Ocean colour remote sensing at high latitudes

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www.takuvik.ulaval.ca
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
Geography
Geography
Arctic vs. Antarctic
Bathymetry

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

Shelves occupy more than 50% of the Arctic Ocean area
Bathymetry
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
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
Light cycle
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

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
Light under sea ice
Back then: Assume a simple slab

Snow covered, thick, multiyear ice

1

0.85

0.4 m snow

<0.001

3 m ice

\sim 0

Courtesy of Don Perovich
Back then: Assume a simple slab

Let the snow melt

Courtesy of Don Perovich
Let the snow melt and add a pond

Back then: Assume a simple slab

Melt pond

3 m ice

~0.03

1

0.45

0.40

Courtesy of Don Perovich
Lefouest et al.

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
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?

\[
\text{Nitrate flux (}10^3\text{ tN/yr)}
\]

- **Bering Strait (minimum flux)**
- **Bering Strait (maximum flux)**
- **Rivers**

**Assuming:**
A total Arctic Ocean PP of \(\sim 350\) 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
Ice algae
Pennate diatoms

Pre-bloom period

Phytoplankton
Centric diatoms

Small phytoplankton
e.g. micromonas

Post-bloom period

GROWING SEASON

Winter period

Courtesy of Mathieu Ardyna
Ongoing changes

Surface Temperature Anomaly, 64°N - 90°N, 1880-2011 (°C)
(base period 1951-1980) (source: NASA GISS)
Ongoing changes
Ongoing changes

Average Monthly Arctic Sea Ice Extent
August 1979 to 2011
Ongoing changes
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
Today: Assume a simple thin slab

Snow covered, thin, first year ice

0.2 m snow

1.5 m ice

<0.005

0.85

1

~0

Courtesy of Don Perovich
Today: Assume a simple thin slab

Let the snow melt

1.5 m ice

1

0.60

0.4

~0.05

Courtesy of Don Perovich
Let the snow melt and add a pond

Today: Assume a simple thin slab

1.5 m ice

Melt pond

1.0

0.30

0.65

~0.4

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
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?

tDOC  \uparrow  \quad E_{PUR}  \downarrow  \\
\frac{d\sigma}{dz}  \uparrow  \quad [\text{Nut}]  \downarrow  \\
\text{Ice cover}  \downarrow  \quad E_{PUR}  \uparrow  \\

PP  \quad ?
And on $P_{\text{DIC}}$?

tDOC $\uparrow$

d$\sigma$/dz $\uparrow$

Ice cover $\downarrow$

$P_{\text{DIC}}$ $\uparrow$

Ice cover

Sun

Diagram illustrating the processes affecting ice cover and $P_{\text{DIC}}$. The diagram shows the interaction between different factors influencing the ice cover and the pressure $P_{\text{DIC}}$. The upward arrows indicate increases, and the downward arrow indicates a decrease.
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)
Beaufort Sea

Bélanger et al. (2008)
Matsuoka et al. (2011)
Matsuoka et al. (2012)
Matsuoka et al. (2012)
Chl-specific absorption is significantly smaller
\( \bar{a}_\phi^* \) is generally lower in the Arctic Ocean because of the light regime.
Matsuoka et al. (2011)
Table 1. Coefficients for the Nonlinear Regression Expressed as 
\[ a_\varphi(\lambda) = \alpha(\lambda)[a_\varphi(440)]^{\beta(\lambda)}, \text{ Where } \lambda \text{ is the Wavelength}^a \]

<table>
<thead>
<tr>
<th>(\lambda) (nm)</th>
<th>(\alpha(\lambda))</th>
<th>(\beta(\lambda))</th>
<th>(r^2)</th>
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<tr>
<td>400</td>
<td>0.8865</td>
<td>1.022</td>
<td>0.917</td>
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<td>0.9035</td>
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<td>0.999</td>
<td>0.980</td>
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<tr>
<td>425</td>
<td>0.9575</td>
<td>0.998</td>
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<tr>
<td>430</td>
<td>0.9614</td>
<td>0.992</td>
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<tr>
<td>435</td>
<td>0.9975</td>
<td>0.997</td>
<td>0.997</td>
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<td>1.000</td>
<td>1.000</td>
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<td>445</td>
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<td>0.990</td>
<td>0.993</td>
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<td>0.8550</td>
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<td>455</td>
<td>0.8322</td>
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<td>0.991</td>
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<tr>
<td>460</td>
<td>0.8104</td>
<td>0.988</td>
<td>0.991</td>
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<tr>
<td>465</td>
<td>0.8011</td>
<td>0.991</td>
<td>0.990</td>
</tr>
<tr>
<td>470</td>
<td>0.7434</td>
<td>0.979</td>
<td>0.989</td>
</tr>
</tbody>
</table>

