Ocean colour remote sensing at high latitudes

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Why a lecture on this specific topic?

- Increasing attention is paid to what’s going on there
- The use of ocean color remote sensing faces specific challenges at high latitudes
  - Low Sun elevation
  - High cloudiness
  - Sea ice
  - Peculiar optical properties
  - Peculiar phytoplankton properties
    - Vertical distribution
    - Optical properties
    - Physiology

Outline

1. Ocean colour remote sensing in polar seas

1.1. Ocean and sea ice in Arctic and Antarctic: relevant features

1.2. Seawater optical properties

1.3. Retrieval of ocean properties from ocean colour

1.3.1. Atmospheric corrections

1.3.2. Contamination of the signal by sea ice

1.3.3. Retrieval of IOPs and AOPs, and biogeochemically relevant variables

1.4. Availability of data as favoured by polar orbits and limited by elevated cloudiness

2. Primary production estimates from OC in polar seas

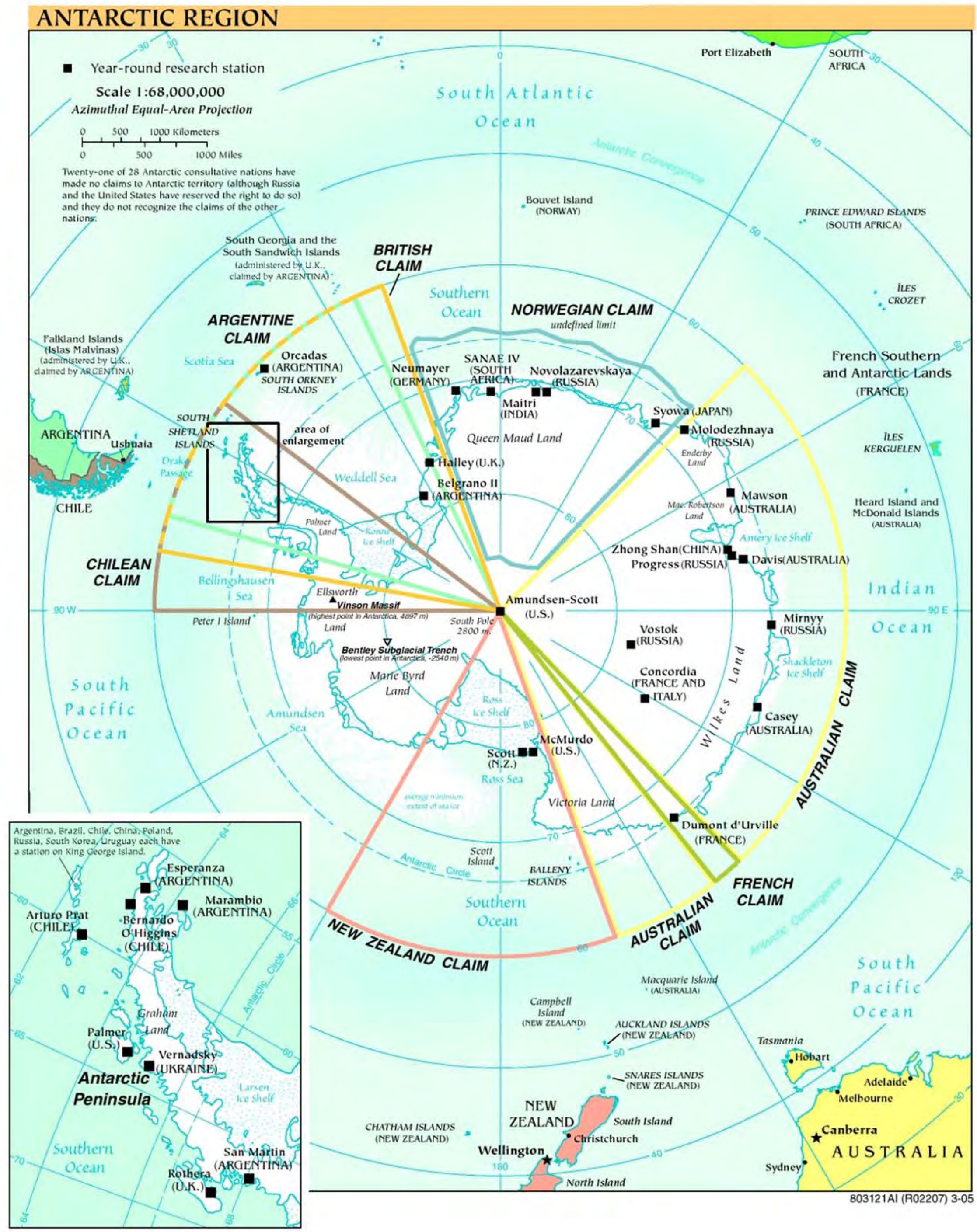
2.1. PP model and validation: an example

2.2. Results from PP models

1. Ocean colour remote sensing in polar seas

1.1. Ocean and sea ice in Arctic and Antarctic: relevant features

Geography


ANTARCTIC REGION
Year-round research station
Scale 1:68,000,000
Azimuthal Equal-Area Projection
0 500 1000 Kilometers
0 500 1000 Miles
Twenty-one of 28 Antarctic consultative nations have made no claims to Antarctic territory (although Russia and the United States have reserved the right to do so) and they do not recognize the claims of the other nations.
South Atlantic Ocean
Port Elizabeth
SOUTH AFRICA
Bouvet Island (NORWAY)
PRINCE EDWARD ISLANDS (SOUTH AFRICA)
ÎLES CROZET
South Georgia and the South Sandwich Islands (administered by U.K., claimed by ARGENTINA)
BRITISH CLAIM
Southern Ocean
NORWEGIAN CLAIM
undefined limit
ARGENTINE CLAIM
Falkland Islands (Islas Malvinas) (administered by U.K., claimed by ARGENTINA)
Scotia Sea
Orcadas (ARGENTINA)
SOUTH ORKNEY ISLANDS
Neumayer (GERMANY)
SANAE IV (SOUTH AFRICA)
Novolazarevskaya (RUSSIA)
Maitri (INDIA)
French Southern and Antarctic Lands (FRANCE)
Syowa (JAPAN)
Molodezhnaya (RUSSIA)
ÎLES KERGUELEN
ARGENTINA
Ushuaia
SOUTH SHETLAND ISLANDS
area of enlargement
Queen Maud Land
Enderby Land
Drake Passage
Halley (U.K.)
Weddell Sea
Belgrano II (ARGENTINA)
Mawson (AUSTRALIA)
Heard Island and McDonald Islands (AUSTRALIA)
CHILE
Mac. Robertson Land
Palmer Land
Ronne Ice Shelf
Amery Ice Shelf
Zhong Shan (CHINA)
Progress (RUSSIA)
Davis (AUSTRALIA)
CHILEAN CLAIM
Bellingshausen Sea
Ellsworth
Vinson Massif
Indian Ocean
Amundsen-Scott (U.S.)
90 W
90 E
Peter I Island
Land
South Pole 2800 m
Mirnyy (RUSSIA)
Vostok (RUSSIA)
Bentley Subglacial Trench
Marie Byrd Land
Concordia (FRANCE AND ITALY)
Shackleton Ice Shelf
South Pacific Ocean
Amundsen Sea
Ross Ice Shelf
Wilkes Land
Casey (AUSTRALIA)
McMurdo (U.S.)
Scott (N.Z.)
Ross Sea
AUSTRALIAN CLAIM
Victoria Land
Dumont d'Urville (FRANCE)
Scott Island
Antarctic Circle
BALLENY ISLANDS
FRENCH CLAIM
Southern Ocean
AUSTRALIAN CLAIM
NEW ZEALAND CLAIM
South Pacific Ocean
Macquarie Island (AUSTRALIA)
Campbell Island (NEW ZEALAND)
AUCKLAND ISLANDS (NEW ZEALAND)
Tasmania
Hobart
SNARES ISLANDS (NEW ZEALAND)
Adelaide
Melbourne
NEW ZEALAND
South Island
Canberra
CHATHAM ISLANDS (NEW ZEALAND)
Christchurch
AUSTRALIA
Wellington
Sydney
North Island
803121AI (R02207) 3-05
Argentina, Brazil, Chile, China, Poland, Russia, South Korea, Uruguay each have a station on King George Island.
Esperanza (ARGENTINA)
Marambio (ARGENTINA)
Arturo Prat (CHILE)
Bernardo O'Higgins (CHILE)
Graham Land
Palmer (U.S.)
Vernadsky (UKRAINE)
Antarctic Peninsula
Larsen Ice Shelf
Southern Ocean
San Martín (ARGENTINA)
Rothera (U.K.)

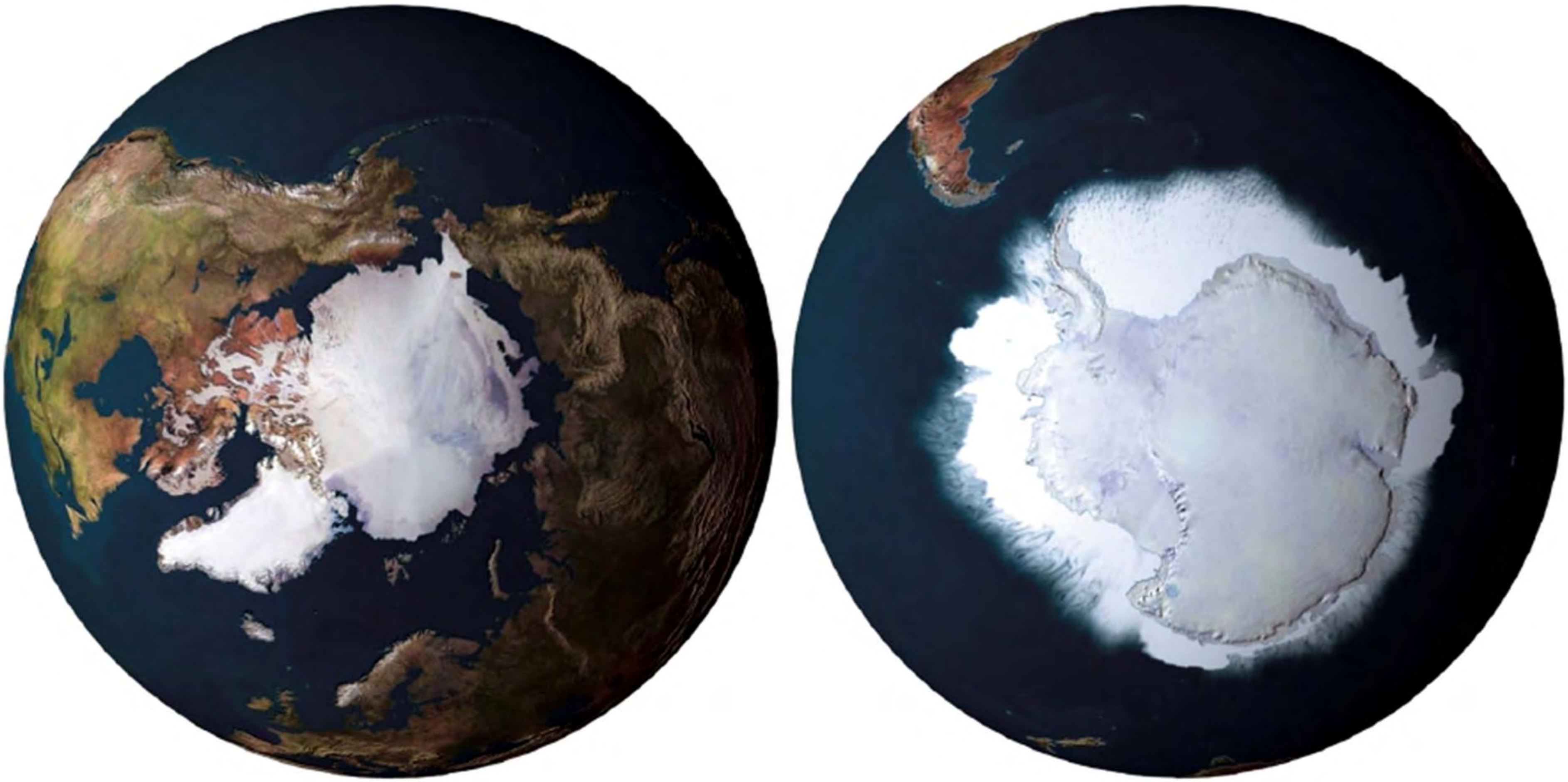
Geography

Aleutian Islands
PACIFIC OCEAN
Bering Sea
Petropavlovsk-Kamchatsky
Kamchatka
Sea of Okhotsk
Gulf of Alaska
10° C July Isotherm
Anchorage
Yukon River
Koryaks Mts.
Anadyr
Magadan
Okhotsk
Juneau
Alaska Range
ALASKA (USA)
Bering Straight
Kolyma Mountains
Kolyma River
Aldan
Whitehorse
Fairbanks
Teslin
Dawson
Brooks Range
Chukchi Sea
Chersky Range
Yakutsk
Rocky Mountains
Mackenzie Mountains
Barrow
Prudhoe Bay
East Siberian Sea
Verkhoyansk
Verkhoyansk Range
Lena River
Calgary
Edmonton
Mackenzie River
Inuvik
Great Bear Lake
New Siberian Islands
Tiksi
Lake Baikal
Great Slave Lake
Yellowknife
Lake Athabasca
Canada Basin
Saskatchewan R.
Banks Island
ARCTIC OCEAN
Laptev Sea
Central Siberian Upland
CANADA
Victoria Island
Lake Winnipeg
Makarov Basin
Taymir Peninsula
North Land
RUSSIAN FEDERATION
Yenisey
Churchill
Arviat
Rankin Inlet
Resolute
Alpha Ridge
Lomonosov Ridge
Amundsen Basin
Nansen-Gakkel Ridge
Norilsk
Yenisey River
Naujat
Ellesmere Island
Alert
Hudson Bay
Ob River
Novosibirsk
Foxe Basin
Qaanaaq
Nansen Basin
Franz Josef Land
Novaya Zemlya
West Siberian Plain
James Bay
Baffin Island
Baffin Bay
Kara Sea
SVALBARD (NORWAY)
Salekhard
Vorkuta
Khanty-Mansiysk
Omsk
Irtysh
Iqaluit
Longyearbyen
Labrador
GREENLAND (DENMARK)
Ilulissat
Fram Strait
Naryan-Mar
Barents Sea
ARCTIC CIRCLE
Davis Strait
Sisimiut
Bjørnøya
Ural Mountains
Yekaterinenburg
Chelyabinsk
Nuuk
Greenland Sea
Murmansk
Syktyvkar
Perm
Kama River
Ufa
Ammassalik
Jan Mayen
Tromsø
Kola Peninsula
Arkhangelsk
N. Dvina
White Sea
FINLAND
Kazan
Norwegian Sea
ICELAND
NORWAY
SWEDEN
Lake Onega
Reykjavik
Lake Ladoga
Volga River
FAROE ISLANDS (DENMARK)
Torshavn
Helsinki
St. Petersburg
Moscow
Gulf of Bothnia
Tallinn
Oslo
Baltic Sea
ATLANTIC OCEAN
Stockholm
Riga
Minsk
North Sea
Vilnius
Copenhagen
Kiev
Warsaw
Dublin
Berlin
London
Amsterdam
Brussels

Geography

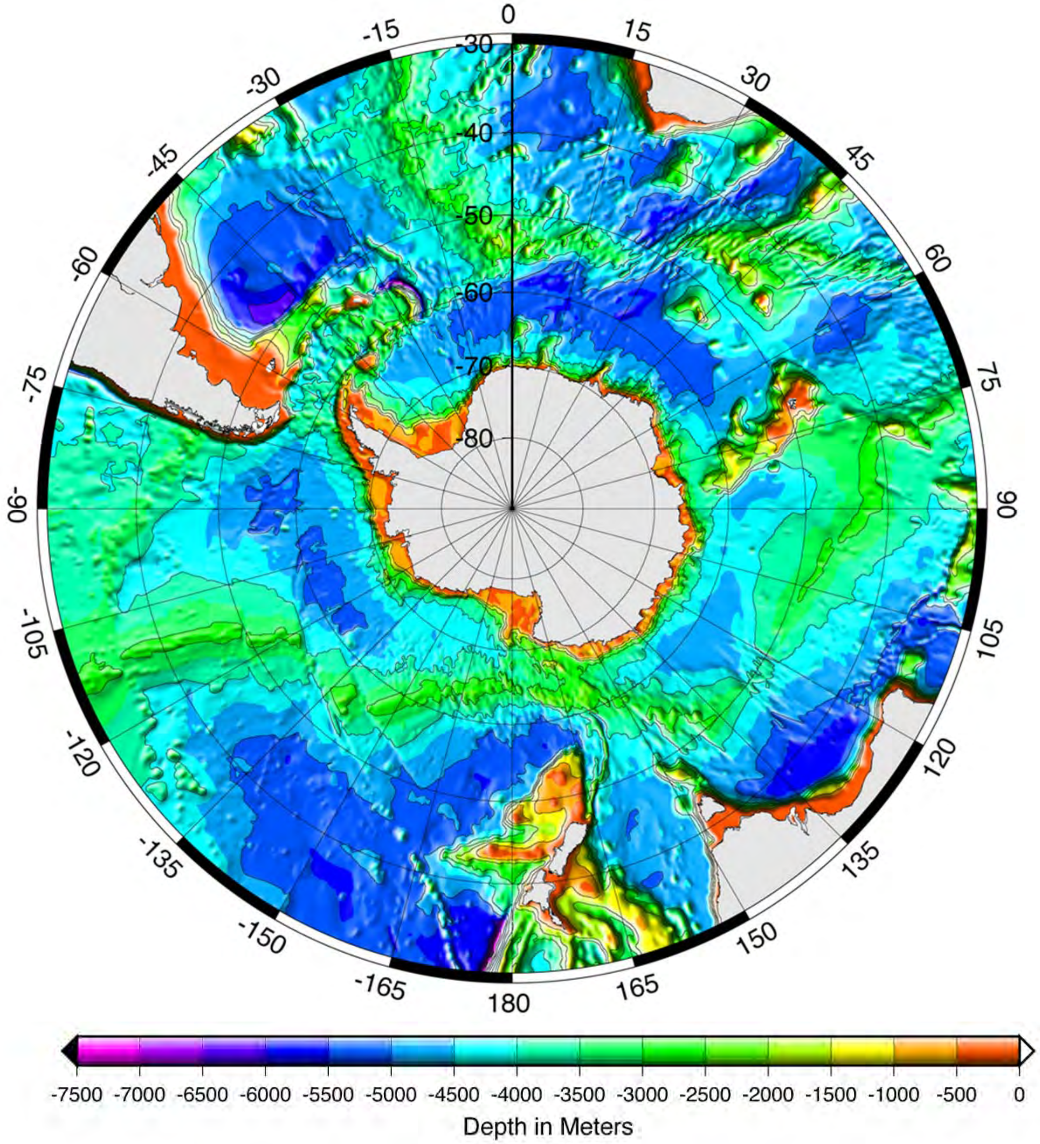
Victoria Island
Canada
Banks Island
Queen Elizabeth Islands
Denmark (Greenland)
Ellesmere Island
USA (Alaska)
Beaufort Sea
Iceland
Chukchi Sea
Greenland Sea
North Pole
WWW.FREEWORLDMAPS.NET
Svalbard
Arctic Ocean
East Siberian Sea
Norwegian Sea
Norway
Franz Josef Land
New Siberian Islands
Severnaya Zamlya
Laptev Sea
Finnland
Barents Sea
Novaya Zemlya
Kara Sea
Russia

Arctic vs. Antarctic



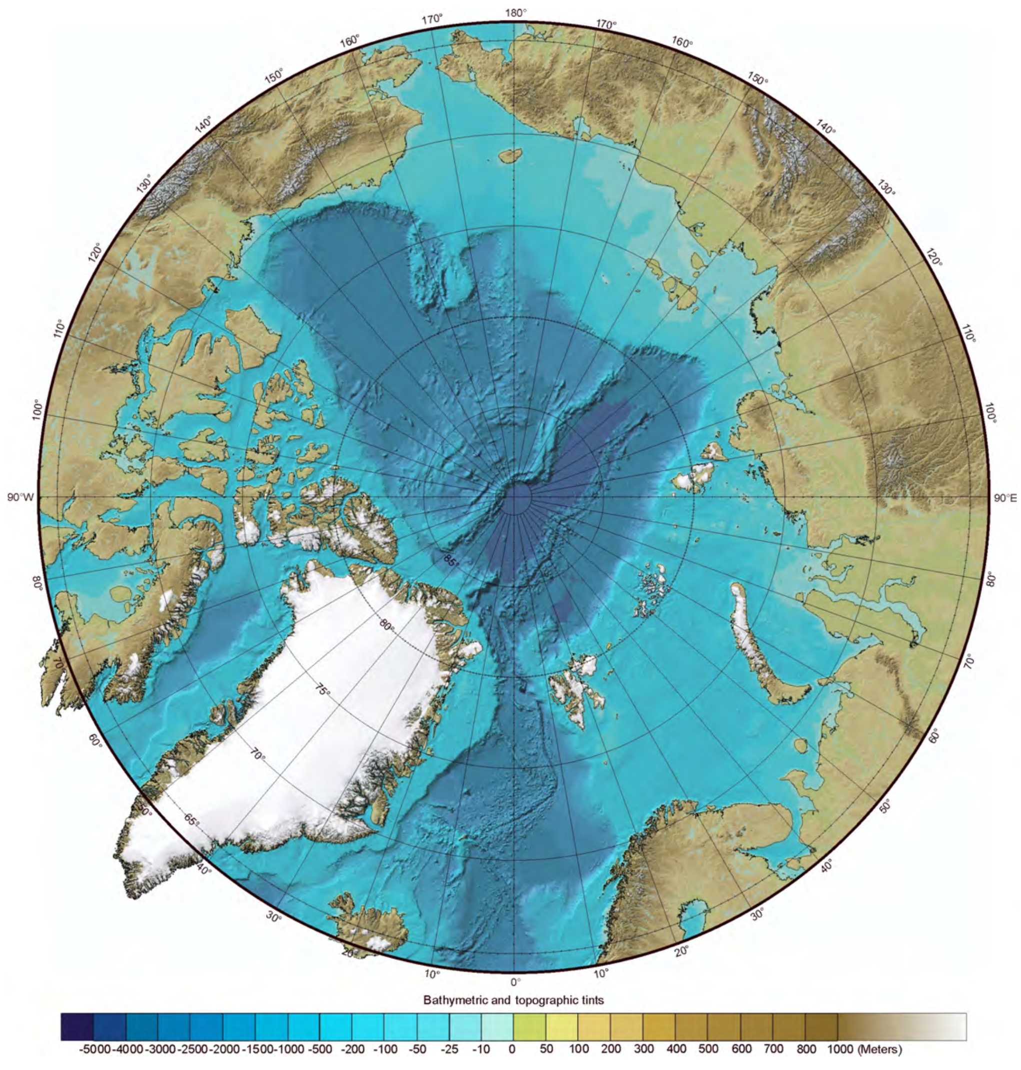
http://www.cnes.fr

Bathymetry



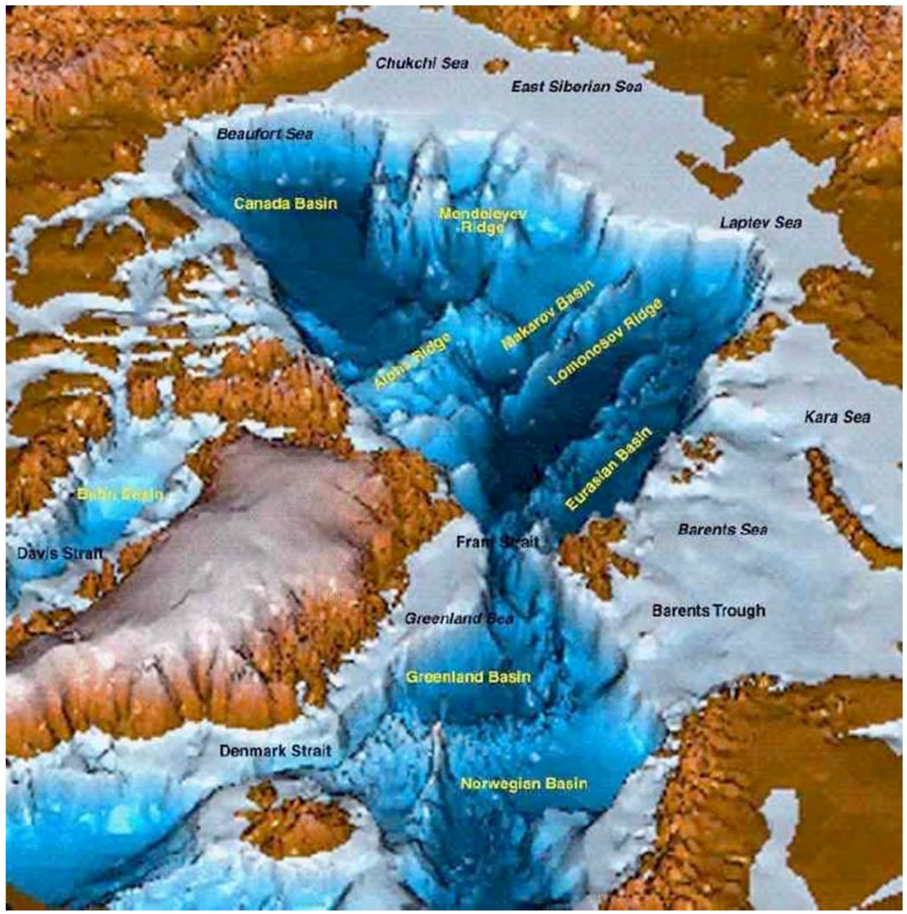
http://www.ngdc.noaa.gov/mgg/bathymetry/apb/

Bathymetry

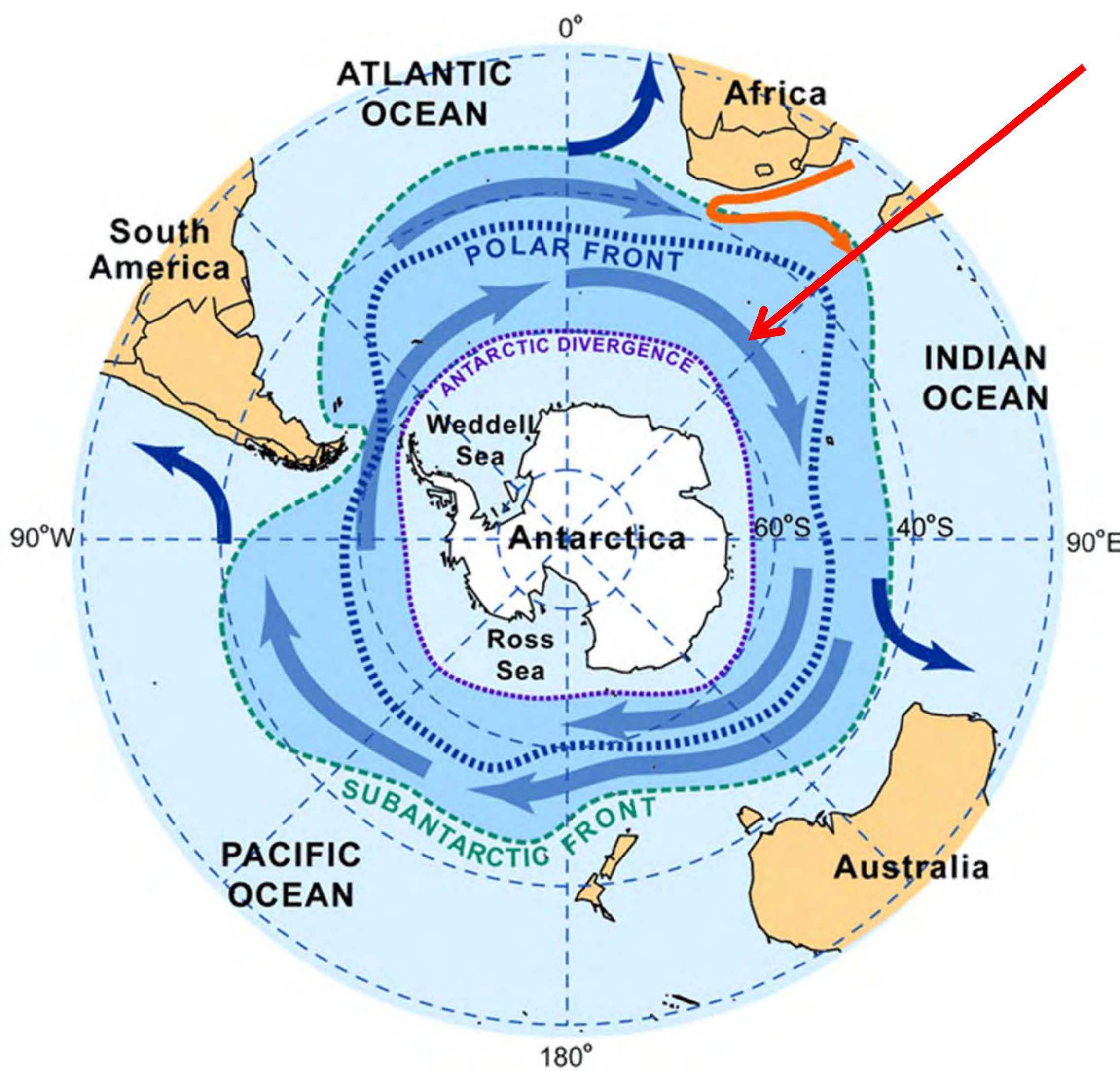


Shelves occupy more than 50% of the Arctic Ocean area

Bathymetry


Chukchi Sea
East Siberian Sea
Beaufort Sea
Canada Basin
Mendeleyev Ridge
Laptev Sea
Makarov Basin
Lomonosov Ridge
Alpha Ridge
Kara Sea
Eurasian Basin
Barents Sea
Davis Strait
Fram Strait
Barents Trough
Greenland Sea
Greenland Basin
Denmark Strait
Norwegian Basin

Circulation

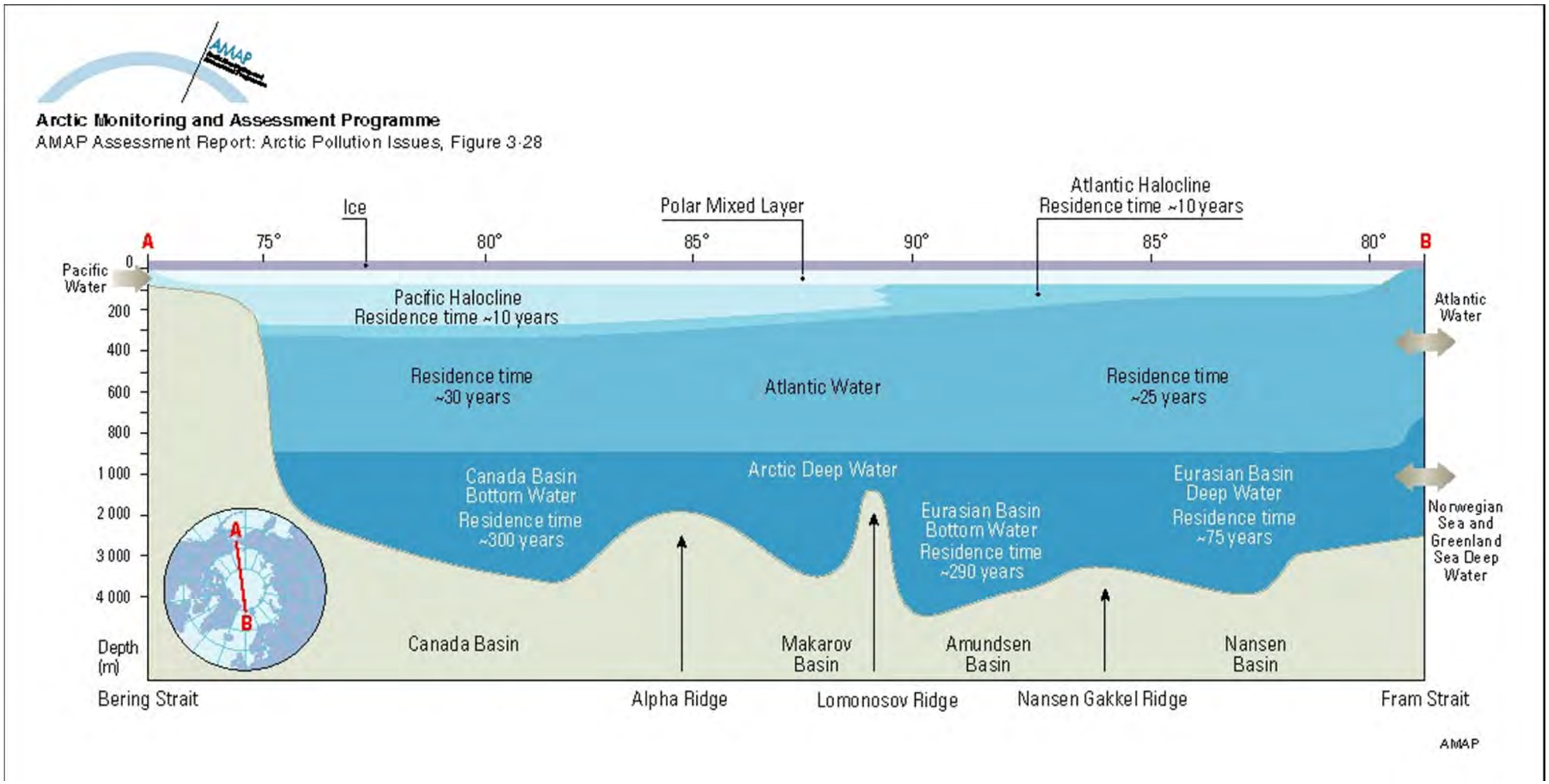


Antarctic Circumpolar Current

http://www.noc.soton.ac.uk

Circulation

Water masses



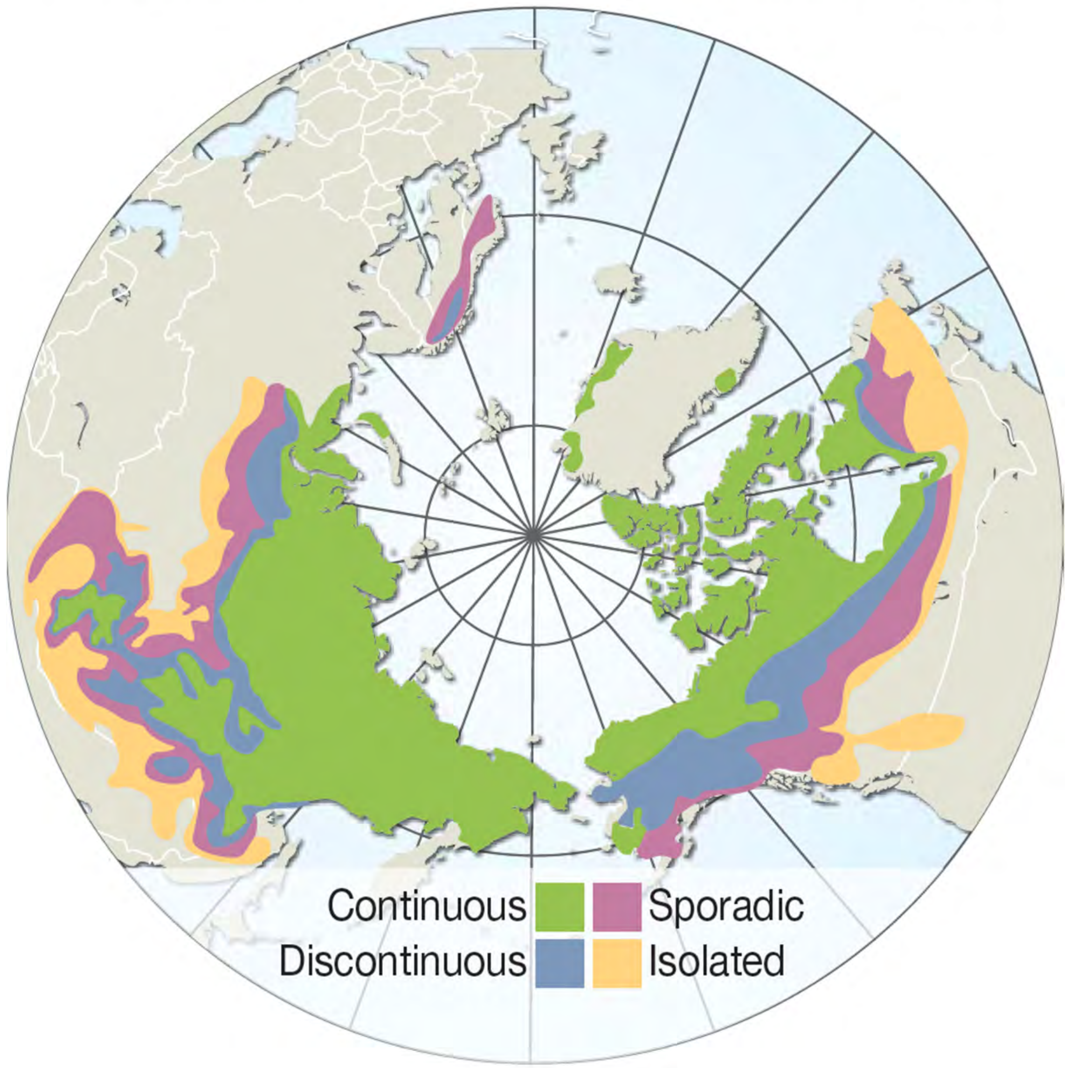
Freshwater discharges

Arctic Ocean = 1% of Global Ocean

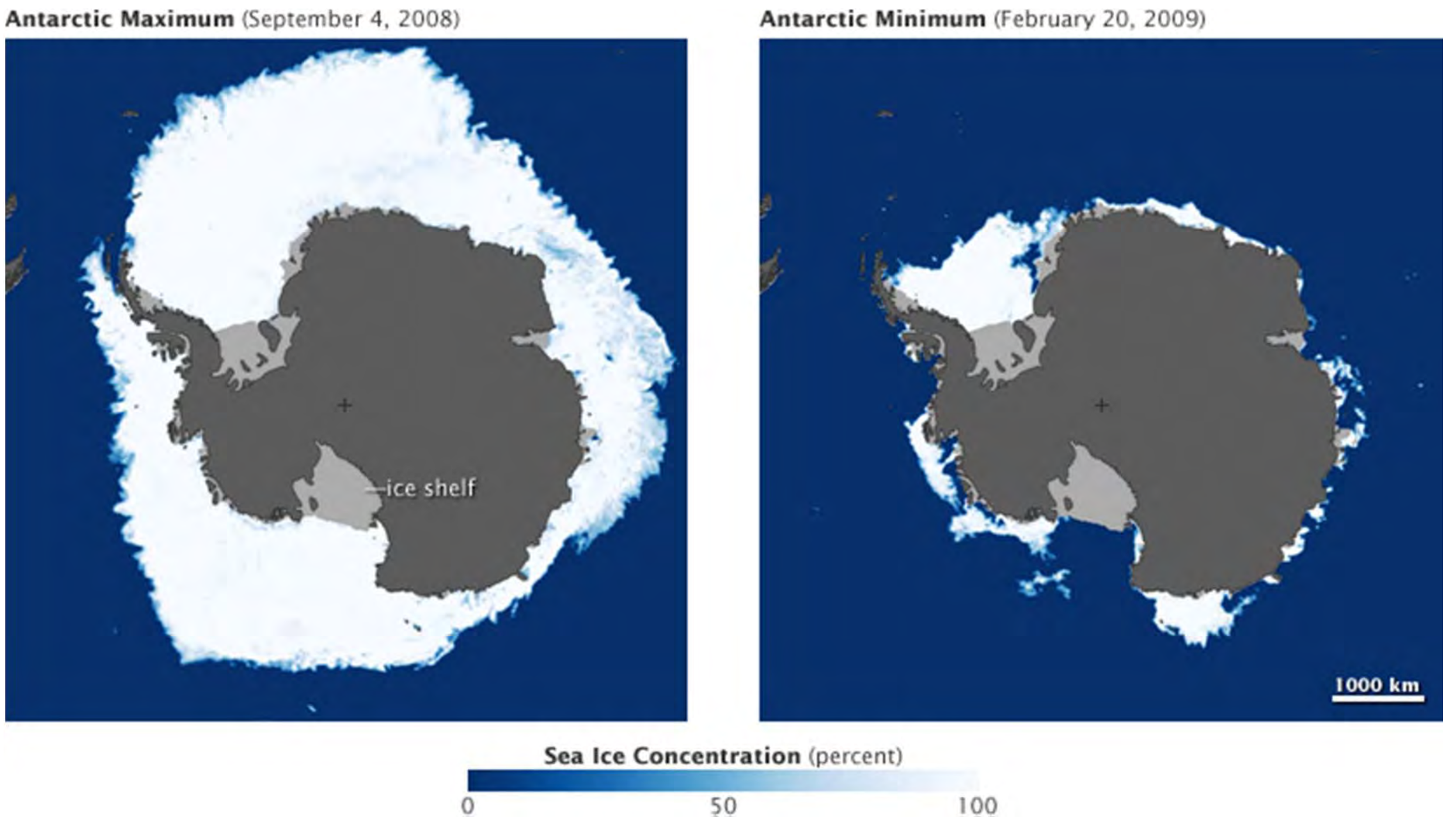
Arctic Ocean receives 10% of global freshwater discharge

AMAP

Observed Distribution of permafrost types

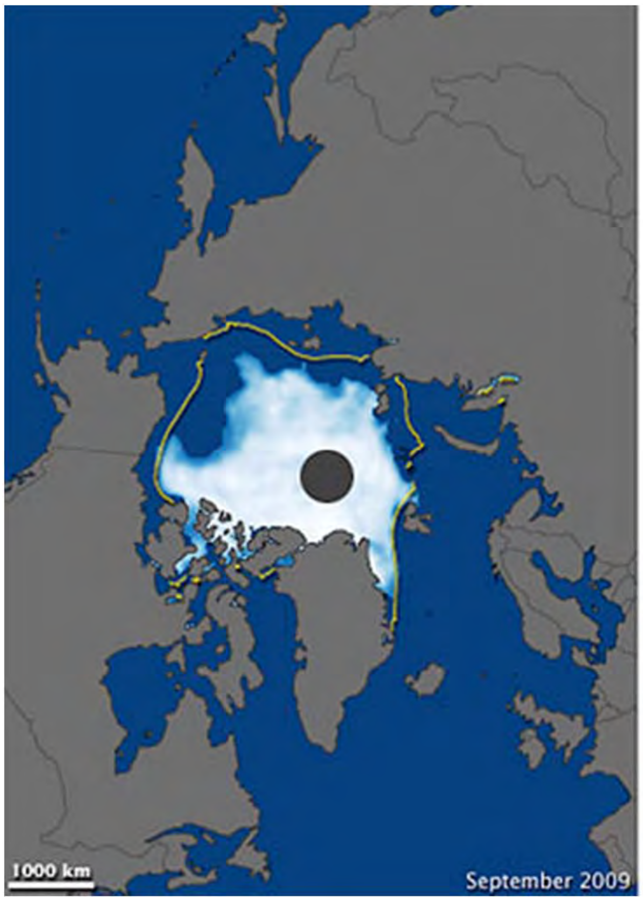


Sea ice



http://earthobservatory.nasa.gov

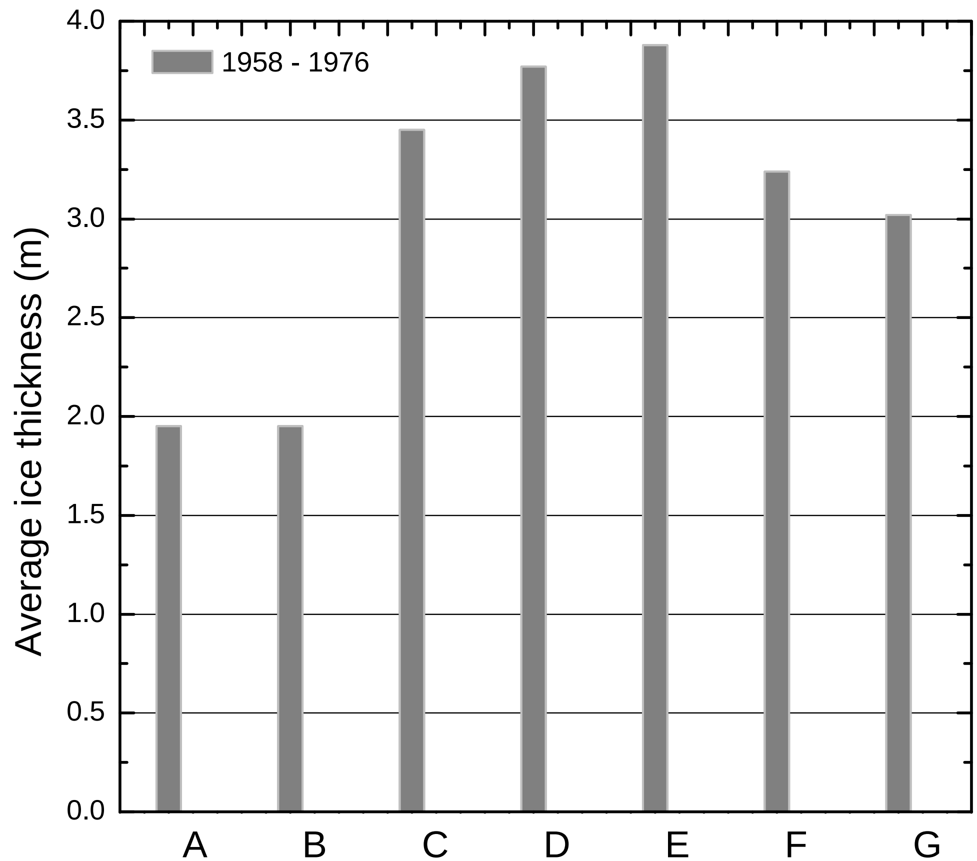
Sea ice



NSIDC

Sea ice thickness: then

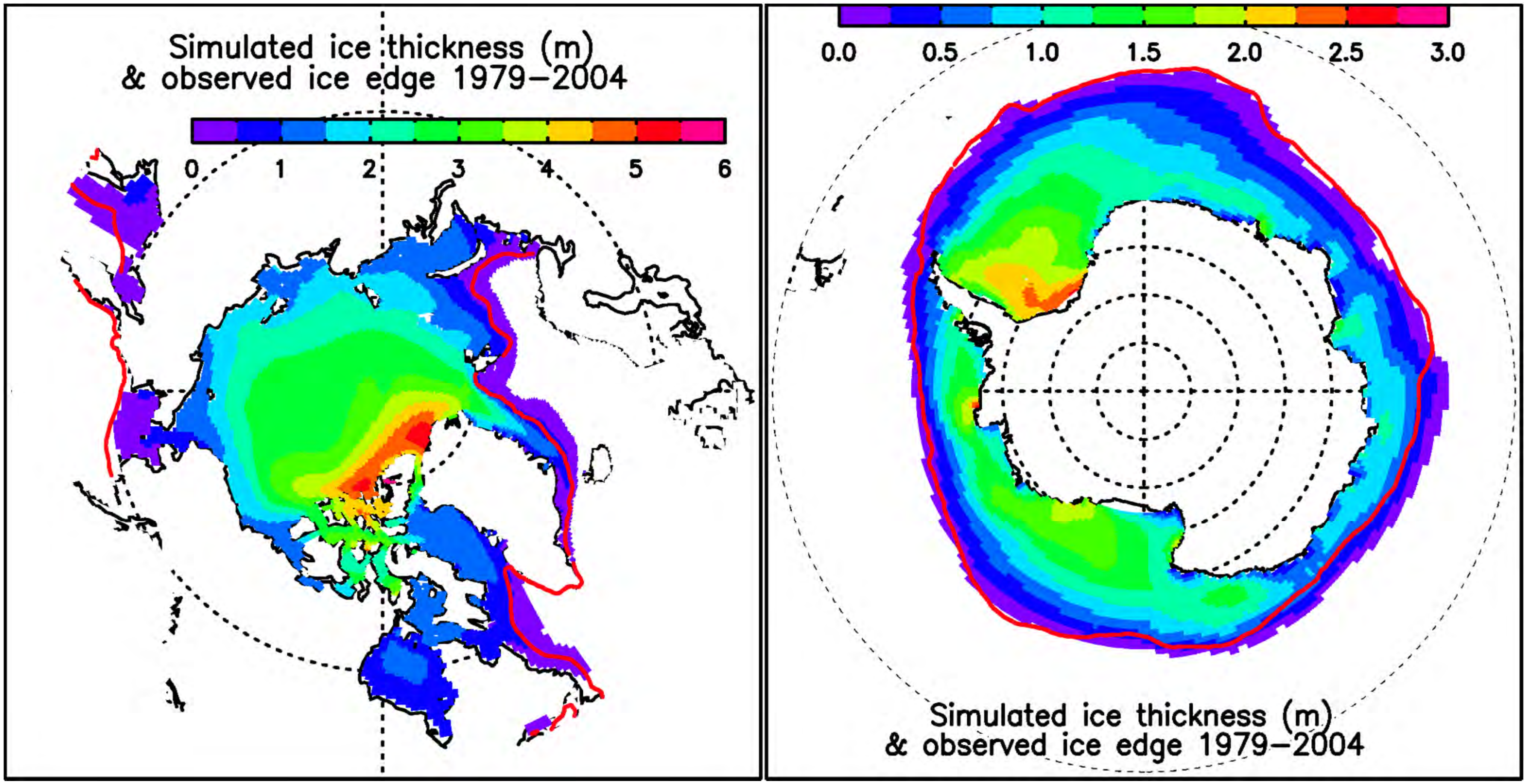
Summer ice thickness from 1958-1976



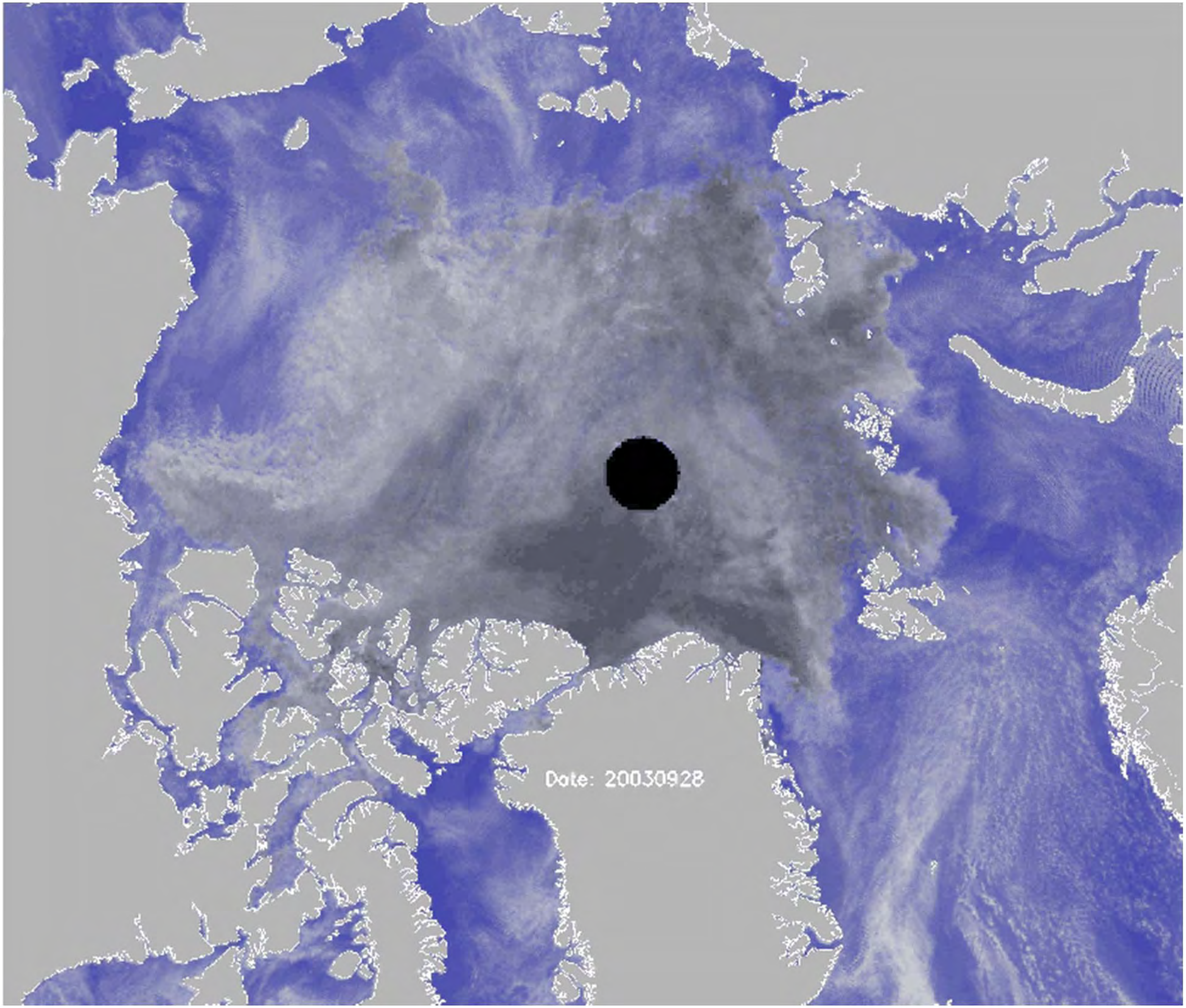
- Analysis of submarine data
- Rothrock et al.

Thick ice everywhere … even in summer

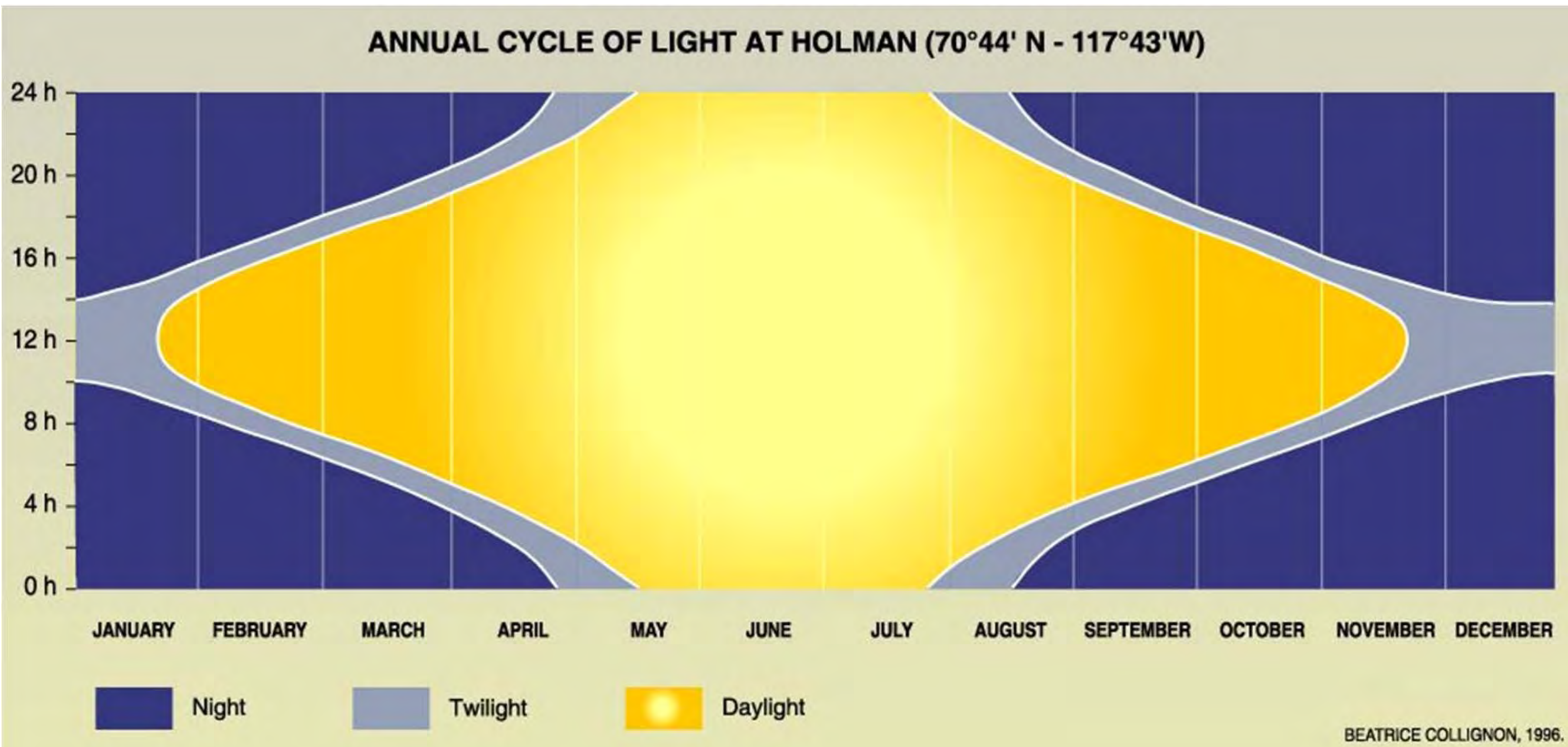
Courtesy of Don Perovich

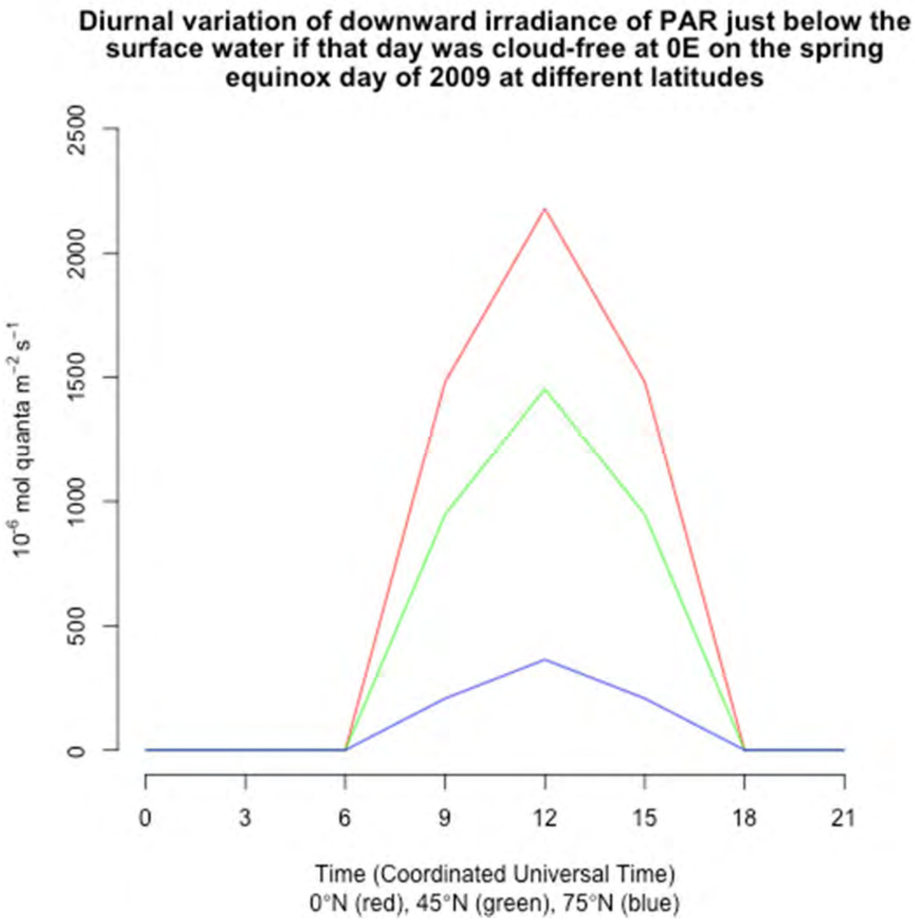


http://psc.apl.washington.edu/zhang/Global_seaice

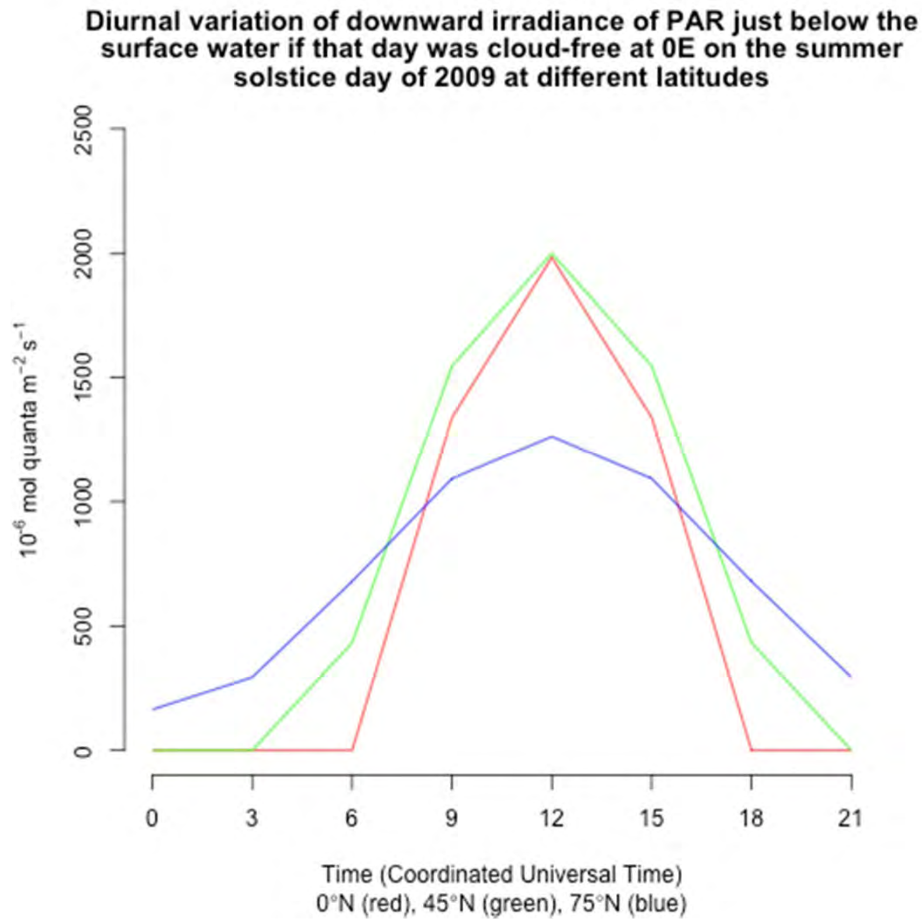

Date: 20030928

Light cycle

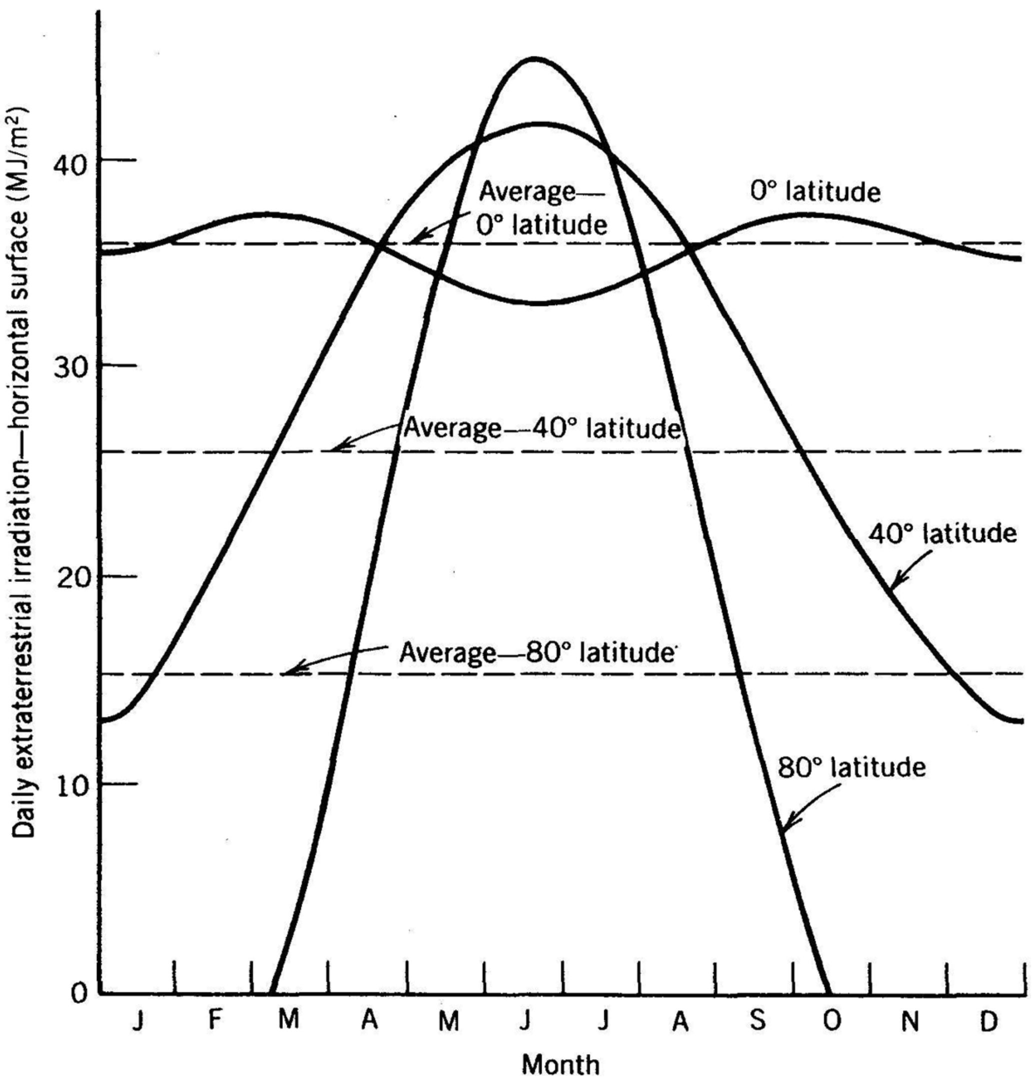

ANNUAL CYCLE OF LIGHT AT HOLMAN (70°44' N - 117°43'W)
24 h
20 h
16 h
12 h
8 h
4 h
0 h
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
Night
Twilight
Daylight
BEATRICE COLLIGNON, 1996.



