Productivity in a Changing Southern Ocean

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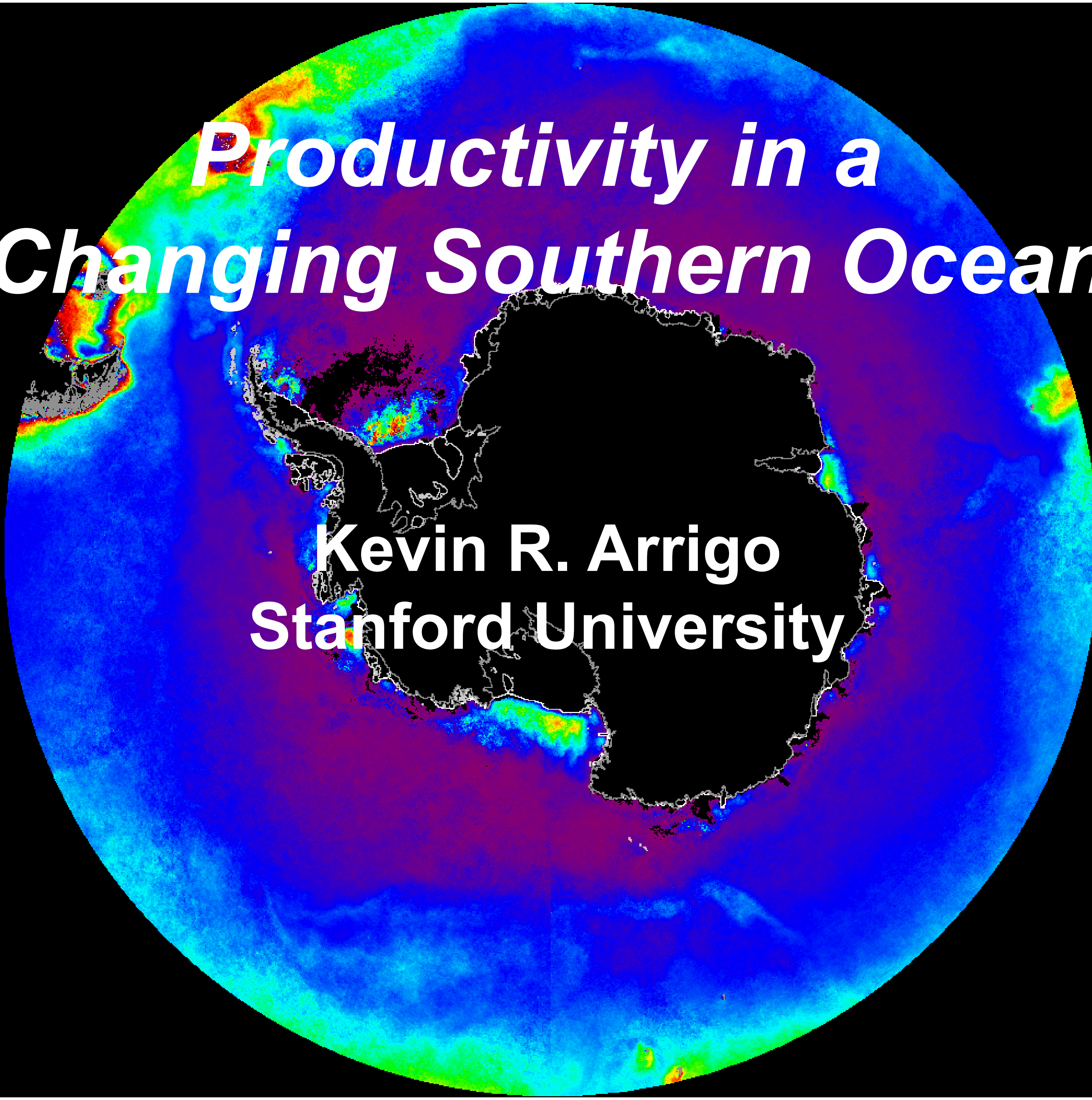
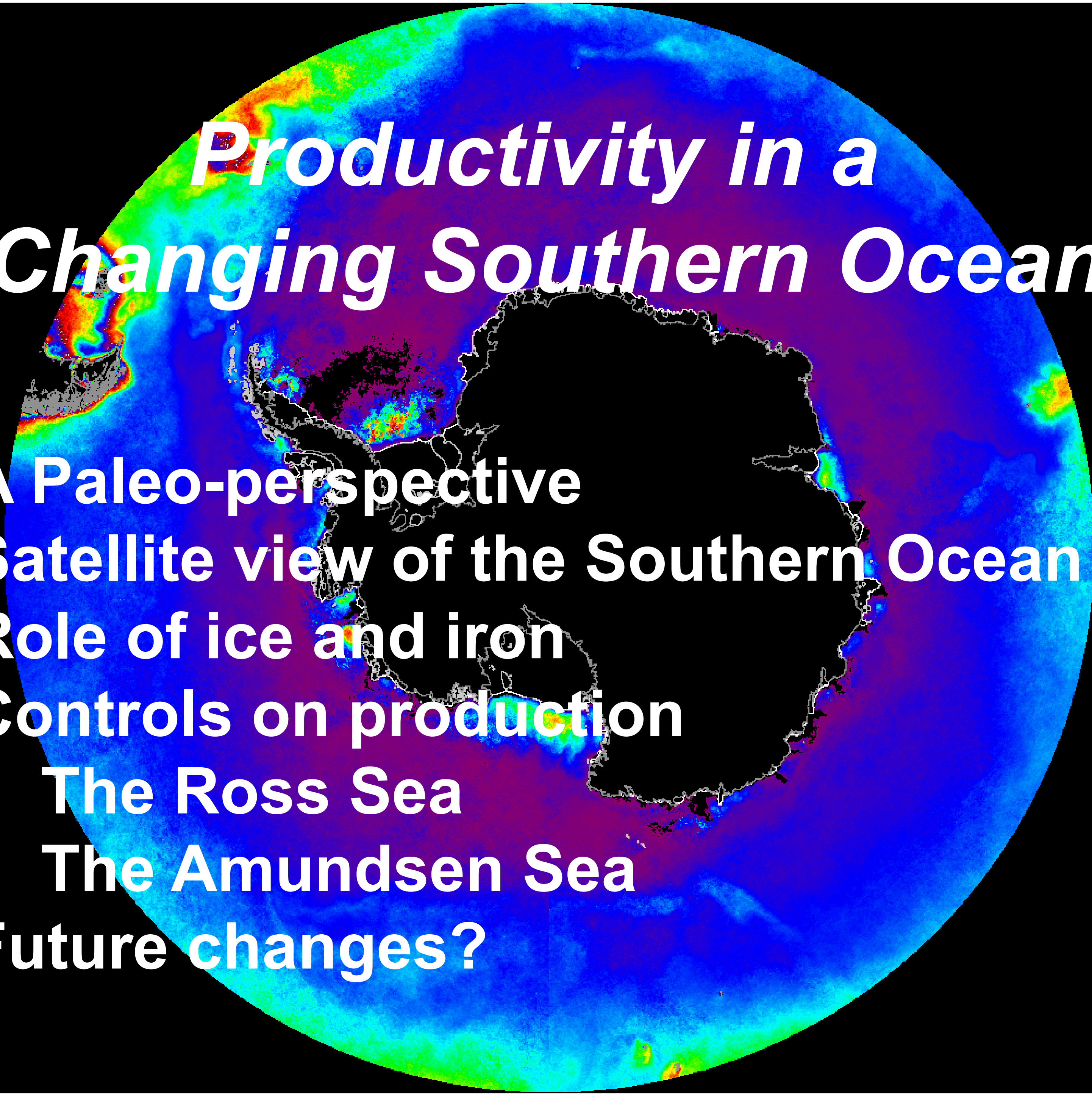




Productivity in a Changing Southern Ocean

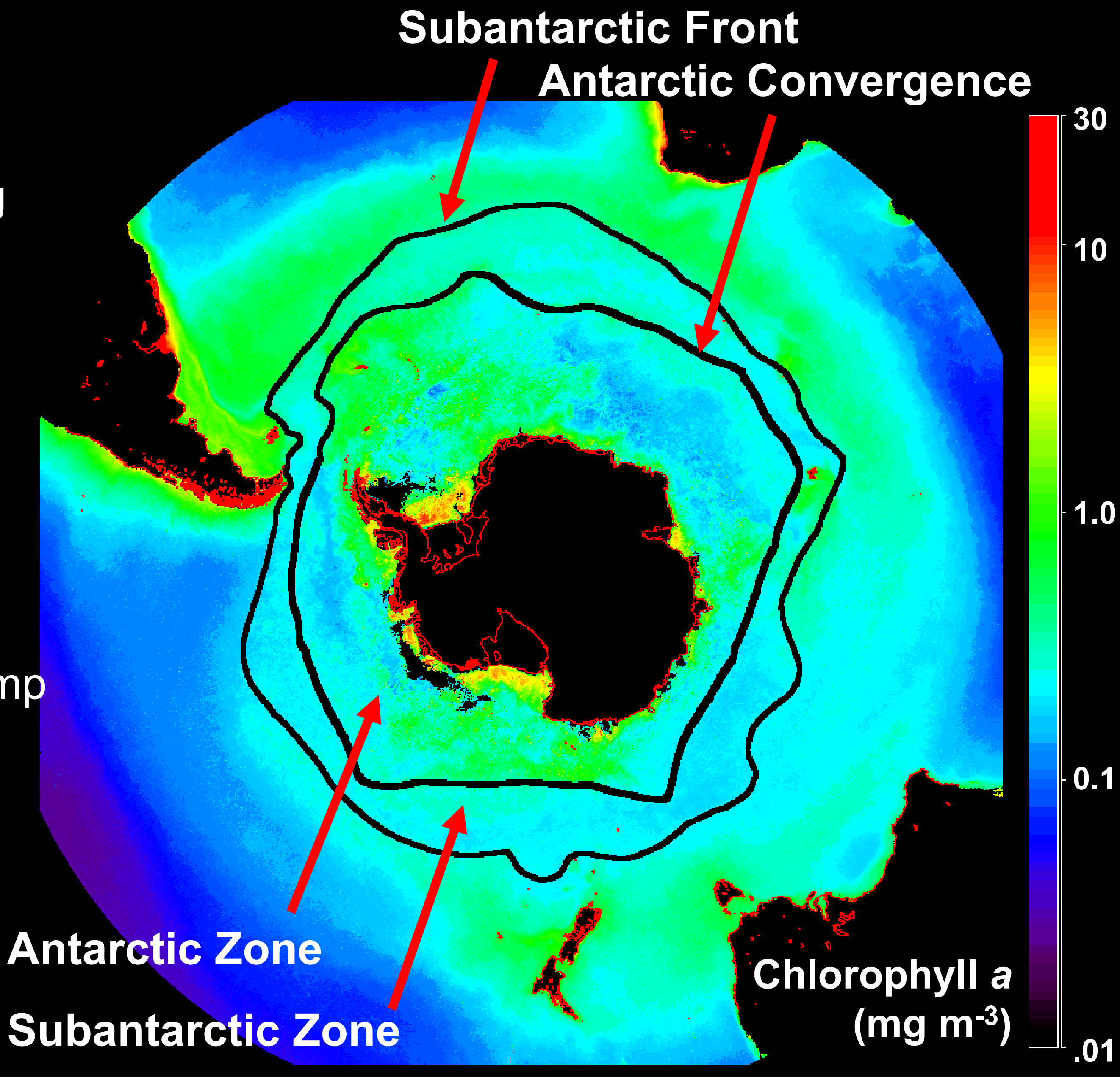
- A Paleo-perspective
- Satellite view of the Southern Ocean
- Role of ice and iron
- Controls on production
    - The Ross Sea
    - The Amundsen Sea
- Future changes?

A Paleo-Perspective

Glacials:

Antarctic Zone
- Reduced overturning
- Low productivity
- High ice cover
- Little air-sea CO_2 exchange

Subantarctic Zone
- Greater dust flux
- High productivity
- Strong biological pump
- Large net CO_2 sink

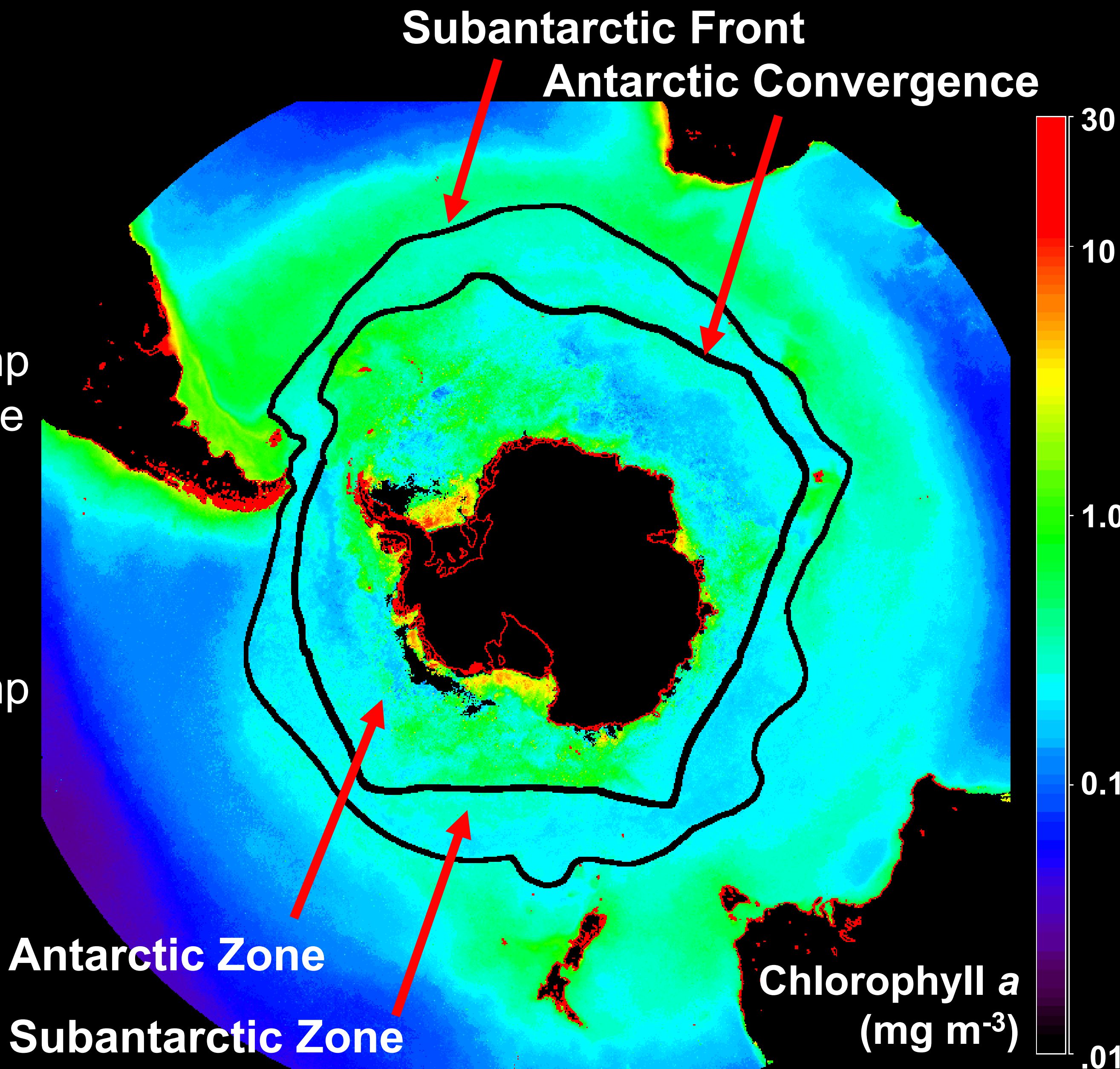


A Paleo-Perspective

Interglacials:

Antarctic Zone
- Greater overturning
- Higher productivity
- Lower ice cover
- Weak biological pump
- Large net CO_2 source

Subantarctic Zone
- Reduced dust flux
- Lower productivity
- Weak biological pump
- Small net CO_2 sink



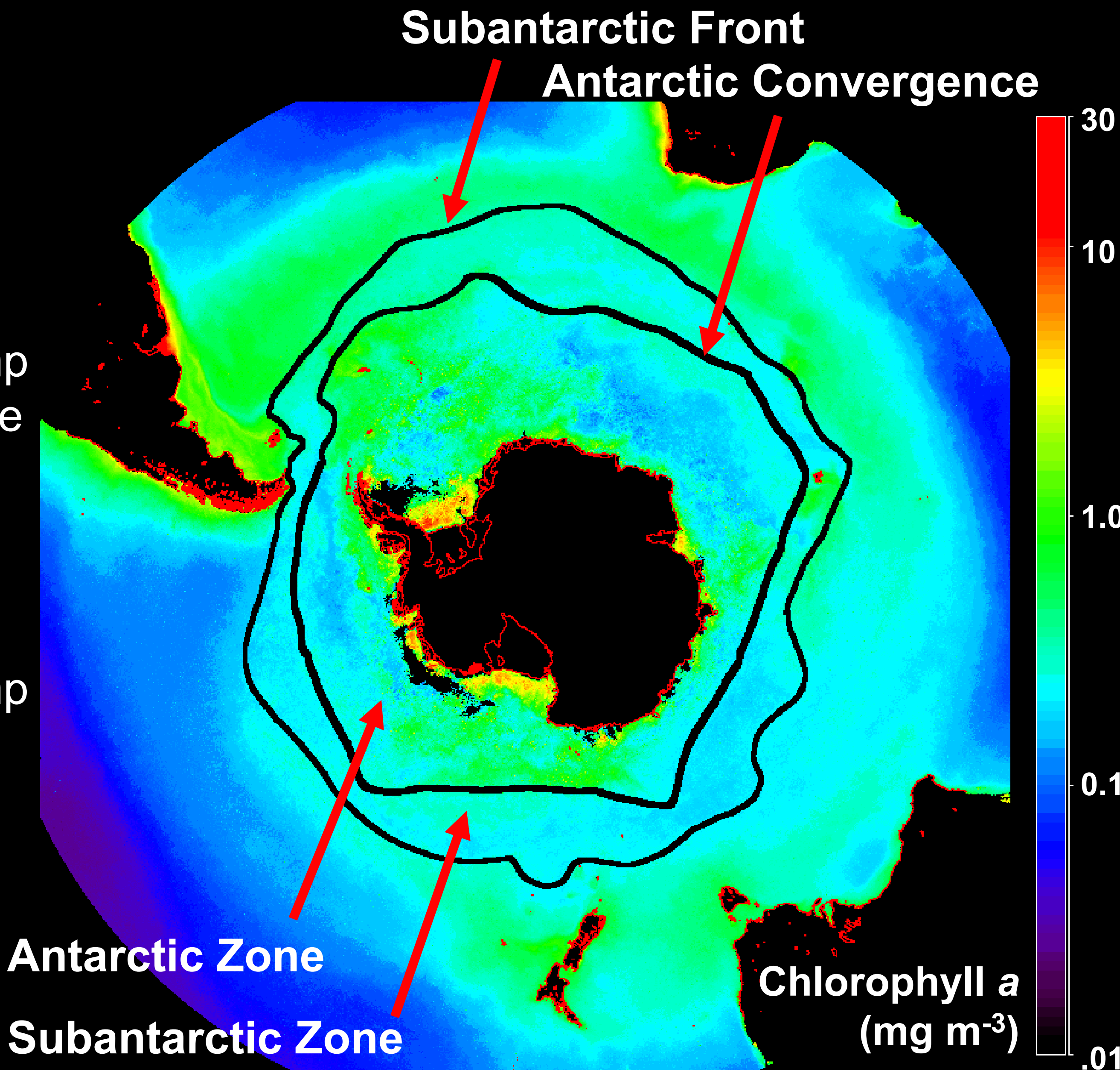
A Paleo-Perspective

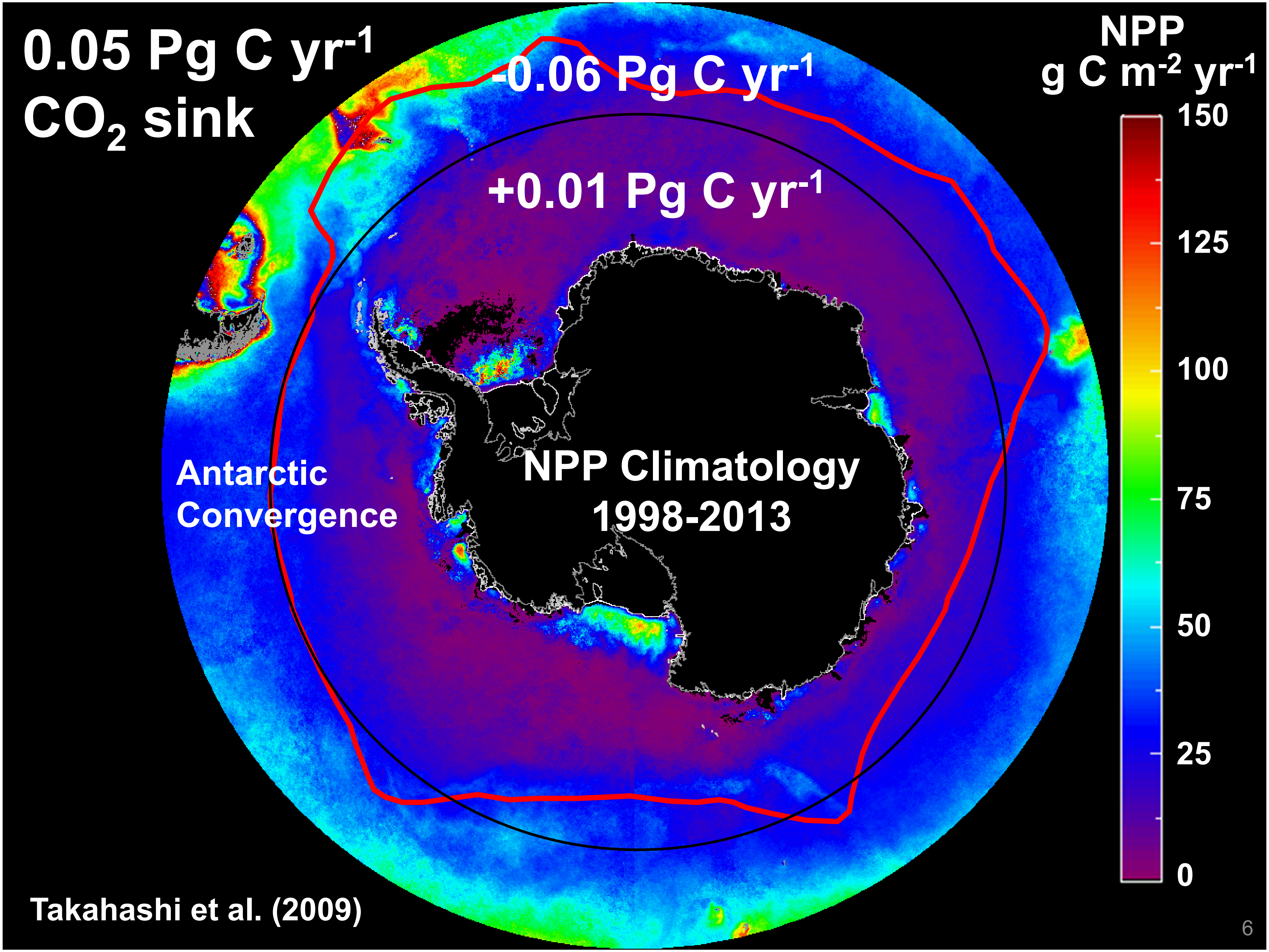
Interglacials:

Antarctic Zone
- Greater overturning
- Higher productivity
- Lower ice cover
- Weak biological pump
- Large net CO_2 source

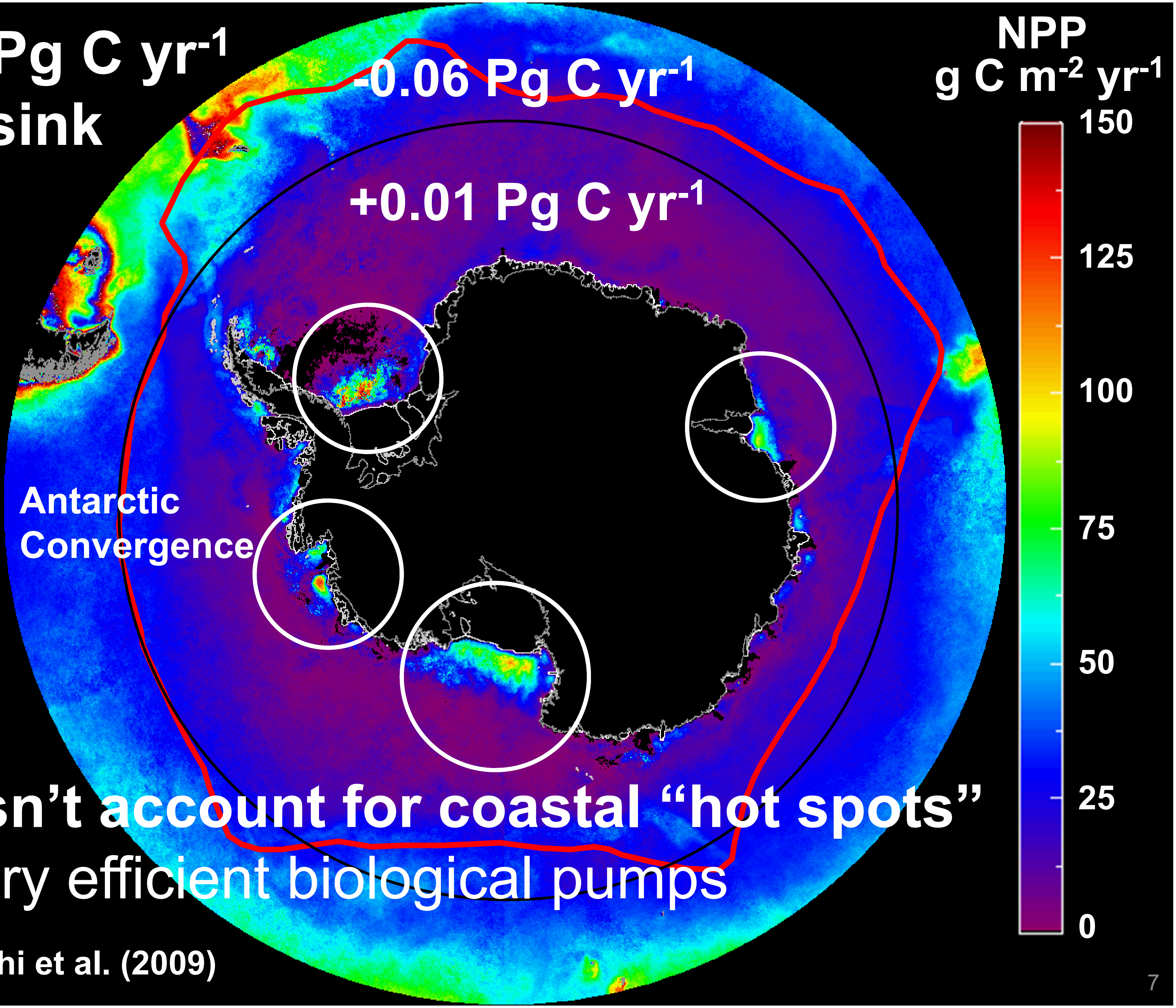
Subantarctic Zone
- Reduced dust flux
- Lower productivity
- Weak biological pump
- Small net CO_2 sink

TODAY:
Southern Ocean is neutral or a net CO_2 source




0.05 Pg C yr-1
CO2 sink
-0.06 Pg C yr-1
+0.01 Pg C yr-1
NPP
g C m-2 yr-1
150
125
100
75
50
25
0
Antarctic
Convergence
NPP Climatology
1998-2013
Takahashi et al. (2009)

0.05 Pg C yr^{-1}
CO_2 sink

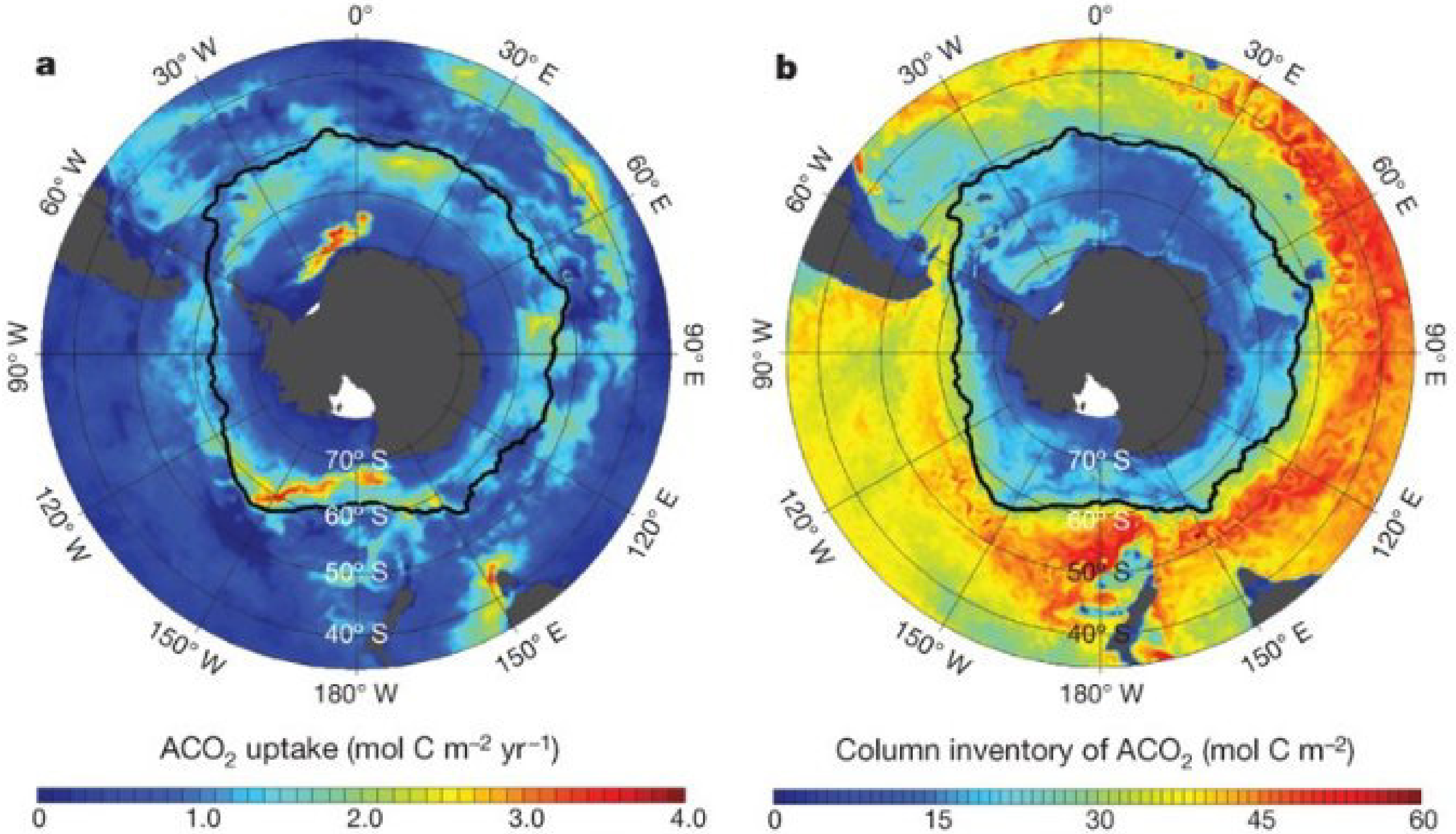


Doesn’t account for coastal “hot spots”

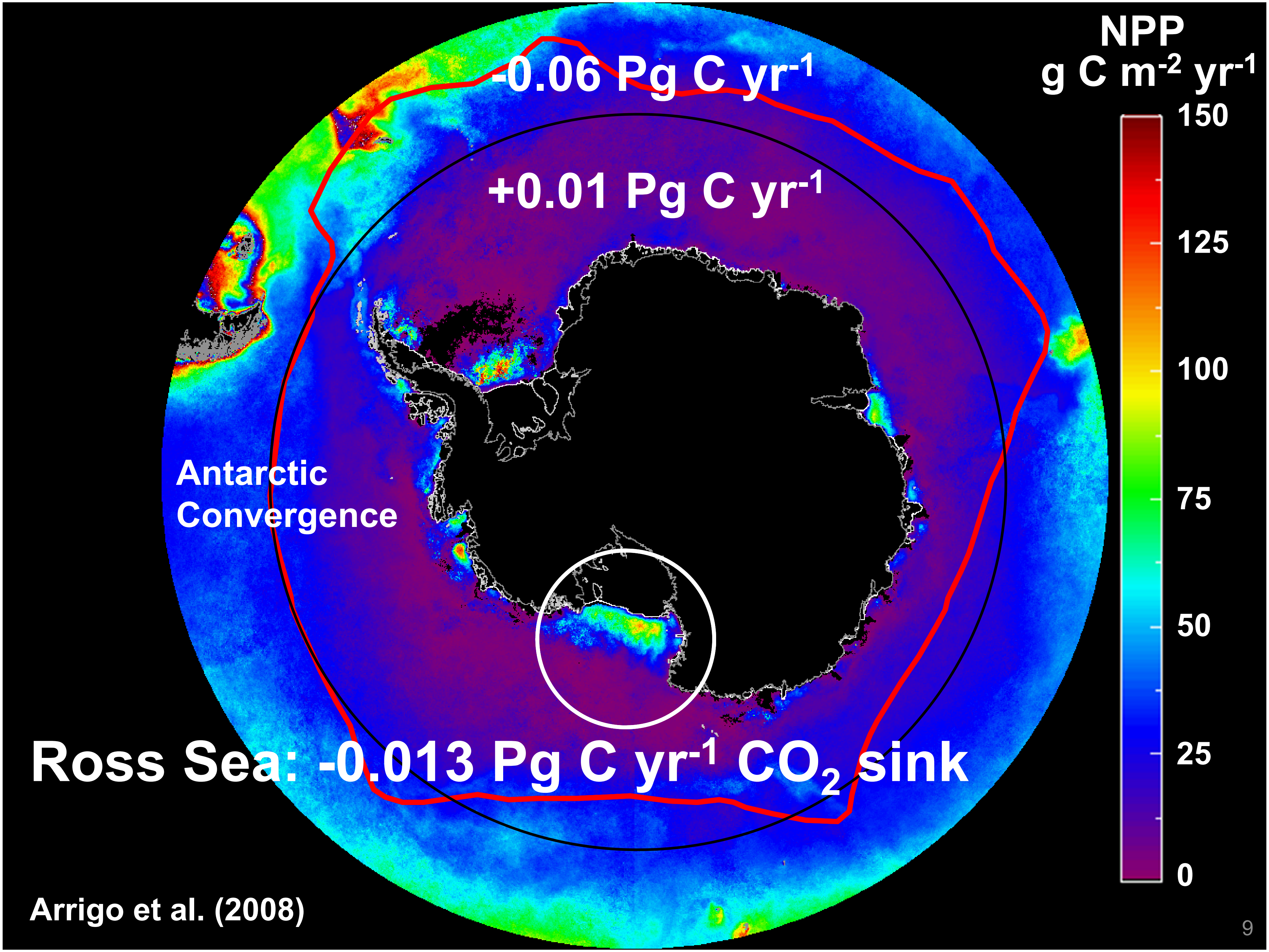
Very efficient biological pumps

Takahashi et al. (2009)

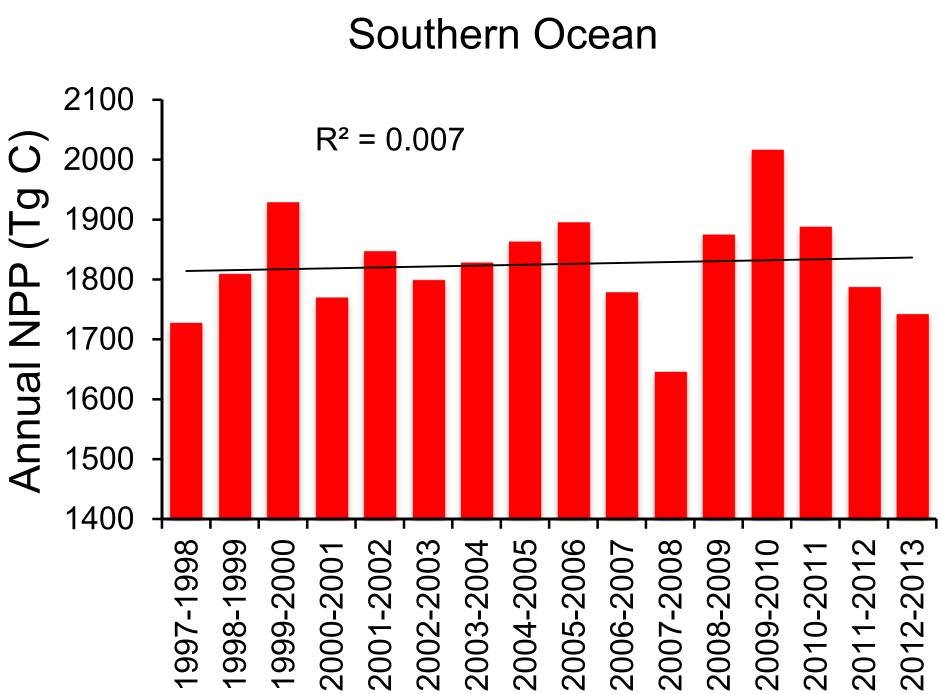
Neither do most models
(even high resolution ones)



Ito et al. (2010)


-0.06 Pg C yr^{-1}
+0.01 Pg C yr^{-1}
NPP
g C m^{-2} yr^{-1}
150
125
100
75
50
25
0
Antarctic Convergence
Ross Sea: -0.013 Pg C yr^{-1} CO_2 sink
Arrigo et al. (2008)

Interannual variability in NPP



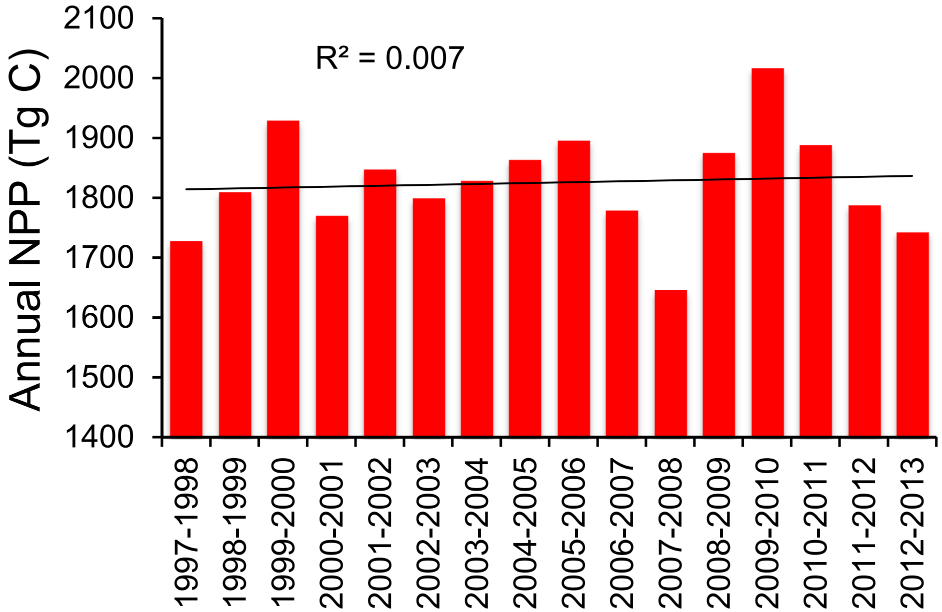
Mean = 1825 Tg C yr^{-1}

Low interannual variability (CV = 4%)

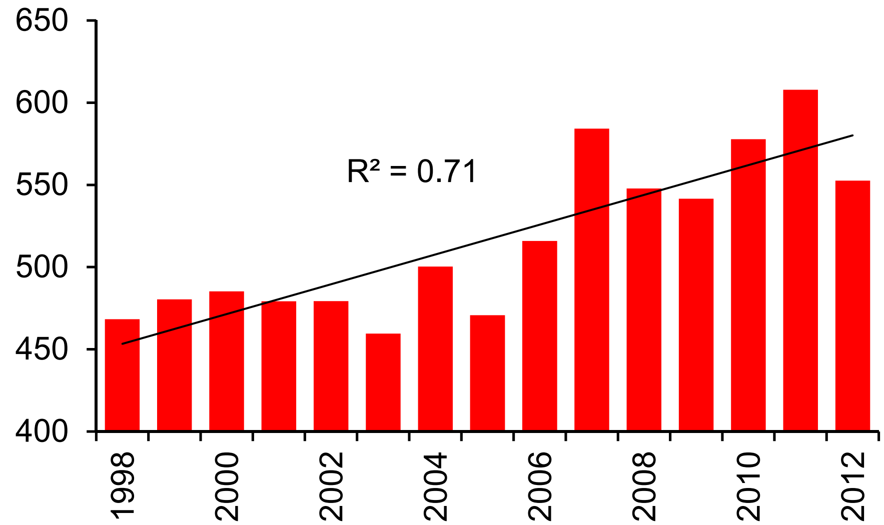
No significant change over time

Interannual variability in NPP

Southern Ocean



Arctic Ocean



Mean = 1825 Tg C yr^{-1}

Low interannual variability (CV = 4%)

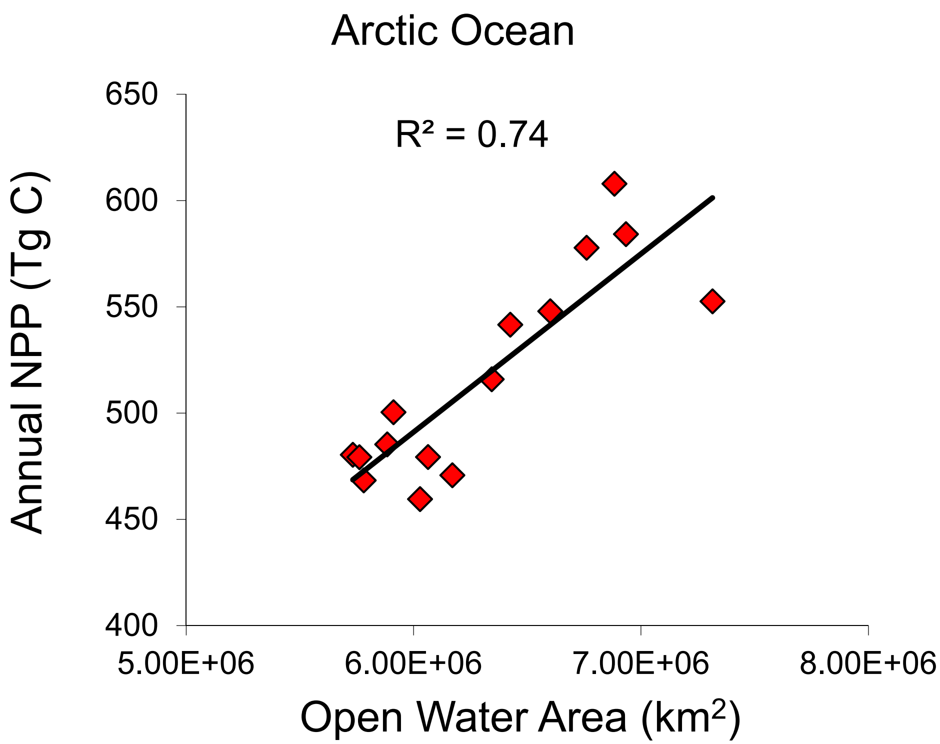
No significant change over time

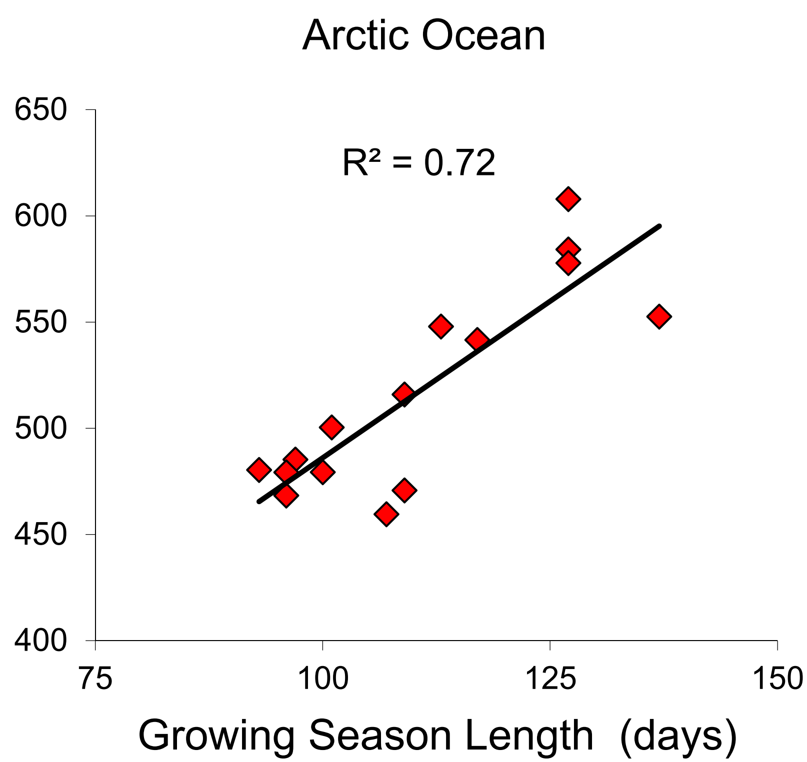
Mean = 524 Tg C yr^{-1}

High interannual variability (CV = 11%)