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
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
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)
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)
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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

Data from:
- Labrador Sea
- Chukchi Sea
- Beaufort Sea

Arctic OC4L algorithm

\[ \text{Chl (Arc)} = 10^{(a_1 + b_1 R)} \]

\[ R = \log\left(\frac{R_{s443>490>510}}{R_{s555}}\right) \]
SeaWiFS Chlorophyll (mg m\(^{-3}\))

Transformed SeaWiFS Chlorophyll (mg m\(^{-3}\))

R = -0.3963
R = 1.0886
Observed range

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)
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 times a day.
Cloud cover

Key et al. (2004)

BFL (August-September)

NOW98 (April-July)
Key et al. (2004)

NOW98 (April-July)

BFL (August-September)
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**

- **SeaWIFS (1998-2010)**
  - Monthly GSM $a_f(443)$
  - Matsuoka et al. (2007)

- **SeaWIFS (1998-2010)**
  - Monthly $L_w(L)$
  - Lee et al. (2005)

- **SBDART (RT code)**
  - ISCCP ($/_{\text{cloud}}$ [cloud], ozone)

- **$E_d(L, 0^+, t)$**

- **$E_d(L, z, t)$**

- **$K_d(L)$**

- **$P_{b}^{\text{max}} = 2$**

- **$E_k(PUR)$**

- **$PP(z,t) = Chl \cdot P_{b}^{\text{max}} \left(1 - e^{-PUR(z)/E_k(PUR)}\right)$**
**Methods – Primary production model**

SeaWIFS (1998-2010)  
Monthly GSM $a_f(443)$

- SeaWIFS (1998-2010)  
  Monthly $L_w(\lambda)$

- SBDART (RT code)  
  ISCCP ($/\text{cloud}$, [cloud], ozone)

- Matsuoka et al. (2007)

- Chl

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

- $P_{\text{max}} = 2$

- $E_K(P_R)$

- Lee et al. (2005)

- $K_d(\lambda)$

- Arrigo et al. (1998)

- $E_d(\lambda, 0^+, t)$

- $E_d(\lambda, z, t)$
**Methods – Primary production model**

- **SeaWIFS (1998-2010)**
  - Monthly GSM $a_f(443)$
  - Matsuoka et al. (2007)

- **SeaWIFS (1998-2010)**
  - Monthly $L_w(\lambda)$
  - Lee et al. (2005)

- **SBDART (RT code)**
  - ISCCP ($/\text{cloud}$, [cloud], ozone)

- **Chl**
- $a_f(\lambda)$
- $E_d(\lambda, 0^+, t)$
- $E_d(\lambda, z, t)$
- $K_d(\lambda)$

- **PUR(z, t)**
- **PUR(z)**

- **$P_b^{max} = 2$**
- **$E_K(PUR)$**

**Primary production model**

$$PP(z, t) = \text{Chl} \cdot P_b^{max} \left(1 - e^{-PUR(z)/E_K(PUR)}\right)$$
Methods – Primary production model

SeaWIFS (1998-2010) Monthly GSM $a_f(443)$

Matsuoka et al. (2007)

Chl $a_f(\lambda)$

SBDART (RT code) ISCCP (cloud, [cloud], ozone)

$E_d(\lambda, 0^+, t)$

$E_d(\lambda, z, t)$

SeaWIFS (1998-2010) Monthly $L_w(\lambda)$

Lee et al. (2005)

$K_d(\lambda)$

PUR($z, t$)

Arrigo et al. (1998)

$P_b^{\text{max}} = 2$

$E_k(PUR)$

$PP(z,t) = \text{Chl} \cdot P_b^{\text{max}} \left(1 - e^{-PUR(z)}E_k(PUR)\right)$
$$PP(z,t) = Chl \ P_B^{\text{max}} \left( 1 - e^{-\text{PUR}(z)/E_\kappa(\text{PUR})} \right)$$
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

Annual production (Tg C yr$^{-1}$)

Year

$R^2 = 0.40$
Arctic Primary Production

Arrigo et al. 2008

In 2007, an abrupt change!