Diurnal variation of downward irradiance of PAR just below the surface water if that day was cloud-free at 0E on the spring equinox day of 2009 at different latitudes
2500
2000
1500
1000
500
0
10^-6 mol quanta m^-2 s^-1
0
3
6
9
12
15
18
21
Time (Coordinated Universal Time)
0°N (red), 45°N (green), 75°N (blue)



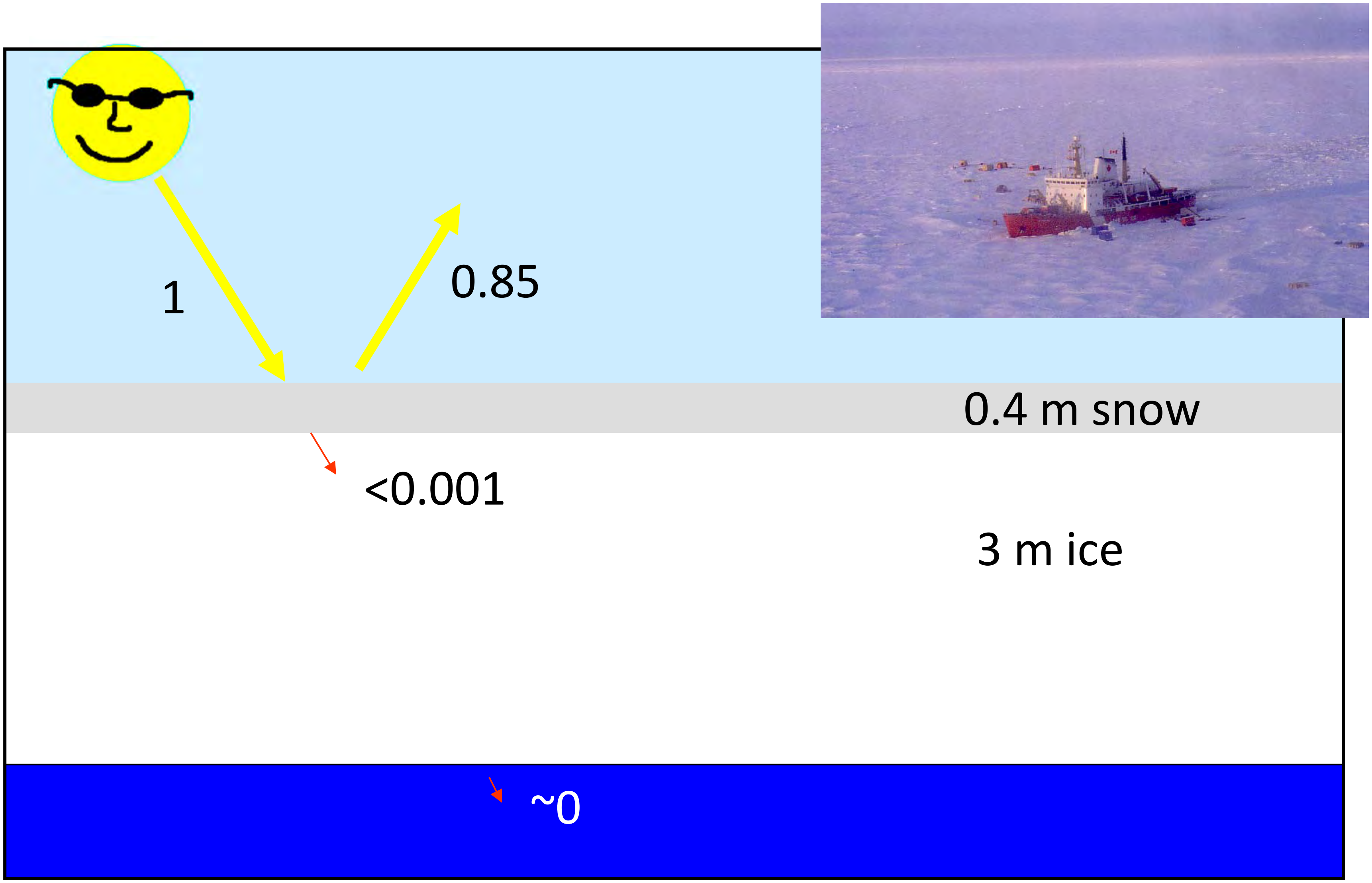
Diurnal variation of downward irradiance of PAR just below the surface water if that day was cloud-free at 0E on the summer solstice day of 2009 at different latitudes
2500
2000
1500
1000
500
0
10^-6 mol quanta m^-2 s^-1
0
3
6
9
12
15
18
21
Time (Coordinated Universal Time)
0°N (red), 45°N (green), 75°N (blue)



http://www.powerfromthesun.net

Light under sea ice

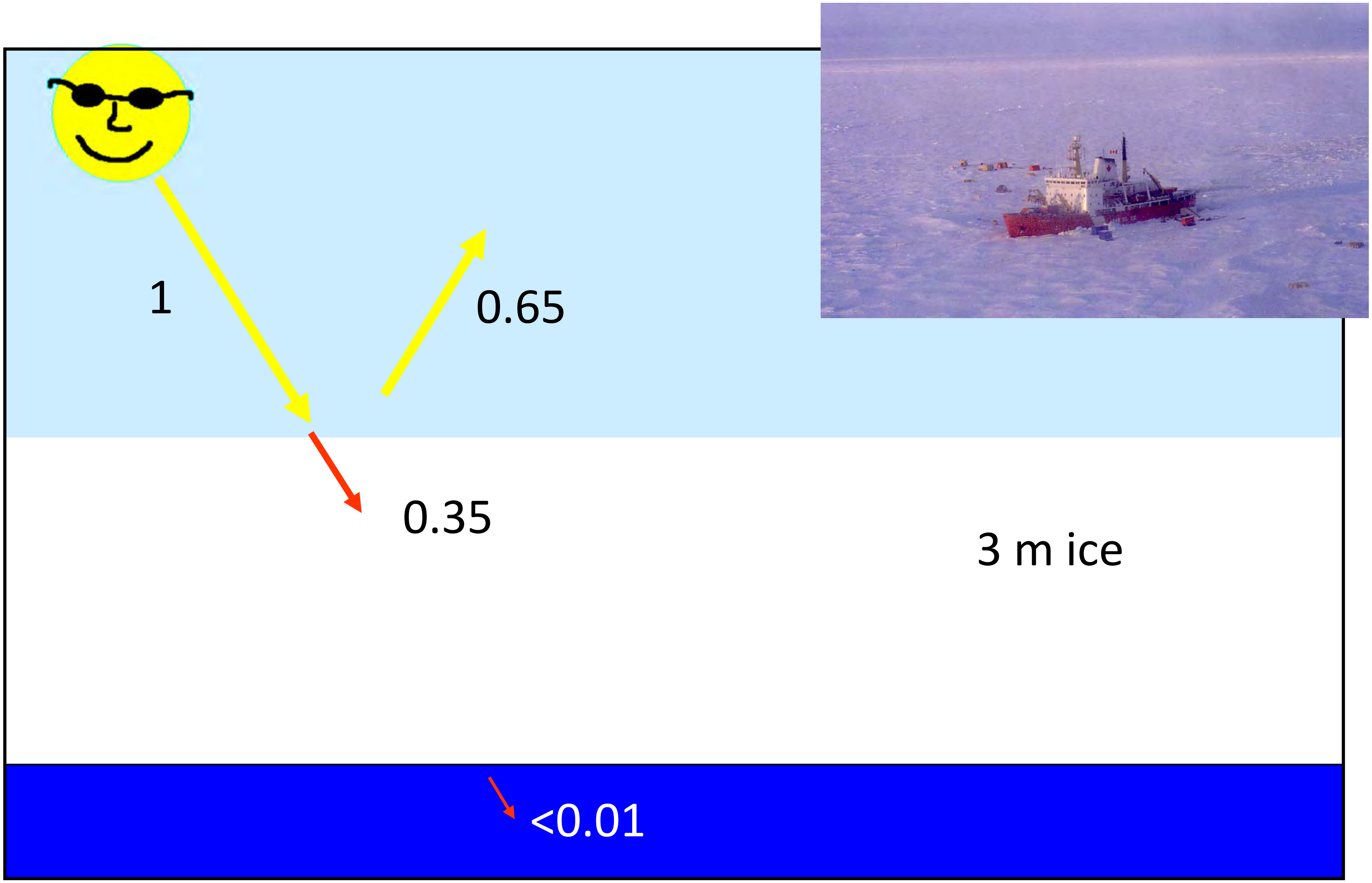
Back then: Assume a simple slab



Snow covered, thick, multiyear ice

Courtesy of Don Perovich

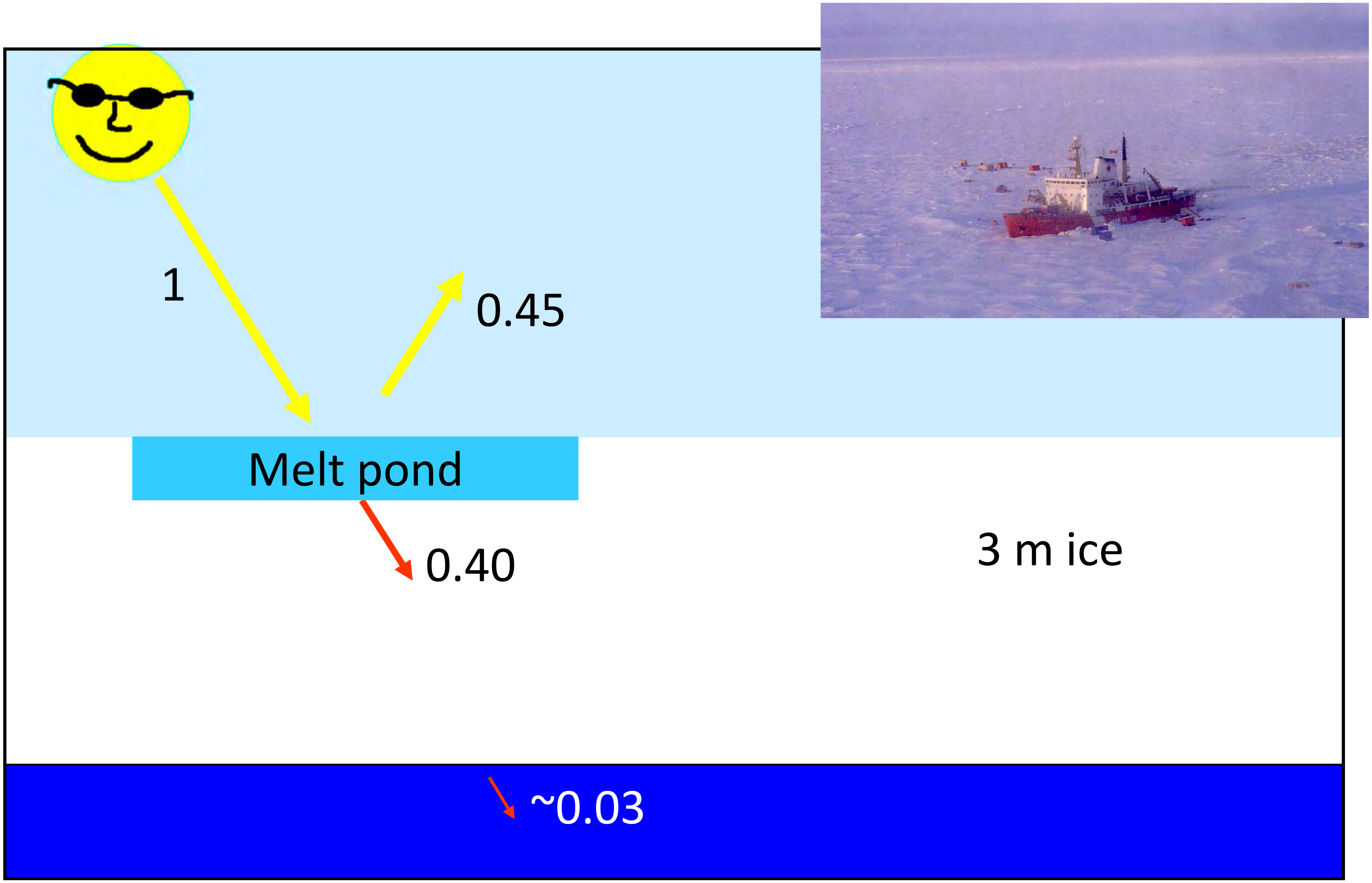
Back then: Assume a simple slab



Let the snow melt

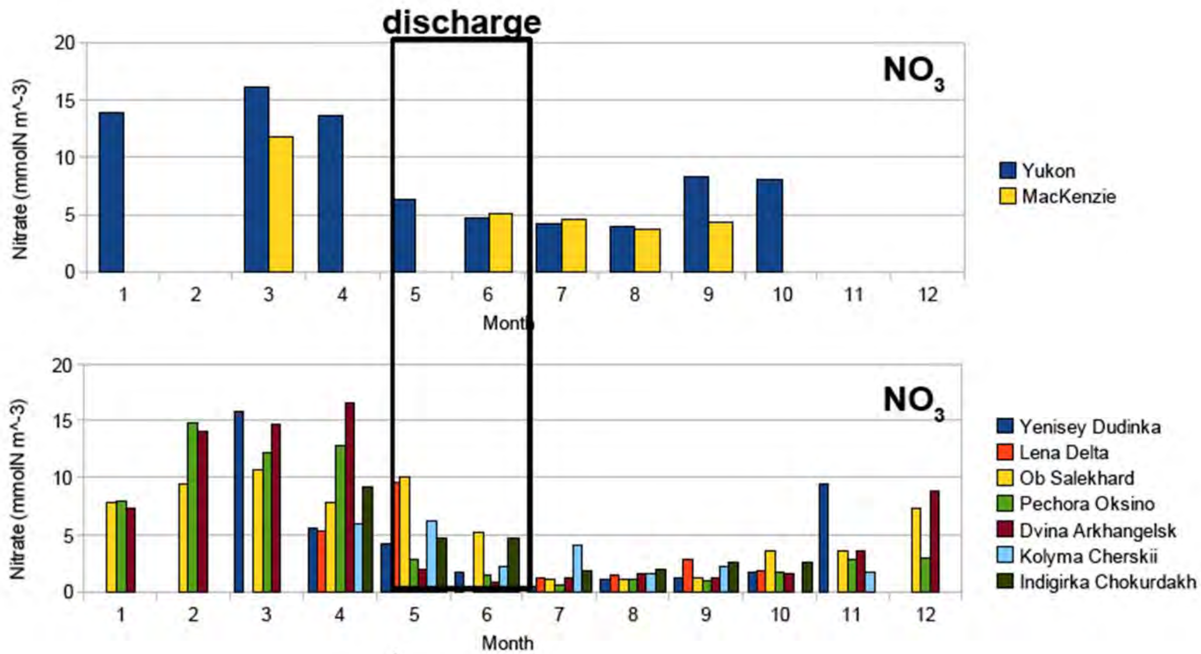
Courtesy of Don Perovich

Back then: Assume a simple slab



Let the snow melt and add a pond

Courtesy of Don Perovich



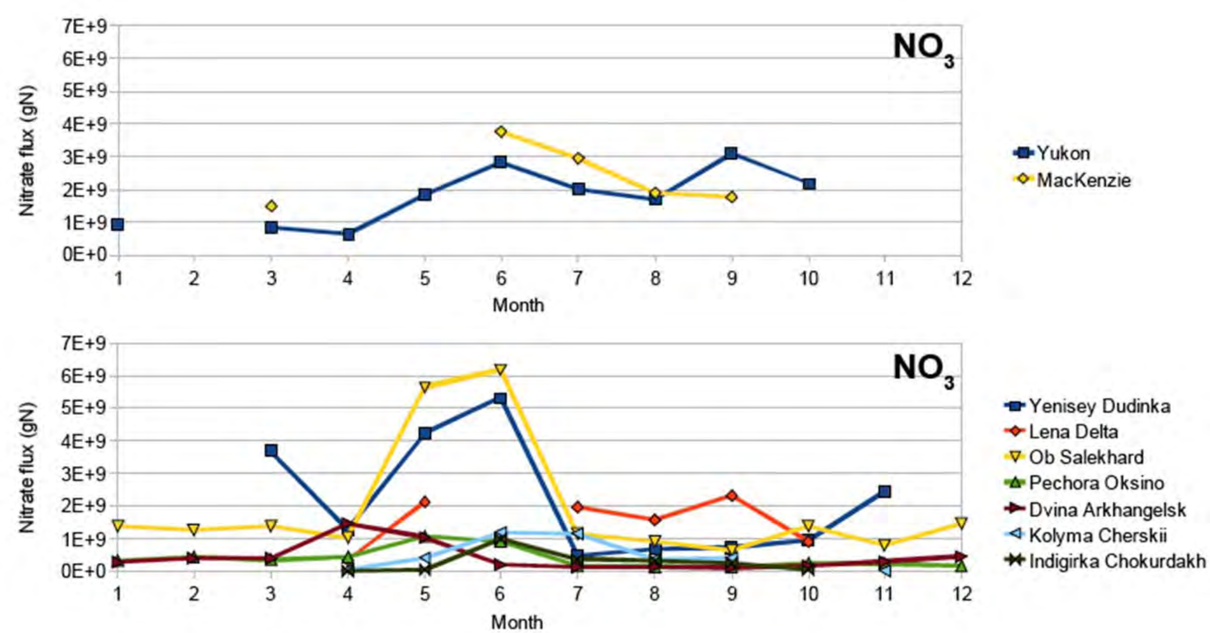
A monthly climatology of nitrate, phosphate, silicate, DON et DOC concentration was built-up:

- 9 publications et 2 databases
- 9 most important pan-arctic rivers

concentration

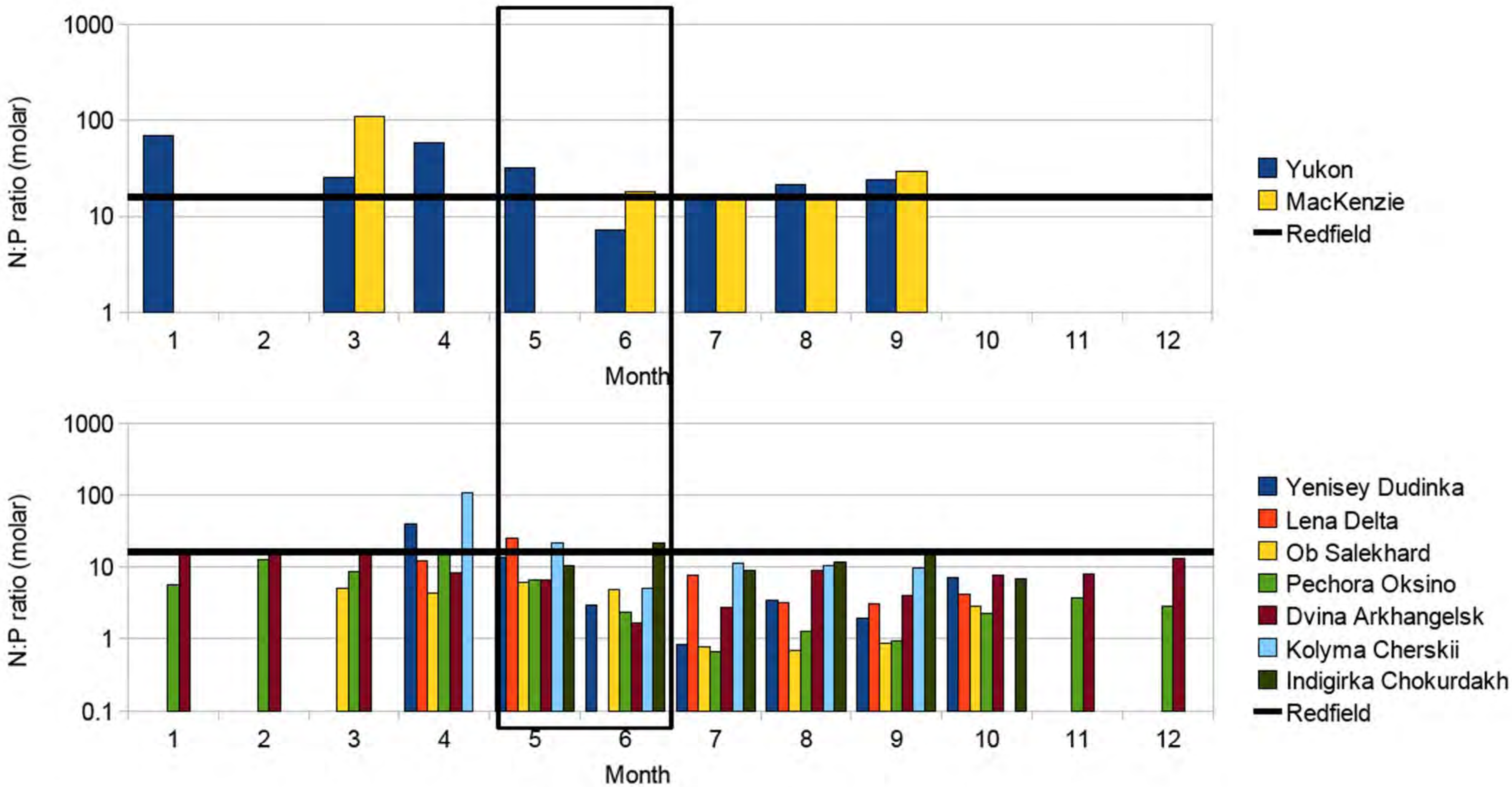
×

discharge



Lefouest et al.

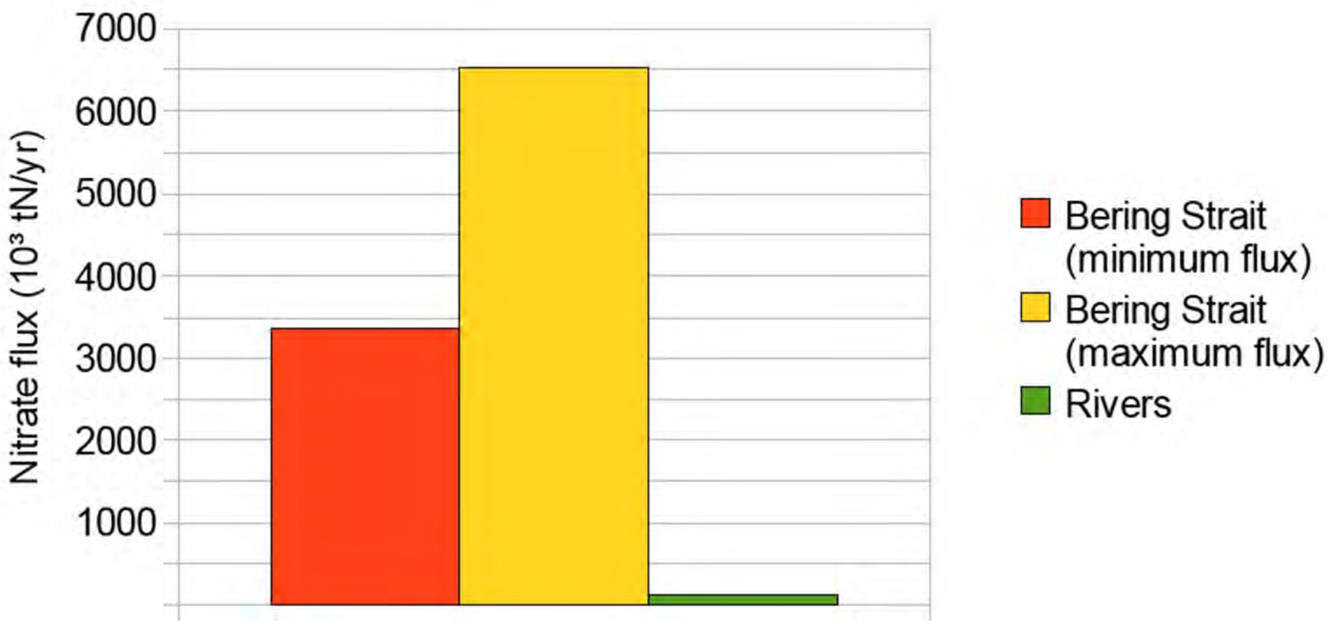
What contribution for riverine nitrate on PP?



During the peak of river discharge (May-June), riverine nitrate is limiting relative to riverine phosphate in 70% of the cases

Lefouest et al.

What contribution for riverine nitrate on PP?

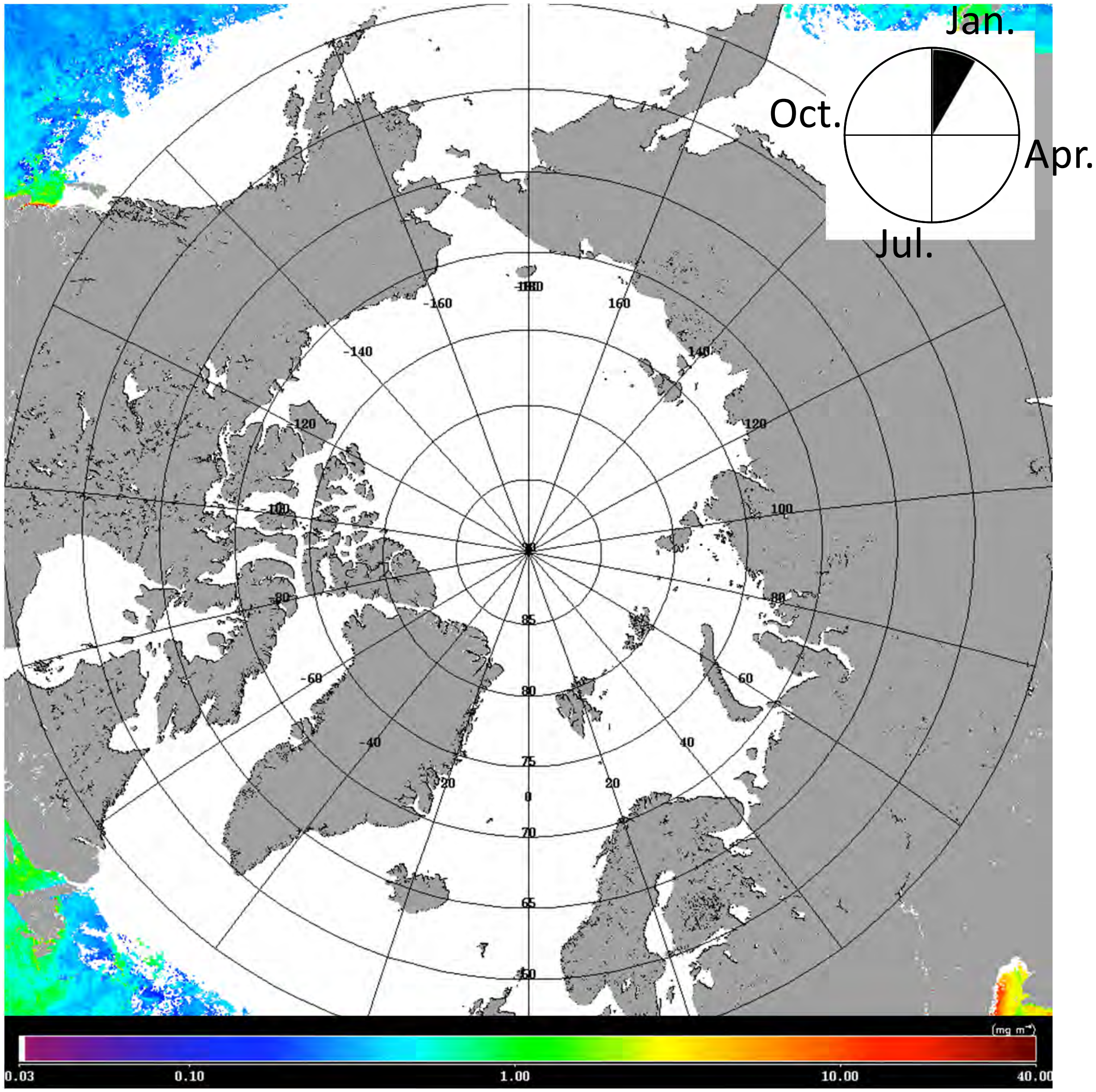


Assuming :
A total Arctic Ocean PP of ~350 TgC/yr
All nitrate are converted into biogenic carbon

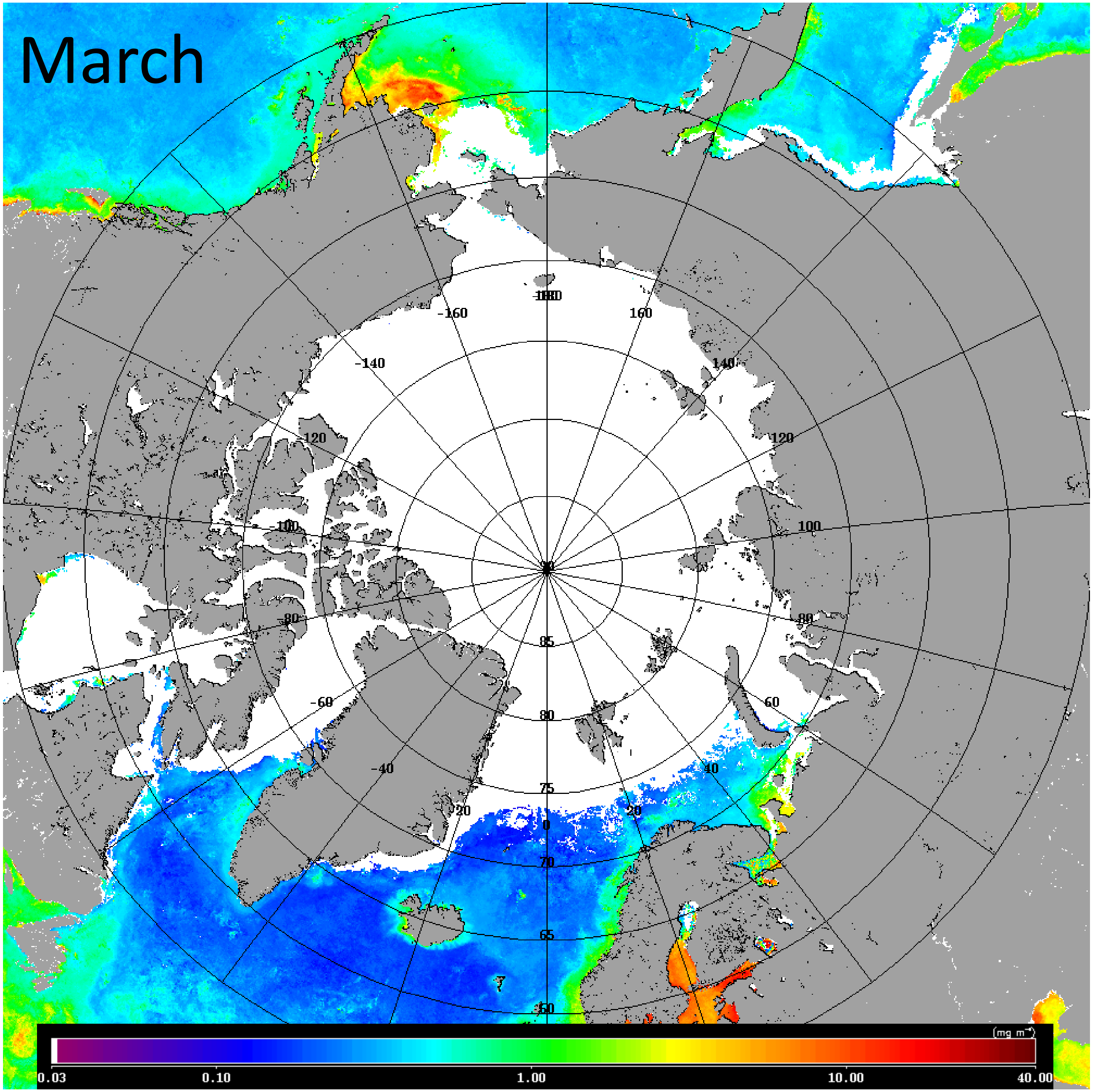
then:
Bering Strait inputs would account for 4-8% of the PP
Riverine inputs would account for 0.14% of the PP

Lefouest et al.

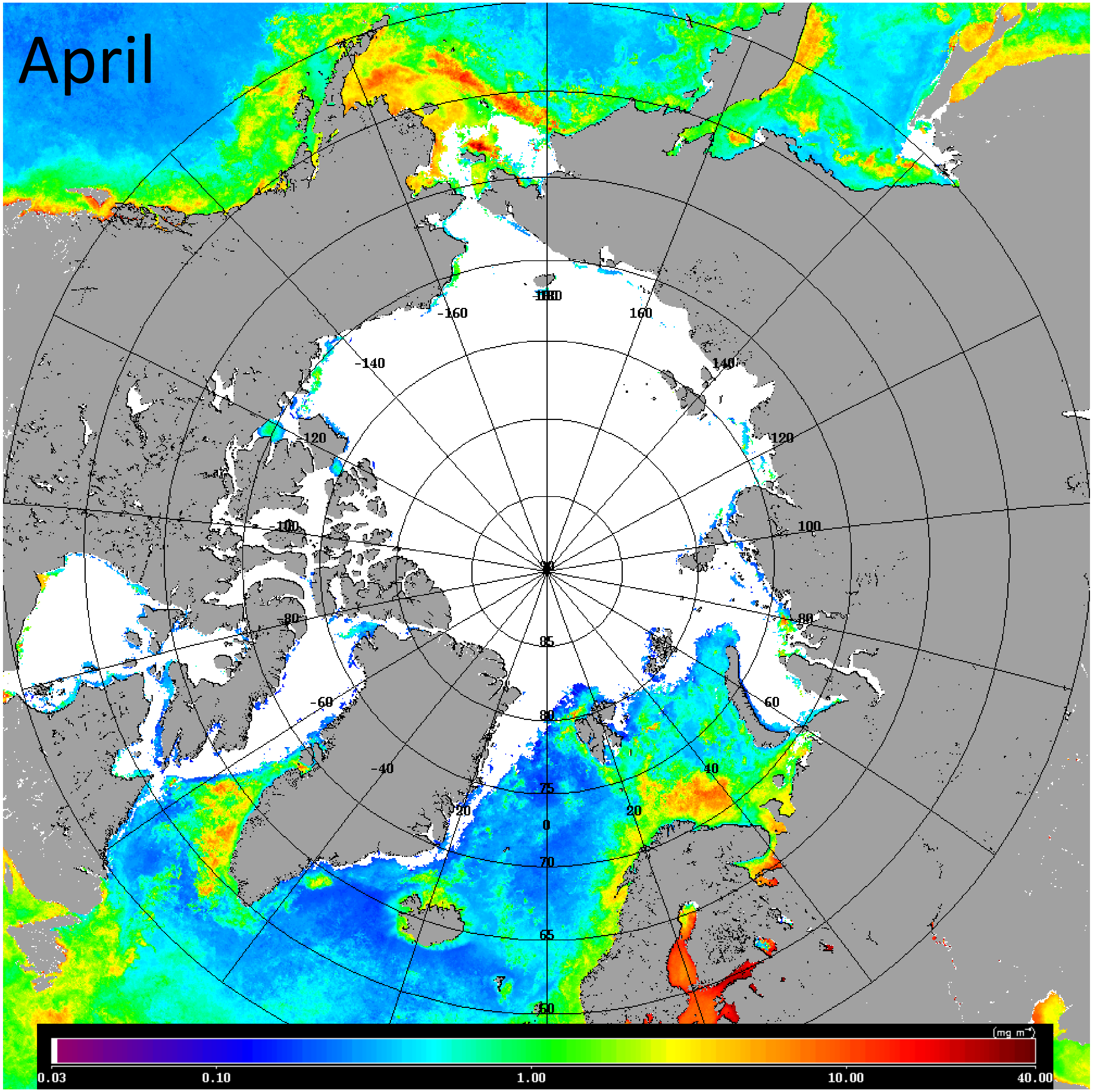
MODIS monthly climatology (2003 à 2011) of chlorophyll concentration

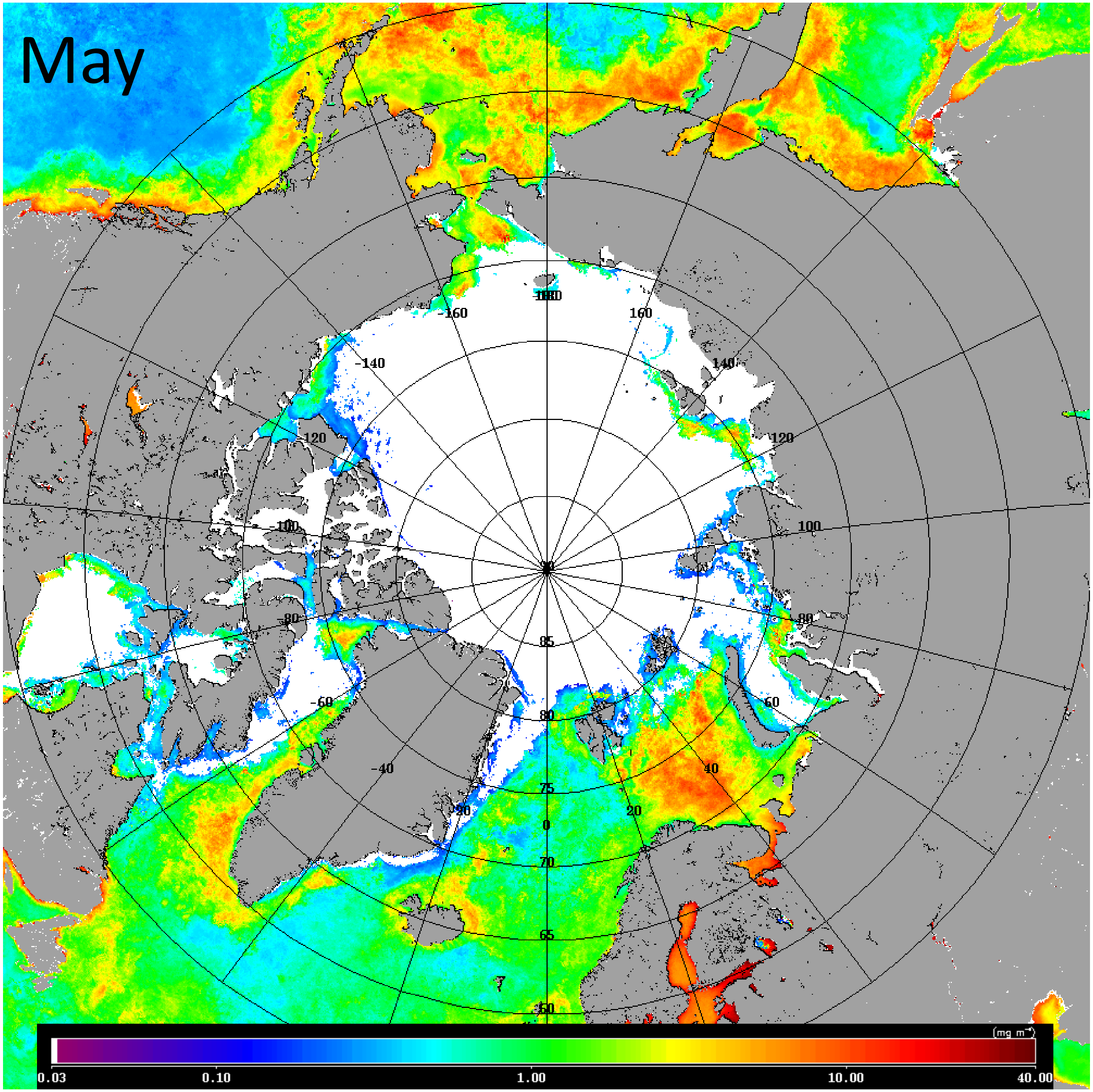


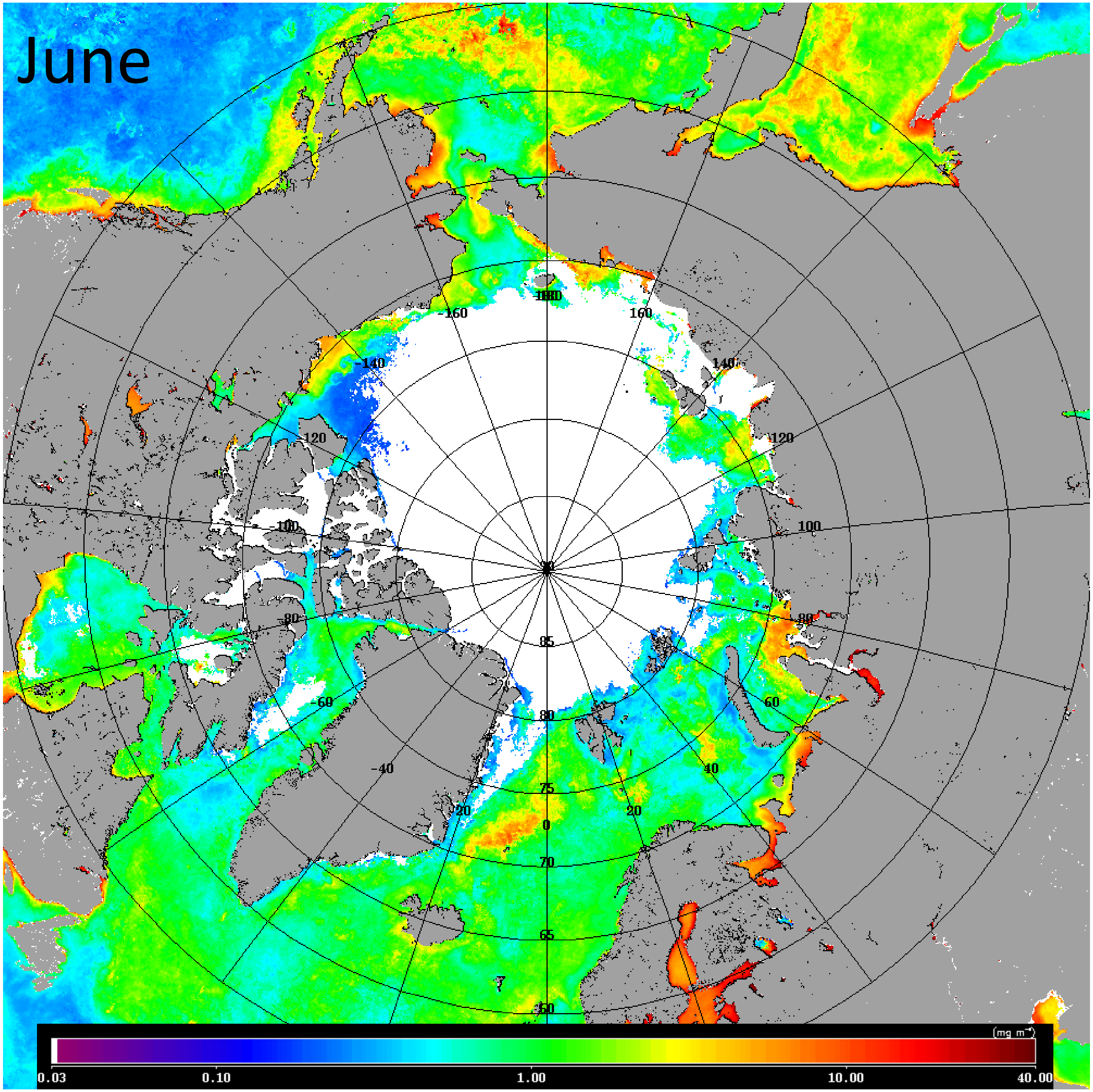
March

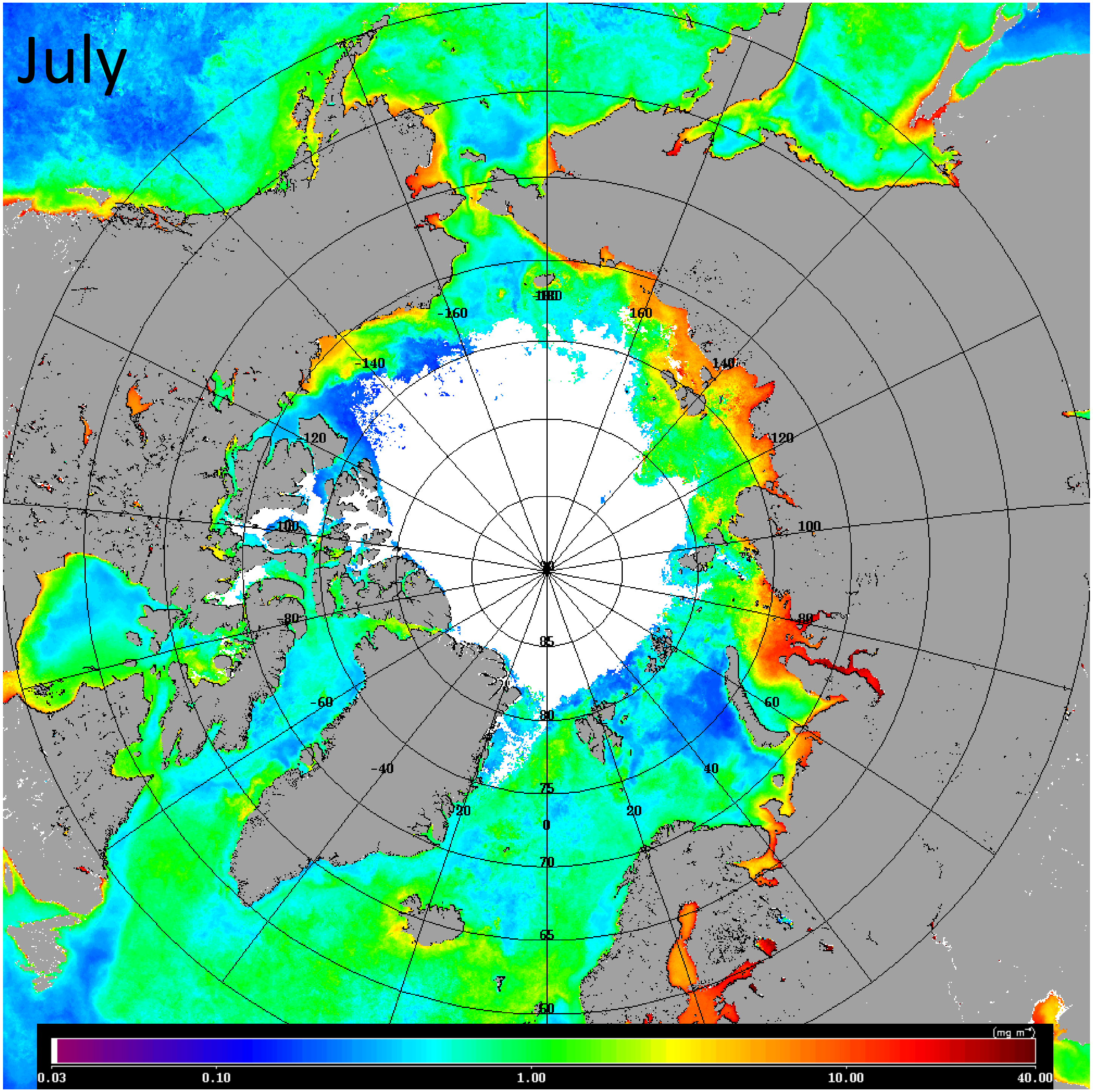


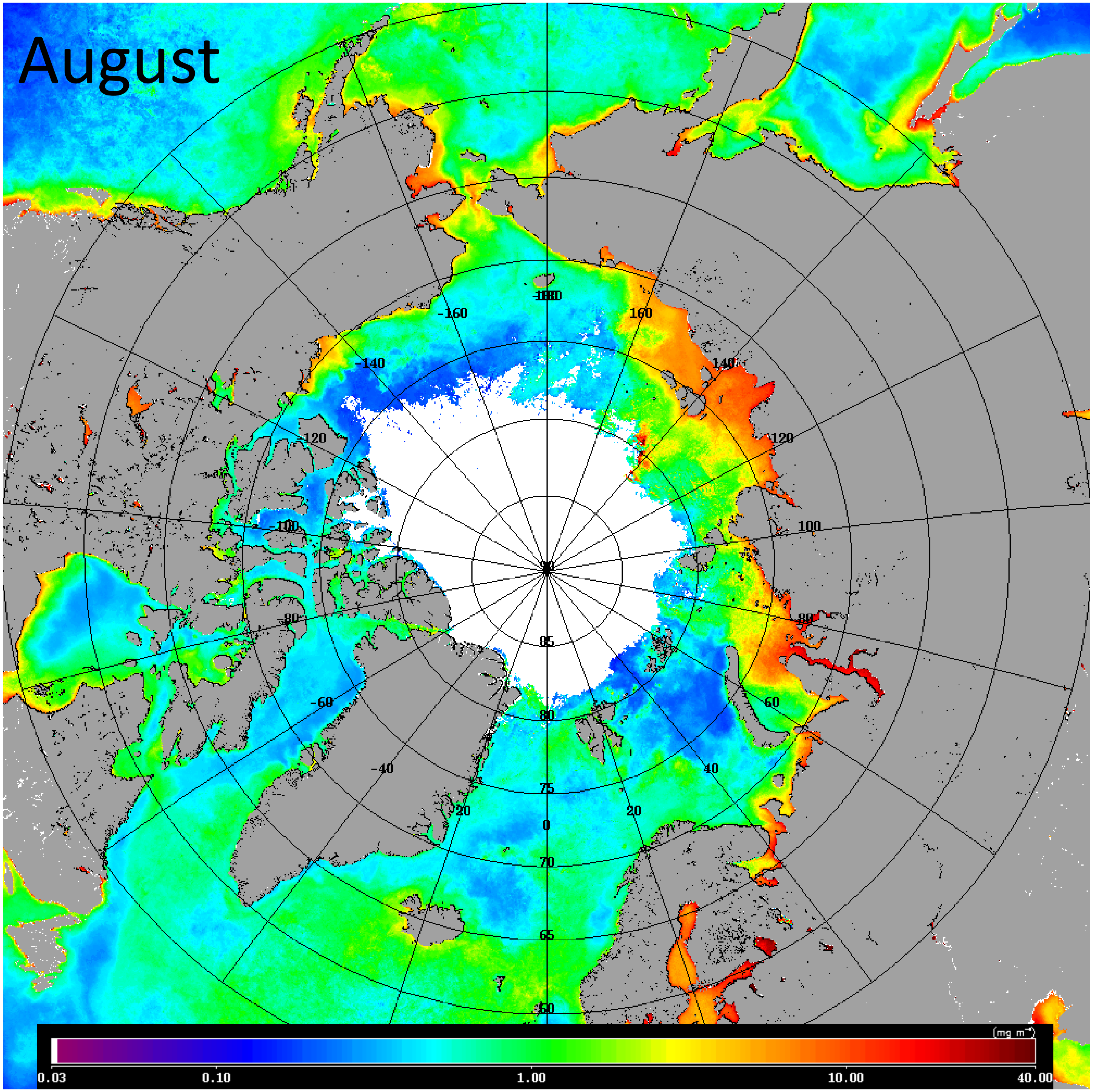
-160
180
160
-140
140
-120
120
-100
100
-80
80
85
-60
60
80
-40
40
75
-20
20
0
70
65
60
(mg m⁻³)
0.03
0.10
1.00
10.00
40.00


April
-160
180
160
-140
140
-120
120
-100
100
-80
80
85
-60
80
60
-40
40
75
-20
20
0
70
65
60
(mg m⁻³)
0.03
0.10
1.00
10.00
40.00

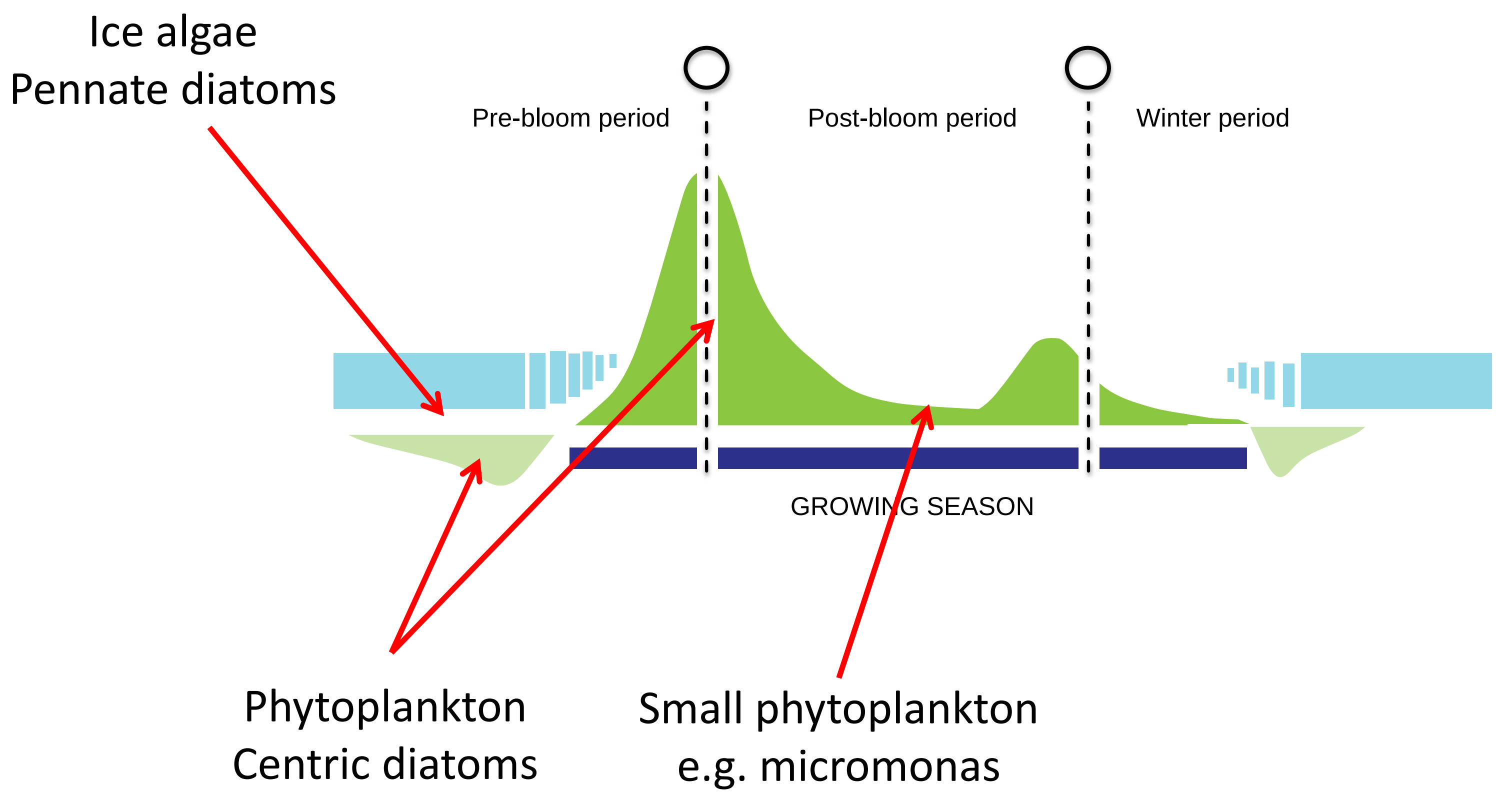

May
-160
180
160
-140
140
-120
120
-100
100
-80
80
-60
60
-40
40
-20
20
0
85
80
75
70
65
60
(mg m^{-3})
0.03
0.10
1.00
10.00
40.00


