Backscattering in the Southern Ocean

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Photo: S. Freeman


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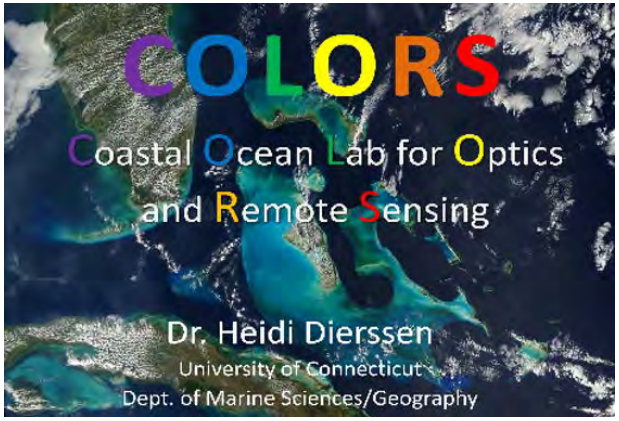
Acknowledge



- Randolph, Garaba, Buonassissi- Univ. Connecticut
- Balch, Drapeau - Bigelow
- Twardowski, Freeman – Harbor Branch
- Xiaodong Zhang – Univ. North Carolina
- Funding: NASA Ocean Biology and Biogeochemistry

Is the SO a CO_2 source or sink?

- Models vary widely
- Models need to improve biological parameterizatons

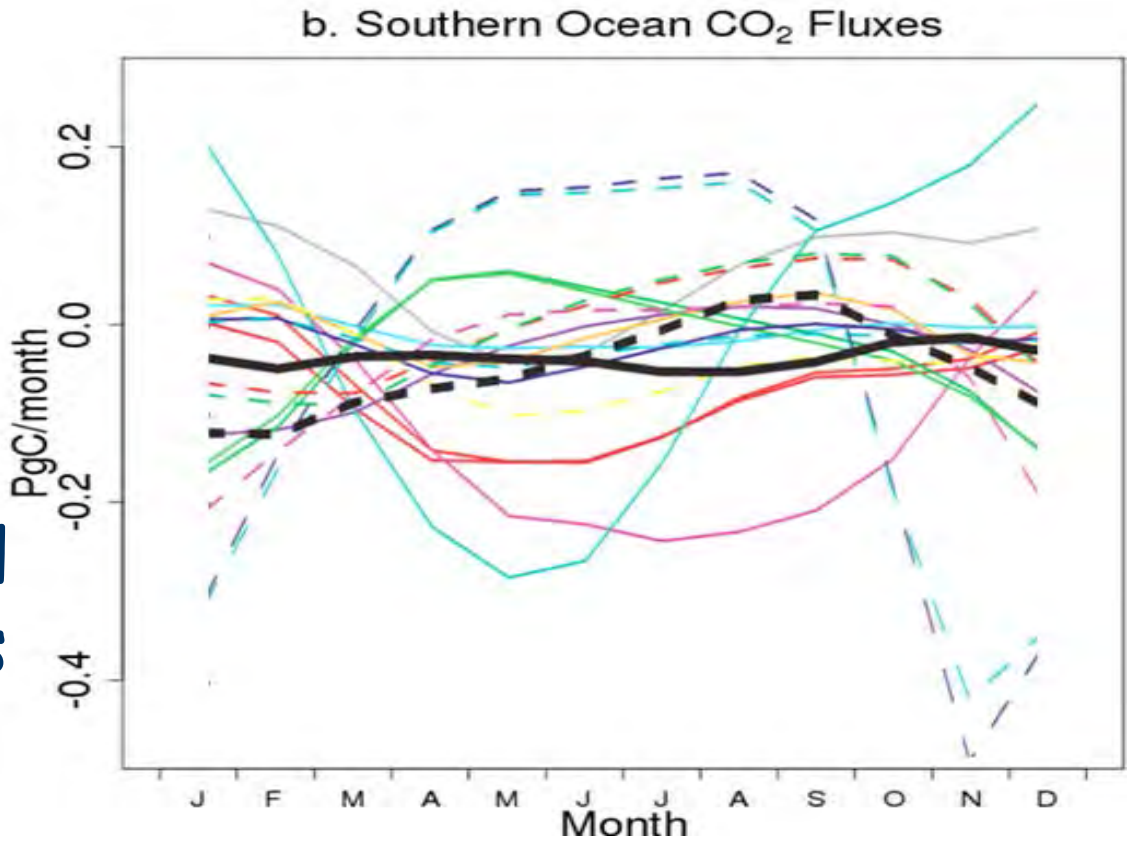


Fig. 3. Air-sea CO_2 fluxes from 19 CMIP5 models (colors) for the Southern Ocean (south of 44° S) compared to estimates based on the pCO_{2oce} climatology (black dash) of Takahashi et al. (2009) and a recent atmospheric inversion (solid black) by Anav et al. (2013).

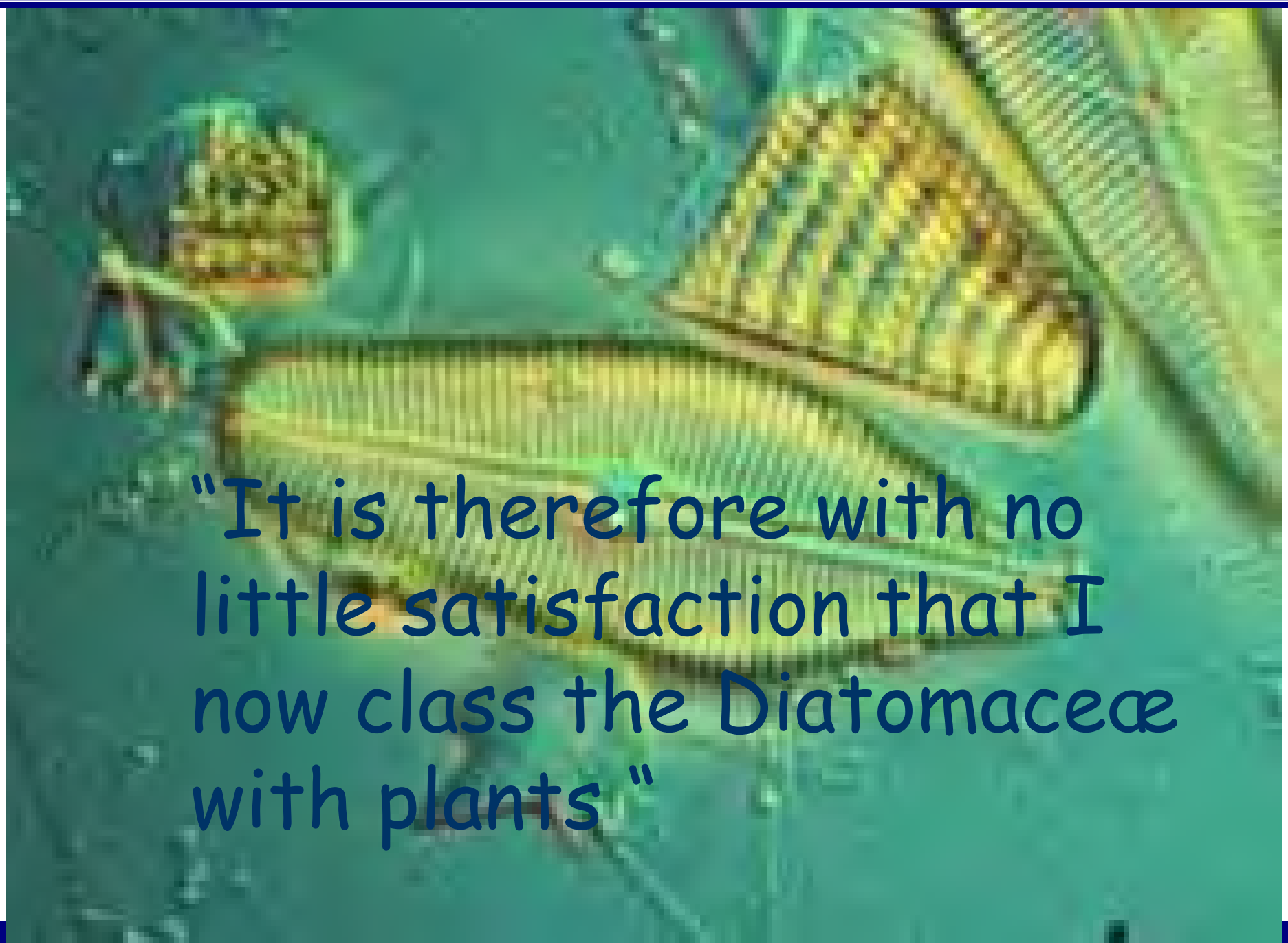
--Dr. J.D. Hooker 1847
"Botany of the Antarctic Voyage"

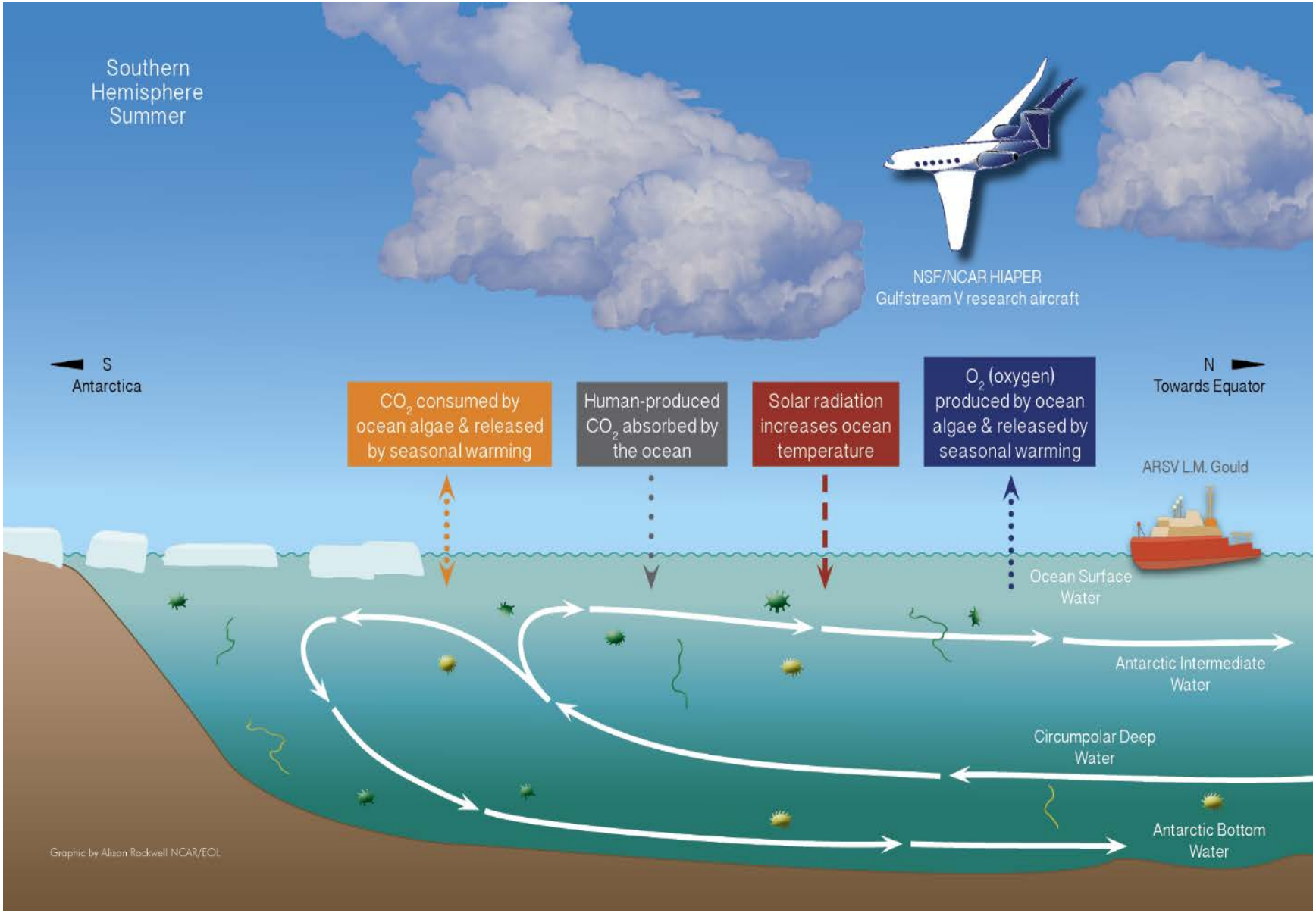
- During the years we spent there, I had been accustomed to regard the phenomena of life as differing totally from what obtains throughout all other latitudes, for

  everything living appeared to be of animal origin.

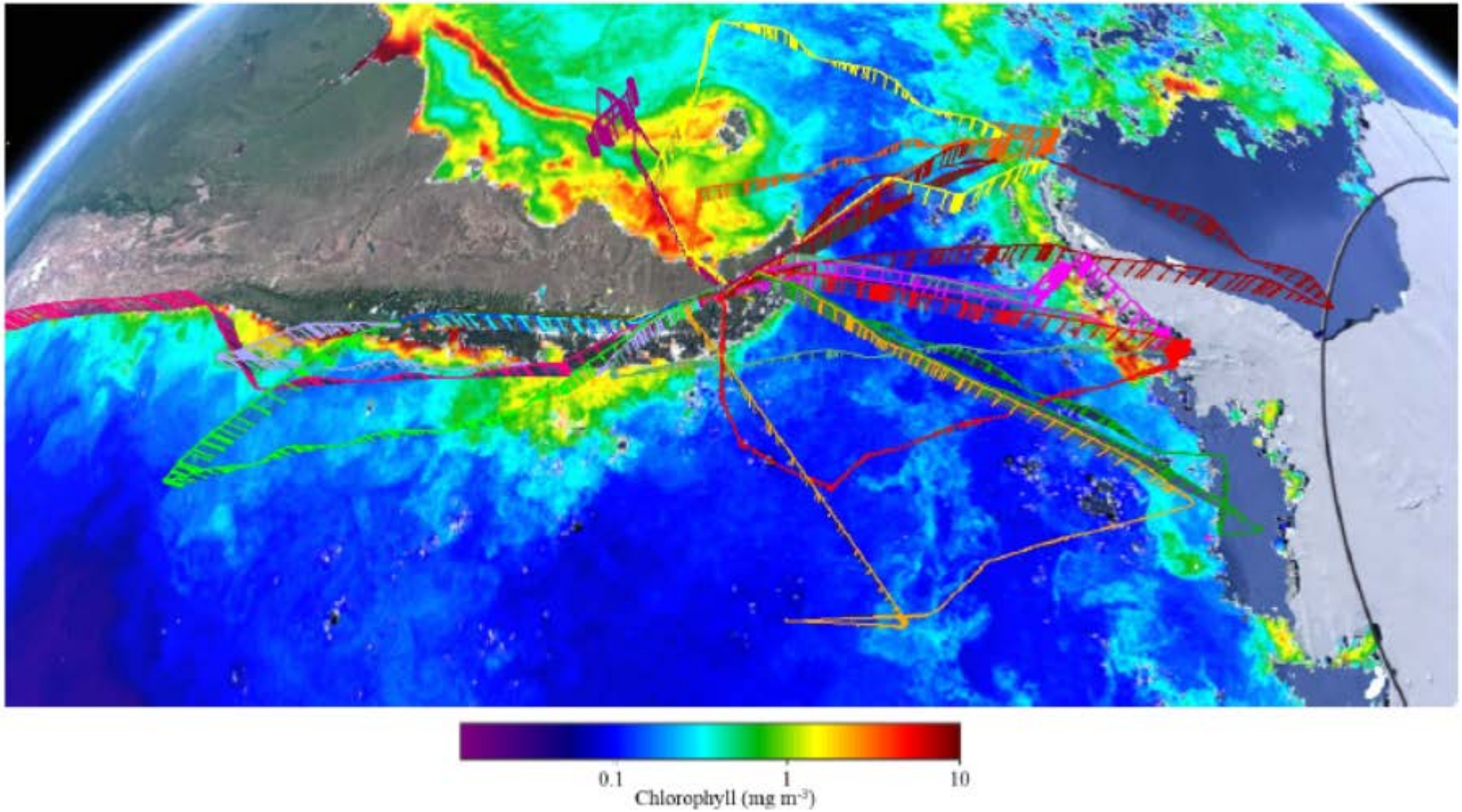
  The ocean swarmed with Mollusca, small whales, and porpoises; the sea abounded with penguins and seals, and the air with birds; the animal kingdom was ever present, the larger creatures preying on the smaller and these again on smaller still; all seemed carnivorous.

