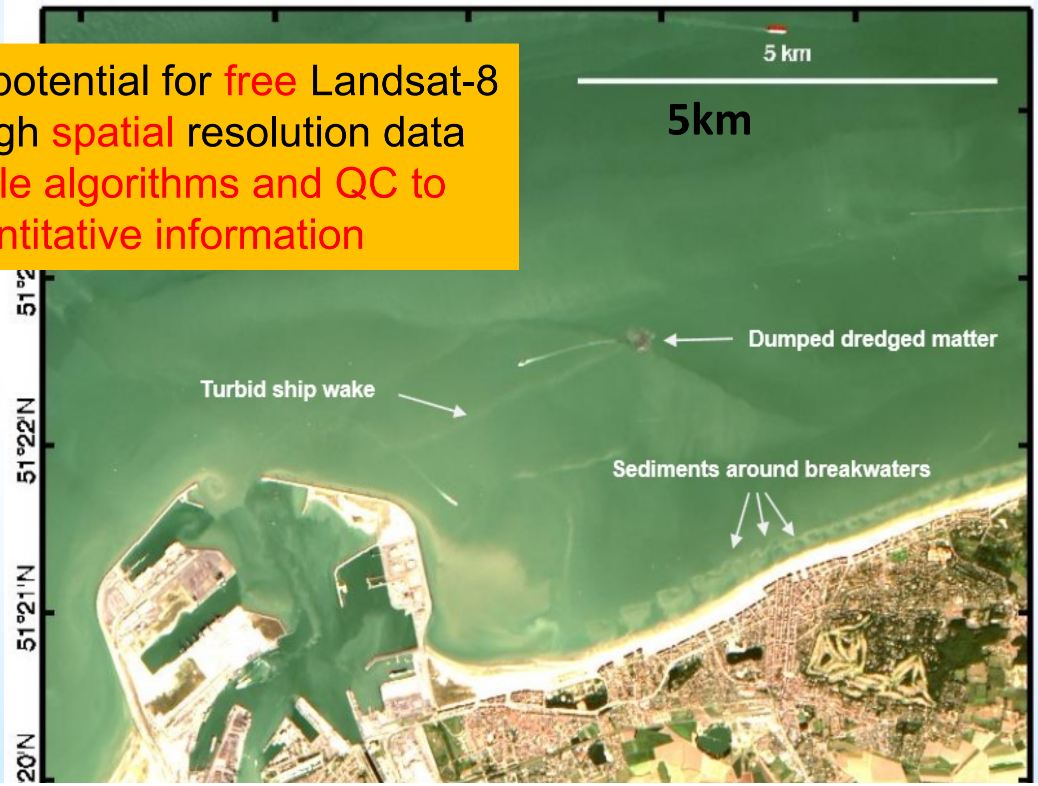
The Motivation for turbid waters

- Many coastal/inland apps are very nearshore: EU WFD 1 n. mile
- New sediment transport features become visible at high spatial resolution, e.g. Sentinel-2 10m (ports, estuaries, dredging plumes, windmill wakes, ...)

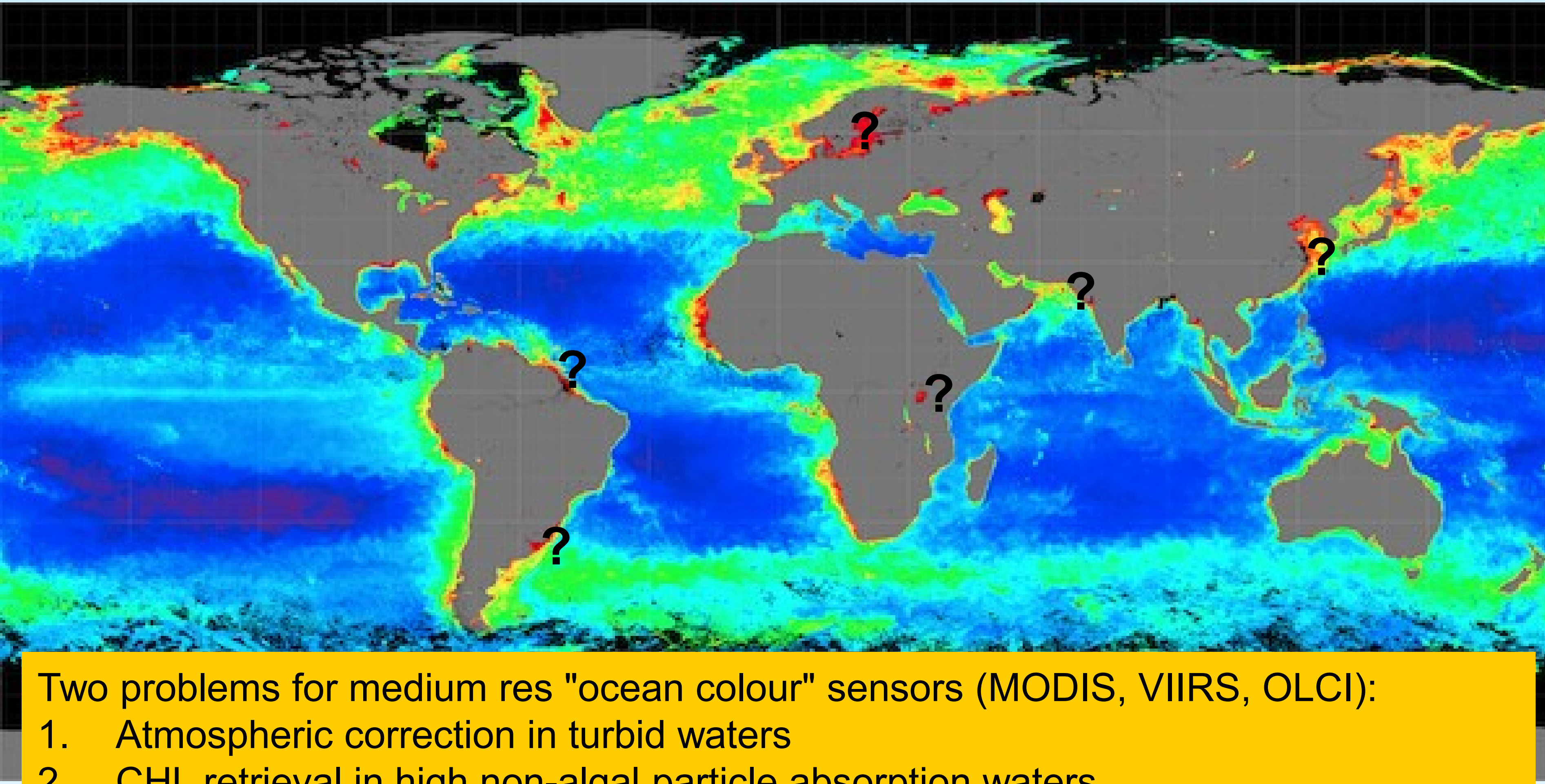
HUGE application potential for free Landsat-8 and Sentinel-2 high spatial resolution data BUT need reliable algorithms and QC to provide quantitative information



Landsat-8 (30m…15m) around port of Zeebrugge

Vanhellemont Q. & Ruddick K. (2014). Landsat-8 as a Precursor to Sentinel-2: Observations of Human Impacts in Coastal Waters. In: Submitted for the proceedings of the Sentinel-2 for Science Workshop held in Frascati, Italy, 20-23 May 2014, ESA Special Publication SP-726.

The problems of turbid waters (from a global CHL perspective)



Two problems for medium res "ocean colour" sensors (MODIS, VIIRS, OLCI):

1. Atmospheric correction in turbid waters
2. CHL retrieval in high non-algal particle absorption waters

e.g. MODIS Aqua chlor_a seasonal composite for Northern hemisphere Spring 2014 [https://oceancolor.gsfc.nasa.gov/atbd/chlor_a/]

RED=high CHLa (or NOT?)

Optical Remote Sensing in turbid coastal and inland Waters

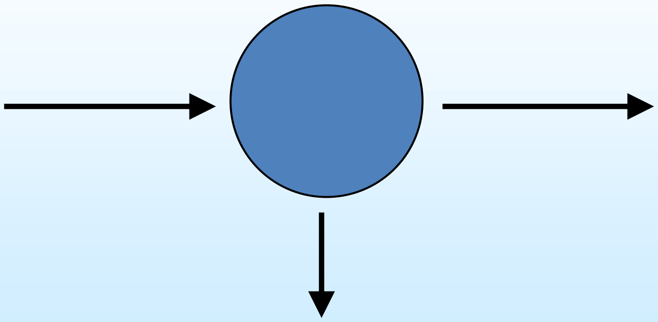
by Kevin Ruddick

with support from RBINS researchers, past and present

(Quinten Vanhellemont, Ana Dogliotti, Clémence Goyens, Héloise Lavigne, Bouchra Nechad, Griet Neukermans, Youngje Park, Dimitry Vanderzande, and HIGHROC/HYPERMAQ project partners