June
180
-160
160
-140
140
-120
120
-100
100
-80
80
-60
60
-40
40
-20
20
0
85
80
75
70
65
60
(mg m⁻³)
0.03
0.10
1.00
10.00
40.00

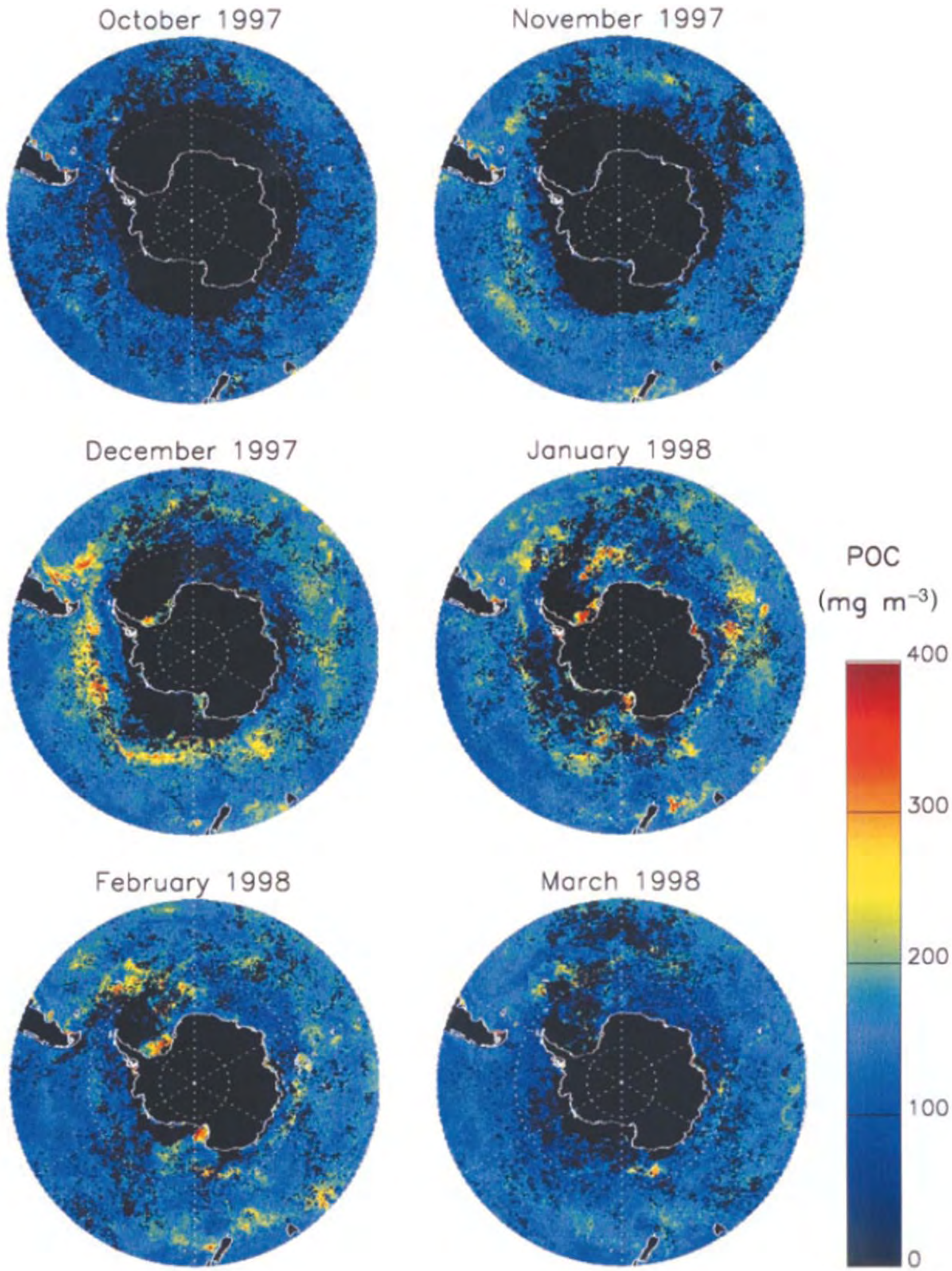

July
180
-160
160
-140
140
120
120
-100
100
-80
80
85
-60
60
80
-40
40
75
-20
20
0
70
65
60
(mg m⁻³)
0.03
0.10
1.00
10.00
40.00



August
-180
180
-160
160
-140
140
-120
120
-100
100
-80
80
-60
60
-40
40
-20
20
0
85
80
75
70
65
60
(mg m⁻³)
0.03
0.10
1.00
10.00
40.00

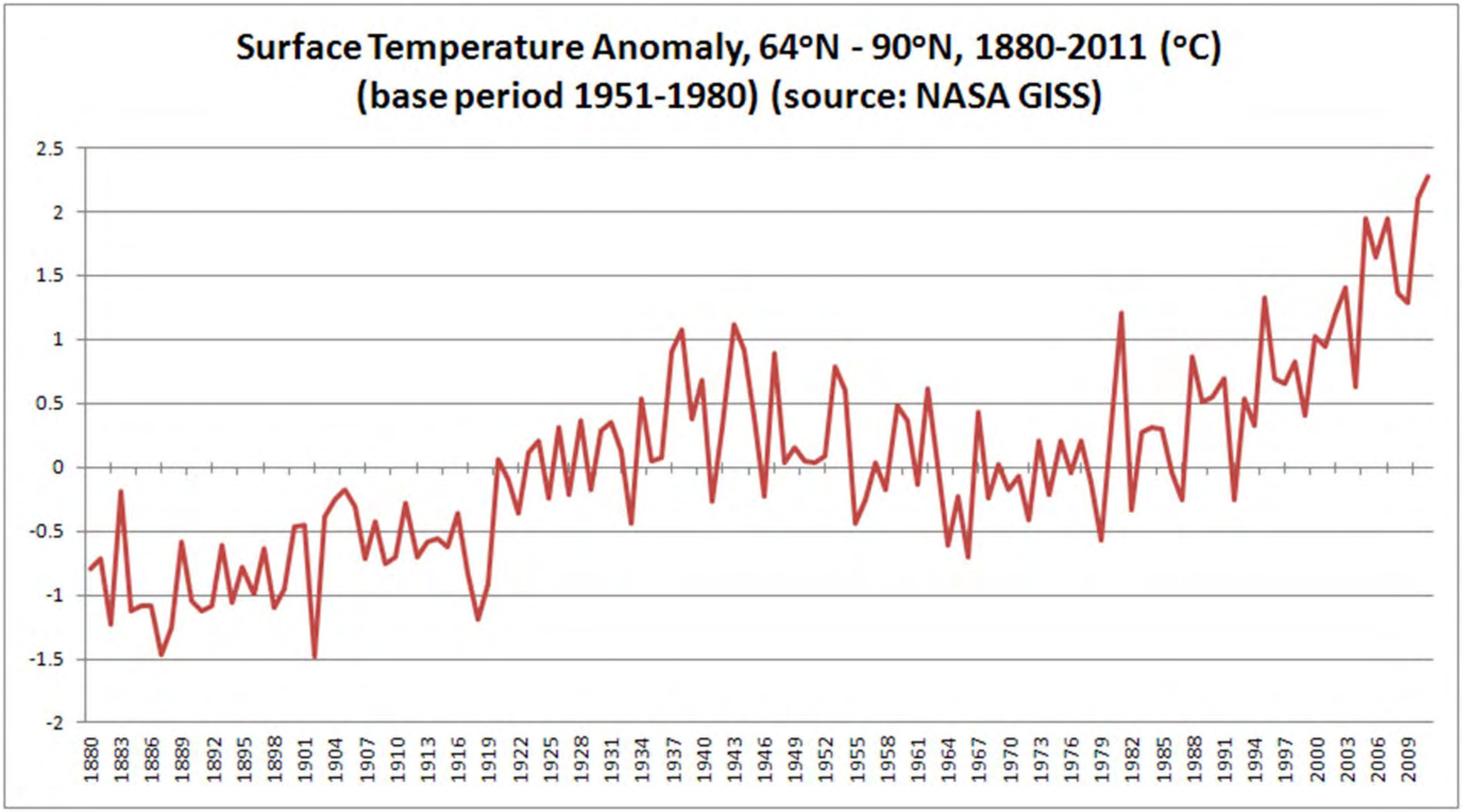


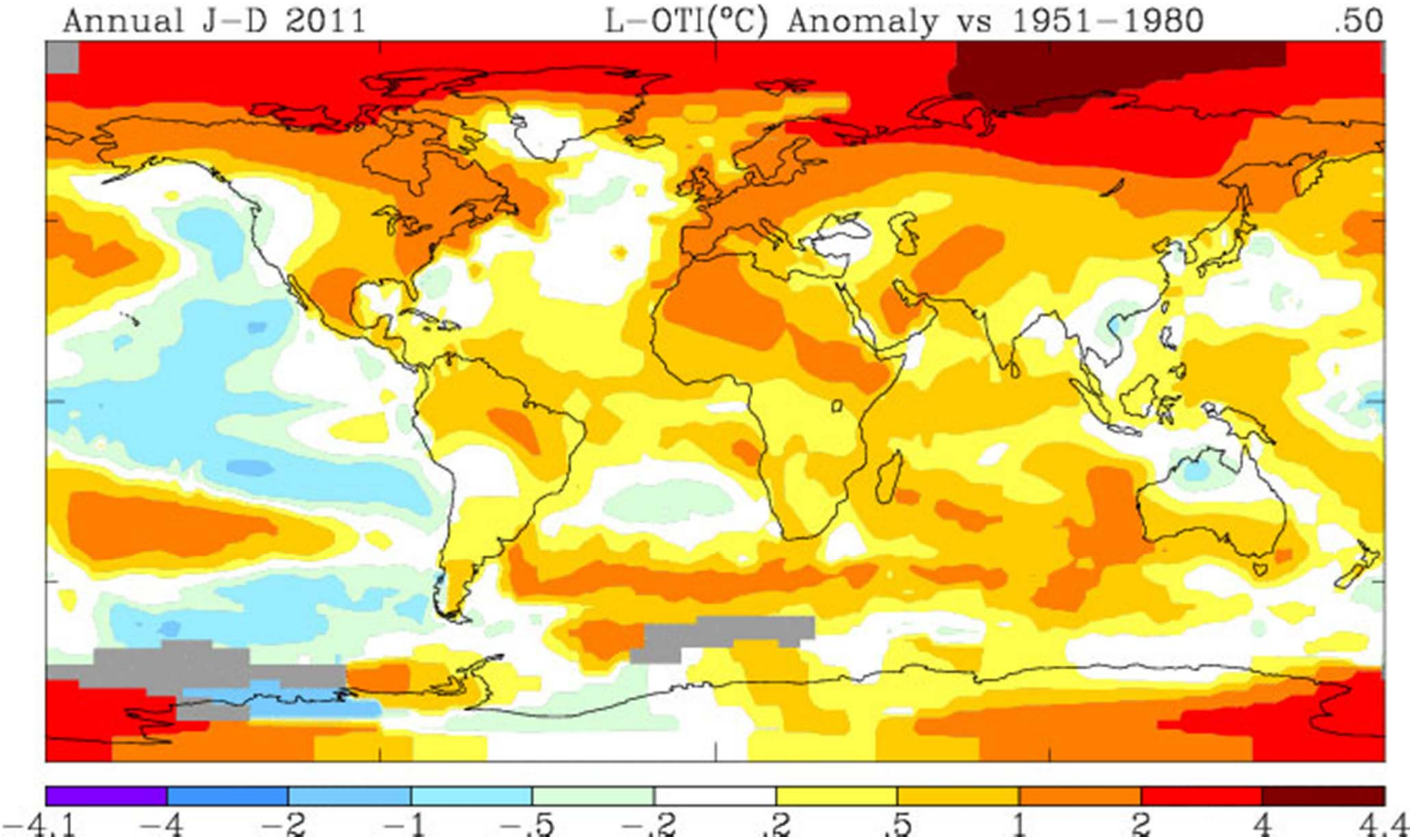
Courtesy of Mathieu Ardyna



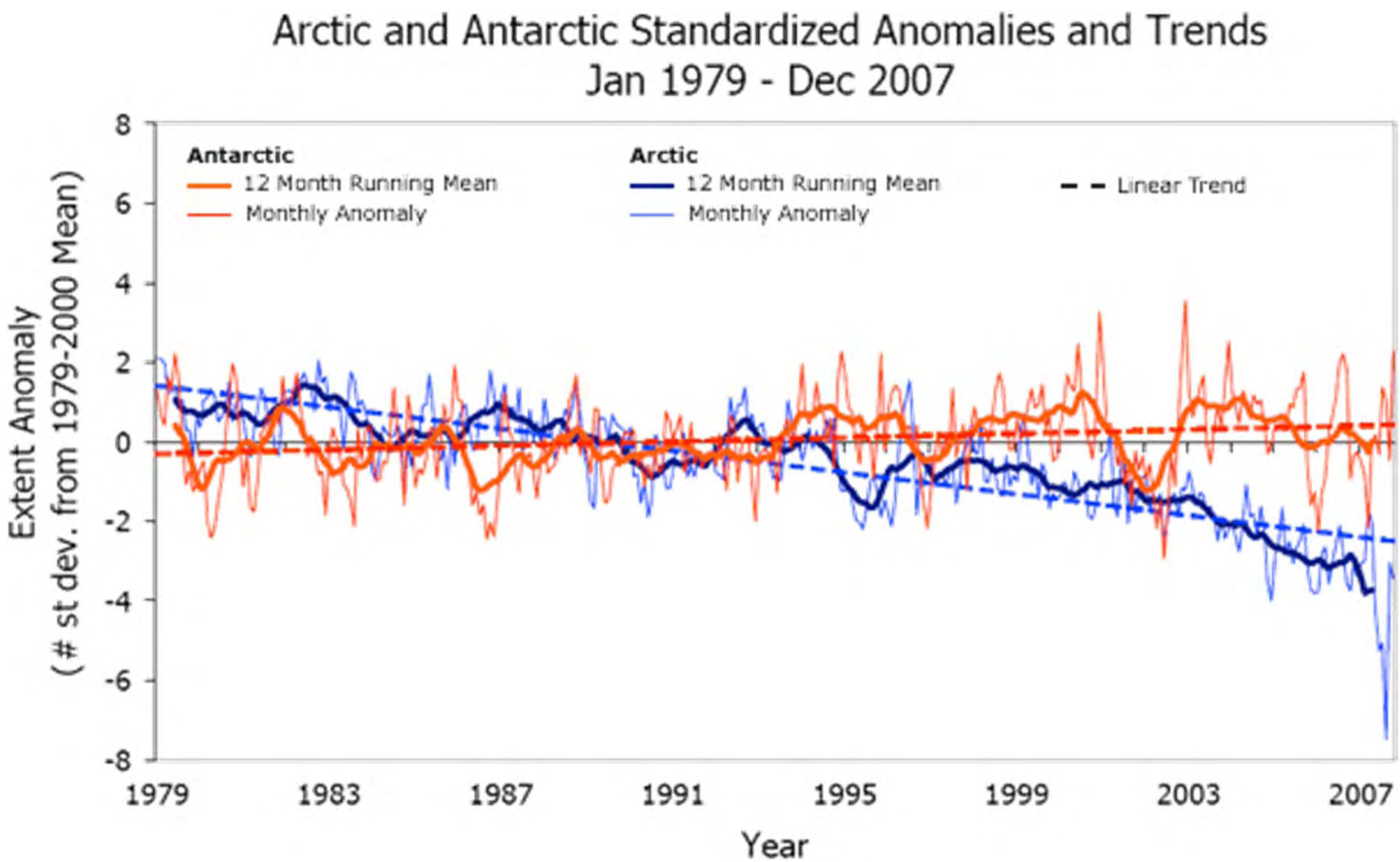
Stramski et al. (1999)

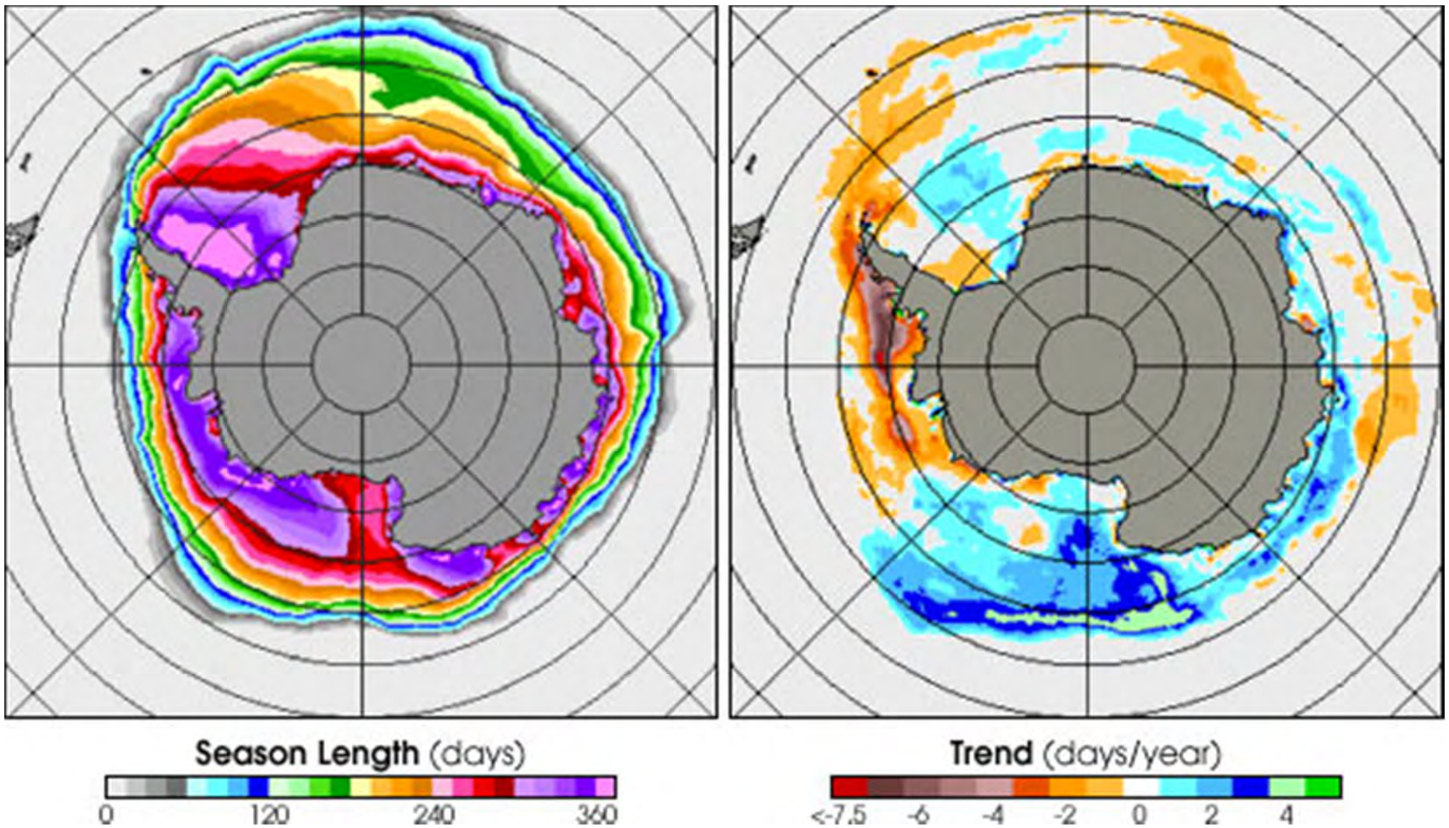
Ongoing changes



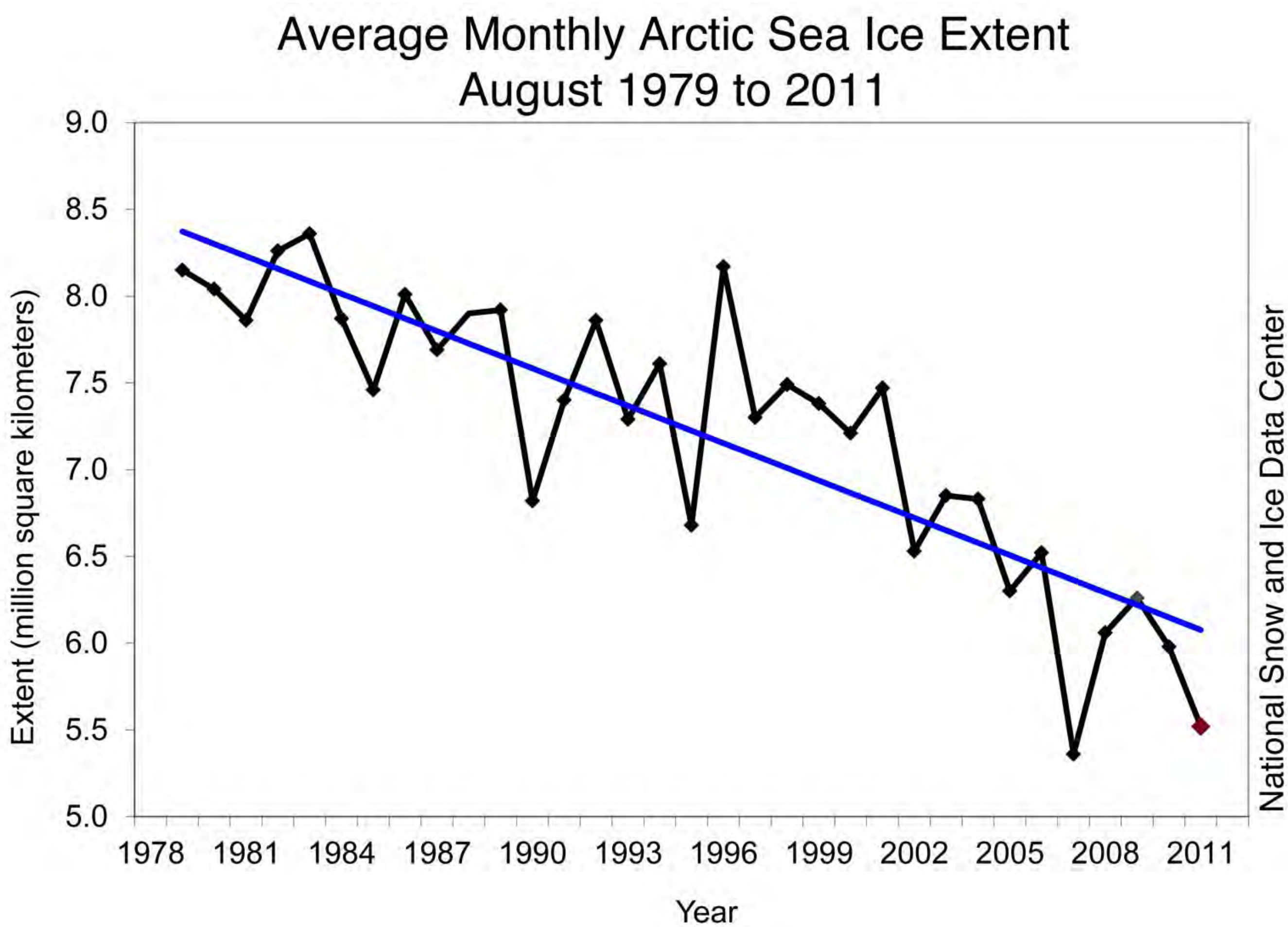

Annual J-D 2011
L-OTI(°C) Anomaly vs 1951-1980
.50
-4.1
-4
-2
-1
-.5
-.2
.2
.5
1
2
4
4.4

Ongoing changes

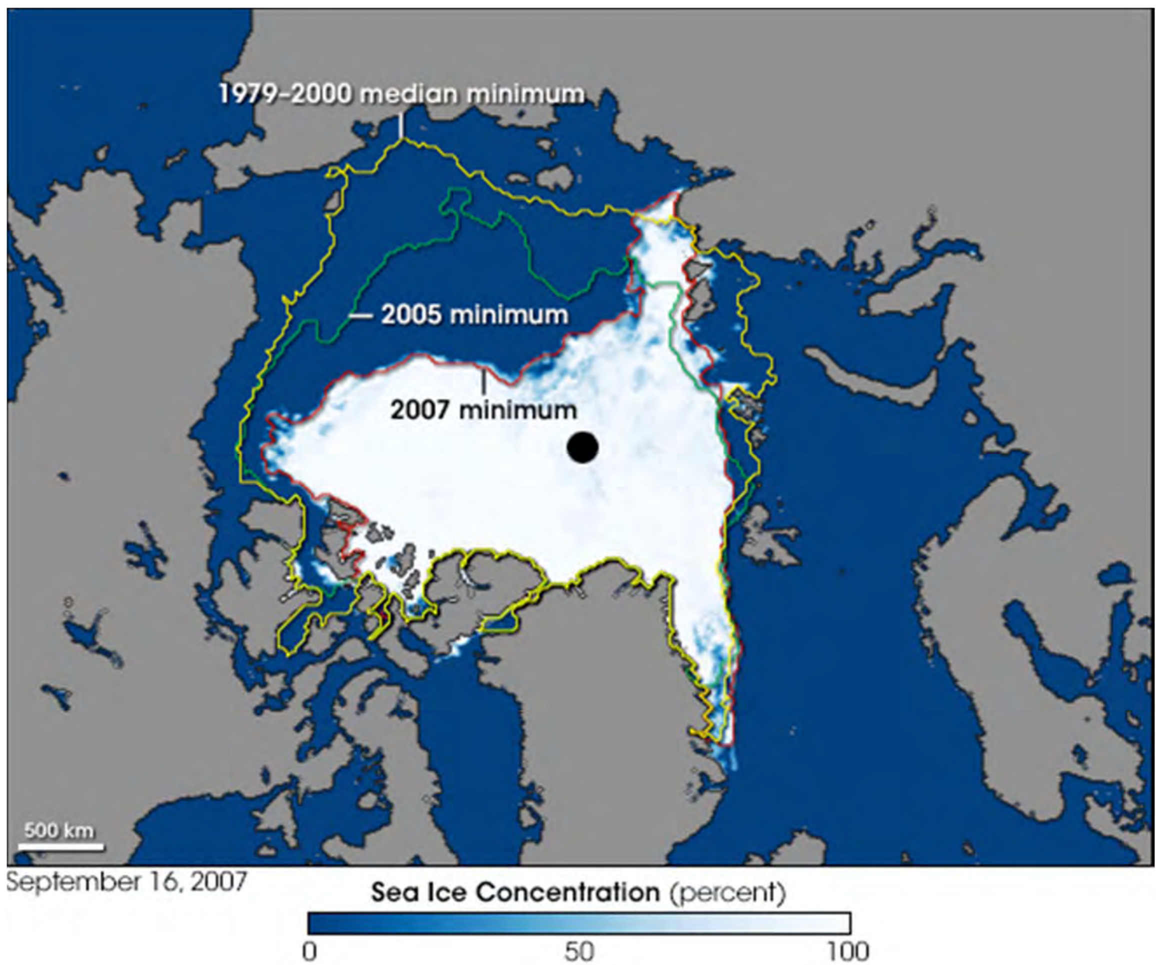


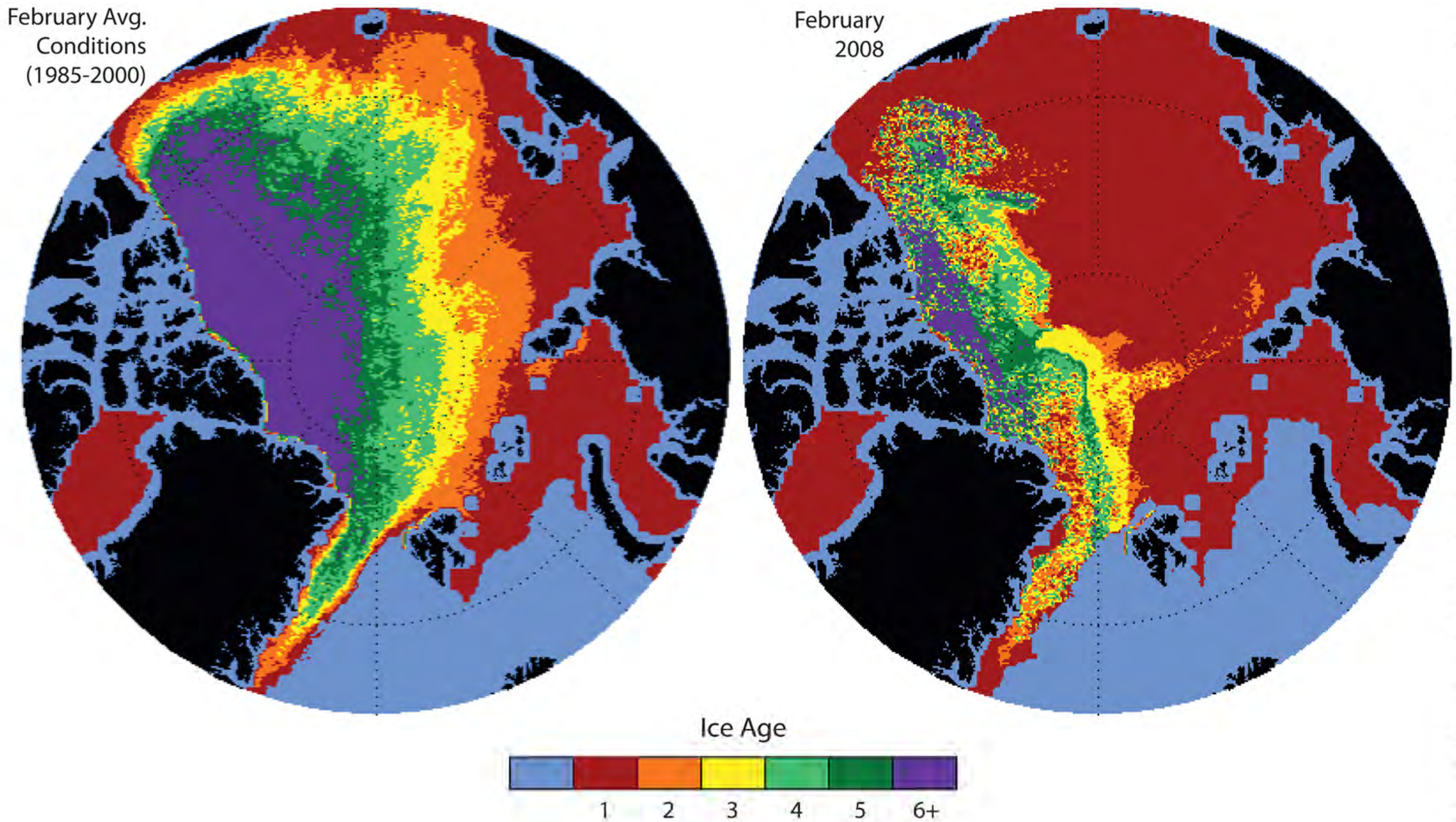

Season Length (days)
0
120
240
360
Trend (days/year)
<-7.5
-6
-4
-2
0
2
4

Ongoing changes



Ongoing changes

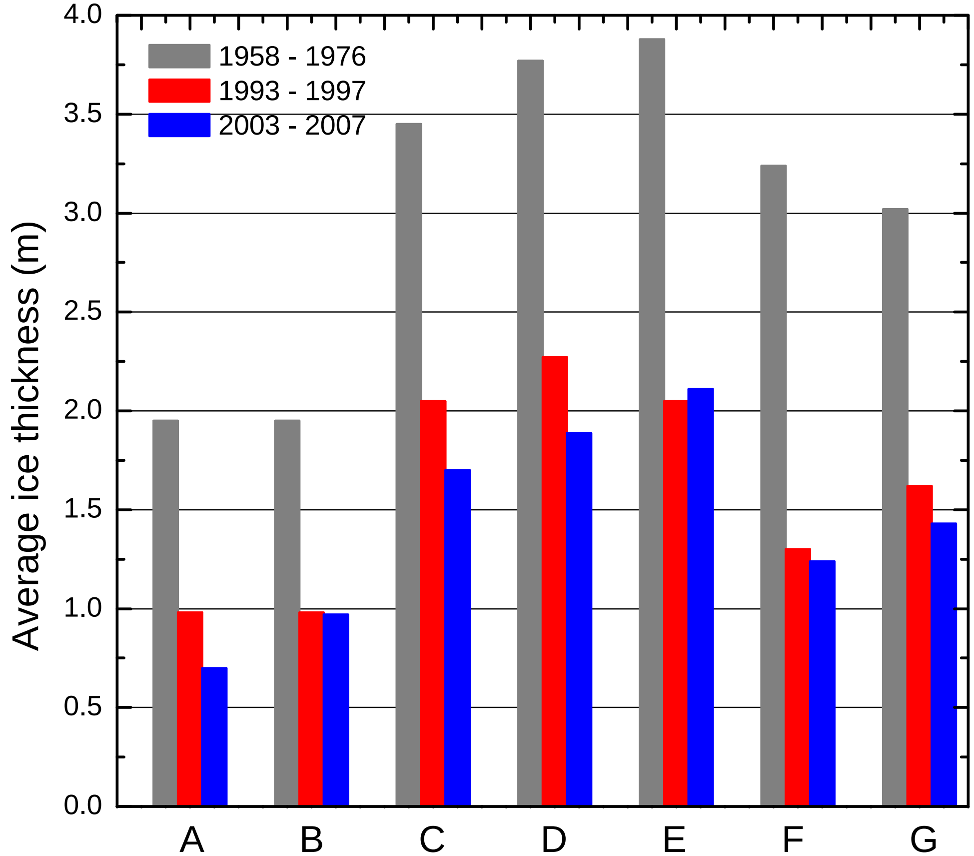




National Snow and Ice Data Center, courtesy S. Drobot, Univ. of Colorado, Boulder

Sea ice thickness: then and now

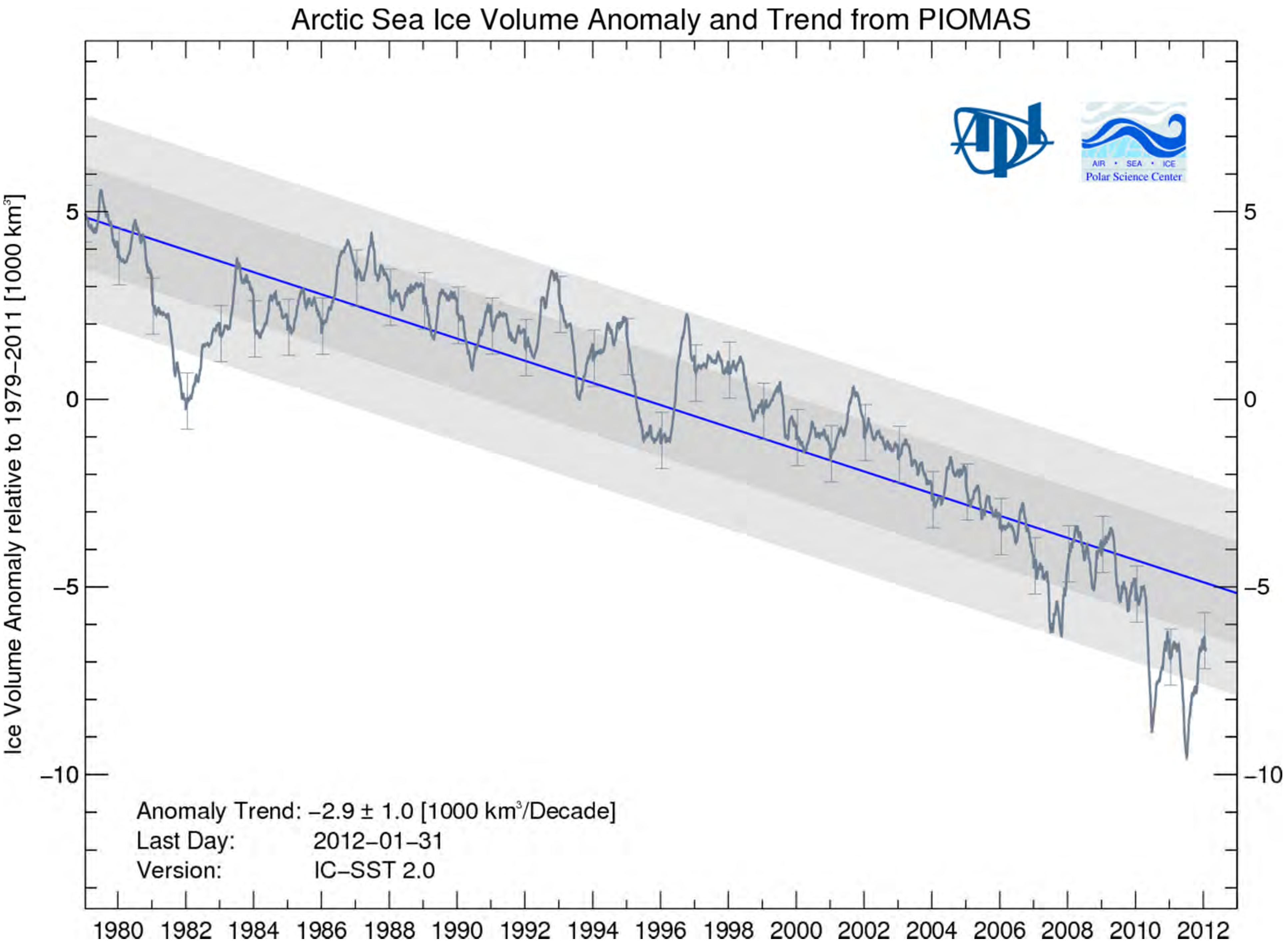
Changes in summer thickness
Comparing 1958-1976 to the 1990's and 2000's

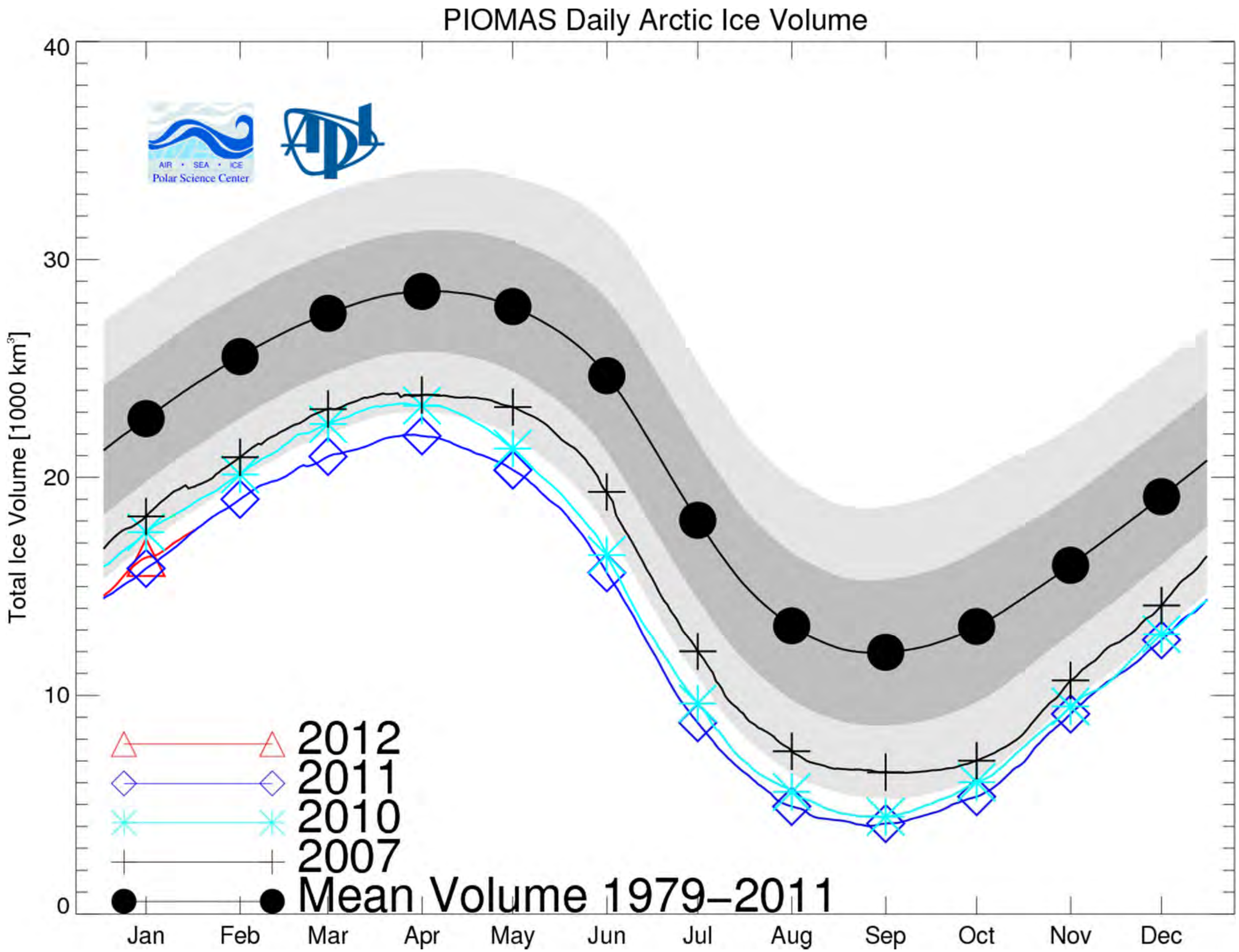


- Analysis of submarine and satellite data
- Rothrock et al. show thinning everywhere!
- Average decrease was 40%
- From 3 m to under 2 m

Sea ice is thinning … everywhere

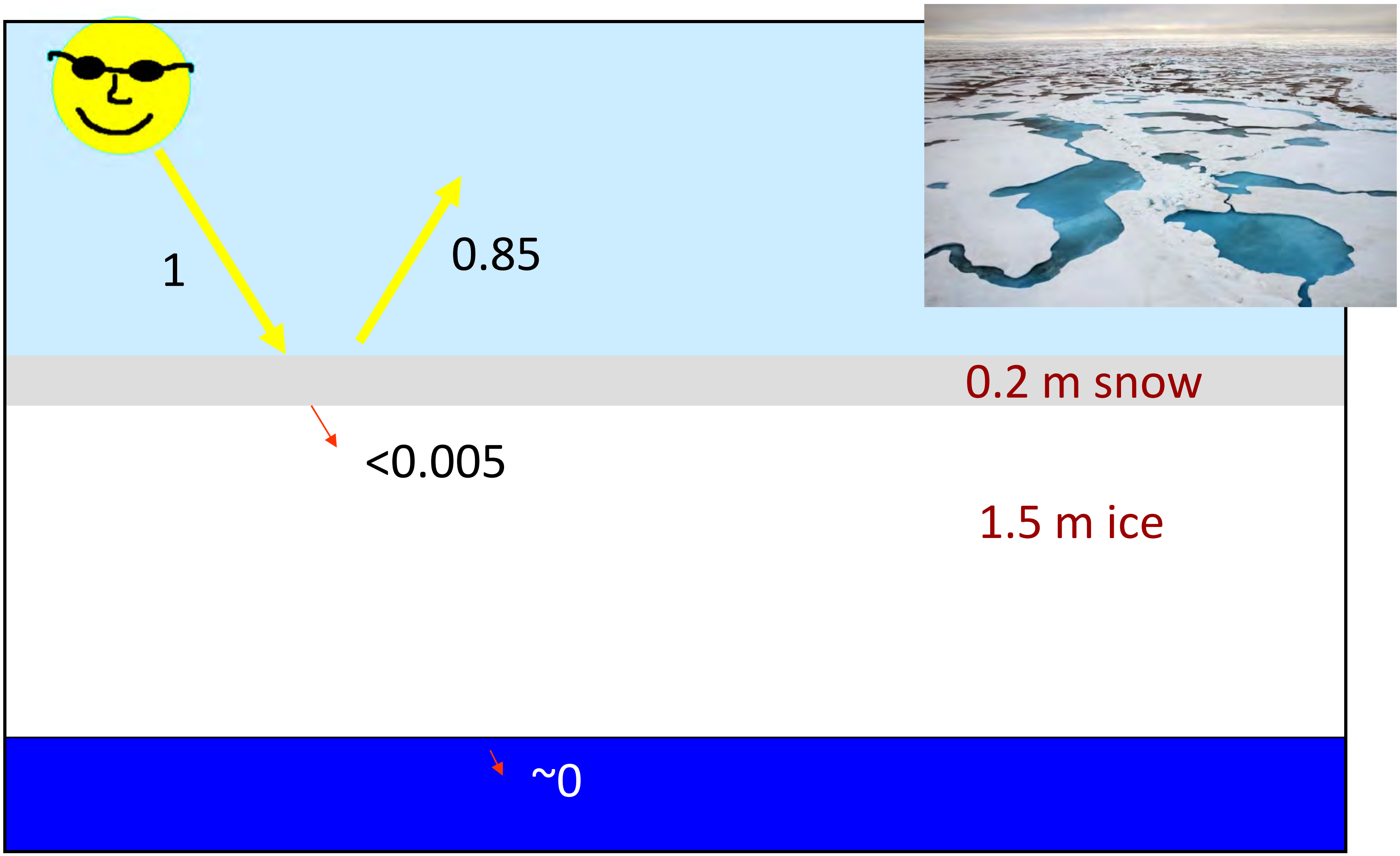
Courtesy of Don Perovich


Arctic Sea Ice Volume Anomaly and Trend from PIOMAS
Ice Volume Anomaly relative to 1979–2011 [1000 km³]
5
0
−5
−10
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
AIR • SEA • ICE
Polar Science Center
Anomaly Trend: −2.9 ± 1.0 [1000 km³/Decade]
Last Day: 2012–01–31
Version: IC–SST 2.0



PIOMAS Daily Arctic Ice Volume
Total Ice Volume [1000 km³]
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
AIR • SEA • ICE
Polar Science Center
2012
2011
2010
2007
Mean Volume 1979–2011

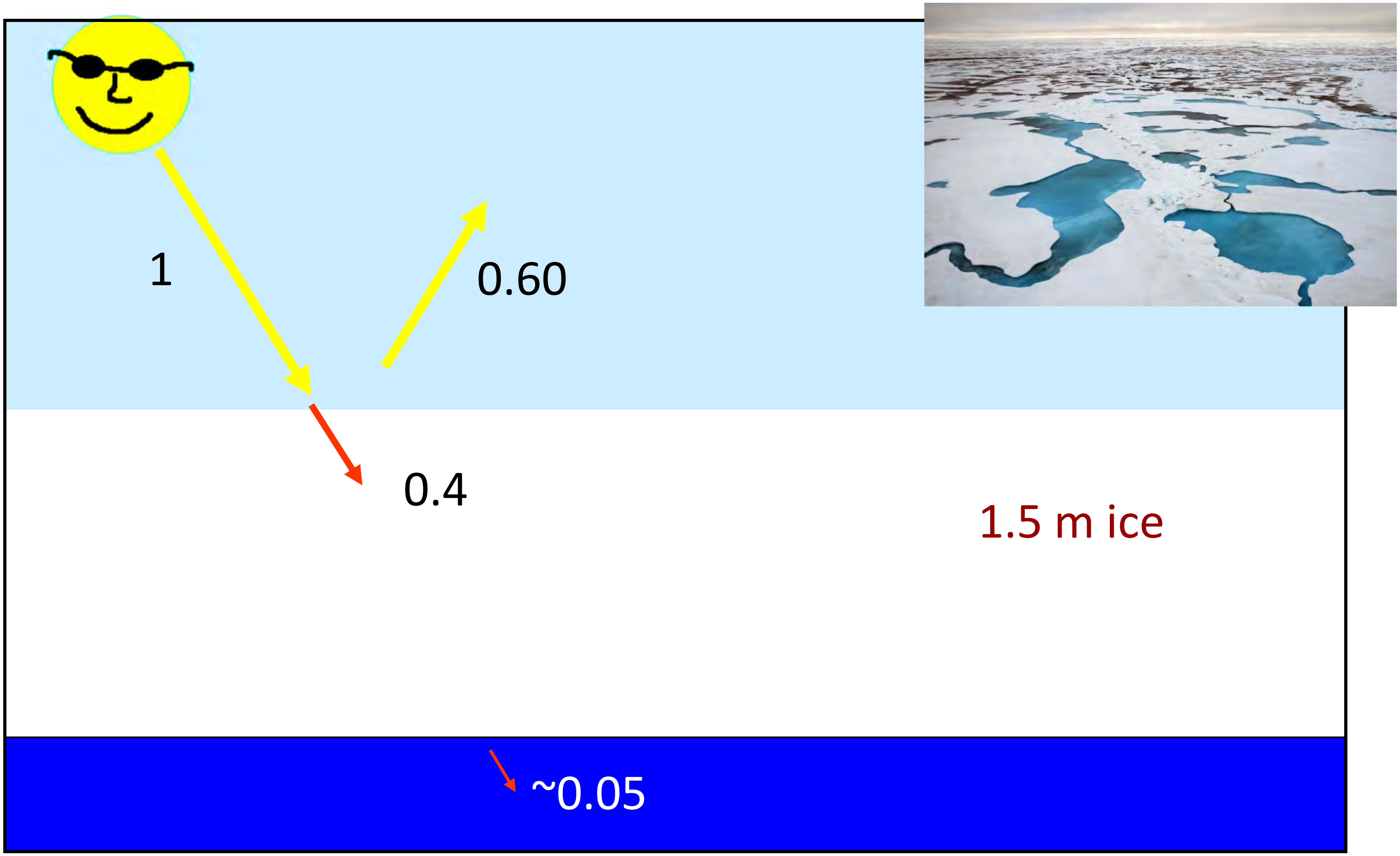
Today: Assume a simple thin slab



Snow covered, thin, first year ice

Courtesy of Don Perovich

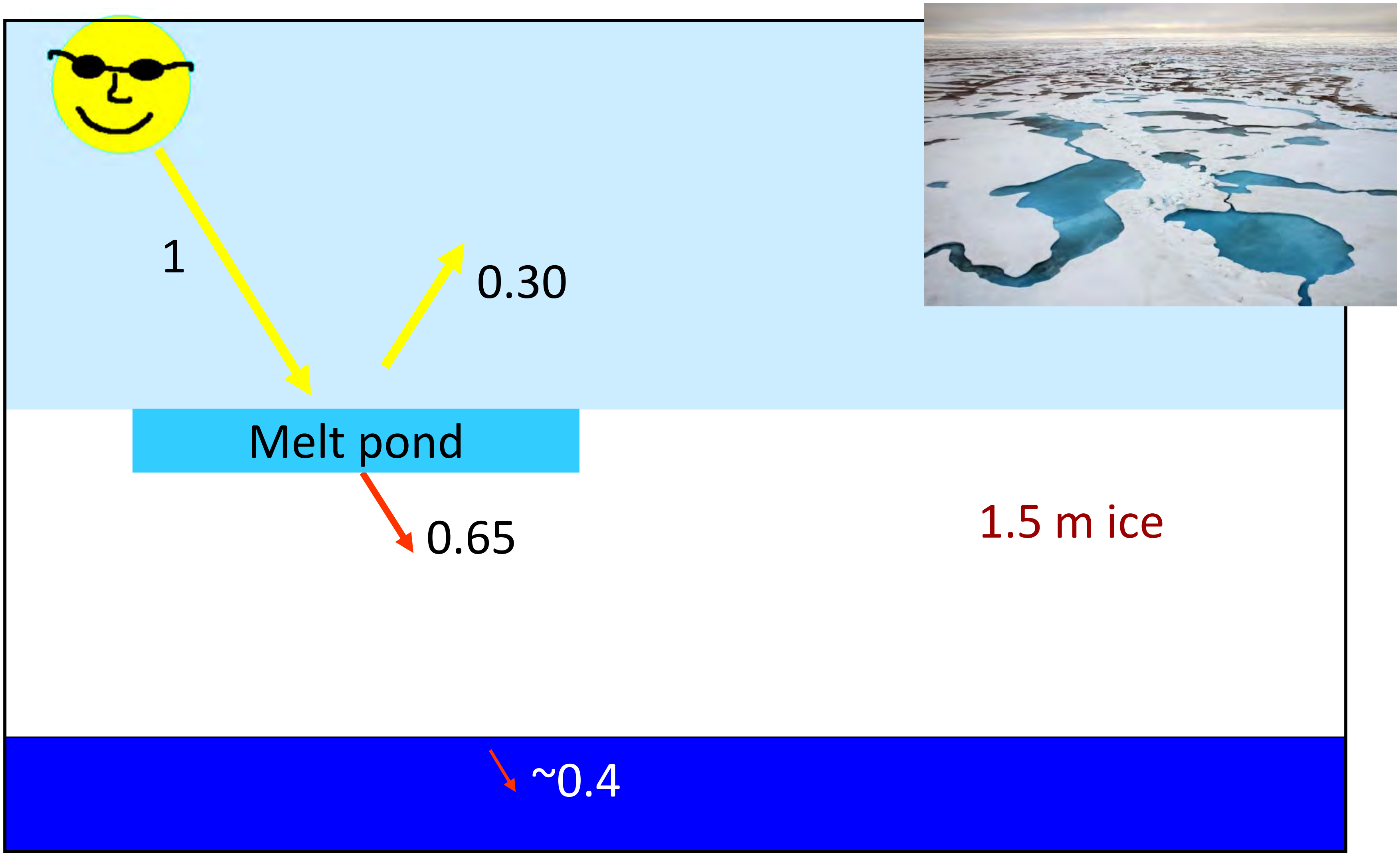
Today: Assume a simple thin slab



Let the snow melt

Courtesy of Don Perovich

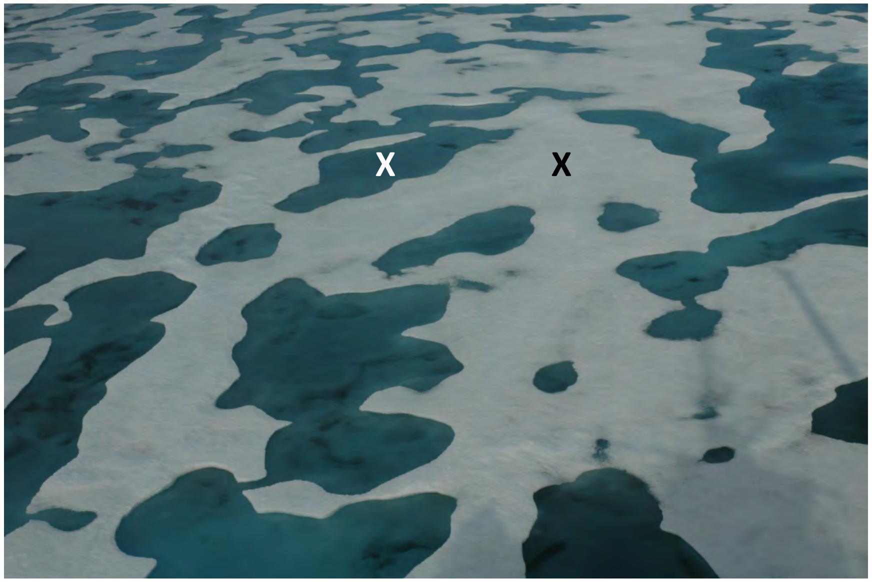
Today: Assume a simple thin slab

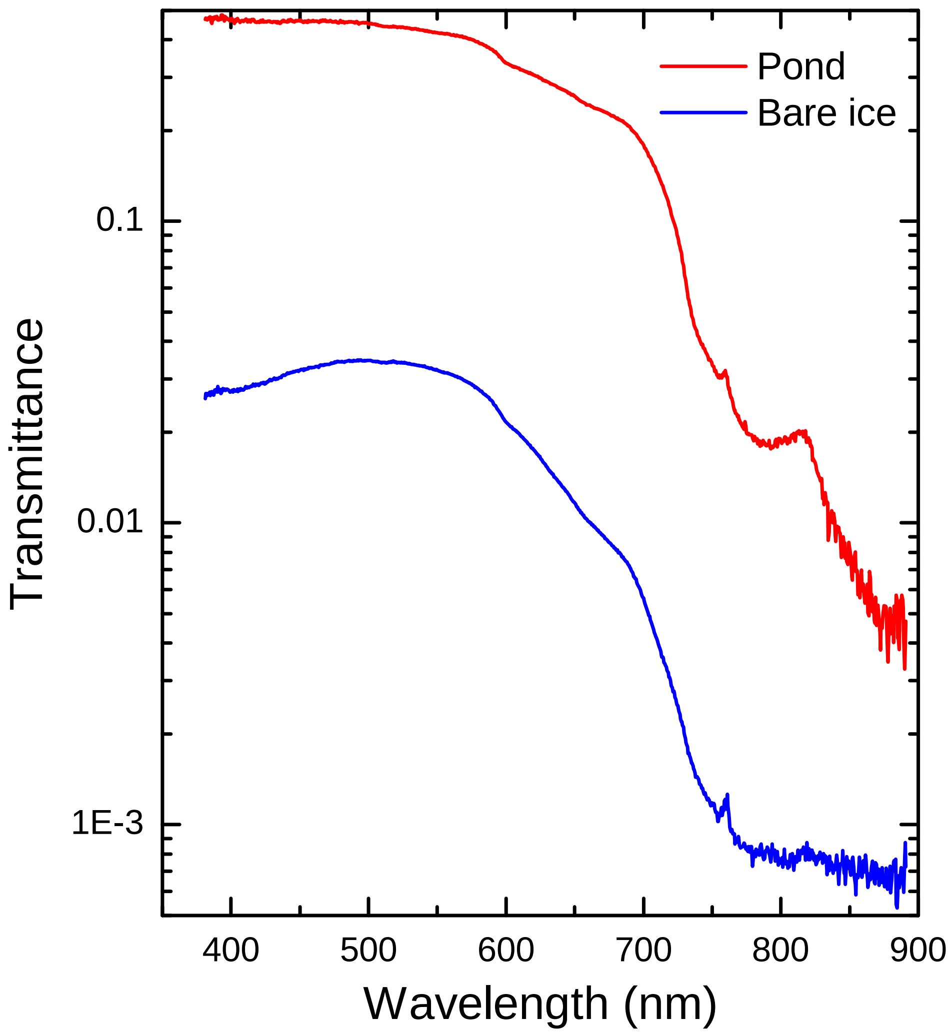


Let the snow melt and add a pond

Courtesy of Don Perovich

Spectral transmittance



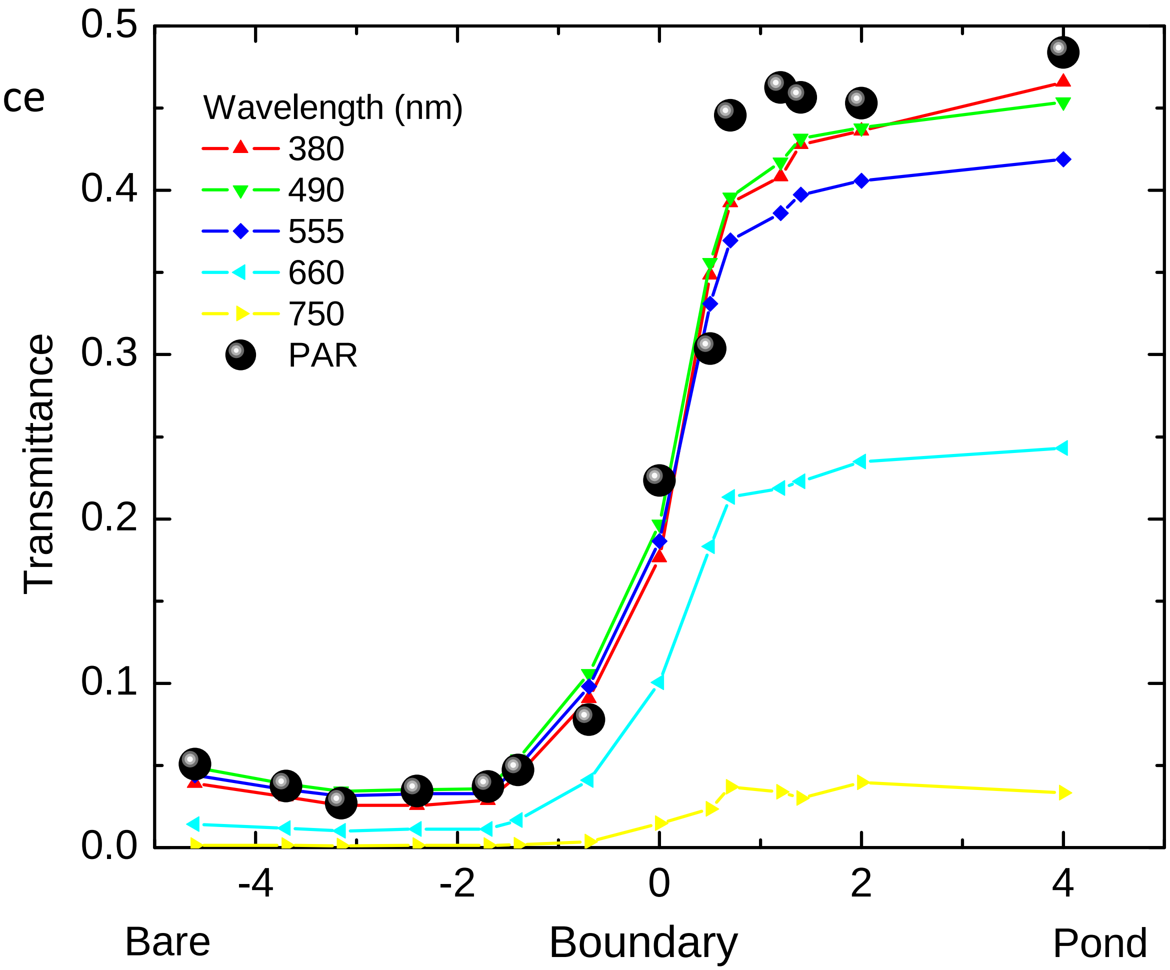


Pond transmittance order of magnitude higher than bare ice

Courtesy of Don Perovich

Spatial variability in light field

- Transmittance transition
- Distance ~ 3 to 4 X thickness
- Short wavelengths = longer distance