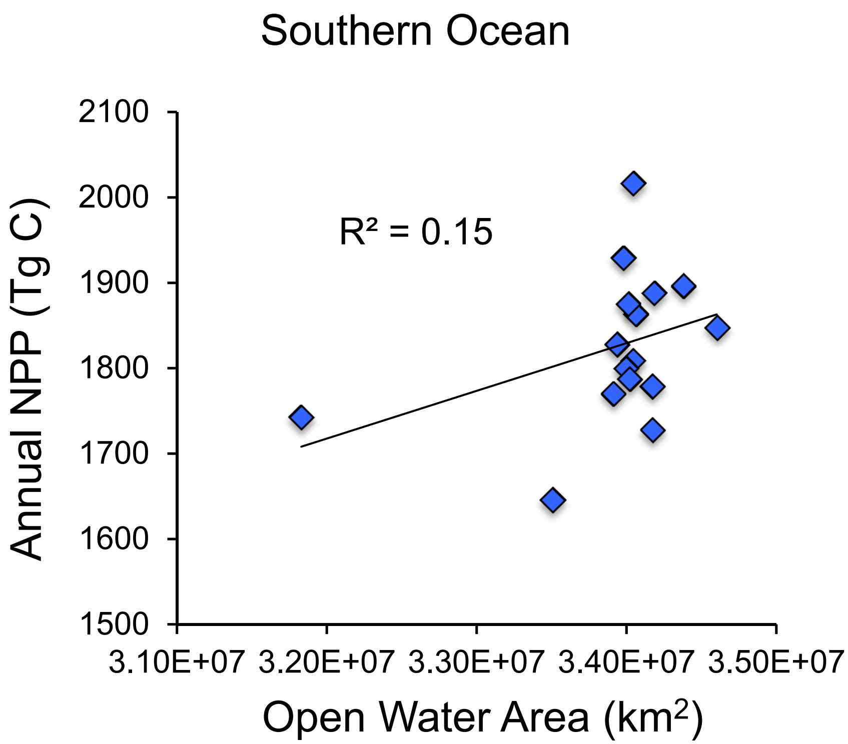
Significant 30% increase since 1998

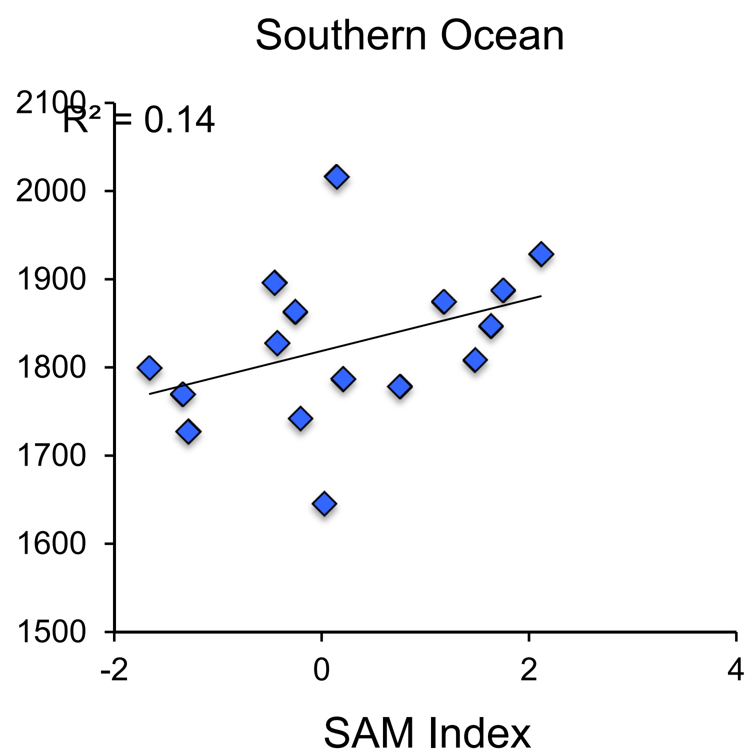
Interannual variability in NPP



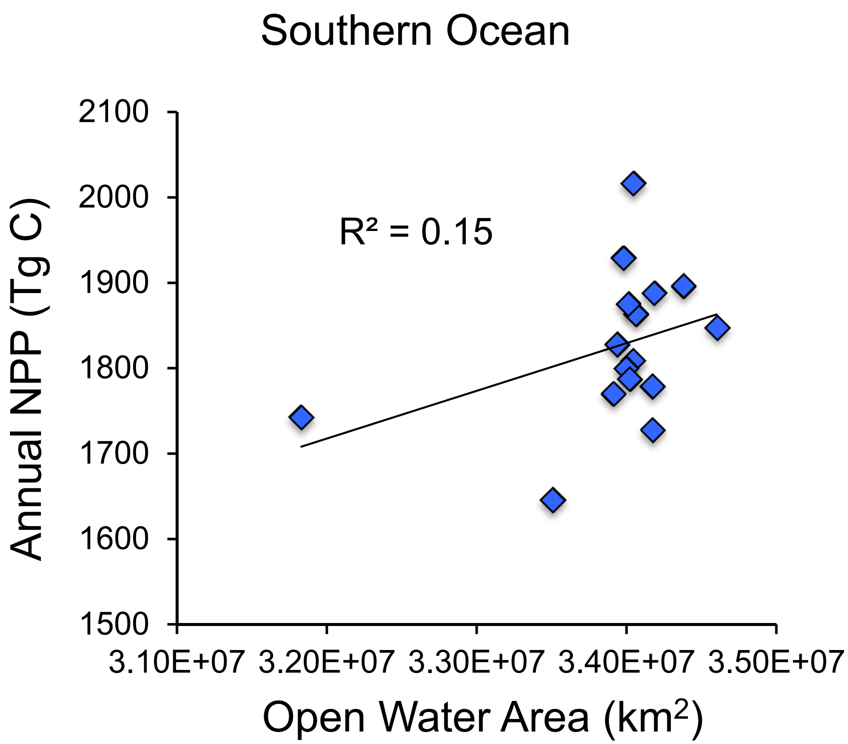


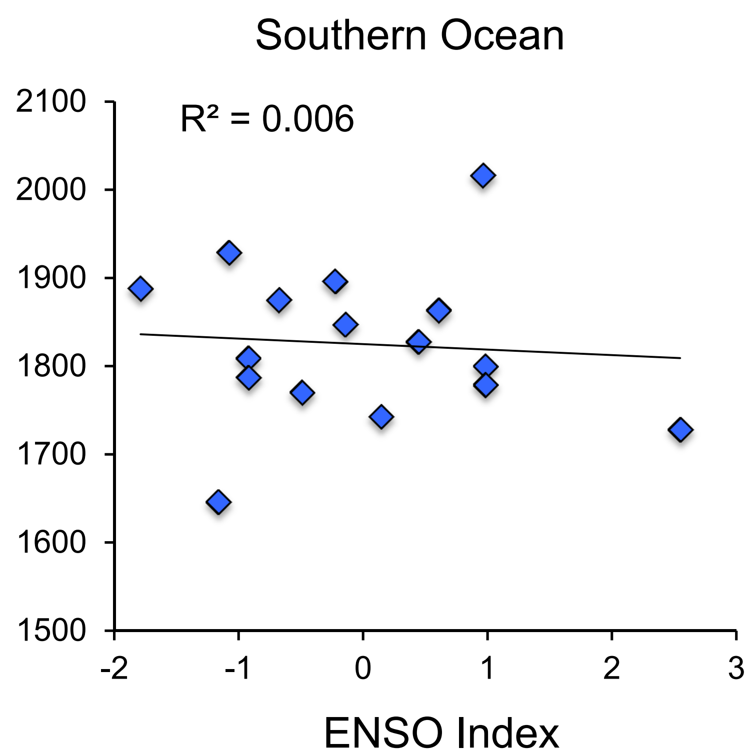
Interannual variability in NPP





Interannual variability in NPP

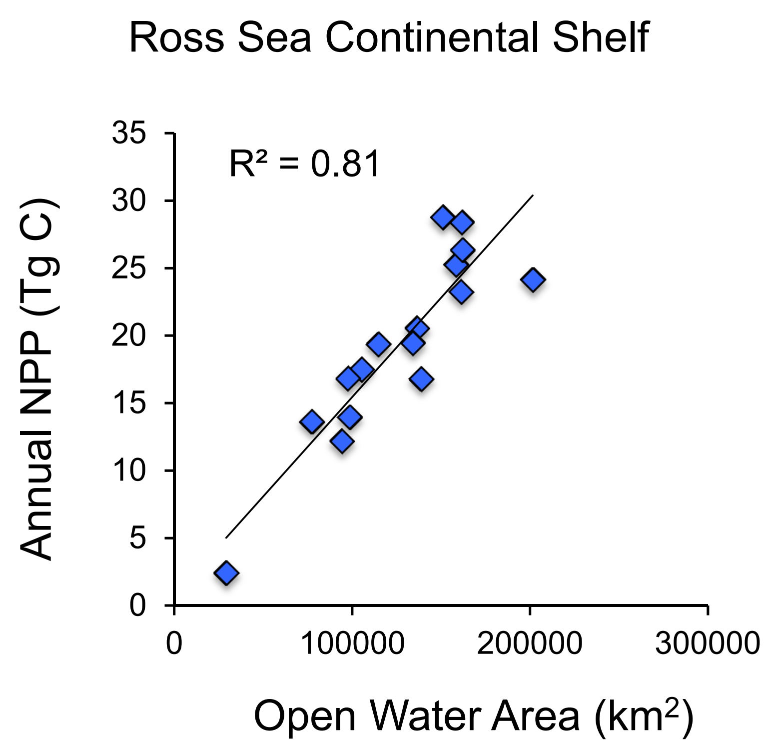




Difficult to predict trajectory of change

Interannual variability in NPP

The exceptions are the continental shelves



The amount of ice cover is very important

(Just like in the Arctic Ocean - which has a large shelf area)

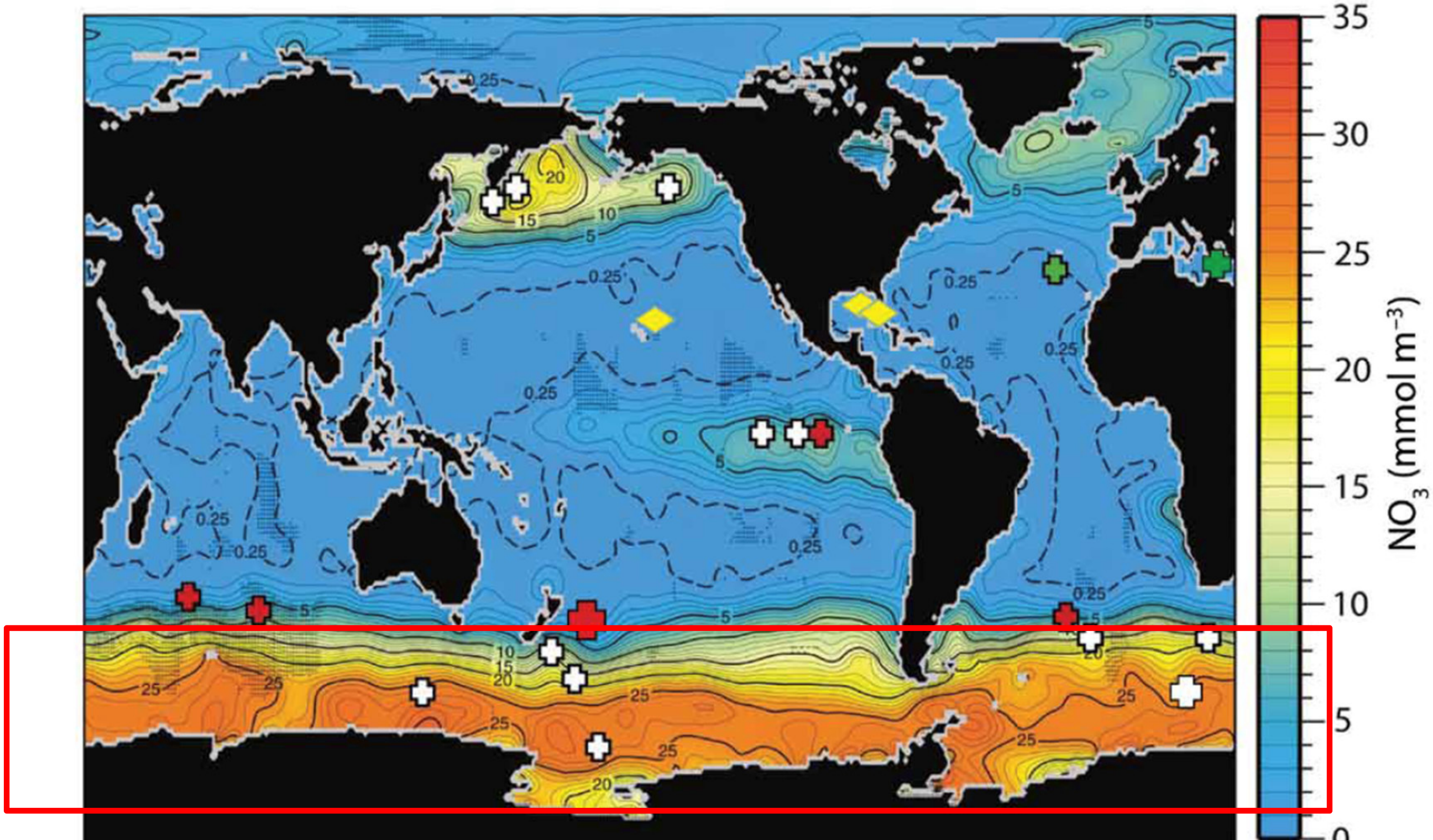
Interannual variability in NPP

Shelves are also the most variable

	Coefficient of Variation	
	Pelagic	Shelf
Weddell Sea	12%	50%
South Indian Ocean	6%	36%
Southwest Pacific Ocean	6%	40%
Ross Sea	7%	34%
Bellingshausen-Amundsen Sea	5%	34%

Controls on NPP

Pelagic Southern Ocean NPP largely limited by iron availability
Evidenced by numerous ocean fertilization experiments



What about continental shelves?

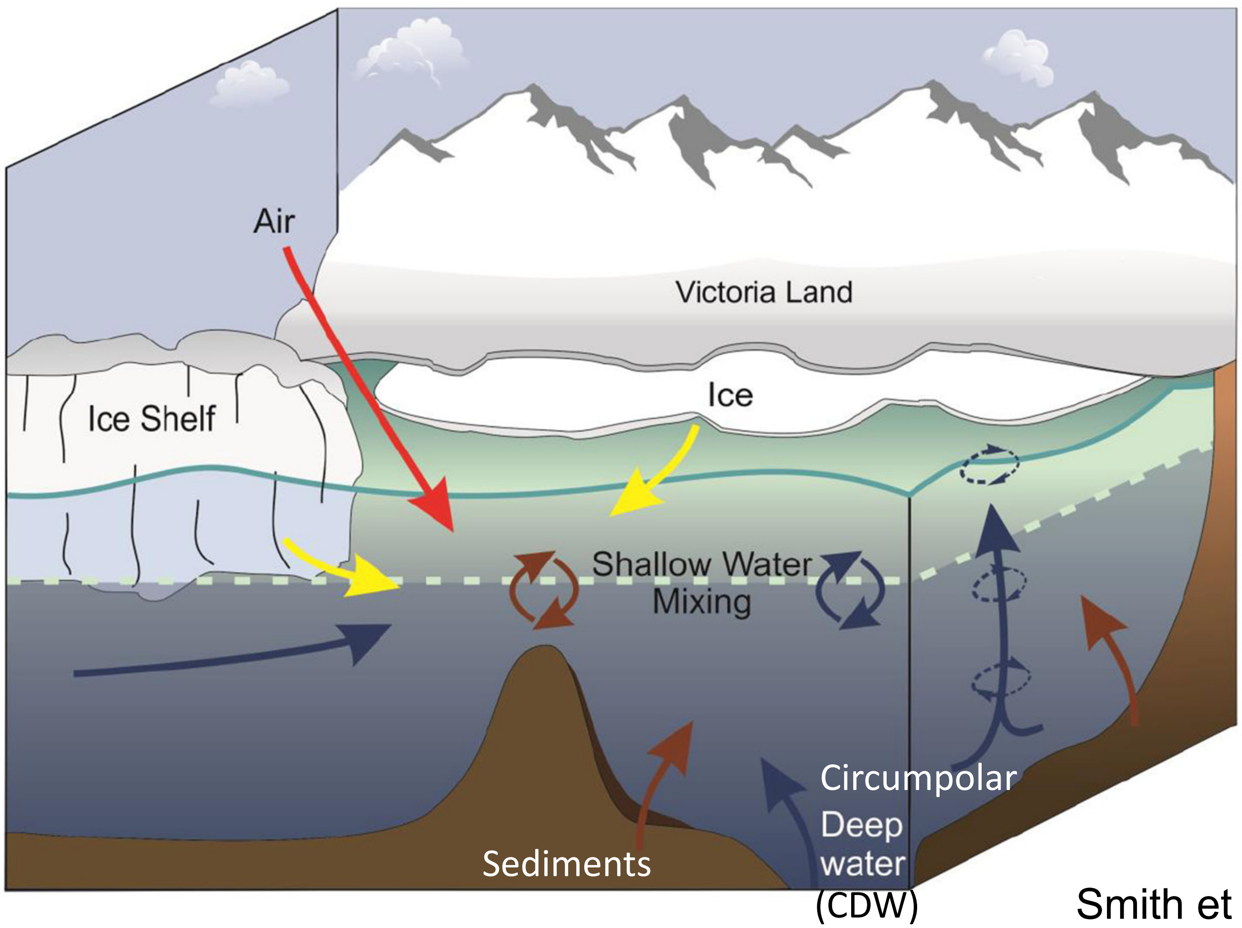
Boyd et al. (2012)

Controls on NPP

Shelves are more light-limited than pelagic Southern Ocean

More sensitive to variations in ice cover

Shelves have higher Fe concentrations – more Fe sources



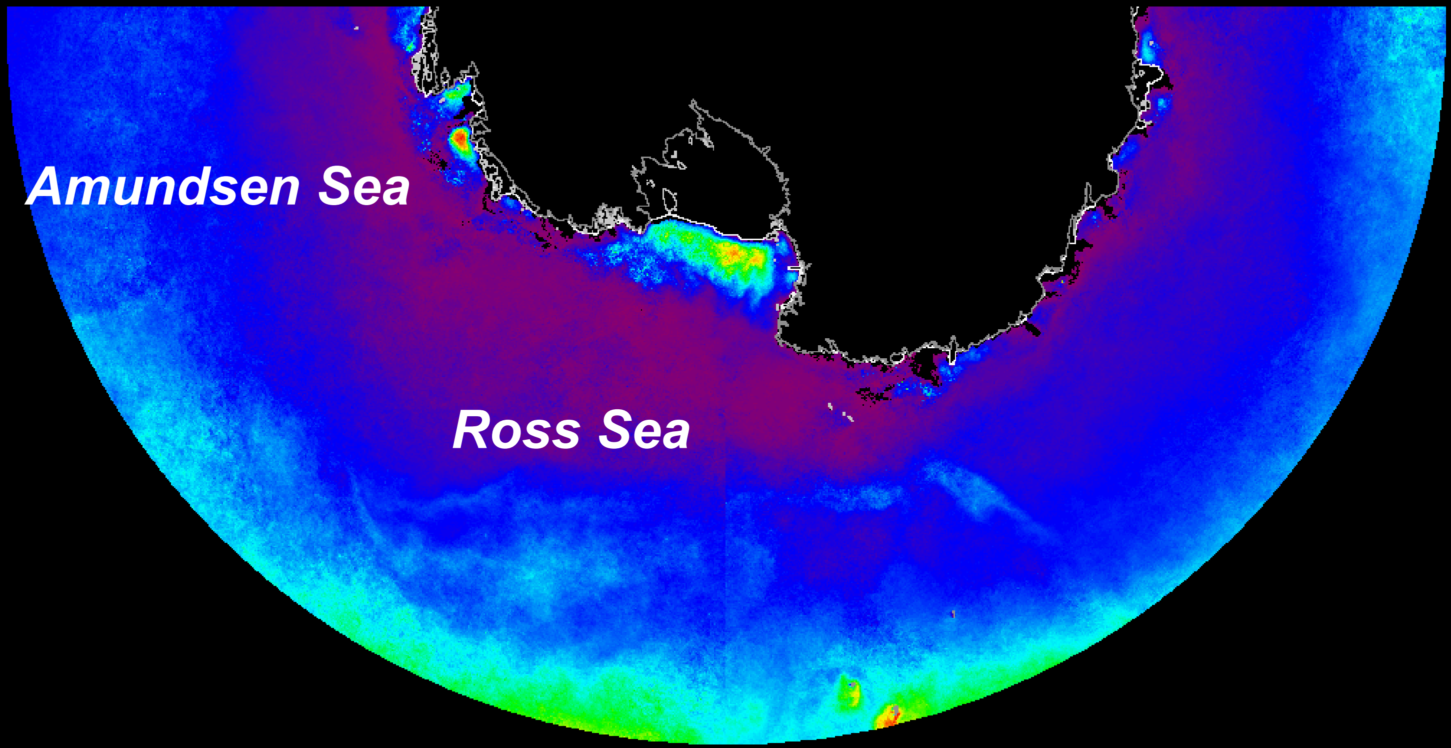
Smith et al. (2012)