![Graph showing primary production in the Arctic, with a significant increase in 2007. The graph indicates a 23% increase compared to the previous years, specifically from 1998 to 2002.](image-url)
Arctic Primary Production

![Graph showing annual primary production in the Arctic from 1998 to 2007. The data shows an increasing trend with an annual mean of 400 Tg C yr⁻¹ and an R² value of 0.40. The graph highlights the increase in production in 2007.]
Antarctic Ocean

Arrigo et al. (2008) JGR

Smith & Comiso (2008) JGR
## Results

### Primary Production

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All Arctic (sensu IHO)</td>
<td>0.62*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>&gt;60°</td>
<td>0.46</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>&gt;66.5°</td>
<td>0.26</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td>&gt;70°</td>
<td>0.19</td>
<td>1.4</td>
<td>0.4</td>
<td>0.6</td>
<td>-</td>
</tr>
</tbody>
</table>

* Gt C y\(^{-1}\)
Results

This study compared primary production (Gt C yr⁻¹) with data from Sakshaug (2004). The Bering Sea shows the highest primary production in this study, exceeding the values reported by Sakshaug (2004).
PP trends 1998–2010 (Sen Slope; p < 0.05)

Bélanger et al.
Ice trend during the last decade

Spring

Summer
Trend in Chlorophyll concentration

June

July
What about CDOM photooxidation?
CDOM Photooxidation model

\[ P_{\text{DIC}}(t) = \int_{300}^{600} E_d(\lambda, 0^\circ, t) \frac{a_{\text{CDOM}}(\lambda)}{a(\lambda)} \phi_{\text{DIC}}(\lambda) d\lambda \]

Bélanger et al. (2006)
Primary Production vs. Photooxidation

Gross PP $\Rightarrow$ $0.62 \times 10^{15}$ gC y$^{-1}$

Photooxidation (CO$_2$) $\Rightarrow$ $2.7 \times 10^{13}$ gC y$^{-1}$

- Photooxidation (CO$_2$) $\Rightarrow$ 4.4% of PP
- Sequestered C $\sim$ 1% of PP (Stein & Mcdonald 2004)

So, potentially

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 for year 2007

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

Circumpolar Arctic: 293 378 29%
Problems & Limitations

• Problems to solve:
  – Optical properties of Arctic seawater
  – Photosynthetic properties of phytoplankton
\[ PP(z,t) = Chl \ P_B^{max} \left( 1 - e^{-\frac{PUR(z)}{E_{\kappa}(PUR)}} \right) \]
Photosynthetic parameters

Barents Sea

Rey (1991)
Photosynthetic parameters

Beaufort Sea in August 2009

$P_{\text{max}}^B \approx 0.6$

$E_k$ (μmole photons m$^{-2}$ s$^{-1}$)

$P_{\text{max}}^B \text{ [mg C (mg chl } a)^{-1} \text{ h}^{-1}]$

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)

DCM

Measured PP
Mundy et al. (2009)
**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$^a$

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Chlorophyll $a$ Constant in the Upper 100 m (Method 2)</strong></td>
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<tr>
<td>Chukchi</td>
<td>-18.9</td>
<td>-12.0</td>
<td>-6.1</td>
<td>3.0</td>
<td>-7.6</td>
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<tr>
<td>Beaufort</td>
<td>-76.9</td>
<td>8.4</td>
<td>-20</td>
<td>18.3</td>
<td>-10.8</td>
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<td>Baffin</td>
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<td>Greenland</td>
<td>-16.8</td>
<td>0</td>
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<td>13.7</td>
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</table>

$^a$Chl $a$ was distributed vertically using methods 2–4.

$^b$ND indicates no in situ data were available.
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$^a$

<table>
<thead>
<tr>
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<th>January–March</th>
<th>April–June</th>
<th>July–September</th>
<th>October–December</th>
<th>Annual</th>
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Chlorophyll $a$ Constant in Upper 100 m (Method 2)

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Chlorophyll $a$ Constant in Upper 20 m and Declines Exponentially With Depth (Method 3)

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Chlorophyll $a$ Constant in Upper 40 m and Declines Exponentially With Depth (Method 4)

$^a$Chl $a$ was distributed vertically using methods 2–4.

$^b$ND indicates no in situ data were available.
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)

% ice cover = 7.5%
% ice cover = 10%
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

<table>
<thead>
<tr>
<th>Region Considered</th>
<th>Relative difference between PP with OC only, and PP for all ice-free areas</th>
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<tr>
<td>All Arctic waters</td>
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<td>&gt; 60°</td>
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<td>Arctic Basin</td>
<td>-47%</td>
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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?
1. Float deployed by ship or aircraft
2. Slow descent to 2000 metres, 6 hours at 10 cm/s
3. Drift for 9 days with ocean currents
4. Oil pumped from internal reservoir to inflate external bladder causing float to rise
5. Temperature & salinity profile recorded during ascent
6. Up to 12 hours at surface to transmit data to satellite
7. Oil pumped back to internal reservoir, new cycle begins
8. Data sent to weather and climate forecasting centres around the world, such as the Met Office in the UK.
END