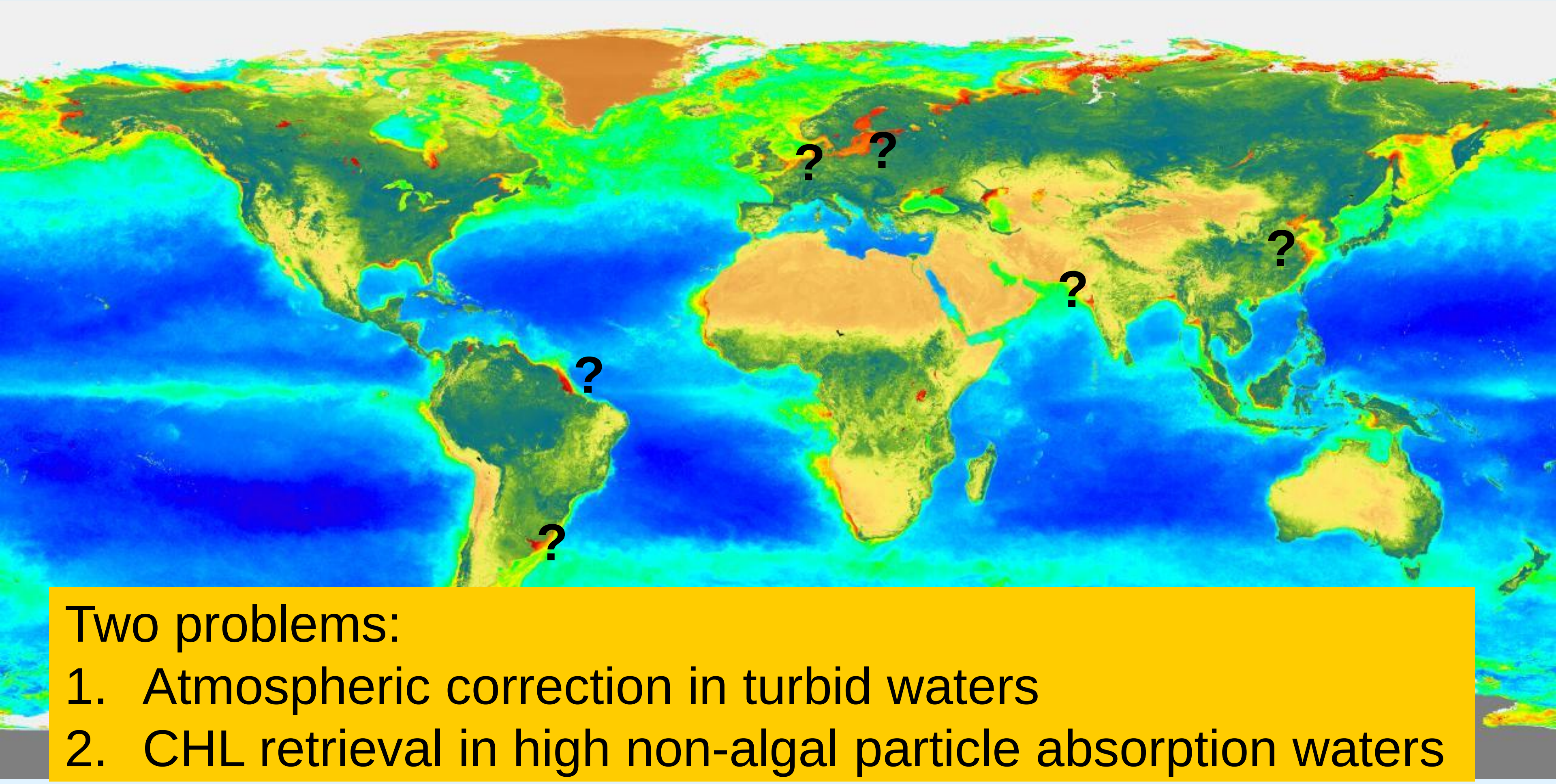
The problems of turbid waters (from a global CHL perspective)



Two problems:

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

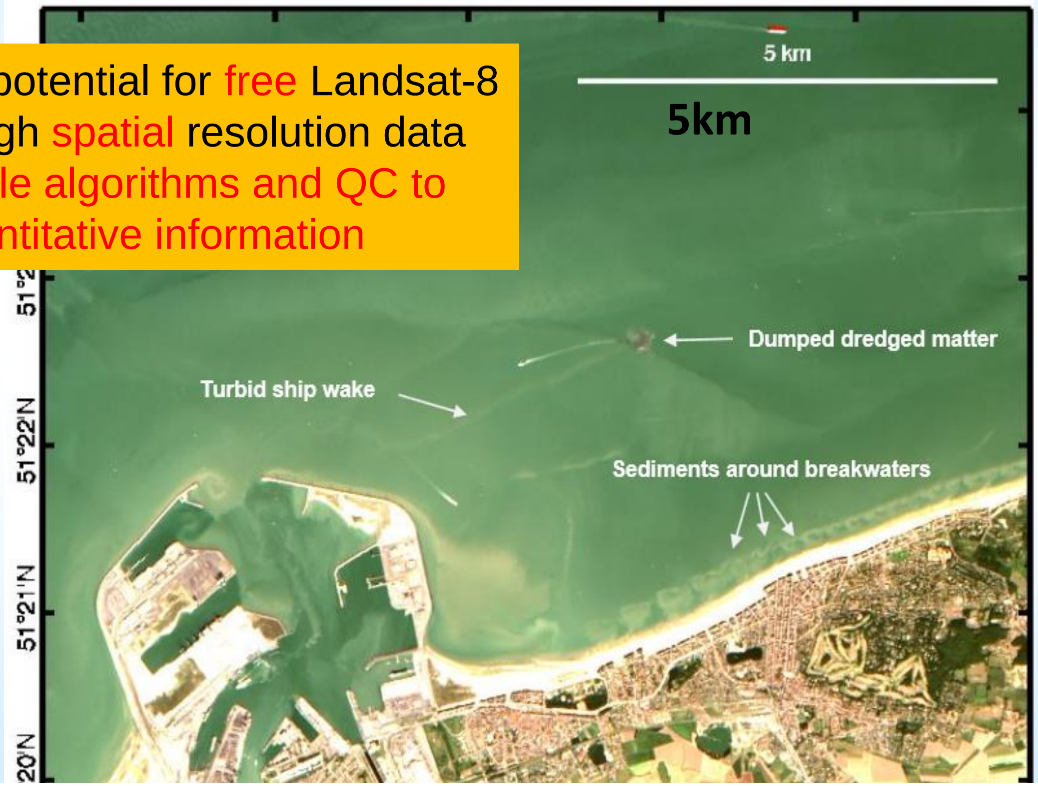
e.g. SeaWiFS CHLa composite Sept1997-Aug1998, v1 processing

RED=high CHLa (or NOT?)

The New (high resolution) World of 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.

Optical ~~Ocean Colour~~ Remote Sensing in (coastal and inland) Turbid Waters

by Kevin Ruddick

with support from RBINS-REMSEM researchers, past and present

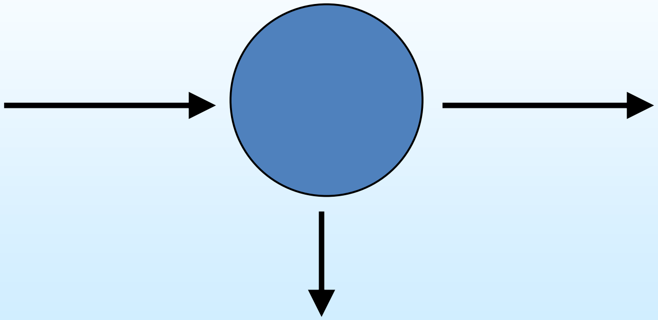
(Ana Dogliotti, Héloise Lavigne, Bouchra Nechad, Griet Neukermans, Youngje Park, Dimitry Vanderzande, Quinten Vanhellemont, Barbara Van Mol) and BELCOLOUR/HIGHROC/HYPERMAQ project partners

Overview of the Lectures

- Scope = issues specific to turbid waters, especially:
  - Chlorophyll and Suspended Particulate Matter conc. retrieval in turbid waters
  - Atmospheric correction in turbid waters: Quinten's practical
  - ALSO new parameters, applications, etc.
- Assumes basic knowledge of:
  - Absorption, scattering and reflectance [Boss, Slivkoff, Stramski, Twardowski]
  - Ocean Colour algorithms [Hedley, Lee]
- Lecture organisation:
  - Weds 4th 14:00-14:45 Lecture 1 - Introduction to turbid waters (Kevin)
  - Weds 4th 14:45-15:30 Lecture 2 - ACOLITE intro and demo (Quinten)
  - Weds 4th 16:00-17:30 ACOLITE practical (The Students)
  - Thurs 5th 09:00-09:30 MORS Excel water colour model intro (Kevin)
  - Thurs 5th 09:30-10:30 MORS Excel water colour modelling (The Students)
  - (Thurs 5th 17:30+ Quinten and Kevin available for ACOLITE practical follow-up)
  - Friday 6th 14:00-15:30 Student presentations of ACOLITE/Copernicus practicals
  - Friday 6th 16:00-17:30 Student presentations of ACOLITE/Copernicus practicals