The sea ice light field has tremendous spatial variability

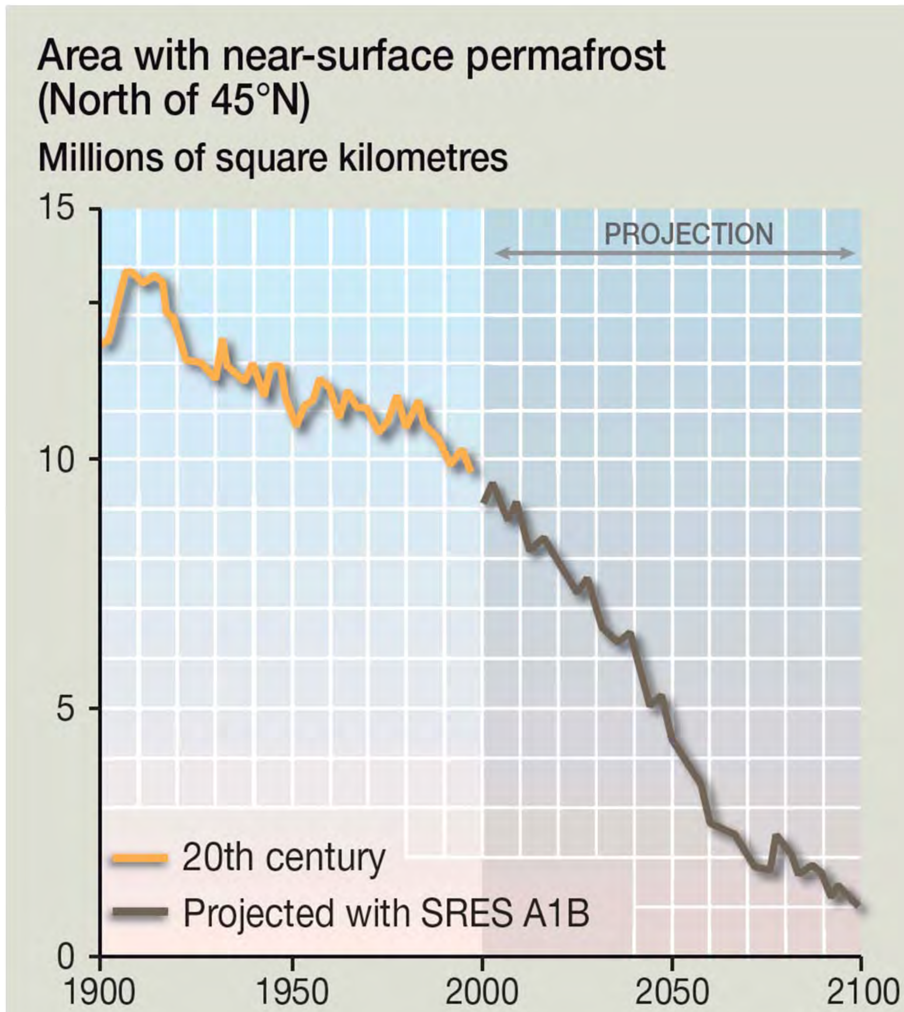
Courtesy of Don Perovich

Ongoing changes

+

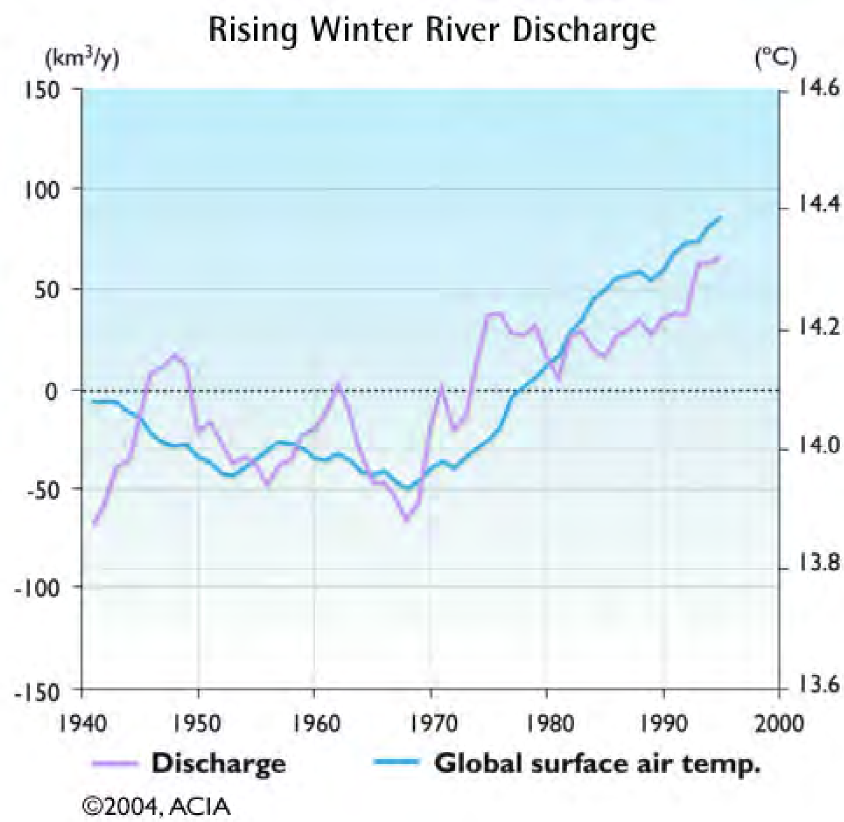
- Permafrost thawing

Ongoing changes



Ongoing changes

Melted permafrost on a Shismaref, Alaska, shoreline
Photograph by Peter Essick


Rising Winter River Discharge
(km³/y)
(°C)
150
100
50
0
-50
-100
-150
14.6
14.4
14.2
14.0
13.8
13.6
1940
1950
1960
1970
1980
1990
2000
Discharge
Global surface air temp.
©2004, ACIA

Ongoing changes

+

- Permafrost thawing
- Increase in river runoff (+7% from 1936 to 1999)
- UV increase (+15% since 1979)

In brief

- Temperature has risen twice faster in the Arctic than in other regions; air temperature is expected to increase by up to 7°C during the next century.

In brief

- Temperature has risen twice faster in the Arctic than in other regions; air temperature is expected to increase by up to 7°C during the next century.

- Permafrost, which represents 25% of the continental surface of the northern hemisphere, has been observed to have undergone a temperature increase since the 1960s and, in many places, to gradually thaw. The permafrost contains up to 50% of all soil organic carbon.

- From 1936 to 1999, an increase of 7% was observed for river discharge to the Arctic Ocean. It may impact on circulation, including deep-water formation.

In brief

- Temperature has risen twice faster in the Arctic than in others regions; air temperature is expected to increase by up to 7°C during the next century.
- Permafrost, which represents 25% of the continental surface of the northern hemisphere, has been observed to have undergone a temperature increase since the 1960s and, in many places, a gradual thaw. The permafrost contains up to 50% of all soil organic carbon.
- From 1936 to 1999, an increase of 7% was observed for river discharge to the Arctic Ocean. It may impact on circulation, including deep-water formation.
- The summer ice cover over the Arctic Ocean decreased by more than 30% since 1979; it is predicted that it will disappear almost completely by the end of the century.

In brief

- Temperature has risen twice faster in the Arctic than in others regions; air temperature is expected to increase by up to 7°C during the next century.
- Permafrost, which represents 25% of the continental surface of the northern hemisphere, has been observed to have undergone a temperature increase since the 1960s and, in many places, a gradual thaw. The permafrost contain up to 50% of all soil organic carbon.
- From 1936 to 1999, an increase of 7% was observed for river discharge to the Arctic Ocean. It may impact on circulation, including deep-water formation.
- The summer ice cover over the Arctic Ocean decreased by 20% over the last 26 years; it is predicted that it will disappear almost completely by the end of the century.
- The amount of atmospheric ozone above the Arctic during the spring, has decreased by 10 to 15 % since 1979.

One may expect that…

1. An increasing fraction of the organic carbon sequestered into the permafrost will be transported toward the Arctic Ocean together with inorganic nutrients

2. The Arctic Ocean surface layer will increasingly be exposed to light, including UV

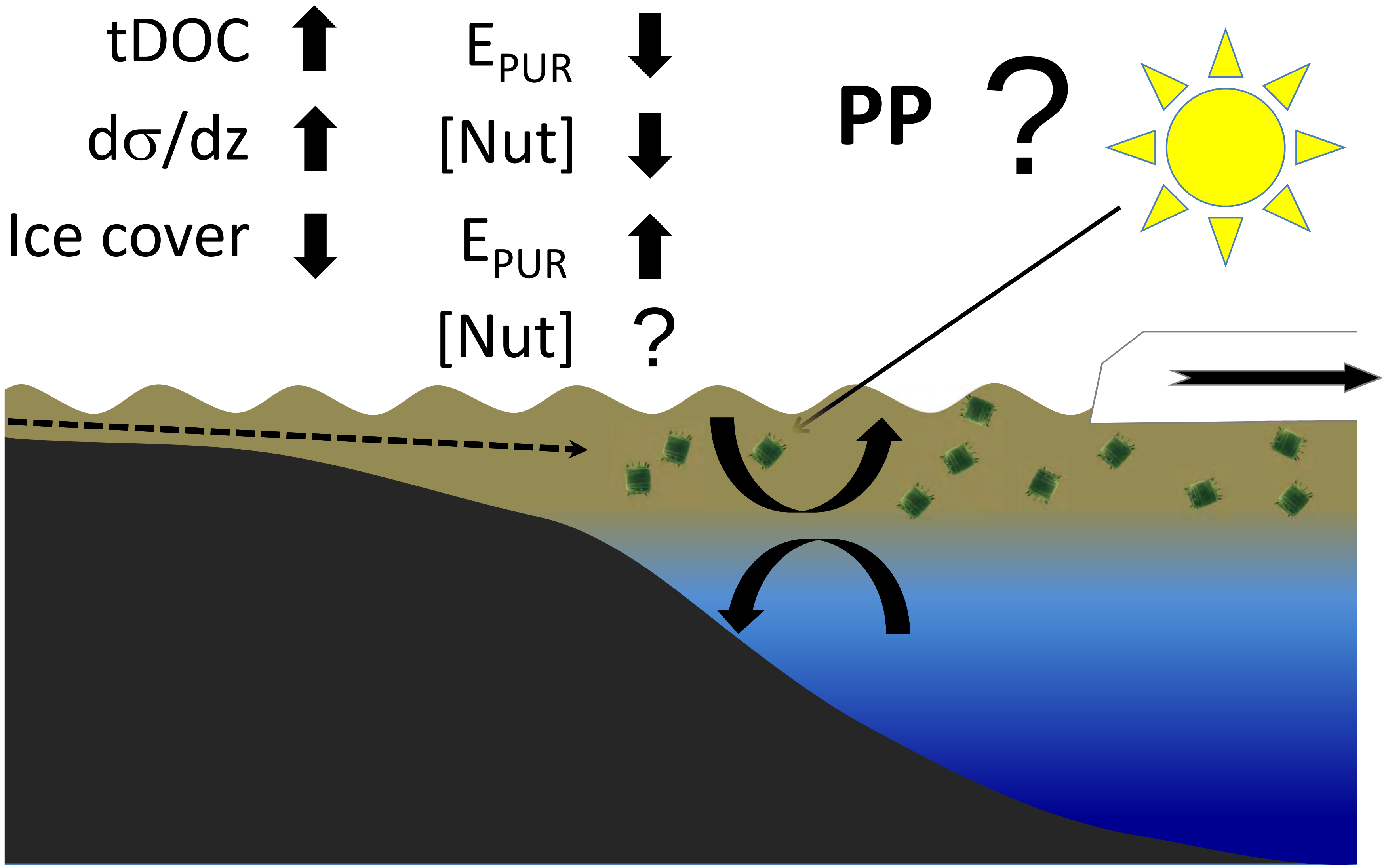
3. The organic matter of terrestrial origin will be oxidized to CO_2 both through photo-oxidation, and bacterial activity amplified by light

4. Photosynthesis will be increasingly stimulated by light and inorganic nutrients, and will lead to more carbon sequestration

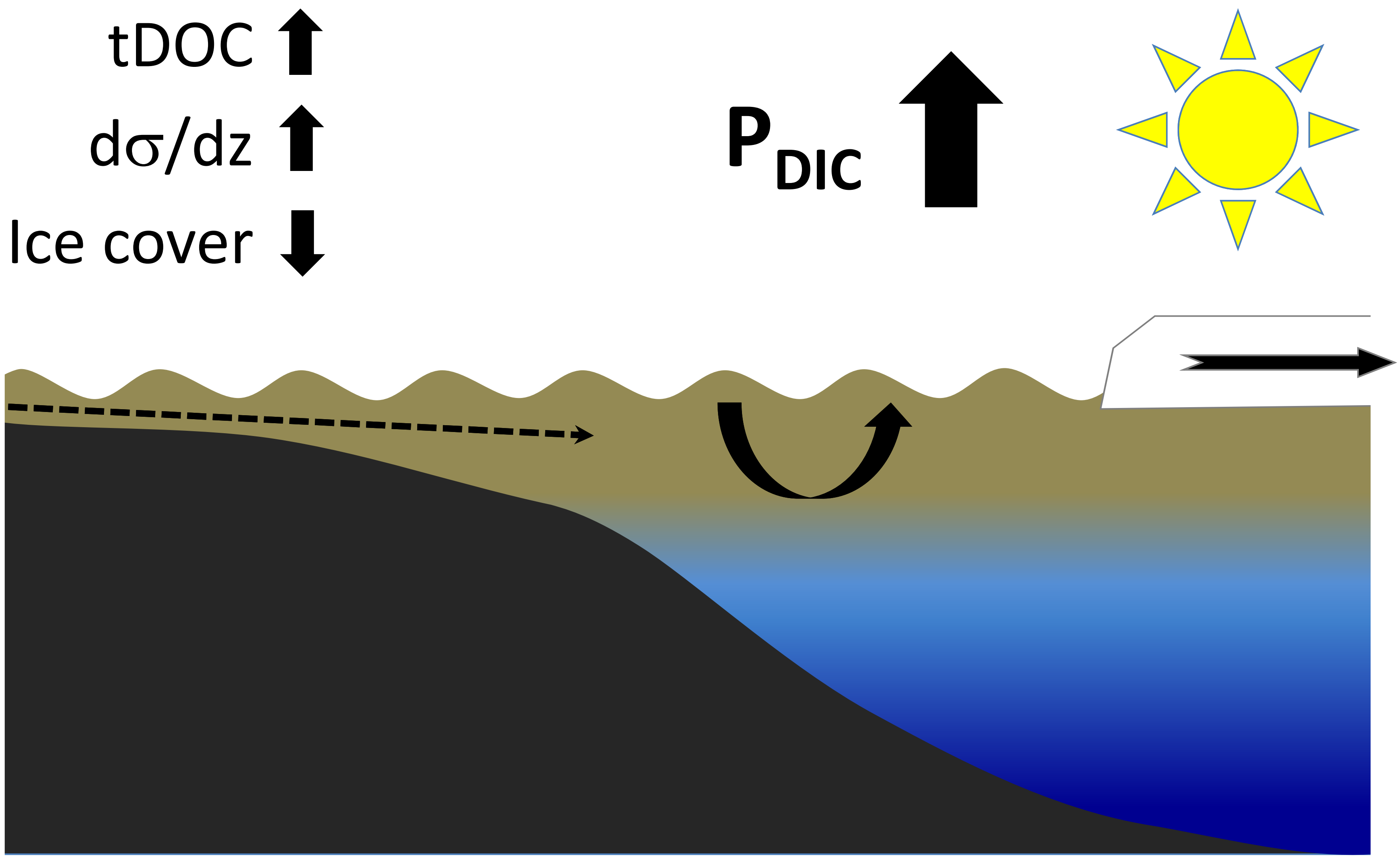
And wonder whether…

The Arctic Ocean will become a new net source of CO_2 originating from organic carbon that was sequestered in the permafrost (analogous to the combustion of fossil fuel), or a stronger biological sink of CO_2 leading to more sequestration of carbon in the sediments

What's the possible impact on PP?



And on P_{DIC}?

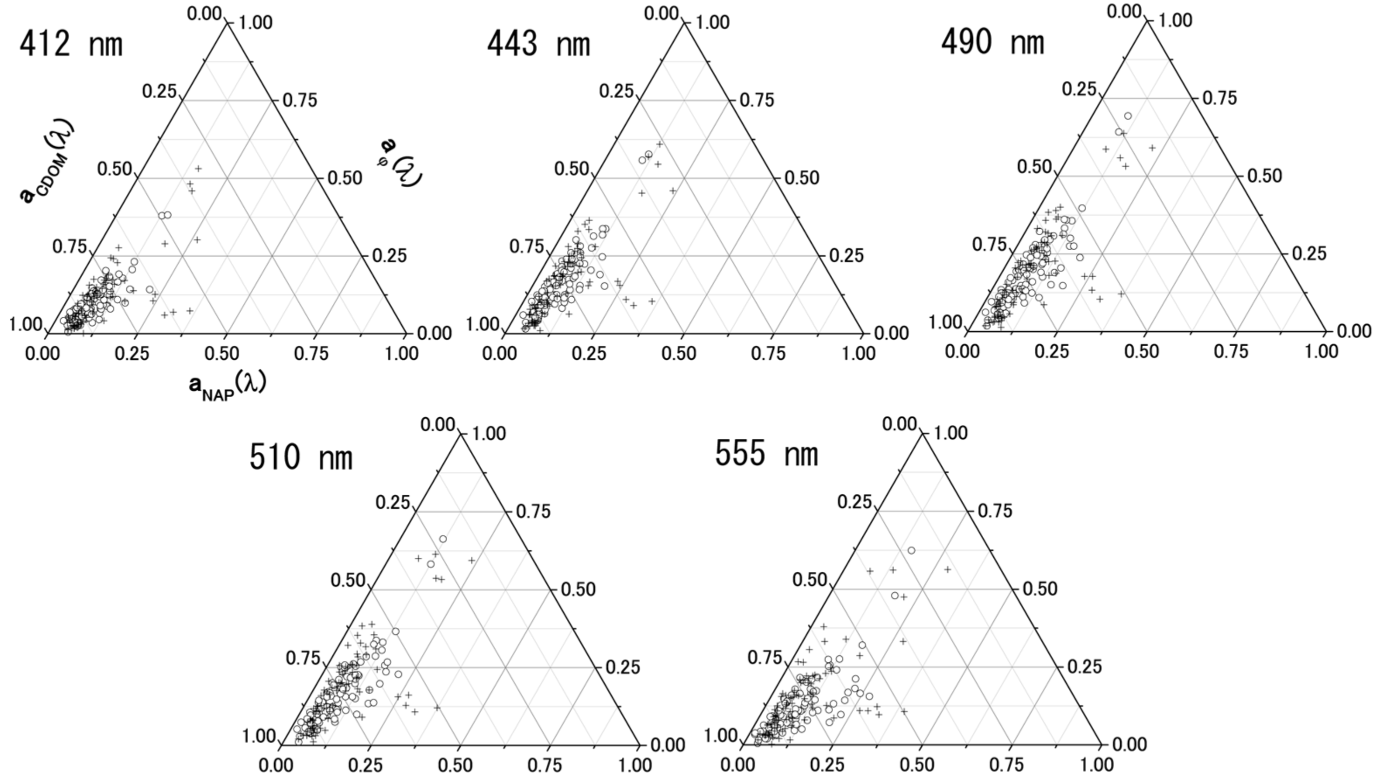


1. Ocean colour remote sensing in polar seas

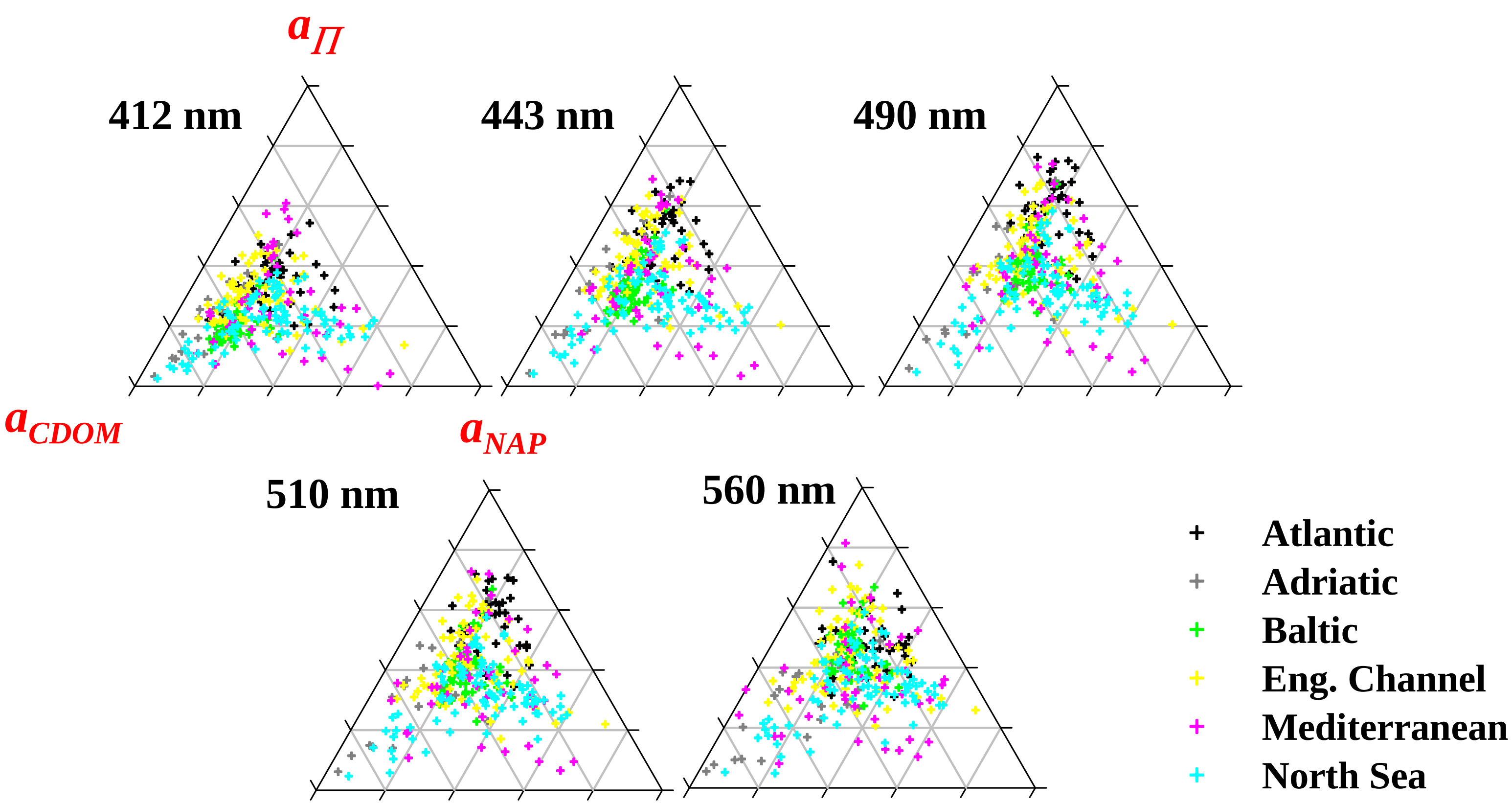
1.2. Seawater optical properties

What’s special?

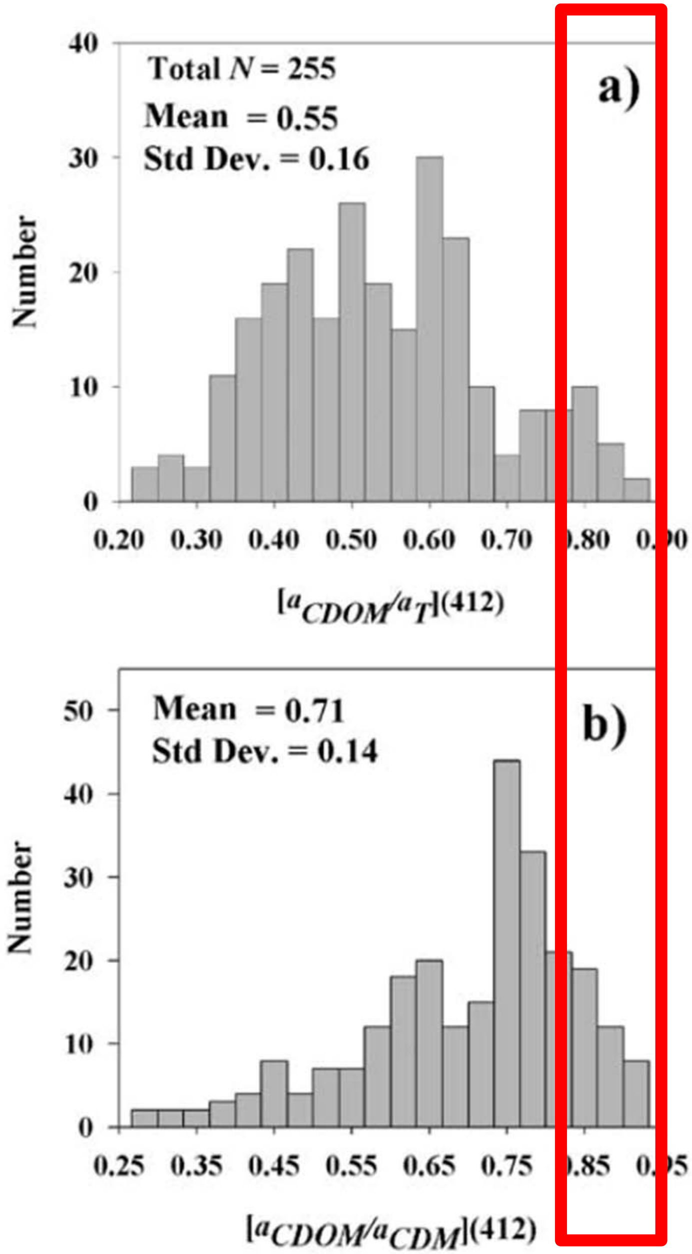
Arctic waters are optically dominated by CDOM



Matsuoka et al. (2007)

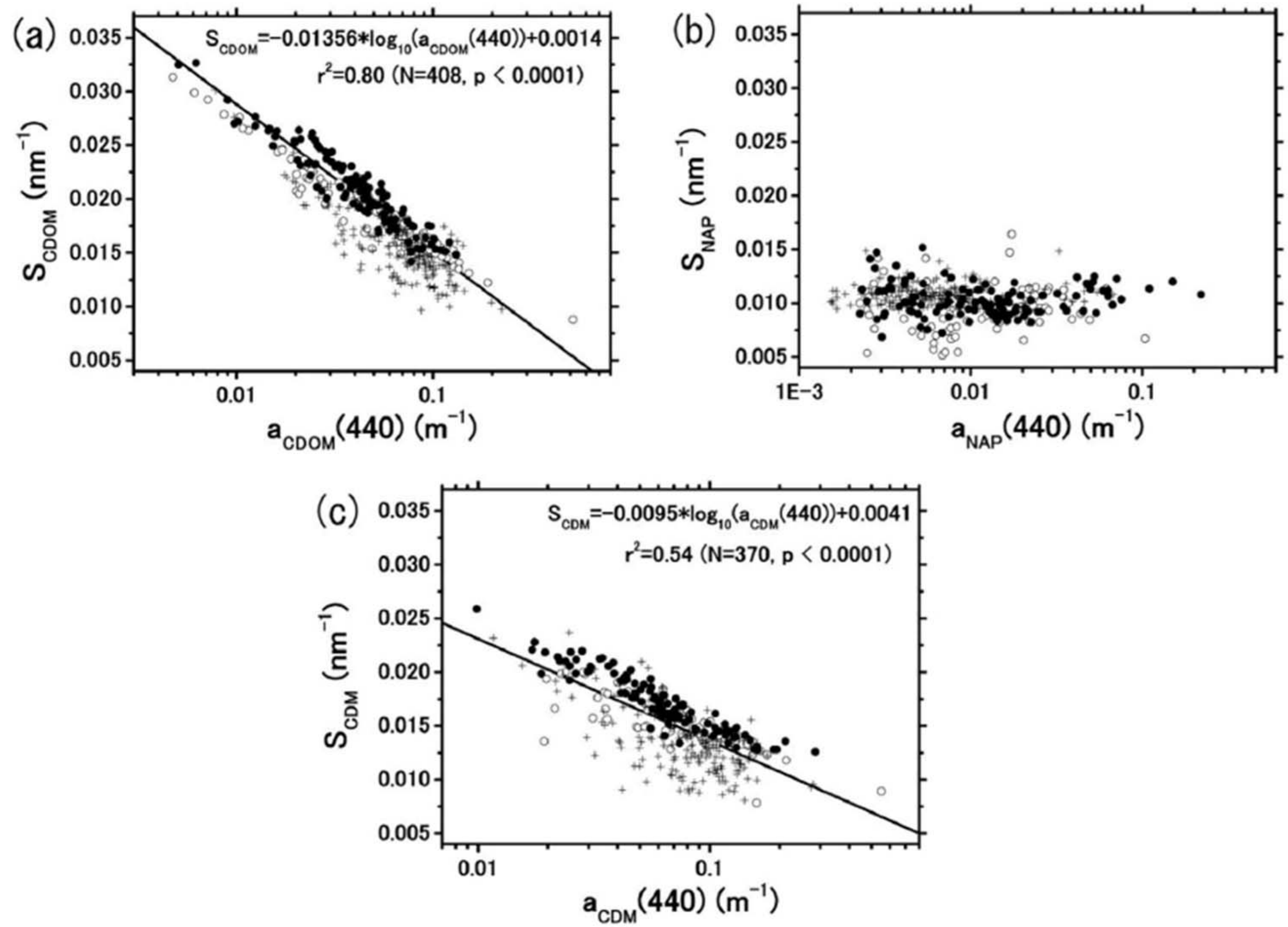


Babin et al. (2003)

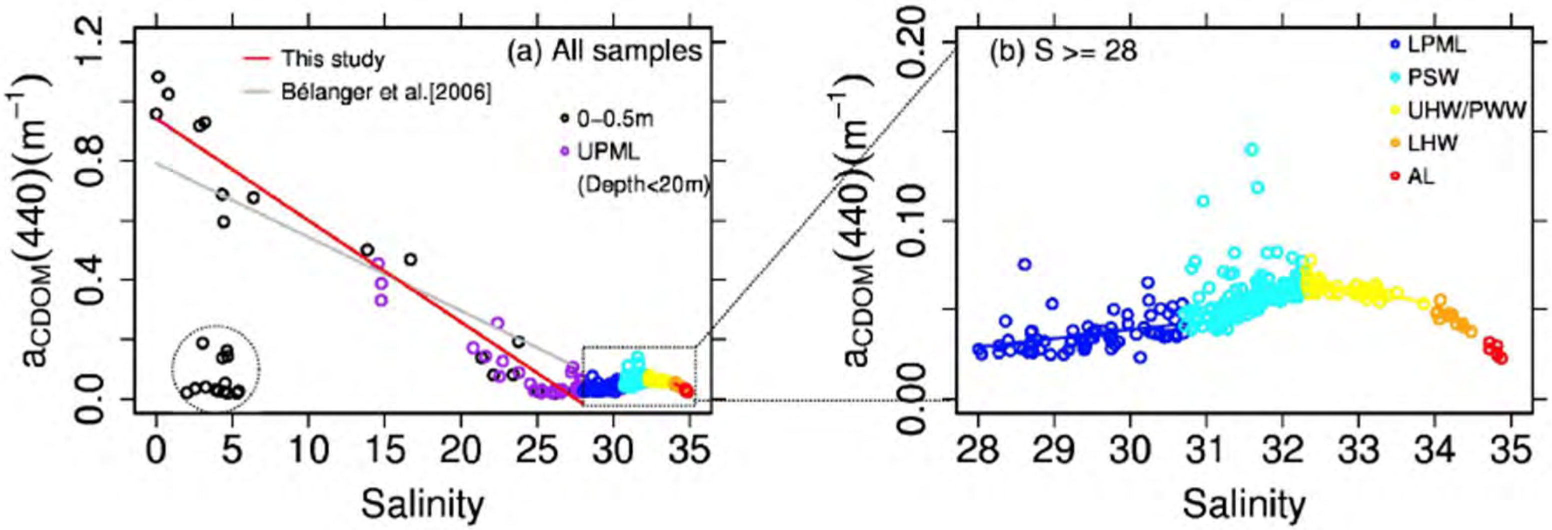


Beaufort Sea

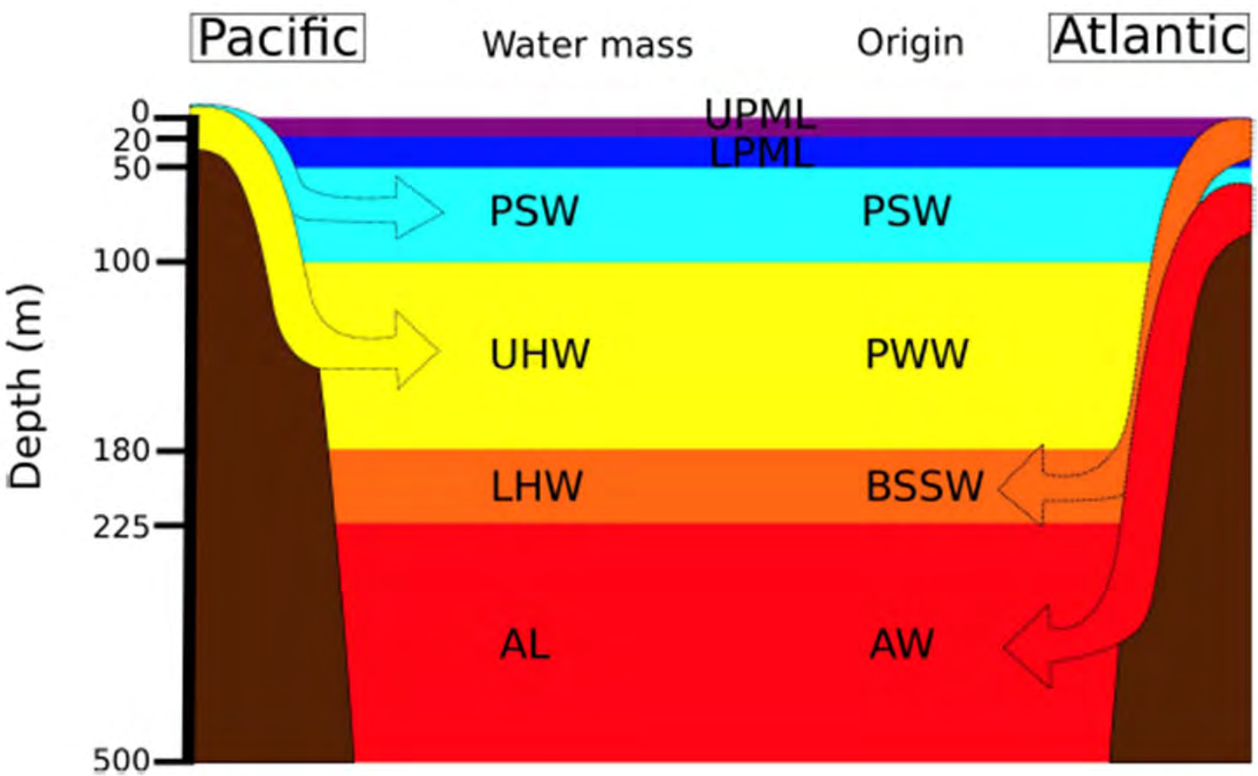
Bélanger et al. (2008)



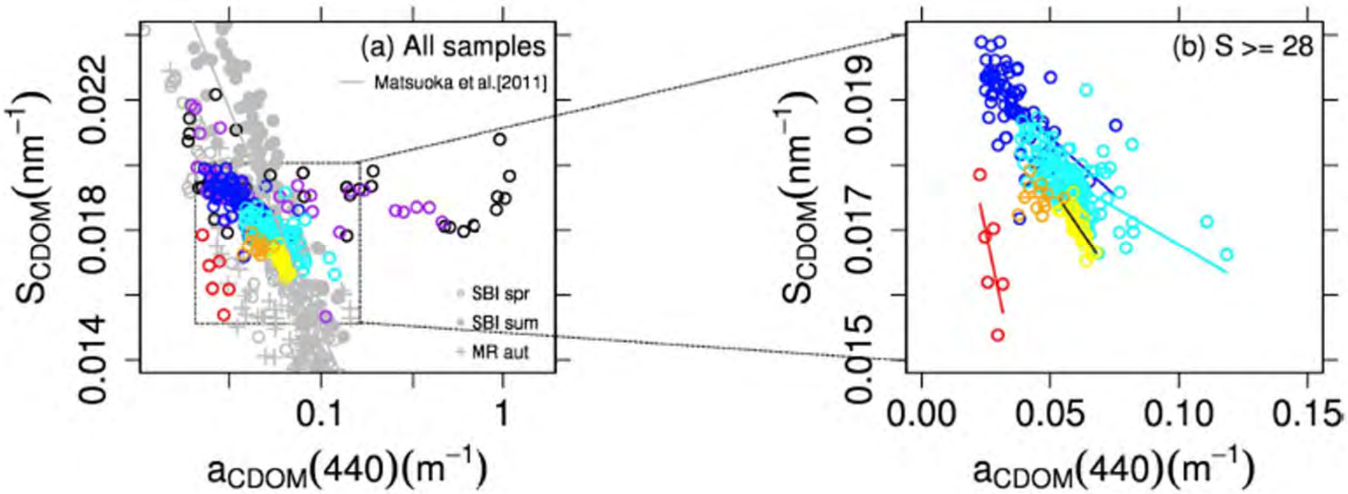
Matsuoka et al. (2011)



Matsuoka et al. (2012)

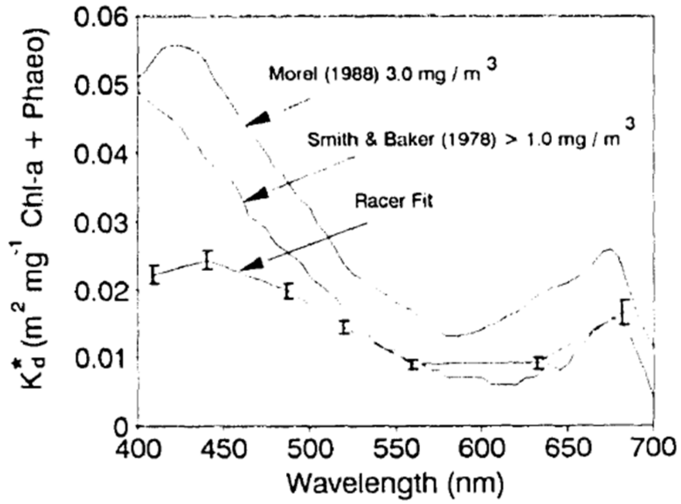


Matsuoka et al. (2012)

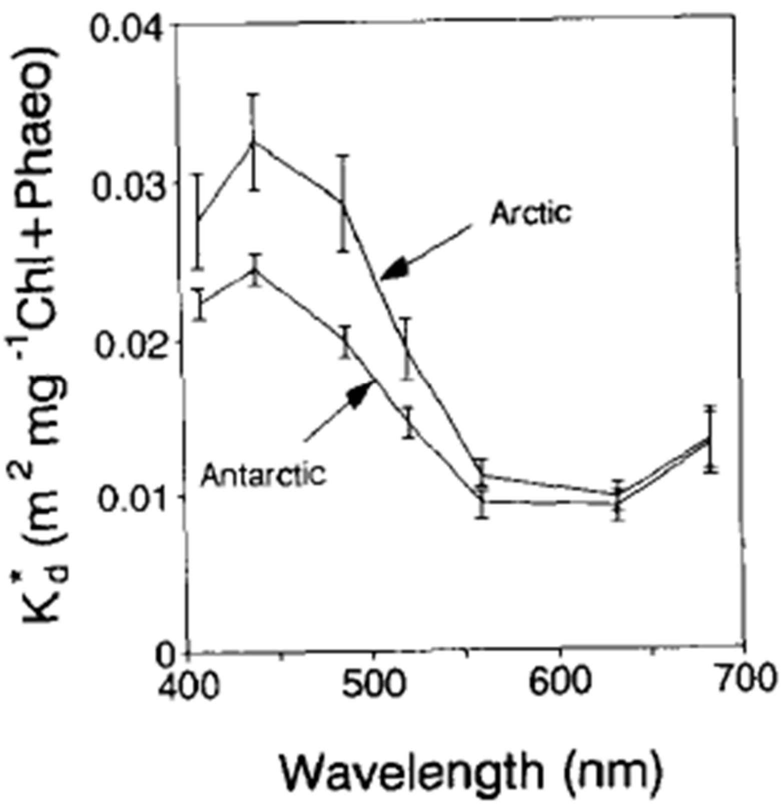


Matsuoka et al. (2012)

Chl-specific absorption is significantly smaller

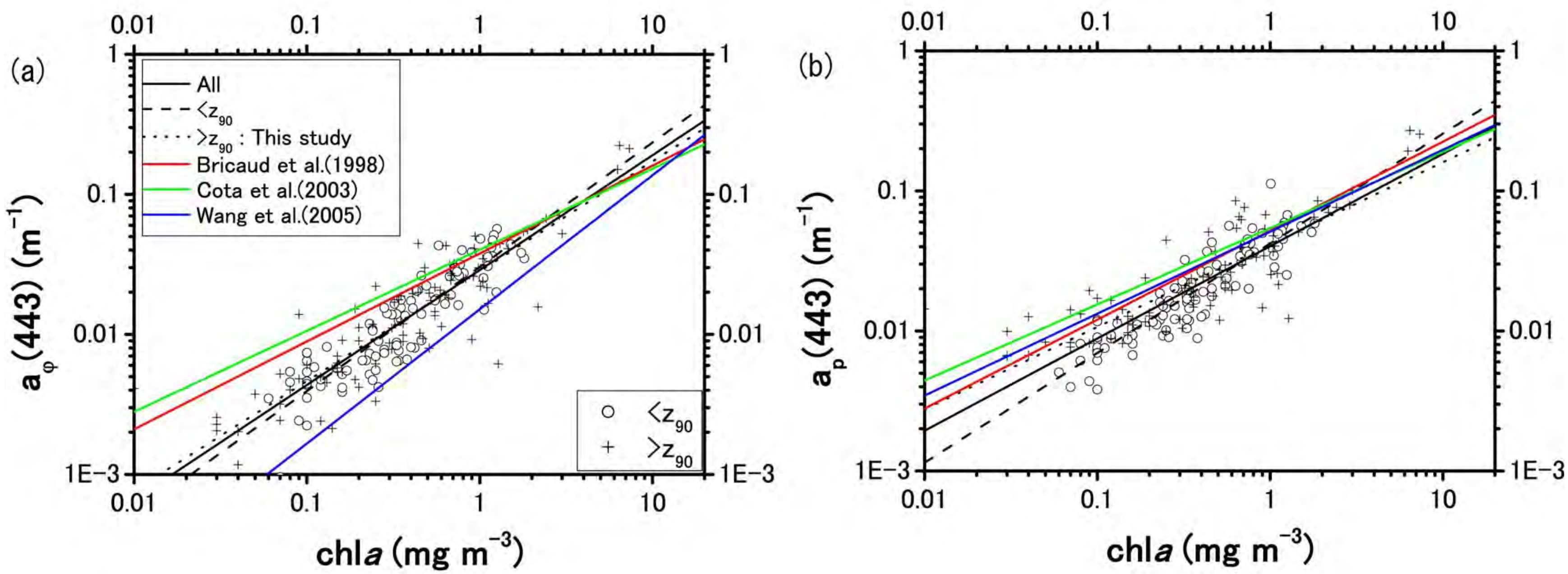


Mitchel and Holm-Hensen (1991)

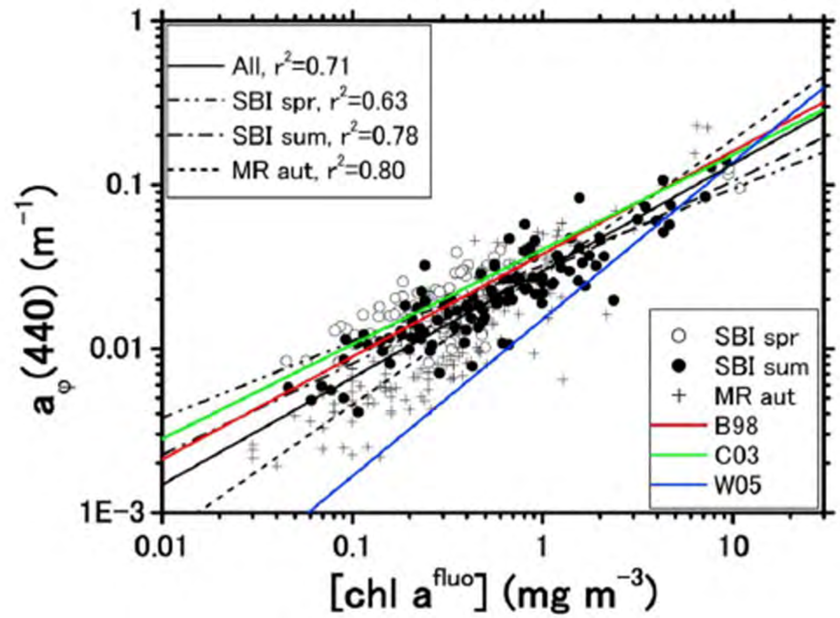


Mitchell (1990)

$\overline{a}_{\phi}*$ is generally lower in the Arctic Ocean because of the light regime



Matsuoka et al. (2007)

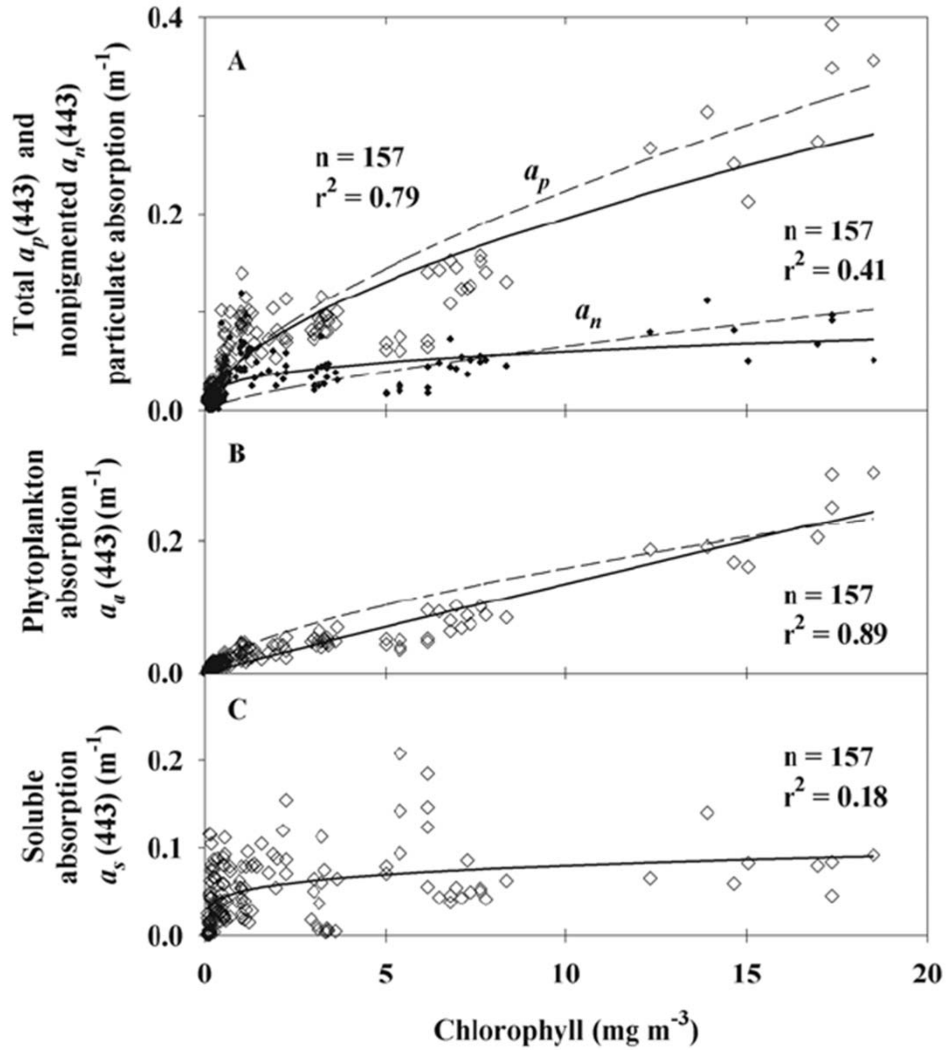


Matsuoka et al. (2011)

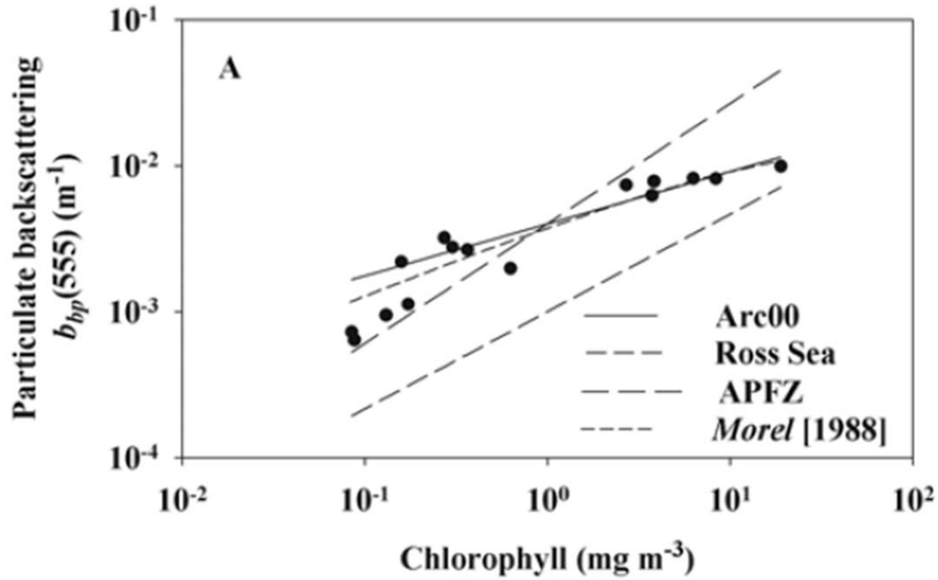
Table 1. Coefficients for the Nonlinear Regression Expressed as $a_\varphi(\lambda) = \alpha(\lambda)[a_\varphi(440)]^{\beta(\lambda)}$, Where λ is the Wavelength[a]

λ (nm)	$\alpha(\lambda)$	$\beta(\lambda)$	r^2
400	0.8865	1.022	0.917
405	0.9035	1.011	0.945
410	0.9318	1.008	0.961
415	0.9422	1.002	0.974
420	0.9475	0.999	0.980
425	0.9575	0.998	0.986
430	0.9614	0.992	0.989
435	0.9975	0.997	0.997
440	1.0000	1.000	1.000
445	0.8995	0.990	0.993
450	0.8550	0.989	0.993
455	0.8322	0.991	0.991
460	0.8104	0.988	0.991
465	0.8011	0.991	0.990
470	0.7434	0.979	0.989

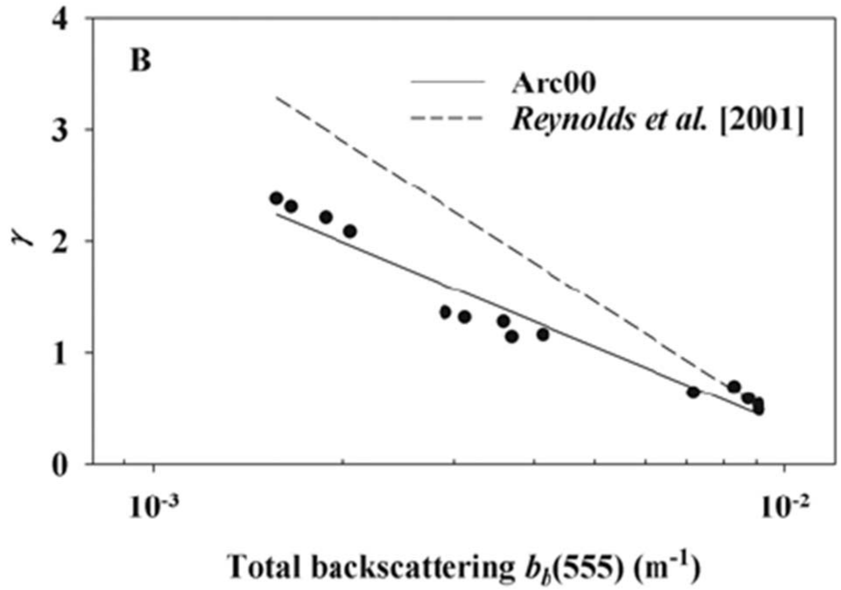
Matsuoka et al. (2011)



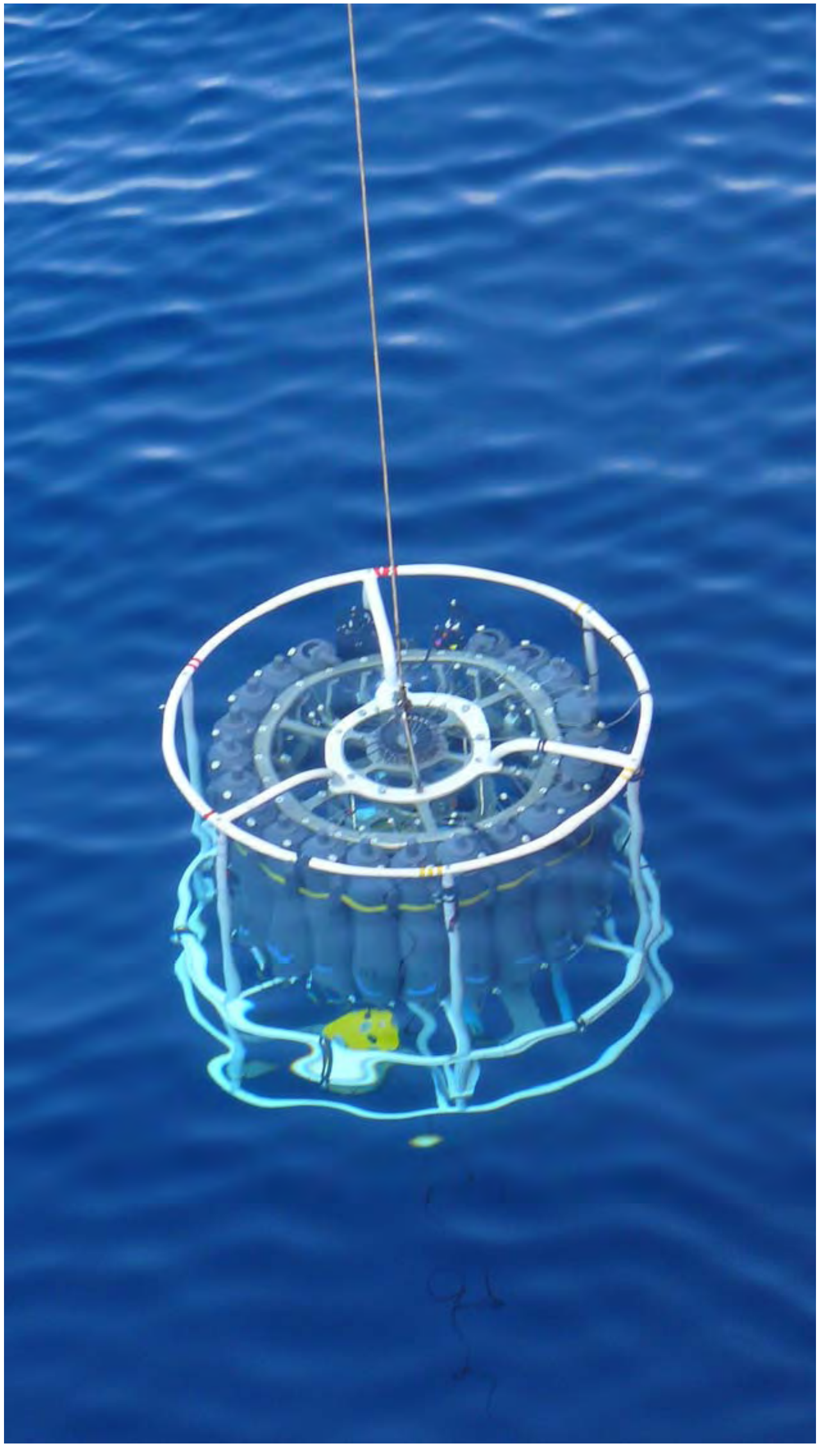
Wang and Cota (2005)



Wang and Cota (2005)



Wang and Cota (2005)



Optical properties, in brief

1. CDOM is relatively high
2. Chl-specific phytoplankton absorption is low
3. Turbid waters at the coast and in river plumes
4. But most of the time: blue clear water!

