Ocean Colour Remote Sensing in Polar Seas

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Today’s talk

1. Why are studies in polar seas so important?
   - Aspect of global CO$_2$ budget

2. Ocean colour remote sensing in polar seas
   - Evaluating existing atmospheric correction algorithms
   - Uniqueness of in-water optical properties

3. Applications
   - Examining trends in fluxes of terrigenous organic carbon
   - Discriminating water sources from space
   - Toward constraining numerical modeling
   - Multi-satellite remote sensing
1. Why are studies in polar seas so important?
Role of Arctic Ocean: Solubility pump

CO$_2$

Volume:
1 % of global ocean

CO$_2$ uptake:
5 – 14% of global ocean

[Bates et al., 2011, Oceanography]
CO$_2$ uptake:
5 – 14% of global ocean

[Bates et al., 2011, Oceanography]

[Updated from Arrigo and van Dijken, 2015, PO]
Role of Antarctic Ocean: Solubility pump

**CO$_2$**

Volume: 5 % of global ocean

**CO$_2$** uptake: 25 % of global ocean

[Takahashi et al., 2002, DSRII]
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Terrestrial effects

- Widespread permafrost containing an enormous amount of organic carbon, 1700 Pg C: > 50 % of global carbon stock, double the atmosphere
- Increase in river discharge in both Eurasian and North American Arctic regions since late 20 century
Will the Arctic Ocean be source or sink of atmospheric $\text{CO}_2$?

IPCC (2007)  
IPCC (2013)
2. Ocean colour remote remote sensing in polar seas
\[ \rho_{\text{total}}(\lambda) = \rho_{\text{pathradiance}}(\lambda) + T(\lambda)\rho_{\text{glint}}(\lambda) + t(\lambda)(\rho_{\text{adjacency}}(\lambda) + \rho_{\text{water}}(\lambda)) \]
Is ocean color useful for polar seas?

Limitations

- Frequent cloud cover
- High solar zenith angles
- Possible signal contamination by sea ice pack
- Unique optical properties

Usefulness (several overpasses per day)

- Environmental monitoring (e.g., export of permafrost-origin organic matter in coastal waters)
- Ecosystem studies
- Risk assessment

IOCCG report (2015)
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IOCCG report (2015)
2. Ocean colour remote remote sensing in polar seas:
   -Evaluating existing atmospheric correction algorithms-
3D radiative transfer model simulation using Monte Carlo method

\[ \rho_{\text{total}}(\lambda) = \rho_{\text{pathradiance}}(\lambda) + T(\lambda)\rho_{\text{glint}}(\lambda) + t(\lambda)(\rho_{\text{adjacency}}(\lambda) + \rho_{\text{water}}(\lambda)) \]

1. Why polar seas?
2. Ocean Colour in polar seas
3. Applications
Evaluating atmospheric correction algorithms

Simulation of $\rho_{\text{total}}(\lambda)$ → Application of atmospheric correction to the $\rho_{\text{total}}(\lambda)$ → Retrieval of $\rho_{\text{water}}(\lambda)$

**Basic**
- Atmosphere-ocean coupled 3-D RT model based on Monte-Carlo method, 3DMCPOL (*Cornet et al.*, 2010, JQSRT) was used.
- Ocean component is based on 6S RT.
- The number of photons used per pixel was $3.0 \times 10^5$ for 51x51 pixels in order to have an uncertainty of $\rho_{\text{TOA}}(\lambda)$ less than 1%.

**Setting**
- Solar zenith was set to be $50^\circ$ (a typical value for polar regions) but $\theta_v$ and $\Delta \phi$ varied.
- OPAC aerosol models with 50% humidity were used.
- Bidirectionality for fresh snow (*Kokhanovsky and Bréon*, 2012, IEEE) was taken into account.
Evaluating atmospheric correction algorithms

Example ($\theta_s = 50^\circ$, $\theta_v = 30^\circ$, $\Delta\phi = 0^\circ$)

True : Known (simulation)
Red : POLYMER algorithm
Black : NASA standard algorithm

1. Why polar seas?
2. Ocean Colour in polar seas
3. Applications

[Steinmetz et al., 2011, OE]
[Bailey et al., 2010, OE]
Bidirectionality of normalized $\rho_{TOA}(\lambda)$

$$\rho^{nor}(\theta_v, \Delta \varphi) = \frac{\rho_{TOA}^{near-ice}(\theta_v, \Delta \varphi)}{\rho_{ocean}^{TOA}(\theta_v, \Delta \varphi)}$$
Application of atmospheric correction algorithms to Aqua/MODIS satellite image