Weddell Seal

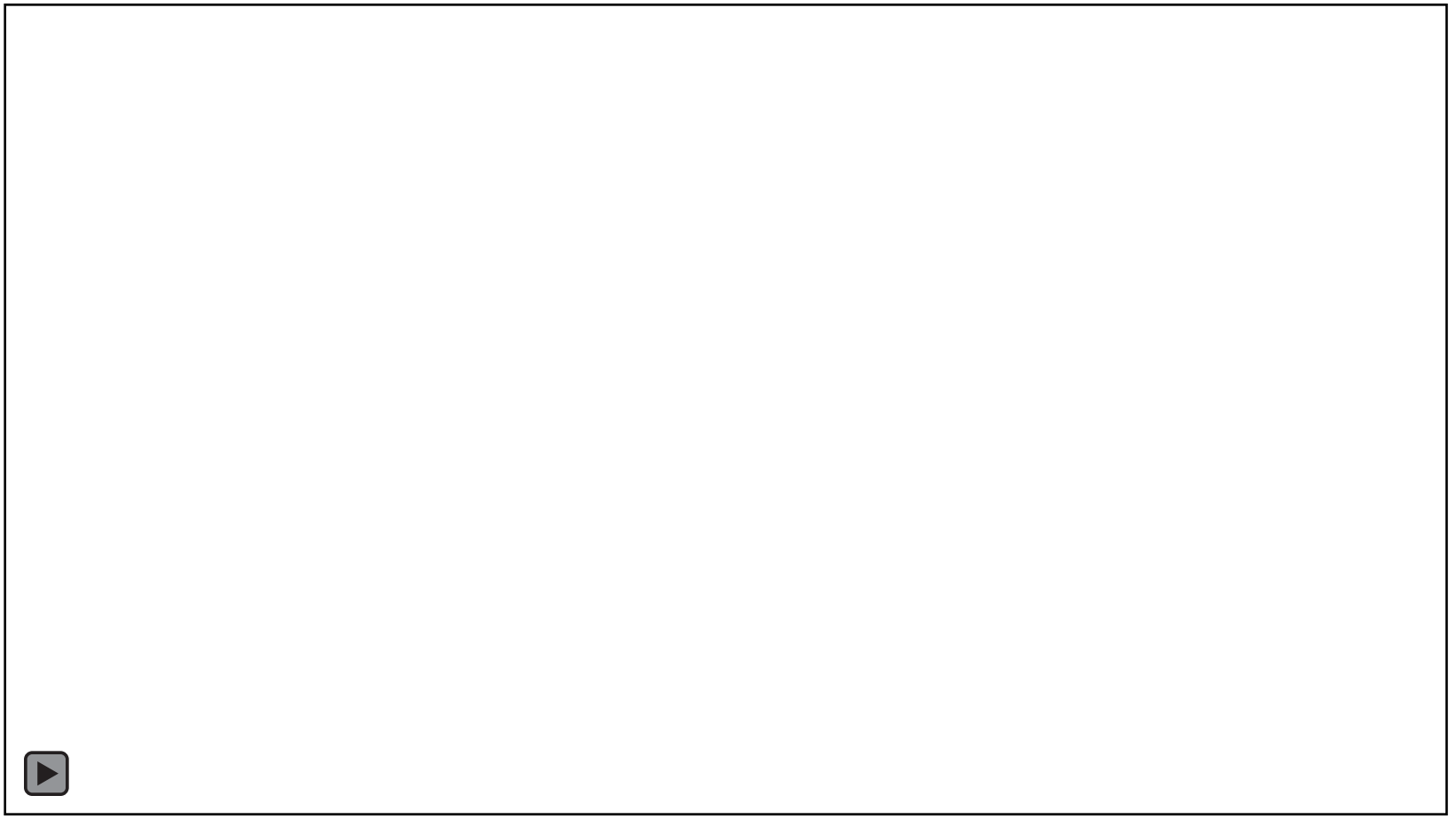

"It is therefore with no little satisfaction that I now class the Diatomaceæ with plants "

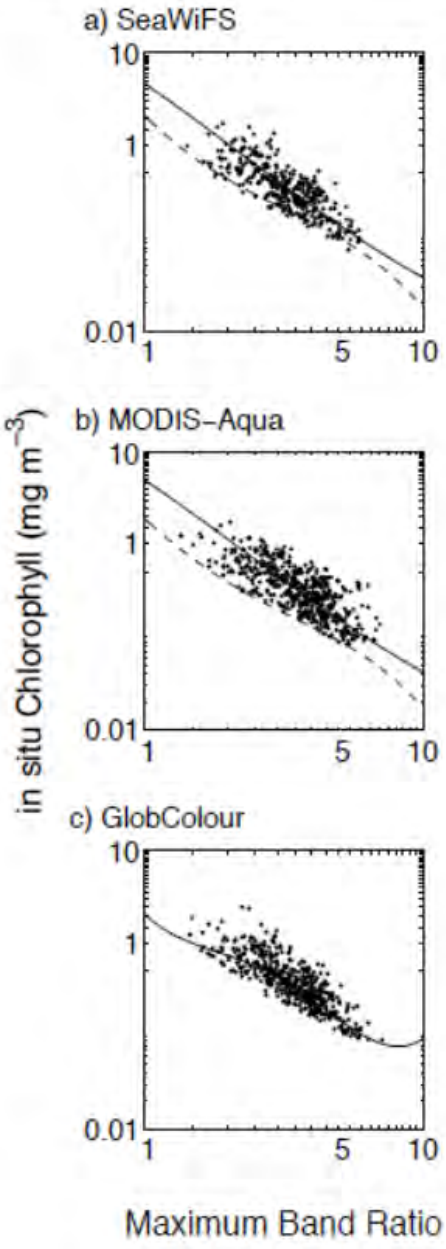

Southern Hemisphere Summer
NSF/NCAR HIAPER
Gulfstream V research aircraft
S
Antarctica
N
Towards Equator
CO_2 consumed by ocean algae & released by seasonal warming
Human-produced CO_2 absorbed by the ocean
Solar radiation increases ocean temperature
O_2 (oxygen) produced by ocean algae & released by seasonal warming
ARSV L.M. Gould
Ocean Surface Water
Antarctic Intermediate Water
Circumpolar Deep Water
Antarctic Bottom Water
Graphic by Alison Rockwell NCAR/EOL

1. **Can we explain discrepancies between different investigations of Southern Ocean bio-optical algorithms based on time, sector, proximity to sea ice and continental shelves, temperature, latitude, and methodology?**
2. Can atmospheric corrections be improved to expand the time-space domain of ocean color data at higher solar zenith angles?
3. What is the pigment concentration, primary production and carbon export for ice-free oceans in winter for which no ocean color data can be retrieved due to solar zenith angle being too large?
4. **What are emerging technologies that can improve the quality and number of observations *in situ* and airborne in the Southern Ocean needed to improve algorithms and models?**
5. How can we merge bio-optical-ARGO and satellite data for a better 4-D representation of plankton biomass and productivity for the SO?
6. **What are the plans in the international community for future field campaigns to advance our understanding of Southern Ocean carbon cycle using satellite ocean color and other observations?**
7. How can we improve the understanding of relationship between surface satellite observations and organic carbon export?


0.1
1
10
Chlorophyll (mg m-3)

ORCAS movie





- Recent study by Johnson et al. 2013
- Also factor of 2

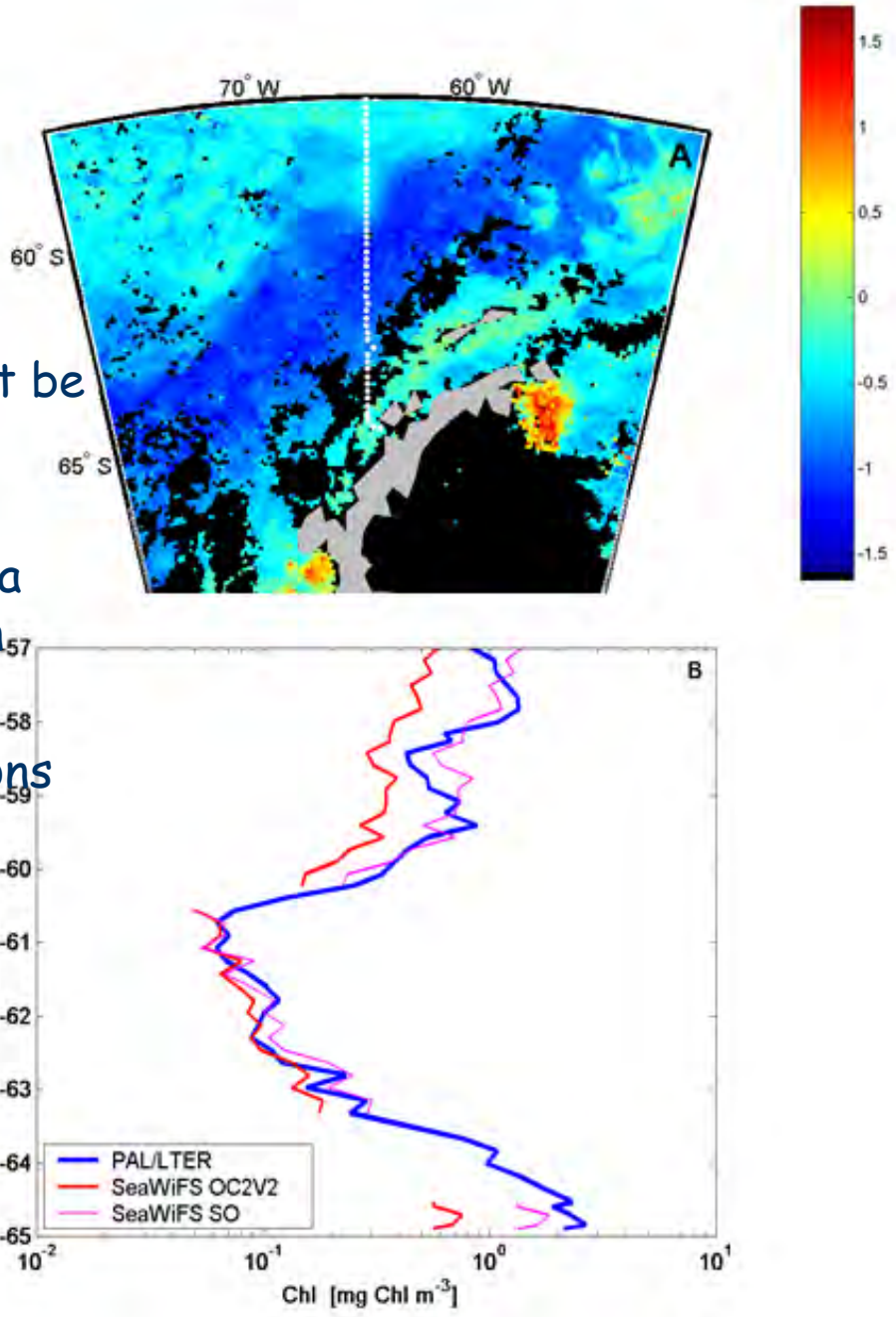
MAIN TAKE HOME POINT

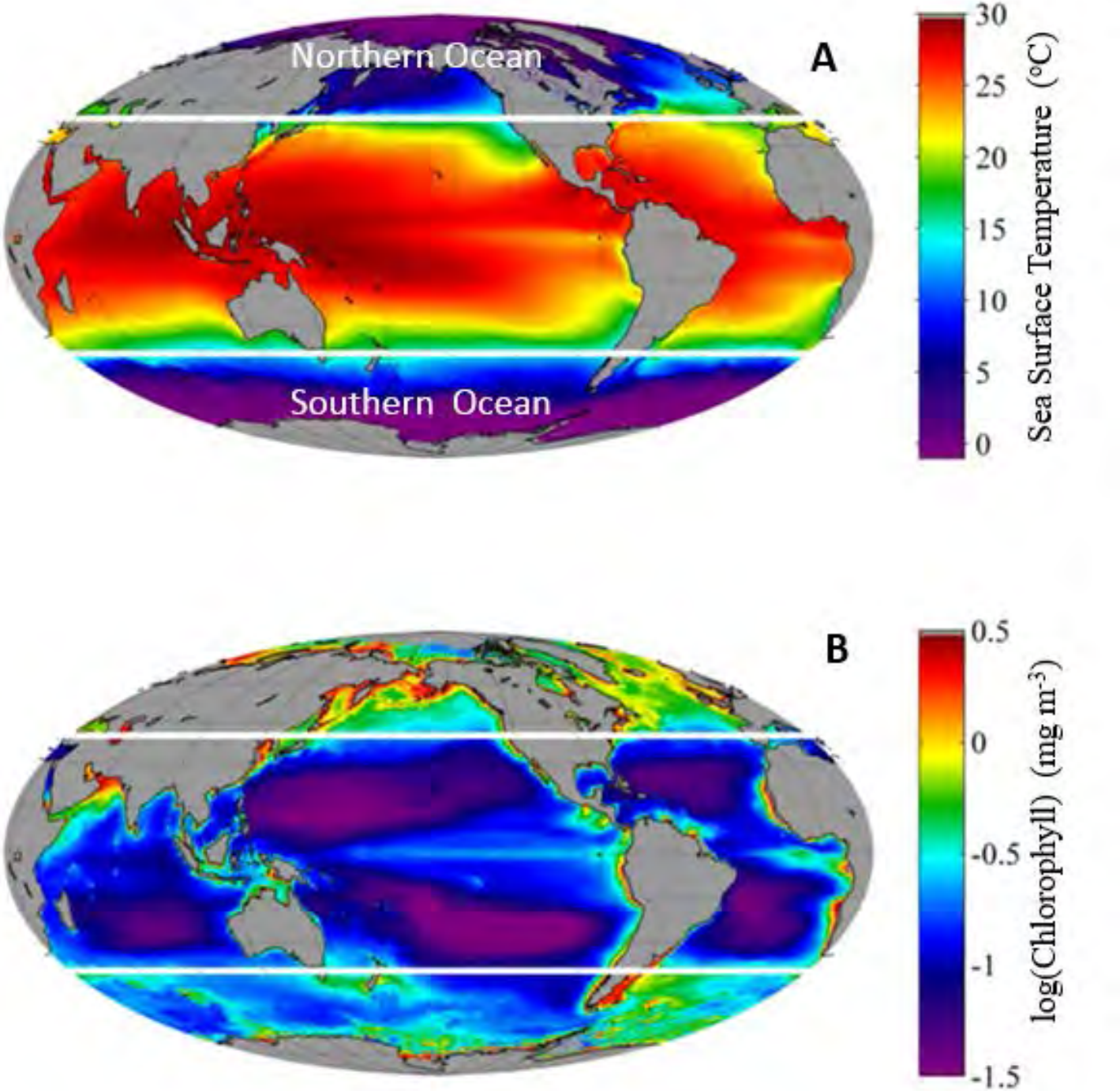
The Southern Ocean should not be taken as a homogenous entity

