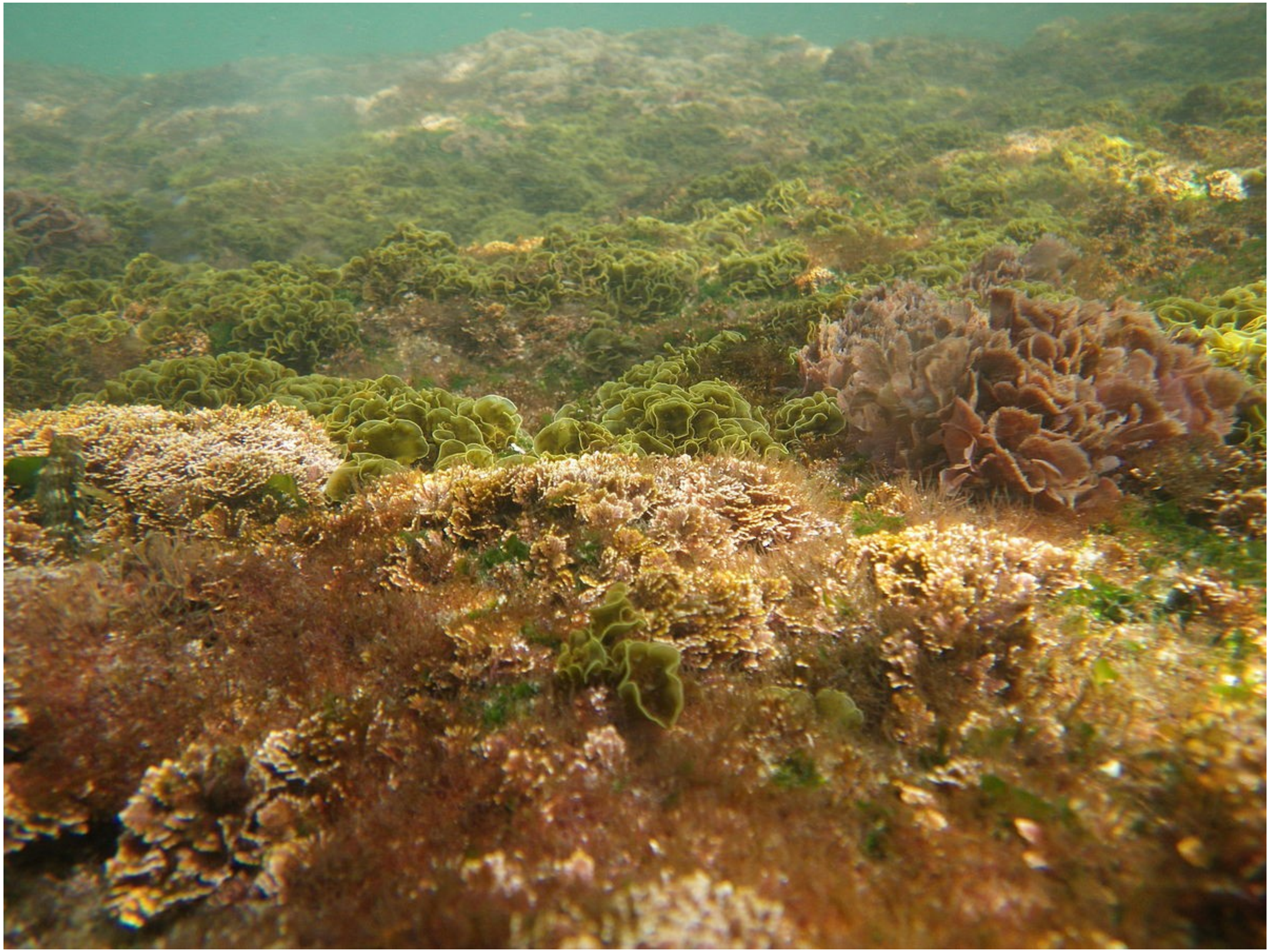
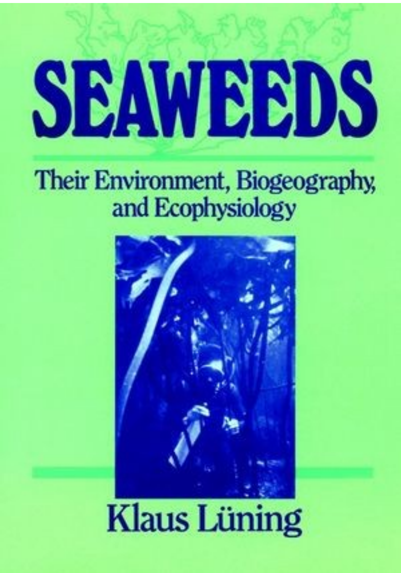
Marine Vegetation 1

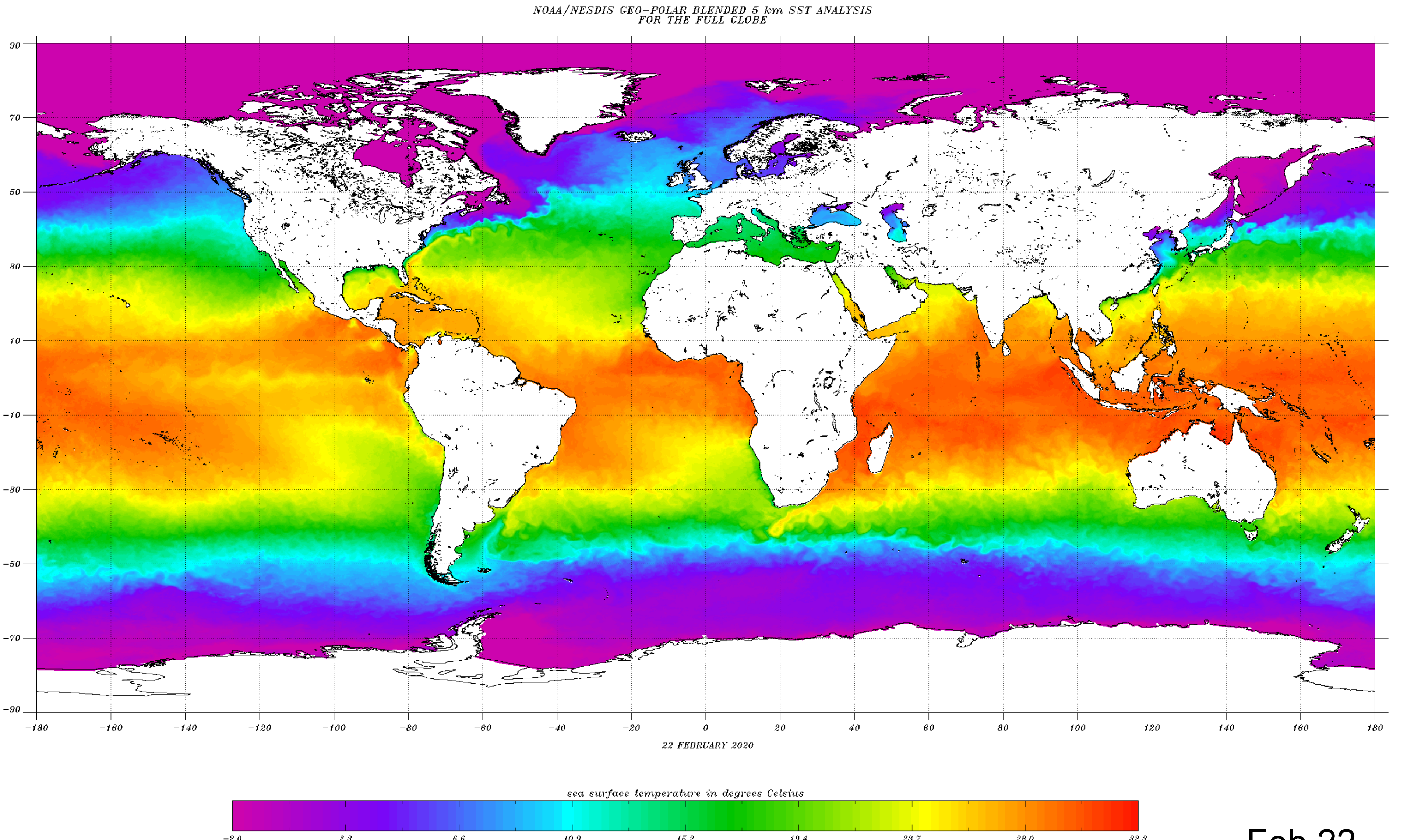
Global biogeography of macroalgae, general distribution patterns, vertical zonation, substrate effects, regional vegetation features, etc.





Marine Vegetation 1

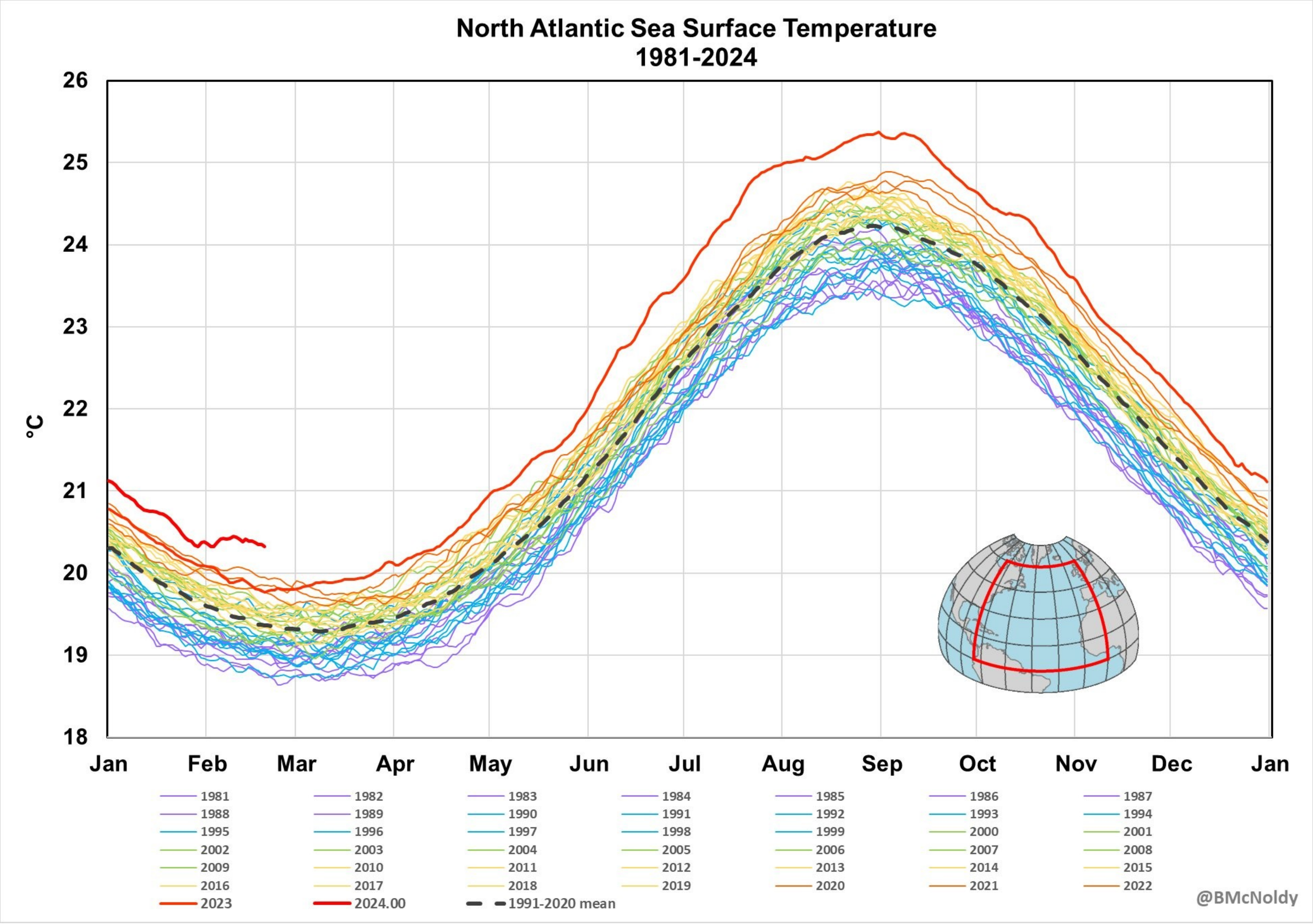
temperature (SST) is the key factor structuring benthic marine vegetation



Feb 22

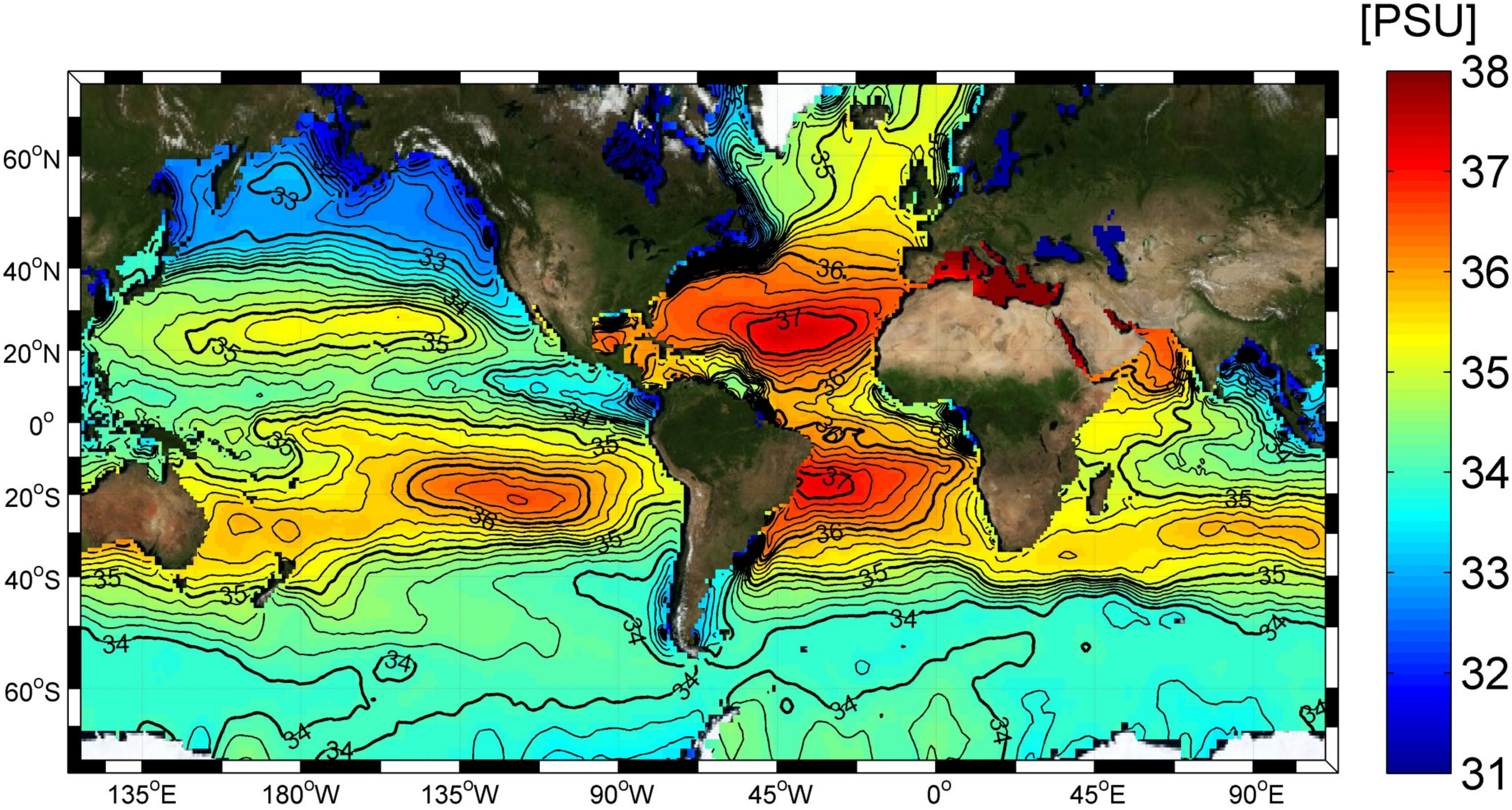
Marine Vegetation 1

... it is also the prime effect of the ongoing climate change in marine surface waters



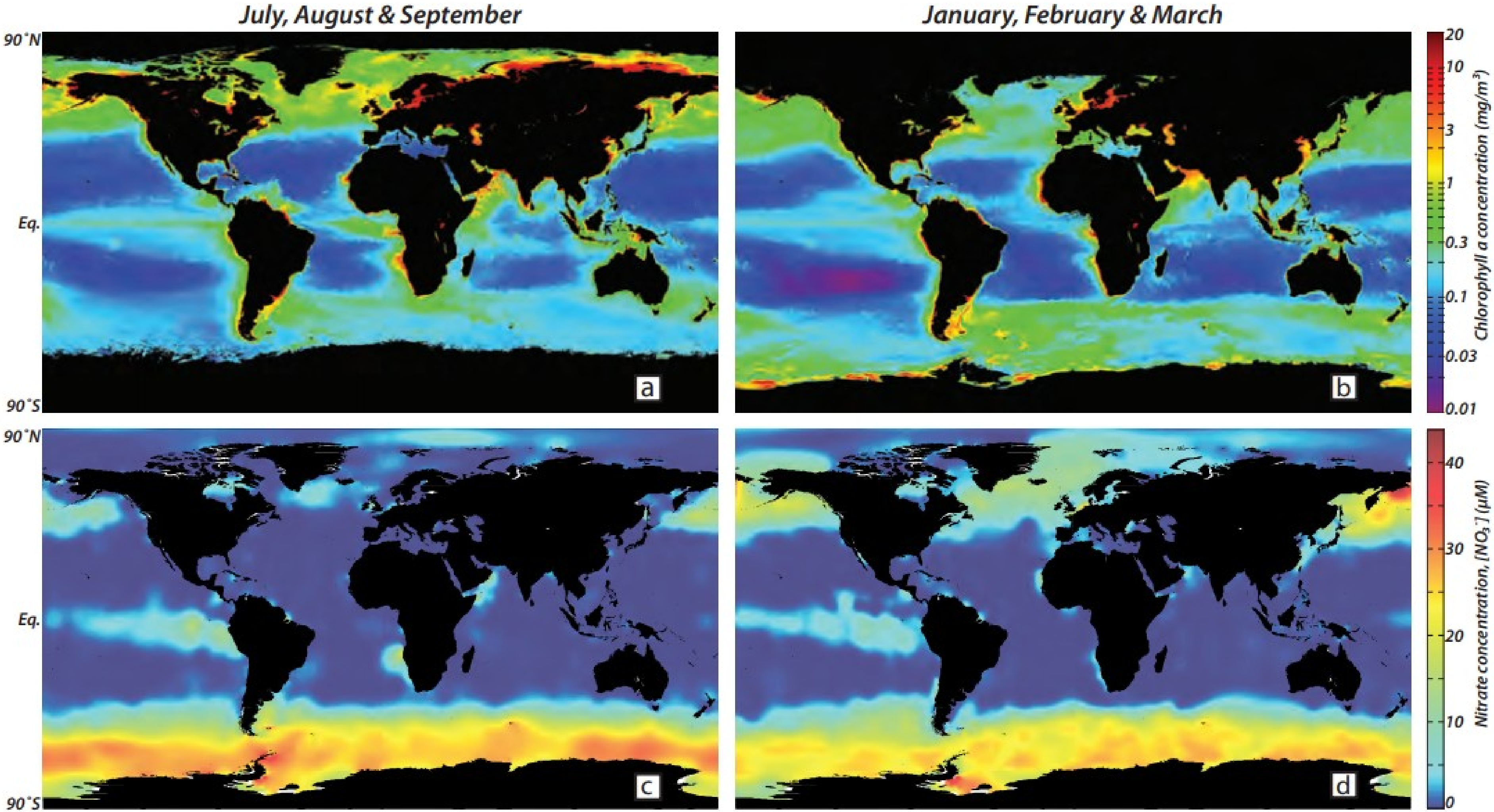
ocean surface salinity patterns

[psu – practical salinity units, 35 psu = cca 50 000 μS.cm^{-1}]



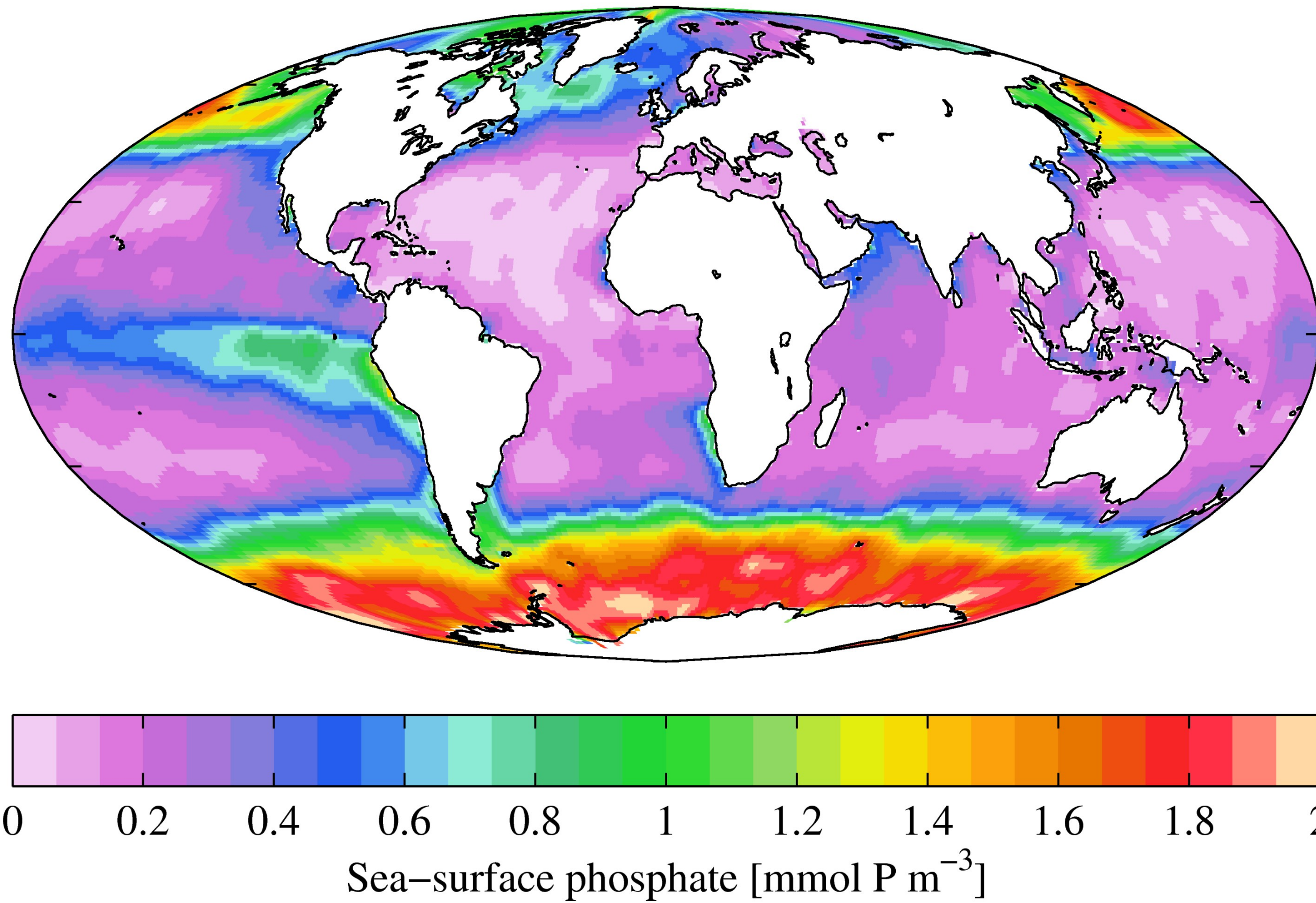
salinityremotesensing.ifremer.fr

global ocean nitrogen patterns, close relation to phytoplankton dynamics

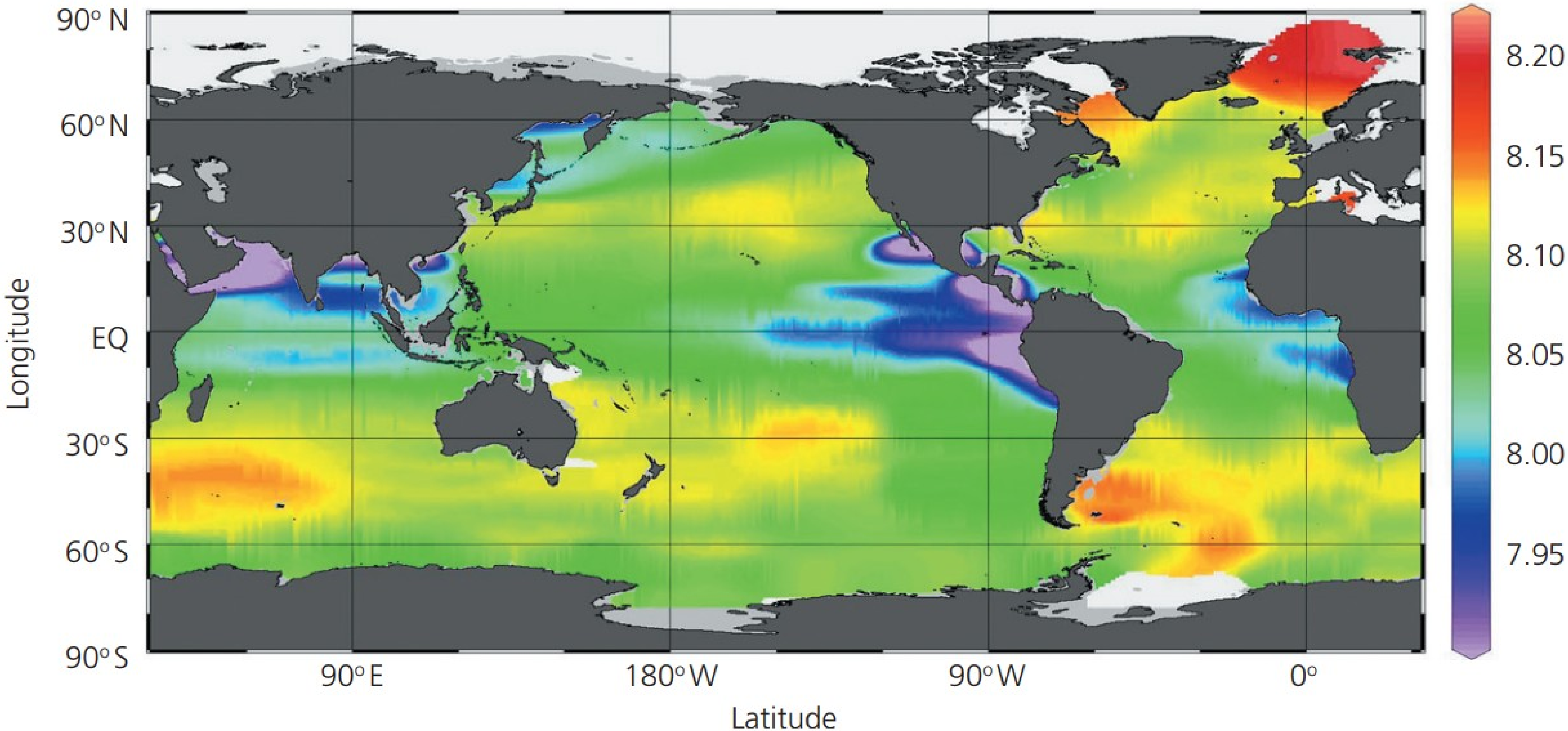


Sigman & Hain, 2012, Nature Ed.

