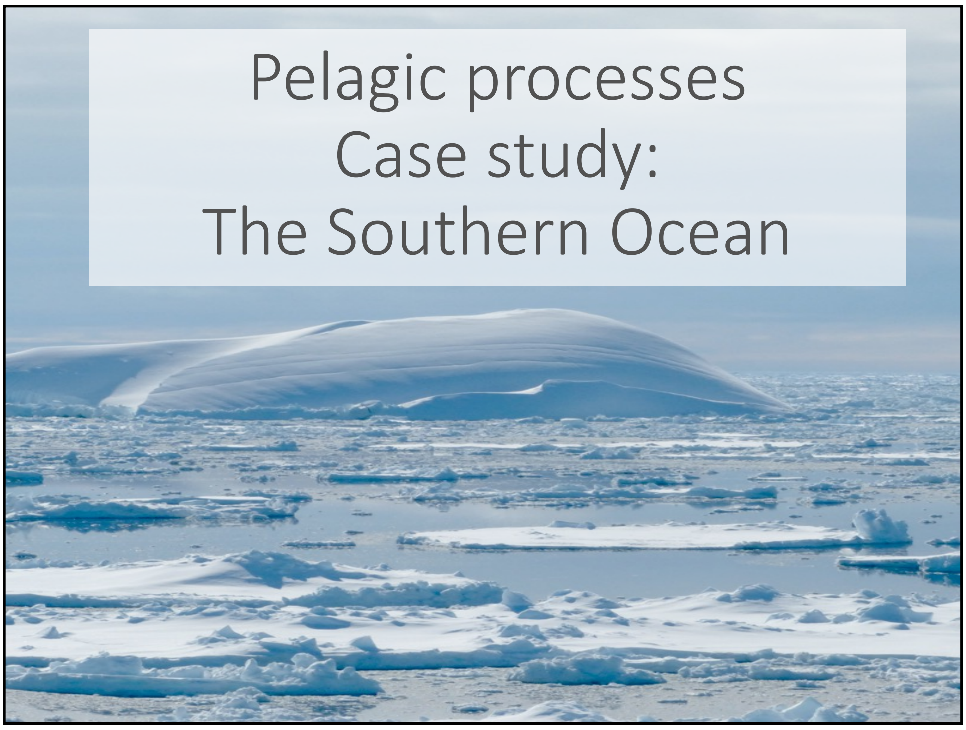
Pelagic processes
Case study:
The Southern Ocean



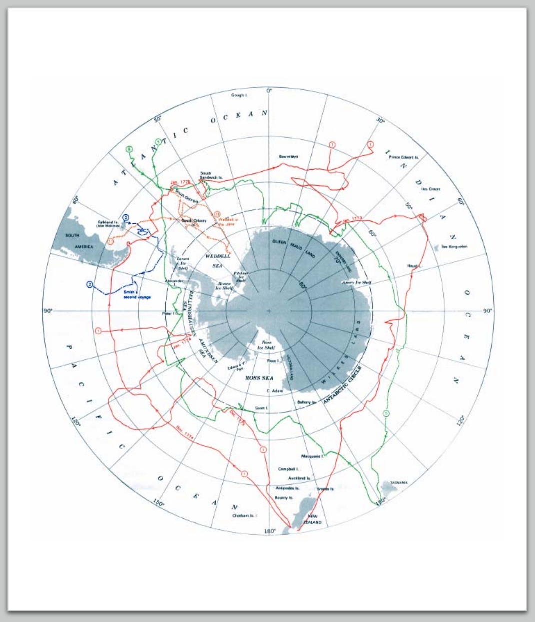
1

1570: World Map by Orteliu

2

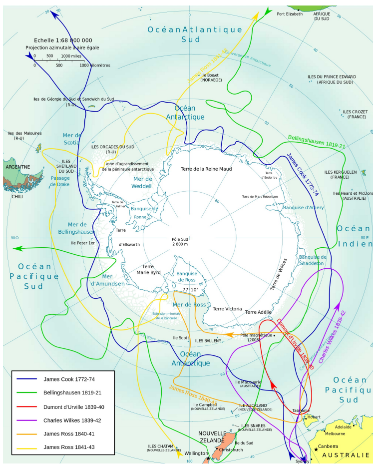
James Cook's Second voyage (1772–75)

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



3

1819-1843



4

Heroic Age 1897-1922

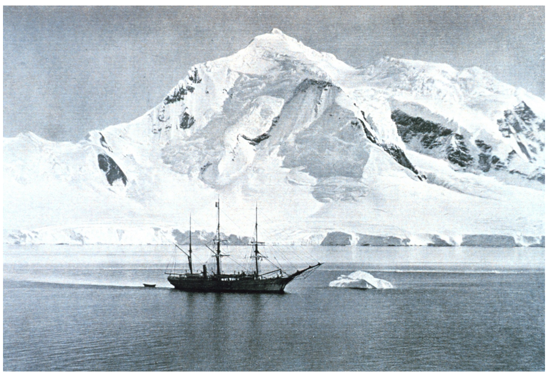
- "The Renewal of Antarctic Exploration", given to the Royal geographical Society in
- London, November 27, 1893



5

1897-1899 Belgian Antarctic expedition

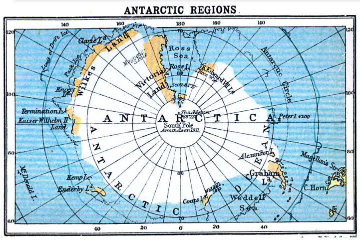
- First international purely scientific expedition
- First expedition to winter within the Antarctic Circle
- 1 year of meteorological observations

