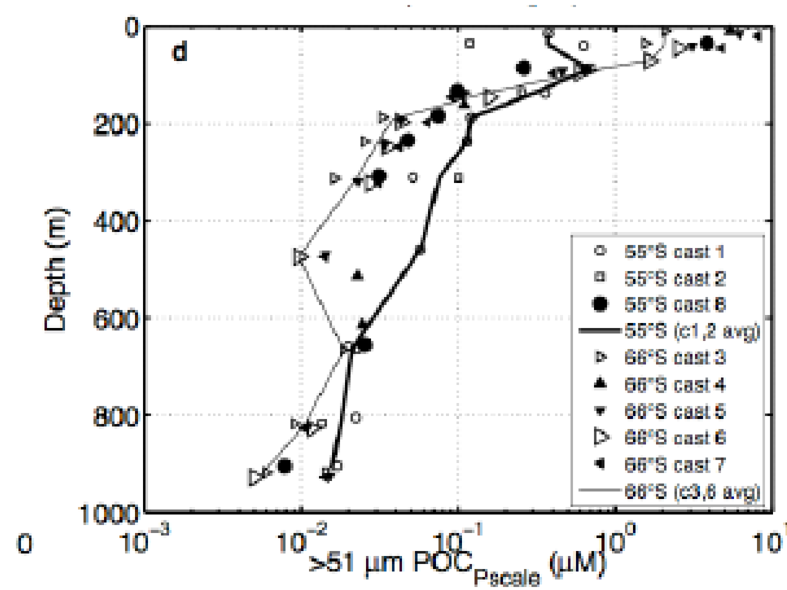
THREE to FOURFOLD

Export data for the Twilight Zone (0.1 to 1 km depth)

"Seasonal production-to-flux analyses indicate during intervals of bloom production, the sinking fraction of NPP is typically half that of other seasons." Lutz et al. (2007)



Buesseler and Boyd (2009)

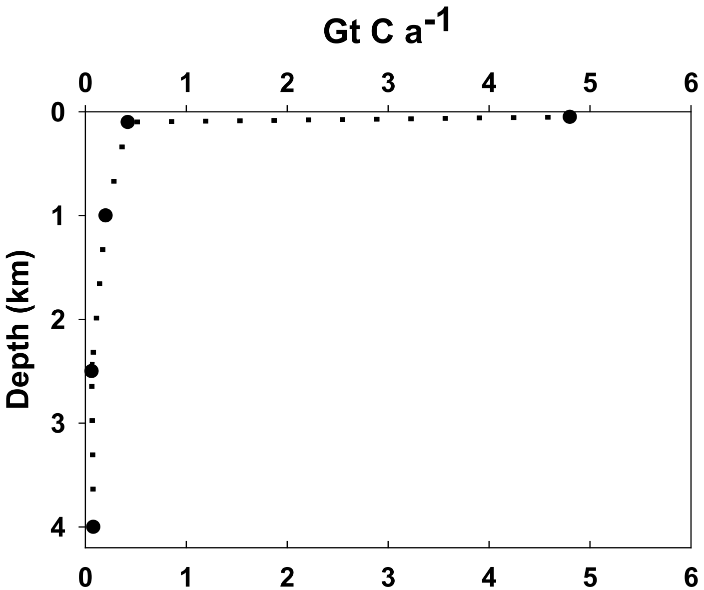


High Biomass Low Export Regimes in the Southern Ocean
Lam & Bishop (2007)