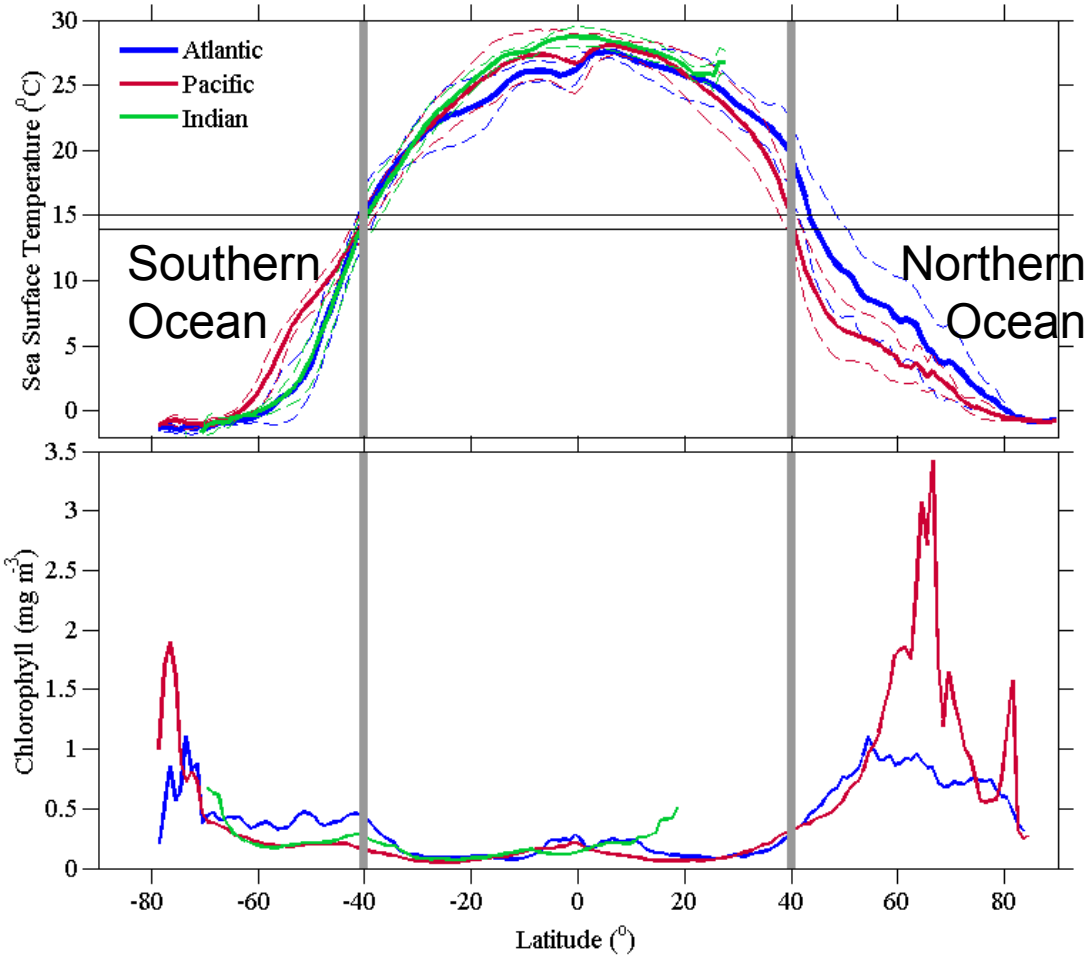
We should likely not bin all data because it is biased by location

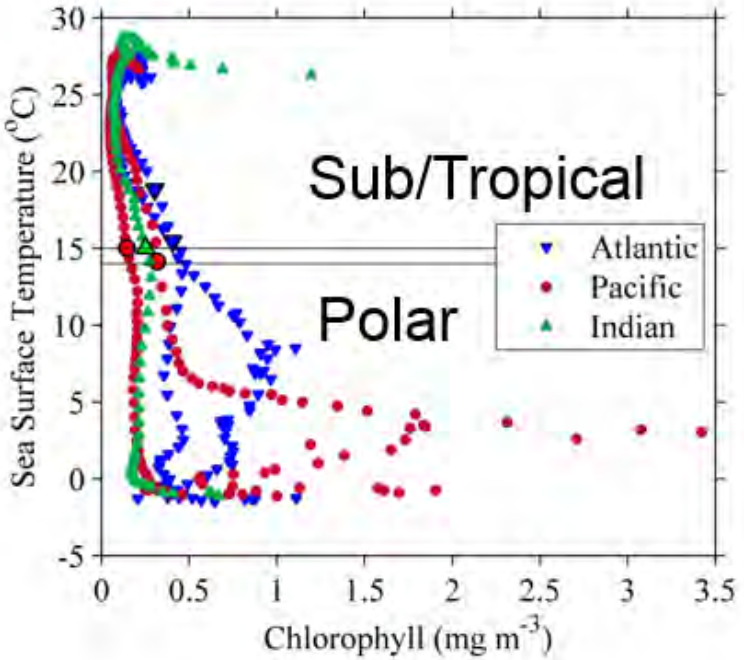
Different processes, adaptations across different zones.

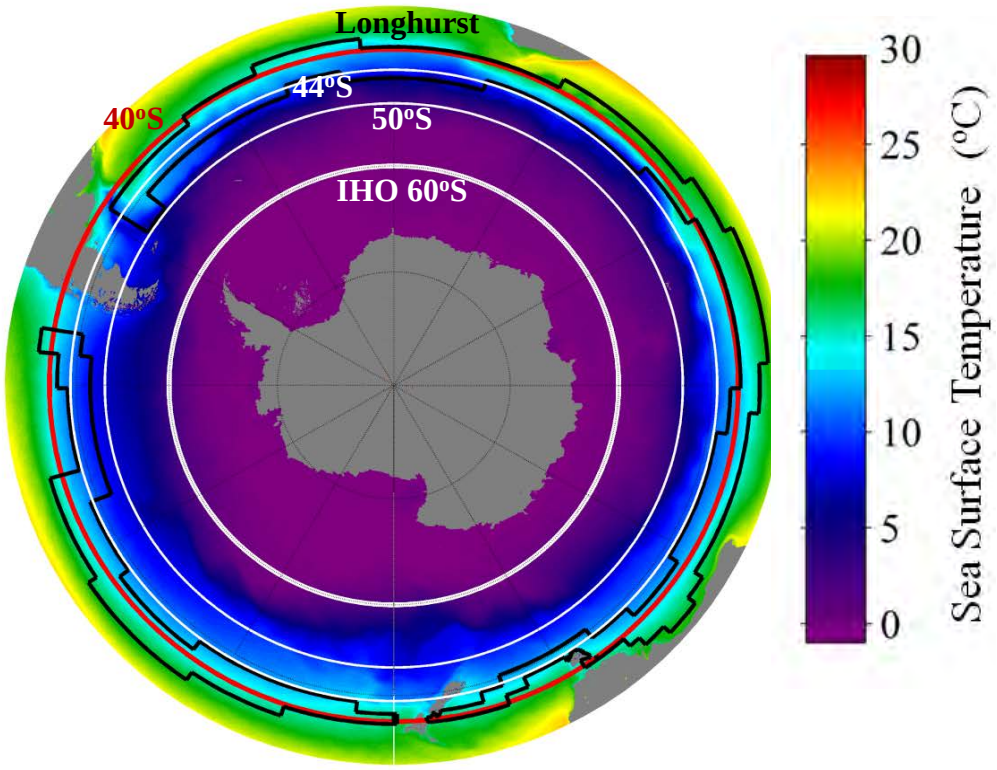
What are the zones?




Northern Ocean
A
Southern Ocean
30
25
20
15
10
5
0
Sea Surface Temperature (°C)
B
0.5
0
-0.5
-1
-1.5
log(Chlorophyll) (mg m-3)

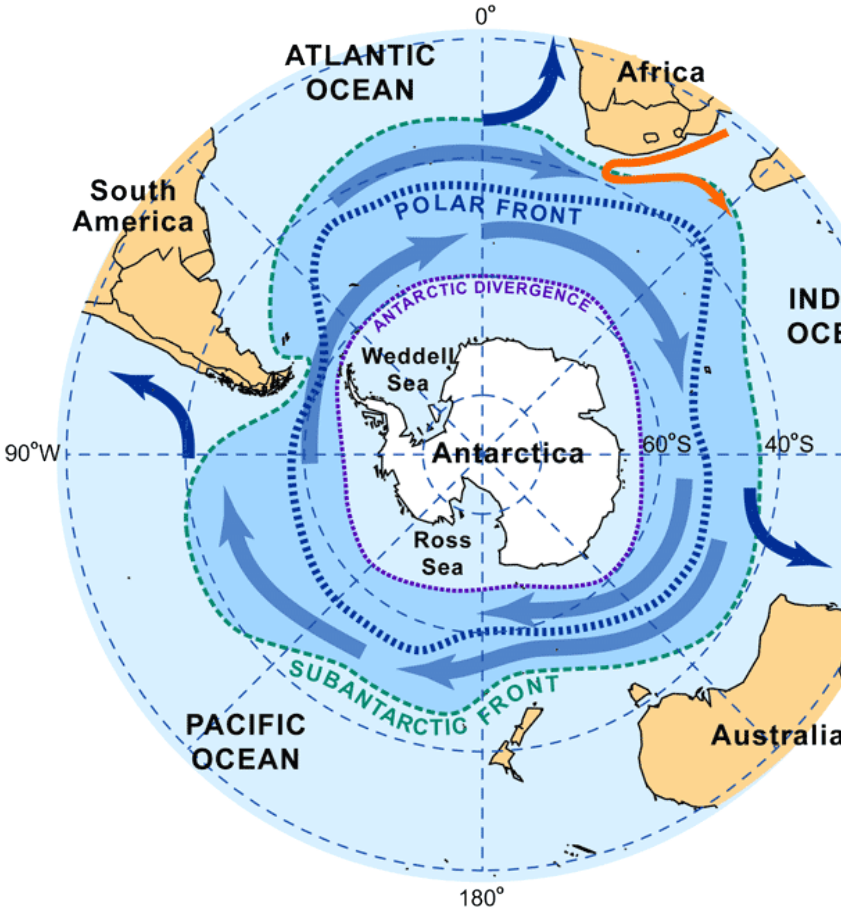

Atlantic
Pacific
Indian
Southern Ocean
Northern Ocean
Sea Surface Temperature (°C)
Chlorophyll (mg m-3)
Latitude (°)


Sub/Tropical
Polar
Atlantic
Pacific
Indian
Sea Surface Temperature (°C)
Chlorophyll (mg m-3)


Longhurst
40°S
44°S
50°S
IHO 60°S

30
25
20
15
10
5
0
Sea Surface Temperature (°C)

A


0°
ATLANTIC OCEAN
Africa
South America
POLAR FRONT
ANTARCTIC DIVERGENCE
Weddell Sea
Antarctica
90°W
60°S
40°S
Ross Sea
SUBANTARCTIC FRONT
PACIFIC OCEAN
Australia
180°

Within these regions the optical properties vary

- Absorption

Absorption	Backscattering

• Phytoplankton absorption per mg Chl
• Other pigments like Chl c
• Non-covarying CDOM
• Unique physiological adaptations
	• Amount of covarying colloids
	• Phytoplankton
	• Other particles
	  • Glacial Flour
	  • Calcite
	  • Bubbles

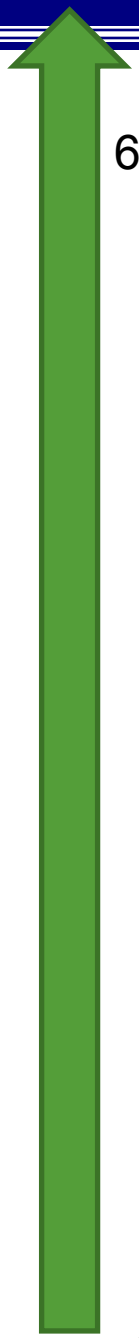
Phytoplankton Taxa will be related to CO2 and O2 flux data

Antarctic Zone
- Diatoms type 1
- Haptophyte type 8
  - *Phaeocystis antarctica*
- Cryptophytes
- Mixed flagellates

Polar Front Zone
- Diatoms
- Haptophytes type 6
  - Coccolithophorids
- Dinoflagellates Type 2

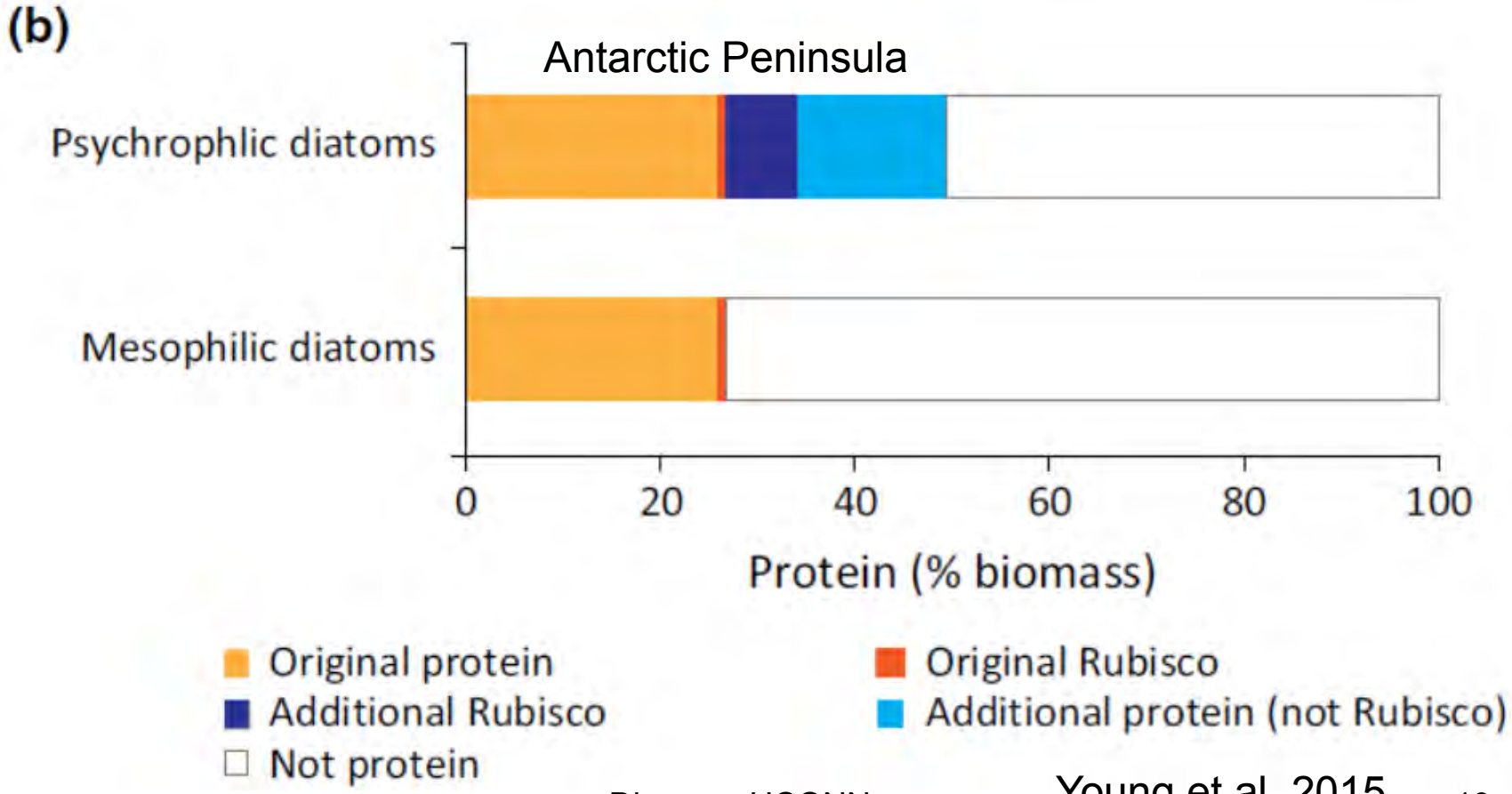
Subantarctic Zone
- Diatom type 2
- Dinoflagellates Type 1
- Haptophytes type 6
  - Coccolithophorids

Subtropical Zone
- Haptophytes type 6
  - Coccolithophorids
- Diatom type 2
- Dinoflagellates Type 1
  - Peridinin /DMSP



Background
- Prasinophytes
- Chlorophytes
- Cryptophytes
  - Except near meltwater
- Cyanobacteria

