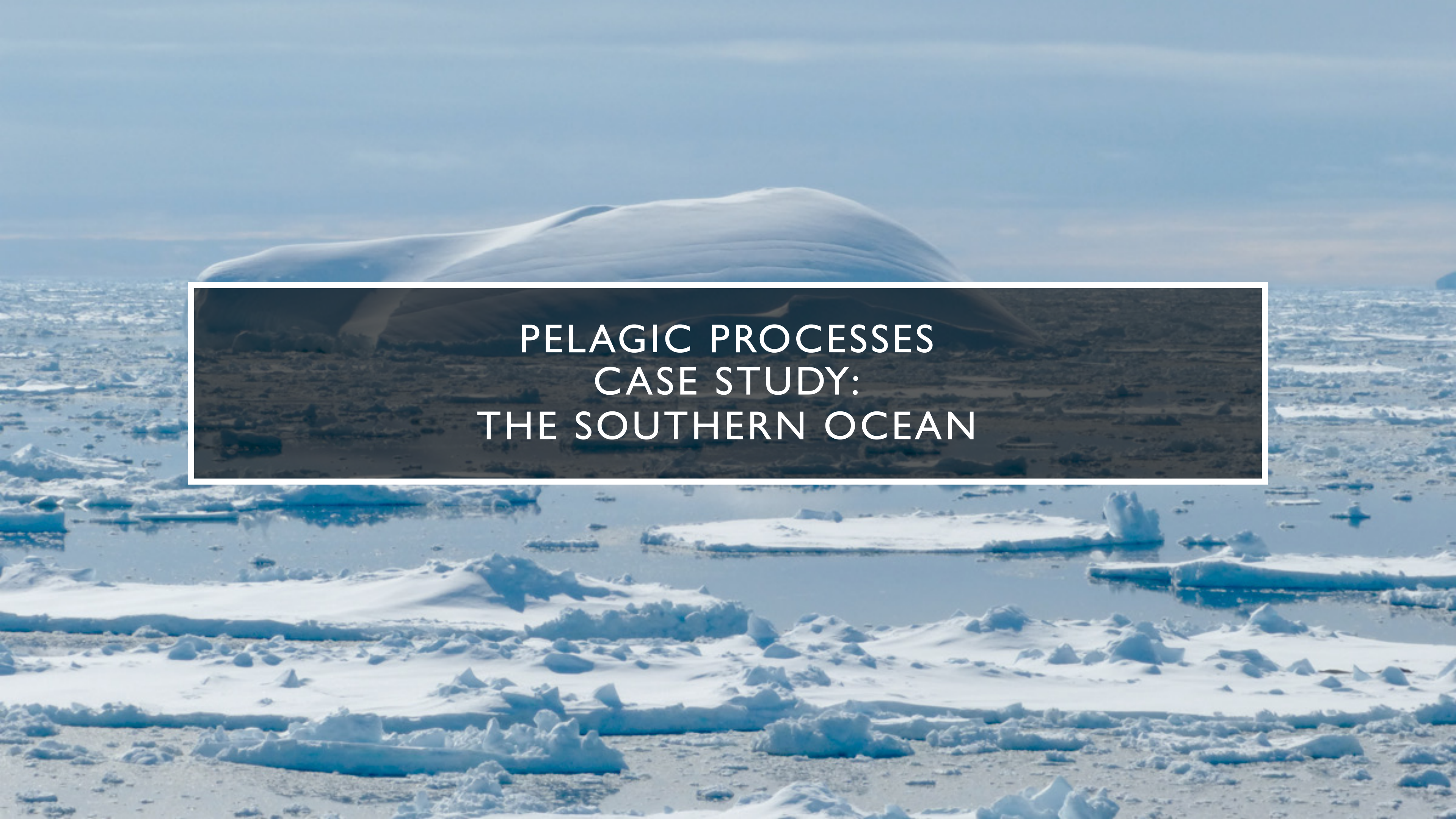
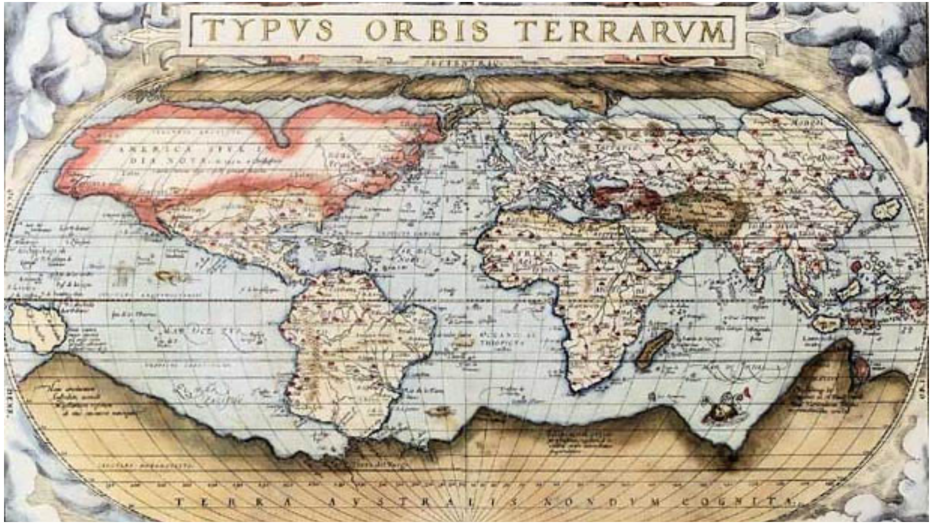


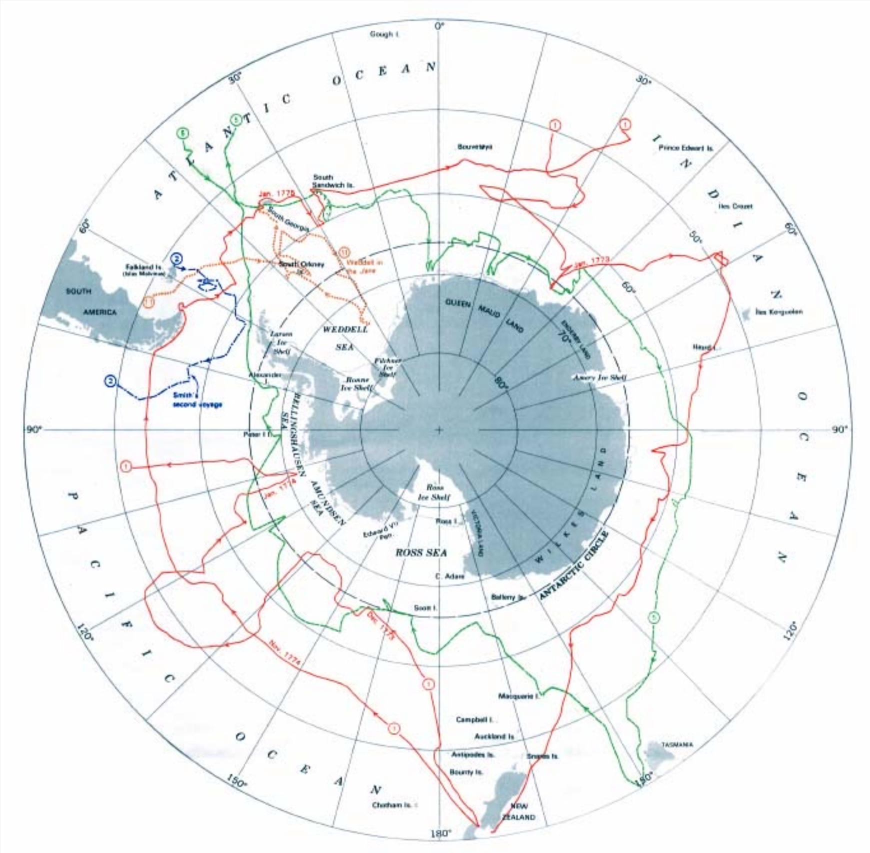
PELAGIC PROCESSES
CASE STUDY:
THE SOUTHERN OCEAN



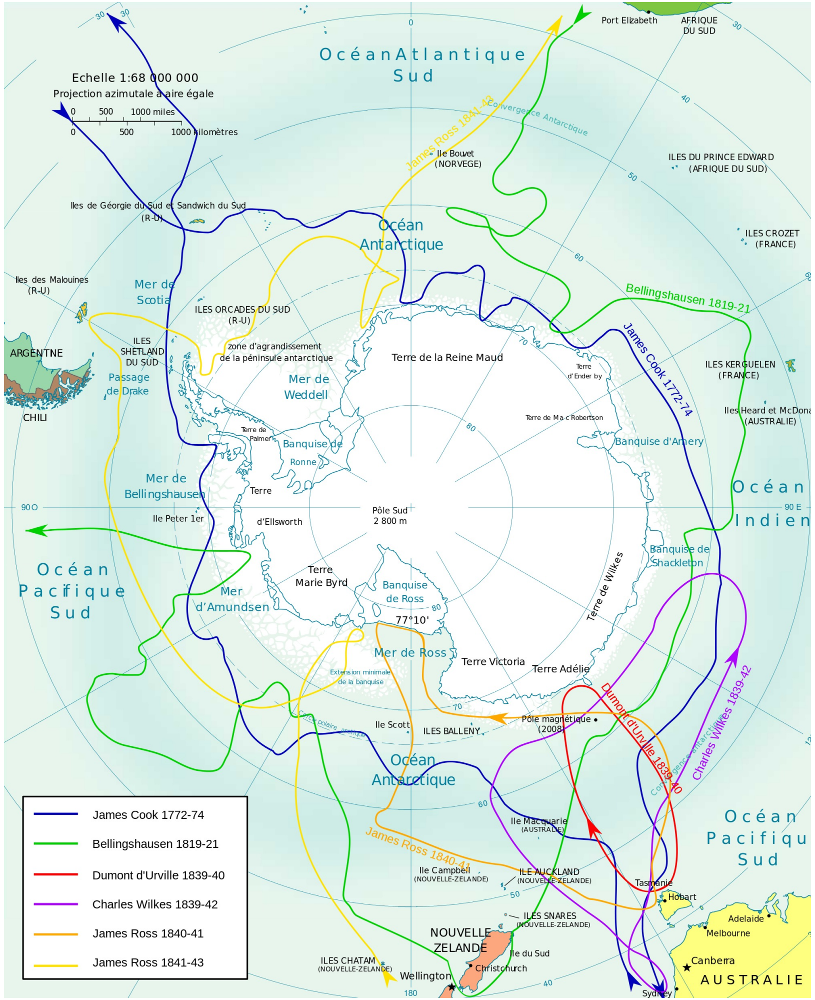
1570: WORLD MAP BY ORTELIU

JAMES COOK'S SECOND VOYAGE (1772–75)

- First to enter the Antarctic Circle, Reports of great numbers of seals and whales
- Image Source: Antarctic Map Folio Series, 1975



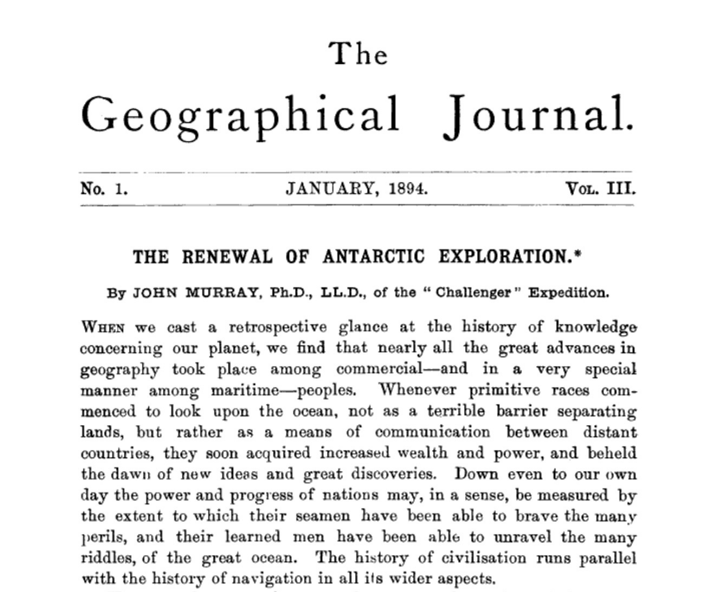
1819-1843



Océan Atlantique Sud
Echelle 1:68 000 000
Projection azimutale à aire égale
0 500 1000 miles
0 500 1000 kilomètres
Port Elizabeth
AFRIQUE DU SUD
Convergence Antarctique
James Ross 1841-43
Ile Bouvet (NORVEGE)
ILES DU PRINCE EDWARD (AFRIQUE DU SUD)
Iles de Géorgie du Sud et Sandwich du Sud (R-U)
Océan Antarctique
ILES CROZET (FRANCE)
Iles des Malouines (R-U)
Mer de Scotia
ILES ORCADES DU SUD (R-U)
Bellingshausen 1819-21
ARGENTINE
ILES SHETLAND DU SUD
zone d'agrandissement de la péninsule antarctique
Terre de la Reine Maud
Terre d'Enderby
James Cook 1772-74
ILES KERGUELEN (FRANCE)
Passage de Drake
Mer de Weddell
CHILI
Terre de Mac Robertson
Iles Heard et McDonald (AUSTRALIE)
Terre de Palmer
Banquise de Ronne
Banquise d'Amery
Mer de Bellingshausen
Terre d'Ellsworth
Océan Indien
Ile Peter 1er
Pôle Sud 2 800 m
Banquise de Shackleton
Océan Pacifique Sud
Terre Marie Byrd
Mer d'Amundsen
Banquise de Ross
Terre de Wilkes
77°10'
Mer de Ross
Terre Victoria
Terre Adélie
Extension minimale de la banquise
Dumont d'Urville 1839-40
Charles Wilkes 1839-42
Ile Scott
ILES BALLENY
Pôle magnétique (2008)
Océan Antarctique
Ile Macquarie (AUSTRALIE)
Océan Pacifique Sud
James Ross 1840-41
Ile Campbell (NOUVELLE-ZELANDE)
ILE AUCKLAND (NOUVELLE-ZELANDE)
Tasmanie
Hobart
ILES SNARES (NOUVELLE-ZELANDE)
Adelaide
Melbourne
NOUVELLE ZELANDE
Ile du Sud
ILES CHATAM (NOUVELLE-ZELANDE)
Christchurch
Canberra
Wellington
Sydney
AUSTRALIE
James Cook 1772-74
Bellingshausen 1819-21
Dumont d'Urville 1839-40
Charles Wilkes 1839-42
James Ross 1840-41
James Ross 1841-43

HEROIC AGE 1897-1922

"The Renewal of Antarctic Exploration", given to the Royal geographical Society in London, November 27, 1893


The

Geographical Journal.

No. 1. JANUARY, 1894. Vol. III.

THE RENEWAL OF ANTARCTIC EXPLORATION.*

By JOHN MURRAY, Ph.D., LL.D., of the "Challenger" Expedition.

When we cast a retrospective glance at the history of knowledge concerning our planet, we find that nearly all the great advances in geography took place among commercial—and in a very special manner among maritime—peoples. Whenever primitive races commenced to look upon the ocean, not as a terrible barrier separating lands, but rather as a means of communication between distant countries, they soon acquired increased wealth and power, and beheld the dawn of new ideas and great discoveries. Down even to our own day the power and progress of nations may, in a sense, be measured by the extent to which their seamen have been able to brave the many perils, and their learned men have been able to unravel the many riddles, of the great ocean. The history of civilisation runs parallel with the history of navigation in all its wider aspects.

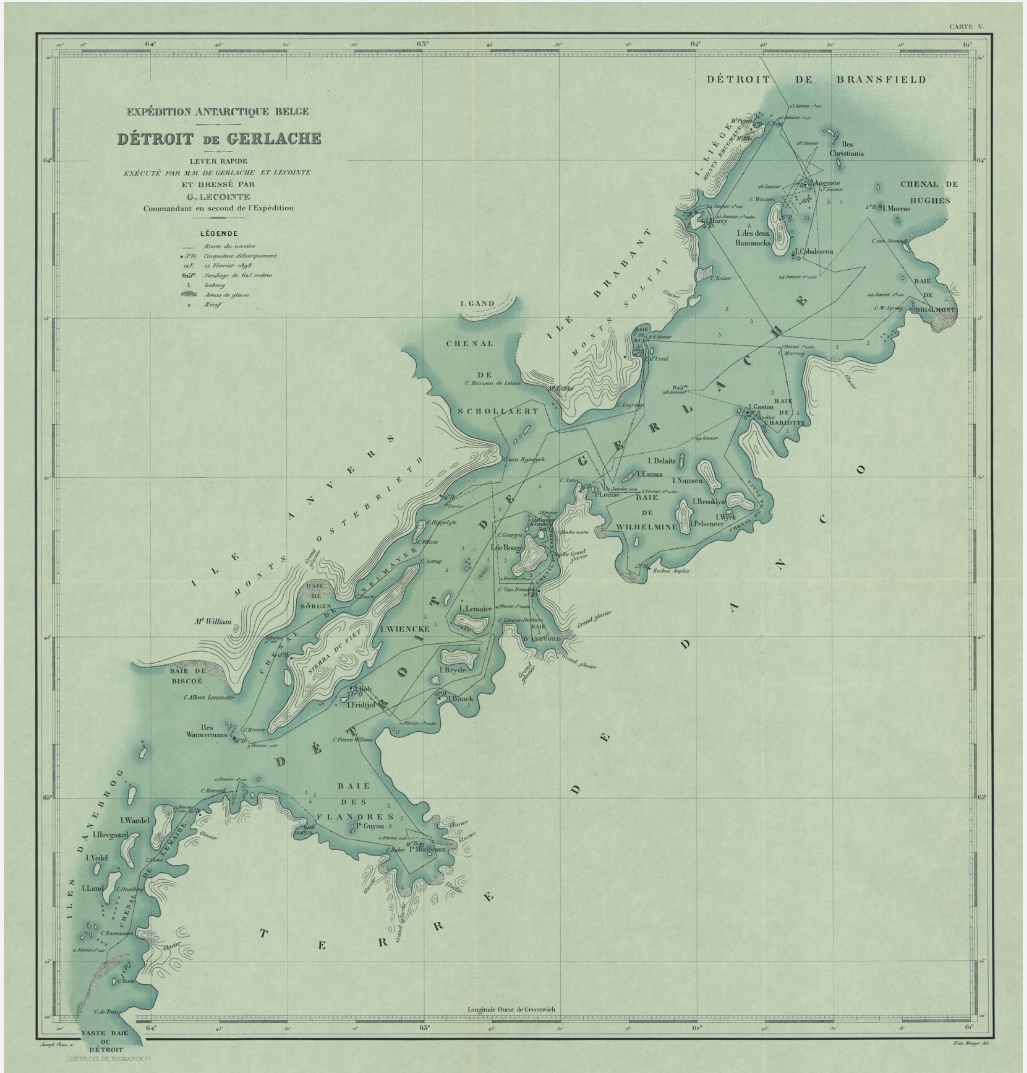
1897-1899 BELGIAN ANTARCTIC EXPEDITION

First international purely scientific expedition

First expedition to winter within the Antarctic Circle

1 year of meteorological observations

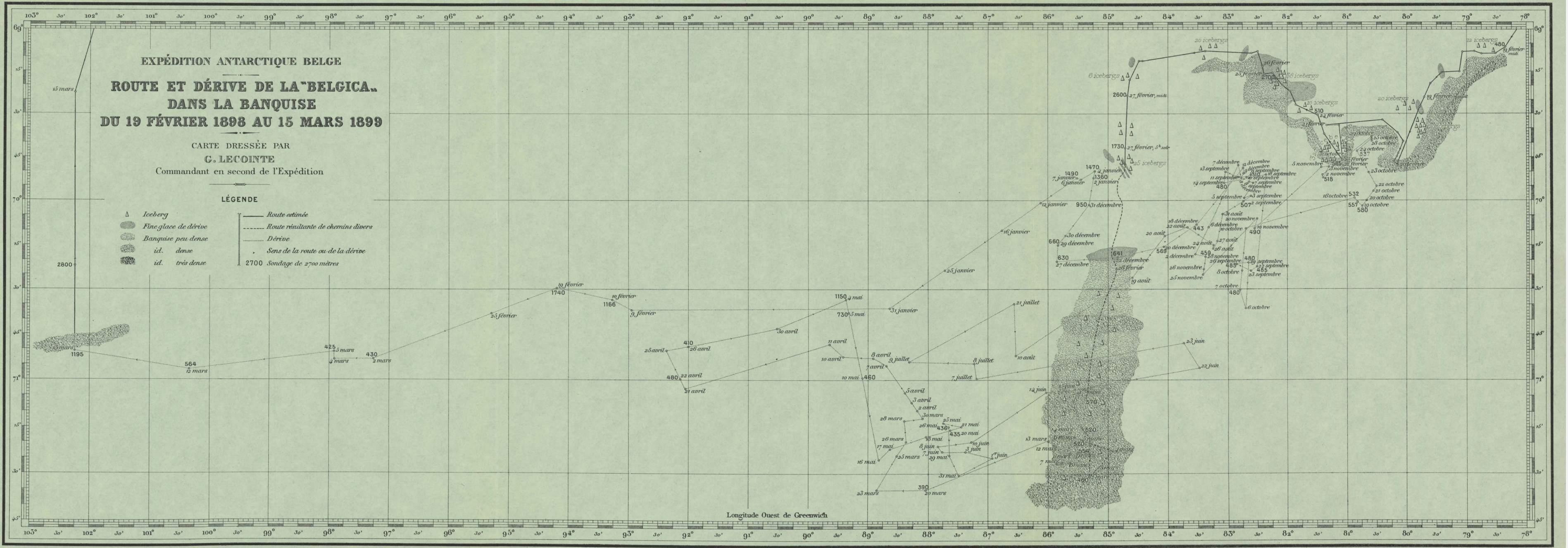
- Detroite de Belgica



June
3th

“The calm before the storm” F. Cook

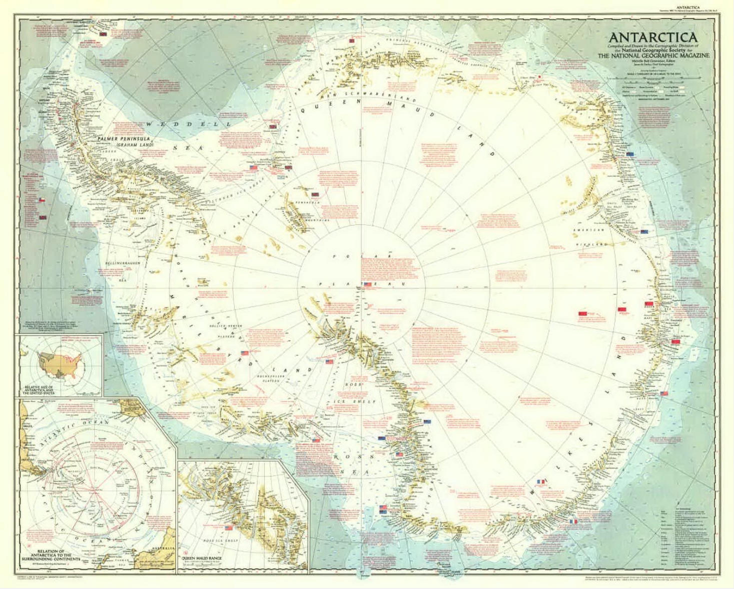
Gerlache Family Collection

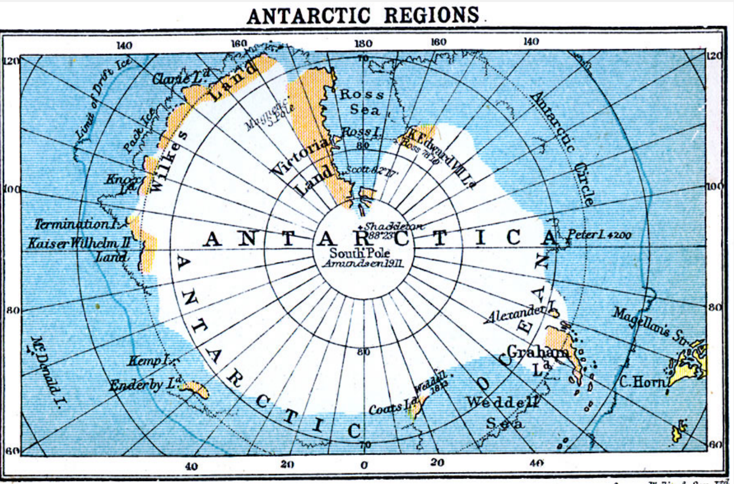


Joseph Claes, sc.

Fritz Menger, del.

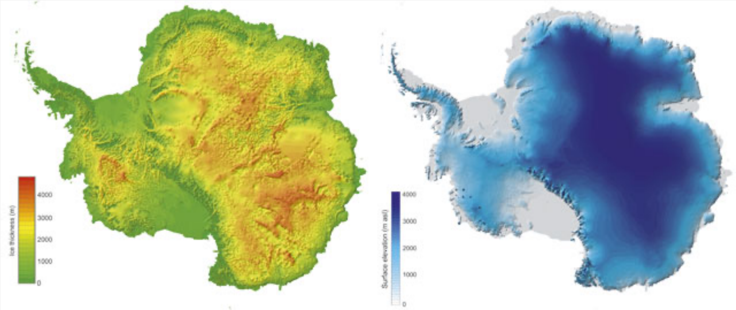
Cutting a Canal to Release the Belgica

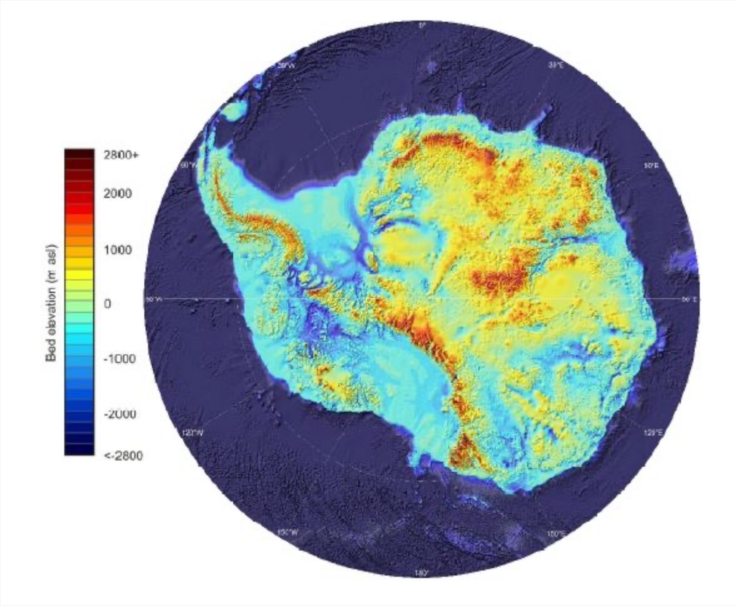




1920-1983

- 2nd International Polar Year
- International Geophysical Year of 1957-1958





Continent: 14 M km^2

Continental shelf deeper than usual (500-900m: 4x global ocean average)

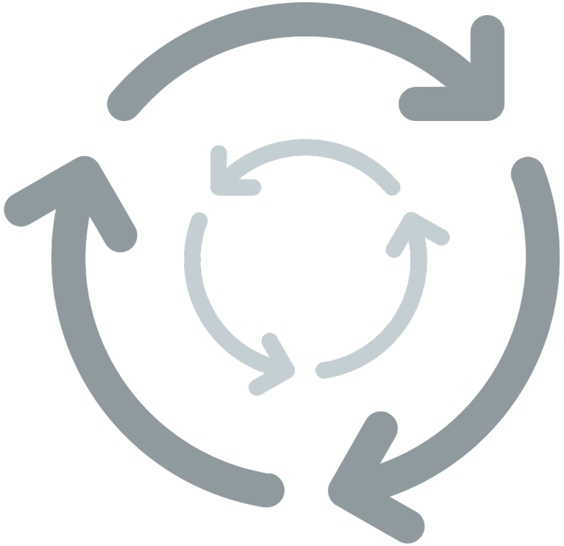
- Due to isostasic subsidence > ice mass on the continent (24.10^{15} T)
- Narrower: 30-200 km (except Ross and Weddell Seas)
- Basins usually deep (≥ 3000m)

Favours offshore and inshore water exchanges

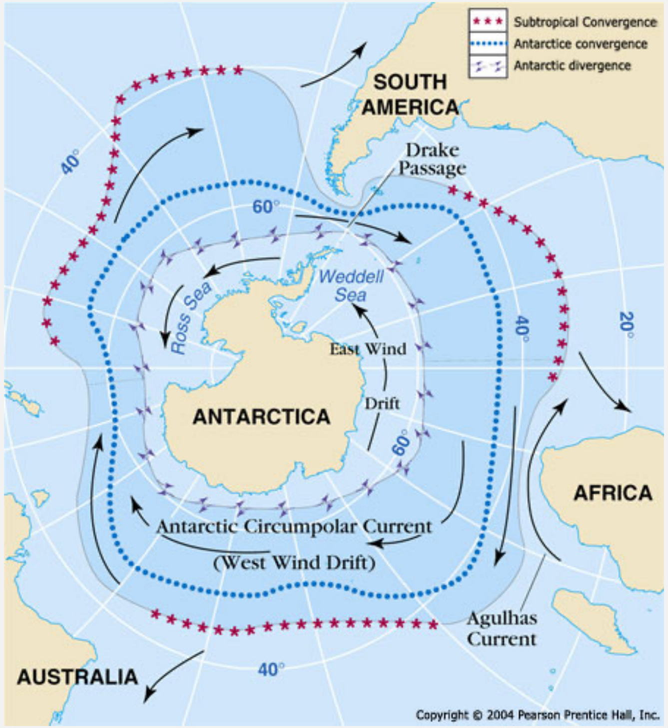
Ocean encircles the continent: increases homogeneity

http://www.antarctica.ac.uk//bas_research/our_research/az/bedmap2/index.php

1. PHYSICO-CHEMICAL ENVIRONMENT



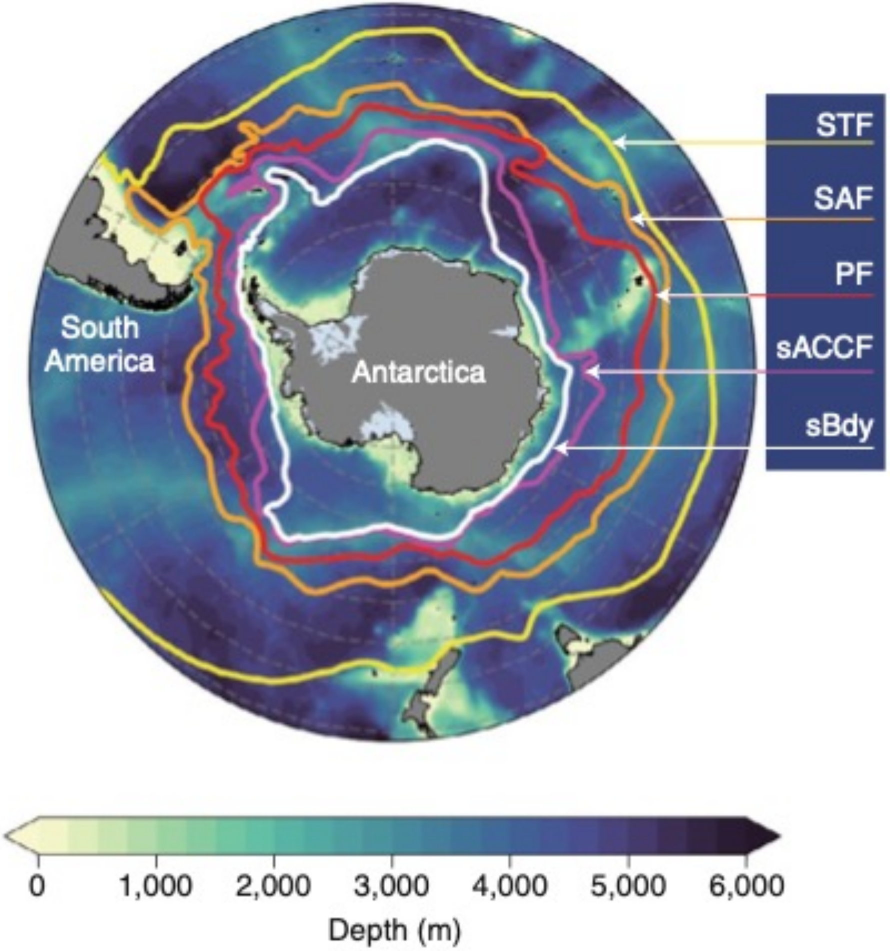
1.1. WATER MASSES AND CIRCULATION



- Coastal current:
  - East wind drift (anticlockwise)
- Offshore current:
  - West wind drift = Antarctic circumpolar current (ACC) (clockwise), main circulation system of Antarctic water masses

FIGURE 4. Circulation of the Southern Ocean, which is bounded by the Antarctic continent and the seafloor south of the Subtropical Convergence (Subantarctic Front Zone). The predominant clockwise trajectory of the West Wind Drift (Antarctic Circumpolar Current) extends south of the Antarctic Convergence (Antarctic Polar Front Zone), which is the northern boundary of the Antarctic marine ecosystem. South of the West Wind Drift is the counter-clockwise East Wind Drift and the Antarctic Divergence between them. (Modified from References 75, 93, and 214.)