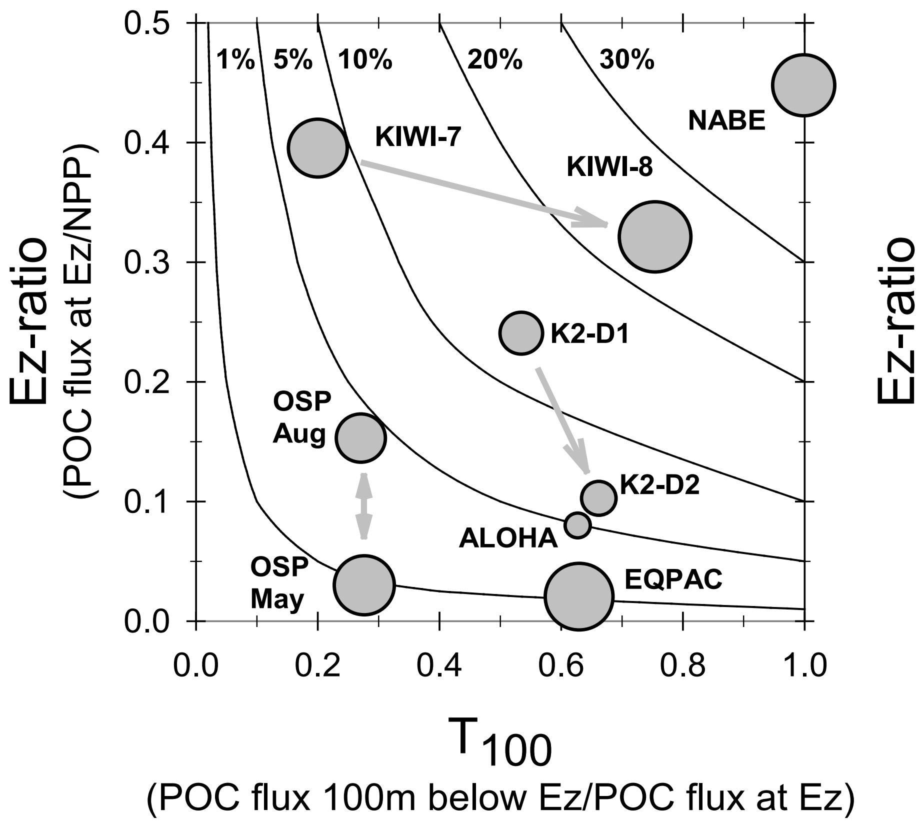
Lack of consensus

NPP and export – coupling and transfer efficiency

Very few studies

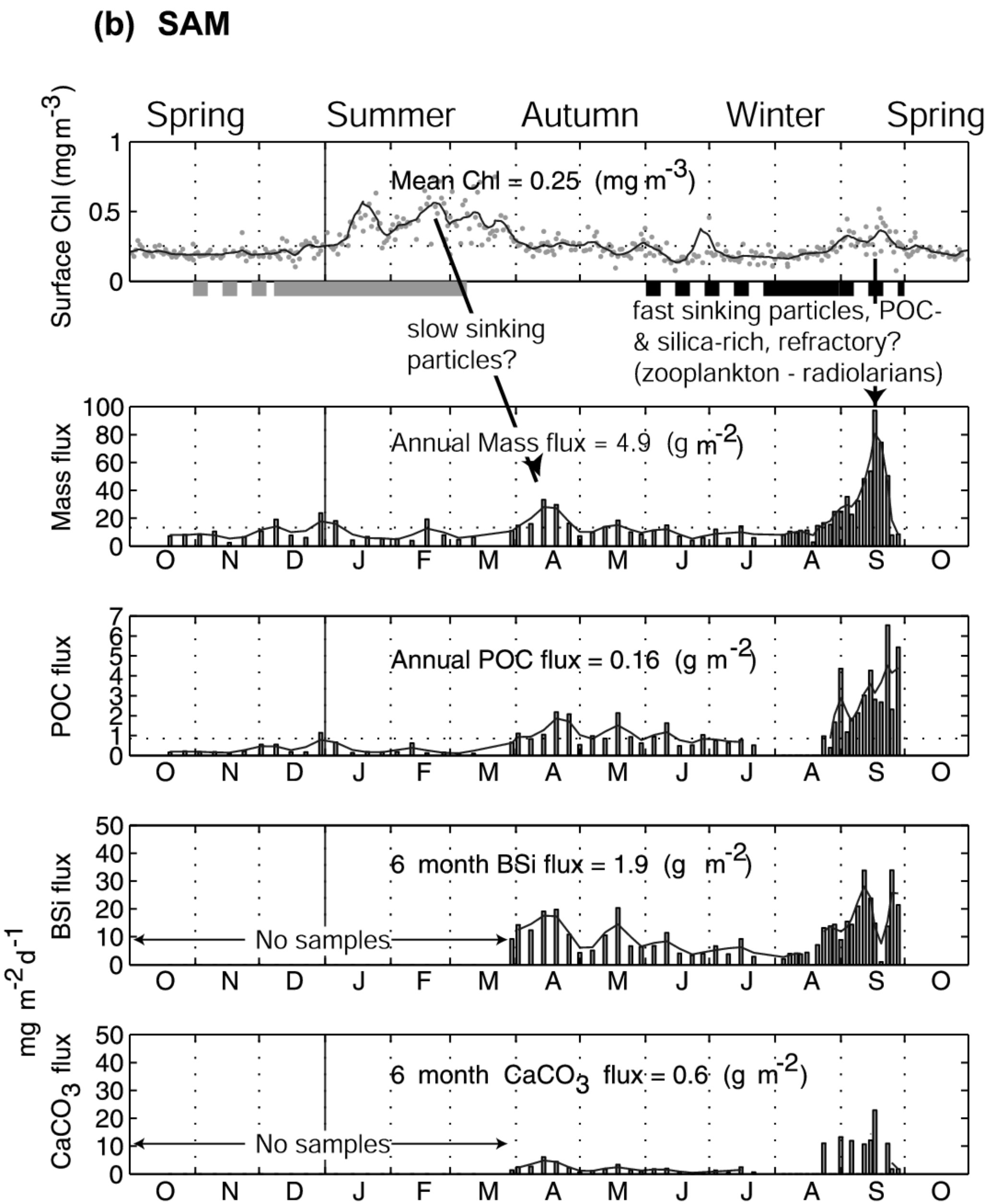


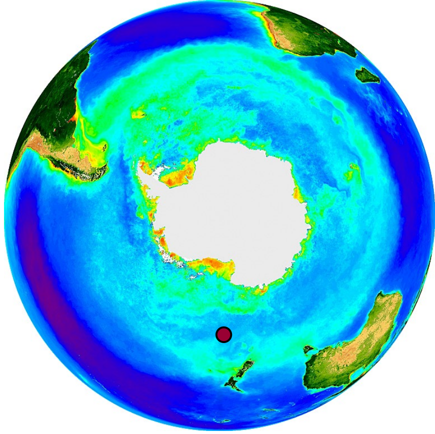
S of 40S
NPP – Arrigo (unpubl.)
Export (Lutz et al. 2007)



Buesseler & Boyd (2009)

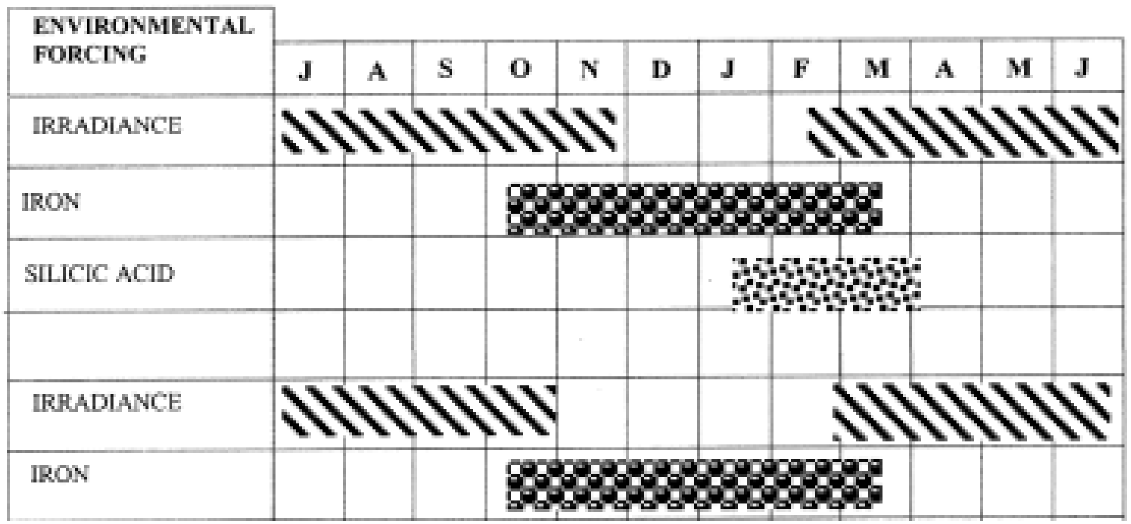
NPP and export – coupling (Nodder et al., JGR 2005)





Climate variability – controls on NPP

Variability (+SAM)



Upwelling
More iron supply?
Deeper mixed layer
Less light

Boyd (2002)

Subantarctic waters – iron, light & silicate
Polar waters – iron and light

Intimate relationships between these factors

Will upwelling increase Fe supply? mismatch between depth of ferricline & nutricline