Psychrophilic phytoplankton packed with protein

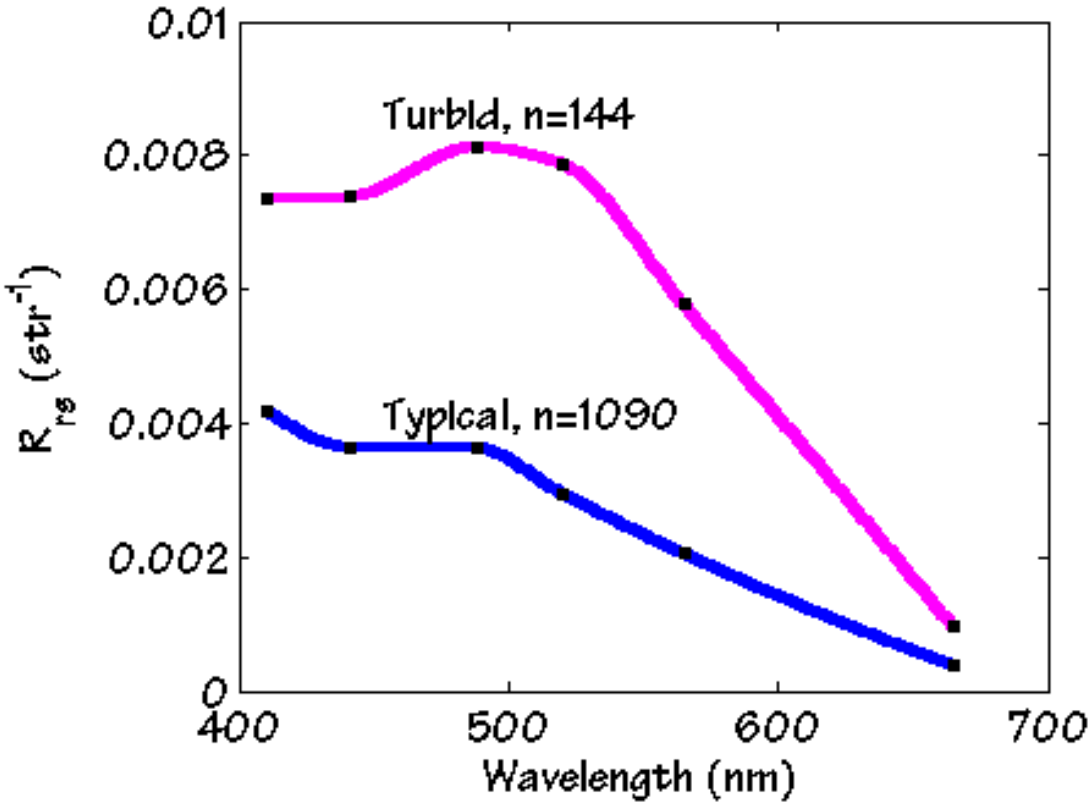


Young et al. 2015

Glacial Meltwater

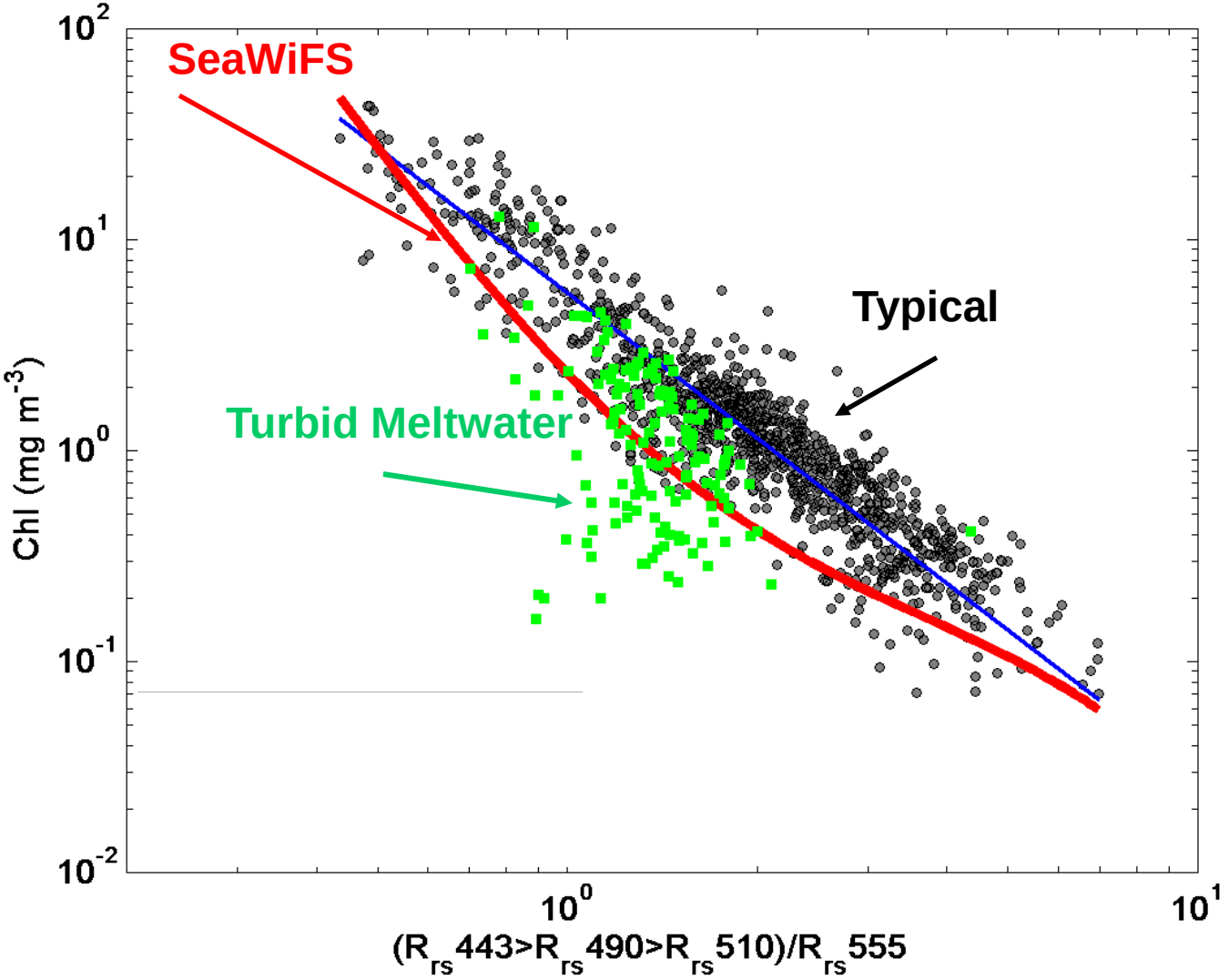
Turbid waters

- high reflectanc
- nearshore only
- spectrum - particulate
- 70% very low salinity
  - < 33.2 ppt

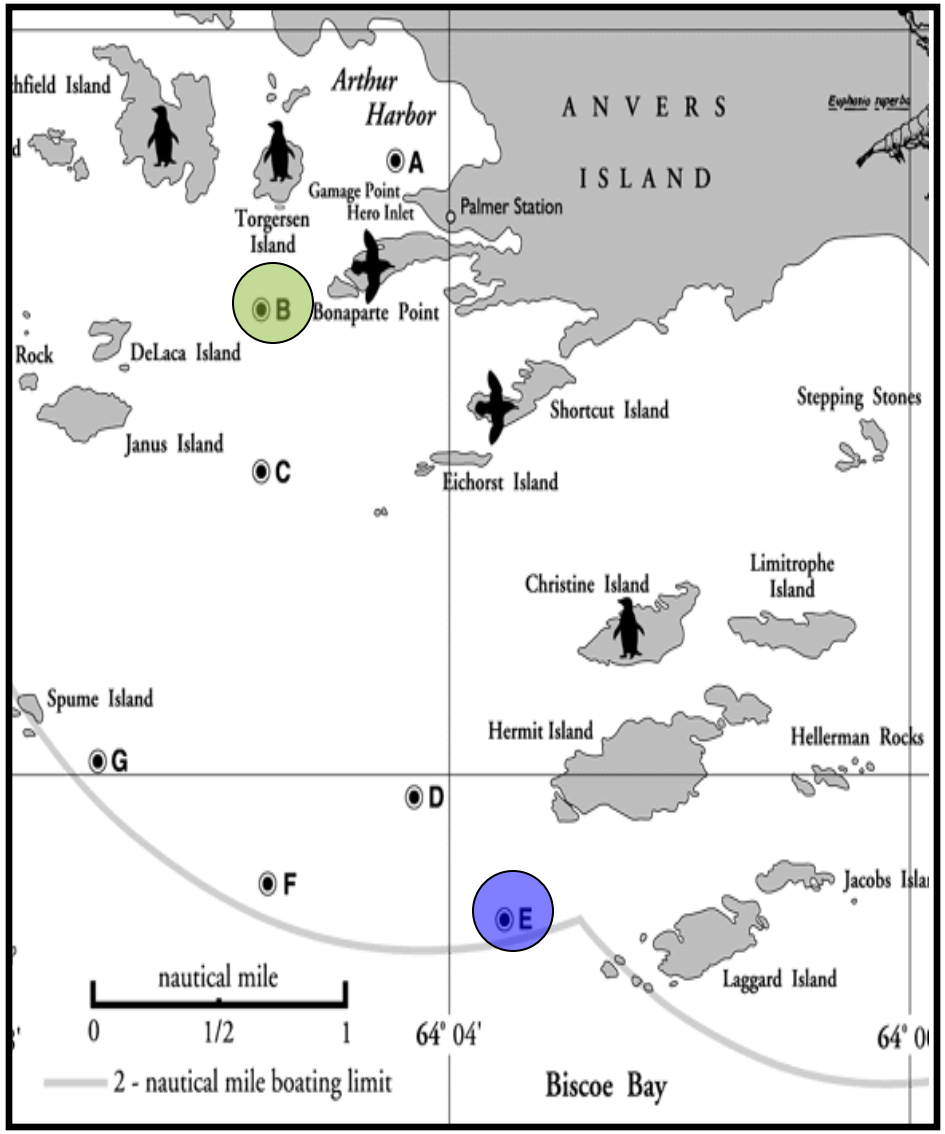


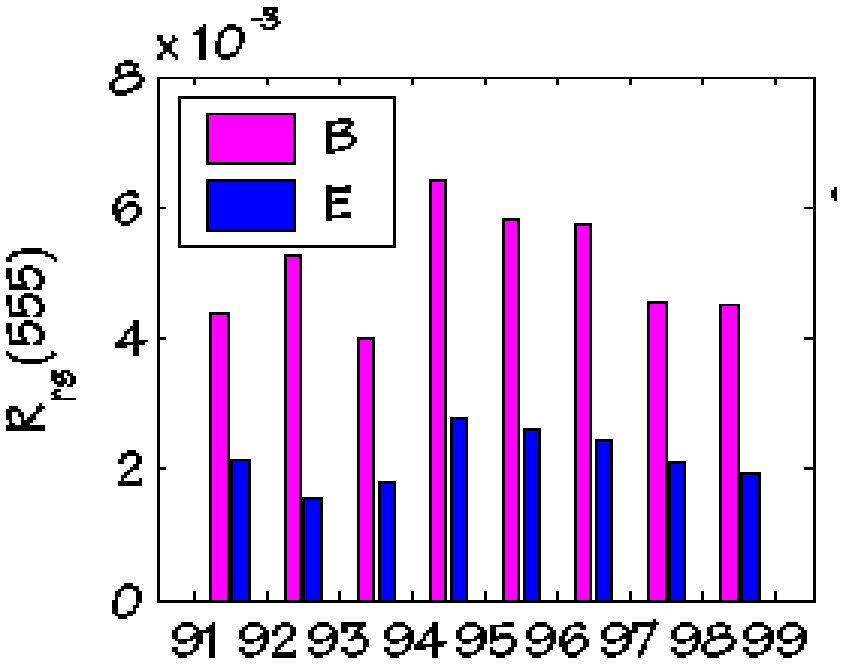
Dierssen, H.M., R.C. Smith, and M. Vernet. 2002. Glacial meltwater dynamics in coastal waters west of the Antarctic Peninsula. *Proc. Nat. Acad. Sci.* 99(4):1790-1795.

SeaWiFS Algorithm Fails

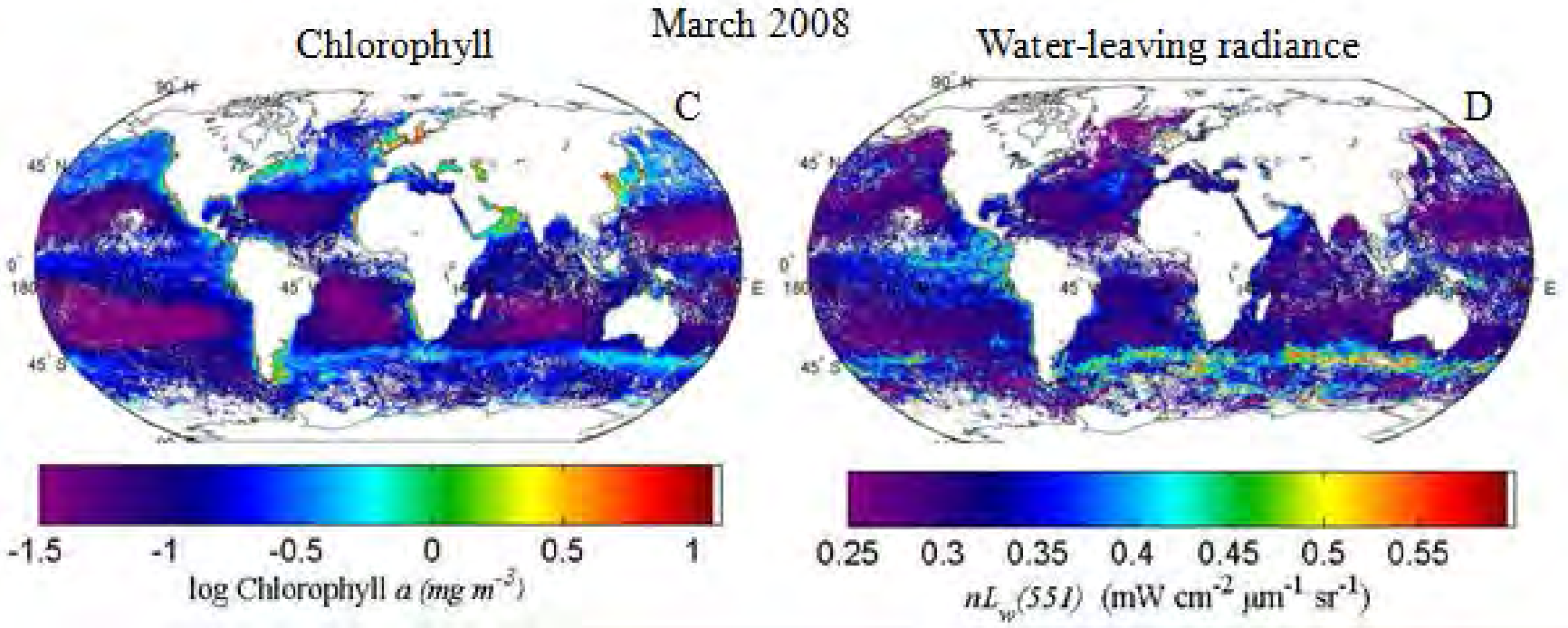


Particles settle nearshore

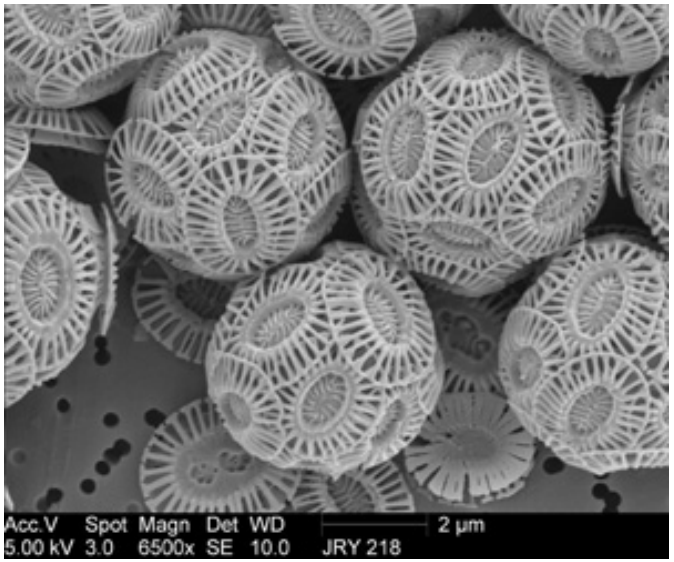




High Backscattering Waters?



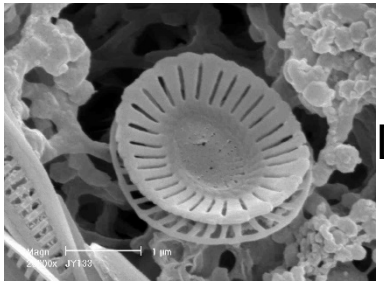
2) *Emiliania huxleyi*



Coccolithophore with a calcite shell
Enhances backscattering

Role in Carbon cycle

1) $CaCO_3$ precipitation produces CO_2 that directly raises pCO_{2surf}
2) the calcite shells provide efficient ballast to transfer organic carbon from the surface to deep ocean potentially increasing NCP, export production and export efficiency which lowers pCO_{2surf}.