What are “turbid” waters

- Wikipedia:
  – Turbidity=“cloudiness or haziness of a fluid caused by individual particles (suspended solids) …, similar to smoke in air. The measurement of turbidity is a key test of water quality.”
- International Standards Organisation (ISO 7027:1999):
  – “Reduction of transparency of a liquid by the presence of undissolved matter”
  – Measured via 90°±2.5° scattering at 860nm (<60nm bandwidth) relative to Formazine (Formazine Nephelometric Units)
  – PLEASE DO NOT USE broadband tungsten lamps (US EPA protocol)



bs860=>Turbidity

Degrees of turbidity

- Unofficial (but very useful) definitions

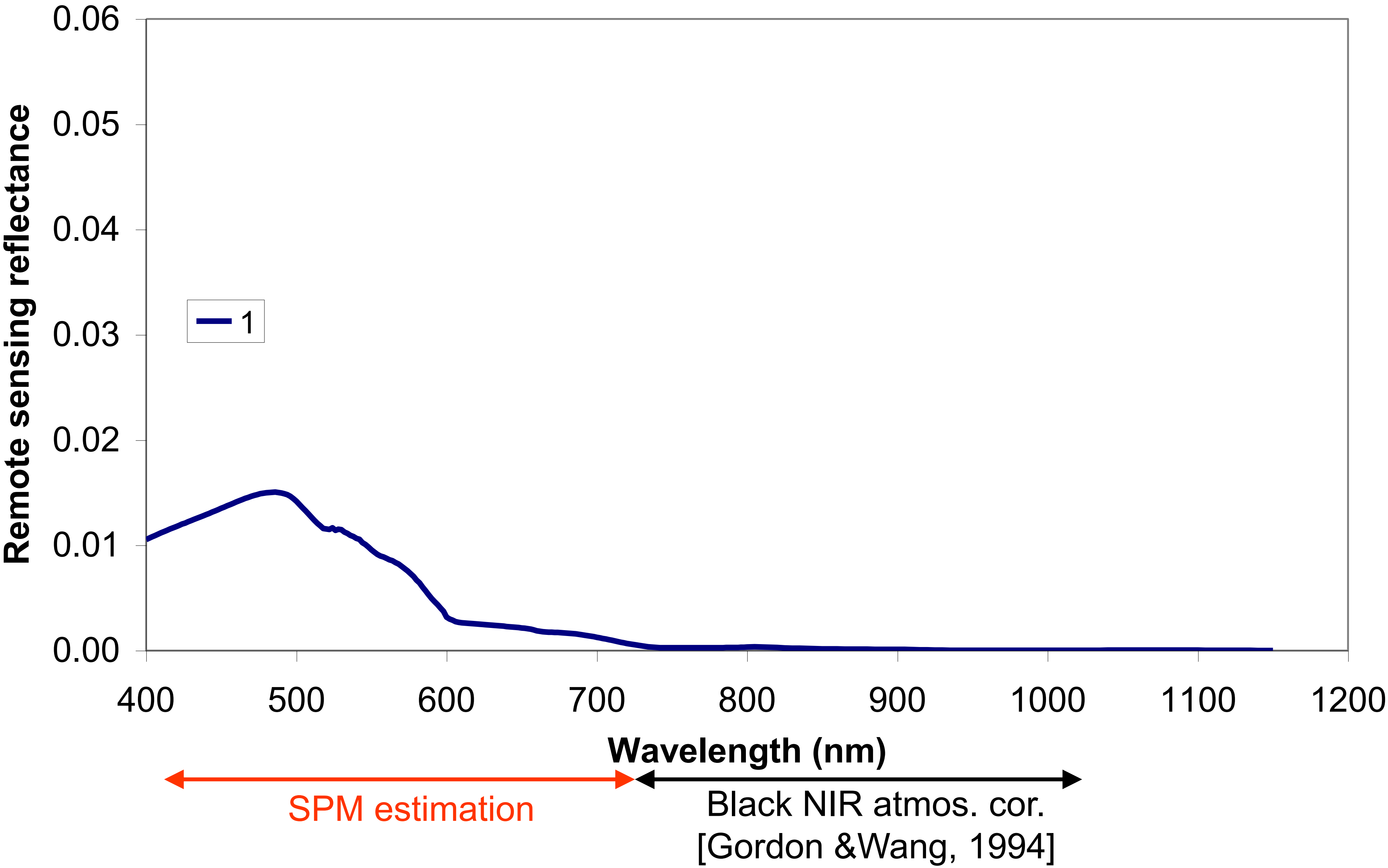
Description	Turbidity, bs (FNU)	Suspended Particulate Matter, SPM (g/m3)	*Secchi depth (m)*	Scattering, b_555 (m-1)	Backscattering, bb_555 (m-1)	Water Reflectance at 778nm=PI*Rrs778
Clear	<1.1	<1	*>10m*	<0.5	<0.01	<0.0008
Moderately turbid	1.1-11	1-10	*2-10m*	0.5-5	0.01-0.1	0.0008-0.008
Very turbid	11-110	10-100	*20cm-2m*	5-50	0.1-1	0.008-0.06
Extremely turbid	110-1100+	100-1000+	*<0.5cm -20cm*	50-500+	1-10	0.06-0.2

NB. Rough values only, mass-specific optical properties do vary

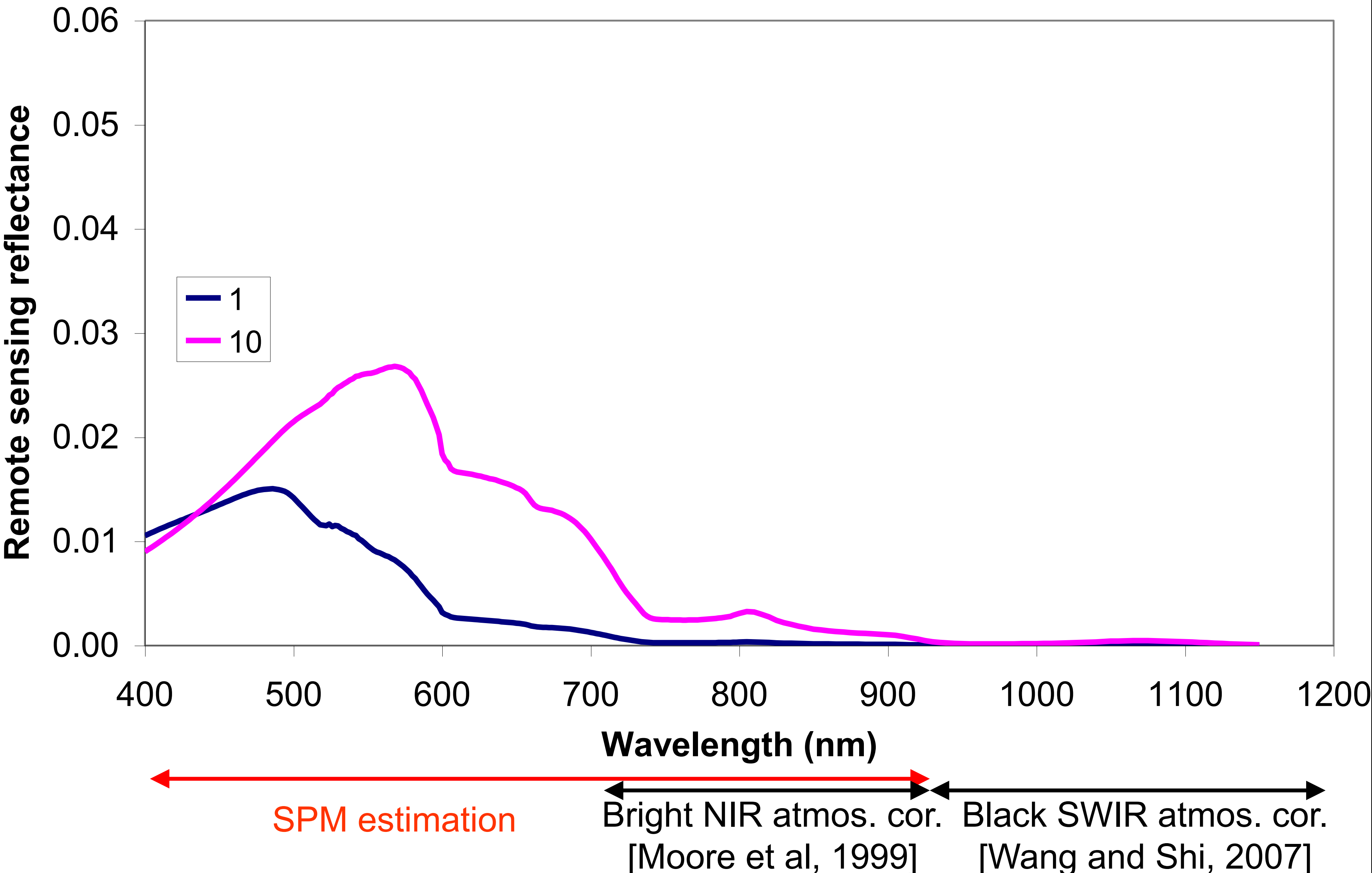
Neukermans et al (2012). In situ variability of mass-specific beam attenuation and backscattering of marine particles with respect to particle size, density, and composition. Limnol Oceanogr. 57, 124–144

Babin, et al (2003). Light scattering properties of marine particles in coastal and oceanic waters as related to the particle mass concentration. Limnol Oceanogr. 48, 843-859

