Productivity in a Changing Southern Ocean

Kevin R. Arrigo
Stanford University
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

**Antarctic Convergence**

**Subantarctic Front**

**Chlorophyll a (mg m$^{-3}$)**
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$^{-1}$ CO$_2$ sink

-0.06 Pg C yr$^{-1}$

+0.01 Pg C yr$^{-1}$

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)
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

- Mean = 1825 Tg C yr\(^{-1}\)
- Low interannual variability (CV = 4%)
- No significant change over time

Arctic Ocean

- Mean = 524 Tg C yr\(^{-1}\)
- High interannual variability (CV = 11%)
- Significant 30% increase since 1998

R\(^2\) = 0.007

R\(^2\) = 0.71
Interannual variability in NPP

Arctic Ocean

R² = 0.74

Annual NPP (Tg C)

Open Water Area (km²)

R² = 0.72

Growing Season Length (days)
Interannual variability in NPP

Southern Ocean

Open Water Area (km²)

Annual NPP (Tg C)

R² = 0.15

Southern Ocean

SAM Index

R² = 0.14
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

<table>
<thead>
<tr>
<th>Region</th>
<th>Pelagic</th>
<th>Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>12%</td>
<td>50%</td>
</tr>
<tr>
<td>South Indian Ocean</td>
<td>6%</td>
<td>36%</td>
</tr>
<tr>
<td>Southwest Pacific Ocean</td>
<td>6%</td>
<td>40%</td>
</tr>
<tr>
<td>Ross Sea</td>
<td>7%</td>
<td>34%</td>
</tr>
<tr>
<td>Bellingshausen-Amundsen Sea</td>
<td>5%</td>
<td>34%</td>
</tr>
</tbody>
</table>
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)
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

+ SAMs are becoming more common
Ross Sea

Annual NPP (g C m⁻² yr⁻¹)

Pelagic
Shelf
MIZ-Pelagic
MIZ-Shelf

Annual NPP (Tg C)
Ross Sea

Shelf and pelagic respond differently to SAM

Retreat (DJF)  Advance (MAM)
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
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 CO₂ 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 km²
Amundsen Sea

Ice edge

Amundsen Polynya

Highest chlorophyll a concentrations in Southern Ocean

Intense blooms dominated by colonial *Phaeocystis antarctica*
Amundsen Sea

Annual NPP (g C m\(^{-2}\) yr\(^{-1}\))

Amundsen Polynya (gray)
Pine Island Polynya (black)

Annual NPP (Tg C yr\(^{-1}\))

Light ice year
Heavy ice year

Arrigo et al (2012)
Amundsen Sea

Amount of annual NPP controlled by sea ice cover

Arrigo et al. (2012)
Amundsen Sea

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

Arrigo et al (2012)
Amundsen Sea

Positive SAM year
Heavy sea ice – Much lower productivity

Arrigo et al (2012)
Response to Fe?

*DynaLiFe*
13 Jan – 18 Feb 2009

*ASPIRE*
14 Dec 2010 – 5 Jan 2011

Arrigo et al (2012)
Satellite Primary Production

Pine Island Polynya

Amundsen Polynya

Arrigo et al (2012)
• 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

Amundsen Polynya is Fe-limited in some locations
Amundsen Sea – Pine Island Polynya

DynaLiFe

Mills et al. (2012)
Amundsen Sea – Pine Island Polynya

\[ \text{pCO}_2 \ (\mu\text{atm}) \quad \text{Chl a (\mu g L}^{-1}) \]

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

Concentrations decrease with distance from Pine Island Glacier
Both dilution and phytoplankton uptake

Gerringa et al. (2012)
Amundsen Sea – Pine Island Polynya

Fe addition bioassay experiments

Phytoplankton in Pine Island Polynya not Fe-limited

NO₃ drawn down to zero
Amundsen Sea – Pine Island Polynya

Fe fluxes in µmol m$^{-2}$ d$^{-1}$

Gerringa et al. (2012)
Amundsen Sea

Pine Island Polynya
No Fe limitation

Amundsen Polynya
Fe limitation offshore

Fe limitation
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 CO₂
  - 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!

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