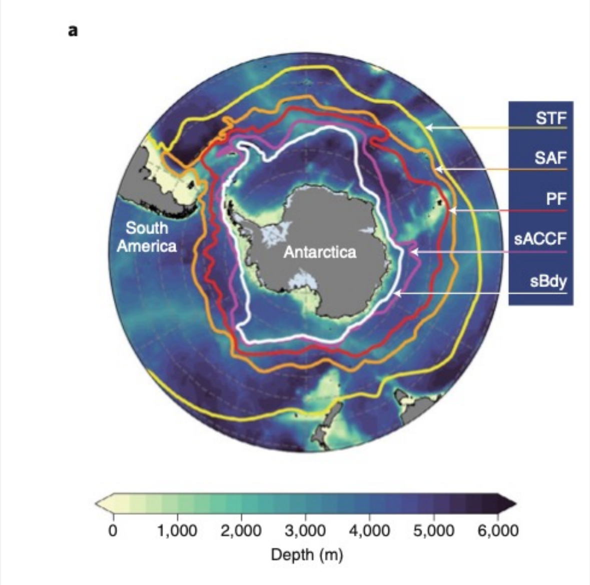
a



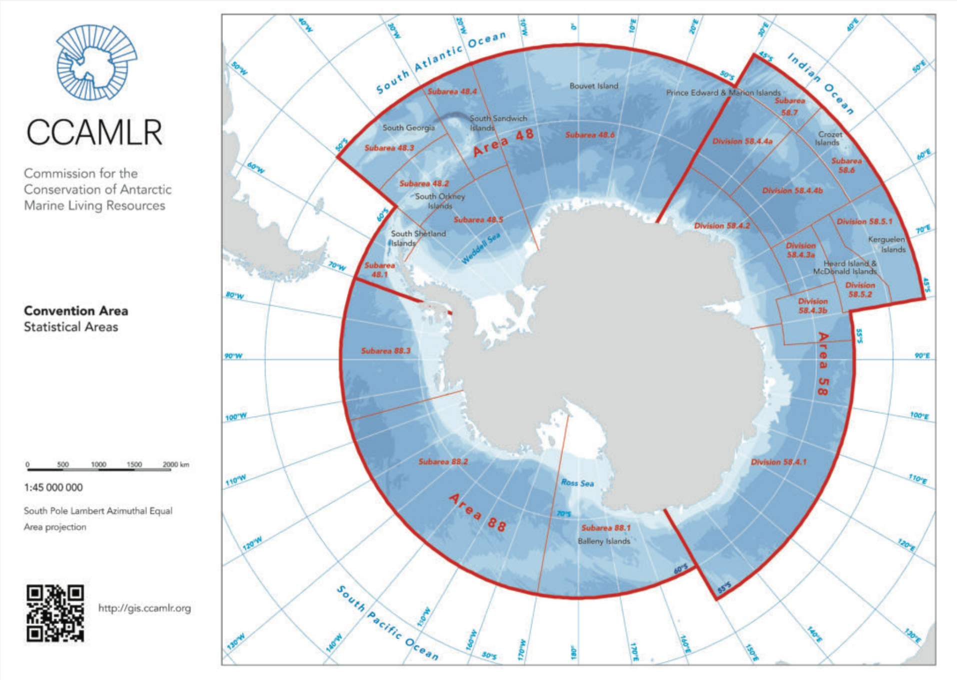
STF
SAF
PF
sACCF
sBdy
South America
Antarctica
0
1,000
2,000
3,000
4,000
5,000
6,000
Depth (m)

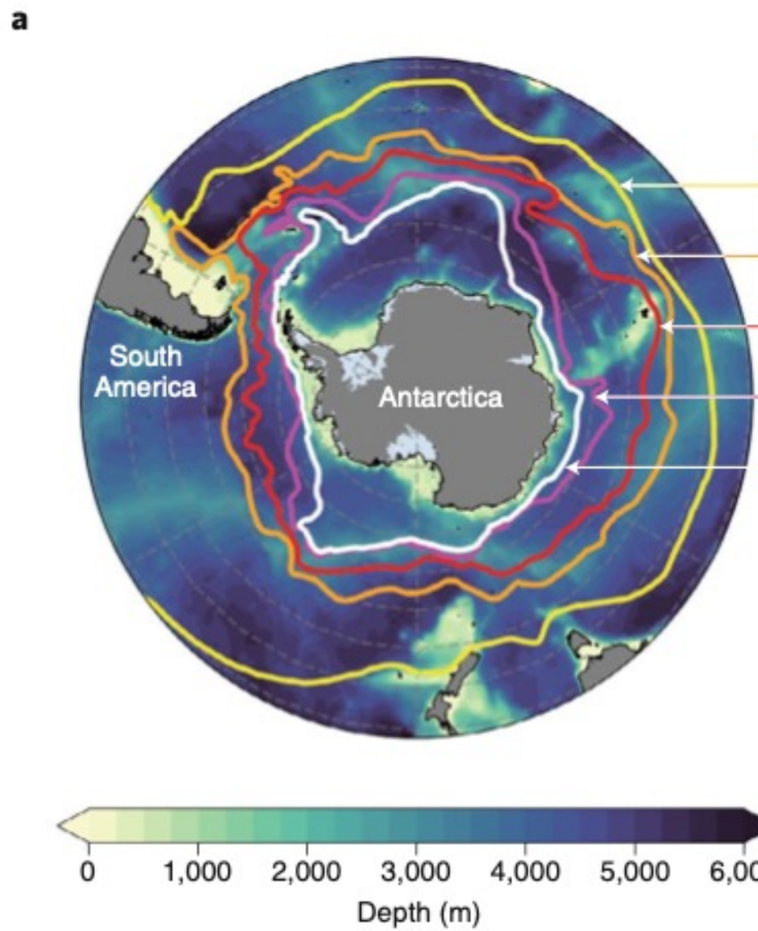
FRONTS

Sub Tropical Front	
Sub Antarctic Front	Antarctic Circumpolar Current
Polar Front	
Southern ACC Front	
Southern Boundary	
	Coastal Current

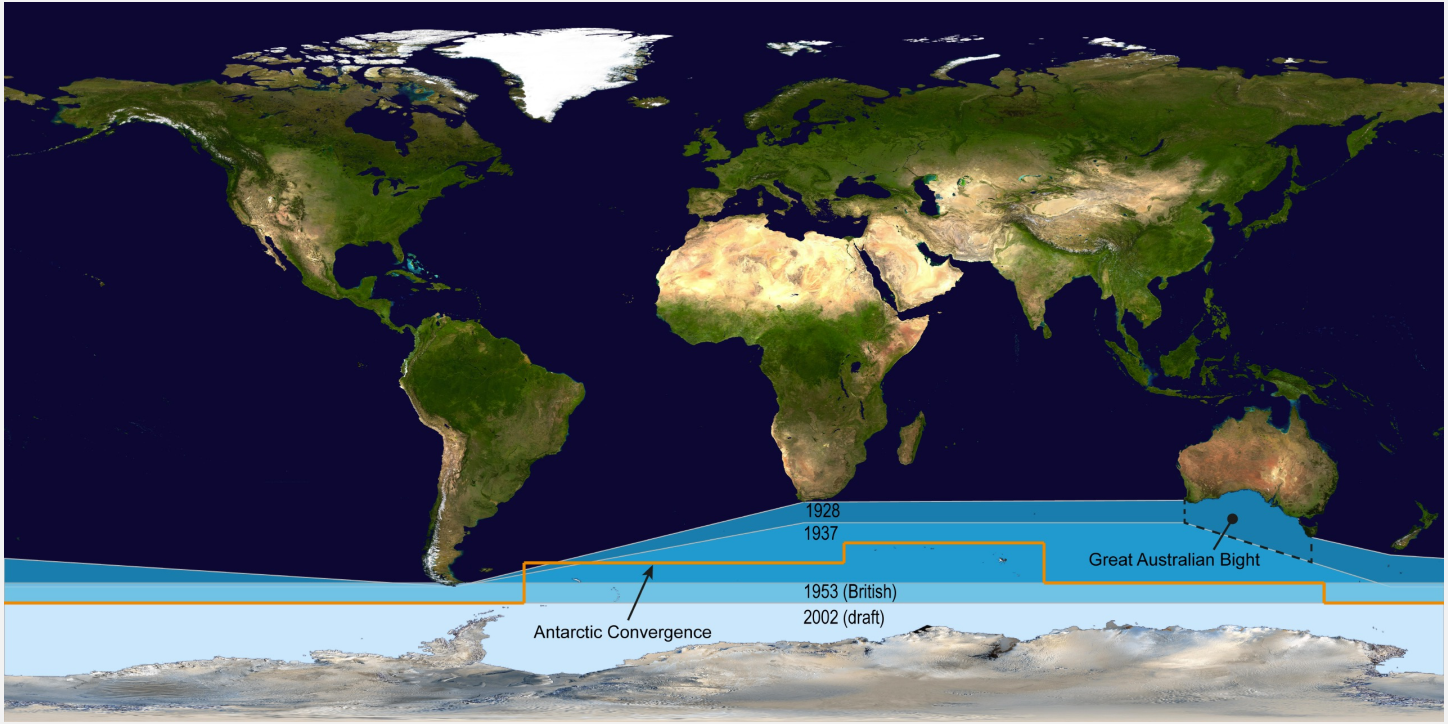


DIFFICULT TO DEFINE…

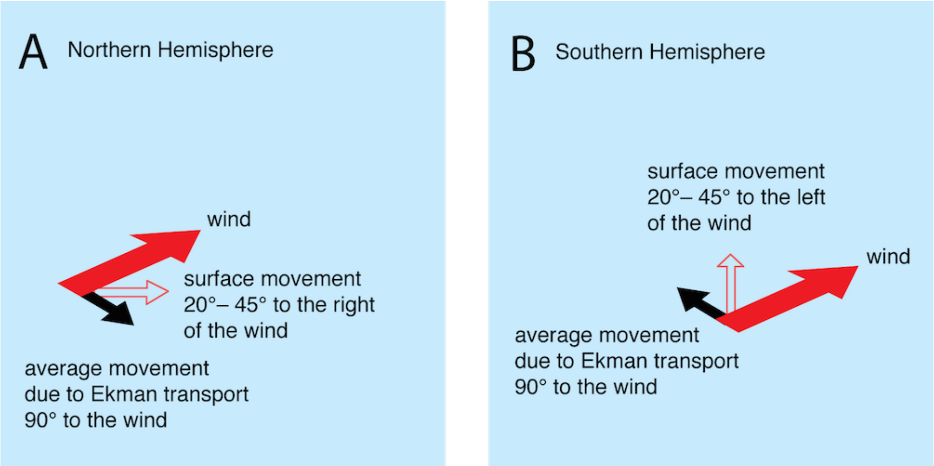

CCAMLR
Commission for the Conservation of Antarctic Marine Living Resources
Convention Area
Statistical Areas
1:45 000 000
South Pole Lambert Azimuthal Equal Area projection
http://gis.ccamlr.org
South Atlantic Ocean
Indian Ocean
South Pacific Ocean
Area 48
Area 58
Area 88
Subarea 48.1
Subarea 48.2
Subarea 48.3
Subarea 48.4
Subarea 48.5
Subarea 48.6
Subarea 58.6
Subarea 58.7
Division 58.4.1
Division 58.4.2
Division 58.4.3a
Division 58.4.3b
Division 58.4.4a
Division 58.4.4b
Division 58.5.1
Division 58.5.2
Subarea 88.1
Subarea 88.2
Subarea 88.3
South Georgia
South Sandwich Islands
South Orkney Islands
South Shetland Islands
Bouvet Island
Prince Edward & Marion Islands
Crozet Islands
Kerguelen Islands
Heard Island & McDonald Islands
Balleny Islands
Weddell Sea
Ross Sea

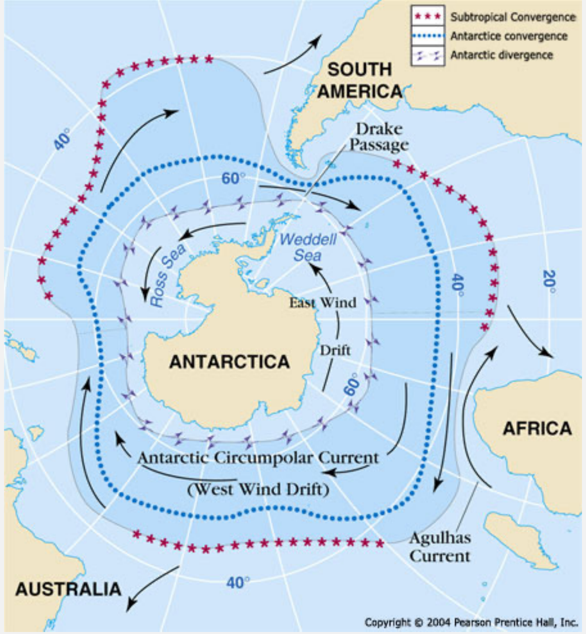

a
South America
Antarctica
0
1,000
2,000
3,000
4,000
5,000
Depth (m)

WHO

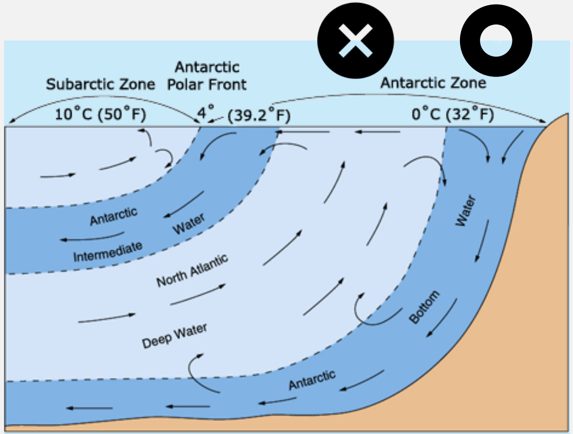

1928
1937
Great Australian Bight
1953 (British)
2002 (draft)
Antarctic Convergence

EKMAN TRANSPORT

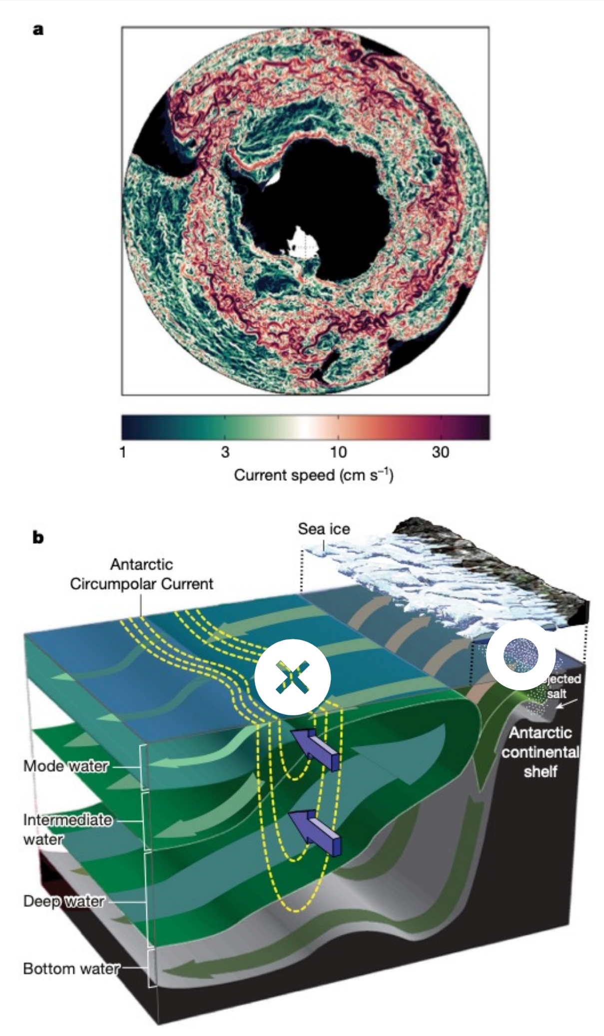




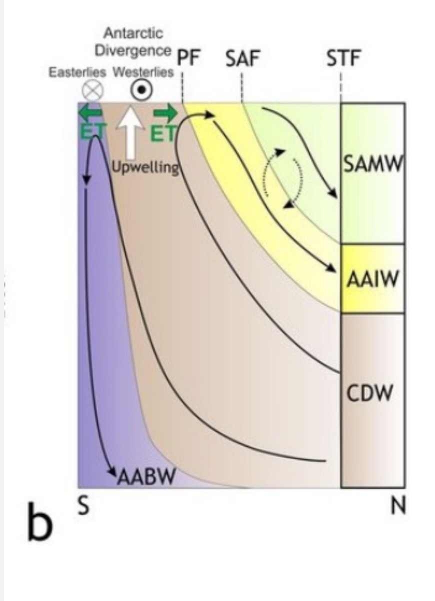
Subtropical Convergence
Antarctice convergence
Antarctic divergence
SOUTH AMERICA
Drake Passage
Weddell Sea
Ross Sea
East Wind
Drift
ANTARCTICA
AFRICA
Antarctic Circumpolar Current
(West Wind Drift)
Agulhas Current
AUSTRALIA
40°
60°
20°
Copyright © 2004 Pearson Prentice Hall, Inc.

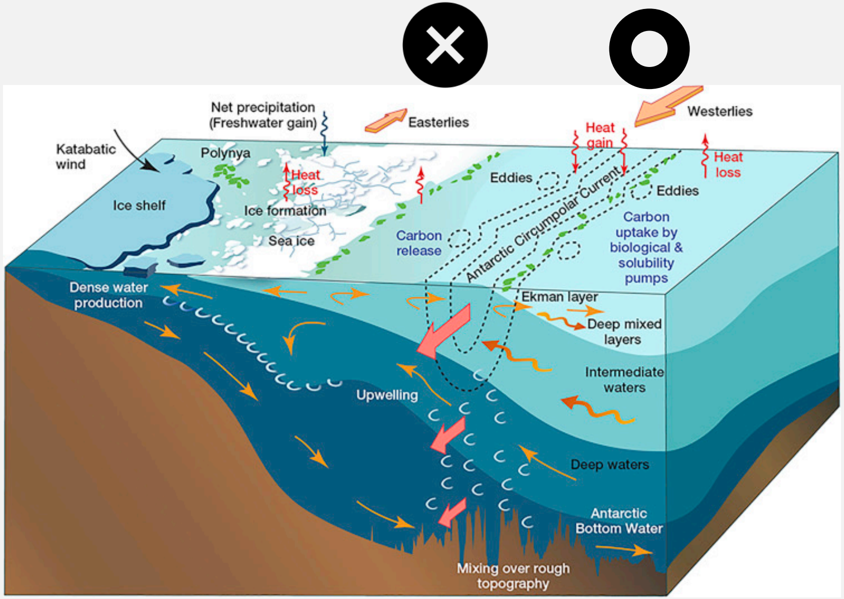


Subarctic Zone
Antarctic Polar Front
Antarctic Zone
10°C (50°F)
4° (39.2°F)
0°C (32°F)
Antarctic Intermediate Water
North Atlantic Deep Water
Antarctic Bottom Water



a
1
3
10
30
Current speed (cm s−1)
b
Sea ice
Antarctic Circumpolar Current
Mode water
Intermediate water
Deep water
Bottom water
salt
Antarctic continental shelf

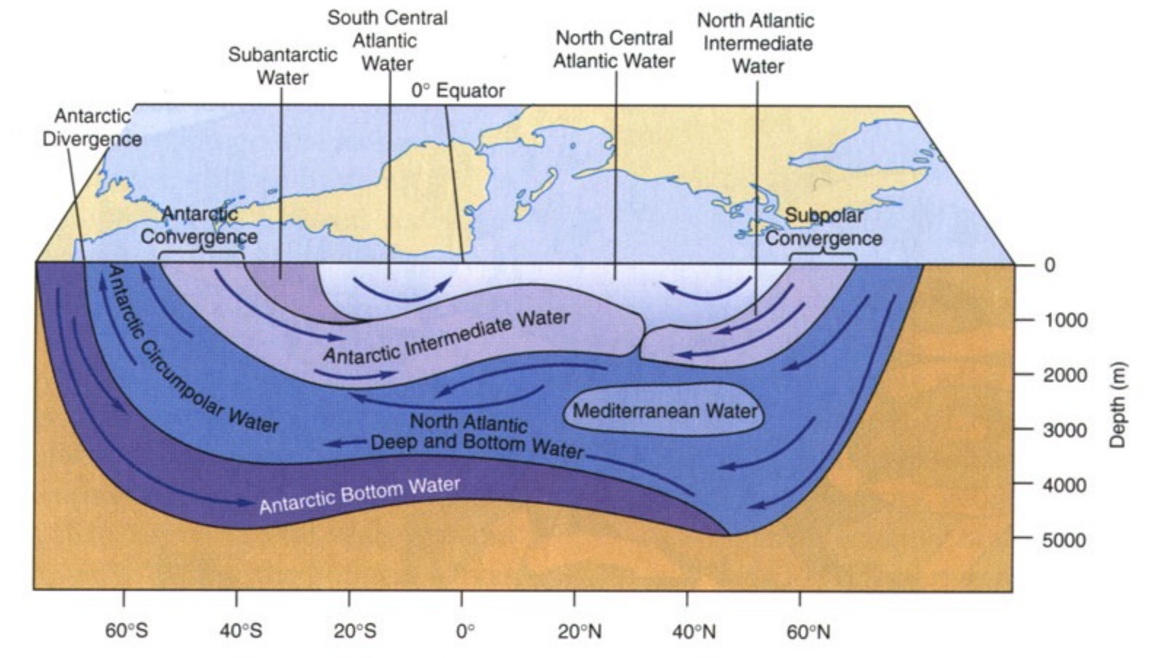




- Upwelling of Circumpolar Deep Water (> North Atlantic Deep Water)
- CDW mixes with cold Ice Shelf Water → sinks as Antarctic Bottom Water (→ up to 5°S)
- CDW also mixes with less salty Antarctic Superficial Water → Antarctic Intermediate Water
- AIW sinks below warmer Subantarctic water = Polar Front = Antarctic Convergence (downwelling)

http://hdrake.github.io/research.html

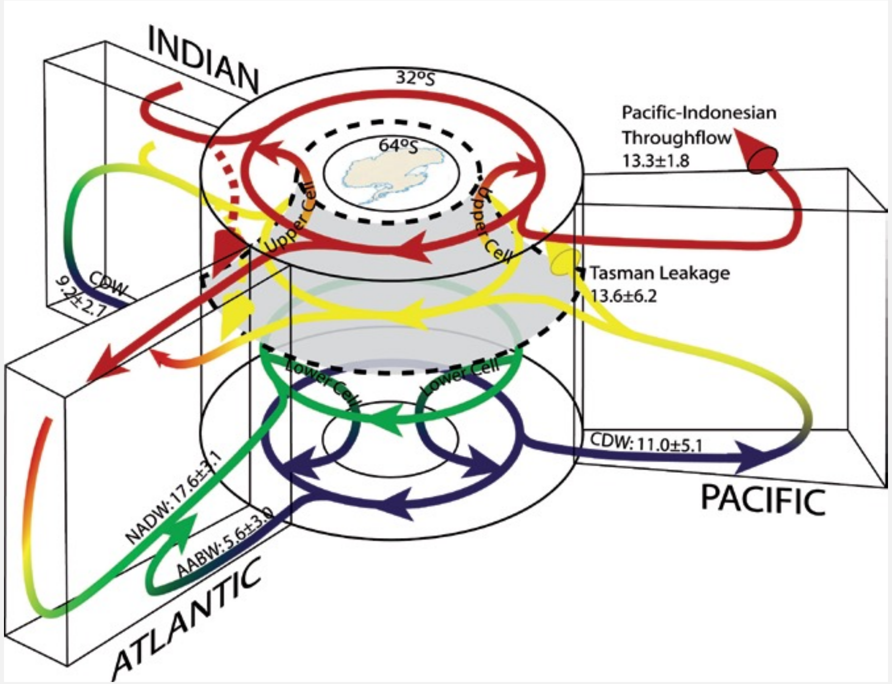
I. PHYSICO-CHEMICAL ENVIRONMENT
I.I. WATER MASSES AND CIRCULATION



Segar 1997

The Southern Ocean plays a key role in the general thermohaline circulation

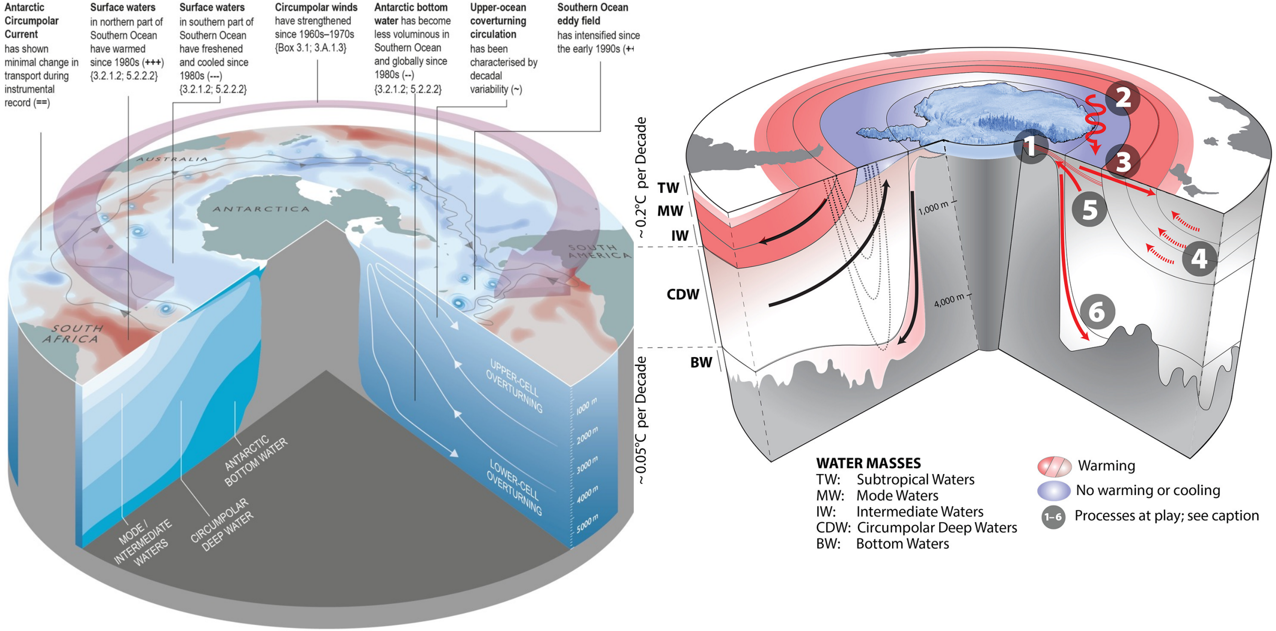
THERMOHALINE CIRCULATION



Lumpkin & Speer 2007

The Southern Ocean plays a key role in the general thermohaline circulation

EFFECTS OF CLIMATE CHANGE



1. Increased surface stratification and shallowing of the Circumpolar Deep Water layer,

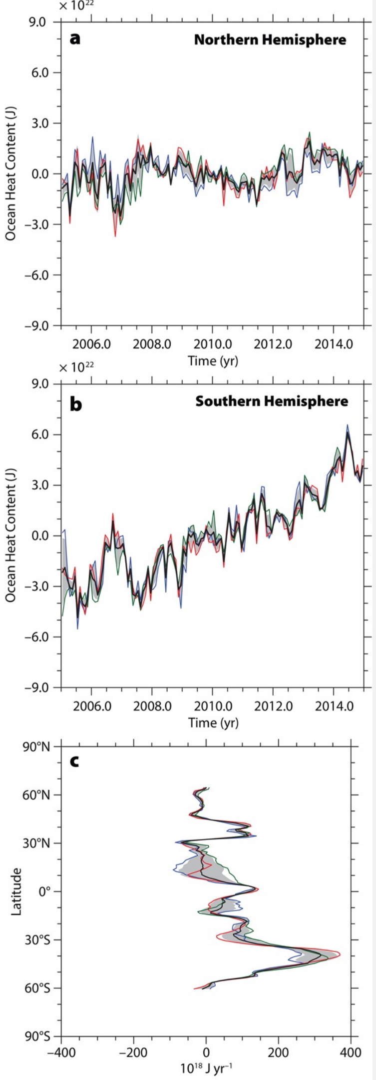
2. increased heat uptake in the subpolar basins

3. increased northward heat transport associated with increased subpolar heat uptake,

4. reduced eddy-mediated southward heat transport across the Antarctic Circumpolar Current