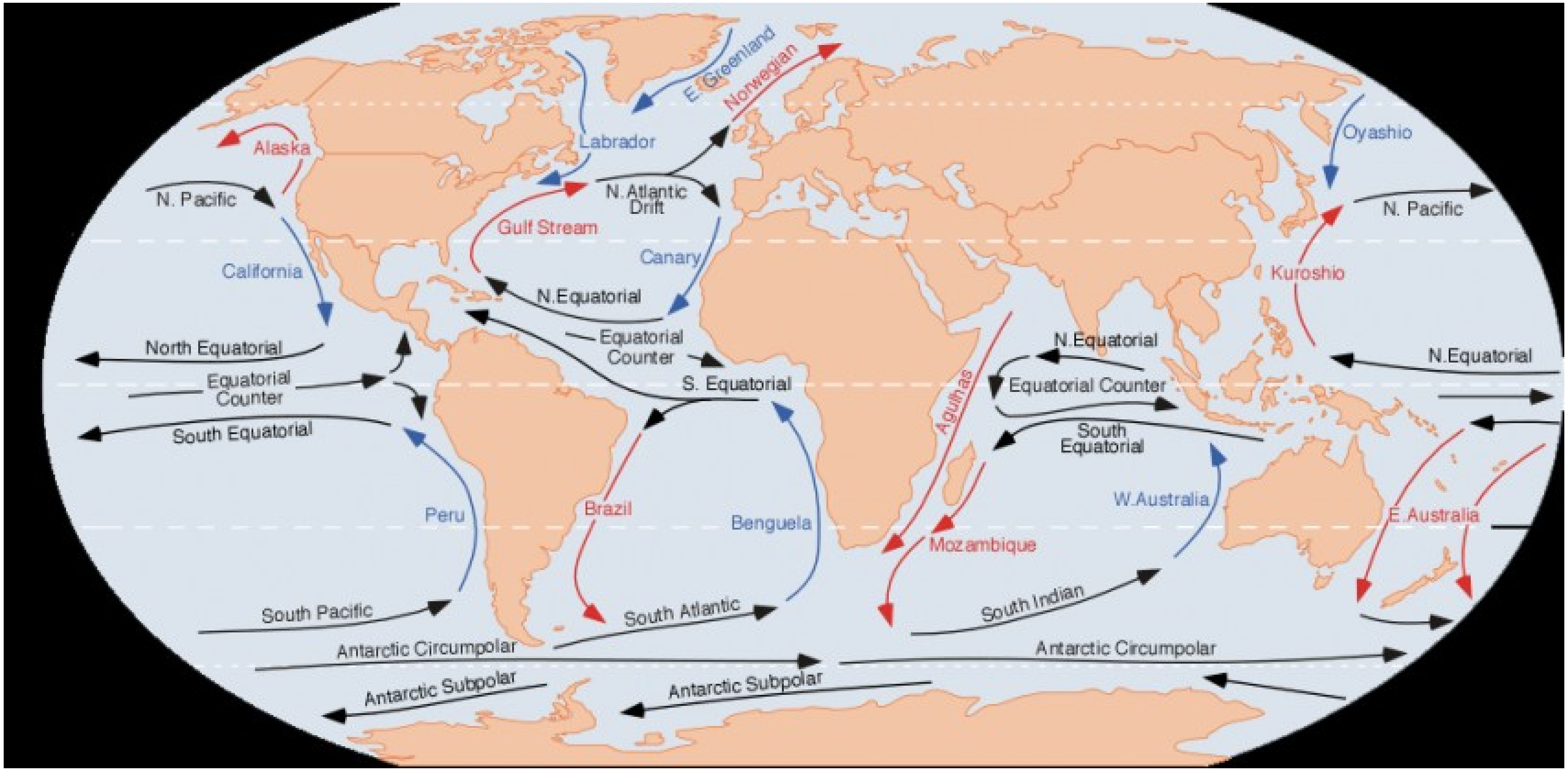
global ocean surface phosphate patterns
(tropics vs. polar regions)



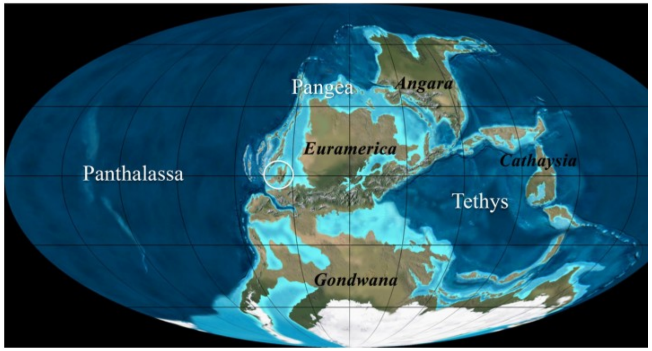
global ocean pH
(surface 50 m mixed layer)



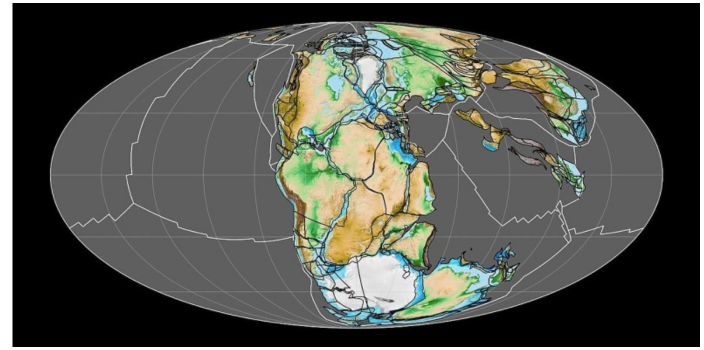
The Royal Society, 2005



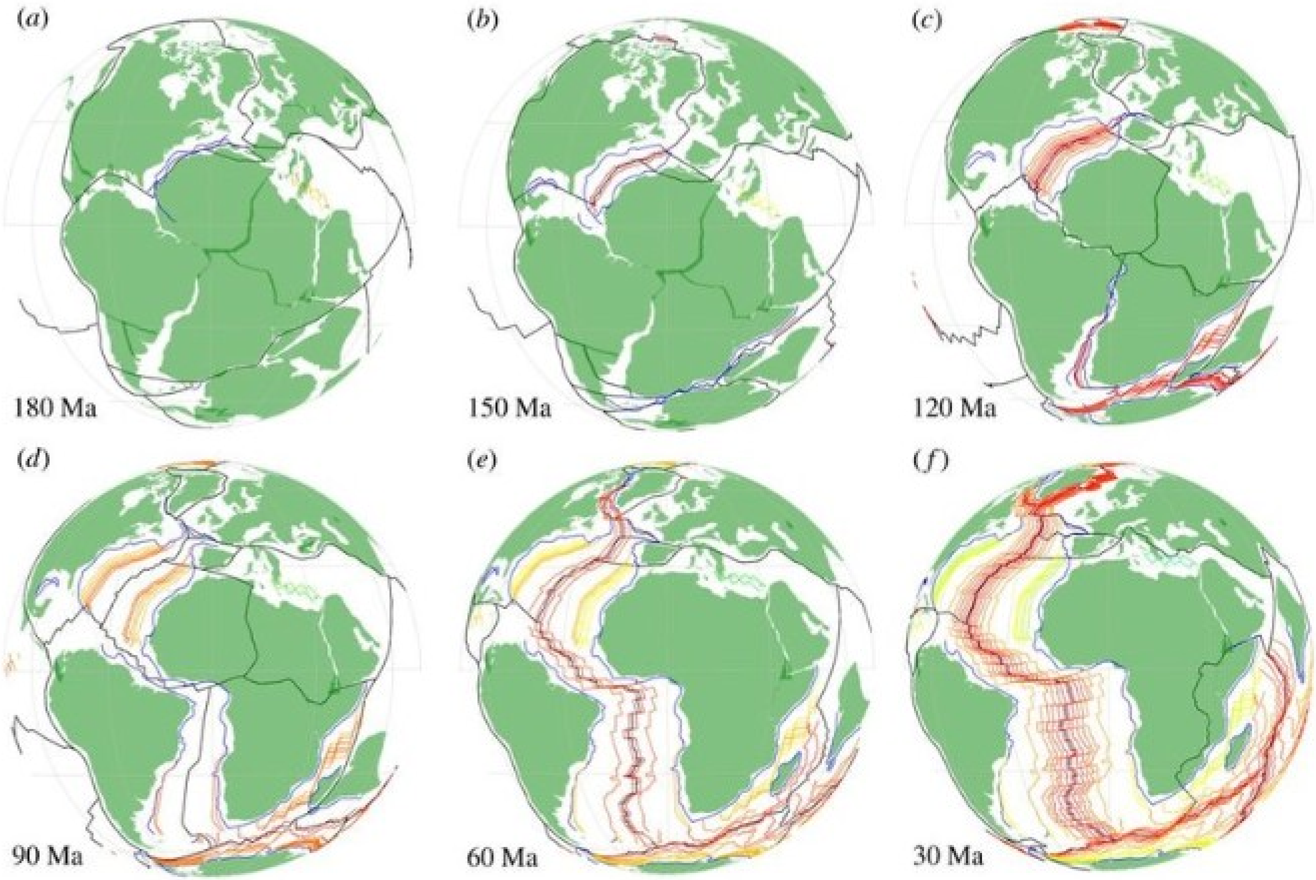
E. Greenland
Norwegian
Labrador
Alaska
Oyashio
N. Pacific
N. Atlantic Drift
N. Pacific
Gulf Stream
Canary
California
Kuroshio
N.Equatorial
Equatorial Counter
North Equatorial
N.Equatorial
N.Equatorial
Equatorial Counter
Equatorial Counter
S. Equatorial
South Equatorial
South Equatorial
Agulhas
W.Australia
Peru
Brazil
Benguela
E.Australia
Mozambique
South Pacific
South Atlantic
South Indian
Antarctic Circumpolar
Antarctic Circumpolar
Antarctic Subpolar
Antarctic Subpolar



-298 Ma

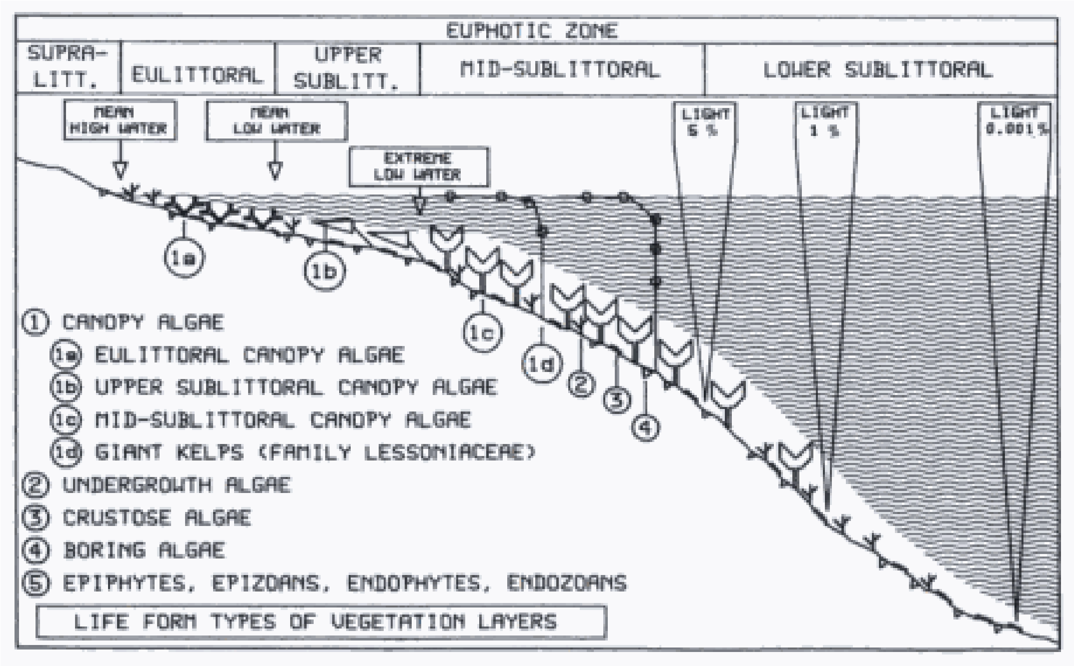


-260 Ma

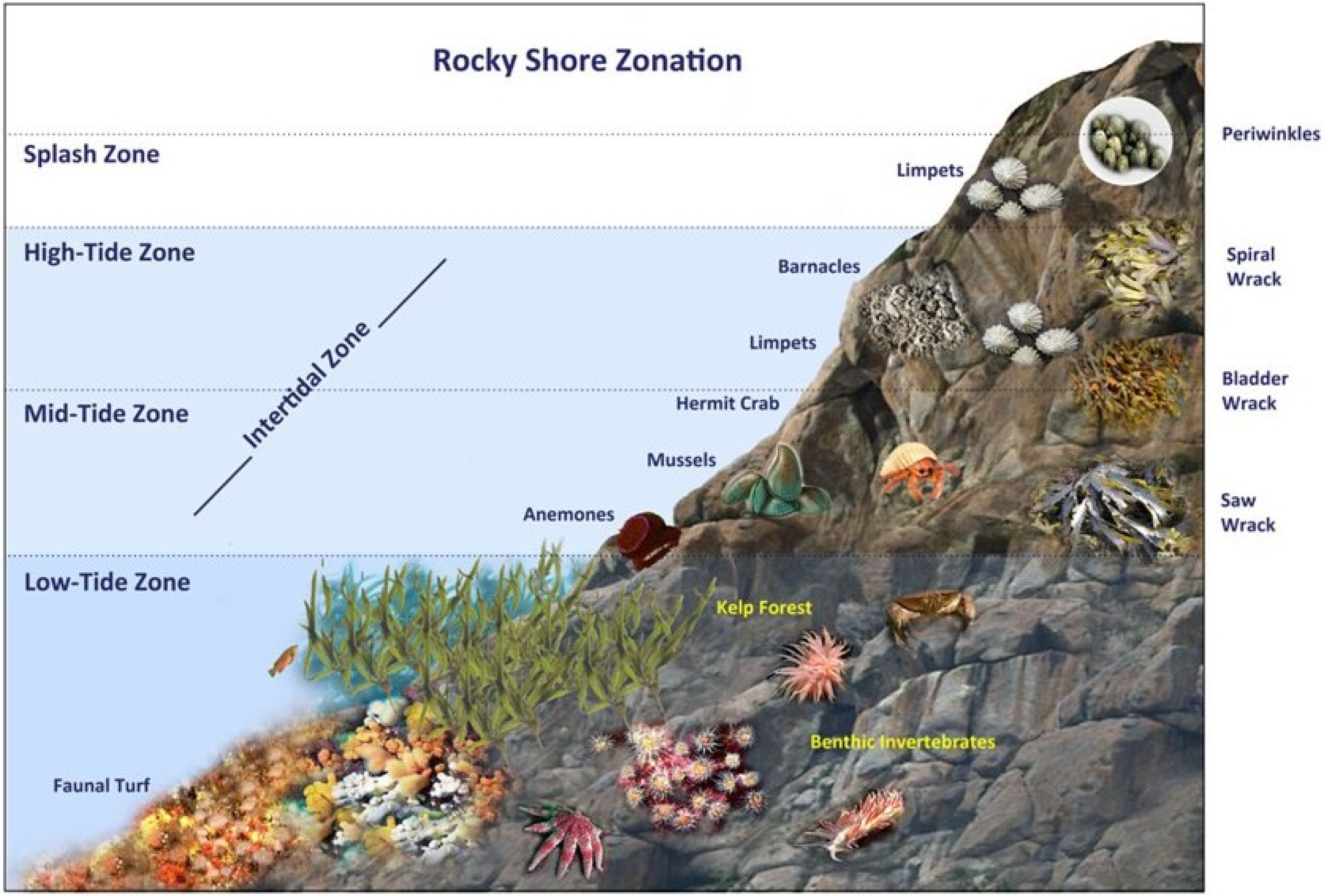


Dea Baets et al., 2016, Proc R Soc; Di Michele et al., 2014

vertical distribution – key local structuring factor in most localities world-wide
(exceptions?)



differential proportions of abiotic and biotic factors
pigmental differences
varying productivity


Rocky Shore Zonation
Splash Zone
High-Tide Zone
Mid-Tide Zone
Low-Tide Zone
Intertidal Zone
Periwinkles
Limpets
Spiral Wrack
Barnacles
Limpets
Bladder Wrack
Hermit Crab
Mussels
Saw Wrack
Anemones
Kelp Forest
Benthic Invertebrates
Faunal Turf

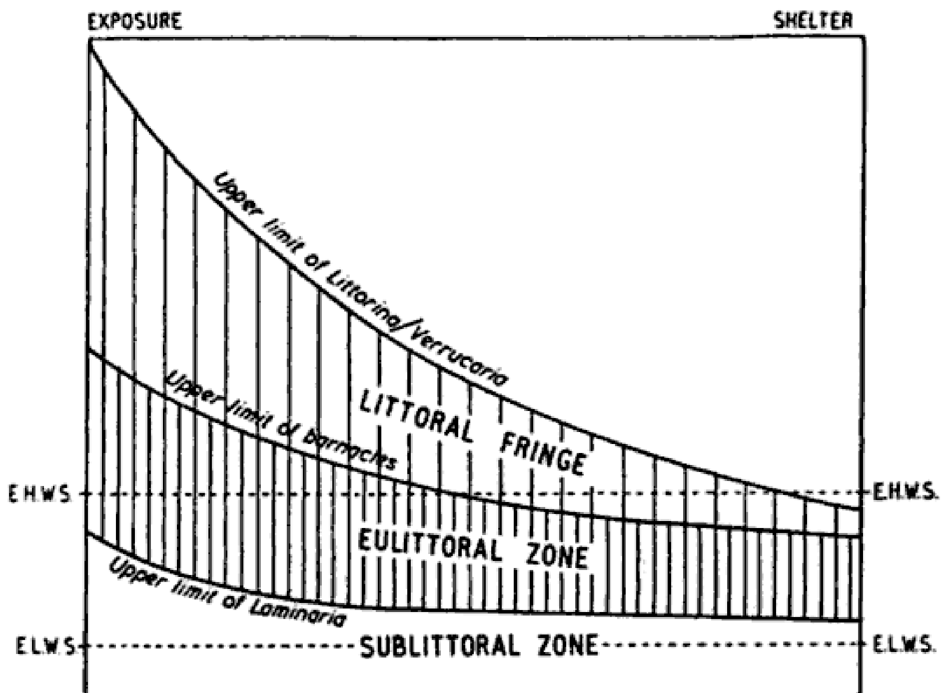
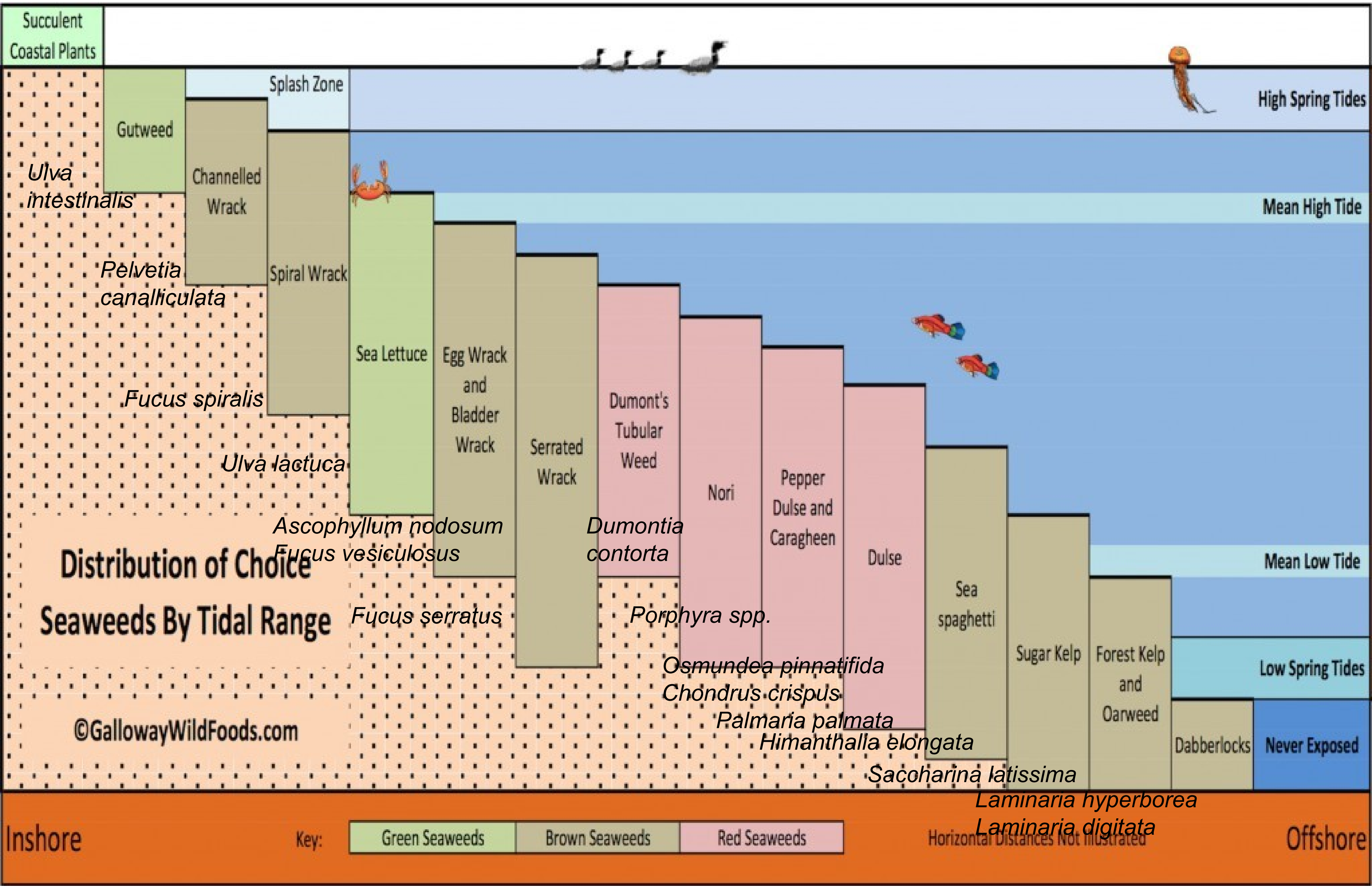
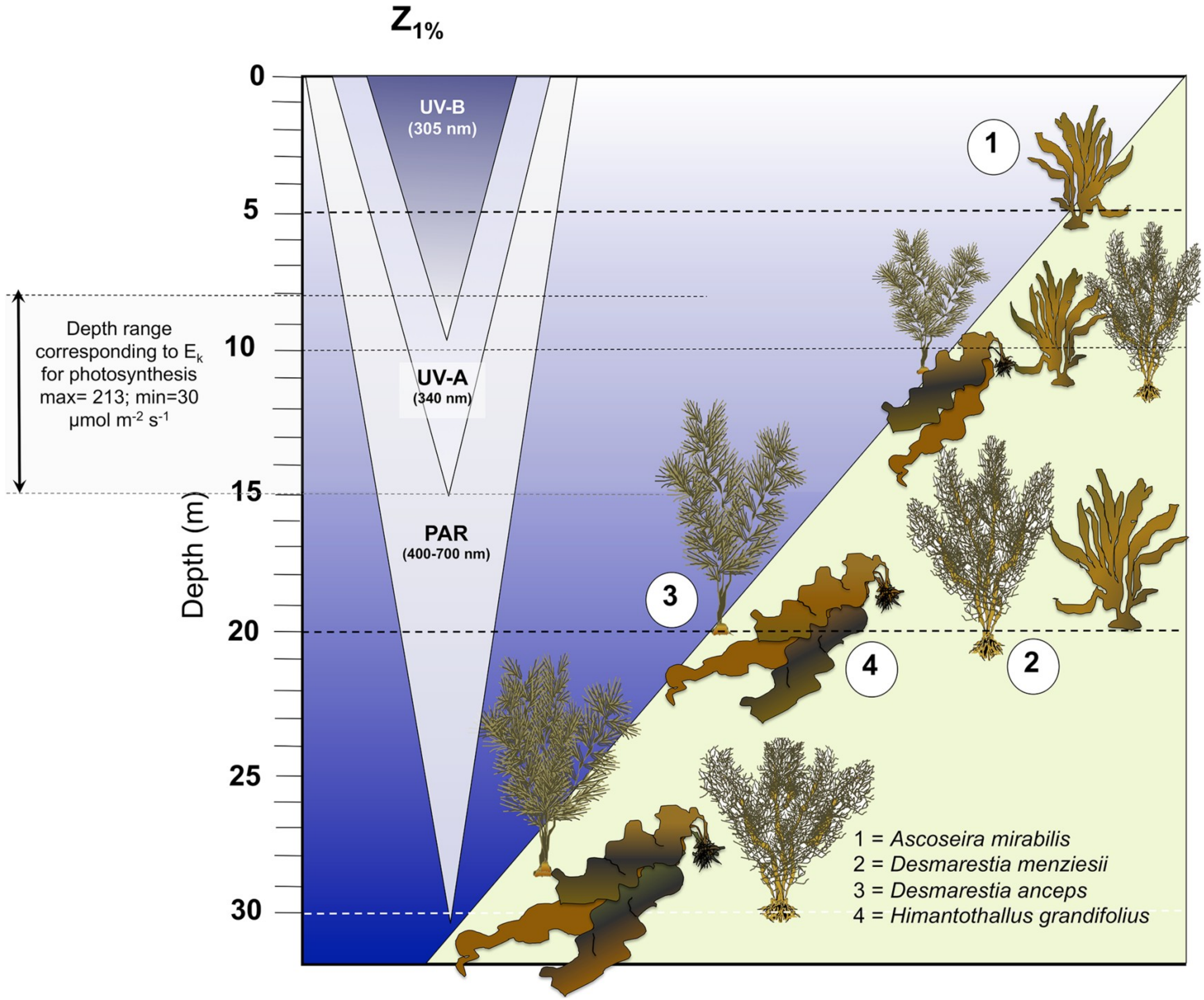


