Optical Remote Sensing of marine and inland waters

Main results of the BELCOLOUR-2 project (2007-2011)

1. Management Unit of the North Sea Mathematical Models (MUMM/RBINS)
2. Laboratoire d'Ecologie des Systèmes Aquatiques (ULB/ESA)
3. Vlaamse Instelling voor Technologisch Onderzoek (VITO)
4. Unité d'Océanographie Chimique, Université de Liège (ULg)
5. Laboratoire d'Océanographie de Villefranche, France (LOV)
6. CSIRO Land and Water, Australia (CSIRO)

"What's in the water"?
(How much information can we extract?)

- **Mass concentration of particles?**
- **Size distribution of particles?**
- **Algal or non-algal?**
- **What species of algae?**
- **How much carbon is it fixing/day?**
- **Dissolved CO_2 concentration?**
- **Conc/typ of Dissolved organic matter?**
- **How transparent?**

+ space-time variation (and cause/effect)

BUT

- **Viewing through atmosphere**
- **Possibly also viewing sea bottom**

Applications

Sediment transport

Ecosystem dynamics (phytoplankton)

Water quality (EU monitoring)

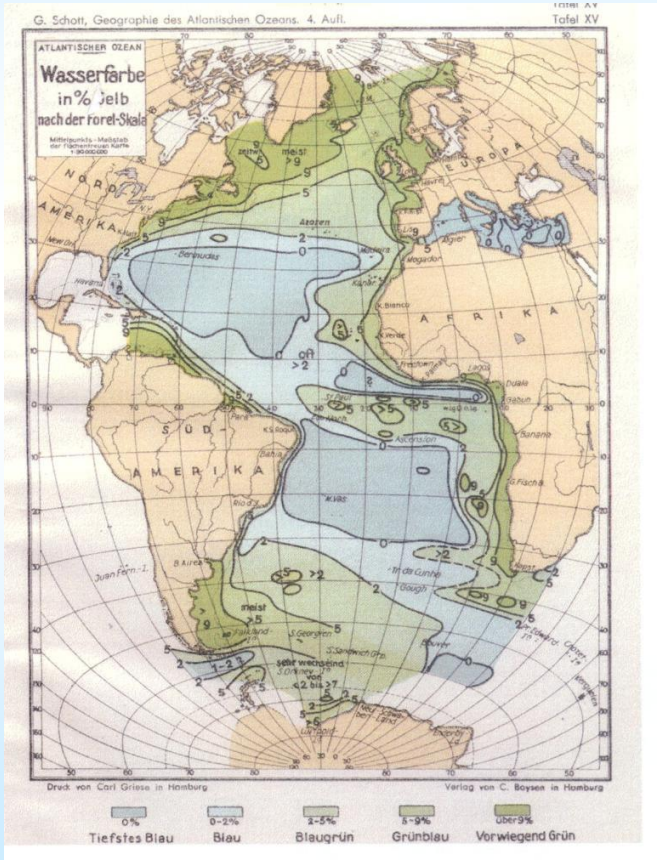
Carbon cycle

Marine science (inc. benthos)

