Lipid pump of deep seasonal migrant zooplankton contributes substantially to Southern Ocean carbon sequestration

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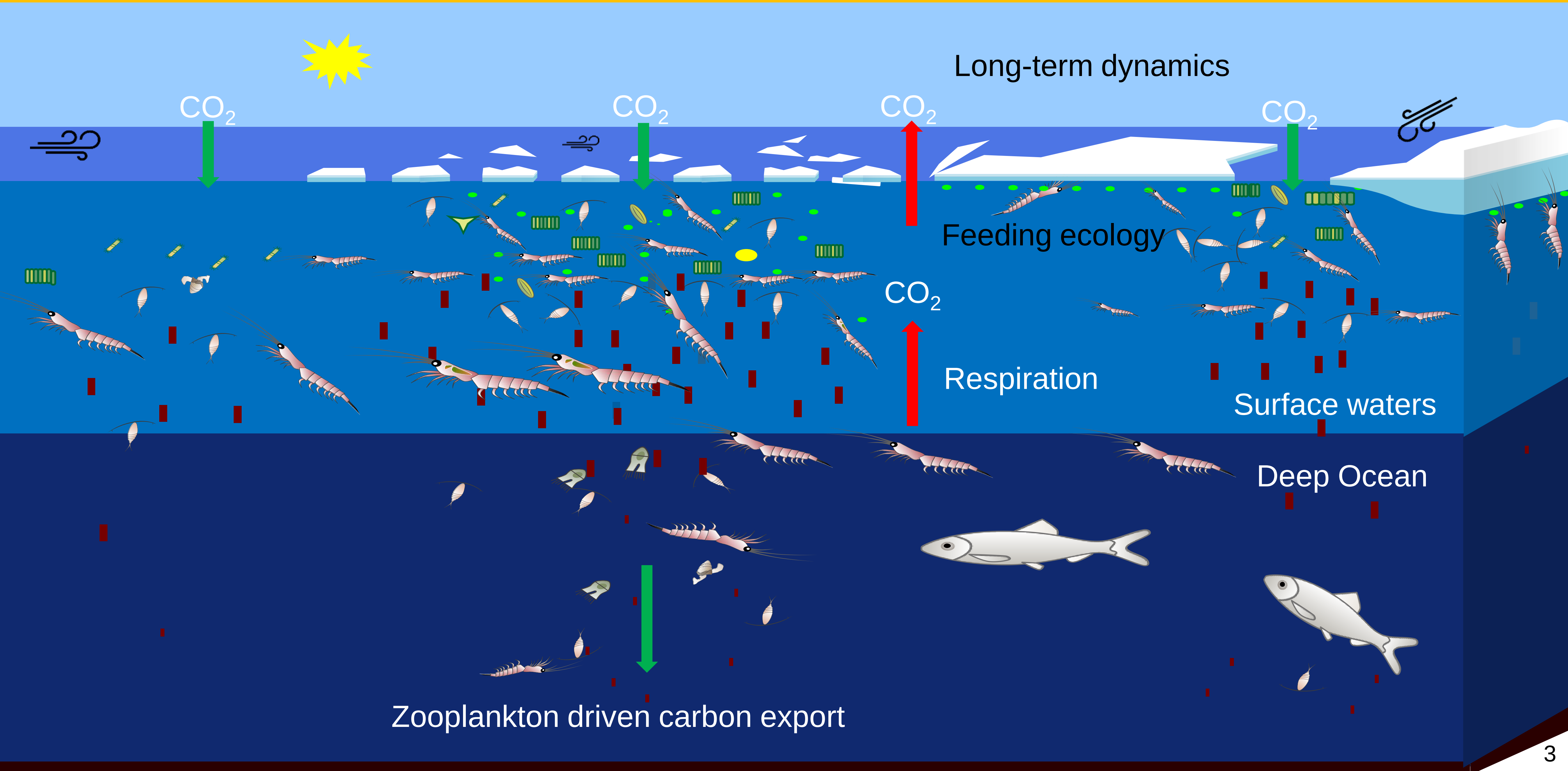
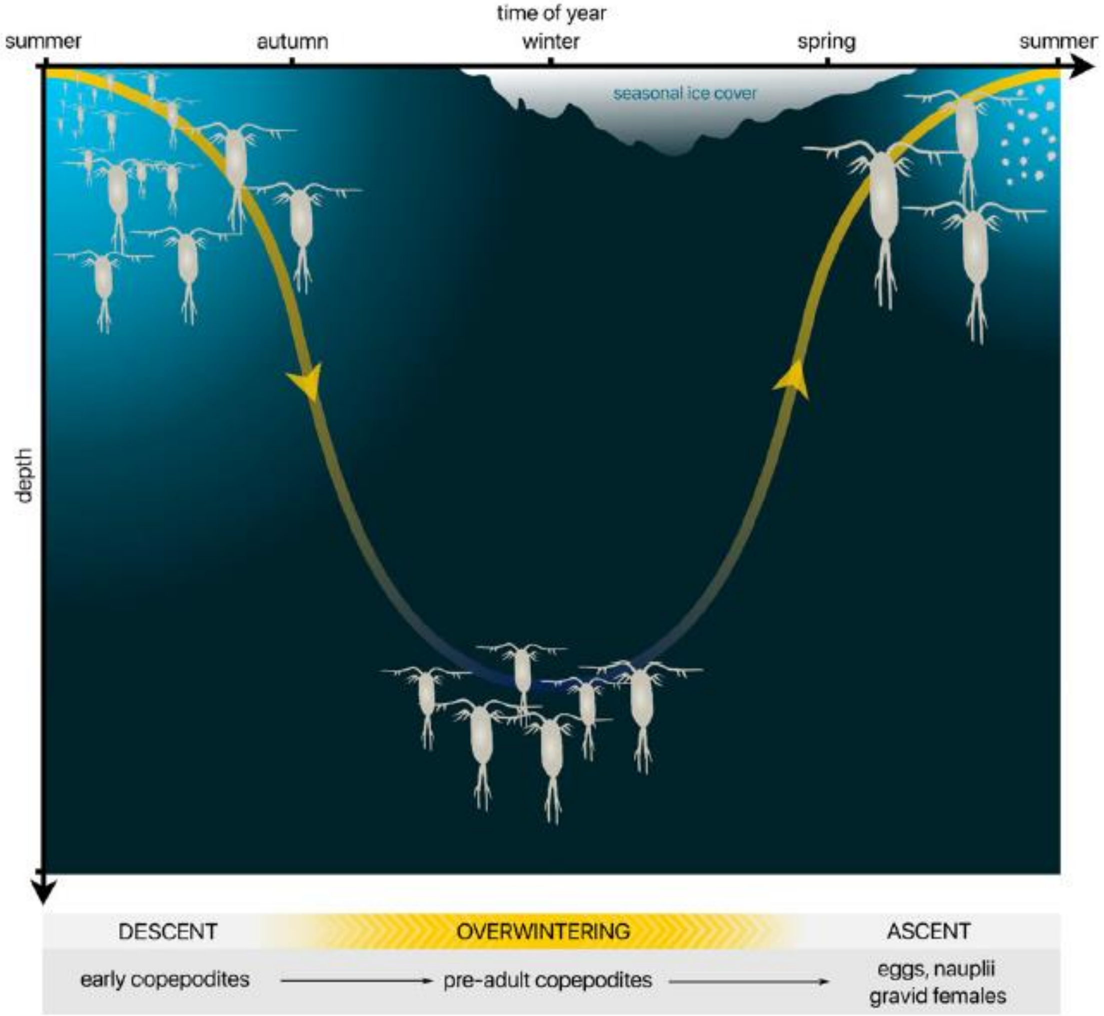
Main content

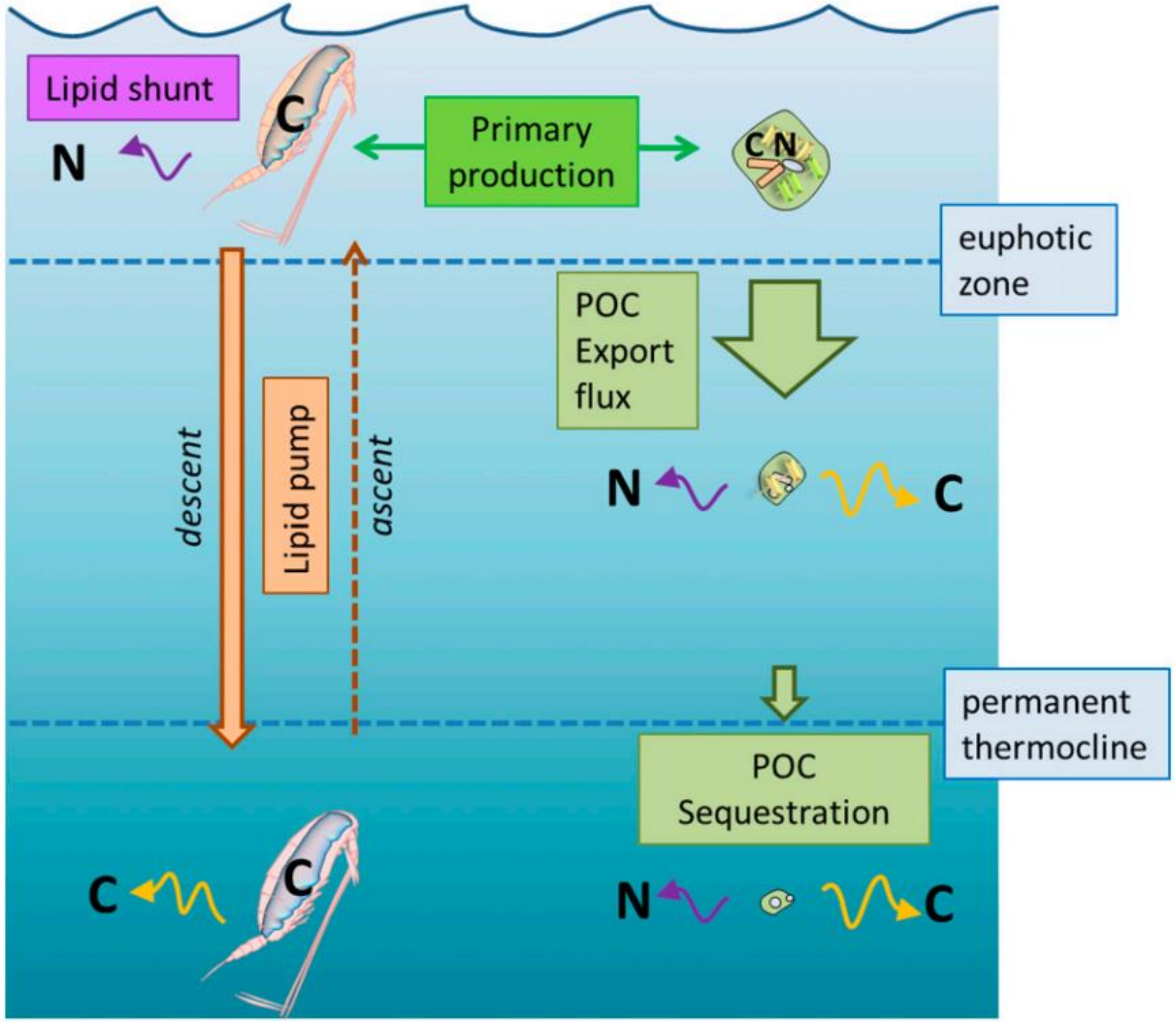
- How the lipid pump in Southern Ocean was estimated
- The magnitude of this lipid pump
- Ecological and biogeochemical implications