5. intrusion of CDW onto the continental shelves

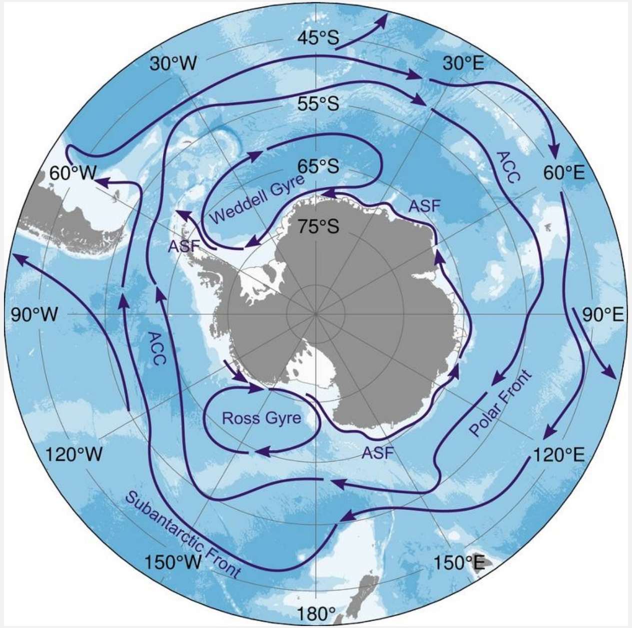
6. warming of the bottom water ventilating the abyssal ocean



- (a–b) Ocean heat content change above 2,000 m depth with respect to the temperature climatology for
- (a) the Northern Hemisphere,
- (b) the Southern Hemisphere.
- (c) Zonally integrated ocean heat content (10^{18} J yr^{-1}).
- Curves show estimates based on different observation-based products from different institutions: (blue curves), (red curves), (green curves).
- mean estimates black curves.
- The gray envelope deviation around the mean.
- *Adapted from Llovel and Terray (2016).* > High res figure

1970's	30-50%
2014	60%, (sparse sampling)
2006–2013	67% to 98%

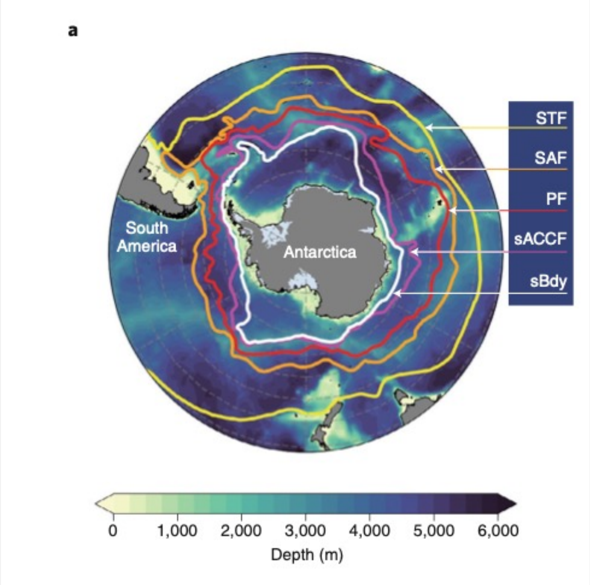
I. PHYSICO-CHEMICAL ENVIRONMENT
1.1. WATER MASSES AND CIRCULATION

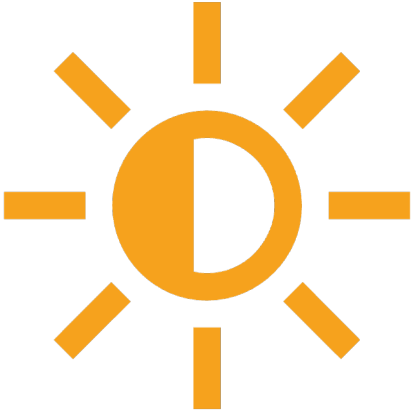


- Antarctic convergence = north limit of Antarctic zone
- Between Antarctic and Subtropical convergences = Subantarctic zone
- Antarctic + Subantarctic zone= Southern Ocean
- Subantarctic zone 2-4°C warmer than Antarctic zone
- ➢ Antarctic convergence (Polar front)= strong biological border

FRONTS

<table>
<tr><th></th><th></th><th></th><th></th></tr>
<tr><td>Sub Tropical Front</td><td></td><td></td><td rowspan="4">Subantarctic Zone</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Sub Antarctic Front</td><td rowspan="7">Antarctic Circumpolar Current</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>Polar Front</td><td>Antarctic Convergence</td><td rowspan="6">Antarctic Zone</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Southern ACC Front</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>Southern Boundary</td><td>Antarctic Divergence</td></tr>
<tr><td></td><td>Coastal Current</td><td></td></tr>
</table>





1.2. LIGHT

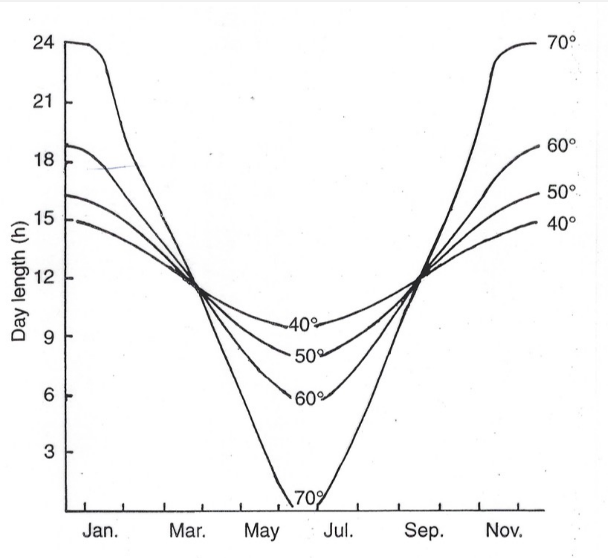
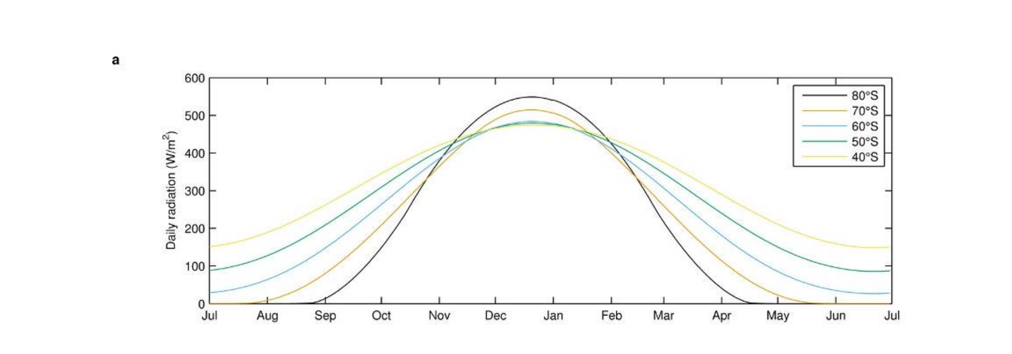


Fig. 2.12. Latitudinal variation in day length over the year and hence in the daily incident radiation in the Southern Ocean.

Knox 1994

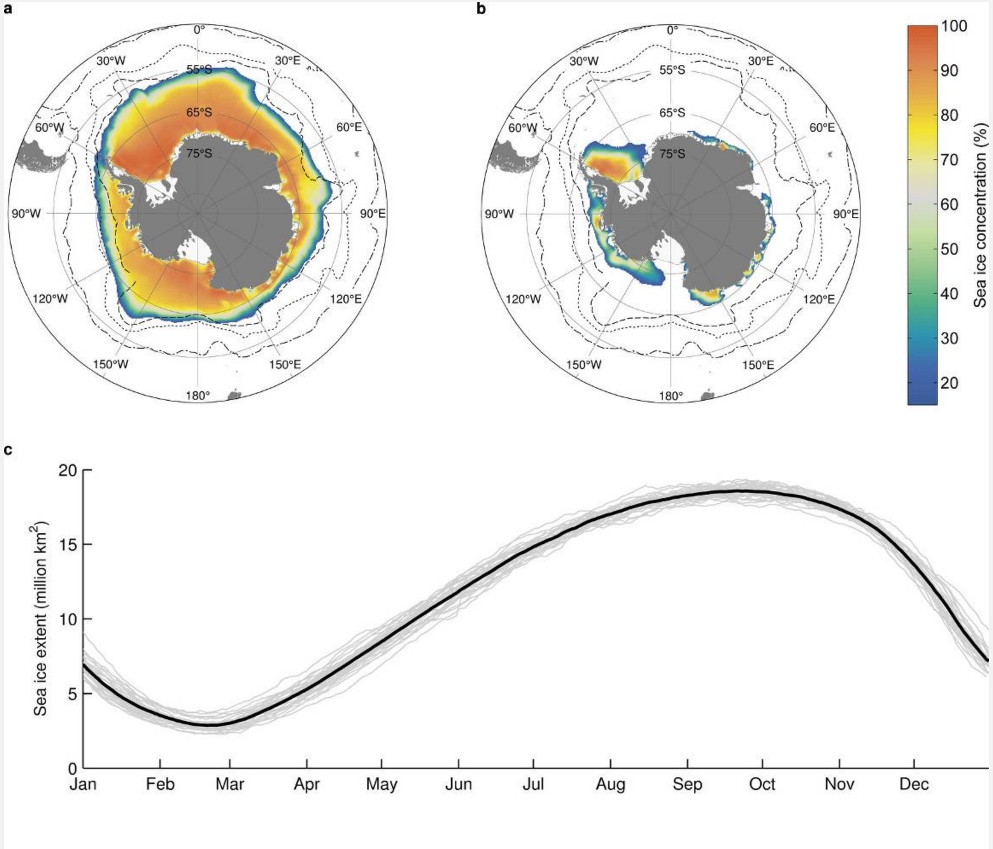


Post et al 2014

- Maximal differences in day length at high latitudes
- 100d darkness at 75°
- Strongly seasonal light availability

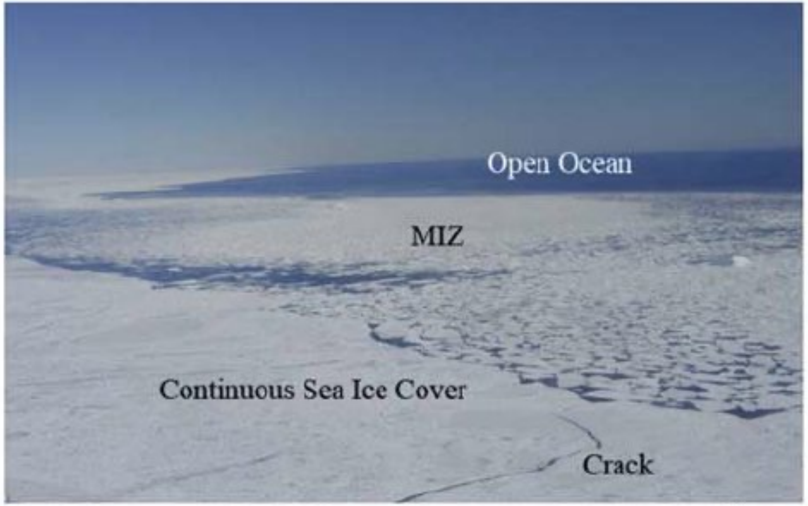
1.3. SEA ICE

- Sea Ice extent:
  - Max June - September
  - Min January – March
- Influence on light availability



Post et al. 2014

	Open Ocean	
Seasonal	Marginal Ice Zone	15-80% Ice cover
Perennial	Pack Ice Zone	smaller, free-floating pieces of sea ice.
	Shear Zone	highly deformed ice along the coast
	Fast Ice Zone	ice anchored to the shoreline



Fast ice (left) and pack ice (right). (Left: Peterfitzgerald (Own work) [CC BY-SA 3.0], via Wikimedia Commons; Right: Markus Trienke, https://www.flickr.com/photos/mtrienke/34281559366/in/photostream/ [CC BY-SA 2.0]).

2. PRIMARY PRODUCTION

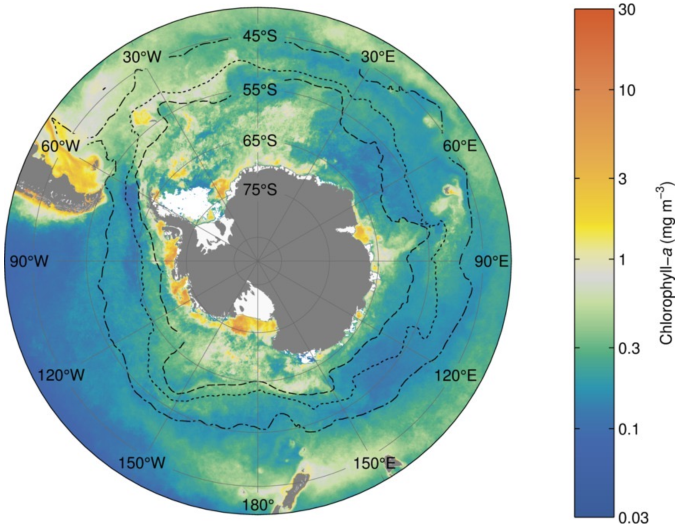
Pico/nanaphytoplankton

- Flagellates
  - Prasinophyceae
  - Cryptophyceae,
  - Prymnesiophyceae
  - Cryptomonas

- Species with a low Ks favoured in low nutrients concentrations but lower capacity → no or limited blooms

microphytoplankton

- centric diatoms (Bacillariophyceae)
  - Corethron
  - Thalassiosira
  - Rhizosolenia,
  - Fragilariopsis
- Phaeocystis colonies (Prymnesiophyceae)
- Species with a high Ks favoured in high nutrients concentrations and able to incorporate high amounts of nutrients → blooms



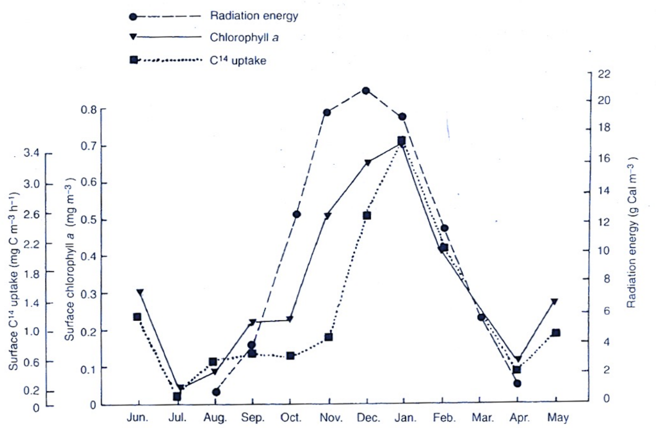
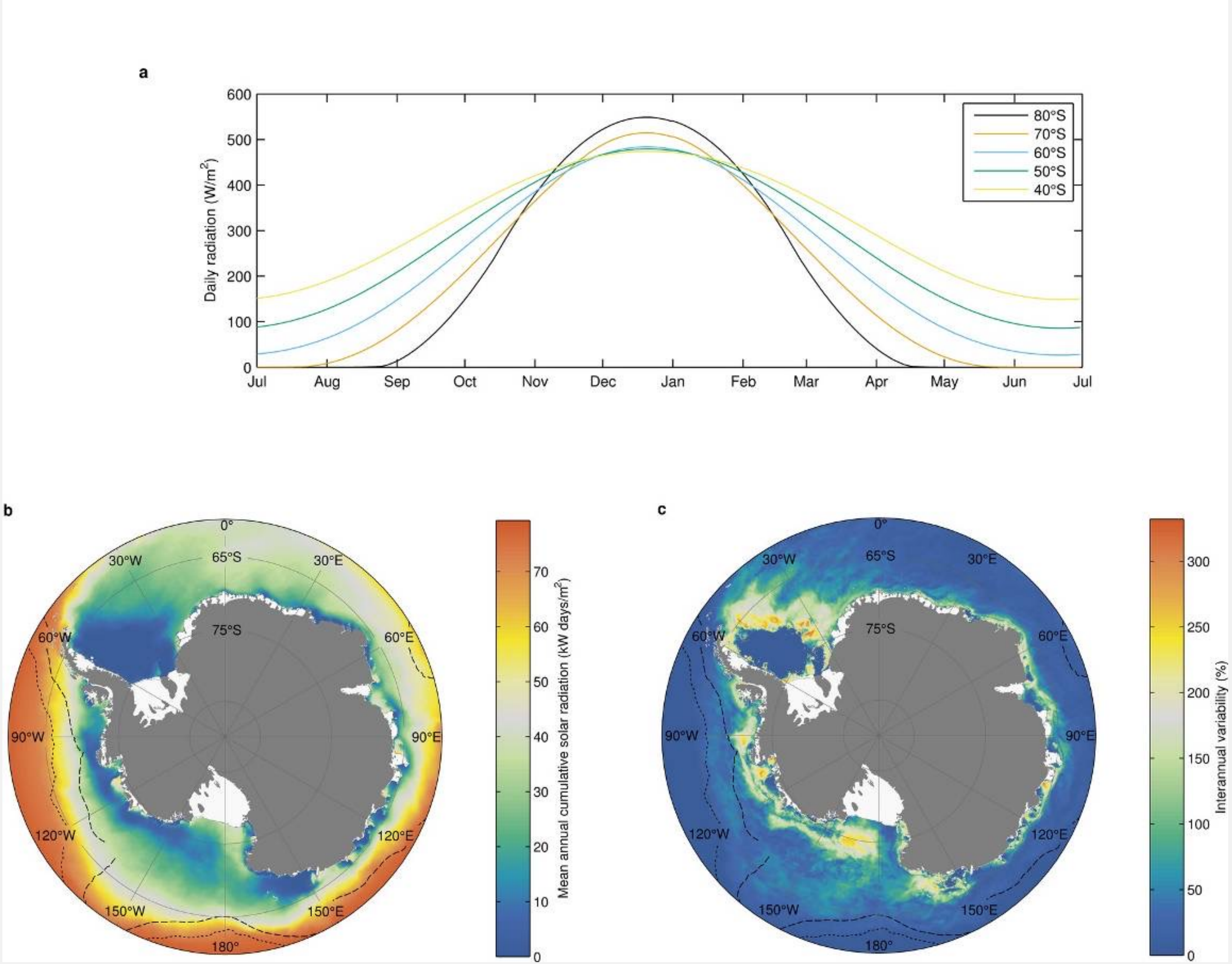


Fig. 2.13. Monthly variation of radiant energy (with average cloudiness) at Maudheim Station (71° 03′ S; 10° 56′ W) compared with monthly changes in surface chlorophyll *a* and C^{14} uptake in Antarctic waters. Redrawn from El-Sayed (1971a).

2.1. CONTROLLING FACTORS: *LIGHT*

2.1. CONTROLLING FACTORS: LIGHT ←→ ICE COVER



Post et al 2014

2.1. CONTROLLING FACTORS: *LIGHT ←→ ICE COVER*

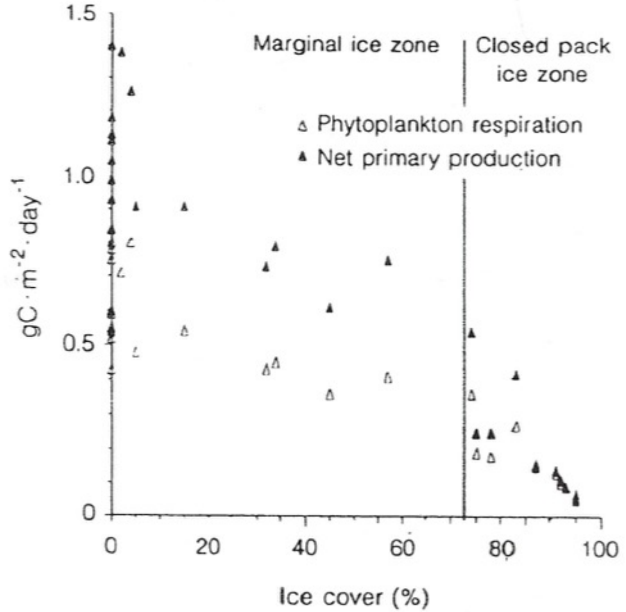
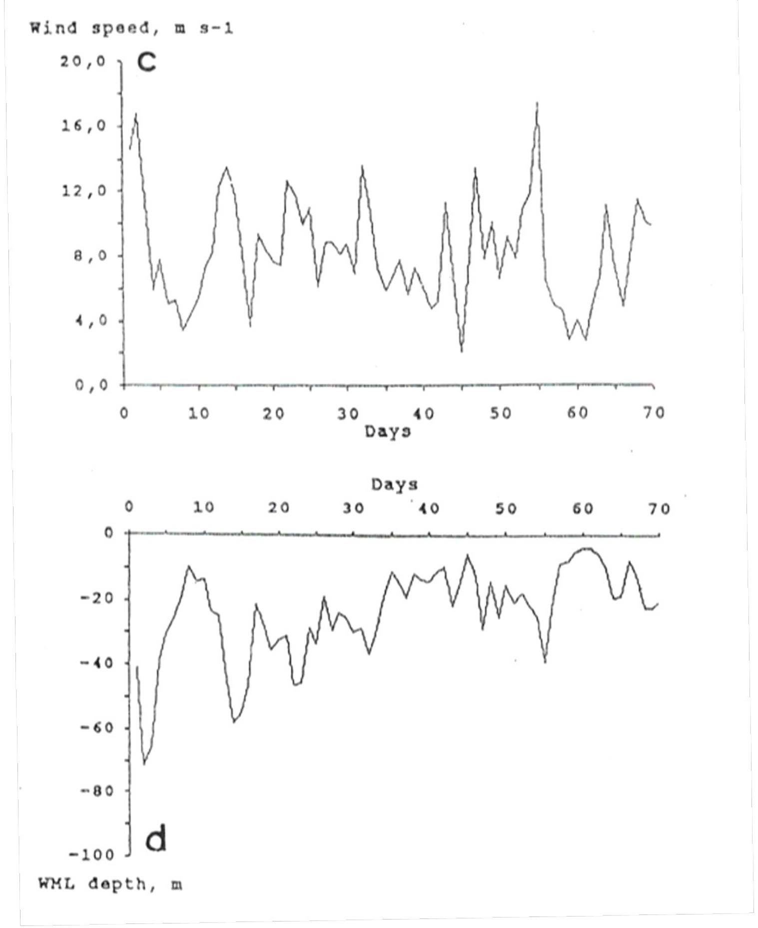


Fig. 7. Relationship between daily rate of net primary production (▲) and ice cover field in the sea ice associated areas (i.e. the marginal ice zone and the closed pack ice zone) of the northwestern Weddell Sea during spring 1988. Phytoplankton respiration (△) is also shown

Mathot et al 1992

- No bloom if ice cover > 20%
- => nanoplanktonic communities

2. PRIMARY PRODUCTION 2.1. CONTROLLING FACTORS: *LIGHT ←→ WIND (MIXING)*



Wind speed and predicted upper mixed layer depth at latitude 59°30 S during spring 1988

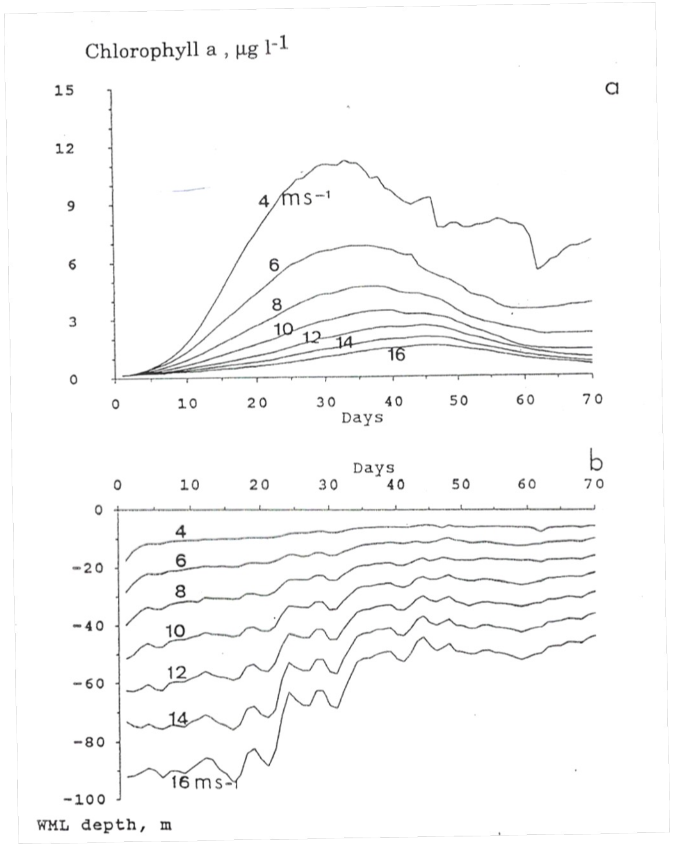
- Depth of mixed layer fast variations

Lancelot et al 1996

2.1. CONTROLLING FACTORS: *LIGHT ←→ WIND (MIXING)*

Predicted chlorophyll *a* concentration and upper mixed layer depth at latitude 59°30 S during the ice melting period under various constant wind speeds

Lancelot et al 1996



- No bloom if wind speed > 8m/sec

2.2. CONTROLLING FACTORS: *NUTRIENTS*

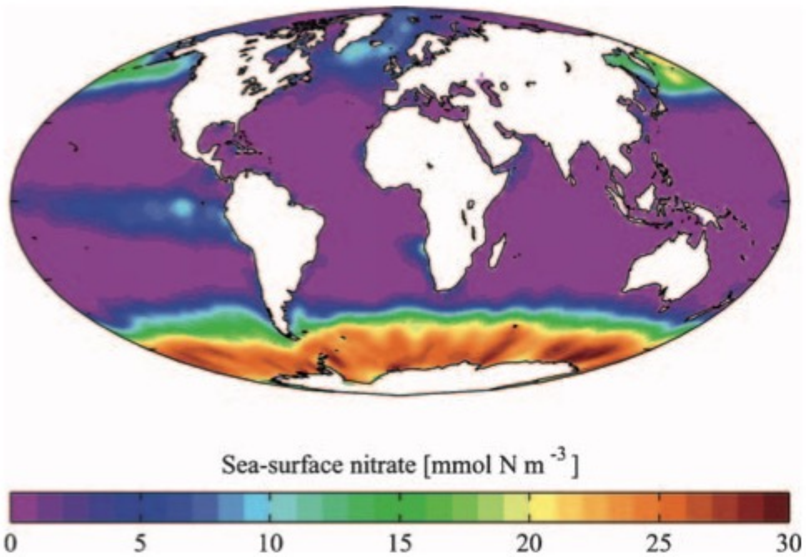


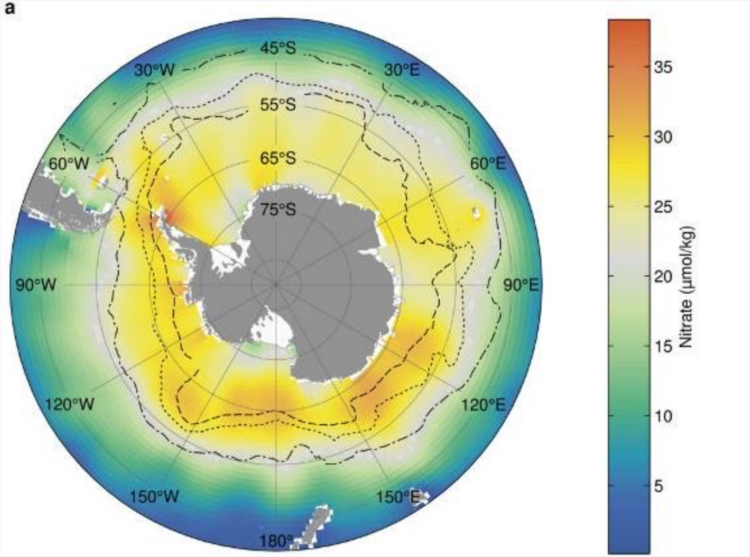
Fig. 17.3 Map of High Nutrient–Low Chlorophyll (HNLC) regions around the world. Measurement in map is of nitrate, with the *scale* as a gradient of color pictured on the bottom (http://www.atmosphere.mpg.de/media/archive/1058.gif)

Offshore upwelling → HNLC zone

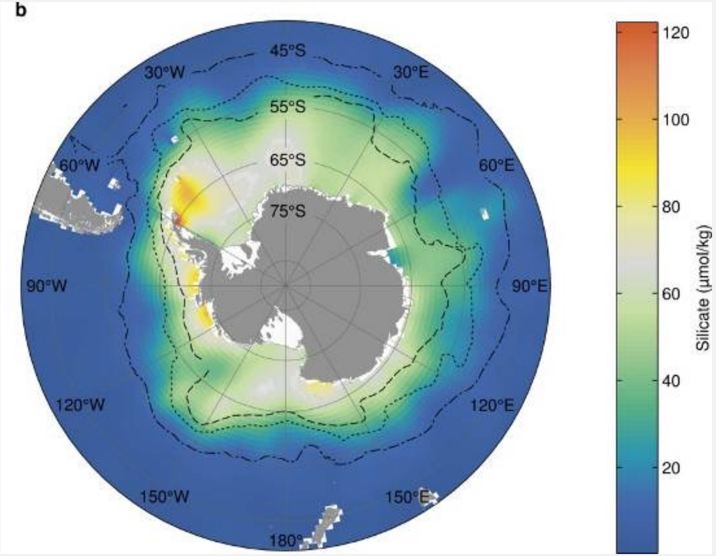
- NO_3^-: 32.5μM
- PO_4^{3-}: 2.5μM
- SiO_4^-: 100 μM

WINTER SURFACE

(A) NITRATE



(B) SILICATE



Mesocosm Fe enrichment experiment in the Antarctic Peninsula:

- Initially: nano- and picoplankton
- After 6d: shift towards diatoms

Agusti & Duarte 2000
MEPS 206: 73

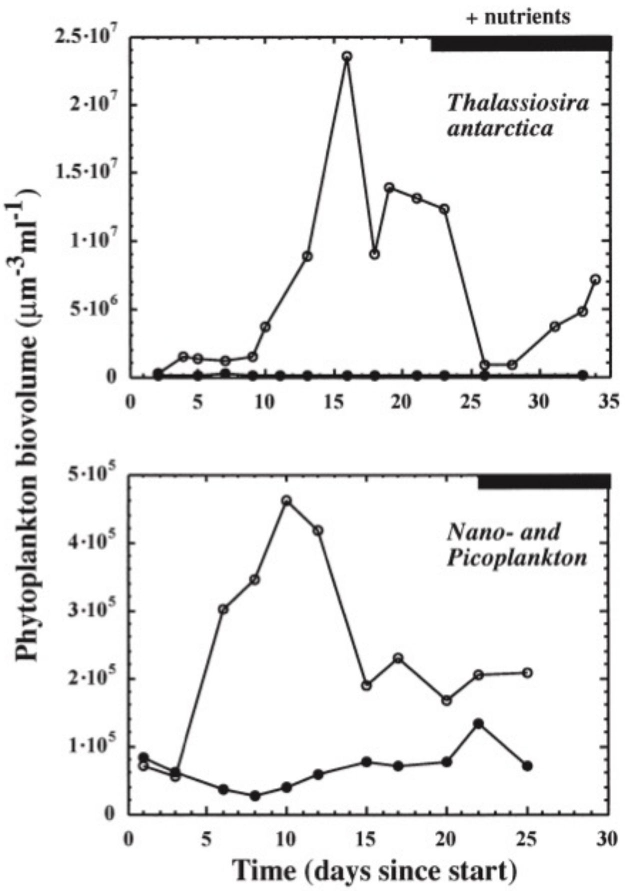
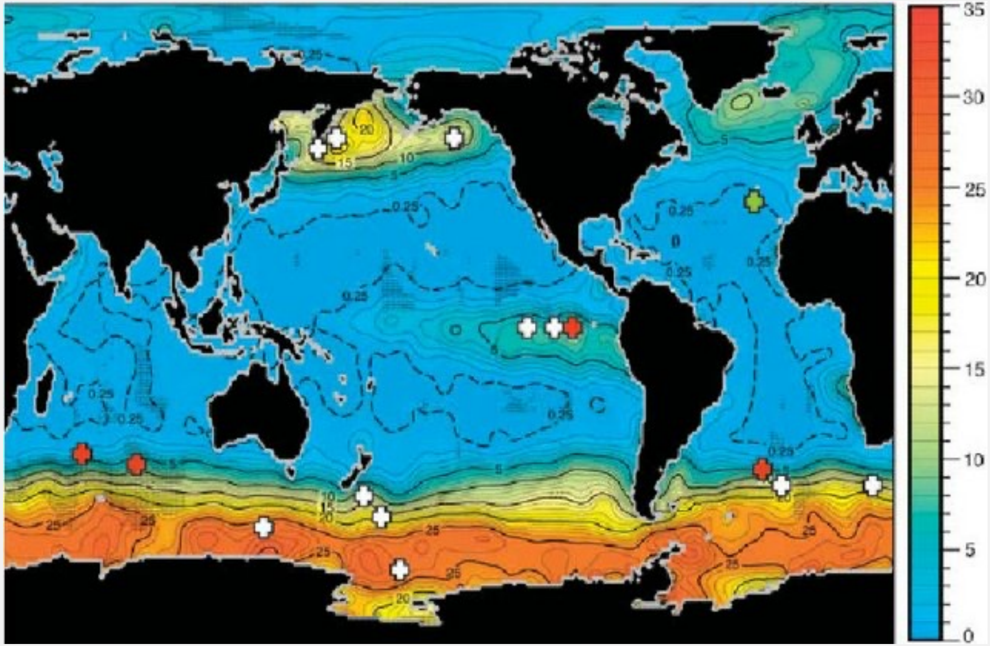
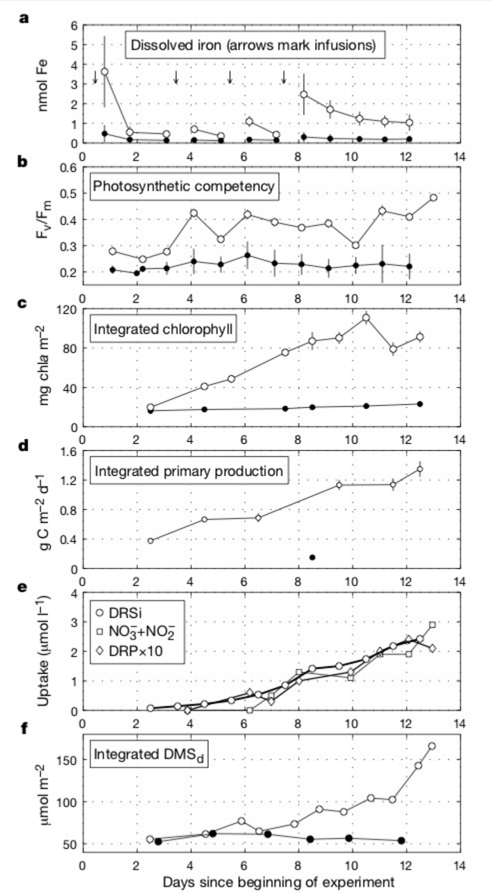


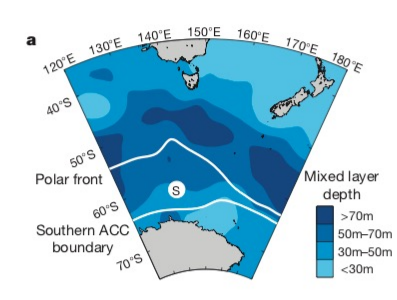
Fig. 8. Depth-integrated biovolume of diatoms and nano- and picophytoplankton in the mesocosm (○) and the ambient waters (●) during the experiment (January 19, 1999, to February 21, 1999)

- Distribution of nitrate in the surface ocean, showing elevated concentrations in the three HNLC regions of the Southern Ocean, Equatorial Pacific and Sub-Arctic Pacific.
- Location of twelve iron fertilization experiments (white crosses), natural iron fertilization experiments (red crosses), and excess surface nitrate concentrations (colors on map). Green cross is an iron plus phosphorus experiment [Boyd et al. , 2007]



P1: X3

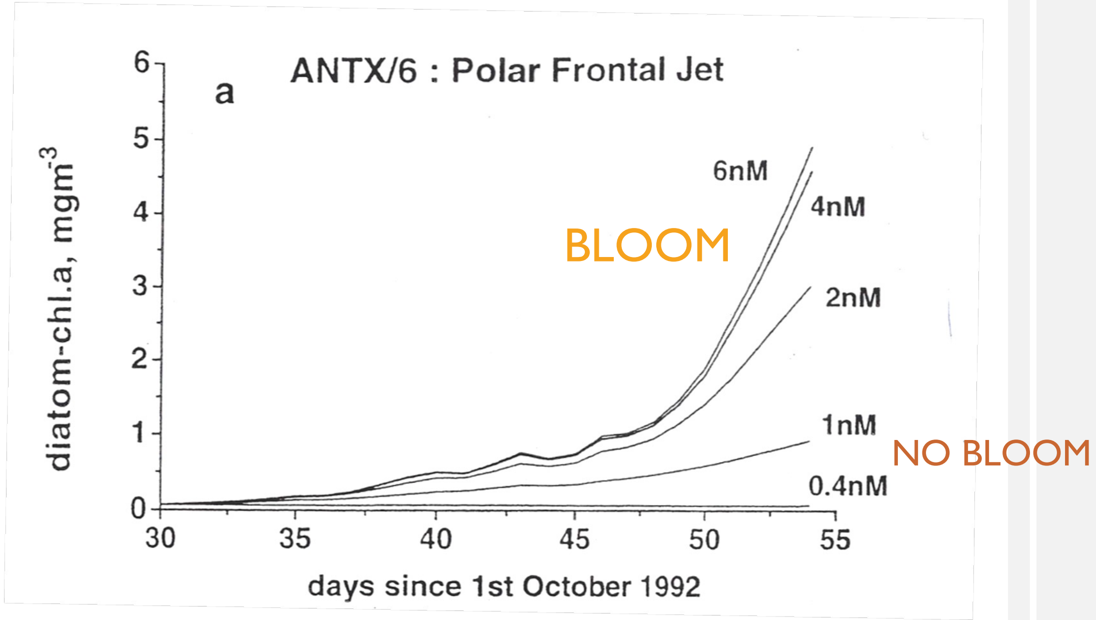




Field Fe enrichment experiment in the Pacific sector SOIREE with multiple enrichments

Figure 3 Time-series measurements made during SOIREE. Open and filled symbols show measurements made respectively inside and outside iron-fertilized waters. Underway data are expressed as the daily mean value for inside (defined as >50% of the peak SF_6 levels on that day) and outside the patch (defined as <10 fmol l^{-1}). Error estimates are expressed as ± 1 standard deviation of the mean for underway data (**a**, **b** and **e**) and ± 1 standard error of the mean for the discrete data (**c**, **d** and **f**). The range of sample sizes during SOIREE is provided in parentheses: **a**, underway sampling of dissolved iron levels (*n* = 5–17 (in); 9–29 (out)) in surface waters (~3 m) and the timing of the four iron infusions; **b**, underway sampling (~5 m) of community photosynthetic competency (F_v/F_m) (*n* = 8–40 (in); 6–84 (out)); **c**, column-integrated chlorophyll *a* (six depths, 0–65 m, *n* = 3 pseudo-replicates); **d**, column-integrated primary production (six depths, 0–65 m, *n* = 3 pseudo-replicates); **e**, macronutrient uptake (silicate: from ^{32}Si uptake[33], *n* = 2 pseudo-replicates, error always <10% of the mean), nitrate and phosphate depletion (underway sampling (~5 m), *n* = 12–18 (in); 14–34 (out), the greatest spatial variability was <15% of the standard deviation of the mean), DRSi is dissolved reactive silica, DRP is dissolved reactive phosphorus; **f**, column-integrated DMS (six depths, 0–65 m, *n* = 3 pseudo-replicates, errors are all smaller than the symbol size). Nitrate and phosphate depletion was obtained by subtraction of levels within the patch from levels in the surrounding waters (which exhibited no significant change in during SOIREE).

Boyd et al 2000
Nature 407: 695



swamco predictions at latitude 47°S (ANTX/6 site, Polar Frontal Jet) : a) diatom development at different iron concentrations; b) wind mixed layer depth; c) dissolved iron

No bloom if Fe < 2nM

Lancelot et al 1996

2. PRIMARY PRODUCTION
CONTROLLING FACTORS

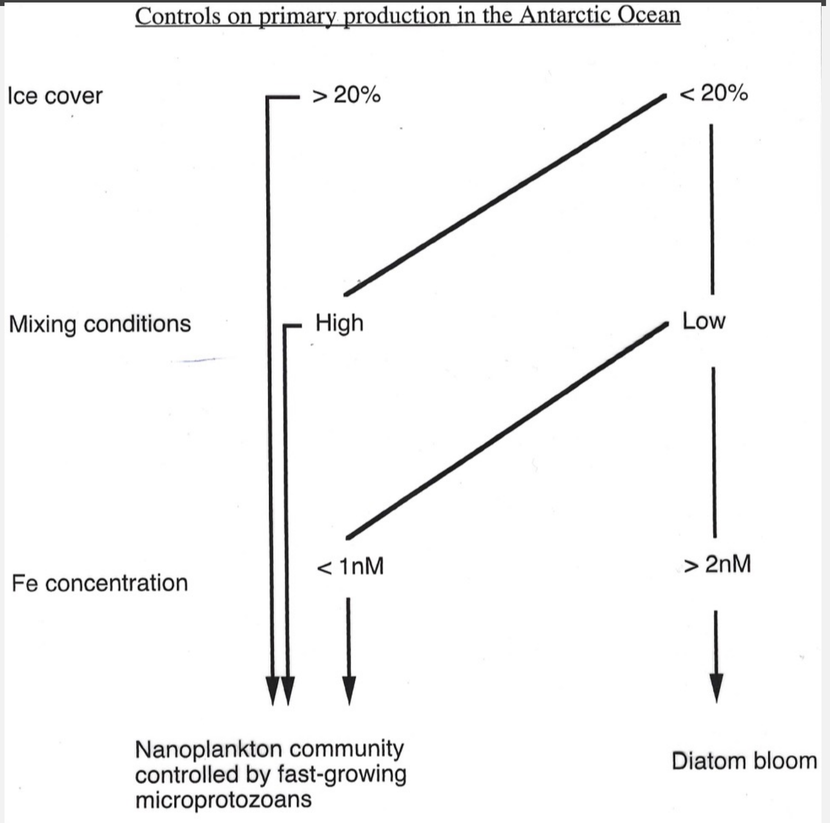


Table 5.I Iron distribution in the Southern Ocean

Site	dissolved iron, nM	Reference
Weddell/Scotia Sea	>1	Nolting et al., 1991
Drake passage		
inshore	5-7	Martin et al., 1990
offshore	0.1-0.9	
Ross Sea		
inshore	>1	Martin et al., 1990
offshore	<1	
Atlantic sector : 6°W		
ACC	<1	de Baar et al., 1996
Polar Front	>1	
Pacific sector : 89°W		de Jong et al., in prep.
subabtarctic	0.5	
Polar Front	0.6-1	
ACC	0.5	
cont. margin	0.6-1	

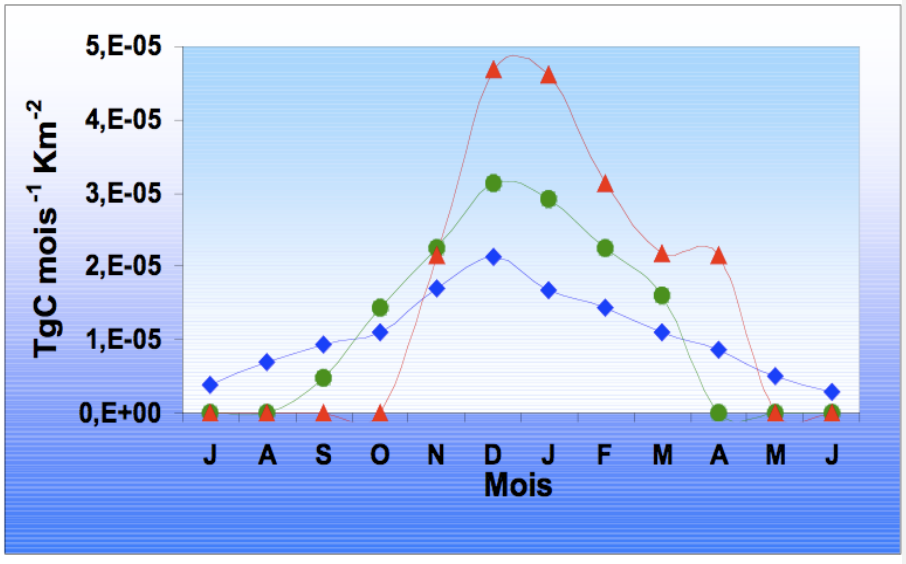
Lancelot et al

Dissolved Fe: usually <1nM except

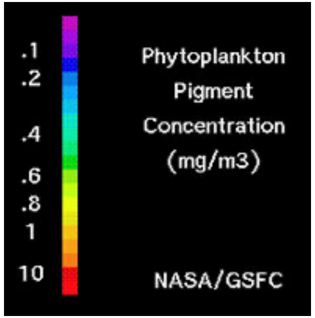
- Coastal zone and above continental plate (Weddell and Ross Seas)
- Downstream Drake passage
- Marginal ice zone

Marginal ice zone

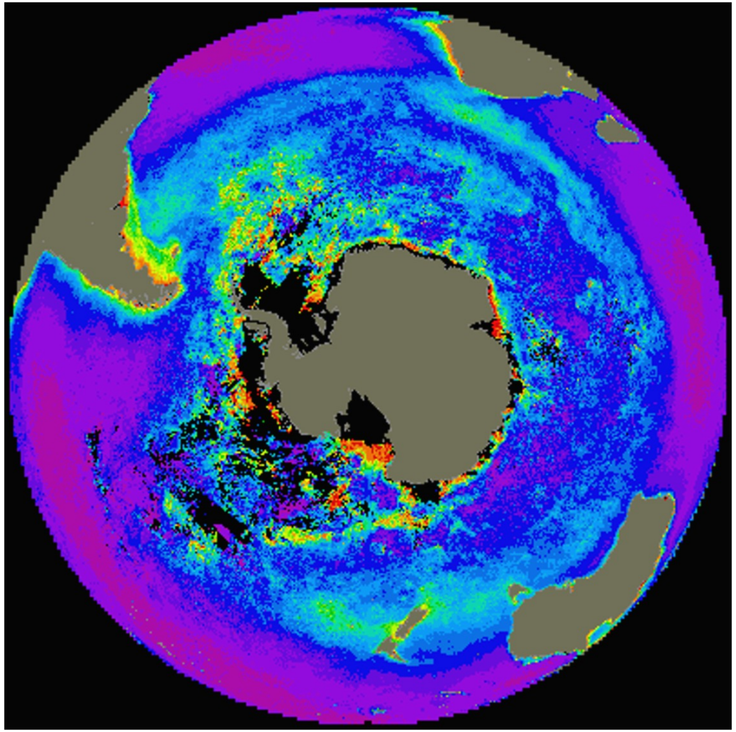
- Sea ice concentrates airborne Fe during winter
- Psychrophilic algae seed the water column when ice melts



- Open ocean:
  - Low P1 (Fe low)
- Under pack ice:
  - Very weak (no light)
- Marginal ice zone and coastal zones:
  - High P1 (Fe high)



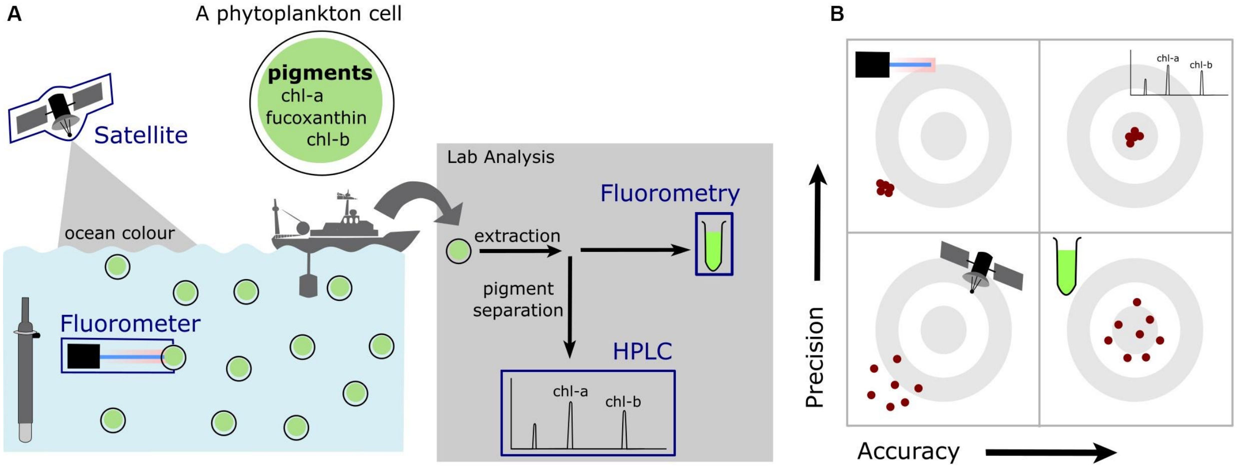
The map displays the composite of all Nimbus-7 Coastal Zone Color Scanner data acquired between Noverber 1978 and June 1986. Approximately 66,000 individual 2 minutes scenes were processed to produce this image



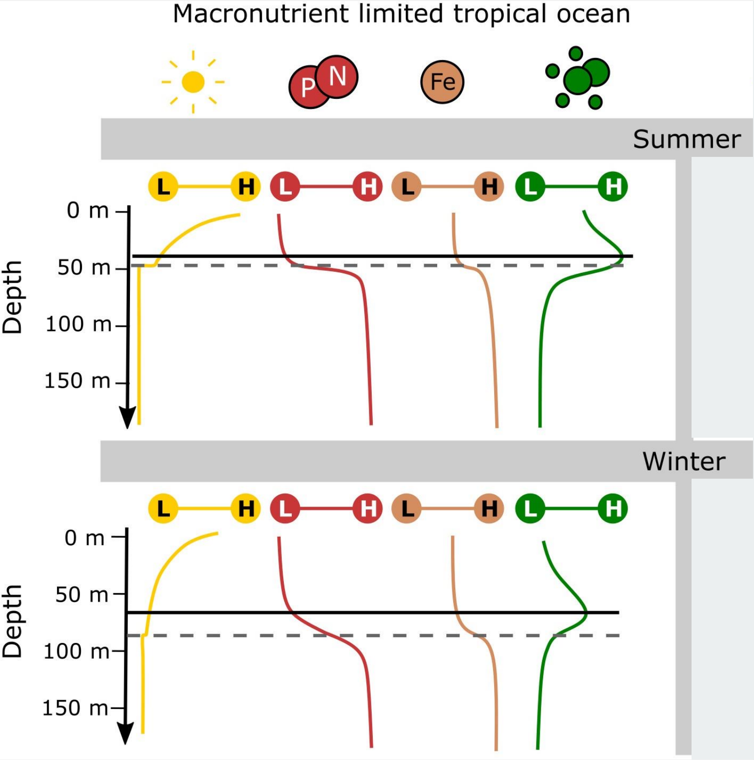
P1 parallels Fe distribution

- Coastal zone and above continental plate (Weddell and Ross Seas)
- Downstream Drake passage
- Marginal ice zone

MEASURING CHLOROPHYLL-*A*



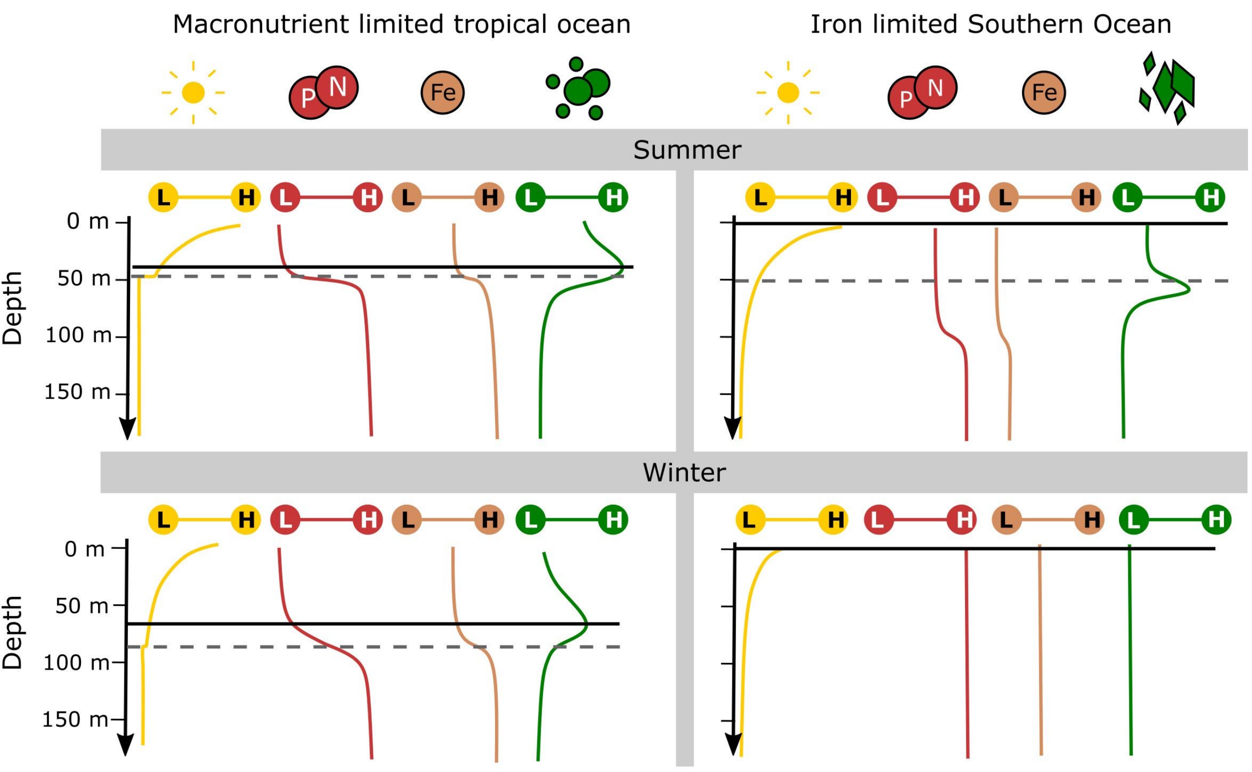
https://doi.org/10.3389/fmars.2020.00671



downward irradiance
macronutrients
Iron

- - - - mixed layer depths
_____ optimum depth of phytoplankton growth

● ● picophytoplankton community
◆ ◆ high silicate community



downward irradiance
macronutrients
Iron

____ mixed layer depths
- - - - optimum depth of phytoplankton growth

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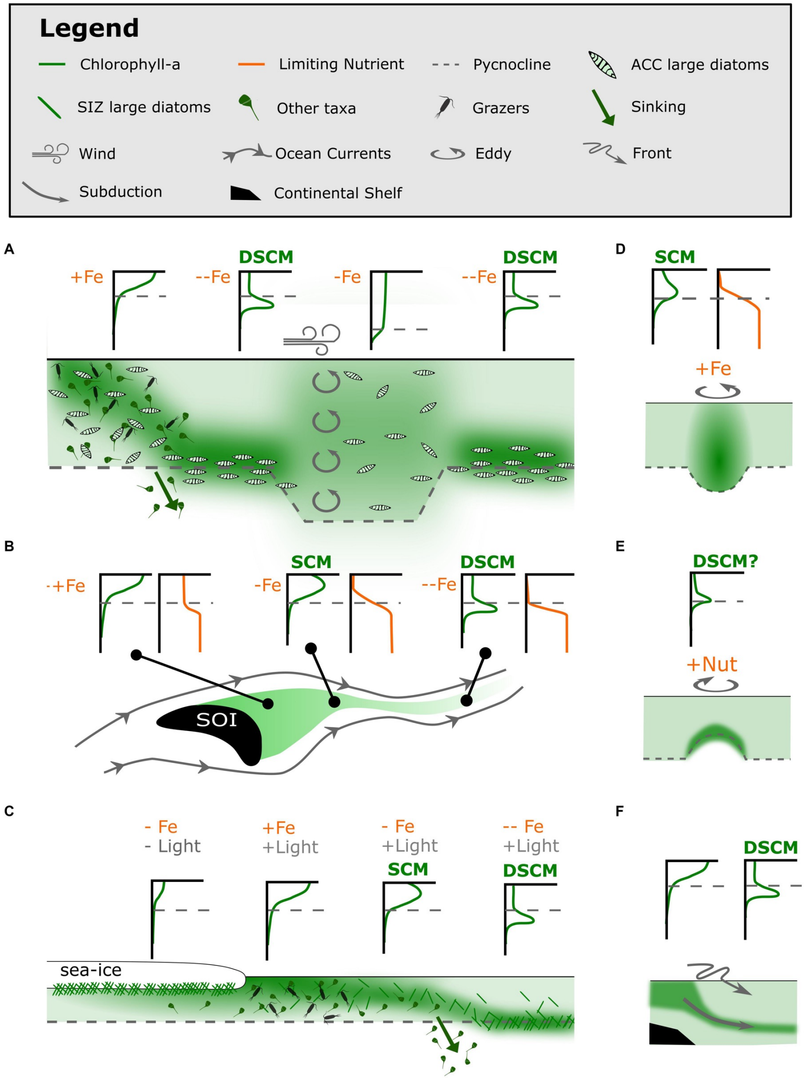
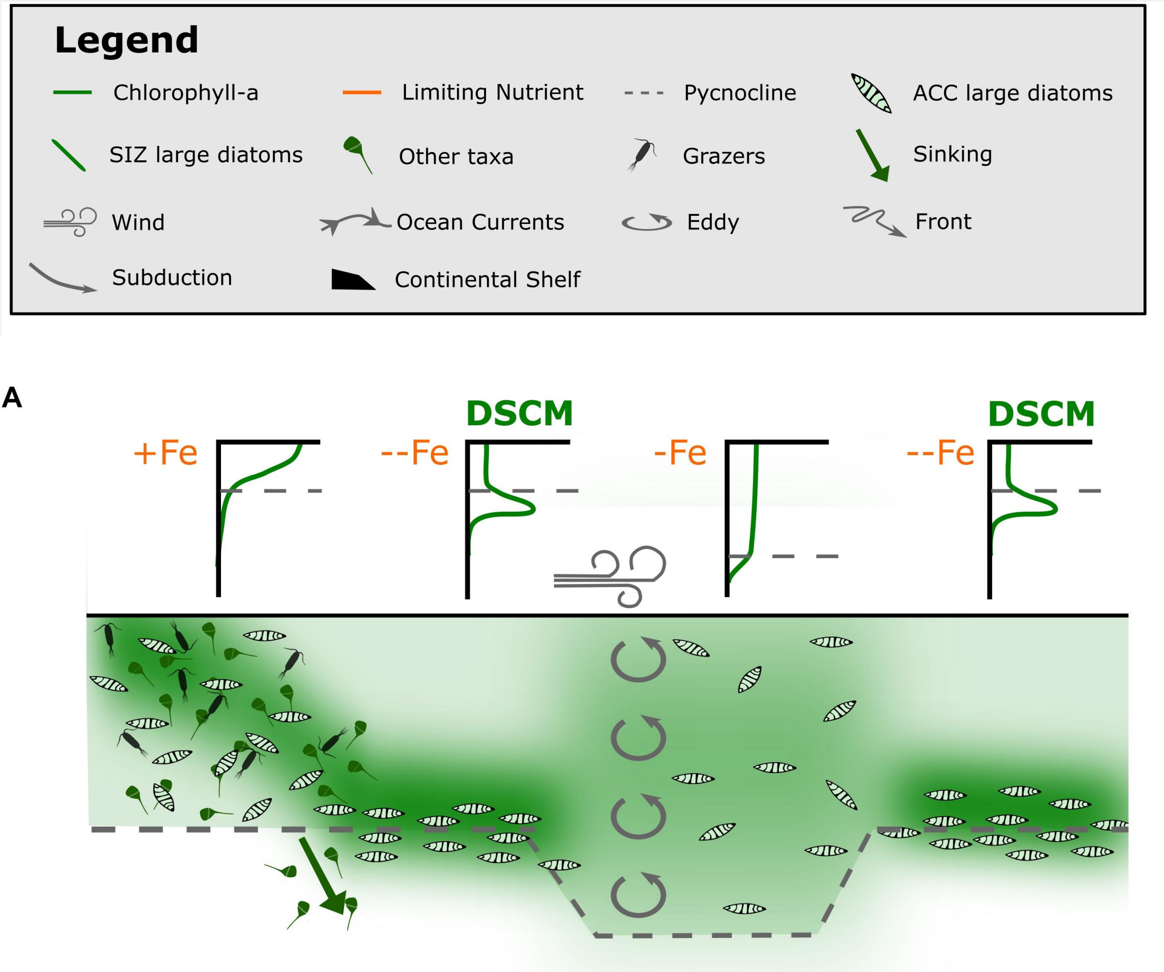
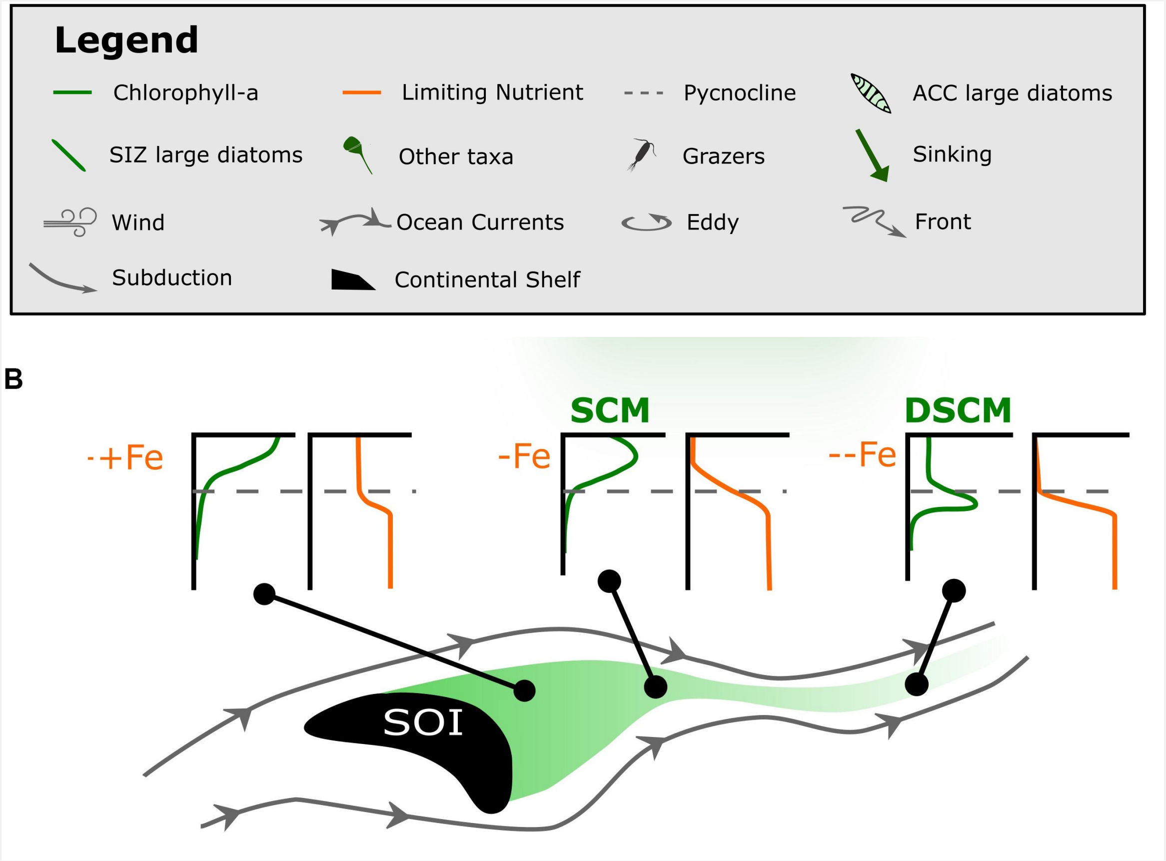
https://doi.org/10.3389/fmars.2020.00671