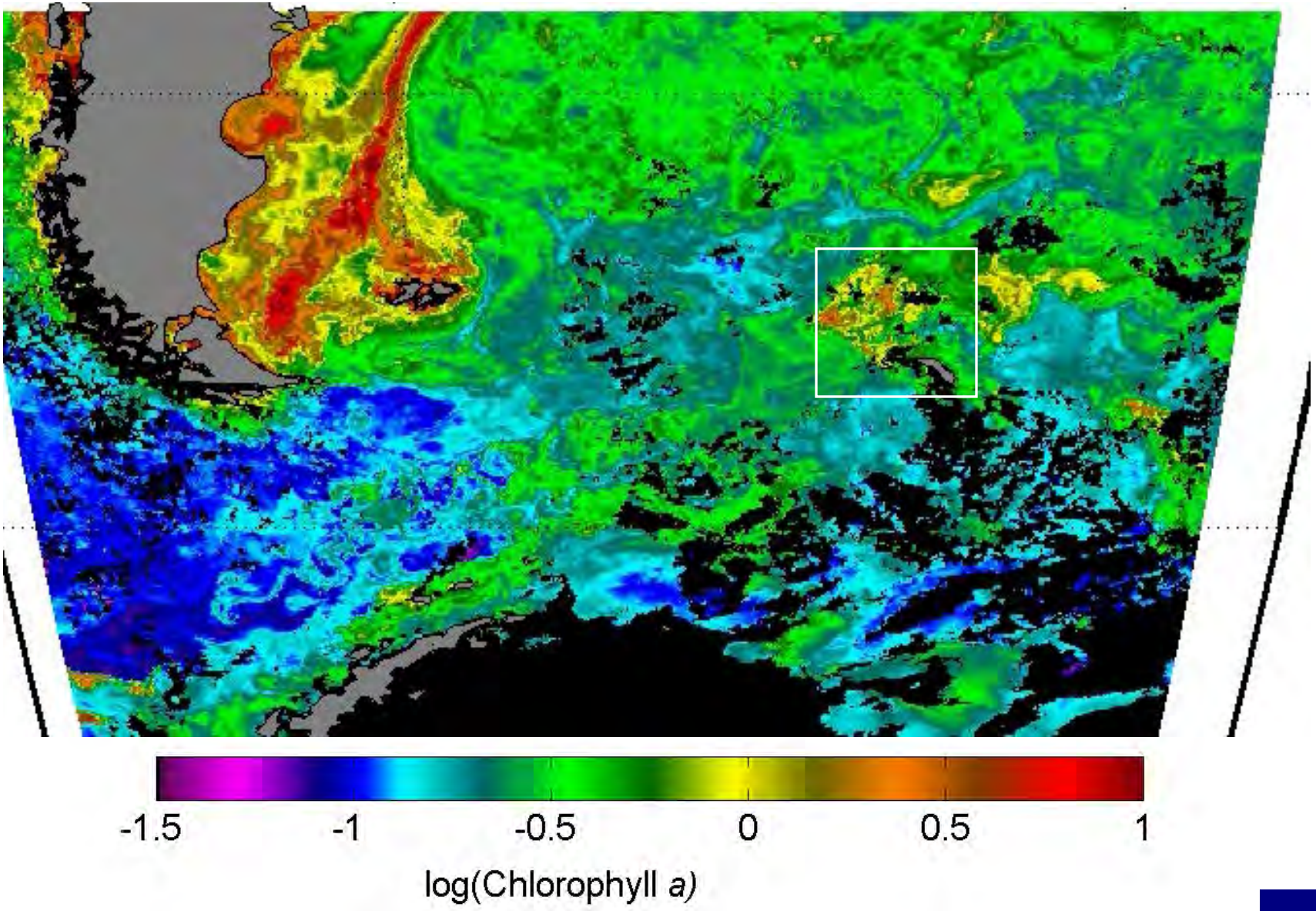


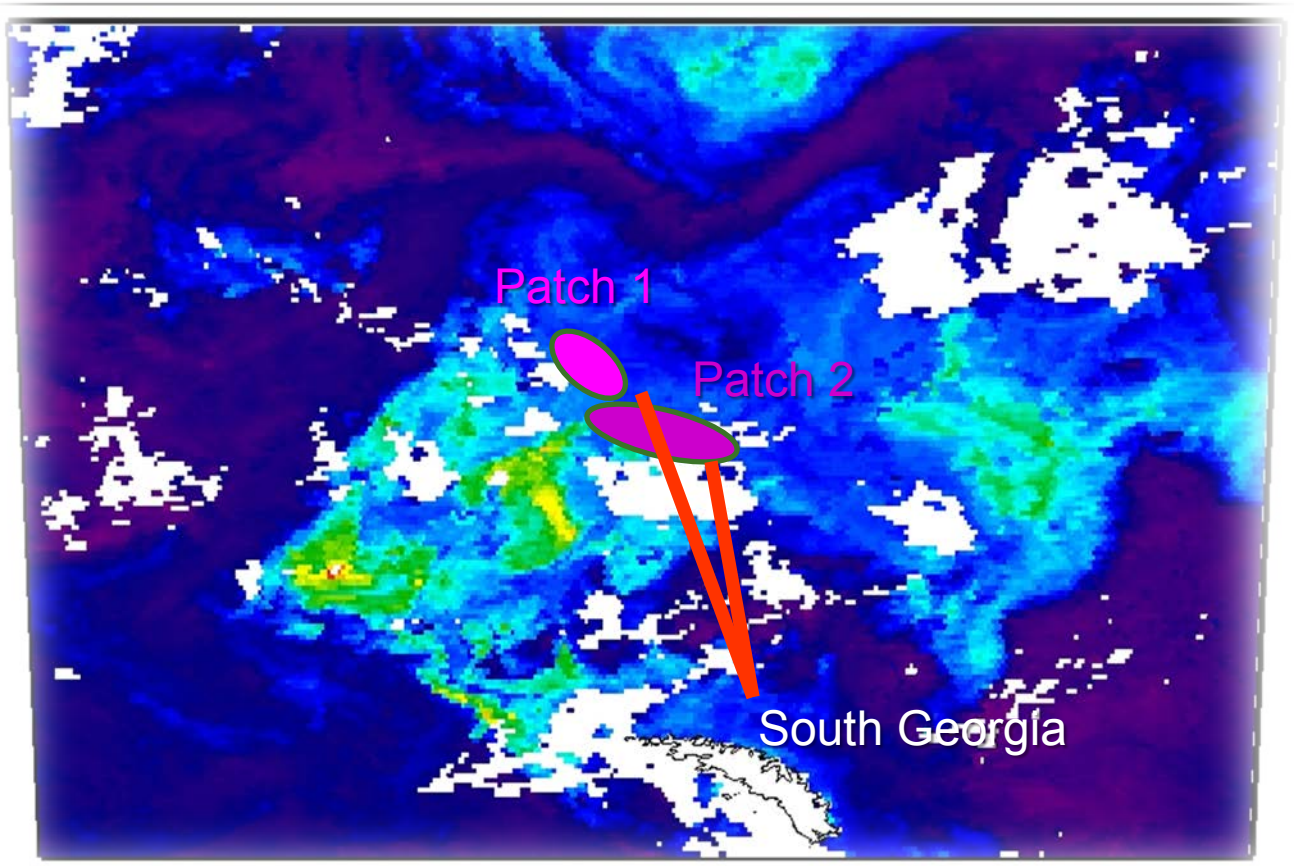
Detached Coccolith

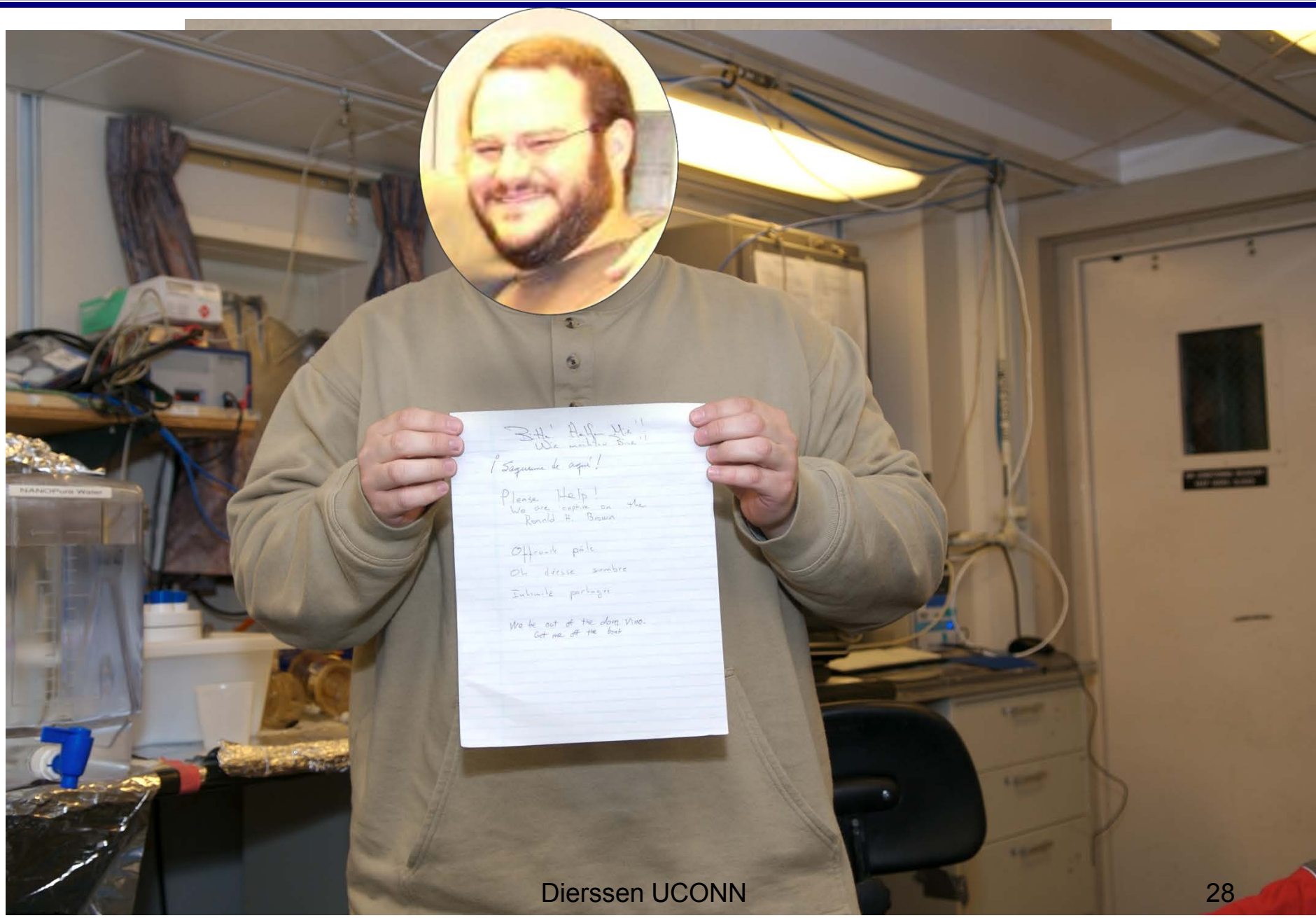
Particulate Inorganic Carbon Measurements

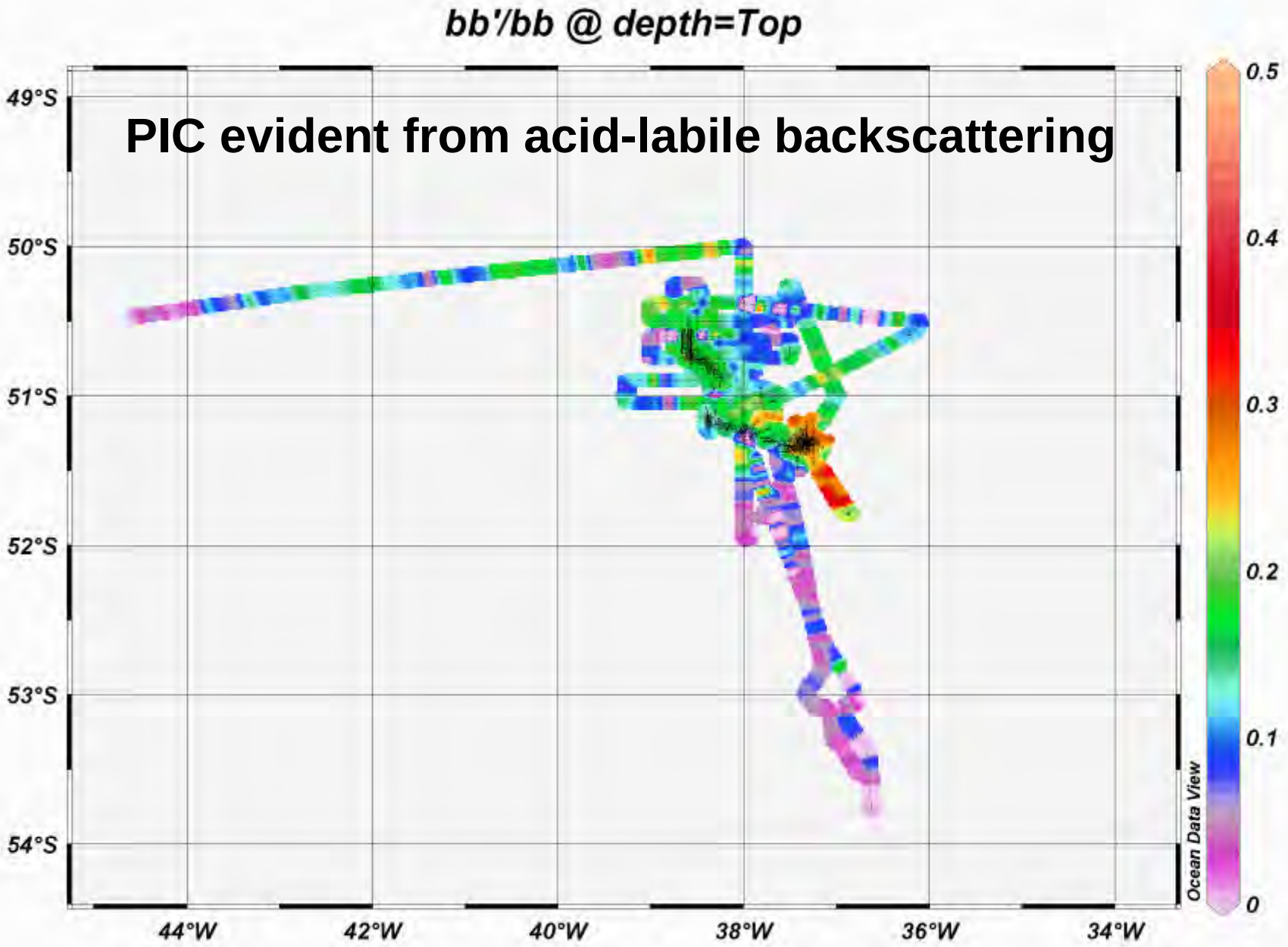
- Acid Labile Backscattering (Balch et al.)
  - Difference between raw and acidified backscattering
- HPLC
  - pigment markers
  - *Prymnesiophytes*
- Calcite measurements
- Coccolithophore/ coccolith enumeration