History

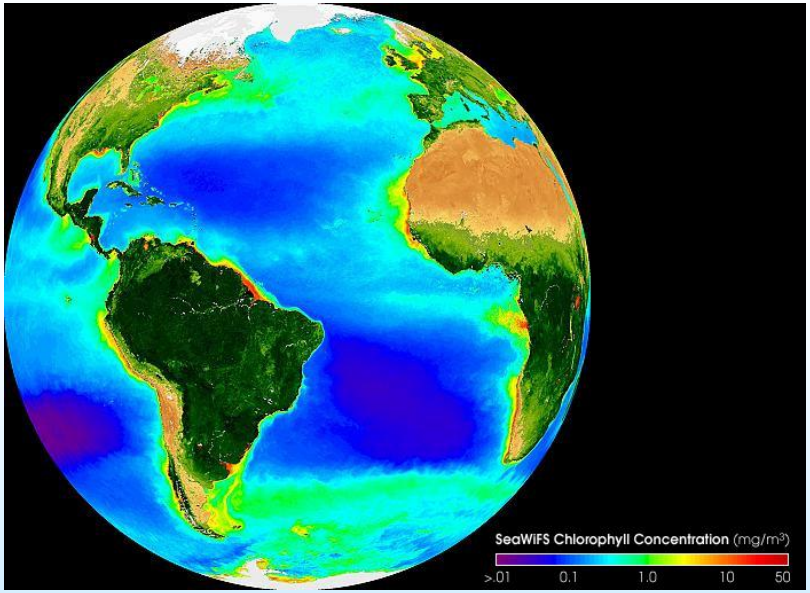
Forel-Ule measurements

[Schott, 1944!] in [Wernand, 2010]



SeaWiFS chlorophyll *a*

[NASA]