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

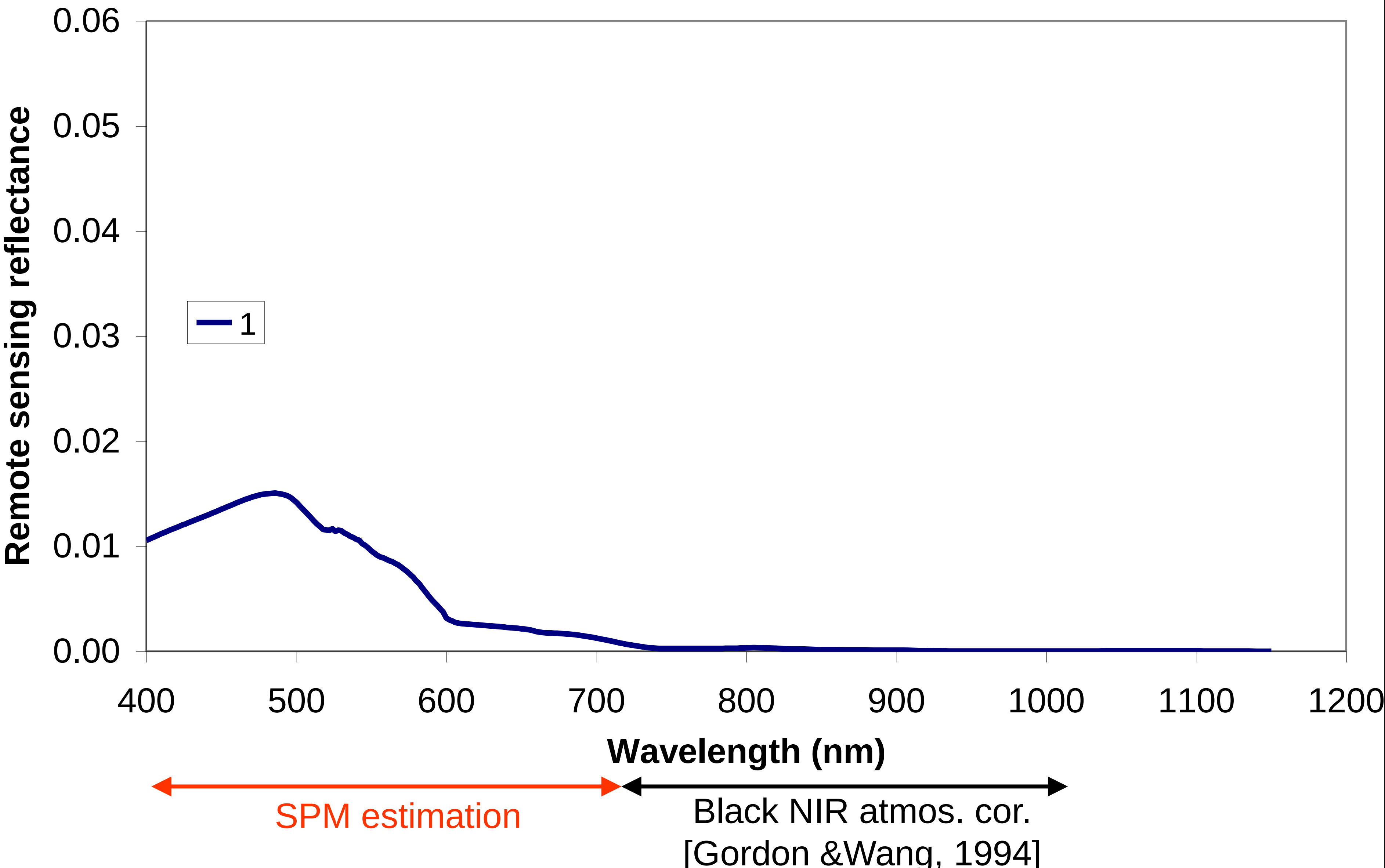
Description	Turbidity, bs (FNU)	Suspended Particulate Matter, SPM (g/m3)	*Secchi depth (m)*	Scattering, b_555 (m-1)	Backscattering, bb_555 (m-1)	Water Reflectance at 778nm=PI*Rrs778
Clear	<1.1	<1	*>10m*	<0.5	<0.01	<0.0008
Moderately turbid	1.1-11	1-10	*2-10m*	0.5-5	0.01-0.1	0.0008-0.008
Very turbid	11-110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

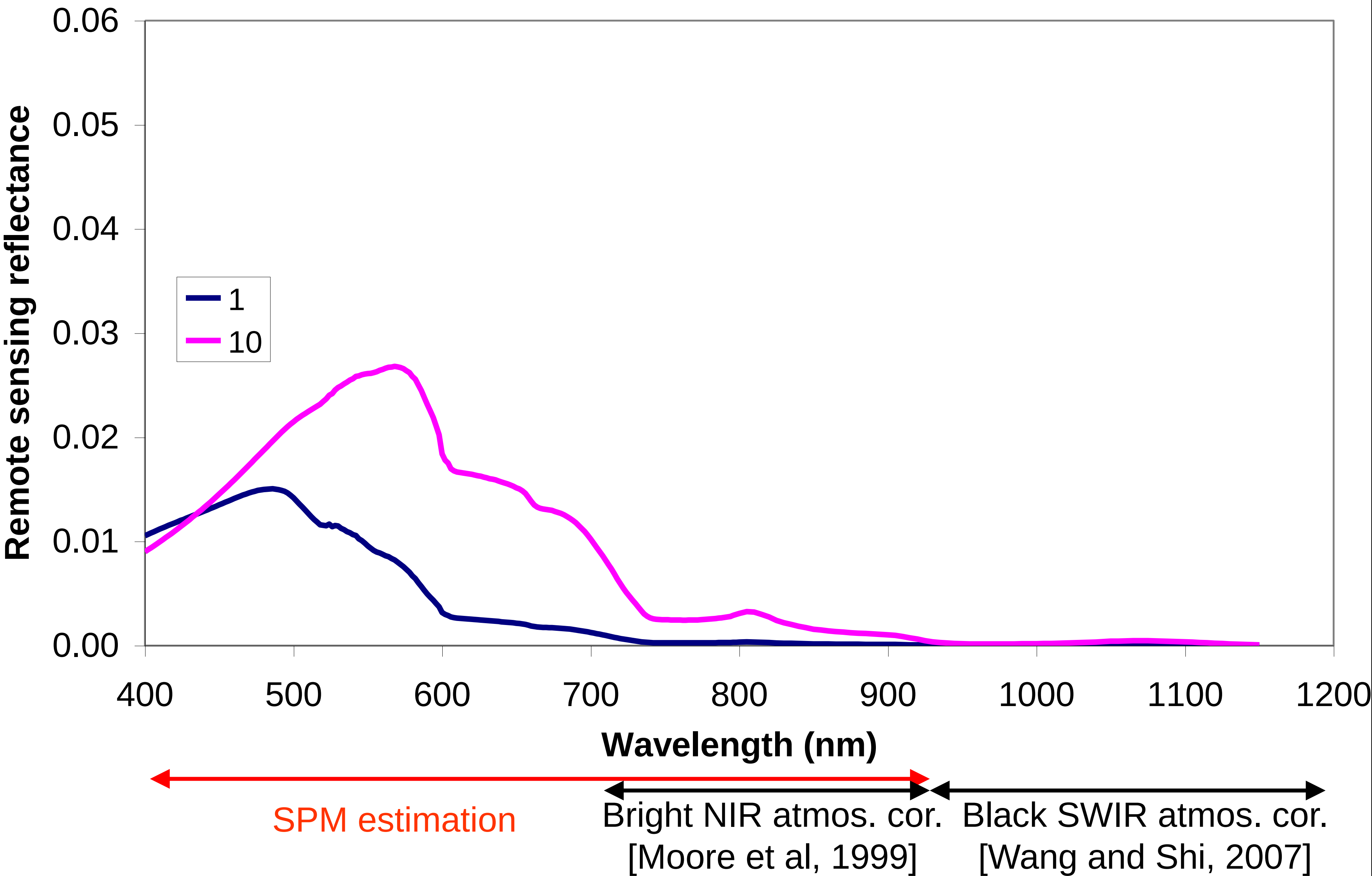
Neukermans et al (2012). In situ variability of mass-specific beam attenuation and backscattering of marine particles with respect to particle size, density, and composition. Limnol Oceanogr. 57, 124–144