1. **Ocean colour remote sensing in polar seas**
    1. 1.3. Retrieval of ocean properties from ocean colour
        - 1.3.1. Atmospheric corrections

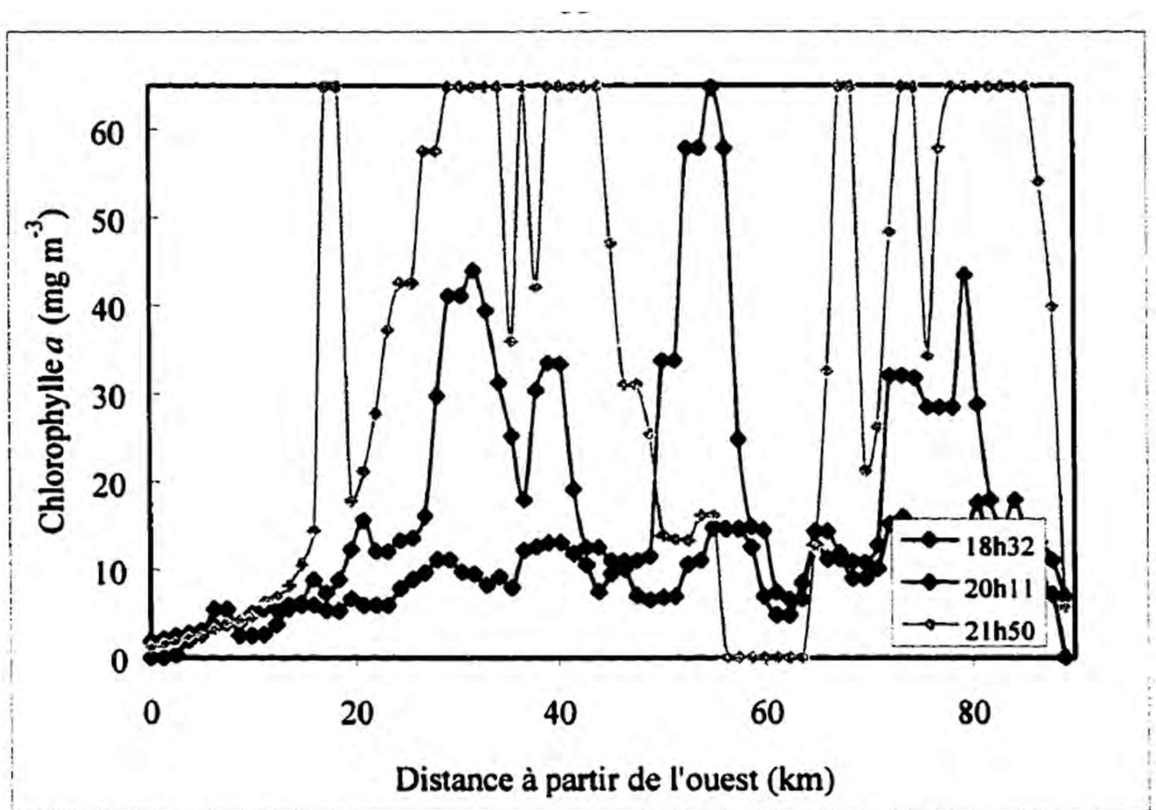
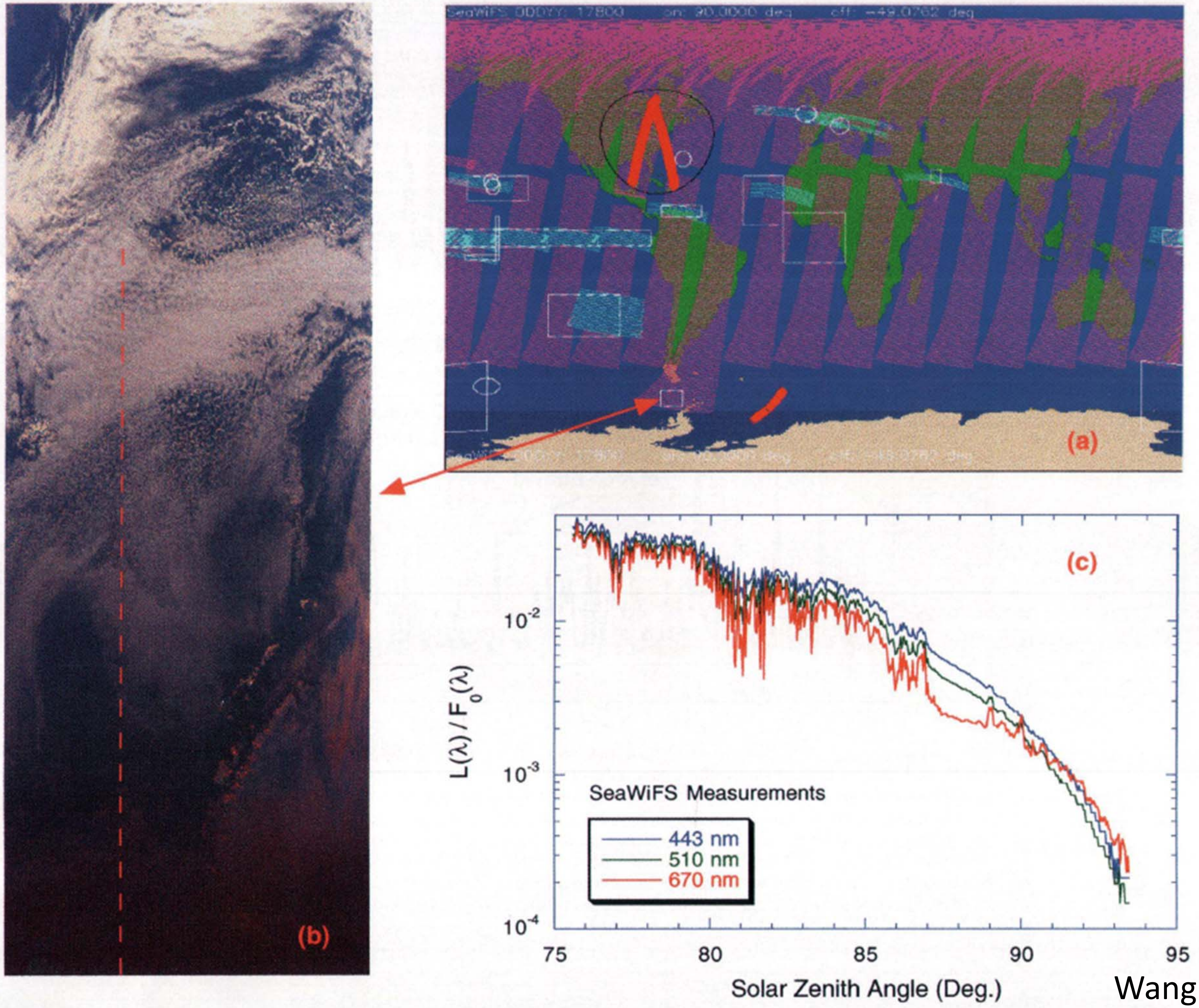


Figure 5.8. – Concentration de chlorophylle *a* pour trois heures d'acquisition le 19 juin 1999

Courtesy of Simon Bélanger

Eos, Vol. 84, No. 48, 2 December 2003



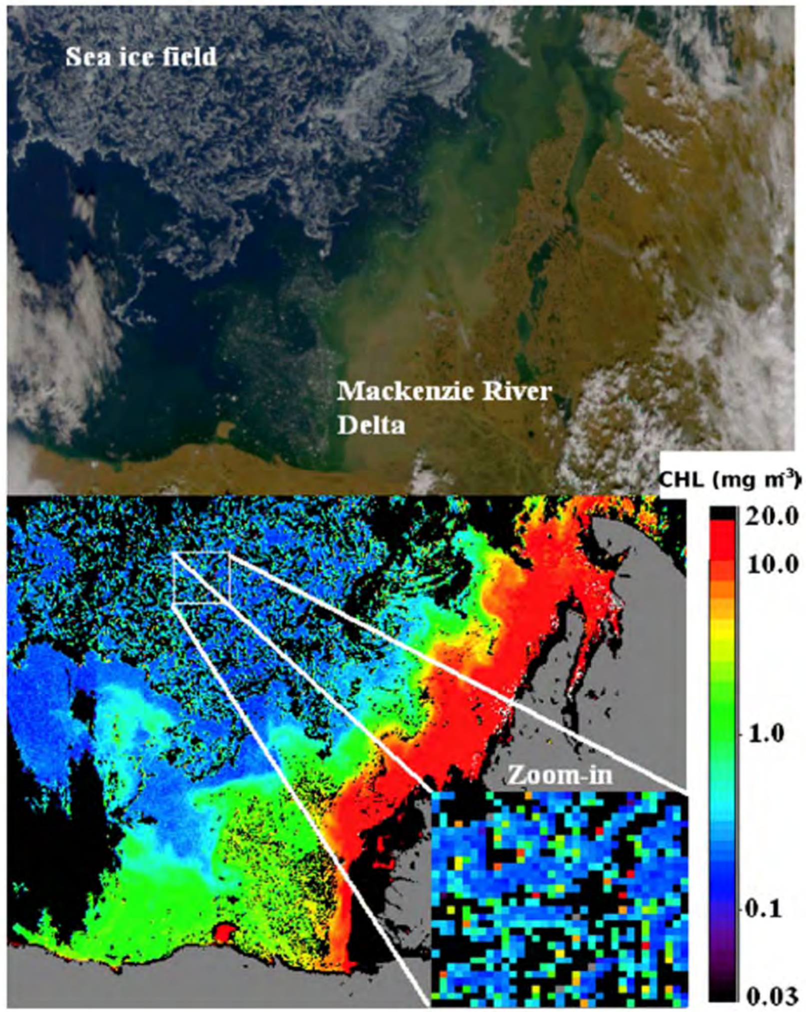
Wang (2003)

1. Ocean colour remote sensing in polar seas

1.3. Retrieval of ocean properties from ocean colour

1.3.2. Contamination of the signal by sea ice

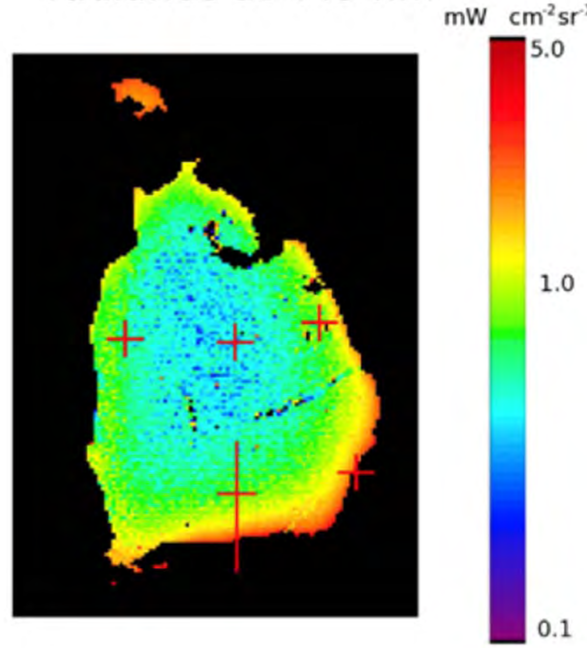
S. Bélanger et al. / Remote Sensing of Environment 111 (2007) 51–68



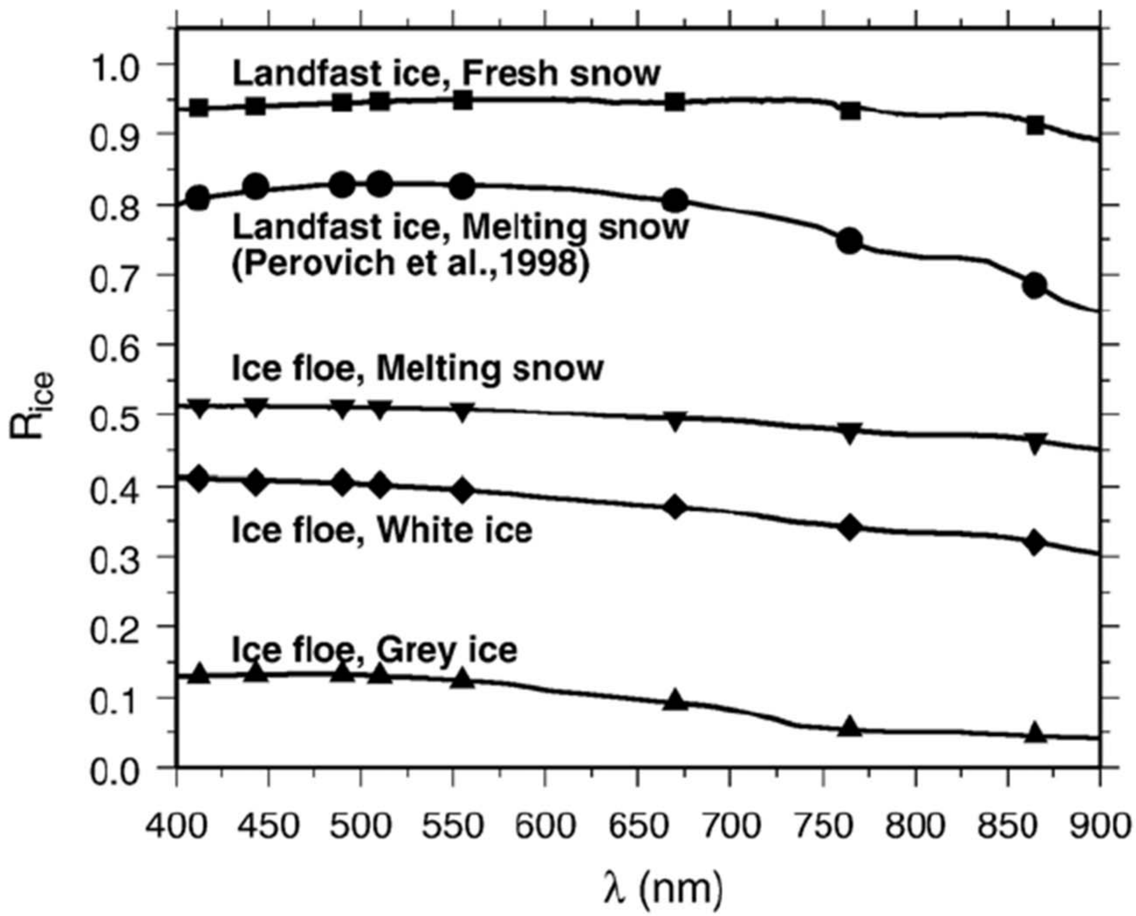
Bélanger et al. (2007)

SeaWiFS quasi-true color

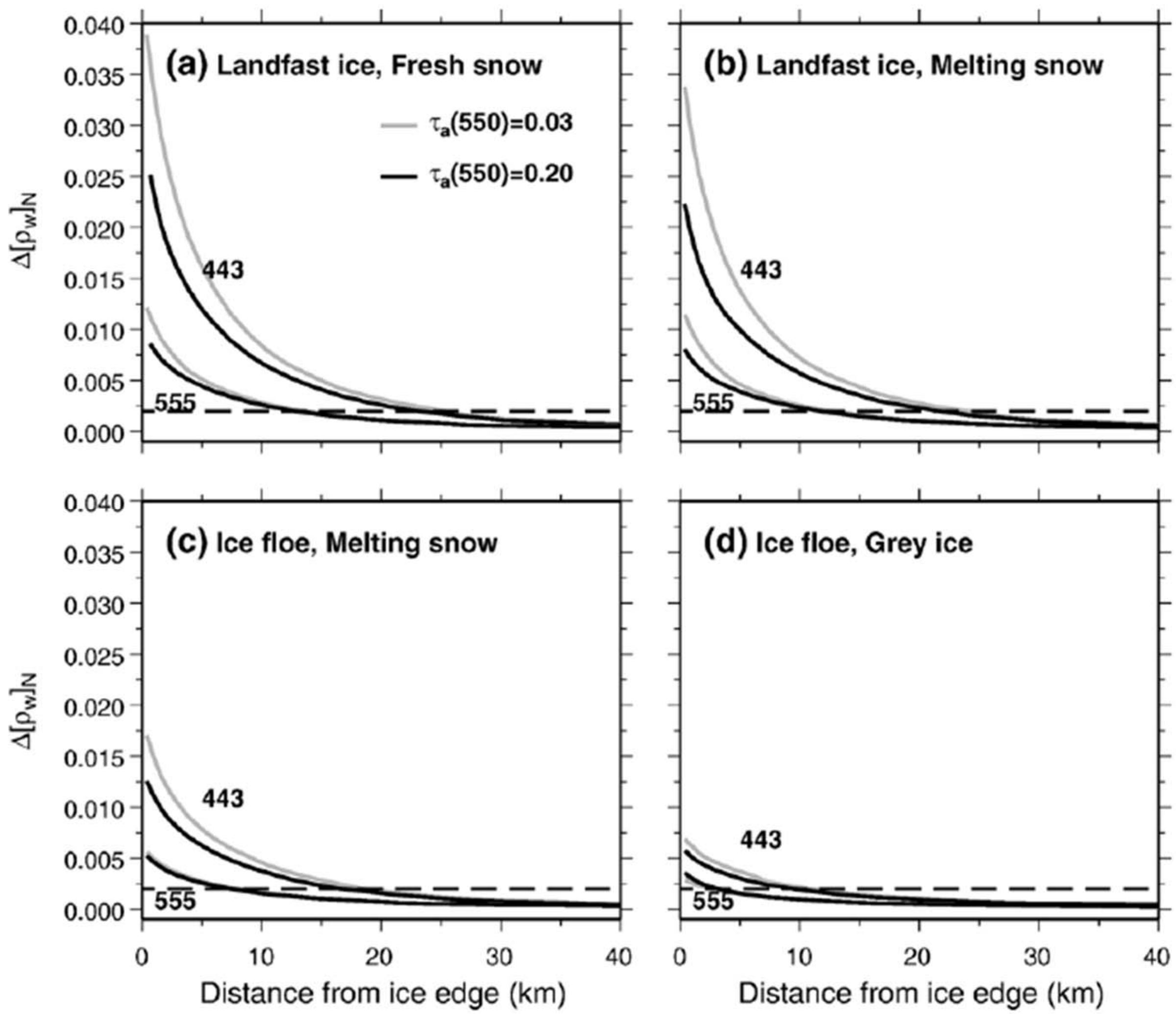
Normalized water-leaving radiance at 443 nm



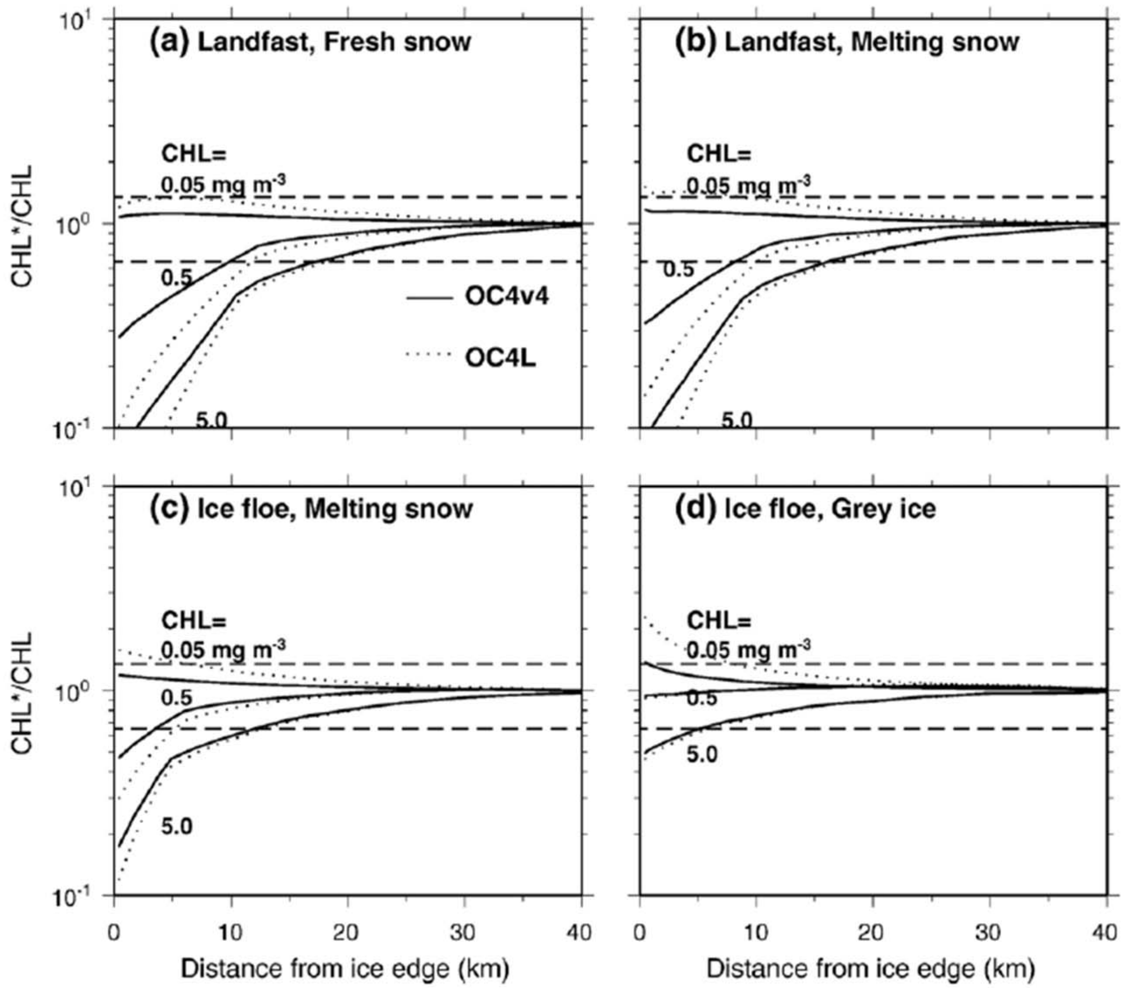
Bélanger et al. (2007)



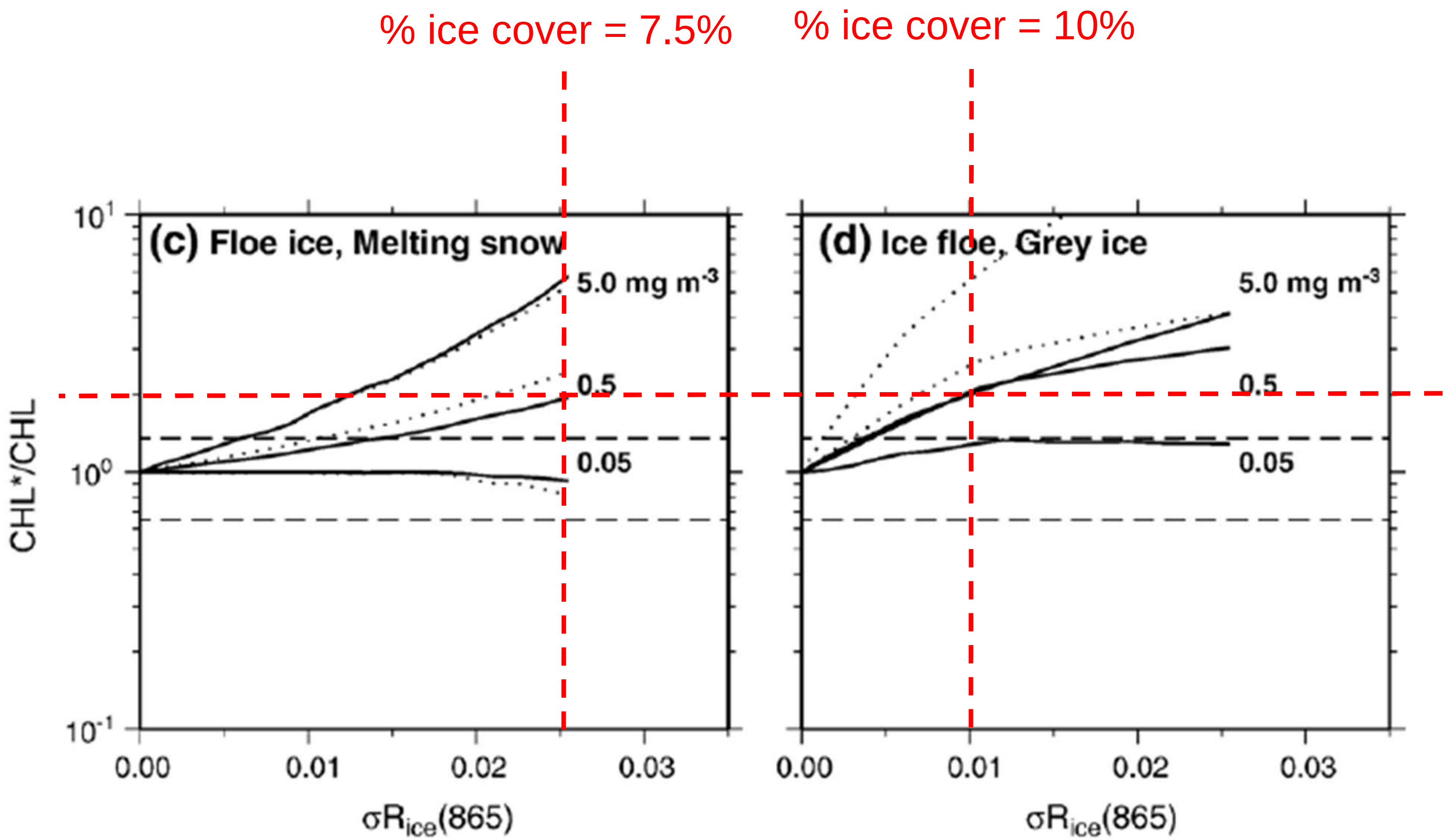
Bélanger et al. (2007)



Bélanger et al. (2007)

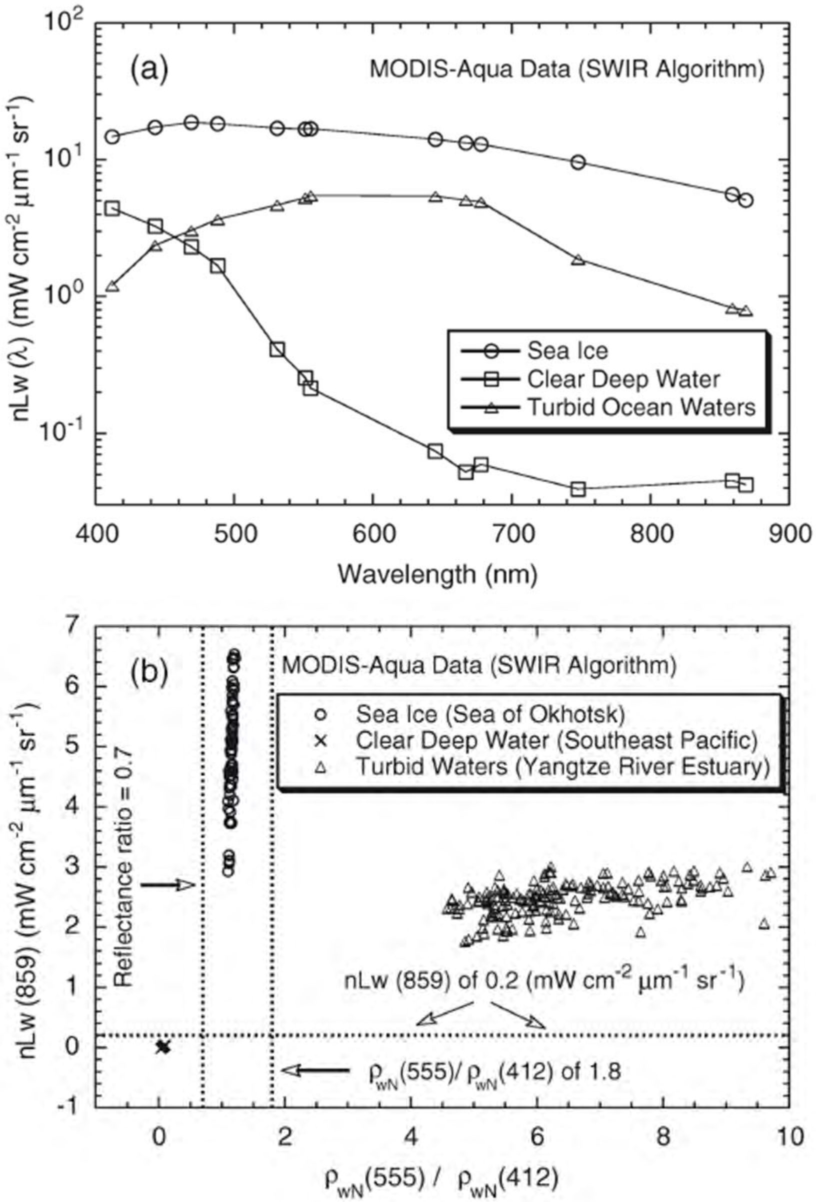


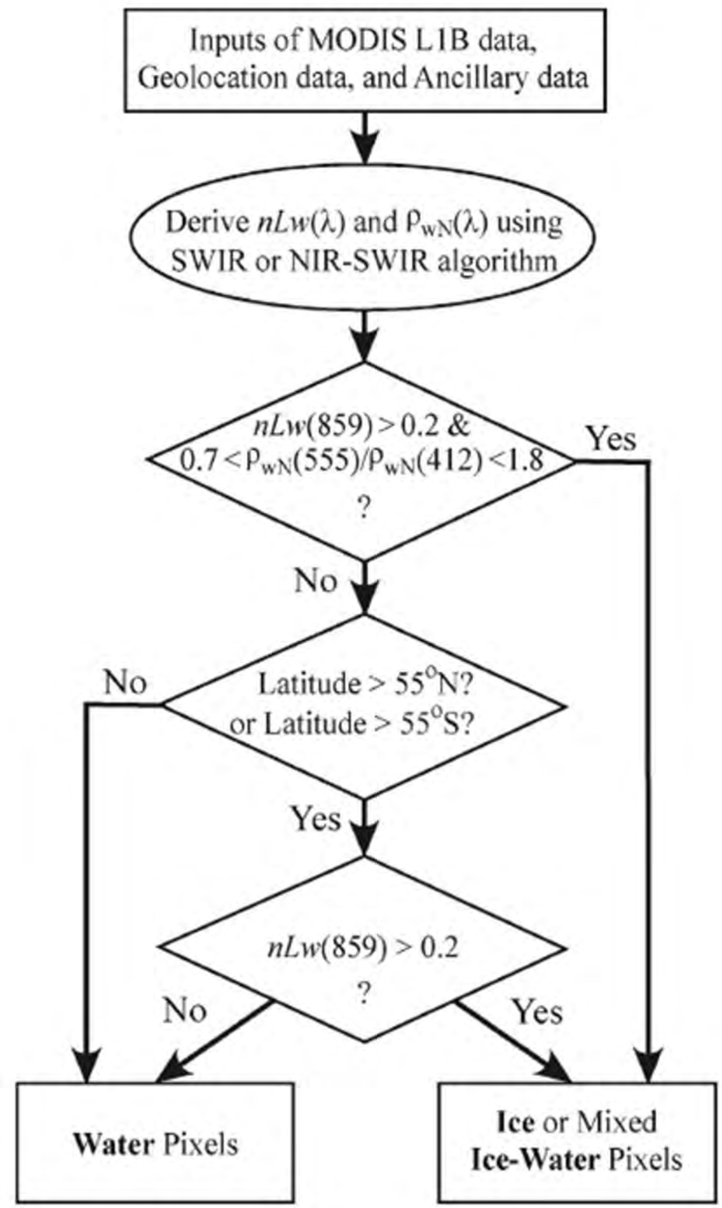
Bélanger et al. (2007)



Bélanger et al. (2007)

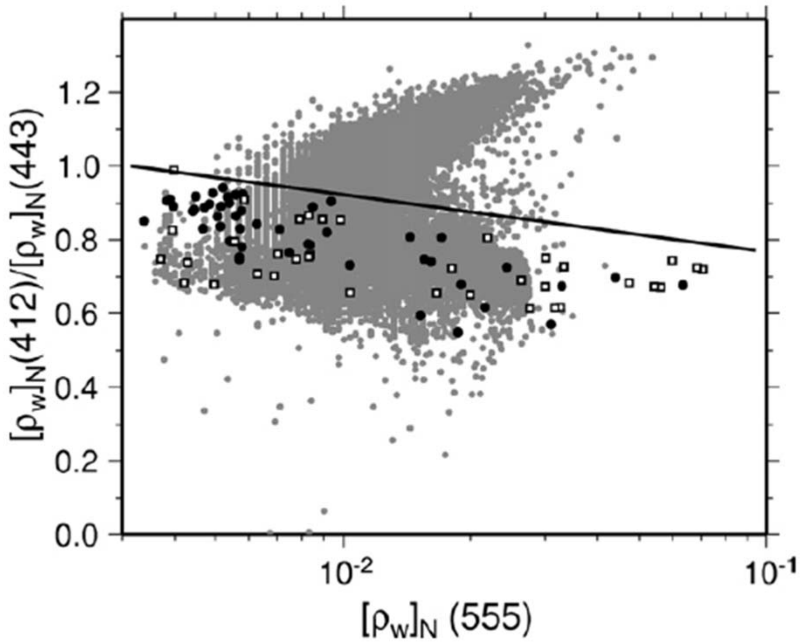
How to flag ice pixels?



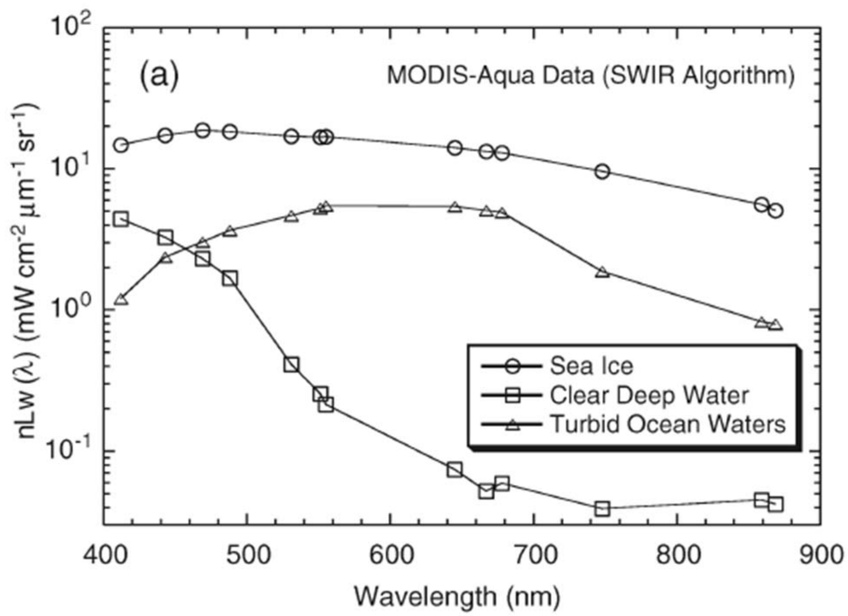


Wand and Shi (2009)

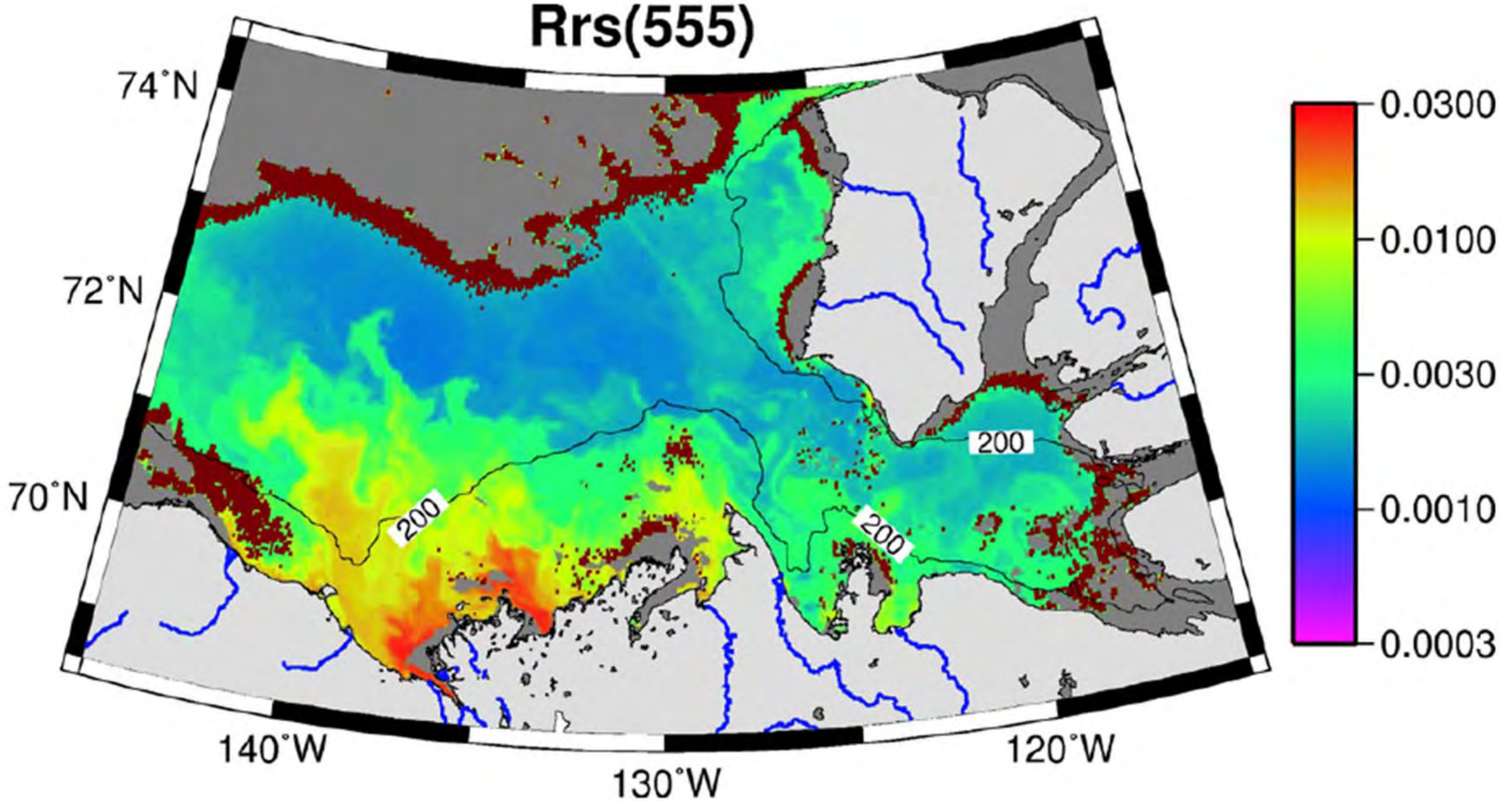
How to flag pixels contaminated by the adjacency effect?



Bélanger et al. (2007)



Wand and Shi (2009)



Bélanger et al. (2007)

Outline

1. Ocean colour remote sensing in polar seas

1.1. Ocean and sea ice in Arctic and Antarctic: relevant features

1.2. Seawater optical properties

1.3. Retrieval of ocean properties from ocean colour

1.3.1. Atmospheric corrections

1.3.2. Contamination of the signal by sea ice

1.3.3. Retrieval of IOPs and AOPs, and biogeochemically relevant variables

1.4. Availability of data as favoured by polar orbits and limited by elevated cloudiness

2. Primary production estimates from OC in polar seas

2.1. PP model and validation: an example

2.2. Results from PP models

1. Ocean colour remote sensing in polar seas

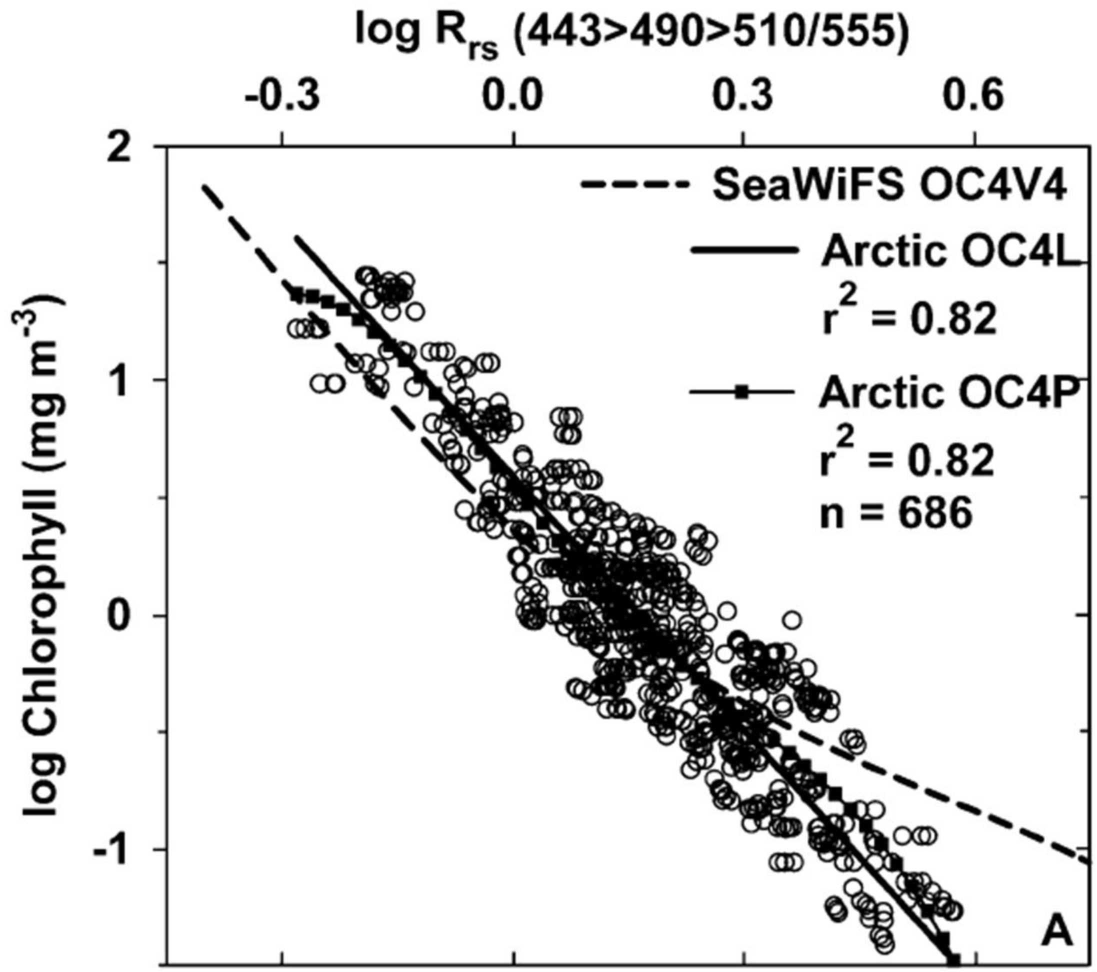
1.3. Retrieval of ocean properties from ocean colour

1.3.3. Retrieval of IOPs and AOPs, and biogeochemically relevant variables

Cota et al. 2004

<u>Data from:</u>

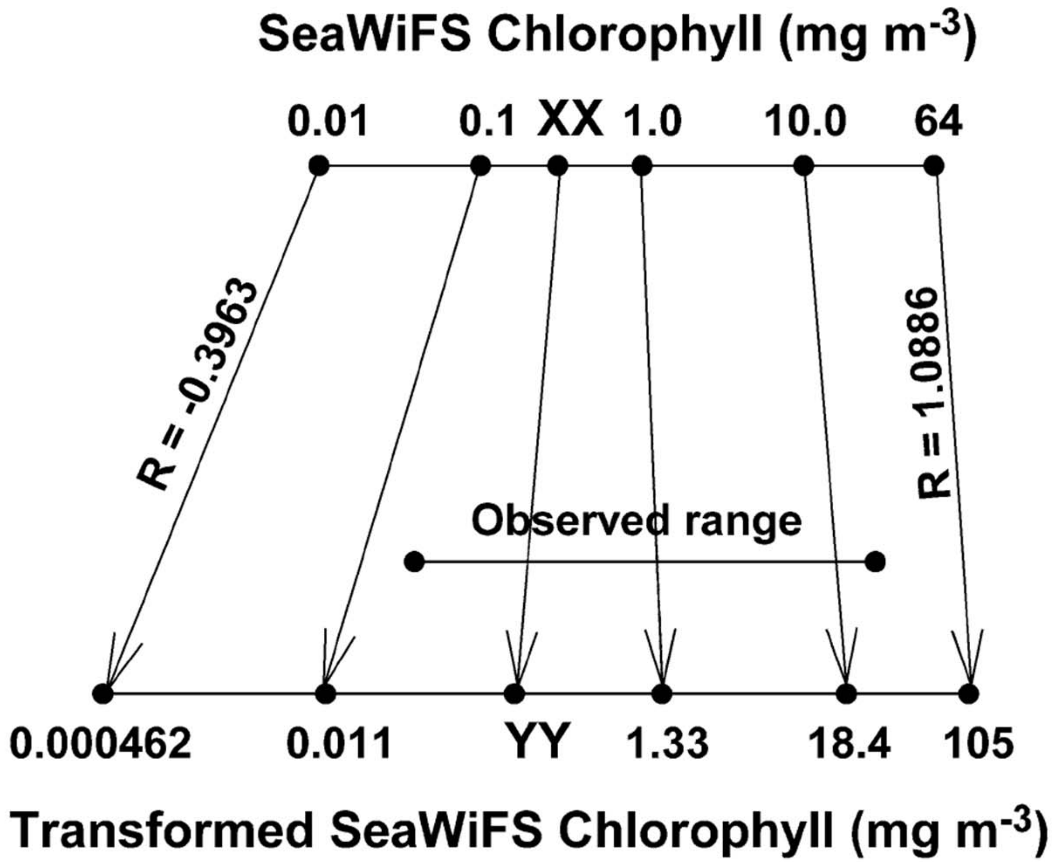
- Labrador Sea
- Chukchi Sea
- Beaufort Sea



Arctic OC4L algorithm

$$\mathrm{Chl\ (Arc)} = 10^{(a_1 + b_1 R)}$$

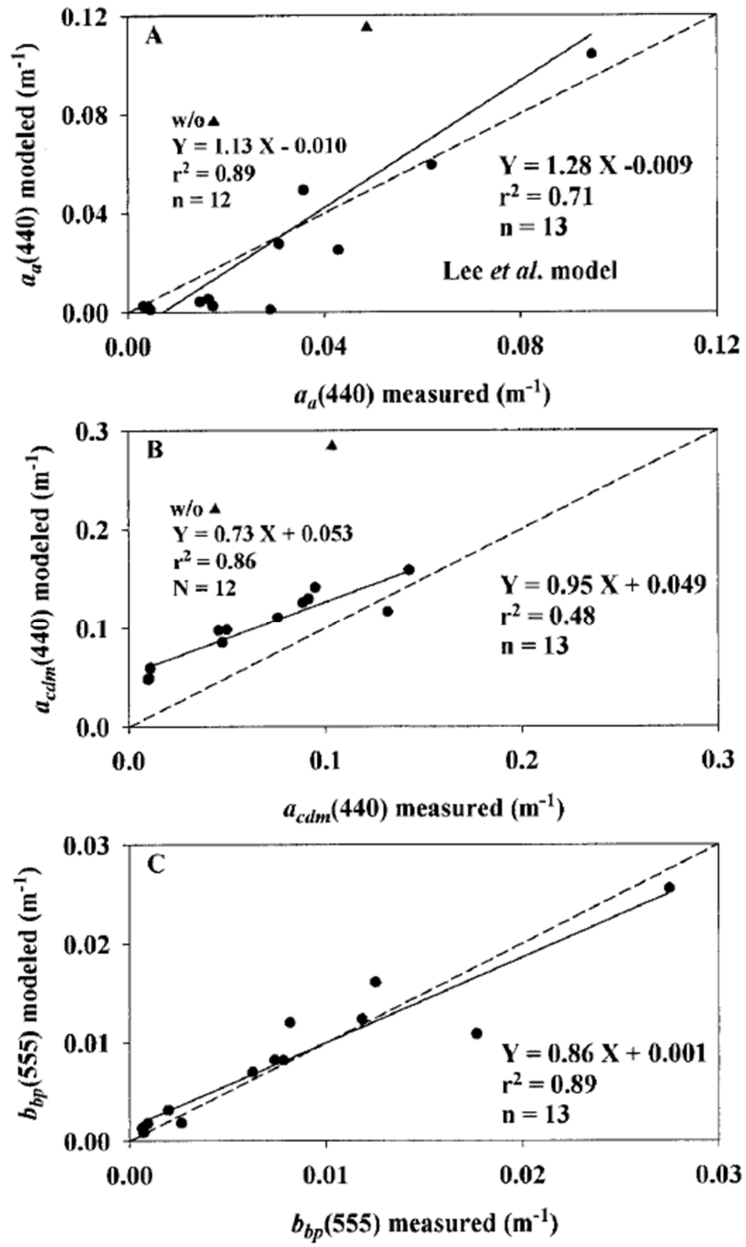
$$R = \log(R_{rs}443>490>510/R_{rs}555)$$



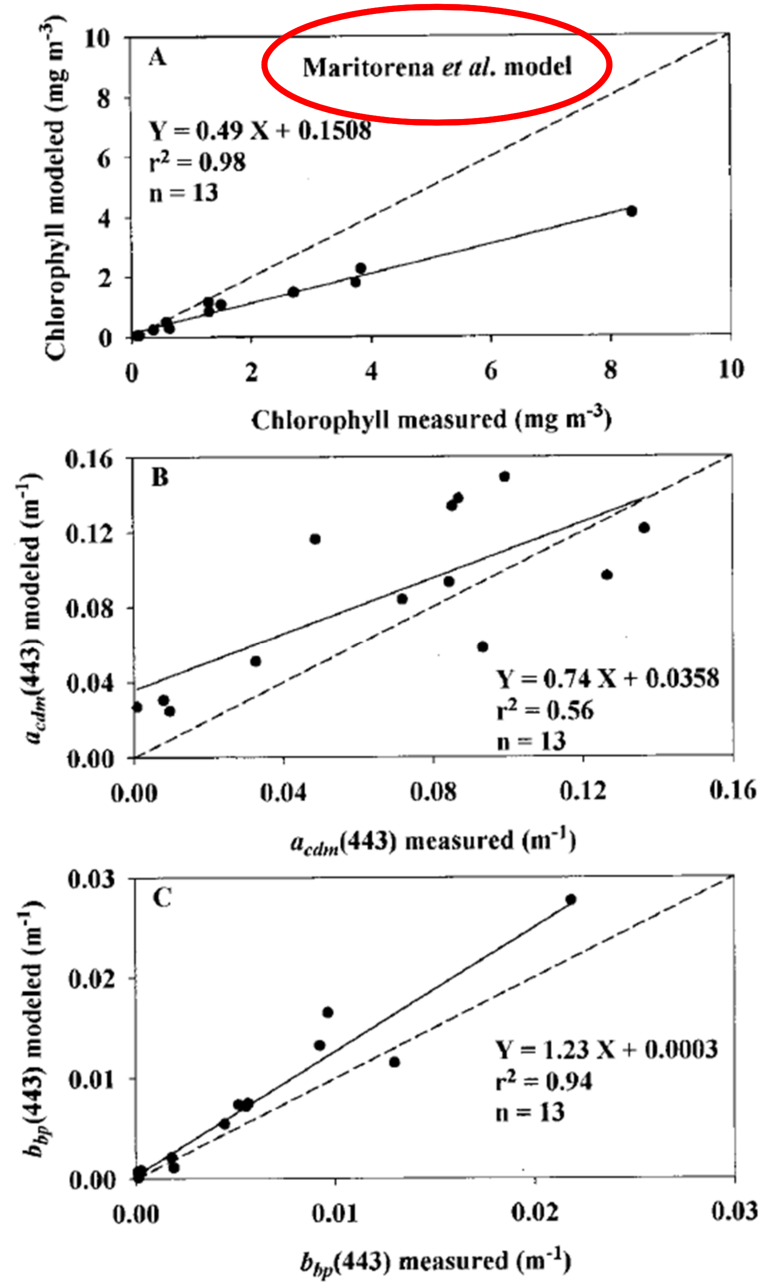
Cota et al. 2004

Wang et al. (2003)

Tuned Lee et al. (2001)

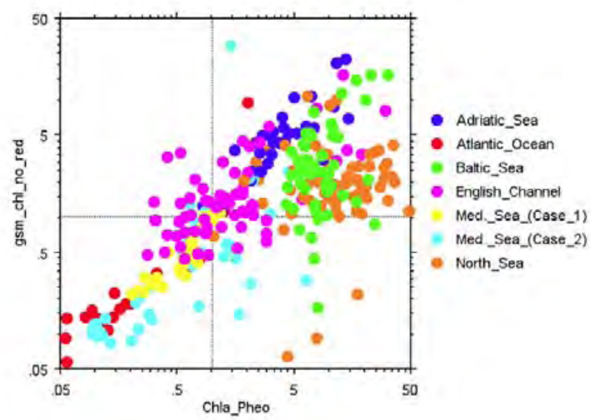


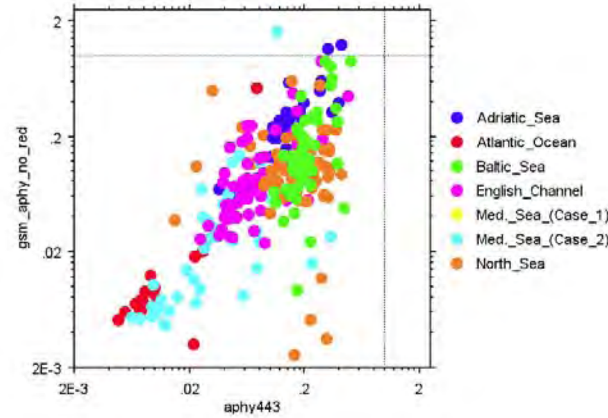
Wang et al. (2003)



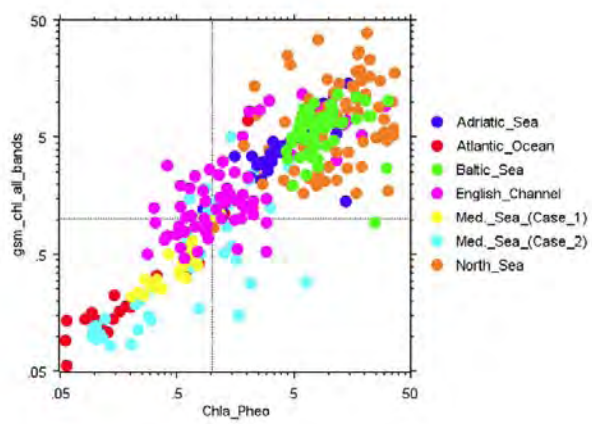
GSM validation using Coastlooc data from Babin (2003)