Zooplankton play great roles in SO carbon export



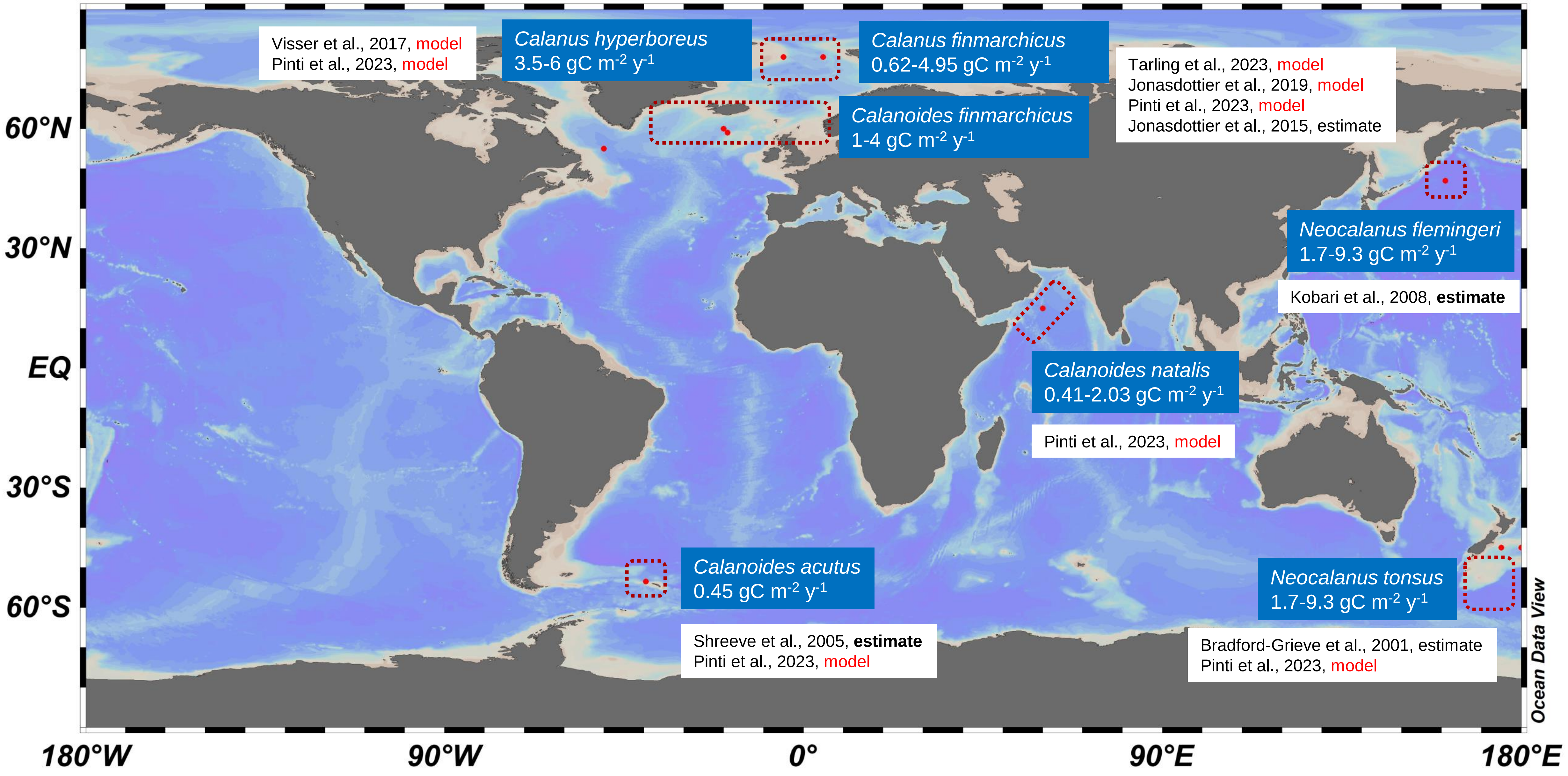
Seasonal vertical migration and lipid pump





Jonasdottir et al., 2015, PNAS

Meta-analysis of lipid pump studies in the world ocean



What we want to do

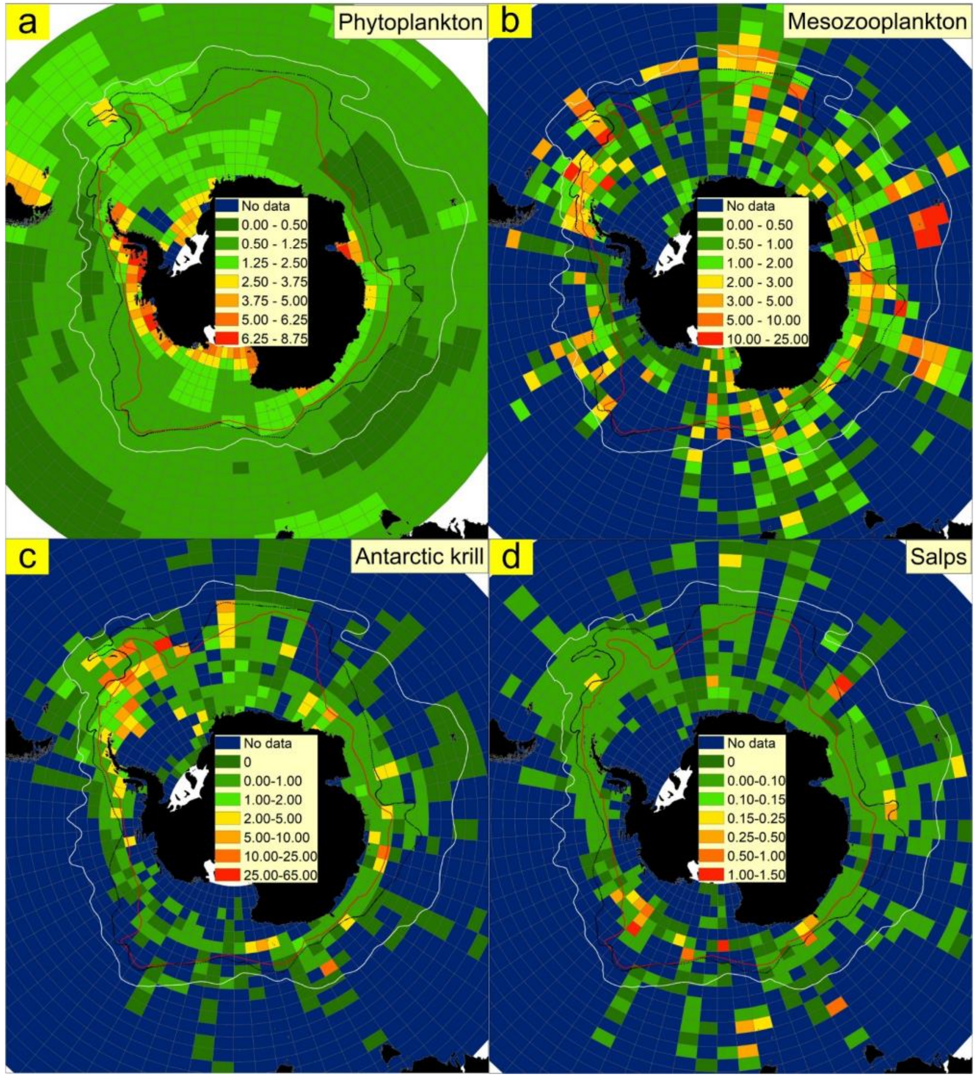
A rough estimation of lipid pump in the Southern Ocean

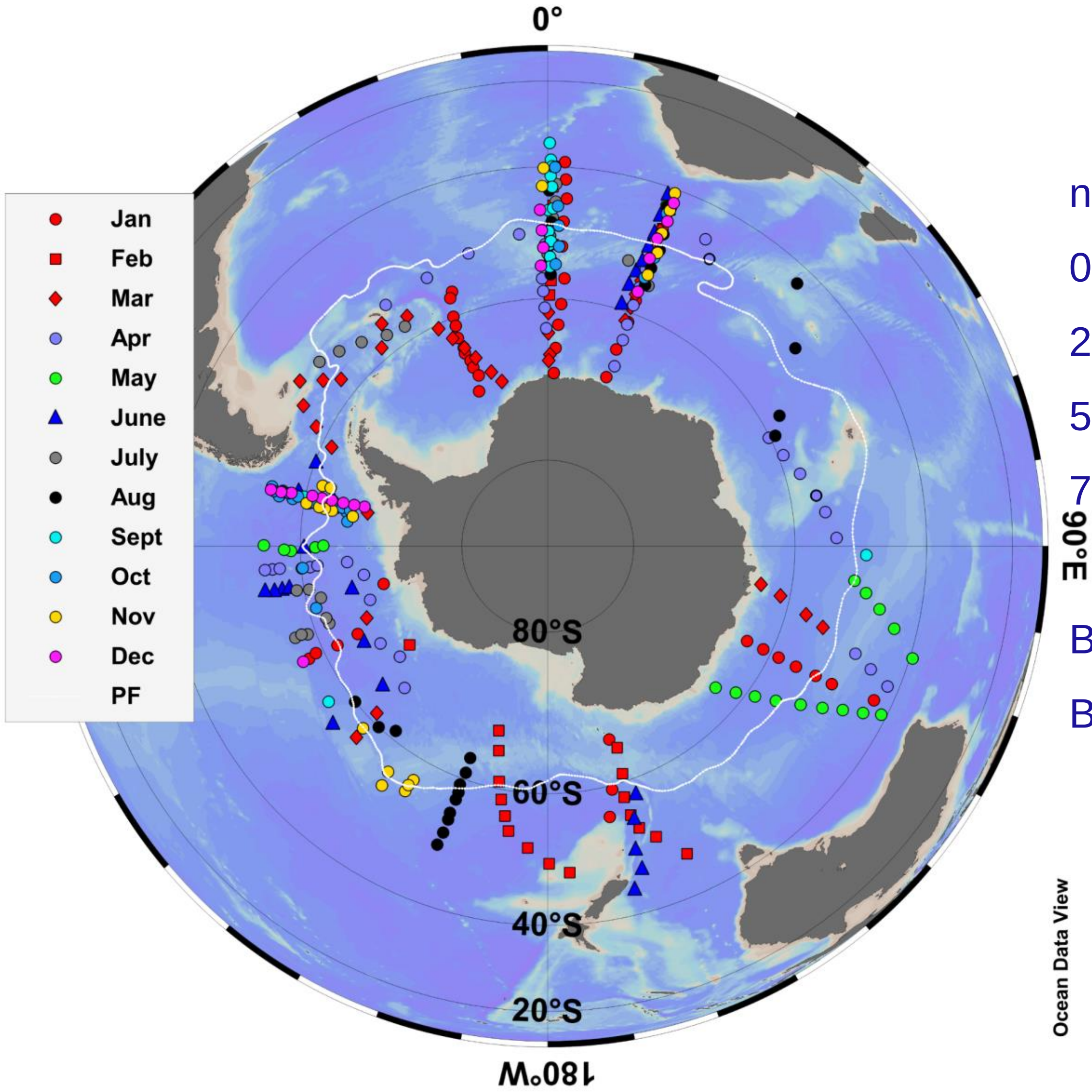
Region: Southern Ocean

Species/group: mesozooplankton, krill and salps

4 parameters: biomass of diapausing population; respiration rate during overwintering; mortality rate during overwintering; duration of overwintering

Biomass_mesozooplankton





n = 334

0-250 m

250-500 m

500-750 m

750-1000 m

$B_{0\text{-}250\ m}/B_{0\text{-}1000\ m}$

$B_{500\text{-}1000\ m}/B_{0\text{-}1000\ m}$

0-250 m, 1926-2020

¾ of the records were from summer (Nov-Mar)