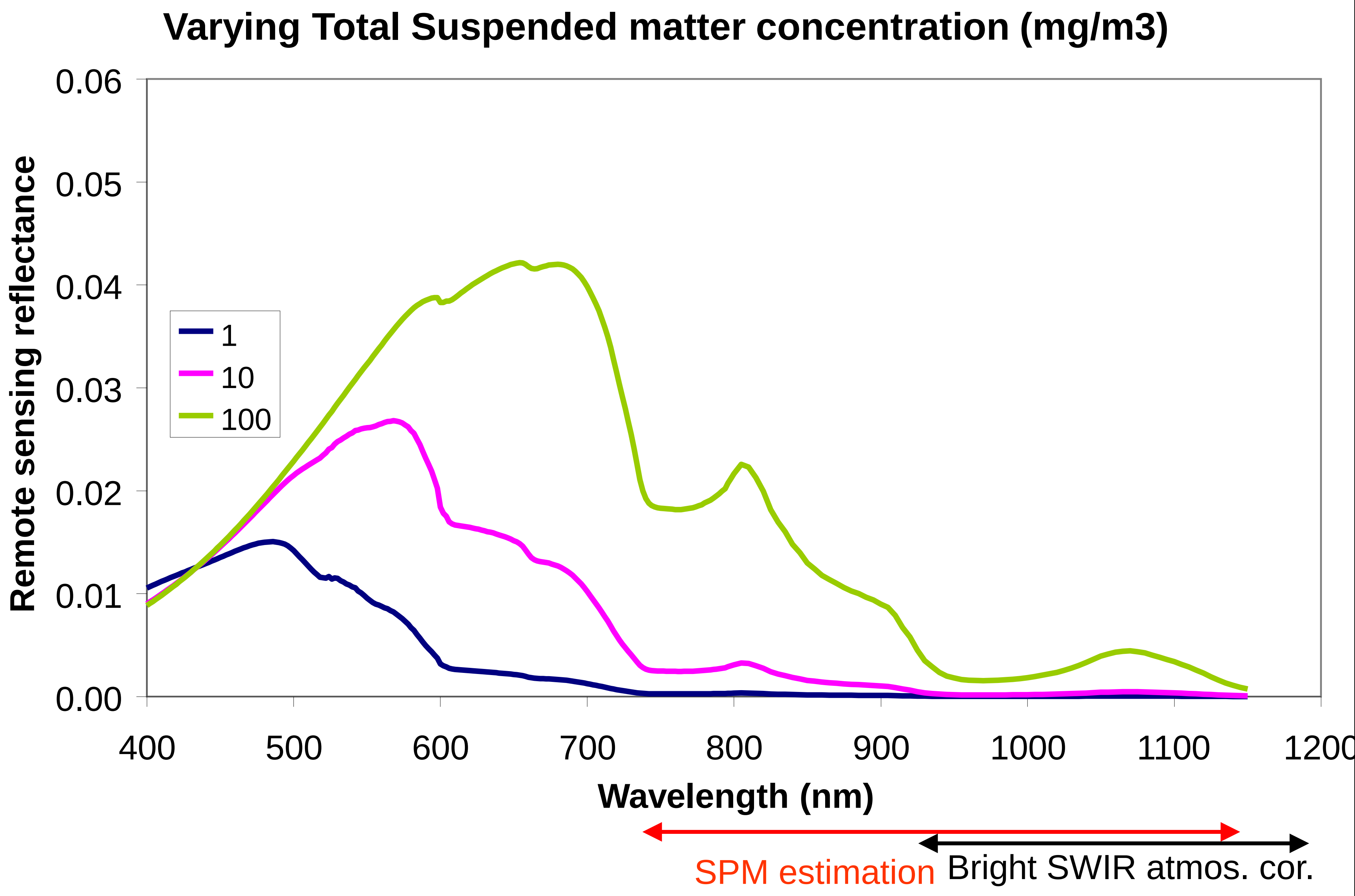
Babin, et al (2003). Light scattering properties of marine particles in coastal and oceanic waters as related to the particle mass concentration. Limnol Oceanogr. 48, 843-859

Varying Total Suspended matter concentration (mg/m3)

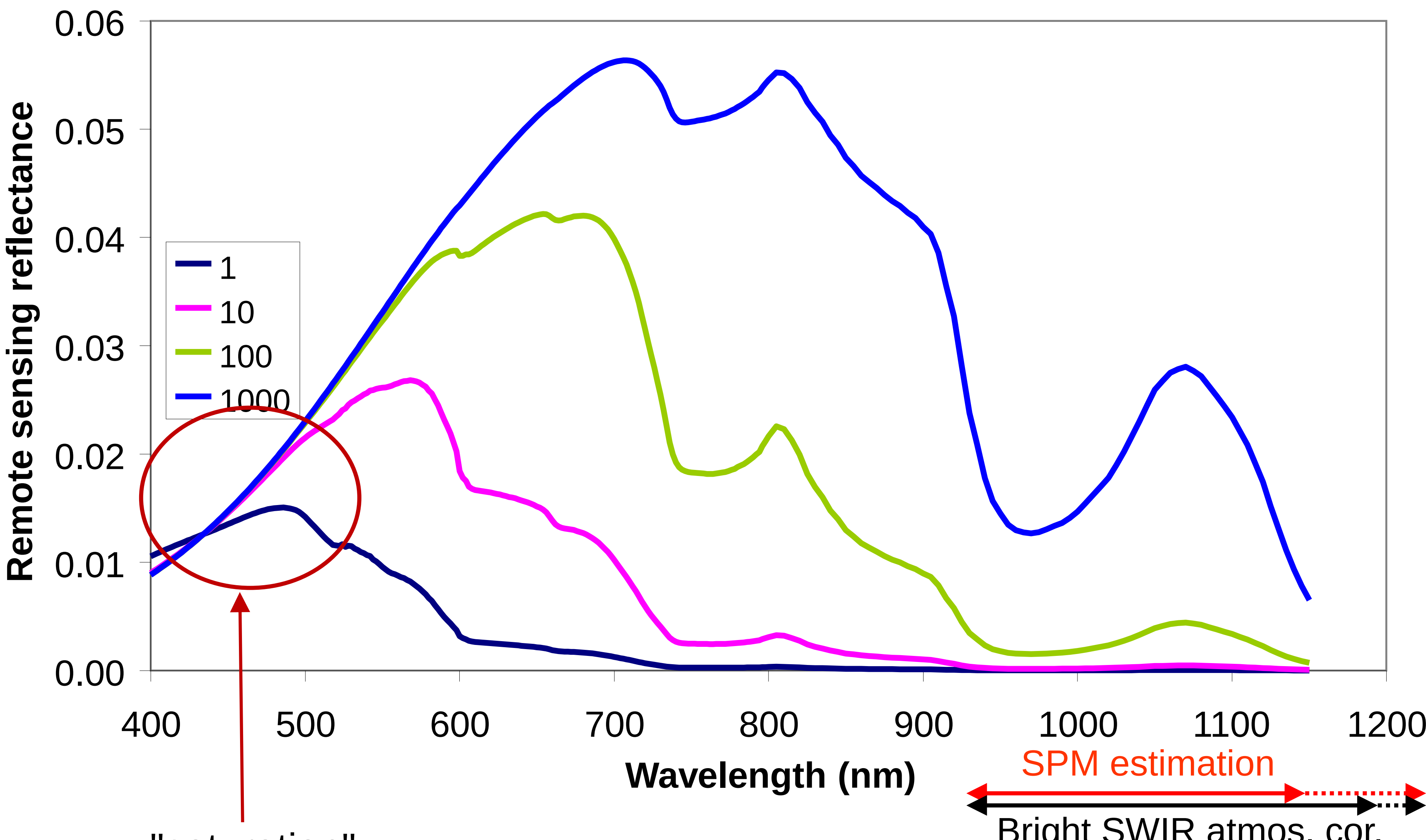


Varying Total Suspended matter concentration (mg/m3)




Varying Total Suspended matter concentration (mg/m3)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Remote sensing reflectance
1
10
100
400
500
600
700
800
900
1000
1100
1200
Wavelength (nm)
SPM estimation
Bright SWIR atmos. cor.

Varying Total Suspended matter concentration (mg/m3)



"saturation"
[Luo, Doxaran et al, 2018]

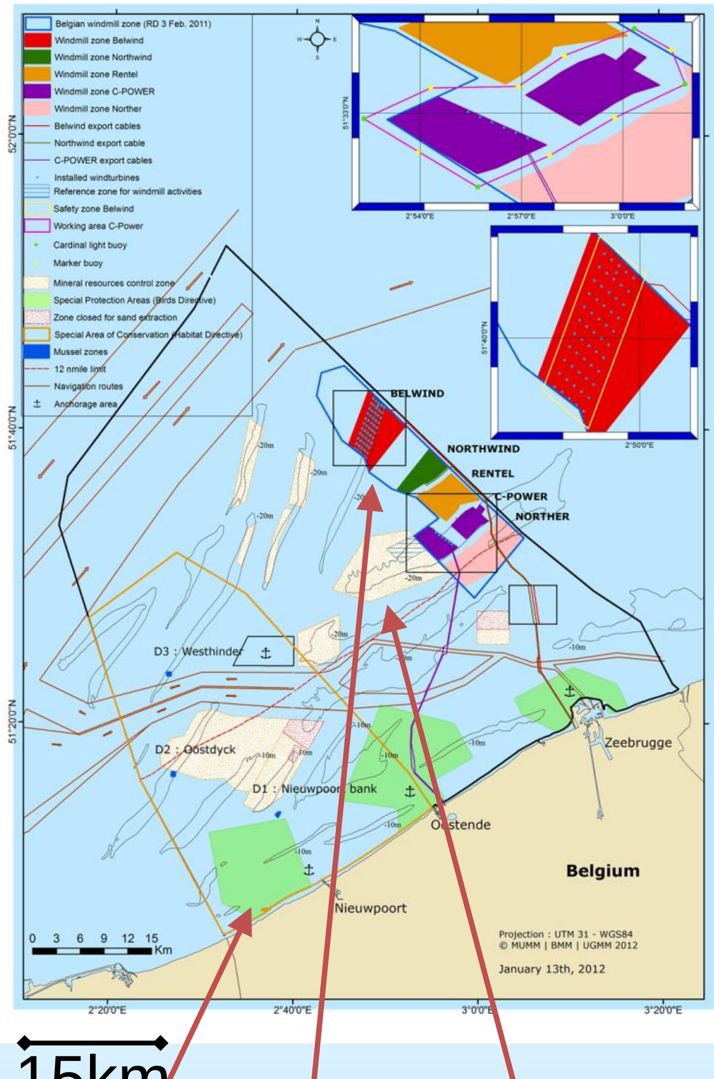
[Knaeps et al, 2012] measured non-zero 1020nm reflectance, proportional to SPM

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



Belgium: windmills, sand extraction, nature [MUMM/BMDC]

Problems AND advantages for remote sensing

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

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

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

    => Can more easily see turbid waters
- AND:
  - Many new applications and parameters compared to Case 1 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 PAR, PAR 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

Useful parameters

Remote sensing reflectance

Total Absorption, a

Total Backscatter, b_b

Spectral or PAR Diffuse atten., K_{ed} (Euphotic depth, Bottom PAR, etc.)