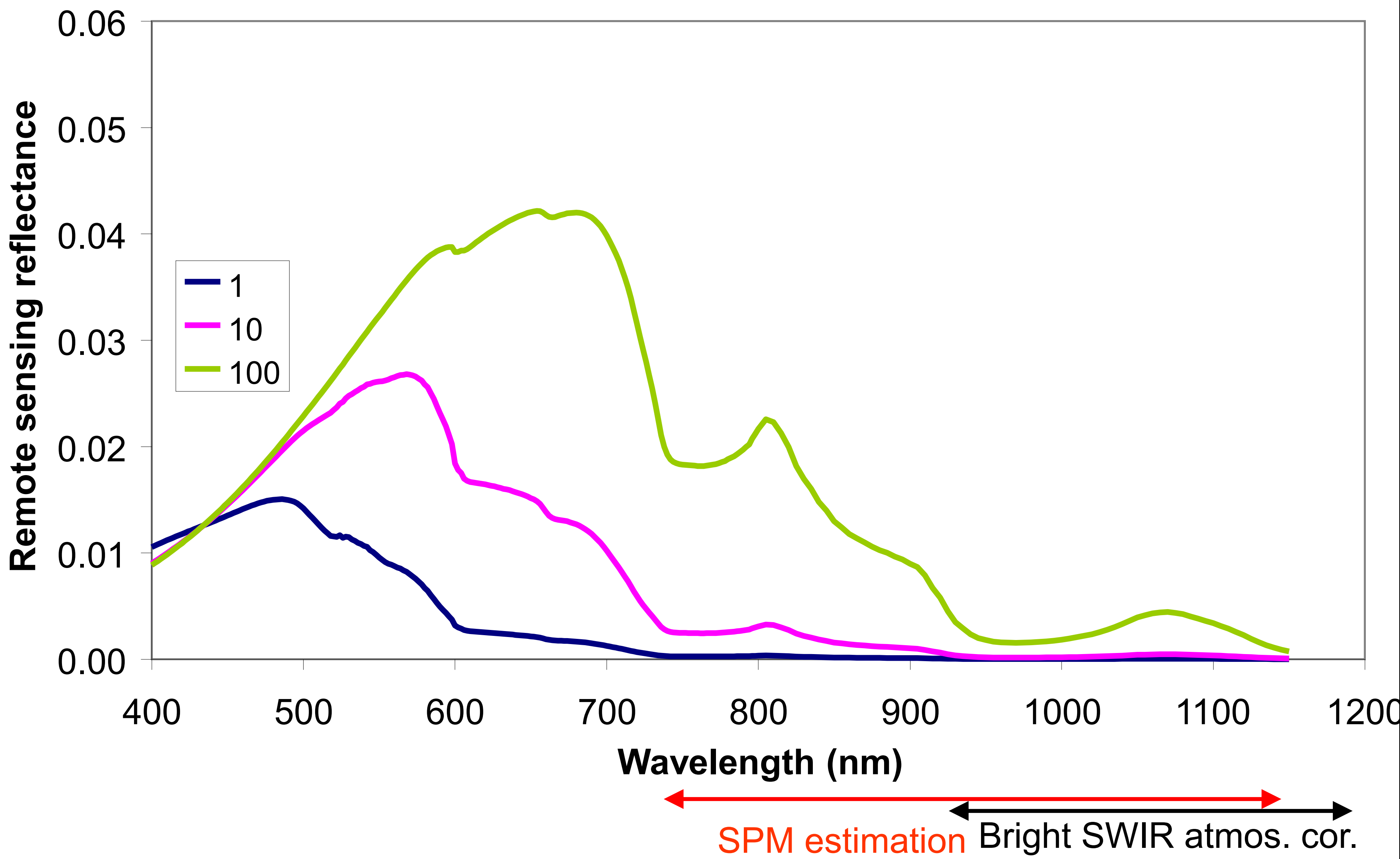
Varying Total Suspended matter concentration (g/m3)



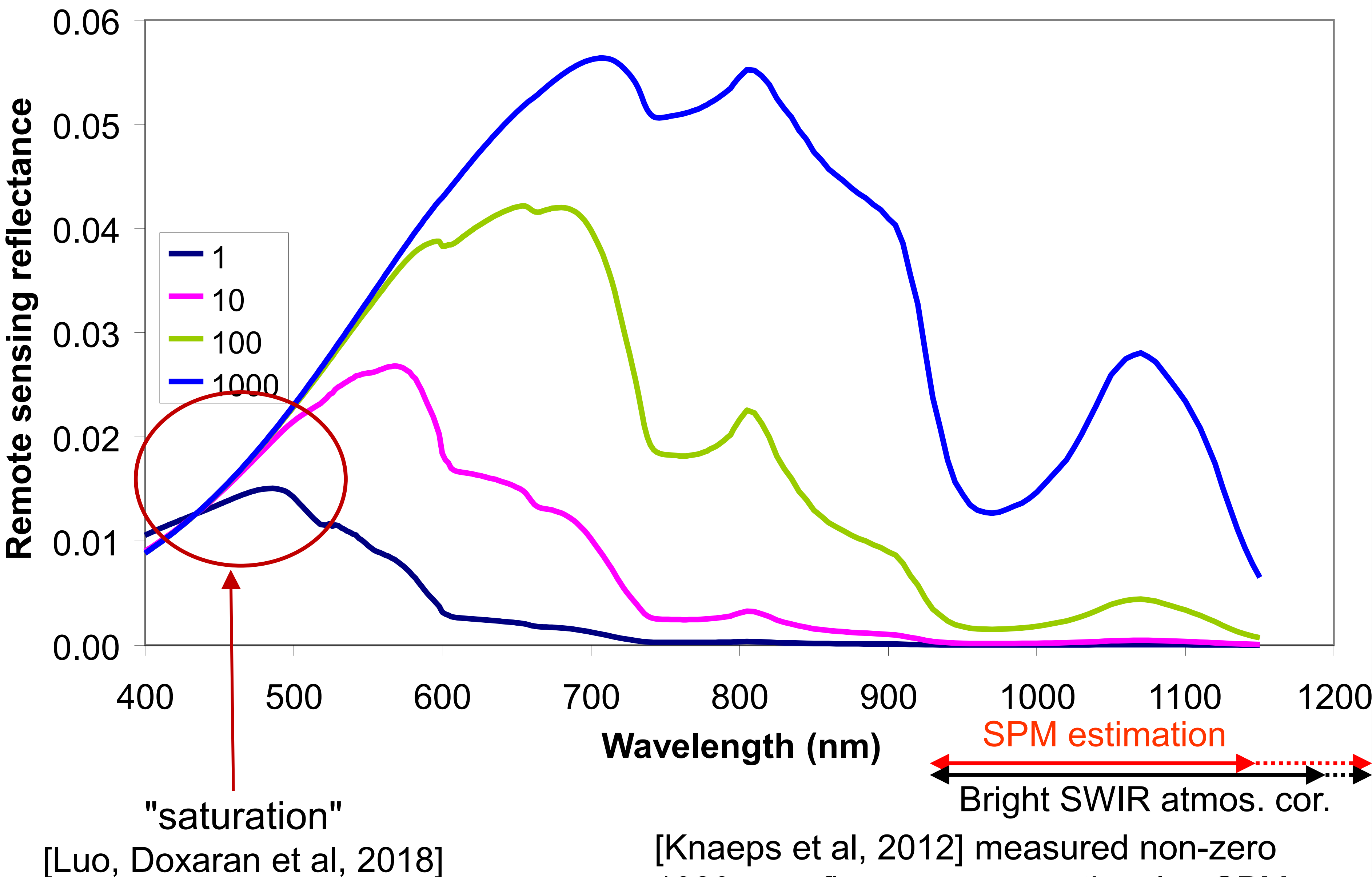
Varying Total Suspended matter concentration (g/m3)



Varying Total Suspended matter concentration (g/m3)



Varying Total Suspended matter concentration (g/m3)



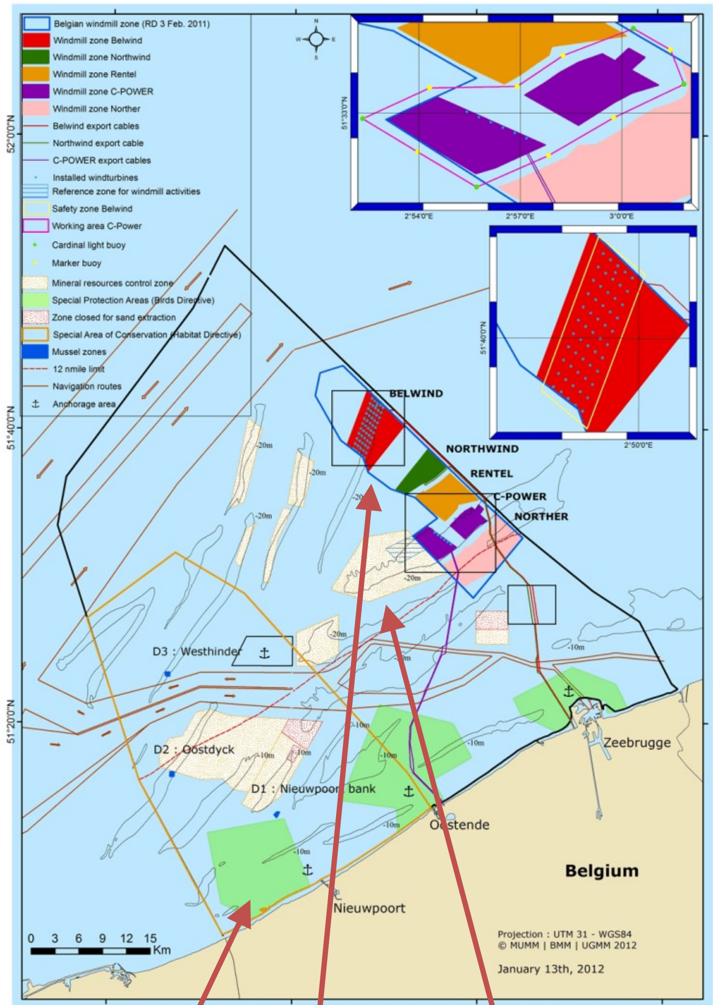
[Knaeps et al, 2012] measured non-zero 1020nm reflectance, proportional to SPM

Where to find turbid water

Description	Suspended Particulate Matter, SPM (g/m3)	Typical cases
Clear	<1	Non-bloom oceanic
Moderately turbid	1-10	Oceanic bloom, "clear" lake, Tidal seas (~20-50m)
Very turbid	10-100	Tidal seas (<20m), lakes River plumes, estuaries
Extremely turbid	100-1000+	Major plumes, estuaries (Amazon, La Plata, Yangtze)

Motivation for turbid waters

- Human pressures and interests are most intense for coastal, estuarine and inland waters, many of which are turbid
  - Eutrophication monitoring (EU Water Framework Directive, etc.)
  - High biomass harmful algal blooms
  - Sediment transport, dredging, coastal engineering (port, windmill constructions, etc.)
  - Riverine sediment plumes (organic carbon flux, impact on euphotic depth, …)
  - Fish larvae nursery/spawning grounds
  - Coastal fisheries and aquaculture
  - Tourism



15km

Belgium: windmills, sand extraction, nature [BMDC]

Problems AND advantages for remote sensing

- In turbid waters:
  - Chlorophyll retrieval by blue:green ("Case 1") algorithms fails because absorption is from algal particles + non-algal particles

    => Need red/near infrared or multispectral (inc red) algorithms
  - Atmospheric correction is more difficult because near infrared (NIR) water reflectance is not zero