Controls on NPP

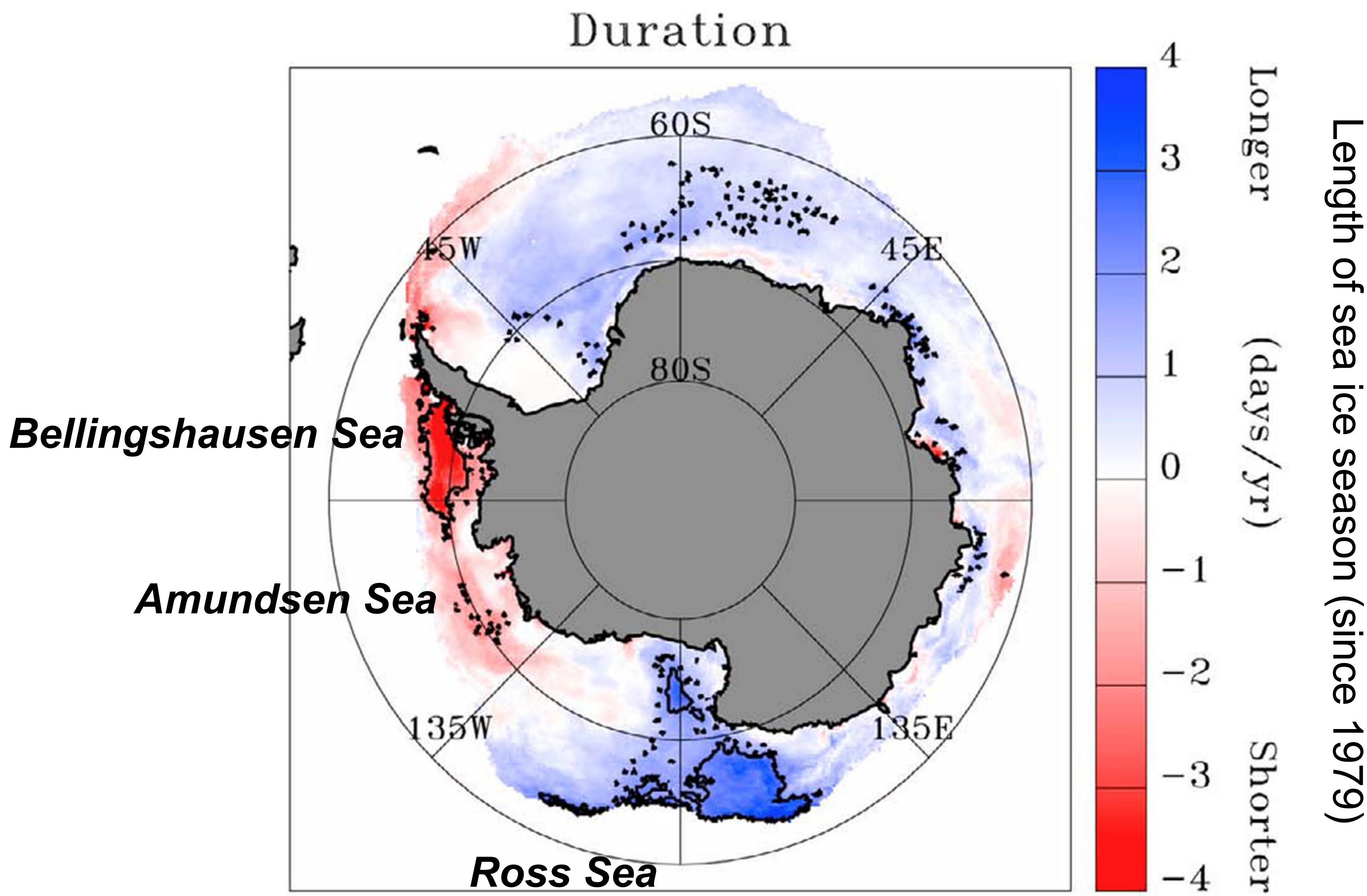
The Ross Sea and Amundsen Sea

Sea ice cover changes

Phytoplankton responses to Fe



Changes in Sea Ice Cover



Stammerjohn et al. (2012)

Changes in Sea Ice Cover

Influenced by Southern Annular Mode (SAM)

Positive phase:

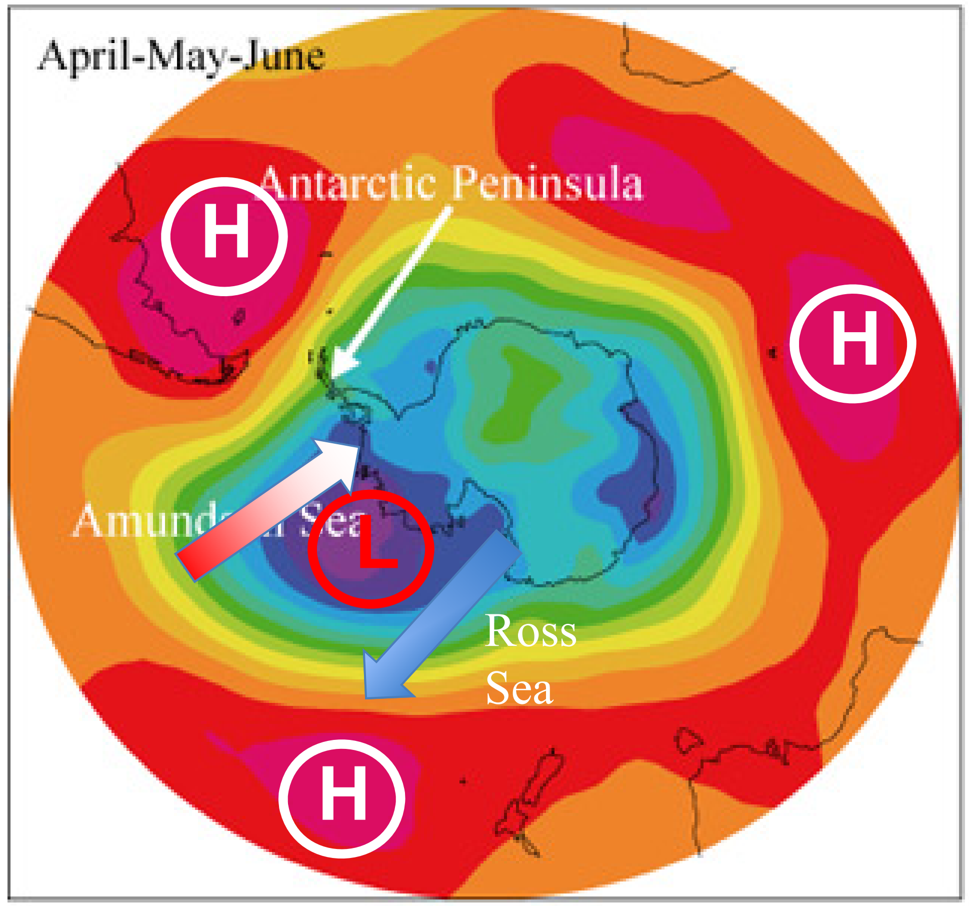
Cold southerly winds blow out of Ross Sea

More sea ice

Warm northerly winds blow into Amundsen Sea

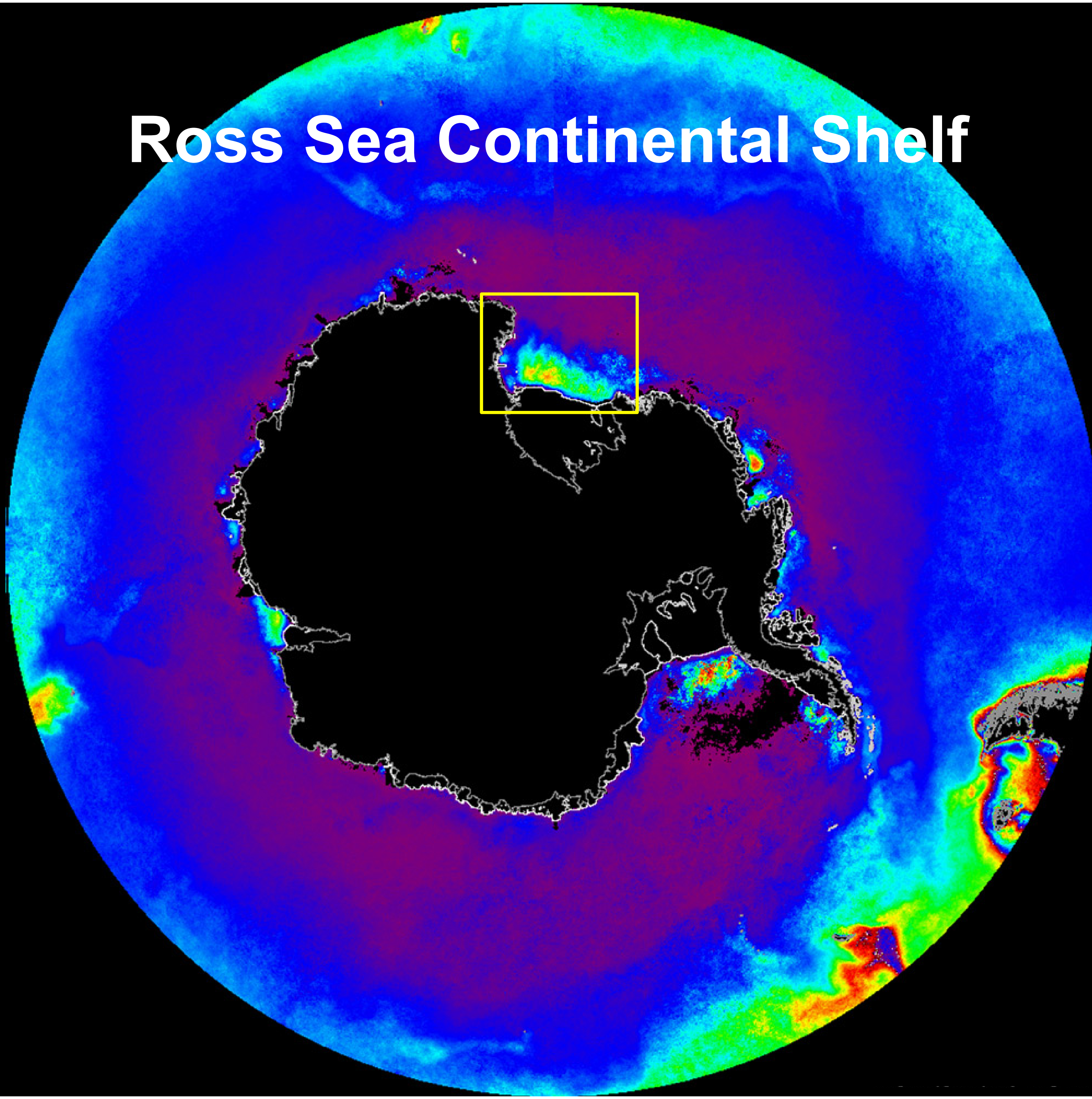
Less sea ice

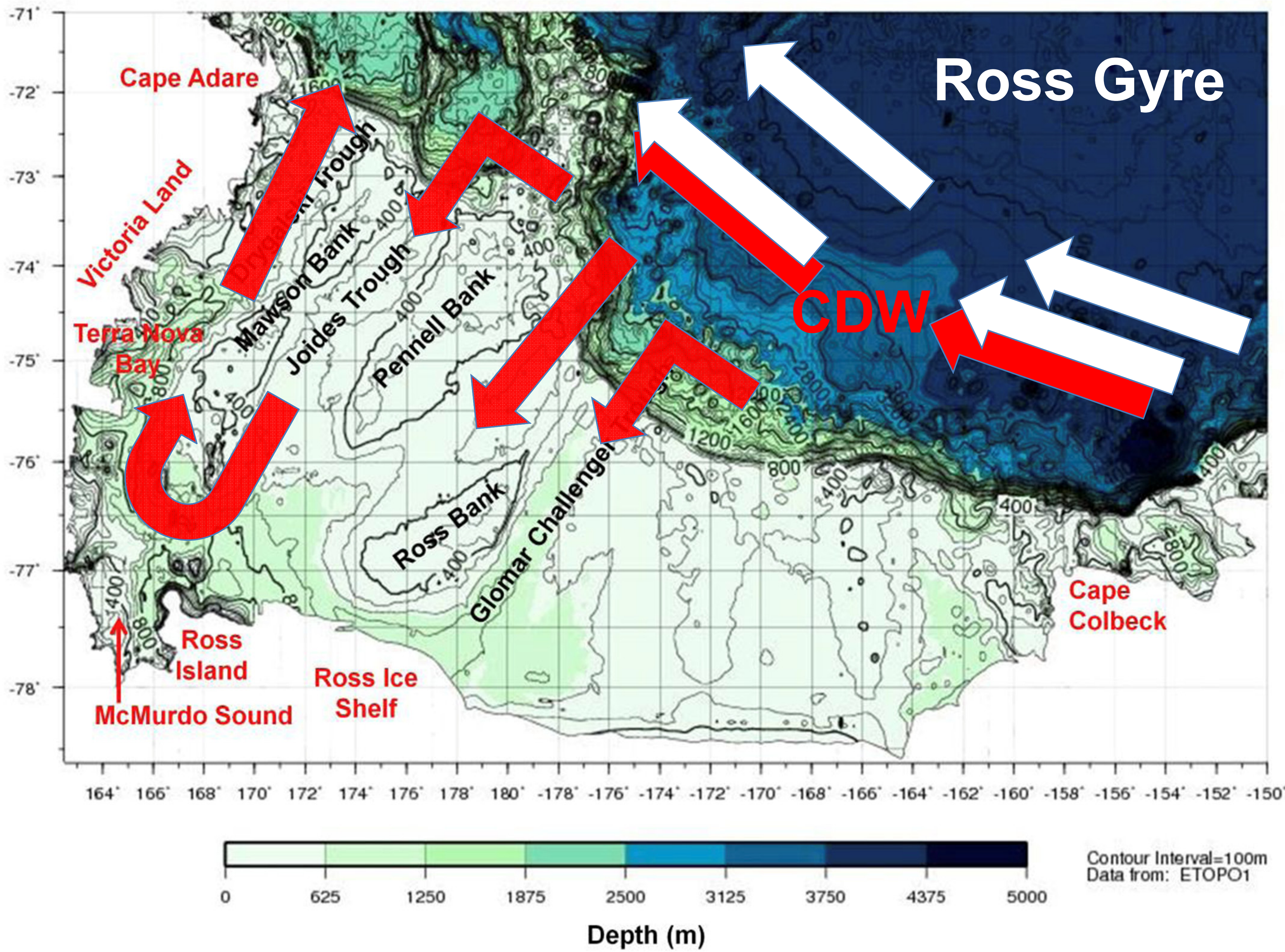
+ SAM



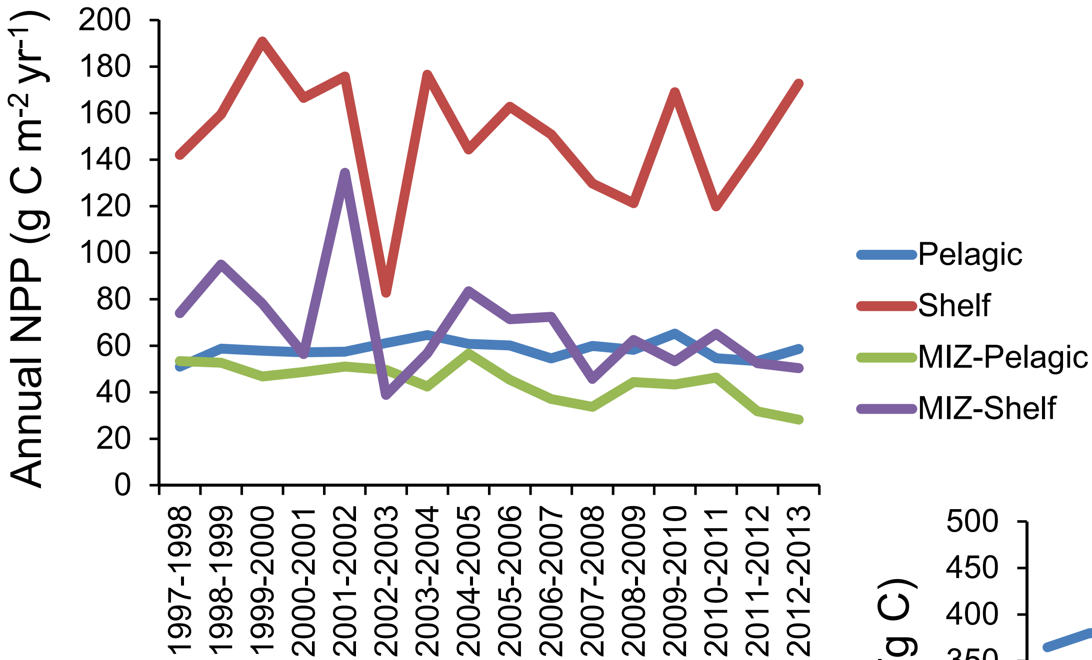
+ SAMs are becoming more common

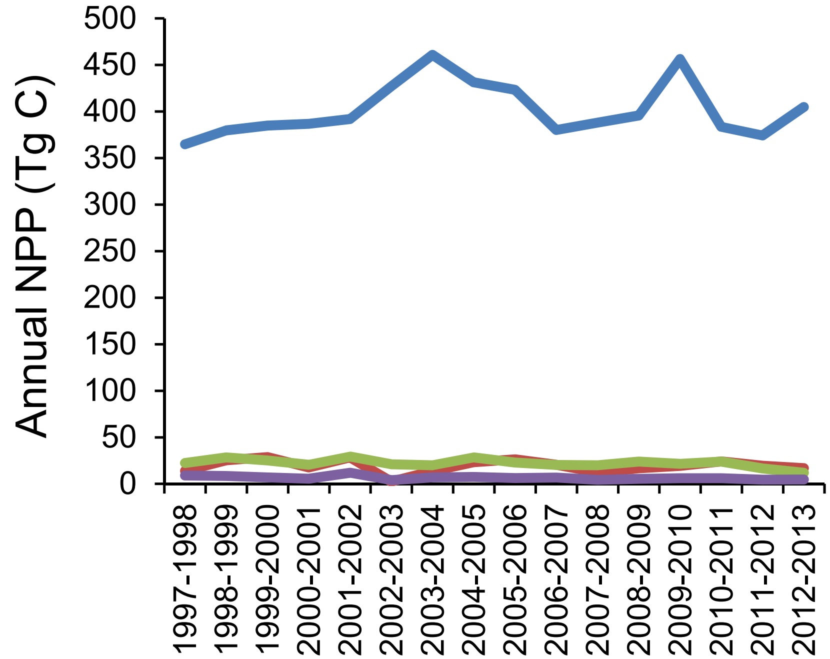
Ross Sea Continental Shelf




Ross Gyre
CDW
Cape Adare
Victoria Land
Terra Nova Bay
Ross Island
McMurdo Sound
Ross Ice Shelf
Cape Colbeck
Mawson Bank
Joides Trough
Pennell Bank
Ross Bank
Glomar Challenger
Depth (m)
Contour Interval=100m
Data from: ETOPO1

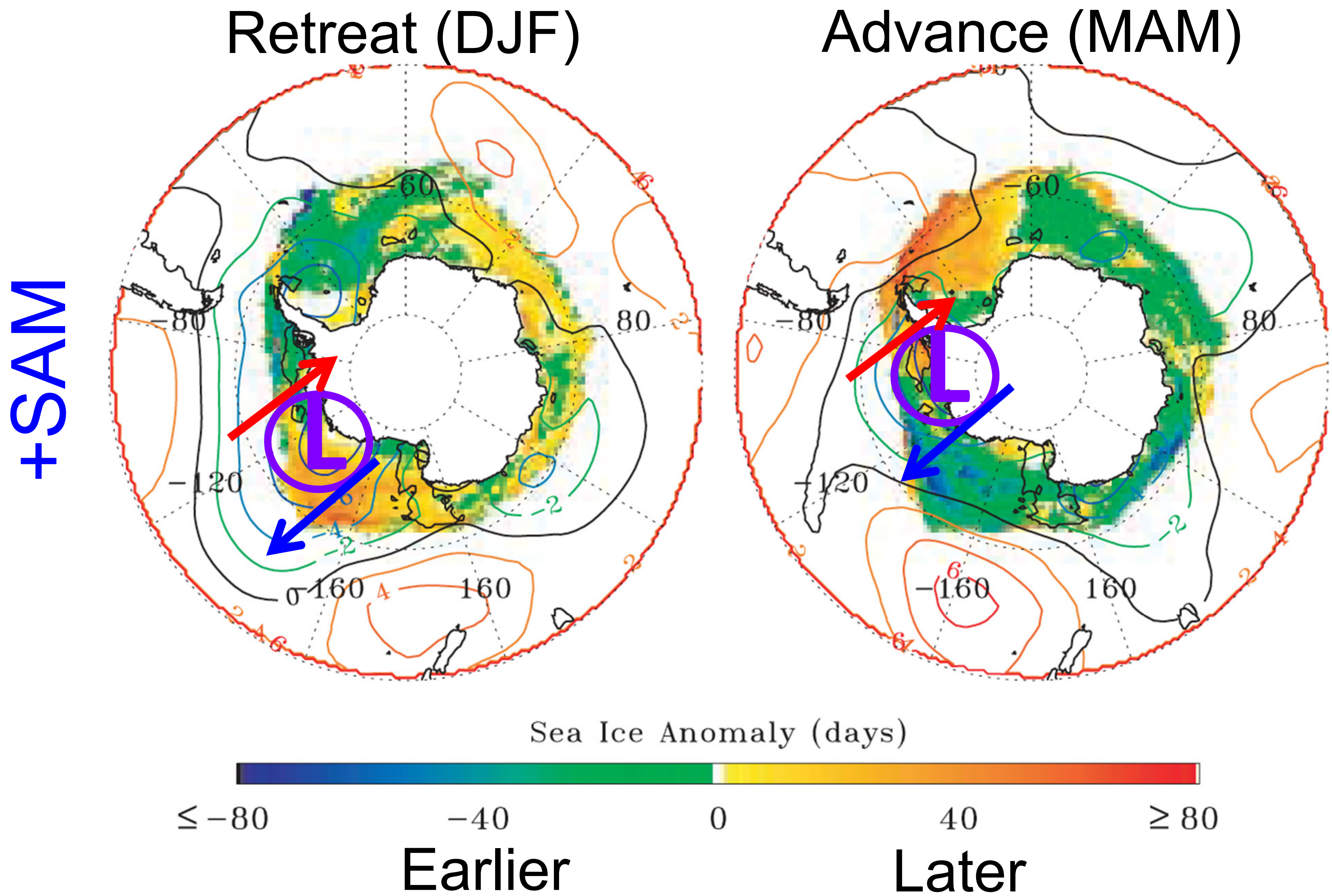
Ross Sea


Annual NPP (g C m-2 yr-1)
200
180
160
140
120
100
80
60
40
20
0
1997-1998
1998-1999
1999-2000
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
2007-2008
2008-2009
2009-2010
2010-2011
2011-2012
2012-2013
Pelagic
Shelf
MIZ-Pelagic
MIZ-Shelf


Annual NPP (Tg C)
500
450
400
350
300
250
200
150
100
50
0
1997-1998
1998-1999
1999-2000
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
2007-2008
2008-2009
2009-2010
2010-2011
2011-2012
2012-2013