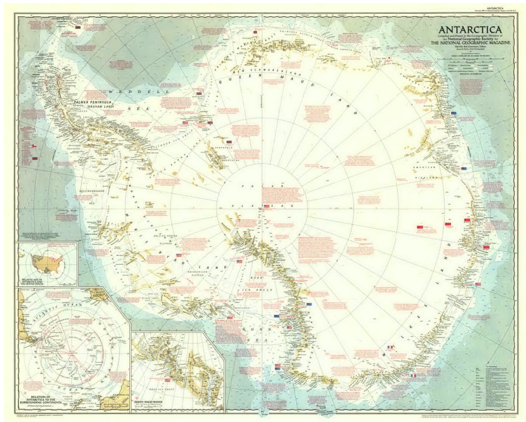



6

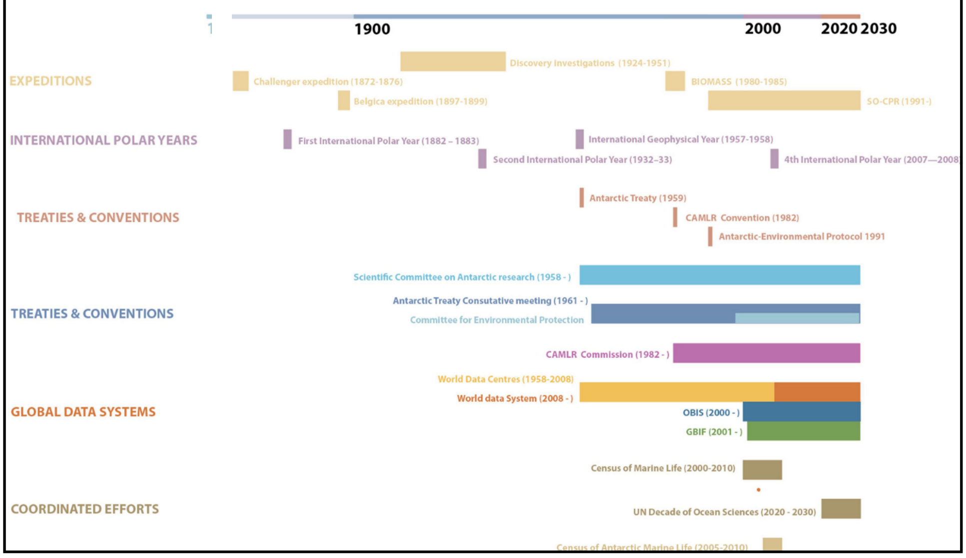
1920

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



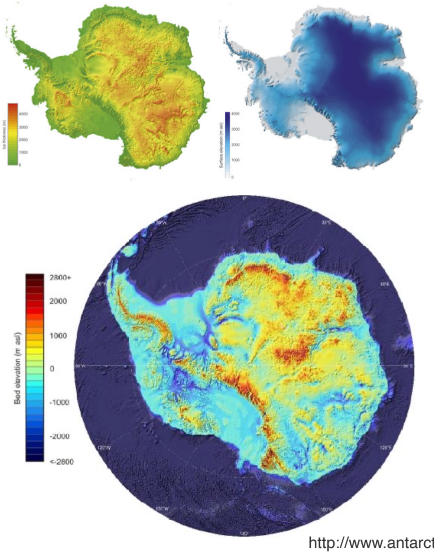


7



8

1. Physico-chemical environment
1.1. Water masses and circulation

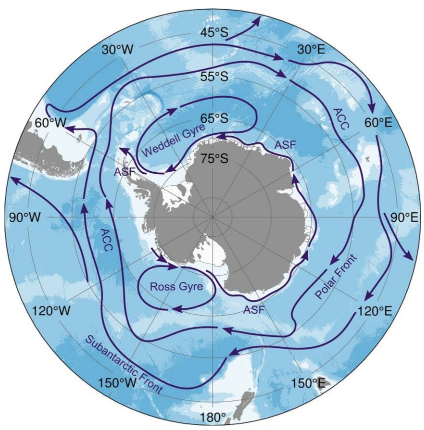


- Continent: 14 M km^2
- Continental shelf deeper than usual (500-900m: 4x global ocean average)
  - Due to isostasic subsidence > ice mass on the continent (24.10^{15} T)
  - Narrower: 30-200 km (except Ross and Weddell Seas)
  - Basins usually deep (≥ 3000m)
- ➢ Favours offshore and inshore water exchanges
- Ocean encircles the continent: increases homogeneity

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

9

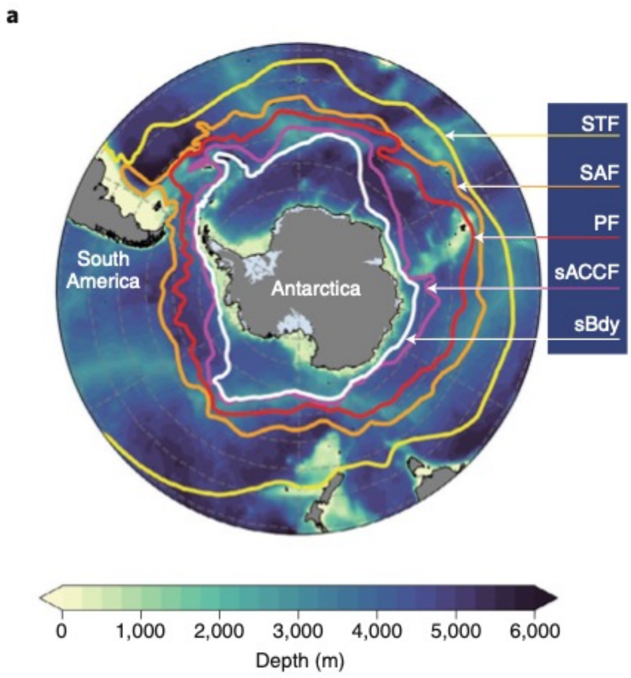
1. Physico-chemical environment
1.1. Water masses and circulation



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

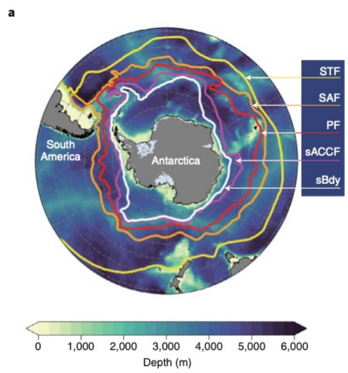
FIGURE 4. Circulation of the Southern Ocean, which is bounded by the Antarctic continent and the seafloor south of the Subtropical Convergence (Subantarctic Front Zone). The predominant clockwise trajectory of the West Wind Drift (Antarctic Circumpolar Current) extends south of the Antarctic Convergence (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.)

10



11

Sub Tropical Front			Subantarctic Zone
Sub Antarctic Front	Antarctic Circumpolar Current		
Polar Front		Antarctic Convergence	Antarctic Zone
Southern ACC Front		Antarctic Divergence	
Southern Boundary			



12

CCAMLR

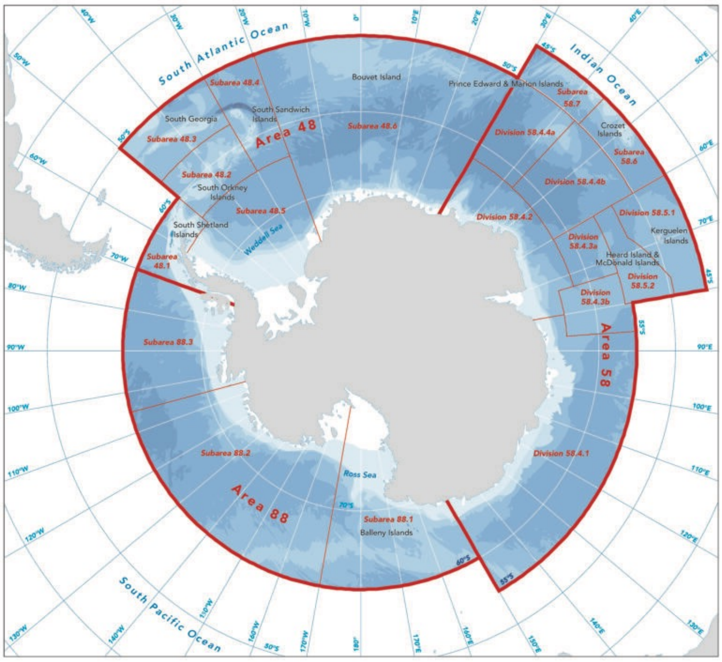
Commission for the Conservation of Antarctic Marine Living Resources