Algal Particle Absorption, a_ph

Chlorophyll a, CHL

Phyto species?

Particulate backscatter, b_bp

Particulate sidescatter, b_bs

Susp Part. Matt. Conc, SPM

Particle size/type?

Settling velocity??

ISO Turbidity, TUR

CDOM absorption, a_CDOM

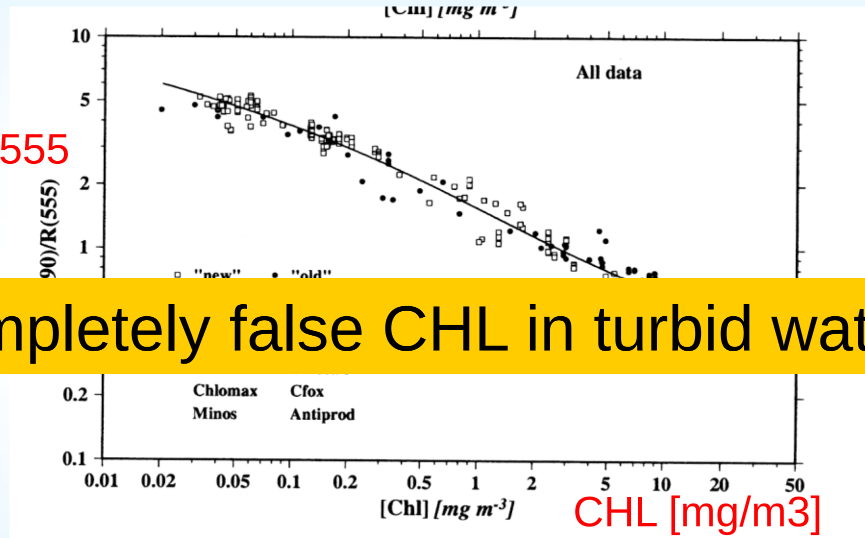
Chlorophyll a (CHL) retrieval

(for IOP inversion approaches see Lecture by Lee, CHL can then be derived from a_phyto using Relationships in "BGC" lecture by Boss)

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

$$\log_{10}\left(CHL - a_4\right) = a_0 + a_1 R + a_2 R^2 + a_3 R^3$$

[O'Reilly et al, 1998]

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

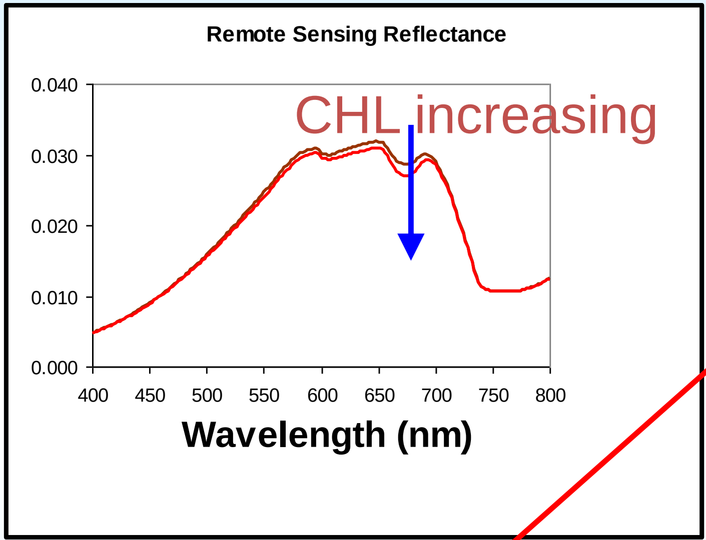
$$\left(a_0, a_1, a_2, a_3, a_4\right) = \left(0.4708, -3.8469, 4.5338, -2.4434, -0.0414\right)$$

Chlorophyll *a* retrieval: red/Near infrared ratios

- In turbid (case 2) 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 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

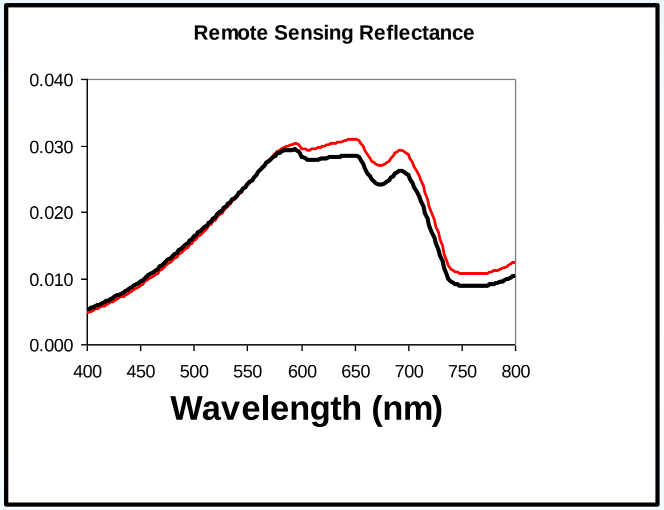
$$b_b = \frac{1.61 * \pi * R_{rs}^{778nm}}{0.082 - 0.6 * \pi * R_{rs}^{778nm}}$$

[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



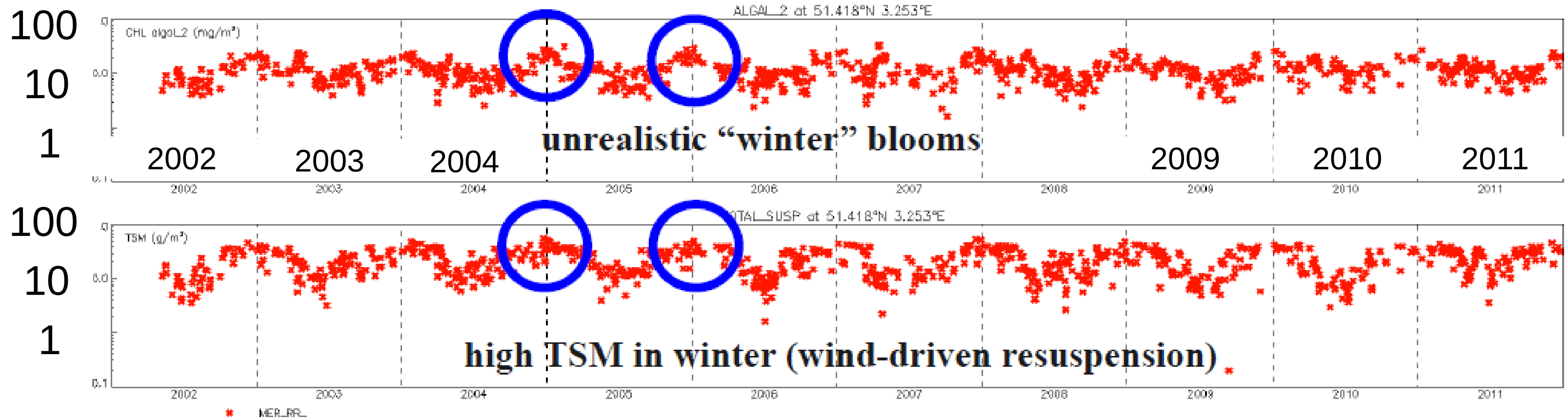
- Best approach for global processing for all waters?
- BUT what about multiple solutions? Understanding of physics ?
- Natural limits (CHL detection limit in high NAP/CDOM waters)

Some typical problems (Belgian turbid coastal location)

Time series from MERIS (R3, MEGS8.1)

CHL (mg/m^3)

TSM (g/m^3)