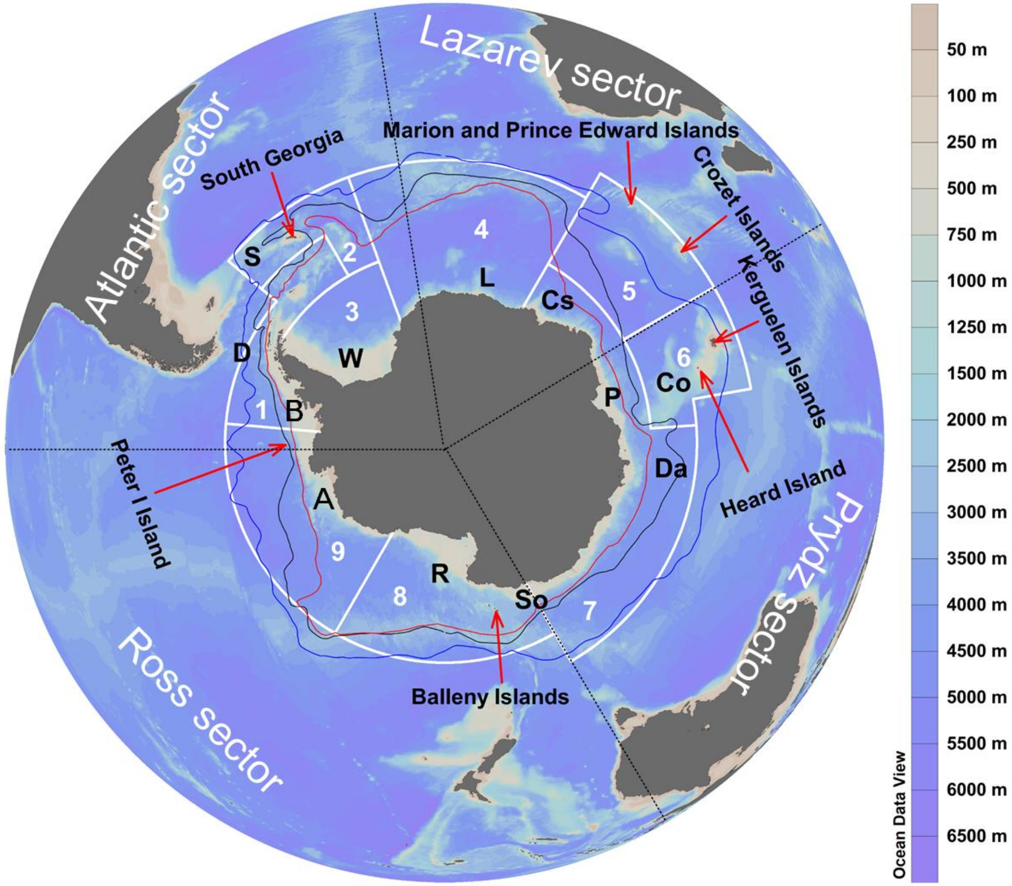
Yang et al., 2022; L&O

Foxton 1956; Hopkins 1971

Biomass_mesozooplankton

$B_{0\text{-}250\ m}$

Southern Ocean: to the region covering the nine marine protected area planning domains defined by Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) around Antarctica, ~36×10^6 km^2, 0-250 m, 67 Mt C (Yang et al., 2022)



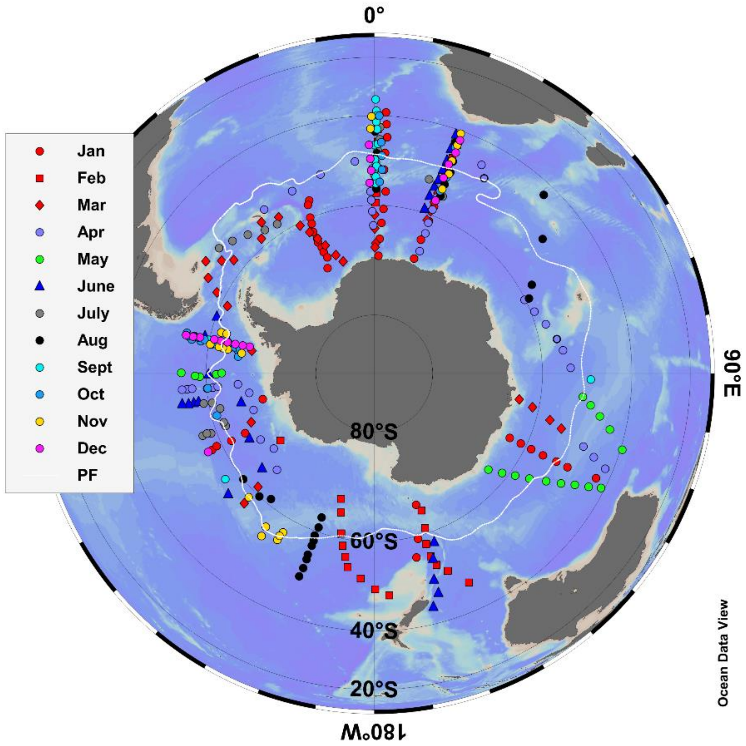
$B_{0\text{-}1000\ m}$

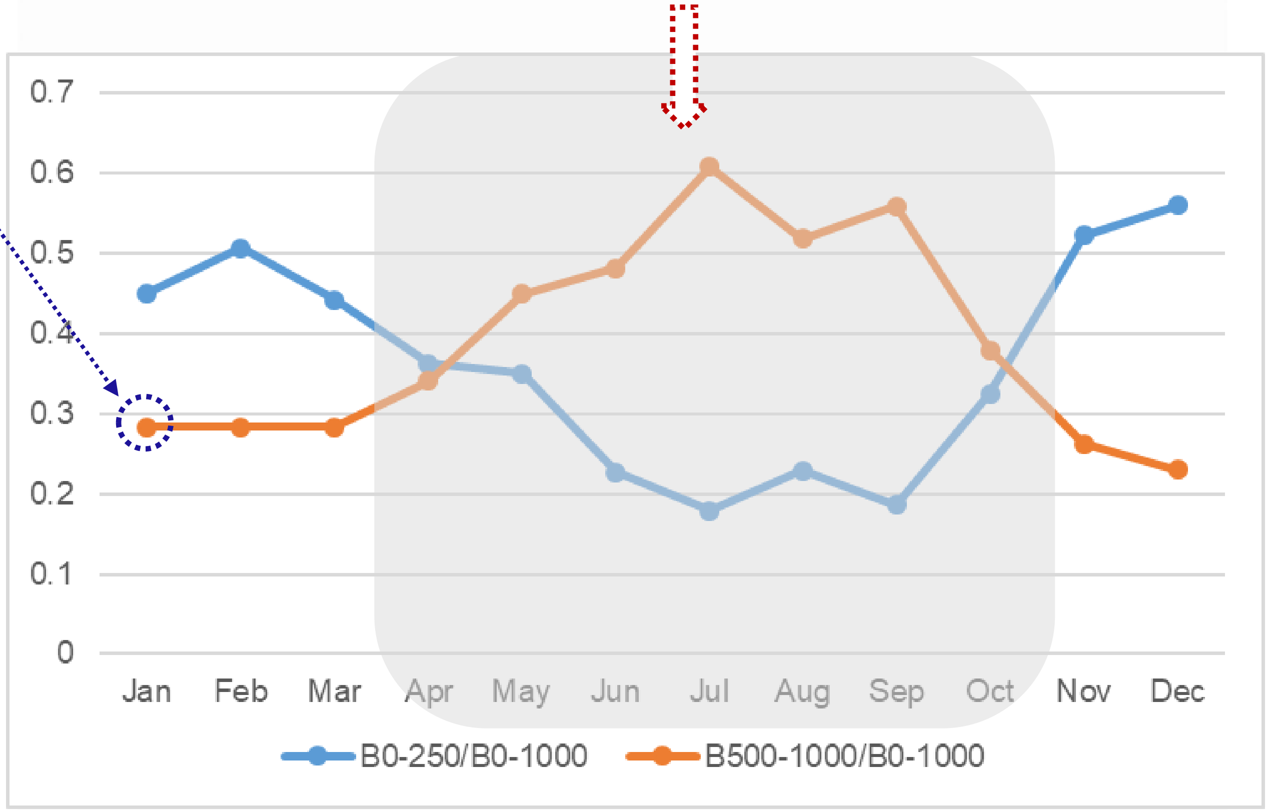
0.51: median of the ratio $B_{0\text{-}250\ m}/B_{0\text{-}1000\ m}$ among Nov, Dec, Jan, Feb and Mar

