# Ocean Colour Remote Sensing in Polar Seas

Atsushi MATSUOKA
(Takuvik Joint International Laboratory)

9-12 April, 2019
IOCS
Busan

# Acknowledgements


- This research is supported by EC NUNATARYUK project (Horizon 2020), Centre Nationale d'Étude Scientifique (CNES), European Space Agency (ESA), Japan Aeronautic Expoloration Agency (JAXA), Centre Nationale Recherche Scientifique (CNRS)/ Université Piérre et Marie Curie (UPMC), Agence Nationale de la Recherche (ANR), European Commission (EC), Natural Sciences and Engineering Research Council of Canada (NSERC), National Science Foundation (NSF), and National Aeronautics of Space Agency (NASA). I thank K. Arrigo and J. Comiso for providing the latest PP estimates and sea ice trend, respectively.

# 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

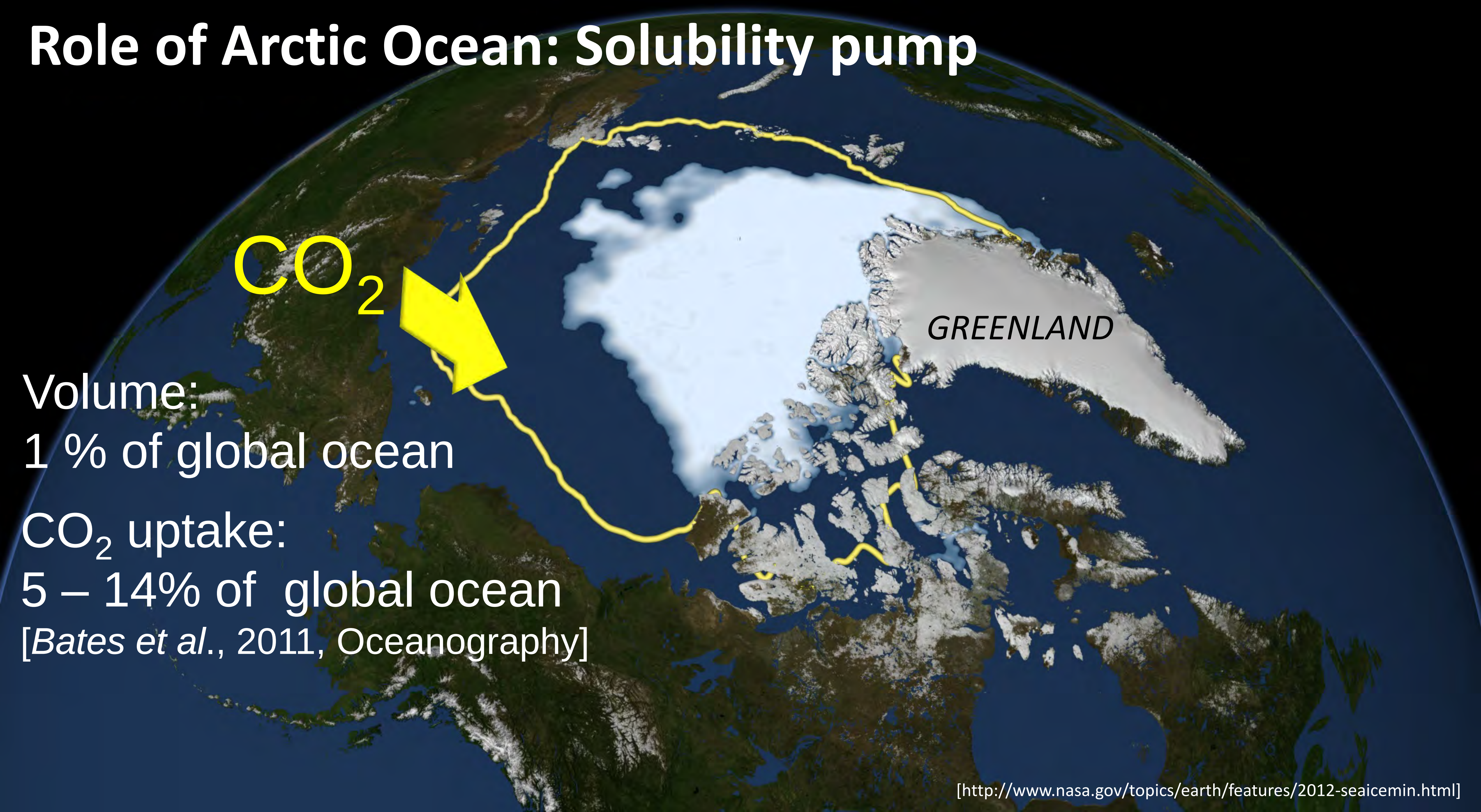
    -Discriminating water sources from space

    -Toward constraining numerical modeling

    -Multi-satellite remote sensing

# 1. Why are studies in polar seas so important?

# Role of Arctic Ocean: Solubility pump




Volume:
1 % of global ocean

$CO_2$ uptake:
5 – 14% of global ocean
[*Bates et al*., 2011, Oceanography]

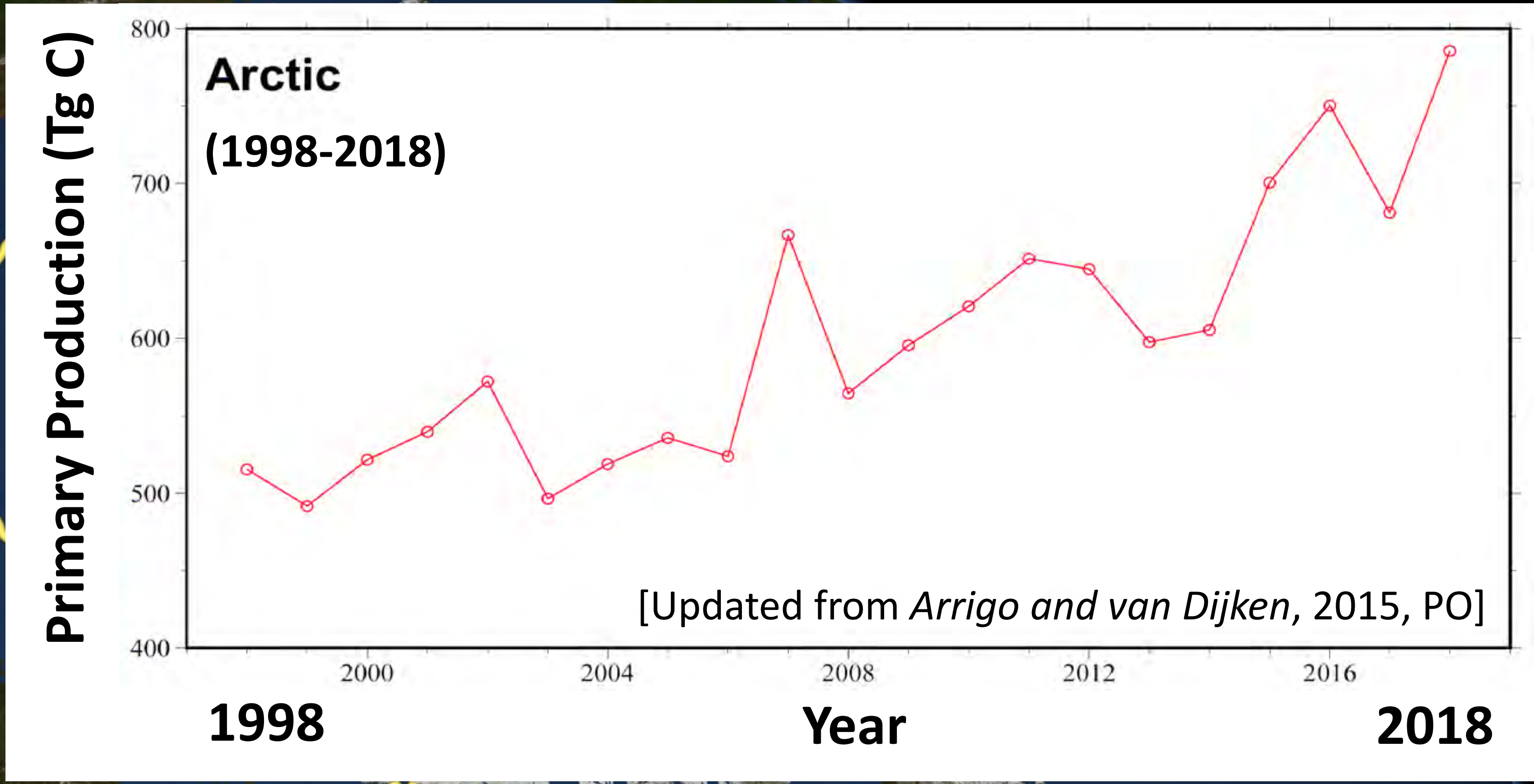
[http://www.nasa.gov/topics/earth/features/2012-seaicemin.html]

# 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]



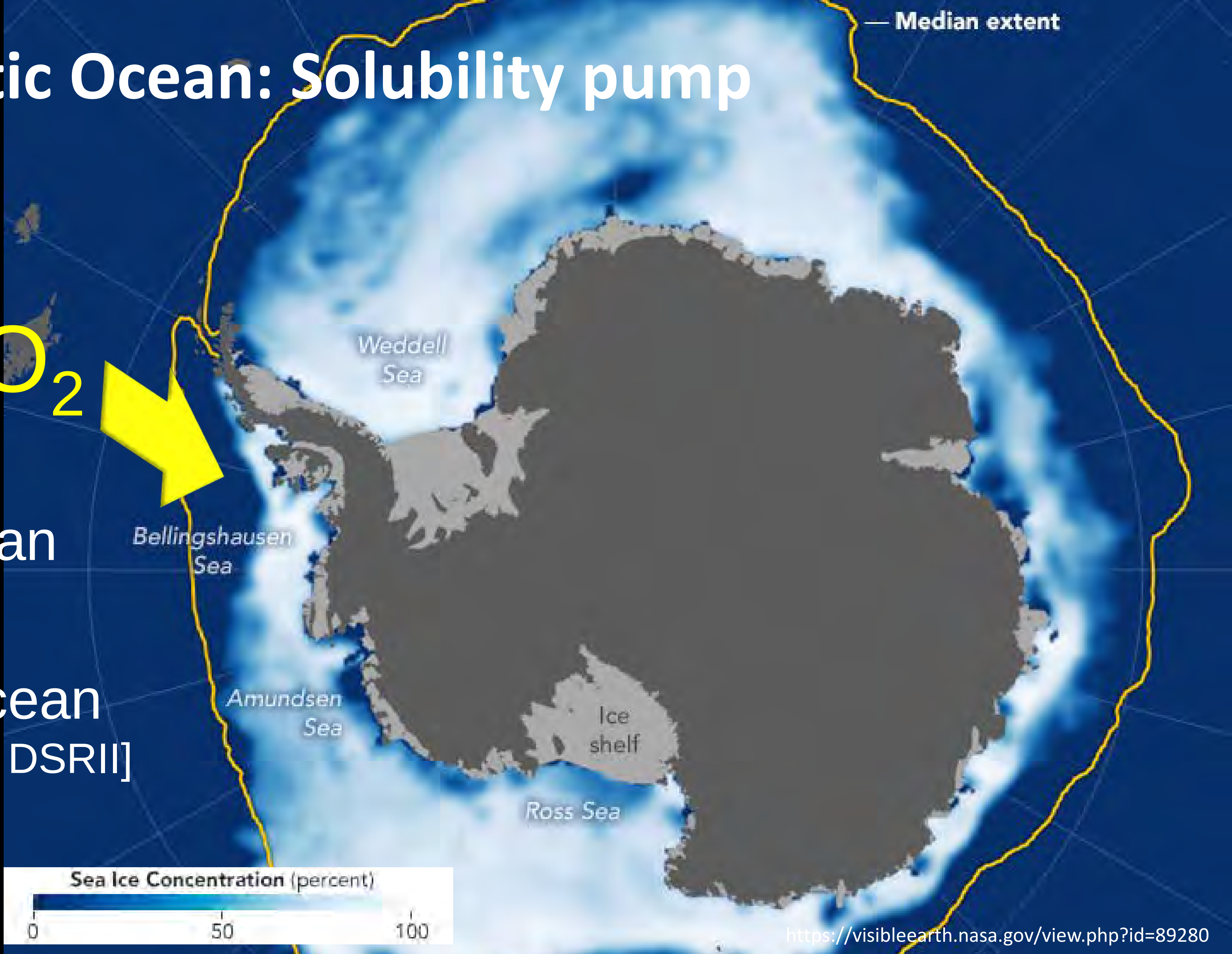

[http://www.nasa.gov/topics/earth/features/2012-seaicemin.html]

# 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]



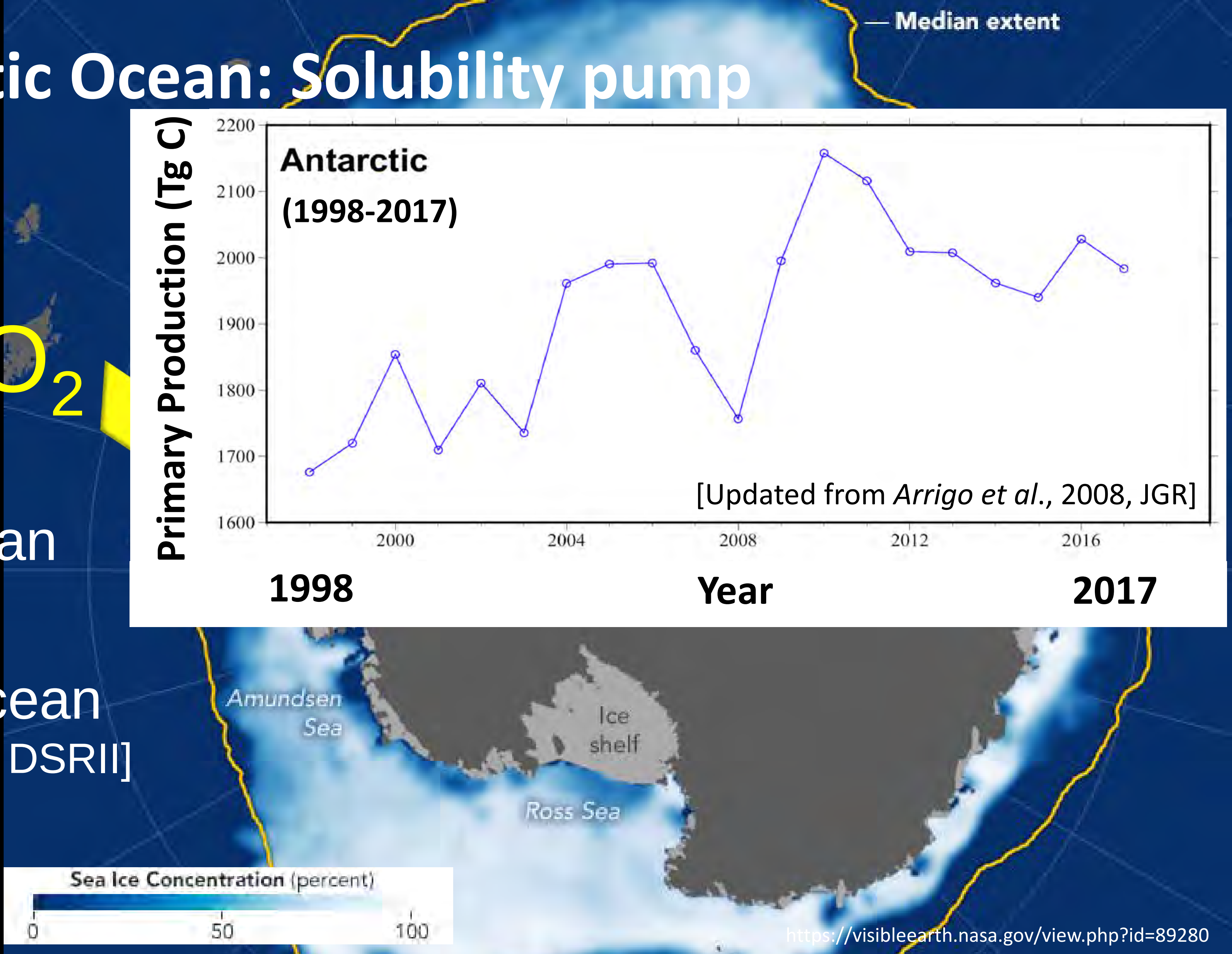

https://visibleearth.nasa.gov/view.php?id=89280

# 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]



# Contributions of polar seas to global $CO_2$ flux

| Contribution | Arctic | Antarctic |
|---|---|---|
| Solubility pump | 5-14 %[1] | 25 %[2,3] |
| Biological pump | 1-2 %[4,5,6,7] | 3 %[3] |
| | | |

[1]Bates et al. (2011, Oceanography); [2]Takahashi et al. (2002, DSRII); [3]Arrigo et al. (2008, JGR); [4]Bélanger et al. (2013, BG); [5]Arrigo and van Dijken (2015, PO); [6]Behrenfeld et al. (2006, Nature); [7]Westberry et al. (2008, GBC)

# Contributions of polar seas to global $CO_2$ flux

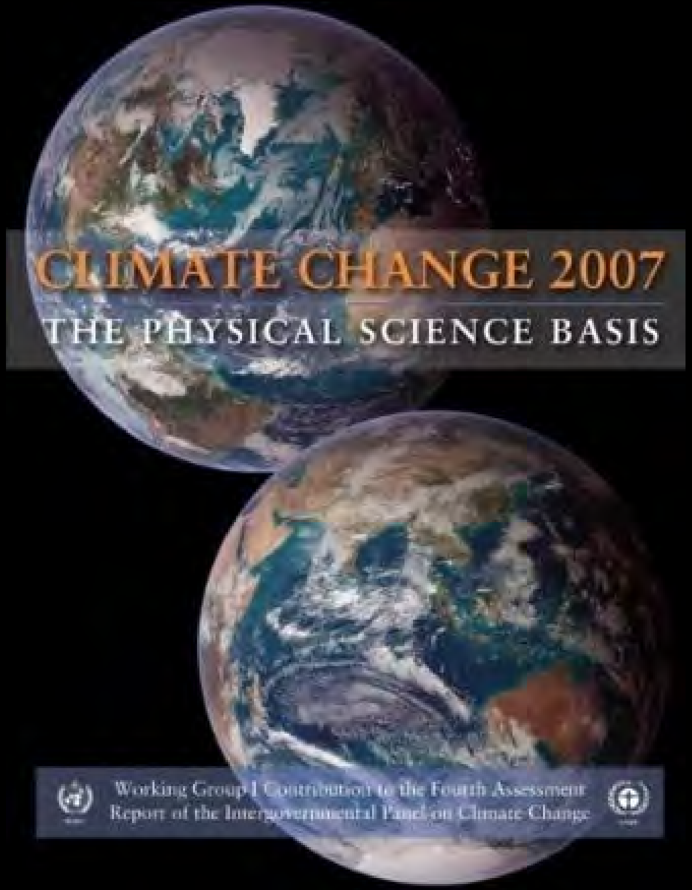
| Contribution | Arctic | Antarctic |
|---|---|---|
| Solubility pump | 5-14 %[1] | 25 %[2,3] |
| Biological pump | 1-2 %[4,5,6,7] | 3 %[3] |
| Terrestrial effect ($CO_2$ release to the atmosphere) |  | - |

[1]Bates et al. (2011, Oceanography); [2]Takahashi et al. (2002, DSRII); [3]Arrigo et al. (2008, JGR); [4]Bélanger et al. (2013, BG); [5]Arrigo and van Dijken (2015, PO); [6]Behrenfeld et al. (2006, Nature); [7]Westberry et al. (2008, GBC)

# 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 $CO_2$?

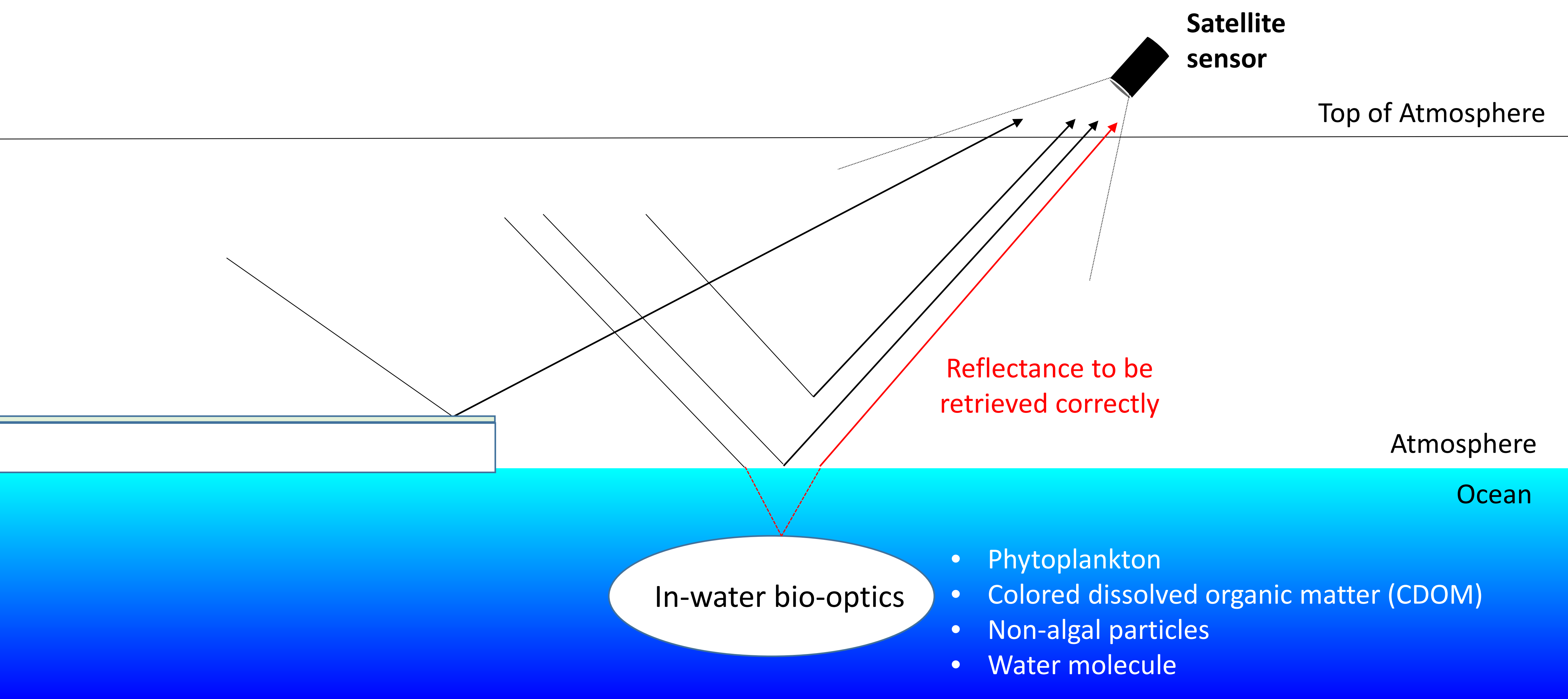



IPCC (2007)


IPCC (2013)