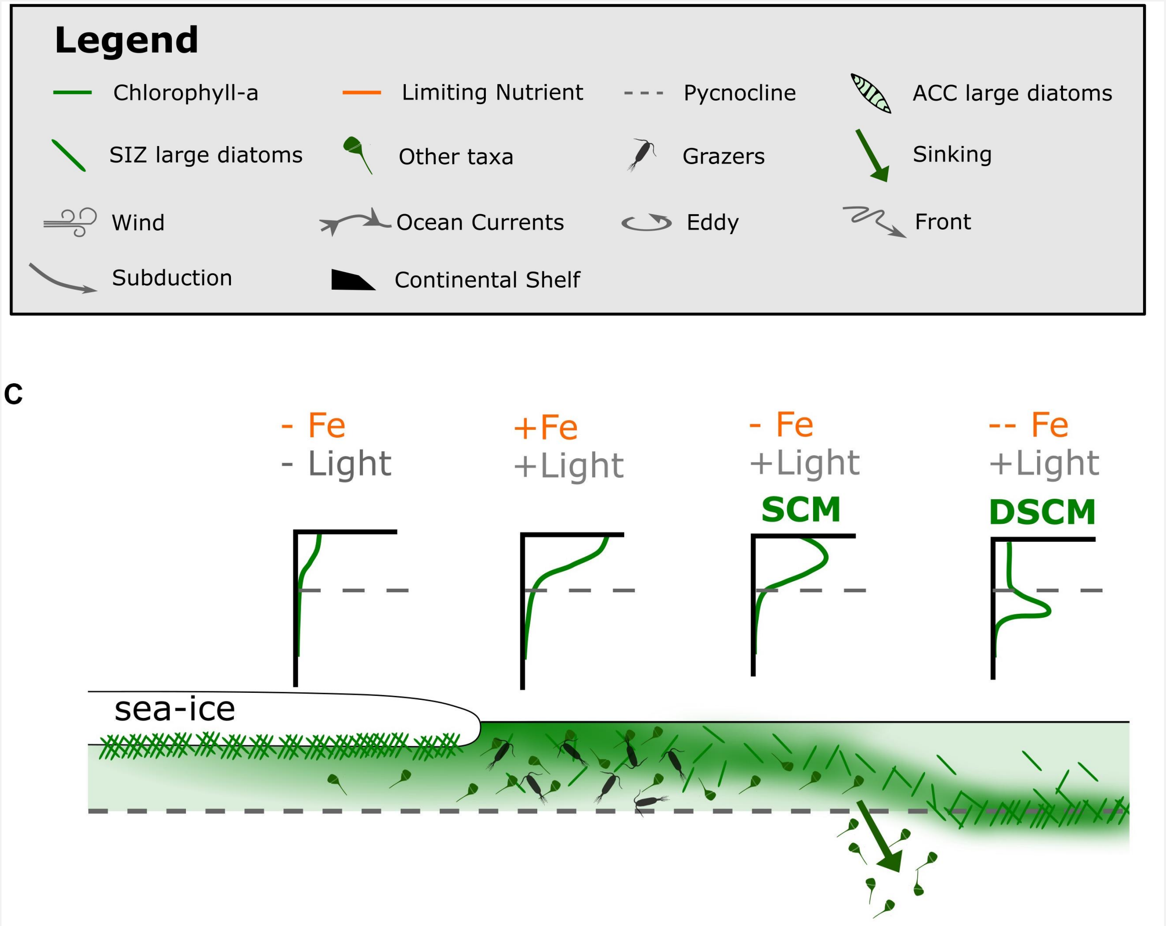
A. in the oceanic HNLC regions
B. downstream of Southern Ocean Islands
C. following sea-ice retreat,
D. in warm-core eddies in the Sub-Antarctic Zone,
E. in cold-core eddies in the Sub-Antarctic Zone and
F. by subduction along the continental shelf



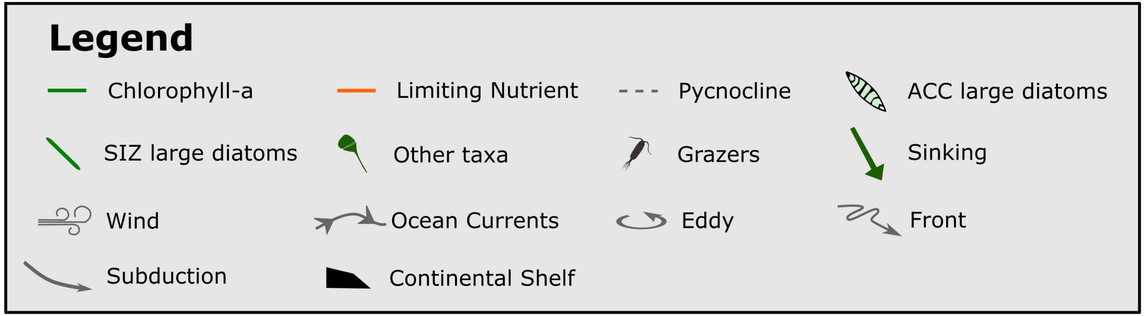
A. in the oceanic HNLC regions



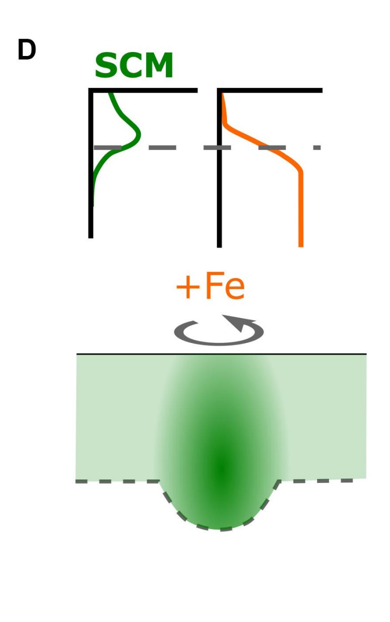
B. downstream of Southern Ocean Islands

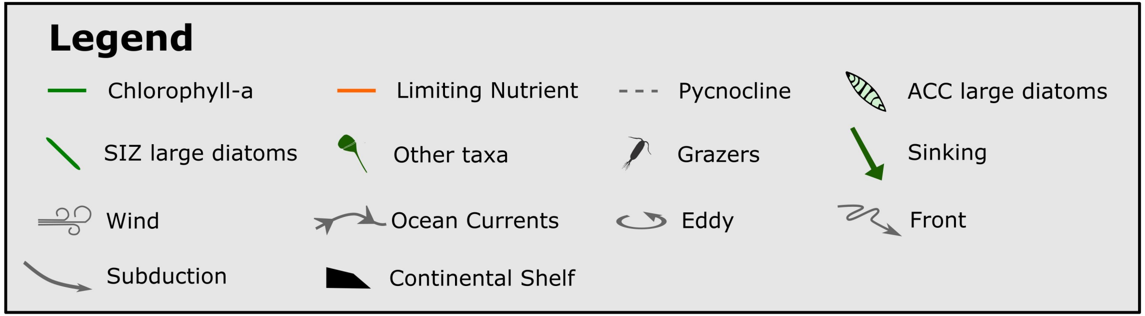


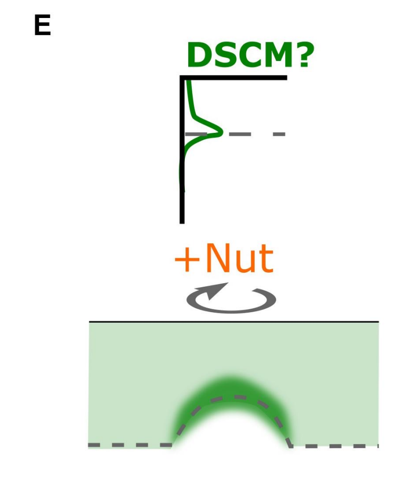
C. following sea-ice retreat,



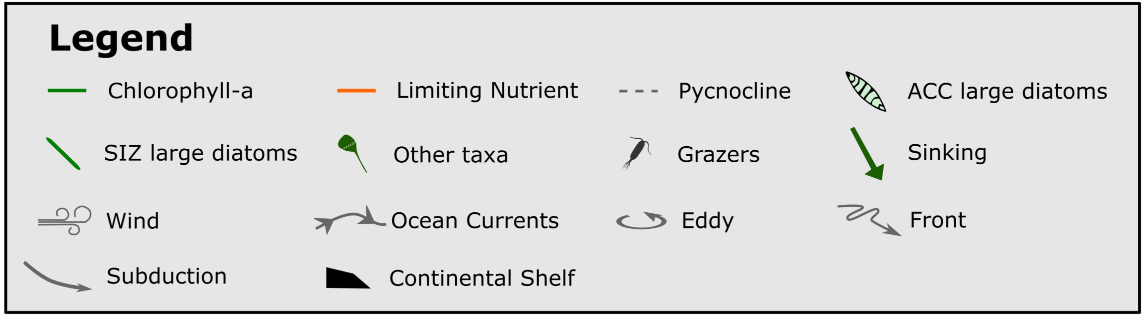
D. in warm-core eddies in the Sub-Antarctic Zone,



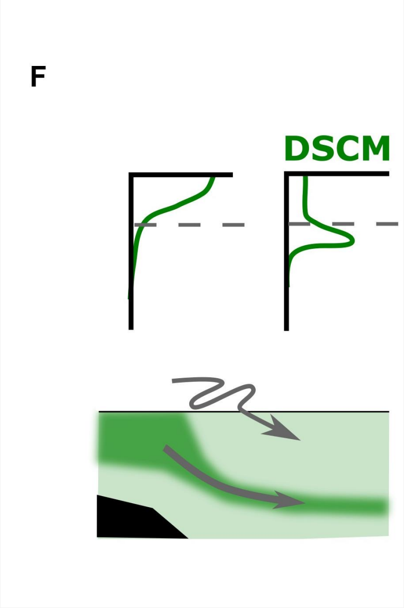




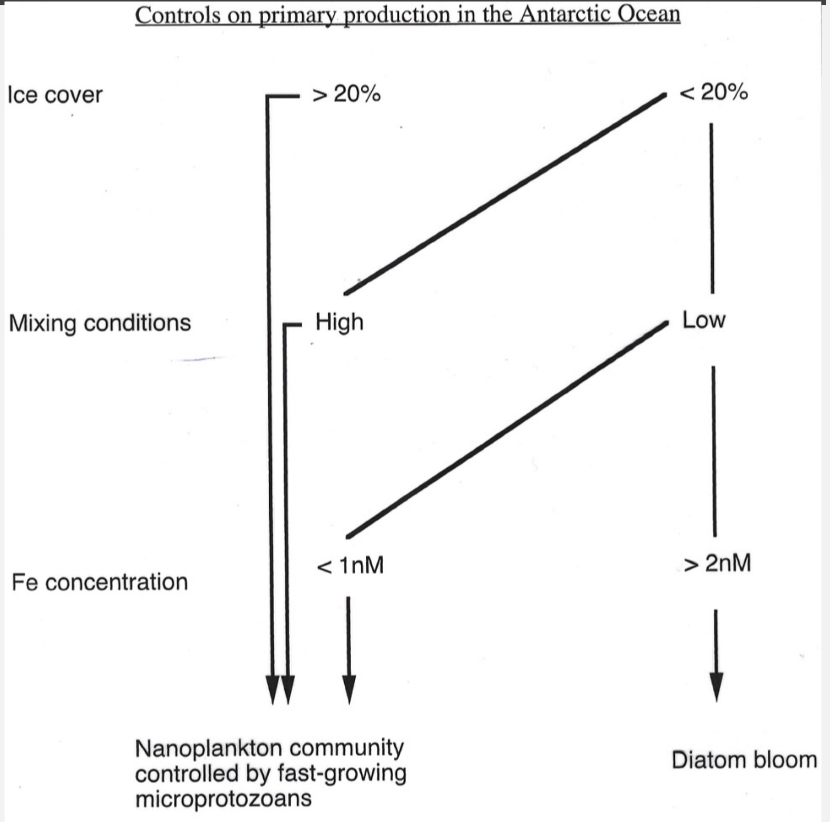
E. in cold-core eddies in the Sub-Antarctic Zone and



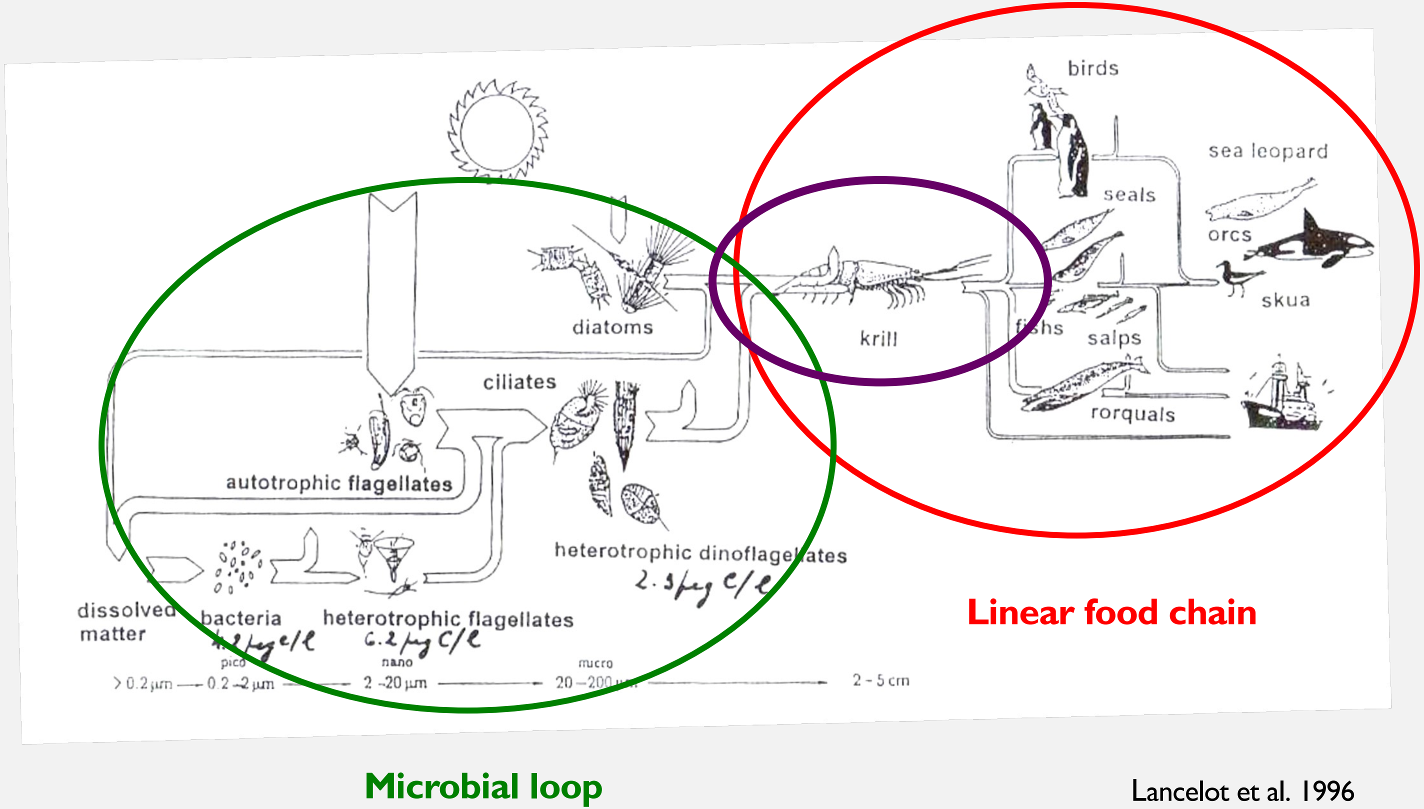
F. by subduction along the continental shelf



2. PRIMARY PRODUCTION
CONTROLLING FACTORS

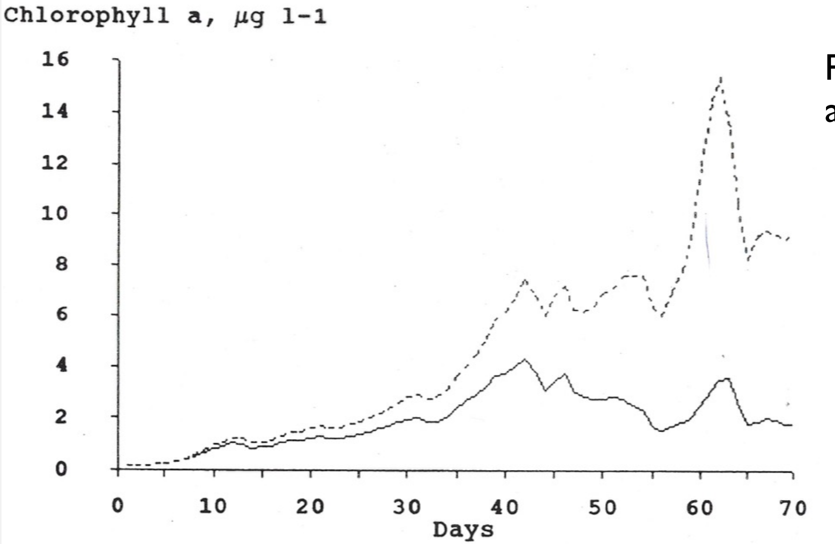


3. CONSUMERS



Lancelot et al. 1996

3.1. MICROBIAL LOOP



Predicted chlorophyll *a* concentration at latitude 59 30⁰ S during the ice melting period under *in situ* grazing pressure by protozoa (solid line) and after protozoa elimination (dashed line).

Lancelot et al. 1996

Protozoa control autotrophic nanoflagellates

Table 3.I.: Estimated protozoan ingestion in the Southern Ocean: in percentage of daily primary and bacterial production.

Area	Period	% of primary production grazed per day	% of bacterial production grazed per day	References
Atlantic sector	October-November	40	32	Becquevort, 1996
ACC	October/ November	34		Klass, in press
Polar front area	October/ November	44		Klass, in press
Weddell/ Scotia Sea	November	10	11	Garrison and Buck, 1989
Weddell/ Scotia Sea	November	68	53	Garrison and Buck, 1989
Weddell/ Scotia Sea	March	58		Garrison and Buck, 1989
Weddell/ Scotia Sea	June/July	53	68	Garrison et al. 1990c,d; 1992, 1993.
McMurdo Sound	December		9	Putt et al., 1991
McMurdo Sound	January		13	Putt et al., 1991
Indian sector	March	50	90	Menon et al., 1995
Indian sector		(47->100)		Taylor and Haberstroh, 1988
Prydz Bay	January	9		Archer et al., submitted
Prydz Bay	February	22		Archer et al., submitted

Protozoa control autotrophic nanoflagellates (*ca.* 50% production) → no nanophytoplankton bloom

Lancelot et al. 1996

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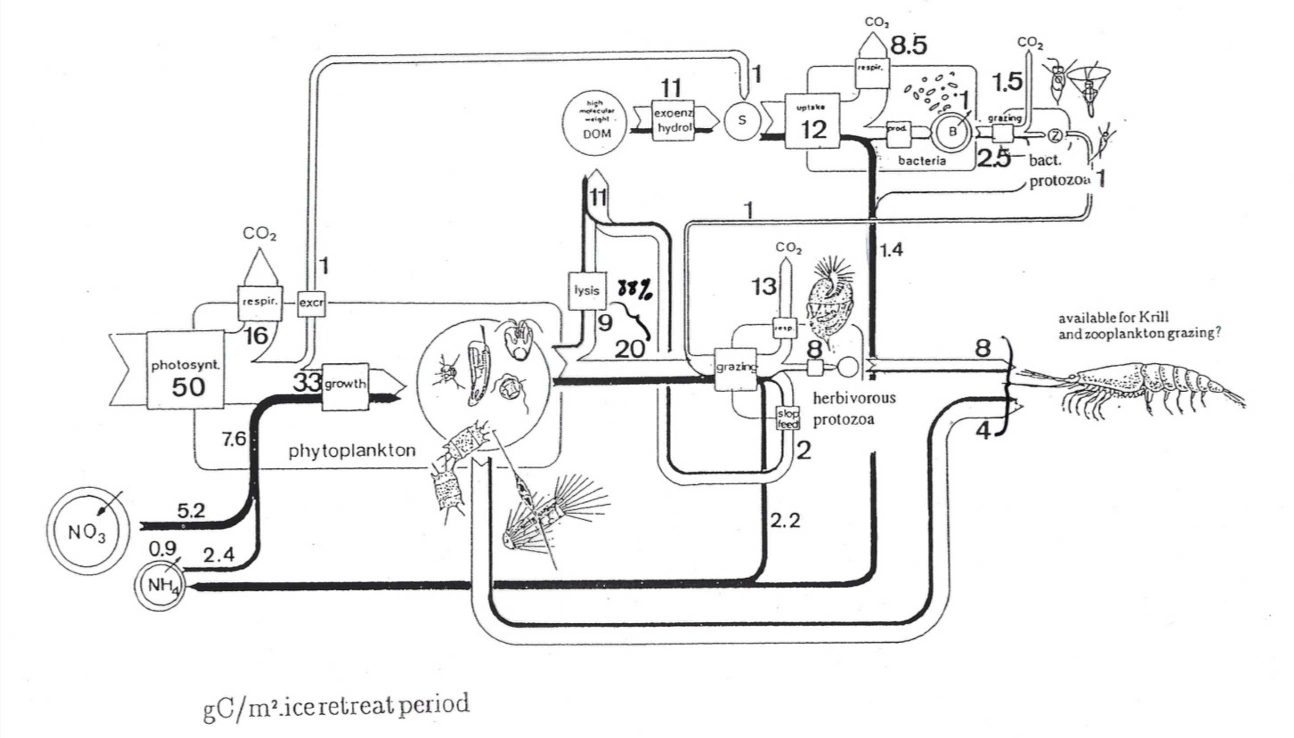
Indian sector		(47->100)		Taylor and Haberstroh, 1988
Prydz Bay	January	9		Archer et al., submitted
Prydz Bay	February	22		Archer et al., submitted

Protozoa control bacterial production
(10- 90% production)

Lancelot et al. 1996

Marginal Sea ice zone

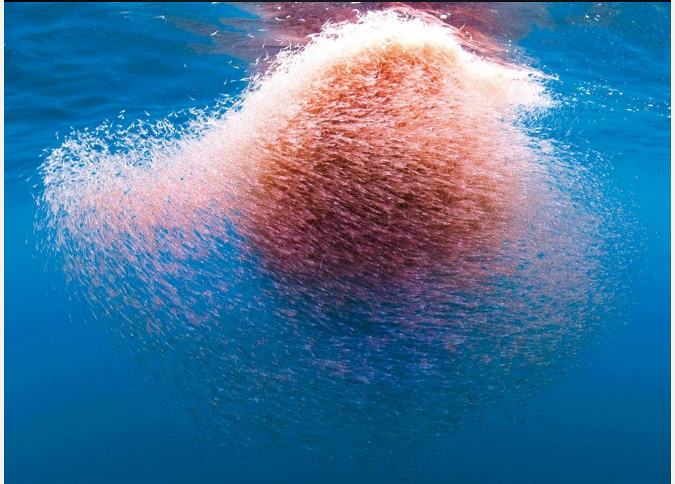


- 88% (29/33 g.C) of net P1 assimilated by the microbial loop
- Net P2 of microbial loop: 25% (8/33 g.C) of P1
- 12.5% (4/33 g.C) of P1 not grazed by microbial loop

Lancelot et al. 1996

Budget of C and N cycling through the microbial network of the northern Weddell Sea during ice retreat 1988.

3.2. Linear food chain: krill (*Euphausia superba*)



- Malacostracea, Eucarid
- Adult 6.5cm long, 1g FW, life span 4-7y
- Swimming speed: 1km/h → nekton!
- Make swarms of millions of T

en.mercopress.com

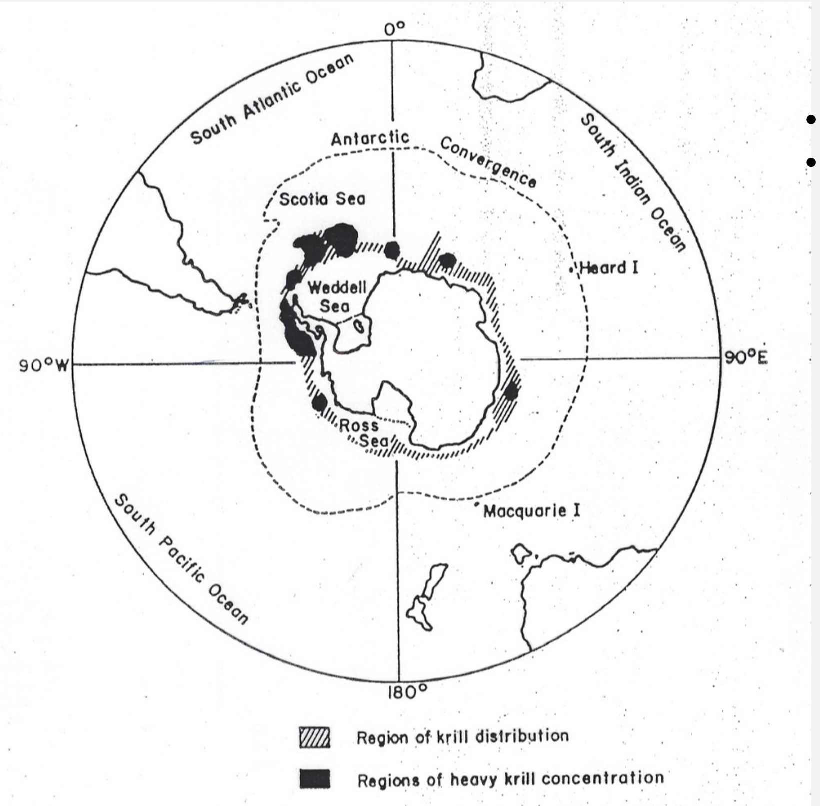
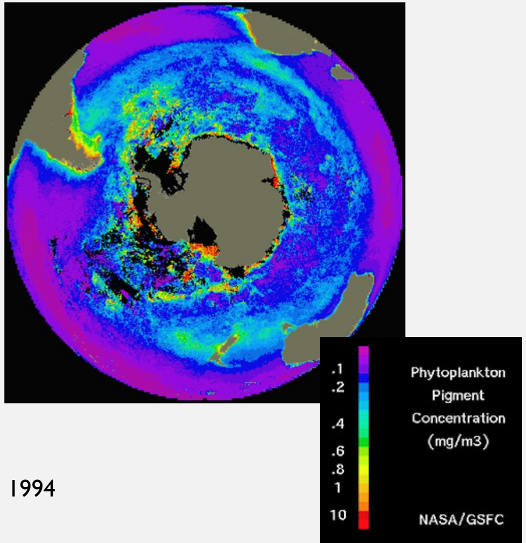
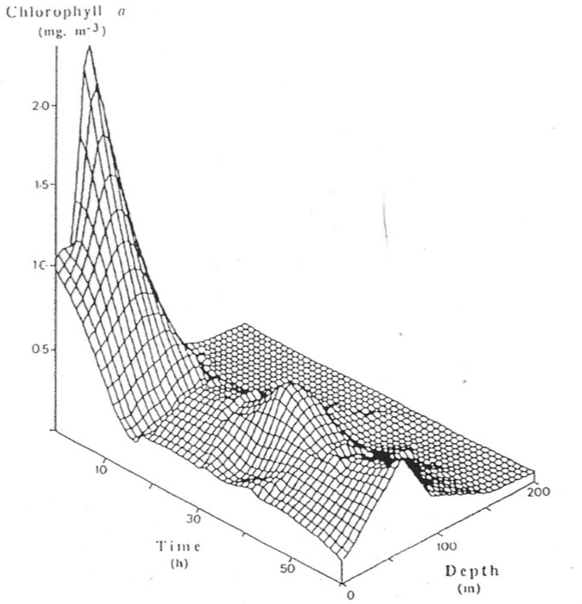


Fig. 3. The generalized distribution of Antarctic krill. Information compiled from a number of sources

- Make swarms of millions of T
- Aggregative distribution corresponding to zones of high PI

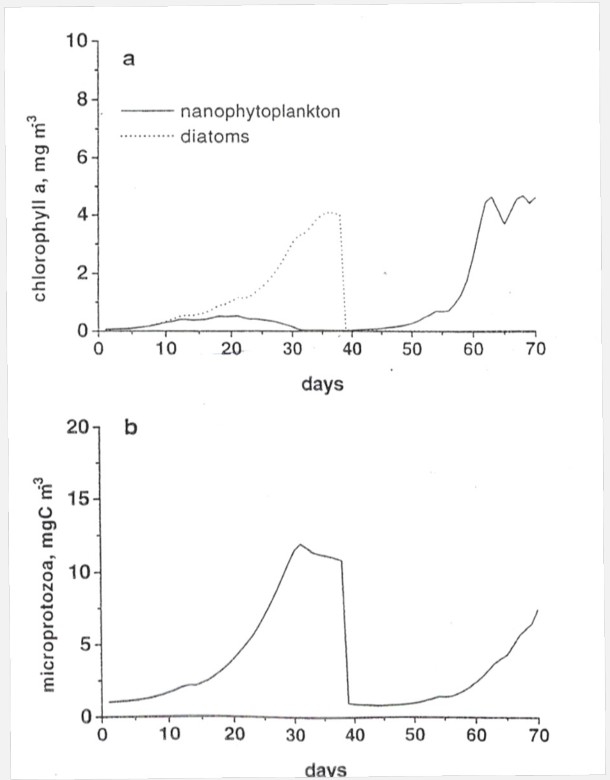


Nicol 1994



Three–dimensional evolution of a diatom bloom at station 157 in the Weddell Sea (5th December 1988). The diatom bloom vanished in less than 10 h, probably grazed down by a krill swarm, and the phytoplankton community toppled towards a flagellate–dominated system (from Jacques & Panouse, 1991).