132.38 Mt C = 67/0.51 in the top 1000 m

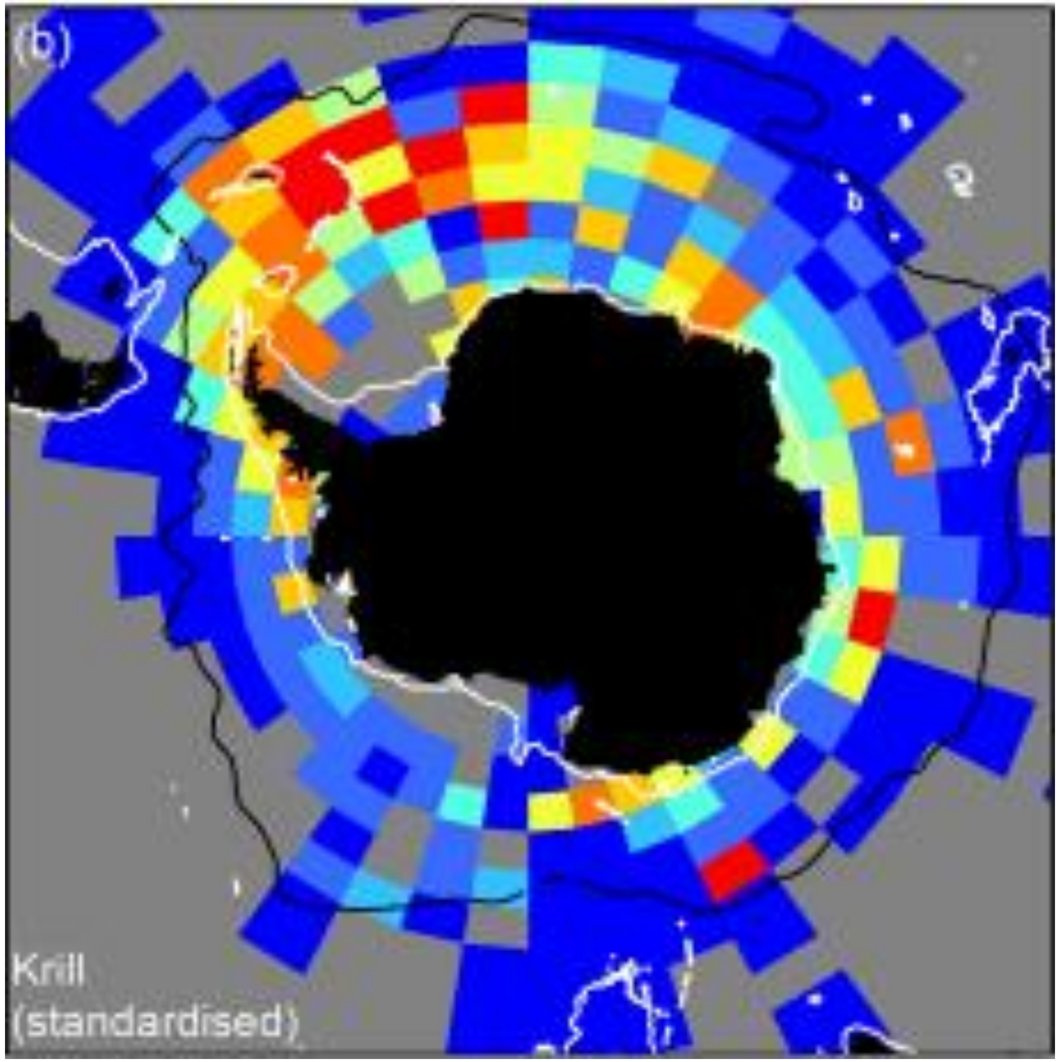
Biomass_mesozooplankton

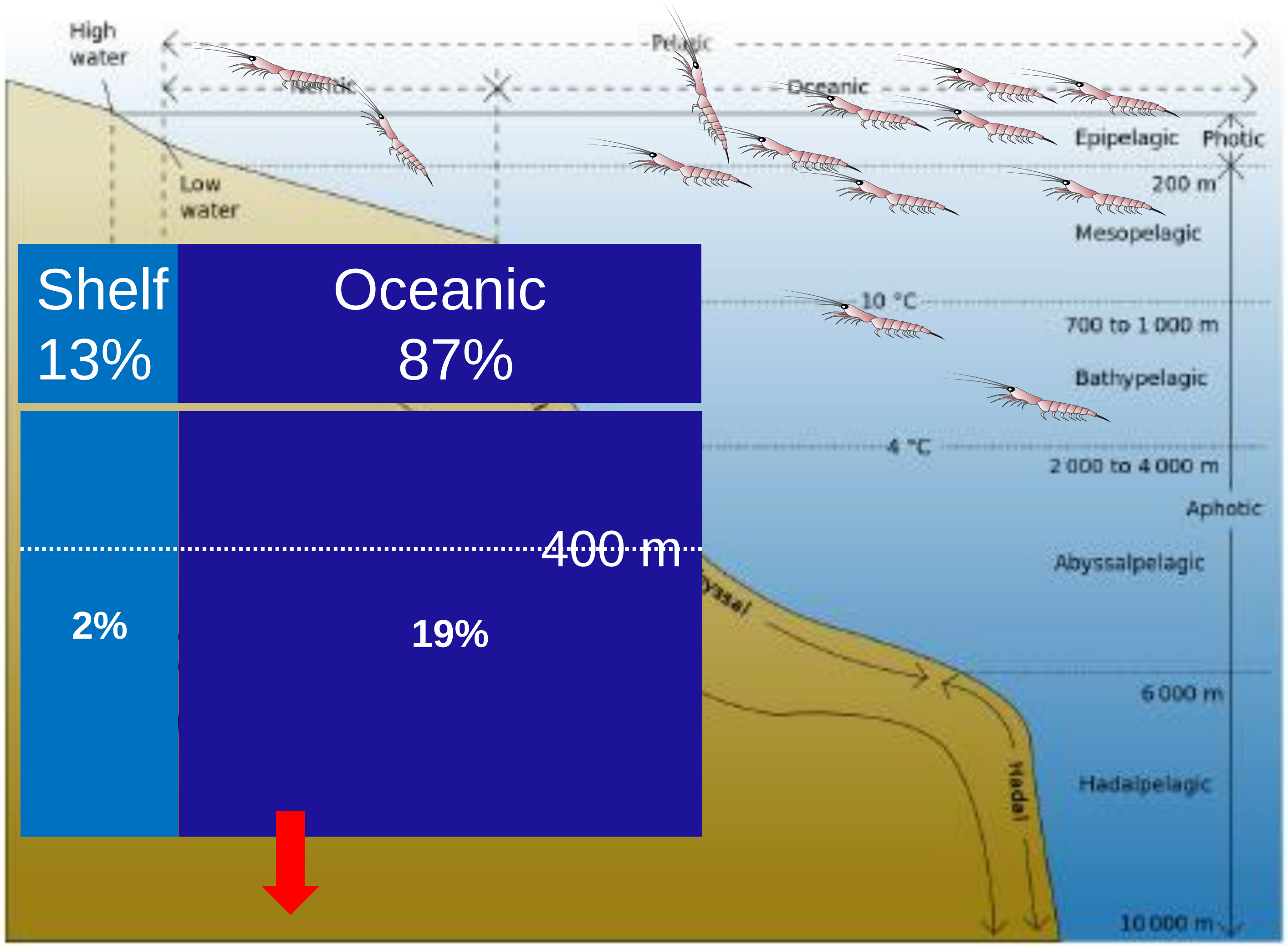
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
n	37	29	42	40	19	25	21	26	17	27	19	16
$B_{0\text{-}250m}/B_{0\text{-}1000m}$	0.44	**0.51**	0.45	0.36	0.35	0.23	0.18	**0.23**	0.21	0.32	0.59	0.54
$B_{500\text{-}1000m}/B_{0\text{-}1000m}$	**0.28**	0.29	0.29	0.34	0.45	0.48	0.59	0.49	0.56	0.38	0.22	0.23
proportion of diapausing zooplankton				0.06	0.17	0.20	0.31	0.21	0.28	0.10		
				0.34-**0.28**	0.45-**0.28**	0.48-**0.28**	0.59-**0.28**	0.49-**0.28**	0.56-**0.28**	0.38-**0.28**		





Biomass_krill



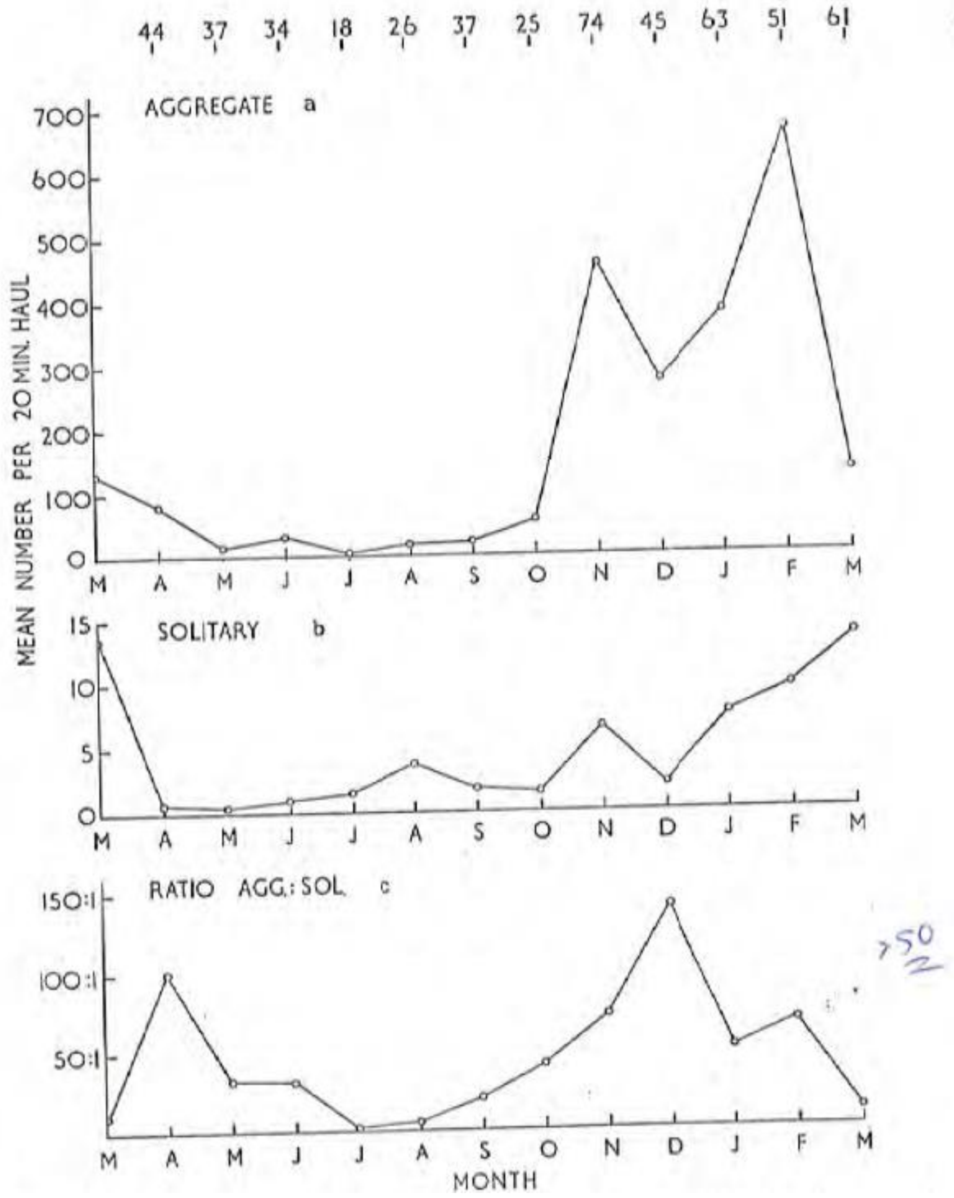


Atkinson et al., 2017, ESSD; 30 Mt

B = 5.04 Mt

Atkinson et al., 2008, MEPS; Schmidt et al., 2011, L&O

Biomass_salps



Foxton 1966

Total biomass: 1.7 Mt

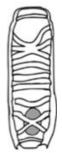
Initial aggregate-to-solitary abundance: 10:1

median oral to atrial opening (OAL) length for aggregates: 16 mm

median OAL length for solitary : 40 mm

$CM = 0.002 \times OAL^{2.148}$

Aggregate: 0.99 Mt



Solitary: 0.71 Mt

Yang et al., 2022; Foxton 1966; Henschke and Pakhomov, 2019; Dubischar et al., 2012

Respiration

	A	B	C	D	E	F	G	H	I	
1	Region	Depth	Year	Month	Species	Respiration rate (raw data)	Unit	Standardized respiration rate (µgC/µgC C	Note	Reference
2	Arctic	2300	2000	Aug	*Calanus hyperboreus*	6.00000	µlO$_2$/mgDM/d	0.007086039		Auel et al., 2003, Marine Biology; Respiratio
3	Weddell Sea	0-200	1988	winter	*Calanus propinquus*	8.37000	µlO$_2$/mgDM/d	0.009885024		Kawall et al., 2001, Hydrobiologia; Effects o
4	Weddell Sea	0-200	1988	winter	*Paraeuchaeta antarctica*	6.37560	µlO$_2$/mgDM/d	0.007529625		Kawall et al., 2001, Hydrobiologia; Effects o
5	Indian sector	0-200	1995	Oct-Nov	*Calanoides acutus* CIV	40.11000	µlO$_2$/mgDM/d	0.04737017	dry weight (µg/ind): 110	Mayzaud et al., 2002, DSR I; Feeding, respi
6	Indian sector	0-200	1995	Oct-Nov	*Calanoides acutus* CV	26.53000	µlO$_2$/mgDM/d	0.031332102	dry weight (µg/ind): 445	Mayzaud et al., 2002, DSR I; Feeding, respi
7	Indian sector	0-200	1995	Oct-Nov	*Calanoides acutus* Fe	24.69000	µlO$_2$/mgDM/d	0.02915905	dry weight (µg/ind): 608	Mayzaud et al., 2002, DSR I; Feeding, respi
8	Indian sector	0-200	1995	Oct-Nov	*Euchirella rostromagna* CVI	10.43000	µlO$_2$/mgDM/d	0.012317898	dry weight (µg/ind): 3360	Mayzaud et al., 2002, DSR I; Feeding, respi
9	Indian sector	0-200	1995	Oct-Nov	*Metridia lucens* CVI	30.94000	µlO$_2$/mgDM/d	0.036540341	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
10	Indian sector	0-200	1995	Oct-Nov	*Oncaea antarctica* CV-CVI	40.71000	µlO$_2$/mgDM/d	0.048078774	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
11	Indian sector	0-200	1995	Oct-Nov	*Paraeuchaeta antarctica* Fe	10.86000	µlO$_2$/mgDM/d	0.012825731	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
12	Indian sector	0-200	1995	Oct-Nov	*Paraeuchaeta antarctica* M	13.60000	µlO$_2$/mgDM/d	0.016061688	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
13	Indian sector	0-200	1995	Oct-Nov	*Paraeuchaeta* sp. CIV	21.72000	µlO$_2$/mgDM/d	0.025651461	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
14	Indian sector	0-200	1995	Oct-Nov	*Pleuromamma robusta* CV	24.79000	µlO$_2$/mgDM/d	0.029277151	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
15	Indian sector	0-200	1995	Oct-Nov	*Pleuromamma robusta* CVI	24.25000	µlO$_2$/mgDM/d	0.028639407	dry weight (µg/ind):	Mayzaud et al., 2002, DSR I; Feeding, respi
16	Indian sector	0-200	1995	Oct-Nov	*Rhincalanus gigas* CIV	26.57000	µlO$_2$/mgDM/d	0.031379343	dry weight (µg/ind): 309	Mayzaud et al., 2002, DSR I; Feeding, respi
17	Indian sector	0-200	1995	Oct-Nov	*Rhincalanus gigas* CV	20.67000	µlO$_2$/mgDM/d	0.024411404	dry weight (µg/ind): 560	Mayzaud et al., 2002, DSR I; Feeding, respi
18	Indian sector	0-200	1995	Oct-Nov	*Rhincalanus gigas* Fe	18.70000	µlO$_2$/mgDM/d	0.022084821	dry weight (µg/ind): 1287	Mayzaud et al., 2002, DSR I; Feeding, respi
19	Southeastern Beaufort Sea	0-250	2004	Apr	*Calanus glacialis*	0.01805	µgC/µgC CM/d	0.01805	carbon weight: 399 µgC	Seuthe et al., 2007, Polar Biol; Winter-sprin
20	Southeastern Beaufort Sea	0-250	2004	Apr/May	*Metridia longa*	0.13091	µgC/µgC CM/d	0.13091	carbon weight: 110 µgC	Seuthe et al., 2007, Polar Biol; Winter-sprin
21	Southeastern Beaufort Sea	0-250	2004	Mar	*Metridia longa*	0.08727	µgC/µgC CM/d	0.08727	carbon weight: 110 µgC	Seuthe et al., 2007, Polar Biol; Winter-sprin
22	Southeastern Beaufort Sea	0-250	2004	Mar/Apr	*Calanus hyperboreus*	0.00353	µgC/µgC CM/d	0.00353	carbon weight: 1360 µgC	Seuthe et al., 2007, Polar Biol; Winter-sprin
23	Southeastern Beaufort Sea	0-250	2004	May	*Calanus glacialis*	0.04211	µgC/µgC CM/d	0.04211	carbon weight: 399 µgC	Seuthe et al., 2007, Polar Biol; Winter-sprin
24	Indian sector	0-250	1980	Jan	*Calanus propinquus*	28.29600	µlO$_2$/ind/d	0.032040038	Dry wt: 1.043 mg/ind	Ikeda et al., 2001, Marine Biol; Metabolic rat
25	Indian Ocean	0-250	1980	Jan	*Metridia gerlachei*	7.68000	µlO$_2$/ind/d	0.034226905	Dry wt: 0.265 mg/ind	Ikeda et al., 2001, Marine Biol; Metabolic rat
26	Atlantic Ocean	0-250	1981	Jan-Mar	*Calanoides acutus* CIV, V	3.12000	µlO$_2$/ind/d	0.016902478	Dry wt: 0.218 mg/ind	Ikeda et al., 2001, Marine Biol; Metabolic rat
27	Atlantic Ocean	0-250	1981	Jan-Mar	*Calanoides acutus* CV	5.06400	µlO$_2$/ind/d	0.015179231	Dry wt: 0.394 mg/ind	Ikeda et al., 2001, Marine Biol; Metabolic rat
28	Indian Ocean	0-250	1982	Nov	*Rhincalanus gigas*	10.51200	µlO$_2$/ind/d	0.01149513	Dry wt: 1.080 mg/ind	Ikeda et al., 2001, Marine Biol; Metabolic rat
29	Kongsfjord	0-300	2010	Feb	*Limacina helicina*	8.25216	µlO$_2$/mgDM/d	0.009745855	dry mass: 0.134/ind	Lischka and Riebesell 2017, Polar Biol; Met
30	Kongsfjord	0-300	2010	Feb	*Limacina retroversa*	6.65011	µlO$_2$/mgDM/d	0.007853825	dry mass: 0.17/ind	Lischka and Riebesell 2017, Polar Biol; Met
31	Antarctic Peninsula	0-50	2019	Aug	*Euphausia superba* Juvenile	11.66400	µlO$_2$/mgDM/d	0.014431224		Bernard et al., 2022, FiMS; Winter condition