Fig. 1.2 Vertical subdivision of the euphotic zone, the upper limits rising on wave-exposed shores. The term "littoral fringe" has been replaced by "supralittoral zone" in the present book (compare with Fig. 1.4). E.H.W.S. = extreme high water of spring tides; E.L.W.S. = extreme low water of spring tides. (From J. R. Lewis 1964.)

strong effects of vertical structure on distribution of taxa – tidal effects in the eulittoral

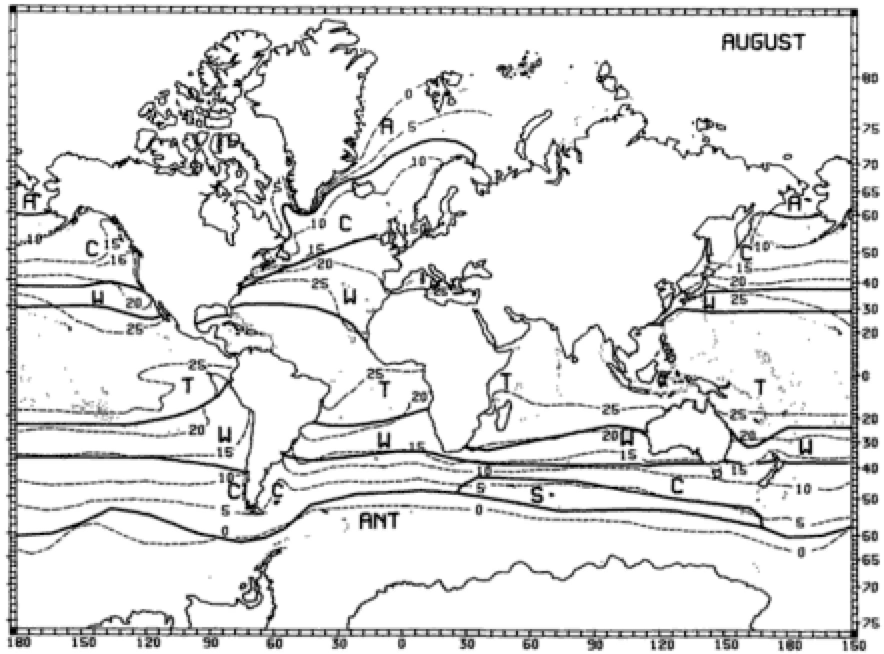




tolerance to high UV irradiation rather than photosynthetic efficiency may structure the vertical gradient in summer polar habitats

Gómez & Huovinen, 2015, Plos One

Biogeographic areas and distribution of seaweed taxa have been primarily determined by surface water temperature



Van den Hoek / Lüning classification - seven phycogeographical areas

<u>simplifed temperature limits:</u>
arctic/antarctic = < 10°C summer isotherm / < 0°C winter isotherm
cold temperate = < 15°C s.i. / < 10°C w.i.
warm temperate = < 25°C s.i. / < 20°C w.i.
tropical

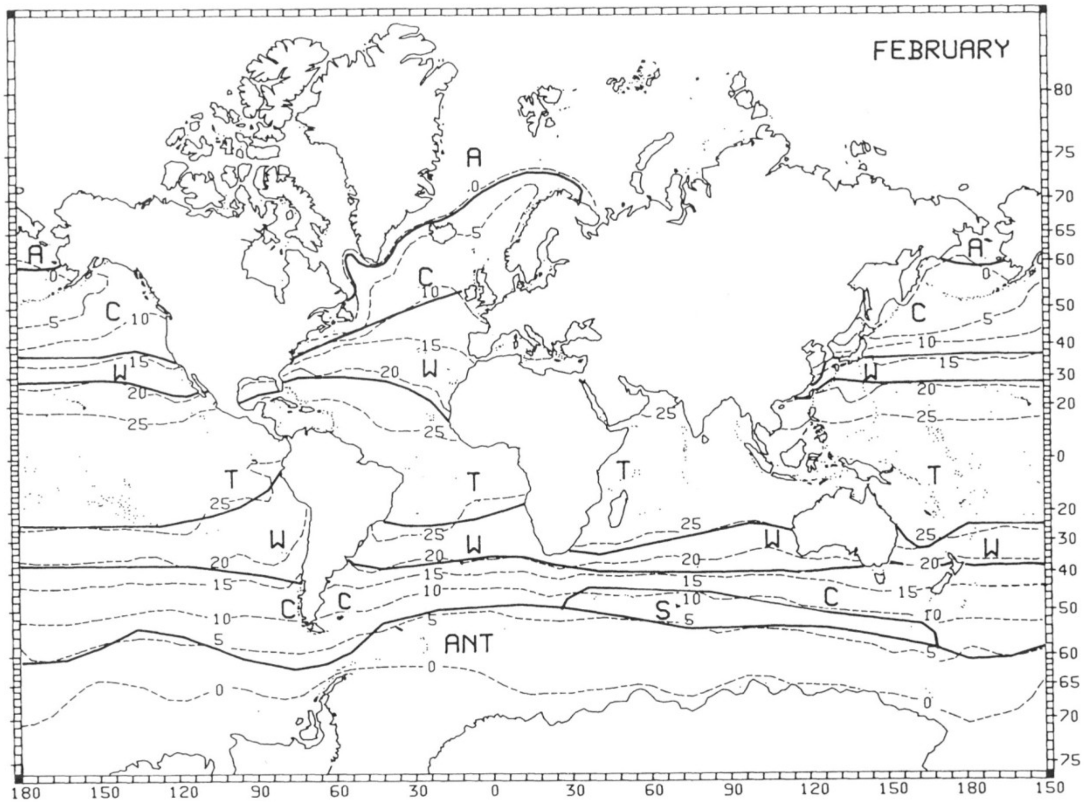


Fig. 1.6 Seven groups of marine biogeographical regions in relation to February isotherms (winter in Northern Hemisphere, summer in Southern Hemisphere). See legend to Fig. 1.5 for further details. (After Briggs 1974.)

simplifed scheme:

arctic/antarctic = < 10°C summer isotherm / < 0°C winter isotherm

cold temperate = < 15°C s.i. / < 10°C w.i.

warm temperate = < 25°C s.i. / < 20°C w.i.

tropical

Table 18.1 Biogeographic regions after Briggs (1995) with the respective northern and southern mean oceanic sea surface isotherms limiting the respective region derived from global sea-surface isotherm maps 1980–1999 (Müller et al. 2009)

	Biogeographic region		Atlantic				Pacific				Indic			
			Western coastlines		Eastern coastlines		Western coastlines[a]		Eastern coastlines		Western coastlines[c]		Eastern coastlines	
			Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Northern hemisphere	Polar-Arctic	SB	<0°C	<10°C	<0/2°C[b]	<9°C	<0°C	<9°C	<0°C	<9°C	–	–	–	–
	Cold-temperate	NB	0°C	10°C	0/2°C[b]	9°C	0°C	9°C	0°C	9°C	–	–	–	–
		SB	10°C	27°C	10°C	17°C	12/14°C[c]	26°C	14°C	18°C	–	–	–	–
	Warm-temperate	NB	10°C	27°C	10°C	17°C	12/14°C[c]	26°C	14°C	18°C	–	–	–	–
		SB	23°C	29°C	21°C	27°C	22°C	29°C	20°C	26°C	–	–	–	–
	Tropical	NB	>23°C	>29°C	>21°C	>27°C	>22°C	>29°C	>20°C	>26°C	–	–	–	–
Southern hemisphere		SB	>22°C	>27°C	>18°C	>24°C	>21°C	>27°C	>21°C	>26°C	20°C	24°C	21°C	25°C
	Warm-temperate	NB	22°C	27°C	18°C	24°C	21°C	27°C	21°C	26°C	20°C	24°C	21°C	25°C
		SB	10°C	19°C	–	–	14°C	20°C	11°C	16°C	–	–	14°C	18°C
	Cold-temperate	NB	10°C	19°C	–	–	14°C	20°C	11°C	16°C	–	–	14°C	18°C
		SB	–	–	–	–	–	–	–	–	–	–	–	–
	Polar-Antarctic	NB	Winter: <1°C / Summer: <4°C											

SB southern boundary, NB northern boundary, – no exact data available as there are no further land masses south of the continents in the southern hemisphere or in the case of the Indian Ocean no ocean-land boundaries further north

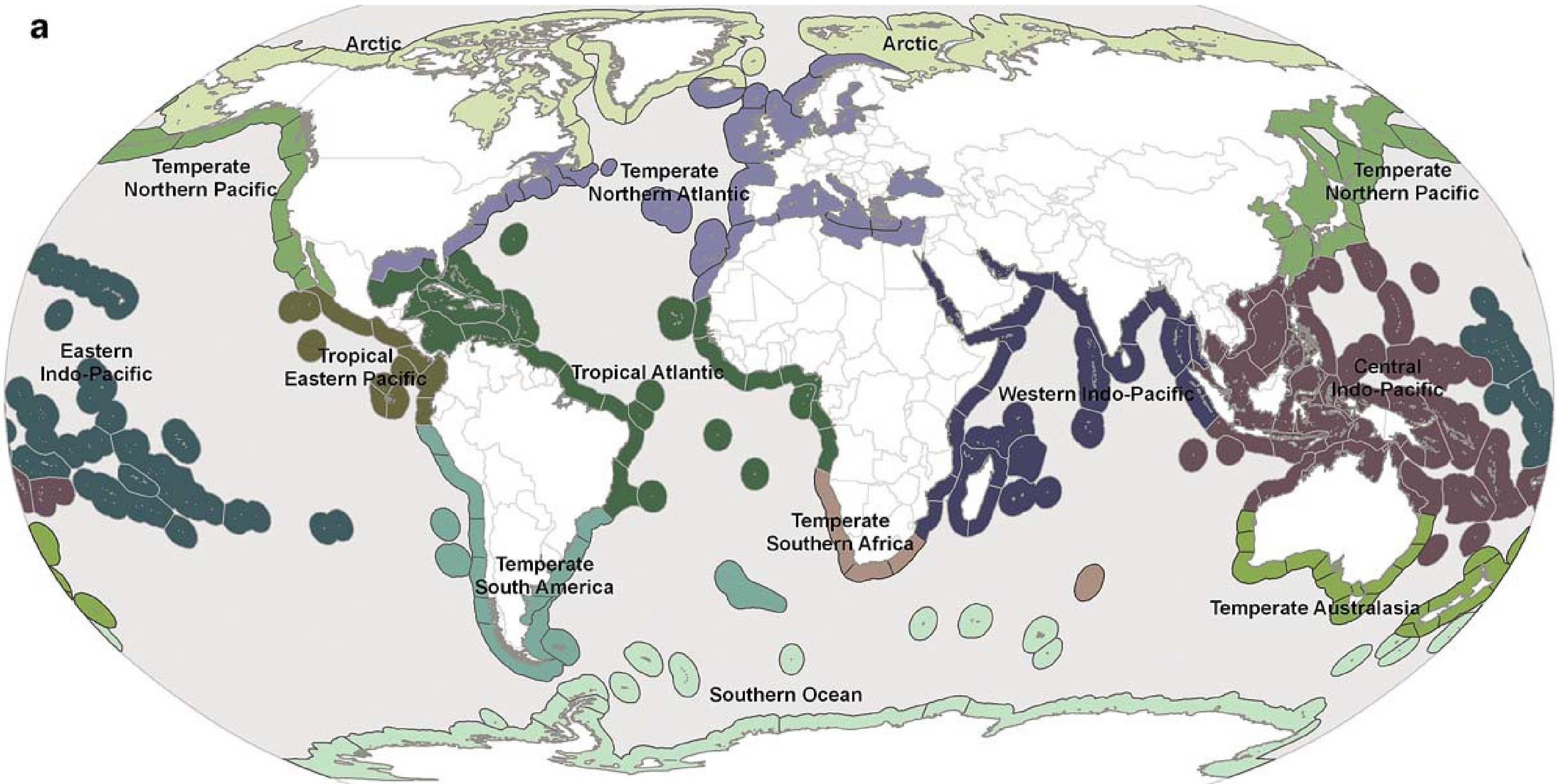
[a] The border of the W-Pacific to the Indian Ocean was considered to be located in central Asia (northern hemisphere) and in southeastern Australia (southern hemisphere)

[b] Temperature boundaries for Barents Sea/North Atlantic

[c] Temperature boundaries for Korea/Japan

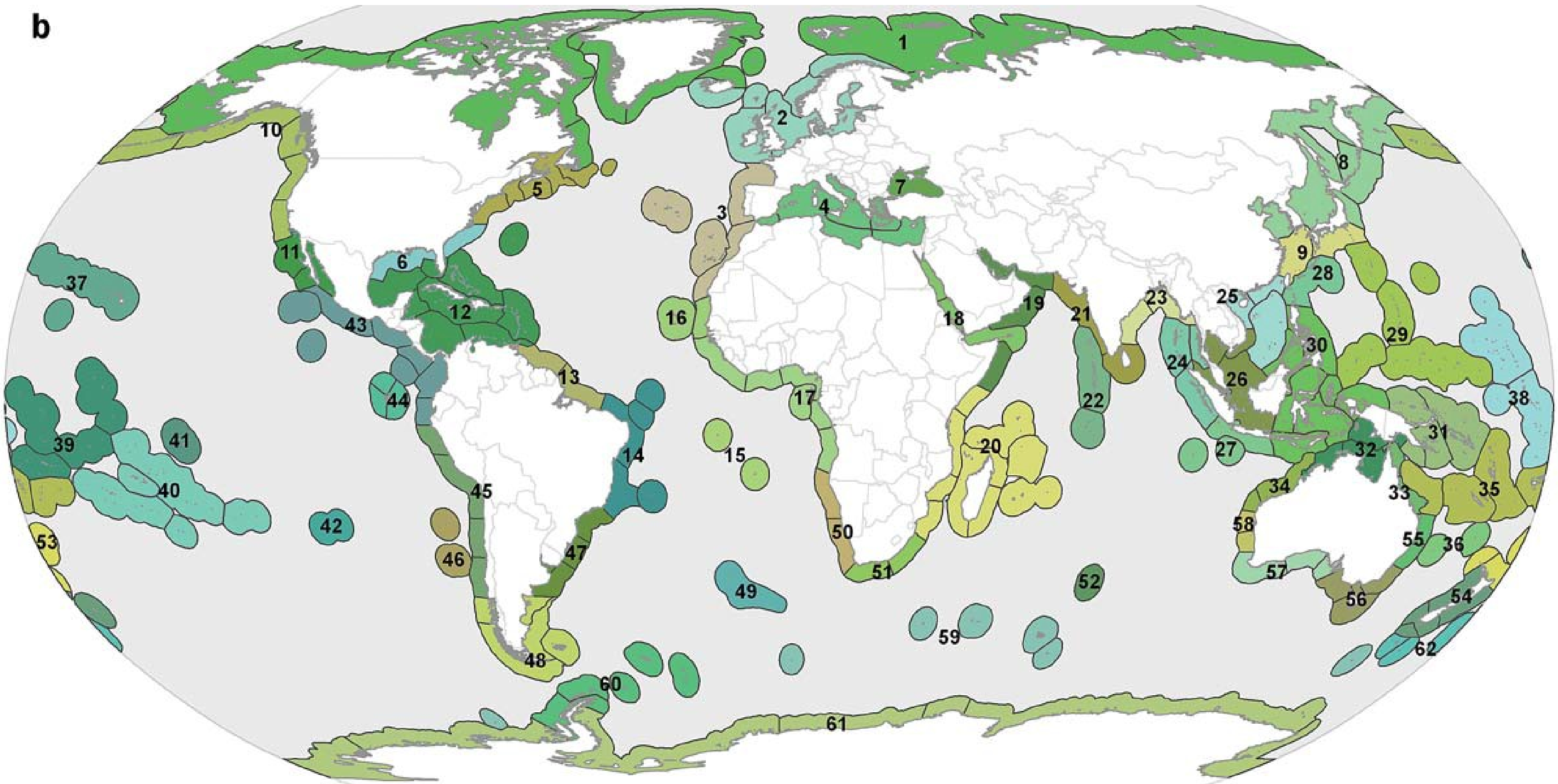
Bartsch et al., 2012, Seaweed Biology, Ecological Studies 219

Marine Ecoregions of the World (Coastal and Shelf Ecosystems)

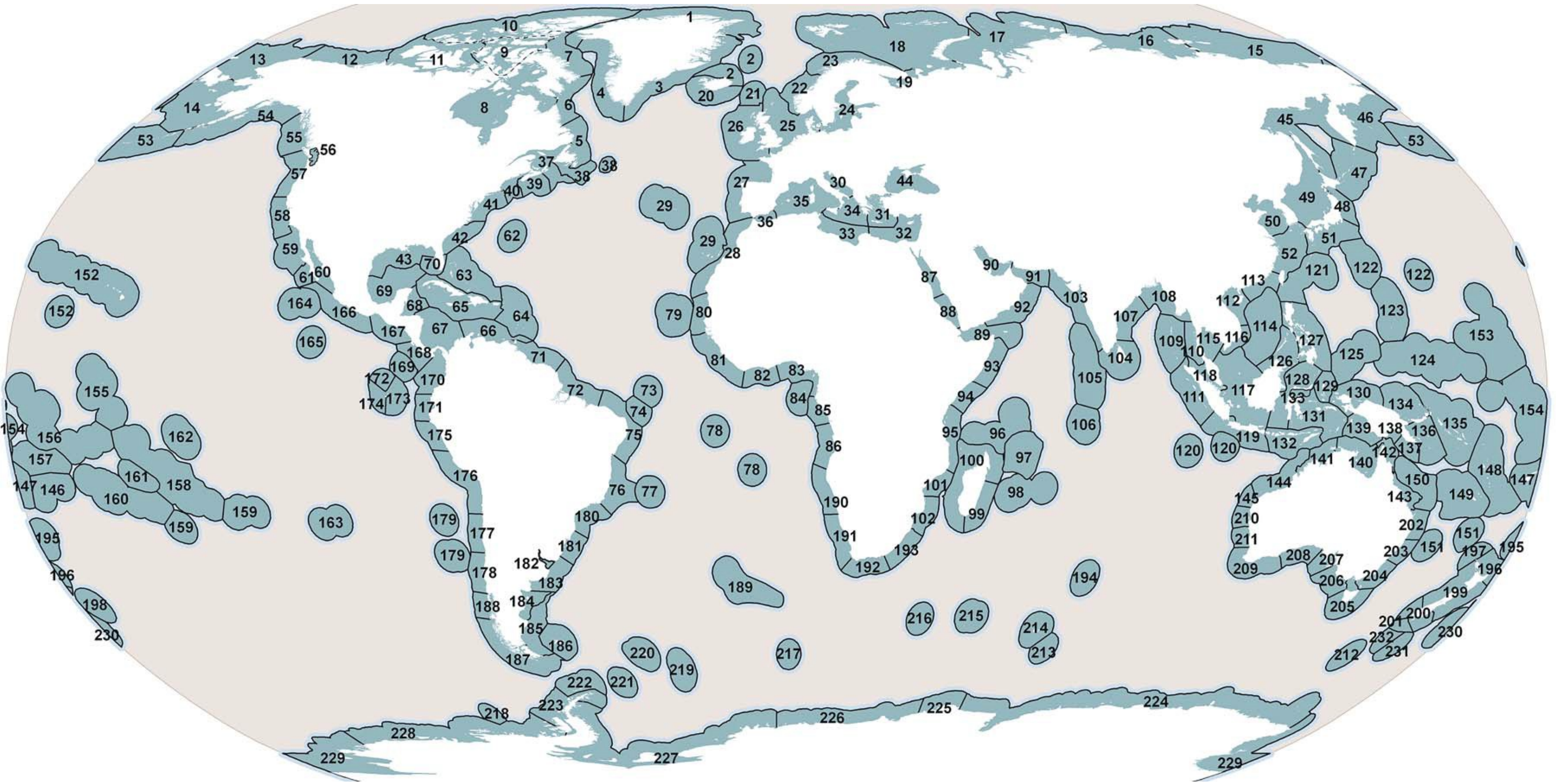


12 **realms** ⊇ 62 provinces ⊇ 232 ecoregions

Spalding et al., 2007, BioScience



12 realms ⊇ 62 **provinces** ⊇ 232 ecoregions



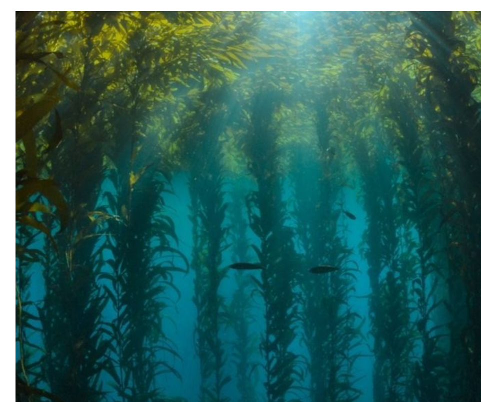
12 realms $\supseteq$ 62 provinces $\supseteq$ 232 **ecoregions**

very simplified three-part classification of macroalgal communities







temperature is the first and the single most important environmental factor explaining differences in species distribution and community structure of different regions

