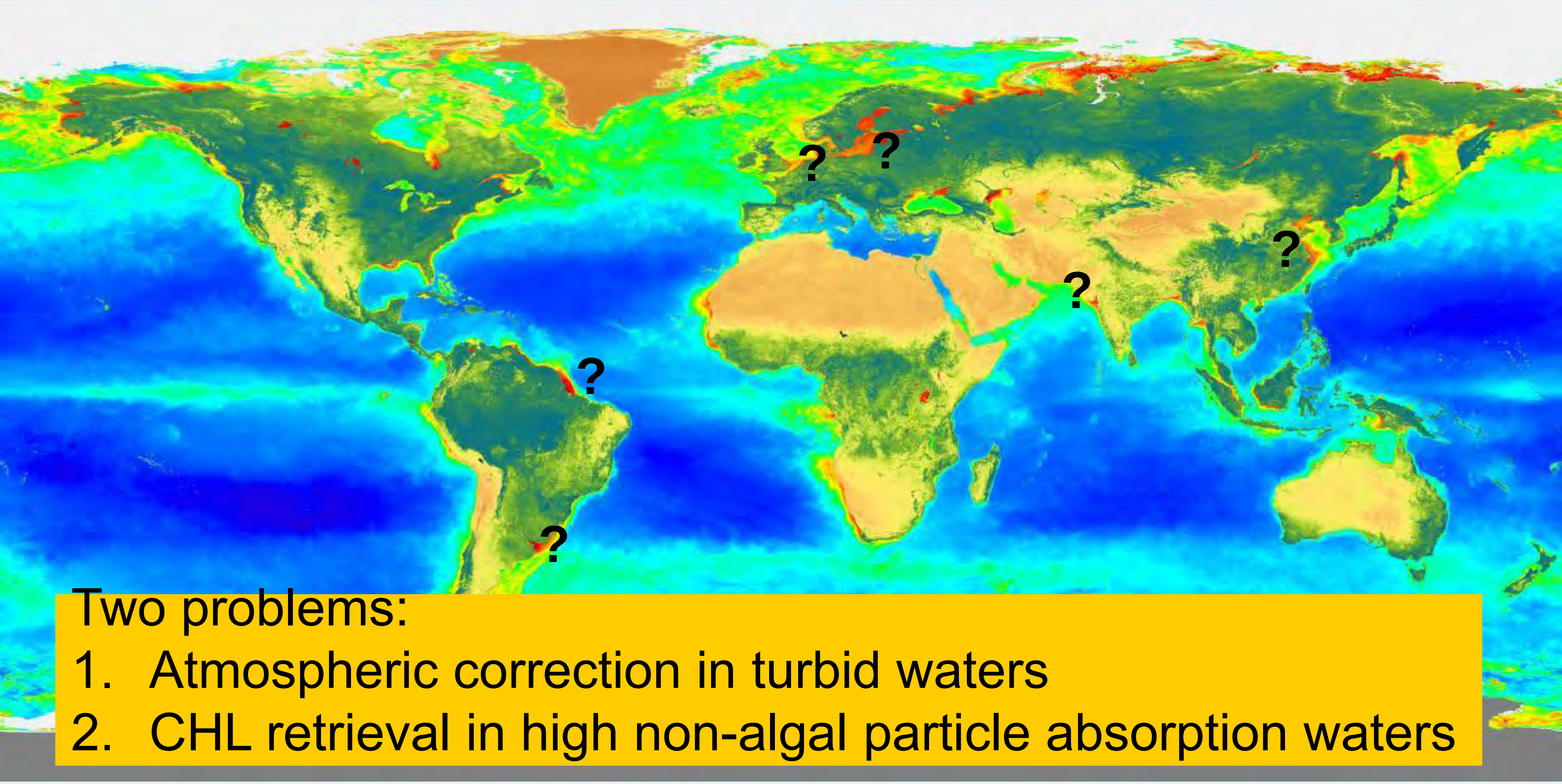


Two problems:

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

e.g. SeaWiFSCHLa composite Sept1997-Aug1998, v1 processing

RED=high CHLa (or NOT?)

Ocean Colour Remote Sensing in Turbid Waters

Lecture 1: Introduction, CHL and TSM retrieval

by Kevin Ruddick

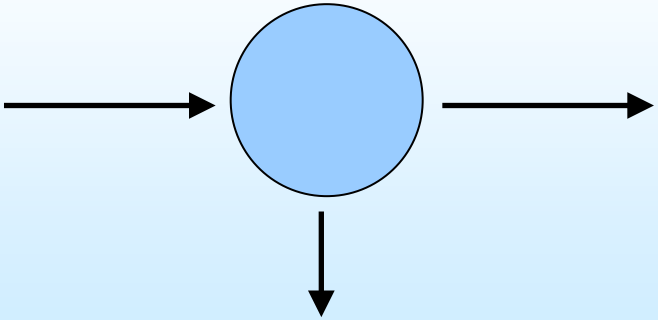
with support from MUMM-REMSEM researchers, past and present
(Ana Dogliotti, Bouchra Nechad, Griet Neukermans, Youngje Park, Dimitry Vanderzande, Quinten Vanhellemont, Barbara Van Mol)
and BELCOLOUR project partners

Overview of the Lectures

- Scope = issues specific to turbid waters, especially:
  - Chlorophyll retrieval in turbid waters
  - Atmospheric correction in turbid waters
  - ALSO new parameters, applications, etc.
- Assumes basic knowledge of:
  - Absorption, scattering and reflectance [Mobley]
  - Ocean Colour algorithms [Davis, Doerffer, Dowell, Lee, Mobley]
  - Atmospheric correction for clear waters [Wang]
- Lecture organisation:
  - Weds 11th 16:00-16:45 Lecture 1 (intro, CHL, TSM)
  - Weds 11th 16:45-17:00 Lecture 2 - Intro to “Colour of Water” Exercise
  - Weds 11th 17:00-17:30 Excel-based exercise 1 (CHL retrieval, etc.)
  - Thurs 12th 14:00-14:15 Lecture 3 - Intro to “Aerosol Correction” Execise
  - Thurs 12th 14:15-15:00 Excel-based exercise 2 (aerosol correction)
  - Thurs 12th 15:00-15:30 Lecture 4 (applications, misc, The Future)
  - Thurs 12th 16:00-17:30 Discussion [with Samiento, Antoine, Wang]