Respiration_standardization

μgC/mgDM/d, μlO_2/ind/d, μlO_2/mgDM/d ⇨ weight-specific respiration rate μgC/μgCM/d

<u>Step 1: convert O_2 to Carbon</u>

$\mu gC\ d^{-1} = \mu L\ O_2\ d^{-1} \times 12/22.4 \times RQ$

12/22.4: the carbon weight in 1 mol (22.4 L) of CO_2

Respiratory quotient (RQ): 0.97 (Ikeda and Bruce 1986)

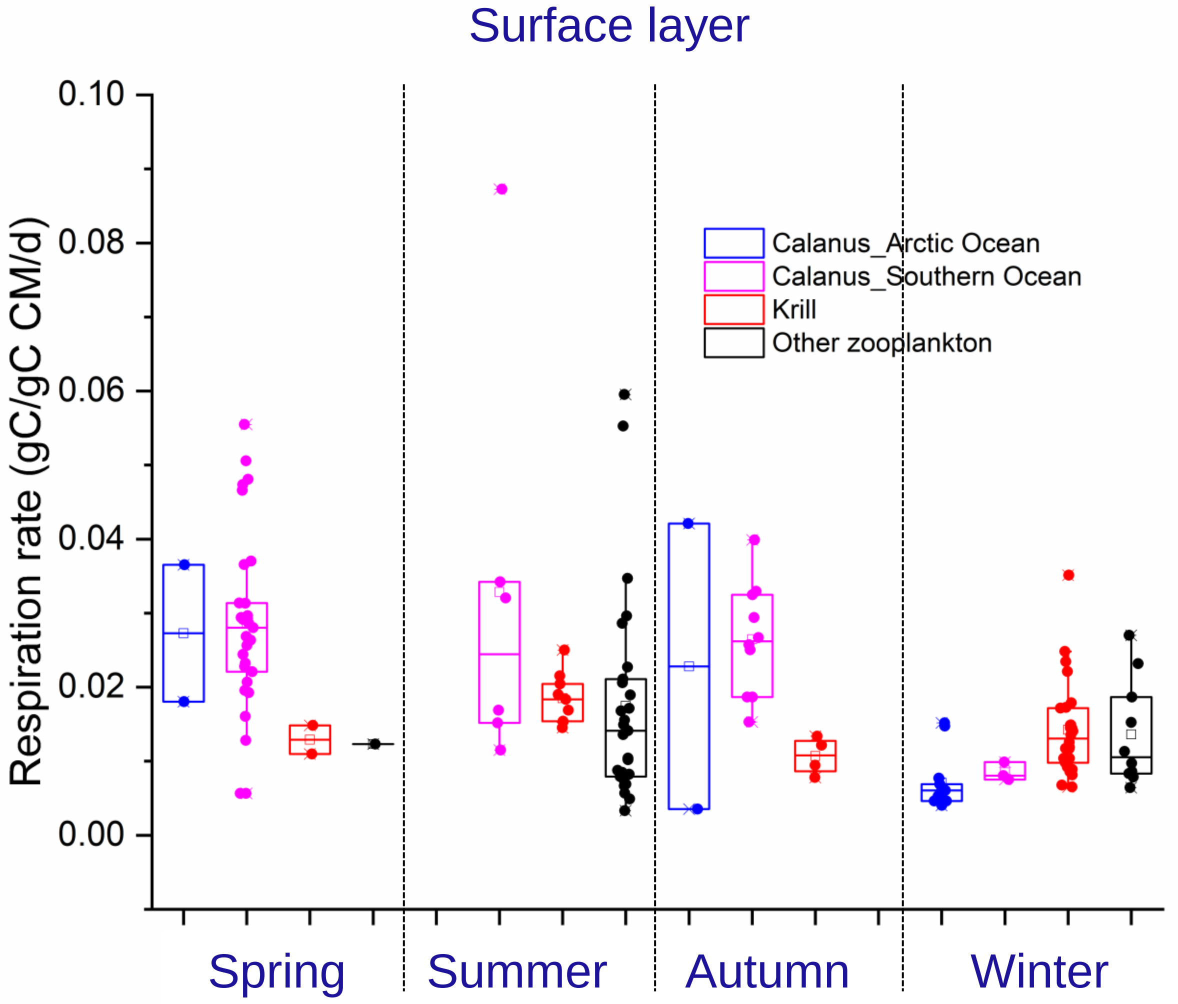
CM = 0.44DM	Copepods	Mean of two large species	Ikeda and Mitchel (1982)
CM = 0.44DM	Copepods	Spring/summer average	Schnack (1985)
CM = 0.27DM	Chaetognaths	Autumn/winter average	Donnelly et al. (1994)
CM = 0.50DM	*E. superba*	Mixed sexes/stages	Färber-Lorda et al. (2009)
CM = 0.42DM	*E. superba*	Mixed sexes/stages	Atkinson et al. (2012)
CM = 0.15DM	*Salpa thompsoni*	Summer/autumn/winter average	Dubischar et al. (2011)
CM = 0.0369DM + 0.0655	*Salpa thompsoni*	Summer/autumn data	Huntley et al. (1989)
CM =0.074DM	Salps	Autumn/winter average	Donnelly et al. (1994)

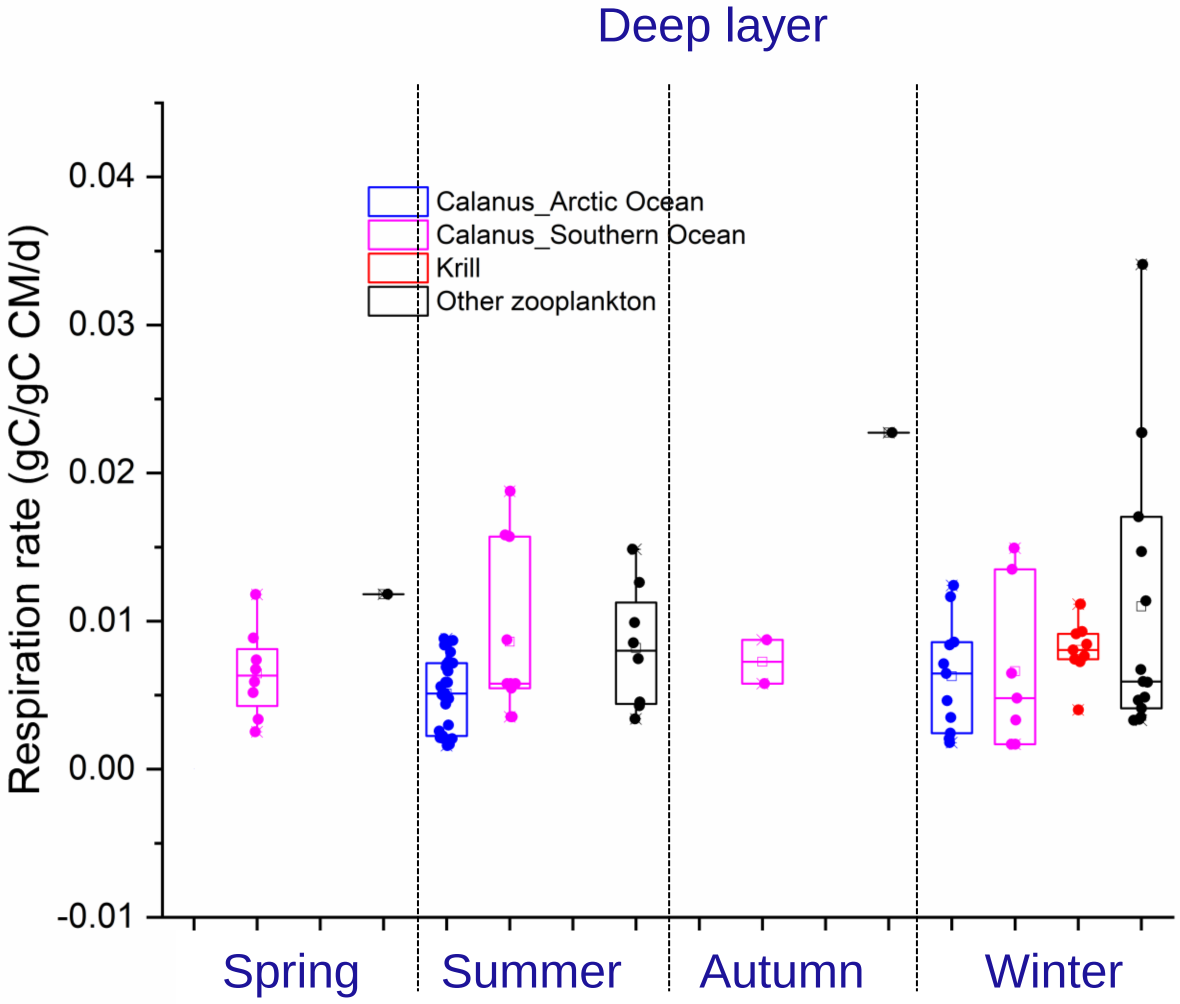
<u>Step 2: weight conversion</u>

Carbon weight of each species

species-specific inter-conversion factors between dry mass and carbon mass (Atkinson et al., 2012)