First reported by Johnson et al. (1997) for low latitude Pacific

Confirmed in subantarctic by Boyd et al. (2005) and Frew et al. (2006)

Other studies – Rodgers et al. (2008) modelling impact of this decoupling

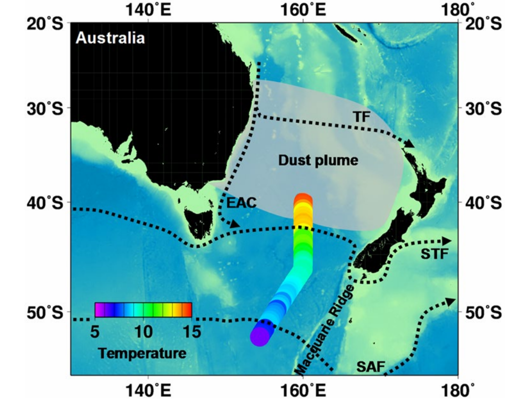
Physical circulation?

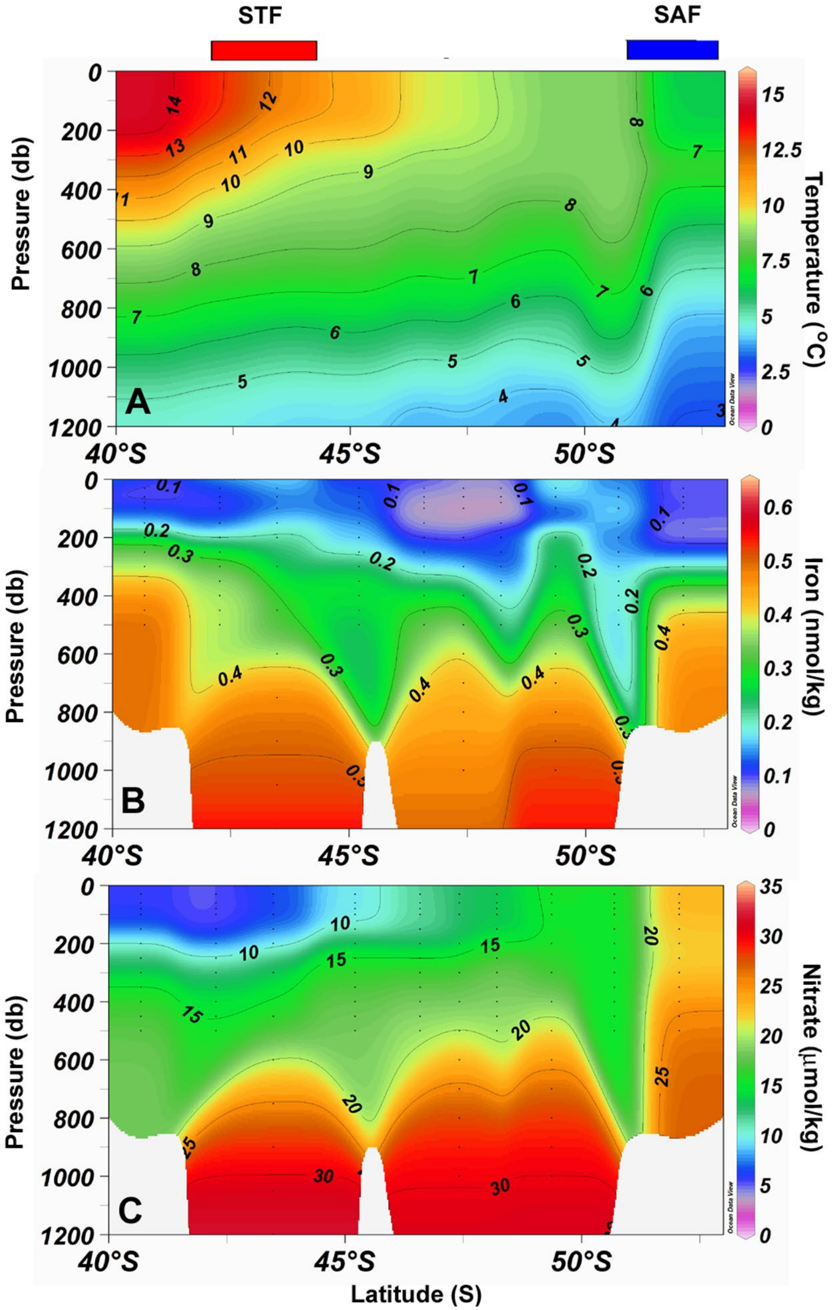
Particle remineralization length scales?
iron chemistry?, ligands?