# 2. Ocean colour remote remote sensing in polar seas

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



# Is ocean color useful for polar seas?

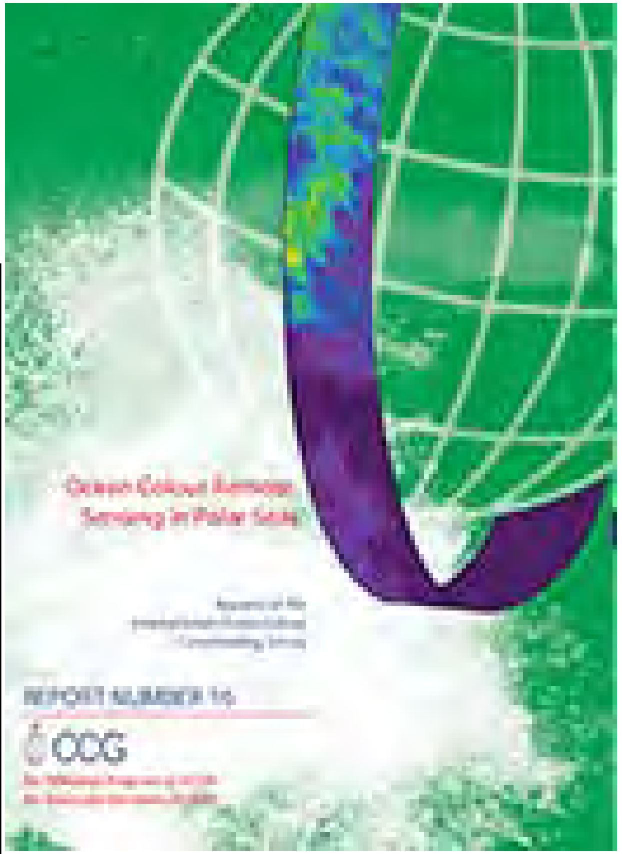
Limitations

- 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)

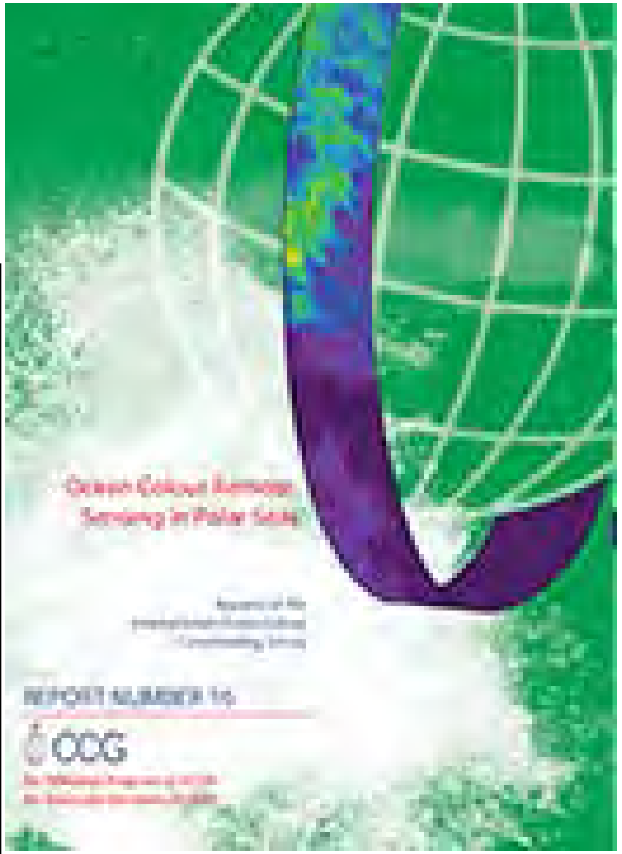


# Is ocean color useful for polar seas?

<u>Limitations</u>

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

IOCCG report (2015)



<u>Usefulness (several overpasses per day)</u>

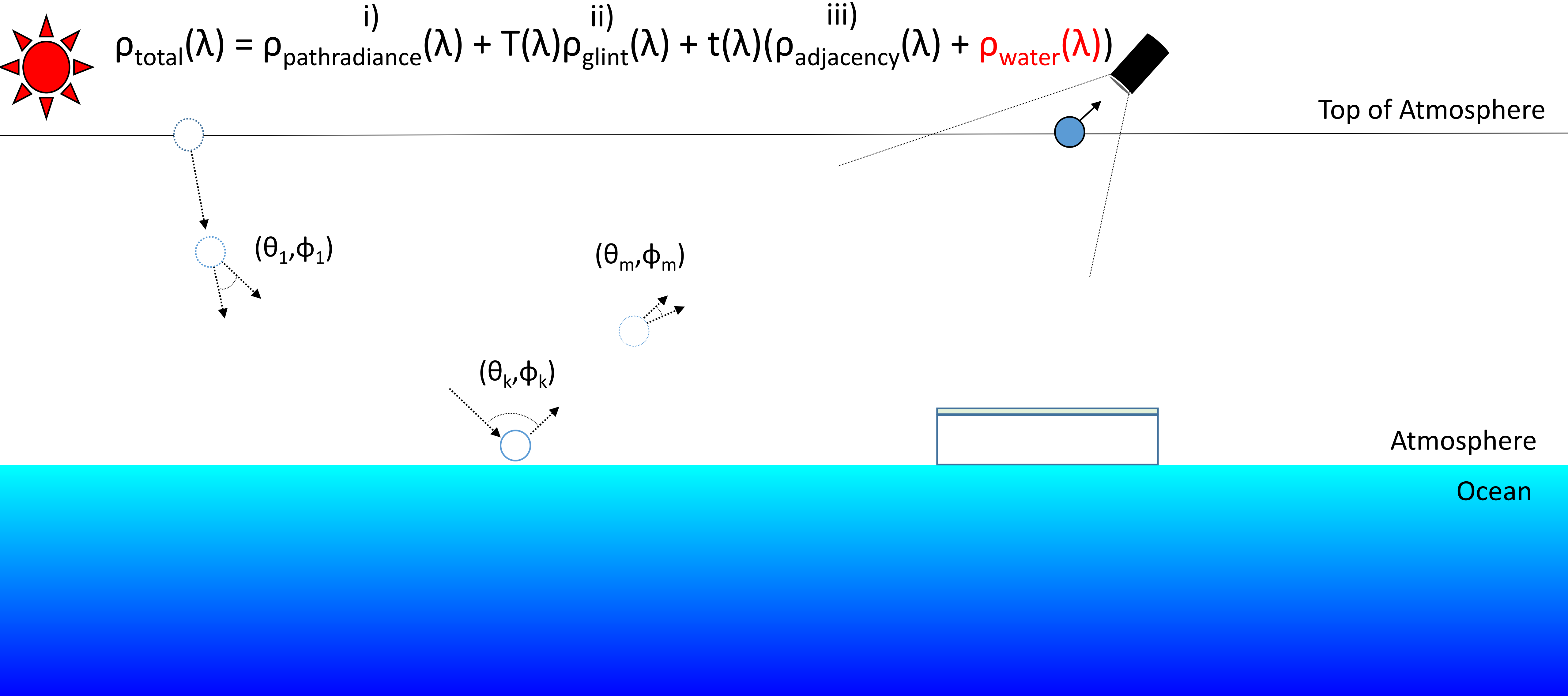
- ➢ Environmental monitoring (e.g., export of permafrost-origin organic matter in coastal waters)
- ➢ Ecosystem studies
- ➢ Risk assessment

# 2. Ocean colour remote remote sensing in polar seas:

## -Evaluating existing atmospheric correction algorithms-

# 3D radiative transfer model simulation using Monte Carlo method

$$\rho_{total}(\lambda) = \overset{i)}{\rho_{pathradiance}}(\lambda) + T(\lambda)\overset{ii)}{\rho_{glint}}(\lambda) + t(\lambda)(\overset{iii)}{\rho_{adjacency}}(\lambda) + \color{red}{\rho_{water}(\lambda)})$$



# Evaluating atmospheric correction algorithms

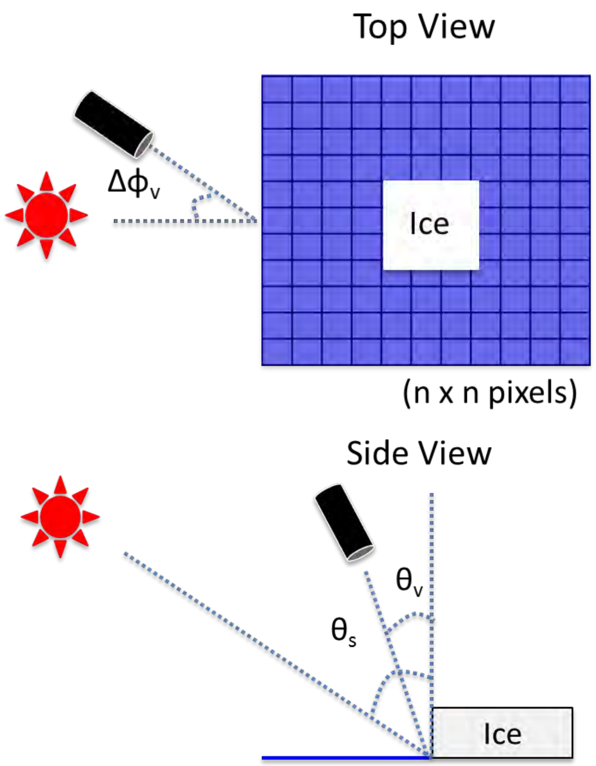
Simulation of $\rho_{total}(\lambda)$ → Application of atmospheric correction to the $\rho_{total}(\lambda)$ → Retrieval of $\rho_{water}(\lambda)$

*Basic*

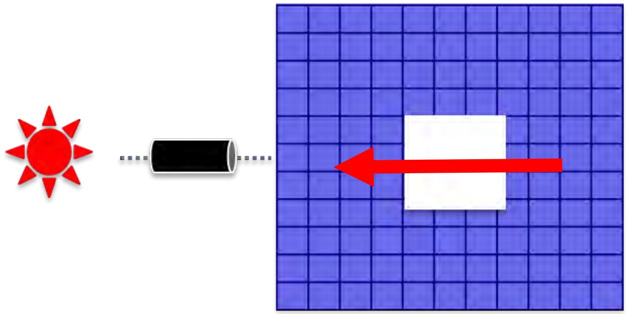
- ✓ Atmosphere-ocean coupled 3-D RT model based on Monte-Carlo method, 3DMCPOL (*Cornet et al*., 2010, JQSRT) was used.
- ✓ Ocean component is based on 6S RT.
- ✓ The number of photons used per pixel was 3.0 x $10^5$ for 51x51 pixels in order to have an uncertainty of $\rho_{TOA}(\lambda)$ less than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

*Setting*

- ✓ Solar zenith was set to be 50º (a typical value for polar regions) but $\theta_v$ and $\Delta\varphi$ 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

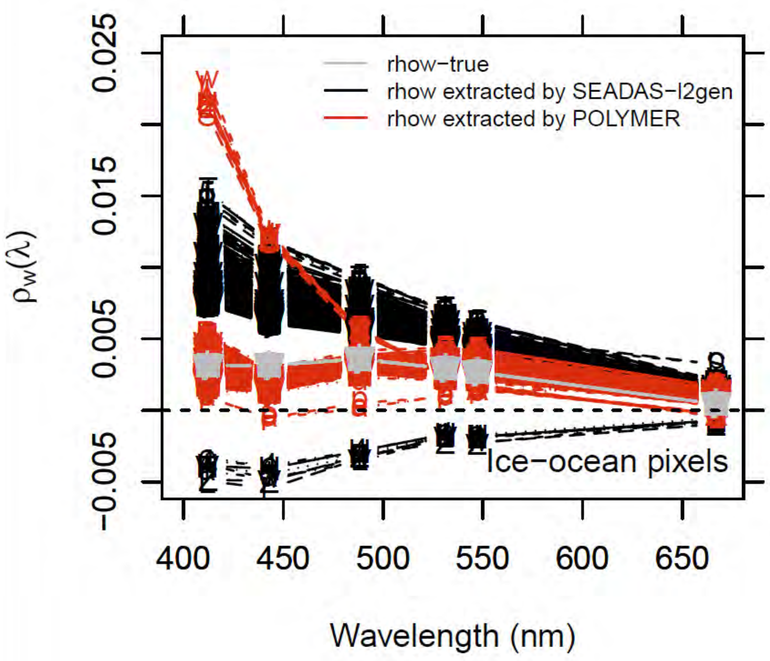


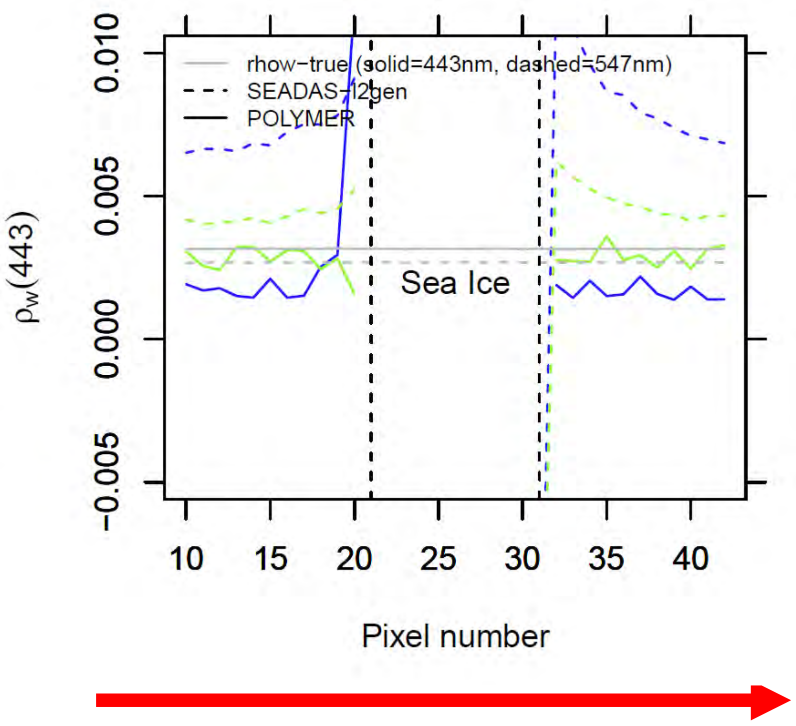
**Example ($\theta_s$ = 50°, $\theta_v$ = 30°, $\Delta\phi$ = 0°)**

True : Known (simulation)

Red : POLYMER algorithm [*Steinmetz et al.*, 2011, OE]

Black : NASA standard algorithm [*Bailey et al.*, 2010, OE]

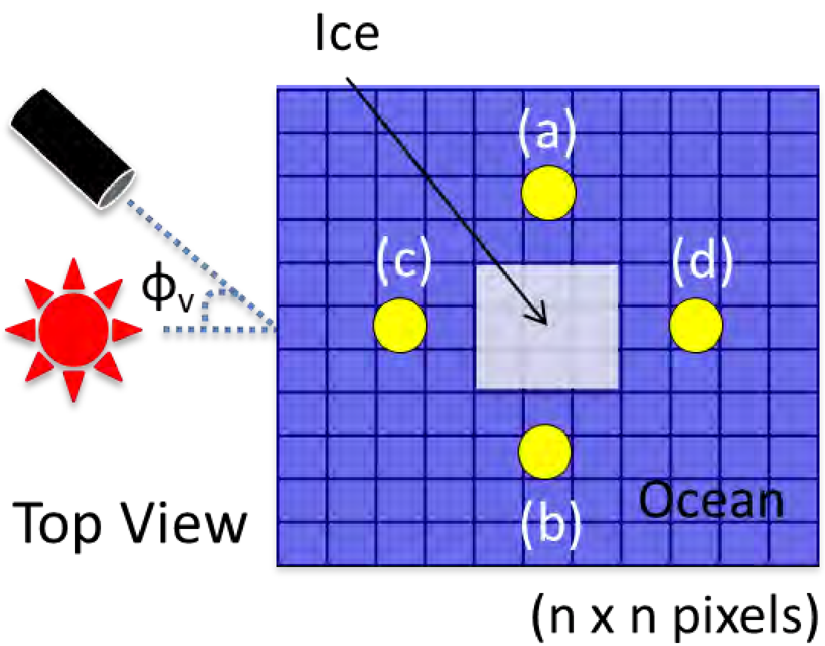


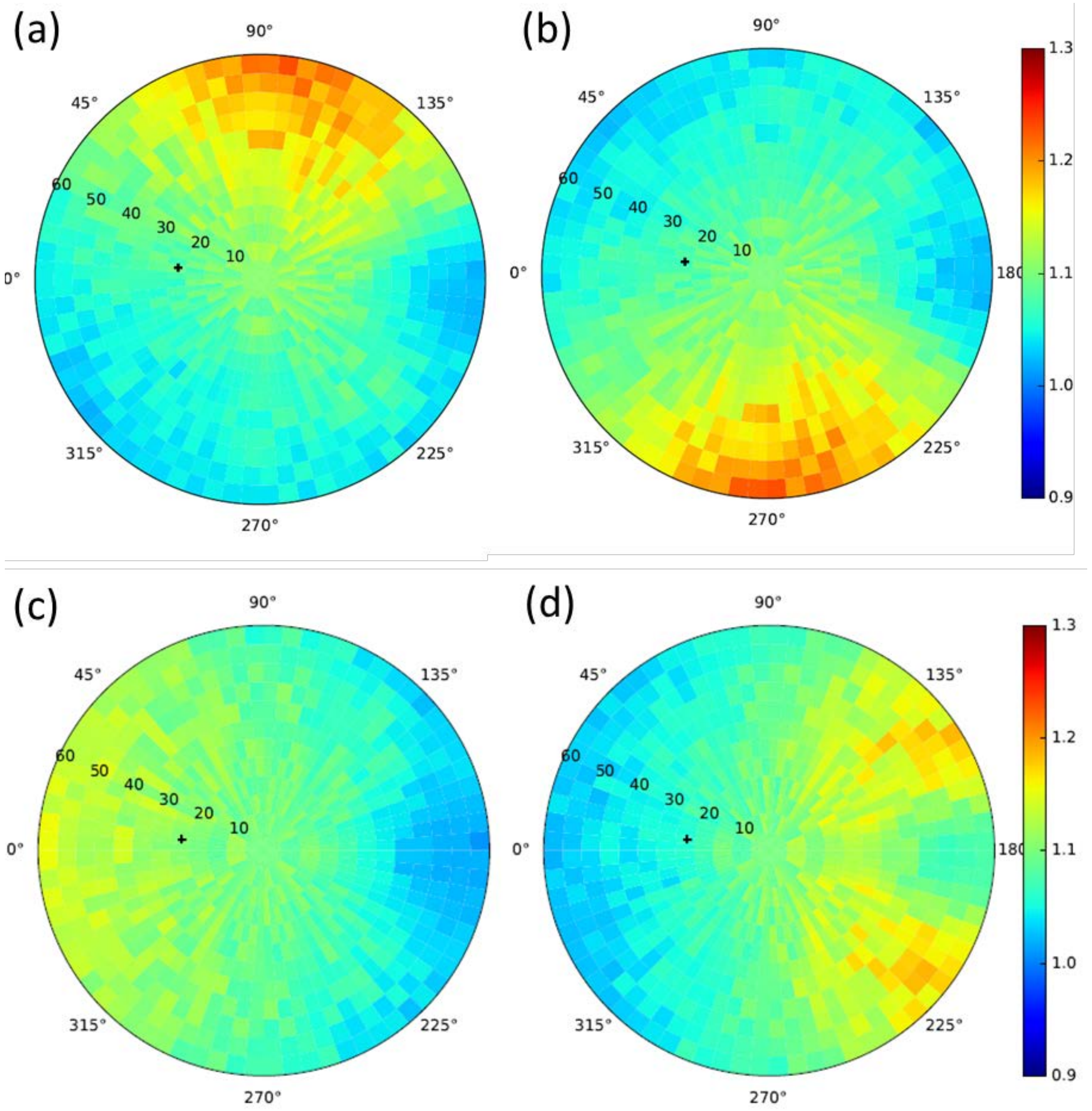




[*Matsuoka et al.*, in prep.]

# Bidirectionality of normalized $\rho_{TOA}(\lambda)$

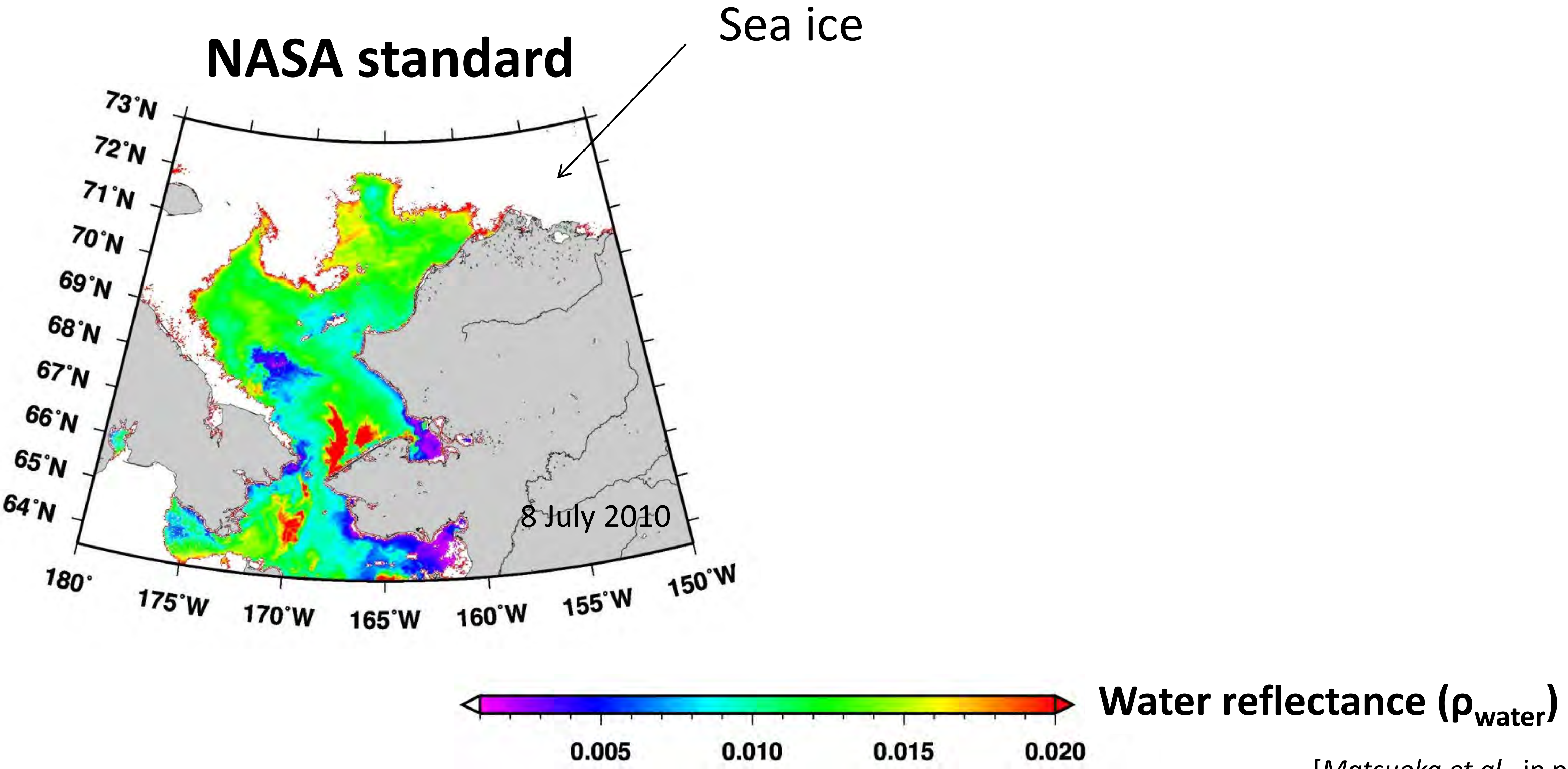
$$\rho^{nor}(\theta_v, \Delta\varphi) = \frac{\rho^{TOA}_{near-ice}(\theta_v, \Delta\varphi)}{\rho^{TOA}_{ocean}(\theta_v, \Delta\varphi)}$$