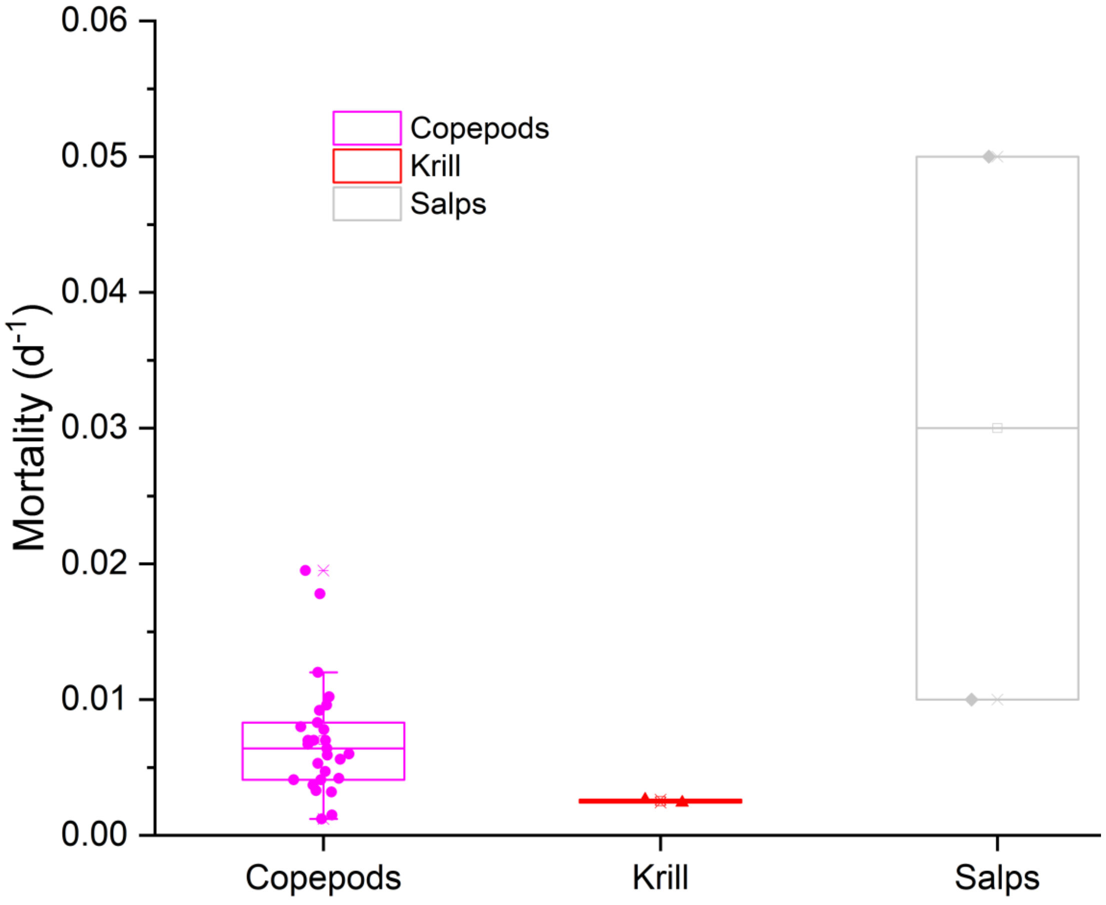
Respiration

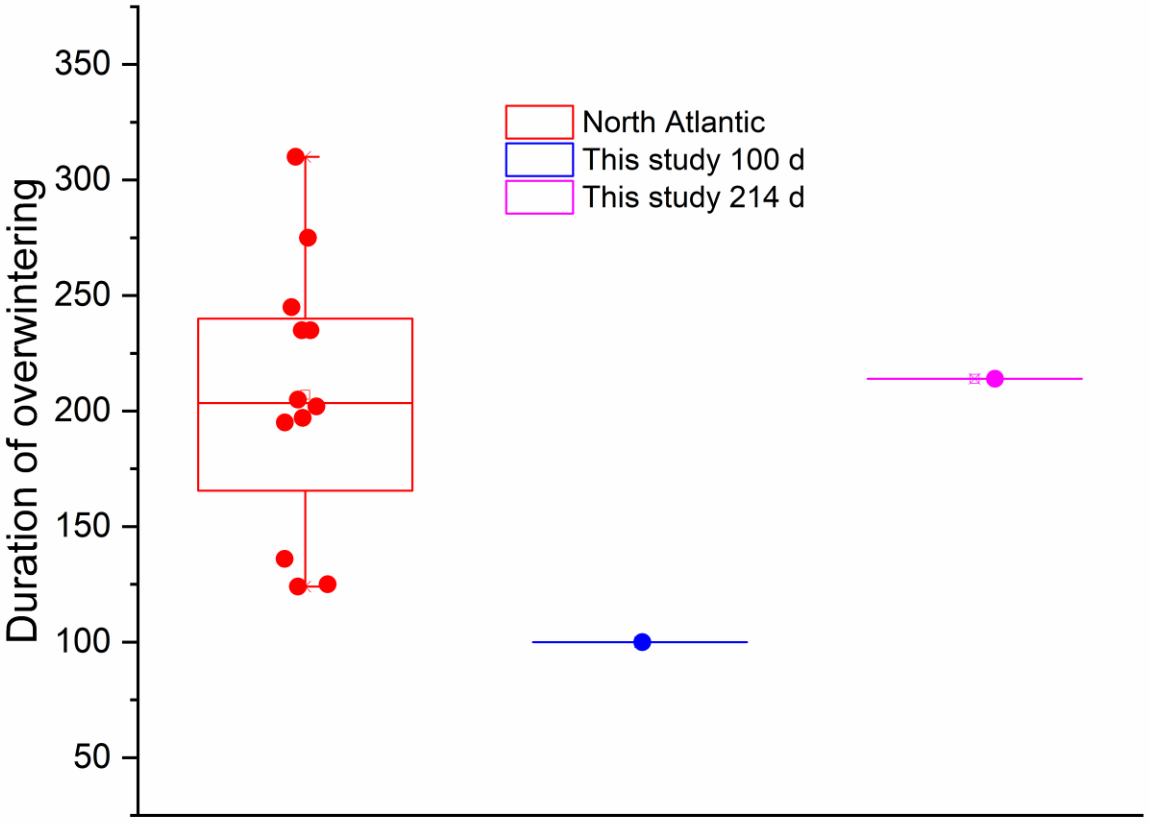




Mesozooplankton: 0.00585 d^{-1}; krill: 0.00805 d^{-1}; Salps: 0.01907 d^{-1}

Mortality and overwintering period





Mesozooplankton: 0.0056 d^{-1}; krill: 0.00252 d^{-1};

overwintering period: 214 d

Lipid pump_mesozooplankton

Assumption: body weight of mezooplankton decreases gradually during overwintering due to mortality and respiration

Day	Biomass (B_0)	$L_{m,\ d}$ (from mortality)	$L_{r,\ d}$ (from respiration)
1	$B_1 = B_0 - L_{m,\ 1} - L_{r,\ 1}$	$L_{m,\ 1} = B_0 * m$	$L_{r,\ 1} = (B_0 - L_{m,\ 1}) * r$
2	$B_2 = B_1 - L_{m,\ 2} - L_{r,\ 2}$	$L_{m,\ 2} = B_1 * m$	$L_{r,\ 2} = (B_1 - L_{m,\ 2}) * r$
3	$B_3 = B_2 - L_{m,\ 3} - L_{r,\ 3}$	$L_{m,\ 3} = B_2 * m$	$L_{r,\ 3} = (B_2 - L_{m,\ 3}) * r$
…			

Assumption: body weight of krill remains unchanged during overwintering

Krill: business as usual, quiescence, flexibility
feed, even at low rates

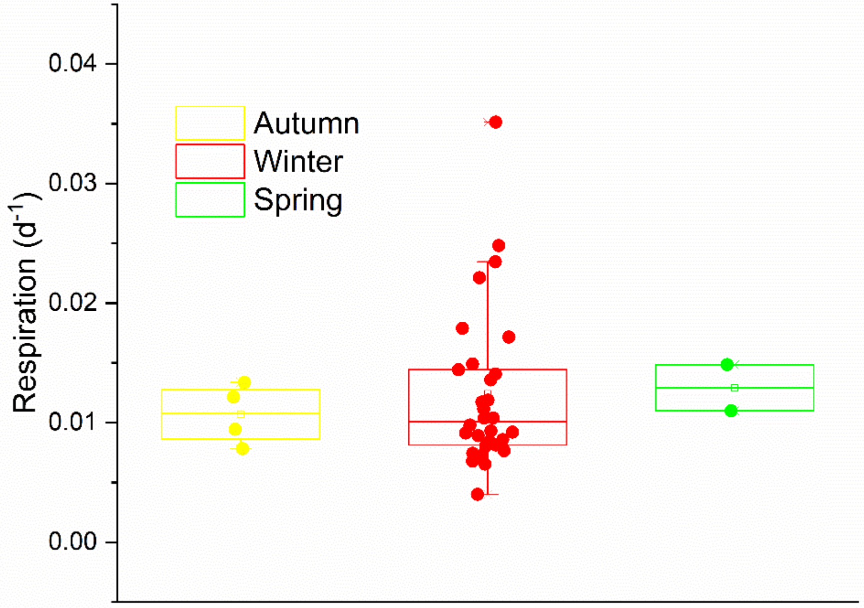
Meyer et al., 2010, MEPS; Schmidt et al., 2014, L&O

Lipid pump by mortality:

$$L_{m,\,n} = B_0 \times (1 - m)^{n-1} \times m$$

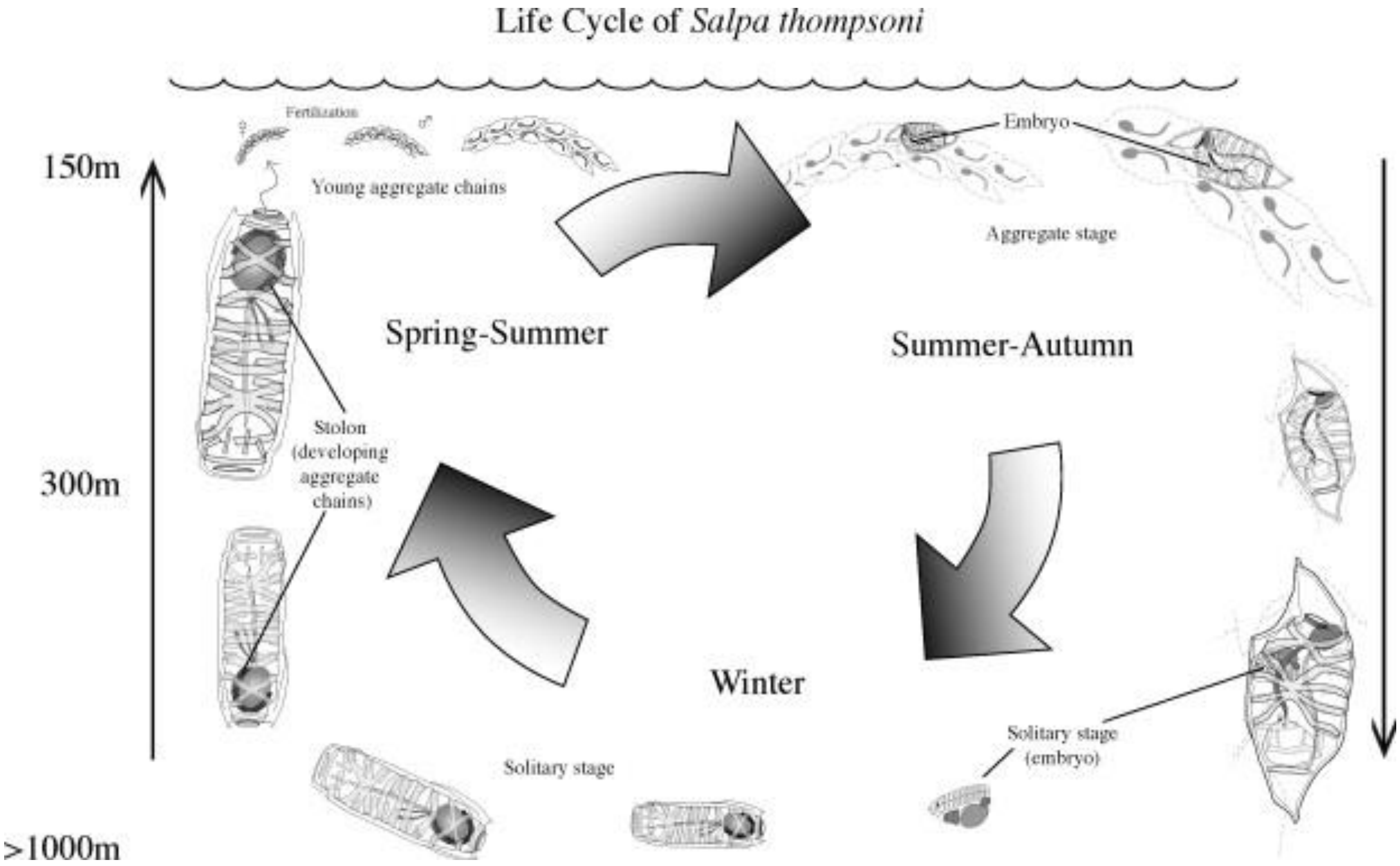
Lipid pump by respiration:

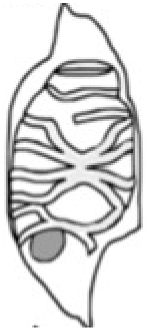
$$L_{r,\,n} = B_0 \times (1 - m)^{n} \times r$$



Apr, May: 0.0108 d^{-1}; Jun-Sep: 0.0101 d^{-1}; Oct: 0.0129 d^{-1}

Lipid pump from Salps

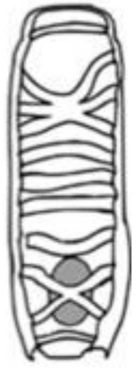




Aggregate

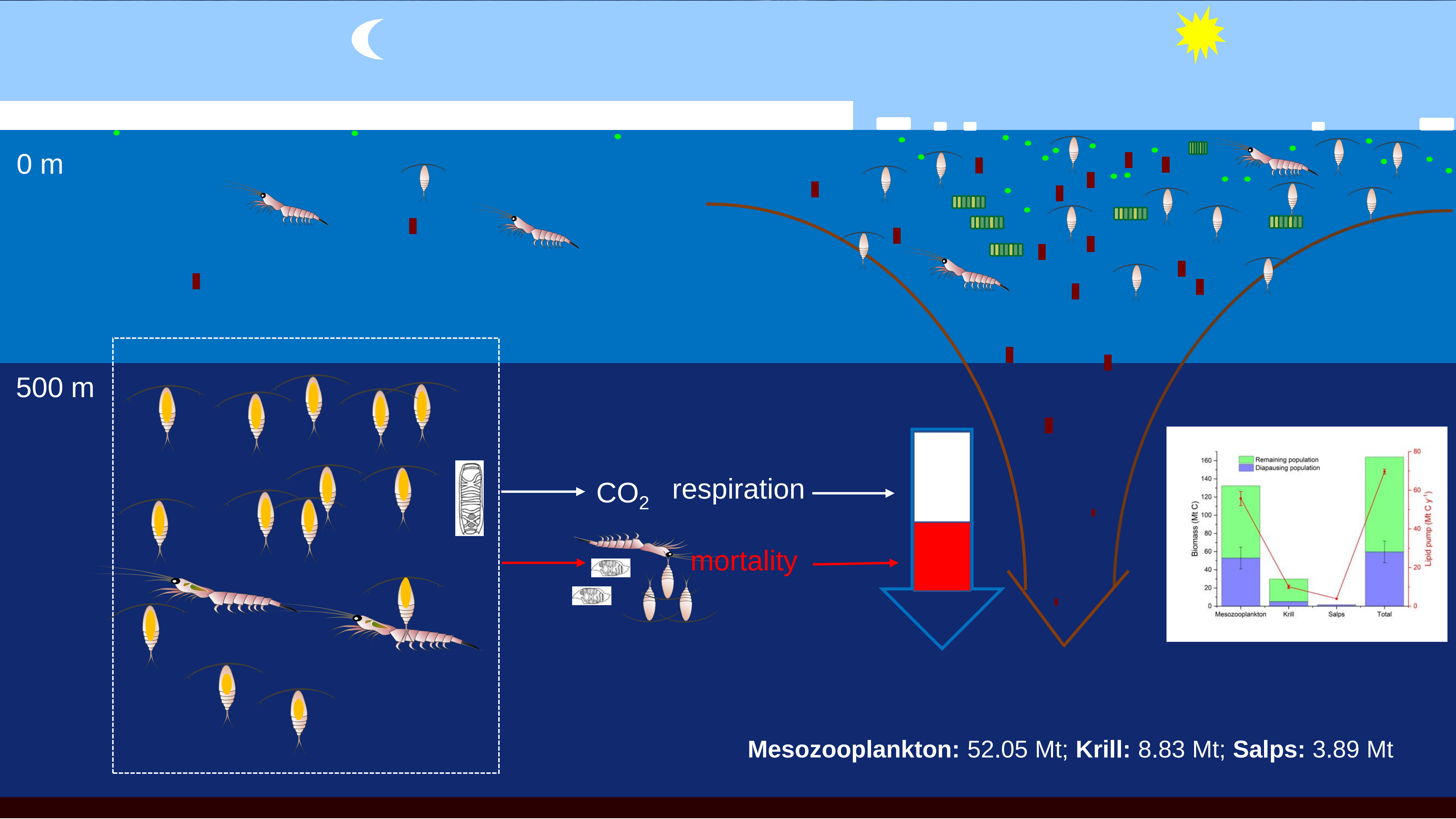
L_m

Die off at the winter onset (0.99 Mt)



Solitary

$L_r = B_s \times r \times L$


0 m
500 m
CO2
respiration
mortality
Remaining population
Diapausing population
Biomass (Mt C)
Lipid pump (Mt C y-1)
Mesozooplankton
Krill
Salps
Total
Mesozooplankton: 52.05 Mt; Krill: 8.83 Mt; Salps: 3.89 Mt

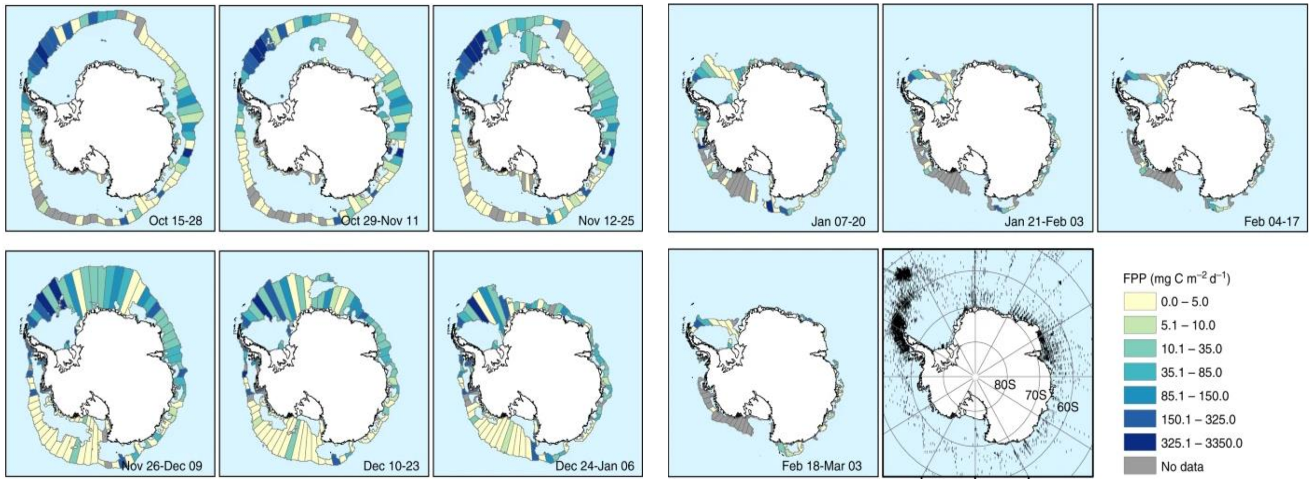
The lipid pump in relation to POC flux

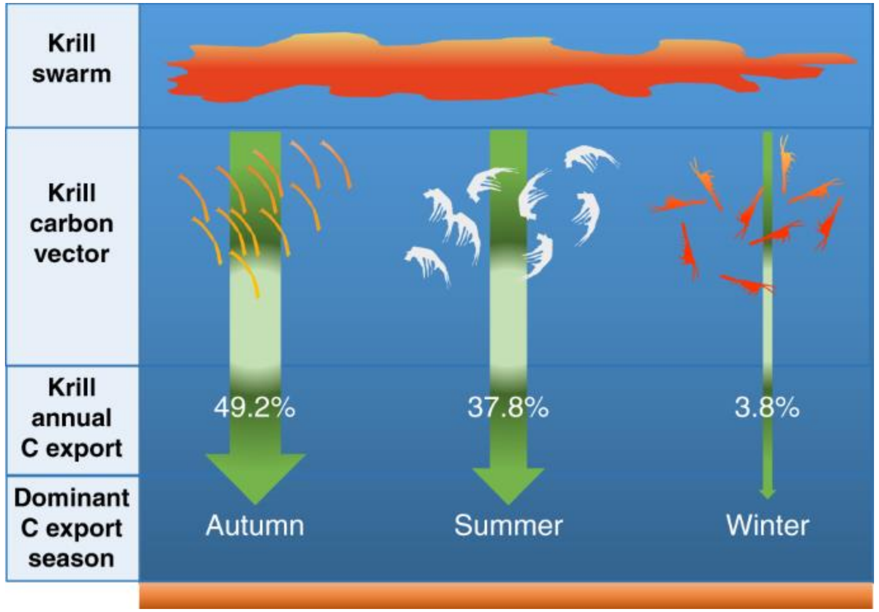
39 Mt, 35% (17% - 61%) of the satellite-derived export flux at 100 meters during the productive season (Oct – Mar)

65 Mt, 38% of the modeled POC flux 500 m

103% of the modeled POC flux 1000 m

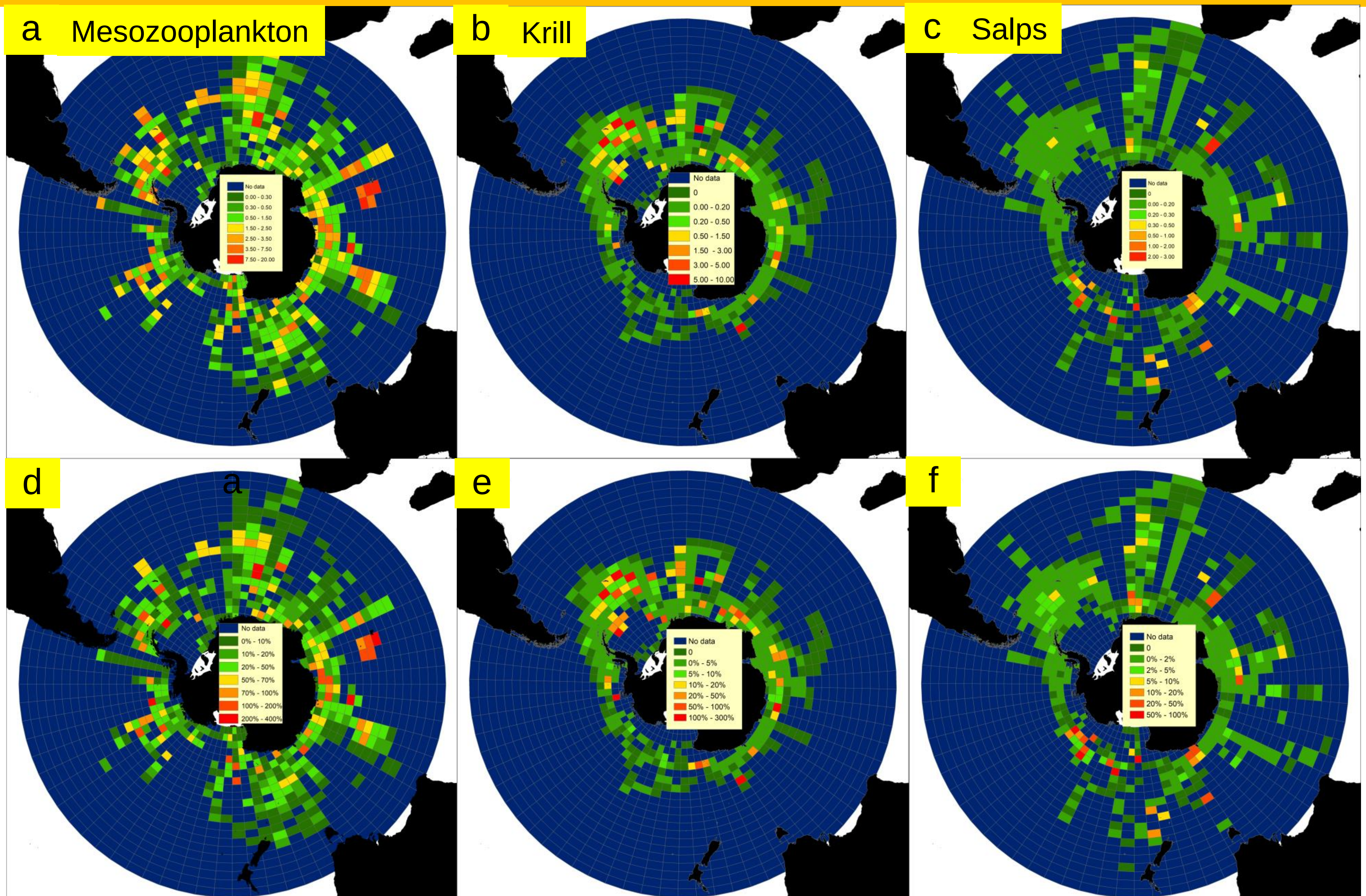
The mean carbon sequestration depth (defined as the depth where the carbon remains sequestered for more than 100 years) in the Southern Ocean is only 381 meters (ranging from 137 to 758 meters) (Cavan et al., 2024)



