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 CHL$a$ composite Sept1997-Aug1998, v1 processing

RED=high CHL$a$ (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

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

by Kevin Ruddick

with support from RBINS-REMSESEM 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 $90^\circ \pm 2.5^\circ$ scattering at 860nm (<60nm bandwidth) relative to Formazine (Formazine Nephelometric Units)
  – PLEASE DO NOT USE broadband tungsten lamps (US EPA protocol)
### Degrees of turbidity

- **Unofficial (but very useful) definitions**

<table>
<thead>
<tr>
<th>Description</th>
<th>Turbidity, bs (FNU)</th>
<th>Suspended Particulate Matter, SPM (g/m⁢³)</th>
<th>Secchi depth (m)</th>
<th>Scattering, b₅₅₅ (m⁻¹)</th>
<th>Backscattering, bb₅₅₅ (m⁻¹)</th>
<th>Water Reflectance at 778nm=Pl*Rrs778</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>&lt;1.1</td>
<td>&lt;1</td>
<td>&gt;10m</td>
<td>&lt;0.5</td>
<td>&lt;0.01</td>
<td>&lt;0.0008</td>
</tr>
<tr>
<td>Moderately turbid</td>
<td>1.1-11</td>
<td>1-10</td>
<td>2-10m</td>
<td>0.5-5</td>
<td>0.01-0.1</td>
<td>0.0008-0.008</td>
</tr>
<tr>
<td>Very turbid</td>
<td>11-110</td>
<td>10-100</td>
<td>20cm-2m</td>
<td>5-50</td>
<td>0.1-1</td>
<td>0.008-0.06</td>
</tr>
<tr>
<td>Extremely turbid</td>
<td>110-1100+</td>
<td>100-1000+</td>
<td>&lt;0.5cm-20cm</td>
<td>50-500+</td>
<td>1-10</td>
<td>0.06-0.2</td>
</tr>
</tbody>
</table>

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

Varying Total Suspended matter concentration (mg/m³)

Remote sensing reflectance

Wavelength (nm)

SPM estimation

Black NIR atmos. cor. [Gordon & Wang, 1994]
Varying Total Suspended matter concentration (mg/m³)

Remote sensing reflectance

Wavelength (nm)

SPM estimation

Bright NIR atmos. cor. [Moore et al, 1999]

Black SWIR atmos. cor. [Wang and Shi, 2007]
Varying Total Suspended matter concentration (mg/m³)

Remote sensing reflectance

SPM estimation
Bright SWIR atmos. cor.
Varying Total Suspended matter concentration (mg/m³)

- Remote sensing reflectance
- Wavelength (nm)

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

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

Bright SWIR atmos. cor.

SPM estimation
## Where to find turbid water

<table>
<thead>
<tr>
<th>Description</th>
<th>Suspended Particulate Matter, SPM (g/m³)</th>
<th>Typical cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>&lt;1</td>
<td>Non-bloom oceanic</td>
</tr>
<tr>
<td>Moderately turbid</td>
<td>1-10</td>
<td>Oceanic bloom, &quot;clear&quot; lake, Tidal seas (~20-50m)</td>
</tr>
<tr>
<td>Very turbid</td>
<td>10-100</td>
<td>Tidal seas (&lt;20m), lakes River plumes, estuaries</td>
</tr>
<tr>
<td>Extremely turbid</td>
<td>100-1000+</td>
<td>Major plumes, estuaries (Amazon, La Plata, Yangtze)</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Application</th>
<th>User</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU Environment Directive (MSFD/WFD) reporting</td>
<td>National govt</td>
<td>CHL – multitemporal (90 percentile) Turbidity (TUR)</td>
</tr>
<tr>
<td>Carbon cycle modelling and Ocean acidification</td>
<td>Ecosystem modellers</td>
<td>CHL ... ocean CO2, air-sea flux and pH PAR, PAR attenuation, euphotic depth</td>
</tr>
<tr>
<td>Harmful Algae Blooms near real-time alert</td>
<td>National govt Fisheries Aquaculture</td>
<td>CHL ... (Harmful?) Algae Bloom</td>
</tr>
<tr>
<td>Marine Science support</td>
<td>Marine scientists (esp. biology)</td>
<td>CHL</td>
</tr>
<tr>
<td>Coastline/Bathymetry change, dredging/dumping</td>
<td>Sediment transport modellers</td>
<td>Suspended Particulate Matter (SPM) or Turbidity (TUR) for model val/initial</td>
</tr>
<tr>
<td>Offshore construction (environmental impact)</td>
<td>Govt + Offshore industry</td>
<td>Suspended Particulate Matter (SPM) or Turbidity (TUR)</td>
</tr>
<tr>
<td>Diving ops; Detection of subs, mines; marine animal vision</td>
<td>Diving industry Military, Biologists</td>
<td>Underwater visibility</td>
</tr>
</tbody>
</table>