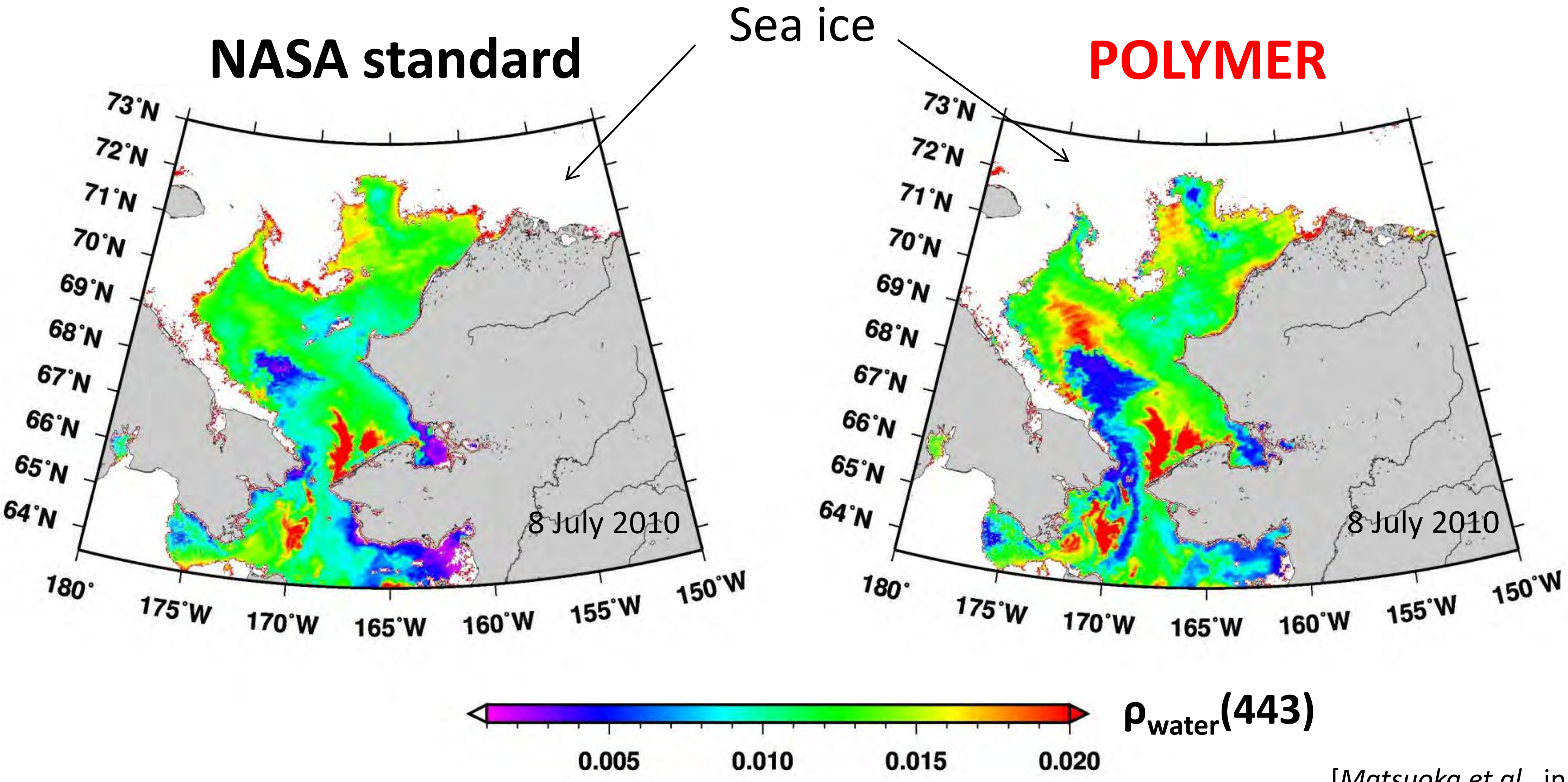

[*Matsuoka et al.*, in prep.]

## Application of atmospheric correction algorithms to Aqua/MODIS satellite image




[*Matsuoka et al.*, in prep.]

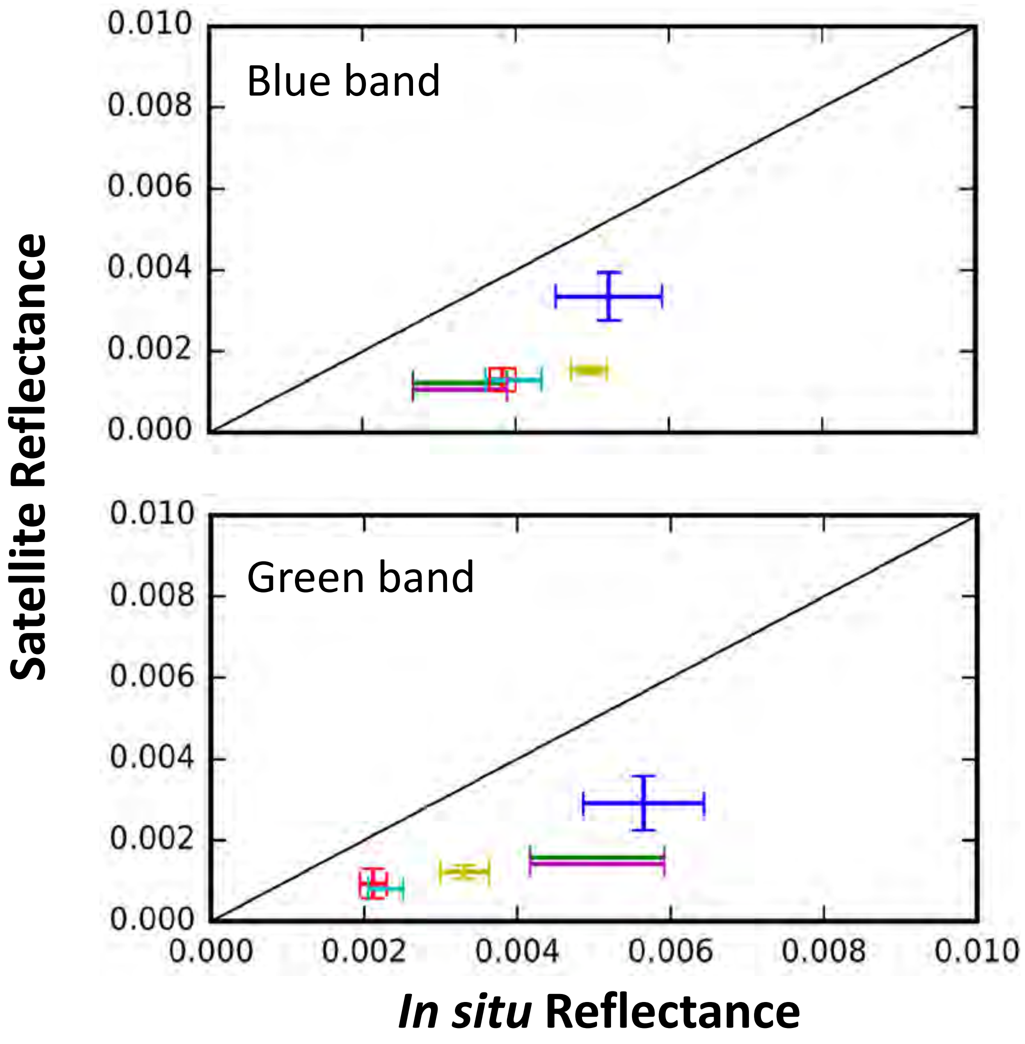
## Application of atmospheric correction algorithms to Aqua/MODIS satellite image




[*Matsuoka et al.*, in prep.]

# Direct comparison between *in situ* and satellite estimates within 3 hours (i.e., NASA protocols)

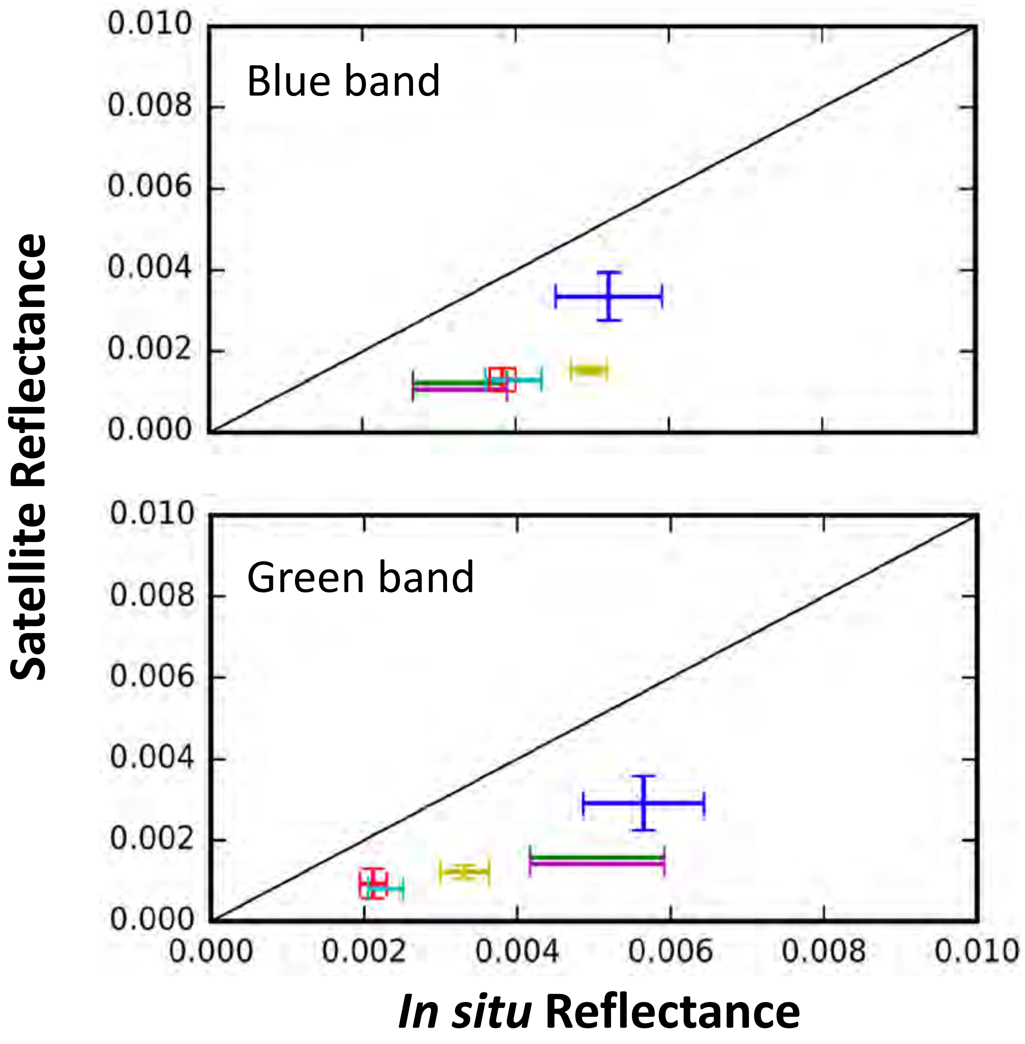
## NASA standard



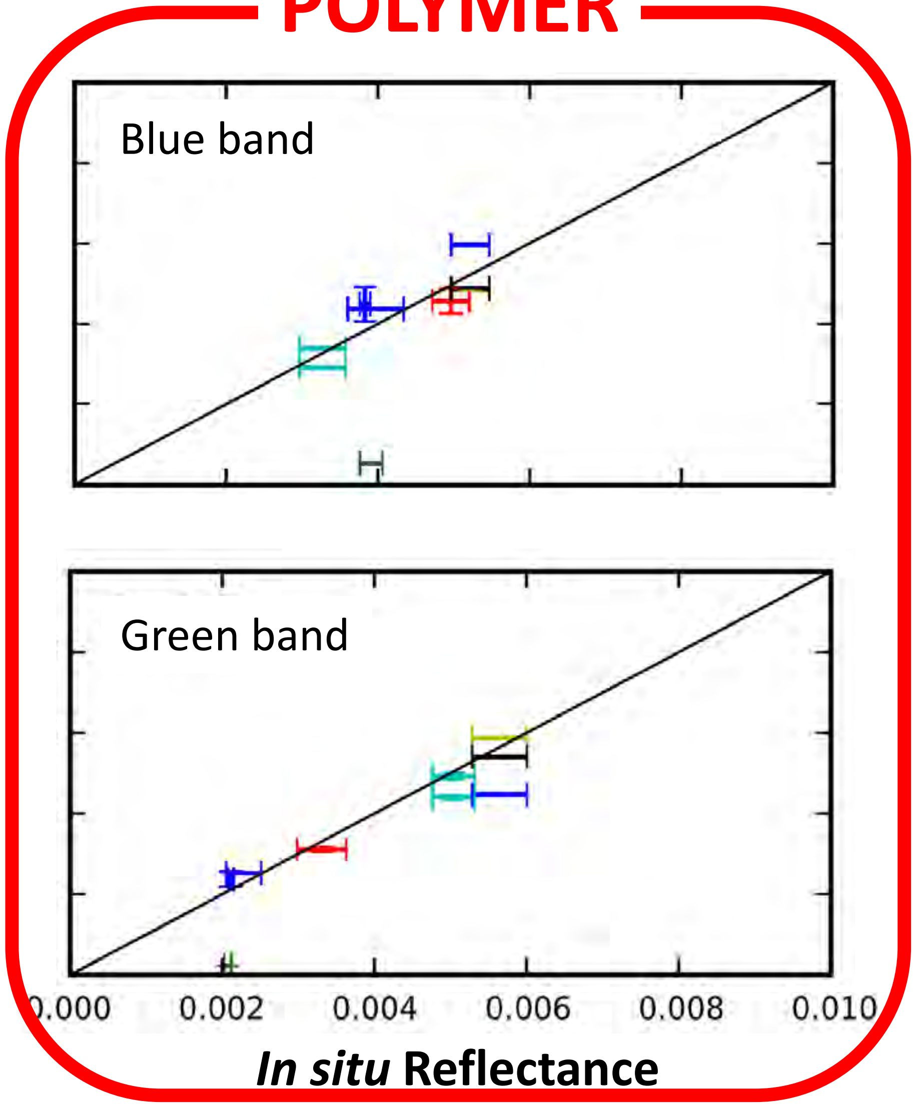

[*Matsuoka et al.*, in prep.]

# Direct comparison between *in situ* and satellite estimates within 3 hours (i.e., NASA protocols)

## NASA standard




## POLYMER



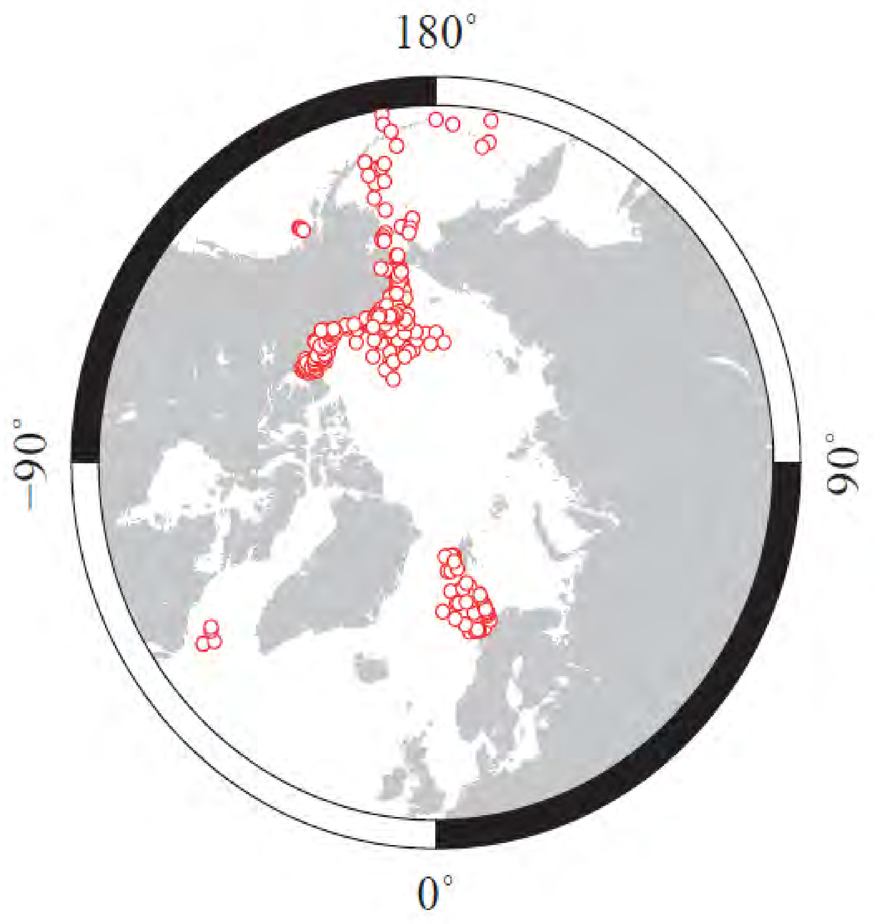

[*Matsuoka et al.*, in prep.]