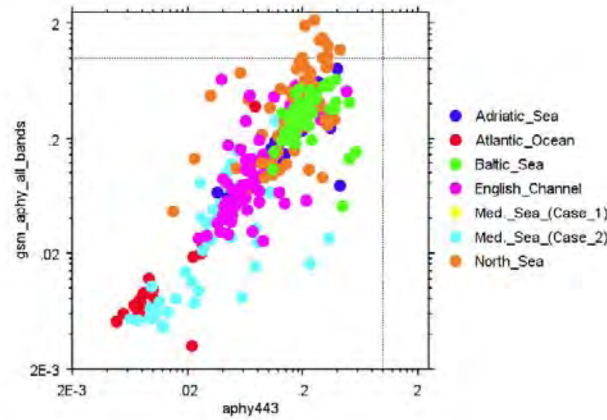
Blue & green channels



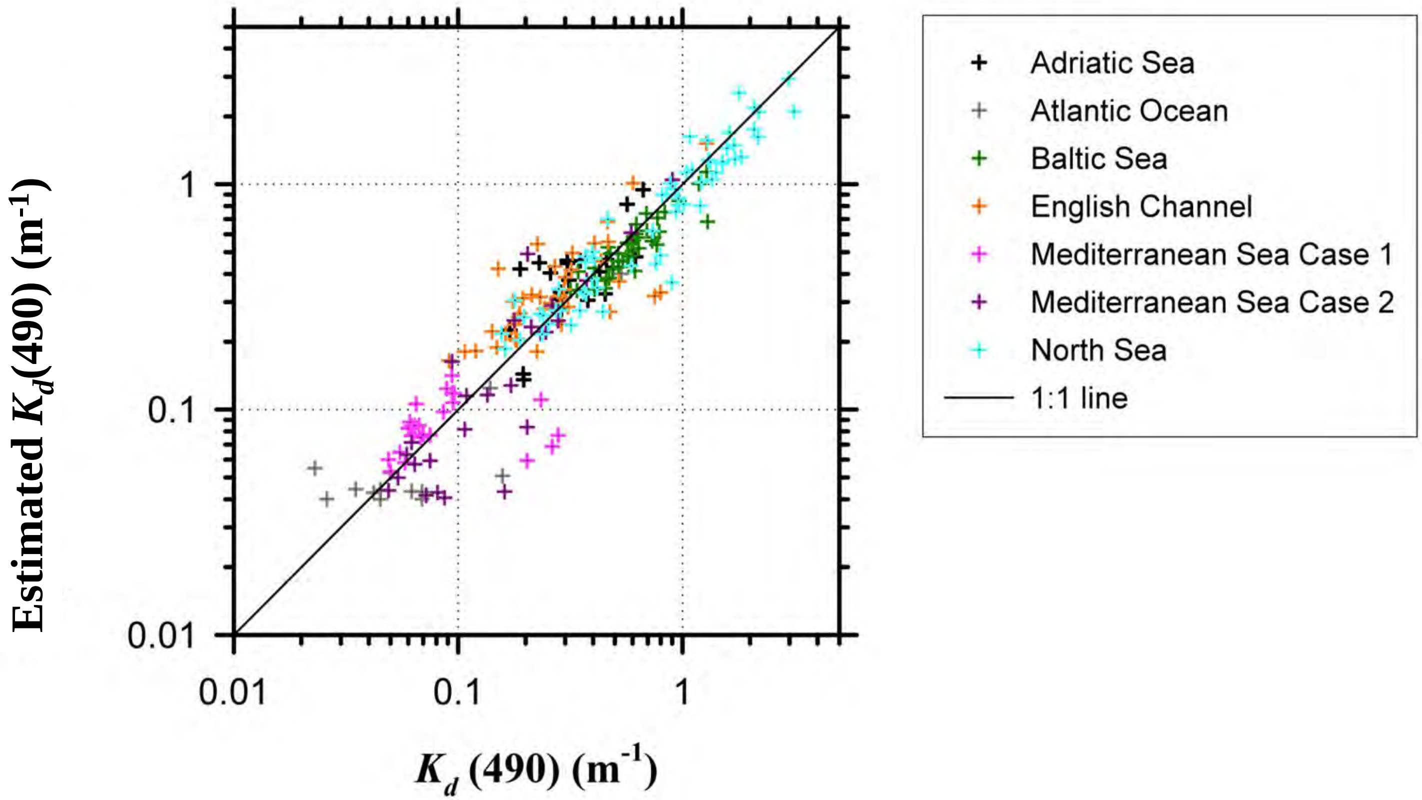


Blue, green & red channels

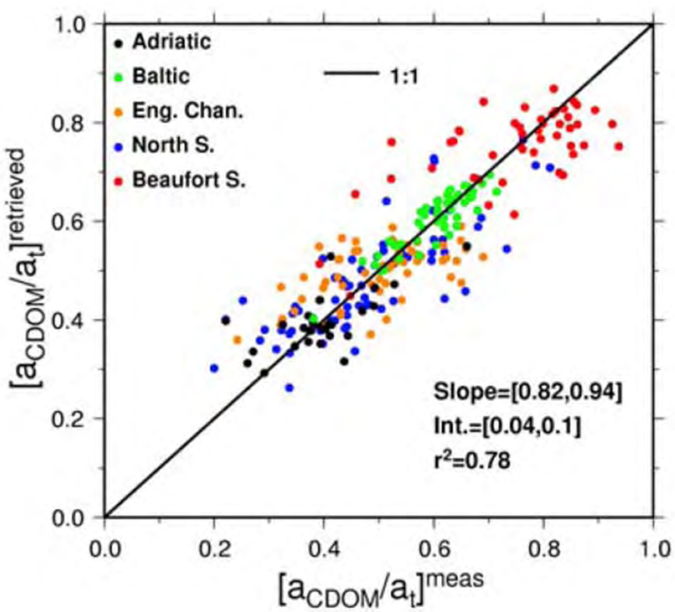




QAA validation in Case 2 waters

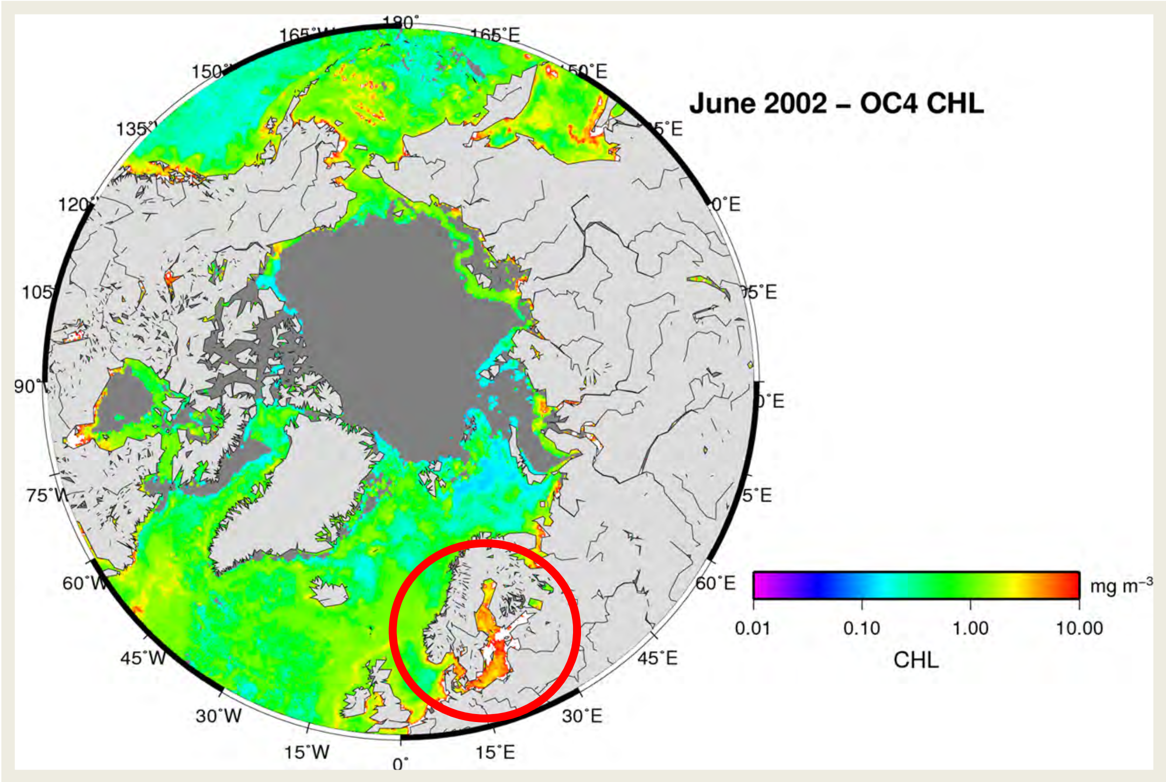


Doron et al. (2007)

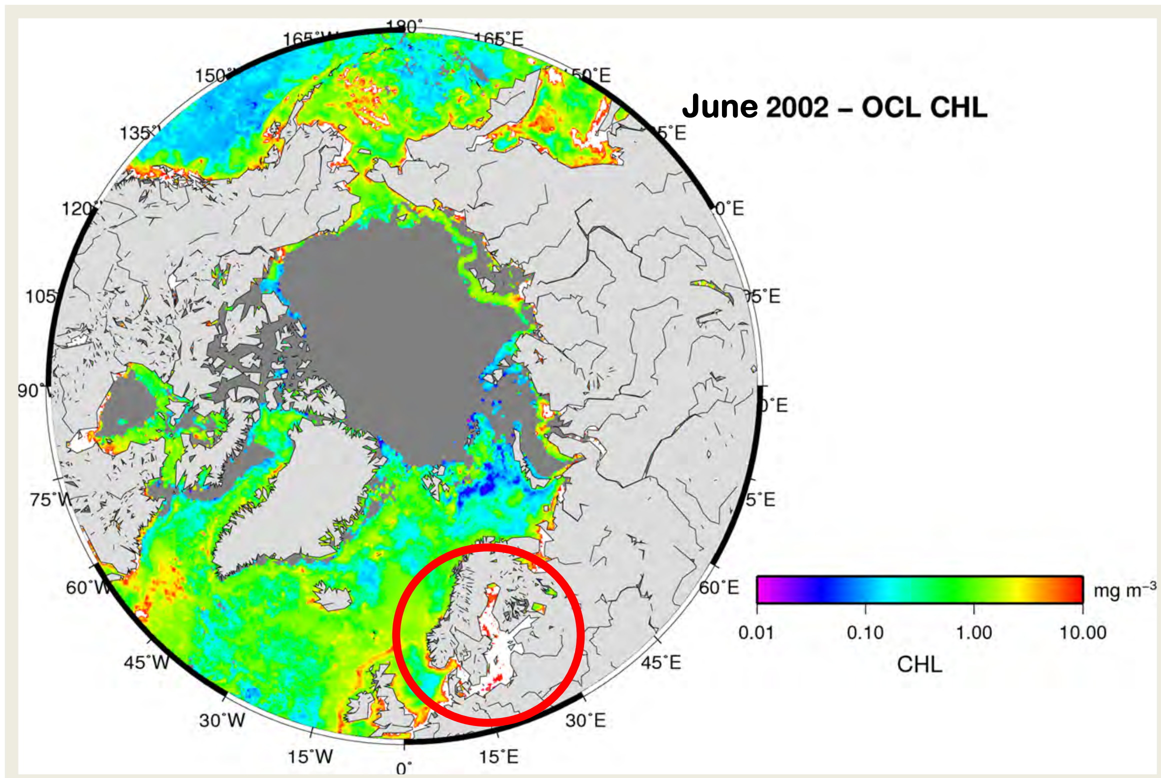


Bélanger et al. (2008)

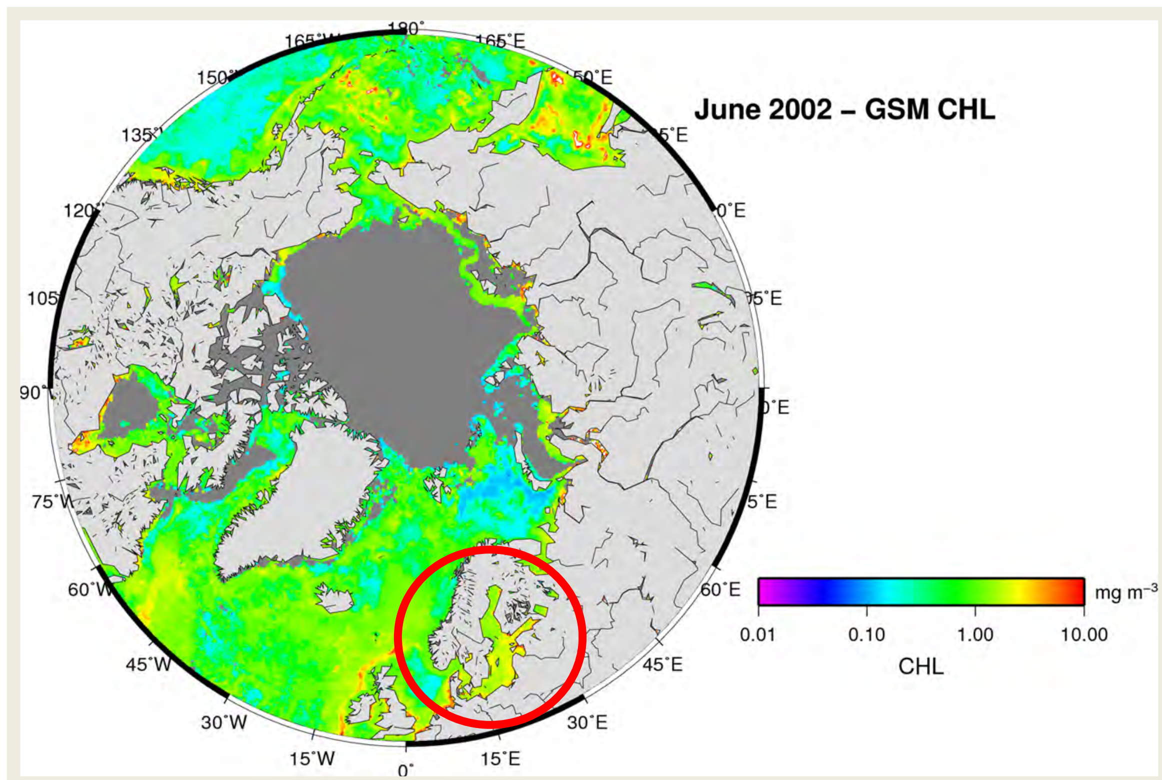
Standard ocean color chl products are not reliable in the Arctic Ocean



Standard ocean color chl products are not reliable in the Arctic Ocean



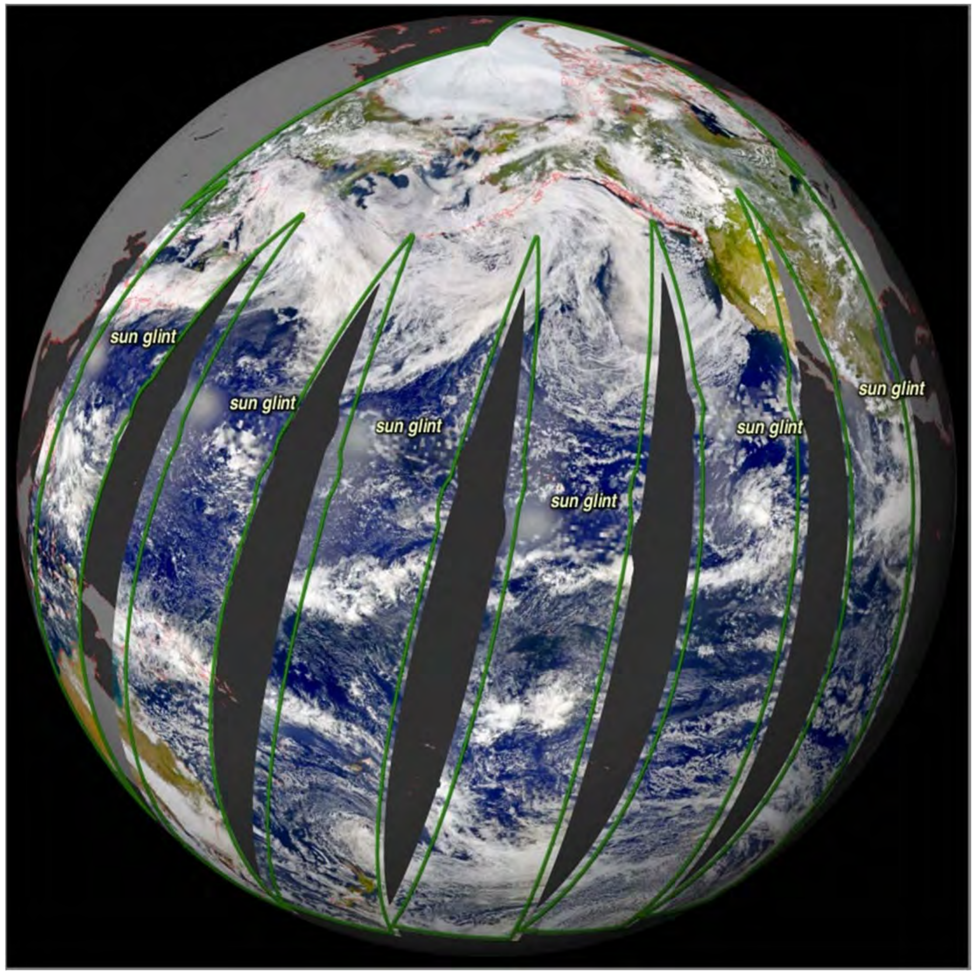
Standard ocean color chl products are not reliable in the Arctic Ocean



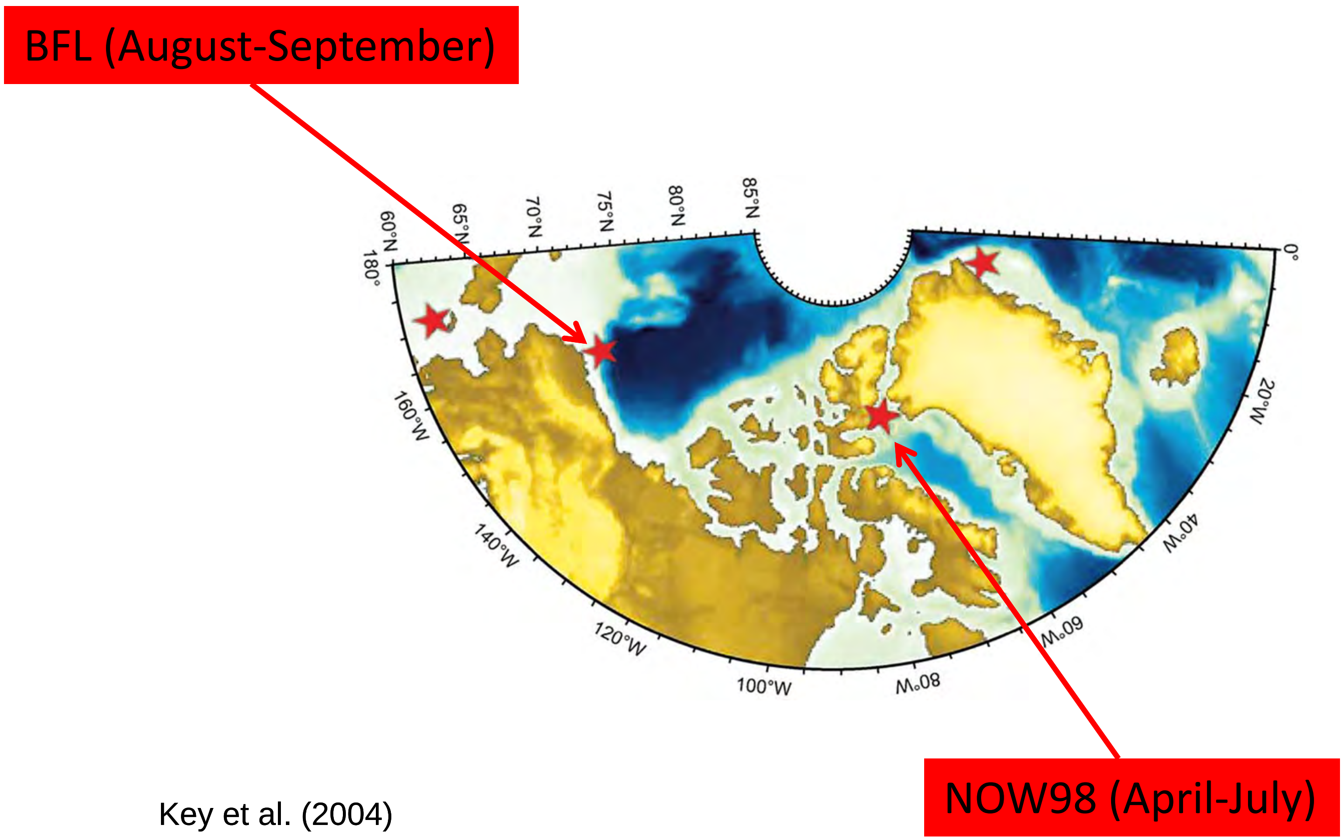
1. Ocean colour remote sensing in polar seas

1.4. Availability of data as favoured by polar orbits and limited by elevated cloudiness

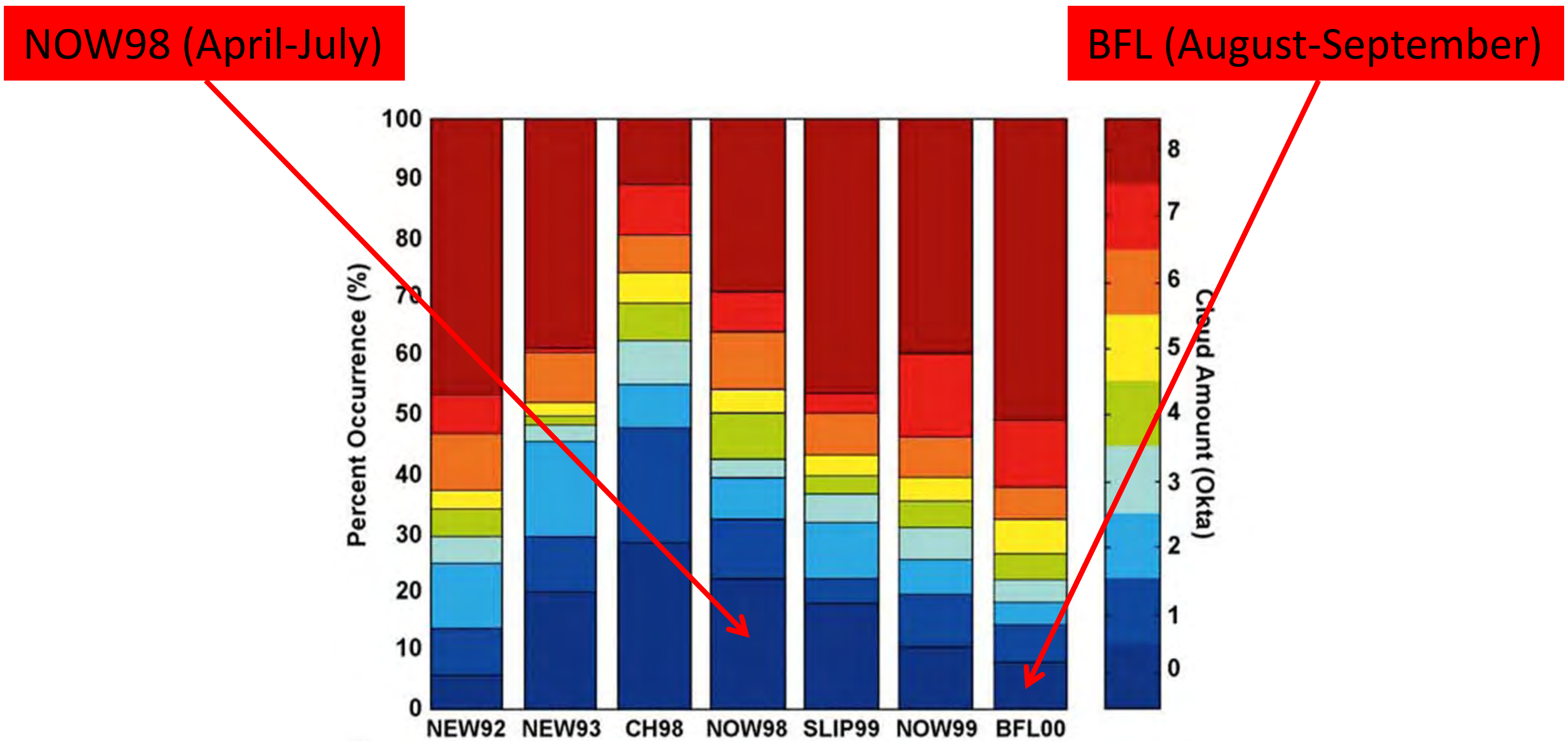
Polar orbiting ocean color sensors provide data several several times a day



Cloud cover



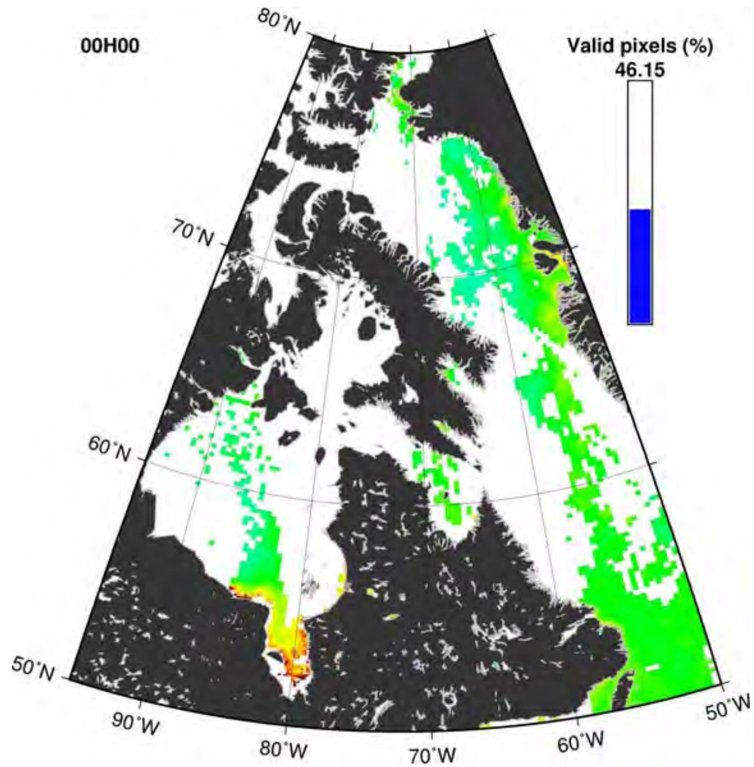
Key et al. (2004)



Key et al. (2004)

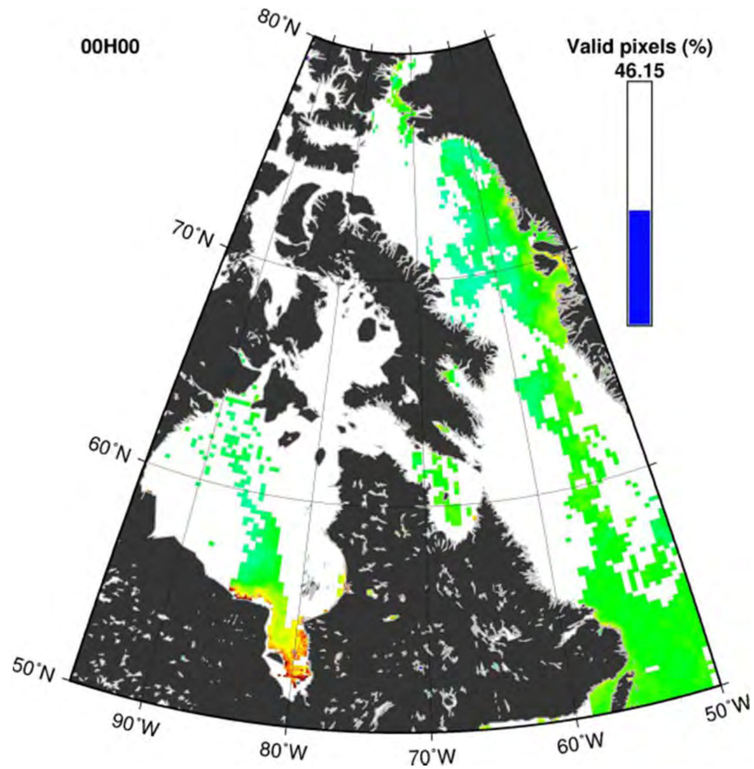
High-frequency observations may help

MERIS L3 Chlorophyll-a Concentration (mg m^{-3})

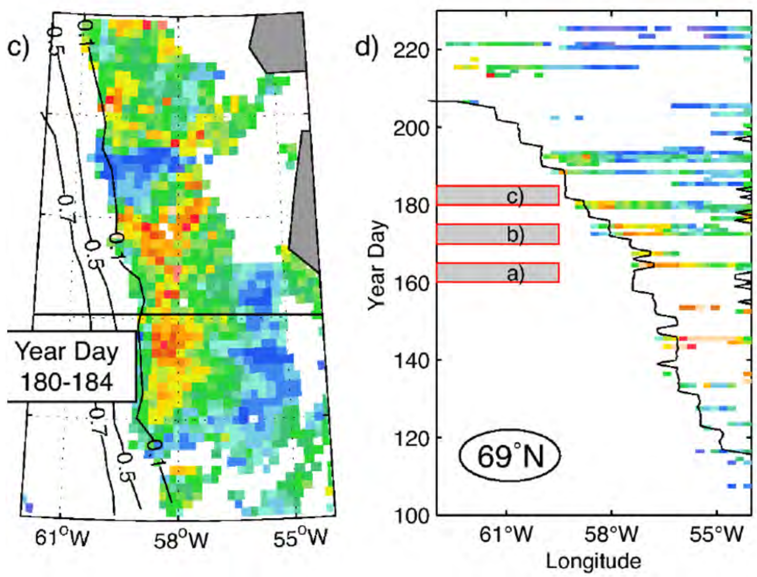


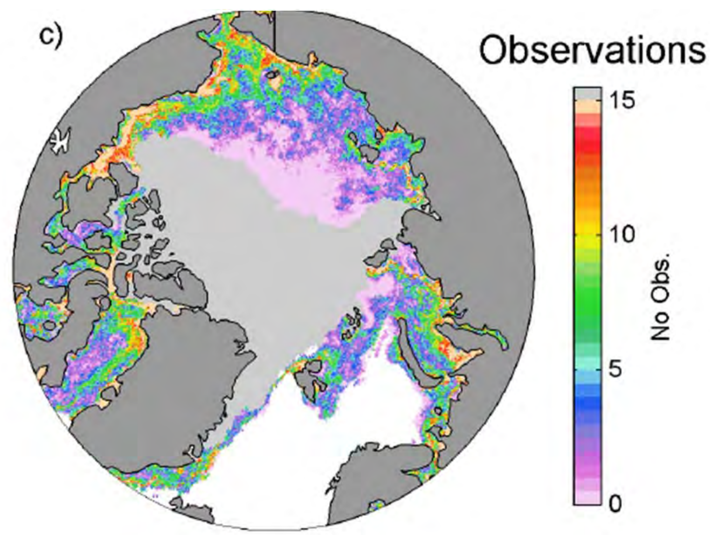
Cloud cover derived using METEOSAT GEMS02 Satellite (15 min resolution)

MERIS L3 Chlorophyll-a Concentration (mg m^{-3})



Cloud cover derived using METEOSAT GEMS02 Satellite (15 min resolution)



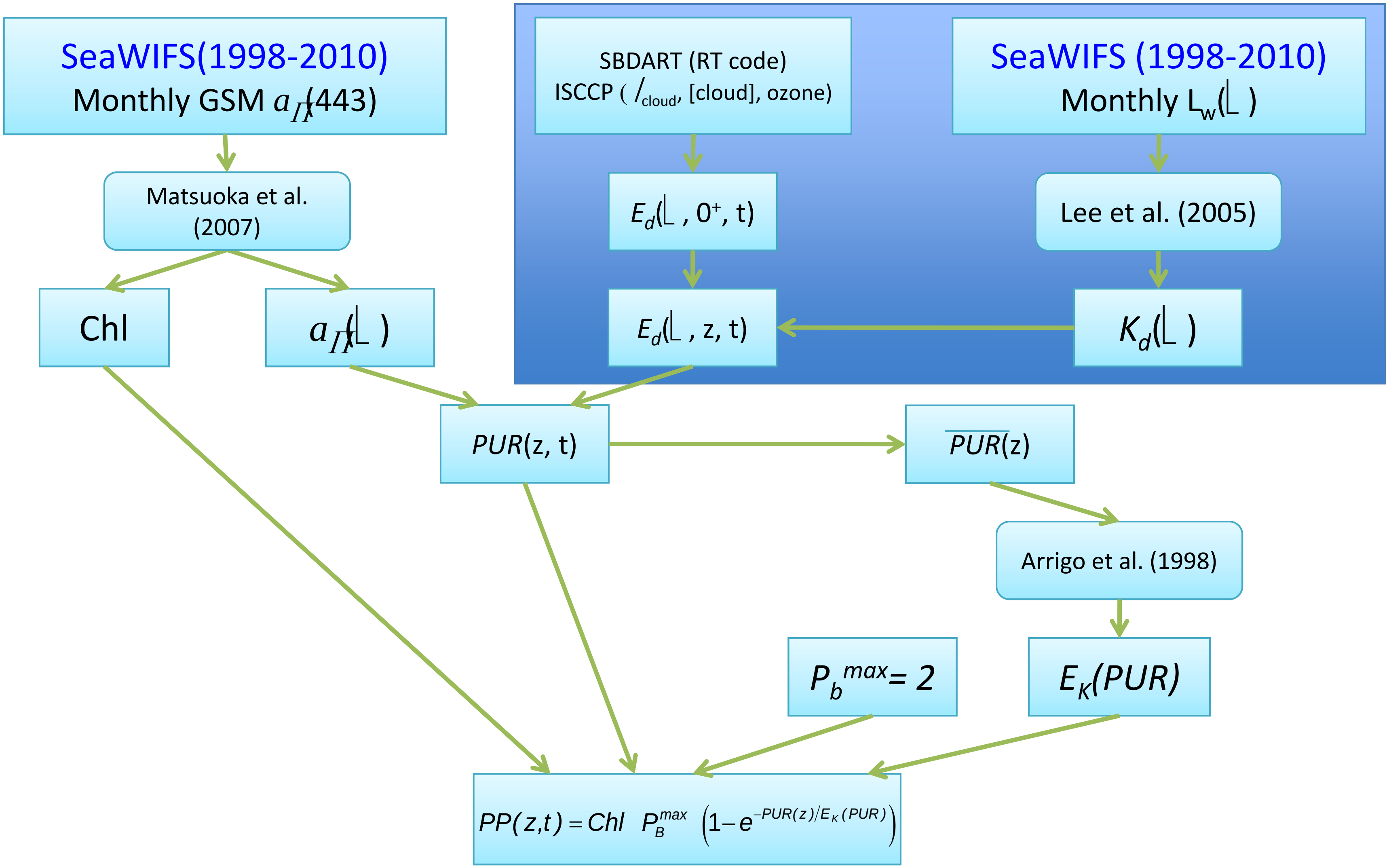


Perrette et al. (2011)

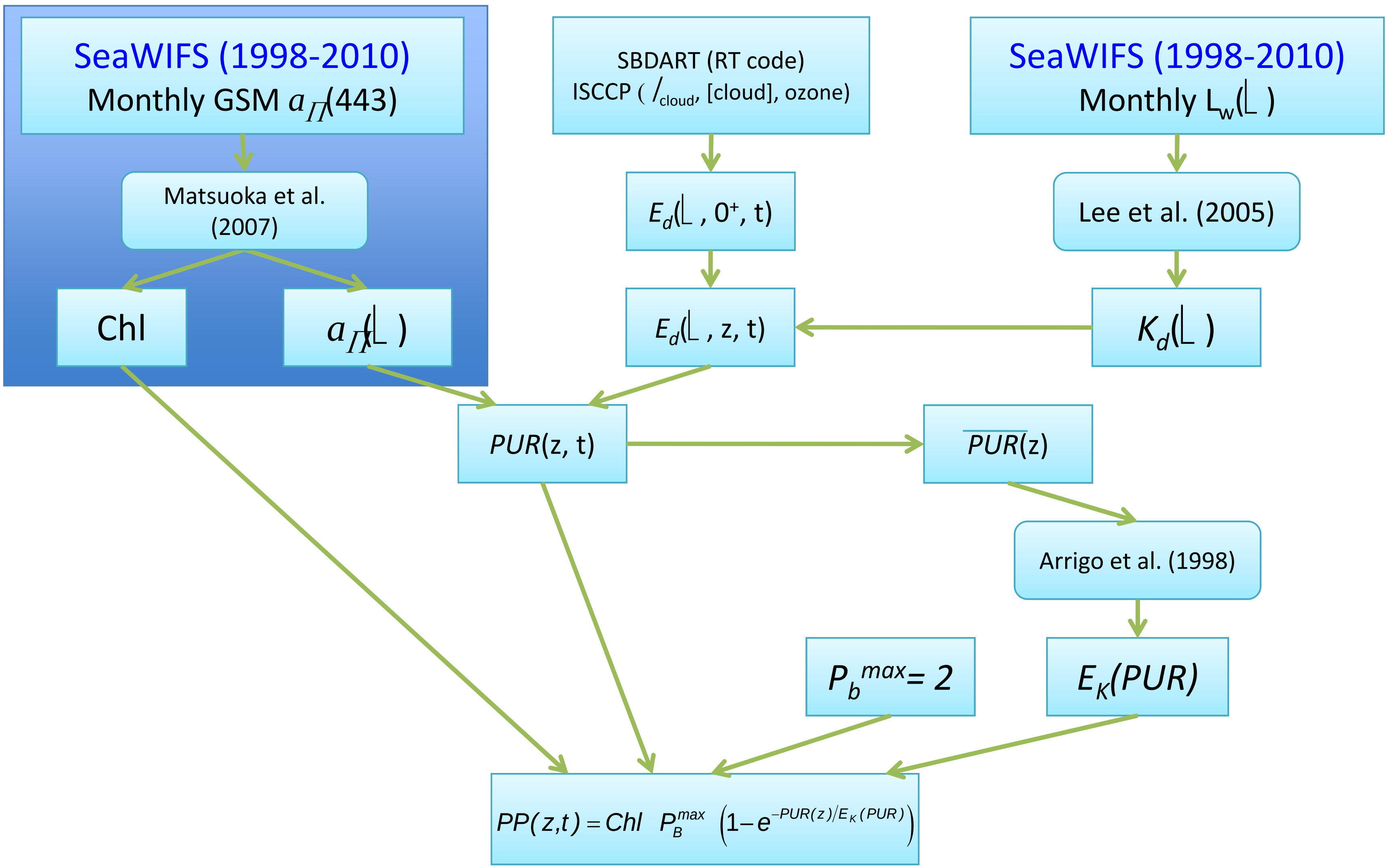
2. Primary production estimates from OC in polar seas

2.1. PP model and validation: an example

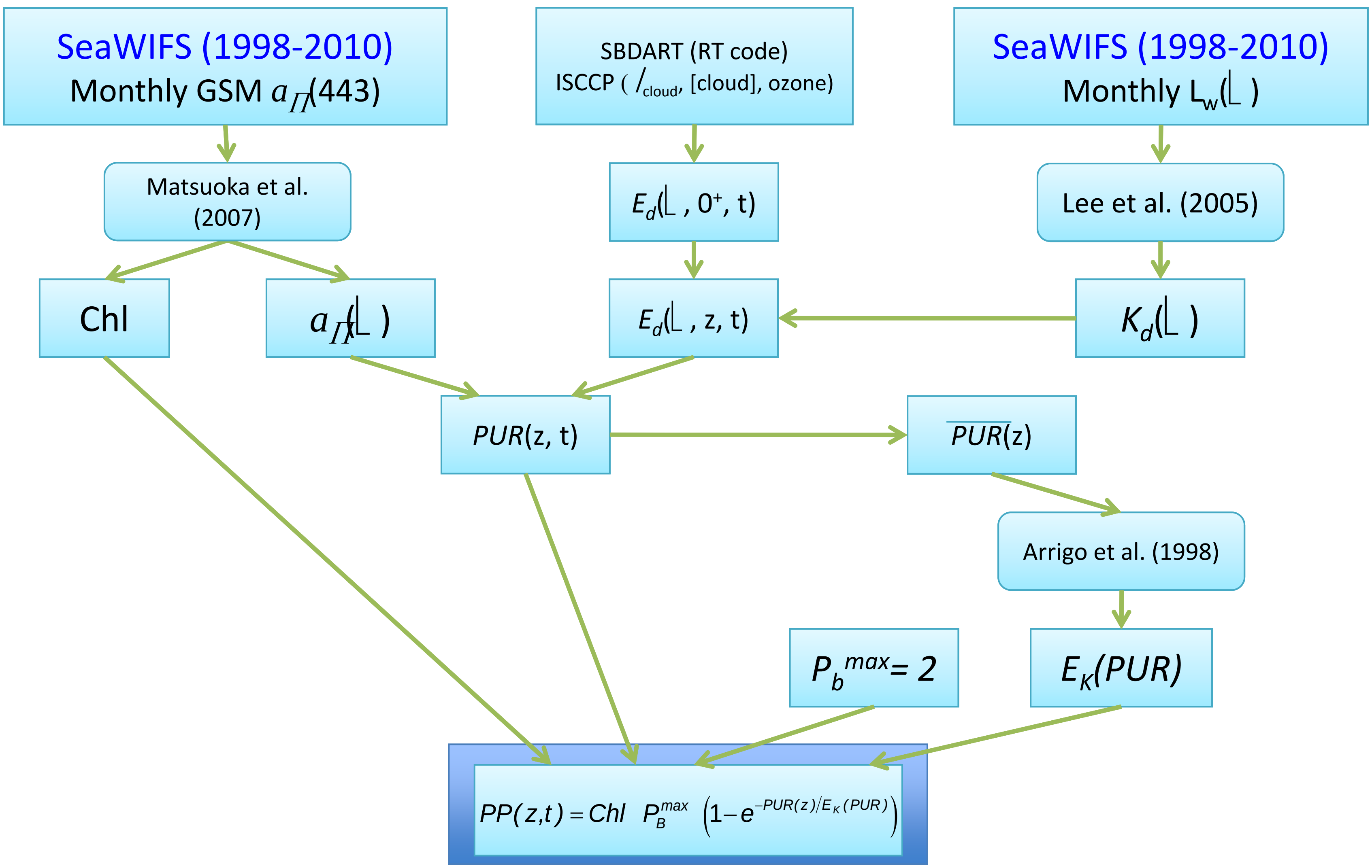
Methods – Primary production model



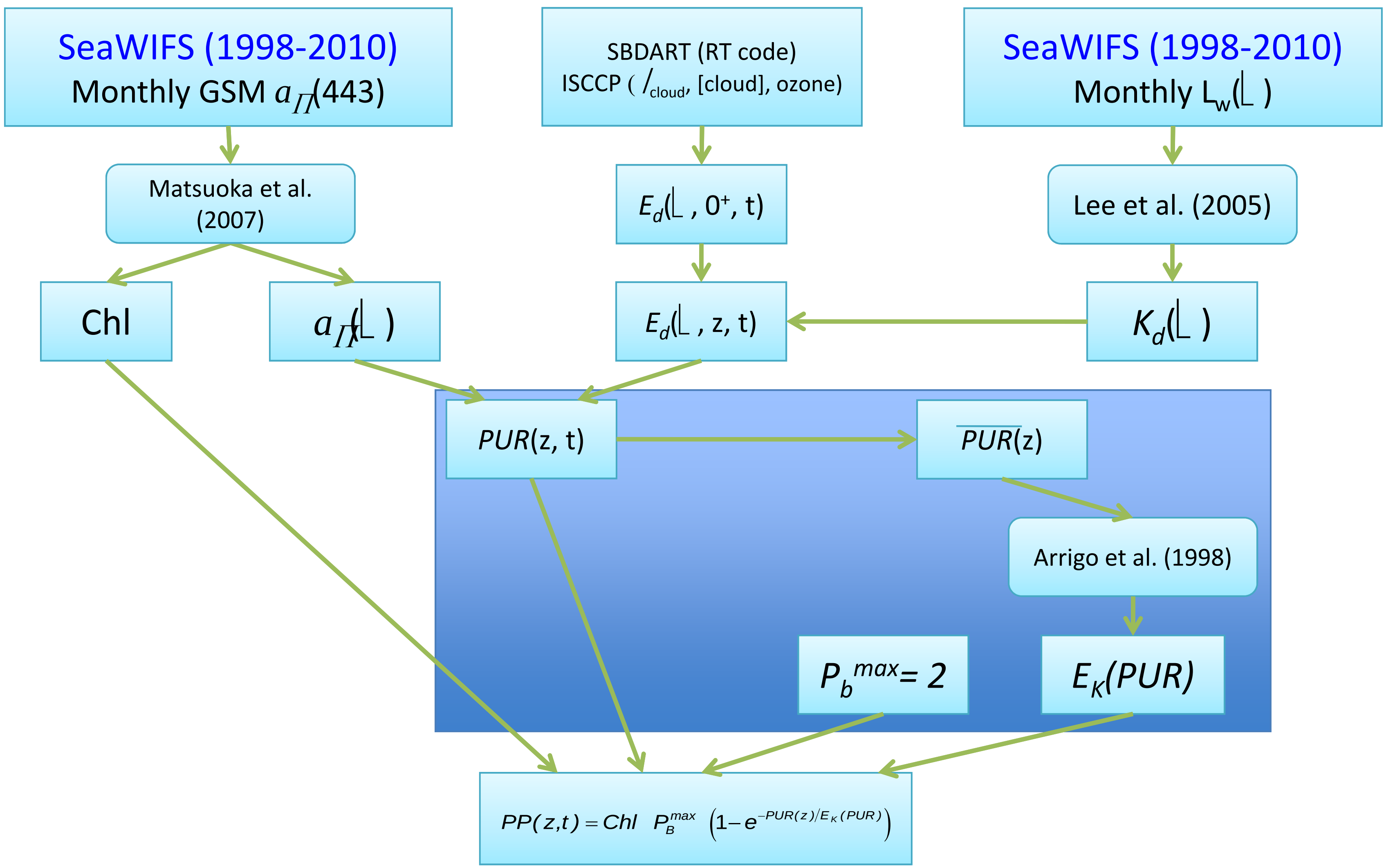
Methods – Primary production model



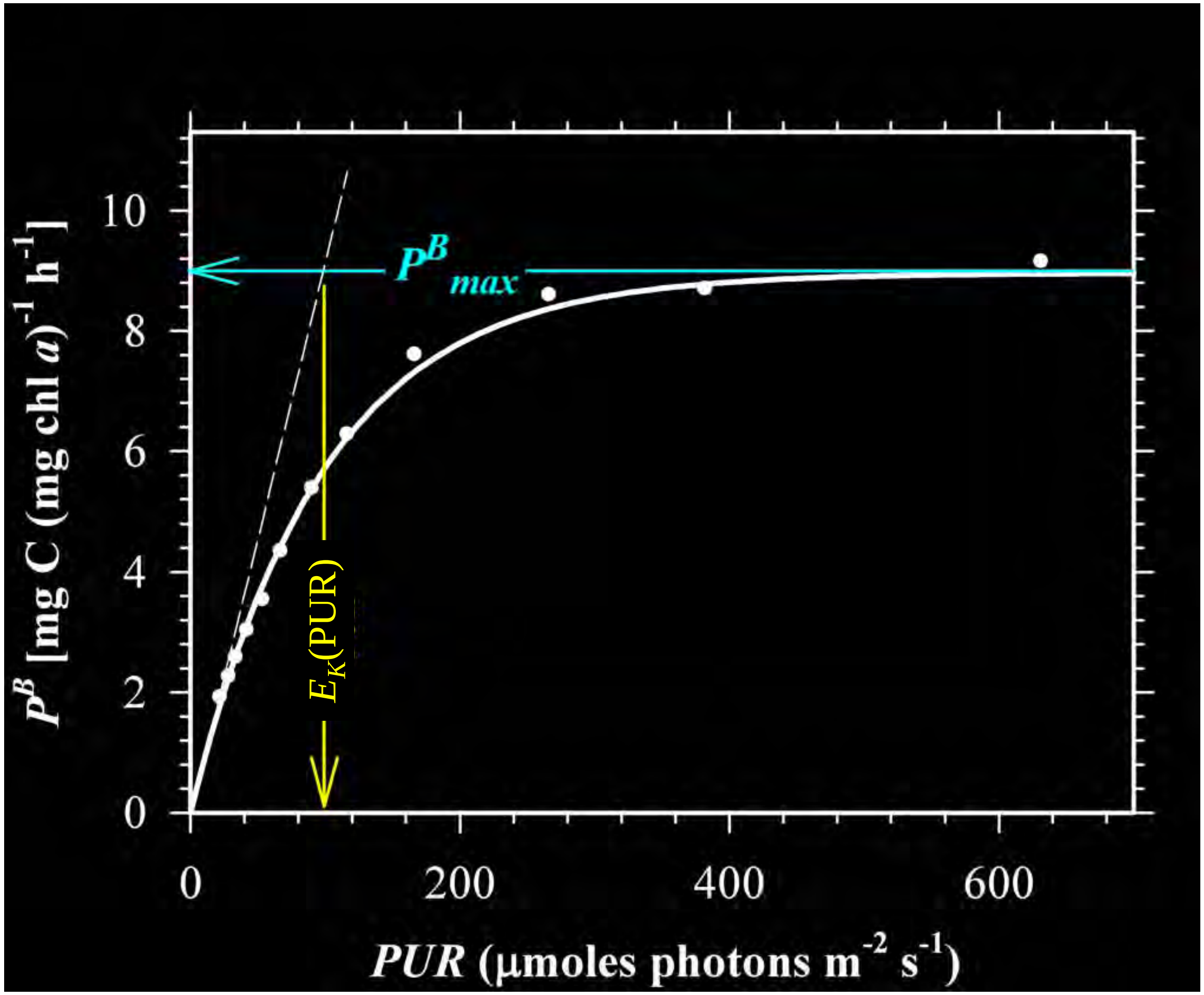
Methods – Primary production model



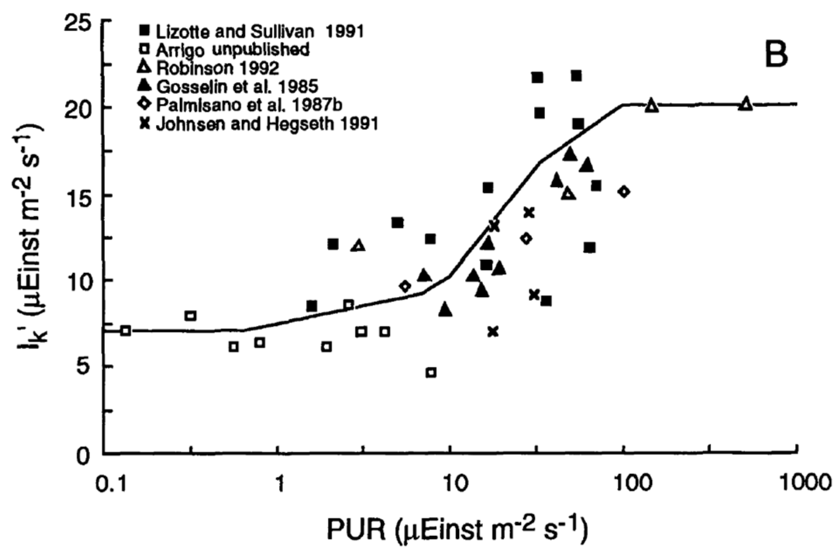
Methods – Primary production model



$$PP(z,t) = Chl \;\; P_B^{max} \left(1 - e^{-PUR(z)/E_K(PUR)}\right)$$



Photosynthetic parameters



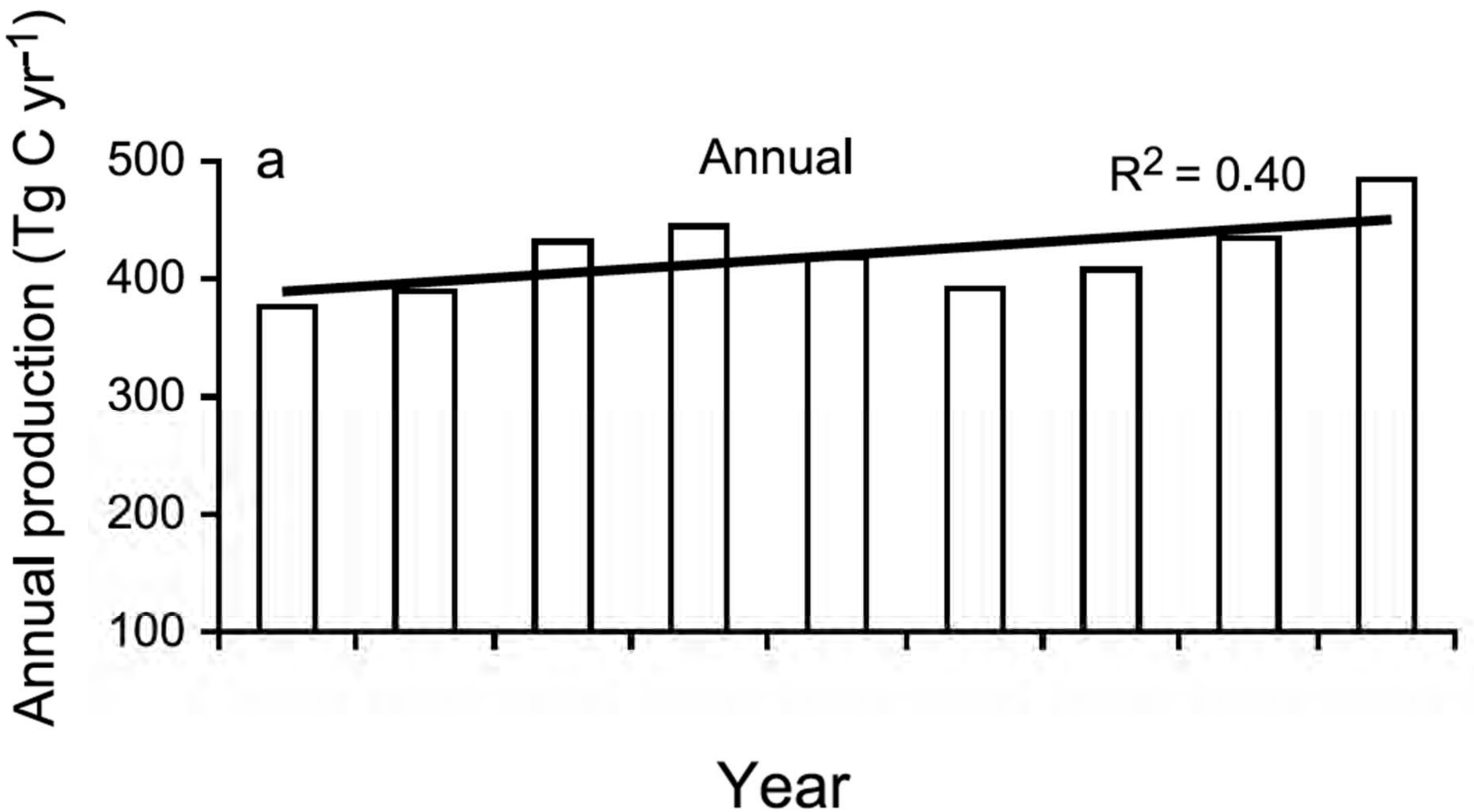
Arrigo and Sullivan (1994)

2. Primary production estimates from OC in polar seas

2.2. Results from this and other PP models

Arctic Primary Production

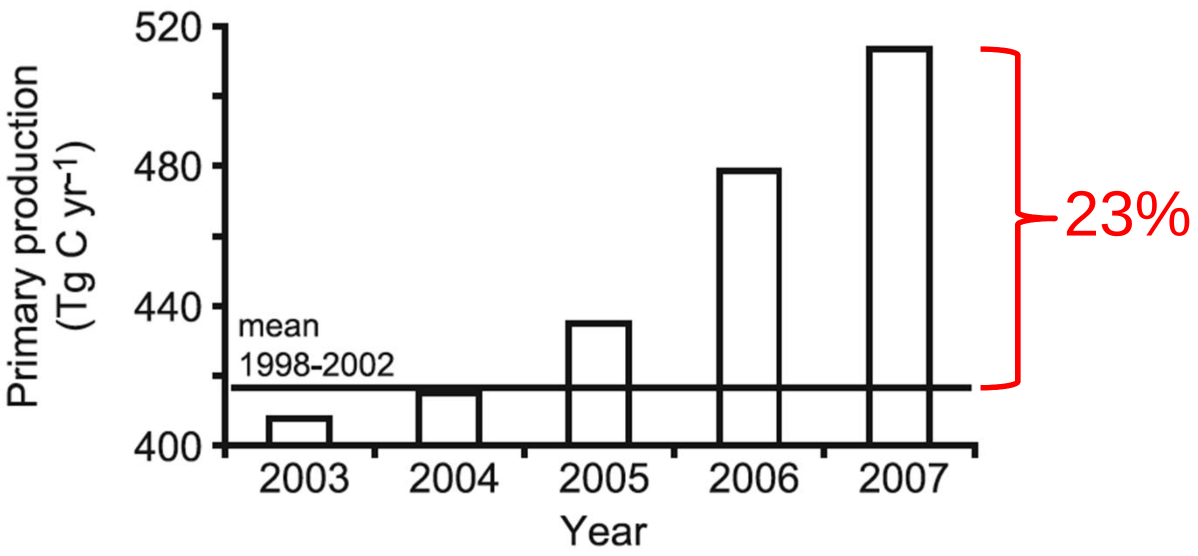
Pabi et al. 2008



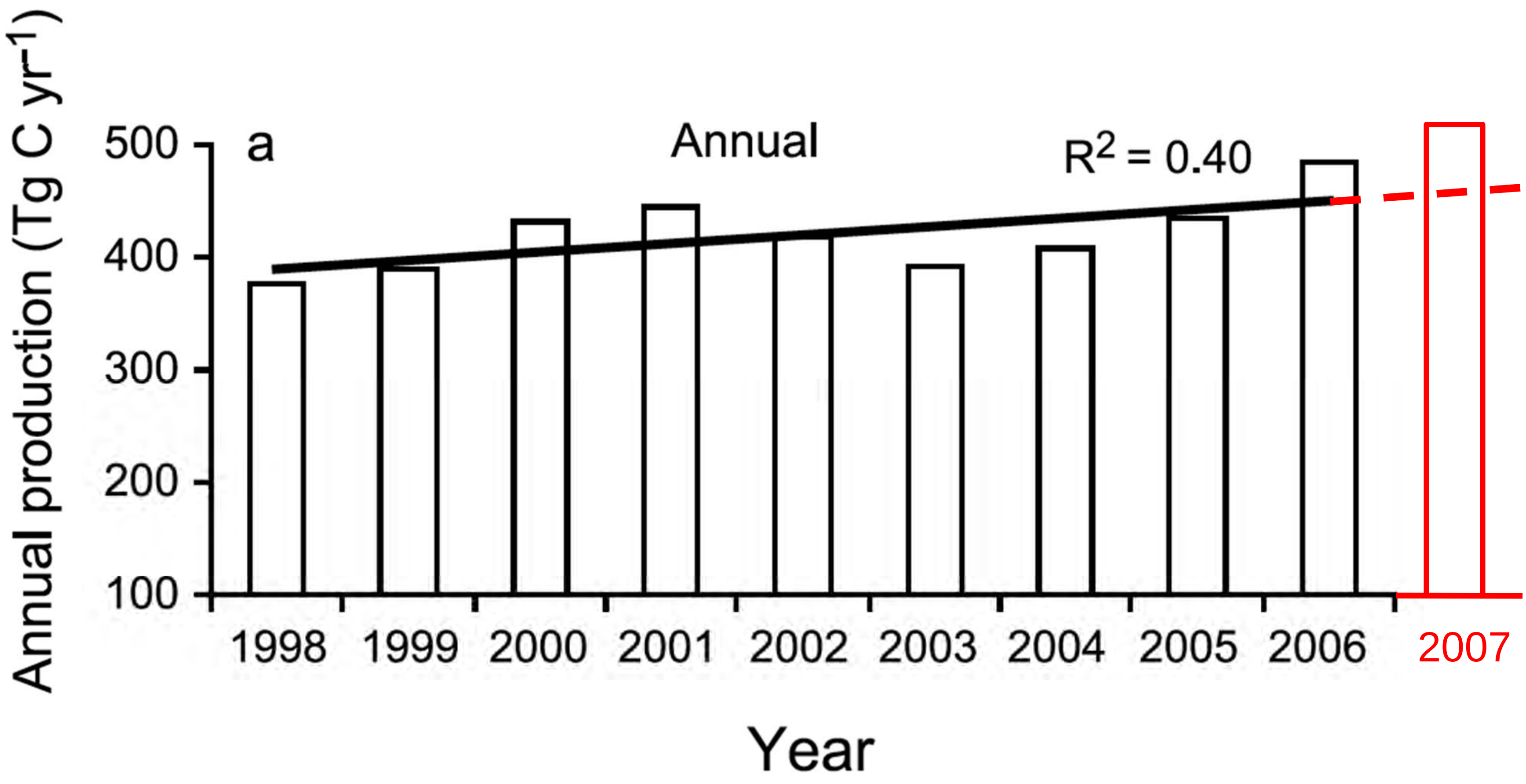
Arctic Primary Production

Arrigo et al. 2008

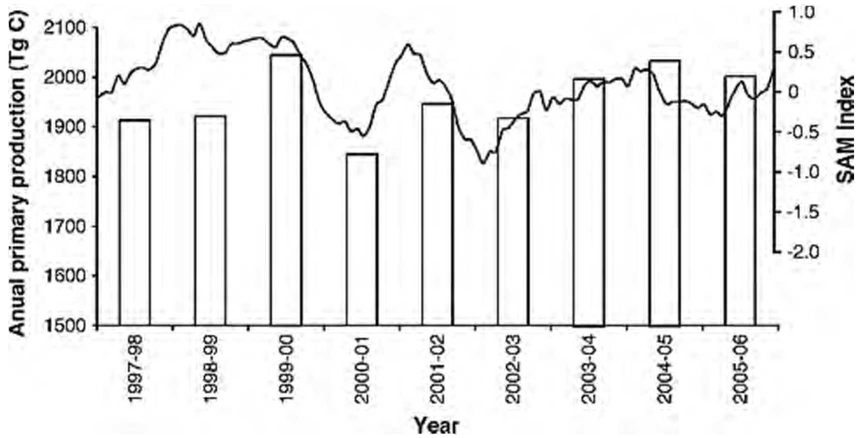
In 2007, an abrupt change!