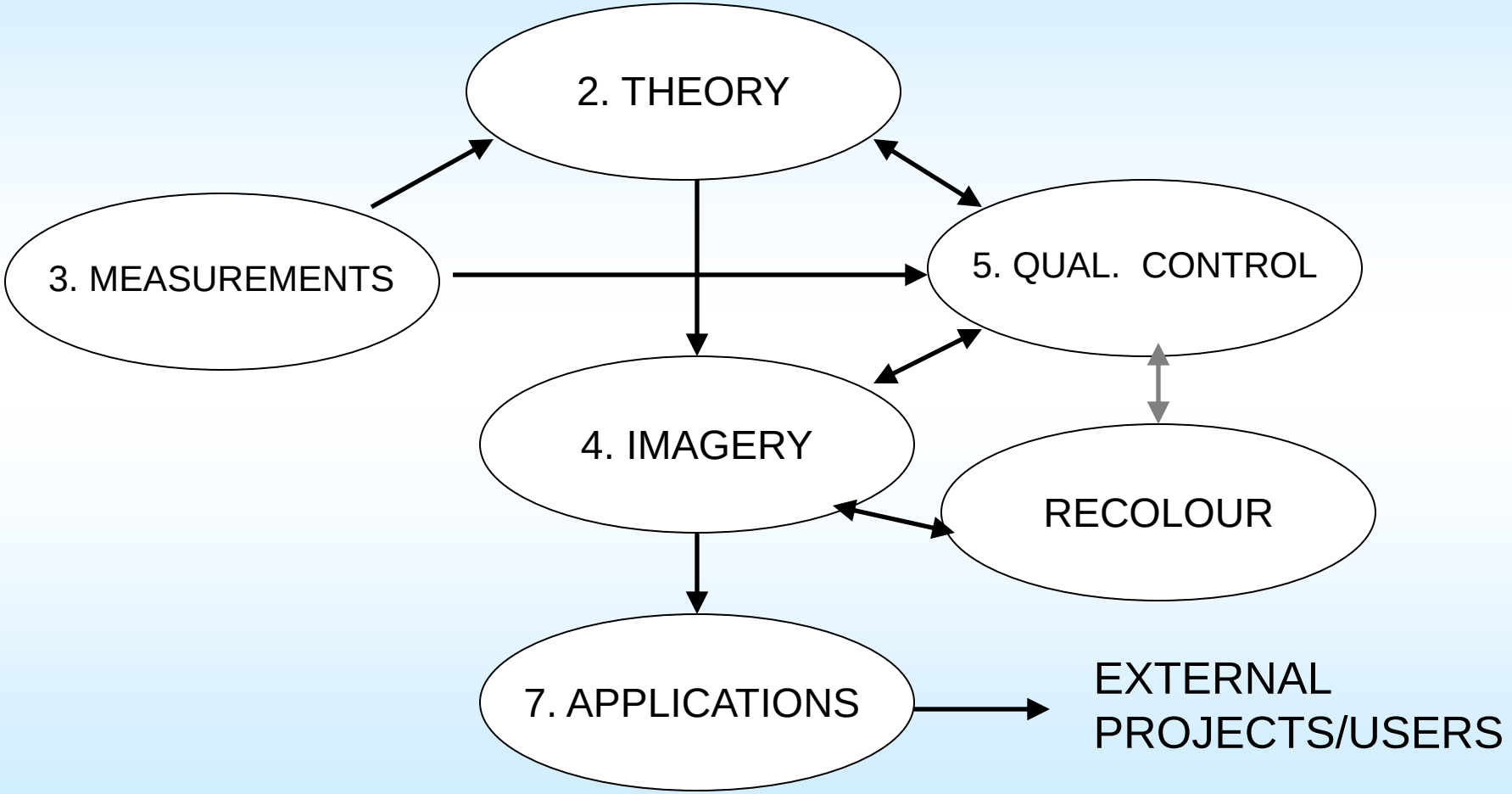
The BELCOLOUR-2 project

- **Objectives:**
  - **To improve the quality of chlorophyll and total suspended matter-based products**
  - **To develop new optical remote sensing products, including pCO2 and primary production**
- **Project duration: January 2007 – December 2011**
- **Funded by Belgian Federal Science Policy Office, STEREO programme (SR/00/03): 1.07M€** (+0.16 M€ RECOLOUR)
  - ✓ 5 years funding
  - ✓ Easy admin (yearly reporting, budget transfers)
  - ✓ Constructive support and Steering Committee
  - ✓ Funding for international partners
- **Partners: MUMM, ULB/ESA, VITO/TAP, ULg-Chim., LOV (Fr), CSIRO (Aus)** + RECOLOUR (2007-8): ULg/GHER + ad hoc intl. (ULCO, etc.)

The Partners

- **BELCOLOUR-2 BE:**
  - MUMM: algorithms, satellite imagery, env . apps
  - ULB/ESA: phytoplankton, primary production, IOPs
  - VITO/TAP: airborne, atmospheric correction, inland waters
  - ULg-Chim: carbon dynamics, air-sea flux, CO_2
- **BELCOLOUR-2 foreign:**
  - LOV: scattering, turbid waters, suspended matter
  - CSIRO: algorithms, satellite imagery, env. apps
- RECOLOUR
  - ULg-GHER: statistical analysis, EOF, data filling

Project structure



Applications

App #1: Eutrophication monitoring (optimisation) Reorganisation of BE monitoring network

[Ruddick et al, in "Remote Sensing of the European Seas", 2008]

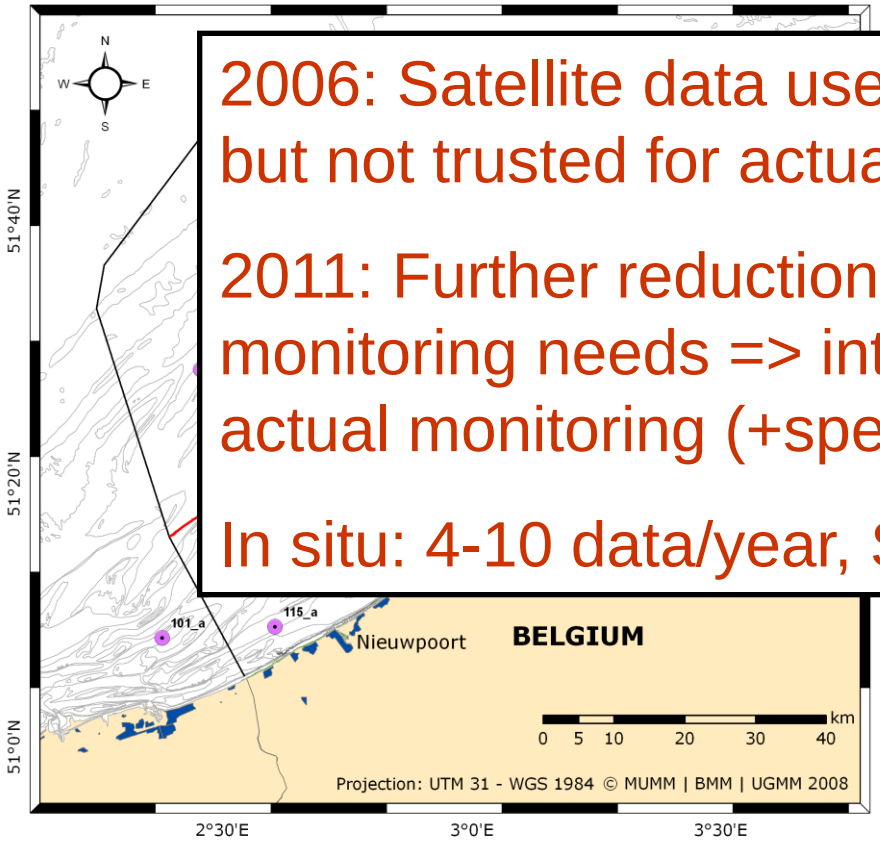
Before 2007 (17+2)