# 2. Ocean colour remote remote sensing in polar seas:

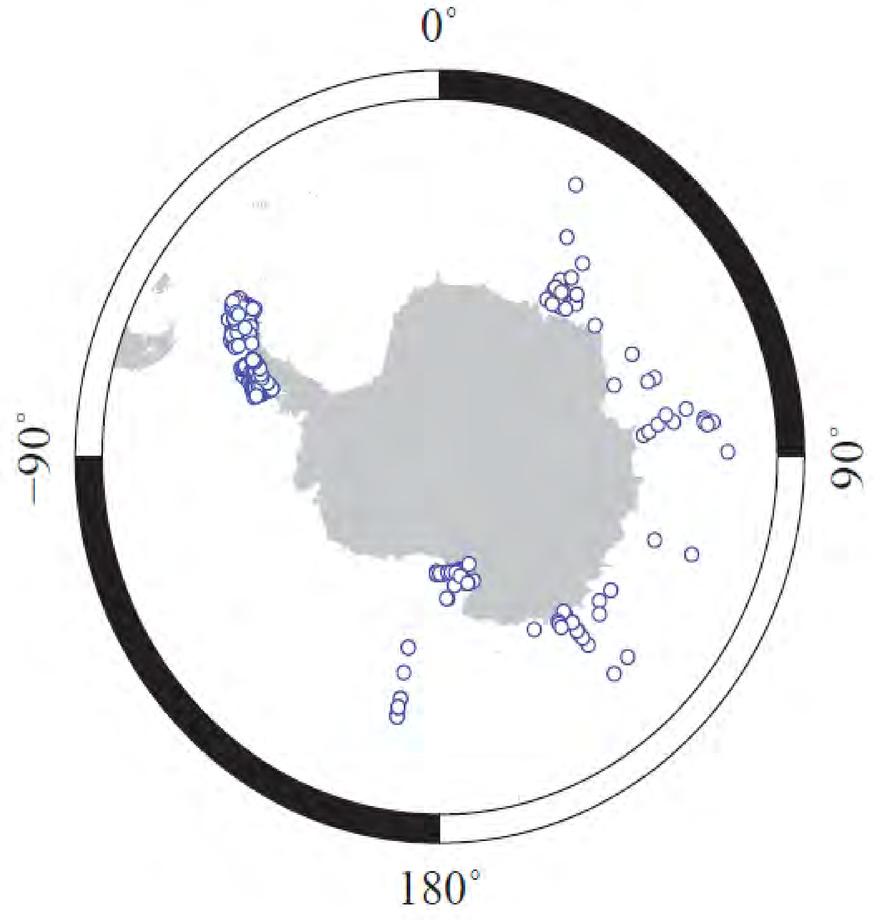
# In-water optical properties

# Optical dataset

## Arctic

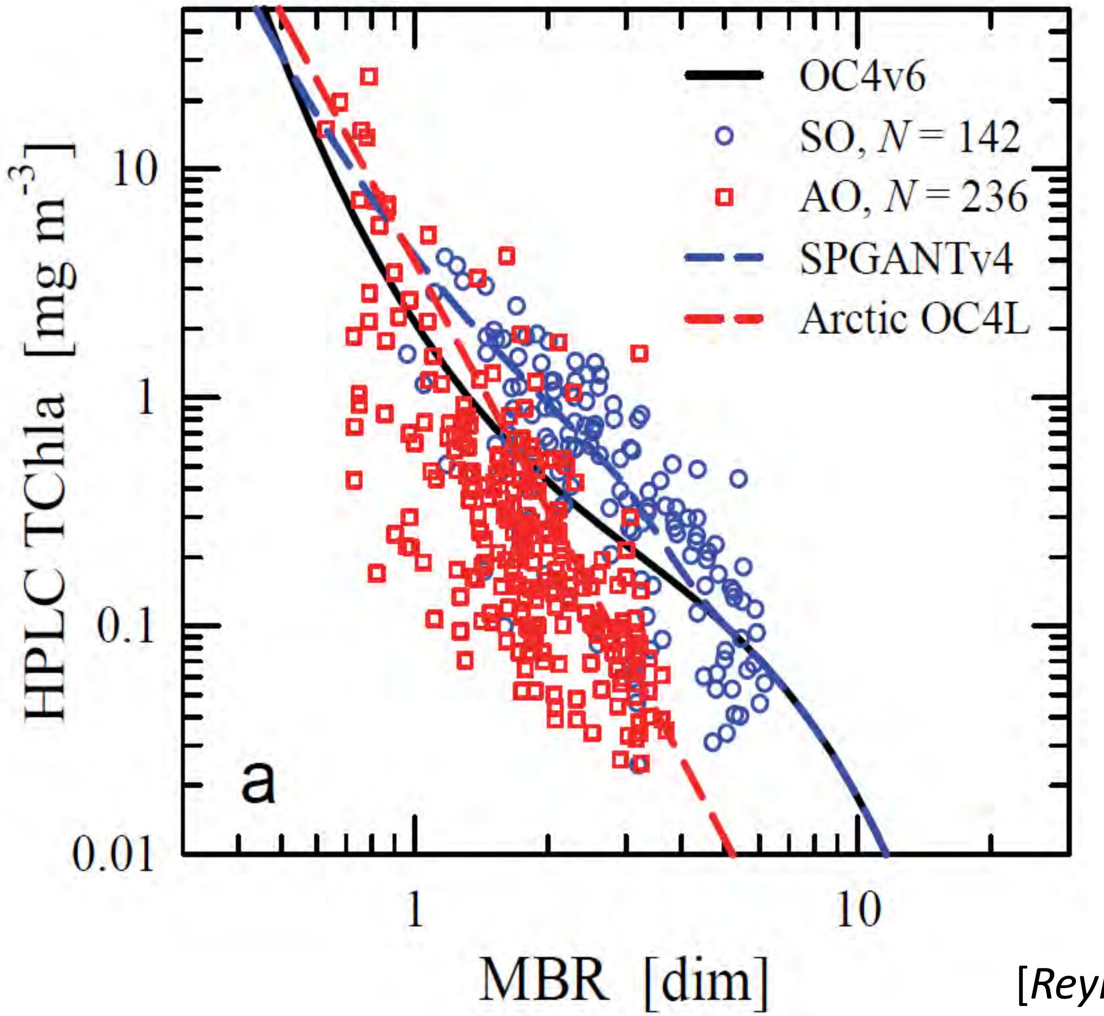



## Antarctic



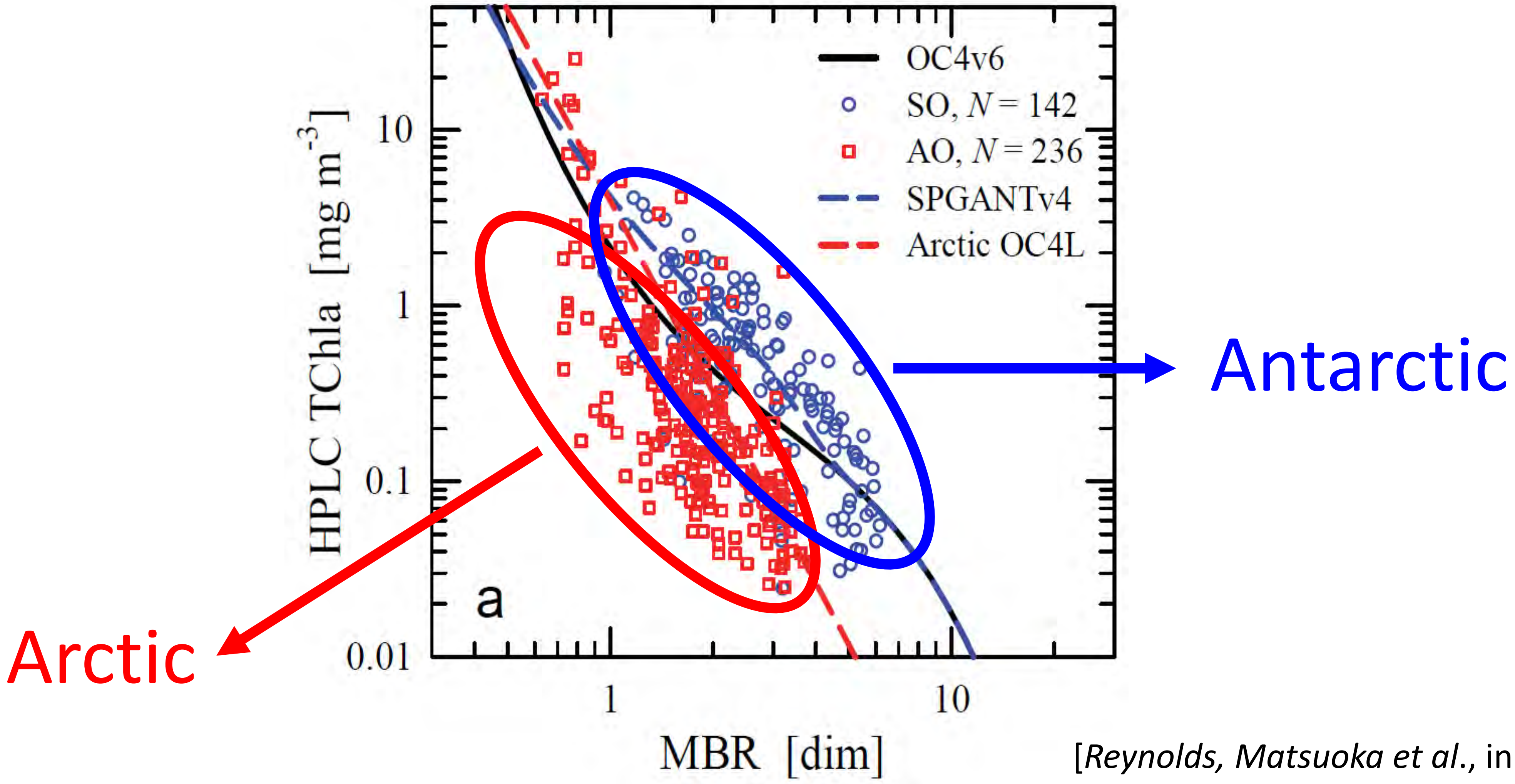

[*Reynolds, Matsuoka et al.*, in IOCCG2015]

# Estimates of chlorophyll *a* concentration: Deviations from the global relationship



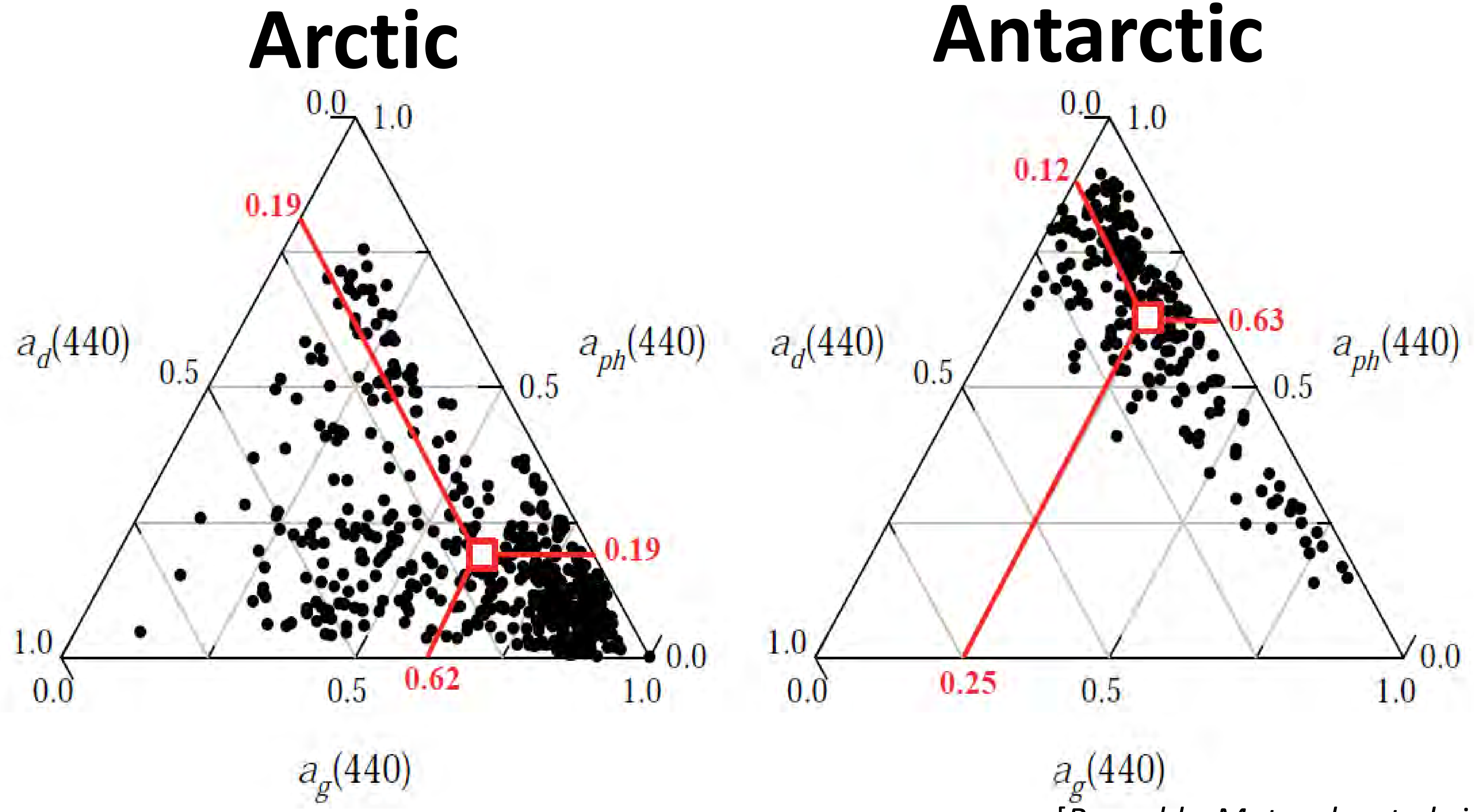

[*Reynolds, Matsuoka et al.*, in IOCCG2015]

# Estimates of chlorophyll *a* concentration: Deviations from the global relationship



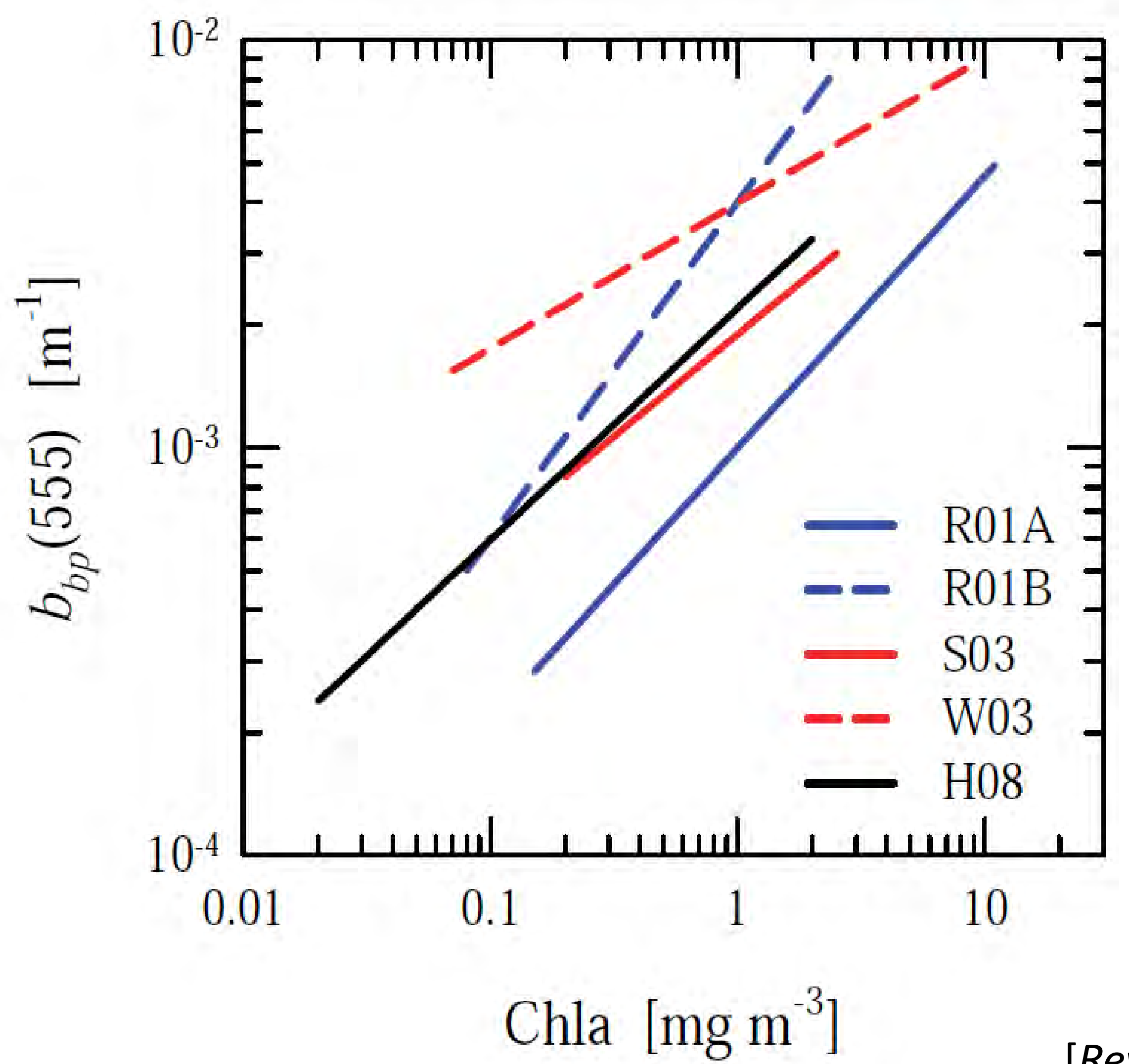

[*Reynolds, Matsuoka et al.*, in IOCCG2015]

# Absorption



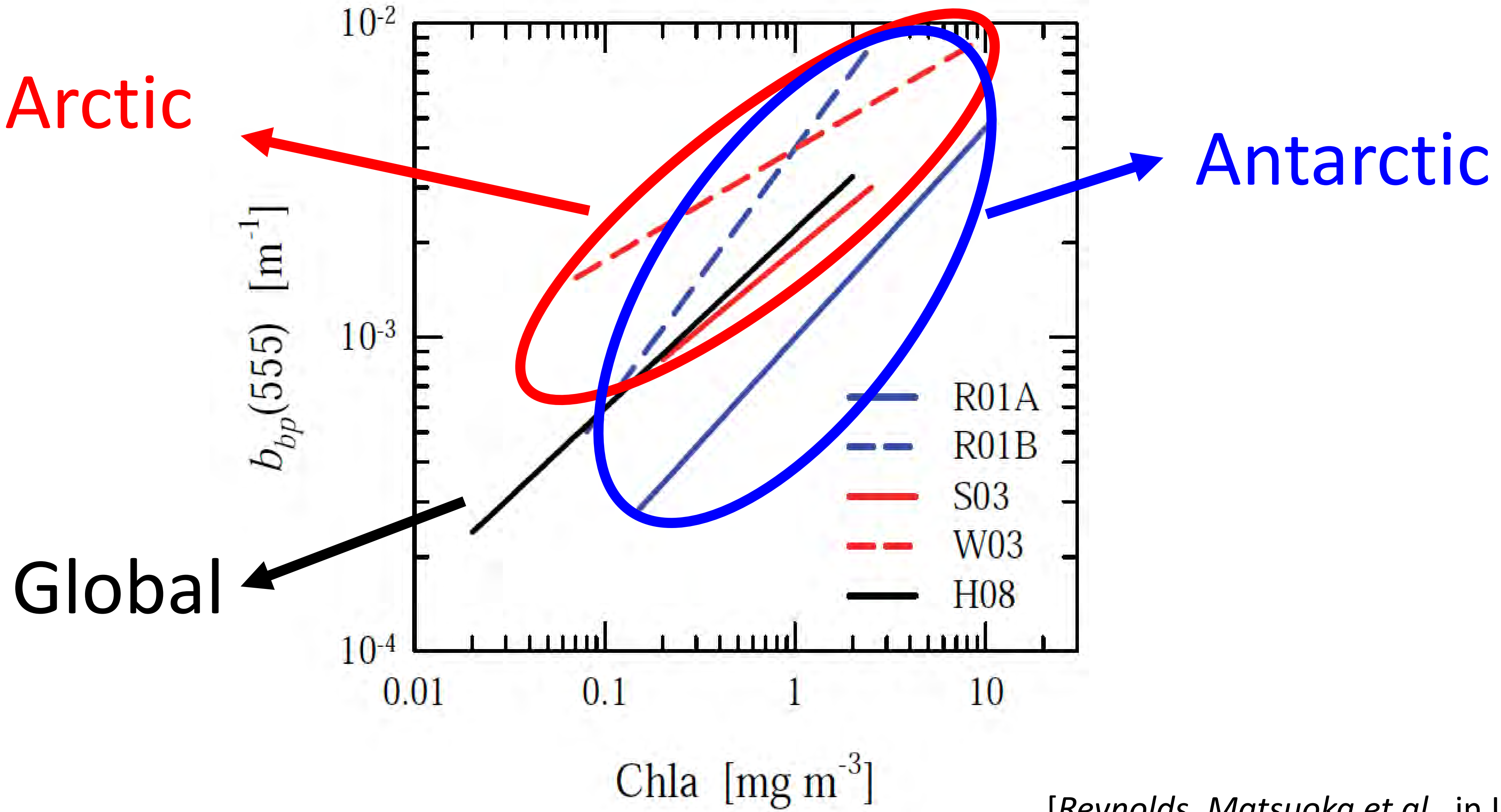

[*Reynolds, Matsuoka et al.*, in IOCCG2015]

# Backscattering



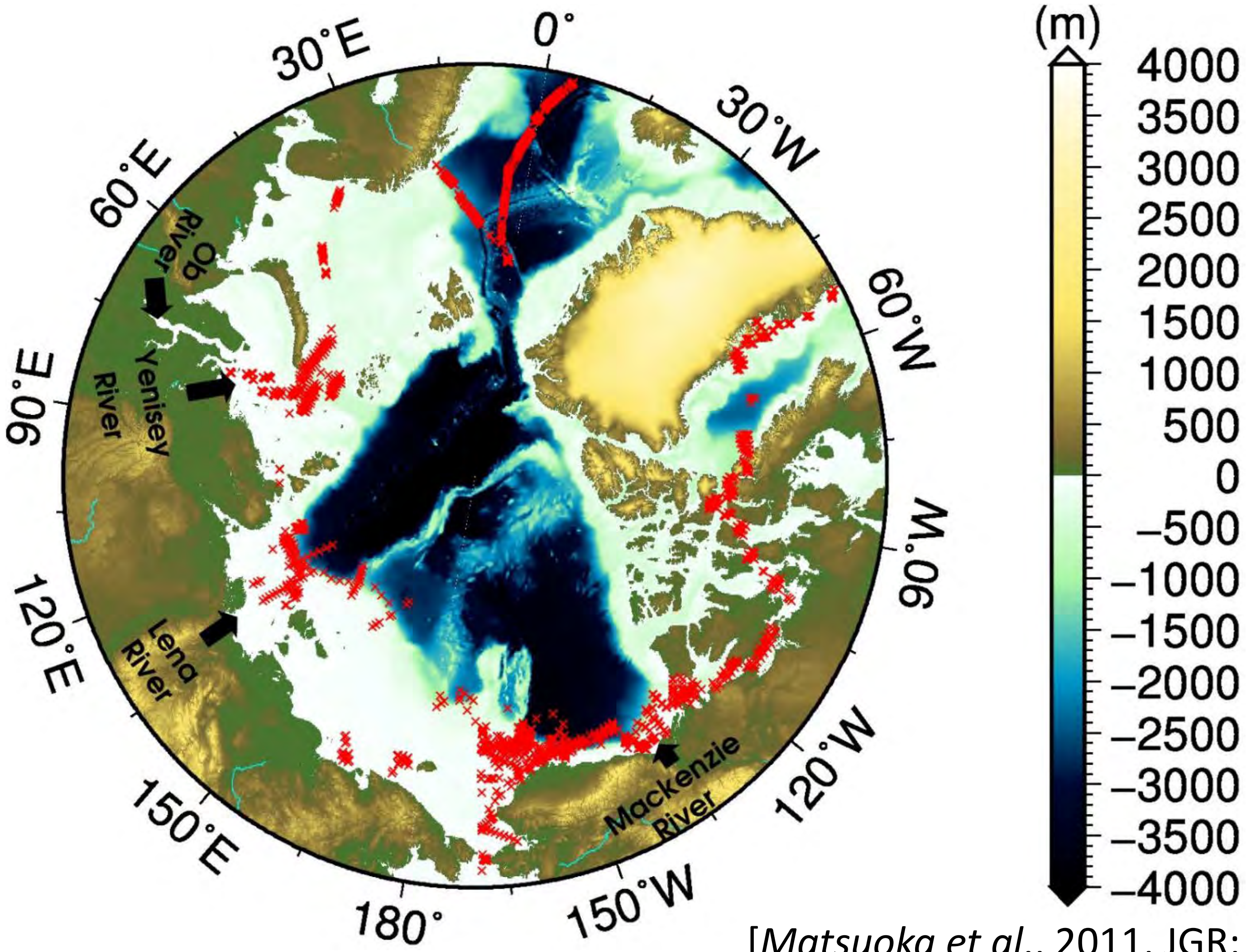

[*Reynolds, Matsuoka et al.*, in IOCCG2015]

# Backscattering




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

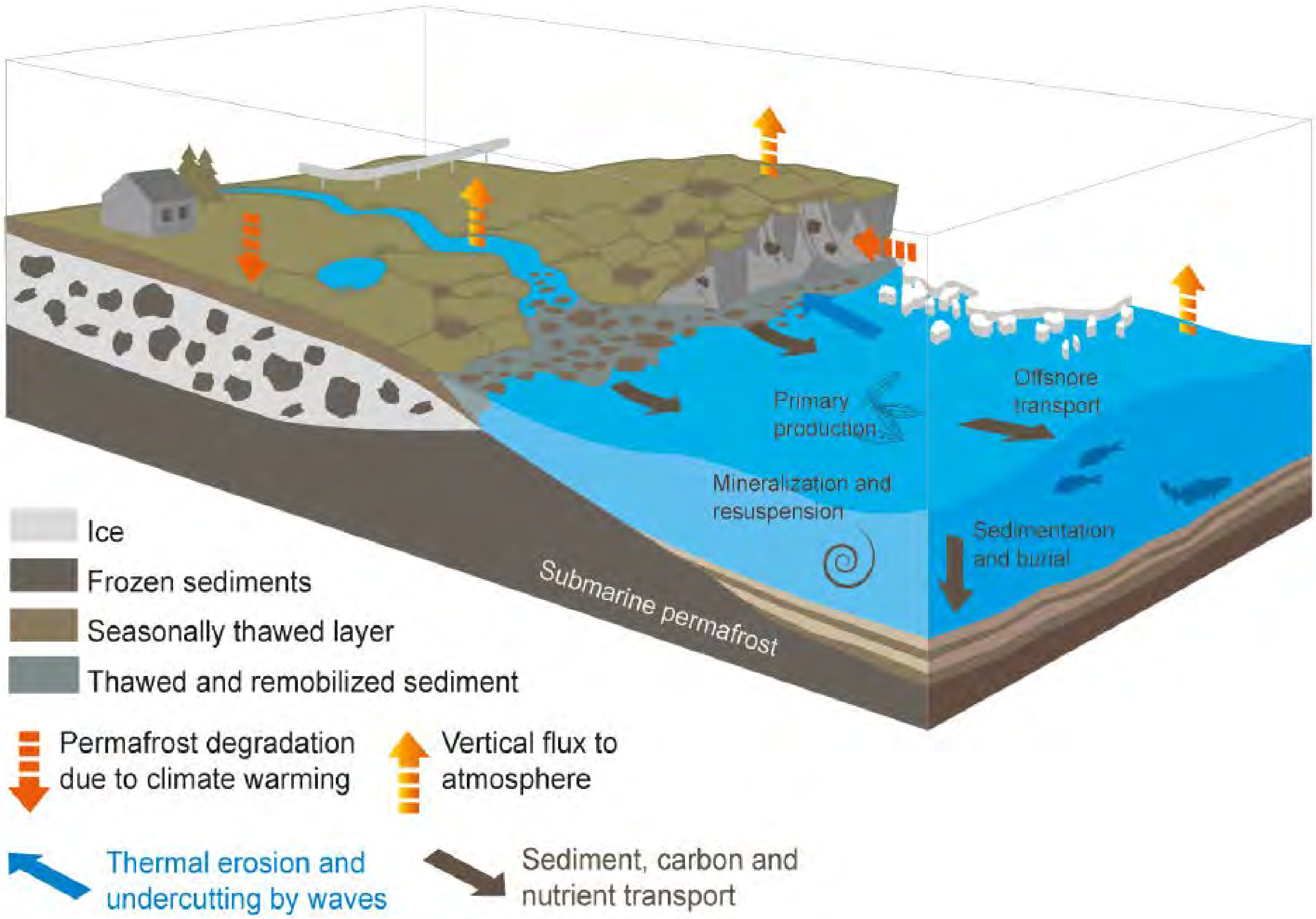
# Compilation of available optical datasets