    => Need turbid water algos, e.g. “bright pixel”, SWIR dark pixel, coupled ocean-atmosphere multispectral, Dark Spectrum Fitting, etc.
- BUT:
  - Water reflectance signal is also stronger compared to atmosphere

    => Can more easily see turbid waters

Aquatics Applications – Spectral resolution

Application	User	Parameter
EU Environment Directive (MSFD/WFD) reporting	National govt	CHL – multitemporal (90 percentile) Turbidity (TUR)
Carbon cycle modelling and Ocean acidification	Ecosystem modellers	CHL ... ocean CO_2, air-sea flux and ph, Kd diffuse attenuation, euphotic depth
Harmful Algae Blooms near real-time alert	National govt Fisheries Aquaculture	CHL ... (Harmful?) Algae Bloom
Marine Science support	Marine scientists (esp. biology)	CHL
Coastline/Bathymetry change, dredging/dumping	Sediment transport modellers	Suspended Particulate Matter (SPM) or Turbidity (TUR) for model val/initial
Offshore construction (environmental impact)	Govt + Offshore industry	Suspended Particulate Matter (SPM) or Turbidity (TUR)
Diving ops; Detection of subs, mines; marine animal vision	Diving industry Military, Biologists	Underwater visibility

Need many λ and high S:N

Need 2-3 λ

Need 2-3 λ

Chlorophyll a (CHL) retrieval

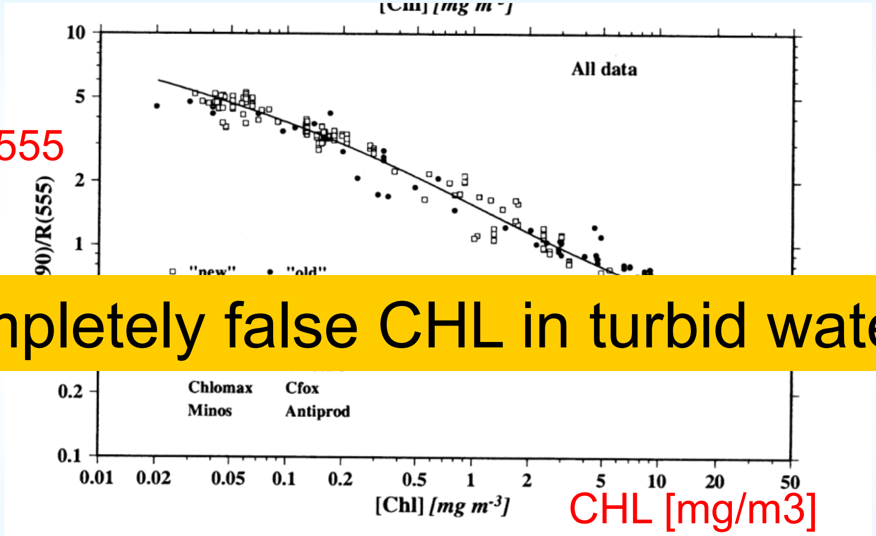
(for inversion approaches see Lectures by Roesler, Chase, etc.

CHL can then be derived from a_phyto using Relationships in lecture by Roesler)

Chlorophyll *a* retrieval: blue/green ratios

- In case 1 waters (phytoplankton only, no non-algae particles, CDOM correlated with phytoplankton), CHL varies continuously with blue:green reflectance ratio, e.g. Rrs490:Rrs555

Rrs490/Rrs555



CHL [mg/m3]

[Morel and Antoine, 2000]

Completely false CHL in turbid waters

$$\log_{10}\left(CHL-a_4\right)=a_0+a_1R+a_2R^2+a_3R^3$$

[O'Reilly et al, 1998]

$$R=\log_{10}\left(\max\left(R_{rs}^{443},R_{rs}^{490},R_{rs}^{510}\right)/R_{rs}^{555}\right)$$

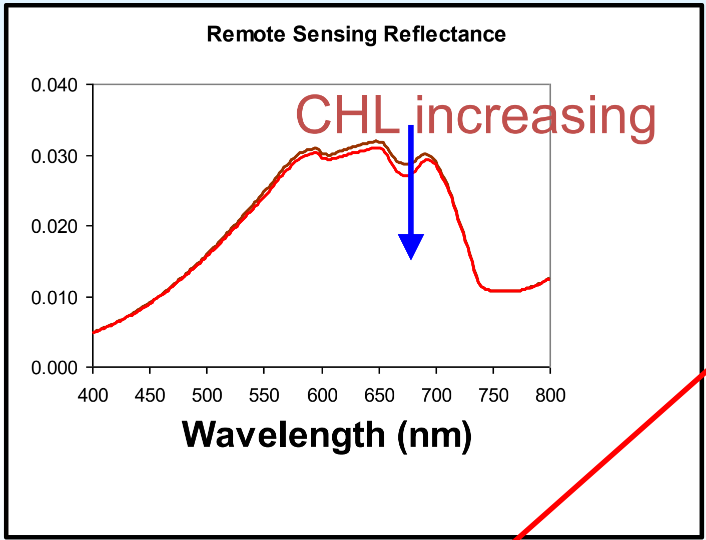
$$\left(a_0,a_1,a_2,a_3,a_4\right)=\left(0.4708,-3.8469,4.5338,-2.4434,-0.0414\right)$$

Chlorophyll *a* retrieval: red/Near infrared ratios

- In turbid waters with high NAP or CDOM absorption, CHL does not affect blue:green reflectance ratio, but CHL does affect red:near infrared ratio [Computer Exercise]

MERIS/OLCI/S2
709nm very useful

MODIS/VIIRS
748nm less useful



a_w708nm

a_w664nm

$$CHL = \frac{1}{0.016}\left\{\frac{R_{rs}^{708nm}}{R_{rs}^{664nm}}\left(0.70 + b_b\right) - 0.40 - b_b^{1.06}\right\}$$

a_φ664nm/CHL

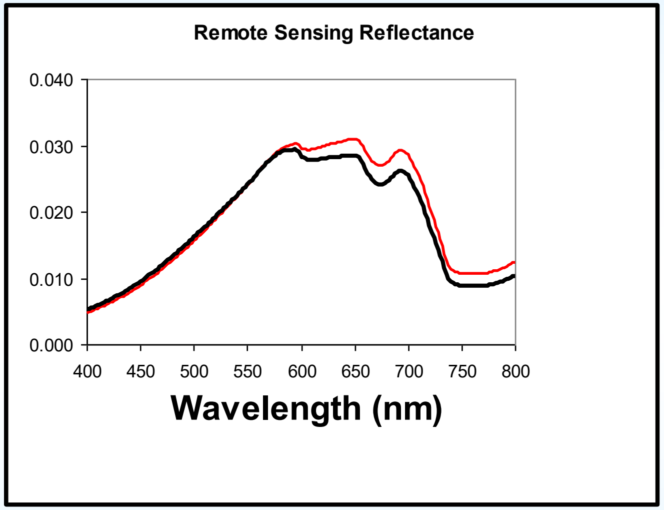
$$b_b = \frac{1.61 * \pi * R_{rs}^{778nm}}{0.082 - 0.6 * \pi * R_{rs}^{778nm}}$$

[Gons et al, 2005]

Also Gitelson, Gilerson, etc.

Chlorophyll a retrieval: multispectral fitting

- In more general case, can use all wavelengths to estimate chlorophyll a, non-algae particles and CDOM simultaneously:
  - Computer Exercise: you performed this interactively
  - Some processors, e.g. S3/OLCI Neural Network, do this automatically



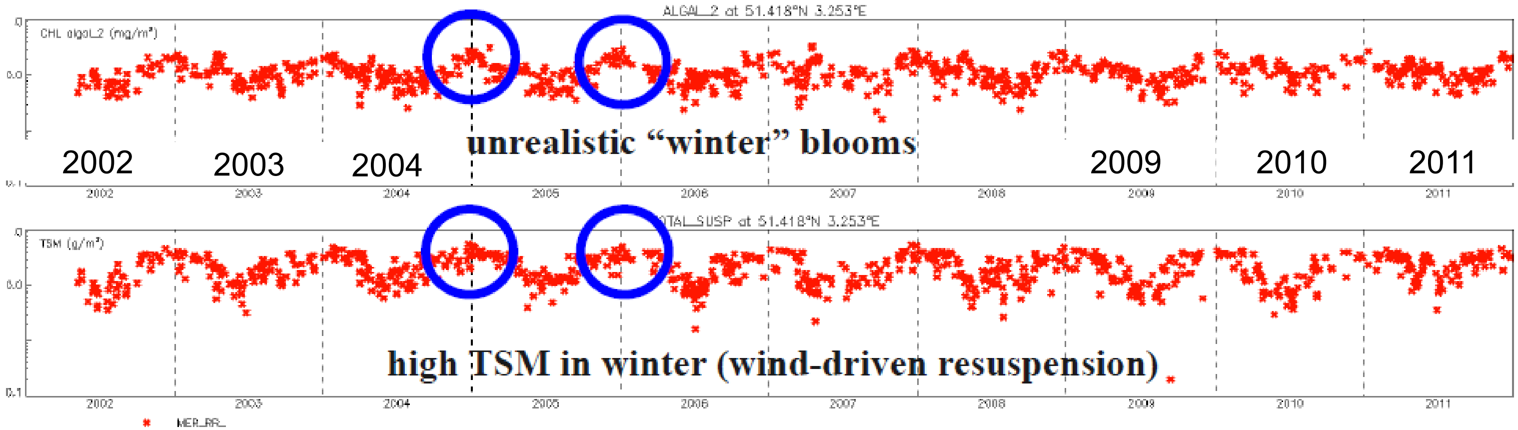
- Best approach for global processing for all waters?
- BUT what about multiple solutions? Understanding of physics ?
- Natural limits (CHL detection limit in high NAP/CDOM waters)

Some typical problems (Belgian turbid coastal location)

Time series from MERIS (R3, MEGS8.1)