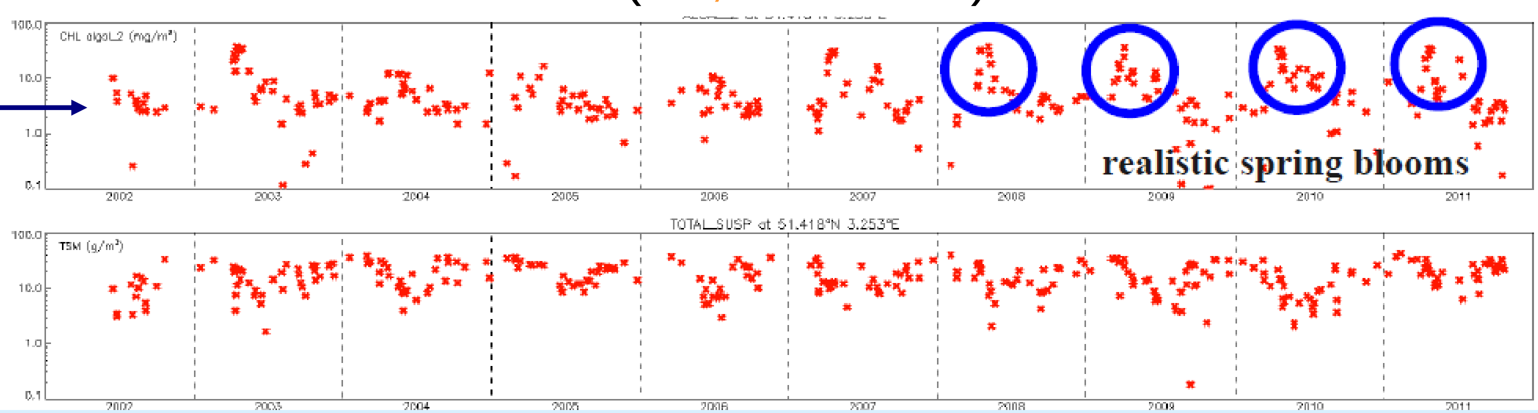


Time series from MERIS (R2, MEGS7.5)

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]

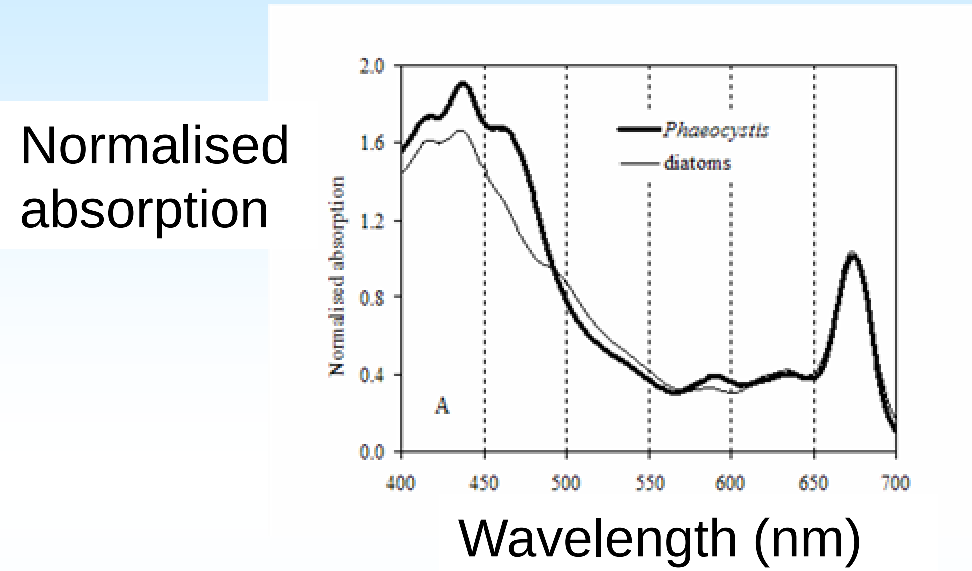
Beyond CHL … Phytoplankton functional types

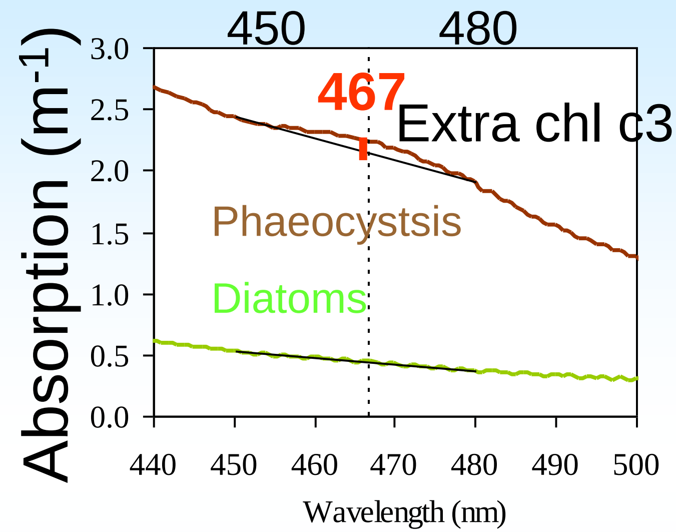
- There is also a strong user need for information beyond CHL:
  - Phytoplankton functional types
  - Species composition
  - Harmfulness
  - BUT CHL is difficult enough in turbid waters and species identification generally possible only in special cases (high biomass, distinctive IOPs)

  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* [Lecture 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)

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

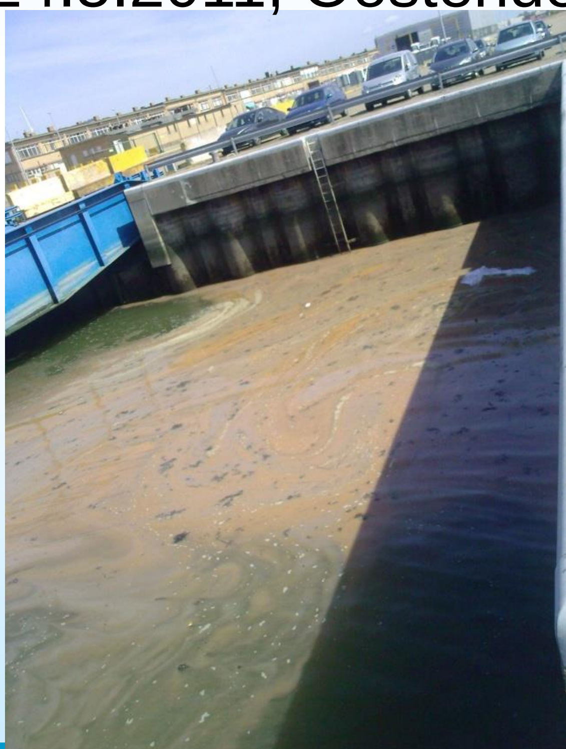
$$a_{c3}(467) = [(1/\rho_w(467)) - (0.43/\rho_w(450)) - 0.57/\rho_w(480)] * a_w(700) * \rho_w(700)$$

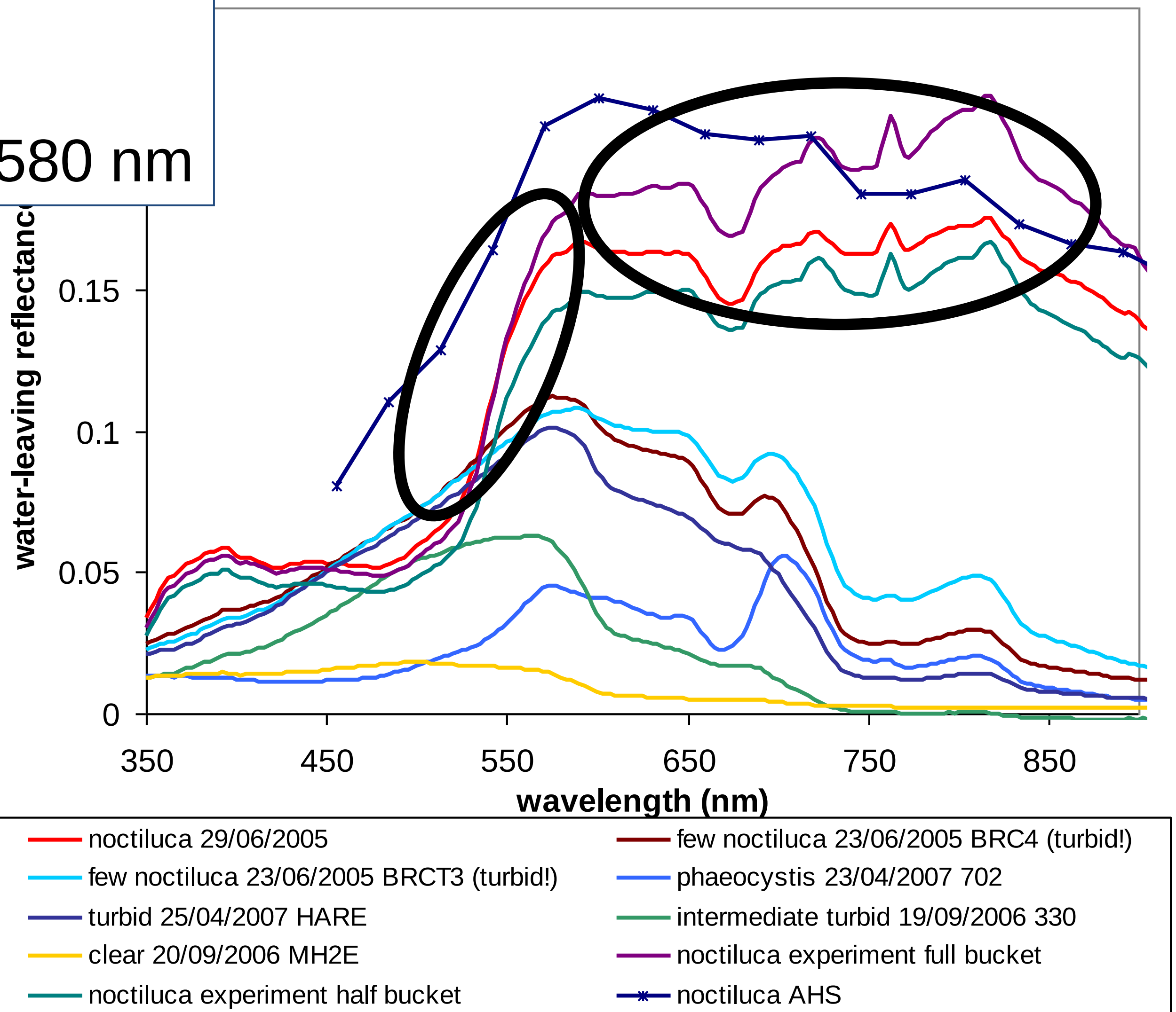
Plankton species: Detection of *Noctiluca scintillans*

[Van Mol et al (2007). Optical detection of a Noctiluca scintillans bloom. EARSeL eProceedings, Vol. 6, pp. 130–137.]