1. Why polar seas?
2. Ocean Colour in polar seas
3. Applications

[Image of map showing water reflectance and sea ice on 8 July 2010]

Water reflectance ($\rho_{\text{water}}$)

Sea ice

[Source: Matsuoka et al., in prep.]
Application of atmospheric correction algorithms to Aqua/MODIS satellite image

1. Why polar seas?
2. Ocean Colour in polar seas
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[Matsuoka et al., in prep.]
Direct comparison between *in situ* and satellite estimates within 3 hours (i.e., NASA protocols)

**NASA standard**

[Graph showing comparison between *in situ* and satellite reflectance for Blue and Green bands]

[1. Why polar seas?]

[2. Ocean Colour in polar seas]

[3. Applications]

[Matsuoka et al., in prep.]
Direct comparison between *in situ* and satellite estimates within 3 hours (i.e., NASA protocols)

**NASA standard**

**In situ Reflectance vs Satellite Reflectance**

[Graph showing comparison between in situ and satellite reflectance for Blue and Green bands]
2. Ocean colour remote remote sensing in polar seas:
In-water optical properties
Optical dataset

Arctic

Antarctic

[Reynolds, Matsuoka et al., in IOCCG2015]
Estimates of chlorophyll a concentration: Deviations from the global relationship

[Reynolds, Matsuoka et al., in IOCCG2015]
Estimates of chlorophyll a concentration: Deviations from the global relationship

[Reynolds, Matsuoka et al., in IOCCG2015]
Absorption

Arctic

Antarctic

[Reynolds, Matsuoka et al., in IOCCG2015]
Backscattering

[Reynolds, Matsuoka et al., in IOCCG2015]
1. Why polar seas?

2. Ocean Colour in polar seas

3. Applications

Backscattering

[Reynolds, Matsuoka et al., in IOCCG2015]
Compilation of available optical datasets

1. Why polar seas?
2. Ocean Colour in polar seas
3. Applications

[Matsuoka et al., 2011, JGR; Matsuoka et al., 2014, BG; Matsuoka et al., 2017, RSE; Li et al., to be submitted]
3. Applications (1/3)
Terrestrial effects
DOC and POC algorithms

DOC concentration

(Matsuoka et al., 2017, RSE)

- Semi-analytical algorithm
- Applicable for river-influenced coastal areas of the Arctic Ocean

Uncertainty: ±28%

SPM/POC concentration

(After Doxaran et al., 2015, BG)

- Empirical algorithm
- Designed for Southern Beaufort sea but can be tuned for other Arctic coastal areas

Uncertainty: ±35%
Monthly DOC concentrations (MODIS)
Monthly POC concentrations (MODIS)
Monthly POC concentrations (MODIS)
Example of the Mackenzie river plume using a high resolution satellite image (30m)
Two-decade trends in DOC and POC fluxes for summer total (1998-2018)

Summer total (Jun. to Sep.)

Satellite DOC flux [TgC summer$^{-1}$]

Satellite POC flux [TgC summer$^{-1}$]
Comparison of satellite DOC flux in the delta with \textit{in situ} data at an upstream pilot station (\textit{Tank et al.}, 2016, ERL)

\textit{In situ} Estimates from space

[Matsuoka et al., to be submitted]
Two-decade trends in DOC and POC fluxes for September only (1998-2018)
Trends in standardized environmental variables:

- Standardized anomalies for 11-year moving averaged data

- River Discharge
- Air Temperature
- Active Layer Depth
- Precipitation
3. Applications (2/3)
Multi-satellite remote sensing approach

- Ocean color
- Sea surface salinity
- Sea ice concentration
- Sea surface temperature
- Sea surface wind
Mass balance equations regarding salinity\(^{\text{sat}}\) and CDOM\(^{\text{sat}}\)

**Approach:**

1. **Fraction (f)**
   \[ f_{\text{SEA}} + f_{\text{MELT}} + f_{\text{RIVER}} = 1 \]

2. **Salinity (S)**
   \[ f_{\text{SEA}} S_{\text{SEA}} + f_{\text{MELT}} S_{\text{MELT}} = S^{\text{sat}} \]