Chlorophyll March 2008

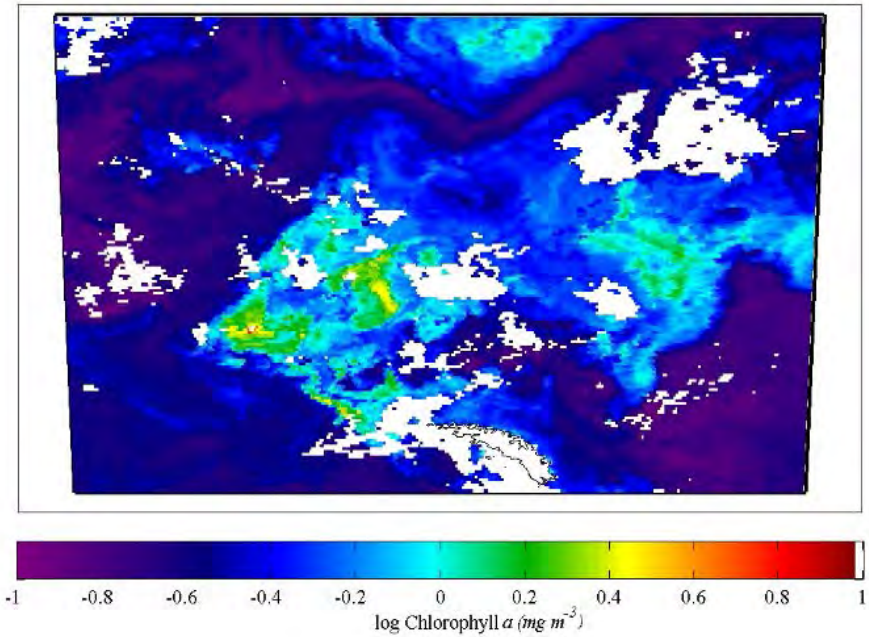



Patch 1
Patch 2
South Georgia

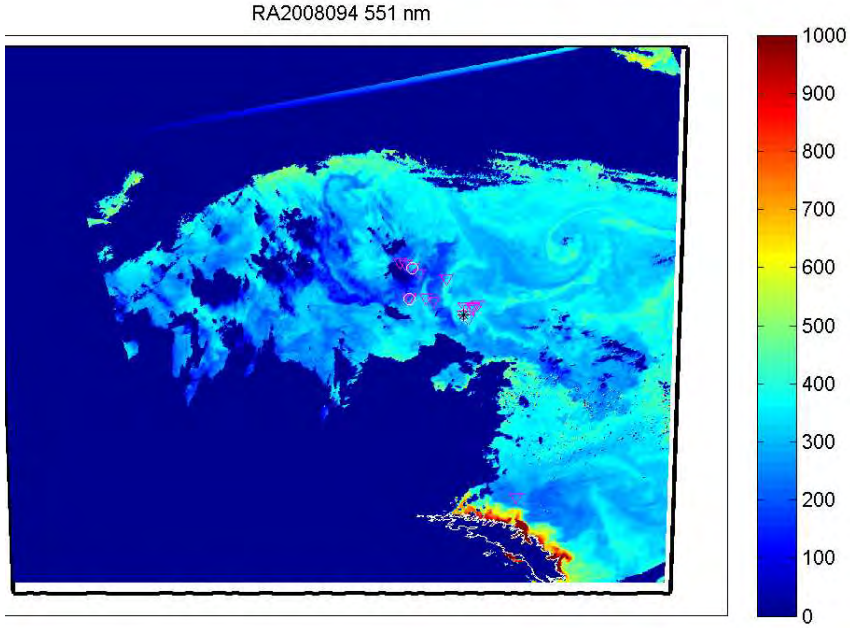

Help! Help!
We are captive on the Ronald H. Brown
Offroute pole
Oh dresse sombre
Intimate portuguese
We be out of the olive vine.
Get me off the boat

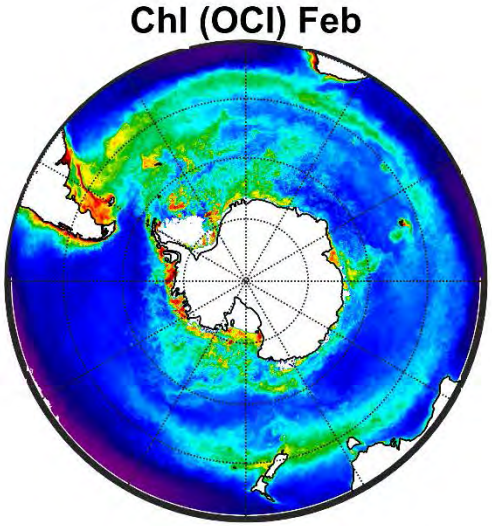

bb'/bb @ depth=Top
PIC evident from acid-labile backscattering
49°S
50°S
51°S
52°S
53°S
54°S
44°W
42°W
40°W
38°W
36°W
34°W
0.5
0.4
0.3
0.2
0.1
0
Ocean Data View

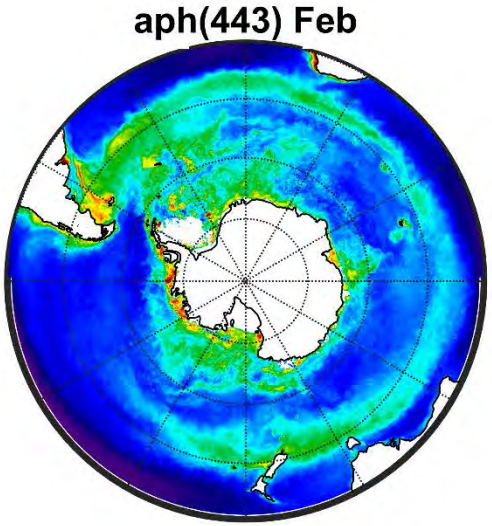
Chlorophyll

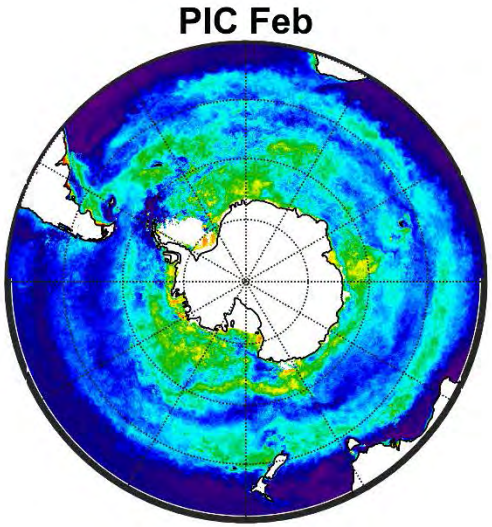


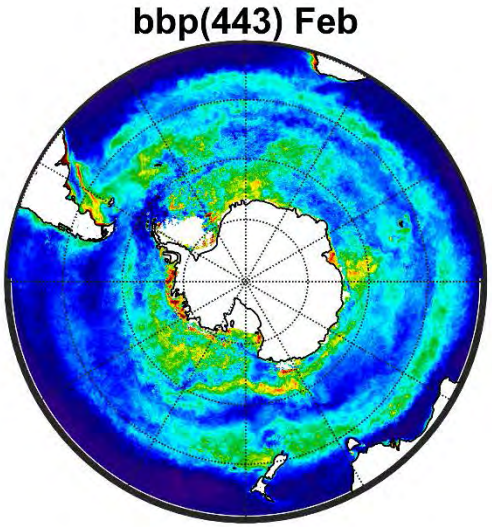
Water leaving radiance



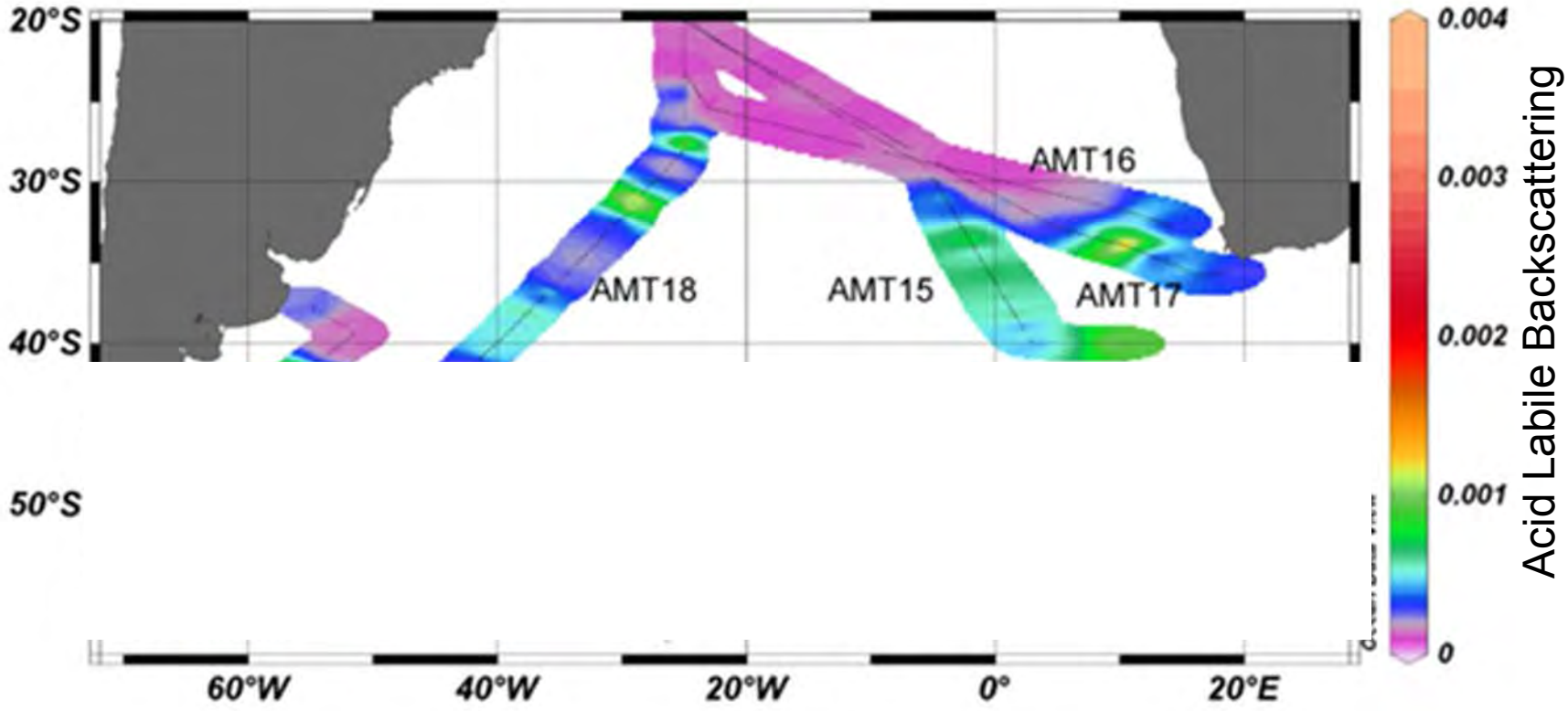

Chl (OCI) Feb

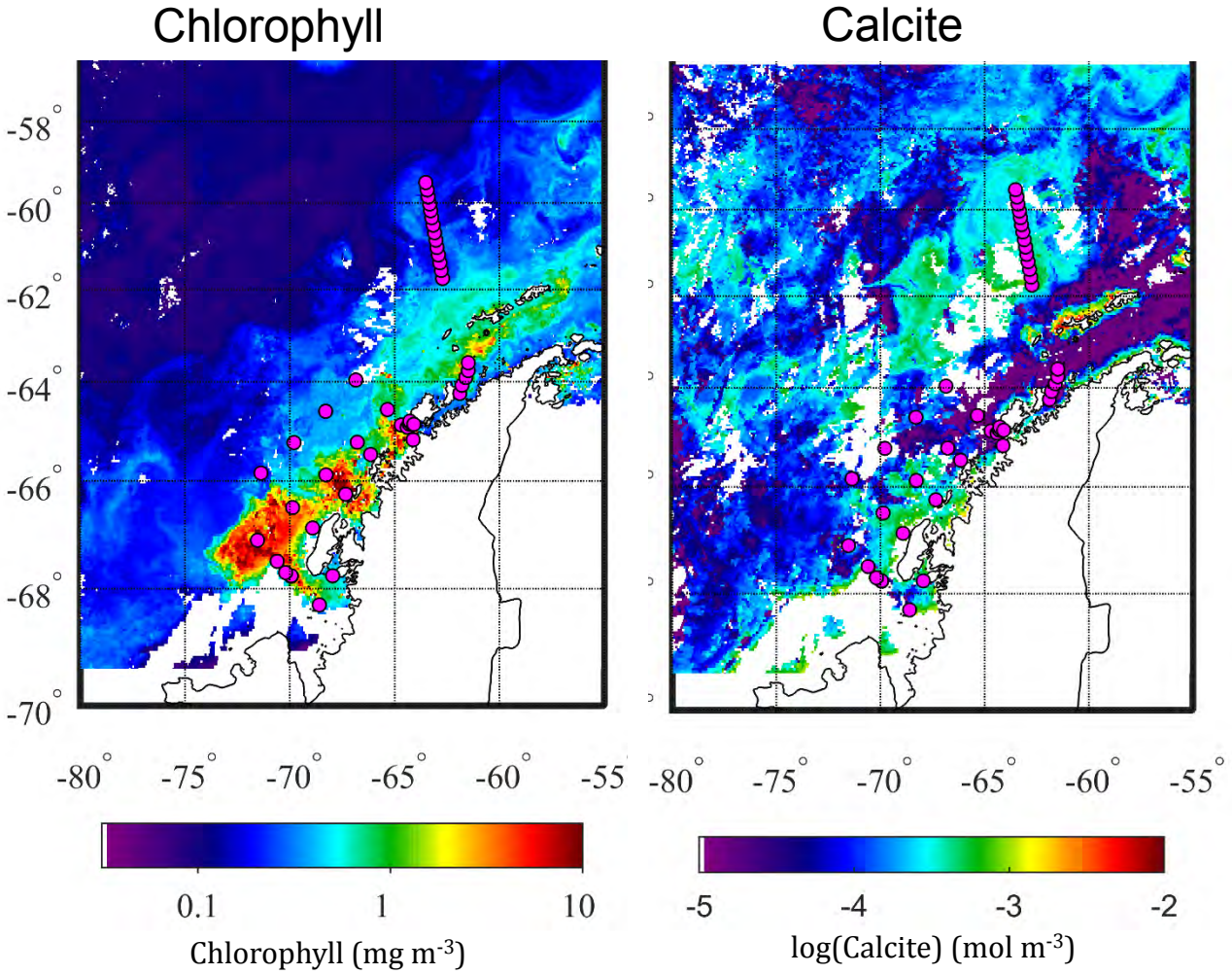

aph(443) Feb


PIC Feb


bbp(443) Feb

PIC evident from acid-labile backscattering





Collected Jan-Feb 2016 by Shungu Garaba
Collaboration ORCAS/PalLTER

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2013JC009227

Optical measurements of small deeply penetrating bubble populations generated by breaking waves in the Southern Ocean

Kaylan Randolph[1], Heidi M. Dierssen[1], Michael Twardowski[2], Alejandro Cifuentes-Lorenzen[1], and Christopher J. Zappa[3]

[1]Department of Marine Sciences, University of Connecticut, Groton, Connecticut, USA, [2]WET Labs Inc., Narragansett, Rhode Island, USA, [3]Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA

Key Points:

- Bubble size distributions (0.5–60 μm radius) were measured during wave breaking
- Bubbles ≤30 μm in radius supplied ~30% of the void fraction at 4 m depth
- Bubble populations were presented