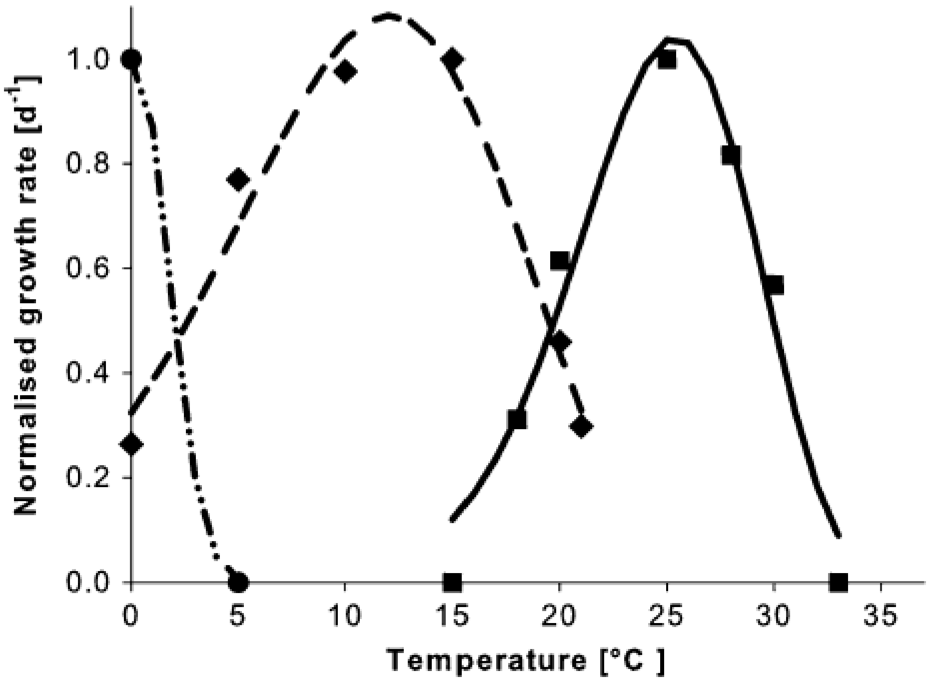


Fig. 3.1 Typical normalized growth temperature–response curves of the stenothermal polar species *Gymnogongrus skottsbergii* (Antarctica, *circles*, Eggert and Wiencke 2000), the eurythermal temperate species *Laminaria digitata* (Helgoland, *diamonds*, tom Dieck 1992), and the tropical species *Wurdemannia miniata* (St. Croix, Caribbean, *squares*, Pakker and Breeman 1996). The temperature–response curves were estimated by fitting the experimental data to the function developed by Blanchard et al. (1996). The temperature optima of the three response curves are 0, 12, and 25°C and the 80%-"performance breadths" are −1–1°C, 7–16°C, and 22–28°C for the Antarctic, temperate, and tropical species, respectively

Eggert, 2012, Seaweed Biology, Ecological Studies 219; https://climatereanalyzer.org

the case study of *Saccorhiza polyschides* (sea furbelows)

– stenothermal species in temperate zone; N lethal and S reproductive boundaries of distribution area

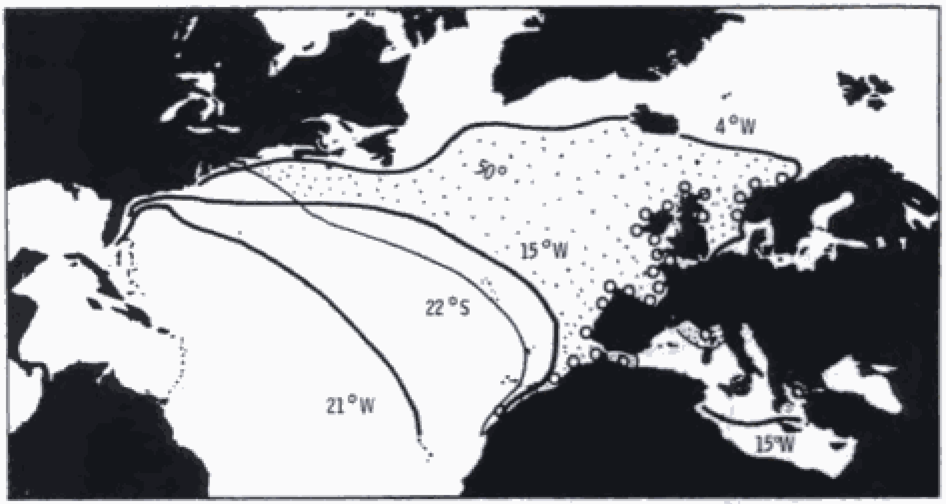


Fig. 1.9 Distribution of the kelp *Saccorhiza polyschides*. Circles represent presence (species is absent on North American coasts); distribution area is dotted (occurring, however, only along the coasts); 4°C-winter isotherm = northern lethal boundary; 15°C-winter isotherm = southern reproduction boundary; 22°C-summer isotherm = southern lethal boundary; 21°C-winter isotherm = southern growth boundary (not reached by the species). (From van den Hoek 1982*b*).

sporophyte – lethal temperatures 3°C and 24°C
gametophyte – successful fertilization in < 17°C

in upper subtidal, in open spaces among L. digitata forest
an annual kelp, an opportunist colonising vacant spaces in the forest
unable to compete with the dominant species

the case study of *Dictyota spp.* (forkweed)

– warm water lineage (tropical/warm temperate), N lethal boundaries (N Am) or N reproductive boundaries (Eu)

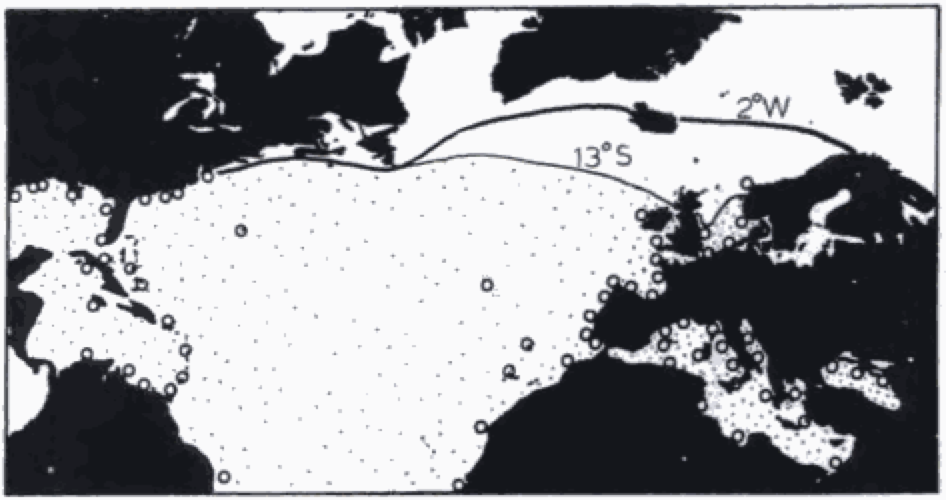
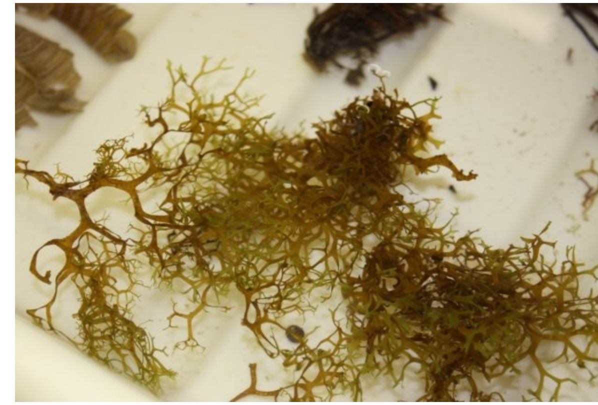


Fig. 1.10 Distribution of the brown alga *Dictyota* spp. on both sides of the North Atlantic: *D. dichotoma* in northwestern Atlantic and *D. menstrualis* in northeastern Atlantic). 2°C-winter isotherm = northern lethal boundary (limiting in North America); 13°C-summer isotherm = northern growth and reproduction boundary (limiting in Europe). (From van den Hoek 1982*a*.)



winter survival lethal temperature limit cca 1-2°C
summer growth temperature limit 12°C

the case study of *Chondrus crispus* (Irish moss, puchratka kadeřavá)
– cold temperate species, S lethal and growth boundaries, N reproductive or growth boundaries

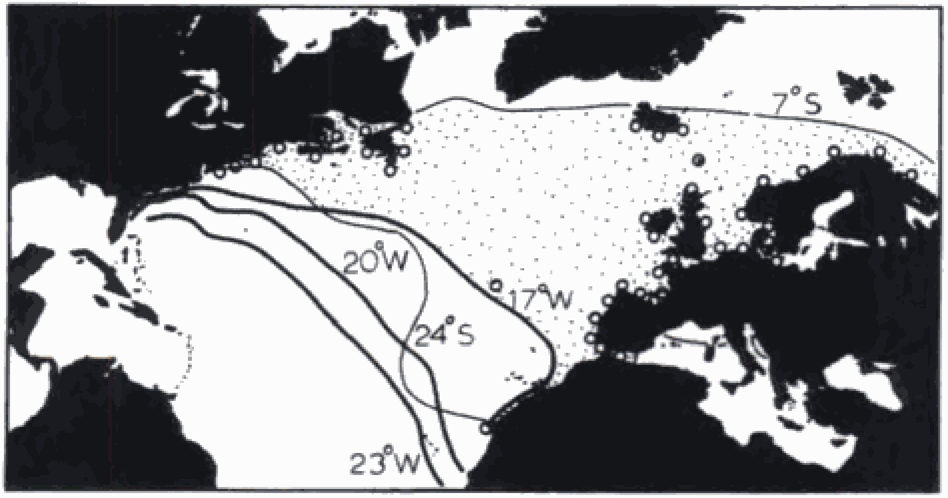


Fig. 1.11 Distribution of the red alga *Chondrus crispus* at both sides of the North Atlantic. 24°C-summer isotherm = southern lethal boundary (limiting on both sides of the Atlantic); 17°C-winter isotherm = southern reproduction boundary (additionally limiting in North Africa); 7°C-summer isotherm = northern growth boundary (limiting on both sides of the Atlantic). A southern growth and reproduction boundary (23°C-winter isotherm) is not reached by the species (From van den Hoek 1982*a*.)

summer temperature survival limit 23-24°C
needs at least 5-7°C in summer for vegetative growth
needs < 17°C in winter for reproduction of gametophytes

the case study of *Bonnemaisonia hamifera*

– combined photoperiodic and temperature control of the heteromorphic life cycle and geographic distribution

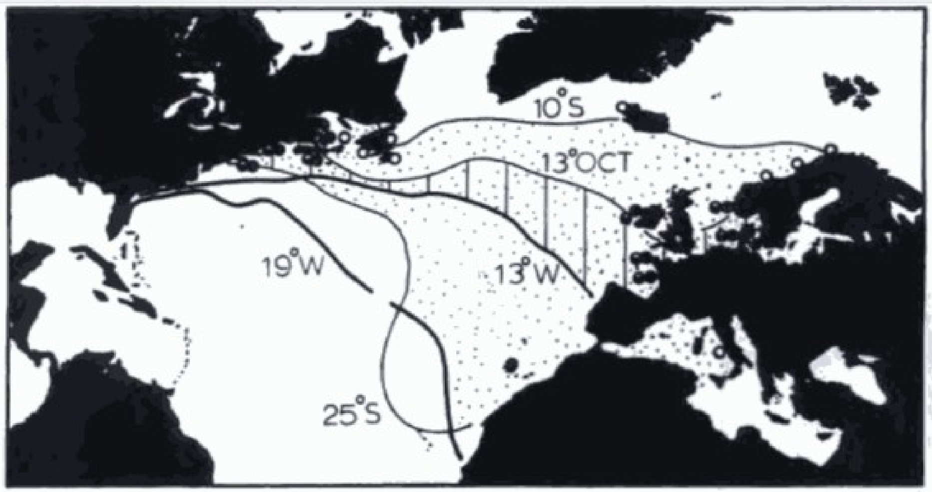


Fig. 1.12 Distribution of the red alga *Bonnemaisonia hamifera* at both sides of the North Atlantic. ◒ and hatched area = distribution area of the gametophyte (*Bonnemaisonia* phase); dotted area = distribution area of the tetrasporophyte (Traillieilla phase) with (⊕) or without (O) tetrasporangia. 10°C-summer isotherm = northern growth boundary of the tetrasporophyte, which propagates vegetatively; 13°C-October isotherm = northern boundary for formation of tetrasporangia and gametophytes evolving from tetraspores; 13°C-winter isotherm = growth and reproduction boundary of gametophyte (limiting in Europe); 25°C-summer isotherm = southern lethal boundary of the gametophyte (limiting in North America). A southern reproduction boundary of the tetrasporophyte (19°C-winter isotherm) is not reached by the species. (From van den Hoek 1982*a*).

Trailiella phase (tetrasporophyte)

originates probably from Japan, first detected in Europe (S England) in late 19th century

tetraspores (on *Trailiella* stages) formed only in days with < 11 hours of daylight and only in temperature 11-18 °C

Polar seaweeds – Arctic and Antarctic

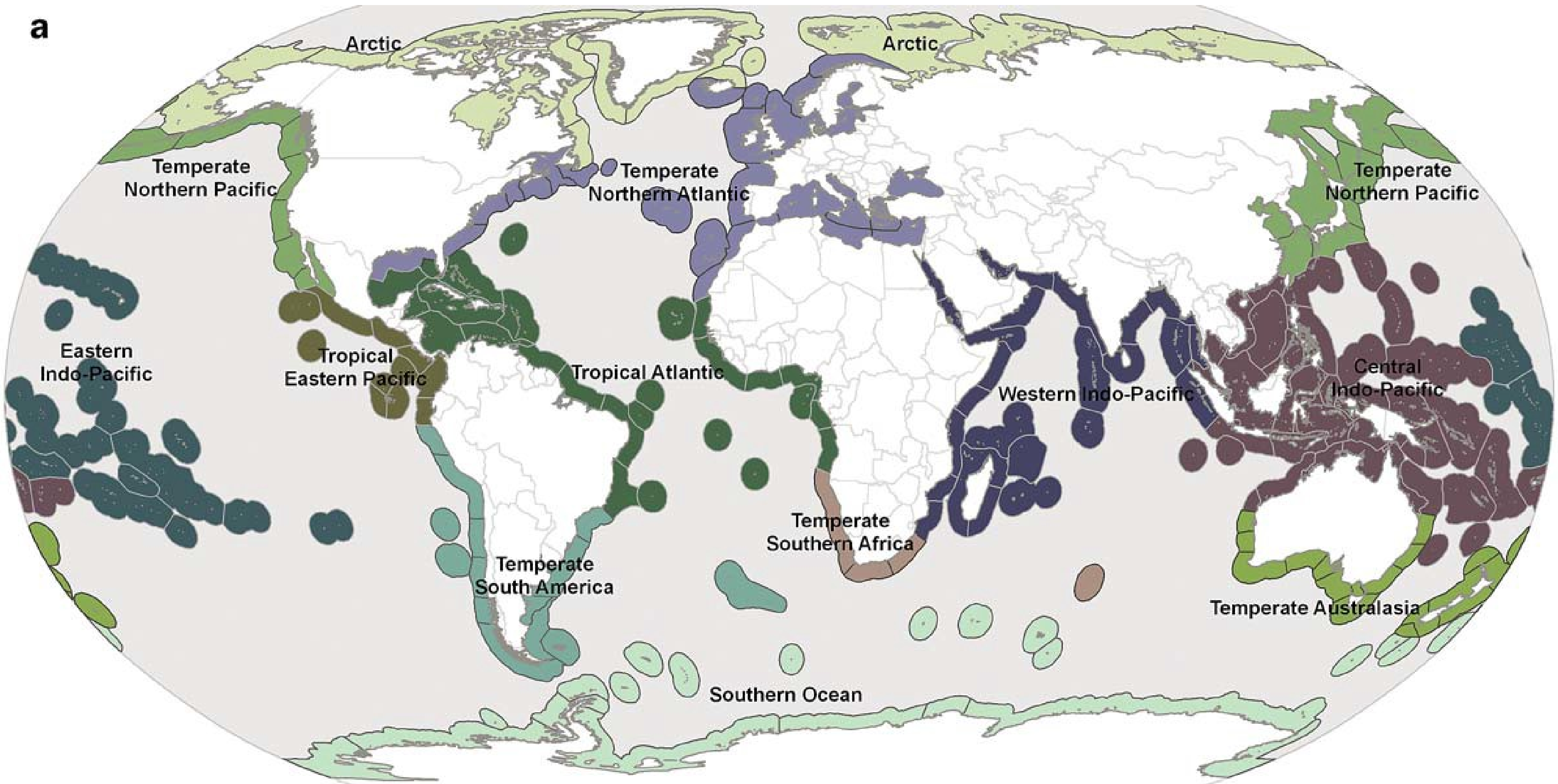


Table 18.1 Biogeographic regions after Briggs (1995) with the respective northern and southern mean oceanic sea surface isotherms limiting the respective region derived from global sea-surface isotherm maps 1980–1999 (Müller et al. 2009)

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			Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Northern hemisphere	Polar-Arctic	SB	<0°C	<10°C	<0/2°C[b]	<9°C	<0°C	<9°C	<0°C	<9°C	–	–	–	–
	Cold-temperate	NB	0°C	10°C	0/2°C[b]	9°C	0°C	9°C	0°C	9°C	–	–	–	–
		SB	10°C	27°C	10°C	17°C	12/14°C[c]	26°C	14°C	18°C	–	–	–	–
	Warm-temperate	NB	10°C	27°C	10°C	17°C	12/14°C[c]	26°C	14°C	18°C	–	–	–	–
		SB	23°C	29°C	21°C	27°C	22°C	29°C	20°C	26°C	–	–	–	–
	Tropical	NB	>23°C	>29°C	>21°C	>27°C	>22°C	>29°C	>20°C	>26°C	–	–	–	–
Southern hemisphere		SB	>22°C	>27°C	>18°C	>24°C	>21°C	>27°C	>21°C	>26°C	20°C	24°C	21°C	25°C
	Warm-temperate	NB	22°C	27°C	18°C	24°C	21°C	27°C	21°C	26°C	20°C	24°C	21°C	25°C
		SB	10°C	19°C	–	–	14°C	20°C	11°C	16°C	–	–	14°C	18°C
	Cold-temperate	NB	10°C	19°C	–	–	14°C	20°C	11°C	16°C	–	–	14°C	18°C
		SB	–	–	–	–	–	–	–	–	–	–	–	–
	Polar-Antarctic	NB	Winter: <1°C / Summer: <4°C											

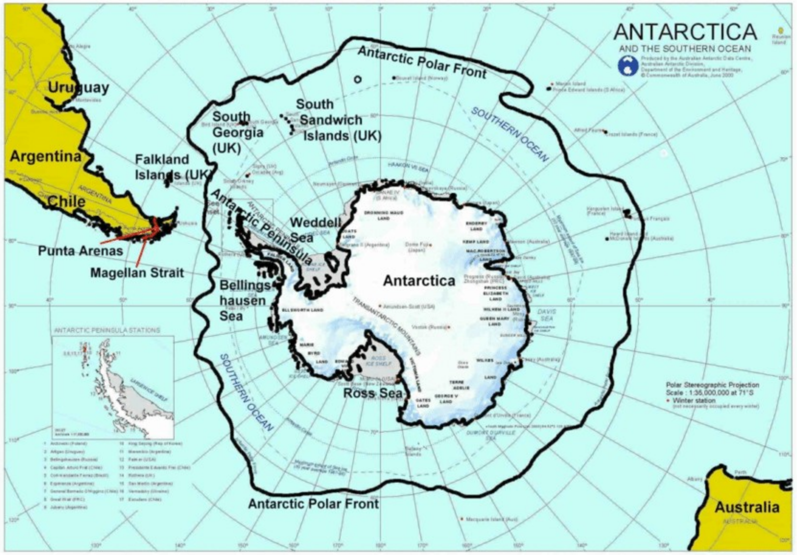
SB southern boundary, NB northern boundary, – no exact data available as there are no further land masses south of the continents in the southern hemisphere or in the case of the Indian Ocean no ocean-land boundaries further north

[a] The border of the W-Pacific to the Indian Ocean was considered to be located in central Asia (northern hemisphere) and in southeastern Australia (southern hemisphere)

[b] Temperature boundaries for Barents Sea/North Atlantic

[c] Temperature boundaries for Korea/Japan

Bartsch et al., 2012, Seaweed Biology, Ecological Studies 219



The Arctic Ocean is a "mediterranean" ocean, whereas the Southern Ocean forms a ring ocean around the Antarctic continent. The coasts of the Arctic Ocean are continuously connected to the temperate coasts of America and Eurasia, whereas the Southern Ocean has had no land bridge to temperate regions since the late Mesozoic when it became further separated from the neighbouring continents to the north by the Antarctic Circumpolar Current.

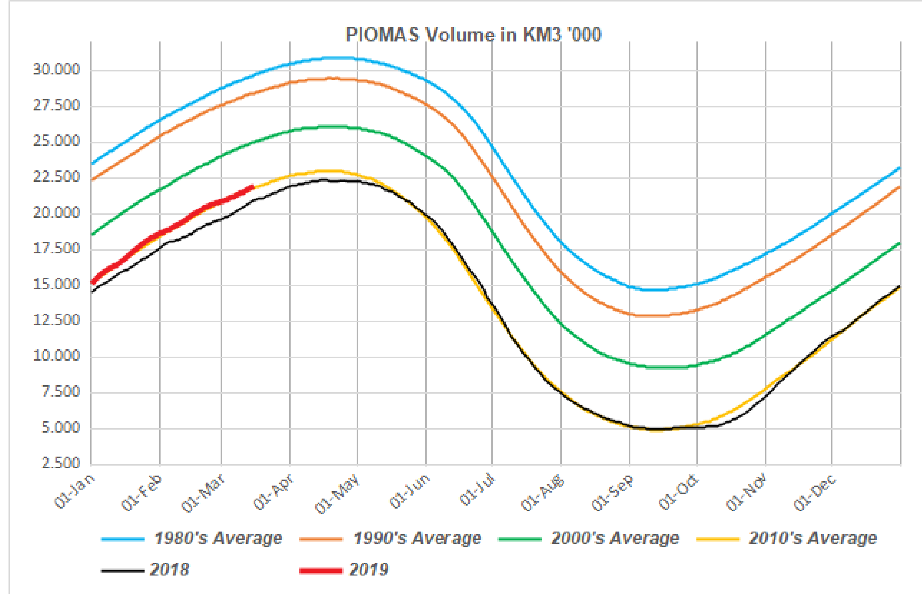
The Arctic Ocean did not develop any permanent sea ice cover until 0.7-2.0 Ma.

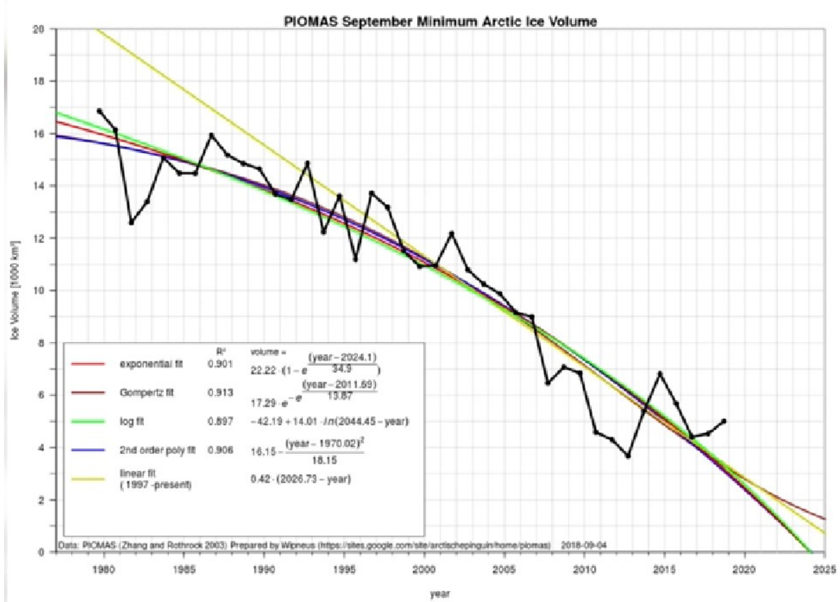
The Southern Ocean has had no land bridge to temperate regions since the late Mesozoic and has been further separated from the neighbouring southern continents by the Antarctic Circumpolar Current since 26 Ma. During the first major glaciation in East Antarctica 14 Ma ago water temperatures decreased and they have been low in the Southern Ocean since then.