- Make swarms of millions of T
- Aggregative distribution corresponding to zones of high P1
- Consumers of microplankton
- Fast and massive consumption of diatom blooms

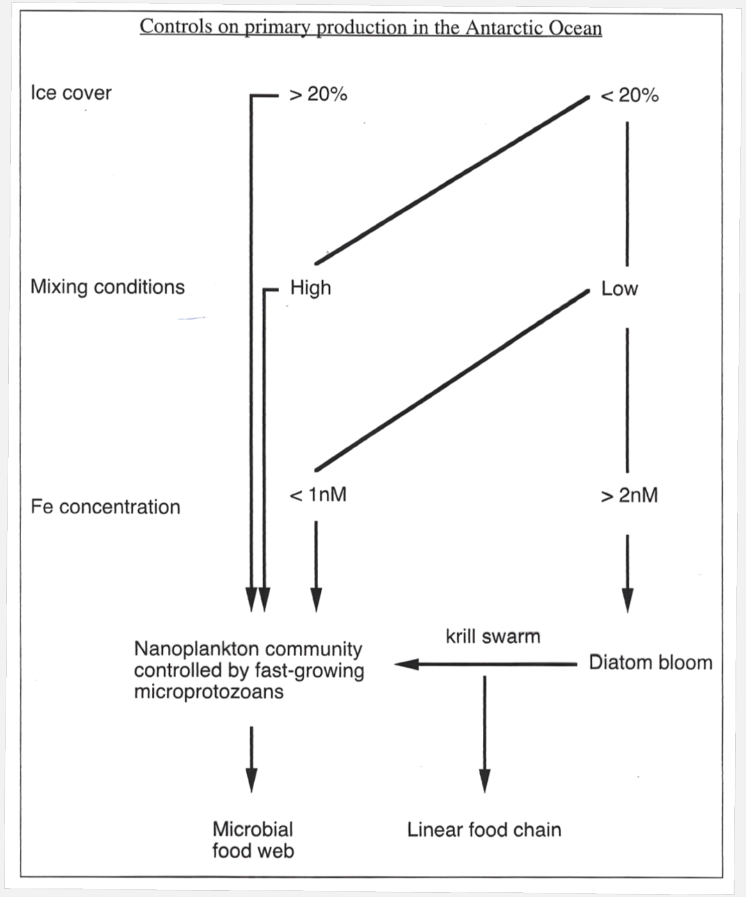


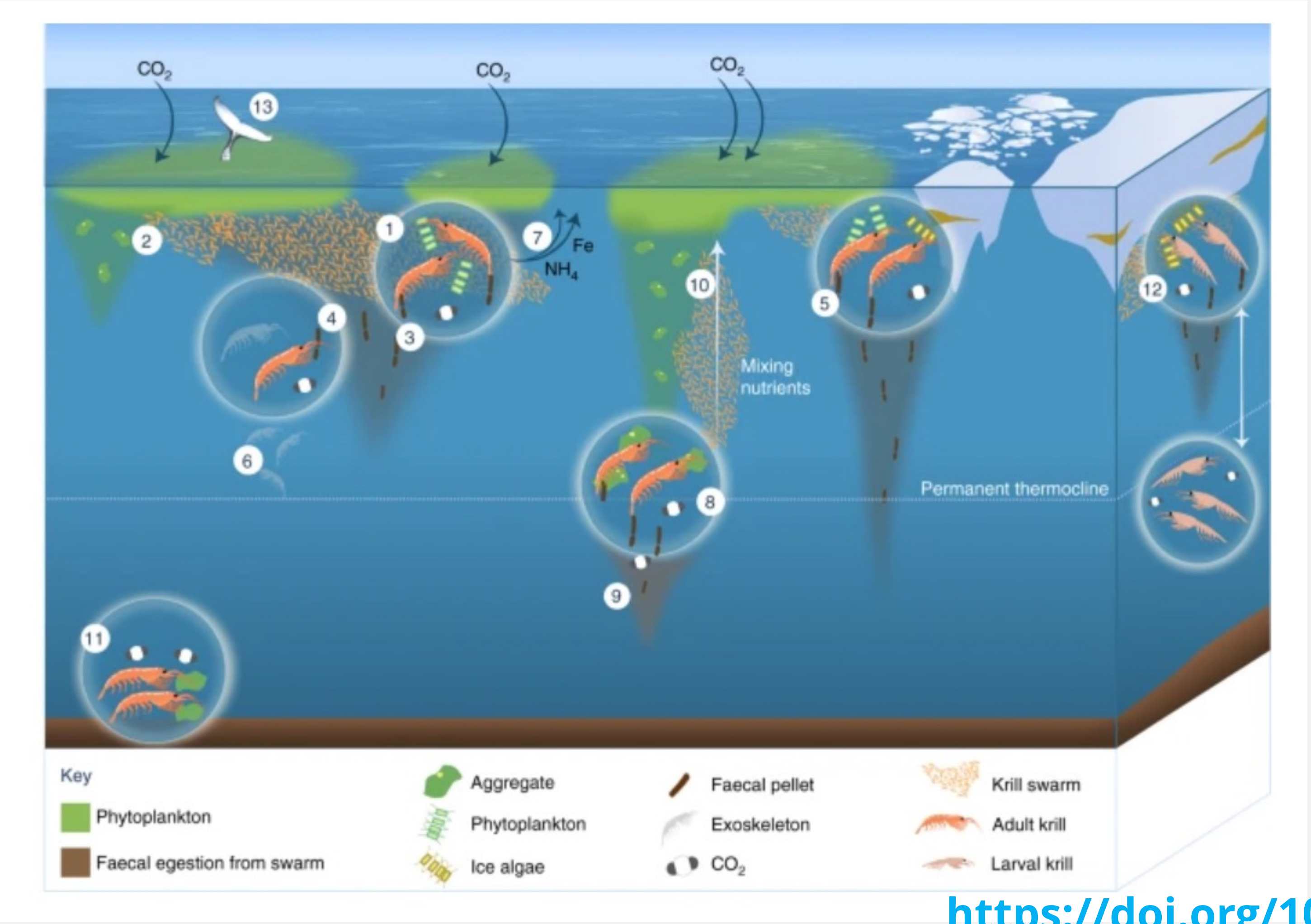
SWAMCO predictions at latitude 59°S (EPOS site) : krill swarm passage at day 40

- Fast and massive consumption of diatom blooms
  - Export of Fe (no new bloom of diatoms)
  - No protozoa
  - Nanophytoplankton bloom possible, progressively controlled by recovering protozoa (short generation time)

Lancelot et al. 1996

Primary production: Controlling factors





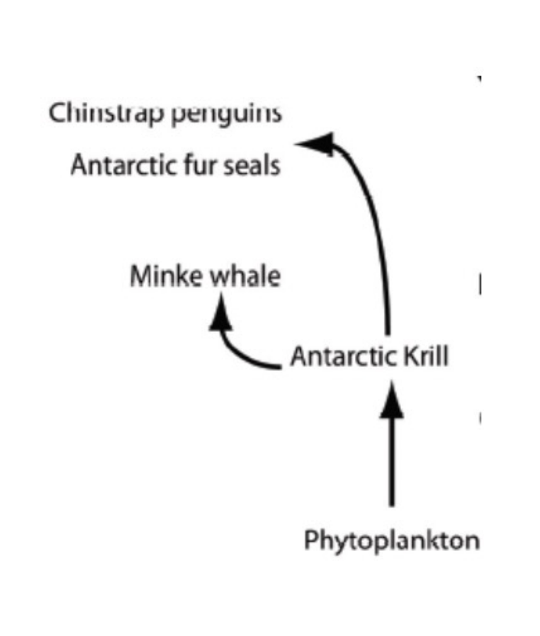
https://doi.org/10.1111/gcb.16009

3. Consumers

3.2. Linear food chain: *Higher ranks*

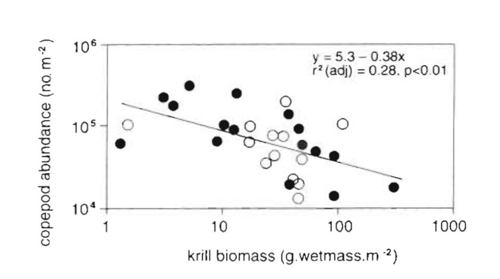
- Vertebrates and squids
- Most are krill eaters

CLASSIC VIEW

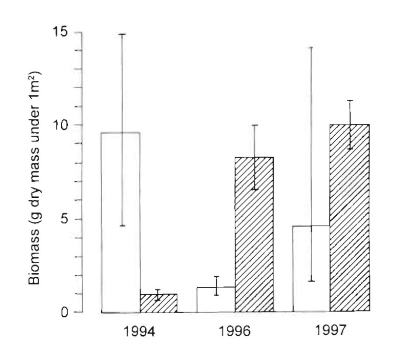


ADDITIONAL GRAZERS

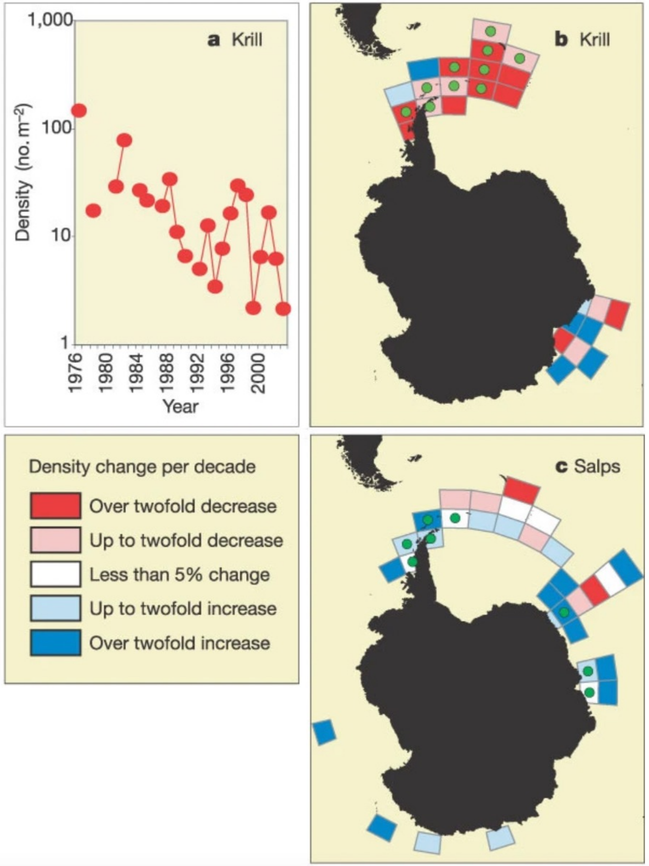
- >Copepods



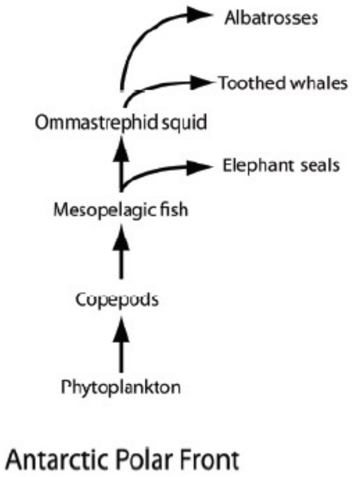
- Salps



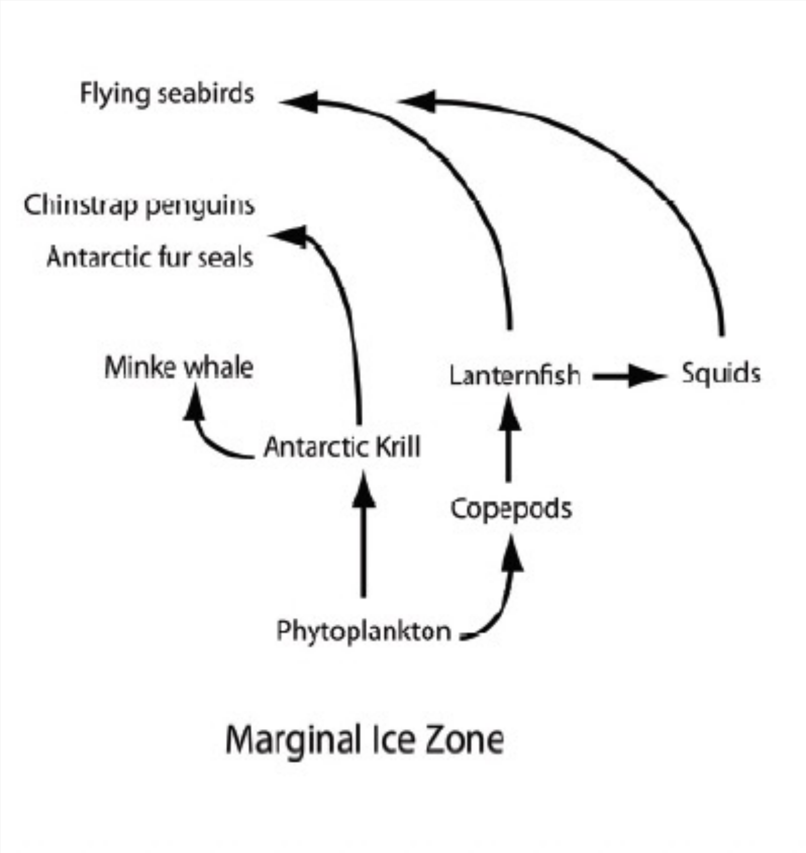
Atkinson et al 1999

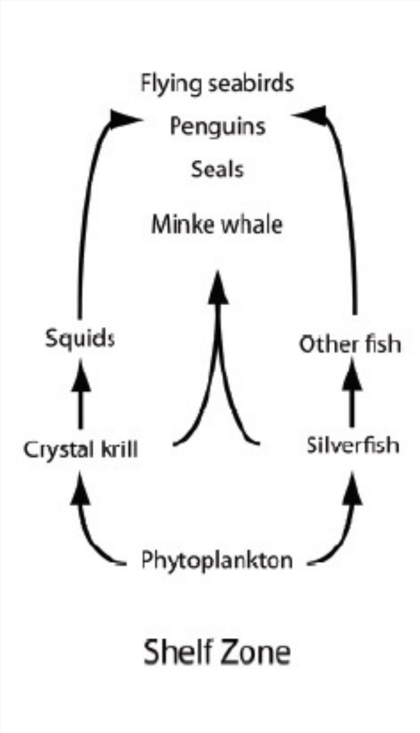


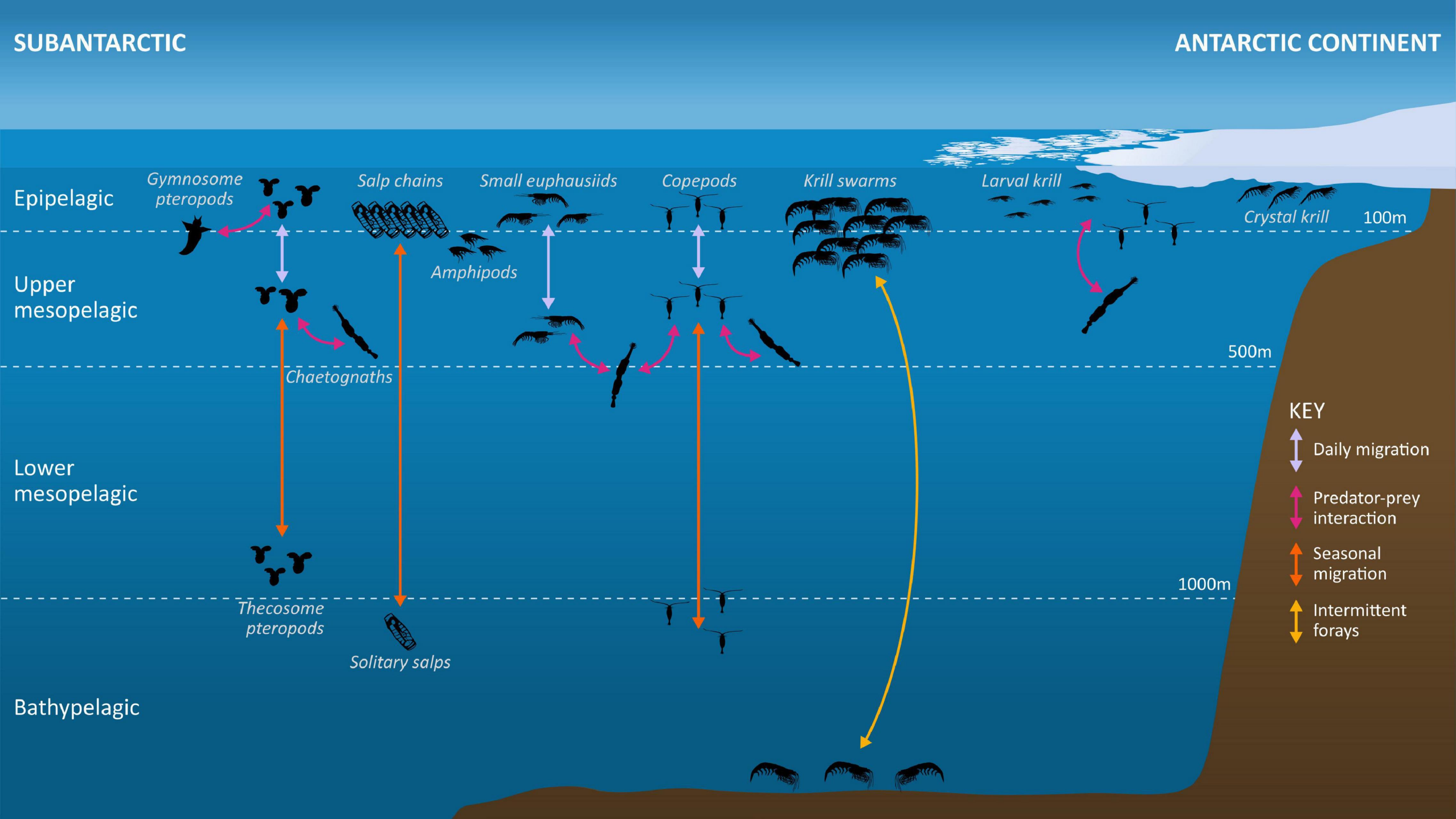
Atkinson, A., Siegel, V., Pakhomov, E. *et al.* Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature* **432**, 100–103 (2004). https://doi.org/10.1038/nature02996


Albatrosses
Toothed whales
Ommastrephid squid
Elephant seals
Mesopelagic fish
Copepods
Phytoplankton
Antarctic Polar Front

- Copopods lower standing biomass but higher productivity




Flying seabirds
Penguins
Seals
Minke whale
Squids
Other fish
Crystal krill
Silverfish
Phytoplankton
Shelf Zone



SUBANTARCTIC
ANTARCTIC CONTINENT
Epipelagic
Upper mesopelagic
Lower mesopelagic
Bathypelagic
Gymnosome pteropods
Salp chains
Small euphausiids
Copepods
Krill swarms
Larval krill
Crystal krill
Amphipods
Chaetognaths
Thecosome pteropods
Solitary salps
100m
500m
1000m
KEY
Daily migration
Predator-prey interaction
Seasonal migration
Intermittent forays

A Living Laboratory of Unique Biodiversity

Antarctic krill are a keystone species, serving as a major food source for more than 25 percent of the species in the diverse Antarctic food web, including penguins, seals, whales, and many fish species. The many remarkable species of the Southern Ocean make up some of the most intact marine ecosystems on the planet, where scientists are continually discovering new marine biodiversity, and can study nature in the absence of human interference. **The following are some of the species that call the Southern Ocean home.**

1 Penguins
- Adélie
- Chinstrap
- Gentoo
- Emperor
- King
- Southern rockhopper
- Macaroni

2 Whales
- Blue
- Southern bottlenose
- Humpback
- Antarctic minke
- Long-finned pilot
- Sperm
- Sei
- Arnoux's beaked
- Fin
- Orca

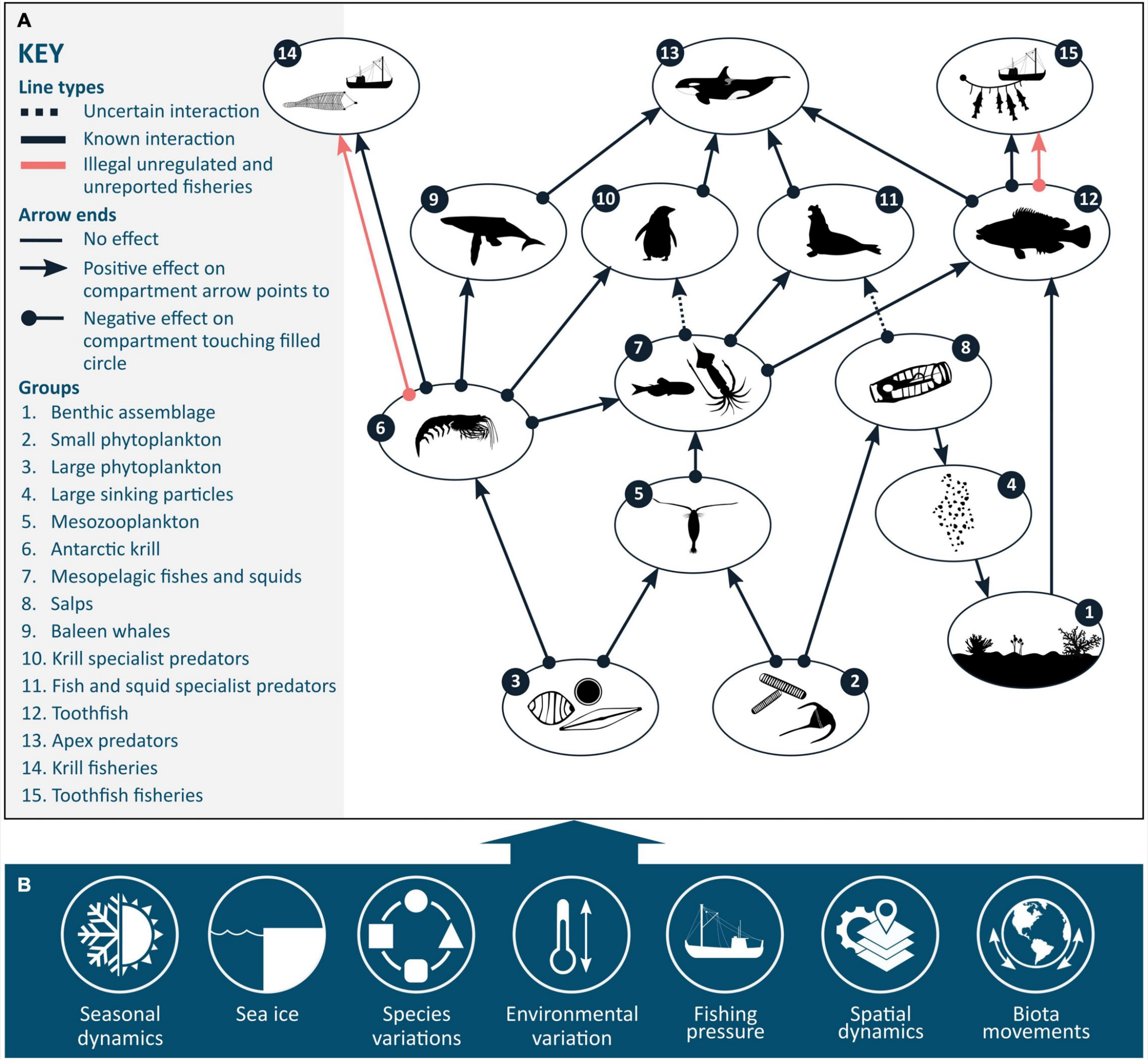
3 Seals
- Antarctic fur
- Crabeater
- Southern elephant
- Leopard
- Ross
- Weddell

4 Seabirds
- Snow petrel
- Wandering albatross
- Antarctic petrel
- Antarctic fulmar

5 Fish
- Antarctic and Patagonian toothfish (Chilean sea bass)
- Icefish
- Lanternfish
- Antarctic eel cod
- Grenadier
- McCain's skate
- Marbled rockcod

6 Invertebrates
- Krill
- Antarctic sea spider
- Crawling and glass sponges
- Antarctic coral
- Bone-eating worm
- Yeti (hairy) crab
- Octopus
- Starfish
- Colossal squid

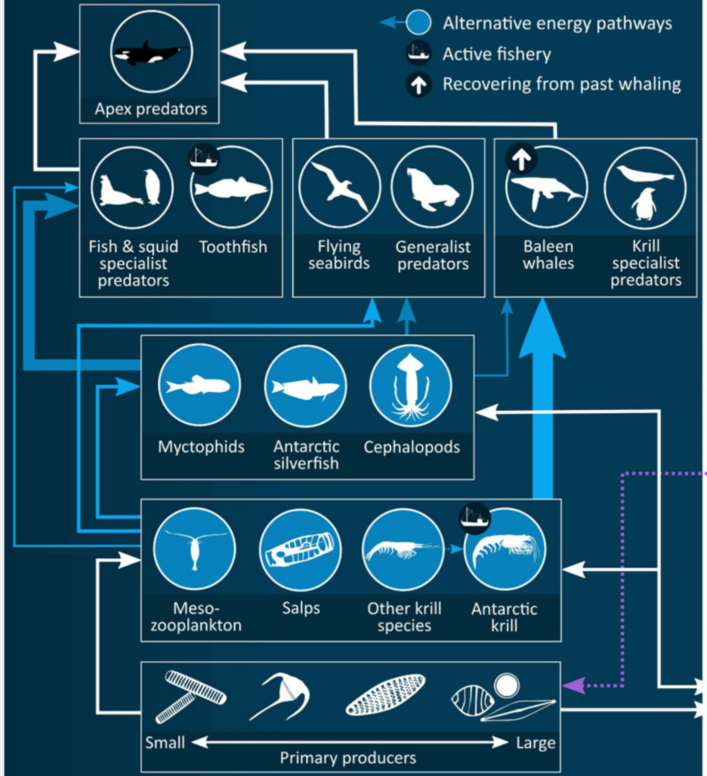
Source: Claude De Broyer et al. (eds.), "Biogeographic Atlas of the Southern Ocean," Scientific Committee on Antarctic Research (2014), http://share.biodiversity.aq/Atlas/example_BASO_web.pdf


A
KEY
Line types
Uncertain interaction
Known interaction
Illegal unregulated and unreported fisheries
Arrow ends
No effect
Positive effect on compartment arrow points to
Negative effect on compartment touching filled circle
Groups
1. Benthic assemblage
2. Small phytoplankton
3. Large phytoplankton
4. Large sinking particles
5. Mesozooplankton
6. Antarctic krill
7. Mesopelagic fishes and squids
8. Salps
9. Baleen whales
10. Krill specialist predators
11. Fish and squid specialist predators
12. Toothfish
13. Apex predators
14. Krill fisheries
15. Toothfish fisheries
14
13
15
9
10
11
12
7
8
6
5
4
3
2
1
B
Seasonal dynamics
Sea ice
Species variations
Environmental variation
Fishing pressure
Spatial dynamics
Biota movements

Southern Ocean food webs

Southern Ocean food webs are of major importance to humans and the global system, underpinning the existence of wildlife populations and supporting high-value fisheries and carbon sequestration. Determining how these food webs may respond to change requires understanding multiple aspects of food web structure and function.

Pelagic food webs



Simplified food web representation. To interpret for individual species, an understanding of what prey they consume is required

Alternative pathways for energy flow

Multiple alternative pathways of energy flow through zooplankton and nekton groups are important for ecosystem function, climate-driven changes and management.

Climate change impacts

Climate changes can cause cascading effects through Southern Ocean food webs. Prominent changes include alterations to habitats (e.g. temperature, pH, changes to sea-ice) that disrupt life cycles and alter physiology generating shifts in the distribution and abundance of many species.

Fisheries impacts

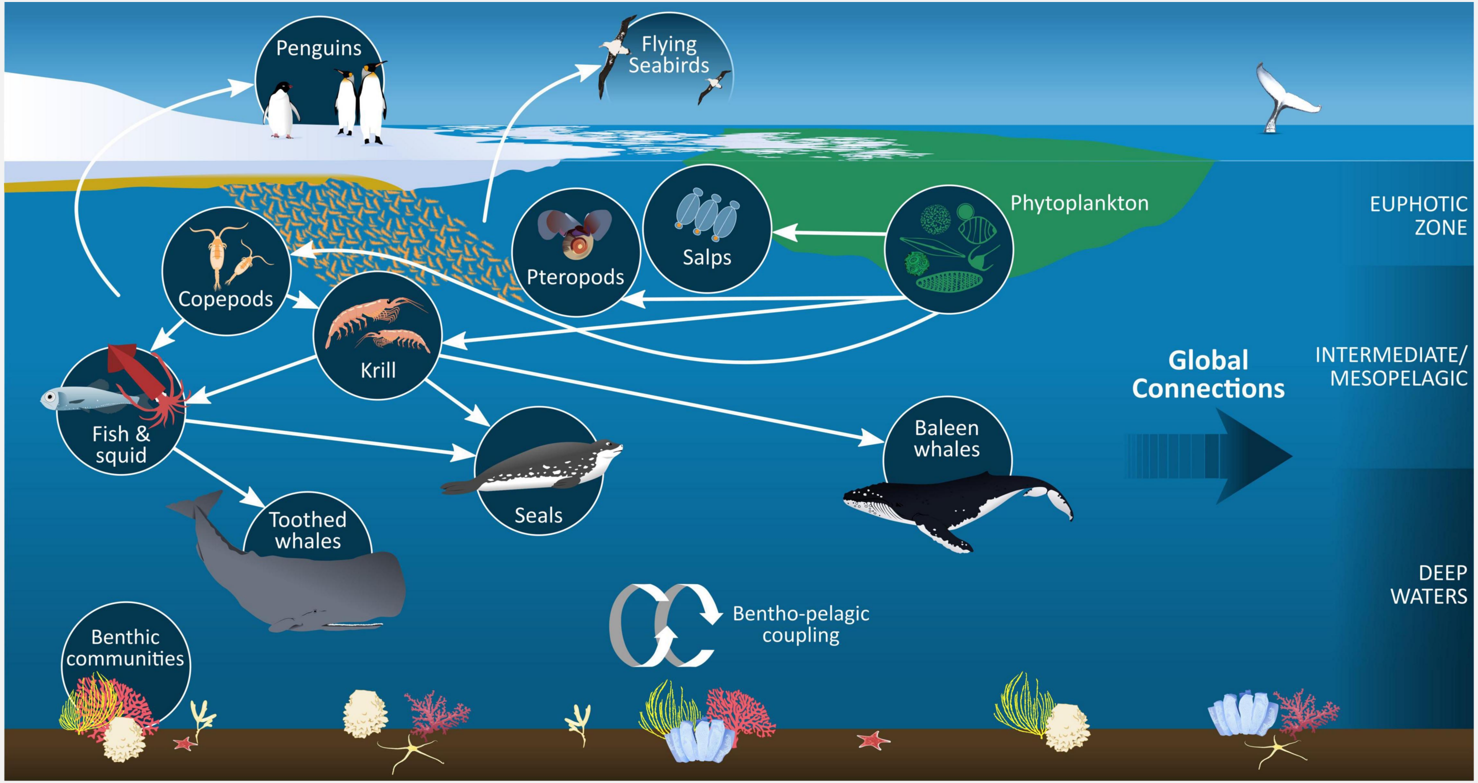
Current and historical harvesting (e.g. past exploitation of whale populations) can alter predator populations and community dynamics. Locally, fishing can generate intense changes to food web structure and dynamics.

