Estimating concentrations of dissolved organic carbon (DOC) for Arctic coastal waters from space - Tracing modifications in the organic carbon budget -

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Thanks to collaboration with:
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B. G. Mitchell, S. Bélanger, and A. Bricaud
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**INTRODUCTION**

**Why DOC for Arctic coastal waters?**

Volume: 1 % of the global ocean
Freshwater: 10 % of the global ocean

- Thawing of the permafrost containing huge DOC
- Increase in river discharge

Such a quantitative algorithm is currently not available for estimating DOC concentrations temporally and geographically for Arctic waters

**Objective:** Develop a robust algorithm for estimating DOC concentrations in Arctic coastal waters from space
Datasets

INTRODUCTION

DATA SETS

METHODS

RESULTS & DISCUSSION

CONCLUSIONS

[Map showing data points in the Arctic region with labels for SBI_spr, SBI_sum, MR Aut, and MALINA.]
Beaufort Sea

Sampling (CTD/Niskin + Barge)

Terra/MODIS
21 August, 2009
**Absorption coefficients**

- Total particles (>0.7 μm), $a_p(\lambda)$
  - Methanol
  - [Kishino et al., 1985]
- Non-algal particles (NAP), $a_{NAP}(\lambda)$
- Phytoplankton, $a_\phi(\lambda)$
- CDOM (<0.2 μm), $a_{CDOM}(\lambda)$
- CDM (= CDOM + NAP), $a_{CDM}(\lambda)$

**Chl a concentration**

**Fluorometric method**
[Holm-Hansen et al., 1965; Suzuki and Ishimaru, 1990]

**HPLC method** [Ras et al., 2008]
**In situ $R_{rs}(\lambda)$**

In-water spectro-radiometer, C-Ops

$L_u(\lambda)$ and $E_d(\lambda)$ measured at 19 wavelengths (320, 340, 380, 395, 412, 443, 465, 490, 510, 532, 555, 560, 625, 665, 670, 683, 710, 780 nm, and PAR)

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(0^+, \lambda)} = \frac{0.54L_u(0^+, \lambda)}{E_d(0^+, \lambda)}$$

[Miller and Austin, 1995; Hooker et al., 2013]

**Satellite $R_{rs}(\lambda)$**

MODIS $R_{rs}(\lambda)$ at 412, 443, 488, 531, 555, and 670 nm

<table>
<thead>
<tr>
<th>Period</th>
<th>Temporal resolution</th>
<th>Data level</th>
<th>Area</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>August, 2009</td>
<td>Daily</td>
<td>L1A</td>
<td>Southern Beaufort Sea</td>
<td>1 km</td>
</tr>
<tr>
<td>2002-2012</td>
<td>Monthly</td>
<td>L3</td>
<td>Pan-Arctic</td>
<td>4 km</td>
</tr>
</tbody>
</table>
Satellite $R_{rs}(\lambda)$ ($\lambda=412$, 443, 488, 531, 555, 667 nm)

$MSD = \frac{1}{N - 1} \sum_{i=1}^{N_{\lambda}} [R_{rs}(\lambda_i) - \hat{R}_{rs}(\lambda_i)]^2$

$a_{\phi}^*(\lambda)$ for Arctic waters
[Matsuoka et al., 2011, JGR]

$S_{CDM} = f(R_{rs}(\lambda))$ or const.
$\eta = f(R_{rs}(\lambda))$ or const.
[Lee et al., 2009]

$\lambda_0 = 443$ nm

$NAP(\lambda_0) = f(b_{bp}(555))$
[Matsuoka et al., 2007, CJRS]

$DOC = f(a_{CDOM}(443))$
[Matsuoka et al., 2013, BG]
DOC estimation for Southern Beaufort Sea waters

-A case study for the Southern Beaufort Sea-
**Evaluation of estimated \( a_{\text{CDOM}}(443) \) vs. in situ \( a_{\text{CDOM}}(443) \)**