Main differences
- high red and NIR
- sharp increase 520 -580 nm

24.5.2011, Oostende





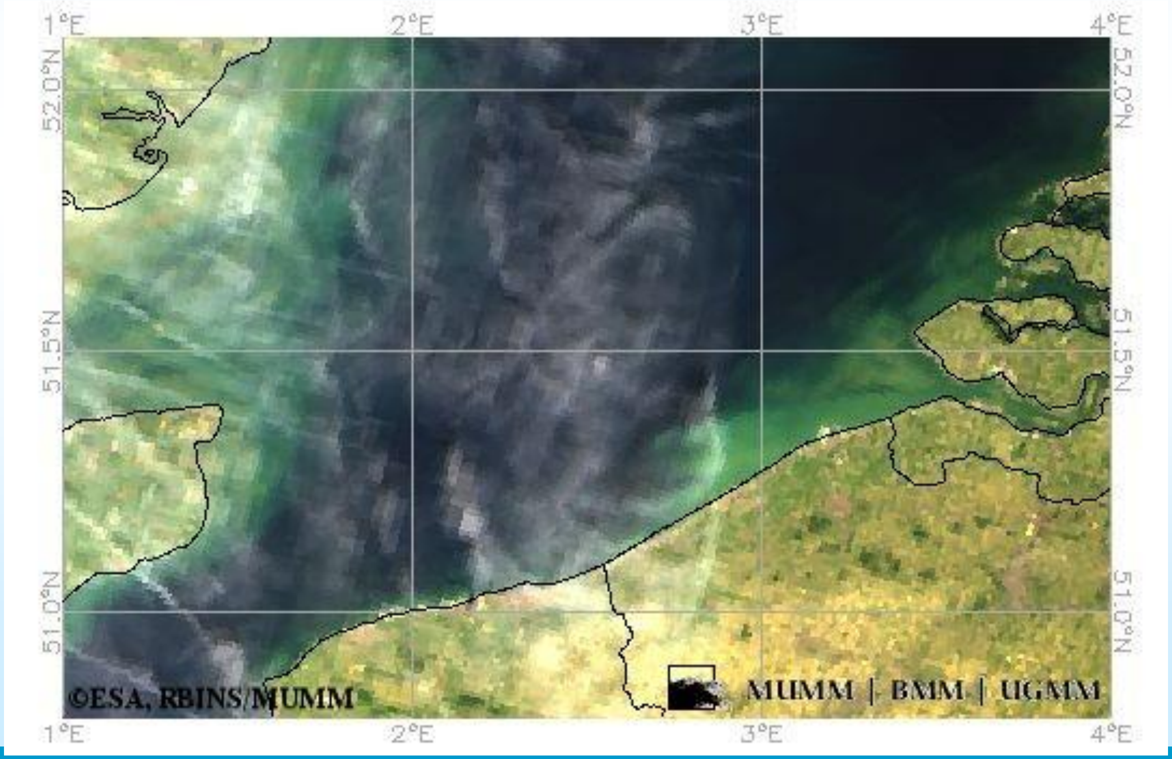
Suspended Particulate Matter (SPM) conc retrieval

=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]



TSM-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

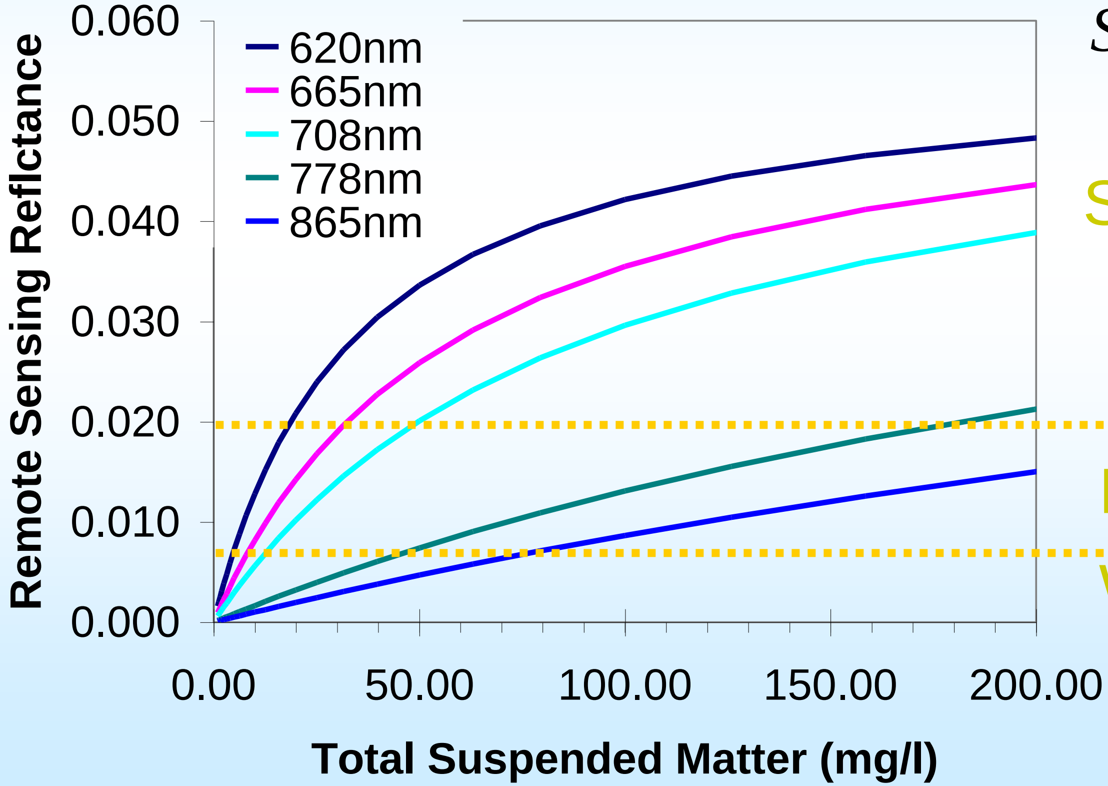
- Then

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

Calibration

TSM 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]

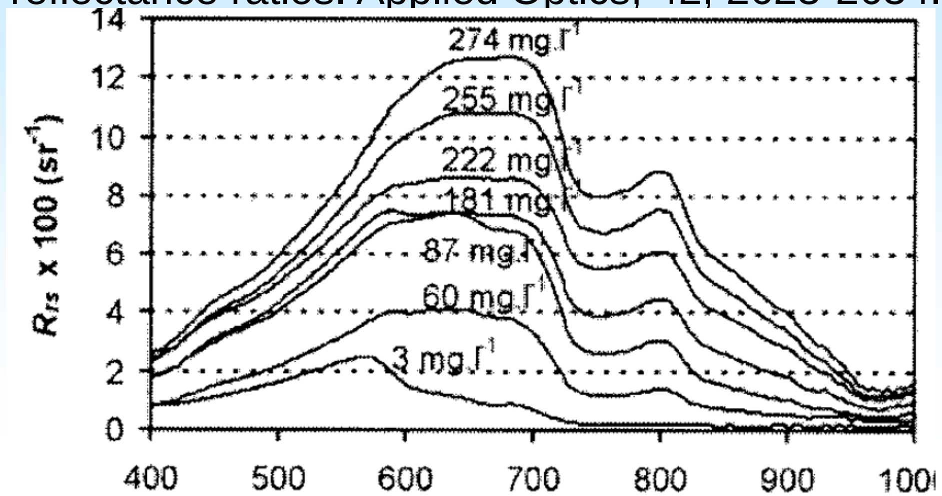
LINEAR (optimal)