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



bs860=>Turbidity

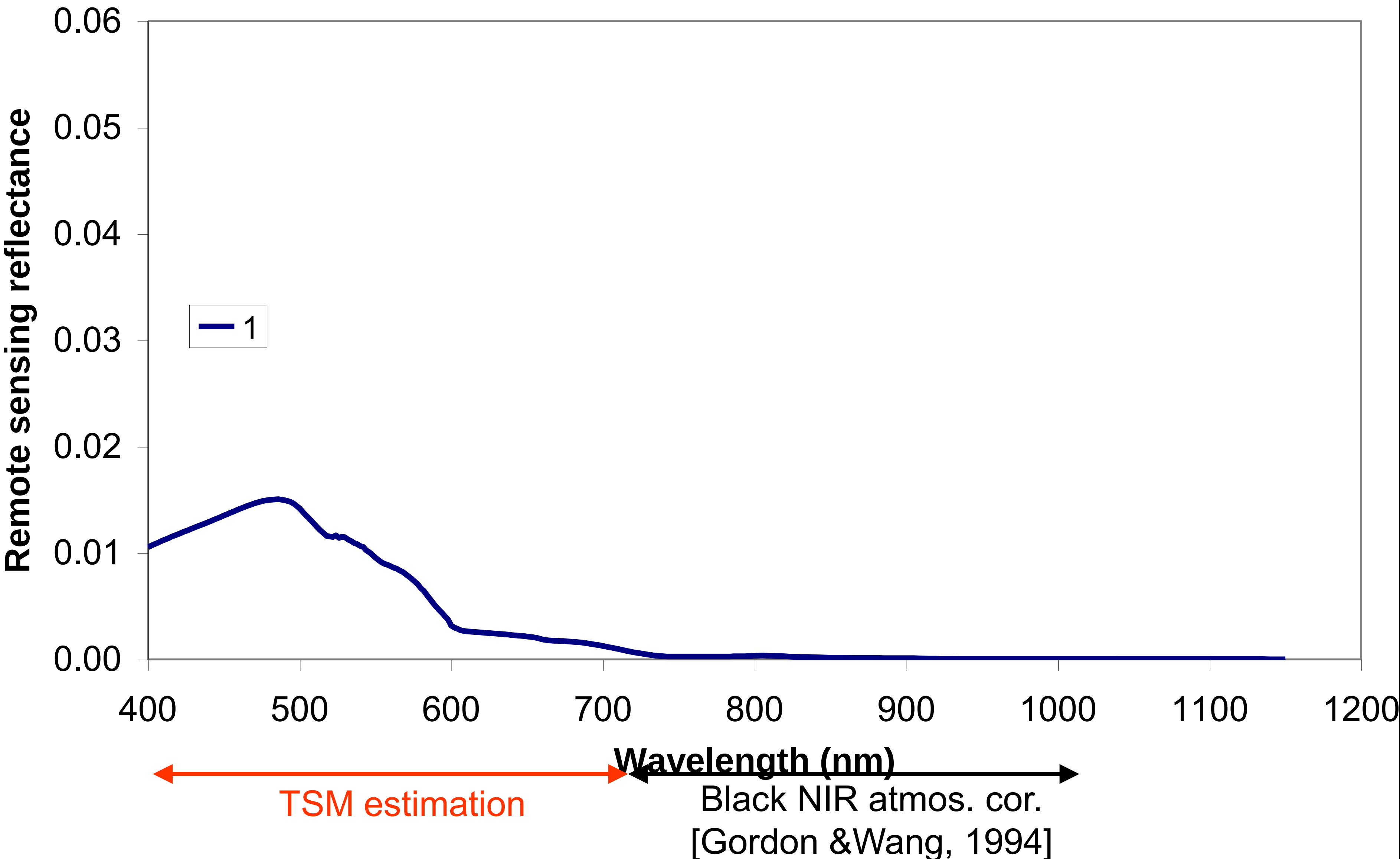
Degrees of turbidity

- Unofficial (but very useful) definitions

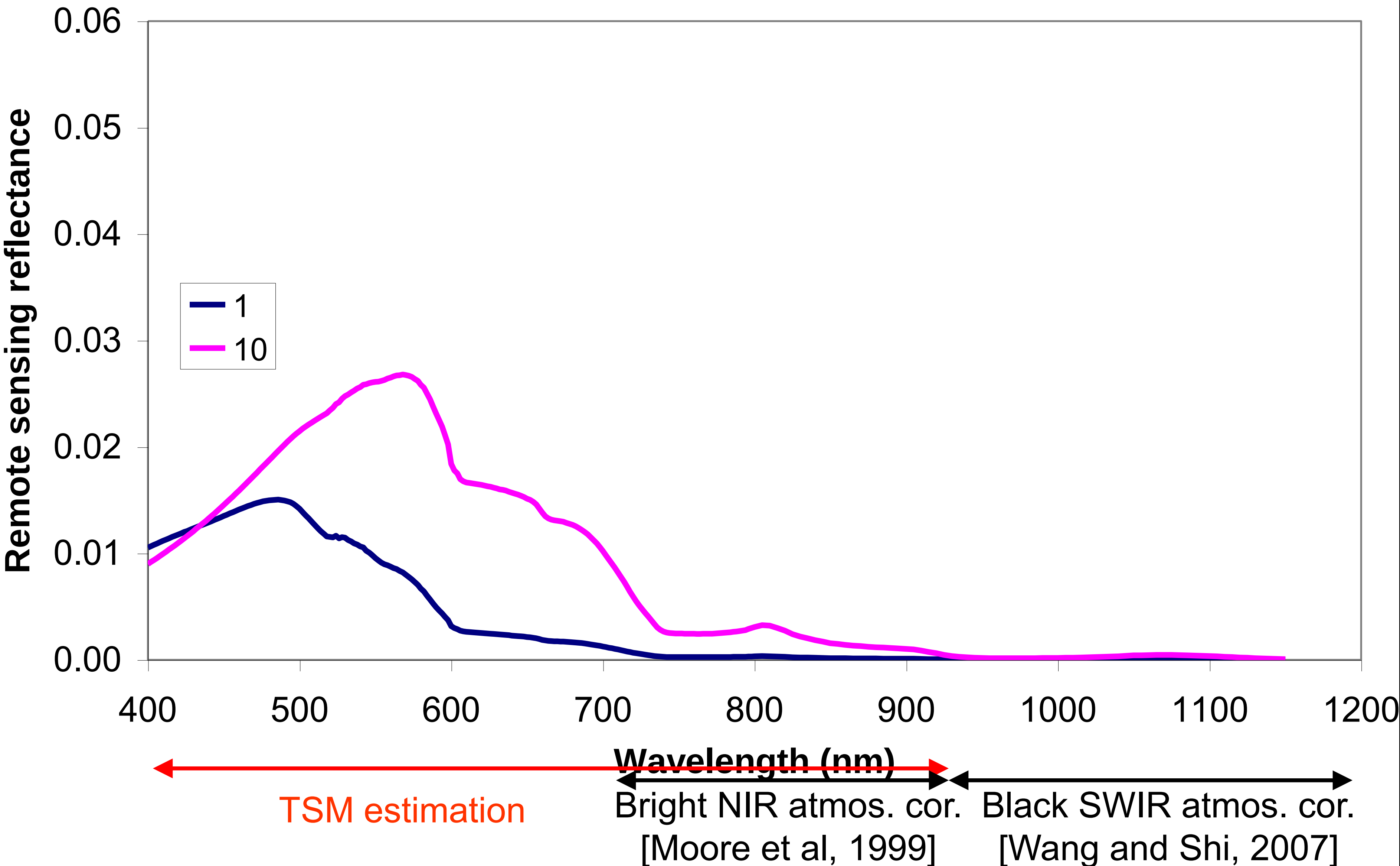
Description	Turbidity, bs (FNU)	Total Suspended Matter, TSM (g/m3)	*Secchi depth (m)*	Scattering, b_555 (m-1)	Backscattering, bb_555 (m-1)	Marine Reflectance at 778nm=PI*Rrs778
Clear	<1.1	<1	*>10m*	<0.5	<0.01	<0.0008
Moderately turbid	1.1-11	1-10	*2-10m*	0.5-5	0.01-0.1	0.0008-0.008
Very turbid	11-110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

NB. Rough values only, mass-specific optical properties do vary e.g. [Neukermans et al, 2012]

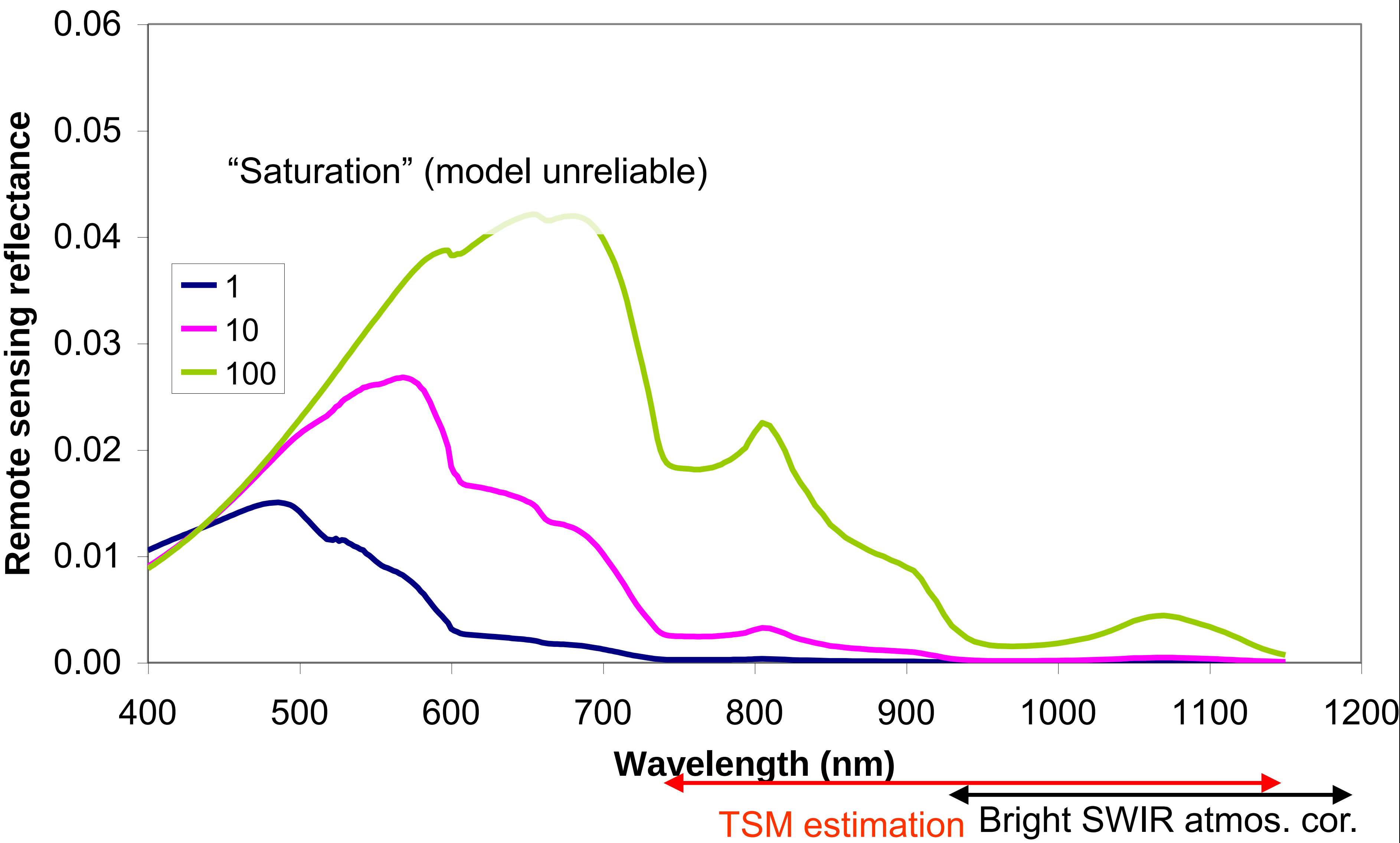
Varying Total Suspended matter concentration (mg/m3)