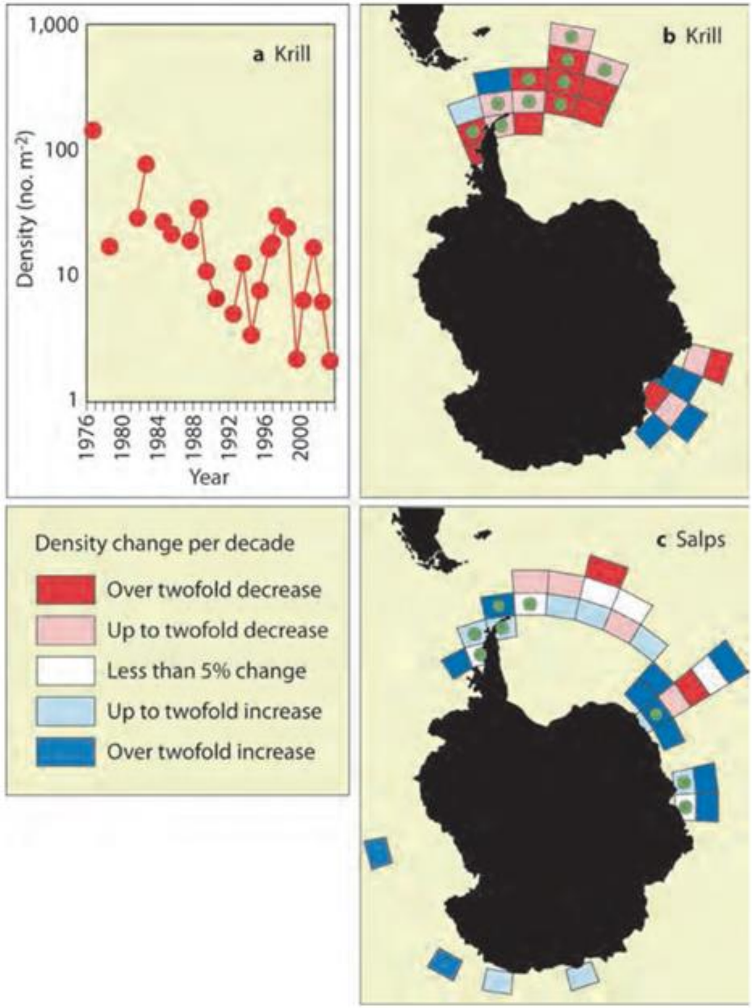


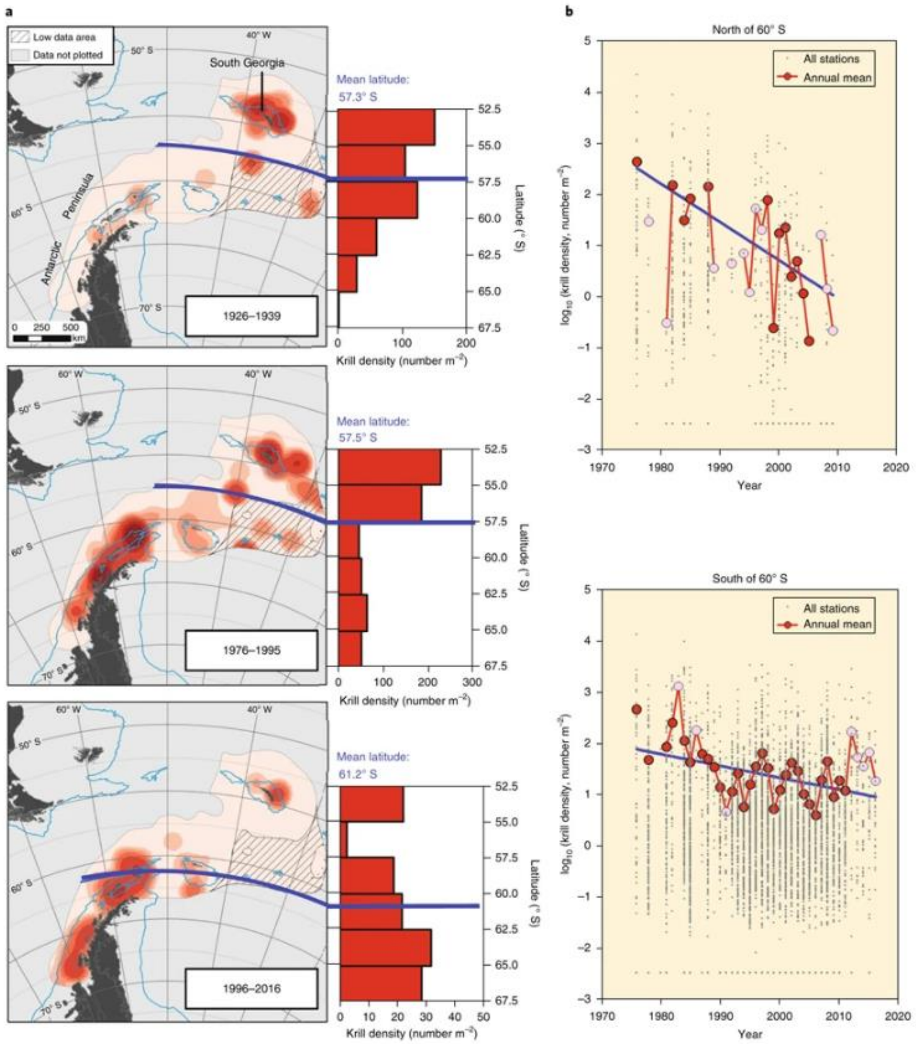
Belcher et al., 2019; NC; Manno et al., 2020; NC

Hotspots of lipid pump



Ecological and biogeochemical implications



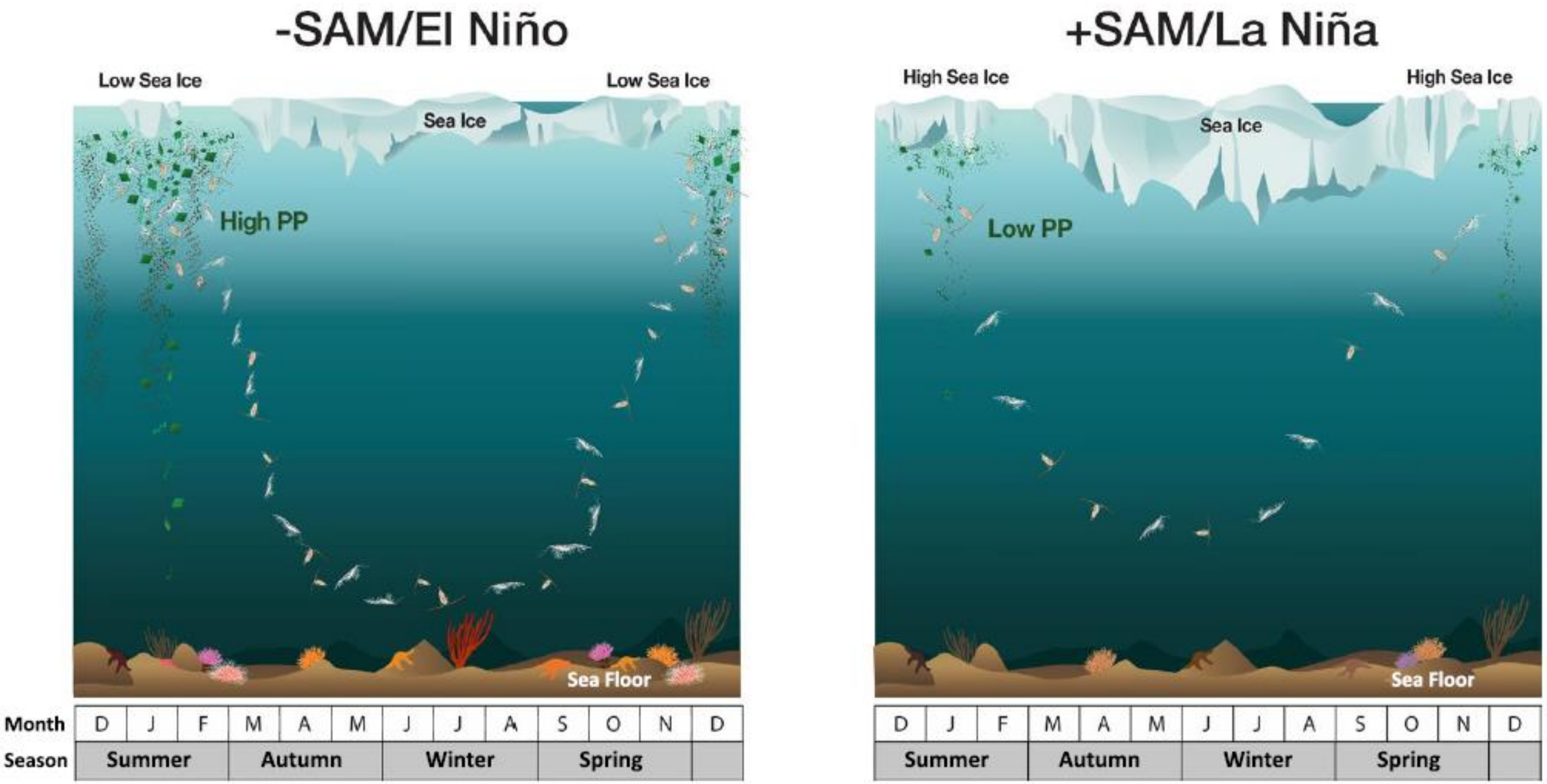


Shifts in dominance among krill, salps and copepods

Krill distribution contracts southward during rapid regional warming

Atkinson et al., 2004, Nature; Atkinson et al., 2019, NCC

Ecological and biogeochemical implications



Diapausing periods: shorter +SAM
More salps but less krill

Reduce the lipid pump strength

La et al., 2019, Sci Rep

Conclusion

- A rough estimate of lipid pump by zooplankton in the SO.
- Mesozooplankton (80%), krill (14%) and salps (6%) collectively transport 65 Mt carbon to depths of at least 500 m.
- The total magnitude of this pump represents a considerable proportion, ranging 0.36 - 0.44 and 1.00 - 1.21 times the annual particulate organic carbon flux at 500 meters and 1000 meters depth in the Southern Ocean, respectively.
- Climate change and its impact on biomass of dominant zooplankton groups and vertical migration behavior, can impact the dynamics of lipid pump.

Thanks !

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