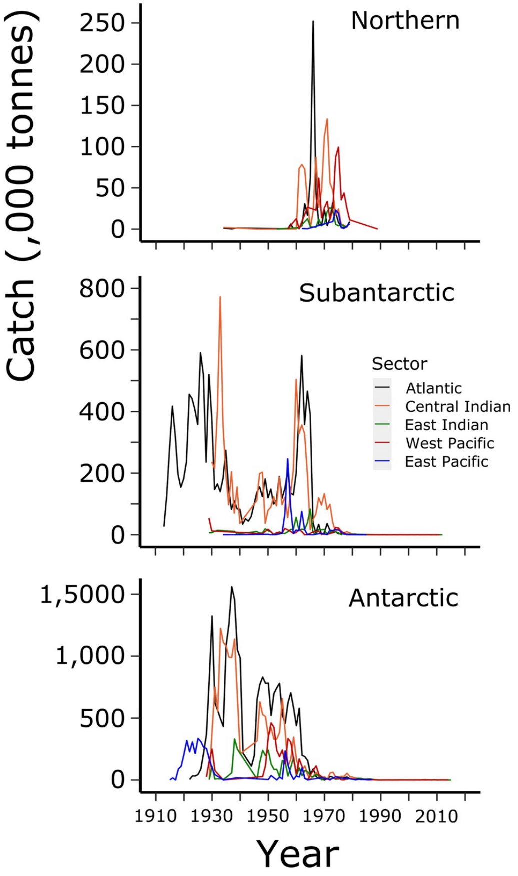
Microbial networks and biogeochemistry

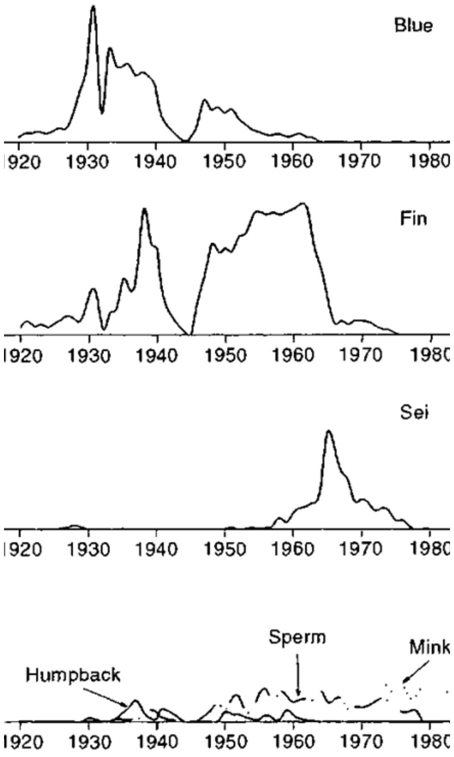
Southern Ocean food web structure, in particular the composition of the main grazing community is crucial in determining the dynamics of the planktonic community and biogeochemical cycling.

Benthic food webs

Benthic systems influence carbon uptake and play an important role in linking pelagic and seafloor systems (bentho-pelagic coupling). Benthic organisms provide important supplementary inputs to the pelagic system such as further food input for plankton, and direct links to higher predators through demersal fish.


Penguins
Flying Seabirds
Phytoplankton
EUPHOTIC ZONE
Salps
Pteropods
Copepods
Krill
Fish & squid
INTERMEDIATE/ MESOPELAGIC
Global Connections
Baleen whales
Seals
Toothed whales
DEEP WATERS
Bentho-pelagic coupling
Benthic communities



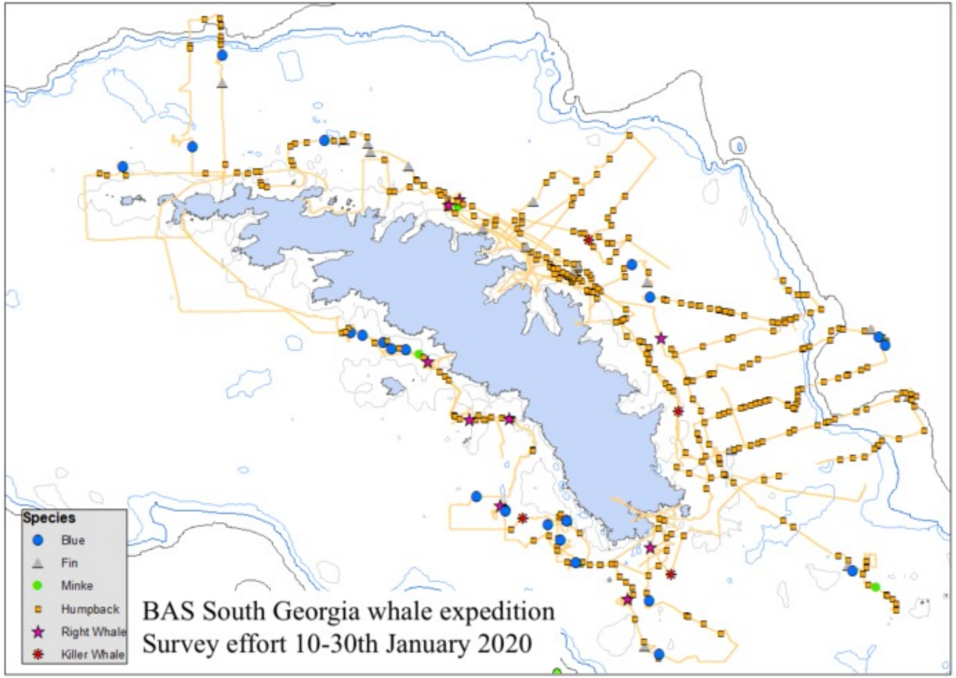


- • exploratory sealing
- • late 18th early 19th century
- • preindustrial sealing and whaling
- • 19th century
- • industrial whaling
- • 20th Century

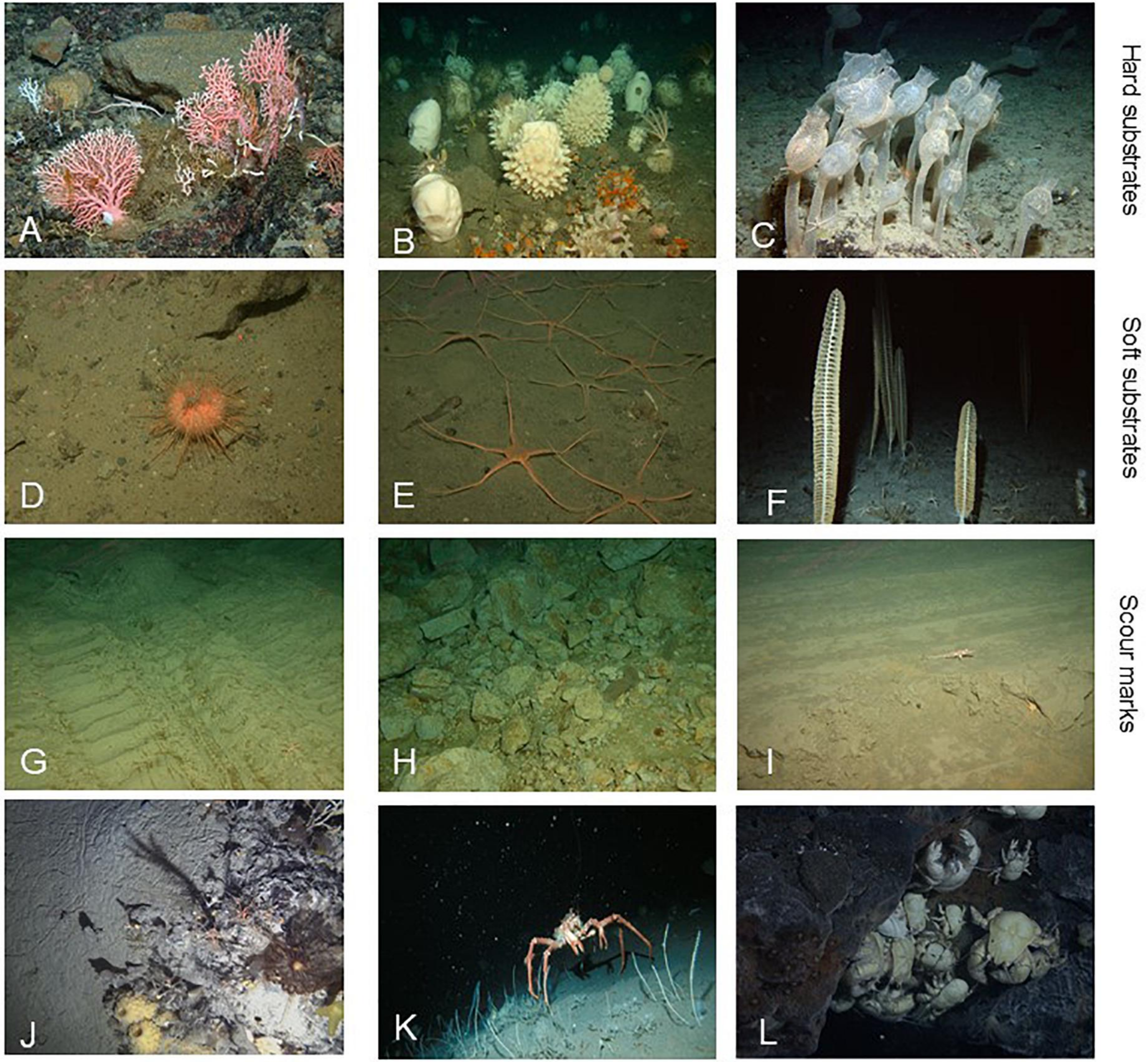
	Lower estimate	Higher estimate
	Krill production (10^6 T/year)	
	400	1385
Present		
Taxa	Krill consumption (10^6 T/year)	
Cetaceans (baleen whales)	34	43
Seals (crabeater seal Lobodon carcinophagus)	64	129
Cephalopods (principally squids of the order Oegopsidea)	30	50
Birds (penguins accounting for 90% of the biomass of and 86% of the food consumed by Antarctic birds)	25	50
Fishes (Champsocephalus gunnari Notothenia rossii)	10 ?	20 ?
Total	163	292
% of krill production	163/1385= 12%	292/400= 73%
Before whale hunting		
Baleen whales		190

- Krill eaters consume a significant part of krill production
- Before whale hunting, most of krill production was probably consumed

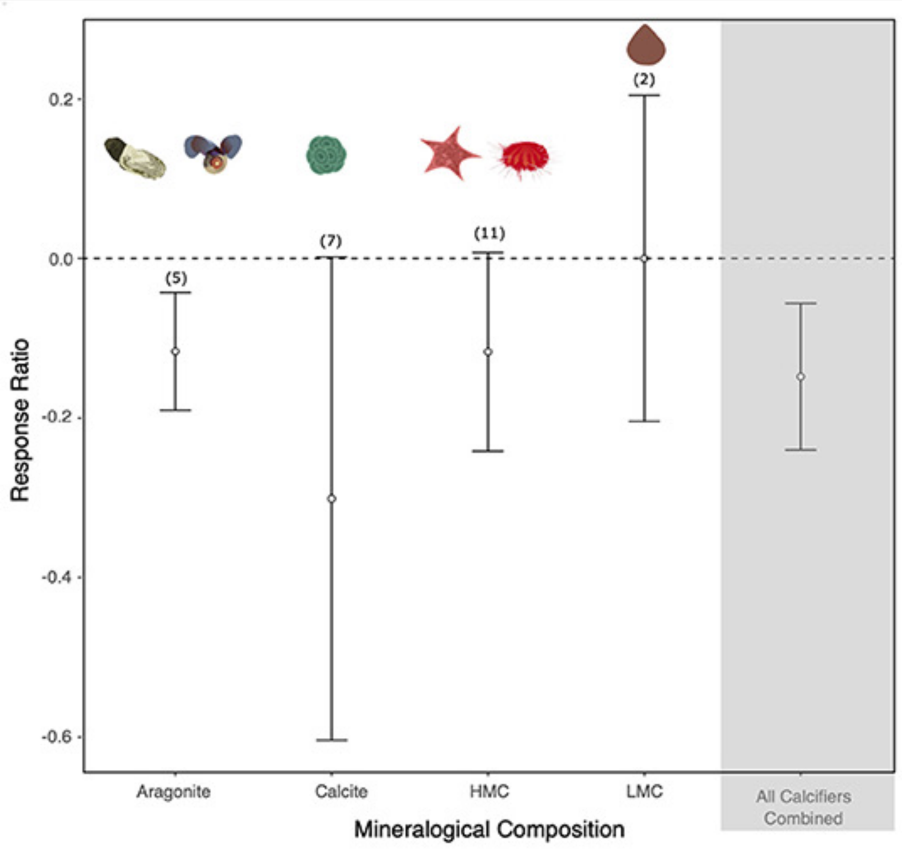
➢ Bottom-up control


Species
Blue
Fin
Minke
Humpback
Right Whale
Killer Whale
BAS South Georgia whale expedition
Survey effort 10-30th January 2020

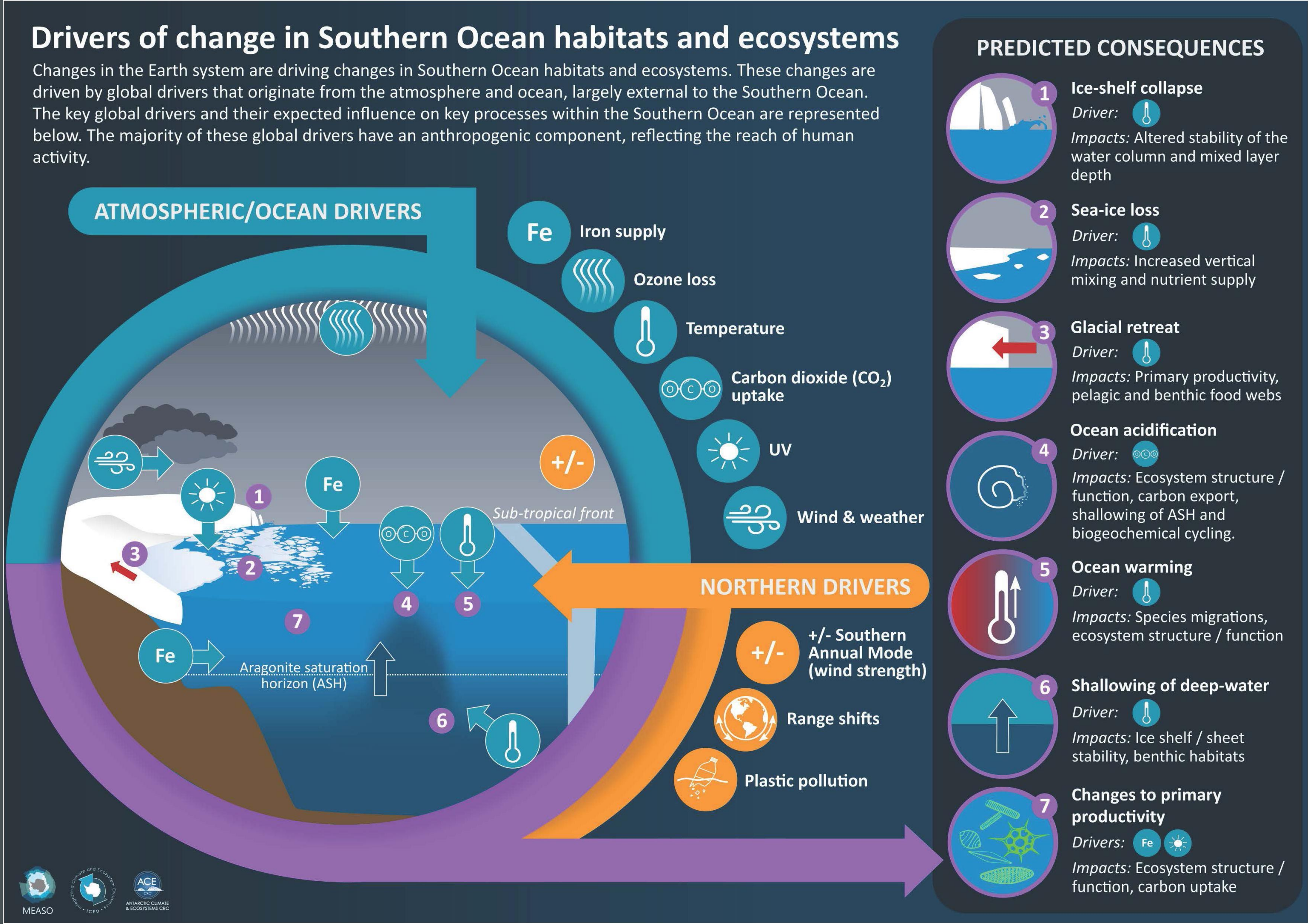

South Georgia blue whale. Photo: Martin Collins


A
B
C
D
E
F
G
H
I
J
K
L
Hard substrates
Soft substrates
Scour marks

- The effect of ocean acidification on aragonitic, calcitic, high-Mg calcite (HMC), and low-Mg calcite (LMC) species. Mean response ratios and 95% confidence intervals are shown, with the number of data points in each category given in brackets. A mean response ratio of zero (hashed line) indicates no effect. Background shading indicates response ratios of all the phyla.

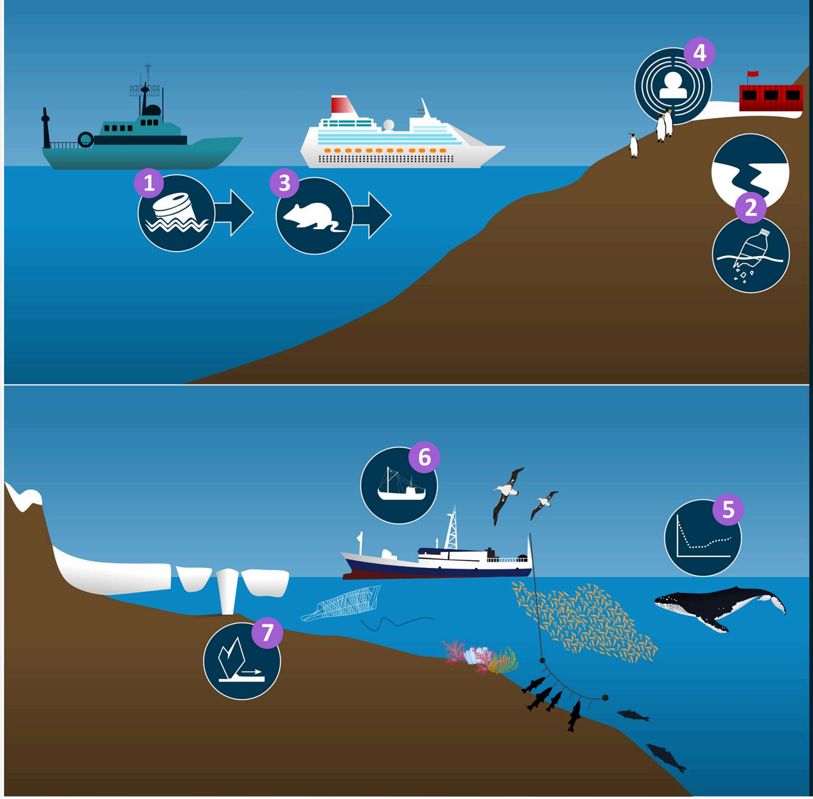


- Front. Mar. Sci., 15 December 2020
- Sec. Global Change and the Future Ocean
- https://doi.org/10.3389/fmars.2020.547188



Local drivers of change in Southern Ocean ecosystems

Local drivers (activities or processes that cause physical or ecological changes) influence Antarctic ecosystems at a particular location or series of locations. These may be associated with current human activities or recovery from past activities within the Antarctic region. The key local drivers and their influence on Southern Ocean ecosystems are represented below.



Marine-derived pollution
The increasing number of science, tourist and fishing vessels visiting the Antarctic region each year poses risks of pollution (plastics, chemicals and hydrocarbons) including oil spills.

Land-derived pollution
Human activities on land, both scientific and tourism-related, increase the risk of sewage runoff and point source pollution (plastics, chemicals and hydrocarbons).

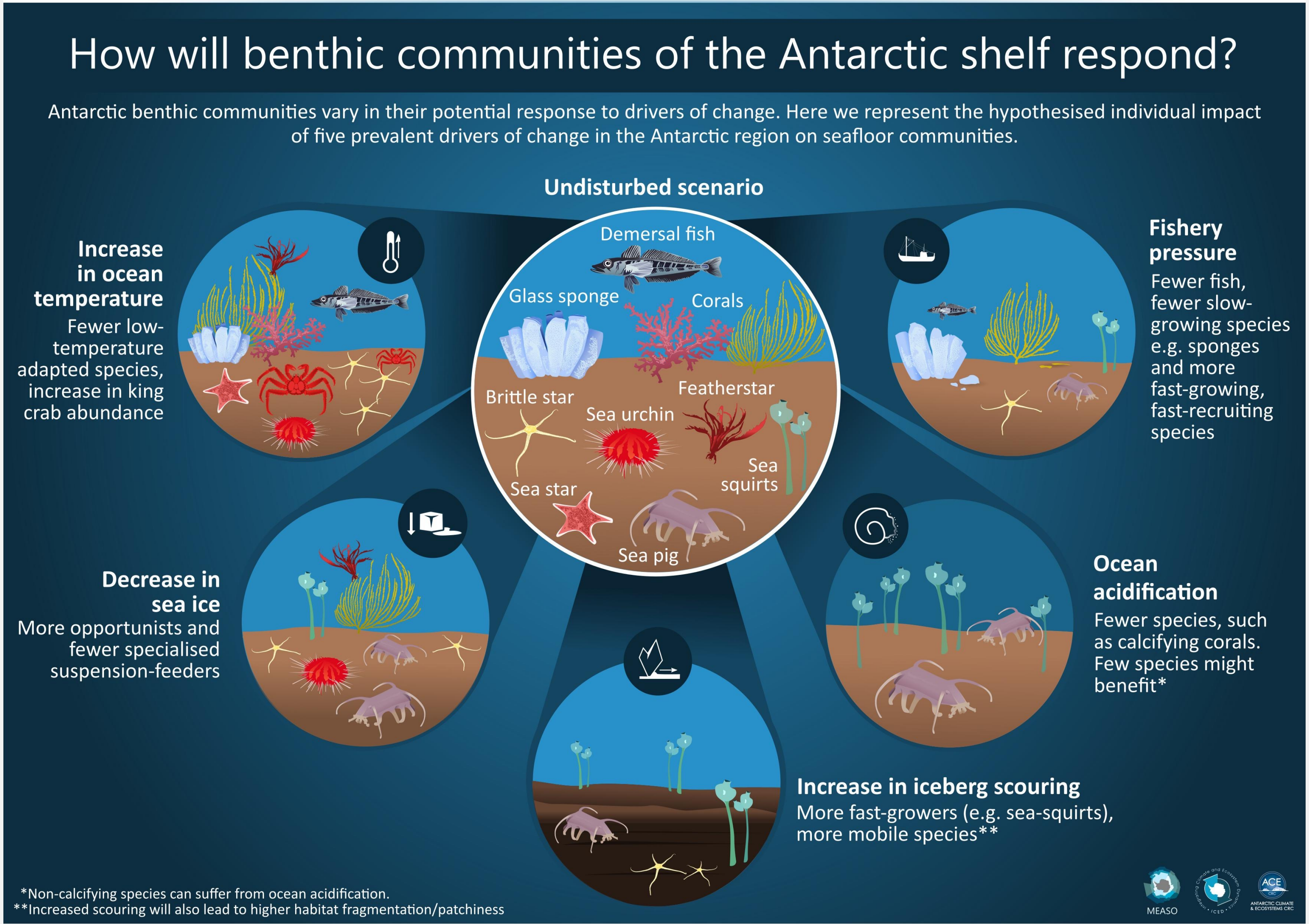
Non-indigenous species
All vessels pose the risk of transporting non-indigenous species (including disease-causing species) to the Antarctic region in ballast water or on hull surfaces, as well as being taken ashore by visitors or in cargo.

Tourism and visitation
In addition to 1 and 3, visitor activities (both tourists and scientists) may cause disturbance to wildlife when visiting land-based colonies, or undertaking activities such as kayaking or diving.

Marine mammal recovery
Many marine mammal species are recovering from past exploitation. Local population increases may influence krill swarms as well as oceanic nutrient enrichment and mixing.

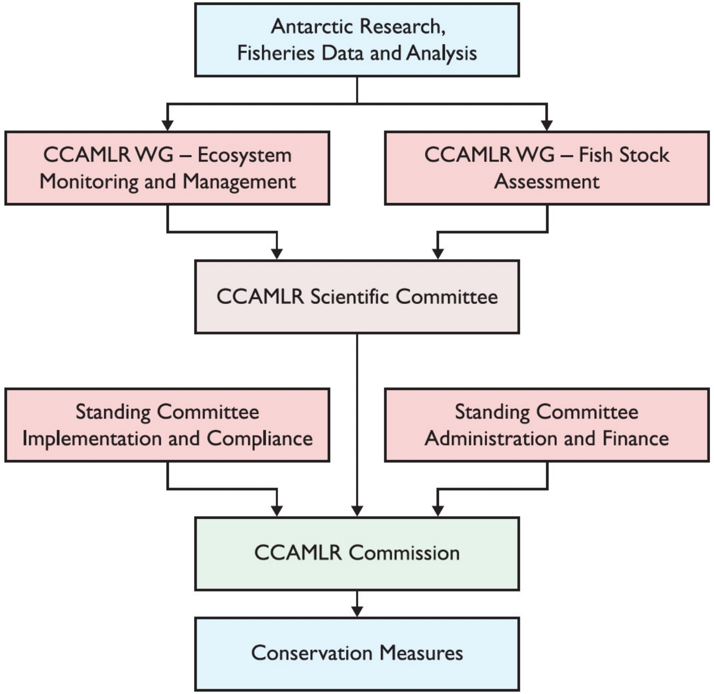
Fishing
In addition to 1 and 3, fishing activities including long-lining and pelagic trawling pose local risks such as depletion of fish/krill stocks, incidental mortality, entanglement, bycatch of non-target species, and physical damage to vulnerable marine ecosystems such as benthic habitats.

Coastal change
Ice loss from coastal glacier retreat and ice shelf collapses may cause increased scouring and impacts on local benthic biodiversity.