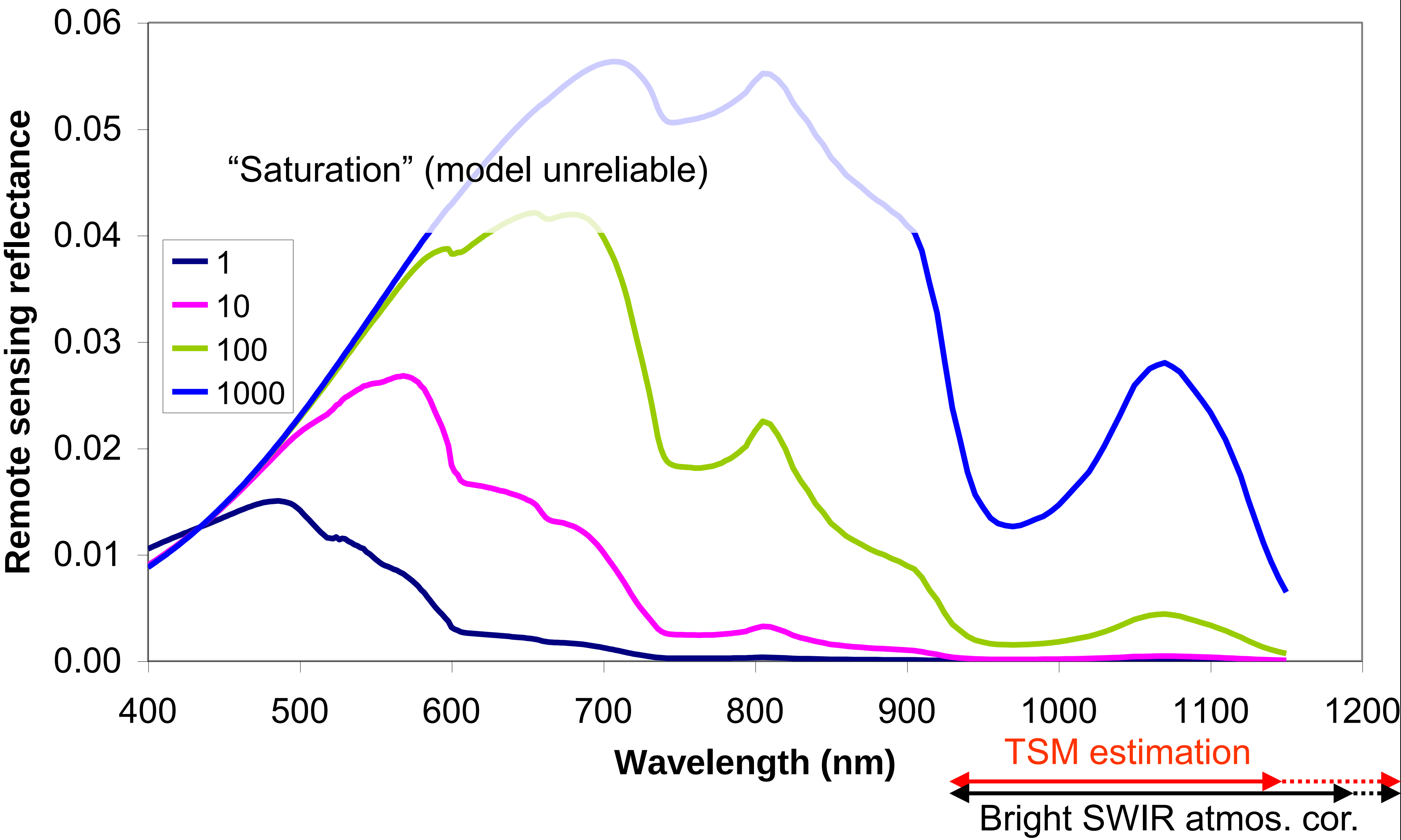
Varying Total Suspended matter concentration (mg/m3)



Varying Total Suspended matter concentration (mg/m3)



Varying Total Suspended matter concentration (mg/m3)



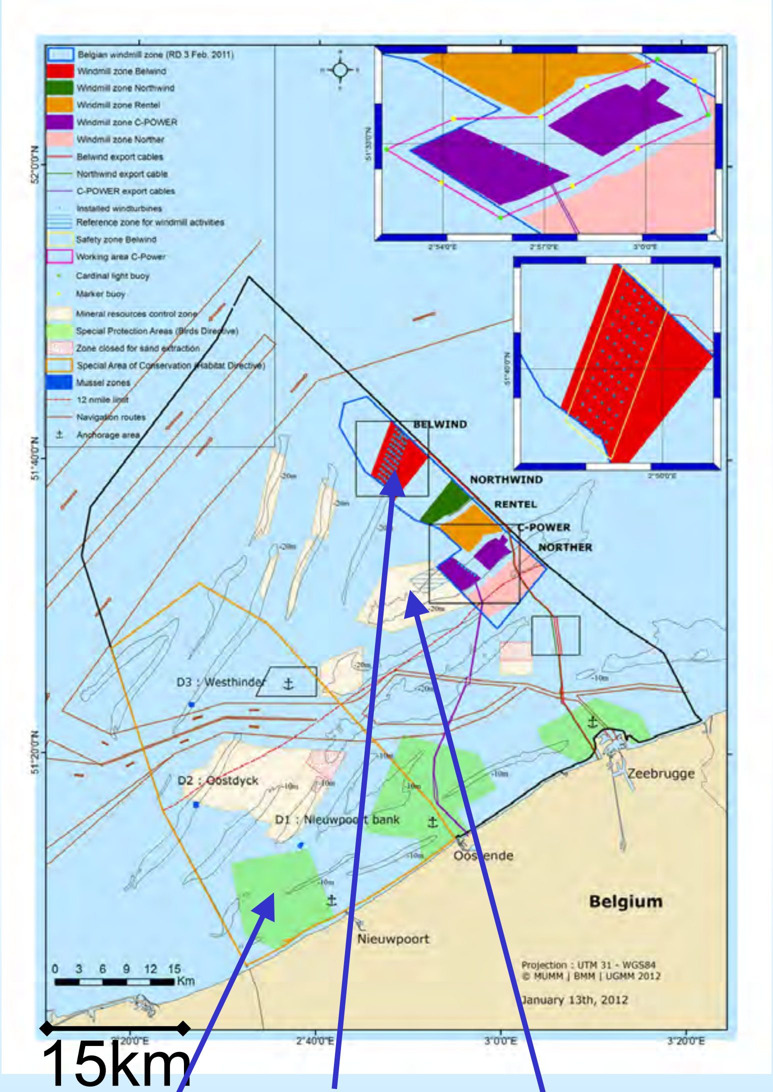
e.g. [Knaeps et al, 2012] measured non-zero 1020nm reflectance

Where to find turbid water

Description	Total Suspended Matter, TSM (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