Ross Sea

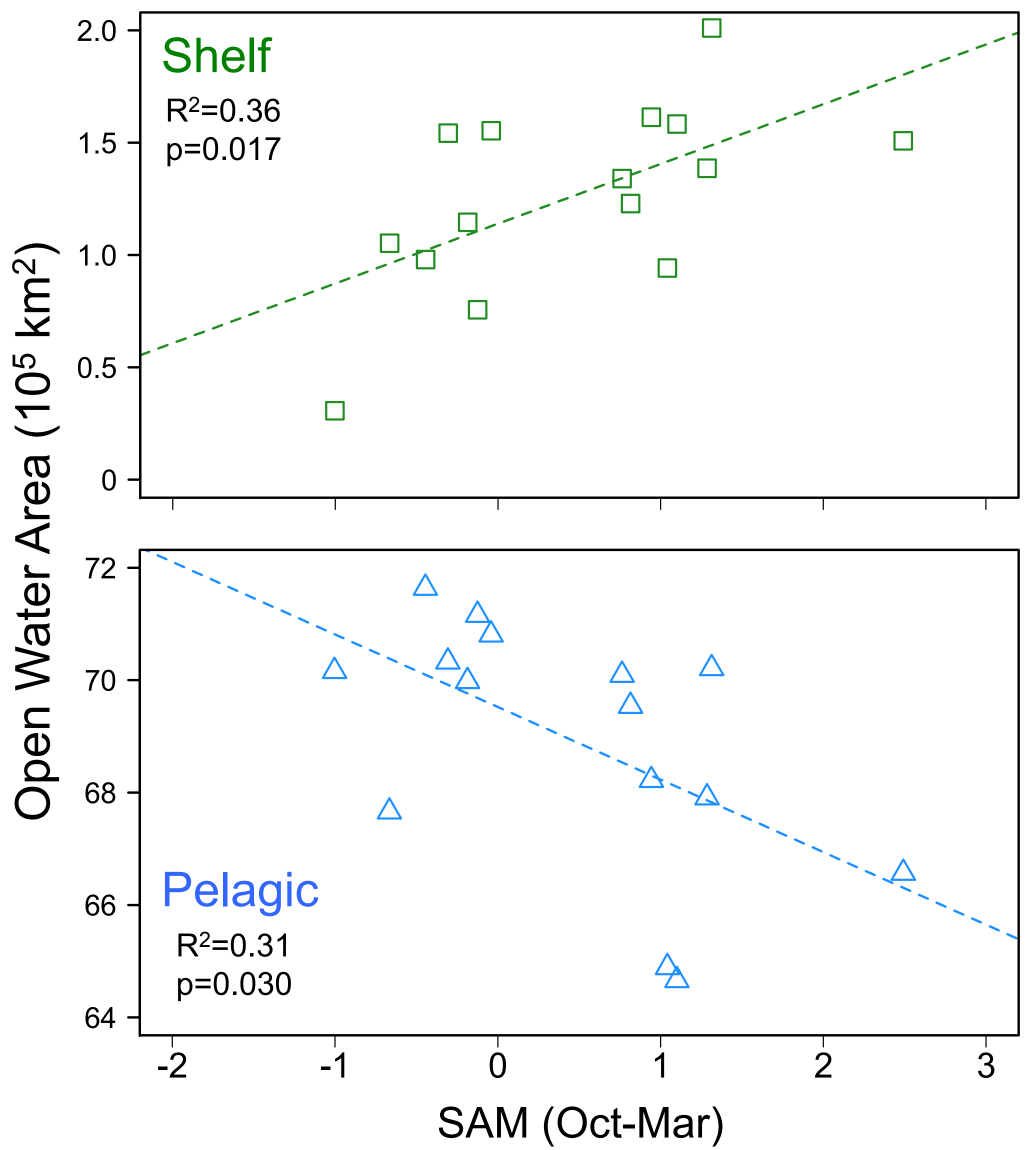
Shelf and pelagic respond differently to SAM



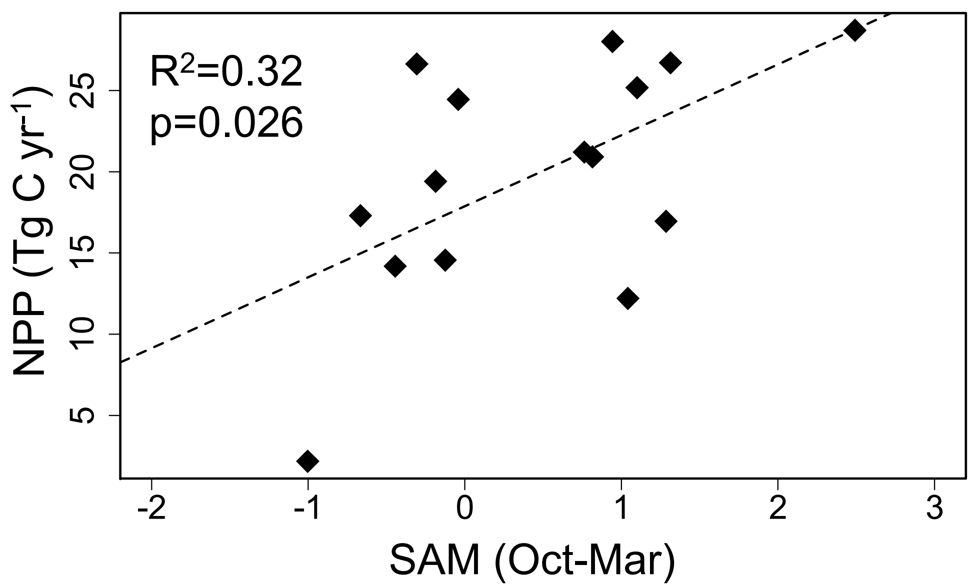
Ross Sea

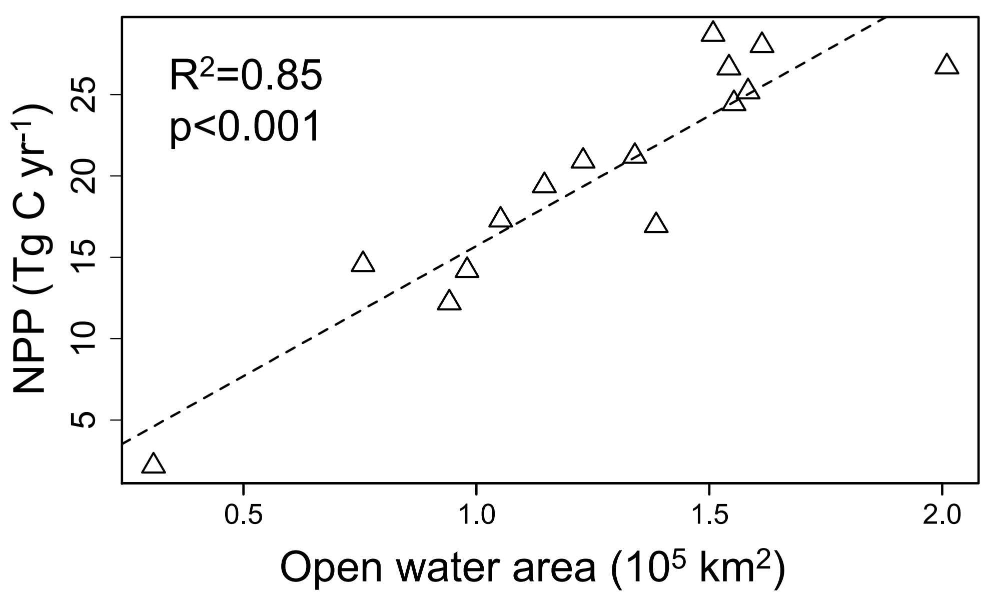
Stronger southerly winds blow ice off shelf when SAM is more positive

Winds are cold so ice doesn't melt and it piles up in pelagic



Ross Sea





NPP on the shelf significantly correlated with SAM

Higher NPP when SAM is more positive

Due to:
Strong relationship between open water area and NPP

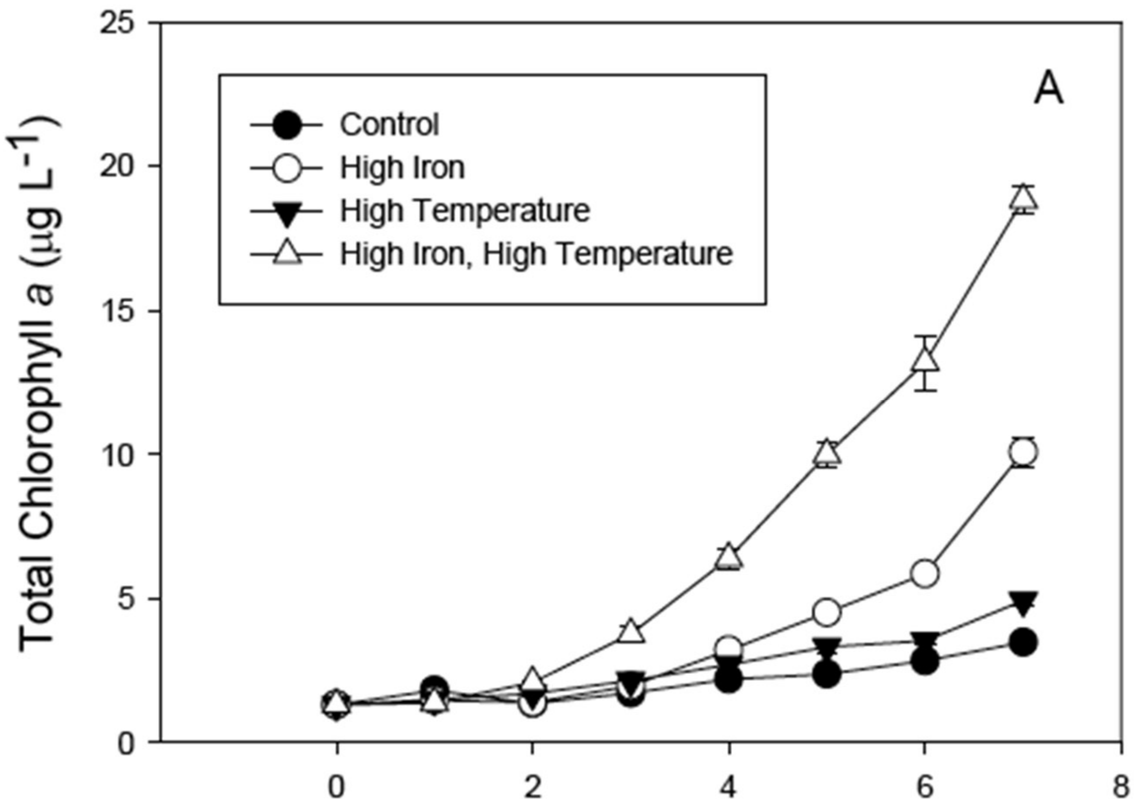
Less ice = More NPP

Ross Sea

Response to Fe?

Iron limits phytoplankton growth in Ross Sea

Especially at high temperature



Rose et al. (2009)

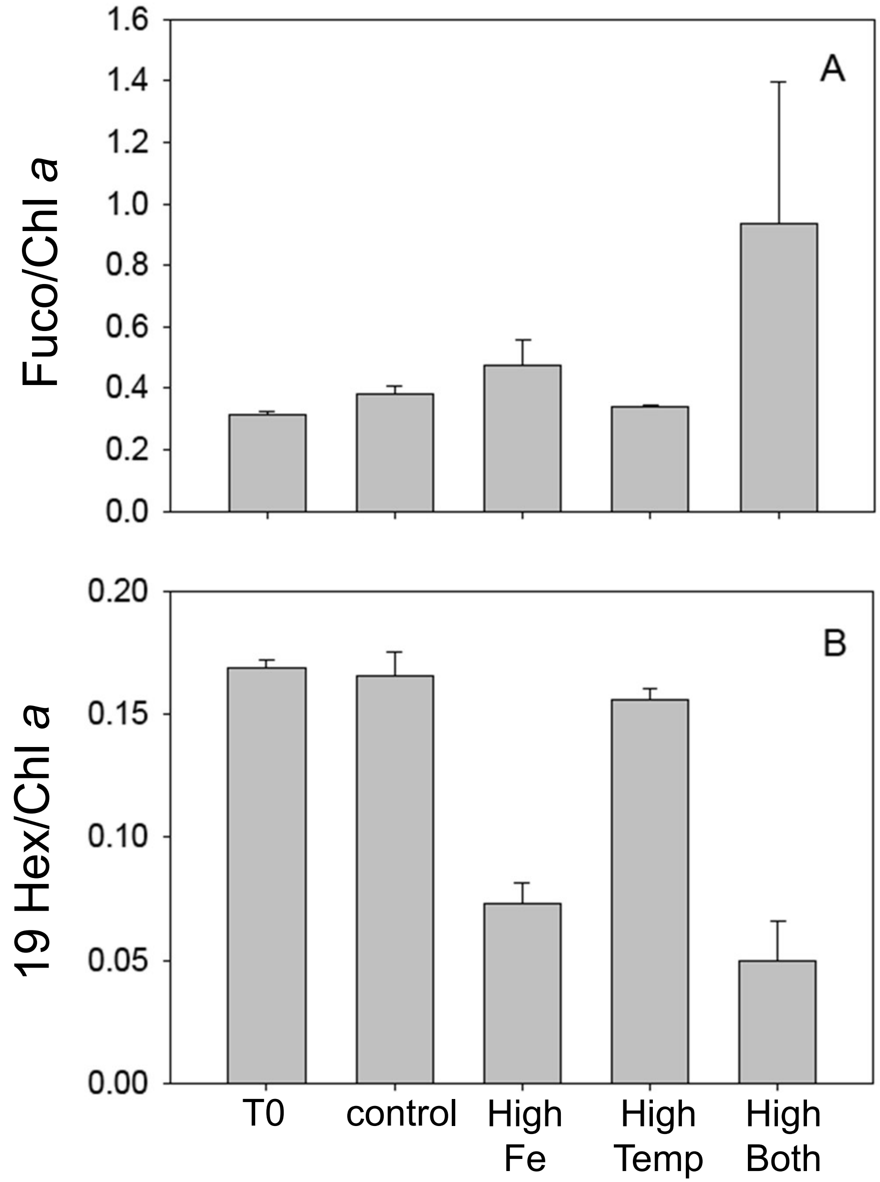
Ross Sea

Response to Fe?

Diatoms come to dominate community

Phaeocystis antarctica declines, especially at high temperature

Are only diatoms Fe-limited?



Rose et al. (2009)

Ross Sea

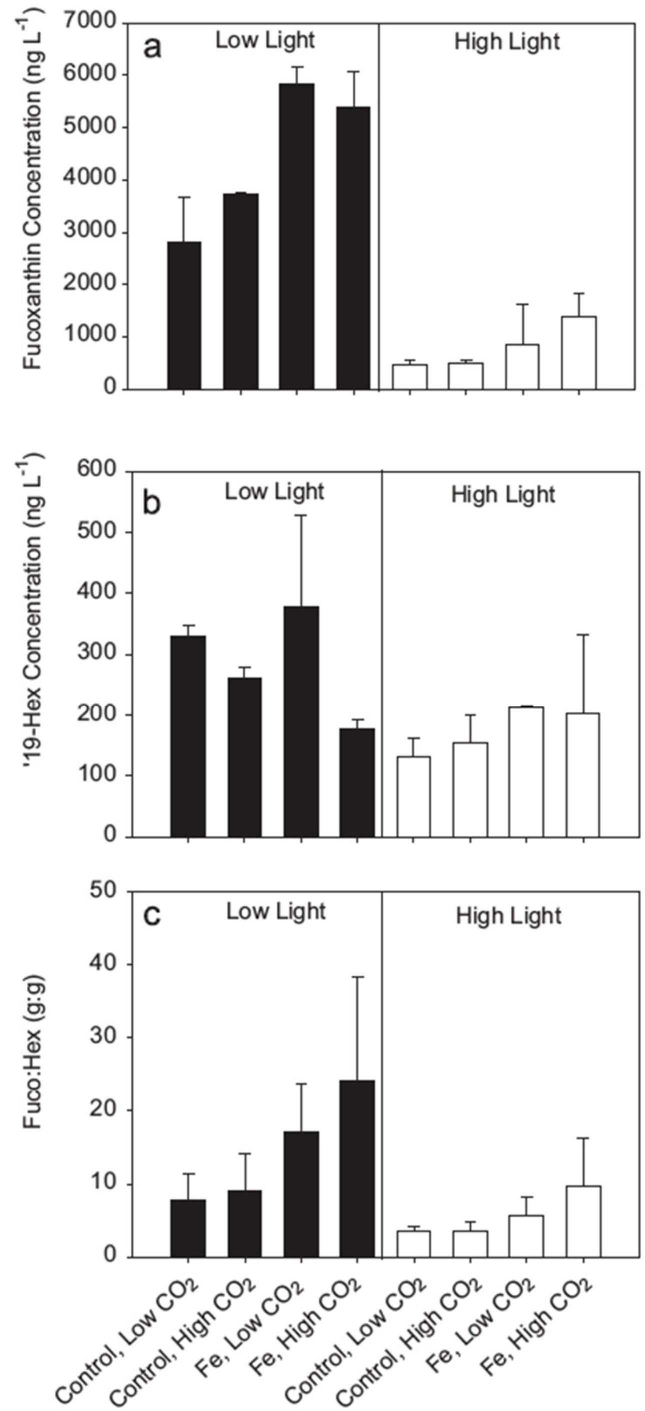
Response to Fe?

Diatoms respond strongly to Fe addition at both high and low light

Phaeocystis did not respond to Fe additions

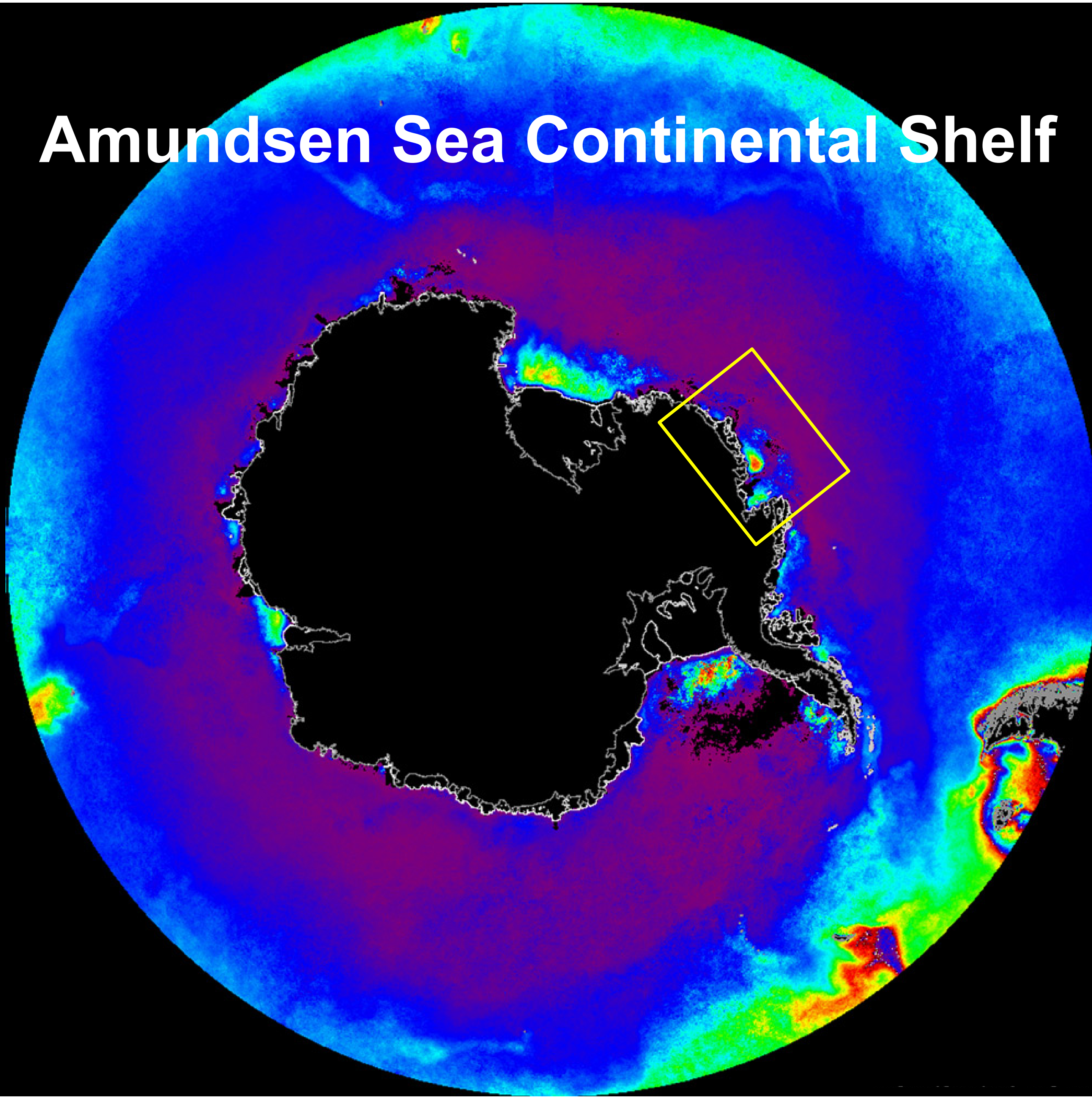
Apparently, only diatoms are Fe-limited in Ross Sea

There is no impact of CO_2 concentration

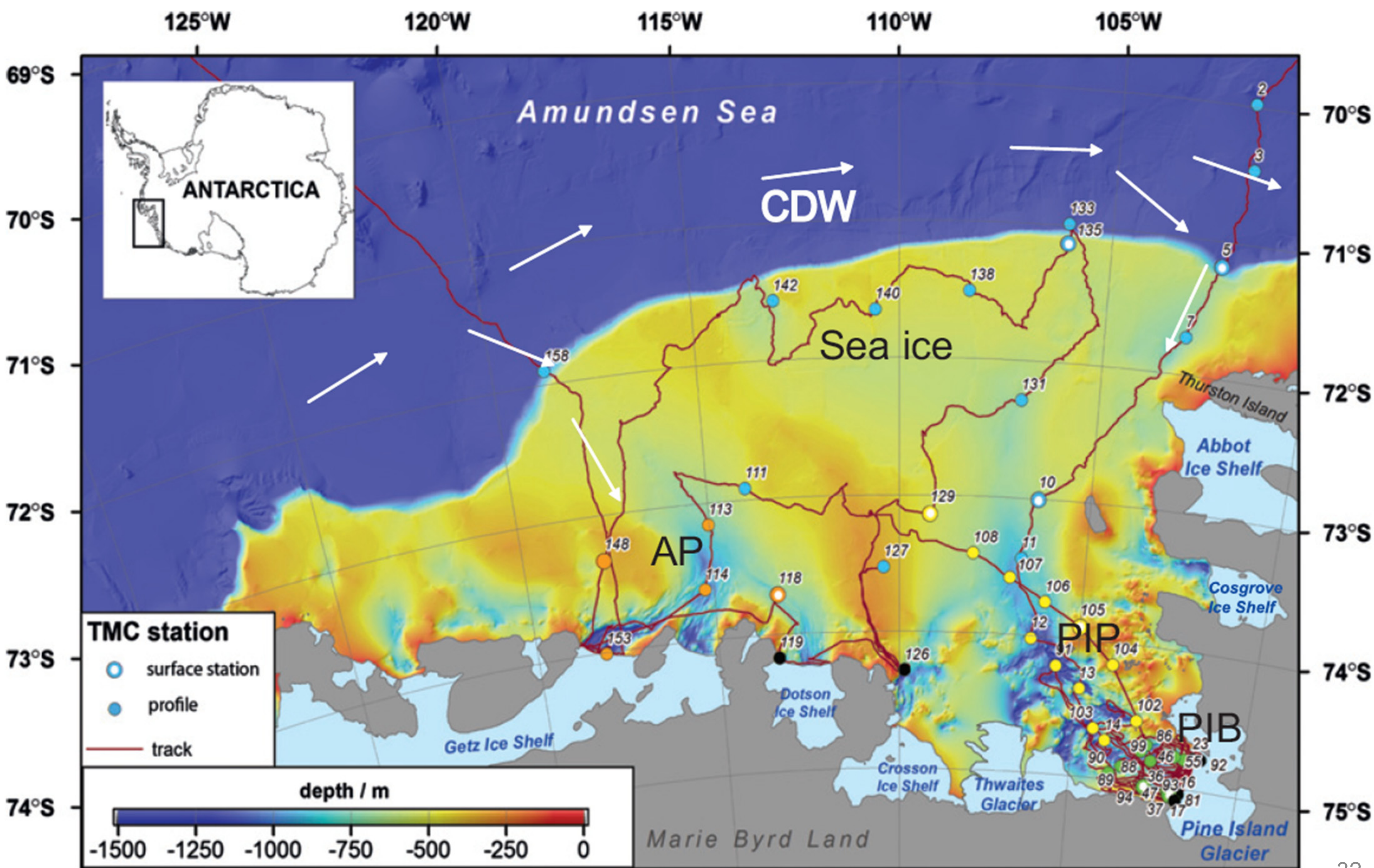


Feng et al. (2010)