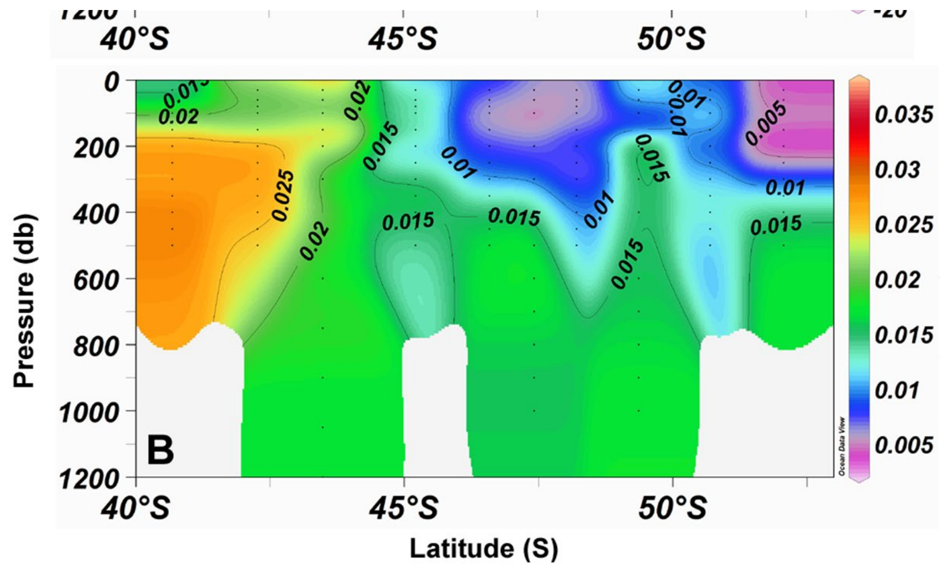
Variability (+SAM)