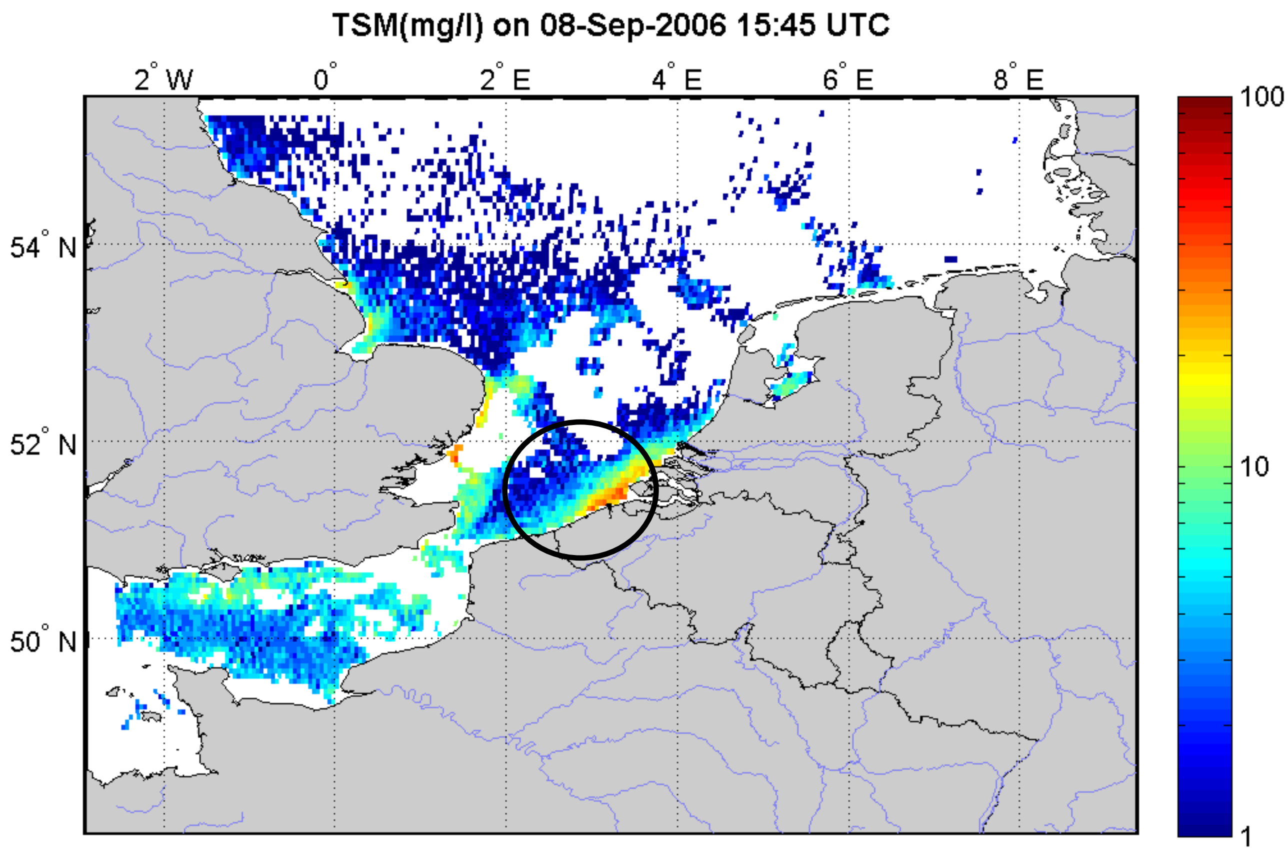
- In turbid waters:
  - Chlorophyll retrieval by blue:green (Case 1) algorithms fails because absorption from algal particles + non-algal particles

    => Need red/near infrared or multispectral 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:
  - marine signal is also stronger compared to atmosphere
  - Can more easily see turbid waters

Feasibility study for Geostationary TSM (SEVIRI)

Total Suspended matter (mg/l)

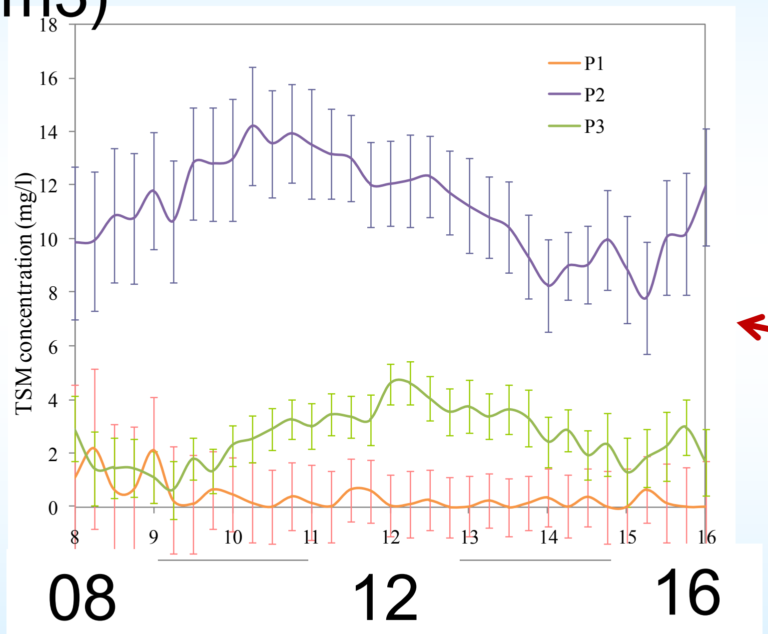


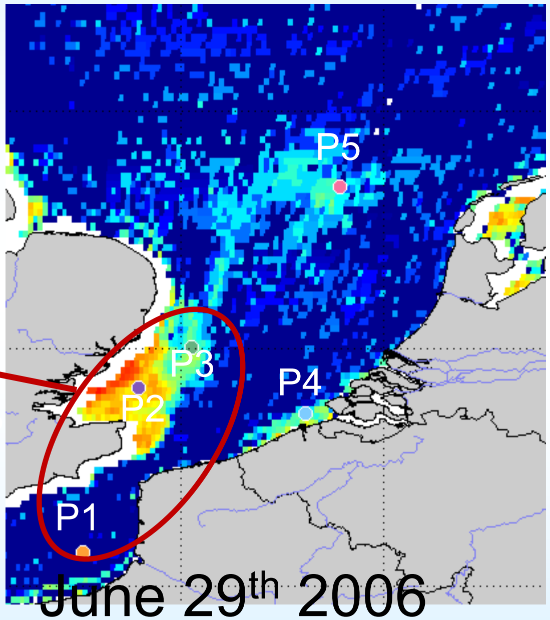
[Neukermans et al, 2009]

- Geostationary orbit (~35790km, over equator) : continuous scanning of specific region => better cloud clearing, tidal/subdiurnal variability …
- BUT distance from earth => low signal or large pixels (or wide bands)

TSM dynamics on cloudfree day

TSM (g/m3)





Time (UTC)

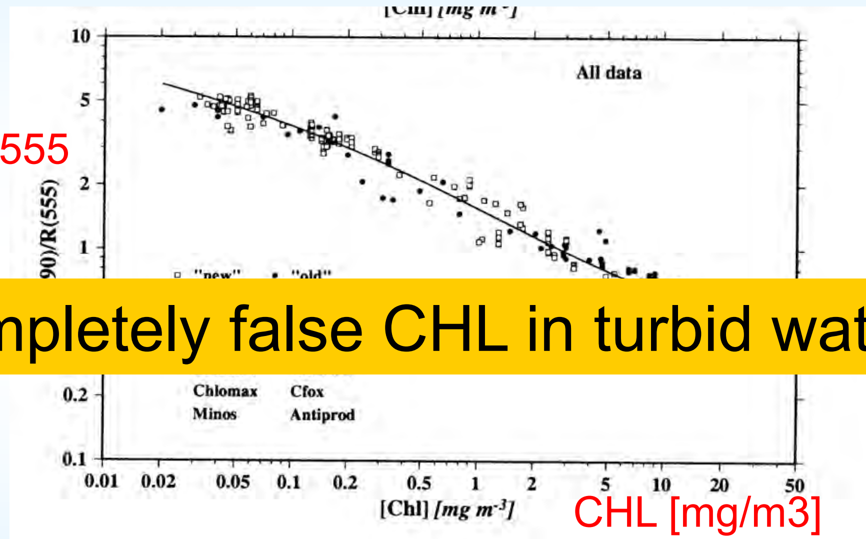
[Neukermans et al, 2009]

Chlorophyll a (CHL) retrieval

Chlorophyll *a* retrieval: blue/green ratios

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

Rrs490/Rrs555



[Morel and Antoine, 2000]

Completely false CHL in turbid waters

$$\log_{10} \; CHL - a_4 \; = a_0 + a_1 R + a_2 R^2 + a_3 R^3$$

[O'Reilly et al, 1998]

$$R = \log_{10} \; \max \; R_{rs}^{443}, R_{rs}^{490}, R_{rs}^{510} \; / R_{rs}^{555}$$