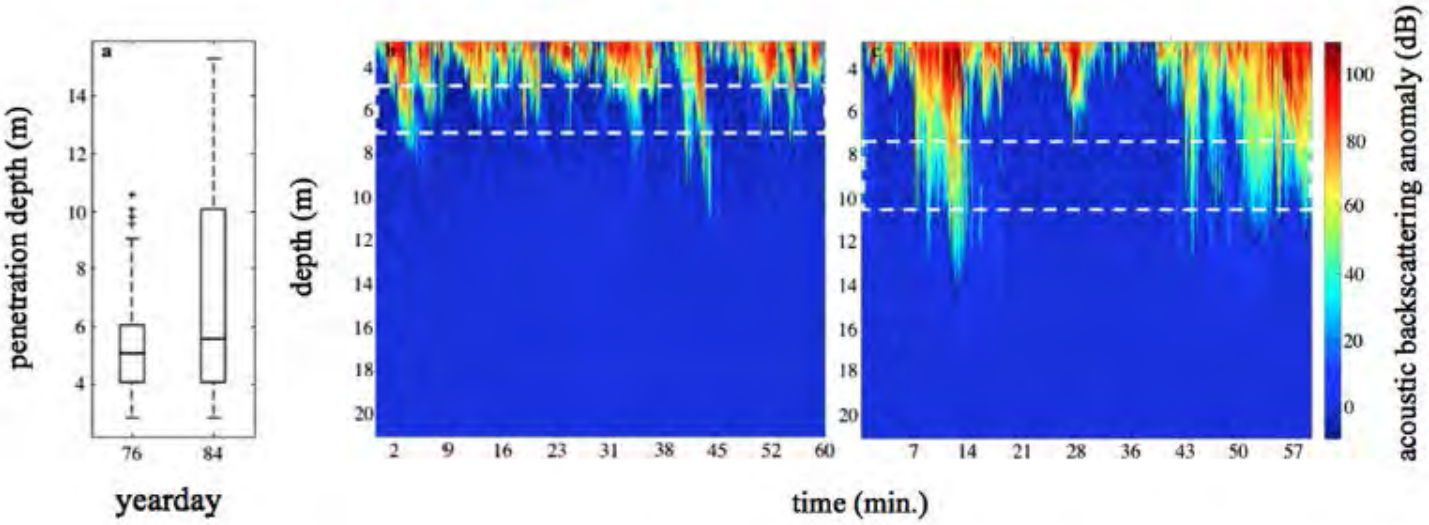
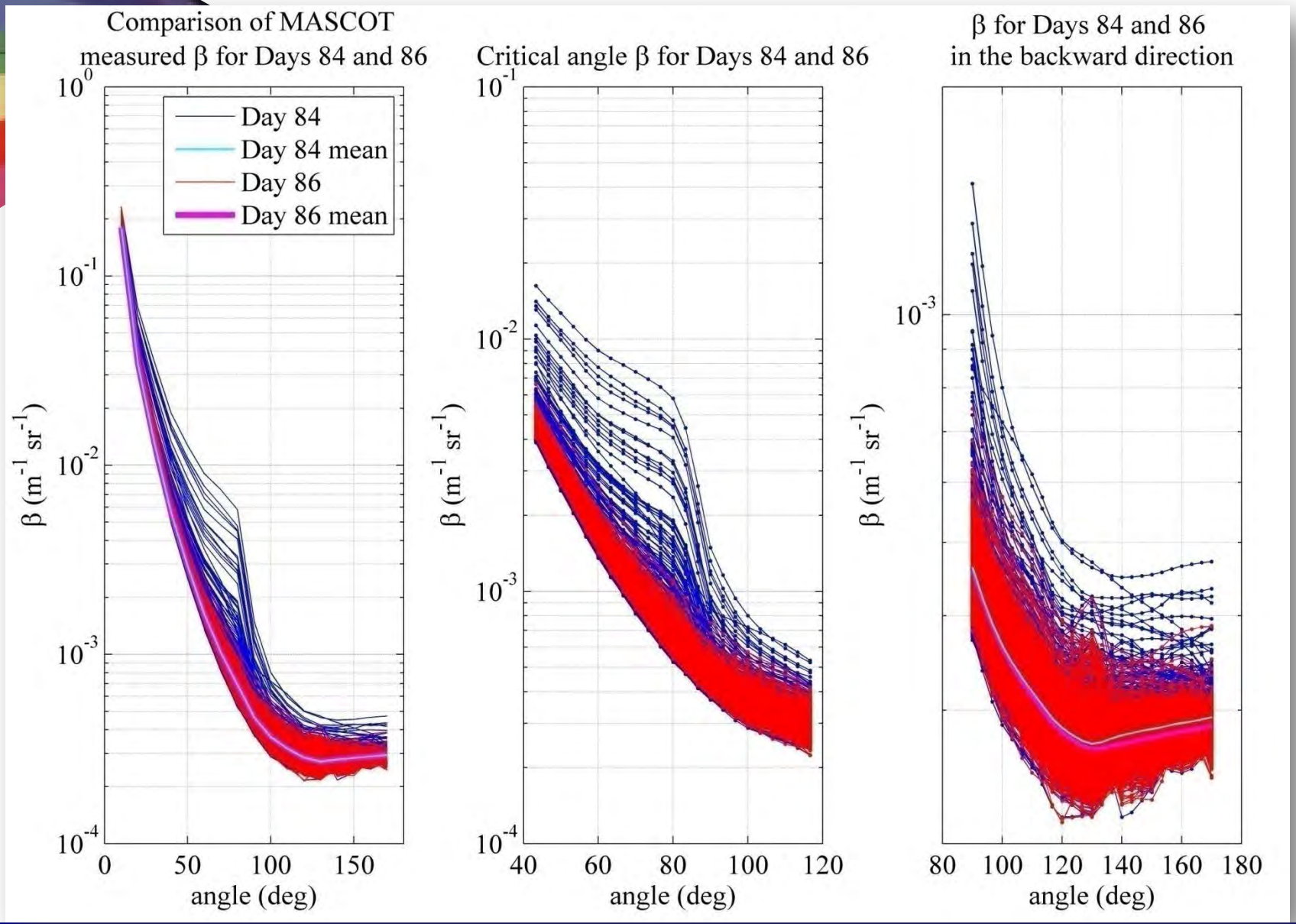
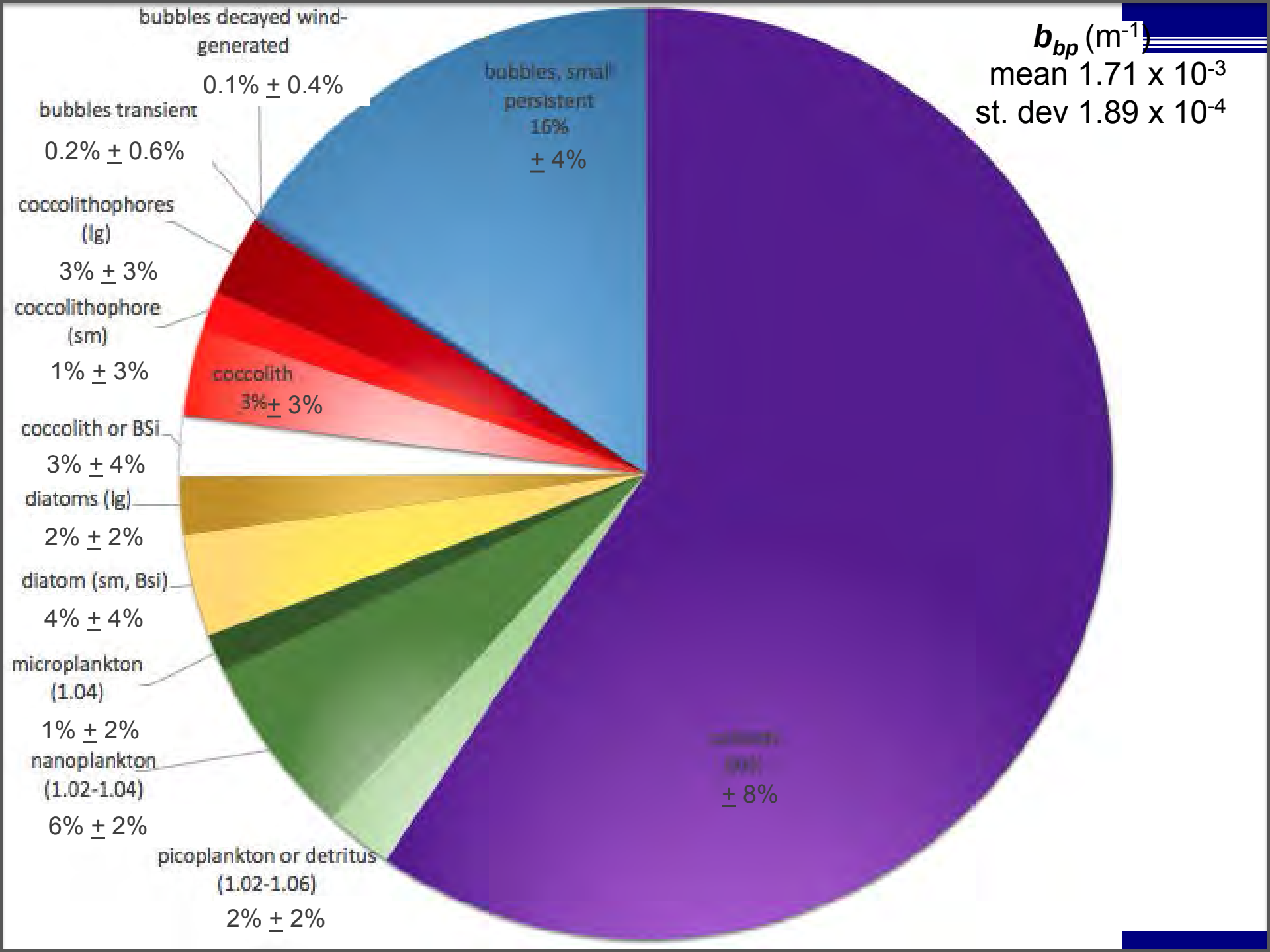
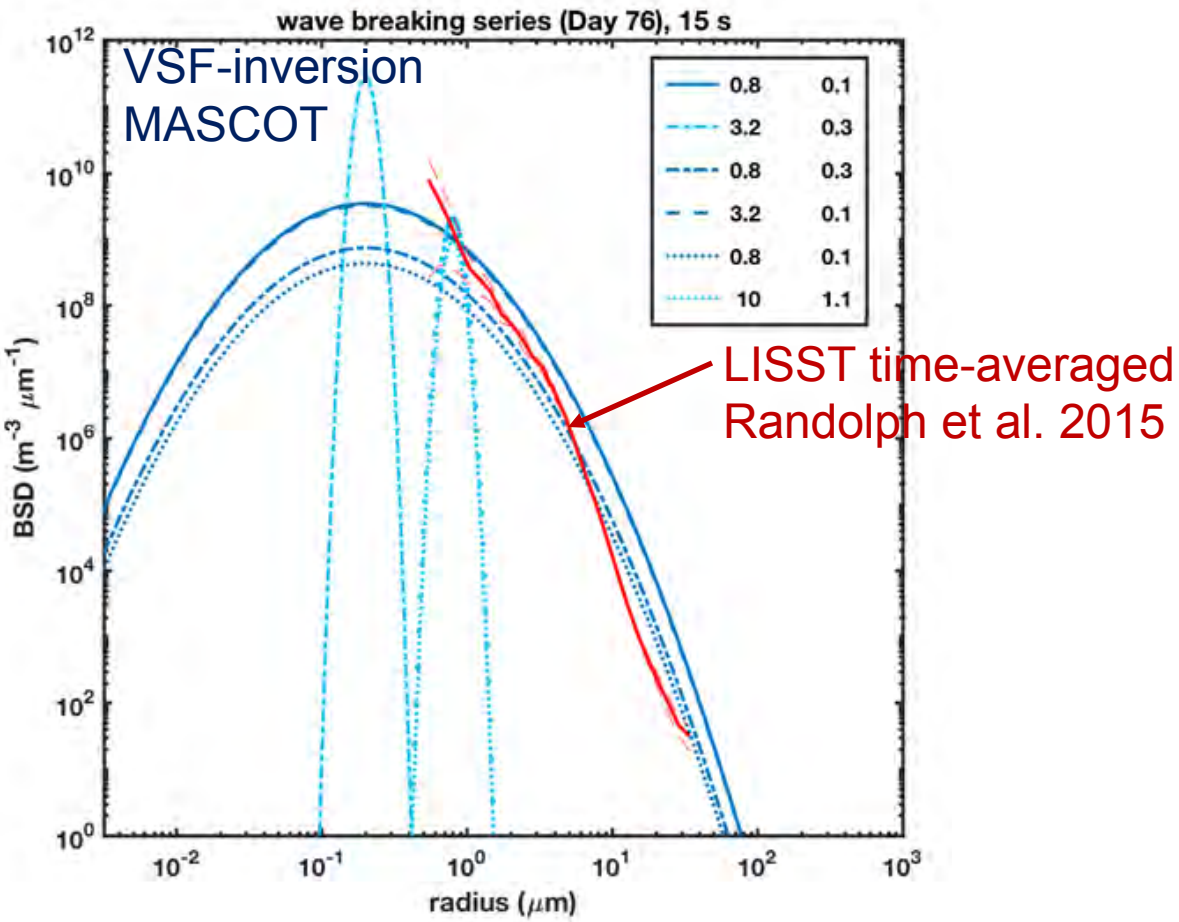


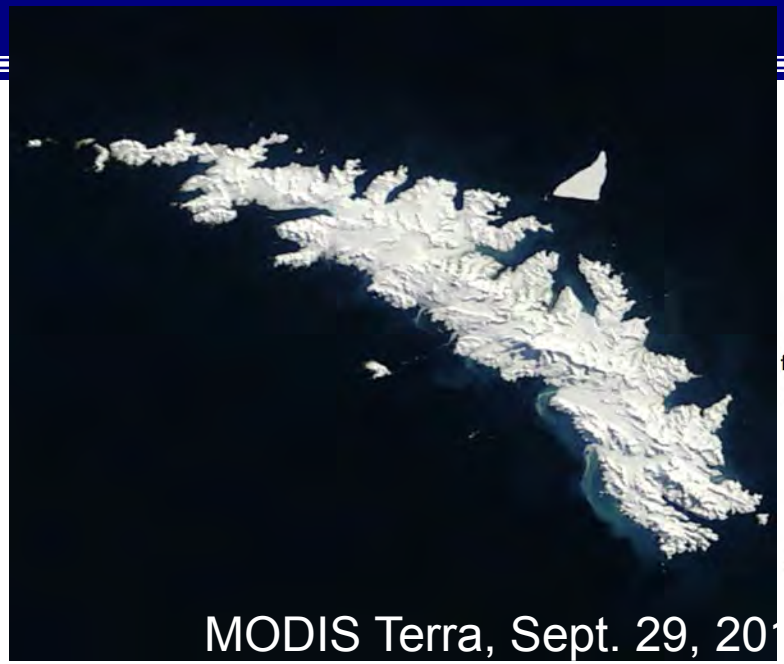
Figure 11. (a) Bubble plume penetration depths estimated using time series measurements of acoustic backscatter anomaly (dB) collected on yeardays, (b) 76, and (c) 84. In Figure 11a, the box denotes the lower quartile, median, and upper quartile penetration depth values. The whiskers show the range of the data and the pluses denote outliers. High temporal resolution plots of the acoustic backscatter anomaly over the 1 h sampling period show intense breaking on (a) yeardays 76 and (b) 84 days produced bubble plumes that extended to 10 and 15 m, respectively. No acoustic data were collected on yearday 80.