Upwelling
More iron supply?
Deeper mixed layer
Less light

GEOTRACES-IPY section in winter



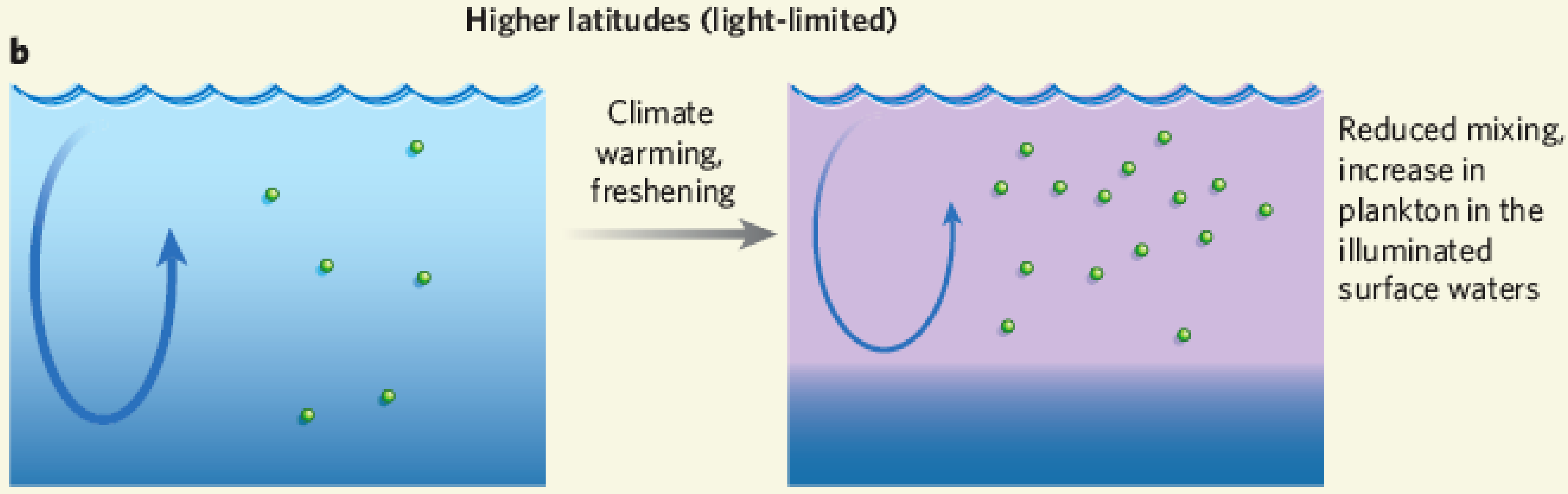




Fivefold range in Fe/NO_3 molar ratios

Ellwood et al. GRL 2008

Climate change – controls on phytoplankton



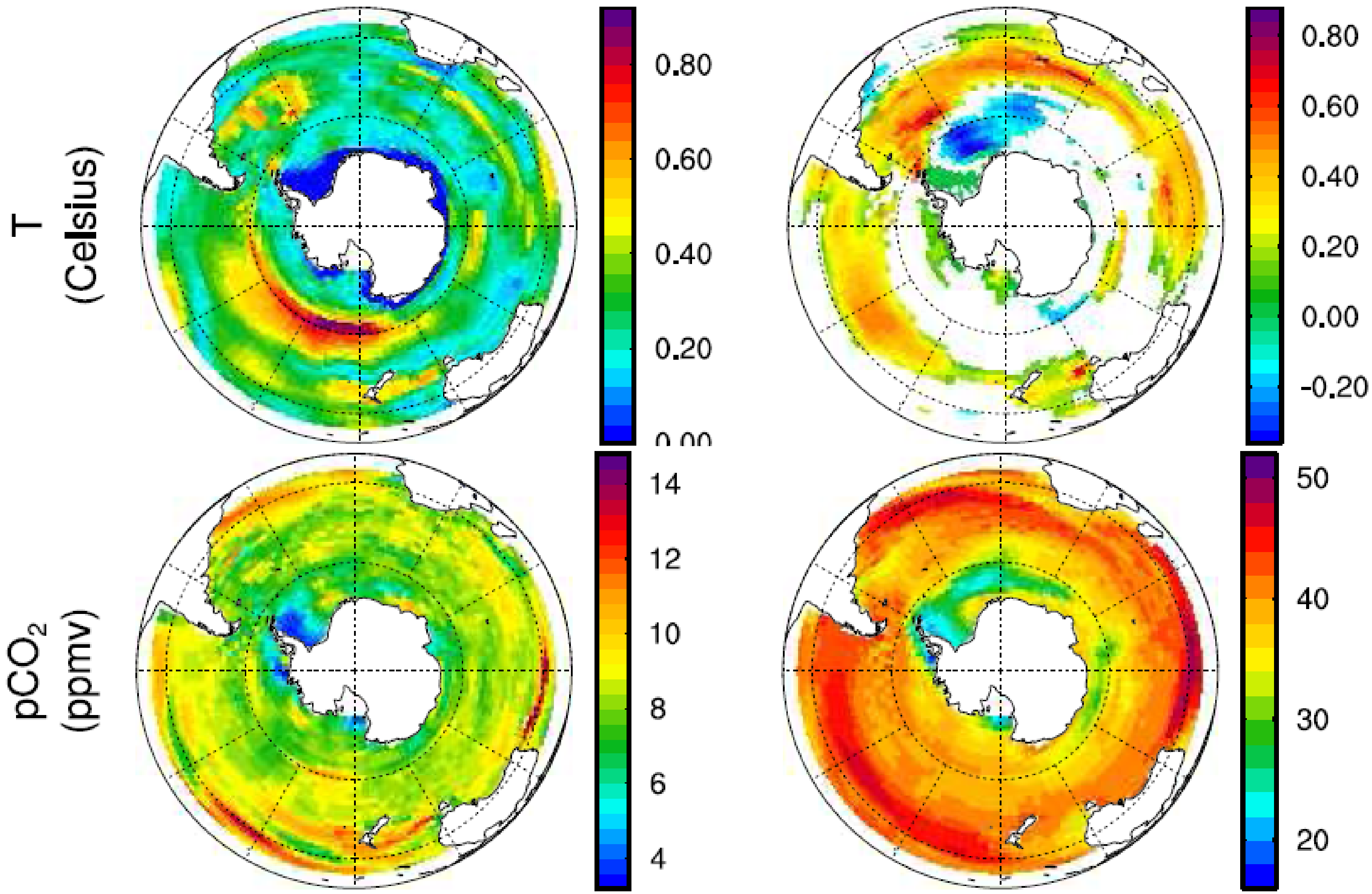
Doney (2006)