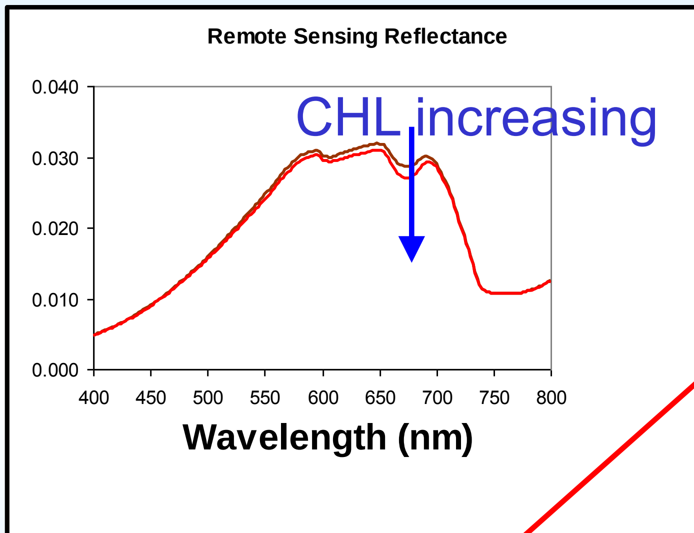
$$a_0, a_1, a_2, a_3, a_4 \; = \; 0.4708, -3.8469, 4.5338, -2.4434, -0.0414$$

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 709nm very useful

MODIS 748nm less useful



a_w708nm

a_w664nm

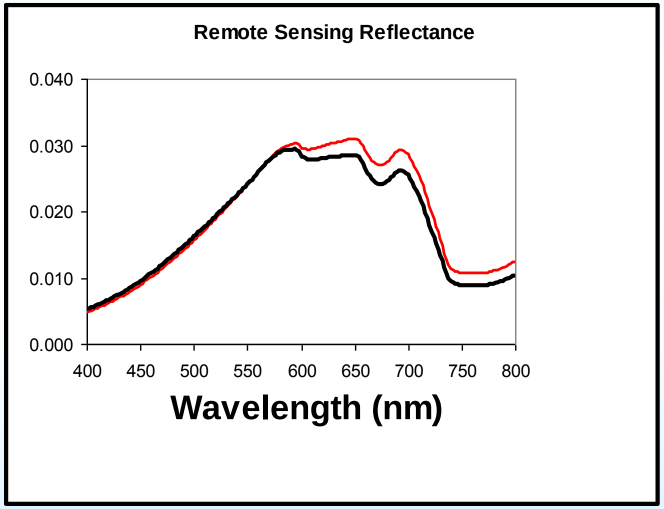
$$CHL = \frac{1}{0.016}\left\{ \frac{R_{rs}^{708nm}}{R_{rs}^{664nm}} \left(0.70 + b_b\right) - 0.40 - b_b^{1.06} \right\}$$

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

[Gons et al, 2005]

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. MERIS Neural Network, do this automatically



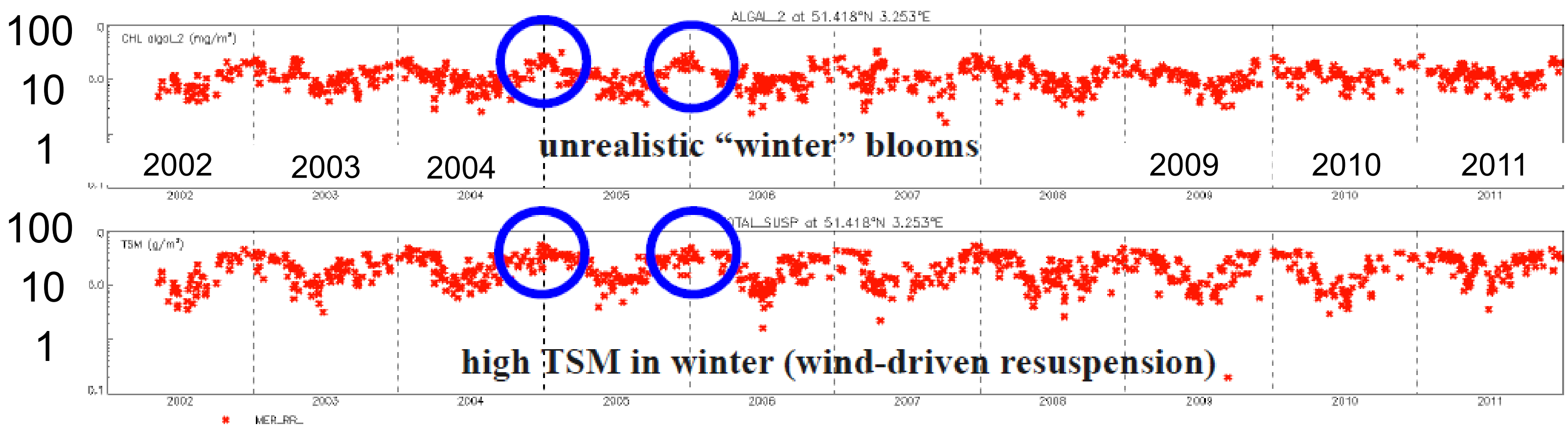
- Best approach for global processing for all waters
- BUT what about multiple solutions? Understanding of physics ?
- Natural limits (CHL detection limit in high NAP/CDOM waters)

Some typical problems (Belgian turbid coastal location)

Time series from MERIS (R3, MEGS8.1)

CHL (mg/m^3)

TSM (g/m^3)

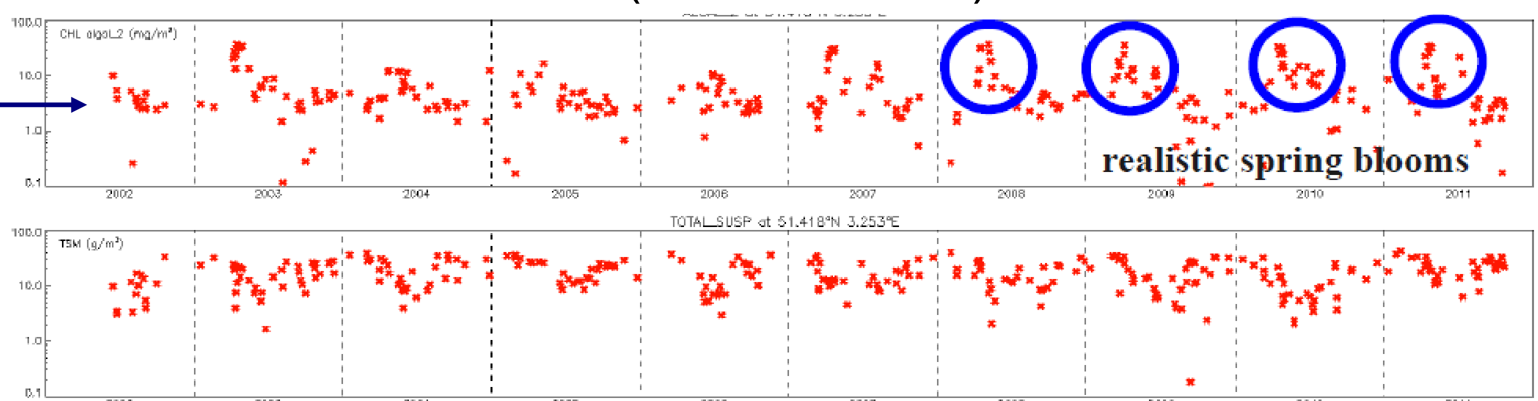


Time series from MERIS (R2, MEGS7.5)

Detection limit

CHL

TSM



[Q. Vanhellemont, ODESA forum, May 2012]

Beyond CHL … Phytoplankton functional types

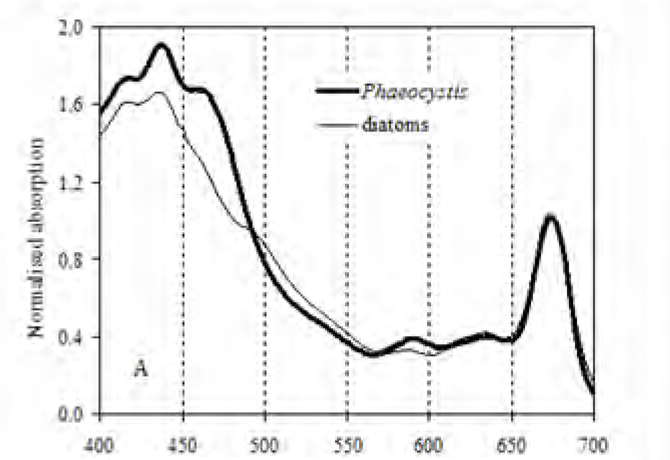
- There is also a strong user need for information beyond CHL:
  - Phytoplankton functional types
  - Species composition
  - Harmfulness
  - BUT CHL is difficult enough in turbid waters and species identification generally possible only in special cases (high biomass, distinctive IOPs)

  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*
  - *Karenia mikimotoi* [Miller et al, 1998]
  - Reviews by [Stumpf et al, 2008; Ruddick et al, 2008] and IOCCG Working Groups [Dowell, Barnard, Alvain, Moulin, etc.]