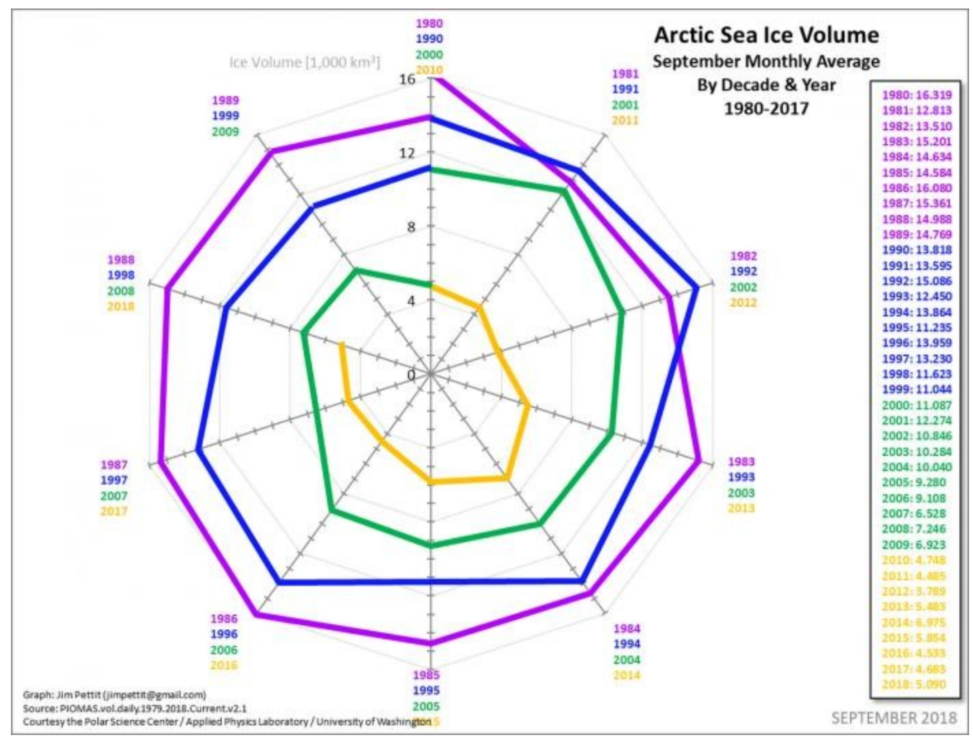
Wulff et al., 2009, Bot. Mar; Wiencke & Amsler, 2012, Seaweed Biology; Wiencke et al., 2007, Rev Environ Sci Biotechnol

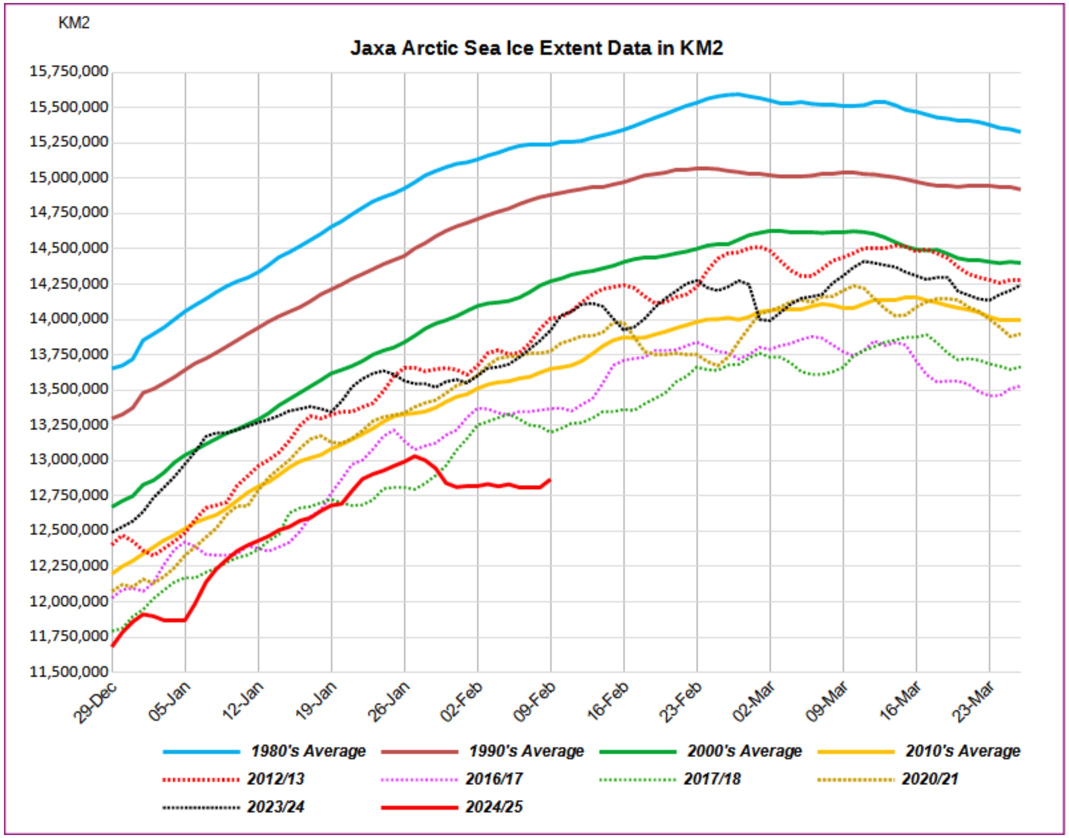
Arctic and Antarctic Sea Ice seasonal timelines
https://www.youtube.com/watch?v=QjFfcPC_4JE
https://www.youtube.com/watch?v=Ymph_i6VWbM
https://www.youtube.com/watch?v=ZkunS0WmYJk

Recent (anthropogenic) decline of Arctic Sea Ice








KM2
Jaxa Arctic Sea Ice Extent Data in KM2
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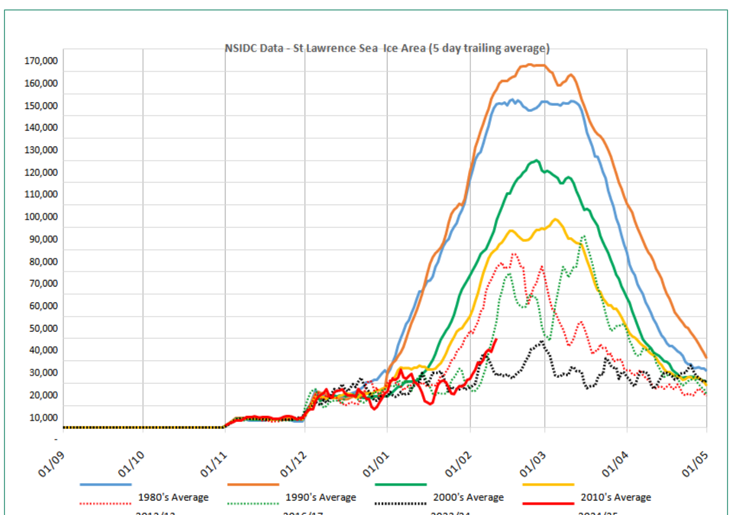
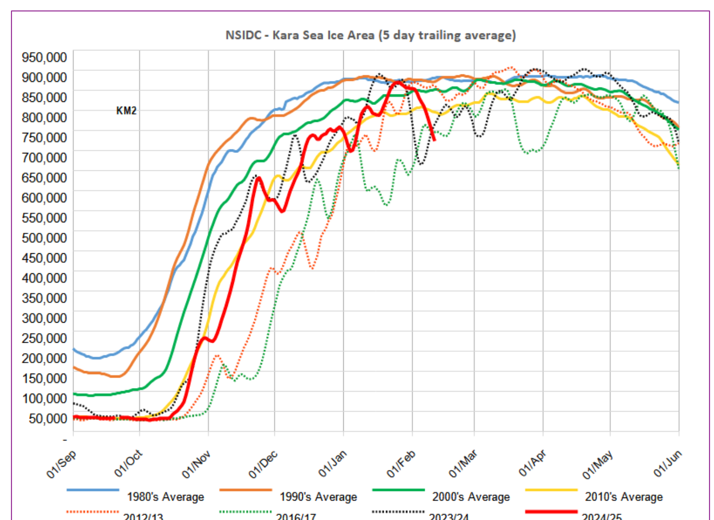
11,500,000
29-Dec
05-Jan
12-Jan
19-Jan
26-Jan
02-Feb
09-Feb
16-Feb
23-Feb
02-Mar
09-Mar
16-Mar
23-Mar
1980's Average
1990's Average
2000's Average
2010's Average
2012/13
2016/17
2017/18
2020/21
2023/24
2024/25

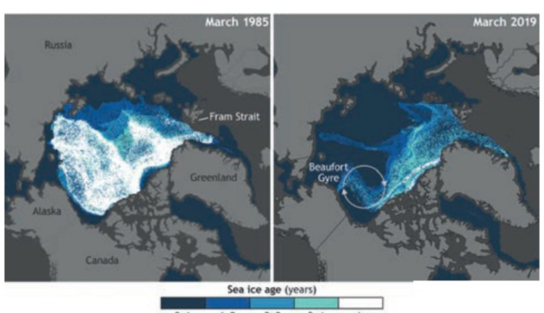

NSIDC Data - St Lawrence Sea Ice Area (5 day trailing average)
170,000
160,000
150,000
140,000
130,000
120,000
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
-
01/09
01/10
01/11
01/12
01/01
01/02
01/03
01/04
01/05
1980's Average
1990's Average
2000's Average
2010's Average
2012/13
2016/17
2023/24
2024/25


NSIDC - Kara Sea Ice Area (5 day trailing average)
KM2
950,000
900,000
850,000
800,000
750,000
700,000
650,000
600,000
550,000
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
-
01/Sep
01/Oct
01/Nov
01/Dec
01/Jan
01/Feb
01/Mar
01/Apr
01/May
01/Jun
1980's Average
1990's Average
2000's Average
2010's Average
2012/13
2016/17
2023/24
2024/25

Arctic region

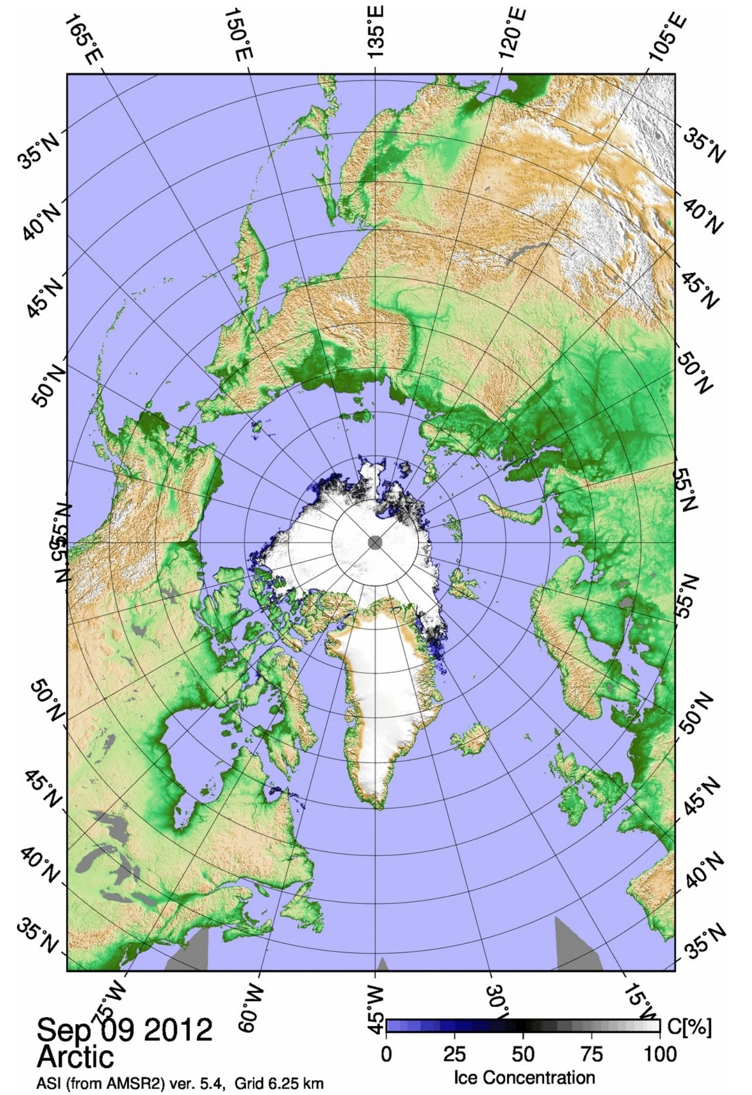
FIG. 2.3 Map of the top of the northern hemisphere with the high and low Arctic zones delineated according to the Circumpolar Arctic Vegetation Map (CAVM Team 2003), together with a tentative demarcation of the sub-Arctic. Lines indicating similar marine zones are sketched. *From CAFF (2013). Arctic biodiversity assessment. Status and trends in Arctic biodiversity. Conservation of Arctic Flora and Fauna, Akureyri. http://www.arcticbiodiversity.is/the-report.*

FIGURE 5-2. **Just 1% of Today's Ice Pack is Old, Thick Ice**



For a NASA video showing the rapid loss of multi-year ice since 1984, see: https://www.50x30.net/disappearance-of-summer-arctic-sea-

IMAGE SOURCE: NOAA CLIMATE.GOV; DATA: ARC 2019



Rigét et al., 2019, World Seas

Arctic region

very few endemites (*Punctaria glacialis, Platysiphon verticillatus, Petrocelis polygyna, Chukchia pedicellata, C. endophytica*)

in total 150 species

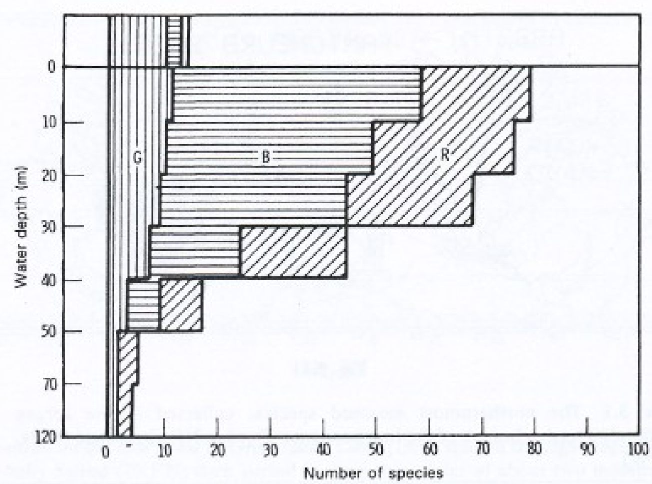


Fig. 3.12 Number of species of green algae (G), brown algae (B), and red algae (R) at different depths on the east coast of Greenland. Total species number is 109. The *x*-axis gives approximately relative percentages of each. (From Lund 1959.)

R:B[:G] ratio in the Arctic ecosystems
(+ changes in it as result of vertical gradient)

Arctic shores have a lot of soft substrates *(due to high deposition of the organic matter from rivers and low decomposition)* that are unsuitable for most macroalgae

- Arctic macroalgae are of Atlantic and Pacific origin, with only a few cosmopolitan or endemic species
- many species with pan-Arctic distributions
- contrary to earlier suggestions that Arctic macroalgae are largely of Atlantic origin recent evidence based on molecular data for Arctic endemic species shows their Pacific origins

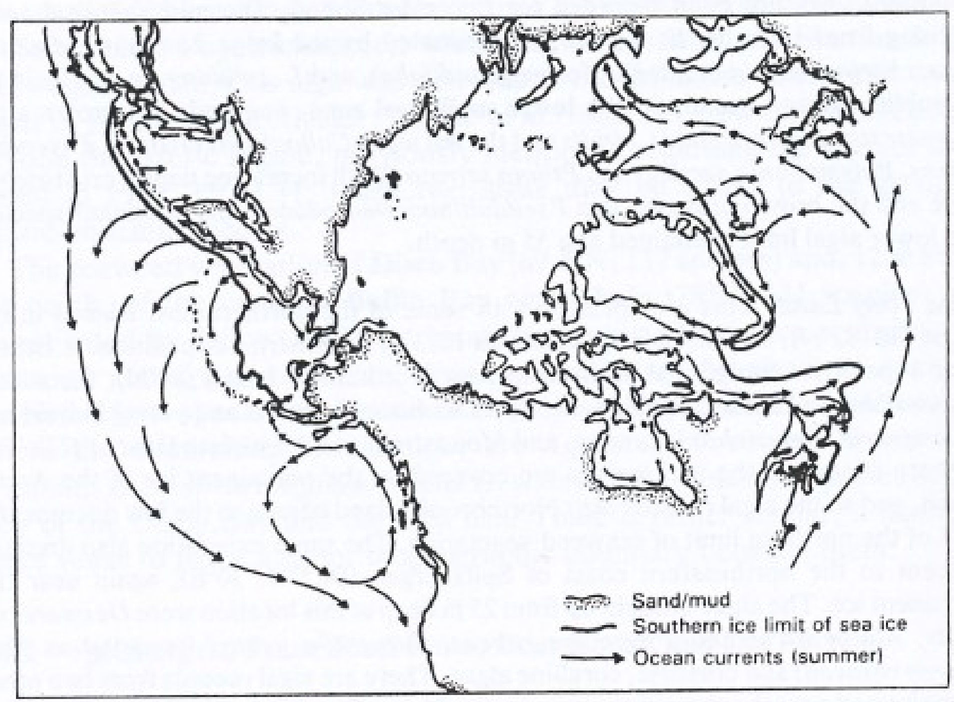


Fig. 3.14 Coastlines with soft substrata, not suitable for seaweeds. (From Widdowson 1971.)

multiple important Arctic macroalgae do not have very low temperature optima/limits

sporophytes of the Arctic kelp ***Laminaria solidungula*** grow up to temperatures of 15°C with optimum growth rates at 5–10°C and an UST of 16°C; gametophytes of this species exhibit an UST of 20°C

the Arctic cold-temperate red alga ***Devaleraea ramentacea*** grows at temperatures up to 10°C and exhibits USTs of 18–20°C

General temperature limit patterns of Arctic macroalgae:

The southern distribution of Arctic-North Atlantic species is often limited both by the USTs and the upper limit of gametogenesis. In the West Atlantic distribution limits are determined by lethal, high summer temperatures, whereas in the East Atlantic they are determined by high winter temperatures inhibiting reproduction.
[Examples for species from this group are Laminaria digitata, Chorda filum, and Halosiphon tomentosus.]

seaweeds in (both) polar regions are almost entirely subtidal (or supratidal) because of **ice scouring**

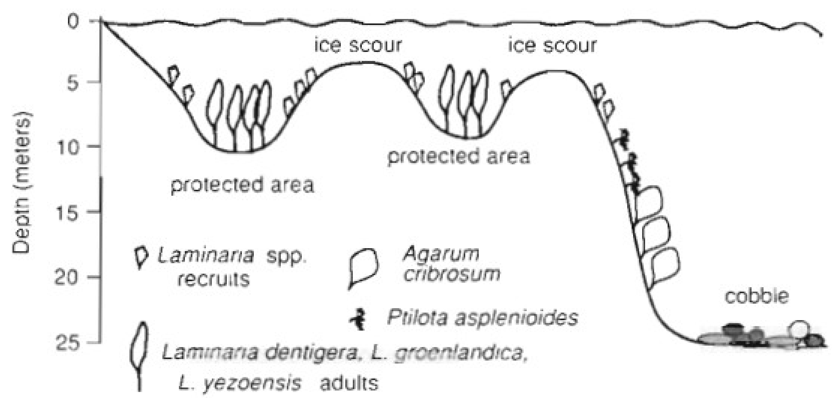


Fig. 3. Diagramatic representation of typical sublittoral habitat in areas of ice scour. Note, plant sizes are not to scale

Figure 6. Tor Bay Provincial Park shortly before the arrival of the drift ice. Picture taken at low tide on 4 April 2014 at a wave-exposed site in Tor Bay Provincial Park, showing a well developed canopy of *Chondrus crispus* at middle-to-low elevations (c) and a kelp canopy at the lowest elevations (k). The little plates that are visible above the *C. crispus* zone were drilled into the rocky substrate to study barnacle recruitment. The sea surface was calm on that day, and sea ice was visible towards the horizon.

Figure 4. Whitehead at the time of arrival of the drift ice. Picture taken at low tide on 3 April 2014 at the wave-exposed site from Whitehead shown in Figure 2. This picture shows the intertidal zone covered by a *Fucus* canopy at high and middle elevations (f) and by *Chondrus crispus* and coralline algae at low elevations (c), which also exhibit the first ice fragments that contacted the shore on that day.

Figure 7. Whitehead after ice scour. Picture taken at low tide on 30 April 2014 at the wave-exposed site from Whitehead shown in Figure 4, showing the extreme removal of algae and invertebrates by the sea ice, which stayed for 9 days on the shore. The little barnacle recruitment plates visible in this picture were drilled to the rocky substrate at an elevation of approximately 2/3 of the full intertidal range (between chart datum, or 0 m in elevation, and the elevation where the barnacles located highest on the shore occurred before the ice scour).

Figure 8. Tor Bay Provincial Park after ice scour. Picture taken at low tide on 27 April 2014 at the wave-exposed site from Tor Bay Provincial Park shown in Figure 6. This picture shows the almost complete loss of the macroalgal cover shown in Figure 6 because of the effects of ice scour.