Convention Area
Statistical Areas

1:45 000 000

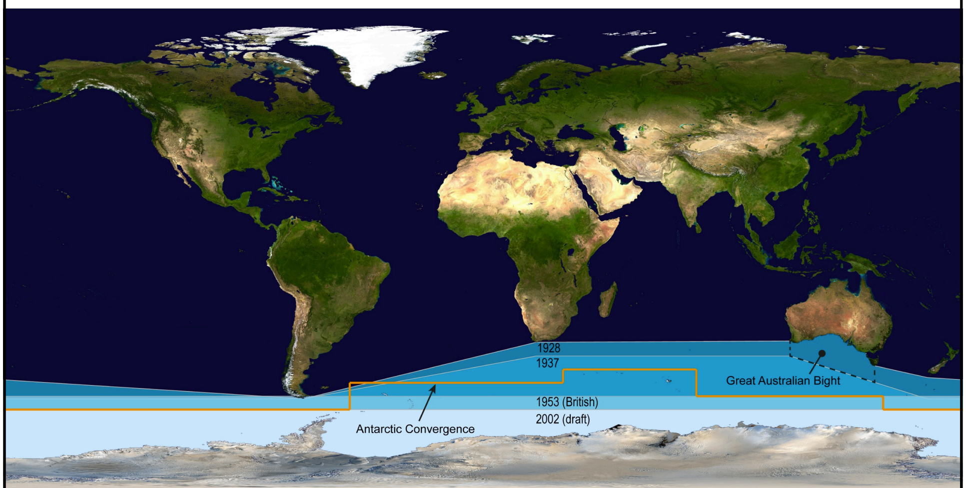
South Pole Lambert Azimuthal Equal Area projection

http://gis.ccamlr.org

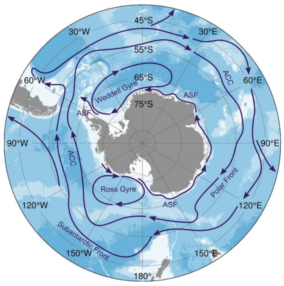


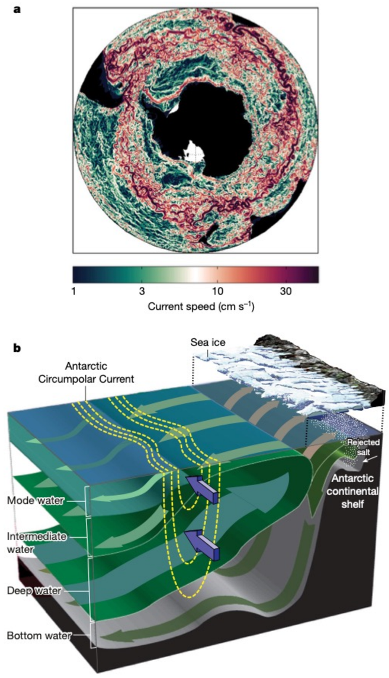
13

WHO



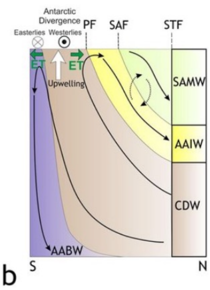
14



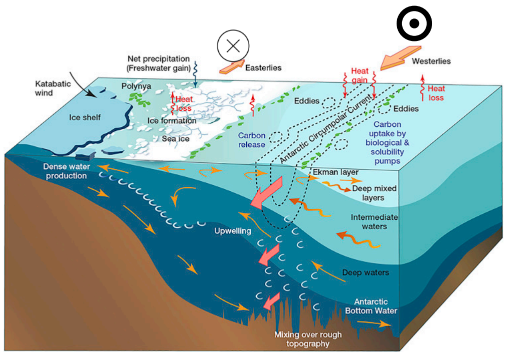


15

1. Physico-chemical environment
1.1. Water masses and circulation



b

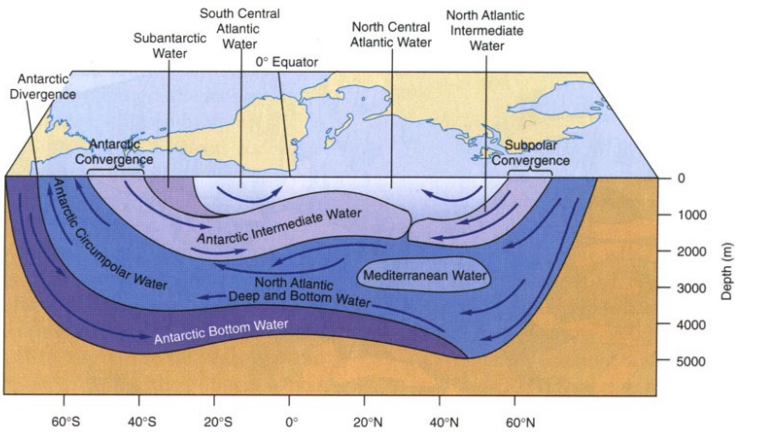


- Upwelling of Circumpolar Deep Water (> North Atlantic Deep Water)
- CDW mixes with cold Ice Shelf Water → sinks as Antarctic Bottom Water (→ up to 5°S)
- CDW also mixes with less salty Antarctic Superficial Water → Antarctic Intermediate Water
- AIW sinks below warmer Subantarctic water = Polar Front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

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

16

1. Physico-chemical environment
1.1. Water masses and circulation

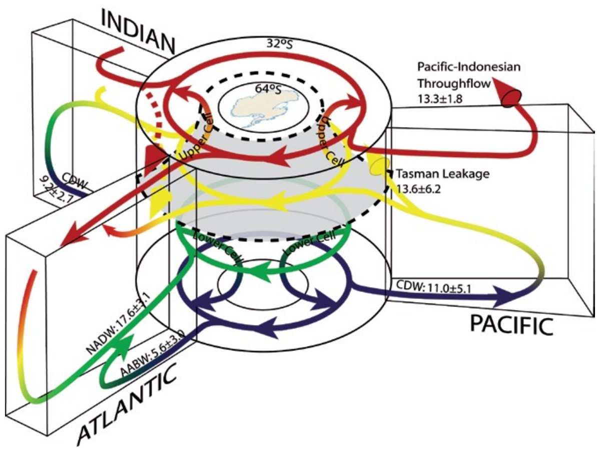


Segar 1997

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

17

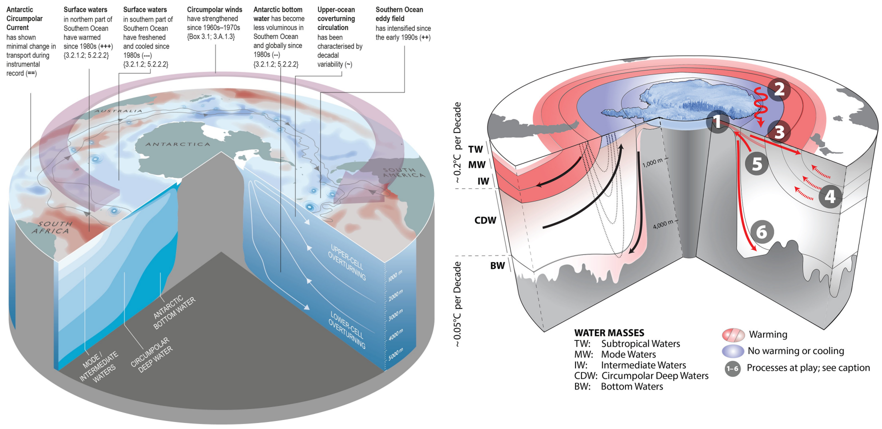
1. Physico-chemical environment
1.1. Water masses and circulation