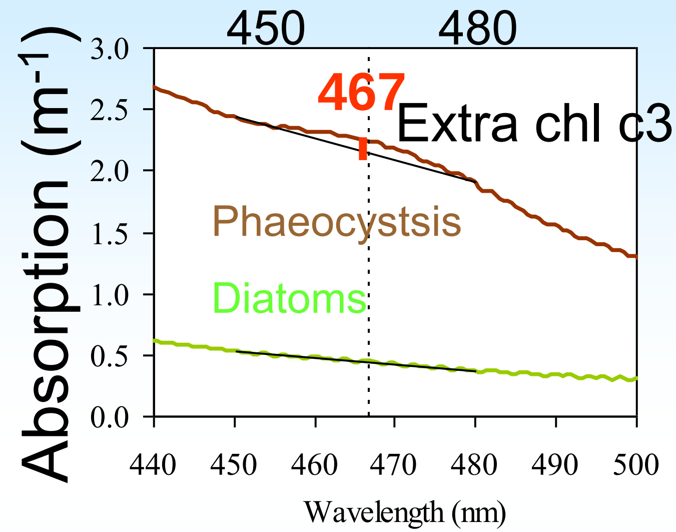
Detection of *Phaeocystis globosa*

[Astoreca et al, J. Plankton Research, 2009]

Normalised absorption



Wavelength (nm)



Absorption algorithm

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

Reflectance algorithm

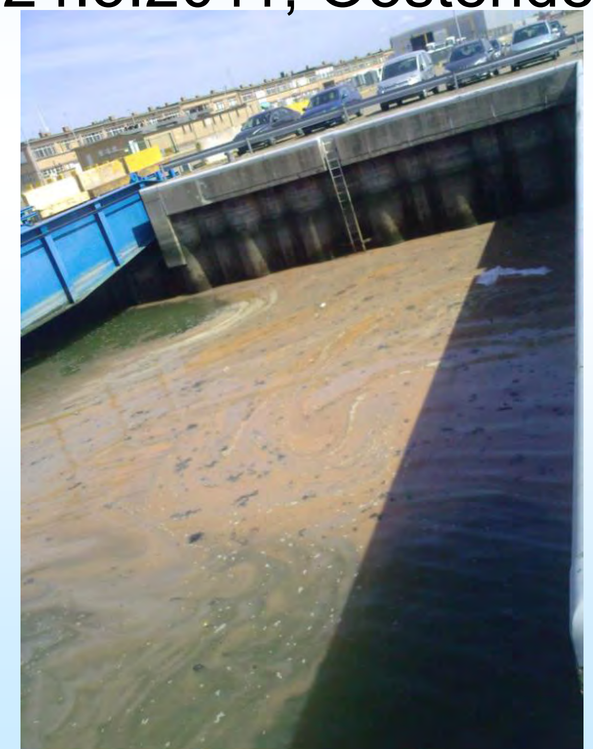
$$a_{c3}(467) = [(1/\rho_w(467)) - (0.43/\rho_w(450)) - 0.57/\rho_w(480)] * a_w(700) * \rho_w(700)$$

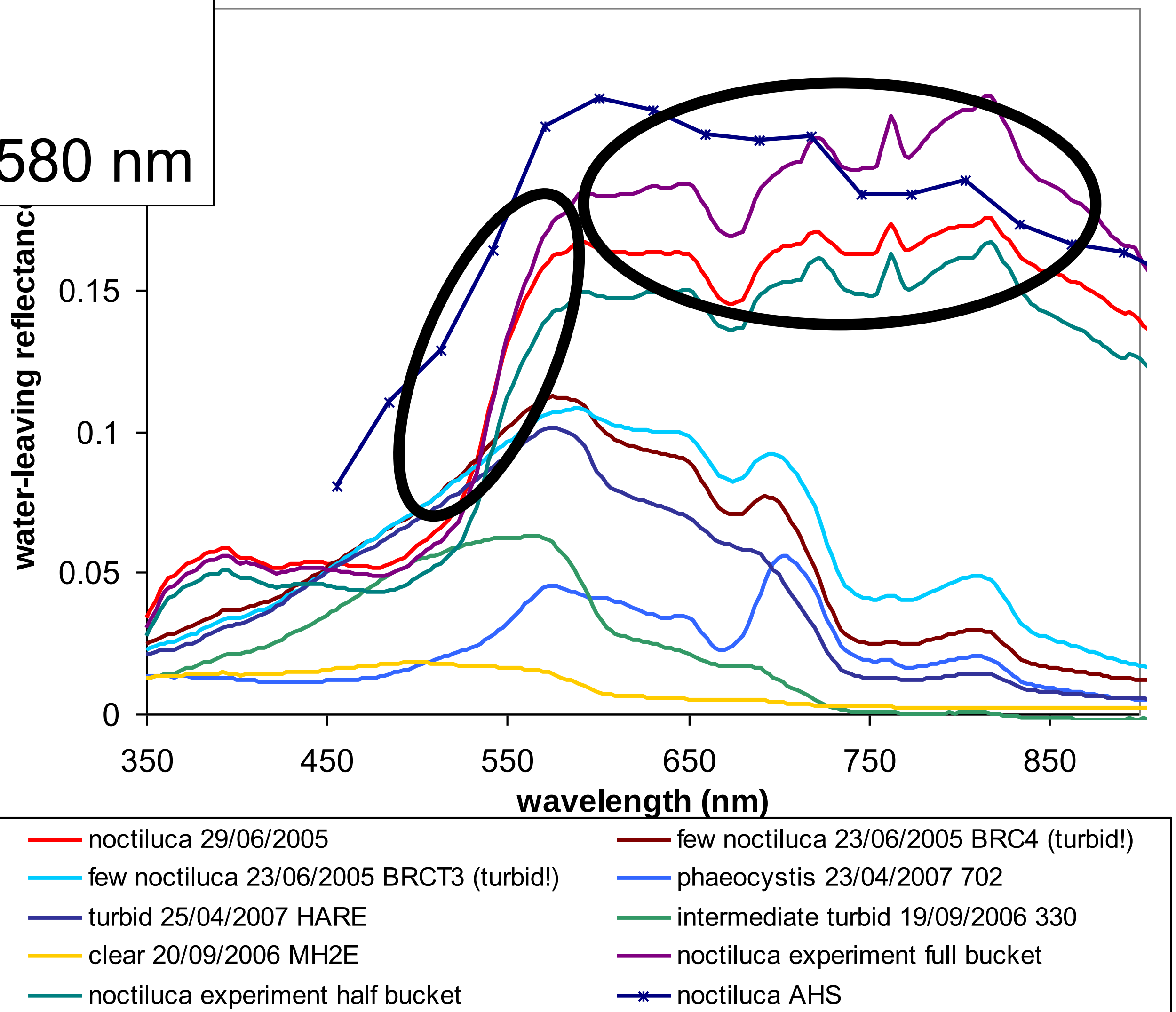
Detection of *Noctiluca scintillans*

[Van Mol et al, EARSEL eProceedings, 2007]