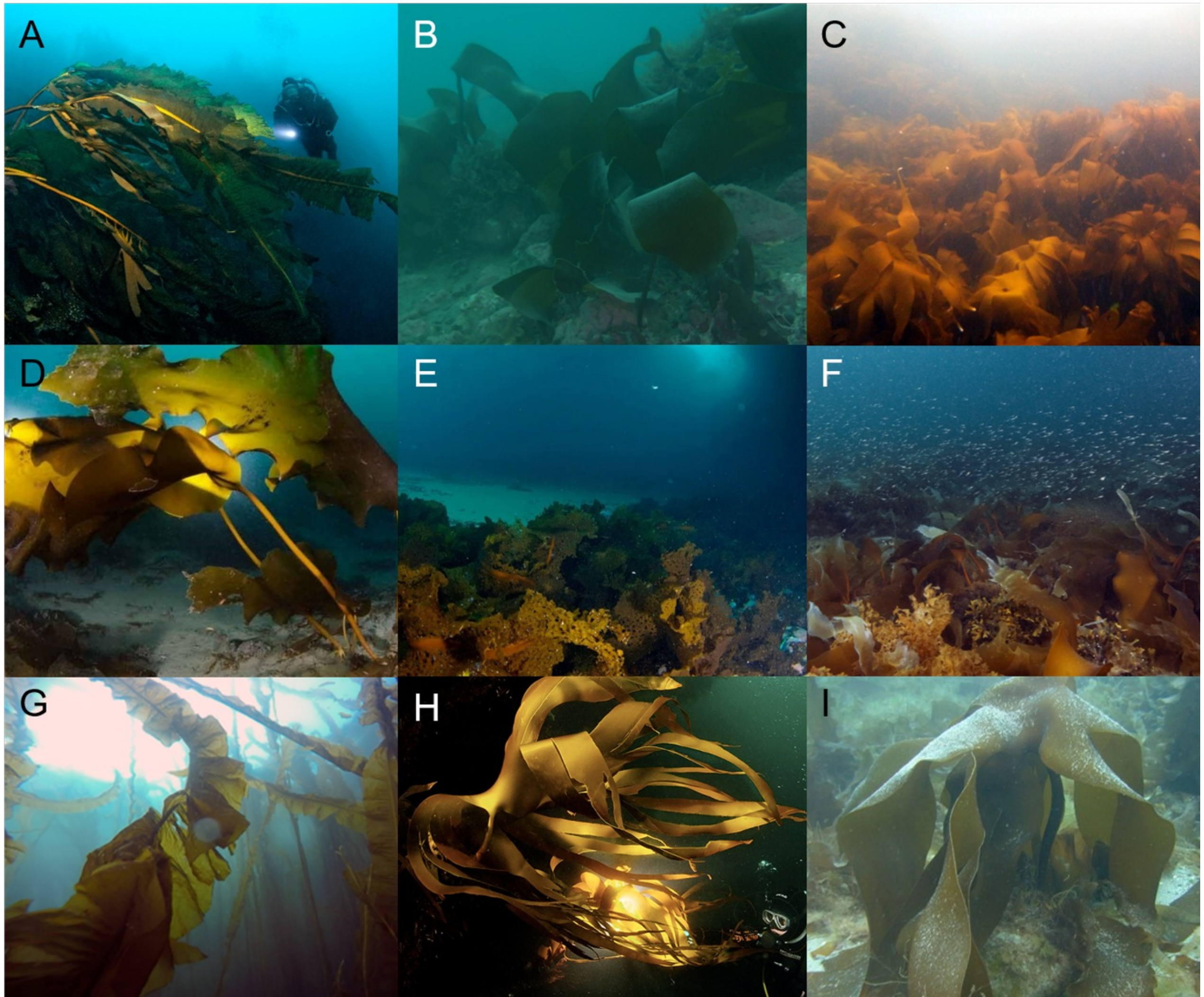
(in the Arctic, the ***barren zone*** reaches at least up to 2 m into the upper subtidal)

Heine, 1989; Petzold et al., 2014

- **diversity patterns**: macroalgal species richness dramatically decreases from the western (Atlantic) sector to the eastern (Pacific) sector

- Svalbard has at least 70 species; only about 10 species are known from the rocky littoral regions in the Alaskan Beaufort Sea

- distribution of most species extends well into the temperate zone; on the other hand, a number of cold-temperate taxa reach into the Arctic



(A) Alaria esculenta in Greenland,

(B) Laminaria solidungula in the Beaufort Sea, Alaska (Ken Dunton)

(C) Laminaria hyperborea in Malangen fjord, Norway (Karen Filbee-Dexter)

(D) Saccharina latissima on sediment in Russia

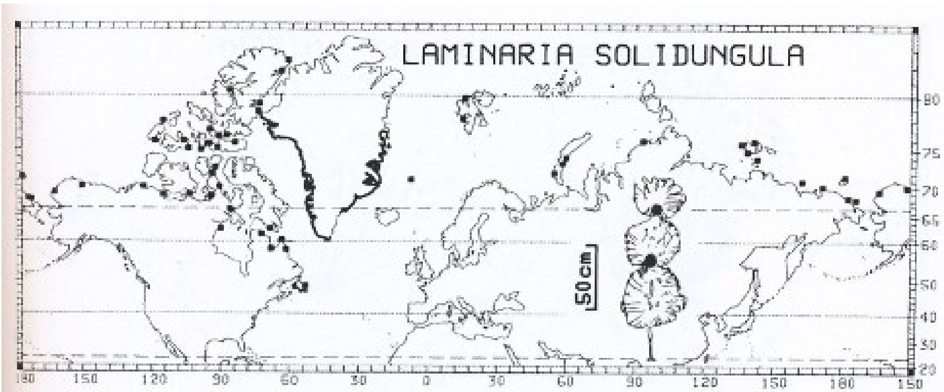
(E) Agarum clathratum

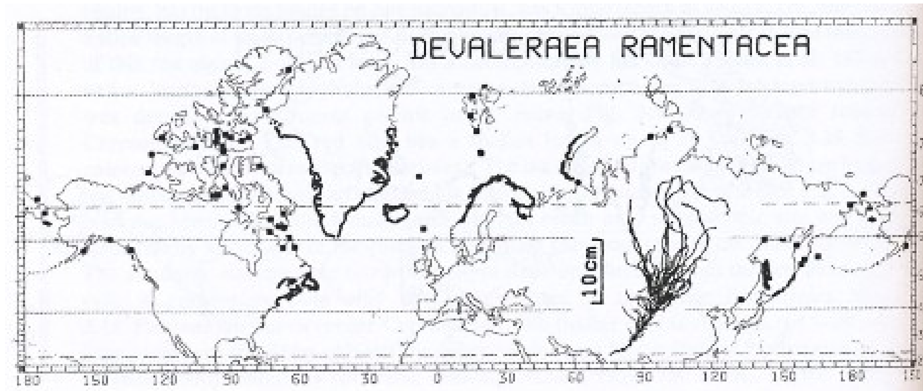
(F) mixed Saccharina latissima, S. longicruris, Alaria esculenta, Laminaria solidungula in Baffin Island, Canada (Frithjof Küpper)

(G) Eularia fistulosa Aleutian Islands, Alaska (Pike Spector)

(H) Laminaria hyperborea in Murmansk, Russia (Dalnie Zelentsy)

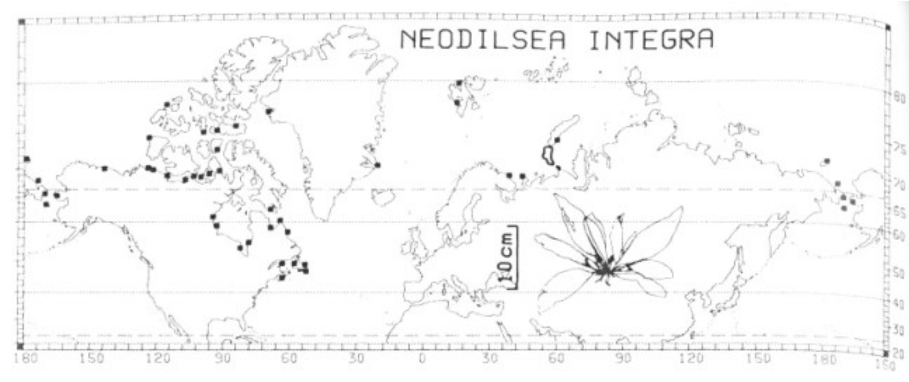
(I) Laminaria digitata in Svalbard, Norway (Max Schwanitz)





basal growth, multiyear blades

flat phylloids/blades; Palmariaceae



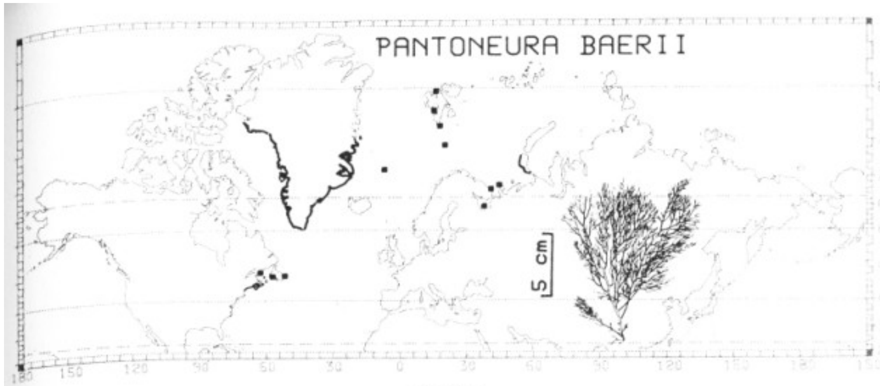
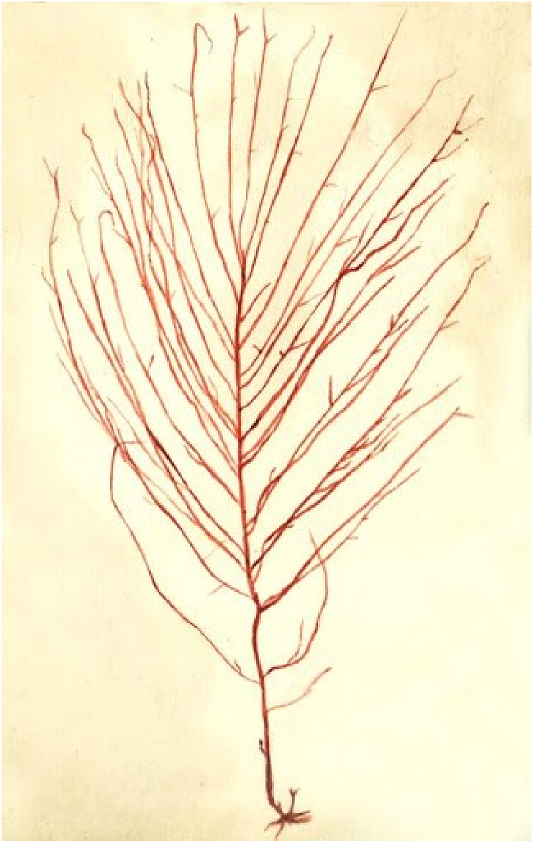
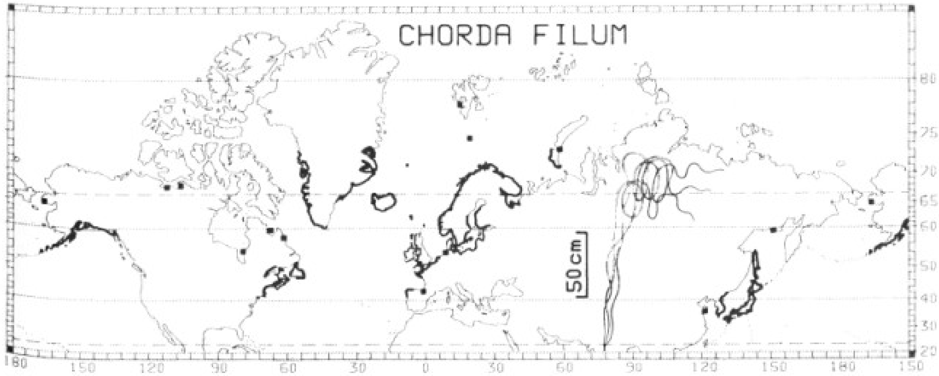


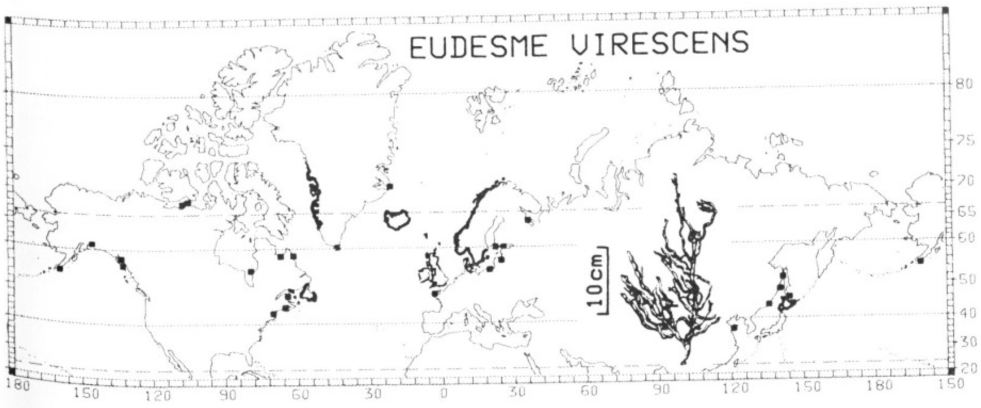
Fig. 3.11

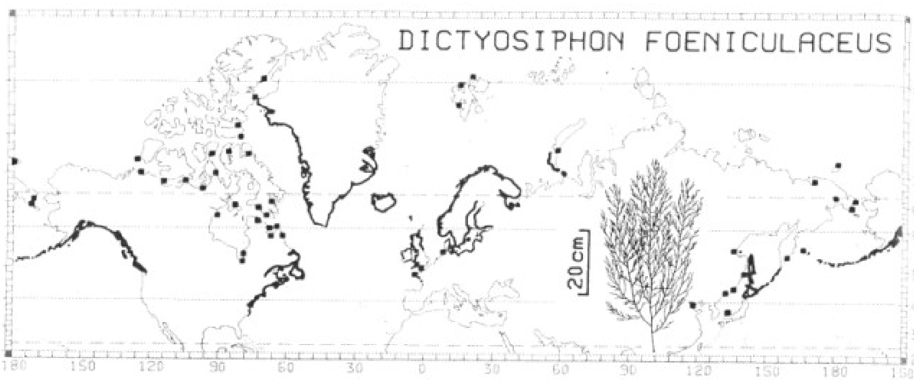


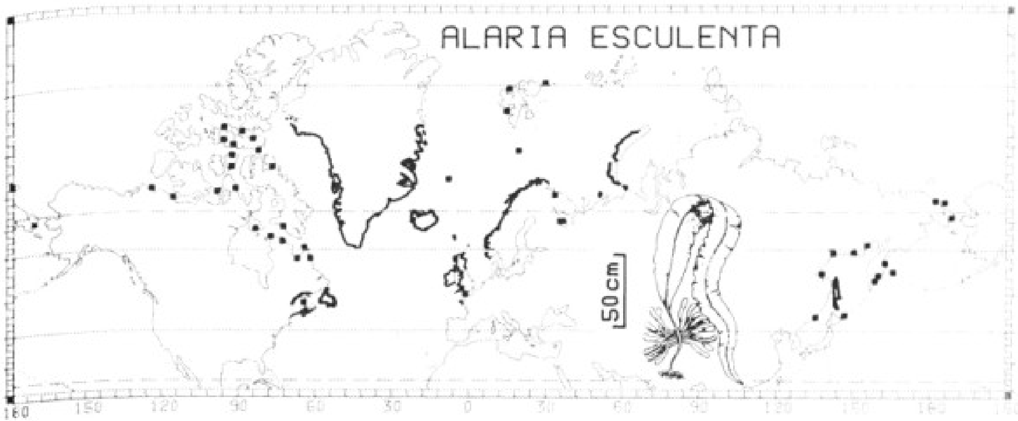
Neodilsea (Gigartinales)

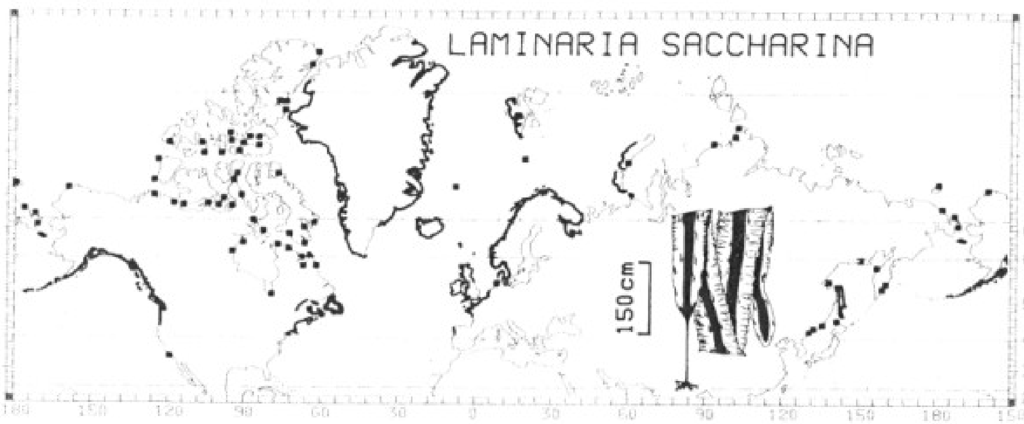
Pantoneura (Delesseriaceae)