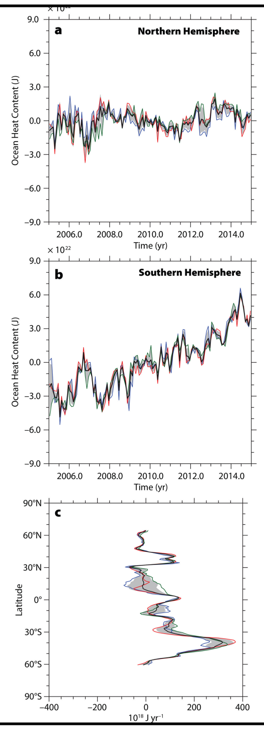
Lumpkin & Speer 2007

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

18



19

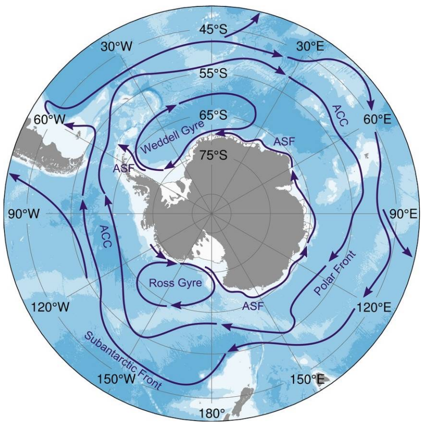


- (a–b) Ocean heat content change above 2,000 m depth with respect to the temperature climatology for
- (a) the Northern Hemisphere,
- (b) the Southern Hemisphere.
- (c) Zonally integrated ocean heat content (10^{18} J yr^{-1}).
- Curves show estimates based on different observation-based products from 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%

20

1. Physico-chemical environment
1.1. Water masses and circulation

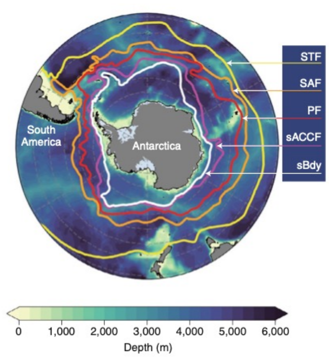


- Antarctic convergence = north limit of Antarctic zone
- Between Antarctic and Subtropical convergences = Subantarctic zone
- Antarctic + Subantarctic zone= Southern Ocean
- Subantarctic zone 2-4°C warmer than Antarctic zone
- ➢ Antarctic convergence (Polar front)= strong biological border

21

Sub Tropical Front			
			Subantarctic Zone
Sub Antarctic Front			
Polar Front	Antarctic Circumpolar Current	Antarctic Convergence	
Southern ACC Front		Antarctic Divergence	Antarctic Zone
Southern Boundary			

a



22

1. Physico-chemical environment
1.2. Light

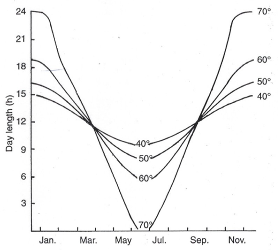
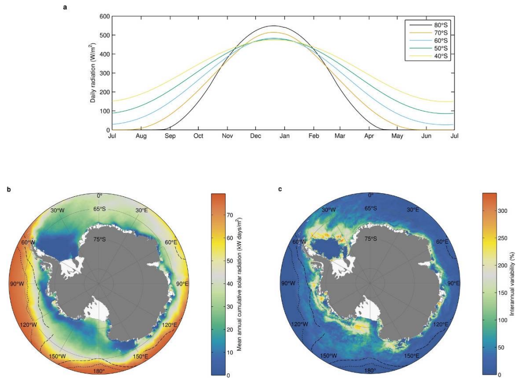


Fig. 2.12. Latitudinal variation in day length over the year and hence in the daily incident radiation in the Southern Ocean.

Knox 1994



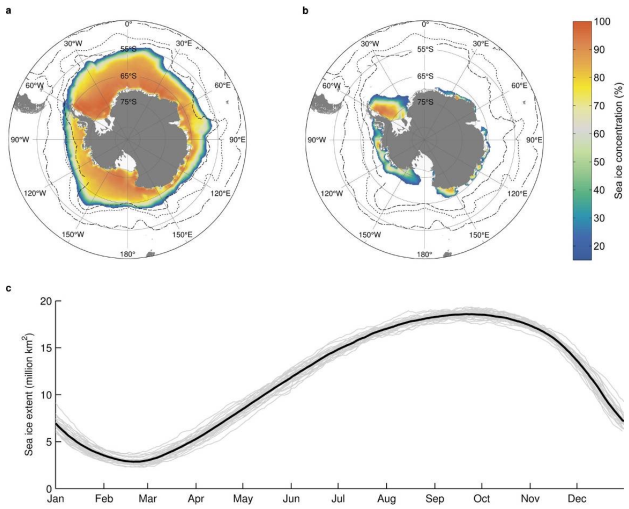
- Maximal differences in day length at high latitudes
- 100d darkness at 75°
- Strongly seasonal light availability

Post et al 2014

23

1. Physico-chemical environment
1.3. Sea ice

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



Post et al. 2014

24

Sea ice zone

	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]).

25

nanophytoplankton

- 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

26

2. Primary production

2.1. Controlling factors: *Light*

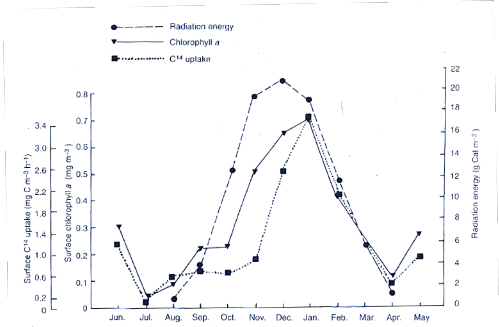
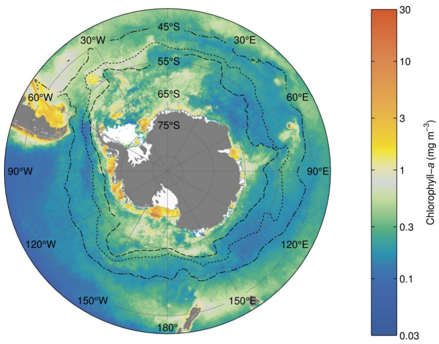


Fig. 2.13. Monthly variation of radiant energy (with average cloudiness) at Maudheim Station (71° 03′ S; 10° 56′ W) compared with monthly changes in surface chlorophyll *a* and C^{14} uptake in Antarctic waters. Redrawn from El-Sayed (1971a).