CHL (mg/m^3) 100 10 1

TSM (g/m^3) 100 10 1

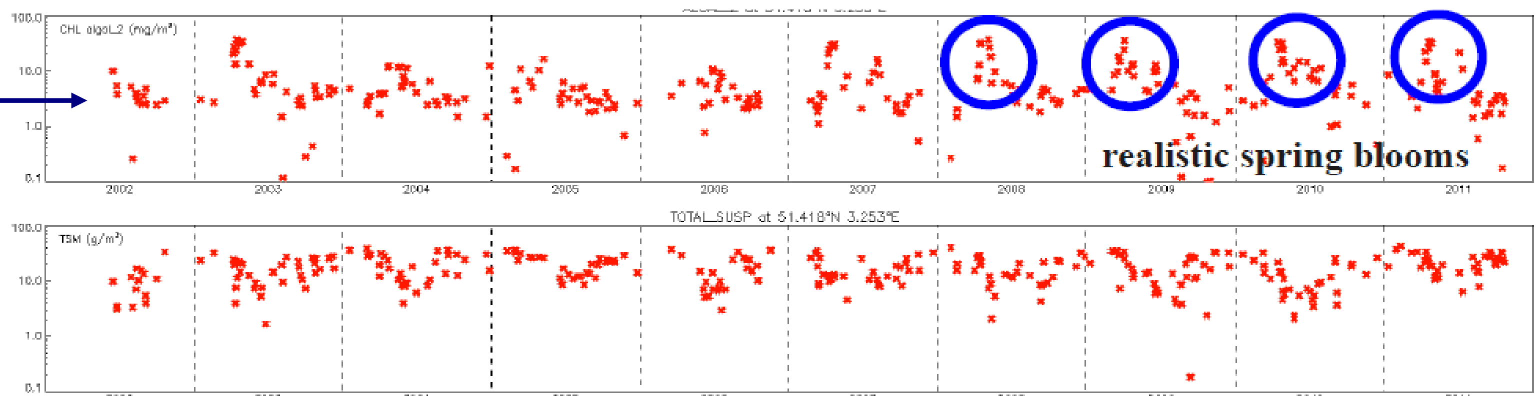


Time series from MERIS (R2, MEGS7.5)

Detection limit of about 3µg/l

CHL

TSM



[Vanhellemont Q. (2012). Invalidation of the MEGS 8.0 chlorophyll product in turbid waters. In: Proceedings of the 3rd MERIS/(A)ATSR and OCLI-SLSTR prep workshop, ESA SP-711]

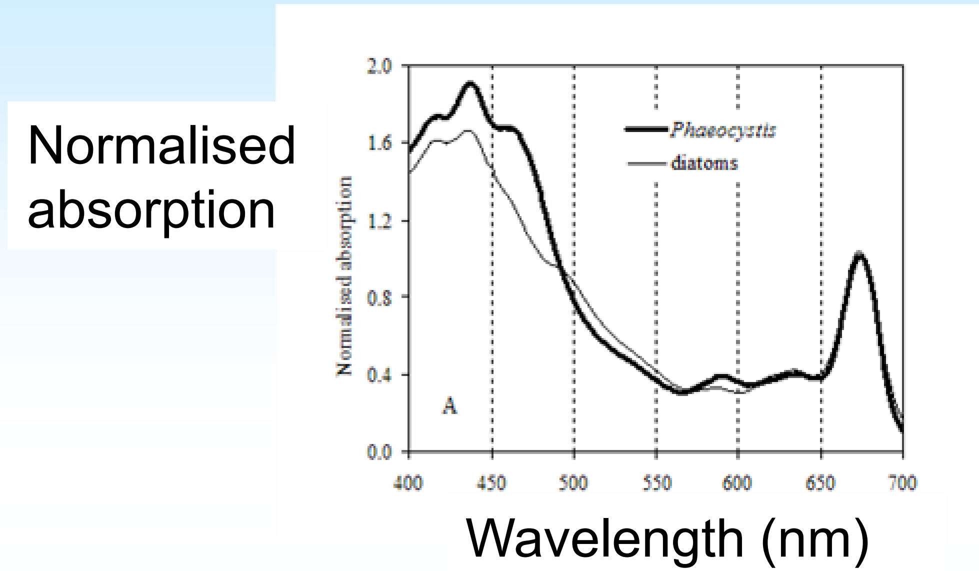
Beyond CHL … Phytoplankton functional types

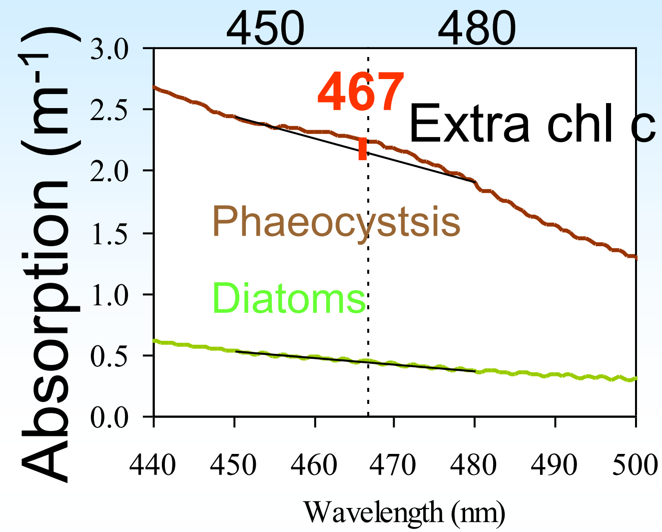
- There is also a strong user need for information beyond CHL:
  - Phytoplankton functional types
  - Species composition
  - Harmfulness
  - BUT CHL is difficult enough in turbid waters and species identification generally possible only in special cases (high biomass, distinctive IOPs)

  E.g.
  - “Red tide” *Noctiluca scintillans* [Van Mol et al, 2007]
  - High biomass (10-50µg/l) *Phaeocystis globosa* [Lubac et al, 2008; Astoreca, 2009]
  - Highly scattering *Coccolithophores* [Neukermans]
  - *Karenia mikimotoi* [Miller et al, 1998]
  - IOCCG Report 15 [Sathyendranath et al, 2014] (but out of 156 pages, Case 2 waters are a 0.5 page section) and [Bracher et al, 2017] (but again very little info for turbid waters)
  - Review by [Dierssen et al. 2020. Data needs for hyperspectral detection of algal diversity across the globe. https://doi.org/10.5670/oceanog.2020.111]

Phytoplankton species: Detection of *Phaeocystis globosa*

[Astoreca et al (2009). Development and application of an algorithm for detecting Phaeocystis globosa blooms in the Case 2 Belgian Waters. J Plankton Research, Vol. 31(3), pp. 287–300.]





Absorption algorithm

$$a_{c3}(467) = a_t(467) - 0.43 * a_t(450) - 0.57 * a_t(480)$$

Reflectance algorithm

$$a_{c3}(467) = [(1/\rho_w(467)) - (0.43/\rho_w(450)) - 0.57/\rho_w(480)] * a_w(700) * \rho_w(700)$$

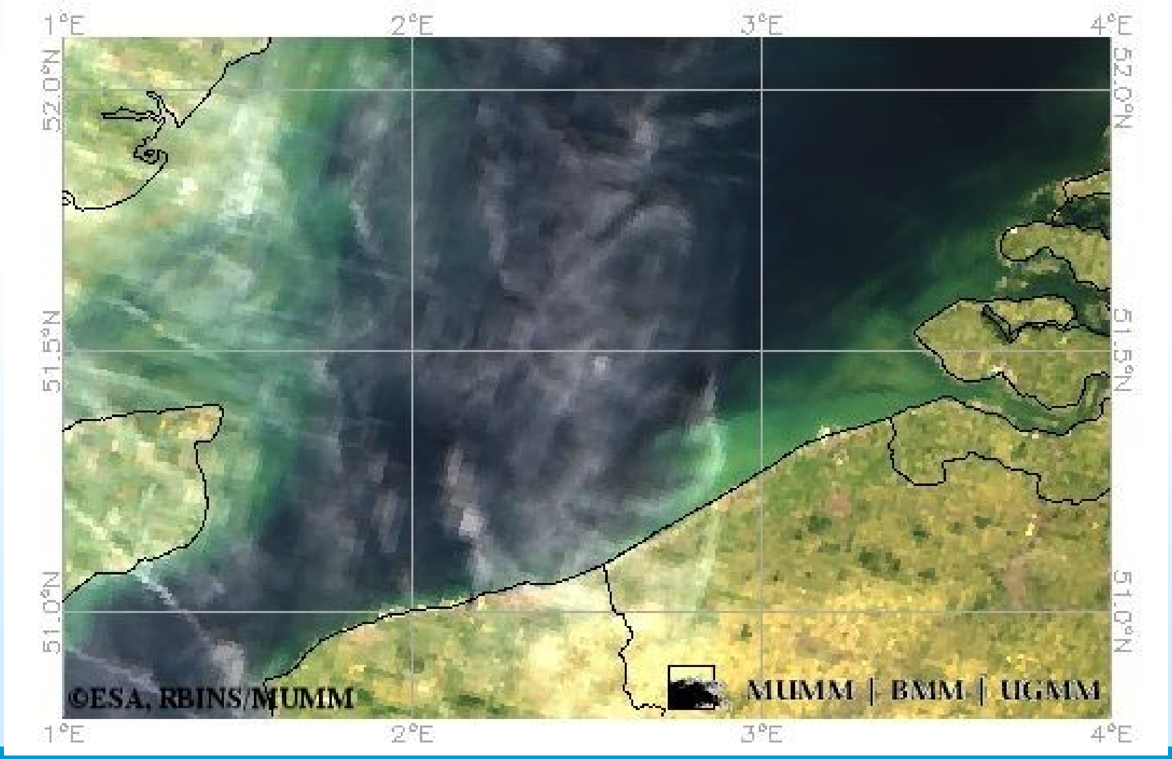
Suspended Particulate Matter (SPM) conc retrieval

=Total Suspended Matter (TSM) conc.
=Total Suspended Solids (TSS) conc.

Also (strongly correlated) turbidity, PAR attenuation, etc.