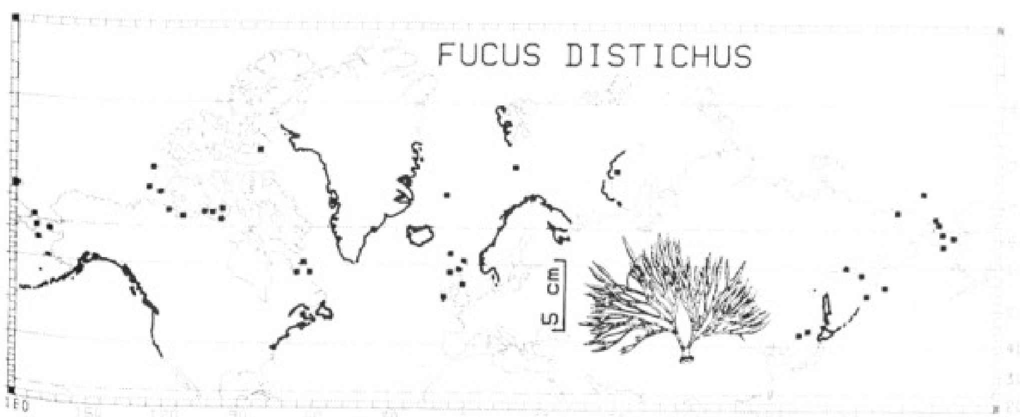

CHORDA FILUM
50 cm

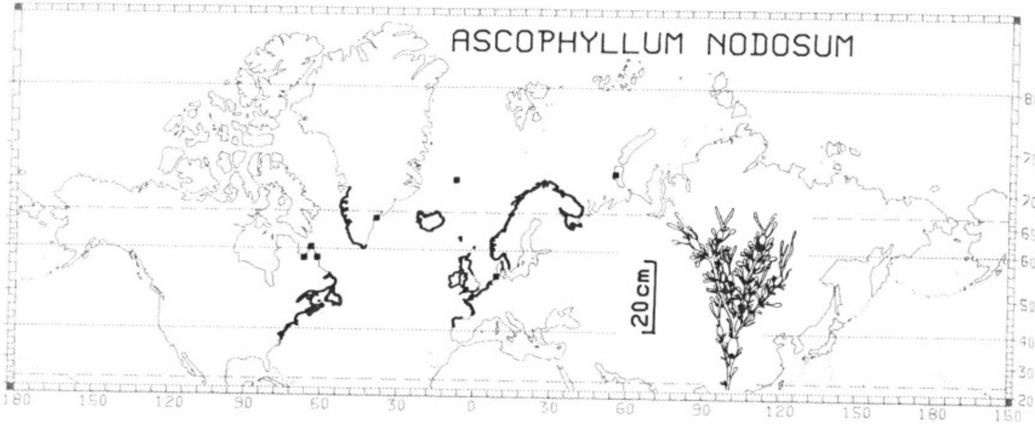

EUDESME VIRESCENS
10 cm

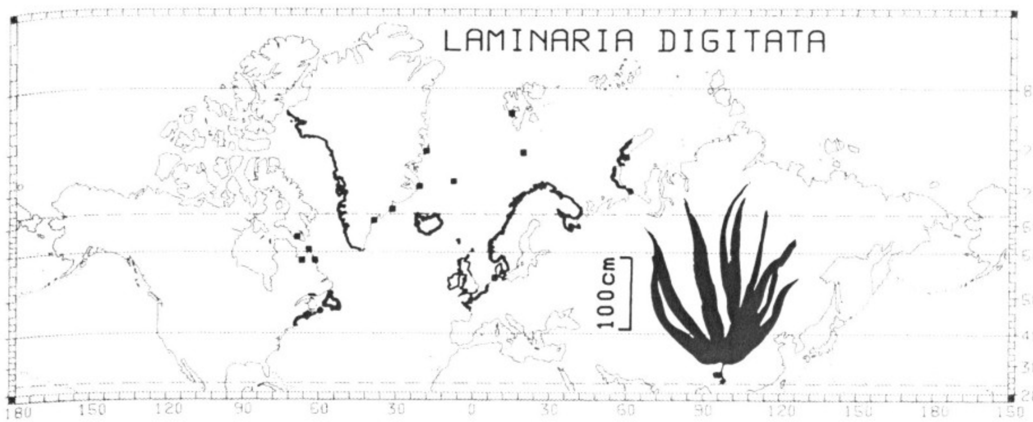

DICTYOSIPHON FOENICULACEUS
20 cm

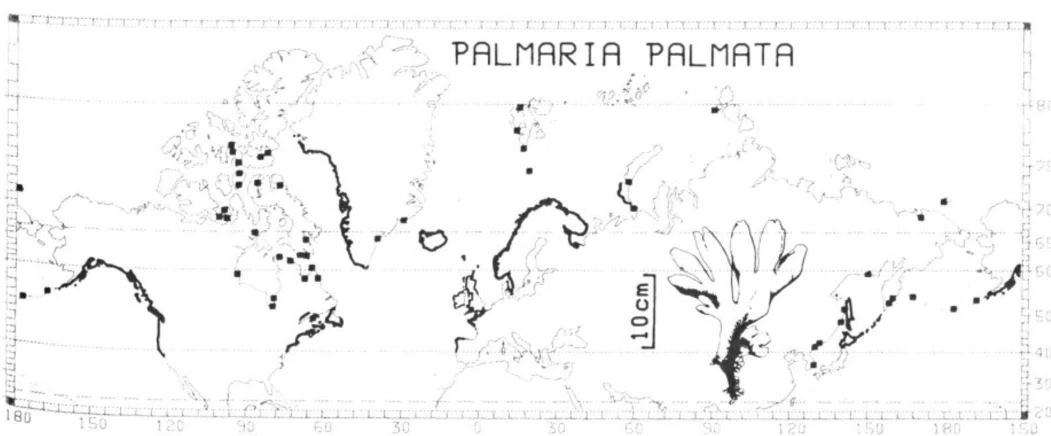

ALARIA ESCULENTA
50cm

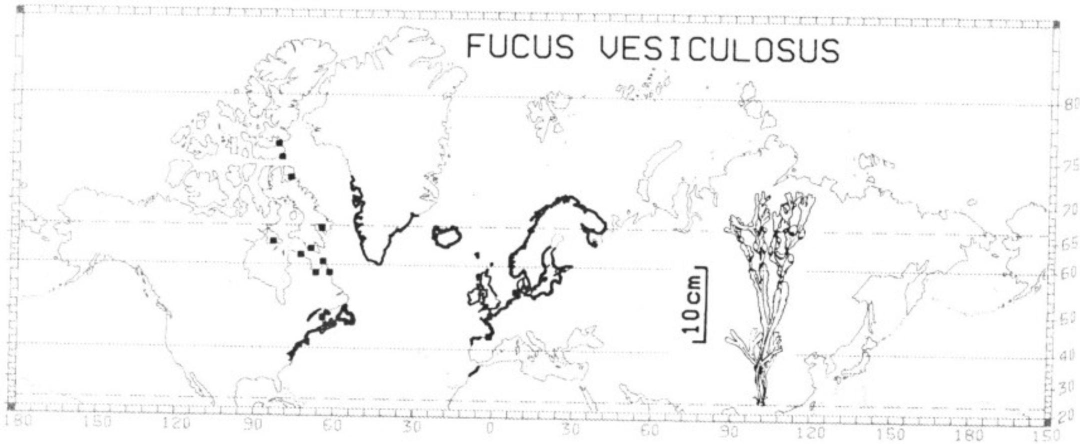

LAMINARIA SACCHARINA
150cm

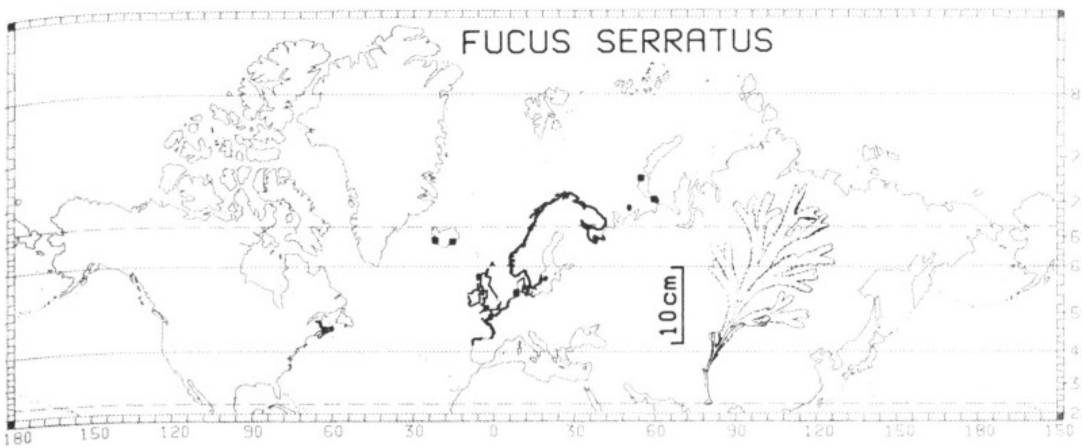

FUCUS DISTICHUS
5 cm

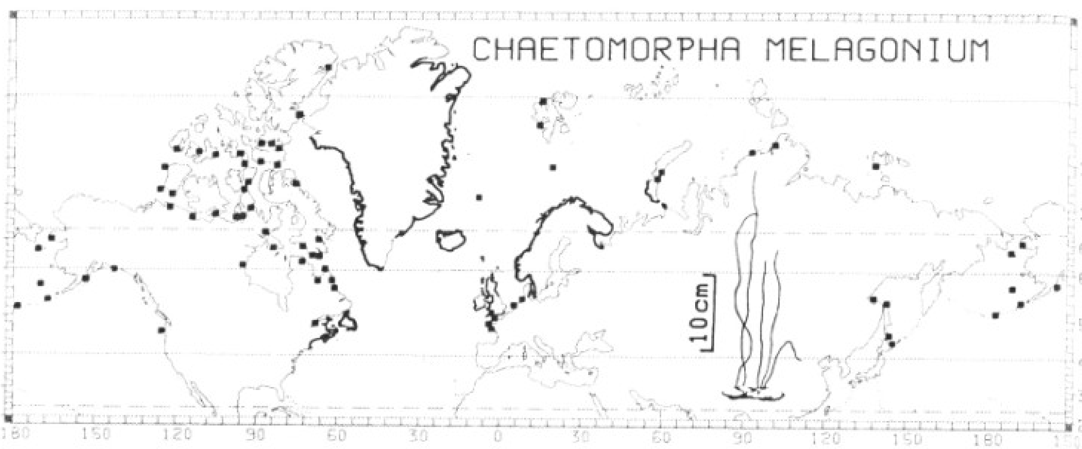

ASCOPHYLLUM NODOSUM
20cm

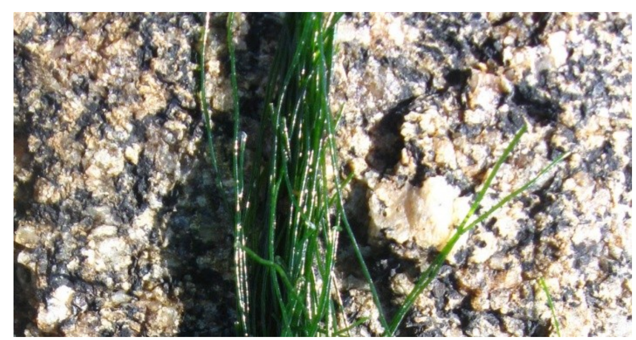

LAMINARIA DIGITATA
100cm


PALMARIA PALMATA
10cm


FUCUS VESICULOSUS
10cm


FUCUS SERRATUS
10cm


CHAETOMORPHA MELAGONIUM
10cm

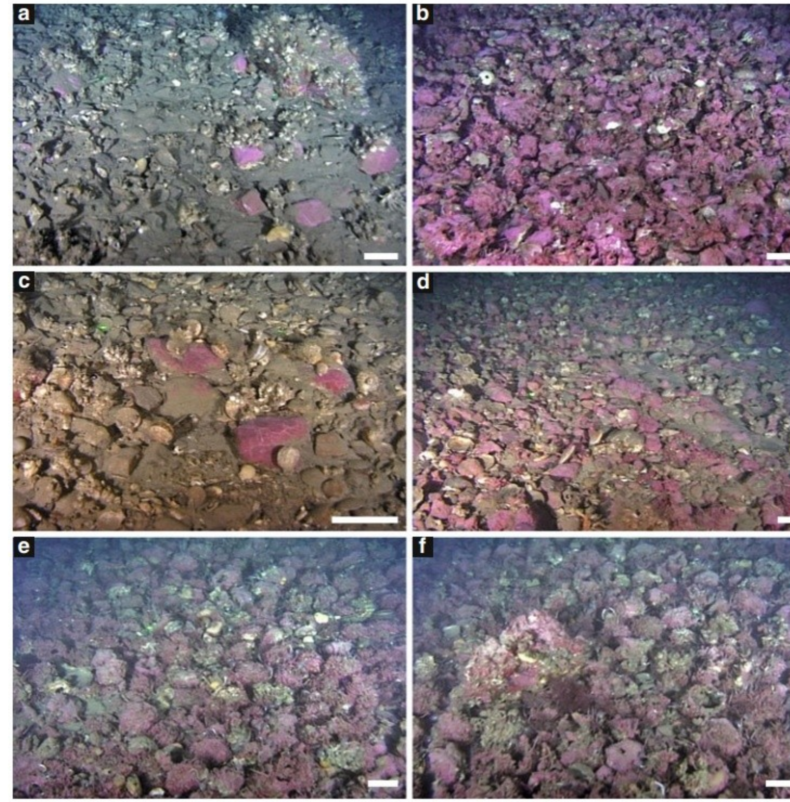


Arctic rhodolith beds

dominating in the lower sublittoral (in general below 25 m)

Spitzbergen
– well developed rhodolith communities 27–47 m (max 75 m) consisting of *Lithothamnion glaciale* and *Phymatolithon tenue*

Fig. 3 JAGO seafloor photographs. **a** Smooth coralline algal encrustations on lithoclastic cobbles free from fine sediment (Floskjeret, dive track 757, 60 m water depth). **b** Rhodoliths up to 20 cm in diameter (Floskjeret, dive track 757, 47 m water depth). **c** Coralline algal encrustations on lithoclastic cobbles above a distinctive size (Krossfjorden, dive track 652, 77 m water depth). **d** Rhodoliths up to 15 cm in diameter (Krossfjorden, dive track 652, 50 m water depth). **e**, **f** Rhodoliths up to 25 cm in diameter and some hollow specimens (Mosselbukta, dive track 671, 42 m water depth); note the connection between coralline algal development and water depth (*scale bars* 10 cm)



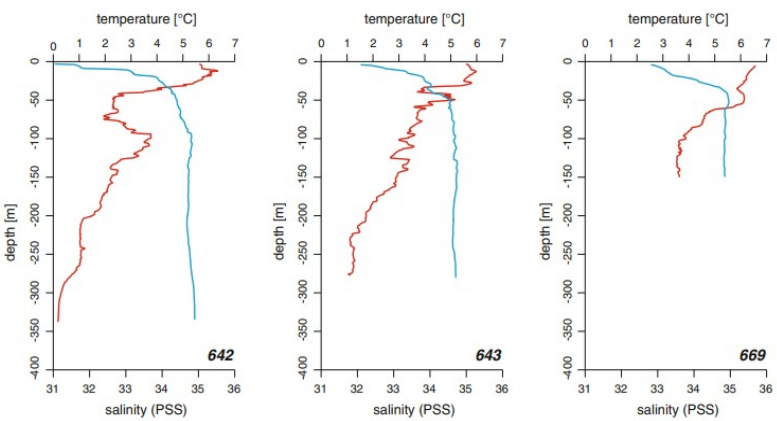
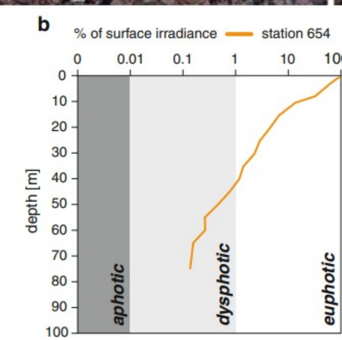


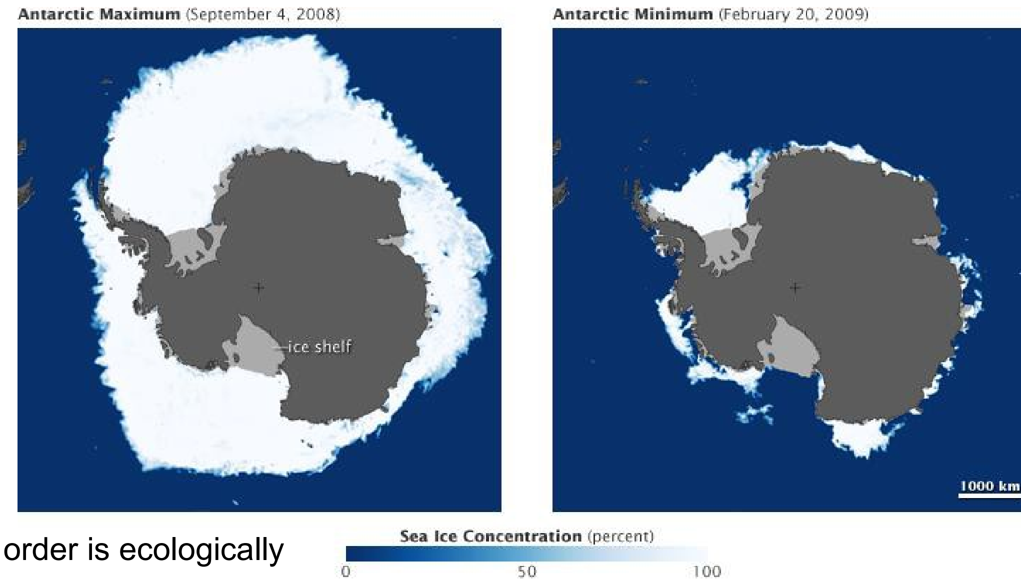
Fig. 4 CTD-profiles from stations 616 (Floskjeret), 632, 640, 641, 642, 643 (Krossfjorden), and 669 (Mosselbukta), showing similar patterns of increasing salinities and decreasing temperatures with increasing water depth



Teichert et al., 2013, Facies

Antarctic region

33% of all seaweed species are endemic to the Antarctic region (Stramenopila 44% > Chlorophyta 18%)
Ascoseirales - the endemic order
endemic browns: *Himantothallus, Cystosphaera* and *Phaeurus*
red algae *Gainia, Notophycus* and *Antarcticothamnion*
greens: *Lambia, Lola*



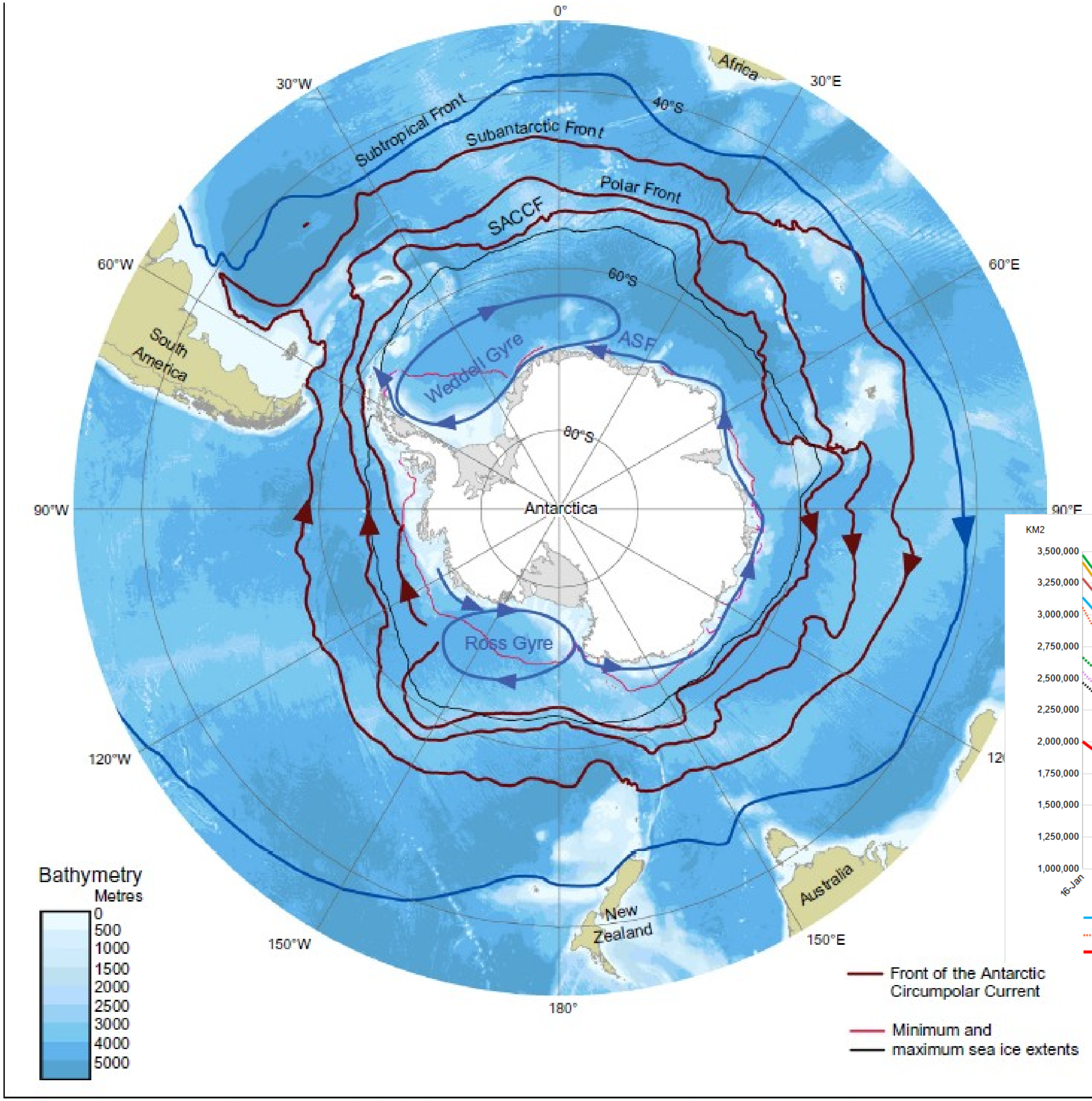
- the only cold region in the world devoid of true kelps; this order is ecologically replaced by the Desmarestiales
- typical scarcity of small macroalgal epiphytes compared to temperate regions

- most species occur in the Antarctic Peninsula region and only very few species are recorded at the southernmost distribution limit in the Ross Sea (77°S).

As a result of the strong effect of the Antarctic Circumpolar Current on the dispersal of seaweed propagules many non-endemic species of the Antarctic seaweed flora have a circumpolar distribution.

Among the species also occurring on sub-Antarctic islands and Tierra del Fuego are the red alga Iridaea cordata, the brown alga Geminocarpus geminatus and the green alga Monostroma hariotii. Some species, e.g. the red alga Ballia callitricha and the brown alga Adenocystis utricularis, even occur in New Zealand and Australia.

At least 20 algal species from the Antarctic are cosmopolitan, e.g. the red alga Plocamium cartilagineum, the brown alga Petalonia fascia and the green alga Ulothrix flacca.



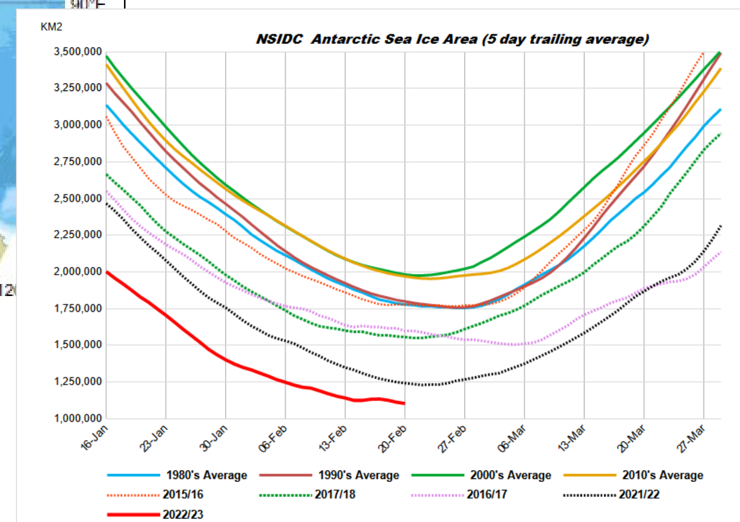


FIG. 1.2 Southern Ocean bathymetry, major fronts, currents, and subpolar gyres. The averaged middle paths of fronts are shown, except for the Southern Antarctic Circumpolar Front (SACCF) which shows its northern extent. ASF is Antarctic Slope Front. *Arrows* indicate direction of current flow. *(Fronts from Sokolov, S., & Rintoul, S. R. (2009). Circumpolar structure and distribution of the Antarctic circumpolar current fronts: 1. Mean circumpolar paths.* Journal of Geophysical Research: Oceans, 114.*)*

Stark et al., 2019, World Seas

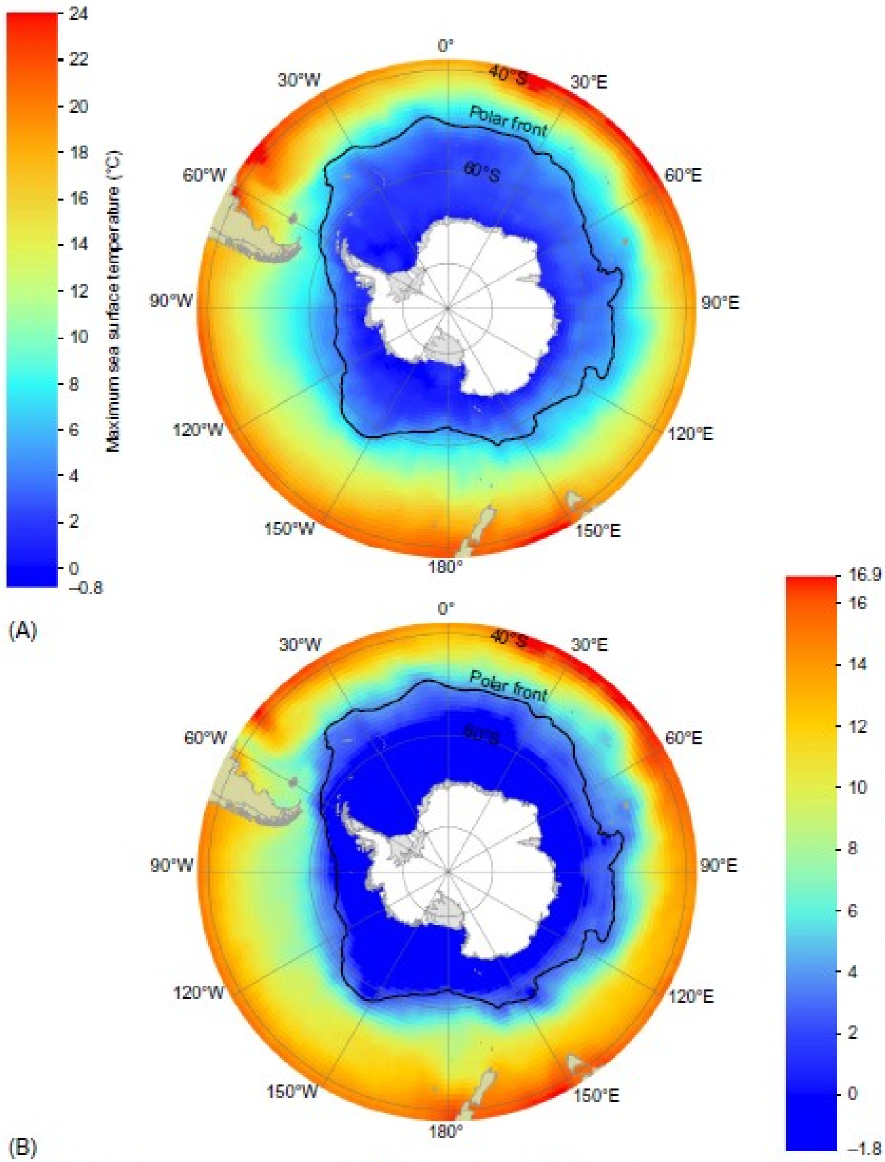


FIG. 1.5 Remotely sensed mean sea surface temperature (SST) between 1981 and 2005 for (A) summer maxima and (B) winter minima. Based on monthly data from OI.v2 SST (see https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html for details). Maximum values are the maximum for each grid cell (over the range 1981–2005), minimum values are minimum for each cell over the same period. The *dark line* shows the Polar Front. *(Mean front position from Sokolov, S., & Rintoul, S. R. (2009). Circumpolar structure and distribution of the Antarctic circumpolar current fronts: 1. Mean circumpolar paths.* Journal of Geophysical Research: Oceans, 114.*)*

Stark et al., 2019, World Seas

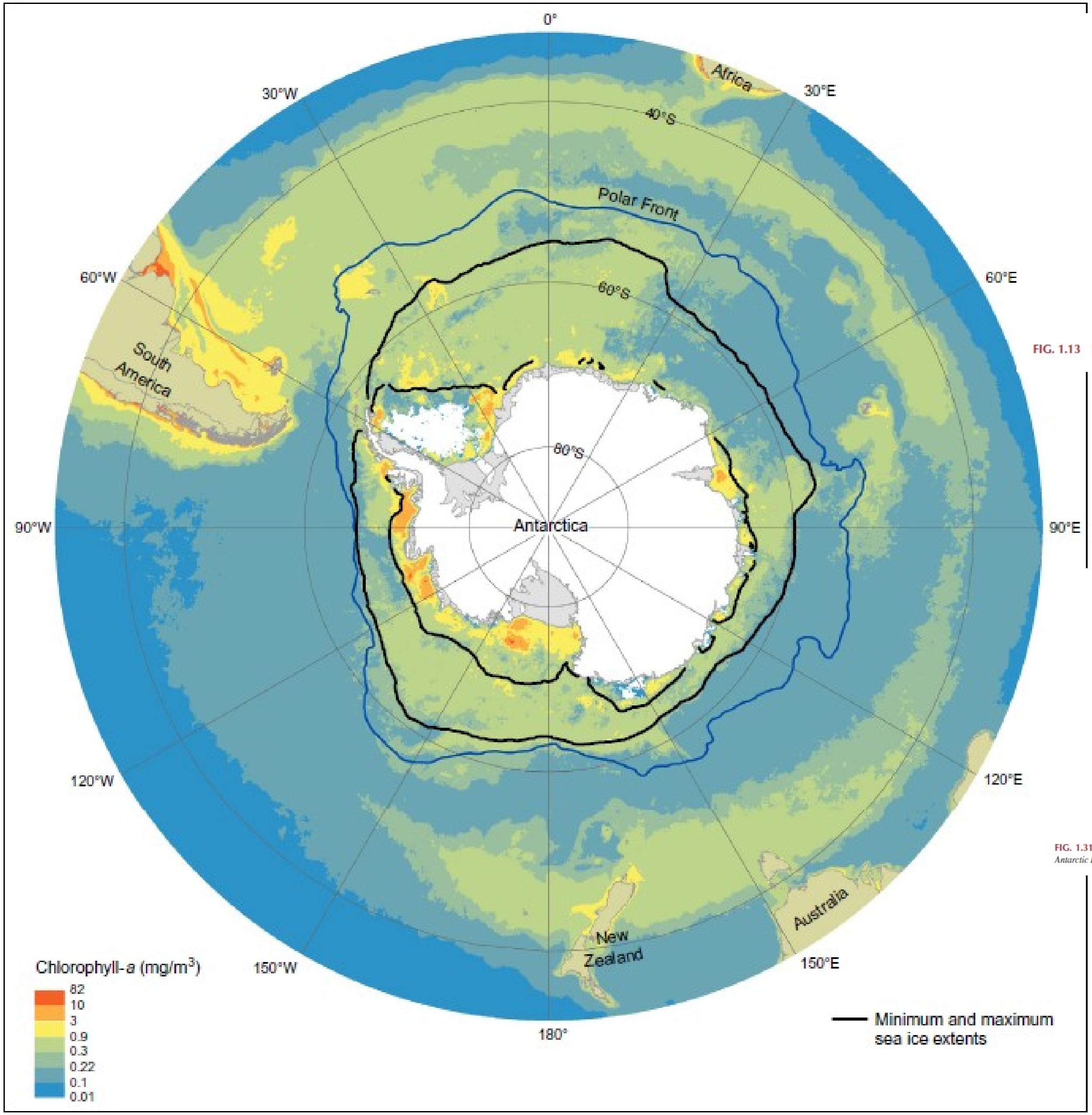
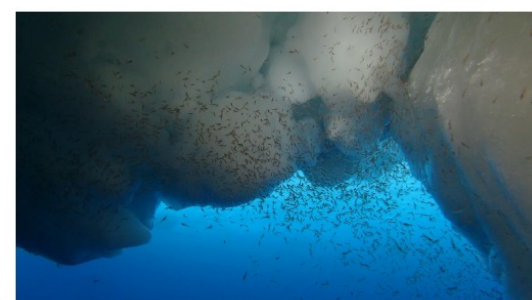


FIG. 1.12 Maximum and minimum extents of sea ice and chlorophyll-a concentration in the Southern Ocean. Chlorophyll-a data are the long-term austral summer chlorophyll-a climatology from 2002–03 to 2015–16, at 9km resolution. *(Data derived from Moderate-resolution Imaging Spectroradiometer (MODIS), NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group.; A20023552016080.L3m_SCWI_CHL_chlor_a_9km.asc; NASA OB.DAAC, https://doi.org/10.5067/AQUA/MODIS/L3M/CHL/2014.)*

FIG. 1.13 Sea ice algae on the underneath of pack ice (overturned by vessel). *(© ACE CRC/Australian Antarctic Division.)*

FIG. 1.31 Antarctic krill *Euphausia superba*. The *green* area behind the head is phytoplankton the krill has eaten. *(© Russell Hopcroft/Australian Antarctic Division.)*



macrobenthos under permanent sea ice cover in (relatively) eutrophic conditions...