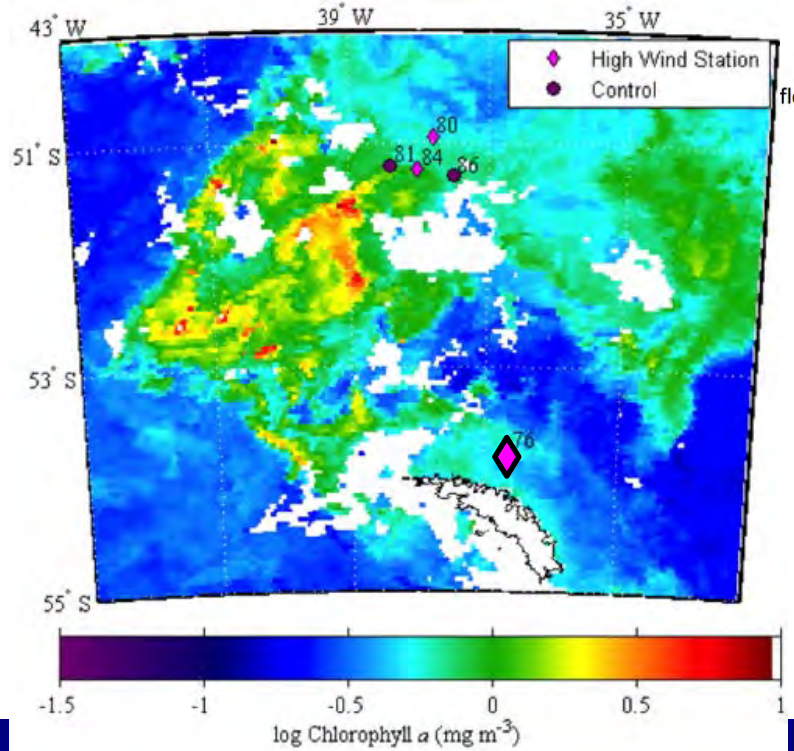

Comparison of MASCOT
measured β for Days 84 and 86
Day 84
Day 84 mean
Day 86
Day 86 mean
β (m-1 sr-1)
angle (deg)
Critical angle β for Days 84 and 86
β (m-1 sr-1)
angle (deg)
β for Days 84 and 86
in the backward direction
β (m-1 sr-1)
angle (deg)


bubbles decayed wind-generated
0.1% ± 0.4%
bubbles transient
0.2% ± 0.6%
coccolithophores (lg)
3% ± 3%
coccolithophore (sm)
1% ± 3%
coccolith or BSi
3% ± 4%
diatoms (lg)
2% ± 2%
diatom (sm, Bsi)
4% ± 4%
microplankton (1.04)
1% ± 2%
nanoplankton (1.02-1.04)
6% ± 2%
picoplankton or detritus (1.02-1.06)
2% ± 2%
bubbles, small persistent
16%
± 4%
coccolith
3% ± 3%
± 8%
b_{bp} (m^{-1})
mean 1.71 x 10^{-3}
st. dev 1.89 x 10^{-4}

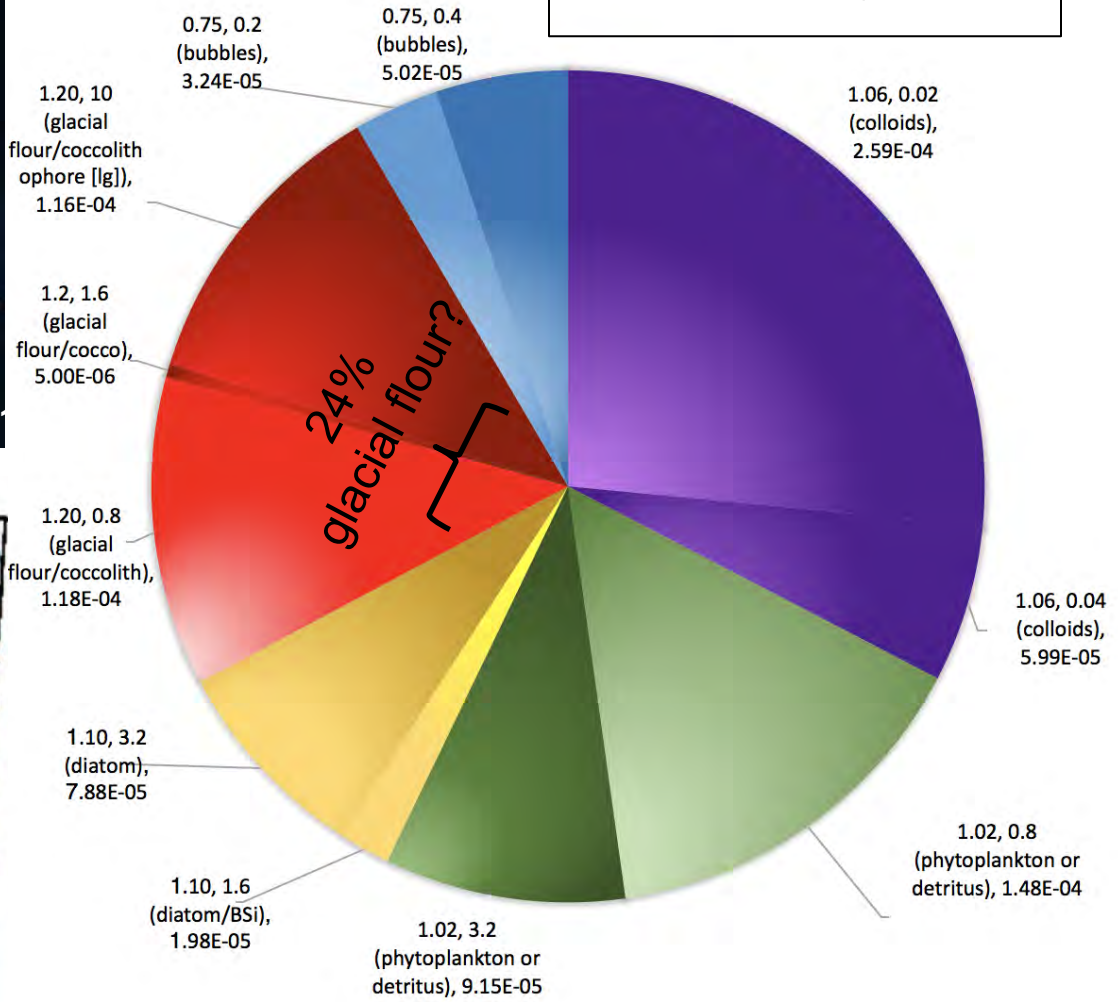


Bubble size distribution measured over 15 s wave breaking event
Shift from large broad distribution to small persistent bubbles 0.1-1 um





PSD Mode radius, σ
Subpopulation b_{bp} (m^{-1})



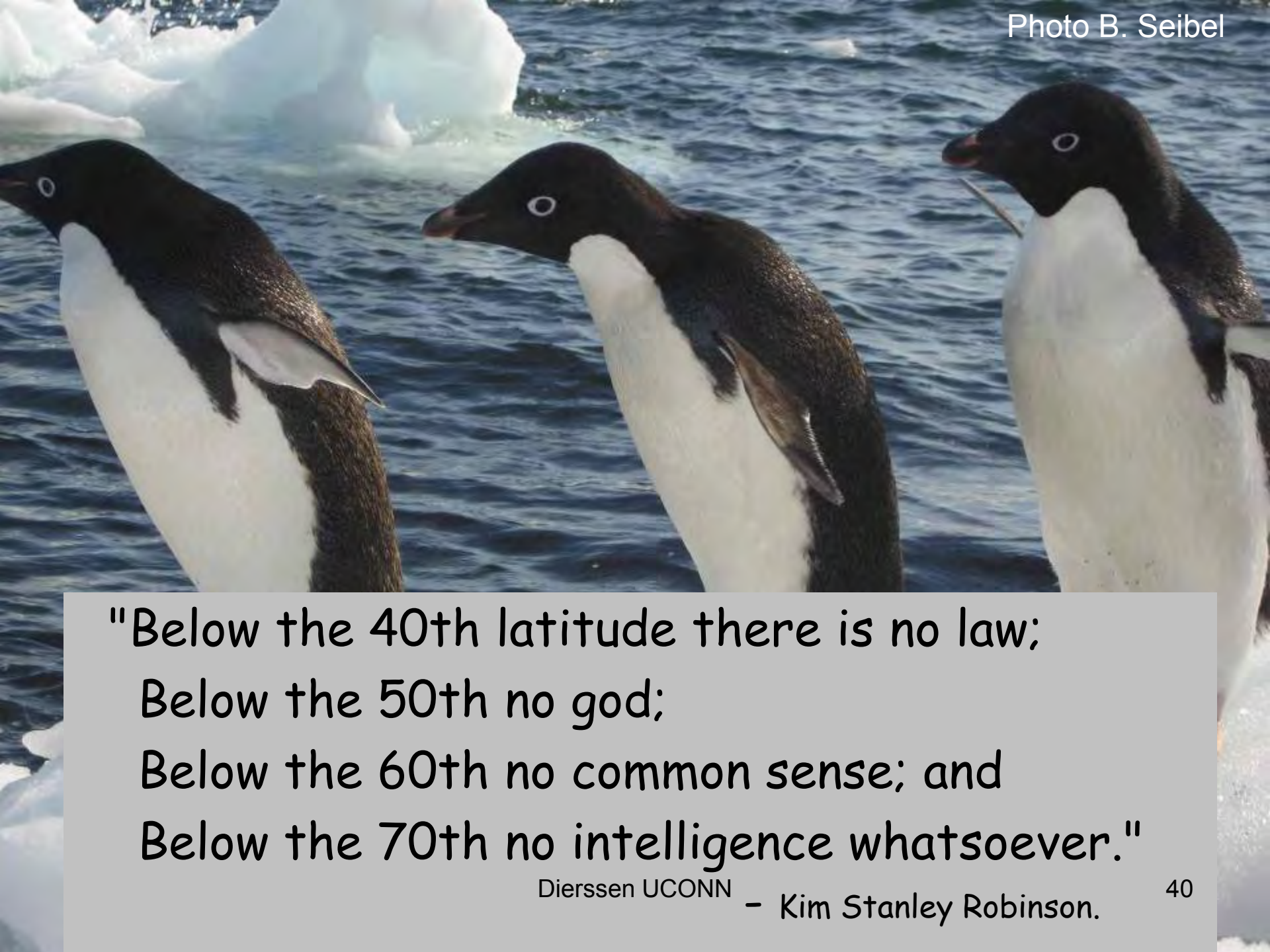
Here, total $b_{bp} = 9.79 \times 10^{-4}$

Some food for thought

- New technology can lead to a better understanding of sources of backscattering to assess algorithms and inorganic and organic carbon

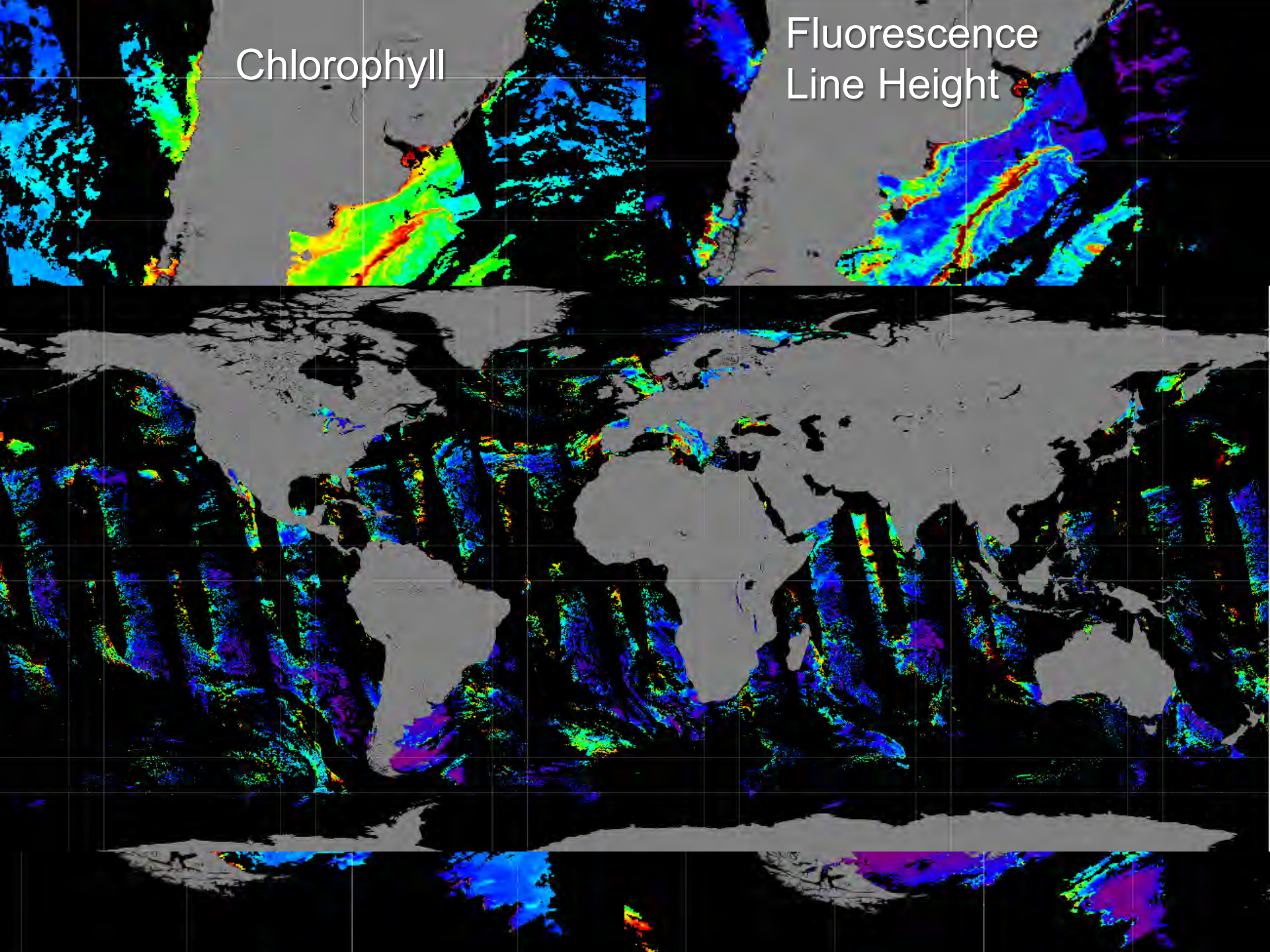
- Move away from band ratio algorithms that are highly sensitive to background bbp in this region – Case 2

- Interaction between backscattering waters and atmospheric correction algorithms need attention

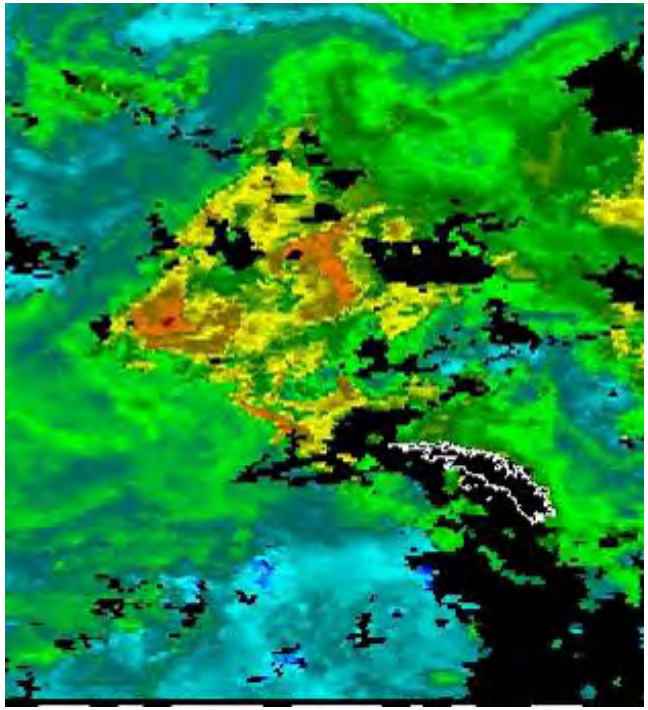


"Below the 40th latitude there is no law;
Below the 50th no god;
Below the 60th no common sense; and
Below the 70th no intelligence whatsoever."

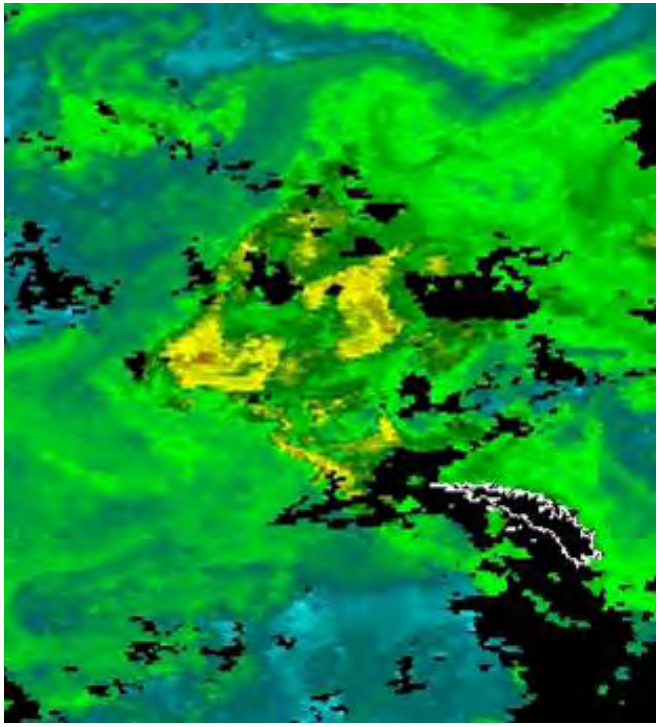
– Kim Stanley Robinson.


Chlorophyll
Fluorescence
Line Height

Enhanced Radiance consistent with chlorophyll patches



Chlorophyll (mg m^{-3})



Normalized Radiance

Lw551 (mW cm^{-2} mm^{-1} sr^{-1})