Photoperiod + sea ice extent:

- ➢ Single P1 peak

Knox 1994

27

2. Primary production

2.1. Controlling factors: *Light* ←→ *Ice cover*

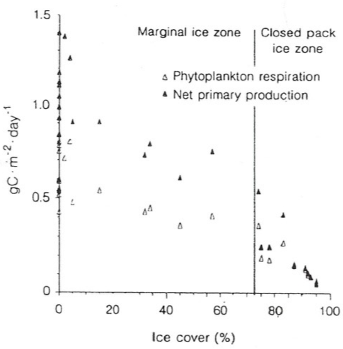


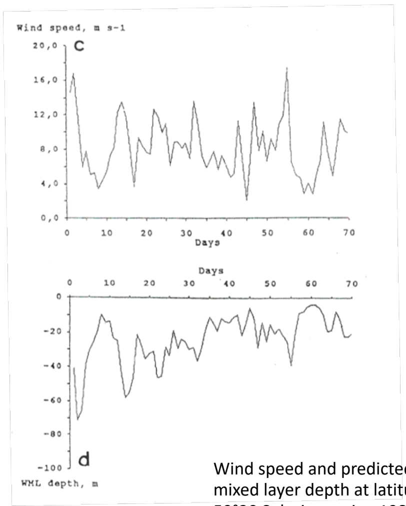
Fig. 7. Relationship between daily rate of net primary production (▲) and ice cover field in the sea ice associated areas (i.e. the marginal ice zone and the closed pack ice zone) of the northwestern Weddell Sea during spring 1988. Phytoplankton respiration (△) is also shown

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

Mathot et al 1992

28

2. Primary production
2.1. Controlling factors: *Light* ←→ *Wind (mixing)*



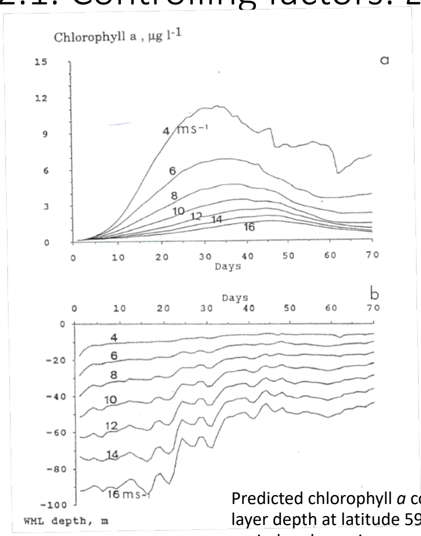
- Depth of mixed layer fast variations

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

Lancelot et al 1996

29

2. Primary production
2.1. Controlling factors: *Light* ←→ *Wind (mixing)*



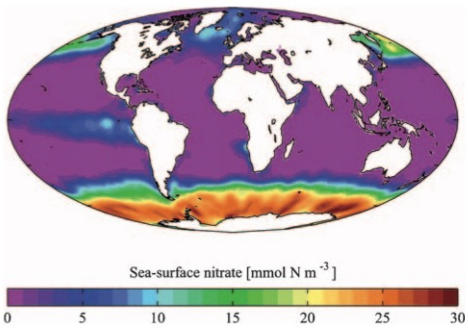
- No bloom if wind speed > 8m/sec

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

30

2. Primary production
2.2. Controlling factors: *Nutrients*

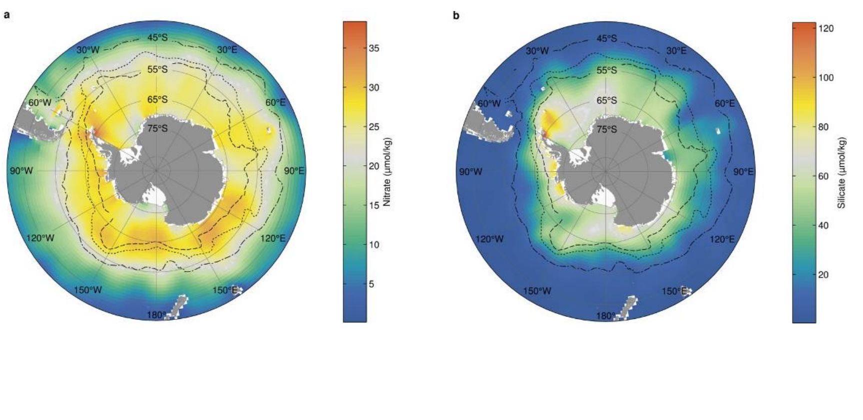


Offshore upwelling → HNLC zone

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

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)

31



32

2. Primary production
2.2. Controlling factors: *Nutrients*

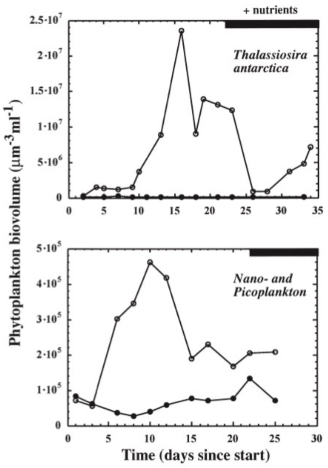


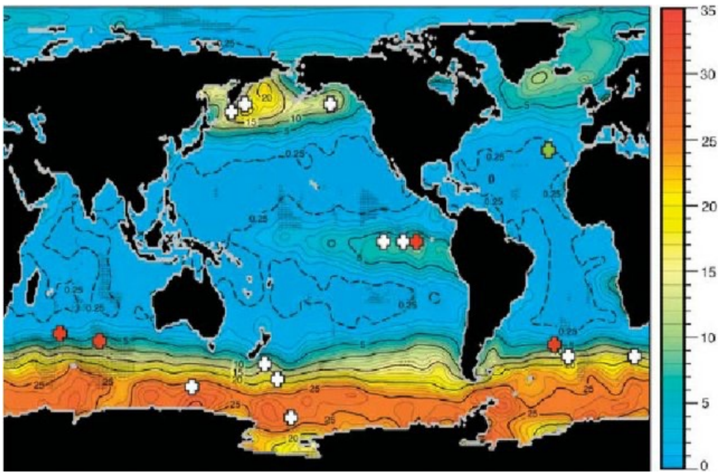
Fig. 8. Depth-integrated biovolume of diatoms and nano- and picophytoplankton in the mesocosm (○) and the ambient waters (●) during the experiment (January 19, 1999, to February 21, 1999)

Mesocosm Fe enrichment experiment in the Antarctic Peninsula:

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

Agusti & Duarte 2000
MEPS 206: 73

33

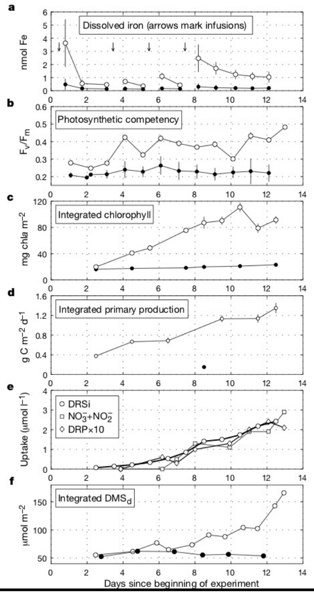


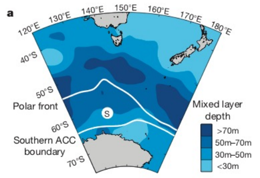
Distribution of nitrate in the surface ocean, showing elevated concentrations in the three HNLC regions of the Southern Ocean, Equatorial Pacific and Sub-Arctic Pacific.
Location of twelve iron fertilization experiments (white crosses), natural iron fertilization experiments (red crosses), and excess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