Suspended Particulate Matter (SPM) conc. retrieval

- SPM retrieval is generally "easier" than CHL in turbid waters because signal is strong - can be seen visually at top of atmosphere ("RGB" quasi true colour) or from aircraft
- e.g. MERIS top of atmosphere 11.6.2006 [Y.Park]



SPM-reflectance relationship

[Nechad et al (2010). Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. Rem Sens Env Vol. 114, pp. 854–866]

- Gordon/Morel reflectance model

$$R_{rs} = \gamma' \frac{b_b}{a + b_b} \quad \text{where} \quad \gamma' = \frac{f'\Re}{Q}$$

- Decompose IOPs:

$$a = a_{np} + a_p^* S$$

$$b_b = b_{bp}^* S$$

Suspended Particulate Matter

SPM-specific scattering, absorption

- Then

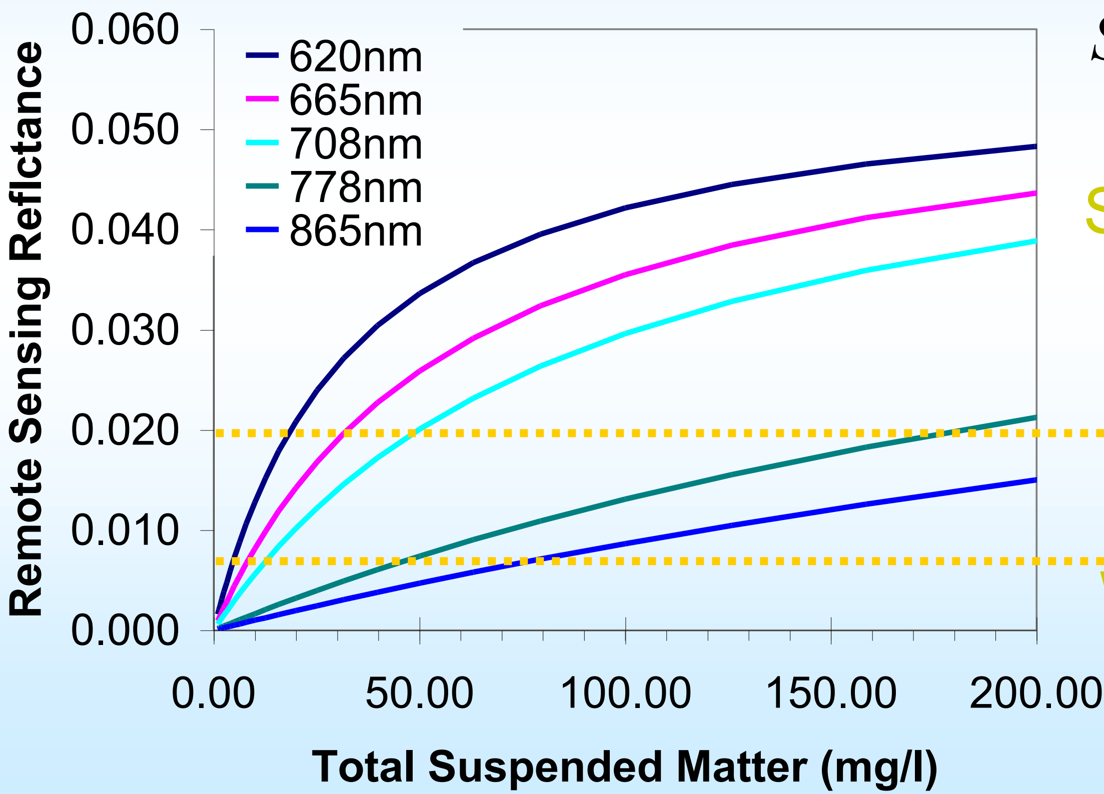
$$S = \left\{ \frac{A(\lambda)}{1 - R_{rs}(\lambda)/C} \right\} R_{rs}(\lambda) \quad \text{where} \quad A = \frac{a_{np}}{\gamma' b_{bp}^*}, \quad C = \frac{\gamma' b_{bp}^*}{a_p^* + b_{bp}^*}$$

Calibration

SPM retrieval algorithms: single band

- Remote-sensing reflectance, R_{rs}, at any single wavelength, λ , is almost linearly related to Suspended Particulate Matter, S

$$S = \left\{ \frac{A(\lambda)}{1 - R_{rs}(\lambda)/C} \right\} R_{rs}(\lambda)$$



SATURATION

[Luo et al, 2018]

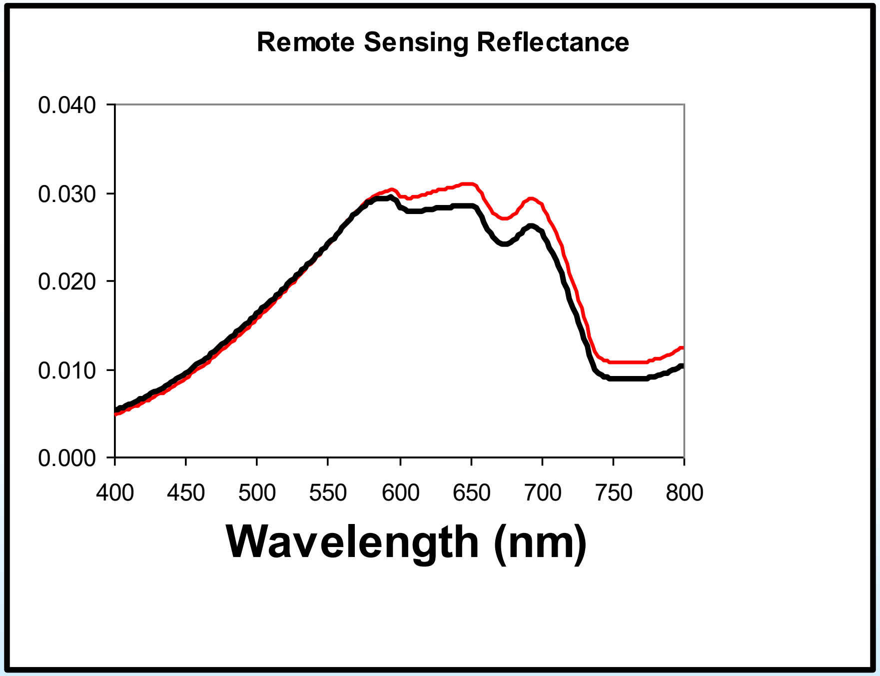
LINEAR (optimal)

WEAK SIGNAL

[Nechad et al, 2010; Shen et al, 2010]

SPM retrieval: multispectral fitting

- As for CHL, SPM can also be estimated by fitting modelled spectrum to full spectrum measured by satellite as in Computer Exercise



Beyond SPM conc … particle size, organic fraction, …

- Sedimentologists and marine biologists want more than "just" SPM concentration
  - Particle Size Distribution?
  - Organic fraction?
  - Carbon content??
- Status is generally in situ not remote sensing, research in progress
- BUT some promising ideas based on:
  - Absorption/Backscatter ratios?
  - Backscatter spectral slope (PSD)? !BEWARE!
  - Angular variation of scattering (multi-look sensors)??
  - Polarization??

Underwater visibility

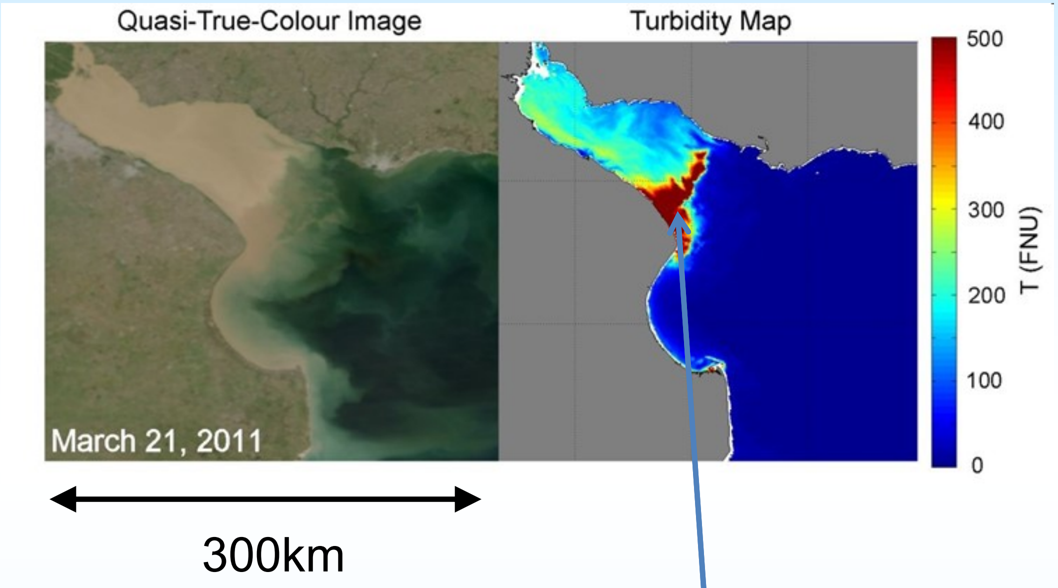
marine humans

… and other marine animals

- RBINS receives requests for visibility predictions ("optimal diving window") for various diving operations

From: [Subsea World News] "Specialist divers battling strong tides and zero-visibility have completed a year-long project to cover parts of an exposed underwater pipeline in the Humber estuary."