*Oceanic waters*

- \( S_{\text{CDM}} = 0.0185 \)
- \( \eta = 1.0 \)
- \( r^2 = 0.98 \)
- RMSE = 0.06
- Slope = 0.88

- \( S_{\text{CDM}} = 0.0185 \)
- \( \eta = f(R_{rs}(\lambda)) \)
- \( r^2 = 0.87 \)
- RMSE = 0.09
- Slope = 0.62
Evaluation of estimated $a_{\text{CDOM}(443)}$ vs. in situ $a_{\text{CDOM}(443)}$

Coastal waters

$S_{\text{CDM}}=0.0185$
$\eta=1.0$

- $r^2 = 0.65$
- RMSE = 0.18
- Slope = 1.51

Coastal waters

$S_{\text{CDM}}=0.0185$
$\eta=f(R_{rS}(\lambda))$

- $r^2 = 0.84$
- RMSE = 0.15
- Slope = 0.93
### Summary of sensitivity analysis

<table>
<thead>
<tr>
<th>Sample Parameter</th>
<th>Oceanic waters</th>
<th>Coastal waters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r²</td>
<td>Int.</td>
</tr>
<tr>
<td>1-1</td>
<td>0.98</td>
<td>0.003</td>
</tr>
<tr>
<td>1-2</td>
<td>0.81</td>
<td>0.022</td>
</tr>
<tr>
<td>2-1</td>
<td>0.87</td>
<td>0.017</td>
</tr>
<tr>
<td>2-2</td>
<td>0.73</td>
<td>0.025</td>
</tr>
</tbody>
</table>

1-1: \( \eta = 1.0 \) and \( S_{CDM} = 0.0185 \)
1-2: \( \eta = 1.0 \) and \( S_{CDM} = f(R_{rs}(\lambda)) \)
2-1: \( \eta = f(R_{rs}(\lambda)) \) and \( S_{CDM} = 0.0185 \)
2-2: \( \eta = f(R_{rs}(\lambda)) \) and \( S_{CDM} = f(R_{rs}(\lambda)) \)
**RESULTS & DISCUSSION**

**DOC for Southern Beaufort Sea**

**CONCLUSIONS**

**CDOM estimation using ocean color data in August, 2009**

<table>
<thead>
<tr>
<th>$a_{CDOM}(443)$ (m$^{-1}$)</th>
<th>G. Mean</th>
<th>G. SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Satellite</strong></td>
<td>0.034</td>
<td>2.776</td>
</tr>
<tr>
<td><strong>In situ</strong></td>
<td>0.055</td>
<td>2.265</td>
</tr>
</tbody>
</table>

[Matsuoka et al., 2013, BG]
An empirical relationship between DOC concentrations and $a_{\text{CDOM}}(443)$ for southern Beaufort Sea waters.

$\text{DOC}^{\text{obs}}$ (μM) vs $a_{\text{CDOM}}^{\text{obs}}(443)$ (m$^{-1}$)

$r^2 = 0.97$

[Matsuoka et al., 2012, BG]
DOC estimation using ocean color data in August, 2009

RESULTS & DISCUSSION - DOC for Southern Beaufort Sea - (6/6)

DOC (μM) outside of the regression

<table>
<thead>
<tr>
<th>DOC (μM)</th>
<th>G. Mean</th>
<th>G. SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>79</td>
<td>1.4</td>
</tr>
<tr>
<td>In situ</td>
<td>75</td>
<td>1.4</td>
</tr>
</tbody>
</table>

[Source: Matsuoka et al., 2013, BG]
DOC estimation for various coastal waters

-Pan-Arctic scale-
Importance of $a_\phi^*(\lambda)$ parameterization

Satellite $R_{rs}(\lambda)$ ($\lambda=412, 443, 488, 531, 555, 667$ nm)

$a_\phi^*(\lambda)$ for Arctic waters
[Matsuoka et al., 2011, JGR]

$S_{CDM} = f(R_{rs}(\lambda))$ or const.
$\eta = f(R_{rs}(\lambda))$ or const.
[Lee et al., 2009]