34

2. Primary production

2.2. Controlling factors: *Nutrients*





P1: X3

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

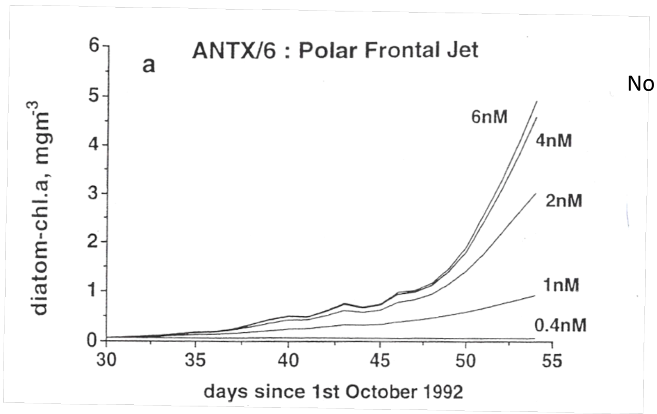
Figure 3 Time-series measurements made during SOIREE. Open and filled symbols show measurements made respectively inside and outside iron-fertilized waters. Underway data are expressed as the daily mean value for inside (defined as >50% of the peak SF_6 levels on that day) and outside the patch (defined 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

35

2. Primary production

2.2. Controlling factors: *Nutrients*



No bloom if Fe < 2nM

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

Lancelot et al 1996

36

2. Primary production
2.2. Controlling factors: *Nutrients*

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 1993

Dissolved Fe: usually <1nM except
- Coastal zone and above continental plate (Weddell and Ross Seas)
- Downstream Drake passage
- Marginal ice zone

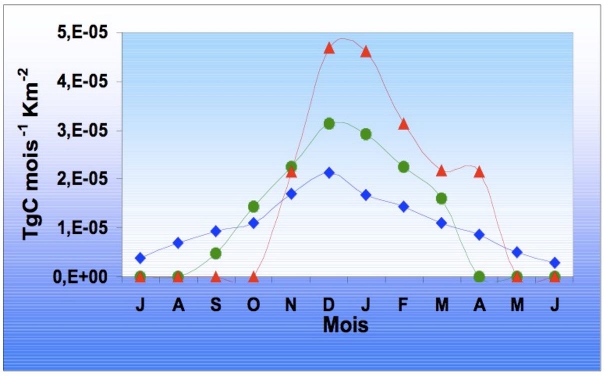
37

2. Primary production
2.2. Controlling factors: *Nutrients*

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

38

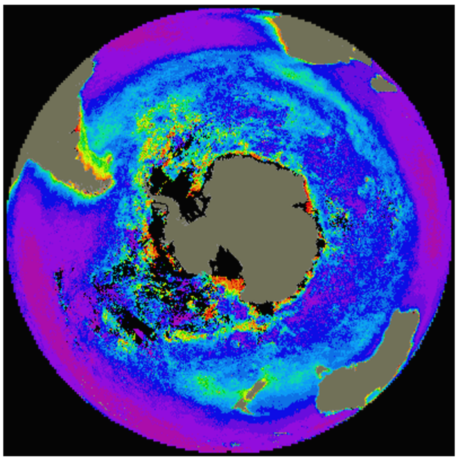
2. Primary production
2.2. Controlling factors: *Nutrients*



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

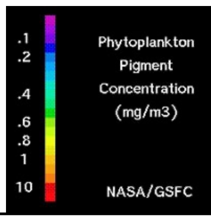
39

2. Primary production
2.2. Controlling factors: *Nutrients*



P1 parallels Fe distribution

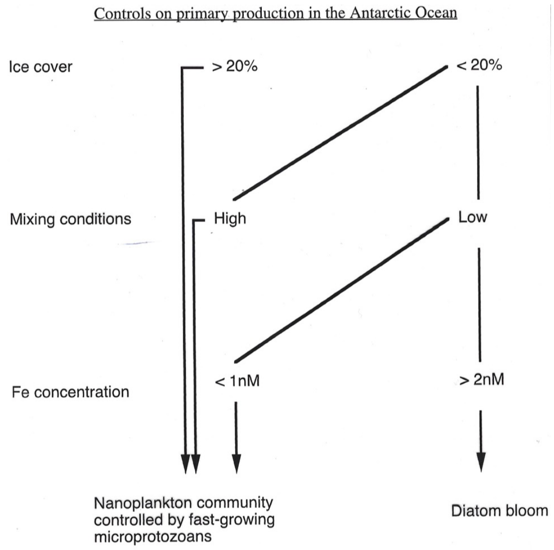
- Coastal zone and above continental plate (Weddell and Ross Seas)
- Downstream Drake passage
- Marginal ice zone