3. **CDOM (C)**
   \[ f_{\text{SEA}} C_{\text{SEA}} + f_{\text{MELT}} C_{\text{MELT}} + f_{\text{RIVER}} C_{\text{RIVER}} = C^{\text{sat}} \]

---


[Matsuoka et al., 2016, RSE]
Relationship between salinity\textsuperscript{sat} and CDOM\textsuperscript{sat}
Relationship between salinity^{sat} and CDOM^{sat}

[Matsuoka et al., 2016, RSE]
Fraction of river-influenced water derived from space

Matsuoka et al., 2016, RSE
3. Applications (3/3)
Comparison of satellite estimates with modeling results: MITgcm coupled with biogeochemical components

3.1. Trends in organic matter fluxes
3.2. Discriminating water sources
3.3. Numerical modelling

[Le Fouest, Matsuoka et al., 2018, BG]
Comparison of satellite estimates with modeling results:
MITgcm coupled with biogeochemical components

Needs for better understanding of seasonal biogeochemical processes

[Le Fouest, Matsuoka et al., 2018, BG]
Field observation plan

- WHEN: April-June-July-August 2019
- WHERE: Delta Mackenzie river
- HOW: Helicopter/Ship
- WHAT VARIABLES/EXPERIMENTS:
  - Concentration and ages of organic matter,
  - Terrestrial organic matter tracer,
  - Phytoplankton pigments, nutrients,
  - Biodegradation experiments
- Optical properties
  - Radiance/Irradiance, light absorption of OM,
  - Light backscatter of particles, Particle size distribution, Fluorescence of OM, etc.

- Mon.
  - Ice covered
    - Apr
      - Helicopter but ice-camp type operation
  - Break-up
    - Jun
      - Helicopter stationary operation
  - Jul-Aug
    - Ship-base operation
  - Aug-Sep
    - Ship-base operation
Field observation plan

Points to be considered

- Avoiding sampling stations in the Stamukhi area (April, June)
- Avoiding sampling stations in bottom-fast ice area (April, June)
- Capturing extension of the river plume
- Focusing on biogeochemical variables at low salinity (mostly 0-3)
- Bathymetry
- Tidal effect
- Comparison of results with the literature

Copernicus Sentinel-1A/1B, Radarsat-2

https://en.wikipedia.org/wiki/Stamukha
Sampling stations in the Mackenzie delta:

88% of the stations are located less than 5 m bottom depth.
False color Image of L8/OLI
3.1. Trends in organic matter fluxes

3.2. Discriminating water sources

3.3. Multi-remote sensing

False color Image of L8/OLI

June
3.1. Trends in organic matter fluxes

3.2. Discriminating water sources

3.3. Multi-remote sensing

False color Image of L8/OLI

April
3.1. Trends in organic matter fluxes

3.2. Discriminating water sources

3.3. Multi-remote sensing

Single band S1 SAR image (HH)
Single band S1 SAR image (HH) + L8/OLI false color
3.1. Trends in organic matter fluxes

3.2. Discriminating water sources

3.3. Multi-remote sensing

**S1 SAR**

**RGB image:**

HV (red), HH (green), HH (blue)
Concluding remarks (1/2)

1. Characteristics of optical properties for Arctic (higher CDOM proportion relative to $a_{tw}$) and Antarctic (high package effect) were shown. These mainly explain deviations from the global relationship of chl $a$ estimate, etc.

2. The performance of POLYMER algorithm likely performs better in icy waters than that of NASA standard AC algorithm.

3. While no trend in DOC flux was observed, POC flux in September significantly increased over the last two decades (1998-2018).

4. An increase in air temperature is likely deepening active layer depth. This might induce hydrological connection in recent years.
5. Source water discrimination will be useful to examine the impact of riverine inputs on coastal marine ecosystems.

6. While comparison of DOC/POC flux between satellite and a numerical model shows promising results, the discrepancy needs to be further minimized by in situ data.

7. Multi-remote sensing approach is required to better understand physical and biogeochemical processes of the ocean.
Multi-satellite remote sensing

Ocean color sensors
Sentinel-2A,2B/MSI, Landsat-8/OLI,
Sentinel-3A,3B/OLCI, GCOM-C/SGLI, Aqua/MODIS, Suomi-VIIRS, NOAA-20/VIIRS

LiDAR
CALIPSO/CALIOP

Active microwave (SAR)
Sentinel-1A,1B, Radarsat-2

Passive microwave
SMOS/MIRAS, GCOM-W/AMSR-2