$\lambda_0 = 443$ nm

$\alpha_{NAP}(\lambda_0) = f(b_{bp}(555))$
[Matsuoka et al., 2007, CJRS]

$\alpha_{CDOM}(\lambda_0)$

$\alpha_{NAP}(\lambda_0)$

$\alpha_{CDOM}(\lambda_0)$

$DOC = f(\alpha_{CDOM}(443))$
[Matsuoka et al., 2012, BG]

[After Matsuoka et al., 2013, BG]
Indirect evaluation of our CDOM absorption algorithm for eastern (Russian side) Arctic waters
Climatology of $a_{CDOM}(443)$ from June to September during the periods 2002-2012
**Histograms of $a_{\text{sat}}^{\text{CDOM}}(443)$ in August for major river mouths**

### Results & Discussion

- **DOC for various coastal waters**

### Conclusions

#### Southern Beaufort Sea (SB)

<table>
<thead>
<tr>
<th>$a_{\text{CDOM}}(443)$ (m$^{-1}$)</th>
<th>G. Mean</th>
<th>G. SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>0.059</td>
<td>2.363</td>
</tr>
<tr>
<td><em>In situ</em> (Matsuoka et al., 2012)</td>
<td>0.055</td>
<td>2.265</td>
</tr>
</tbody>
</table>

#### Laptev Sea (LP)

<table>
<thead>
<tr>
<th>$a_{\text{CDOM}}(443)$ (m$^{-1}$)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>&lt; 3.3</td>
</tr>
<tr>
<td><em>In situ</em> (Stedmon et al., 2011; Heim et al., 2013)</td>
<td>&lt; 3.5</td>
</tr>
</tbody>
</table>

#### Kara Sea (KR)

<table>
<thead>
<tr>
<th>$a_{\text{CDOM}}(443)$ (m$^{-1}$)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>&lt; 4.4</td>
</tr>
<tr>
<td><em>In situ</em> (Stedmon et al., 2011)</td>
<td>&lt; 4.5</td>
</tr>
</tbody>
</table>

![Map showing distribution of $a_{\text{CDOM}}(443)$ in August for various coastal waters]
DOC versus $a_{\text{CDOM}}(443)$ relationship for Eastern and Western Arctic Ocean

RESULTS & DISCUSSION - DOC for various coastal waters – (5/7)
Climatology of DOC concentrations for coastal waters from June to September during the periods 2002-2012
### RESULTS & DISCUSSION

DOC for various coastal waters – (7/7)

#### CONCLUSIONS

<table>
<thead>
<tr>
<th>DOC (µM)</th>
<th>G. Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Satellite</strong></td>
<td>82</td>
<td>&lt; 808</td>
</tr>
<tr>
<td><strong>In situ</strong></td>
<td>79</td>
<td>&lt; 577</td>
</tr>
</tbody>
</table>

#### Histograms of DOC\textsuperscript{sat} in August for major river mouths

- **Southern Beaufort Sea**
  - DOC (µM)
  - **Satellite**: 82
  - **In situ (Matsuoka et al., 2012)**: 79

- **Laptev Sea**
  - DOC (µM)
  - **Satellite**: < 808
  - **In situ (Le Fouest et al., 2013)**: < 577

- **Kara Sea**
  - DOC (µM)
  - **Satellite**: < 992
  - **In situ (Le Fouest et al., 2013)**: < 465-857
CONCLUSIONS

1. Our inversion algorithm for deriving $a_{\text{CDOM}}(443)$ performs accurately within 35% and 50% errors for oceanic and turbid waters, respectively. Results showed that $a_{\text{CDOM}}(443)$ retrievals for Arctic waters using ocean color data were reasonable compared to *in situ* measurements based on statistics.

2. DOC estimates from space were also reasonable compared to *in situ* measurements.

3. Further evaluation will be made to further confirm the reliability of the $a_{\text{CDOM}}(443)$ and DOC algorithms.
ACKNOWLEDGEMENTS

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Matchup of DOC estimates against in situ measurements during CFL cruise in 2008

[In situ DOC data were provided by M. Gosselin]