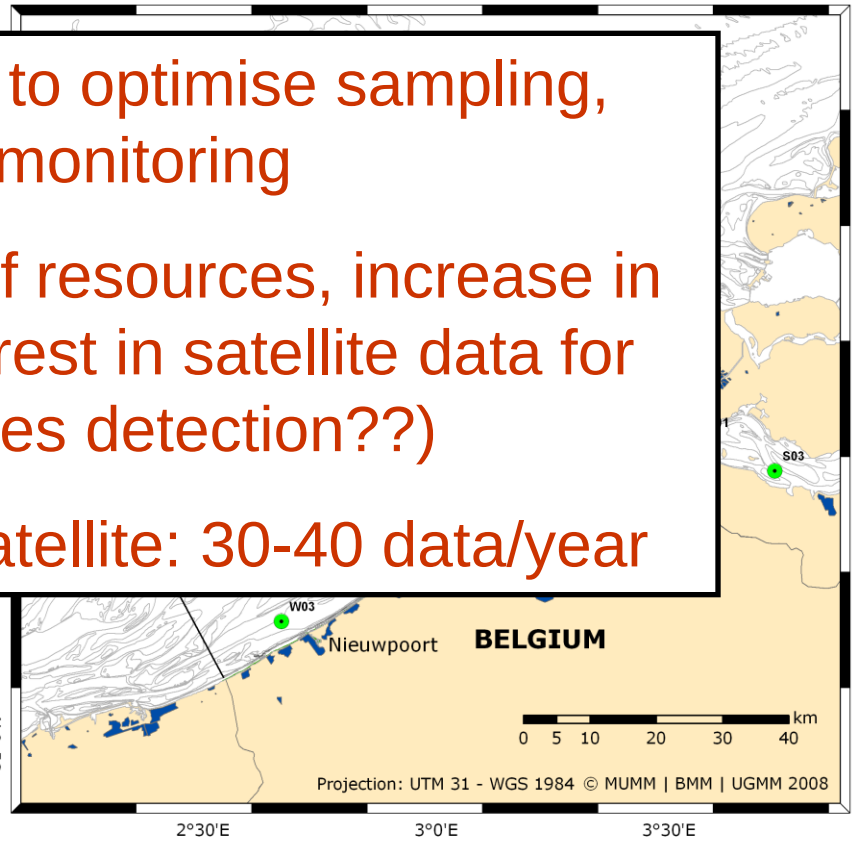
After 2007 (10+2)

2006: Satellite data used to optimise sampling, but not trusted for actual monitoring

2011: Further reduction of resources, increase in monitoring needs => interest in satellite data for actual monitoring (+species detection??)