FIG. 1.16 Shallow water benthic community under sea ice. Such communities are dominated by invertebrates as there is insufficient light for macroalgae, and are vulnerable to climate change such as changes in sea ice duration. *(© J.S Stark/Australian Antarctic Division.)*

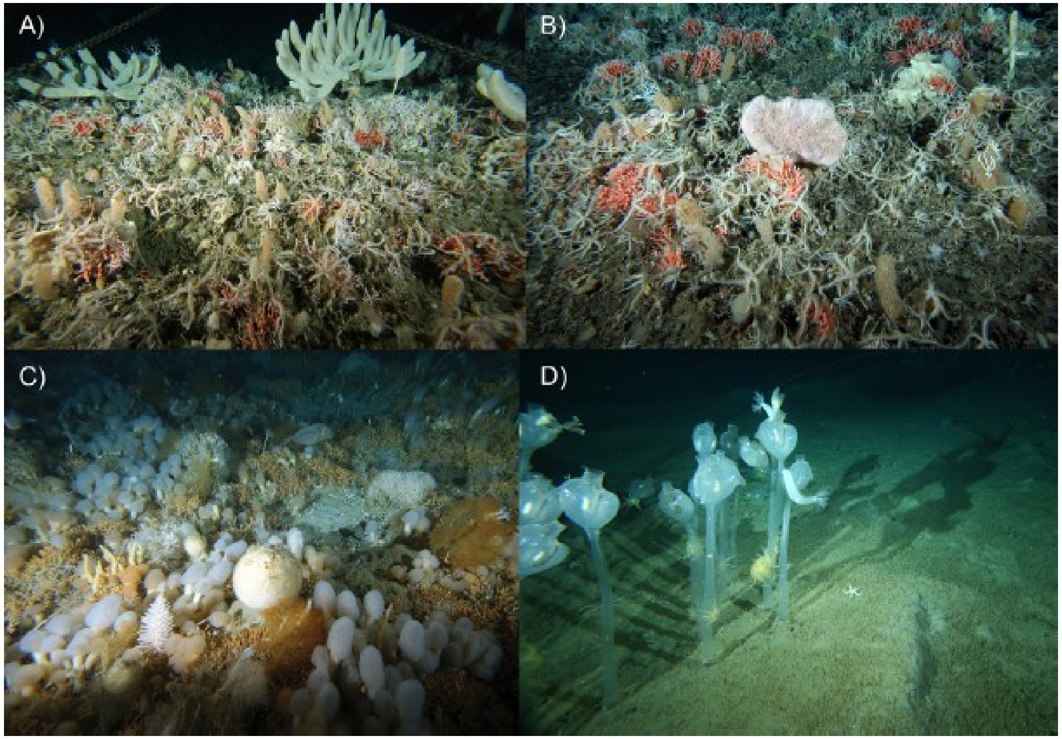
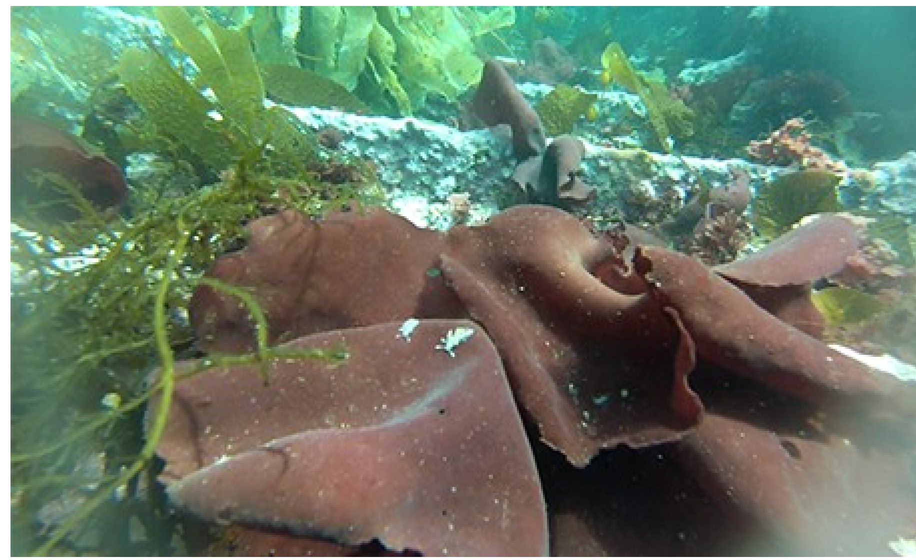


FIG. 1.15 Benthic communities on the Antarctic shelf photographed during the CEAMARC voyage in East Antarctica. Such communities are vulnerable to effects of trawling and these have been declared a vulnerable marine ecosystem (VME) by CCAMLR. (A, B) Communities dominated by habitat forming bryozoans, deepwater corals, and sponges with associated mobile epifauna including asteroids, ophiuroids and crinoids; (C) community dominated by sponges and ascidians with some bryozoans; (D) soft-sediment community with glass ascidians and attached mobile epifaunal holothurians and crinoids. (Australian Antarctic Division). *((A, B, D) © Martin Riddle/Australian Antarctic Division, and (C) © Australian Antarctic Division.)*

multiple important Antarctic macroalgae have very low temperature optima/limits;
i.e. strong adaptation of Antarctic seaweeds to low temperatures

Antarctic Desmarestiales:
sporophytes - grow up to 5°C and exhibit upper survival temperatures (USTs) of 11–13°C
gametophytes - grow up to 10 or 15°C with USTs between 15 and 18°C

Antarctic red algae:
Georgiella confluens, Gigartina skottsbergii, and Plocamium cartilagineum grow at 0°C, but not at 5°C and have USTs as low as 7–11°C



glacial refugia of Antarctic macroalgae - sub-Antarctic islands and the southern tip of South America

General temperature limit patterns of Arctic macroalgae:

maximum photosynthetic rates of endemic Antarctic species are at 0°C in a similar range compared to temperate species measured at comparatively higher temperatures

northern distribution of endemic Antarctic species is often limited by the temperature demands for growth; endemic Antarctic Desmarestiales for example occur only south of the Antarctic Polar Front in areas with maximum temperatures 5°C allowing sufficient growth of their sporophytes

Table 4. Variation of mean monthly seawater temperatures during the course of the year at various locations. Source: Gorshkov (1985a, b). Classification of biogeographic regions after Lüning (1985)

Location	Temperature (°C)
Antarctic Region:	
Antarctic Peninsula (east coast), Victoria Land, Adelie Coast, Wilkes Land, Queen Mary Coast, Mac Robertson Coast, Enderby Land	≤− 1.8 throughout the year
Antarctic Peninsula (west coast, polar circle), Balleny Islands	≤− 1.8 to −0.2
South Shetlands	≤− 1.8 to +1.2
South Orkneys	≤− 1.8 to +1.4
South Georgia	− 0.6 to +4.8
Heard Island	+ 1.5 to +5.2
Cold-temperate (incl. Subantarctic) region:	
Macquarie Island	+ 5.0 to +8.0
Falklands	+ 4.2 to +8.5
Crozet	+ 5.0 to +9.0
Tierra del Fuego	+ 6.6 to +10.4
Auckland Islands	+ 8.0 to +11.0
Victoria, South Australia	+15.0 to +18.8
Warm-temperate region:	
South Africa (Capetown)	+15.5 to +20.0

Table 2. Temperature tolerance of the investigated species determined in 2 wk exposures to the given temperatures. x: specimen alive; (x): old parts of the specimen dead, but young parts (buds, meristems) living; –: specimen dead, no growth during 4 wk postculture under favorable conditions. Every developmental stage was tested in 2 to 4 experimental series, indicated in the table on separate lines

Species, developmental stage tested	9 °C	10 °C	11 °C	12 °C	13 °C	14 °C	15 °C	16 °C	17 °C	18 °C	19 °C	20 °C	21 °C	Maximum survival temp. (°C)
Ascoseira mirabilis	x	x	x	–	–	–								11
1-yr-old plants	x	x	x	–	–									
Phaeurus antarcticus	x	x	x	–	–	–	–	–	–	–	–	–	–	11
Sporophyte, 1-yr-old plants	x	x	x	–	–	–	–	–	–	–	–	–	–	
Desmarestia anceps	x	x	x	–	–	–								11–12
Sporophyte, ½-yr-old plants		x	x	–	–	–								
		x	x	(x)										
Himantothallus grandifolius														
Sporophyte, 1-yr-old plants	x	x	x	–	–	–								11–13
		x	x	–	–	–	–							
½-yr-old plants		x	x	(x)	(x)	–								
	x	x	(x)	(x)	(x)									
Ligulate *Desmarestia* sp.			x	x	x	–								13
Sporophyte					x	–	–	–	–					
Desmarestia anceps	x	x	x	x	x	–								13
Male gametophyte		x	x		x	–	–	–	–					
Desmarestia anceps	x	x	x	x	x	–								13
Female gametophyte		x	x	x	x	–	–	–	–					
Phaeurus antarcticus							x	–	–					15
Female gametophyte				x	x	x	x	–						
							x	–	–	–	–	–	–	
Phaeurus antarcticus						x	x	x	–					15–16
Male gametophyte				x	x	x	x	x	–					
							x	x	–					
							(x)	–	–	–	–	–	–	
Himantothallus grandifolius						x	x	x	–	–	–			15–16
Male gametophyte						x	x	–	–	–				
						x	x	x	–	–				
Himantothallus grandifolius						x	x	x	–	–	–			15–16
Female gametophyte						x	x	x	–	–	–			
						x	x	–	–	–				
Palmaria decipiens			x	x	x	x	x							16–17
Gametophyte						x		x	–	–				
						x	x	x	x					
							x	x	–					
Elachista antarctica							x	x	x	x	–	–	–	18
Microthalli							x	x	x	x	–	–	–	

Wiencke & Dieck, 1989


South Africa
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
Antarctic Convergence
Crozet
South Georgia
Falklands
South Orkneys
Tierra del Fuego
South Shetlands
Antarctic Peninsula
Enderby Land
Heard Island
South America
Mac Robertson Coast
Queen Mary Coast
Wilkes Land
Victoria Land
Adelie Coast
Balleny Islands
Antarctic Convergence
Macquarie Island
SOUTH PACIFIC OCEAN
Auckland Islands
1000 km
14
New Zealand
Australia

vertical structure of Antarctic pseudokelps

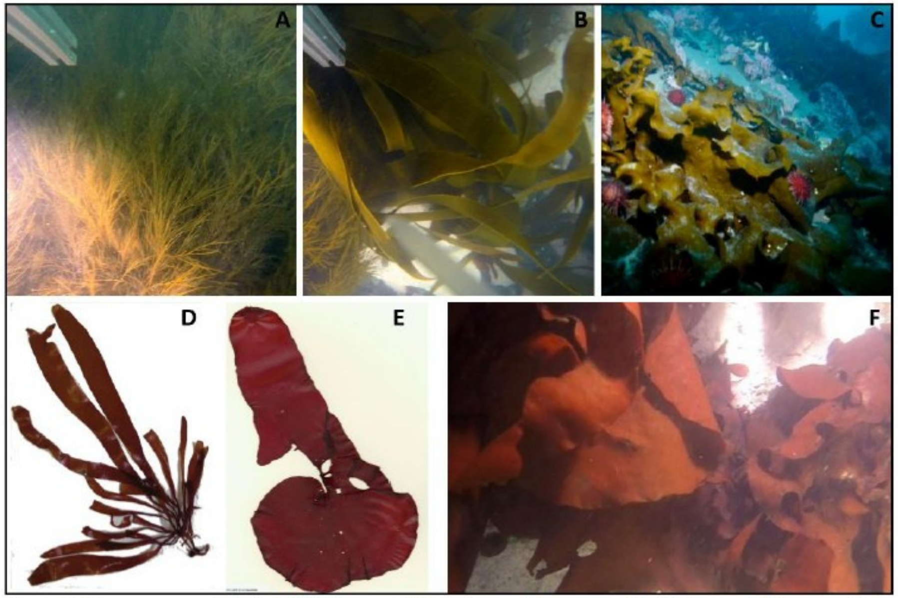


Figure 4: Common macroalgae in PC. Upper row: *Phaeophyceae*; lower row: *Rhodophyceae*. **A** *Desmarestia* genus (species are hard to distinguish (Zacher pers. comm.)) **B** *Ascoseira mirabilis* **C** *Himantothallus grandifolius* **D** *Palmaria decipiens* **E** *Iridaea cordata* **F** *Rhodophyceae* (probably *I. cordata* (Zacher pers. comm.))

supralittoral - Prasiola

eulittoral – ephemerous filamentous algae (Urospora, Ulothrix, Spongomorpha, Monostroma, Porphyra, Adenocystis

the upper 5–15 m of the sublittoral are exposed to ice floes and are often devoid of large, perennial algae; only crustose species or developmental stages can persist here

below this zone, large brown algae dominate the sublittoral in West Antarctica: Ascoseira mirabilis and Desmarestia menziesii occur in the upper sublittoral, D. anceps in the mid sublittoral and Himantothallus grandifolius grows in the lower sublittoral

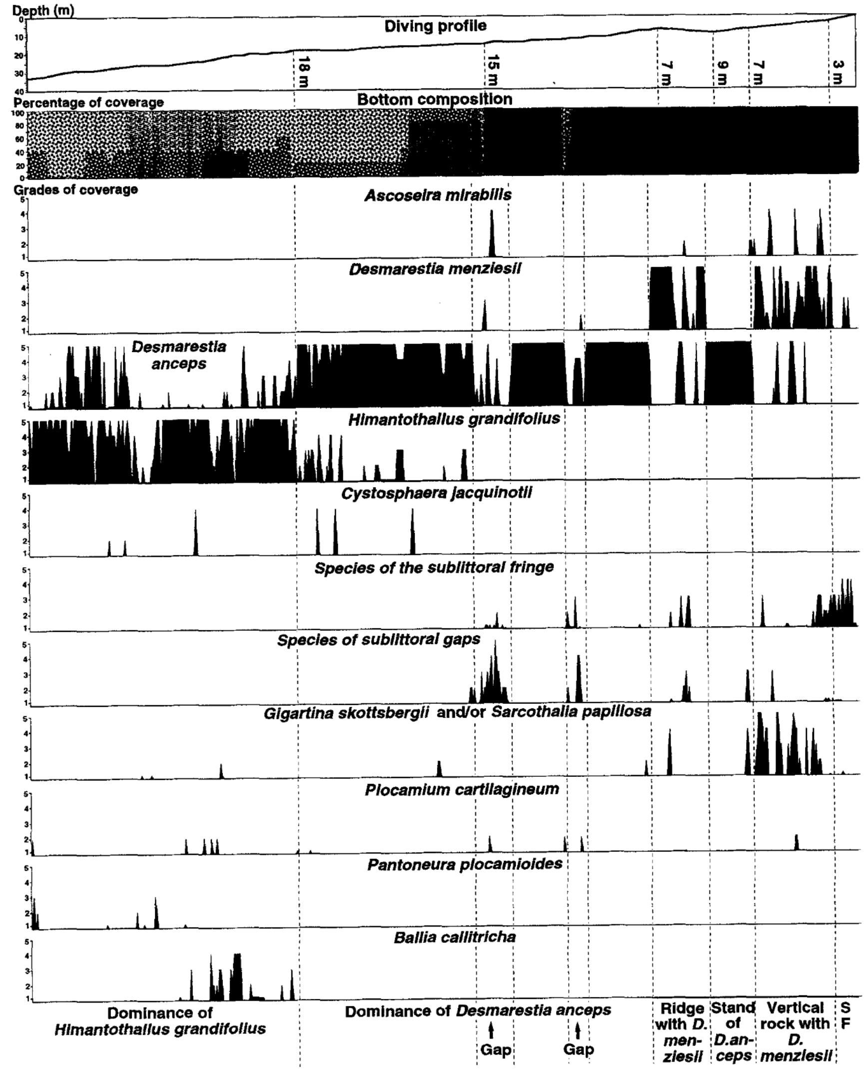
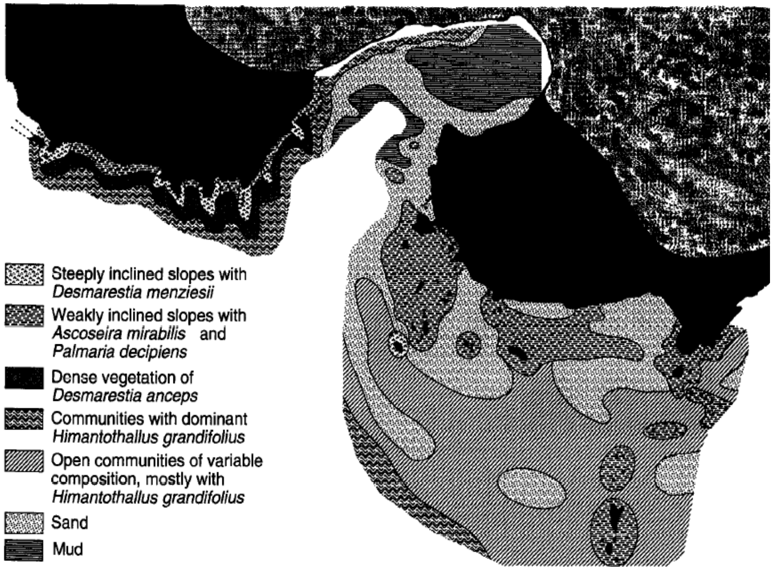


Figure 4. Profile 3. The upper bar gives the diving profile, which refers to the position of the diver regardless true distances or slope inclinations; the true depth profile is given in Figure 2. The second bar gives types of substratum (for graphic key, please refer to Figure 6). The other bars indicate coverage grades of species or species groups: 0 = not observed, 1 = less than 5% of the visible area covered; 2 = between 5 and 25% of the visible area covered; 3 = 25 to 50% of the visible area covered; 4 = 50 to 75% of the visible area covered; 5 = 75% to 100% of the visible area covered. Species of the sublittoral fringe include *Phaeurus antarcticus*, *Myriogramme manginii*, *Curdiea racovitzae* and *Iridaea cordata* and/or *Notophycus fimbriatus*. Species of sublittoral gaps include *Desmarestia antarctica*, *Monostroma hariotii* and *Palmaria decipiens*. Species, which have been omitted due to the minor importance and inconclusive distribution patterns, are: *Hymenocladiopsis crustigena*, *Callophyllis* spec., *Phyllophora appendiculata*, *Kallymenia antarctica*, *Georgiella confluens*, *Gymnogongrus antarcticus* and *Geminocarpus geminatus*. Note gap in the dense vegetation of *Desmarestia anceps* above 15 m coinciding with loose substratum.

Klöser et al., 1996



D. anceps

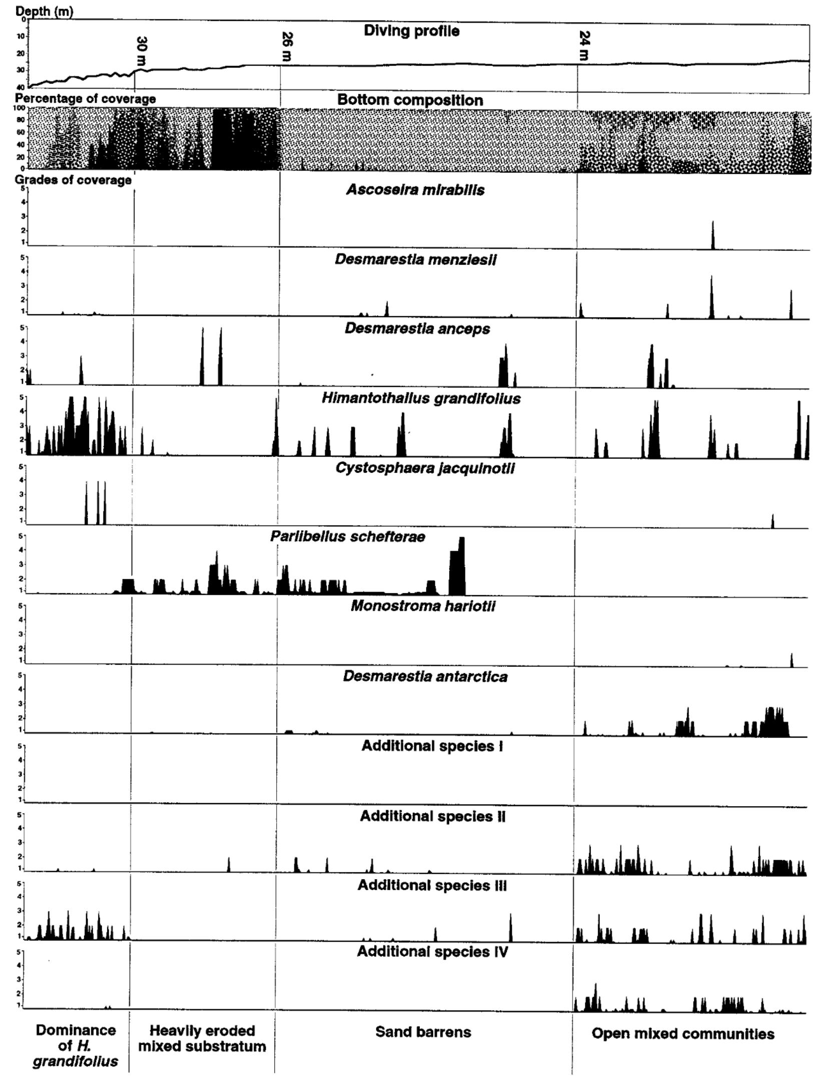
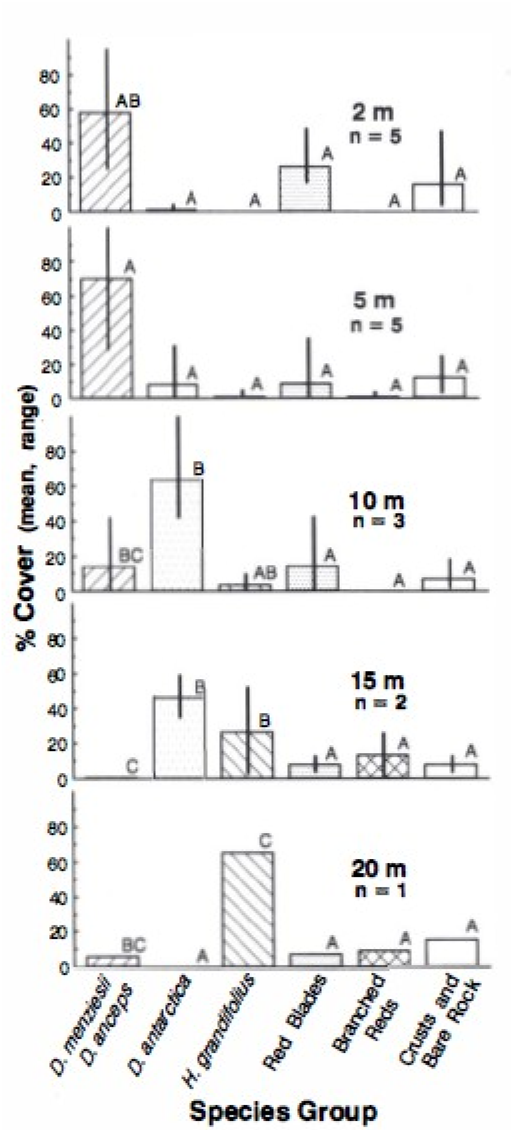


Figure 5a. Profile 13, seaward side of Em Rock, 39 m to 20 m. Arrangement like Figure 4. The species groups are composed as follows: Additional species I: *Phaeurus antarcticus*, *Gymnogongrus antarcticus*, *Phyllophora appendiculata*, *Curdiea racovitzae* and *Iridaea cordata* and/or *Notophycus fimbriatus*; Additional species II: *Myriogramme manginii*, *Palmaria decipiens*, *Plocamium cartilagineum*, *Delesseria lancifolia* and *Georgiella confluens*; Additional species III: *Gigartina skottsbergii* and/or *Sarcothalia papillosa*; *Kallymenia antarctica*; *Pantoneura plocamioides*, *Hymenocladiopsis crustigena* and *Picconiella plumosa*; Additional species IV: *Rhodymenia subantarctica*, *Phycodrys austrogeorgica*, *Phycodrys antarctica*, *Myriogramme smithii* and *Ballia callitricha*. Species, which have been omitted due to minor importance and inconclusive distribution patterns, are: *Sarcodia montagneana*, *Callophyllis* spec. and *Geminocarpus geminatus*.

Klöser et al., 1996



H. grandifolius with twisted cauloids and complex holdfast

Amsler et al., 1995, Phycologia

polar macroalgae with disjunct amphiequatorial distribution

disjunct amphiequatorial distribution - both in the Antarctic and the Arctic:
Acrosiphonia arcta, Desmarestia viridis/confervoides complex

phylogeographic disjunctions of these species are recent and probably date back to the maximum of the Würm/ Wisconsin glaciation approximately 18 000 years ago
transequatorial transfer – during glacial maximum via currents, resting stages

stringy acid kelp