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

24.5.2011, Oostende





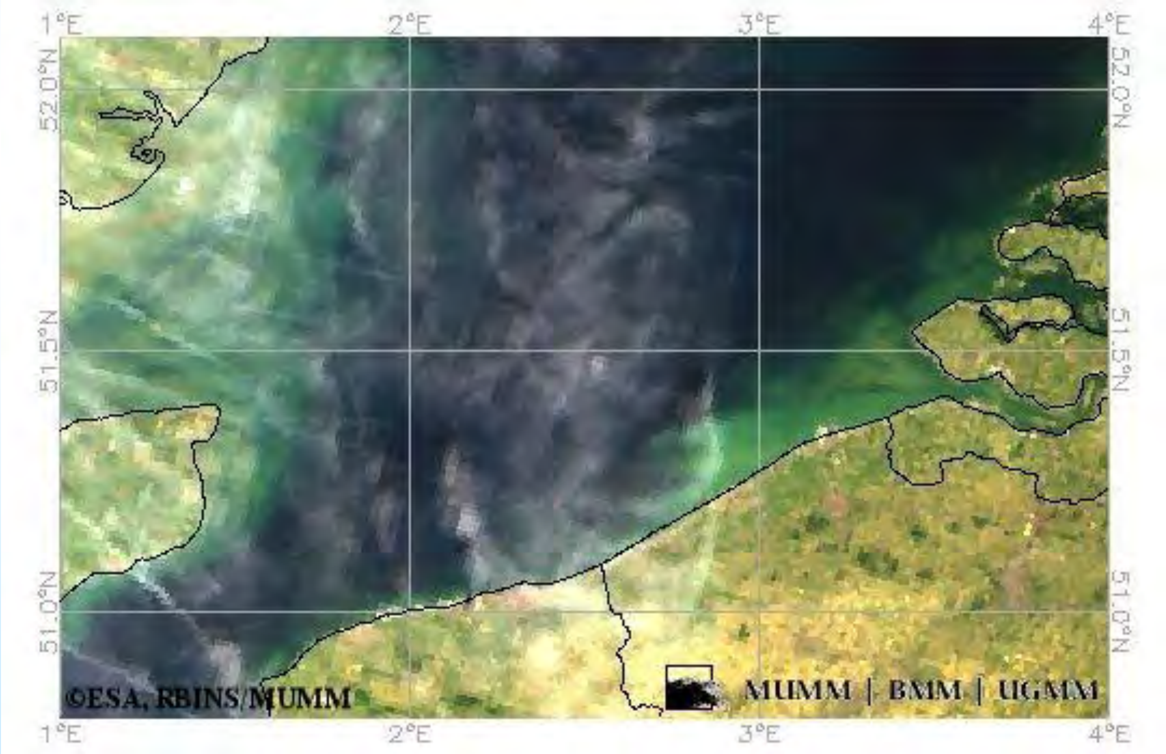
Total Suspended Matter (TSM) retrieval

=Suspended Particulate Matter (SPM)
=Total Suspended Solids (TSS)

also turbidity, PAR attenuation, etc.

Total Suspended Matter (TSM) retrieval

- TSM 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

- Gordon/Morel reflectance model

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

- Decompose IOPs:

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

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

Total Suspended Matter

TSM-specific scattering, absorption

- Then

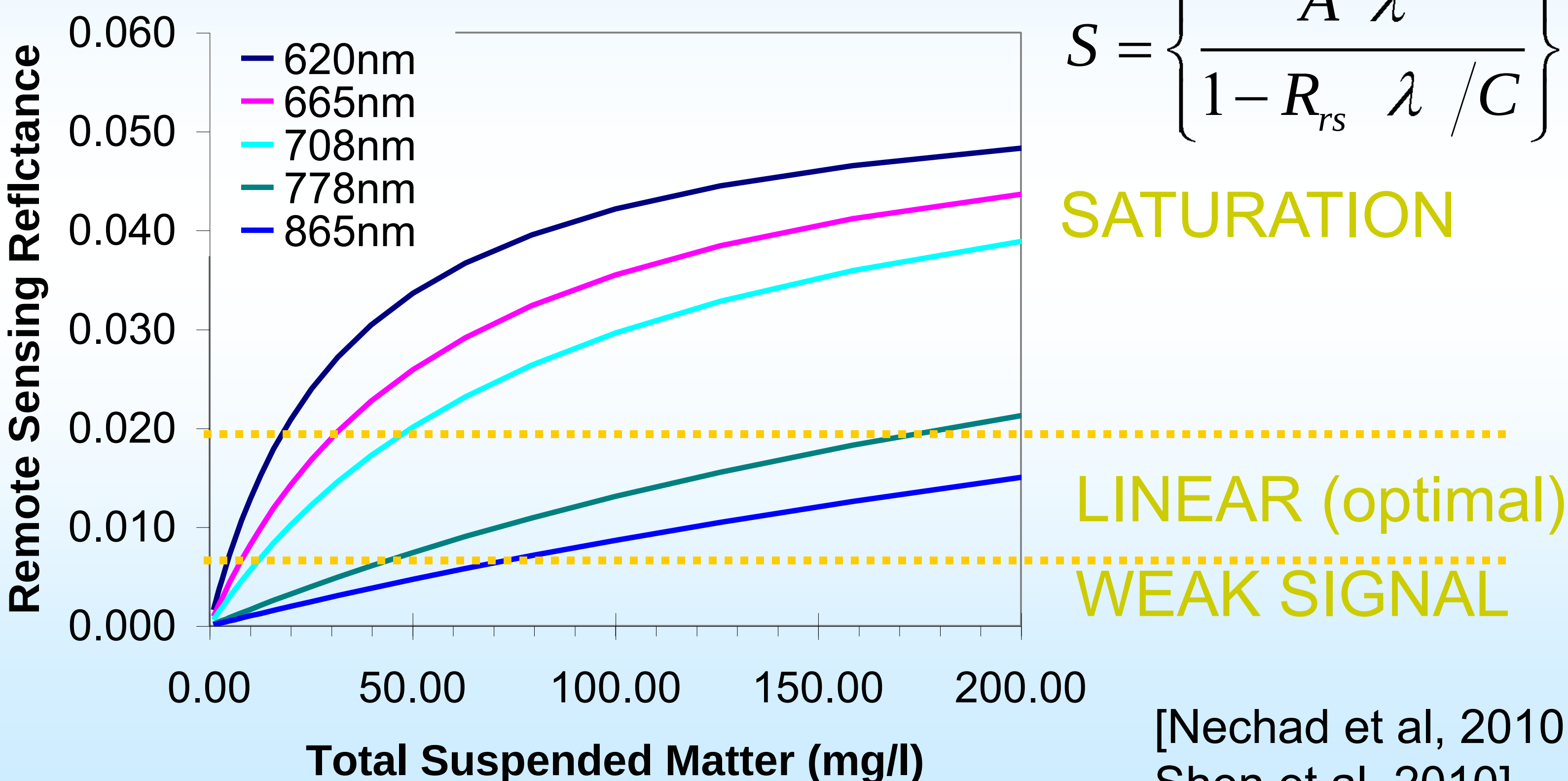
$$S = \left\{ \frac{A(\lambda)}{1 - R_{rs}(\lambda)/C} \right\} R_{rs}(\lambda) \quad \text{where} \quad A = \frac{a_{np}}{\gamma' b_{bp}^*}, \quad C = \frac{\gamma' b_{bp}^*}{a_p^* + b_{bp}^*}$$