[*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

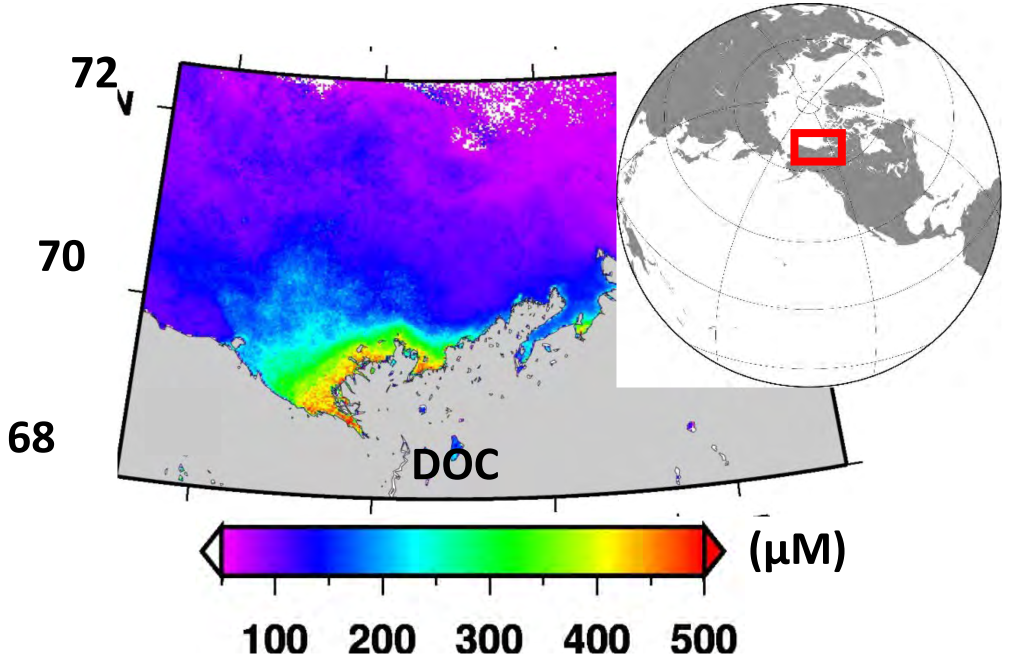


# DOC and POC algorithms

- **DOC concentration (*Matsuoka et al.*, 2017, RSE)**

**Uncertainty: ±28 %**

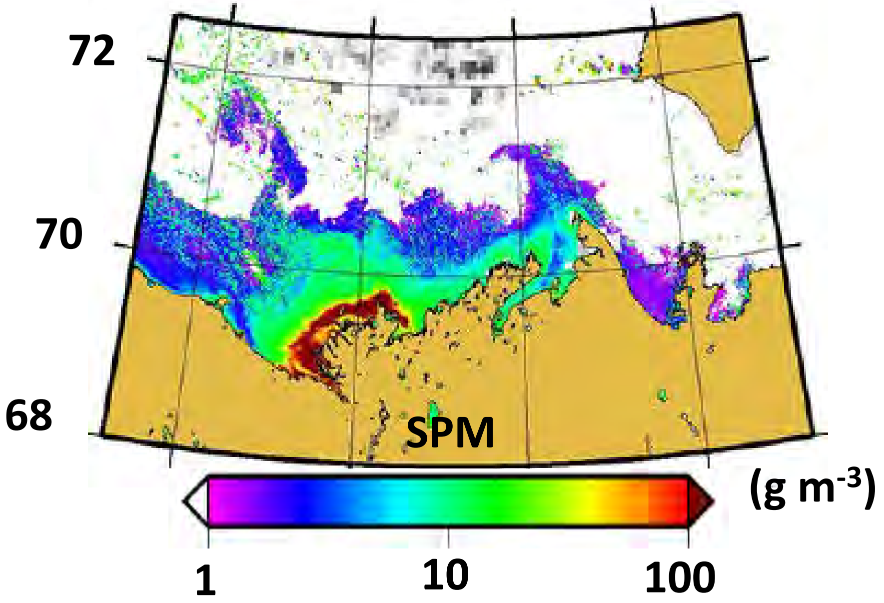
- Semi-analytical algorithm
- Applicable for river-influenced coastal areas of the Artic Ocean



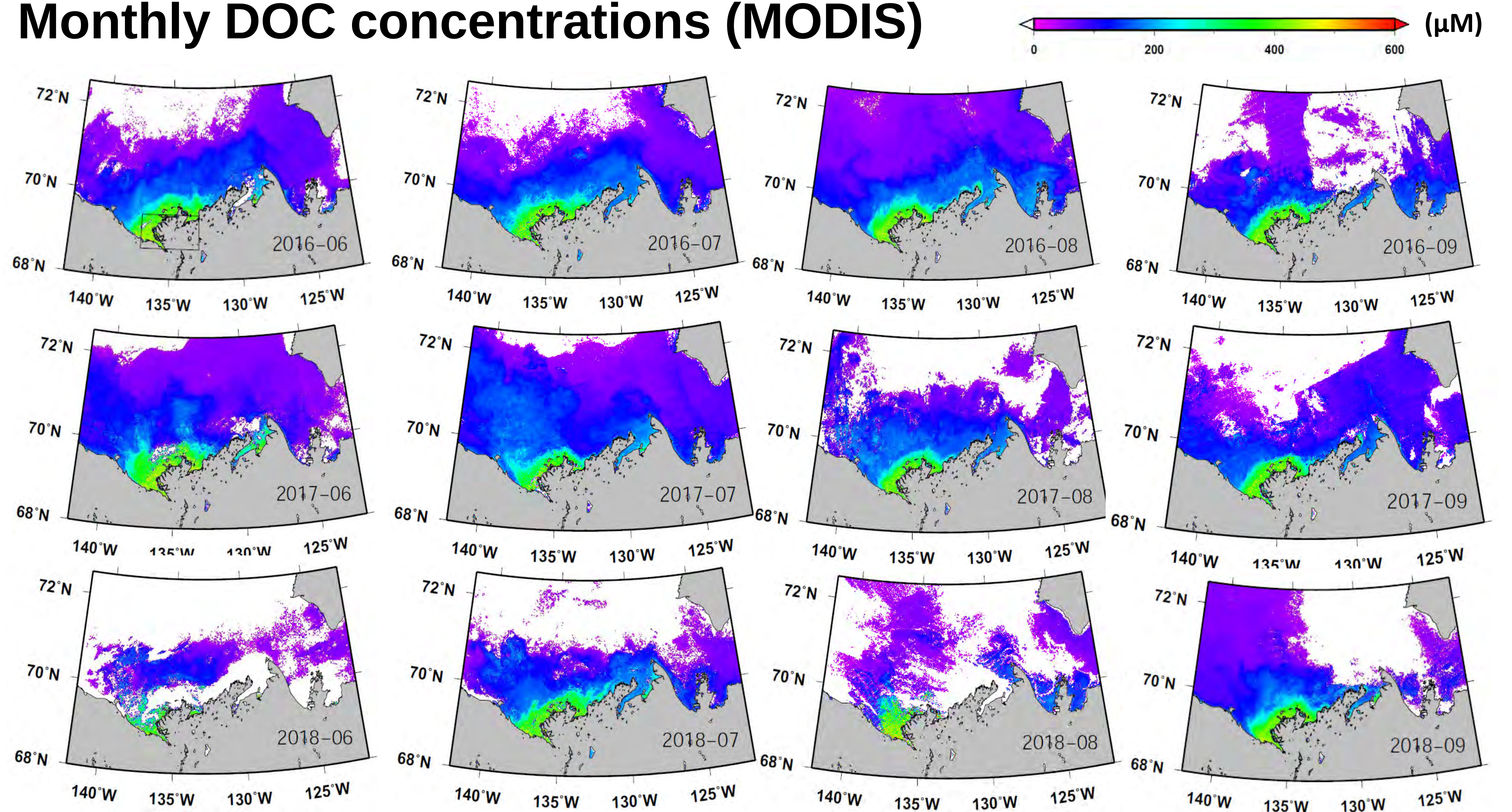

- **SPM/POC concentration (After *Doxaran et al.*, 2015, BG)**

**Uncertainty: ±35 %**

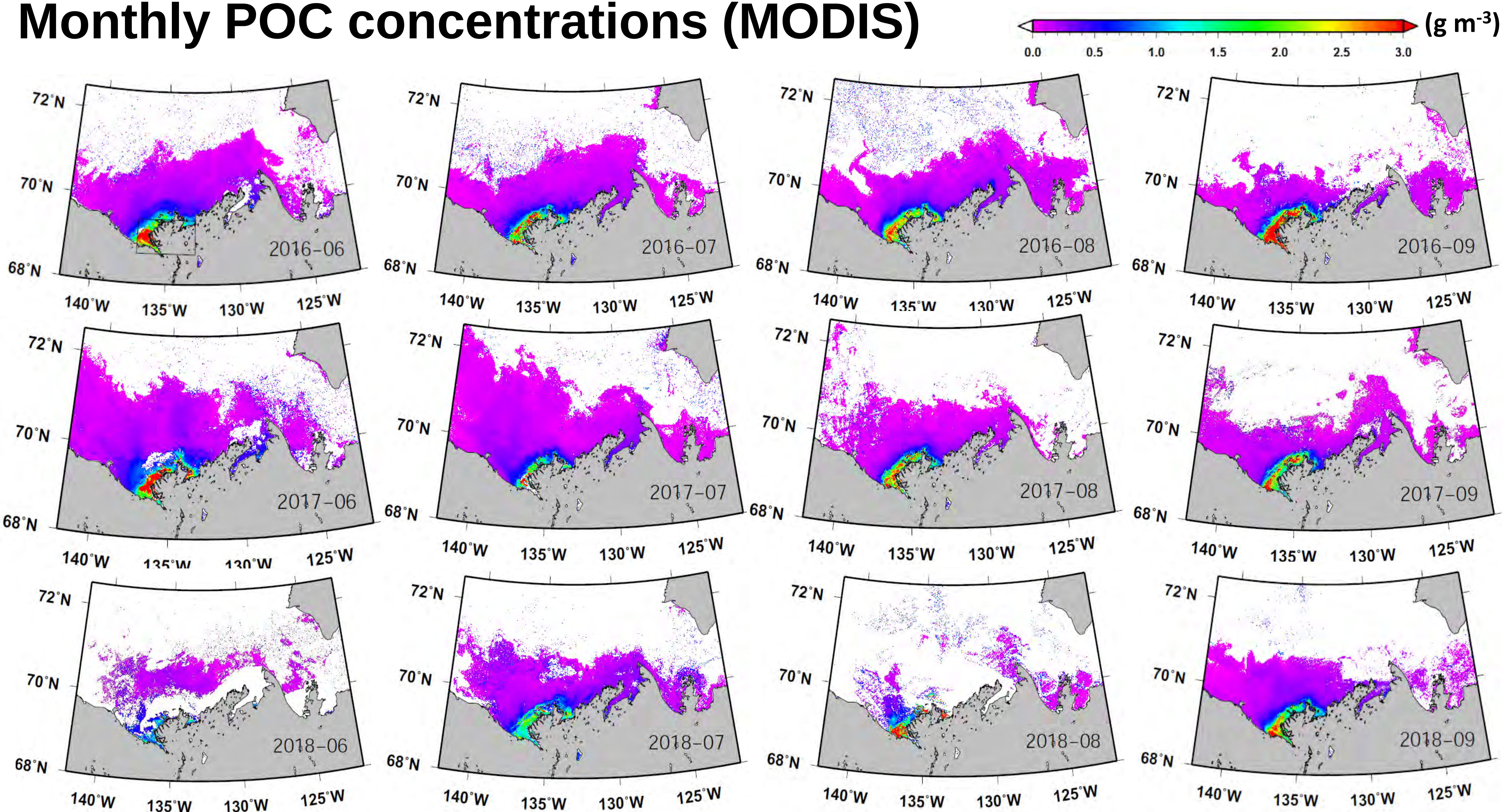
- Empirical algorithm
- Designed for Southern Beaufort sea but can be tuned for other Arctic coastal areas



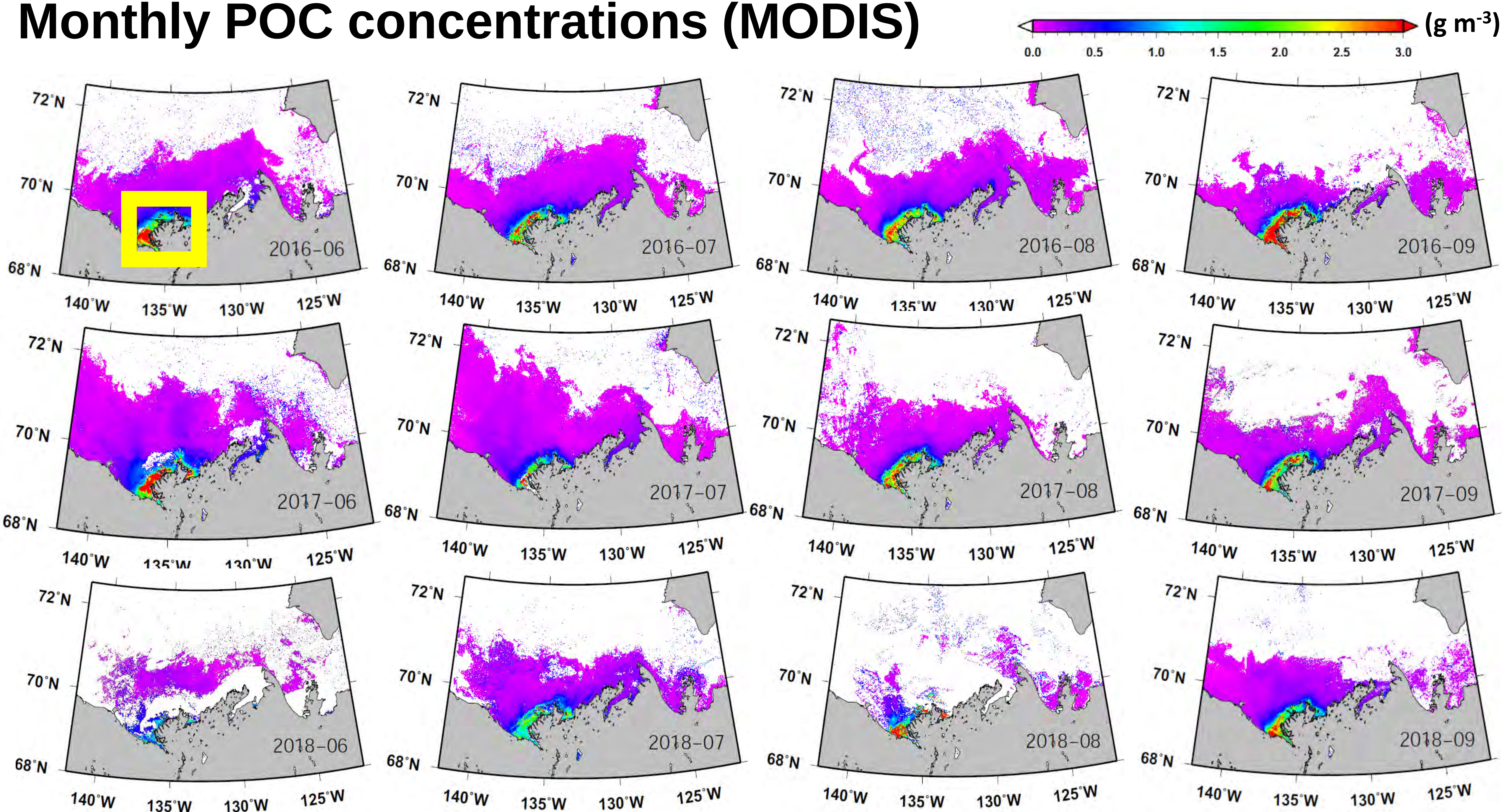
# Monthly DOC concentrations (MODIS)



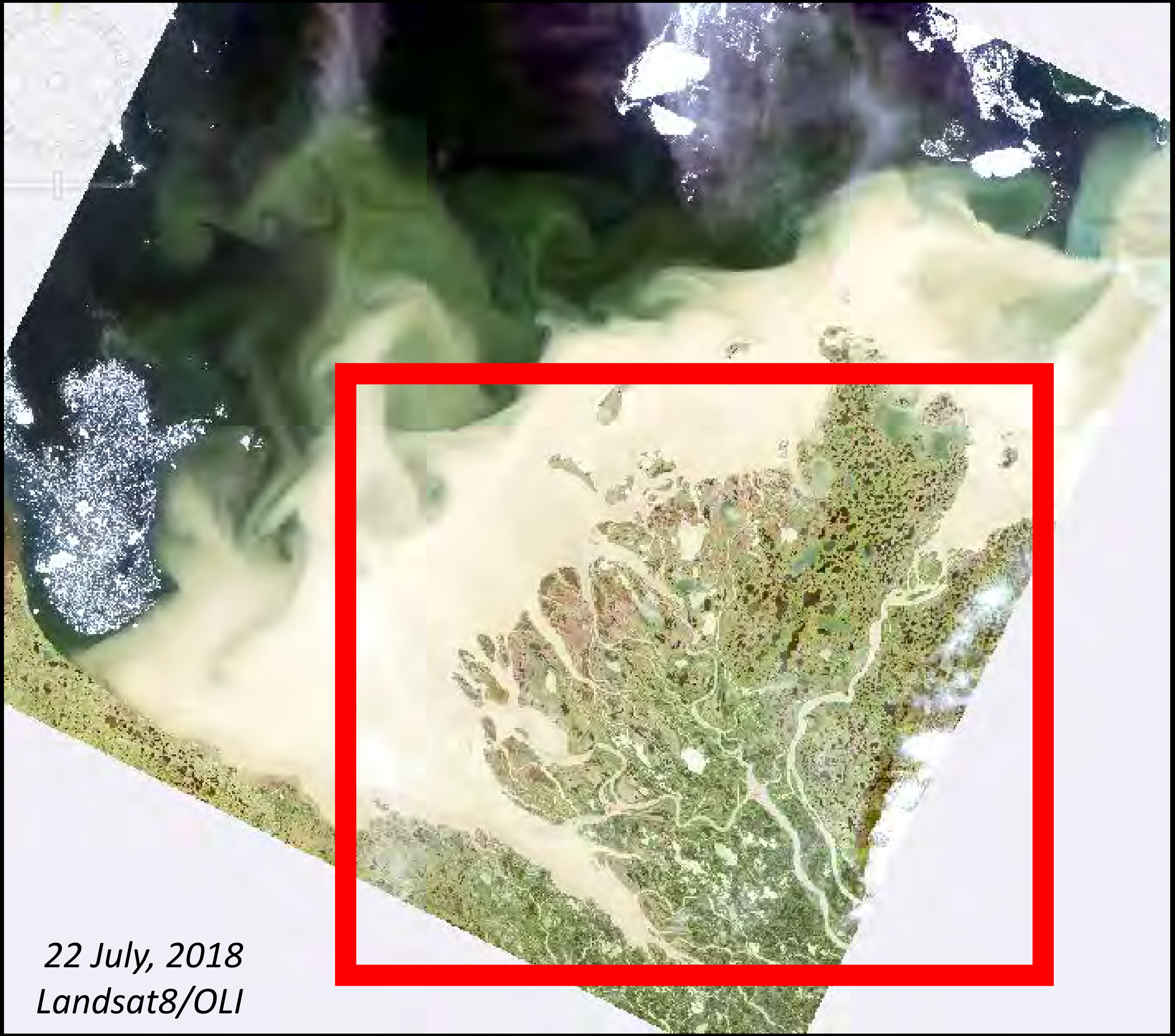
# Monthly POC concentrations (MODIS)



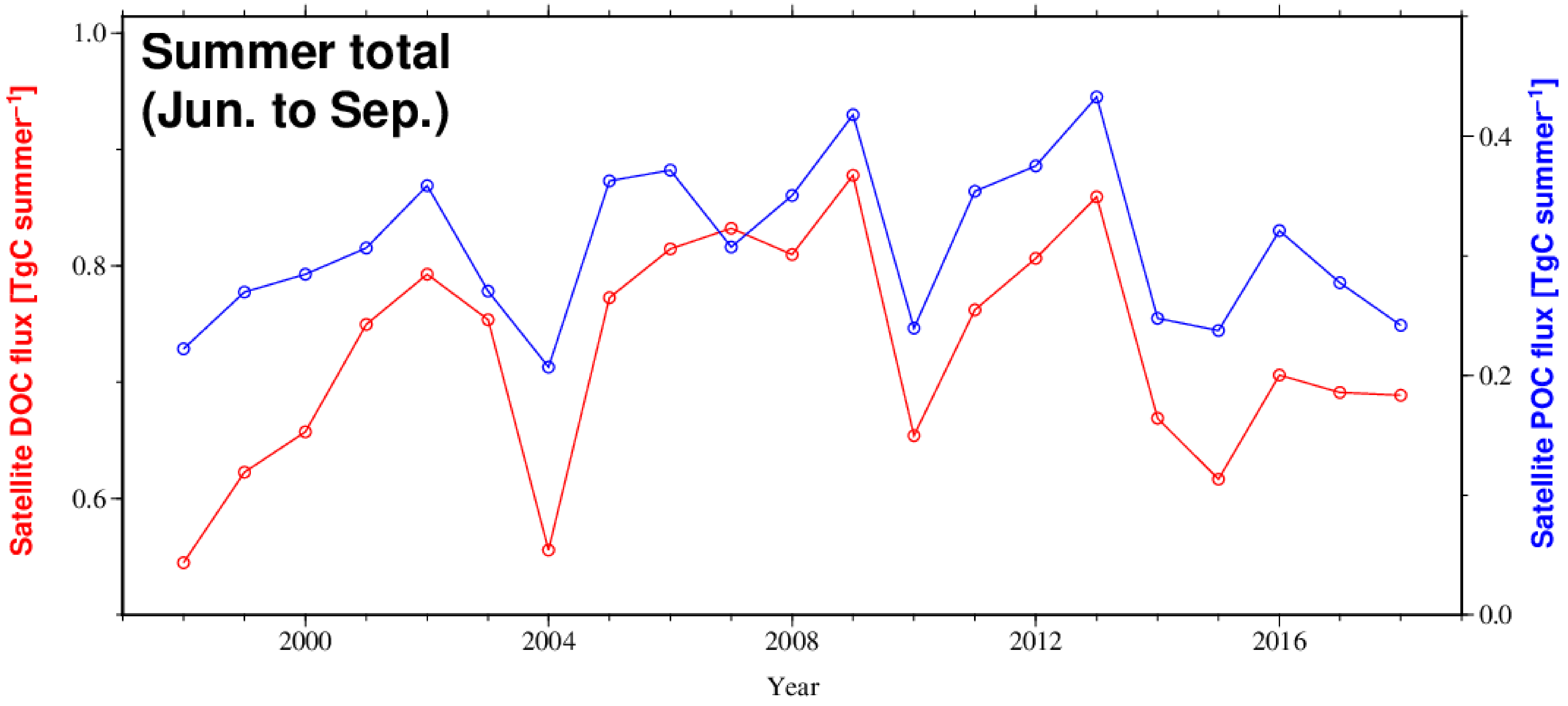
# Monthly POC concentrations (MODIS)



Example of the Mackenzie river plume using a high resolution satellite image (30m)