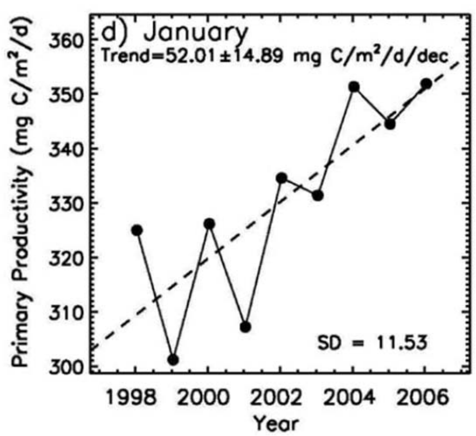
Arctic Primary Production



Antarctic Ocean



Arrigo et al. (2008) JGR



Smith & Comiso (2008) JGR

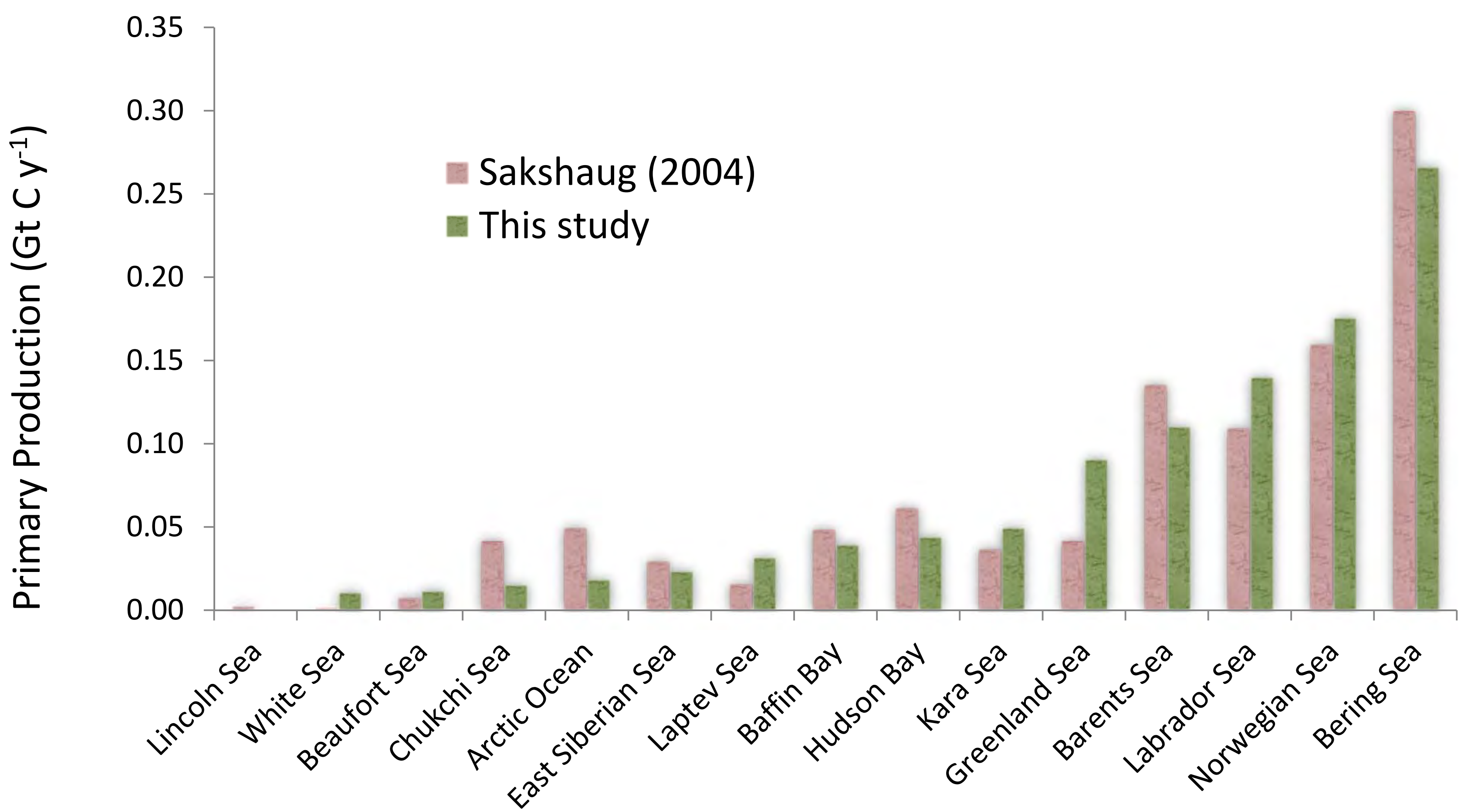
Results

Primary Production

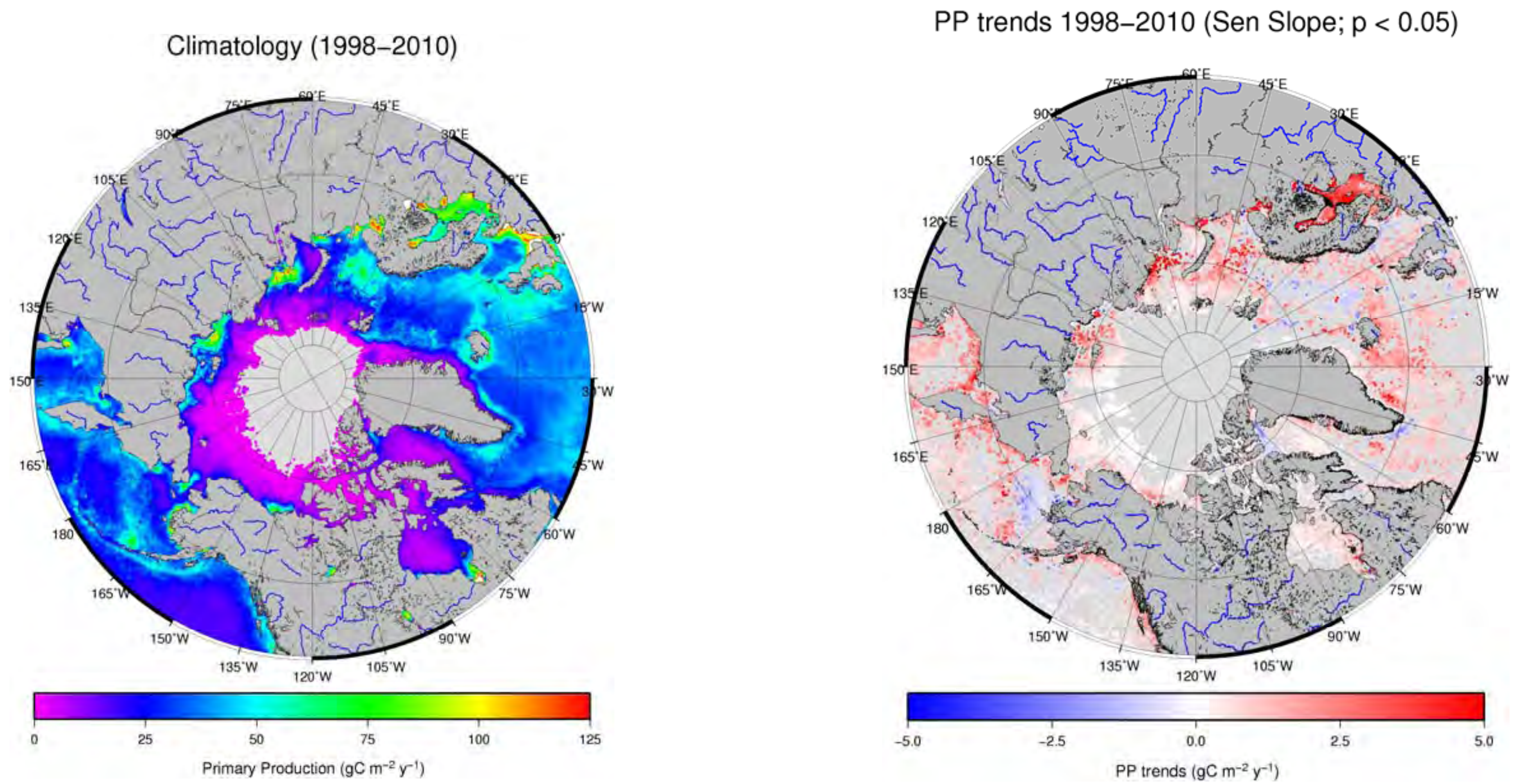
Latitude criterion	This study	Longhurst et al. (1995)	Behrenfeld & Falkowski (1997)	Antoine et al. (1996)	Pabi et al. (2008)
All Arctic (sensu IHO)	0.62*	-	-	-	-
>60°	0.46	-	-	-	-
>66.5°	0.26	-	-	-	0.42
>70°	0.19	1.4	0.4	0.6	-

* Gt C y^{-1}

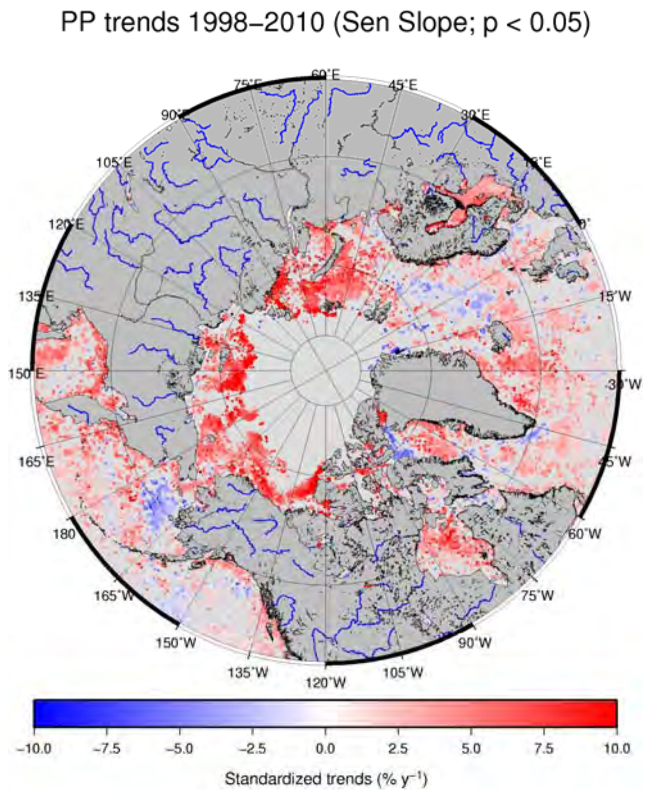
Results



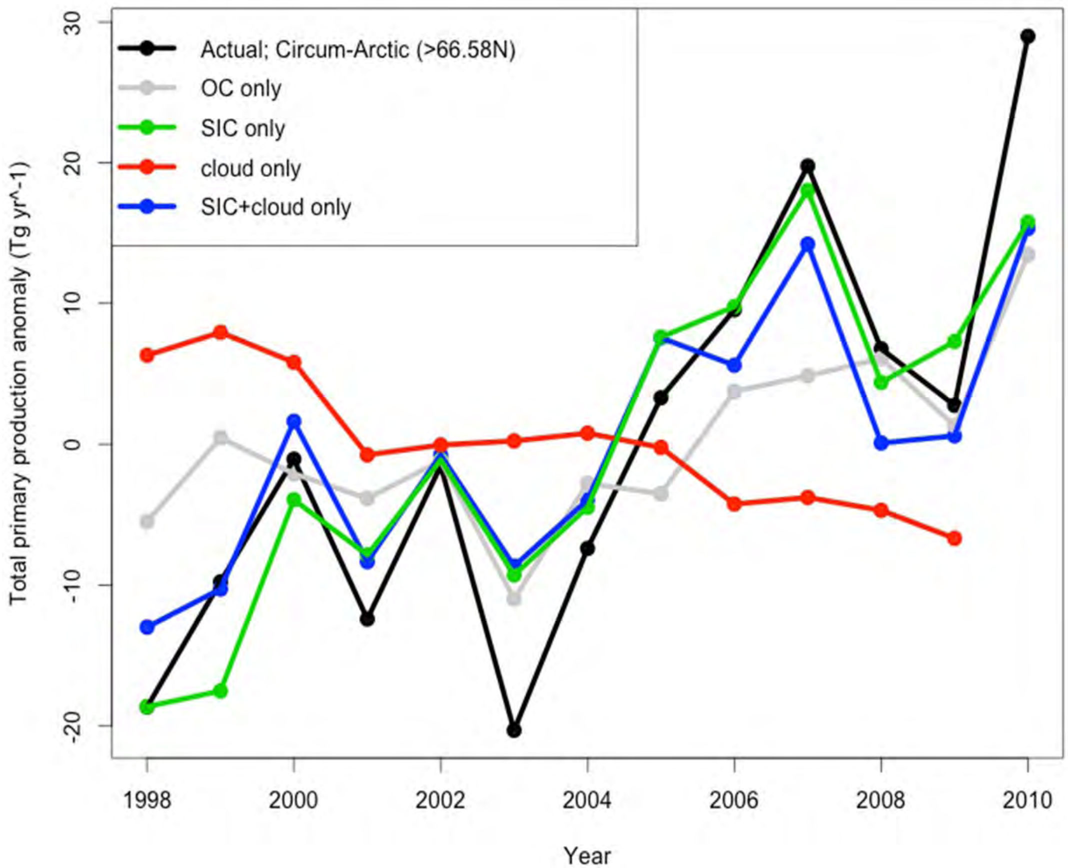
Primary Production (Gt C y-1)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Sakshaug (2004)
This study
Lincoln Sea
White Sea
Beaufort Sea
Chukchi Sea
Arctic Ocean
East Siberian Sea
Laptev Sea
Baffin Bay
Hudson Bay
Kara Sea
Greenland Sea
Barents Sea
Labrador Sea
Norwegian Sea
Bering Sea



Bélanger et al.

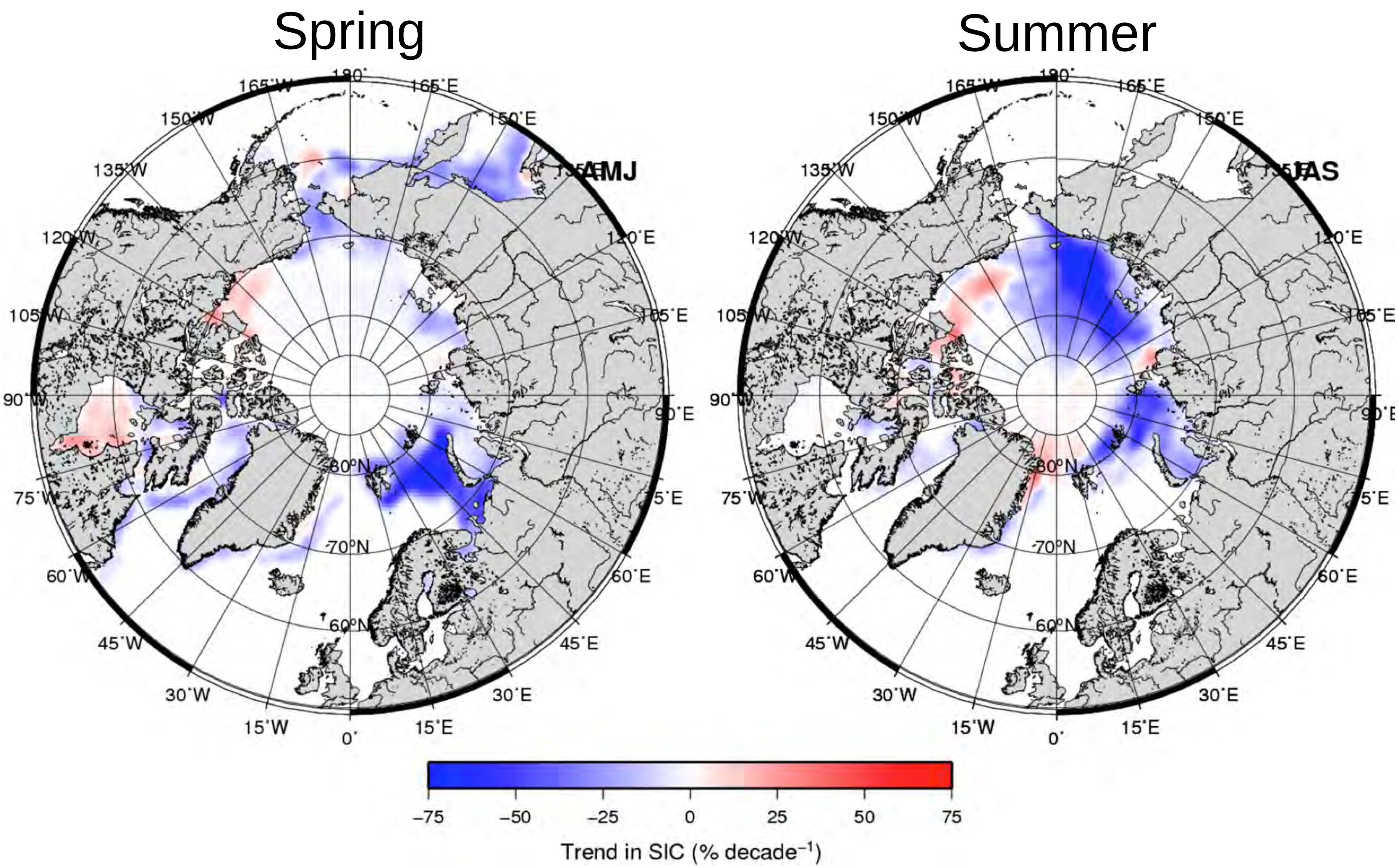


Bélanger et al.



Bélanger et al.

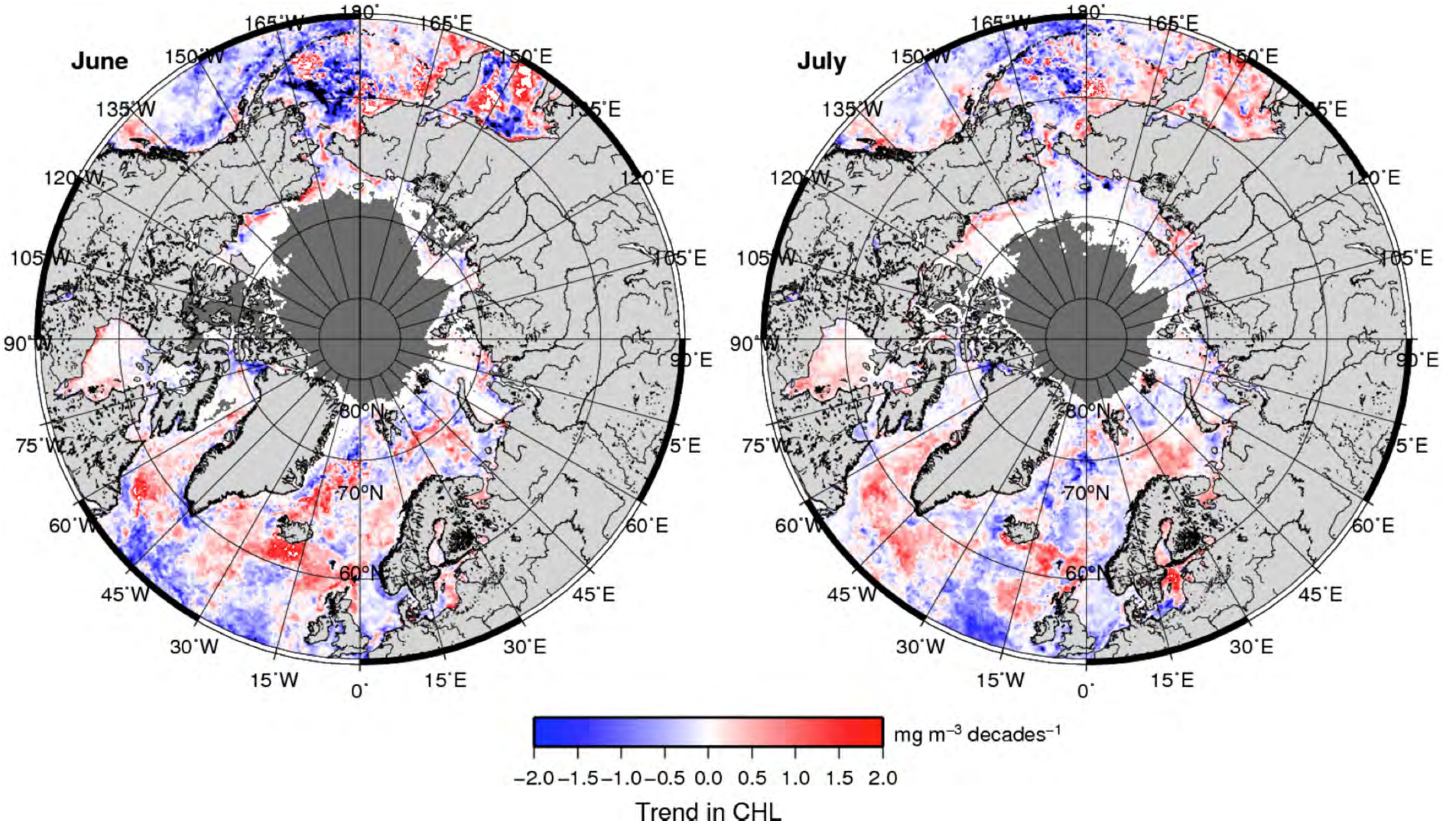
Ice trend during the last decade



Trend in
Chlorophyll concentration

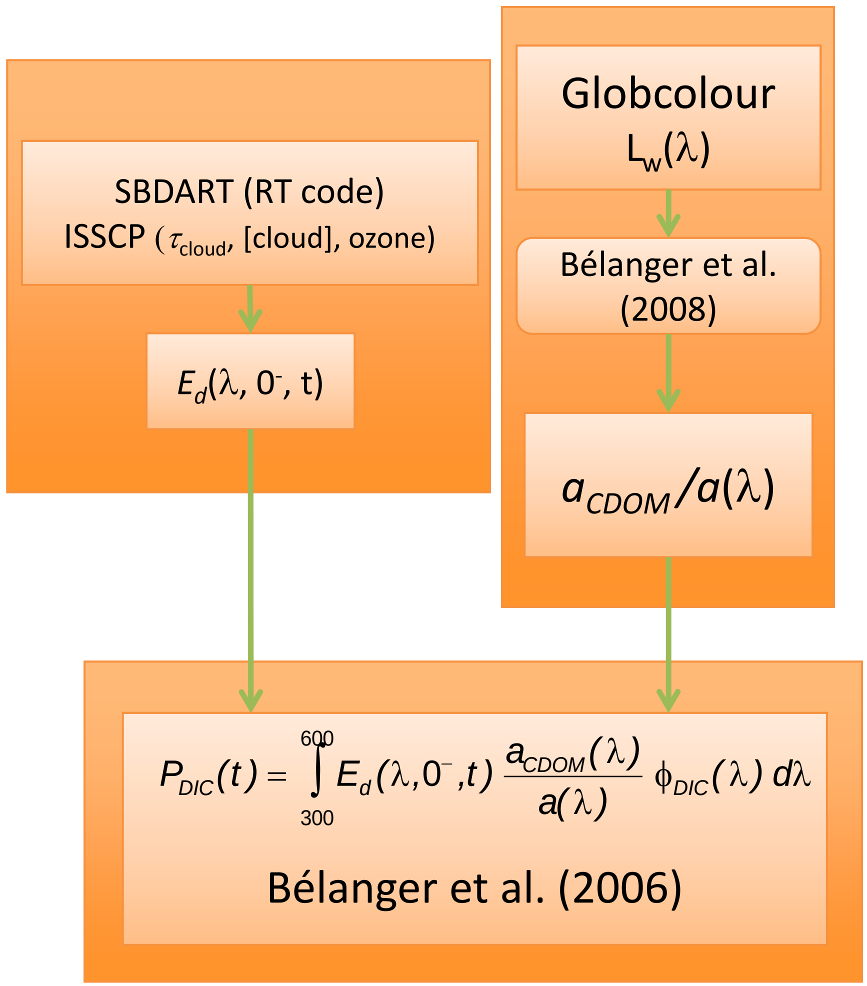
June

July



What about CDOM photooxidation?

CDOM Photooxidation model



Primary Production vs.Photooxidation

Gross PP ➔ 0.62×10^{15} gC y^{-1}

Photooxidation (CO_2) ➔ 2.7×10^{13} gC y^{-1}

Photooxidation (CO_2) ➔ 4.4% of PP

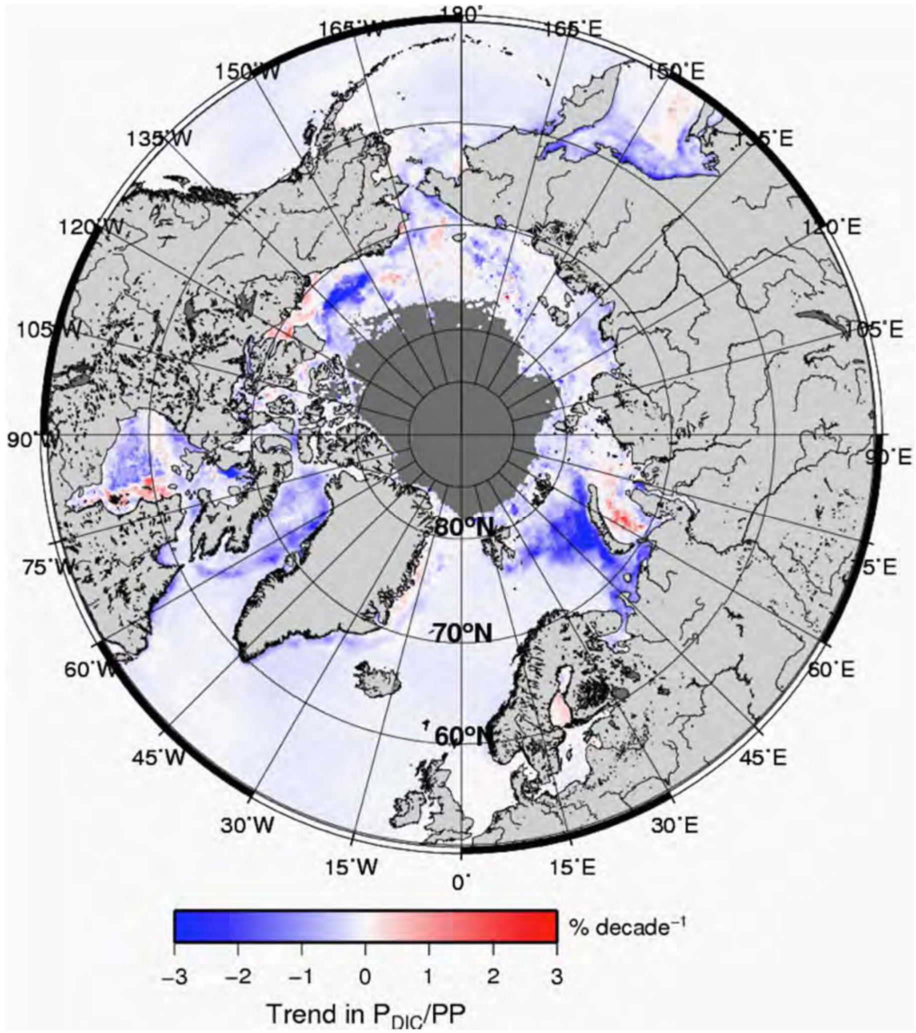
Sequestered C ~ 1% of PP (Stein & Mcdonald 2004)

<u>So, potentially</u>

PO of DOM > Sequestered C from PP

Trend in

Photooxidation / Primary Production



Problems & Limitations

- Problems to solve:
  - Optical properties of Arctic seawater

PP : GSM VS OC4v4 <u>for year 2007</u>

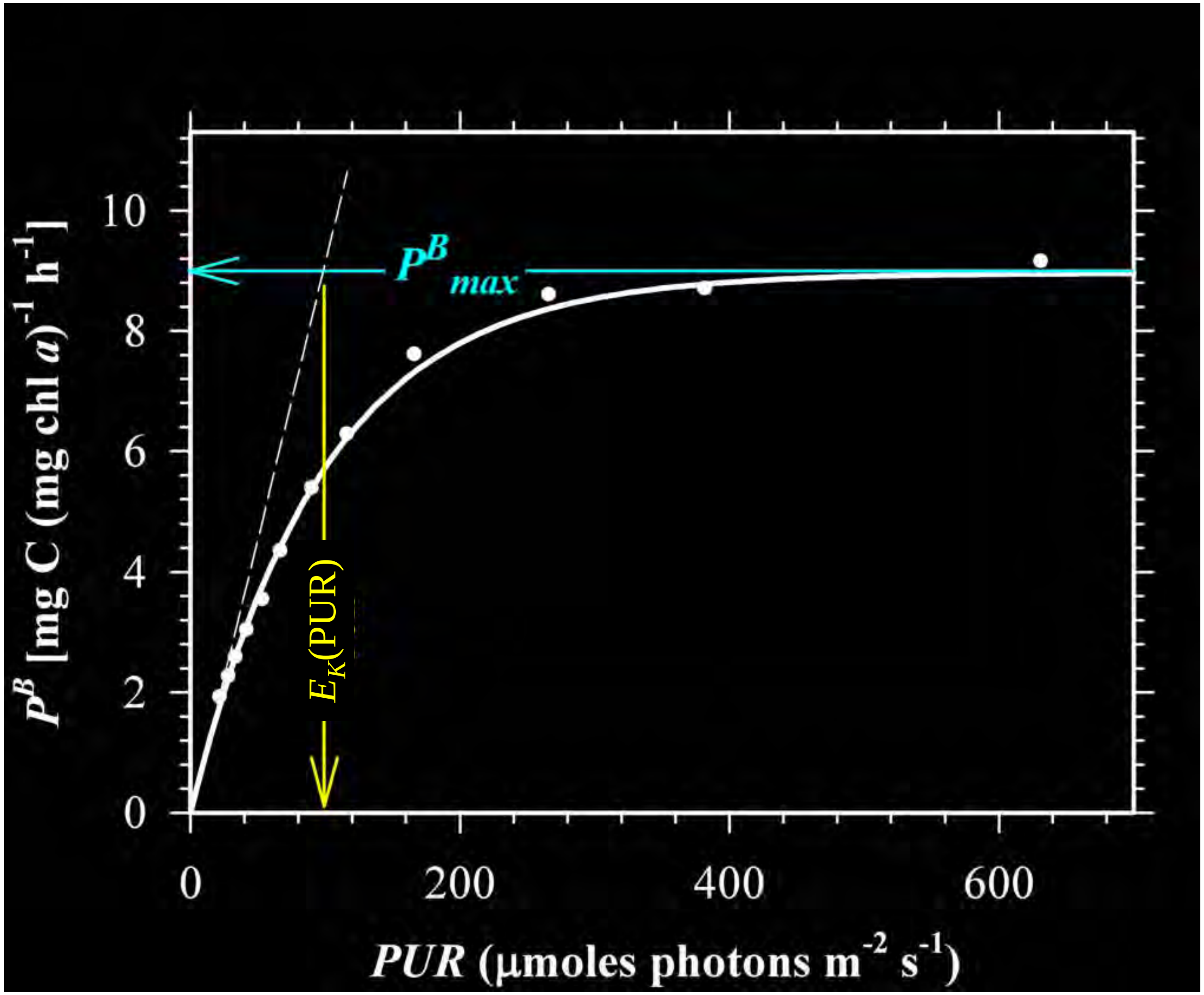
Region	GSM	OC4v4	%diff
Greenland	51.9	65	25.2%
Norwegian	97.7	98.3	0.6%
Barents	70.9	80	13%
Kara	**24.5**	**39.5**	**61%**
Laptev	15.3	22	44%
East Sib Sea	16.5	22.7	38%
Chukchi	9.6	14	46%
Beaufort	**6.7**	**11.3**	**69%**
Baffin Bay	**11.9**	**18.1**	**52%**
Hudson Bay	18.3	27.3	49%
Arctic Ocean	**14.2**	**22.4**	**57%**

Circumpolar Arctic: 293 378 29%

Problems & Limitations

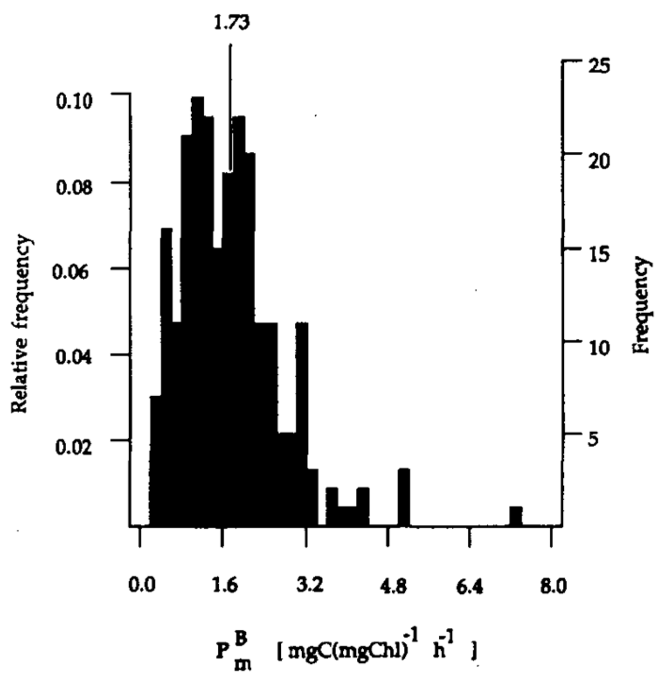
- Problems to solve:
  - Optical properties of Arctic seawater
  - **Photosynthetic properties of phytoplankton**

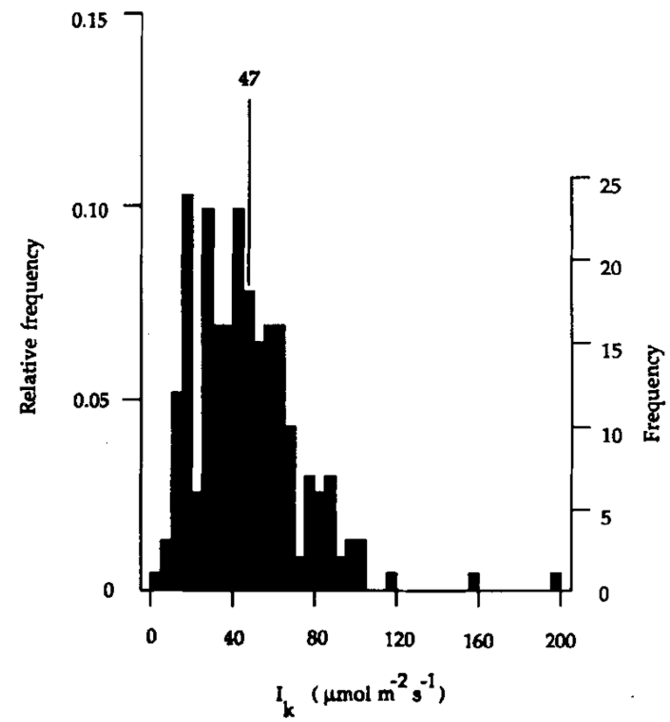
$$PP(z,t) = Chl \quad P_B^{max} \left(1 - e^{-PUR(z)/E_K(PUR)}\right)$$



Photosynthetic parameters

Barents Sea

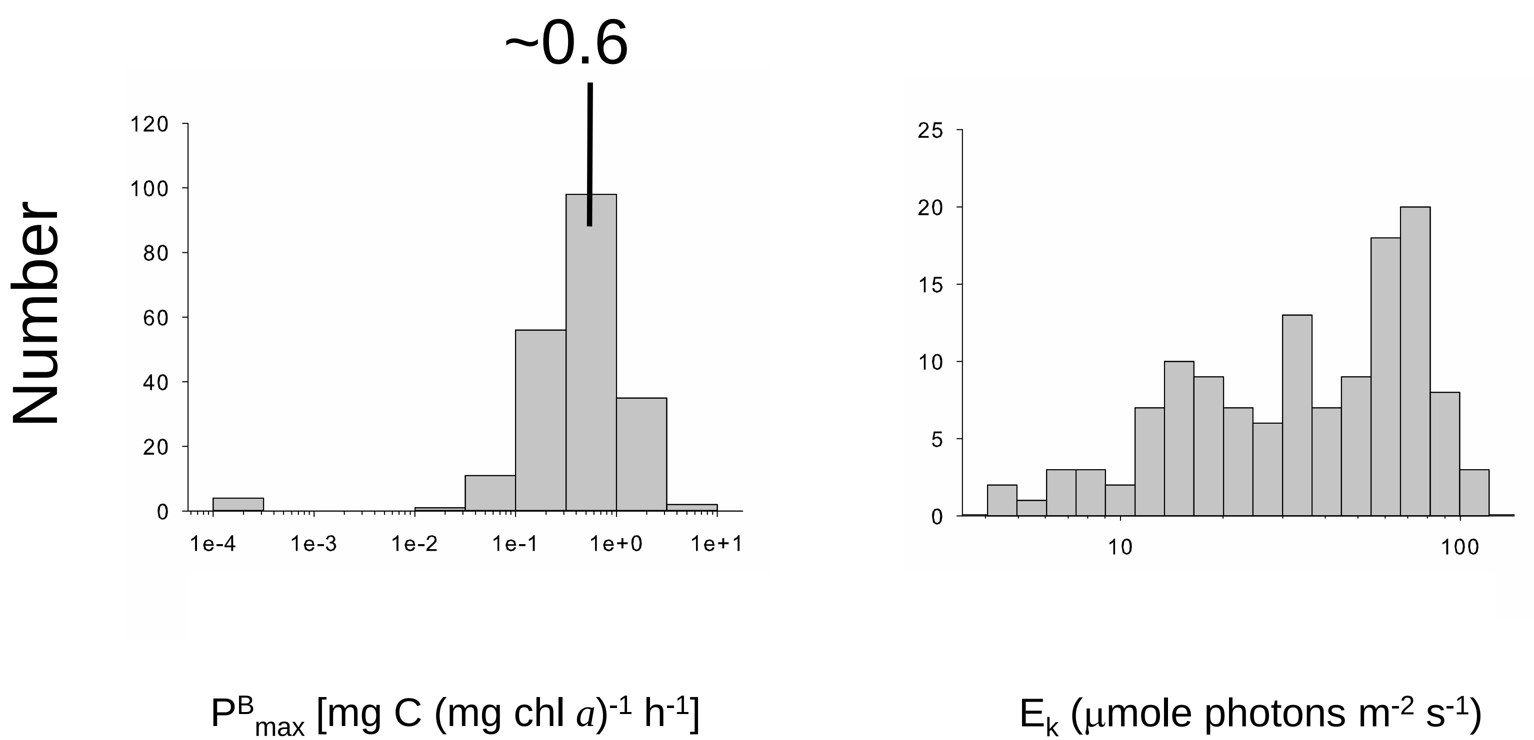




Rey (1991)

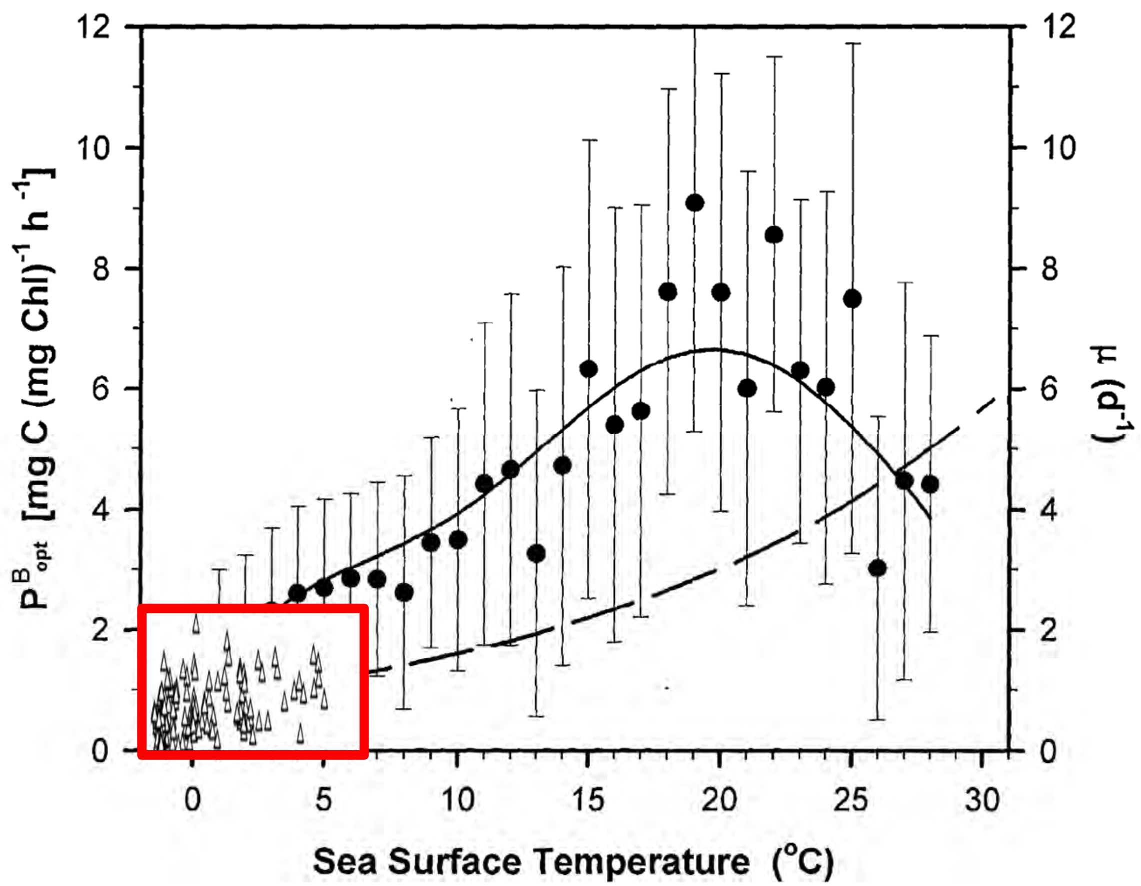
Photosynthetic parameters

Beaufort Sea in August 2009



Huot et al.

Photosynthetic parameters

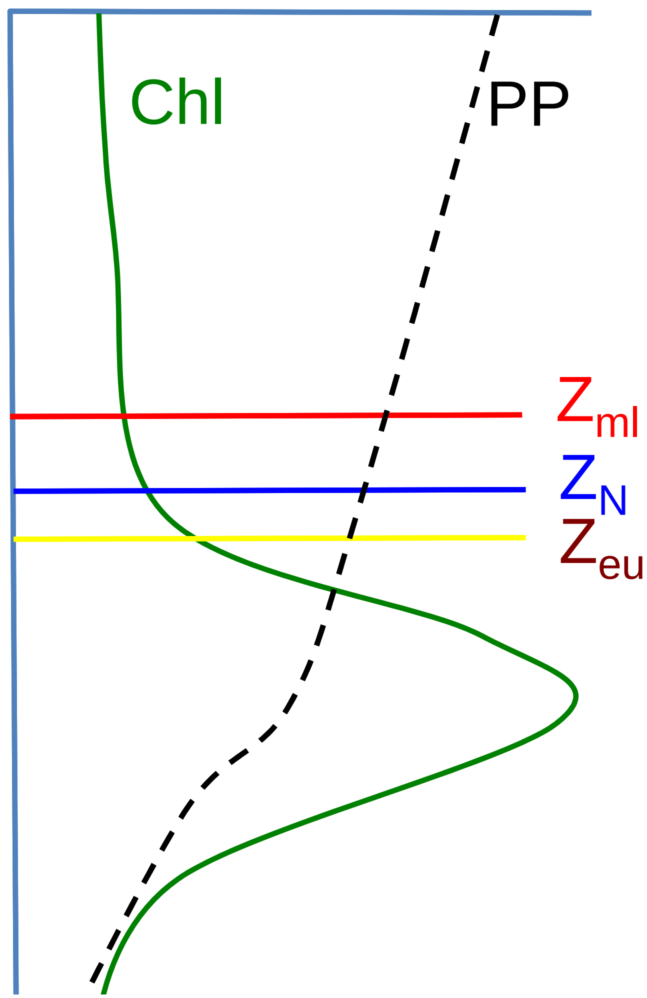


Problems & Limitations

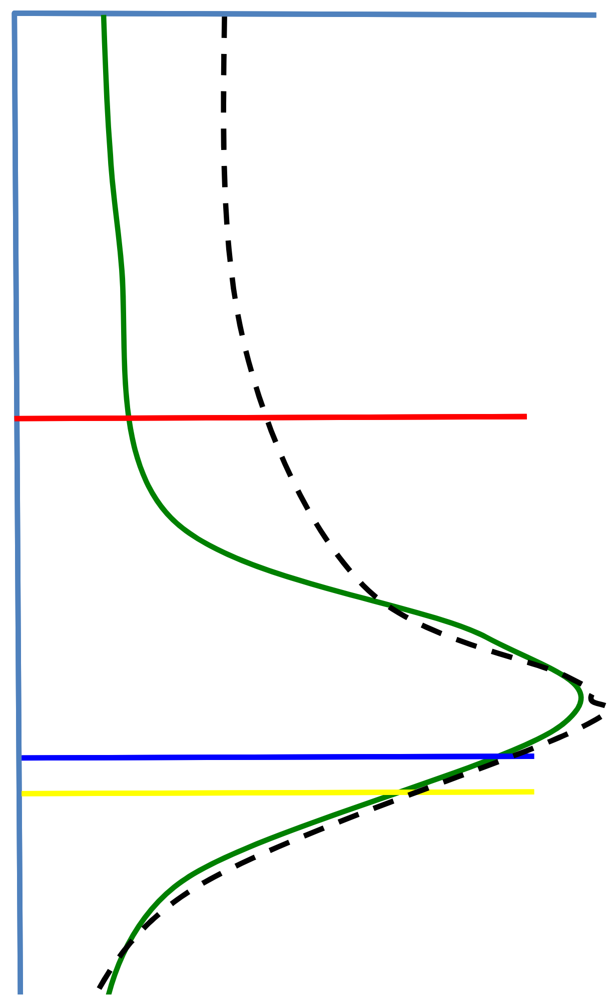
- Problems to solve:
  - Optical properties of Arctic seawater
  - Photosynthetic properties of phytoplankton
  - **Deep chlorophyll maximum**

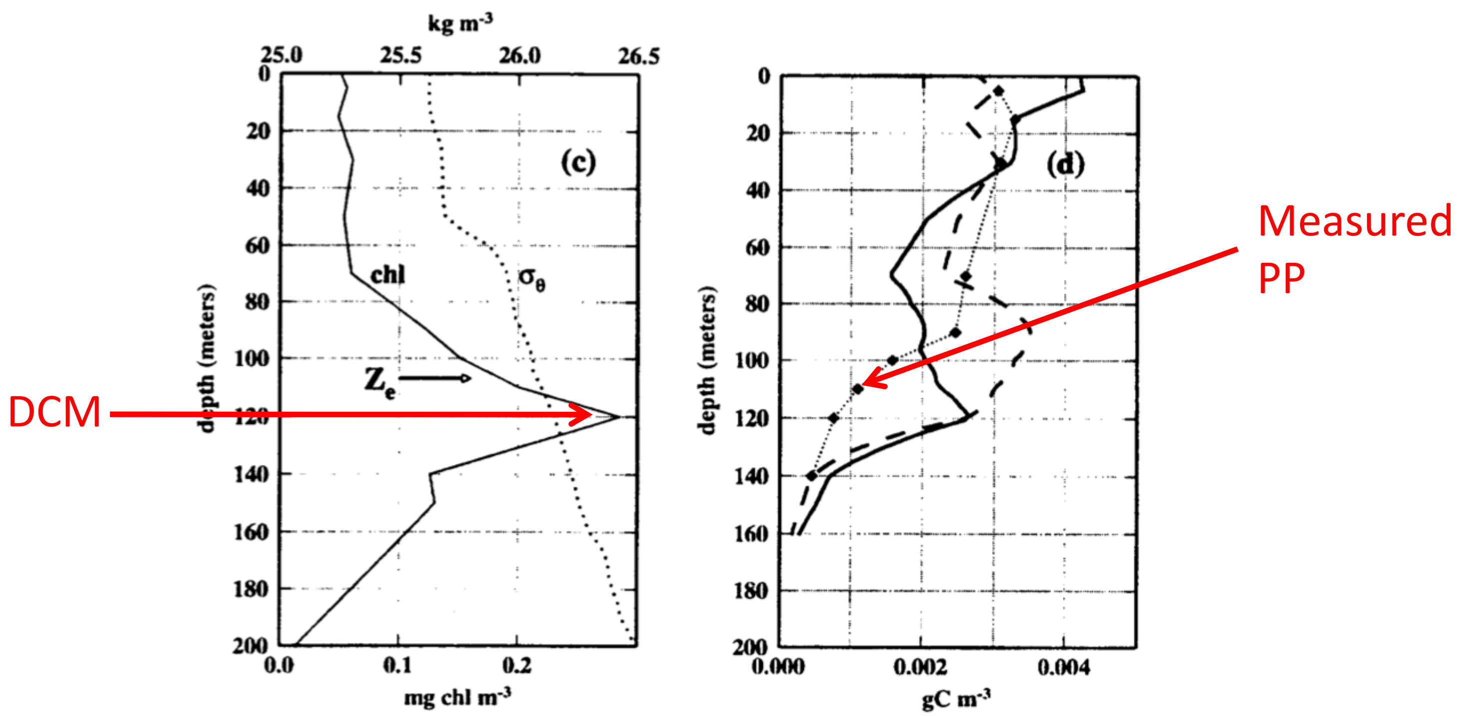
The DCM in the Arctic Ocean

At lower latitudes

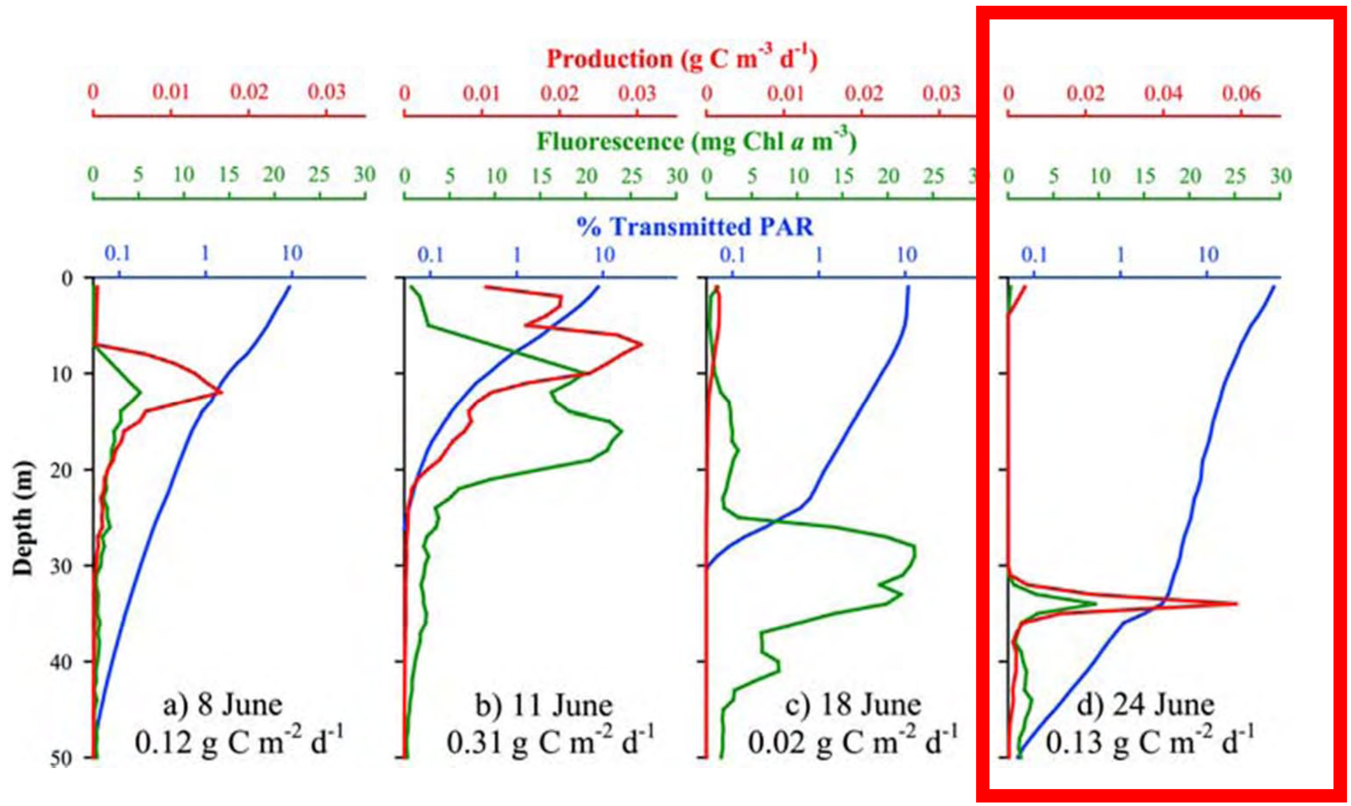


In the Arctic Ocean

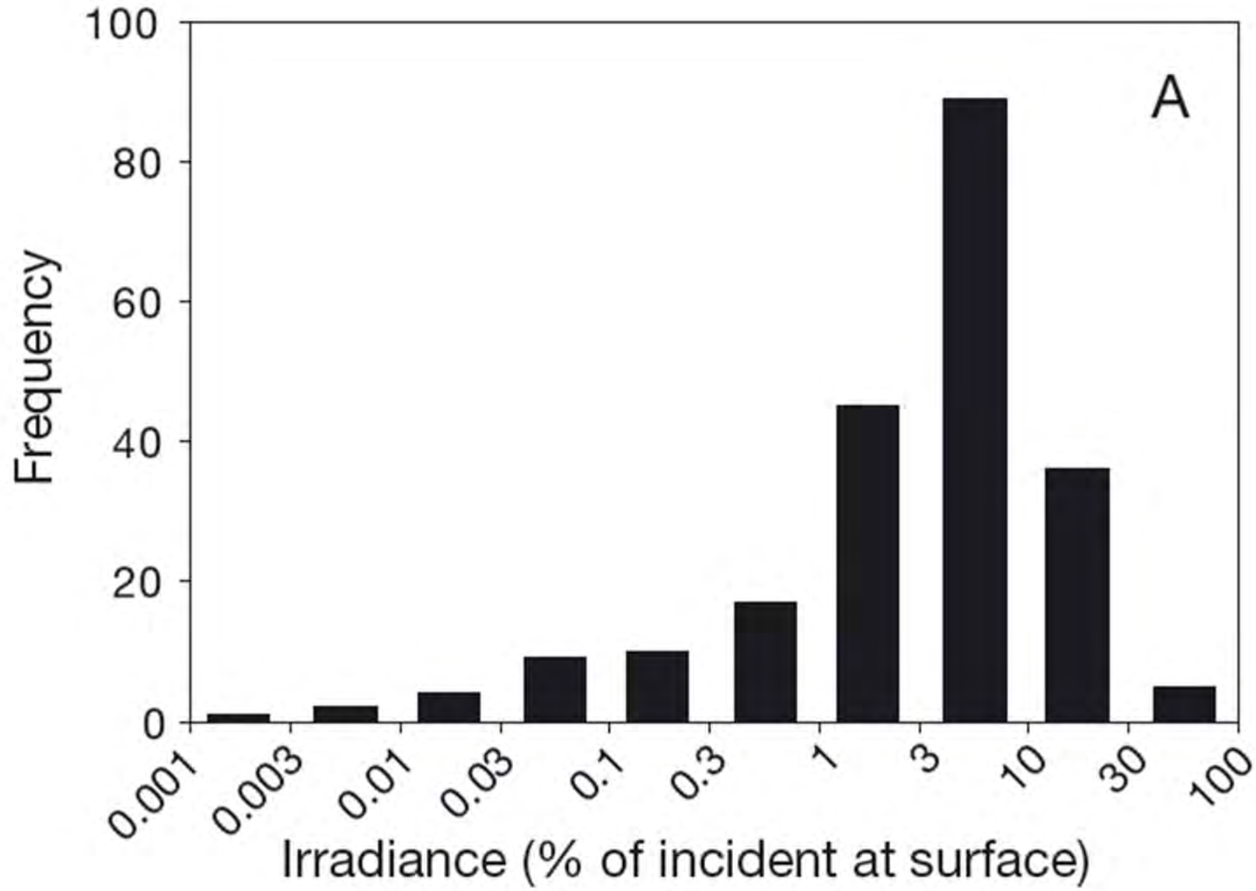




Morel et al. (1996)



Mundy et al. (2009)



Martin et al. 2010

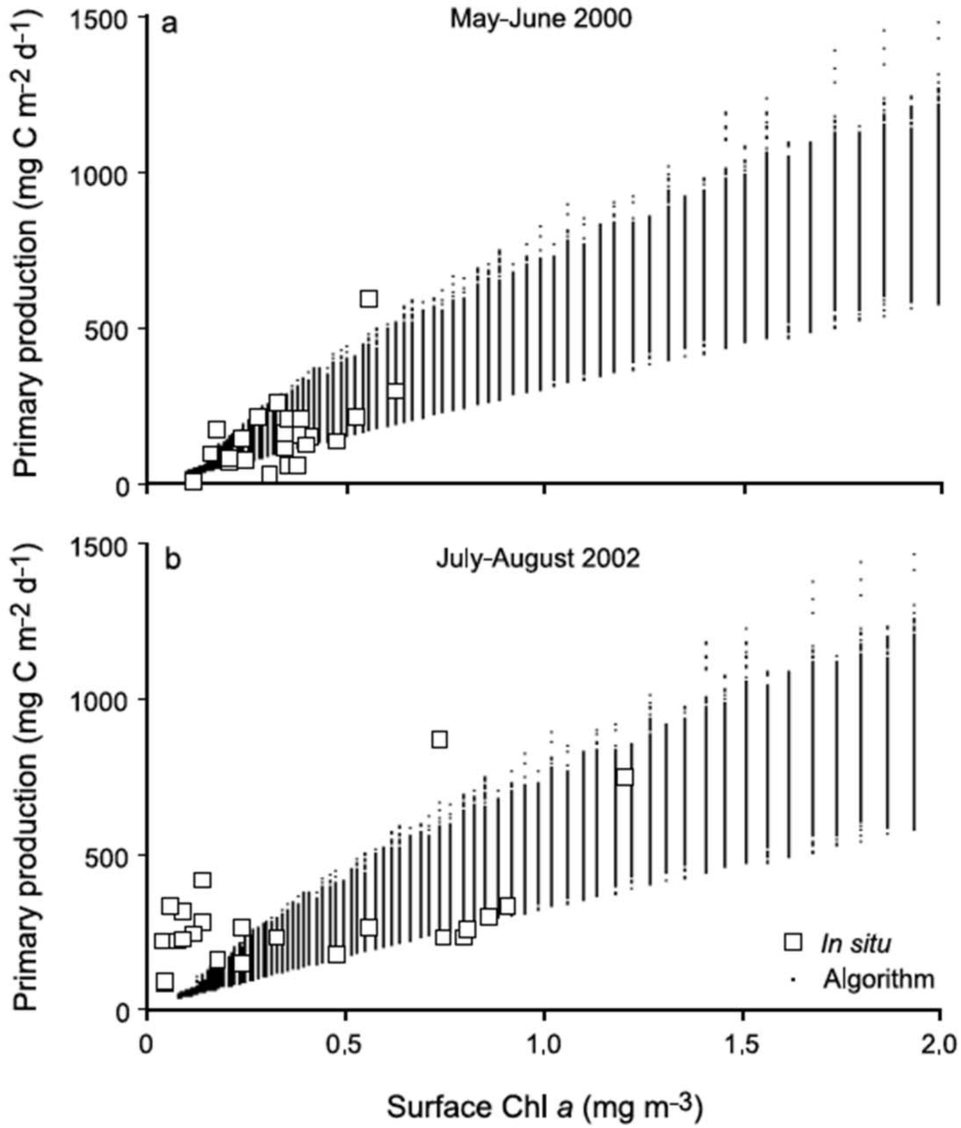

a
May-June 2000
b
July-August 2002
Primary production (mg C m-2 d-1)
1500
1000
500
0
0
0,5
1,0
1,5
2,0
Surface Chl a (mg m-3)
In situ
Algorithm

Table 3. Percent Change in Depth-Integrated Daily Net Primary Production Due to Removal of the Subsurface Chl *a* Maximum for Different Geographic Sectors and Different Time Periods[a]

	Jan–Mar	Apr–Jun	Jul–Sep	Oct–Dec	Annual
		Chlorophyll a Constant in the Upper 100 m (Method 2)			
Chukchi	−18.9	−12.0	−6.1	3.0	−7.6
Beaufort	−76.9	8.4	−20	18.3	−10.8
Baffin	3.1	2.2	−3.8	−2.9	−3.7
Greenland	−16.8	0	−5.1	13.7	−3.0
Barents	18.8	0.9	−0.1	7.5	1.9
Kara	ND[b]	8.6	9.1	2.4	8.9
Laptev	ND	ND	ND	ND	ND
Siberian	ND	ND	0.3	ND	0.3
All	10.3	−9.0	−6.6	−5.9	−7.4
		Chlorophyll a Constant in Upper 20 m and Declines Exponentially With Depth (Method 3)			
Chukchi	−25.9	−15.5	−10.7	−9.1	−12.3
Beaufort	−85.4	2.1	−30.7	−12.8	−20.8
Baffin	−10.8	−5.2	−5.4	−16.4	−6.1
Greenland	−26.6	−8.4	−16.6	−10.9	−13.0
Barents	−10.9	−8.2	−14.6	−23.4	−9.9
Kara	ND	6.3	1.9	−5.9	4.7
Laptev	ND	ND	ND	ND	ND
Siberian	ND	ND	−7.9	ND	−7.9
All	−7.3	−14.7	−12.0	−19.7	−13.2
		Chlorophyll a Constant in Upper 40 m and Declines Exponentially With Depth (Method 4)			
Chukchi	−19.9	−12.3	−6.5	0.7	−8.0
Beaufort	−81.0	7.8	−22.3	6.6	−12.6
Baffin	0.1	1.3	−3.9	−5.9	−3.8
Greenland	−18.7	−1.2	−7.4	5.9	−4.7
Barents	8.1	−0.5	−3.4	−4.9	−0.3
Kara	ND	8.5	8.3	1.2	8.6
Laptev	ND	ND	ND	ND	ND
Siberian	ND	ND	−0.9	ND	−0.9
All	6.0	−9.6	−7.1	−9.1	−8.1

[a]Chl *a* was distributed vertically using methods 2–4.
[b]ND indicates no in situ data were available.