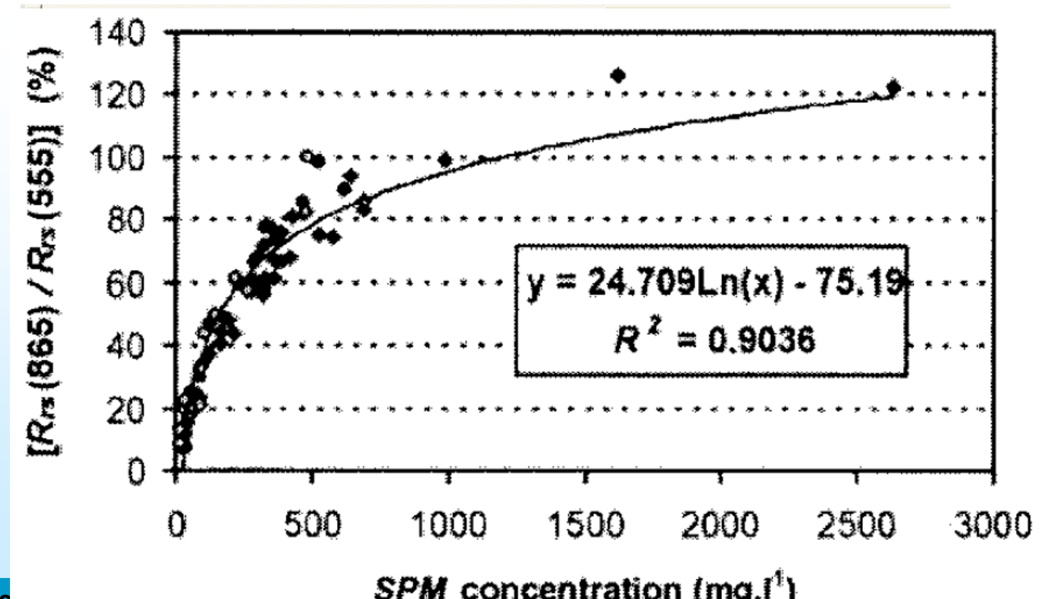
WEAK SIGNAL

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

SPM retrieval – Band ratios, e.g. SPM=f(Rrs865/Rrs555)

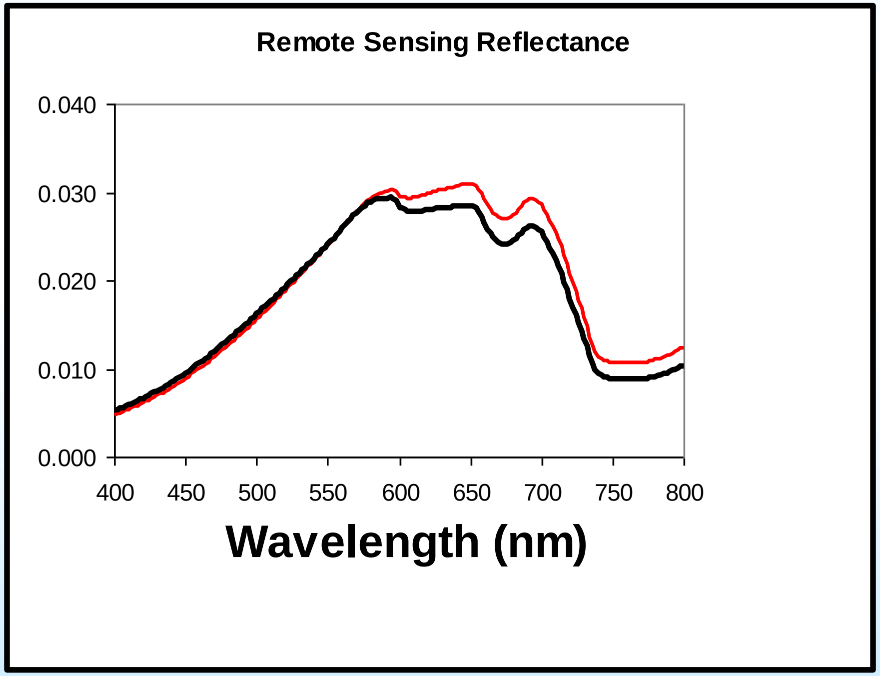
[Doxaran et al (2003). Remote sensing reflectance of turbid sediment- dominated waters. Reduction of sediment type variations and changing illumination conditions effects using reflectance ratios. Applied Optics, 42, 2623-2634.]





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:
  - Backscatter spectral slope (PSD)?
  - Absorption/Backscatter ratios?
  - Angular variation of scattering (multi-look sensors)?
  - Polarization ??

Underwater visibility

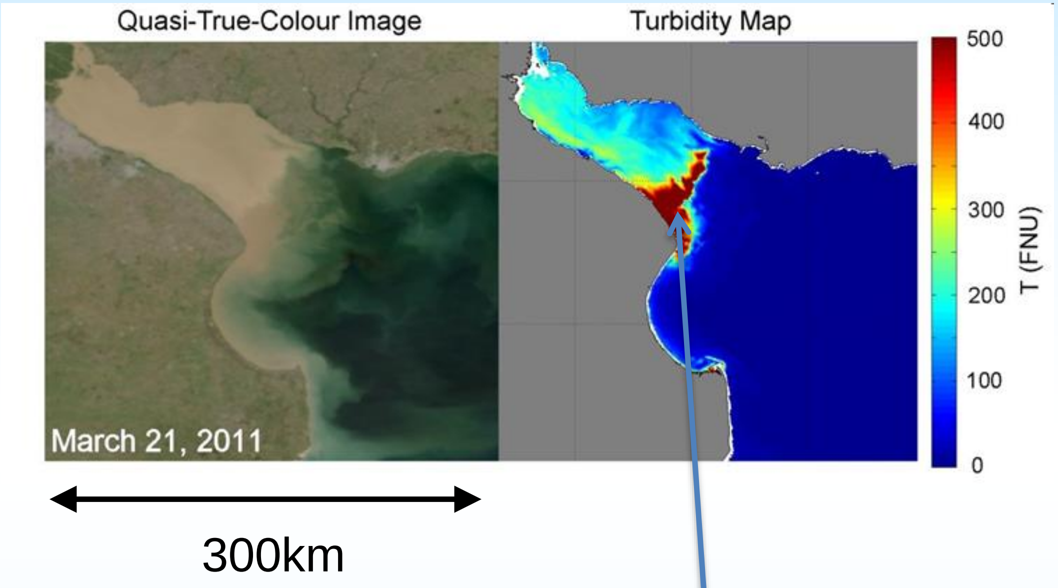
marine humans

- 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."

… and other marine animals

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)

Transparency/Visibility-related products

- Historically, the main focus of ocean colour had been oceanic CHL
- Current standard products for MODIS/MERIS/OLCI do not include turbid water transparency (just Case 1 Kd490)
- BUT fast-growing interest in transparency-related products:

User	Product
Ecosystem modellers	Euphotic depth, PAR attenuation
Benthic biologists	bottom light availability (habitat)
Fish biologists	horizontal visibility (visual predation habitat)
Commercial/scientific divers	horizontal visibility
Water quality monitoring/Environmental Impact Assessement (windmill/port construction, dredging)	transparency/turbidity, even Secchi depth

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]
- Transparency and/or diffuse attenuation algos for turbid waters are emerging (not so difficult)

Turbid waters - Miscellaneous

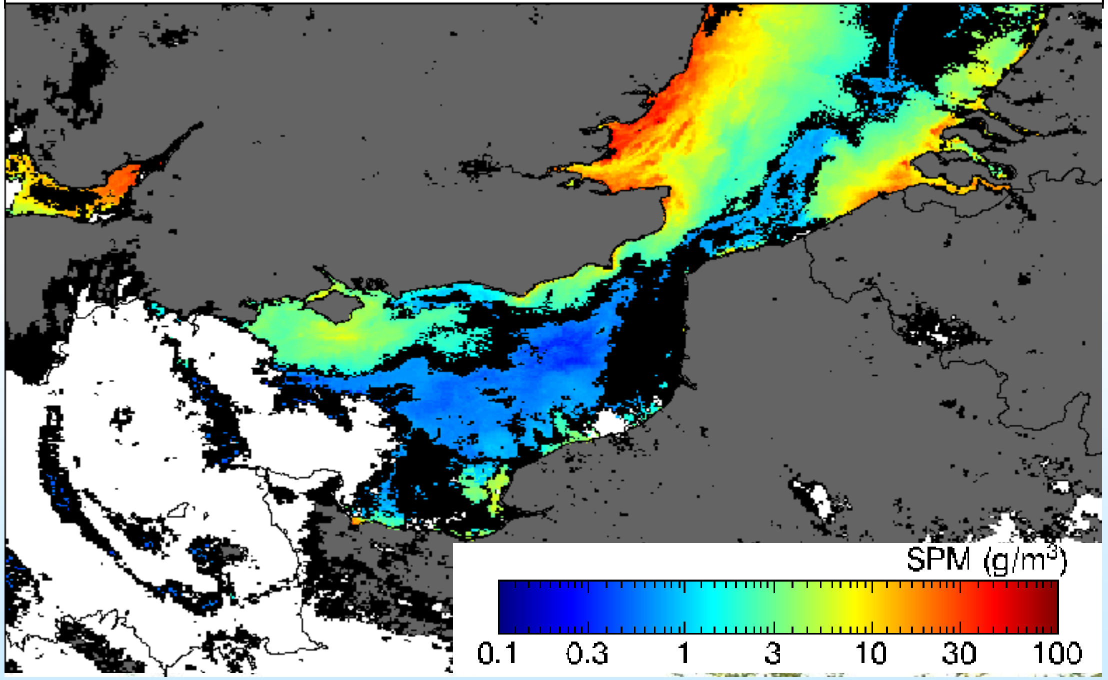
- Cloud flagging in turbid waters
  - Simple TOA 865nm reflectance thresholds (SeaDAS) do not work because turbid water is also bright
  - Raise threshold or use better multi-spectral algos, e.g. [Nordqvist et al, 2009] … spatial heterogeneity, thermal bands (when present), etc.
- Bidirectional effects
  - Light field is more diffuse, BRDF less important than in Case 1 waters but some variability [Loisel and Morel, 2001; Park and Ruddick, 2005]
  - Case 1 CHL-based BRDF corrections, f/Q [Morel and Gentili], are not appropriate => DO NOT USE
  - Case 2 BRDF corrections are emerging, e.g. neural net-based [Fan et al, 2016], IOP-based [Lee et al, 2011]
- Stratification
  - Remote sensor sees "near-surface" (but depth depends on wavelength)