- Need many $\lambda$ and high S:N
- Need 2-3 $\lambda$
Useful parameters

Remote sensing reflectance

- Total Absorption, $a$
- Total Backscatter, $b_b$
- Algal Particle Absorption, $a_{ph}$
- Particulate backscatter, $b_{bp}$
- Particulate sidescatter, $b_{bs}$
- CDOM absorption, $a_{CDOM}$

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

Chlorophyll a, CHL
Phyto species?

Susp Part. Matt. Conc, SPM
Particle size/type?
Settling velocity??
ISO Turbidity, TUR
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

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

\[
R = \log_{10} \left( \max \left( R_{443}, R_{490}, R_{510} \right) / R_{555} \right)
\]

\[
(a_0, a_1, a_2, a_3, a_4) = (0.4708, -3.8469, 4.5338, -2.4434, -0.0414)
\]

[Morel and Antoine, 2000]
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]

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

\[a_{\varphi, 664nm}/CHL\]

\[b_b = \frac{1.61 \times \pi \times R_{rs}^{778nm}}{0.082 - 0.6 \times \pi \times R_{rs}^{778nm}}\]

[Gons et al, 2005]

Also Gitelson, Gilerson, etc.

MERIS/OLCI/S2
709nm very useful
MODIS 748nm
less useful

Remote Sensing Reflectance

\( a_w^{708nm} \)
\( a_w^{664nm} \)

\( R_{rs} \)

\( R_{rs}^{708nm} \)
\( R_{rs}^{664nm} \)
\( R_{rs}^{778nm} \)

[Computer Exercise]
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)

Detection limit of about 3µg/l

Time series from MERIS (R3, MEGS8.1)

Time series from MERIS (R2, MEGS7.5)

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*


Absorption algorithm

\[ a_{c3}(467) = a_t(467) - 0.43 \times a_t(450) - 0.57 \times a_t(480) \]

Reflectance algorithm

\[ a_{c3}(467) = \left[ \frac{1}{\rho_w(467)} - \frac{0.43}{\rho_w(450)} - \frac{0.57}{\rho_w(480)} \right] \times a_w(700) \times \rho_w(700) \]
Plankton species: Detection of *Noctiluca scintillans*


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

24.5.2011, Oostende

![Image of water body with text overlay](image-url)
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


- Gordon/Morel reflectance model

\[ R_{rs} = \gamma' \frac{b_b}{a + b_b} \quad \text{where} \quad \gamma' = \frac{f'R}{Q} \]

- Decompose IOPs:
  \[ a = a_{np} + a_p S \]
  \[ b_b = b_{bp} S \]

- Then

\[ S = \left\{ \frac{A(\lambda)}{1 - R_{rs}(\lambda)/C} \right\} R_{rs}(\lambda) \quad \text{where} \quad A = \frac{a_{np}}{\gamma'b_{bp}}, \quad C = \frac{\gamma'b_{bp}}{a_p + b_{bp}} \]
TSM retrieval algorithms: single band