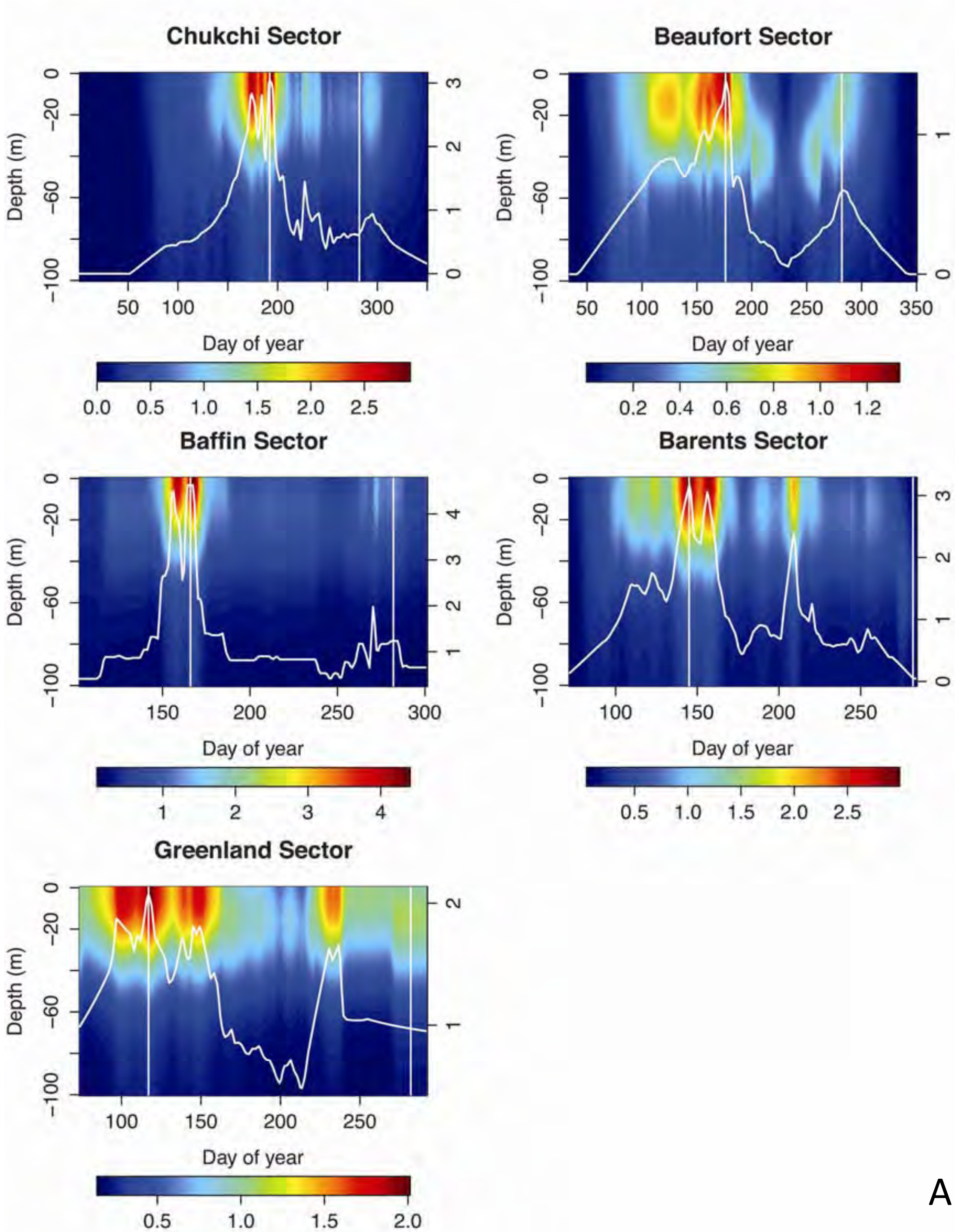
Arrigo et al. (2011)

Table 4. Percent Change in Depth-Integrated Net Primary Production Caused by Increasing in Situ Chl *a* by the RMSE of Satellite-Derived Chl *a* for Different Geographic Sectors and Different Time Periods[a]

	January–March	April–June	July–September	October–December	Annual
			Chlorophyll a Constant in Upper 100 m (Method 2)		
Chukchi	−10.7	−7.5	−0.4	18.1	−1.9
Beaufort	274.0	15.8	−6.0	121.8	1.6
Baffin	21.5	10.7	−0.9	15.2	0.0
Greenland	−4.5	9.7	9.2	66.1	9.1
Barents	104.0	11.4	20.1	145	16.5
Kara	ND[b]	12.4	17.5	11.9	14.5
Laptev	ND	ND	ND	ND	ND
Siberian	ND	ND	9.7	ND	9.7
All	36.4	−2.4	−0.3	13.4	−0.7
			Chlorophyll a Constant in Upper 20 m and Declines Exponentially With Depth (Method 3)		
Chukchi	−17.4	−10.8	−4.8	6.4	−6.3
Beaufort	156.2	9.9	−16.4	77.6	−8.1
Baffin	7.9	3.8	−2.4	2.0	−2.3
Greenland	−14.0	1.8	−1.8	37.9	−0.5
Barents	65.0	2.8	5.7	93.0	5.2
Kara	ND	10.2	10.7	4.1	10.4
Laptev	ND	ND	ND	ND	ND
Siberian	ND	ND	2.0	ND	2.0
All	18.6	−7.7	−5.3	−0.3	−6.1
			Chlorophyll a Constant in Upper 40 m and Declines Exponentially With Depth (Method 4)		
Chukchi	−11.6	−7.7	−0.8	16.1	−2.3
Beaufort	209.9	15.3	−7.9	108.6	−0.0
Baffin	19.0	9.9	−0.9	12.7	−0.1
Greenland	−6.0	8.7	7.3	58.8	7.6
Barents	92.8	10.2	17.3	128.6	14.7
Kara	ND	12.3	16.8	11.0	14.2
Laptev	ND	ND	ND	ND	ND
Siberian	ND	ND	8.8	ND	8.8
All	32.7	−2.9	−0.8	10.7	−1.2

[a]Chl *a* was distributed vertically using methods 2–4.
[b]ND indicates no in situ data were available.

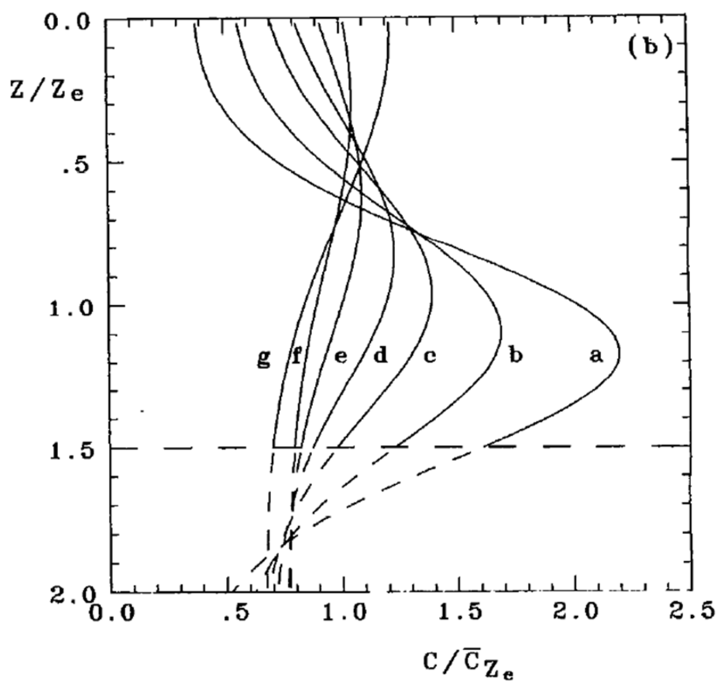
Arrigo et al. (2011)



Chukchi Sector
Beaufort Sector
Baffin Sector
Barents Sector
Greenland Sector
Depth (m)
Day of year

Ardyna et al.

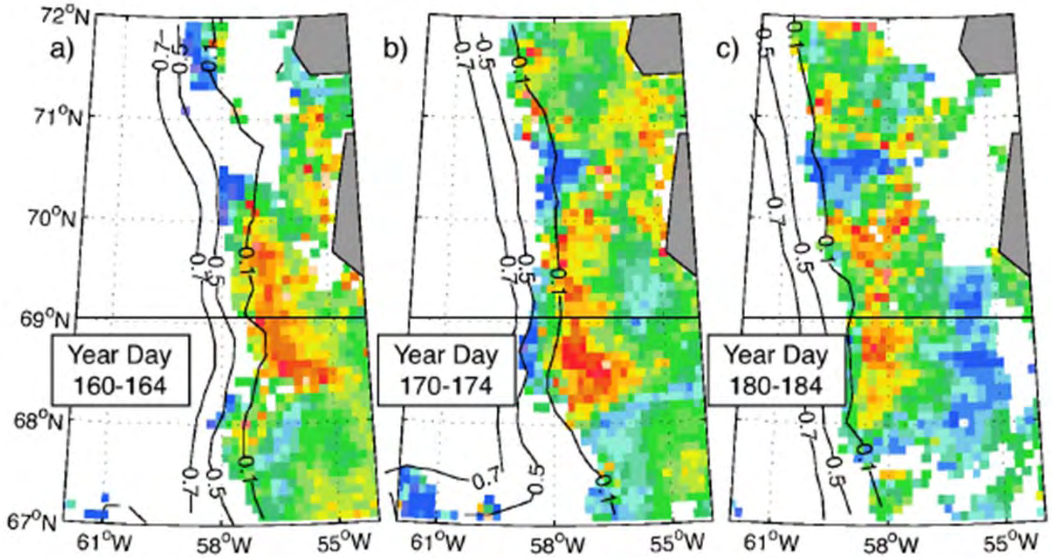
The DCM in the Arctic Ocean

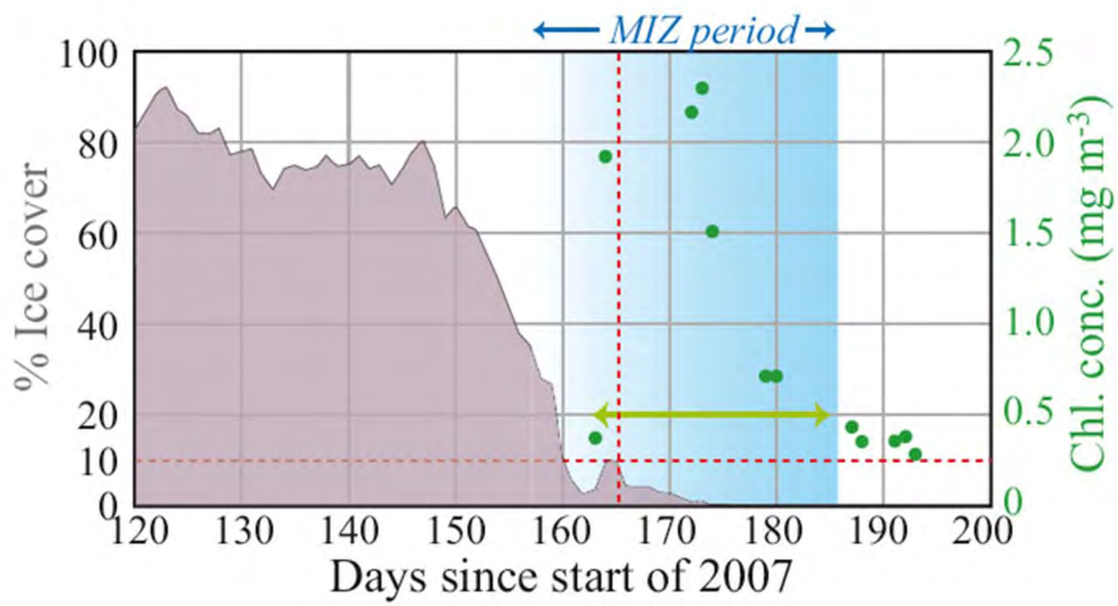


Morel & Berthon (1989)

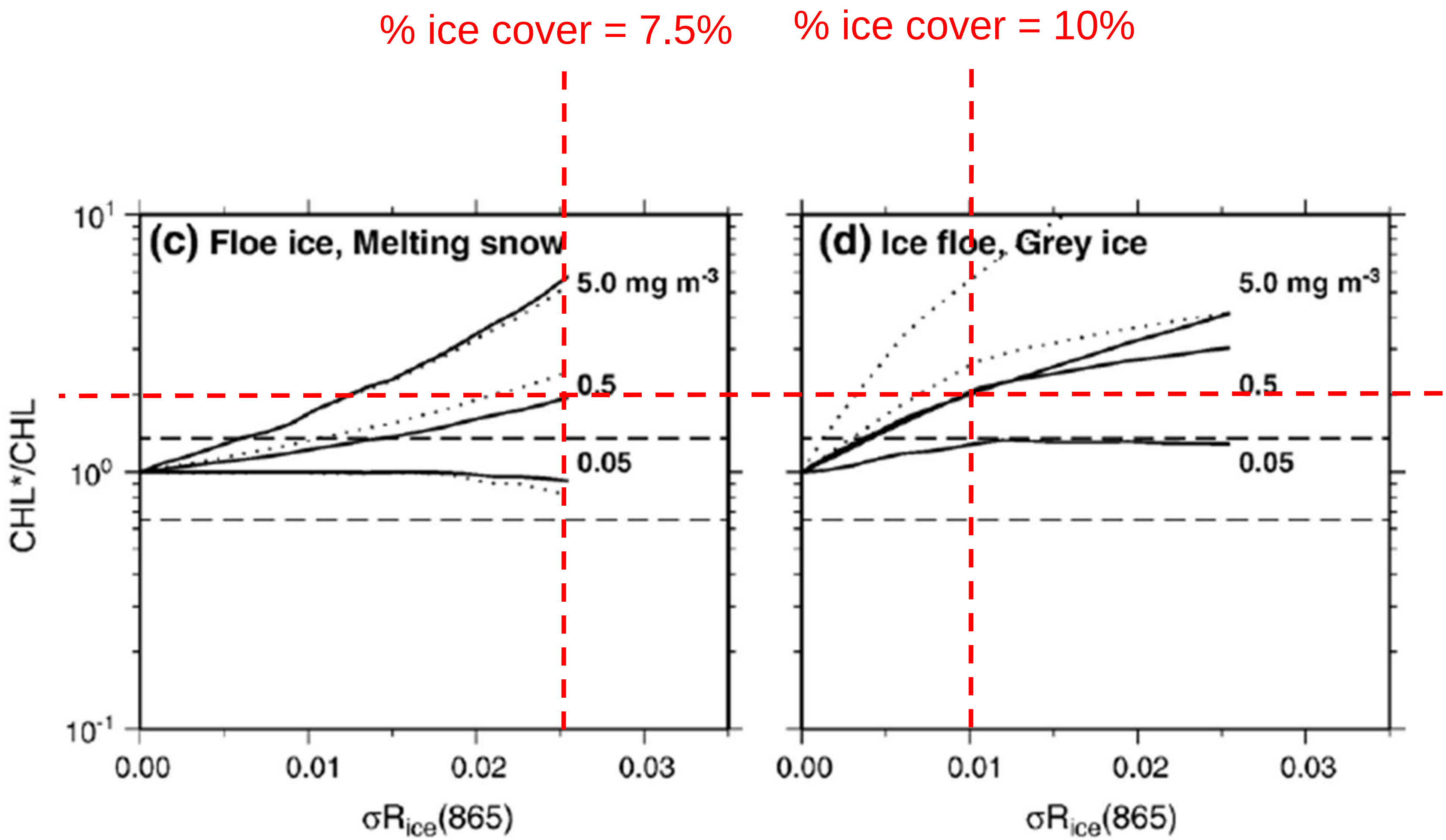
Problems & Limitations

- Problems to solve:
  - Optical properties of Arctic seawater
  - Photosynthetic properties of phytoplankton
  - Deep chlorophyll maximum
  - **Ice**

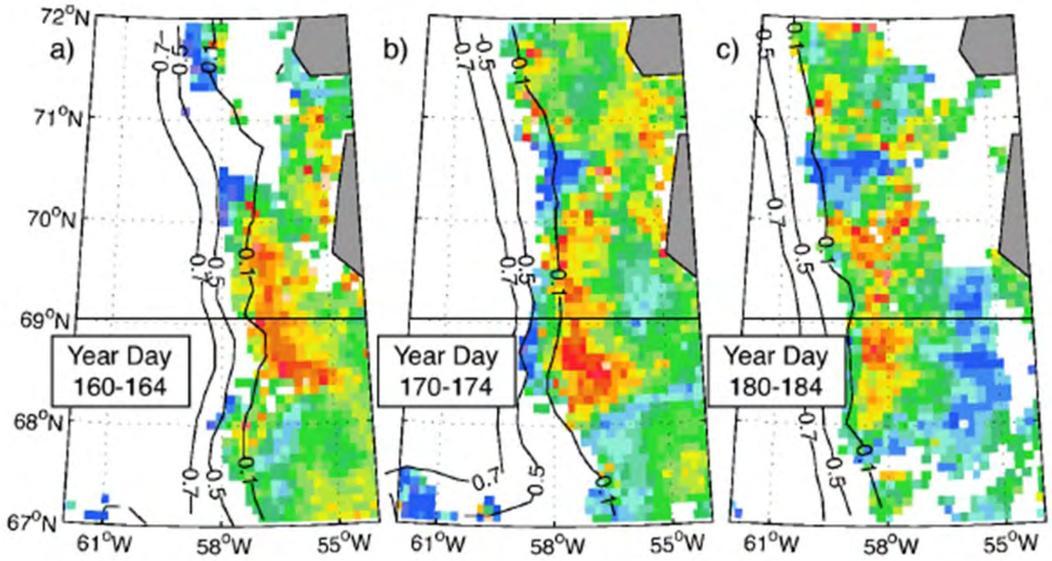


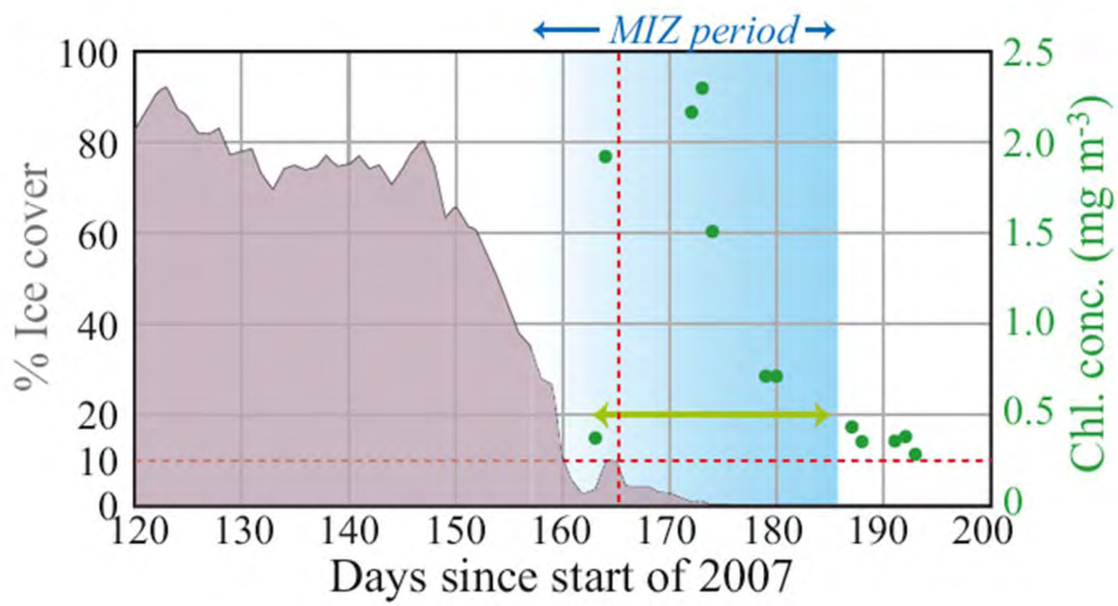


Perrette et al. 2011



Bélanger et al. (2007)





Perrette et al. 2011

Problems & Limitations

- Problems to solve:
  - Optical properties of Arctic seawater
  - Photosynthetic properties of phytoplankton
  - Deep chlorophyll maximum
  - Ice

- Limitations:
  - **Low Sun elevation**

Impact of pixels with no OC data

Region Considered	Relative difference between PP with OC only, and PP for all ice-free areas
All Arctic waters	-6.7%
> 60°	-30%
Arctic Basin	-47%

Problems & Limitations

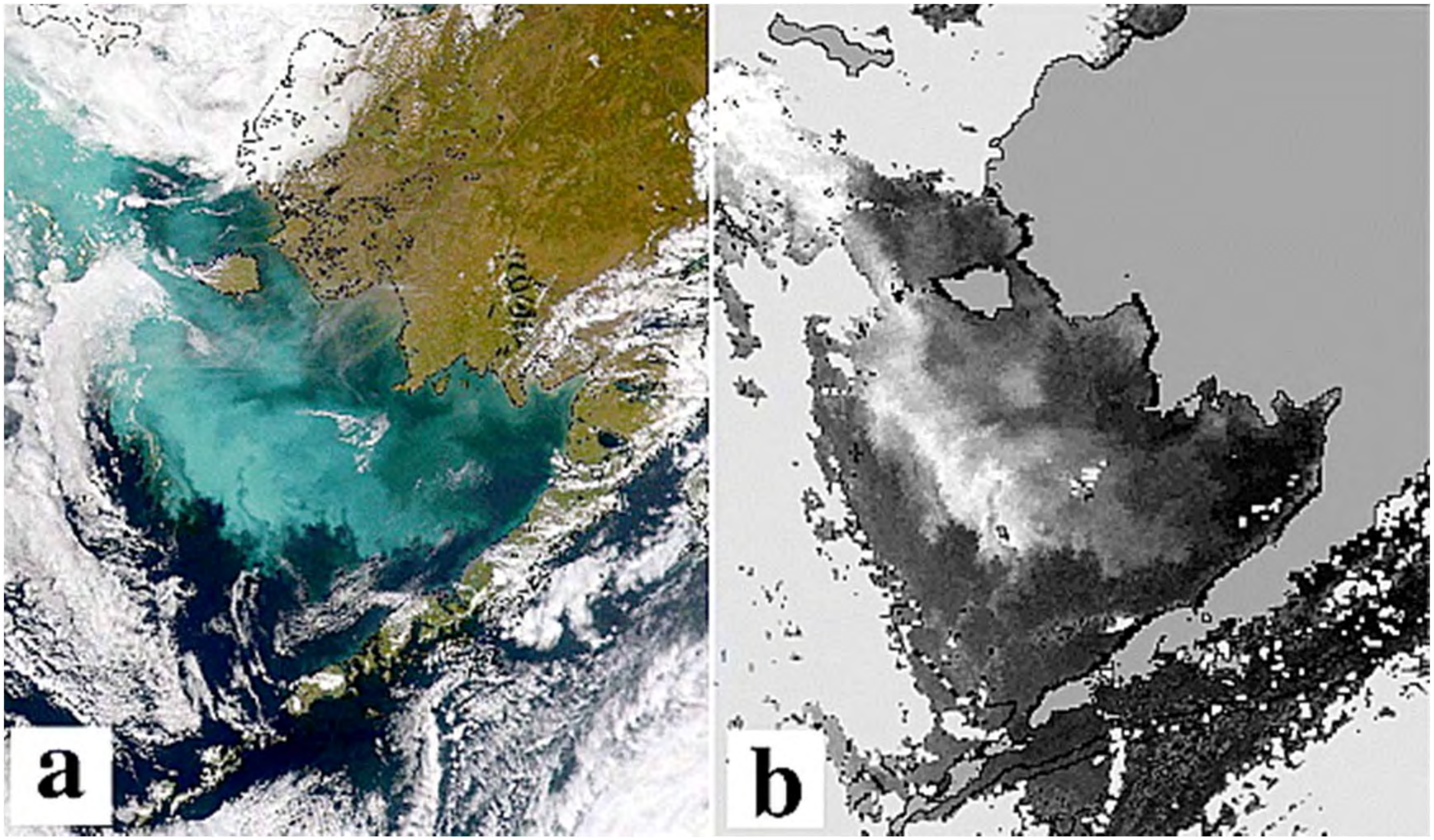
- Problems to solve:
  - Optical properties of Arctic seawater
  - Photosynthetic properties of phytoplankton
  - Deep chlorophyll maximum
  - Ice

- Limitations:
  - Low Sun elevation
  - **Clouds & fog**

Tracking regime shifts with OC?

Other examples:

- Northward migration of phytoplankton groups/species



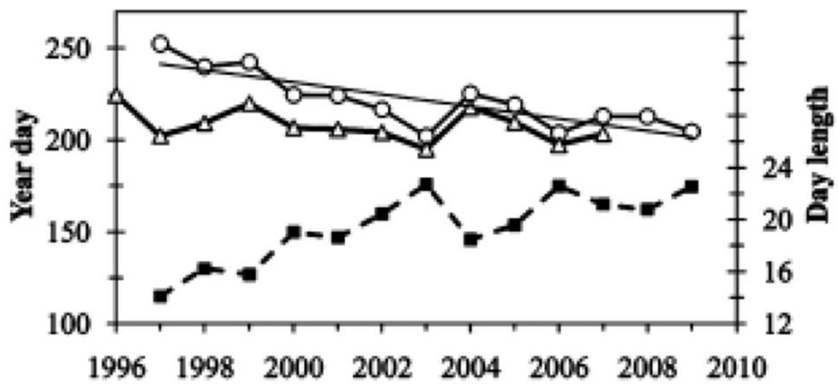
Merico et al. (2006)

Tracking regime shifts with OC?

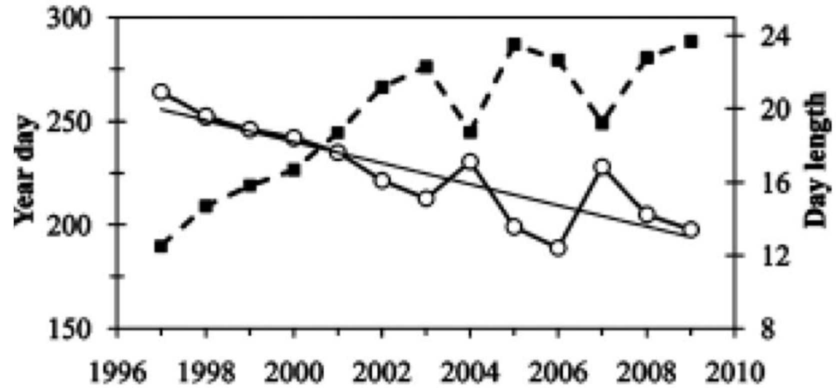
Other examples:

- Northward migration of phytoplankton groups/species
- **Timing of the phytoplankton bloom**

Baffin Bay



Kara Sea



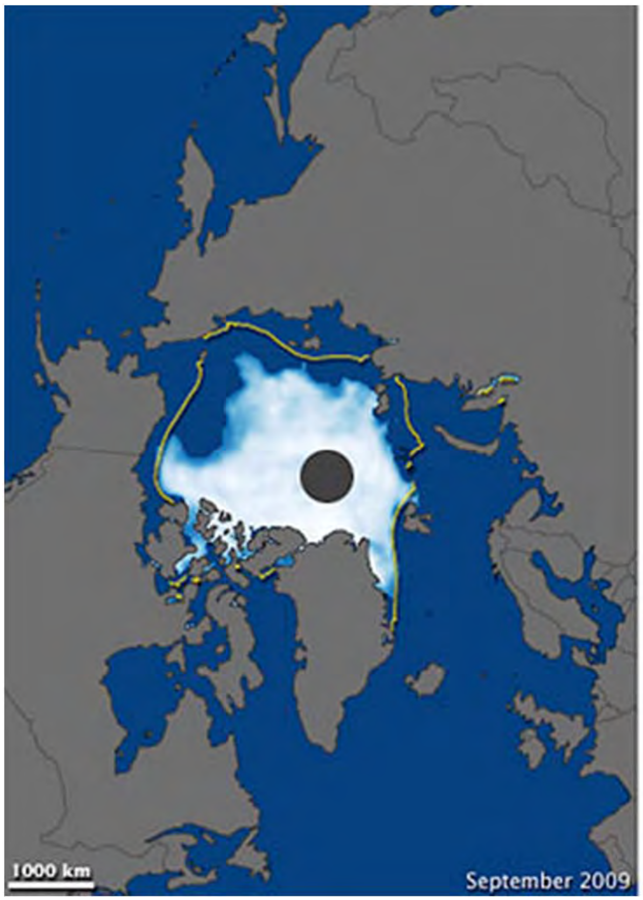
Kahru et al. 2010

What’s next?

- To better document Arctic Ocean optical properties
- To improve and validate OC algorithms
- To address the DCM problem
- To further document phytoplankton photosynthesis
- …

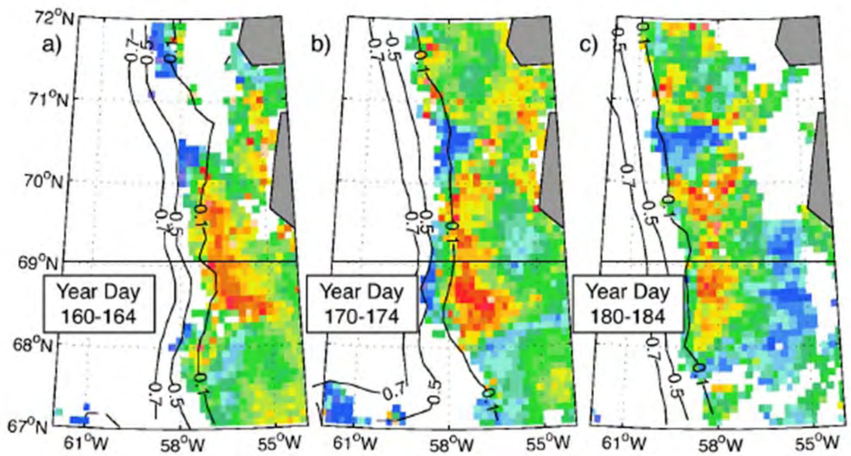
The importance of ice-edge blooms

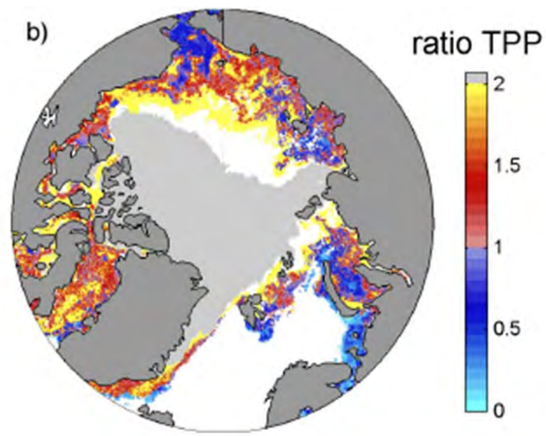
Sea ice

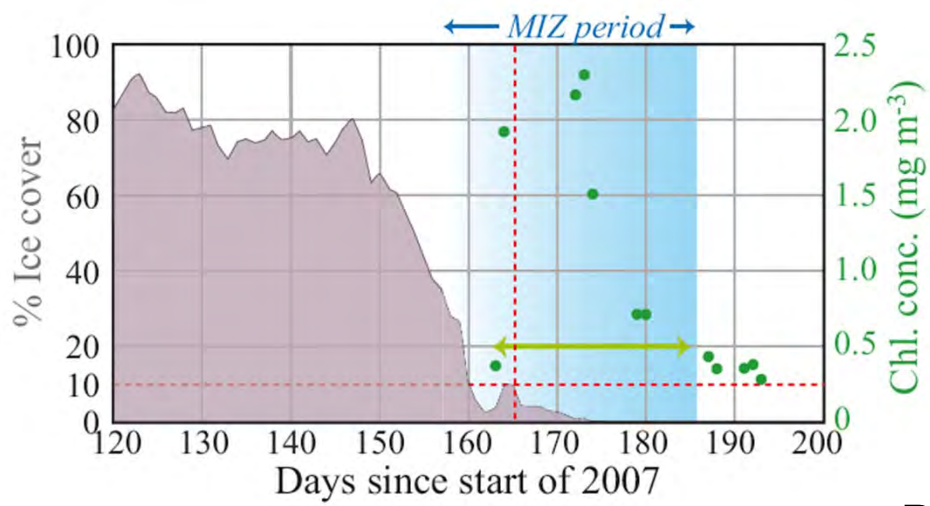


NSIDC

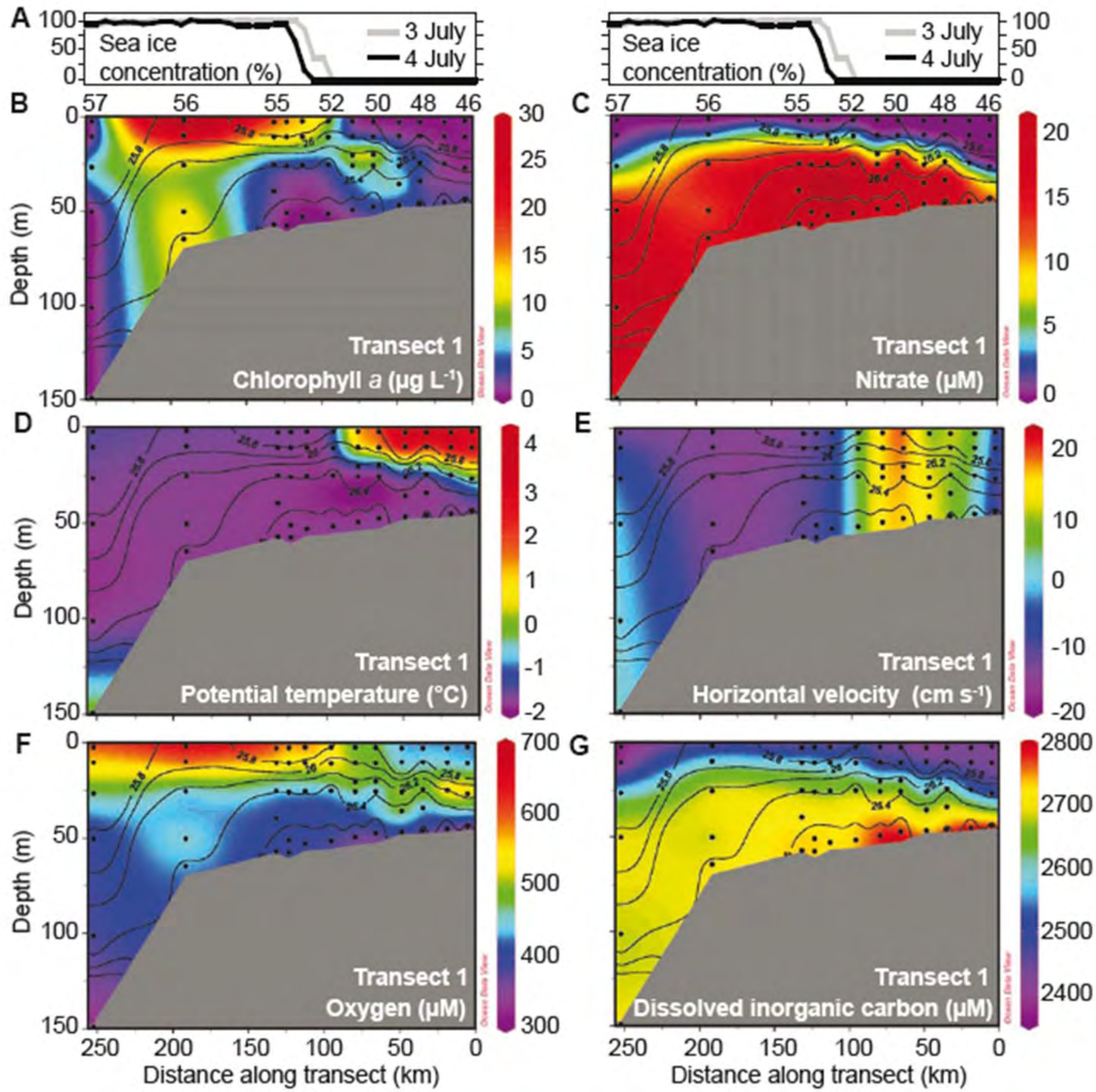
Efflorescences de marge de banquise







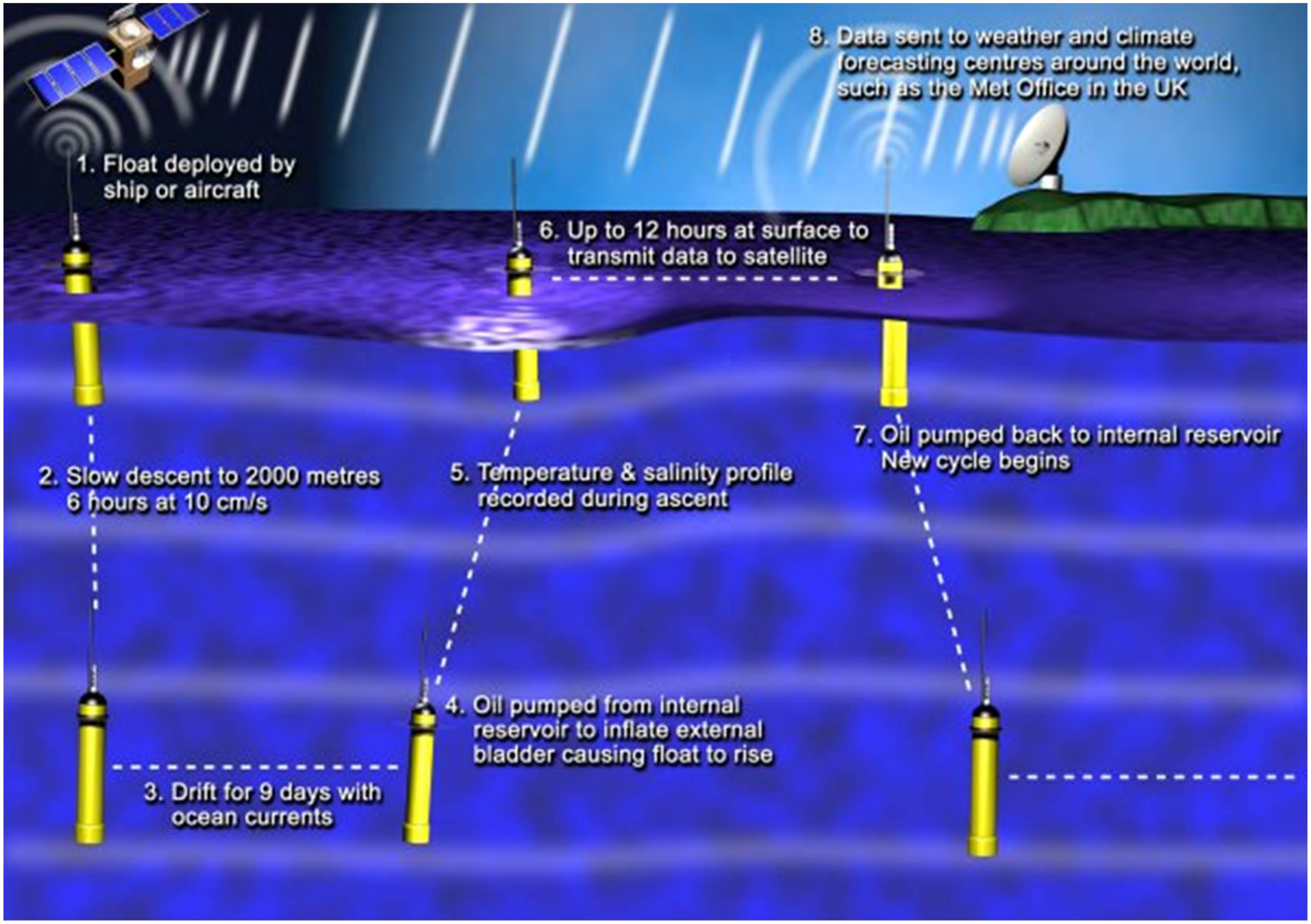
Perrette et al. 2011

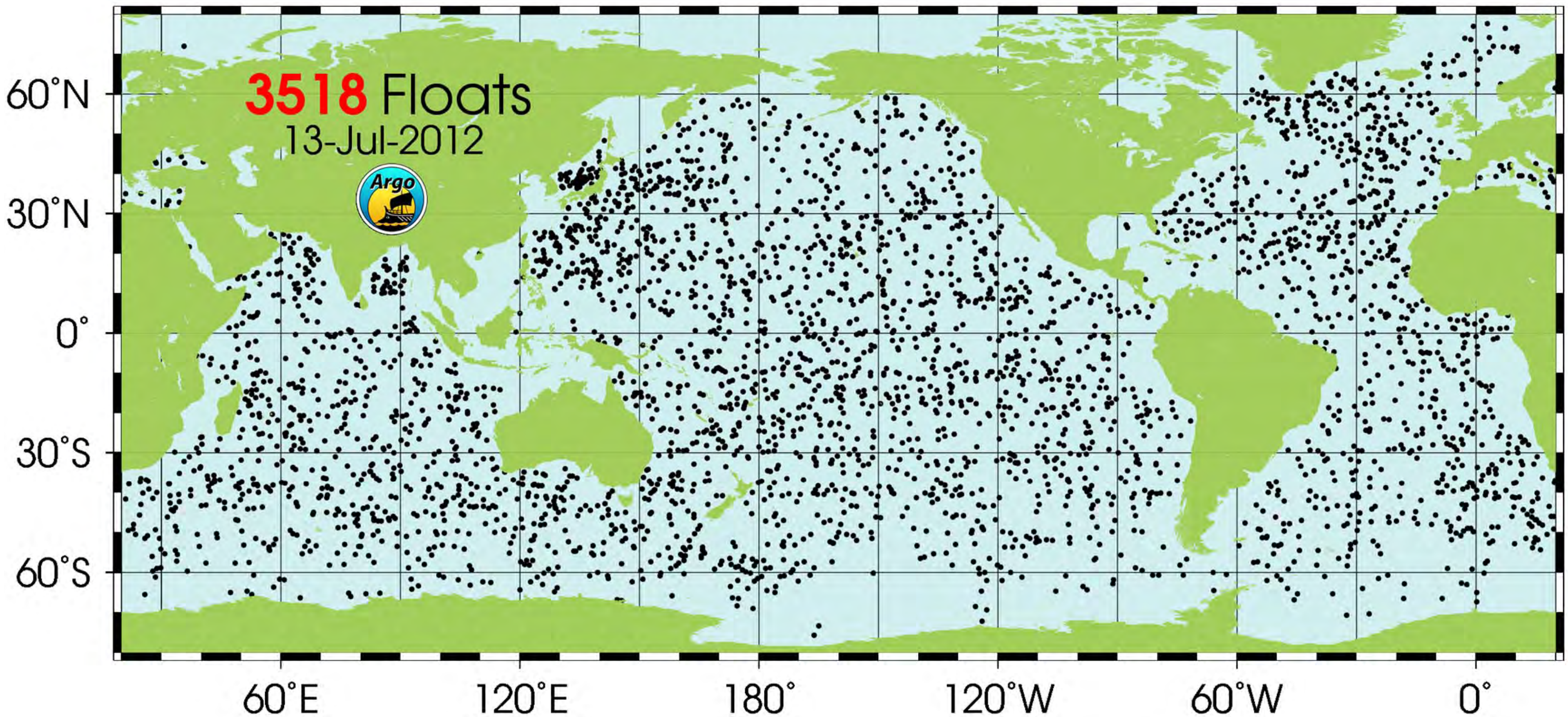


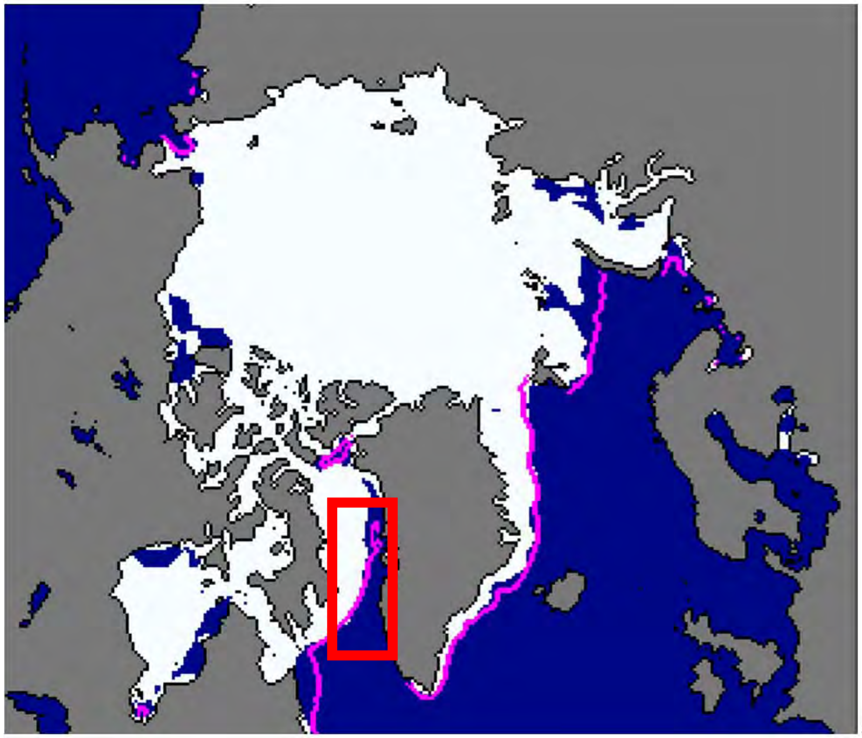
Arrigo et al. (2012), Science

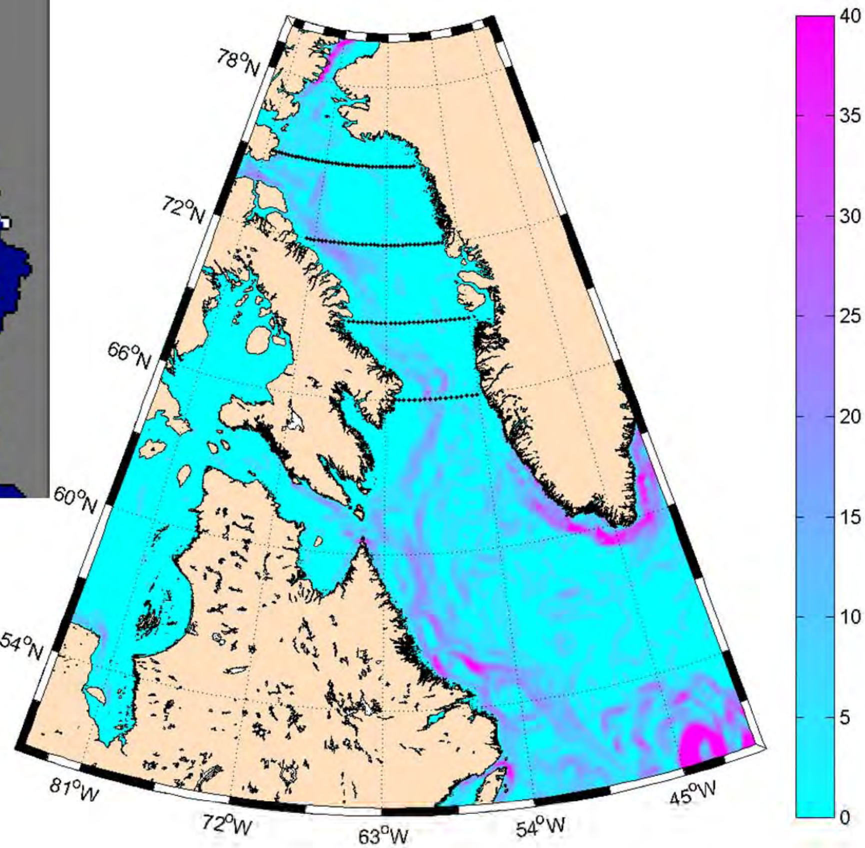
How to monitor phytoplankton blooms under the ice pack?


WRC
SLOCUM
ELECTRIC

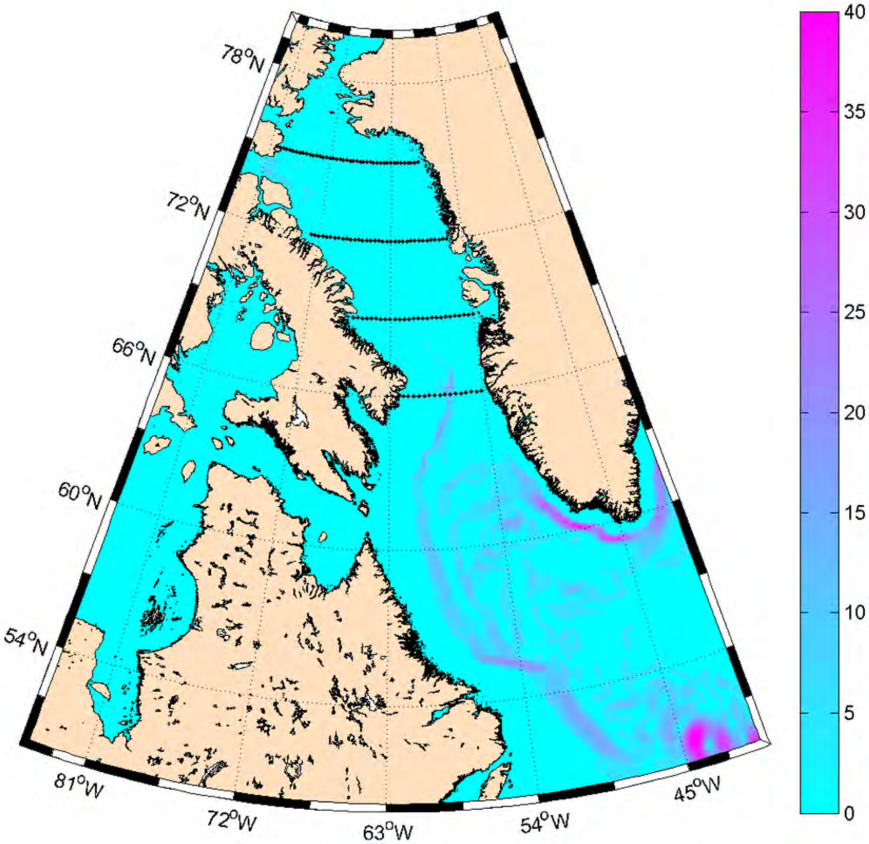

8. Data sent to weather and climate forecasting centres around the world, such as the Met Office in the UK
1. Float deployed by ship or aircraft
6. Up to 12 hours at surface to transmit data to satellite
7. Oil pumped back to internal reservoir New cycle begins
2. Slow descent to 2000 metres 6 hours at 10 cm/s
5. Temperature & salinity profile recorded during ascent
4. Oil pumped from internal reservoir to inflate external bladder causing float to rise
3. Drift for 9 days with ocean currents


3518 Floats
13-Jul-2012
Argo
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°





78°N
72°N
66°N
60°N
54°N
81°W
72°W
63°W
54°W
45°W
40
35
30
25
20
15
10
5
0



78°N
72°N
66°N
60°N
54°N
81°W
72°W
63°W
54°W
45°W
40
35
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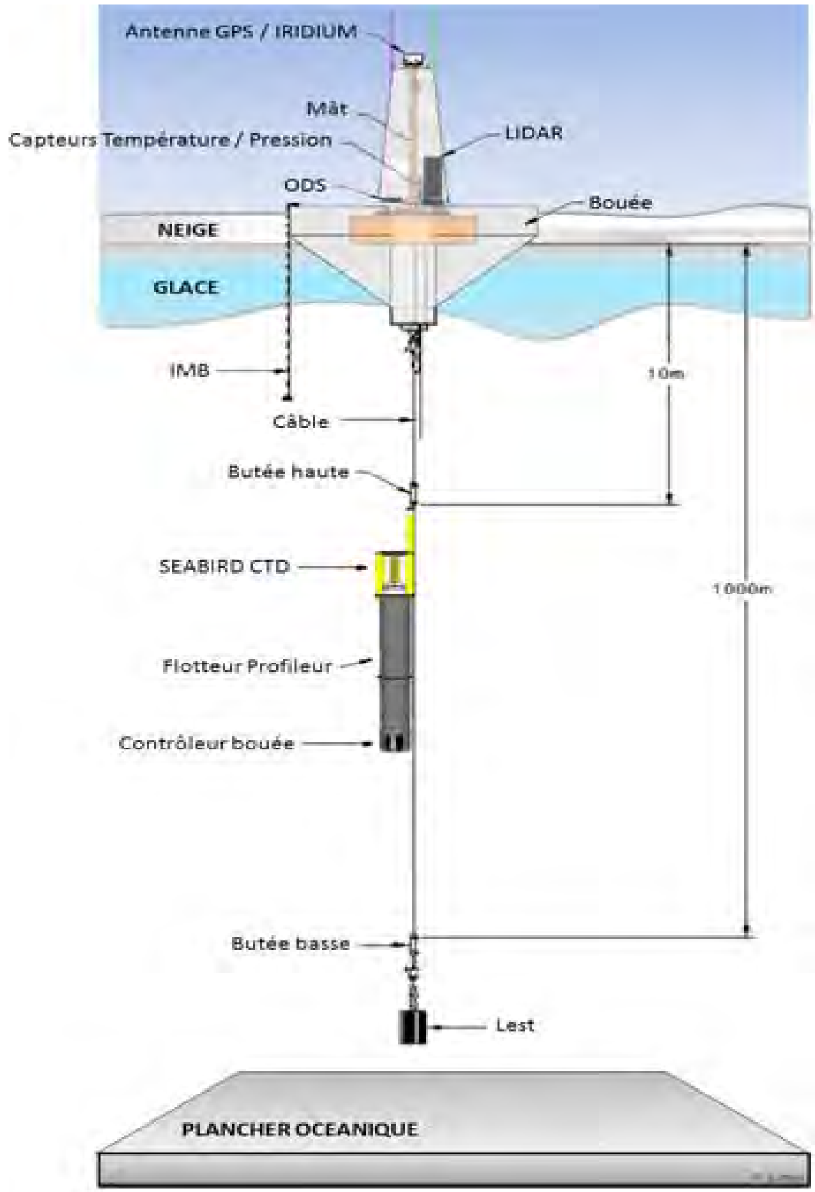
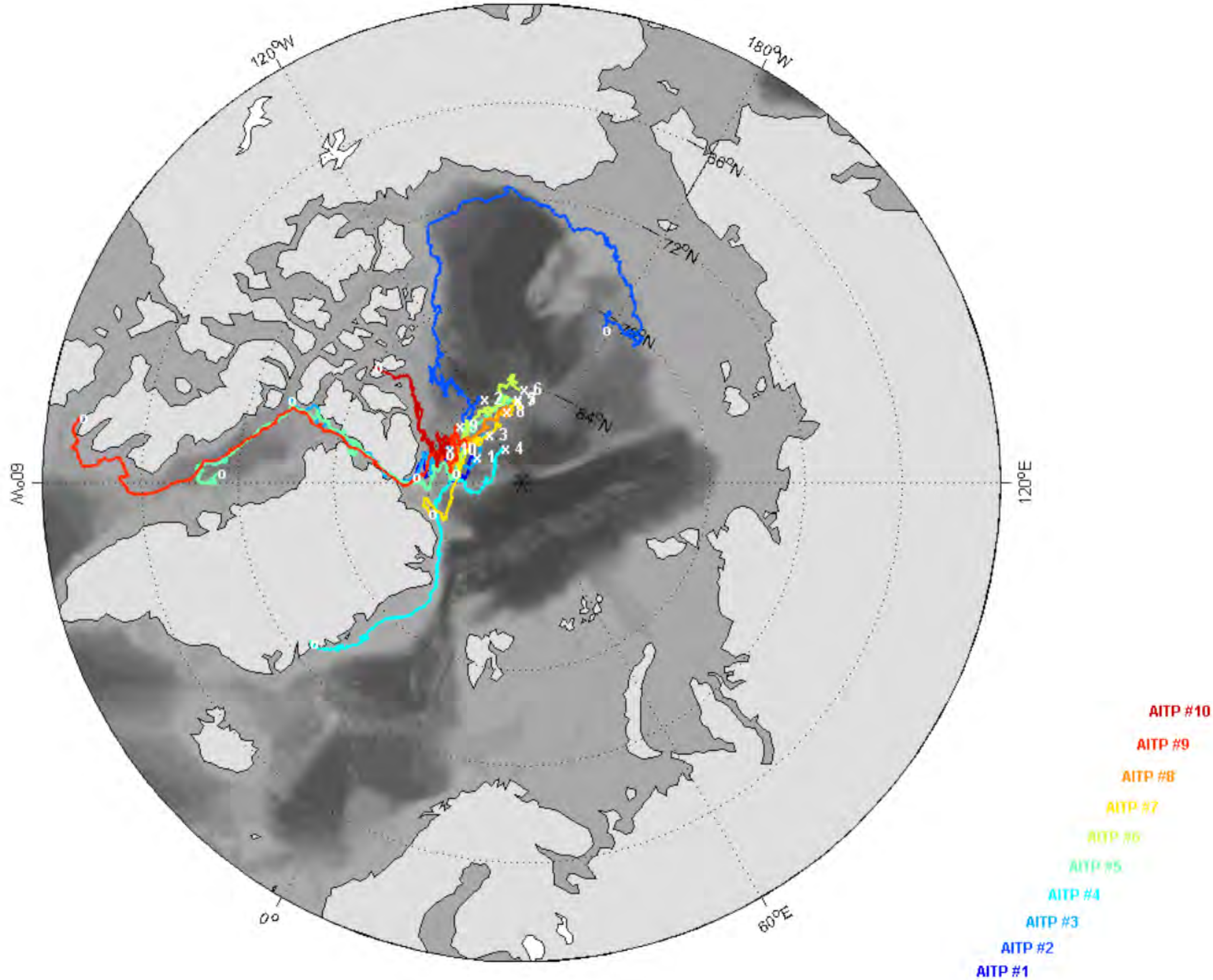
0


Antenne GPS / IRIDIUM
Mât
Capteurs Température / Pression
LIDAR
ODS
Bouée
NEIGE
GLACE
IMB
10m
Câble
Butée haute
SEABIRD CTD
1000m
Flotteur Profileur
Contrôleur bouée
Butée basse
Lest
PLANCHER OCEANIQUE



120°W
180°W
60°W
120°E
0°
60°E
66°N
72°N
78°N
84°N
AITP #10
AITP #9
AITP #8
AITP #7
AITP #6
AITP #5
AITP #4
AITP #3
AITP #2
AITP #1

END