Miscellaneous

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

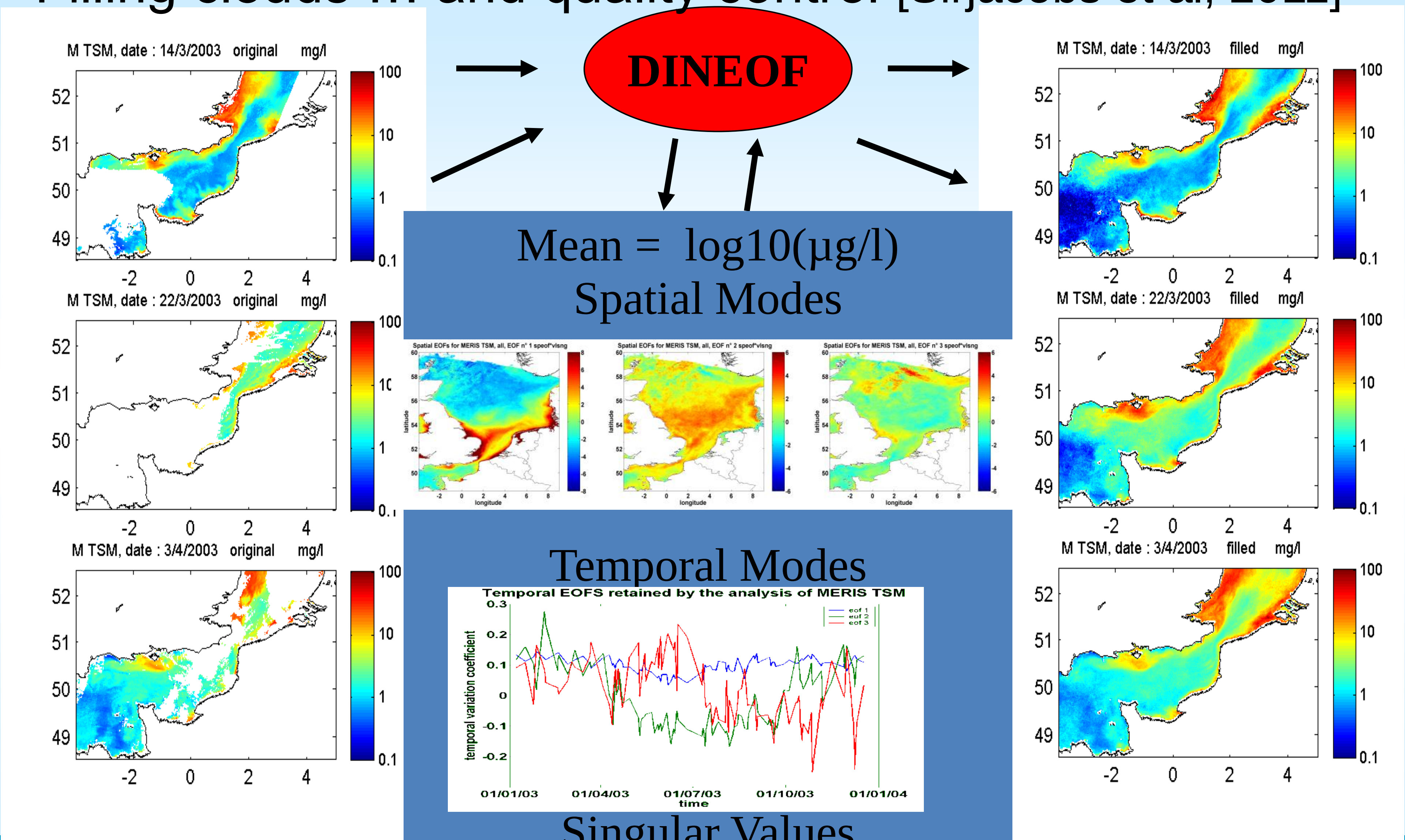
e.g. MERIS Product Confidence Flag [Processing: Y.Park]

MERIS image 31.3.2004 (suspended matter QCed)



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]



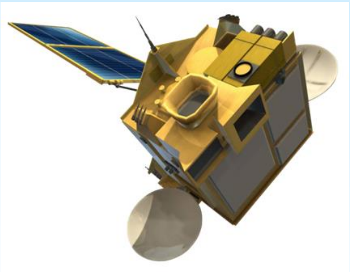
Ocean colour remote sensing in turbid waters

	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	
Spatial	~~300m~~-1000km 10m (some ~1m)		
SPM Conc.	0.1-~~500~~ g/m3 2000	Extreme high conc.	
Accuracy	Absolute: 30-50% SPM? Relative: good		
Issues		Near land (~1km) Atmospheric Corr. Sunglint	

Optical Remote Sensing – future systems

Platform

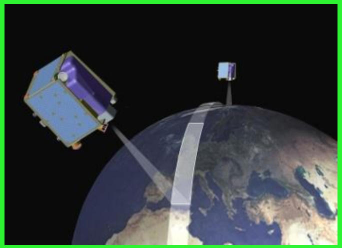
Geostationary



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

Europe/US plans not soon

Pointable minisats



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

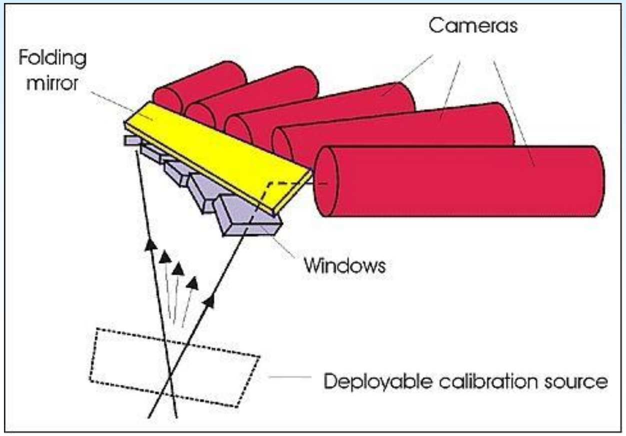
Unmanned airborne

[www.gatewing.com]

Optical Remote Sensing – future systems

Platform

Sensor



Processing/Distribution

$S = A\frac{\;}{1-\;}$

Higher spatial resolution

Better signal:noise

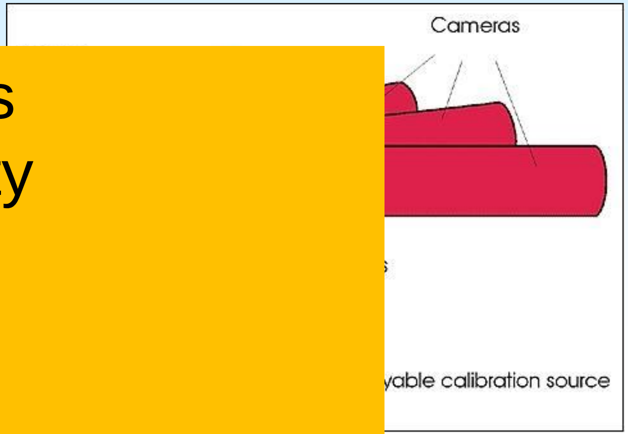
More spectral bands … hyperspectral

From UV (350nm) to SWIR (2.3µm)

Optical Remote Sensing – future systems

Platform

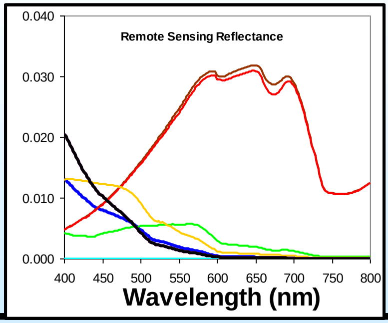
Sensor

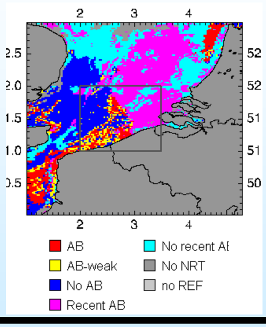


Algorithms for more products
Algorithms for QC/uncertainty
+
Multimission processing
(time series, synergies, etc.)

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+	250m	Daily
MODIS-AQUA	2002+	250m	Daily
ENVISAT-MERIS	2002-2012	300m	~4/week
VIIRS	2011+	1000m	Daily
Sentinel-3AB/OLCI	2015+	300m	~4/week (1 sat)
PROBA-V	2013+	100m	Every 5 days
Landsat-5	1984-2013	30m	Every 16 days
Landsat-8	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 marine reflectance non-zero

- Many new algorithms are products are emerging:
  - Inherent Optical Properties
  - Spectral diffuse attenuation, turbidity
  - Specific phytoplankton blooms
  - Quality and/or uncertainity estimates

Programming skills are most important!

- What does the future hold?
  - High frequency data from geostationary (SEVIRI, GOCI, …)
  - 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!) …