- Remote-sensing reflectance, $R_{rs}$, at any single wavelength, $\lambda$, 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)**

[Shen et al, 2010; Nechad et al, 2010]
SPM retrieval – Band ratios, e.g. $SPM = f(R_{rs685}/R_{rs555})$

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 ... 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)
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:

<table>
<thead>
<tr>
<th>User</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecosystem modellers</td>
<td>Euphotic depth, PAR attenuation</td>
</tr>
<tr>
<td>Benthic biologists</td>
<td>bottom light availability (habitat)</td>
</tr>
<tr>
<td>Fish biologists</td>
<td>horizontal visibility (visual predation habitat)</td>
</tr>
<tr>
<td>Commercial/scientific divers</td>
<td>horizontal visibility</td>
</tr>
<tr>
<td>Water quality monitoring/Environmental Impact Assessement (windmill/port construction, dredging)</td>
<td>transparency/turbidity, even Secchi depth</td>
</tr>
</tbody>
</table>
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 \textit{a priori} uncertainty estimation

Filling clouds … and quality control [Sirjacobs et al, 2011]
# Ocean colour remote sensing in turbid waters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Capabilities</th>
<th>Limitations</th>
<th>Research</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
<td>SPM, CHLA, Kd (and IOPs)</td>
<td>Just SPM, CHLa, Kd No vertical structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No flux info</td>
<td></td>
</tr>
<tr>
<td><strong>Temporal</strong></td>
<td>~Daily since 2003</td>
<td>Clouds!</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Near Real Time (~2h)</td>
<td>No tidal info</td>
<td></td>
</tr>
<tr>
<td><strong>Spatial</strong></td>
<td>300m-1000km</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10m (some ~1m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SPM Conc.</strong></td>
<td>0.1-500 g/m³</td>
<td>Extreme high conc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>Absolute: 30-50% SPM?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relative: good</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Issues</strong></td>
<td></td>
<td>Near land (~1km) Atmospheric Corr. Sunglint</td>
<td></td>
</tr>
</tbody>
</table>
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

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!)

<table>
<thead>
<tr>
<th>Satellite/Sensor</th>
<th>Period</th>
<th>Spatial Resolution</th>
<th>Temporal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeaWiFS</td>
<td>1997-2010</td>
<td>1000m</td>
<td>Daily</td>
</tr>
<tr>
<td>MODIS-TERRA</td>
<td>1999+</td>
<td>250m</td>
<td>Daily</td>
</tr>
<tr>
<td>MODIS-AQUA</td>
<td>2002+</td>
<td>250m</td>
<td>Daily</td>
</tr>
<tr>
<td>ENVISAT-MERIS</td>
<td>2002-2012</td>
<td>300m</td>
<td>~4/week</td>
</tr>
<tr>
<td>VIIRS</td>
<td>2011+</td>
<td>1000m</td>
<td>Daily</td>
</tr>
<tr>
<td>Sentinel-3AB/OLCI</td>
<td>2015+</td>
<td>300m</td>
<td>~4/week (1 sat)</td>
</tr>
<tr>
<td>PROBA-V</td>
<td>2013+</td>
<td>100m</td>
<td>Every 5 days</td>
</tr>
<tr>
<td>Landsat-5</td>
<td>1984-2013</td>
<td>30m</td>
<td>Every 16 days</td>
</tr>
<tr>
<td>Landsat-8</td>
<td>2013+</td>
<td>30m</td>
<td>Every 8 or 16 days</td>
</tr>
<tr>
<td>Sentinel-2AB</td>
<td>2015+</td>
<td>10m</td>
<td>~3/week (2 sats)</td>
</tr>
<tr>
<td>Pléiades</td>
<td>2011+</td>
<td>2m/70cm</td>
<td>On demand</td>
</tr>
<tr>
<td>SEVIRI-MSG</td>
<td>2004+</td>
<td>5000m</td>
<td>Every 5 minutes</td>
</tr>
</tbody>
</table>
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 uncertainty 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!) …