La Plata turbidity mapping [Dogliotti et al, 2011]



Visual predators cannot see here, safe haven for prey , e.g. fish larvae

Larmuseau et al (2009) suggest that Wavelength of Maximally Transmitted Light may affect genetic adaptation of fish (rhodopsin in sand gobies)

CHL and SPM algos - summary

- CHL problems in turbid waters because of non-algae particle absorption
  - => use RED/NIR or multispectral algos, which include RED
- SPM retrieval in turbid waters is « easy »
  - Can use single band, band ratio, multispectral algos

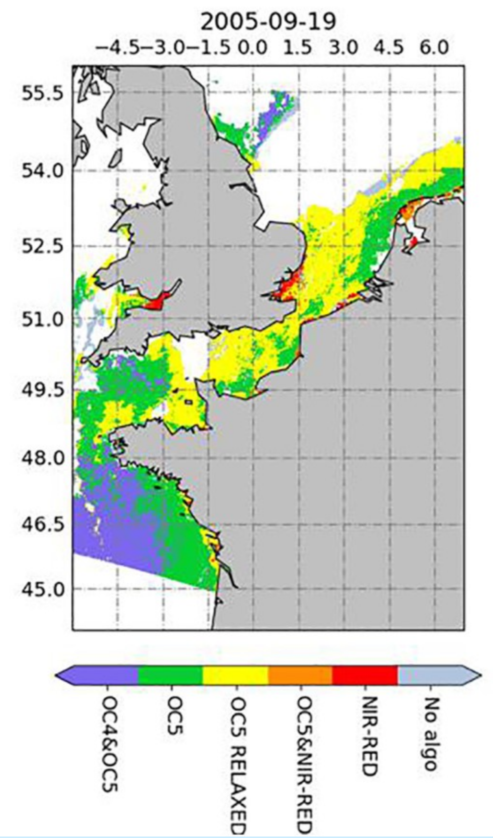
    Increase wavelength for increasing SPM
    [Shen et al, 2010; Nechad et al 2010; Dogliotti et al, 2015; Novoa et al 2017]
- Transparency and/or diffuse attenuation algos for turbid waters exist (not so difficult)
- Other issues:
  - Cloud masking
  - BRDF
  - Stratification

Miscellaneous

- Quality flagging and product uncertainty estimation are an important research field:
  - E.g. a) Spectral fit-based uncertainty, b) multitemporal EOF [Sirjacobs et al, 2011], c) theoretical *a priori* uncertainty estimation d) QC applicability of algo

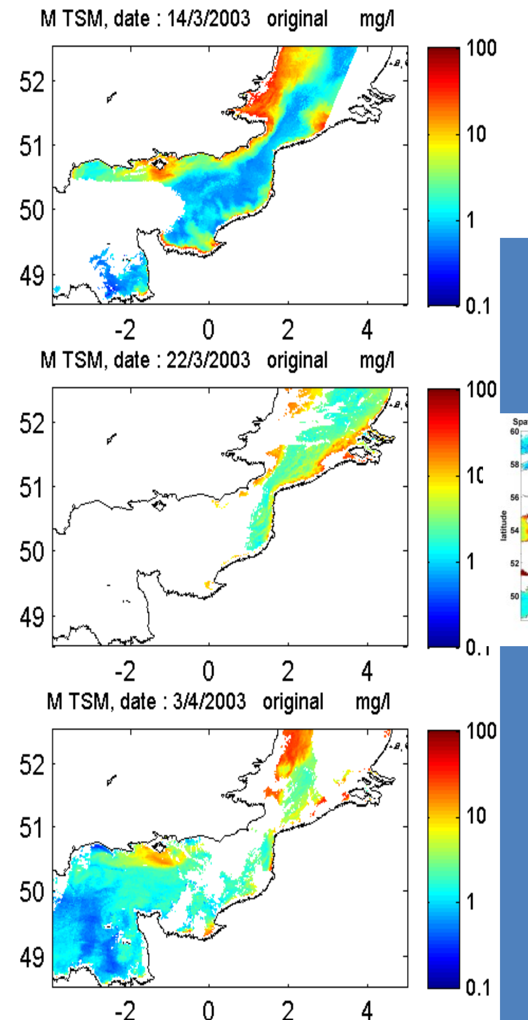
e.g. Lavigne H. et al. Quality-control tests for OC4, OC5 and NIR-red satellite chlorophyll-a algorithms applied to coastal waters (2021)

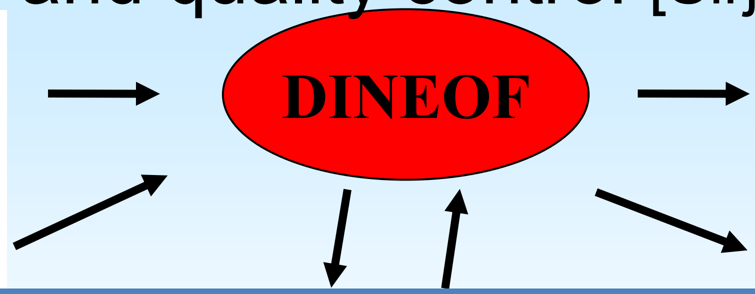
https://doi.org/10.1016/j.rse.2020.112237



D. Sirjacobs, et al. Cloud filling of ocean color and sea surface temperature remote sensing products over the Southern North Sea by the Data Interpolating Empirical Orthogonal Functions methodology. Journal of Sea Research, 65(1):114-130. 2011.

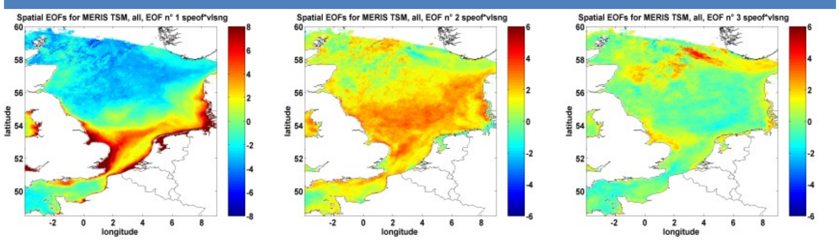
Filling clouds … and quality control [Sirjacobs et al, 2011]



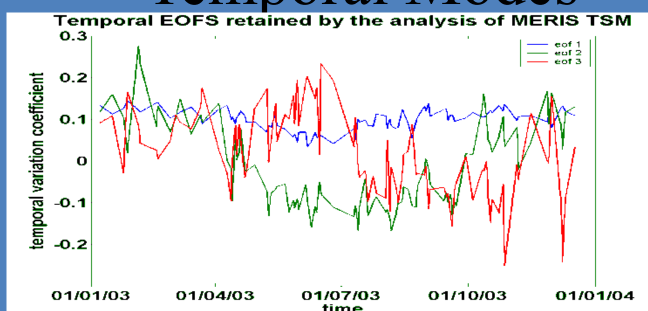


Mean = log10(µg/l)

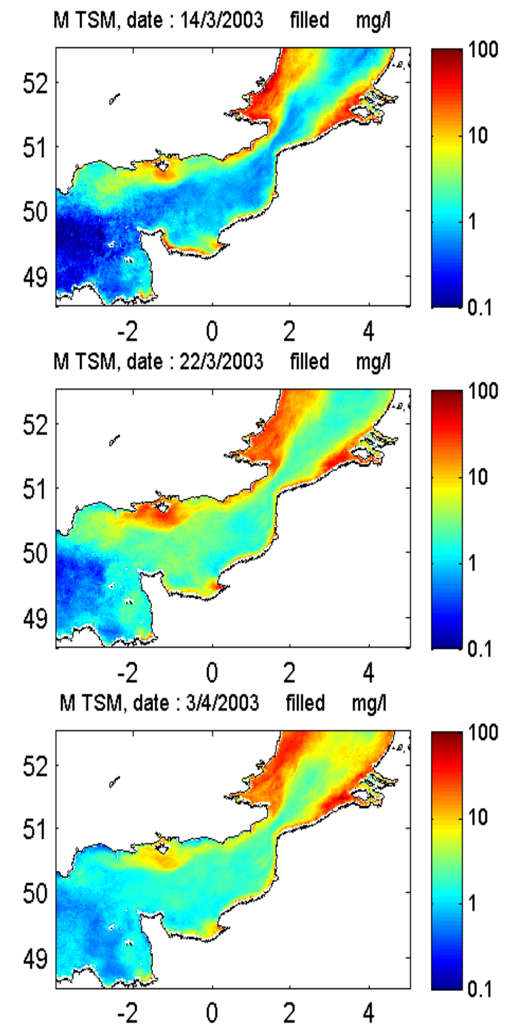
Spatial Modes



Temporal Modes



Singular Values



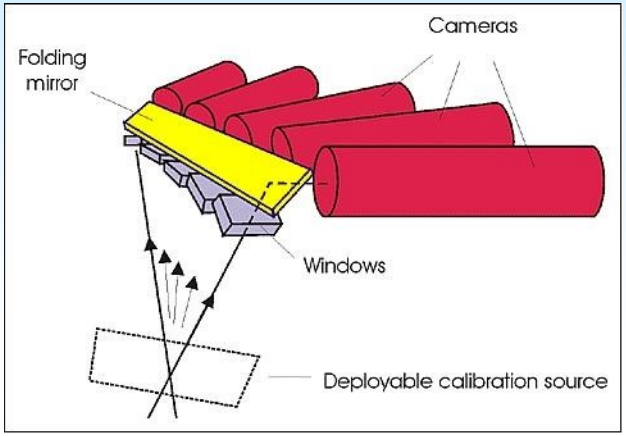
Optical remote sensing in turbid waters

	Capabilities	Limitations	Research
Parameter	SPM, CHLa, Kd (and IOPs)	Just SPM, CHLa, Kd No vertical structure No flux info	
Temporal	~Daily since 2003 Near Real Time (~2h)	Clouds! No tidal info ex GEO	
Spatial	1m-1000km		
SPM Conc.	0.1-2000 g/m3	Need SWIR for highest conc	
Accuracy	Absolute: 30-50% SPM? Relative: good		
Issues		Near land (~1km) Sunglint Atmospheric Corr. Clouds + Shadows	