How will phytoplankton adapt to concurrent effects of climate variability and climate change?
(Boyd et al. 2008)

Biogeosciences, 5, 847–864, 2008

Climate-mediated changes to mixed-layer properties in the Southern Ocean: assessing the phytoplankton response

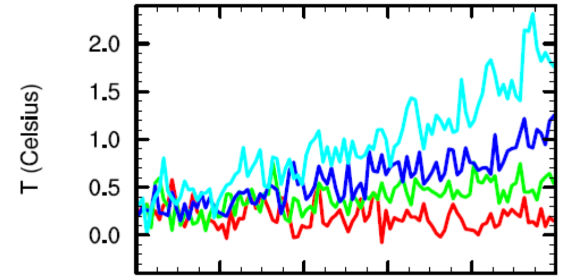
P. W. Boyd[1], S. C. Doney[2], R. Strzepek[1,3], J. Dusenberry[2], K. Lindsay[4], and I. Fung[5]



Climate variability
SD of annual mean from 10 yr segment

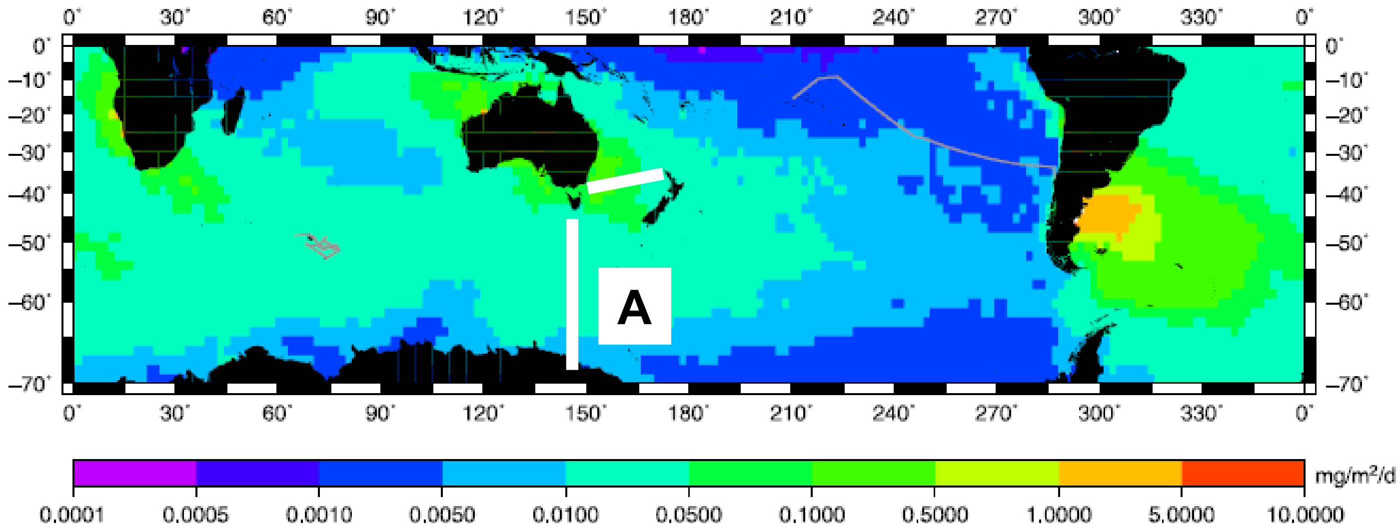
Climate change - difference over a 20 yr time period (2020-2029 minus 200-2009)

Property	Rate of change per decade (climate change)	RMS variability (climate variability)
Temperature deg. C	+0.03 to +0.17	0.13
Salinity psu	-.014 to -.042	0.027
Mixed layer depth m	-0.3 to -0.8	2.0
Stratification $kg/m^4 \times 10^{-4}$	+0.28 to +1.49	0.77
Surface PO_4 µmol/l	+.001 to -.004	0.012
Surface Fe nmol/l x 10^{-3}	**-1.89 to -5.58**	**3.85**
pCO_2 ppmv	+37.4 to +41.0	1.2
Light climate (mixed layer)	0.003 to 0.005 W/m2	0.05 to 0.07 W/m2
Ice fraction	-.003 to -.013	0.013