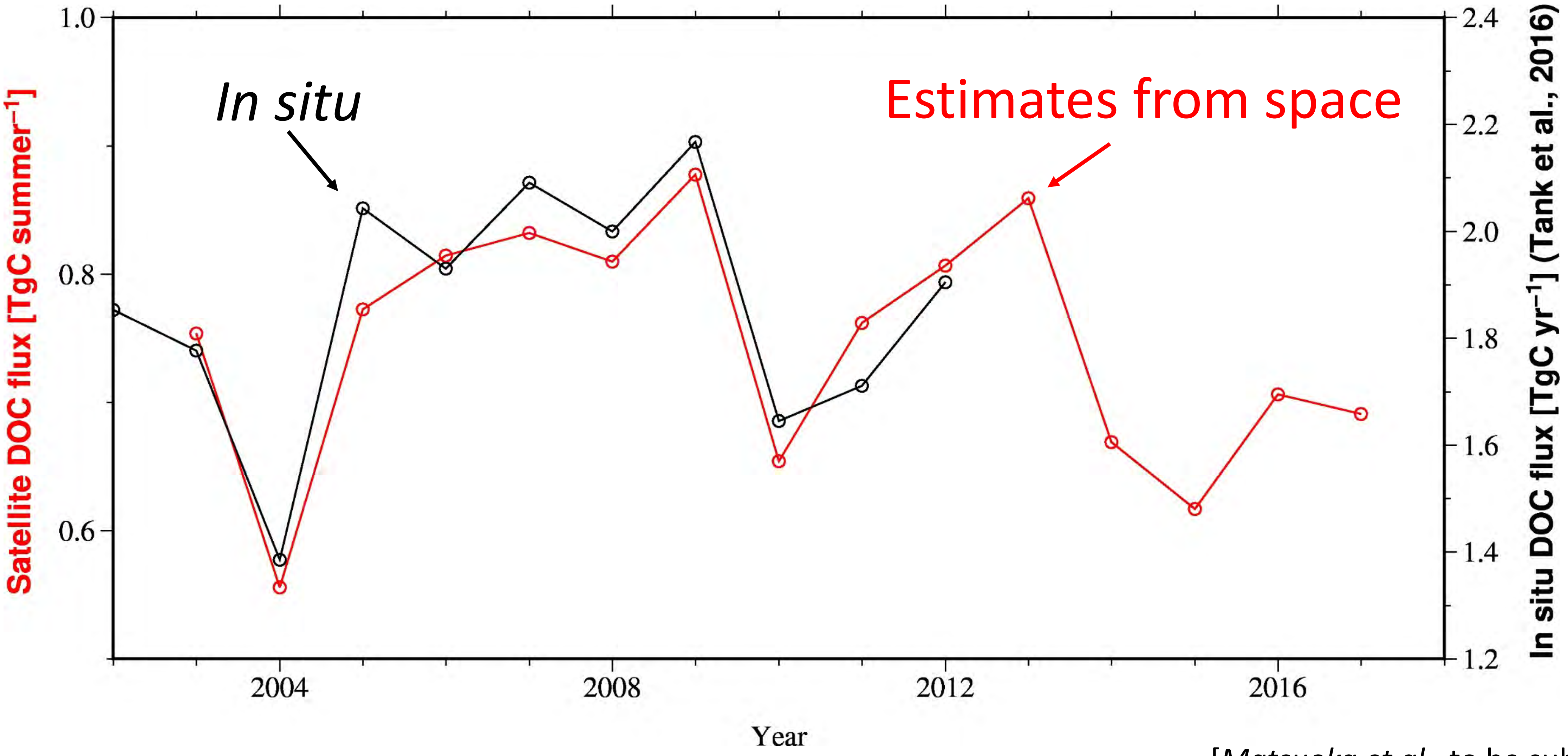


# Two-decade trends in DOC and POC fluxes for summer total (1998-2018)



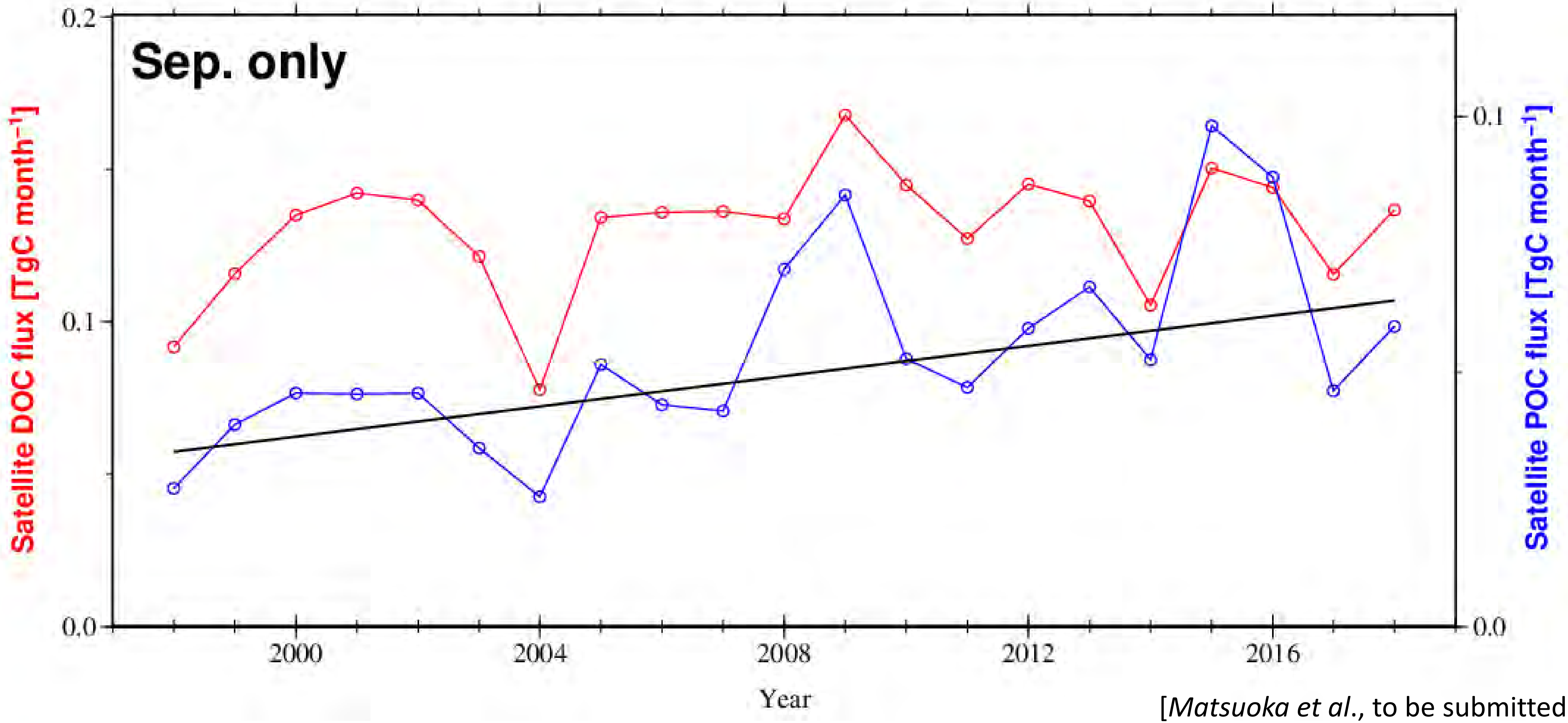

[*Matsuoka et al.*, to be submitted]

# Comparison of satellite DOC flux in the delta with *in situ* data <u>at an upstream pilot station</u> (*Tank et al*., 2016, ERL)




[*Matsuoka et al*., to be submitted]

# Two-decade trends in DOC and POC fluxes for September only (1998-2018)




[*Matsuoka et al.*, to be submitted]

# Trends in standardized environmental variables:

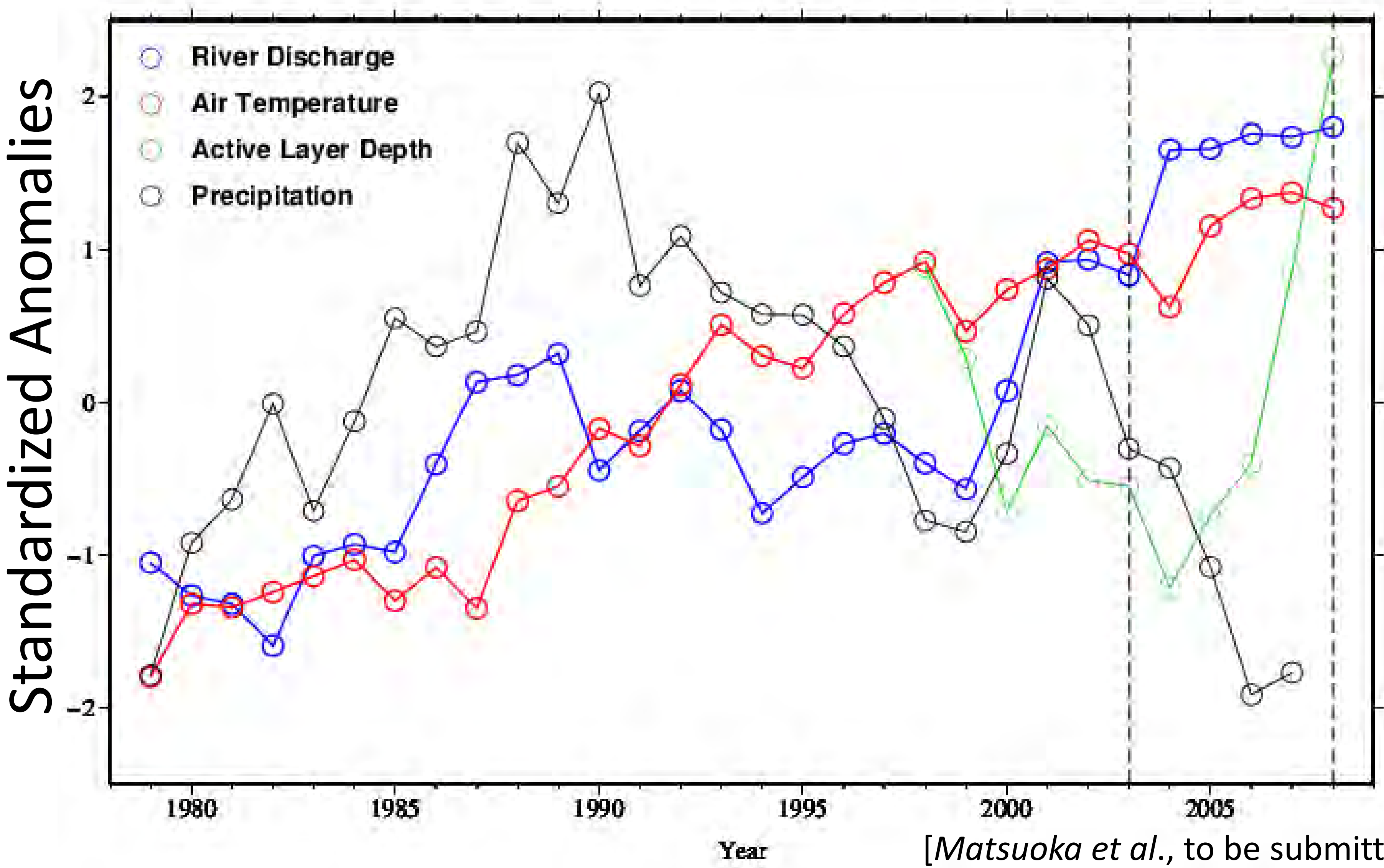
➢ **Standardized anomalies for 11-year moving averaged data**

**River Discharge**

**Air Temperature**

**Active Layer Depth**

**Precipitation**

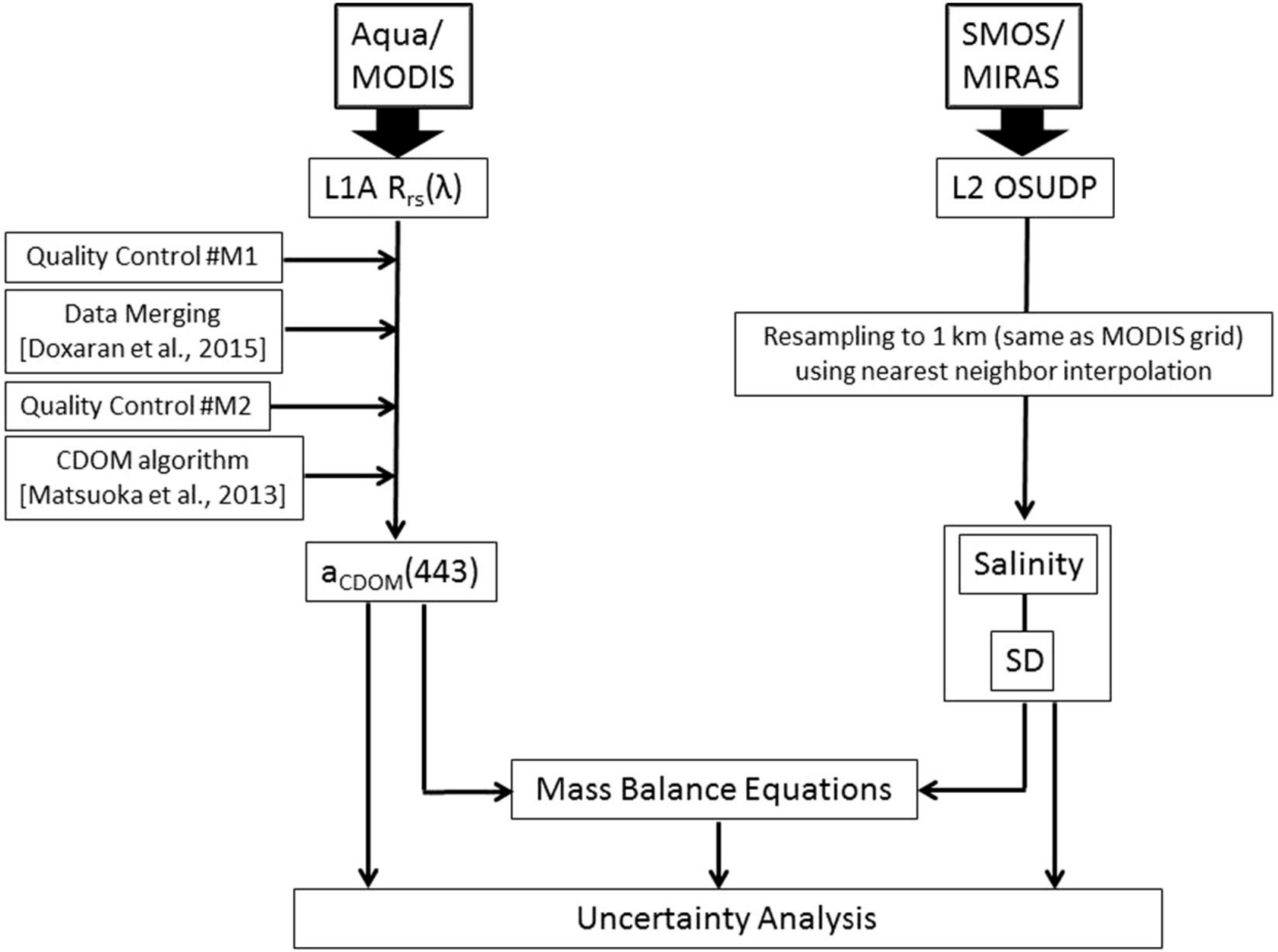



[*Matsuoka et al.*, to be submitted]

# 3. Applications (2/3)

# Multi-satellite remote sensing approach

- Ocean color
- Sea surface salinity
- Sea ice concentration
- Sea surface temperature
- Sea surface wind




[*Matsuoka et al.*, 2016, RSE]

# Mass balance equations regarding salinity$^{sat}$ and CDOM$^{sat}$

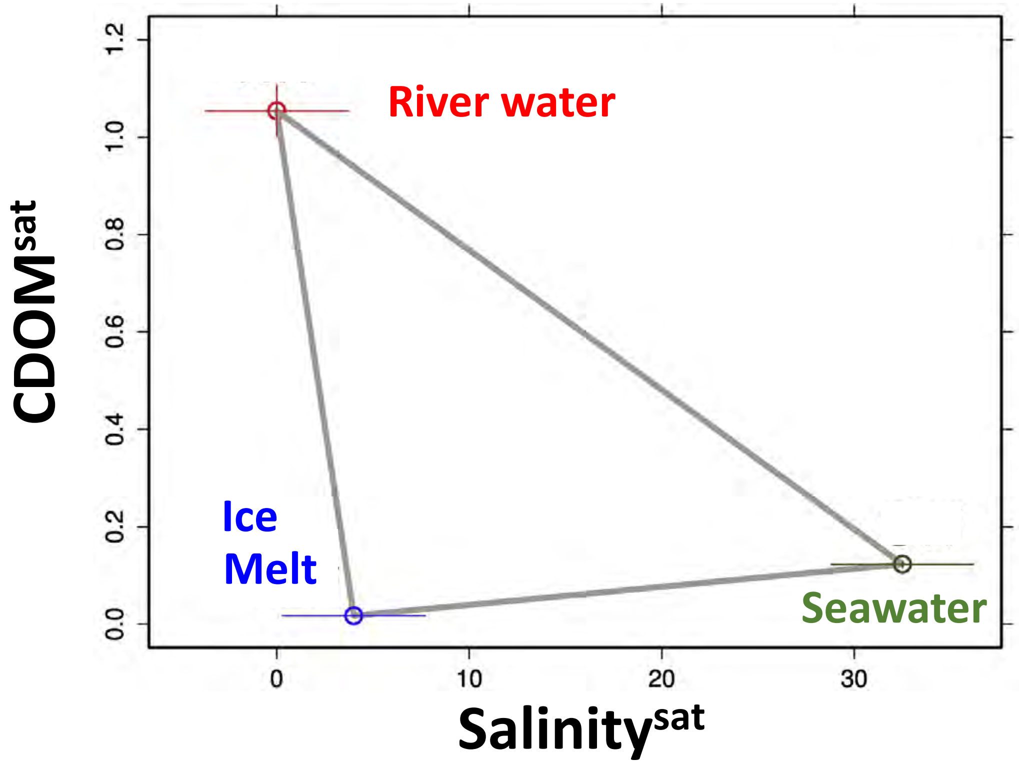
*Approach*:

3 water sources

Fraction (f) → $f_{SEA} + f_{MELT} + f_{RIVER} = 1$

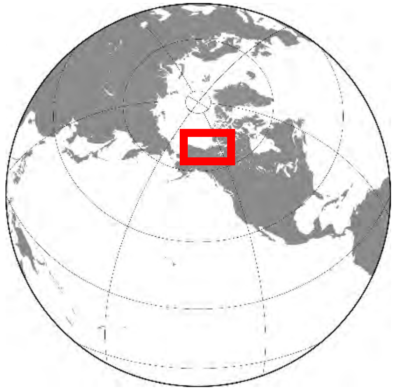
Salinity (S) → $f_{SEA}S_{SEA} + f_{MELT}S_{MELT} = S^{sat}$

CDOM (C) → $f_{SEA}C_{SEA} + f_{MELT}C_{MELT} + f_{RIVER}C_{RIVER} = C^{sat}$

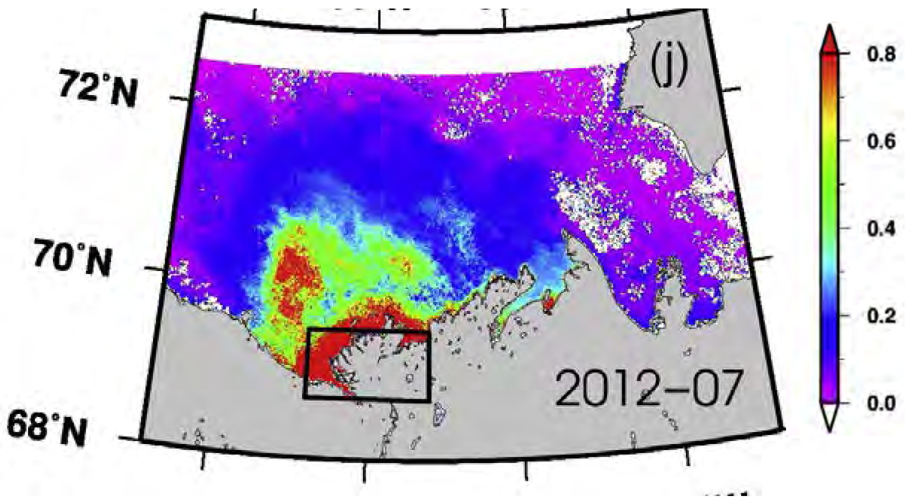



[*Matsuoka et al.*, 2016, RSE]

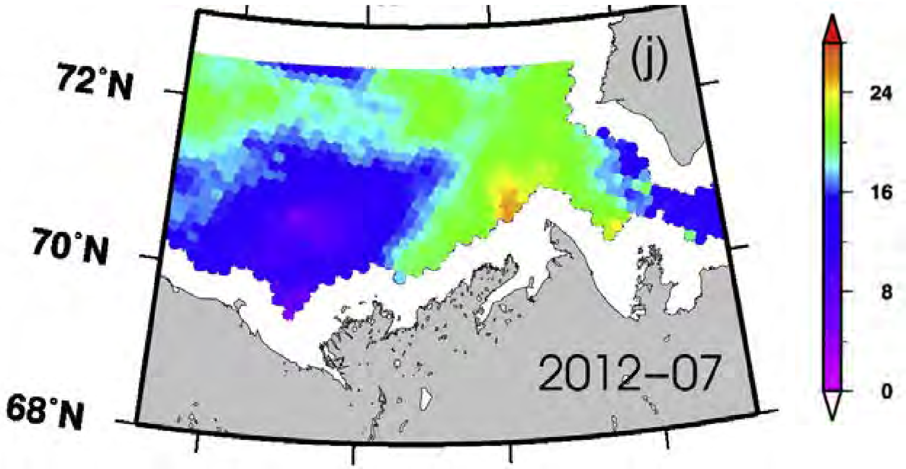
# Relationship between salinity$^{sat}$ and CDOM$^{sat}$



CDOM$^{sat}$ ($m^{-1}$)