Optical Remote Sensing – future systems

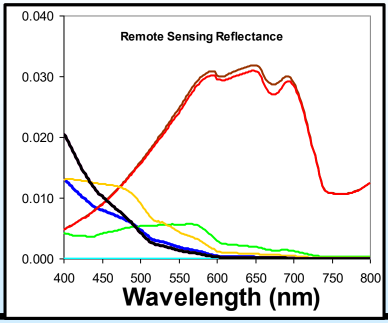
Platform

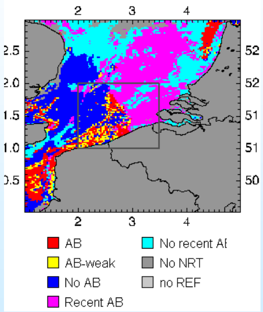
Sensor



Processing/Distribution

$$S = A\frac{\rho_w}{1-\rho_w/C}$$

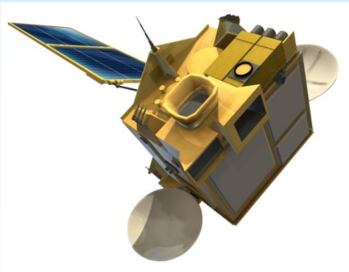




Optical Remote Sensing – future systems

Platform

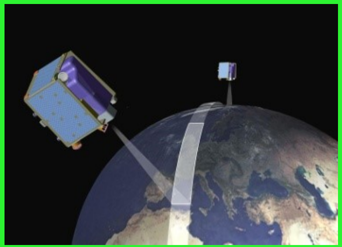
Geostationary



Hourly GOCI data since 2010 (Korea/Japan/China)

US plans ramping up (GLIMR)

Pointable minisats

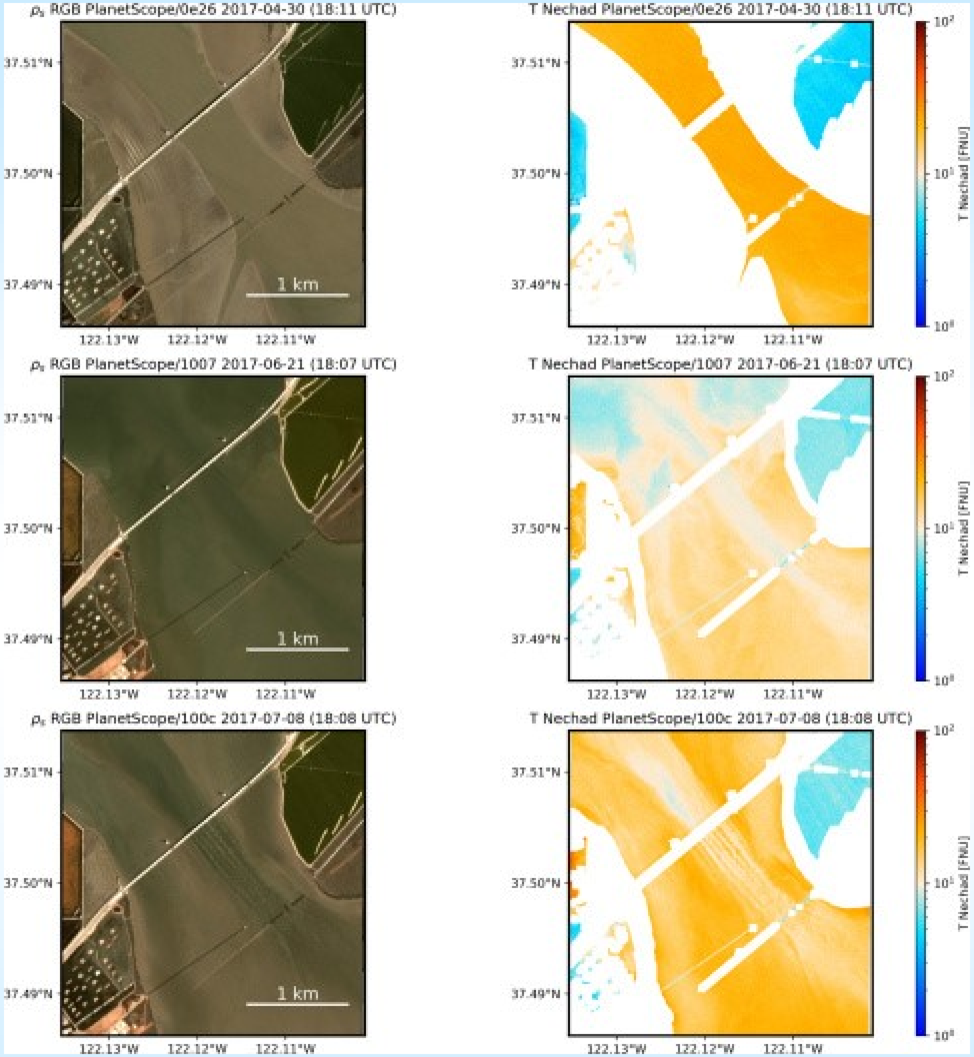


e.g. Planetscope Constellation: daily revisit, 4m

Unmanned airborne

[www.gatewing.com]

Hot topic - cubesat constellations

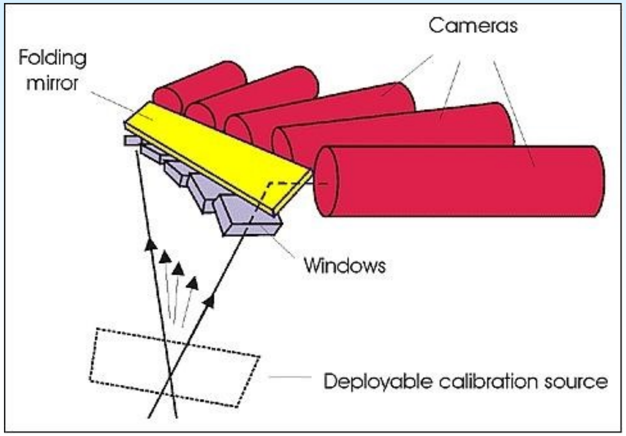


[Vanhellemont Q. **Daily metre-scale** mapping of water turbidity using CubeSat imagery (2019), https://doi.org/10.1364/OE.27.0A1372]

Optical Remote Sensing – future systems

Platform

Sensor



Processing/Distribution

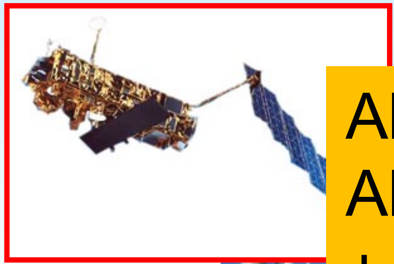
$S = A$

$1-$

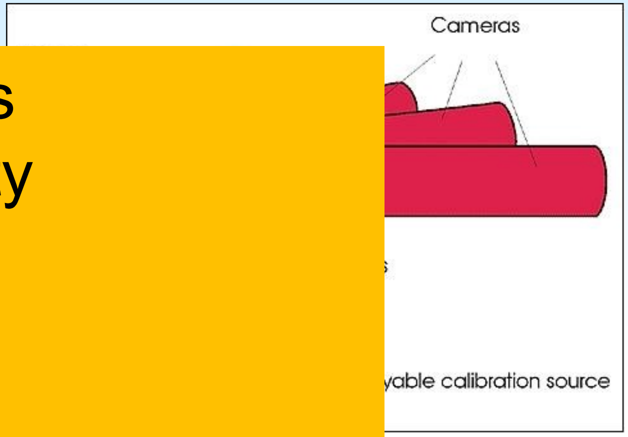
Higher spatial resolution
Better signal:noise
More spectral bands … hyperspectral
From UV (380nm) to SWIR (2.3µm)

Optical Remote Sensing – future systems

Platform



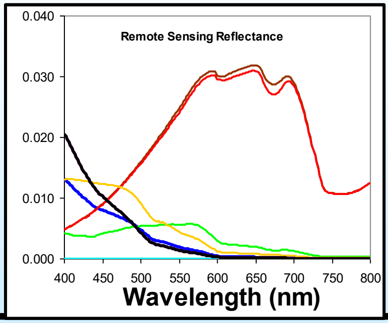
Sensor

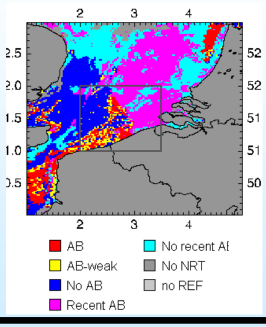


Algorithms for more products
Algorithms for QC/uncertainty
+
Multimission processing
(time series, synergies, etc.)

Processing/Distribution

$$S = A\frac{\rho_w}{1-\rho_w/C}$$





Multi-mission context for sediment transport (not exhaustive!)

Satellite/Sensor	Period	Spatial Resolution	Temporal Resolution
SeaWiFS	1997-2010	1000m	Daily
MODIS-TERRA	1999-2022?	250m	Daily
MODIS-AQUA	2002-2022?	250m	Daily
ENVISAT-MERIS	2002-2012	300m	~4/week
VIIRS	2011+	1000m	Daily
Sentinel-3AB/OLCI	2015+	300m	Daily (2 sats)
Planetscope/Doves	2015+	4m	Daily
Landsat-5	1984-2013	30m	Every 16 days
Landsat-8 and -9	2013+	30m	Every 8 or 16 days
Sentinel-2AB	2015+	10m	~3/week (2 sats)
Pléiades	2011+	2m/70cm	On demand
SEVIRI-MSG	2004+	5000m	Every 5 minutes

CONCLUSIONS

- Turbid waters have high socio-economic importance
  - User need => more intensive use of r/s for science, monitoring, etc.

- Processing problems include:
  - CHL retrieval in presence of high non-algal particle absorption
  - Aerosol correction where near infrared water reflectance non-zero
  - Sunglint for near nadir-viewing sensors (Sentinel-2, Landsat-8/9)
  - Adjacency effects for small inland waters
- Many new algorithms are products are emerging:
  - Inherent Optical Properties
  - Spectral diffus
  - Specific phytoplankton blooms
  - Quality and/or uncertainity estimates

Programming skills are most important!

- What does the present/future hold?
  - High frequency data from geostationary (SEVIRI, GOCI, …, GLIMR)
  - More and more information on particles? (size, type, organic content…)
  - High spatial resolution (Landsat-8, Sentinel-2, Pléiades, Rapideye/Planetscope, Unmanned Airborne Vehicles)
  - Hardware improvements very fast both for satellites and computers (Google Earth Engine!) …

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