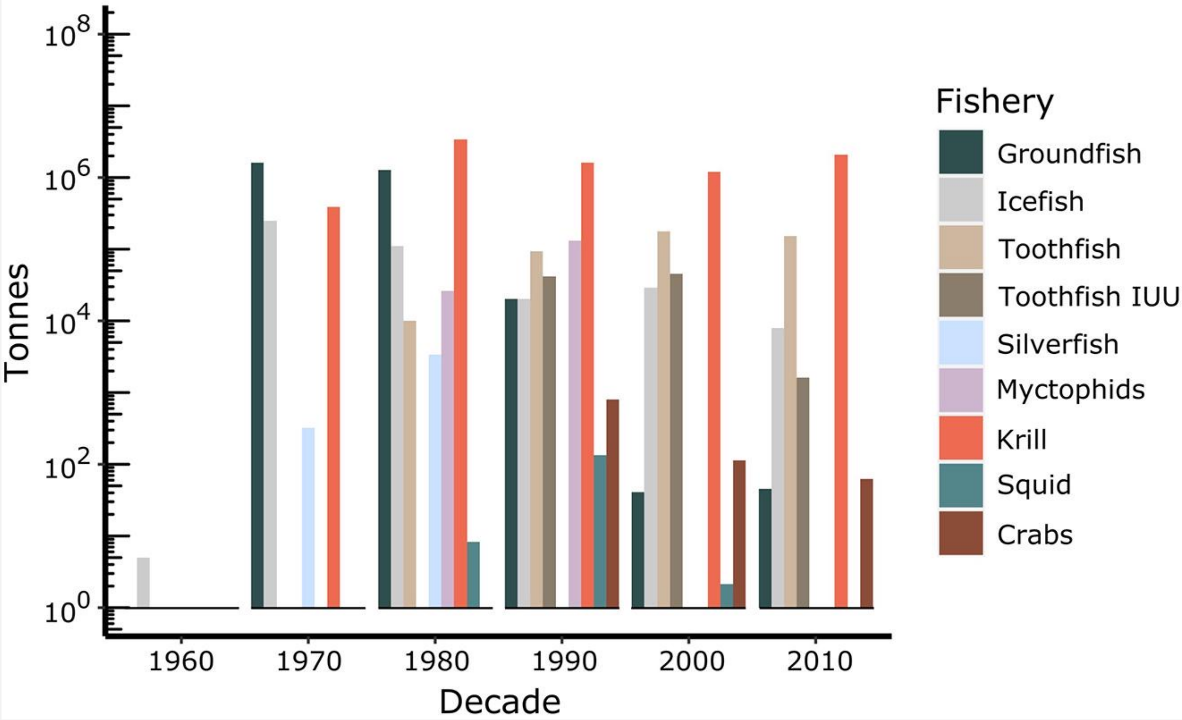

How will benthic communities of the Antarctic shelf respond?
Antarctic benthic communities vary in their potential response to drivers of change. Here we represent the hypothesised individual impact of five prevalent drivers of change in the Antarctic region on seafloor communities.
Undisturbed scenario
Demersal fish
Glass sponge
Corals
Brittle star
Sea urchin
Featherstar
Sea squirts
Sea star
Sea pig
Increase in ocean temperature
Fewer low-temperature adapted species, increase in king crab abundance
Fishery pressure
Fewer fish, fewer slow-growing species e.g. sponges and more fast-growing, fast-recruiting species
Decrease in sea ice
More opportunists and fewer specialised suspension-feeders
Ocean acidification
Fewer species, such as calcifying corals. Few species might benefit*
Increase in iceberg scouring
More fast-growers (e.g. sea-squirts), more mobile species**
*Non-calcifying species can suffer from ocean acidification.
**Increased scouring will also lead to higher habitat fragmentation/patchiness
MEASO
ICED
ACE CRC
ANTARCTIC CLIMATE & ECOSYSTEMS CRC

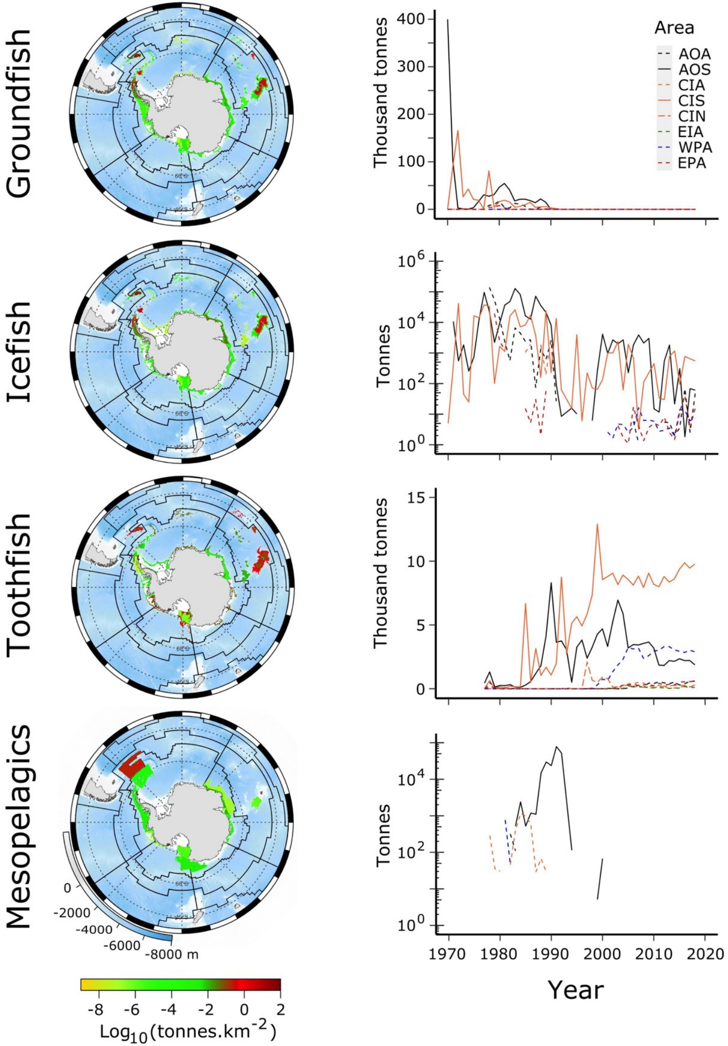
MANAGING THE SOUTHERN OCEAN

CCAMLR

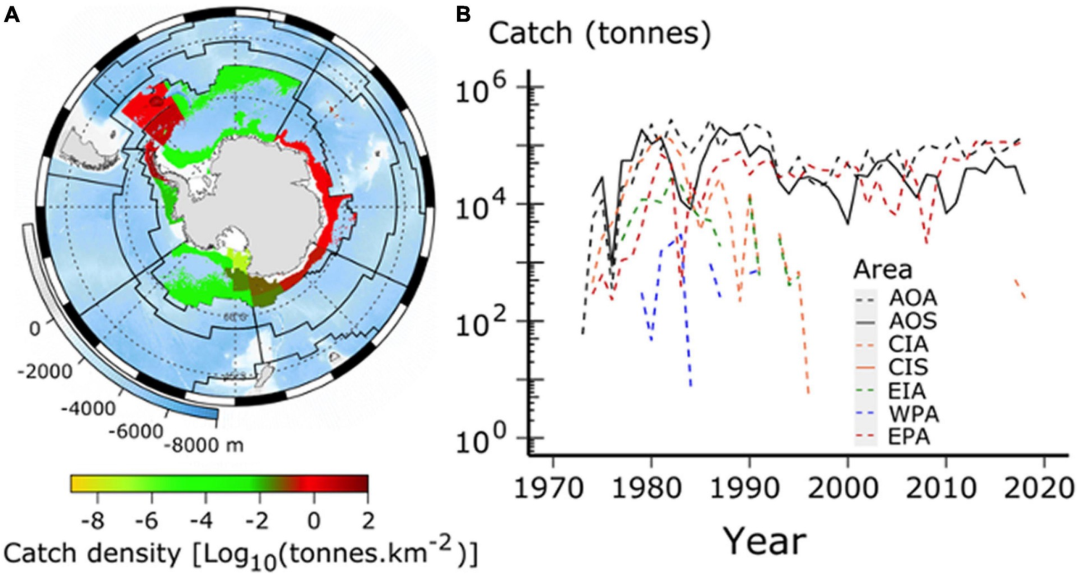

Antarctic Research,
Fisheries Data and Analysis
CCAMLR WG – Ecosystem Monitoring and Management
CCAMLR WG – Fish Stock Assessment
CCAMLR Scientific Committee
Standing Committee Implementation and Compliance
Standing Committee Administration and Finance
CCAMLR Commission
Conservation Measures

FISHERIES BIOMASS





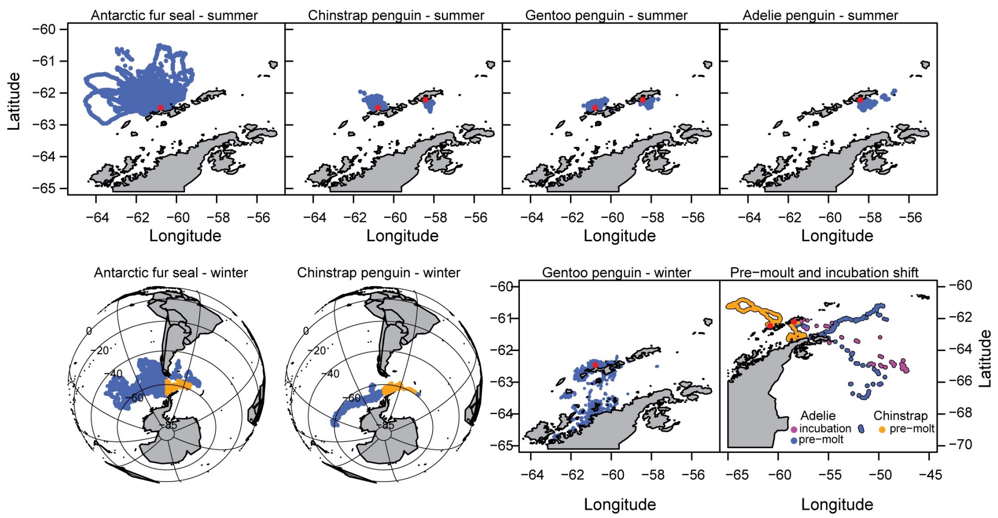
CATCHES OF GROUNDFISH TOOTHFISH ICEFISH MESOPELAGIC FISH 1970 TO 2018

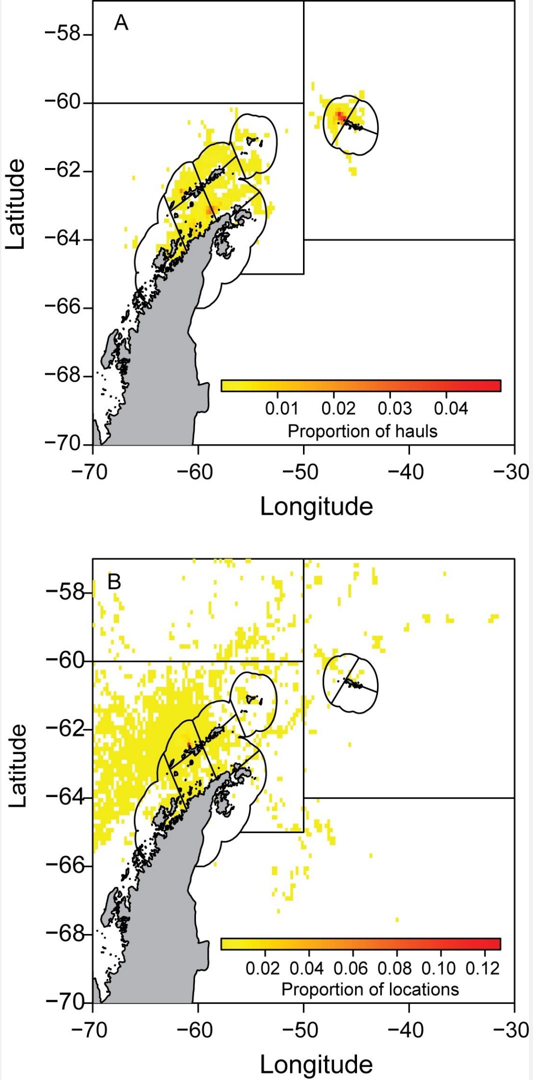


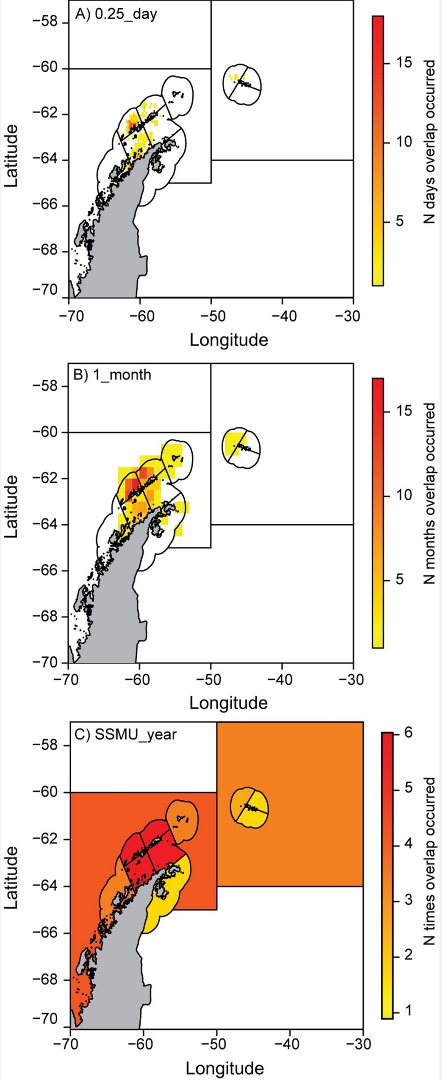
CATCHES OF ANTARCTIC KRILL *EUPHAUSIA SUPERBA* 1970 TO 2018

Sectors are Atlantic (AO), Central Indian (CI), East Indian (EI), West Pacific (WP), and East Pacific (EA). Zones are Antarctic (A), Subantarctic (S), and Northern (N).

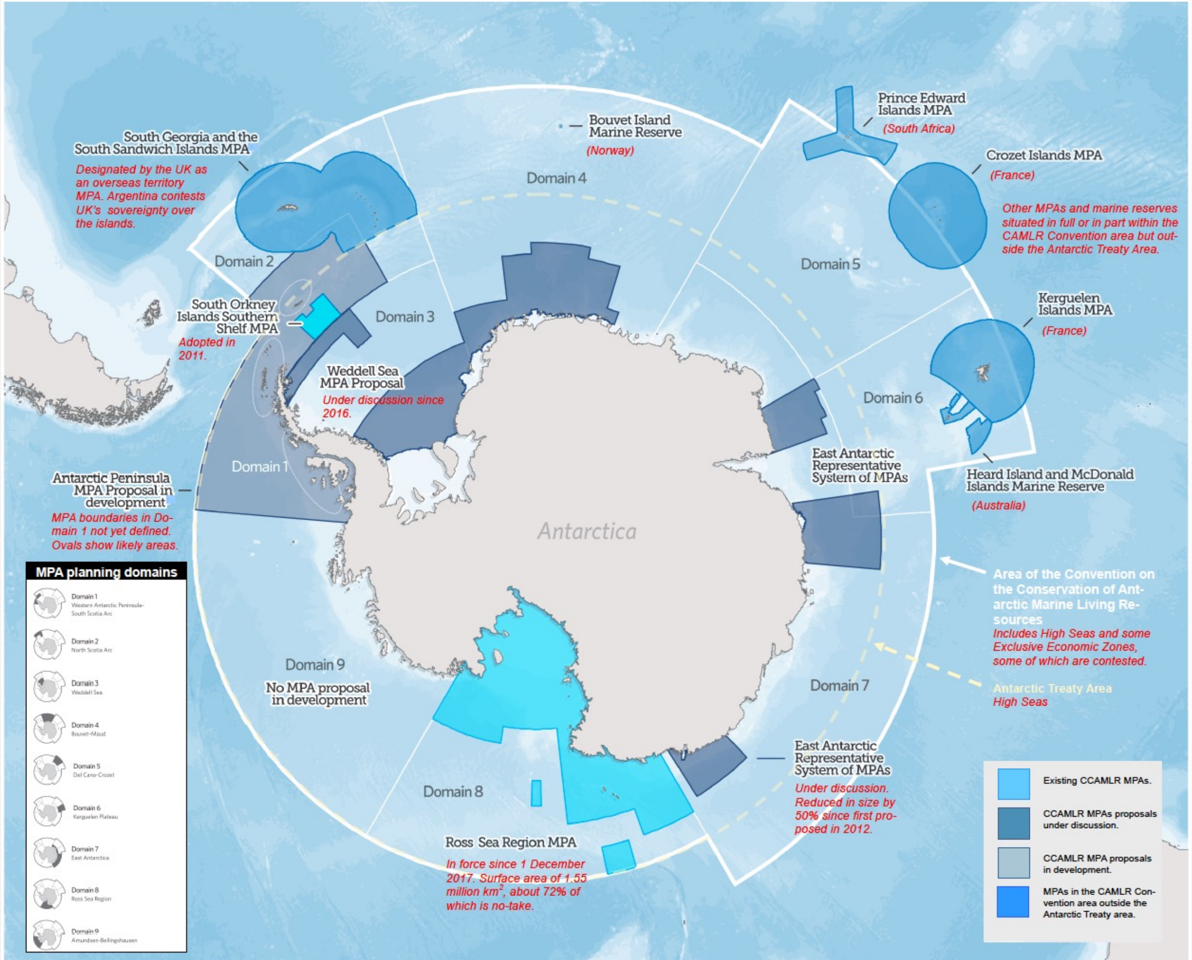
TRACKING TOP PREDATORS



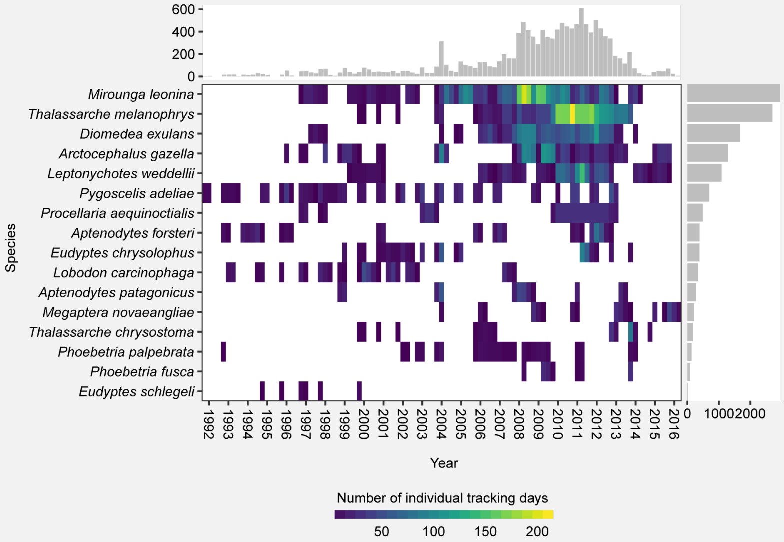

A
Latitude
Longitude
0.01 0.02 0.03 0.04
Proportion of hauls
B
Latitude
Longitude
0.02 0.04 0.06 0.08 0.10 0.12
Proportion of locations
−58 −60 −62 −64 −66 −68 −70
−70 −60 −50 −40 −30

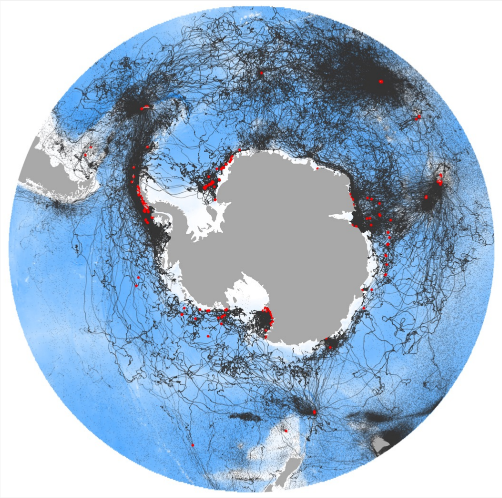

A) 0.25_day
N days overlap occurred
B) 1_month
N months overlap occurred
C) SSMU_year
N times overlap occurred
Latitude
Longitude
−58 −60 −62 −64 −66 −68 −70
−70 −60 −50 −40 −30

Marine Protected Areas in the Southern Ocean (Dec. 2017)

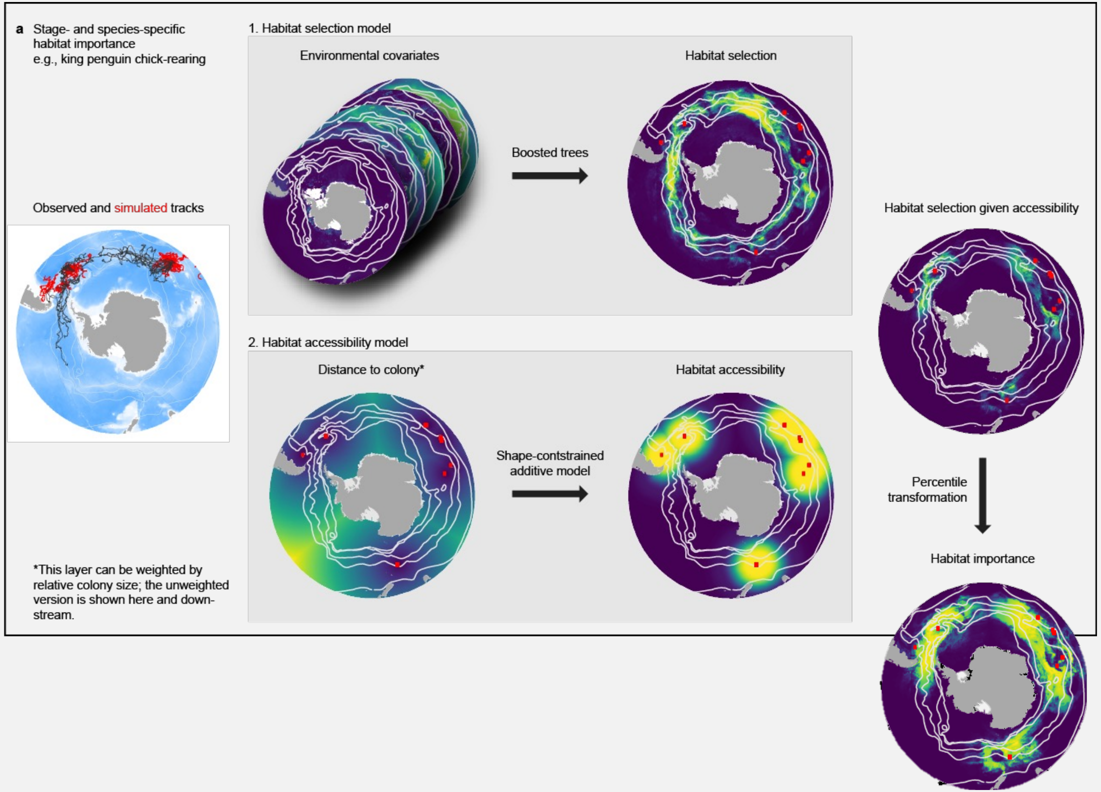


4,060 tracks from
17 marine predator species



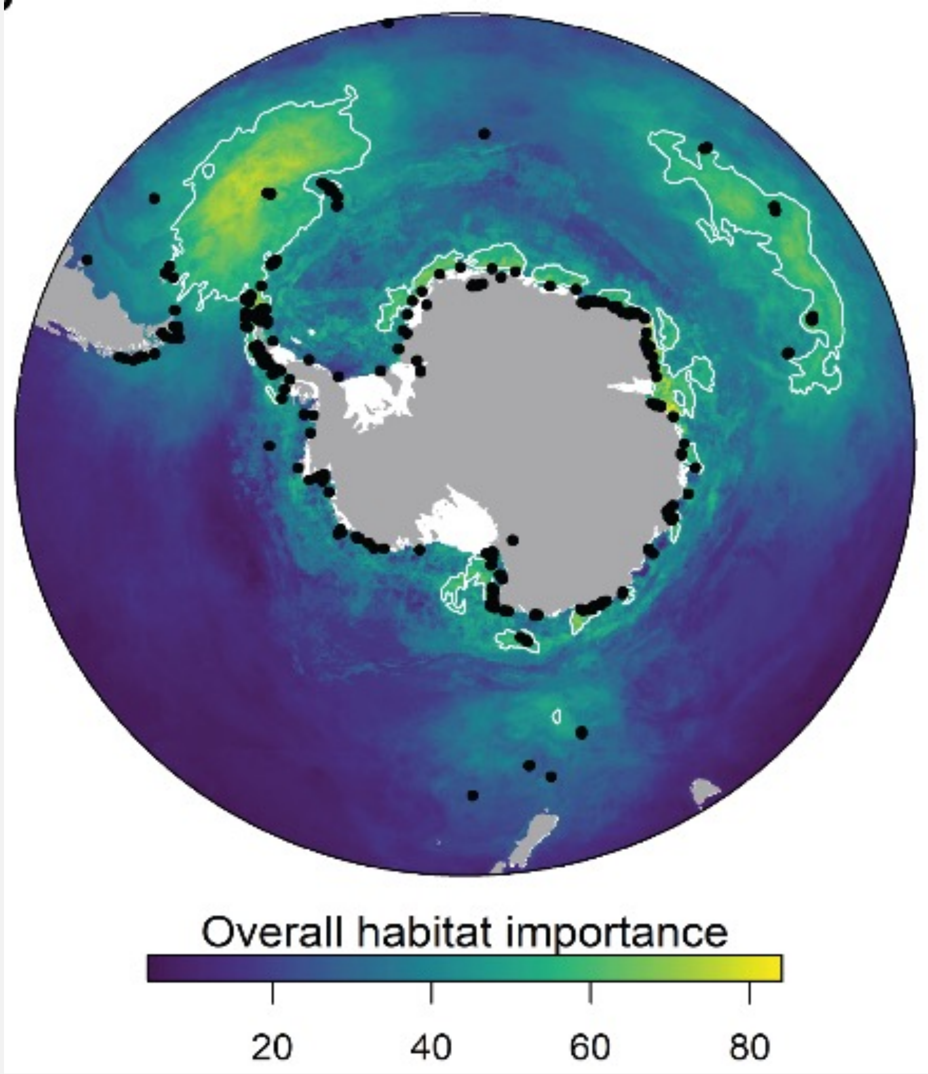


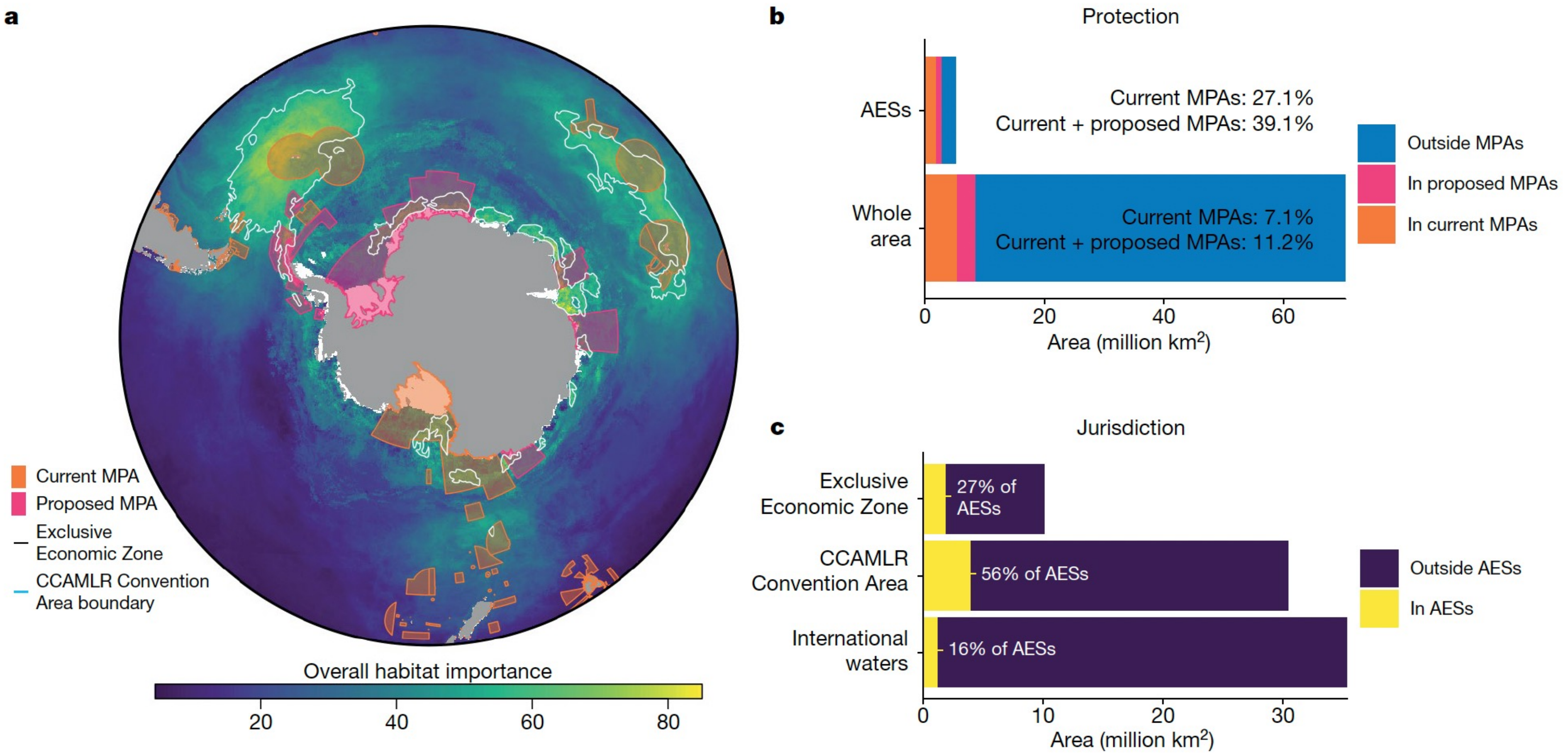
Hindell, Reisinger, Ropert-Coudert et al. in 2020
Ropert-Coudert, Van de Putte, Bornemann et al. 2020


a
Stage- and species-specific
habitat importance
e.g., king penguin chick-rearing
Observed and simulated tracks
1. Habitat selection model
Environmental covariates
Boosted trees
Habitat selection
2. Habitat accessibility model
Distance to colony*
Shape-contstrained
additive model
Habitat accessibility
Habitat selection given accessibility
Percentile
transformation
Habitat importance
*This layer can be weighted by
relative colony size; the unweighted
version is shown here and down-
stream.

OVERALL HABITAT IMPORTANCE

Combination of species specific models of habitat importance.

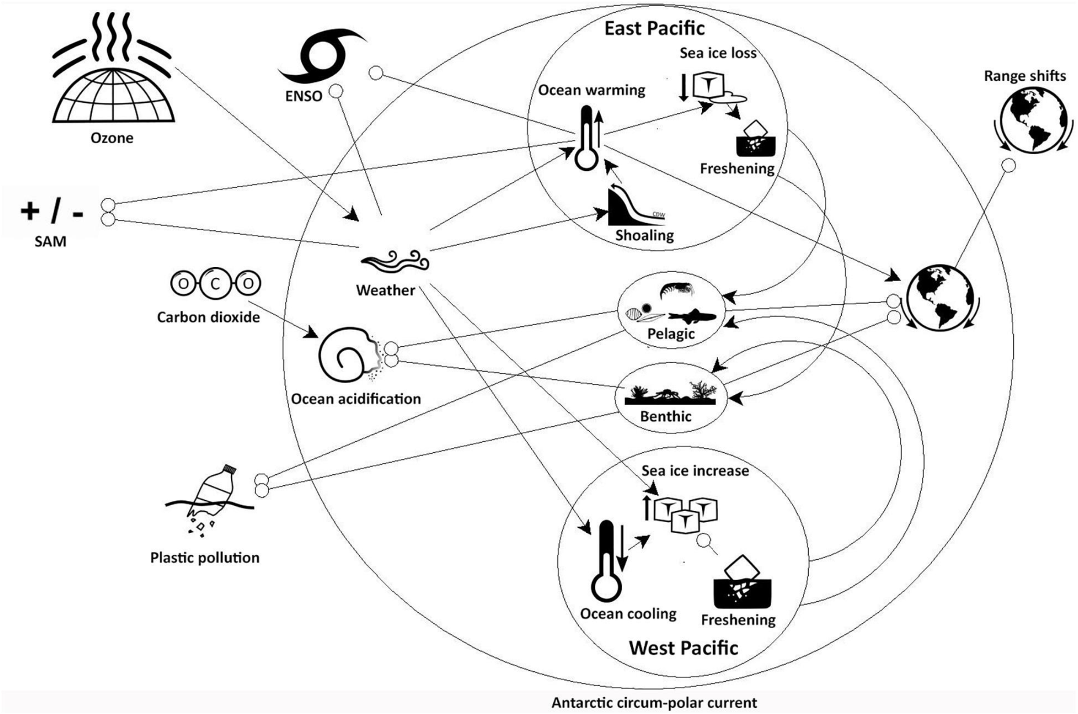



a
Current MPA
Proposed MPA
Exclusive Economic Zone
CCAMLR Convention Area boundary
Overall habitat importance
20
40
60
80
b
Protection
AESs
Whole area
Current MPAs: 27.1%
Current + proposed MPAs: 39.1%
Current MPAs: 7.1%
Current + proposed MPAs: 11.2%
Outside MPAs
In proposed MPAs
In current MPAs
0
20
40
60
Area (million km²)
c
Jurisdiction
Exclusive Economic Zone
CCAMLR Convention Area
International waters
27% of AESs
56% of AESs
16% of AESs
Outside AESs
In AESs
0
10
20
30
Area (million km²)

- The exam will be 30 min long, starting with a PowerPoint presentation of a scientific article in direct relationship with the course, in 10 min (strict maximum!), including a critical view and followed by a discussion of the subject. For that discussion, the **knowledge of the course is necessary!**. This discussion may possibly bring you to other subjects (transverse comparisons). So, if you choose an article on the impact of global change on coral reefs, expect questions dealing with coral reefs but also on chemical oceanography or on top-down control in benthic ecosystems (for instance).

- The article
  - You chose the article
  - It should be
    - a recent (not earlier than 2015) scientific research article
    - not a review, not a descriptive faunistic list, not a data paper, not a popular science paper
    - avoid inventories or natural history of a species or taxon
    - in relationship with the course
      - ecological processes; effects of global change; connectivity in the marine environment
      - in case of a modelling article, be sure to master the modelling aspects (be able to explain how an independent variable is acting on the dependent variables)
  - Examples:
    - Are fisheries impacting breeding seabirds of the North Sea?
    - Are coral reef sea urchins controlled by bottom-up or top-down factors?
    - Do the introduced starfish *Asterias amurensis* have an impact in Southern Australia?
    - Do food or wave impact control biodiversity on sandy beaches?

- Contents of the presentation (10 min maximum)
  - Short introduction to the question
  - Short explanation of the experiments designed to answer the question (do not enter into the details of the "Materials and Methods" section)
  - Results (to be supported by graphs/tables)
  - Discussion and conclusions
  - Your own critical assessment of the presented article
    - are the results convincing?
    - is the statistical support sufficient?
    - do results support the conclusions?



THE LINKAGES BETWEEN THE GLOBAL DRIVERS AND THE BENTHIC AND PELAGIC SOUTHERN OCEAN ASSEMBLAGES. NORTHERN