Calibration

TSM retrieval algorithms: single band

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

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

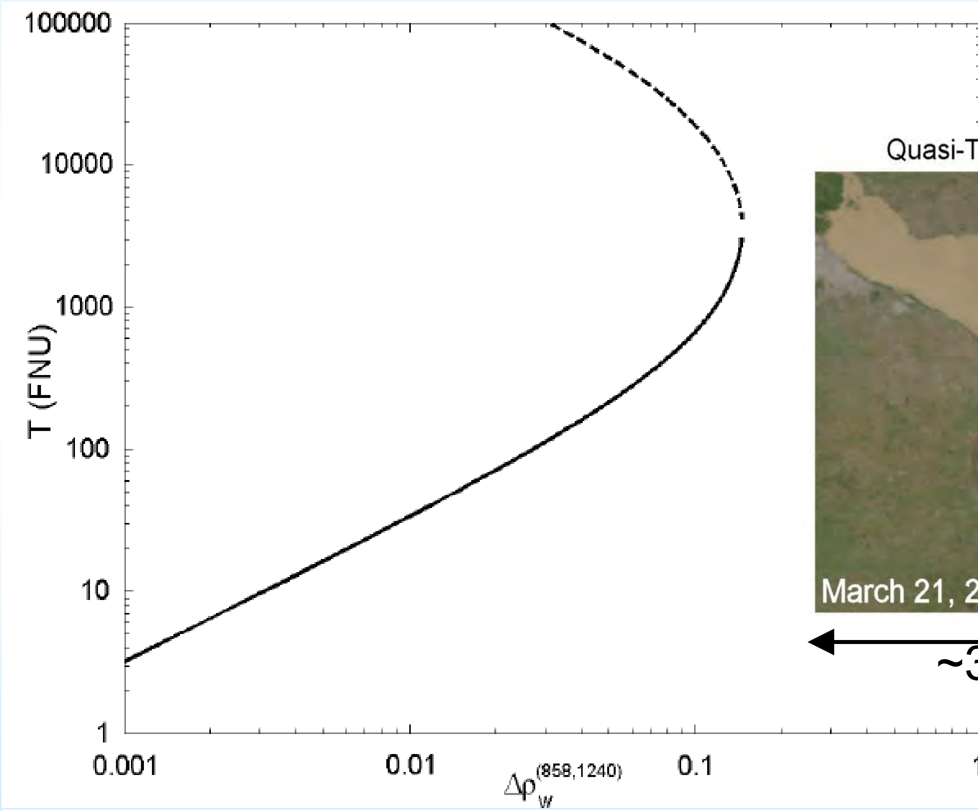


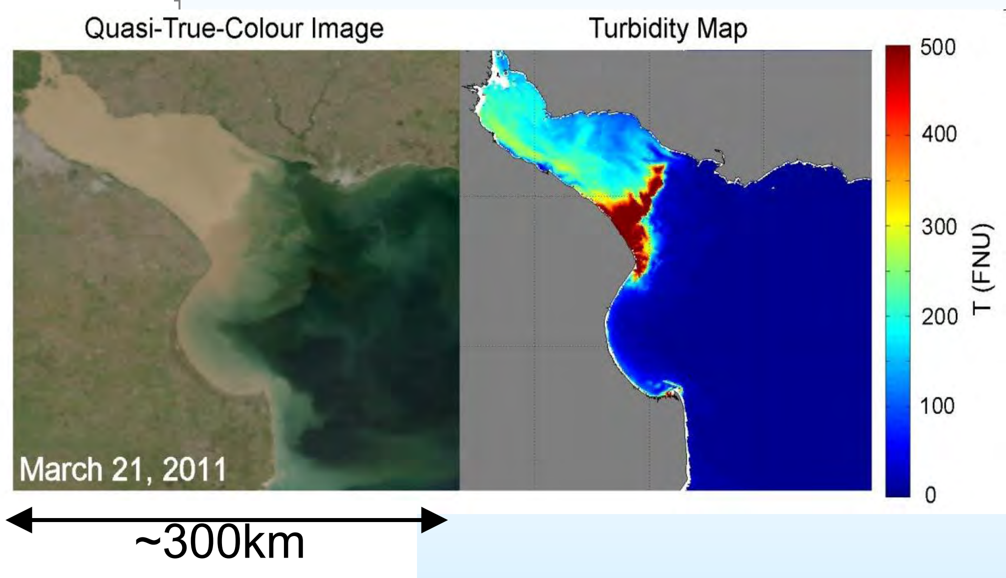
[Nechad et al, 2010; Shen et al, 2010]

TSM (or turbidity) retrieval – Band differences

- As single band but reduces impact of white Rhow error (aerosol)

e.g. [Dogliotti et al, 2011] extremely turbid La Plata (without aerosol corr.)

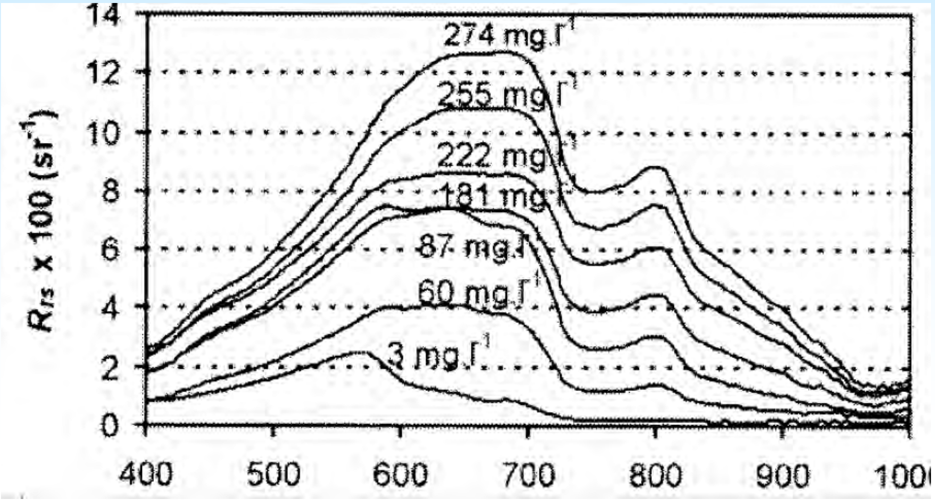


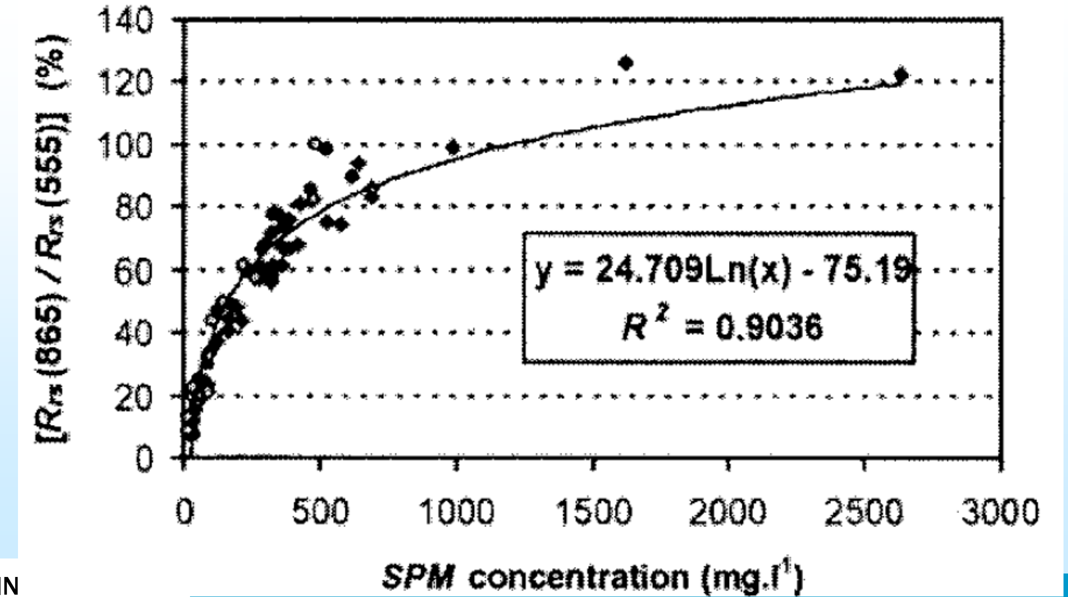


Rhow858-Rhow1240

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

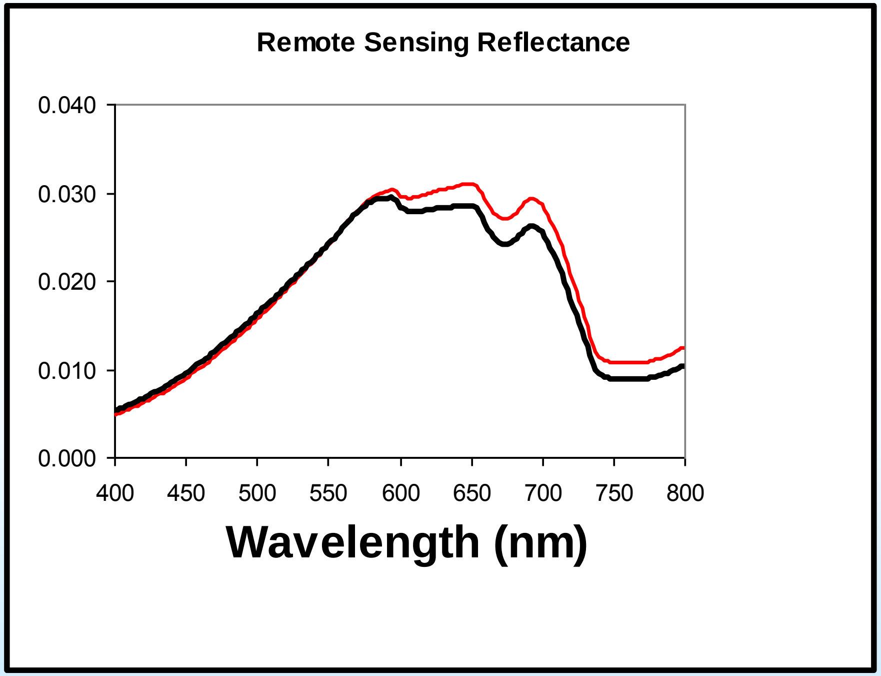
[Doxaran et al, 2003]





TSM retrieval: multispectral fitting

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



Beyond TSM … particle size, organic fraction, …

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

Transparency-related products and applications

- Historically, the main focus of ocean colour had been oceanic CHL
- Current standard products for MODIS/MERIS do not include turbid water transparency (except 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

CONCLUSIONS (CHL and TSM algos)

- CHL problems in turbid waters because of non-algae particle absorption
  - => use RED/NIR or multispectral algos

- TSM retrieval in turbid waters is « easy »
  - Can use single band, band difference, band ratio, multispectral algos

- Transparency and/or diffuse attenuation algos for turbid waters are emerging

- Next:
  - Computer Exercise « The Colour of Water » to consolidate
  - Aerosol correction in turbid waters (The Other Problem)
  - Applications and Future Perspectives (final lecture)