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

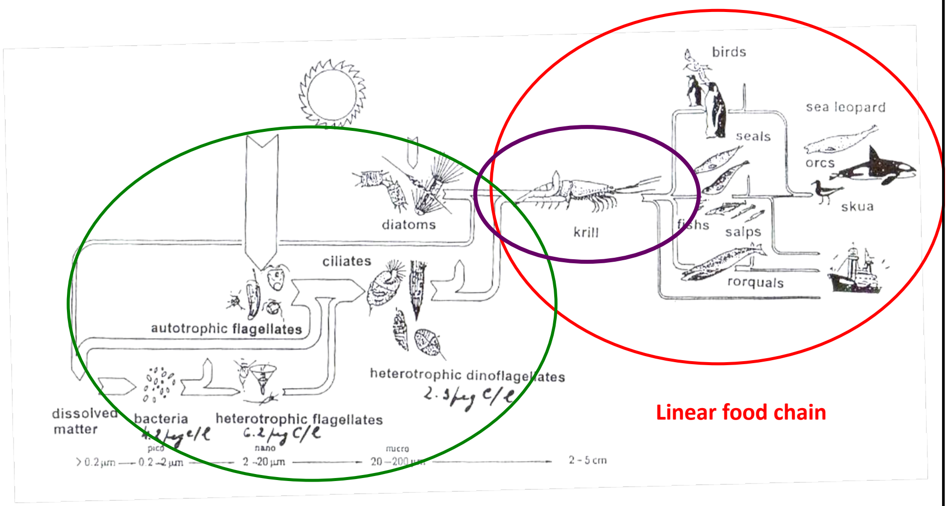
40

2. Primary production
Controlling factors



41

3. Consumers

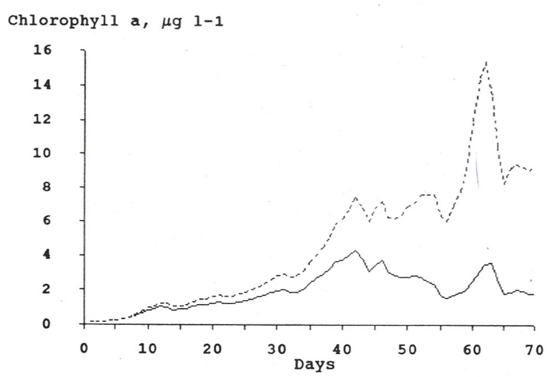


Microbial loop

Lancelot et al. 1996

42

3. Consumers
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

43

3. Consumers
3.1. Microbial loop

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

44

3. Consumers
3.1. Microbial loop

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

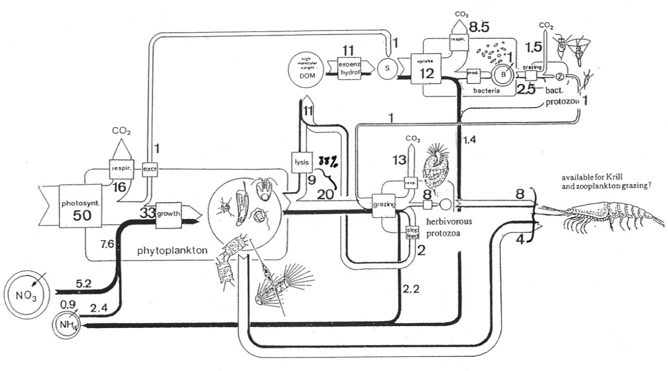
Area	Period	% of primary production grazed per day	% of bacterial production grazed per day	References
Atlantic sector	October-November	40	32	Becquevort, 1996
ACC	October/ November	34		Klass, in press
Polar front area	October/ November	44		Klass, in press
Weddell/ Scotia Sea	November	10	11	Garrison and 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 bacterial production (10- 90% production)

Lancelot et al. 1996

45

3. Consumers
3.1. Microbial loop budget



gC/m².ice retreat period

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

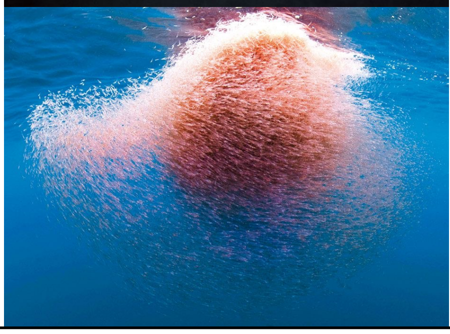
- 88% (29/33 g.C) of net P1 assimilated by the microbial loop
- Net P2 of microbial loop: 25% (8/33 g.C) of P1
- 12.5% (4/33 g.C) of P1 not grazed by microbial loop

Lancelot et al. 1996

46

3. Consumers

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

47

3. Consumers

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

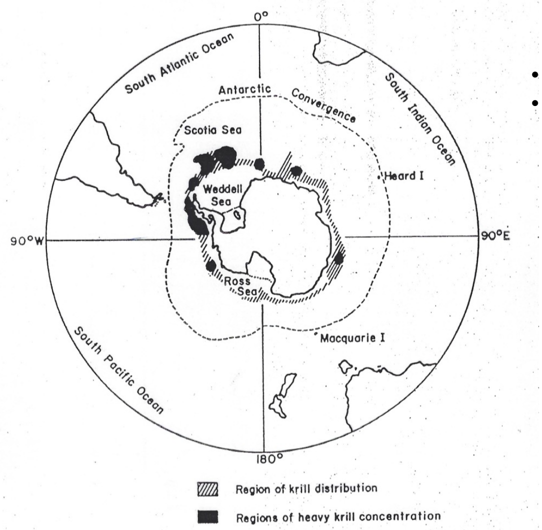
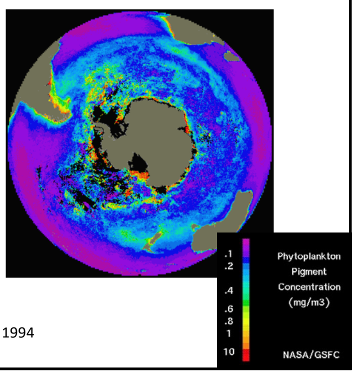


Fig. 3. The generalized distribution of Antarctic krill. Information compiled from a number of sources

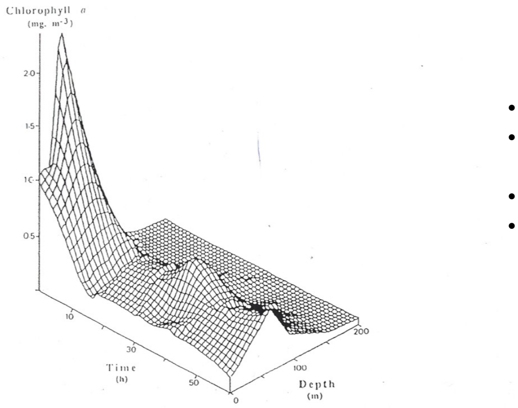
- Make swarms of millions of T
- Aggregative distribution corresponding to zones of high P1



Nicol 1994

48

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

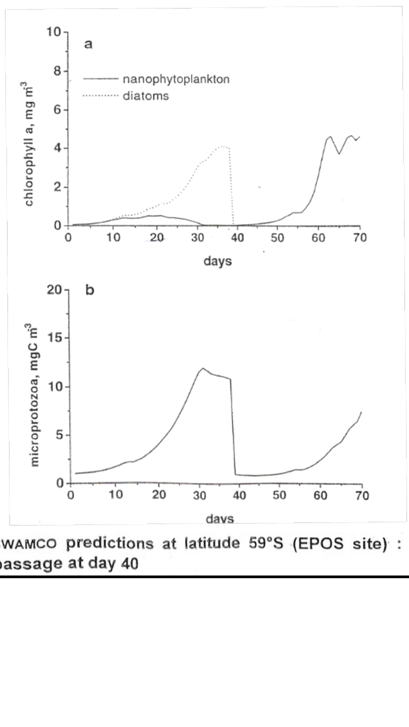


Three–dimensional evolution of a diatom bloom at station 157 in the Weddell Sea (5th December 1988). The diatom bloom vanished in less than 10 h, probably grazed down by a krill swarm, and the phytoplankton community toppled towards a flagellate–dominated system (from Jacques & Panouse, 1991).

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

49

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



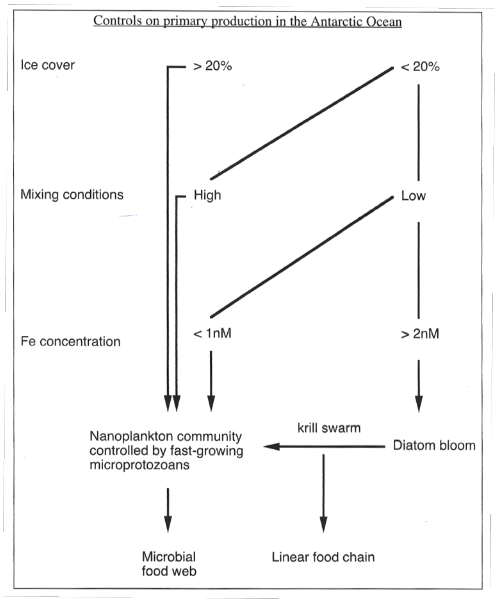
SWAMCO predictions at latitude 59°S (EPOS site) : krill swarm passage at day 40