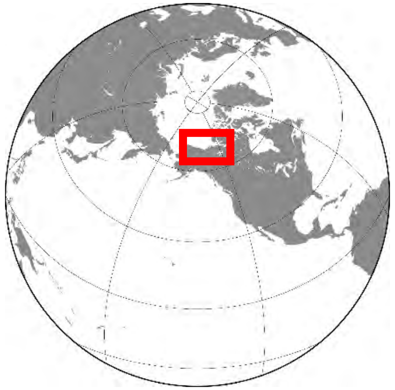


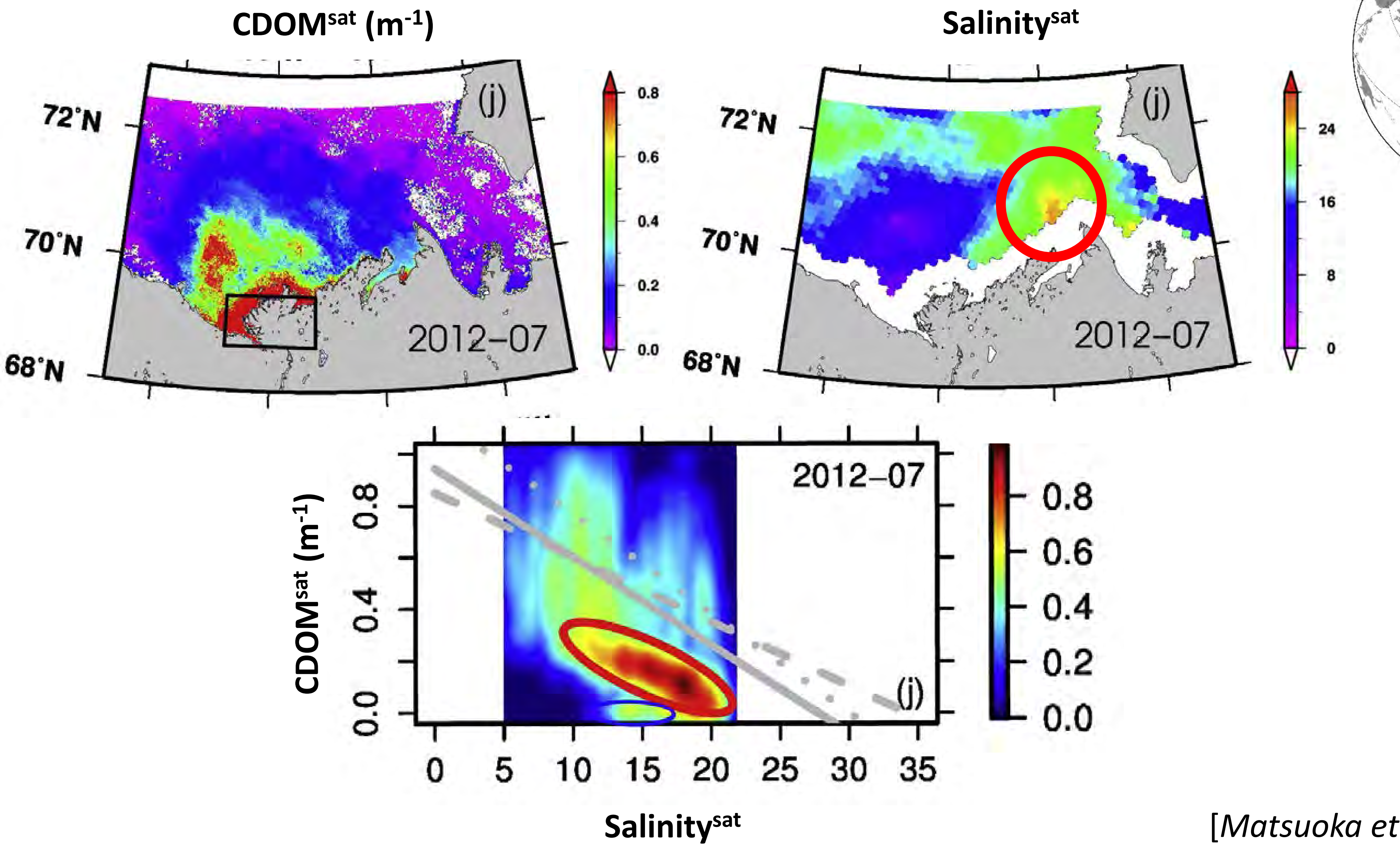

Salinity$^{sat}$




[*Matsuoka et al.*, 2016, RSE]

# Relationship between salinity$^{sat}$ and CDOM$^{sat}$

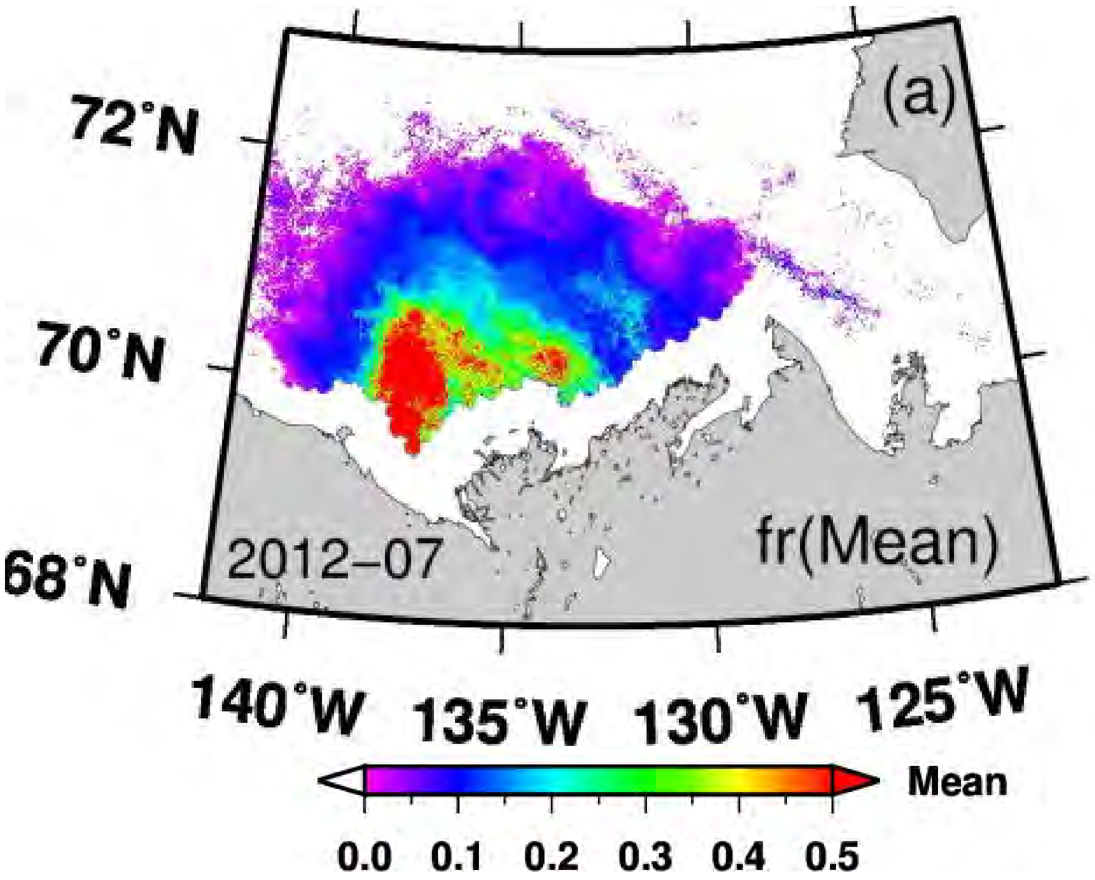




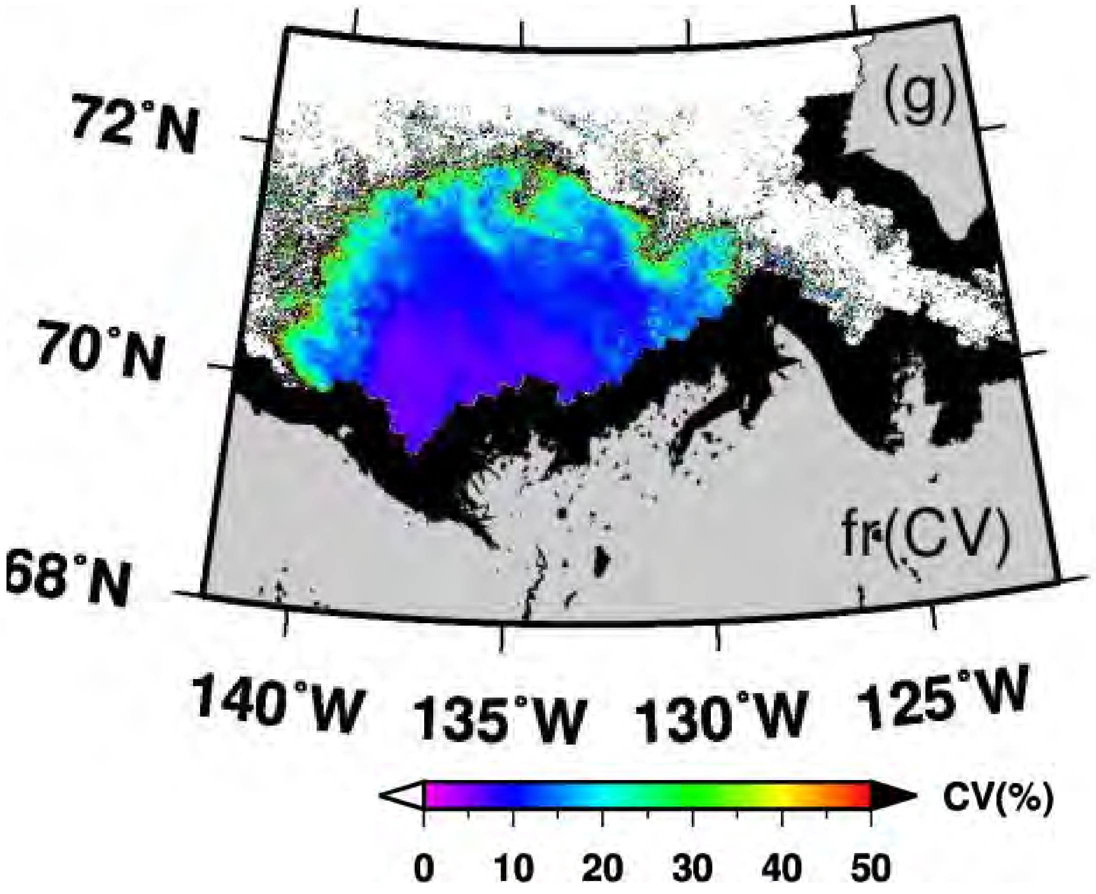

[*Matsuoka et al.*, 2016, RSE]

# Fraction of river-influenced water derived from space

## Mean river fraction



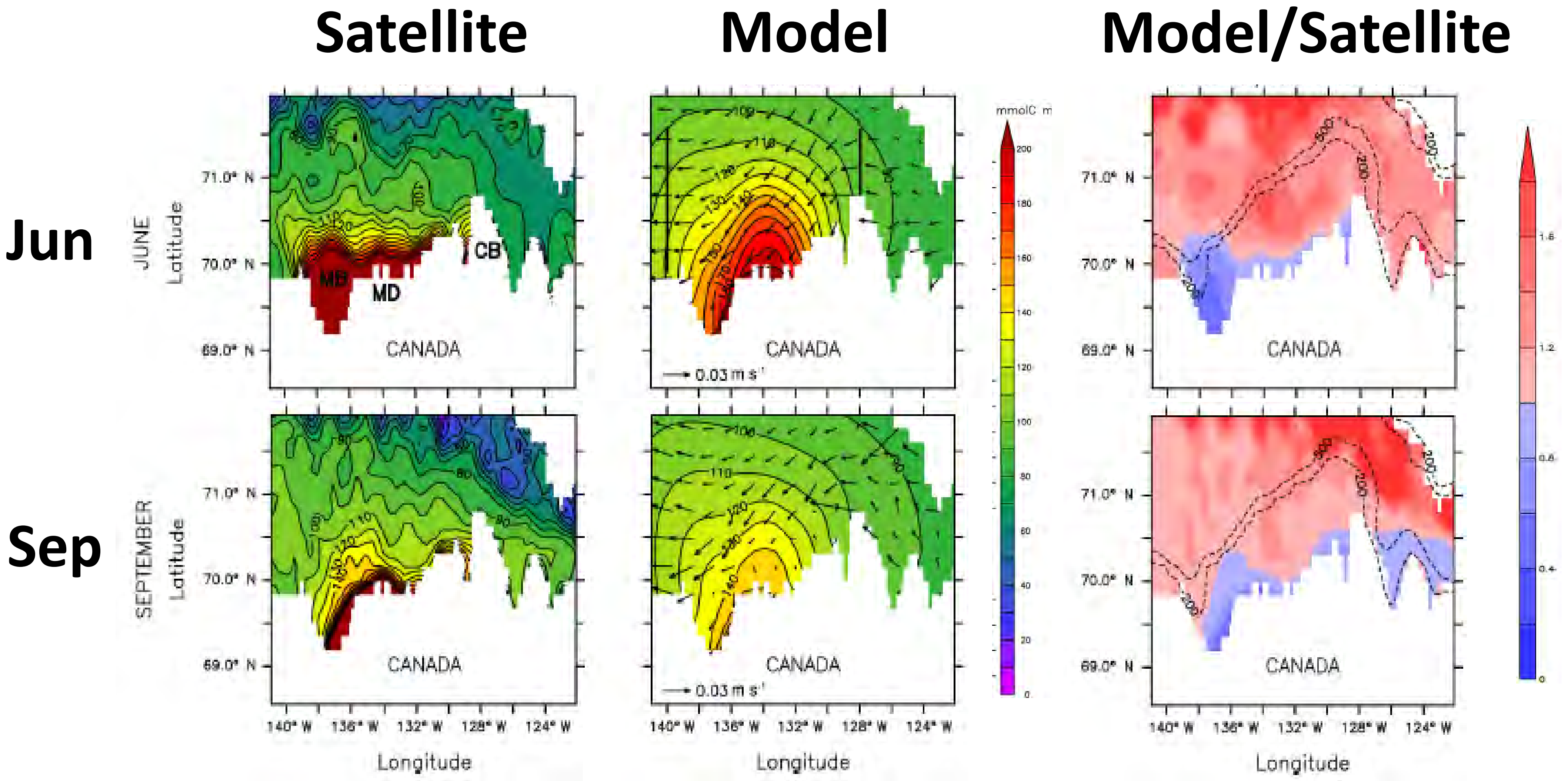

## Error




[*Matsuoka et al.*, 2016, RSE]

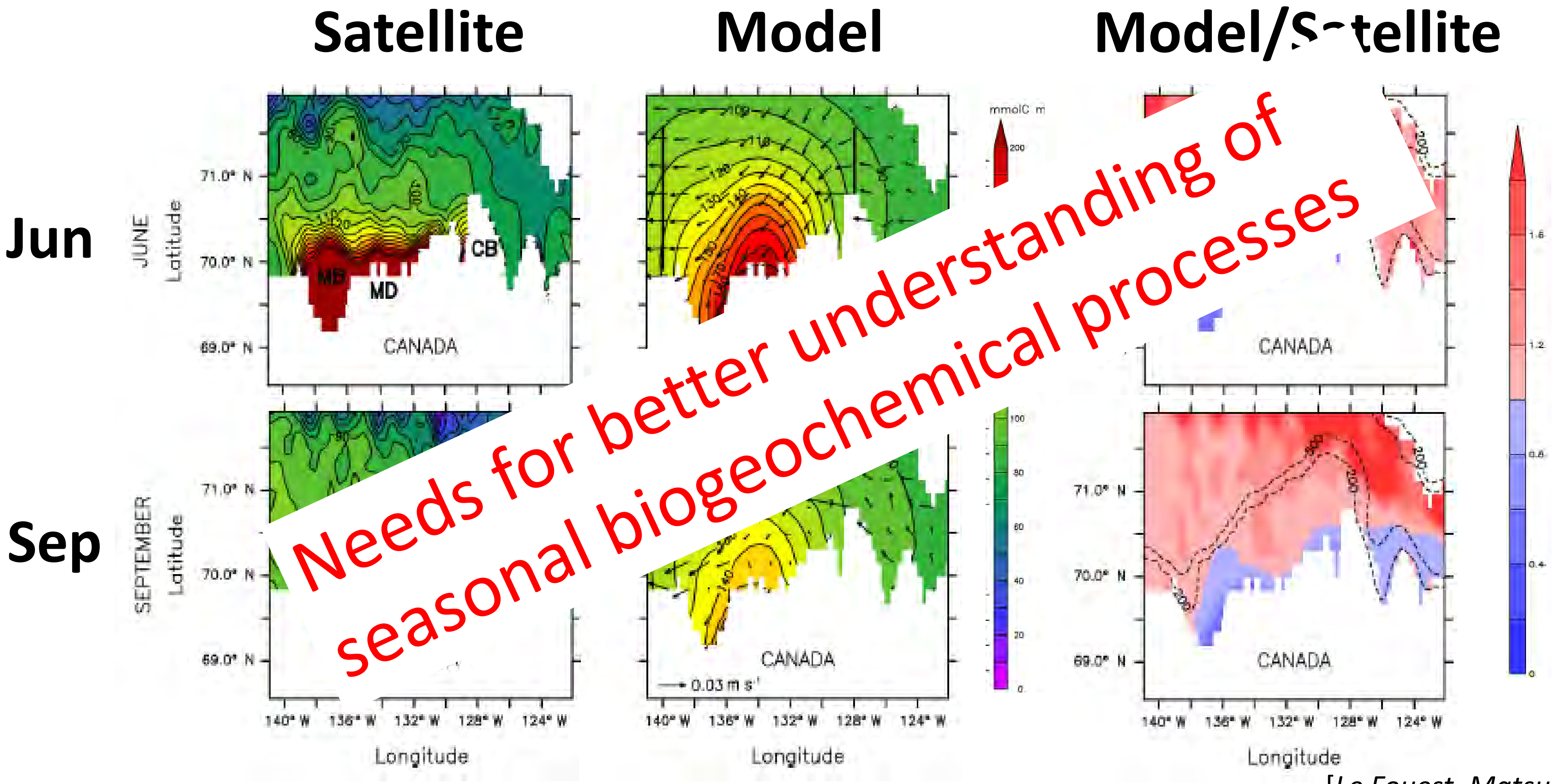
# 3. Applications (3/3)

# Comparison of satellite estimates with modeling results : MITgcm coupled with biogeochemical components




[*Le Fouest, Matsuoka et al.*, 2018, BG]

# Comparison of satellite estimates with modeling results : MITgcm coupled with biogeochemical components




[*Le Fouest, Matsuoka et al.*, 2018, BG]

# Field observation plan

NUNATARYUK

- **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

<u>Optical properties</u>

Radiance/Irradiance, light absorption of OM,
Light backscatter of particles, Particle size
distribution, Fluorescence of OM, etc.

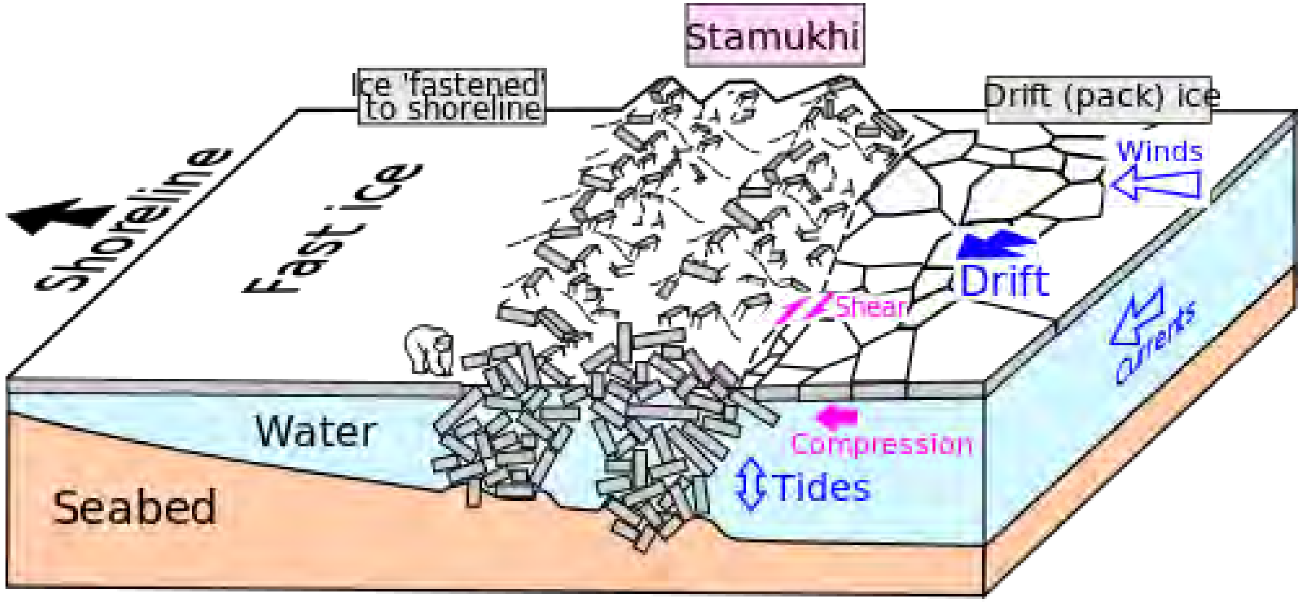
| | **Mon.** | **Plan** |
|---|---|---|
| Ice covered | Apr | Helicopter but ice-camp type operation |
| Break-up | Jun | Helicopter stationary operation |
| Open water | Jul-Aug | Ship-base operation |
| Open water | Aug-Sep | Ship-base operation |