Boyd et al. (2008) Biogeosciences

Dust isn't the only game in town



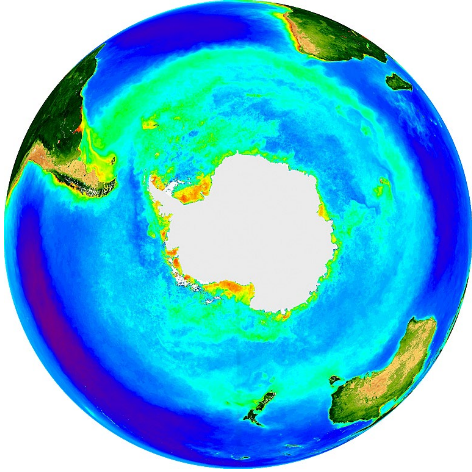
'*Dust and iron deposition are up to 2 orders of magnitude lower than former predictions.'* Wagener et al. (2008)

A denotes ship-of-opportunity dust sampling

Other Fe supply terms include sediment resuspension & sea ice retreat

Climate variability vs. Change

Boyd et al. (2008)



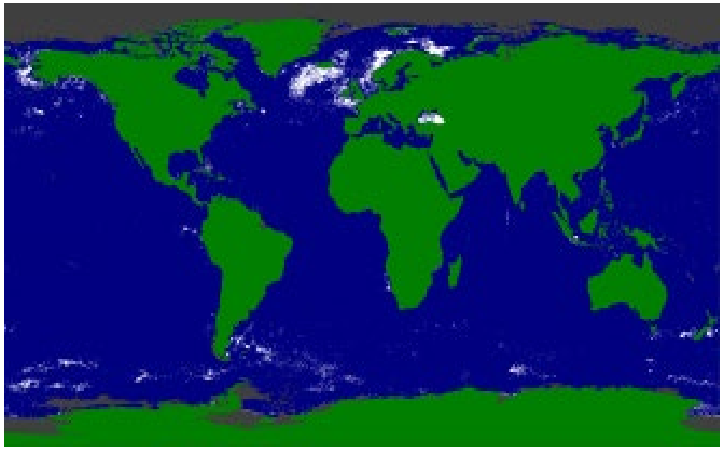
Climate change will initially be of a similar magnitude (and sometimes different sign) to climate variability

Climate change may only induce significant biological effects when the magnitude of the environmental perturbations exceed the background natural variability on seasonal to interannual time-scales.

Sign of feedback due to climate change on S Ocean phytoplankton - UNKNOWN

Detection and attribution of the effects of climate change on S. Ocean phytoplankton

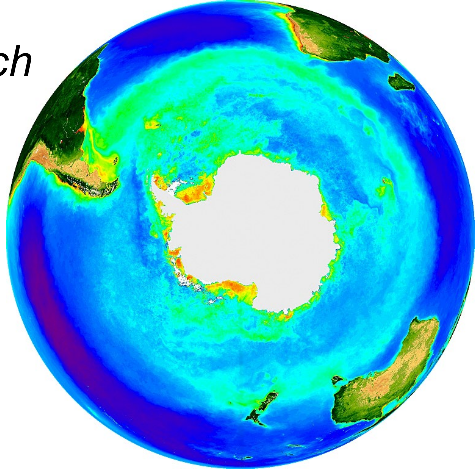
Boyd et al. (2008)



3 Scenarios

1) **ecosystems are very "plastic" with no or limited changes in community structure due to the ability of resident cells to adapt to climate change over years to decades *DIFFICULT TO DETECT***
2) **the climate change signal can be treated as simply a poleward migration of "fixed" biomes (e.g. *Sarmiento et al.* [2004]) *EASIER TO DETECT AND MONITOR***
3) **conditions change enough that a "new" community or ecosystem arises that has no analogue in current ocean [*Boyd and Doney*, 2003] *???***

STOP PRESS – see Montes-Hugo et al. and Moy et al. (2009)



Key issues to address

Stoichiometry of Fe and nutrient supply
Fe biogeochemistry – regional studies
Fe/light interactions - phytoplankton
Twilight zone and fast export

More process studies – such as SAZSENSE – or FeCycle II – 1st GEOTRACES process study

Lab culture experiments with S. Ocean isolates

Better integration of satellite, remote-sensing and the above process and physiological studies