- 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

50

Primary production: Controlling factors



51

3. Consumers

3.2. Linear food chain: *Higher ranks*

- Vertebrates and squids
- Most are krill eaters

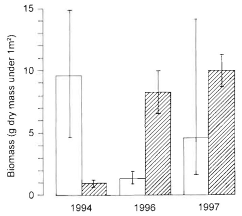
52

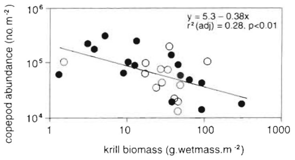
Classic view

53

Additional grazers

- >Copepods

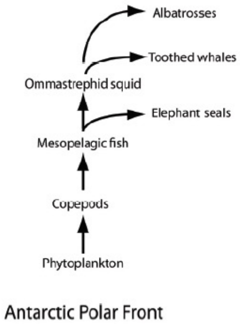




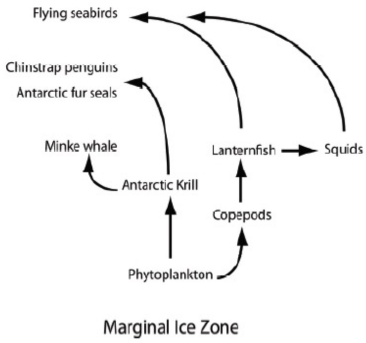
- Salps

Atkinson et al 1999

54

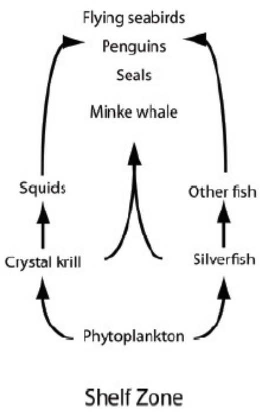


55

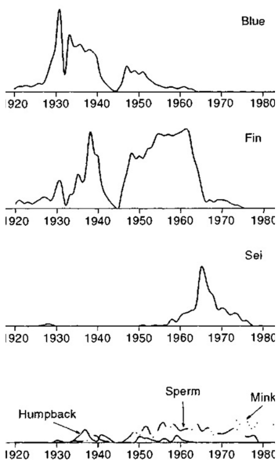


- Copopods lower standing biomass but higher productivity

56



57



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

58

3. Consumers

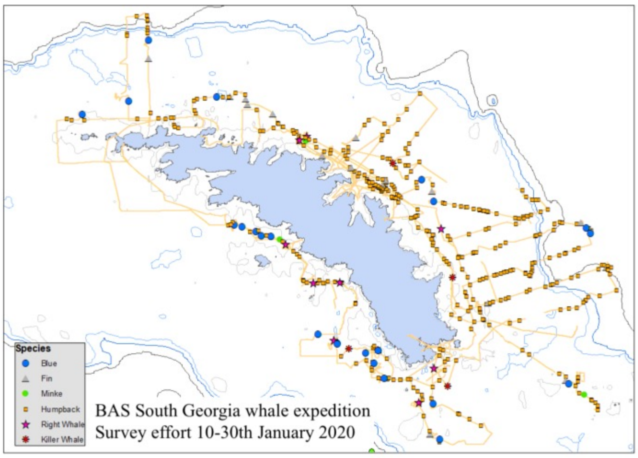
3.2. Linear food chain: *Higher ranks*

	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

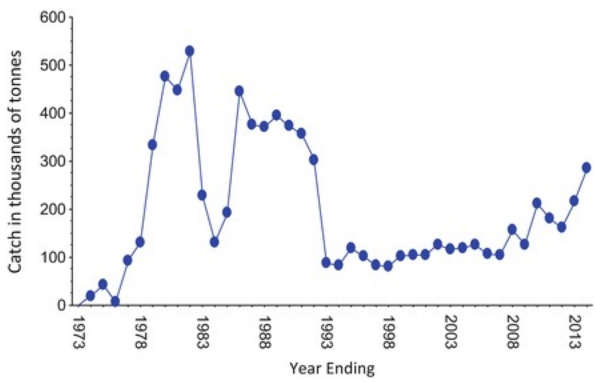
59



60

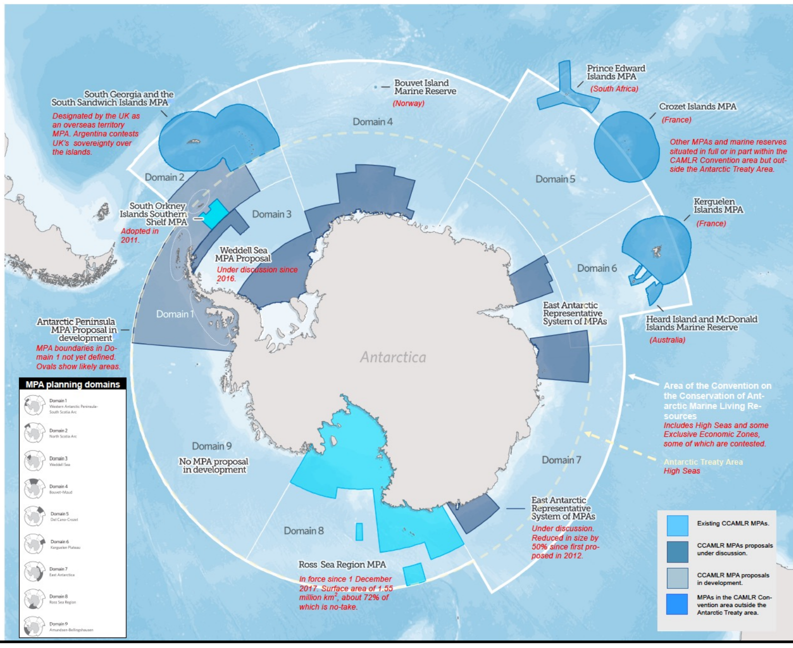
61

Krill Catches Southern OCean

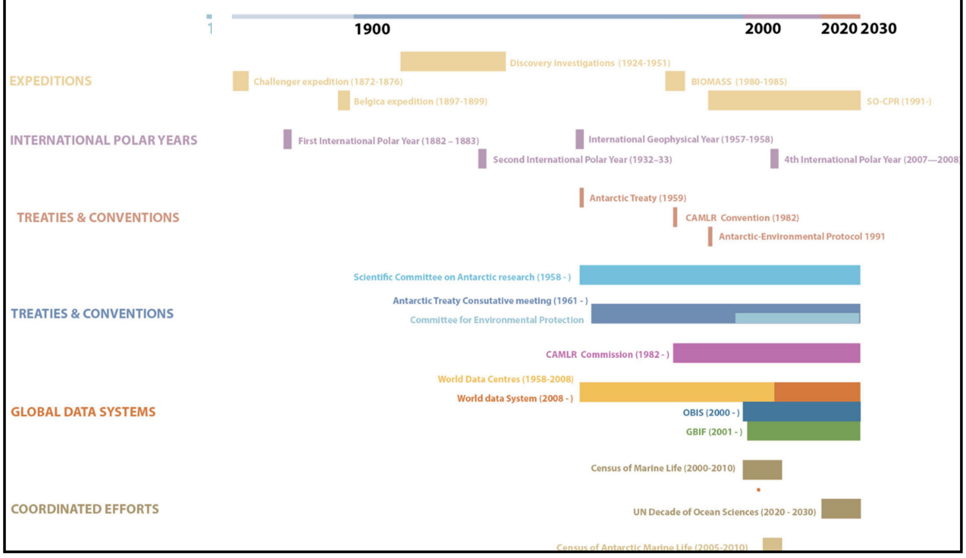


62

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



63



64

- 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).

65

- 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?

66

- 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?

67