# 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

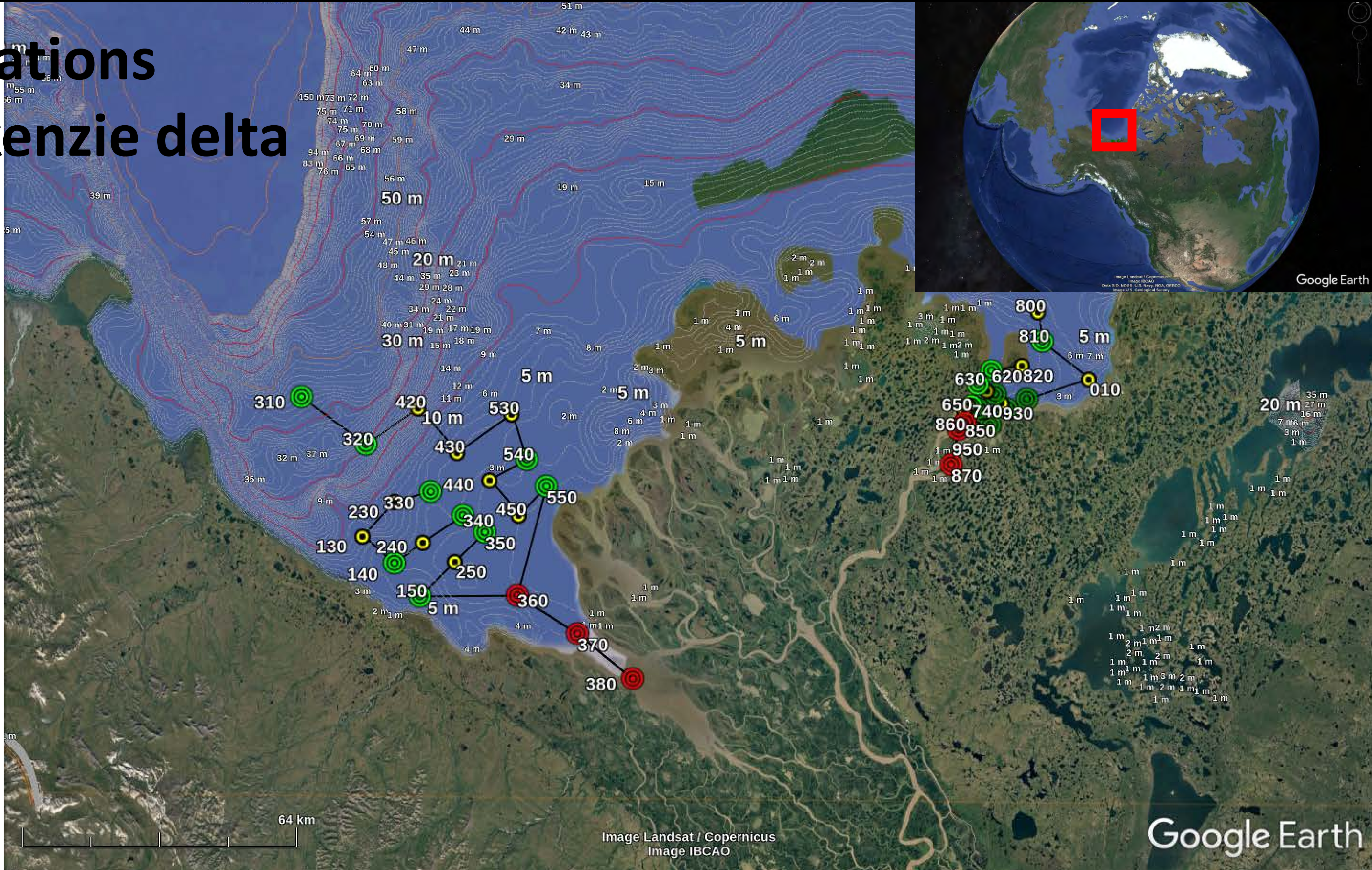
Copernicus Sentinel-1A/1B, Radarsat-2



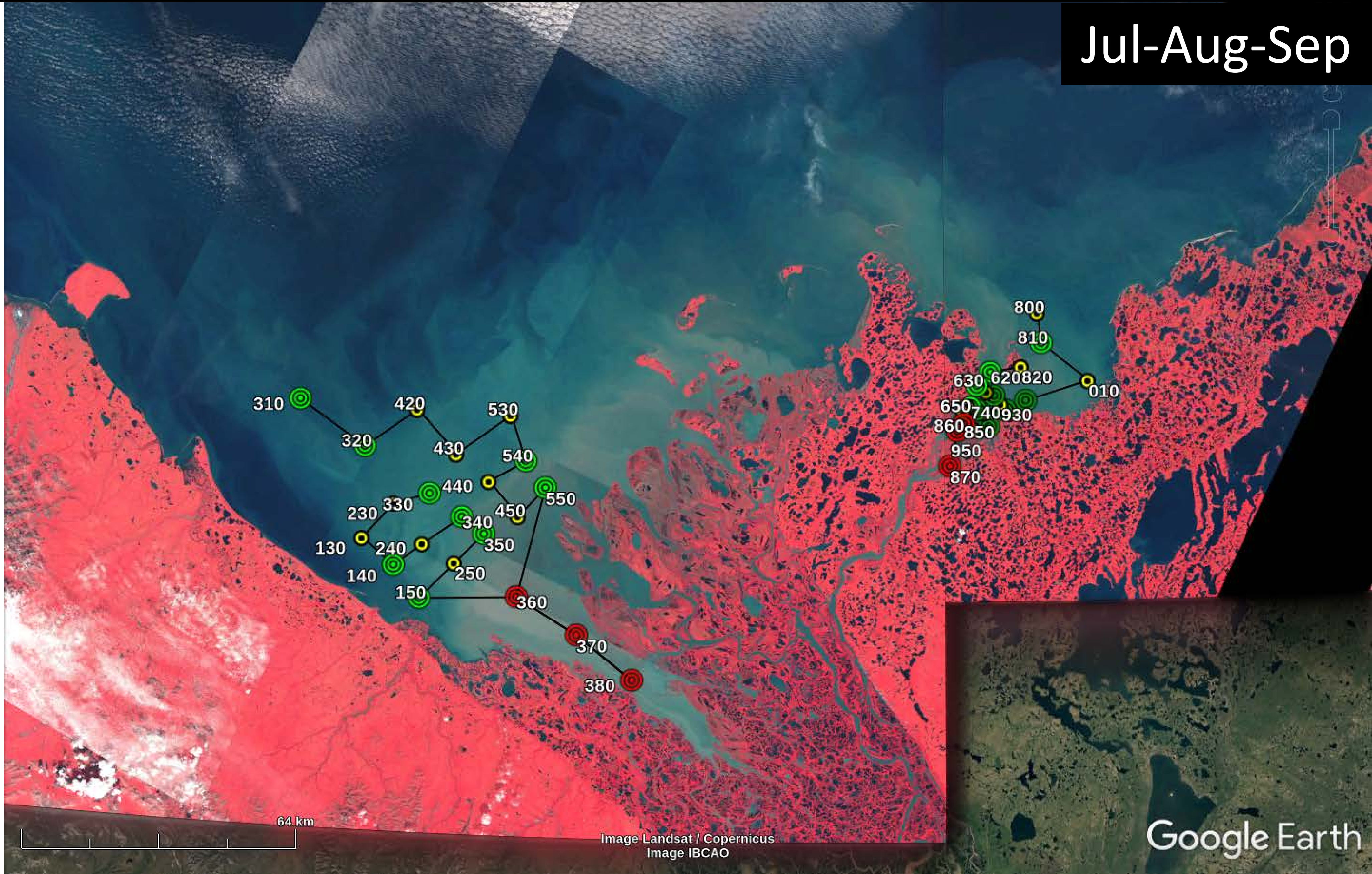

https://en.wikipedia.org/wiki/Stamukha

# Sampling stations
# In the Mackenzie delta

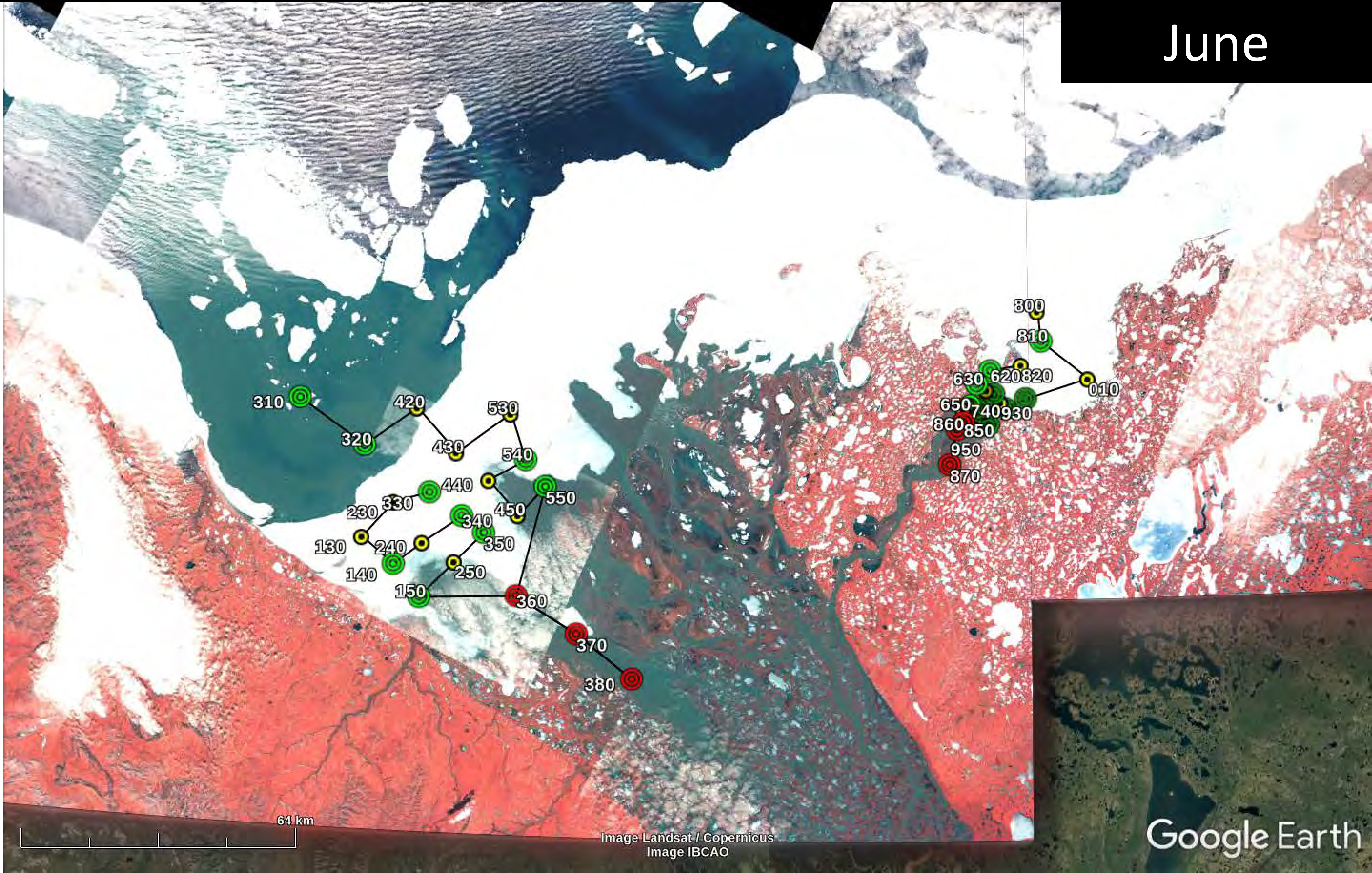
88% of the stations are located less than 5 m bottom depth



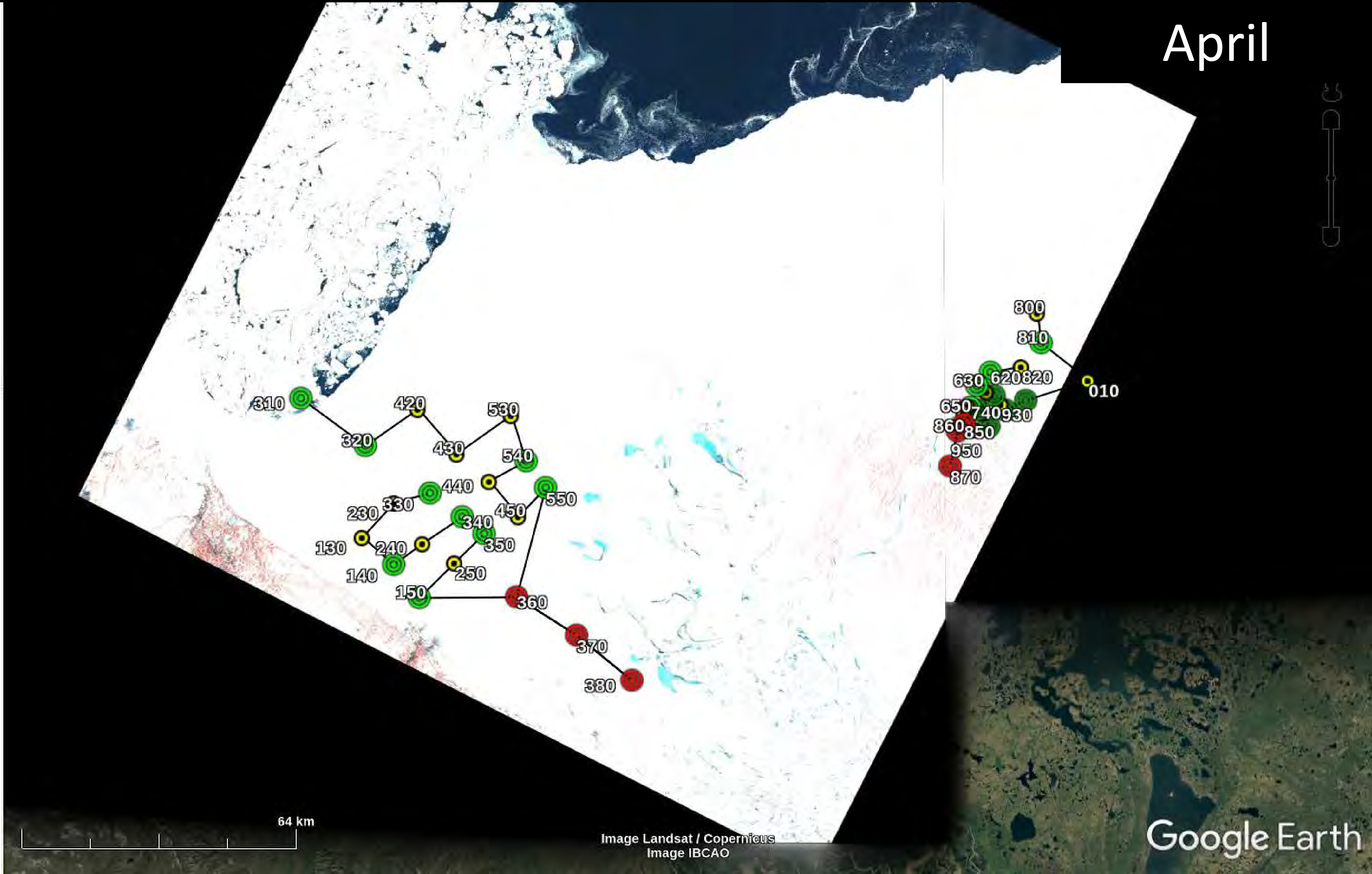
# False color Image of L8/OLI



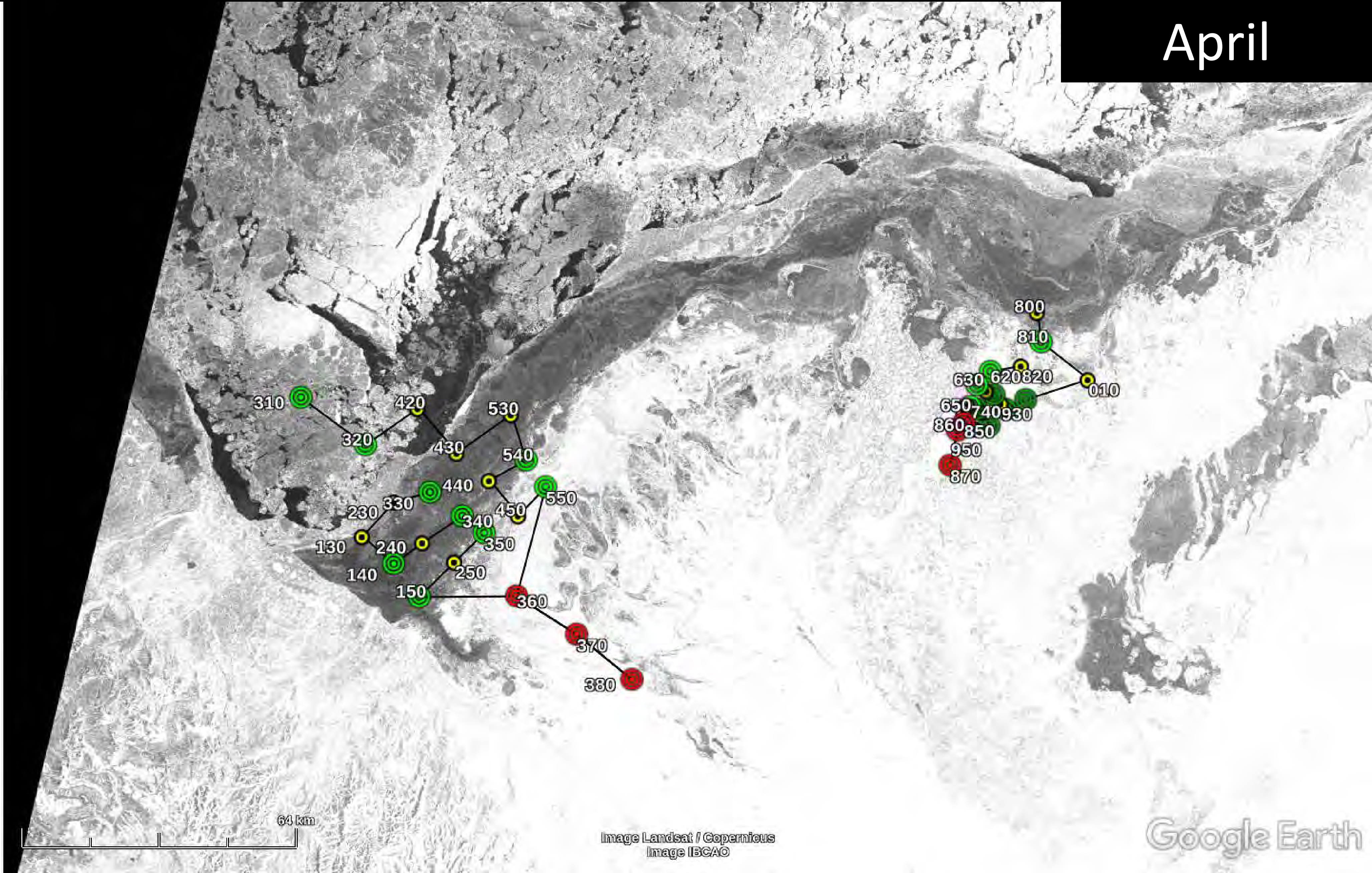
# False color Image of L8/OLI



# False color Image of L8/OLI



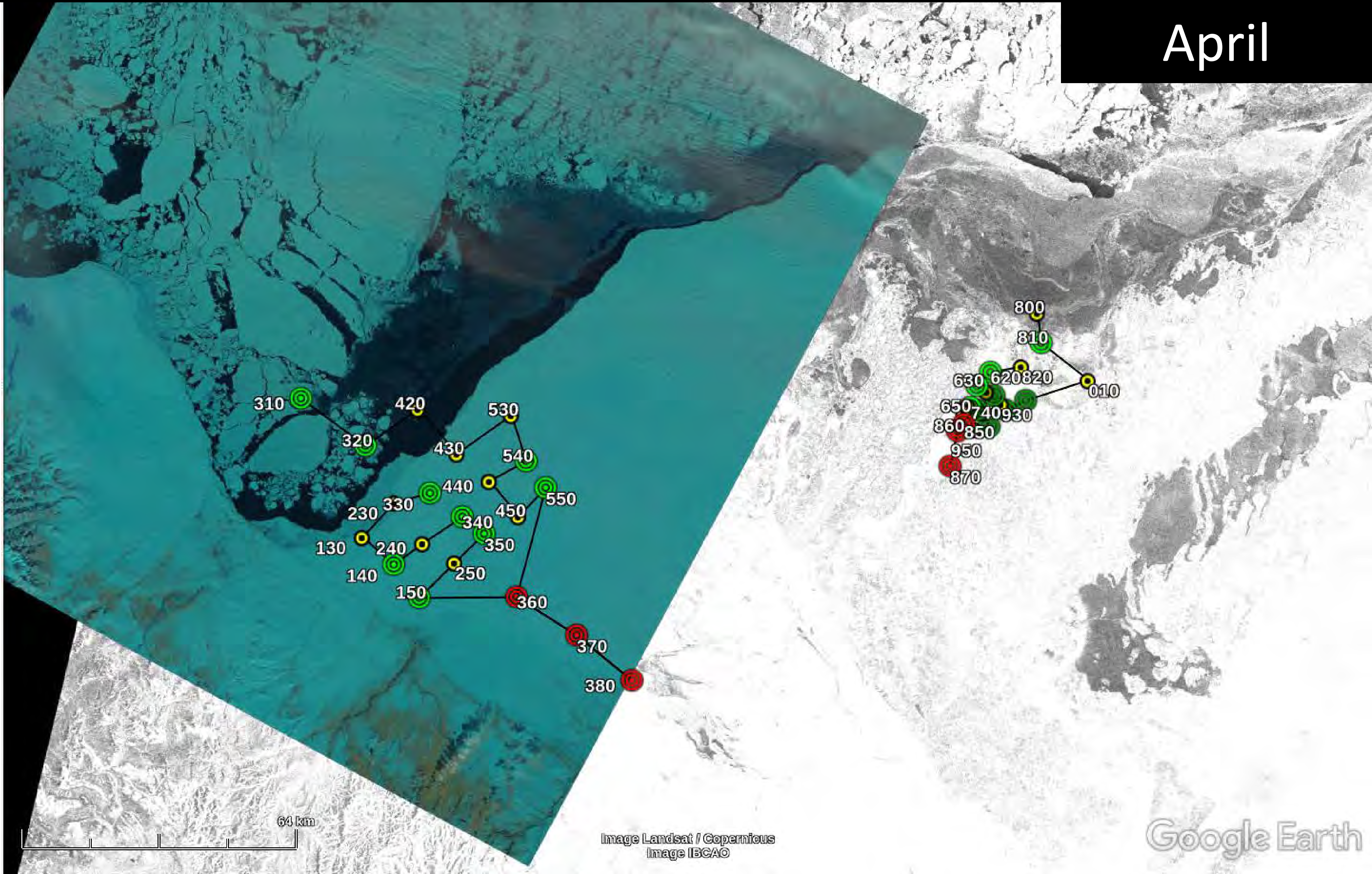
# Single band S1 SAR image (HH)



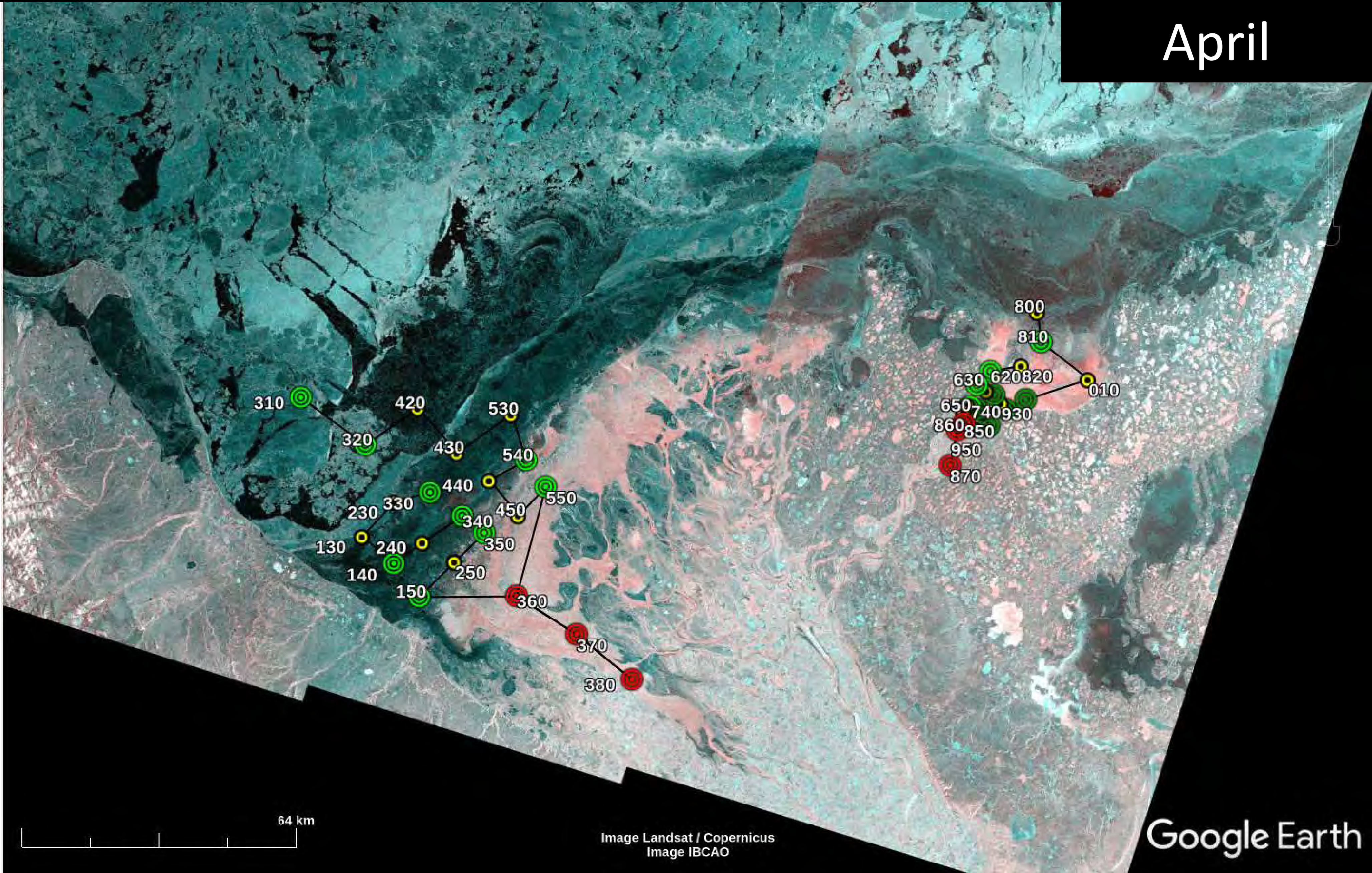
**Single band S1 SAR image (HH)**

**+**

**L8/OLI false color**



# 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.**

# Concluding remarks (2/2)

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

https://techcrunch.com/2018/04/18/earthnow-promises-real-time-views-of-the-whole-planet-from-a-new-satellite-constellation/