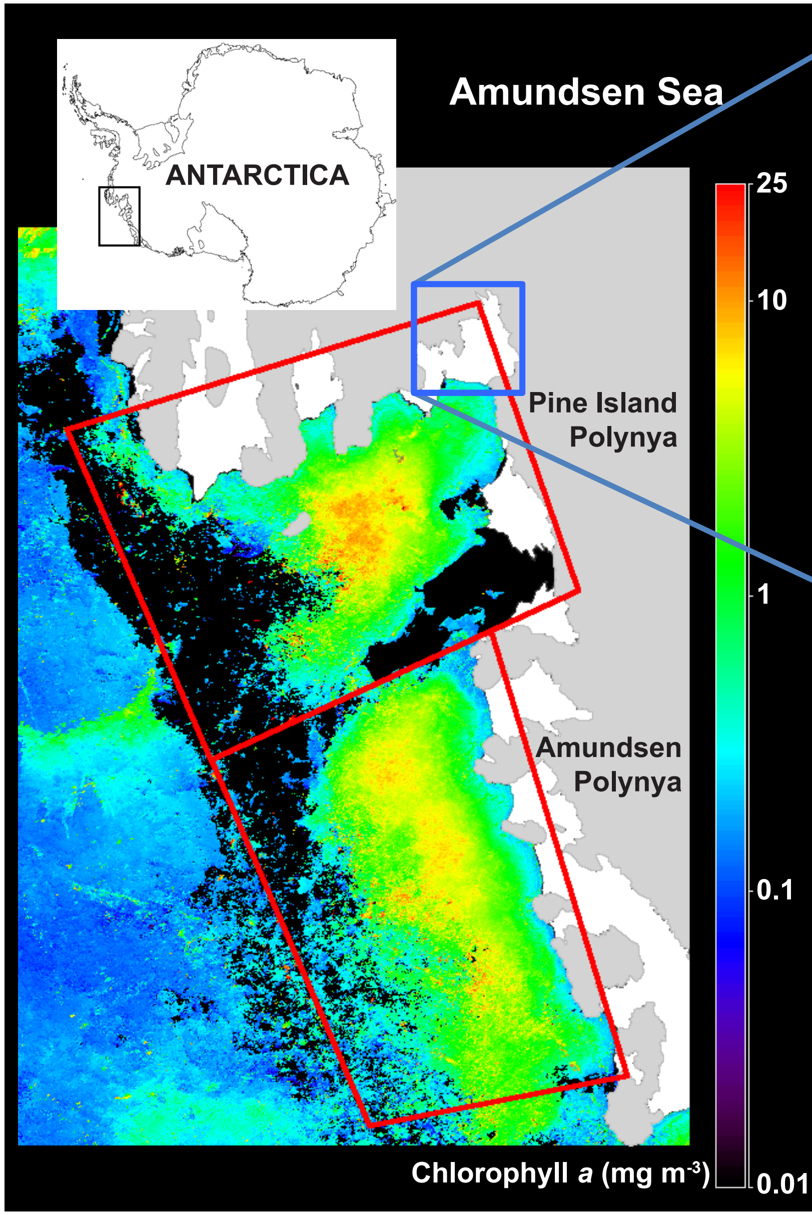
Amundsen Sea Continental Shelf

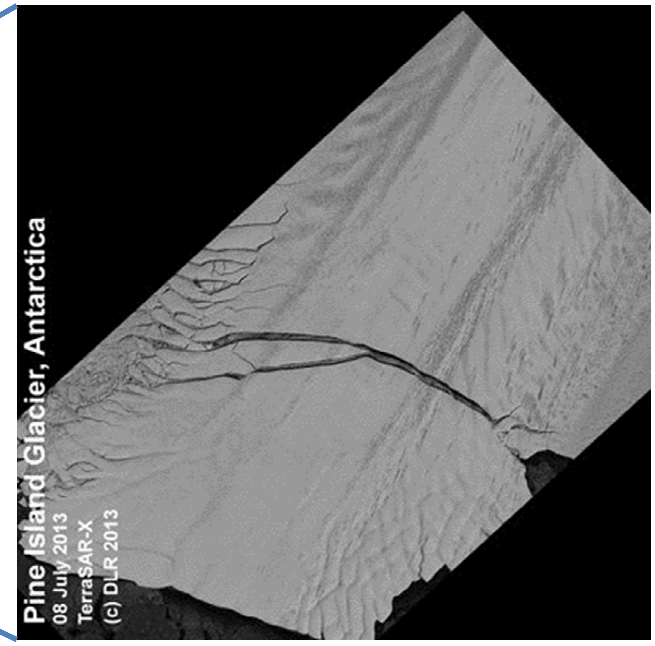


Amundsen Sea



Amundsen and Pine Island polynyas





Pine Island Glacier (PIG) just calved in July 2013

720 km^2

Amundsen Sea

Ice edge

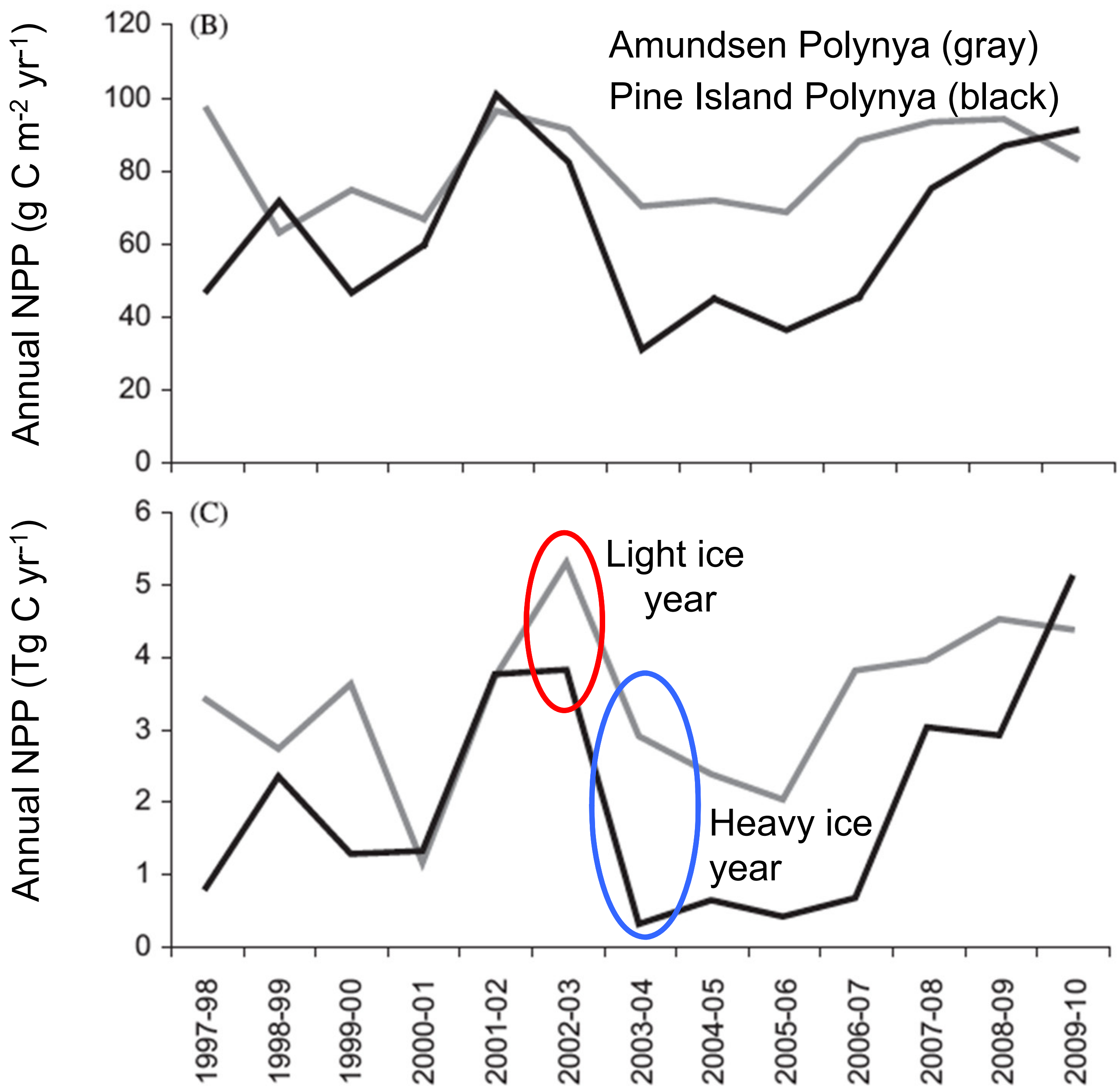
Amundsen Polynya

Photo: Dave Munroe

Highest chlorophyll *a* concentrations in Southern Ocean

Intense blooms dominated by colonial *Phaeocystis antarctica*

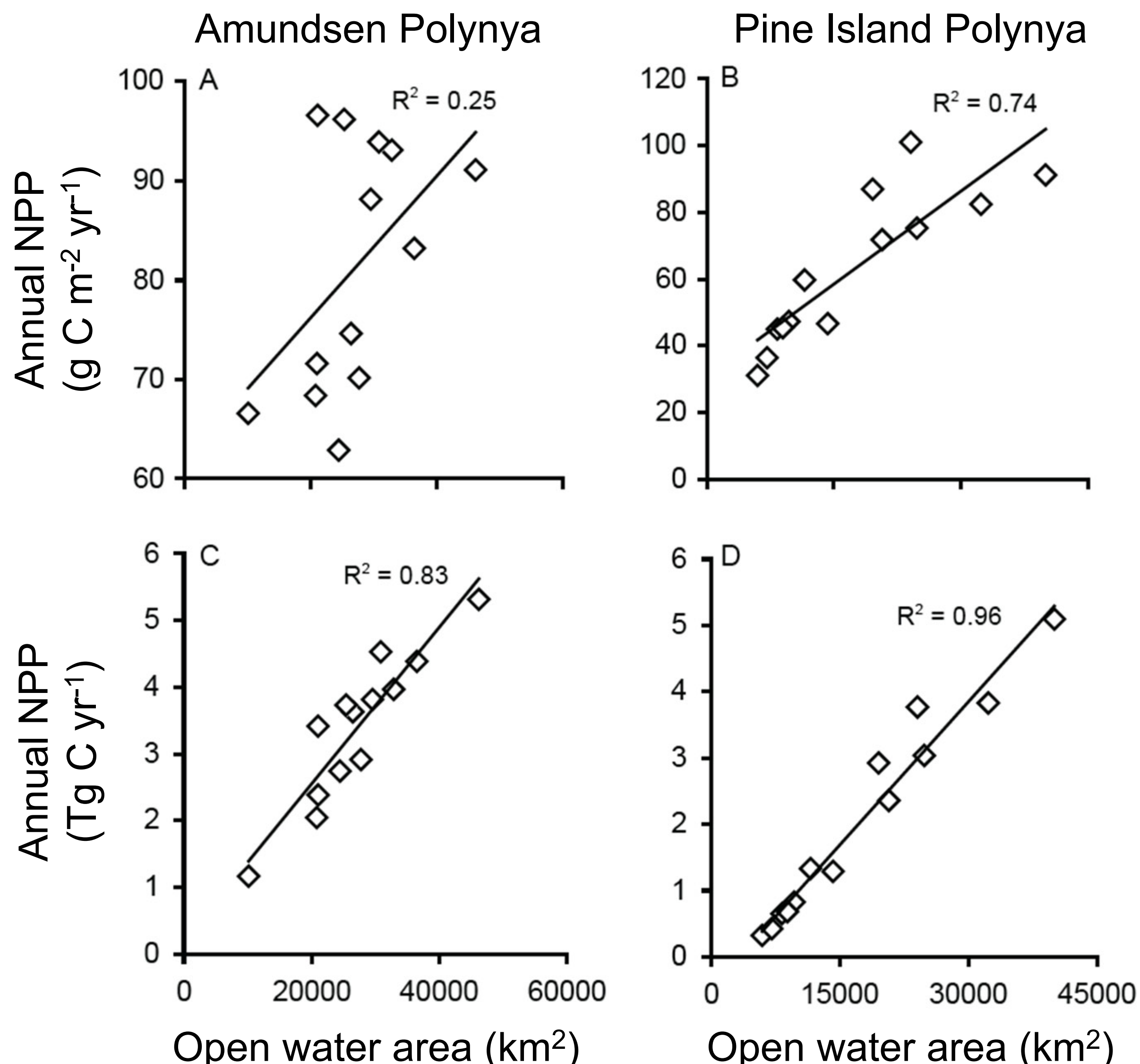
Amundsen Sea



Arrigo et al (2012)

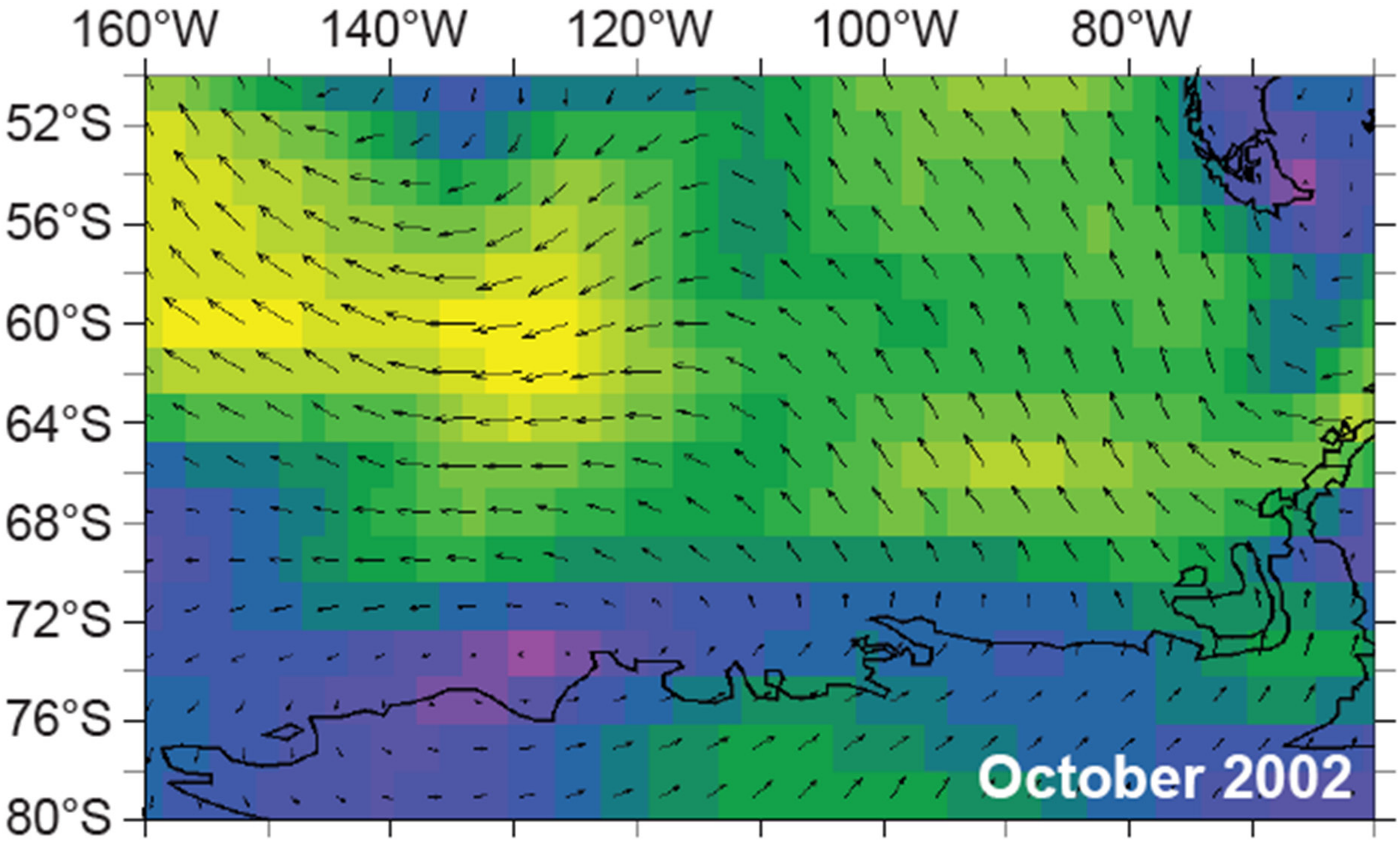
Amundsen Sea

Amount of annual NPP controlled by sea ice cover



Arrigo et al (2012)

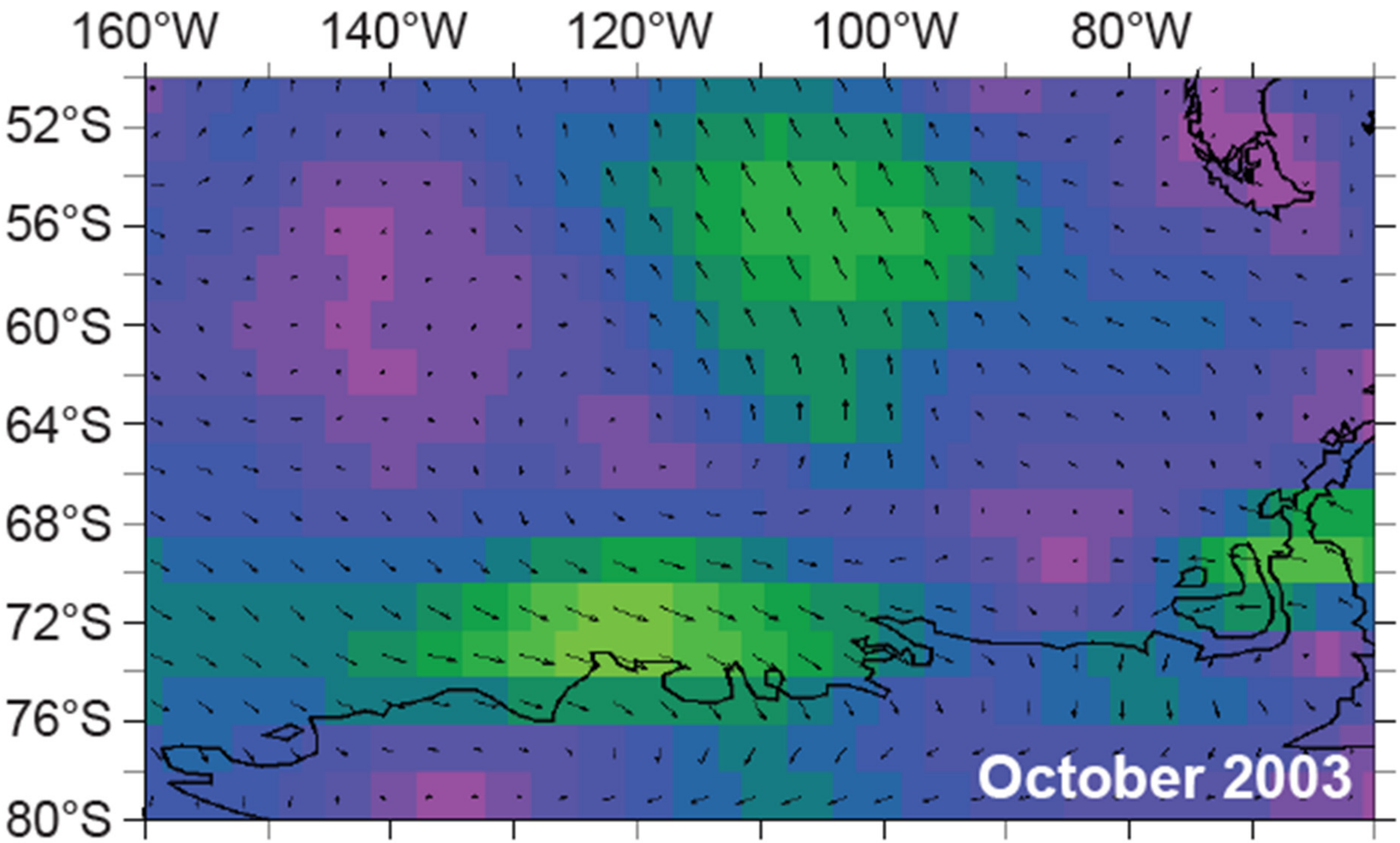
Amundsen Sea



Arrigo et al (2012)

Light ice year - Negative SAM
Cold winds blow offshore – clear out sea ice from coast

Amundsen Sea



Arrigo et al (2012)

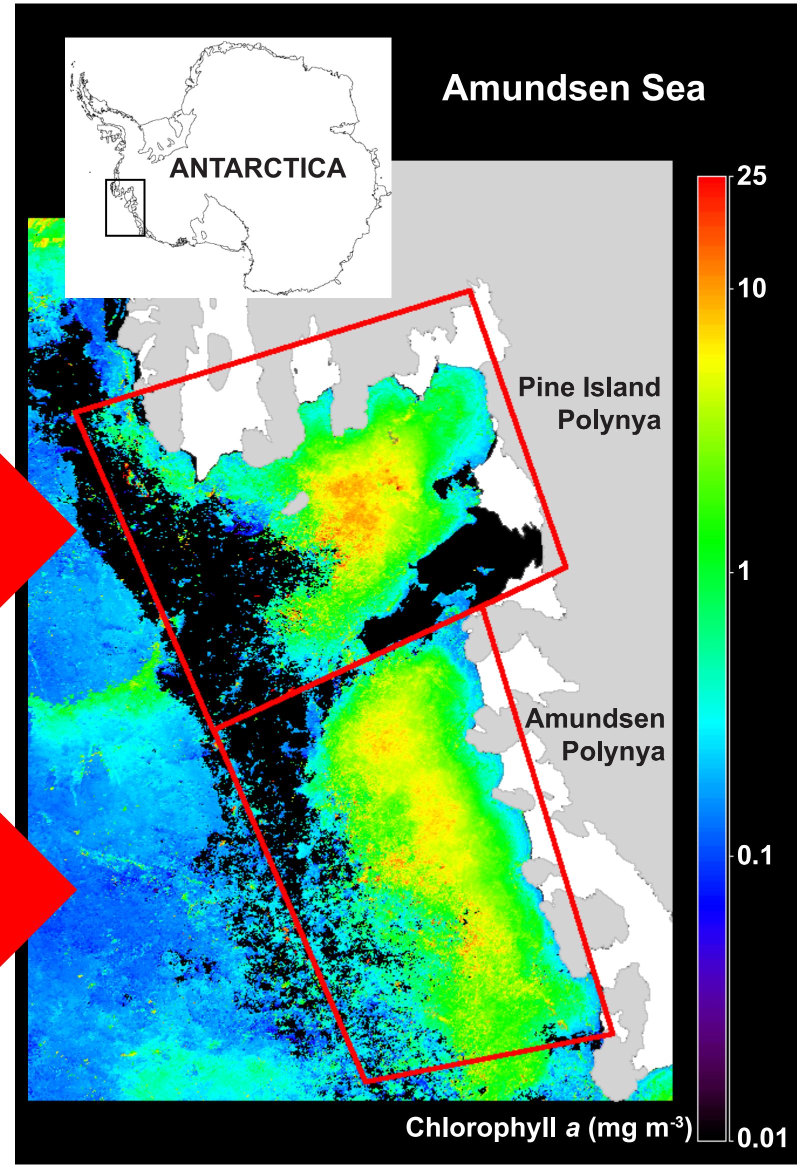
Positive SAM year
Heavy sea ice – Much lower productivity

Amundsen Sea

Response to Fe?

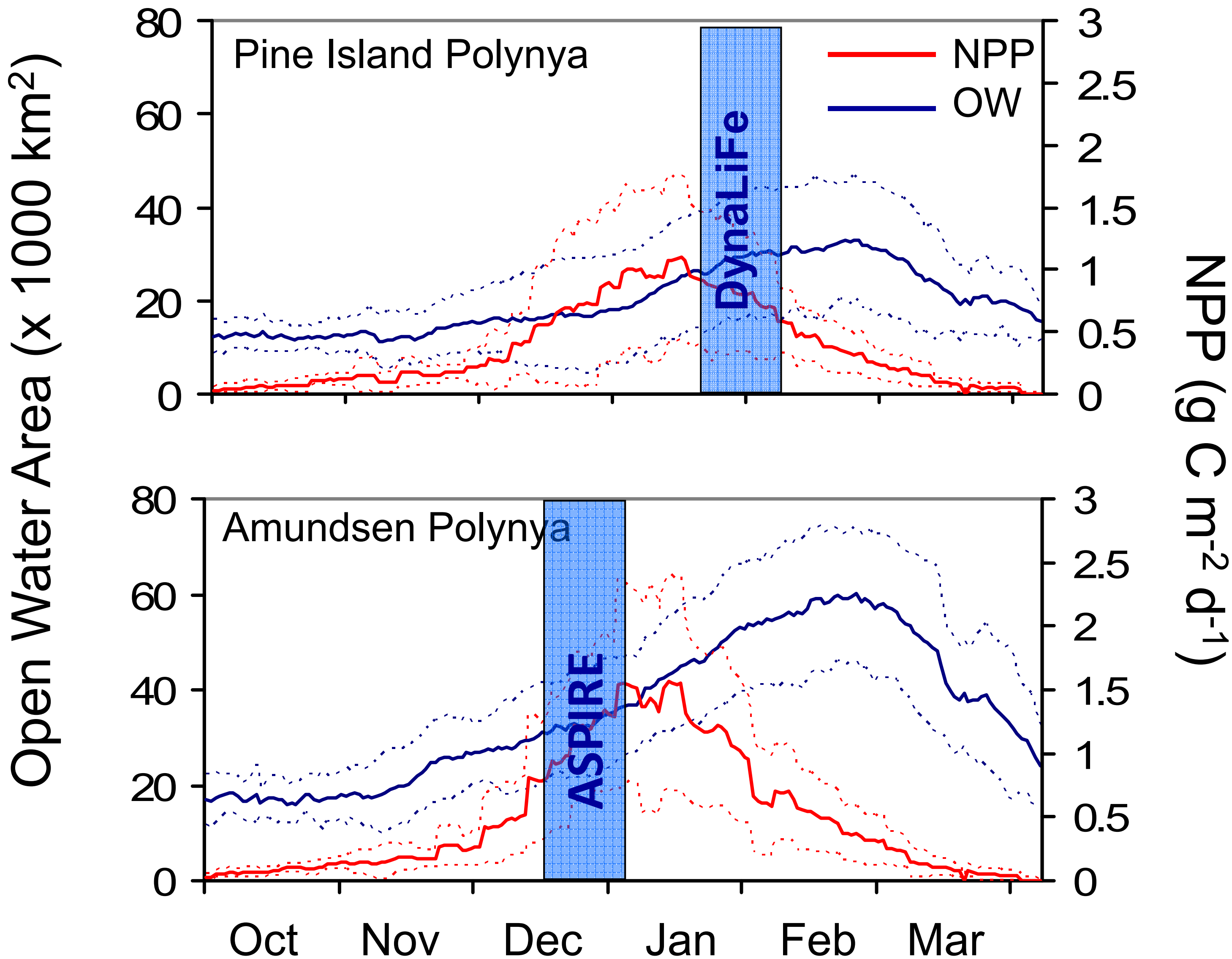
DynaLiFe
13 Jan – 18 Feb 2009

ASPIRE
14 Dec 2010 – 5 Jan 2011



Arrigo et al (2012)

Satellite Primary Production

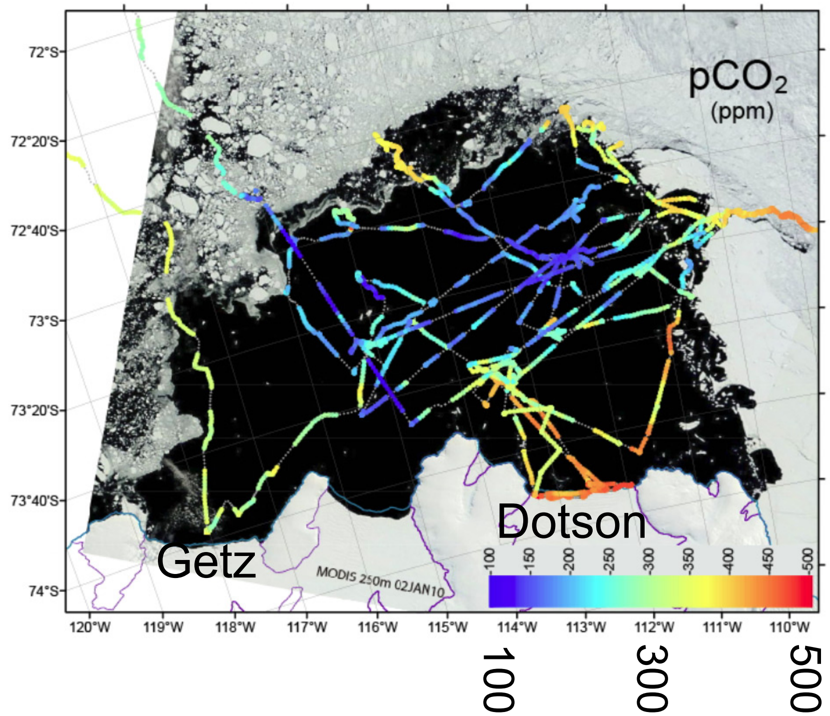


Arrigo et al (2012)

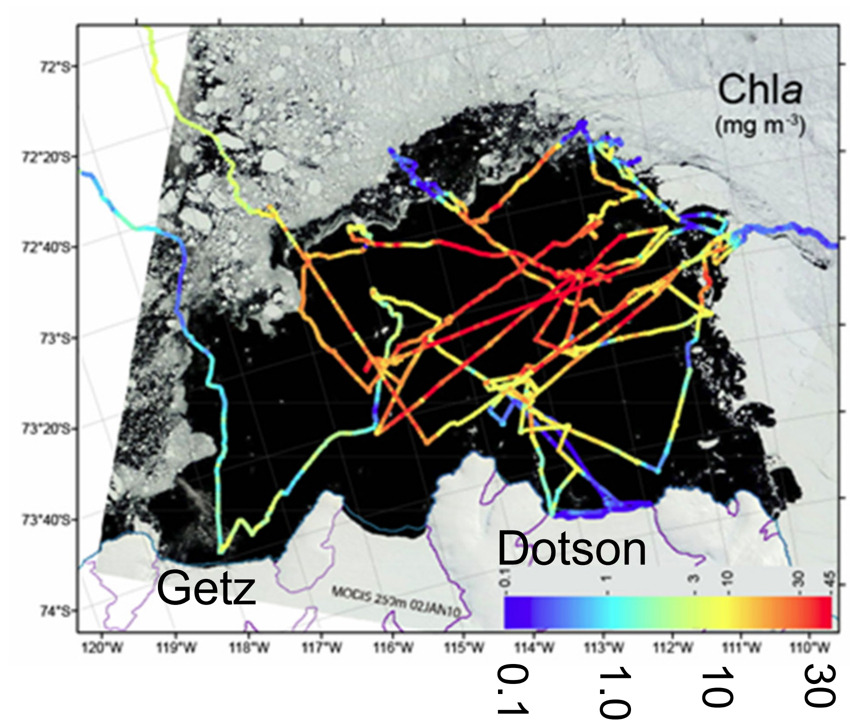
Amundsen Sea – Amundsen Polynya

ASPIRE

pCO_2 (ppm)



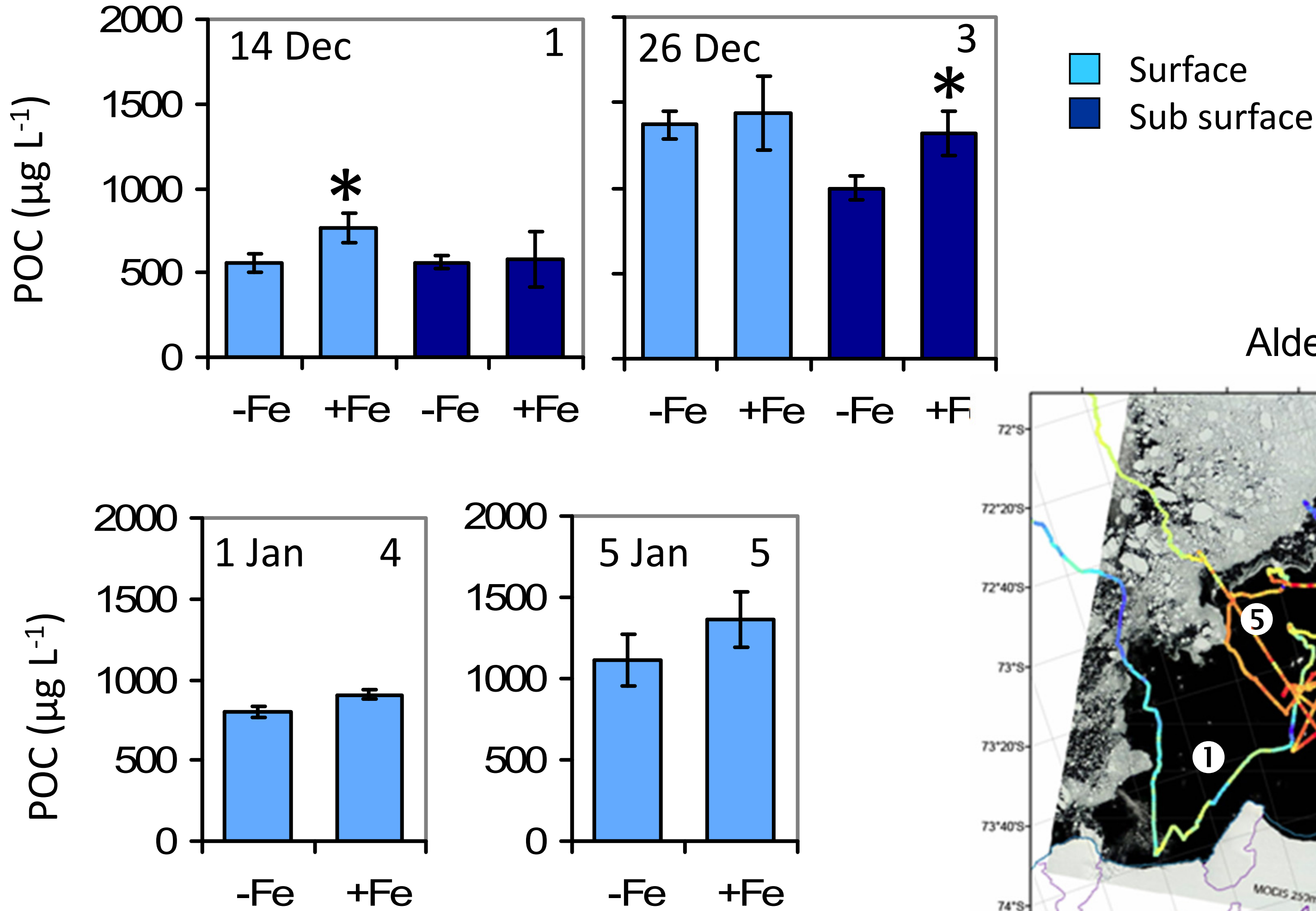
Chl *a* (µg L^{-1})



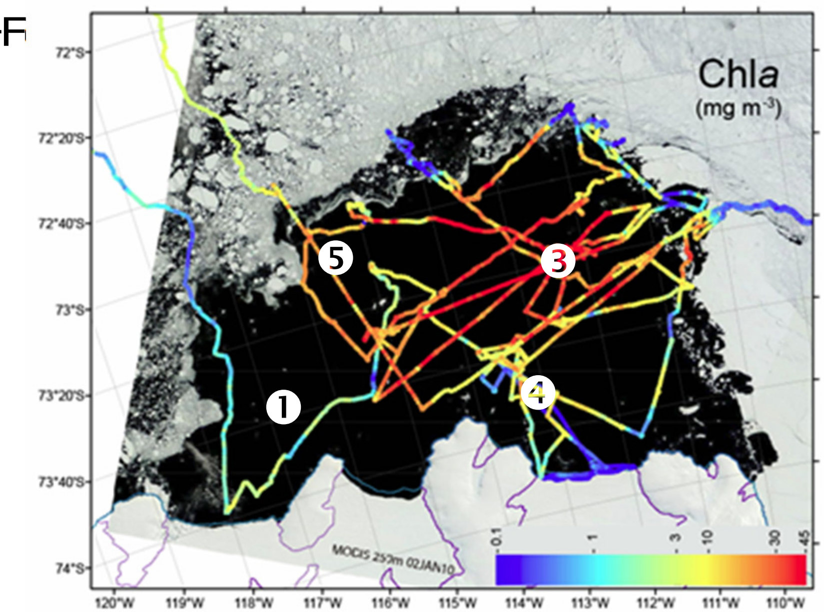
- Upwelled MCDW outflow in front of Dotson Ice Shelf
  Low phytoplankton biomass
- High biomass in central polynya (>20 µg Chl *a* L^{-1})

Amundsen Sea – Amundsen Polynya

Fe addition bioassay experiments



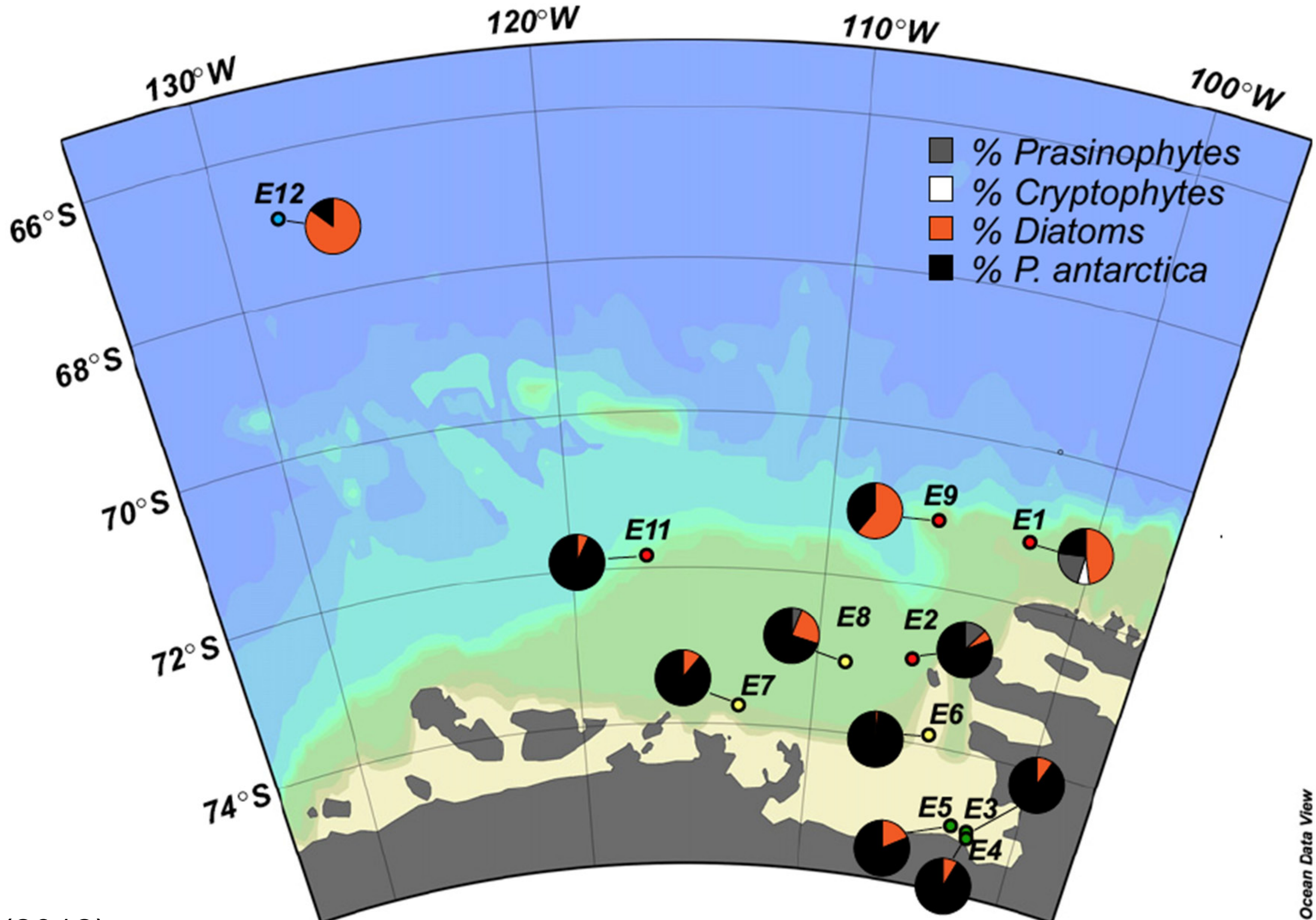
Alderkamp et al. (in prep.)



Amundsen Polynya is Fe-limited in some locations

Amundsen Sea – Pine Island Polynya

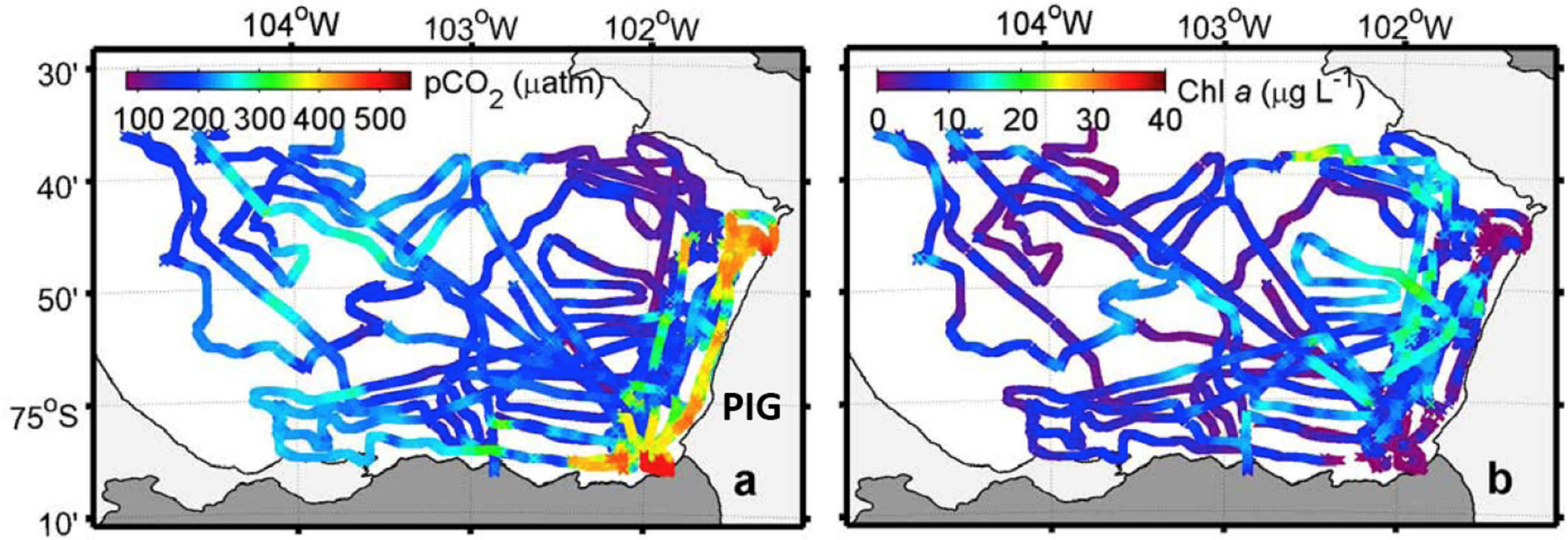
DynaLiFe



Mills et al. (2012)

Amundsen Sea – Pine Island Polynya

pCO$_2$ (μatm) Chl *a* (μg L^{-1})

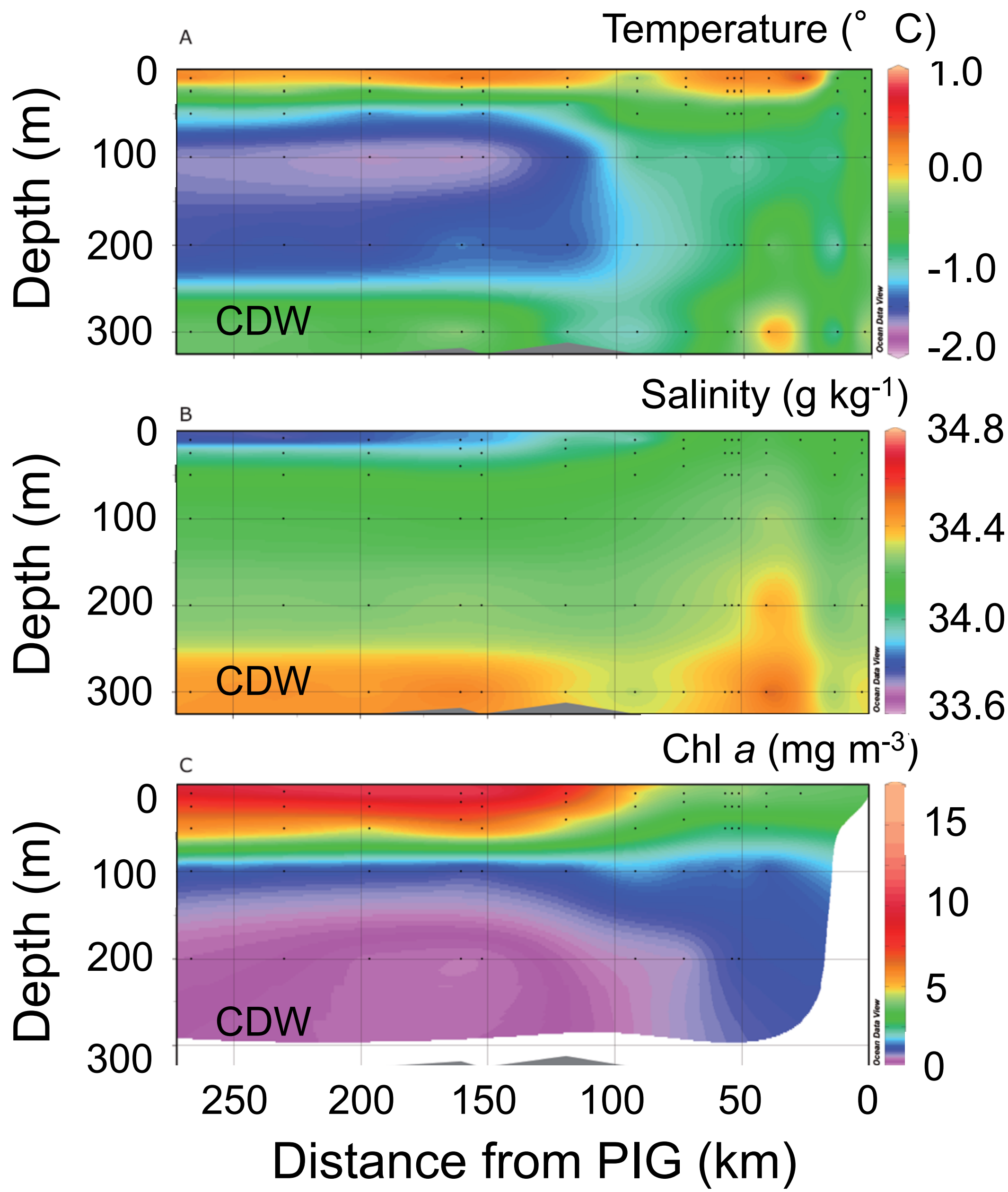


Tortell et al. (2012)

Amundsen Sea – Pine Island Polynya

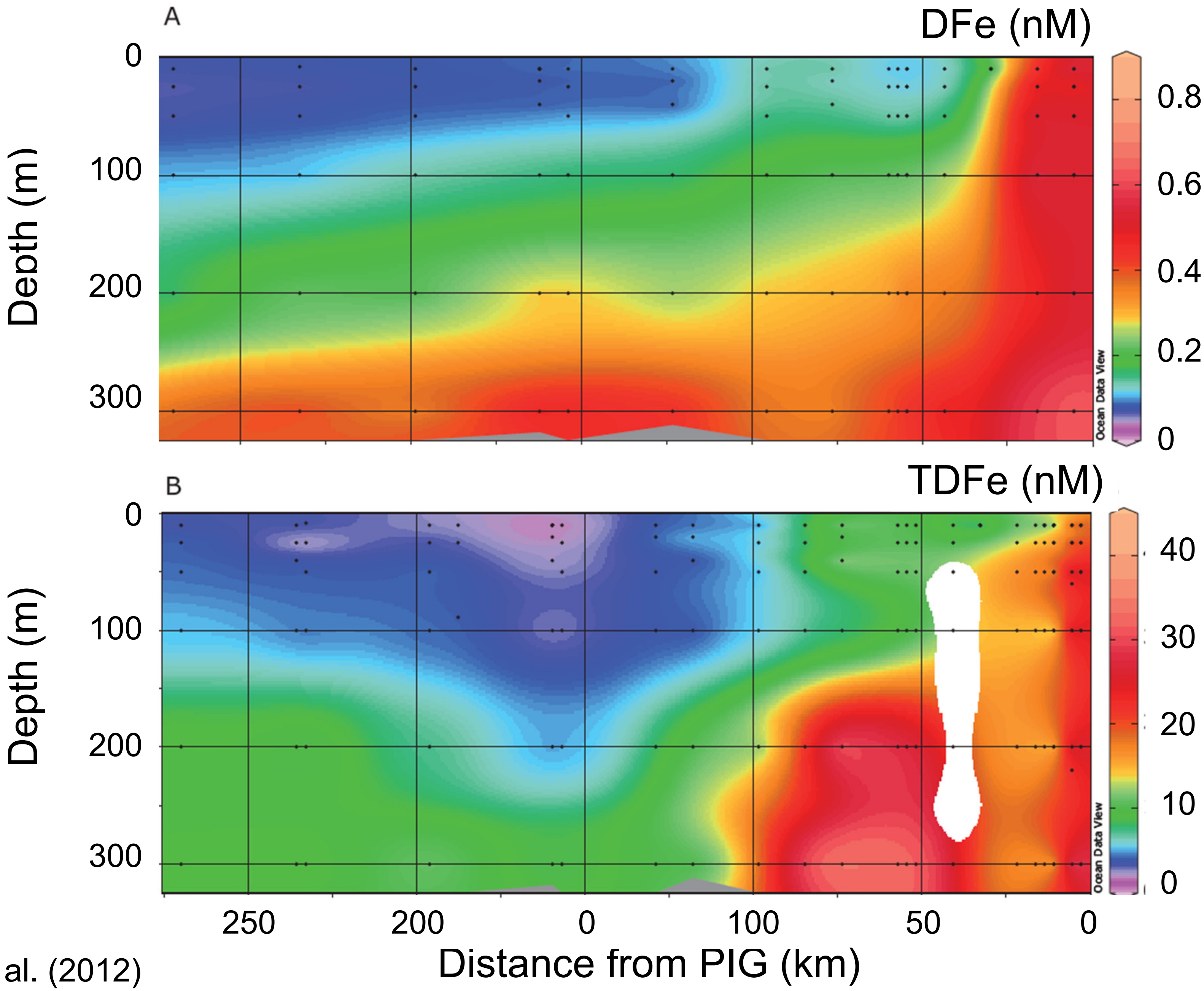
CDW upwells onto shelf

CDW upwells to the surface in front of the PIG



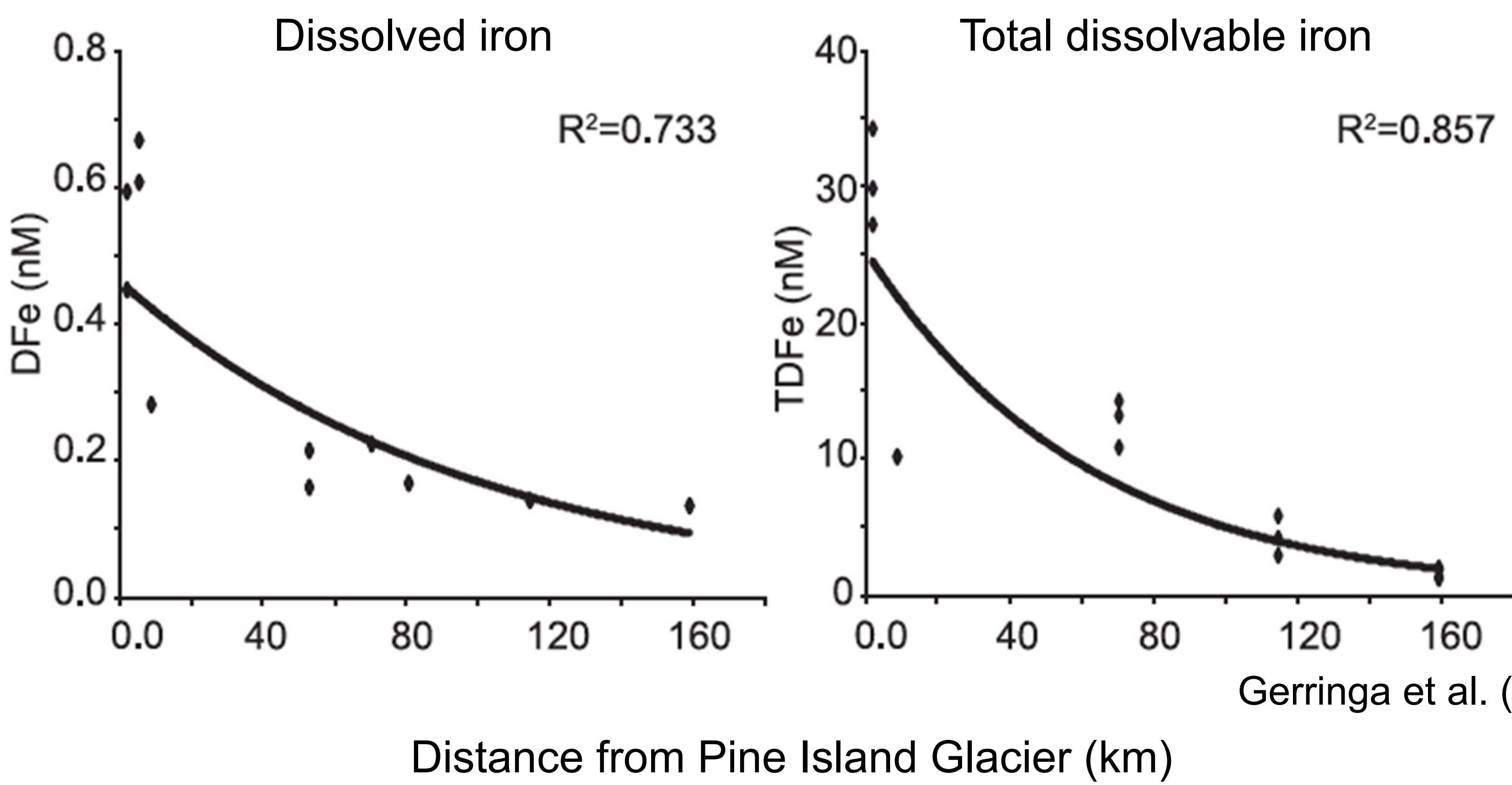
Gerringa et al. (2012)

Amundsen Sea – Pine Island Polynya



Gerringa et al. (2012)

Amundsen Sea – Pine Island Polynya



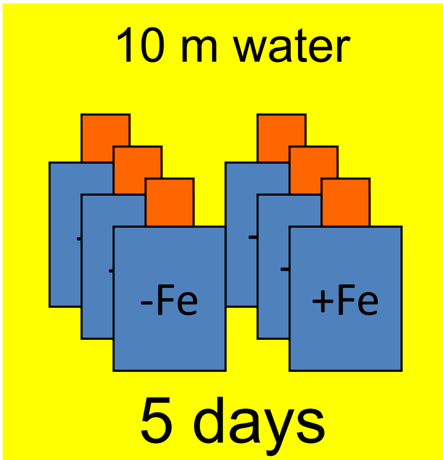
Gerringa et al. (2012)

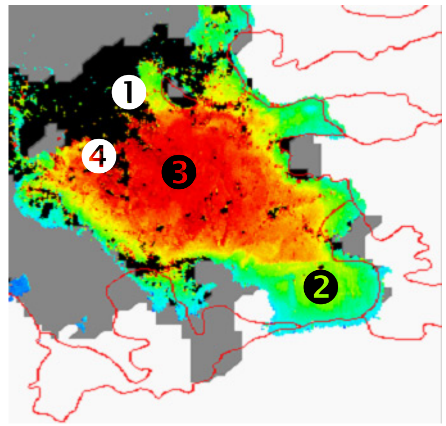
Concentrations decrease with distance from Pine Island Glacier

Both dilution and phytoplankton uptake

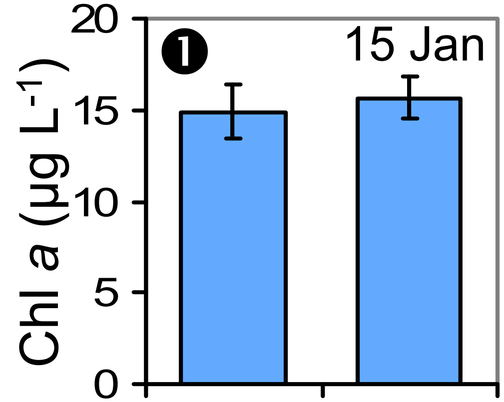
Amundsen Sea – Pine Island Polynya

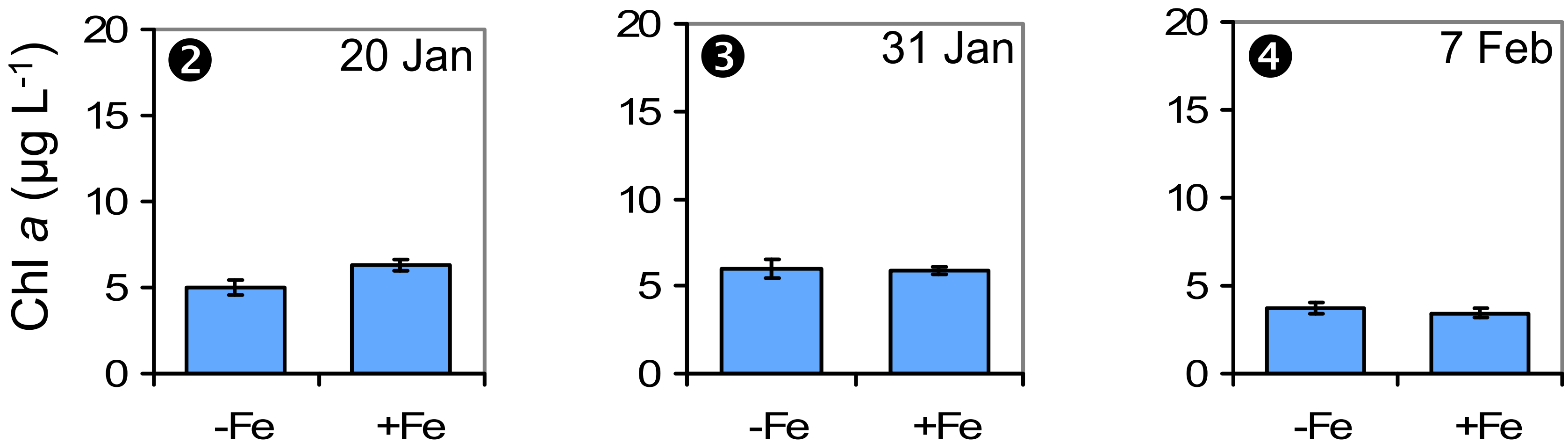
Fe addition bioassay experiments





Mills et al. (2012)

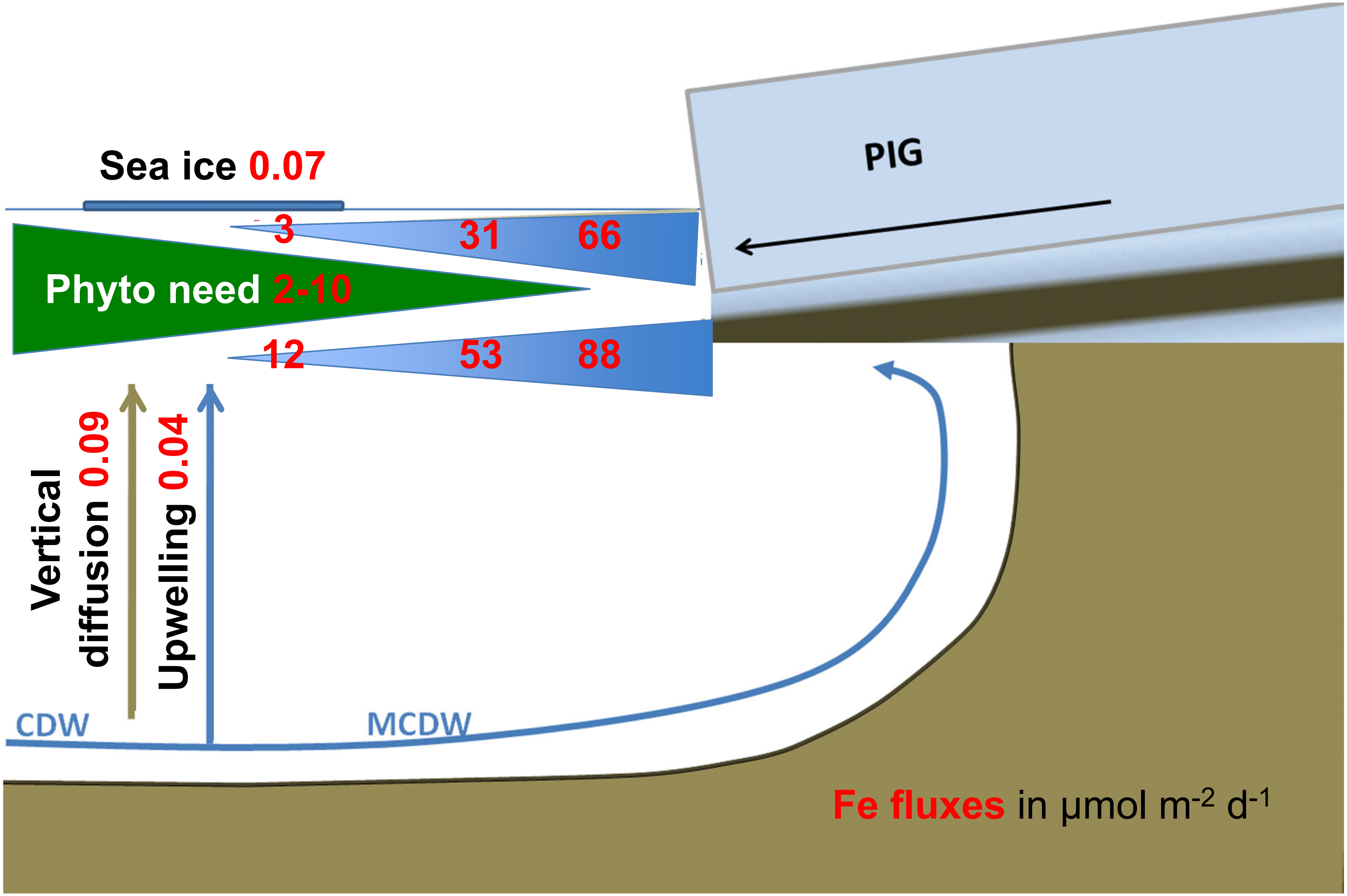




Phytoplankton in Pine Island Polynya not Fe-limited

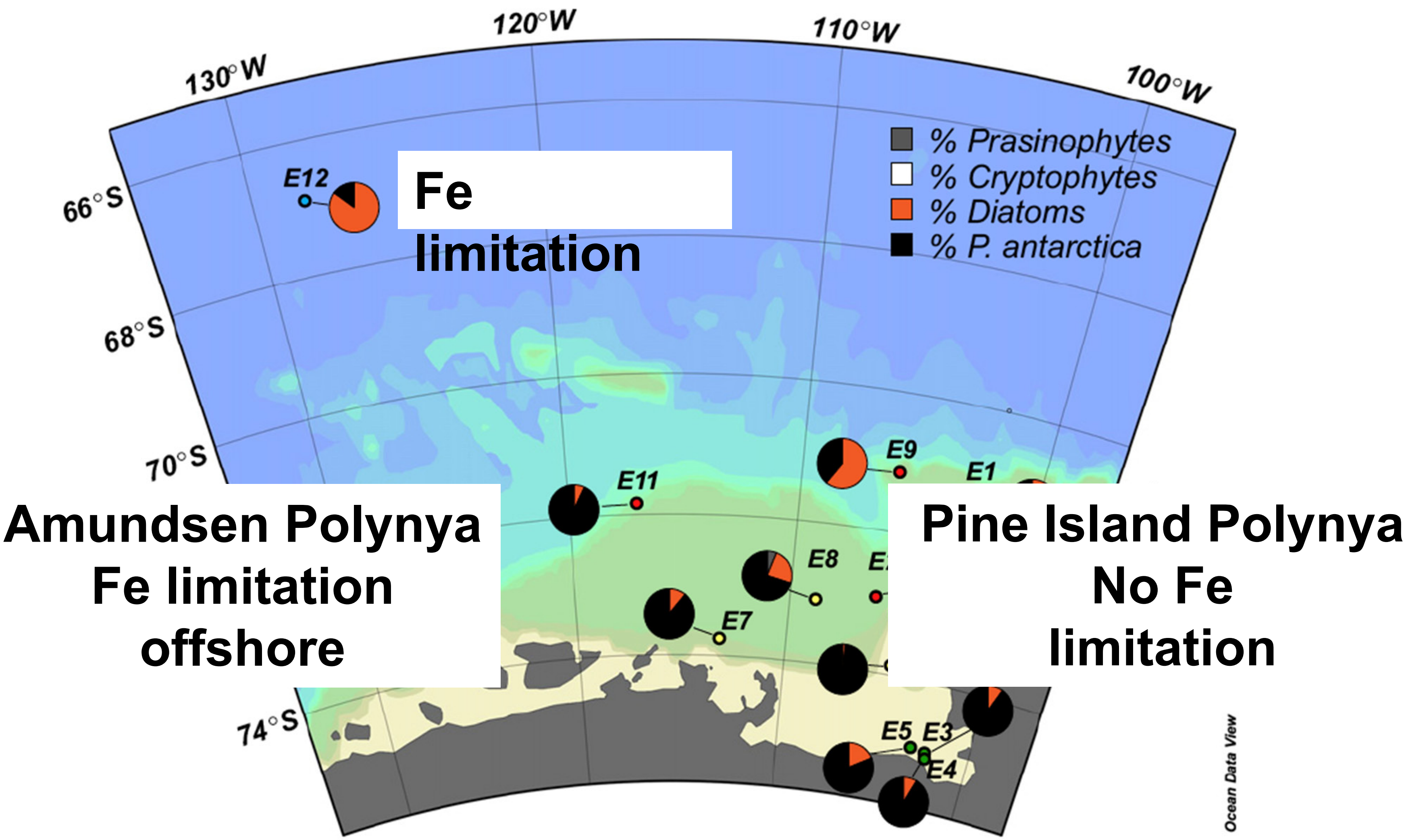
NO_3 drawn down to zero

Amundsen Sea – Pine Island Polynya



Gerringa et al. (2012)

Amundsen Sea



Conclusions

Southern Ocean a source of CO_2 to the atmosphere during interglacials

- Not clear if this applies to anthropogenic warming conditions (e.g., today)

Little interannual variation in NPP in pelagic Southern Ocean

Largest changes in NPP and biggest CO_2 sinks are on shelves

Positive SAMs are becoming more common

- Increases ice cover in pelagic Ross Sea
- Decreases ice cover in pelagic Amundsen Sea
  - Very small net change in annual NPP
- Decreases ice cover on Ross Sea shelf
  - Large increase in annual NPP

Conclusions

Shelves likely to experience largest NPP changes due to anthropogenic warming

- More positive SAM will reduce ice cover on Ross Sea shelf
  - And other shelves as well
  - NPP likely to rise
- More glacial melt will increase Fe input into shelf waters
  - Already large sinks for CO_2
  - May increase NPP in Fe-limited shelf regions
- Phytoplankton community composition could change
  - Diatoms dominate pelagic – likely to continue
  - Warmer temperatures and additional Fe could favor diatoms on shelves
    - Would reduce efficiency of biological pump
  - But Pine Island Bay experiences high Fe and *Phaeocystis* dominates

THANK YOU!

Gert van Dijken
Kate Lowry
Casey Smith
Anne-Carlijn Alderkamp
Matt Mills
Tish Yager (ASPIRE)
Hein de Baar
Loes Gerringa
Philippe Tortell

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