In situ: 4-10 data/year, Satellite: 30-40 data/year



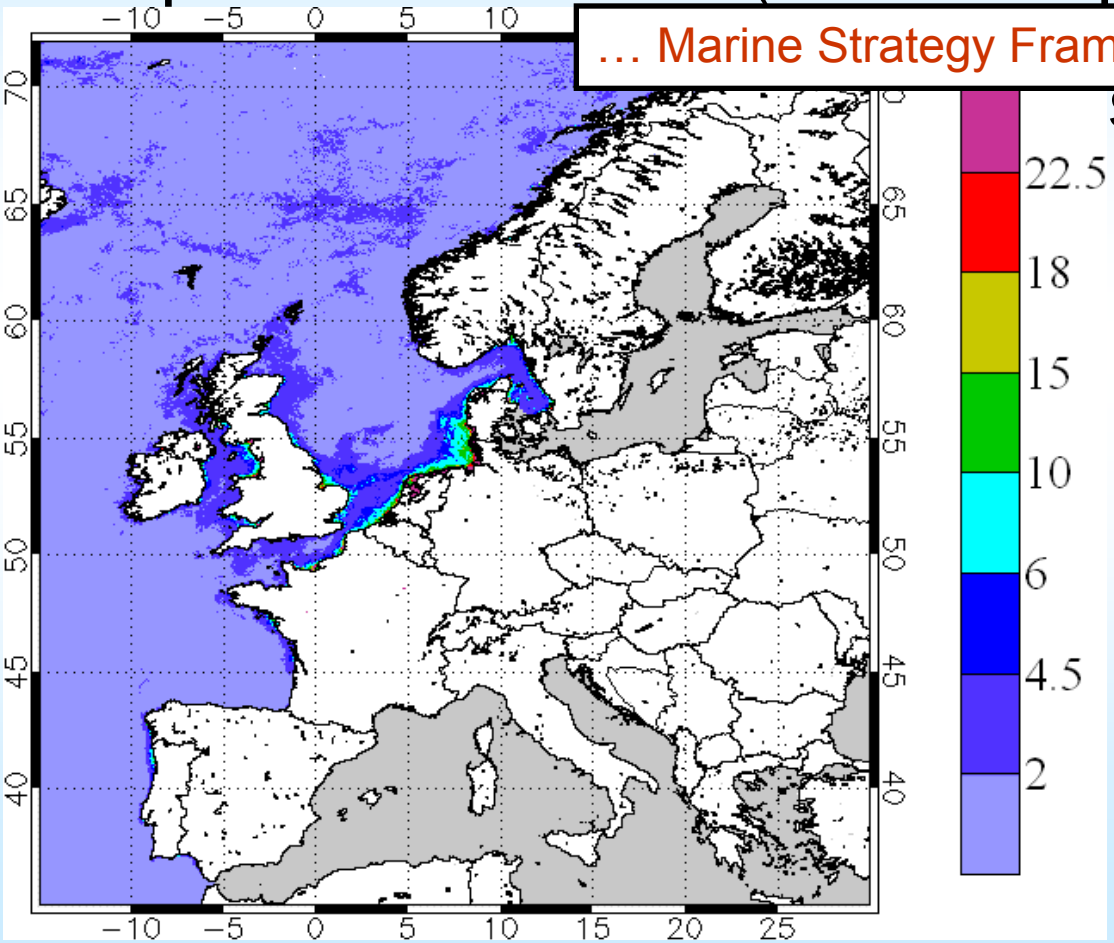


App #2: Eutrophication assessment

[In "Second OSPAR Integrated Report on the Eutrophication Status …", 2008]

- **90 percentile CHL in 2006 (OSPAR Eutrophication cttee)**

… Marine Strategy Framework Directive (2014)



Satellite data is:

- **Neutral, transparent**
- **Spatially extensive**
- **Cross-boundary**

Relevant for:

- **OSPAR "screening"**
- **Supplementing *in situ* [F. Gohin]**

[MERIS data from ACRI/ MARCOAST, processed MUMM]

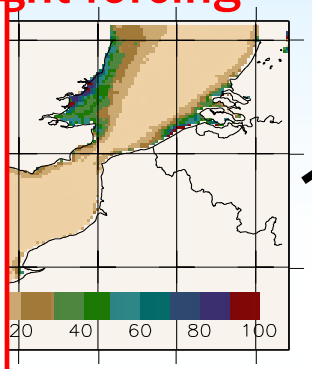
App #3: Ecosystem model support

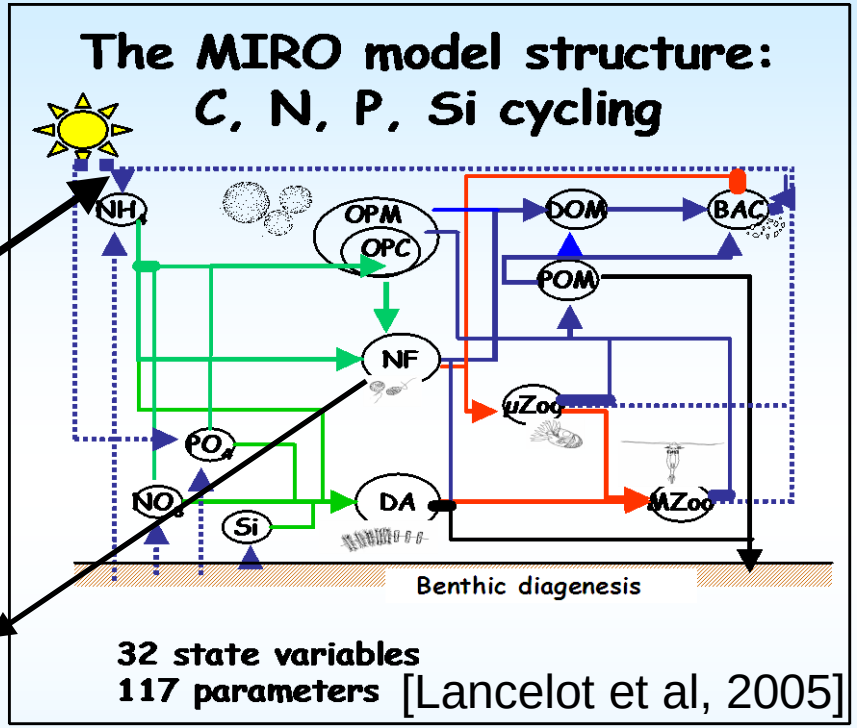
1. TSM for light forcing

2008 4-season TSM climatology

2010 RECOLOUR daily TSM 2003-6

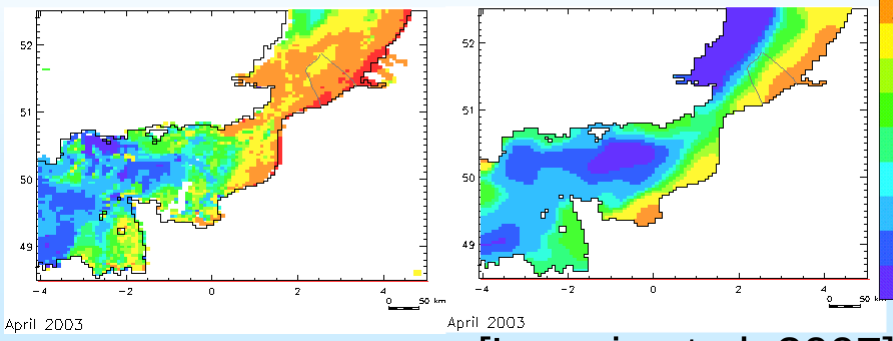
2012 SEVIRI/DINEOF 15-min KdPAR?





[Lancelot et al, 2005]

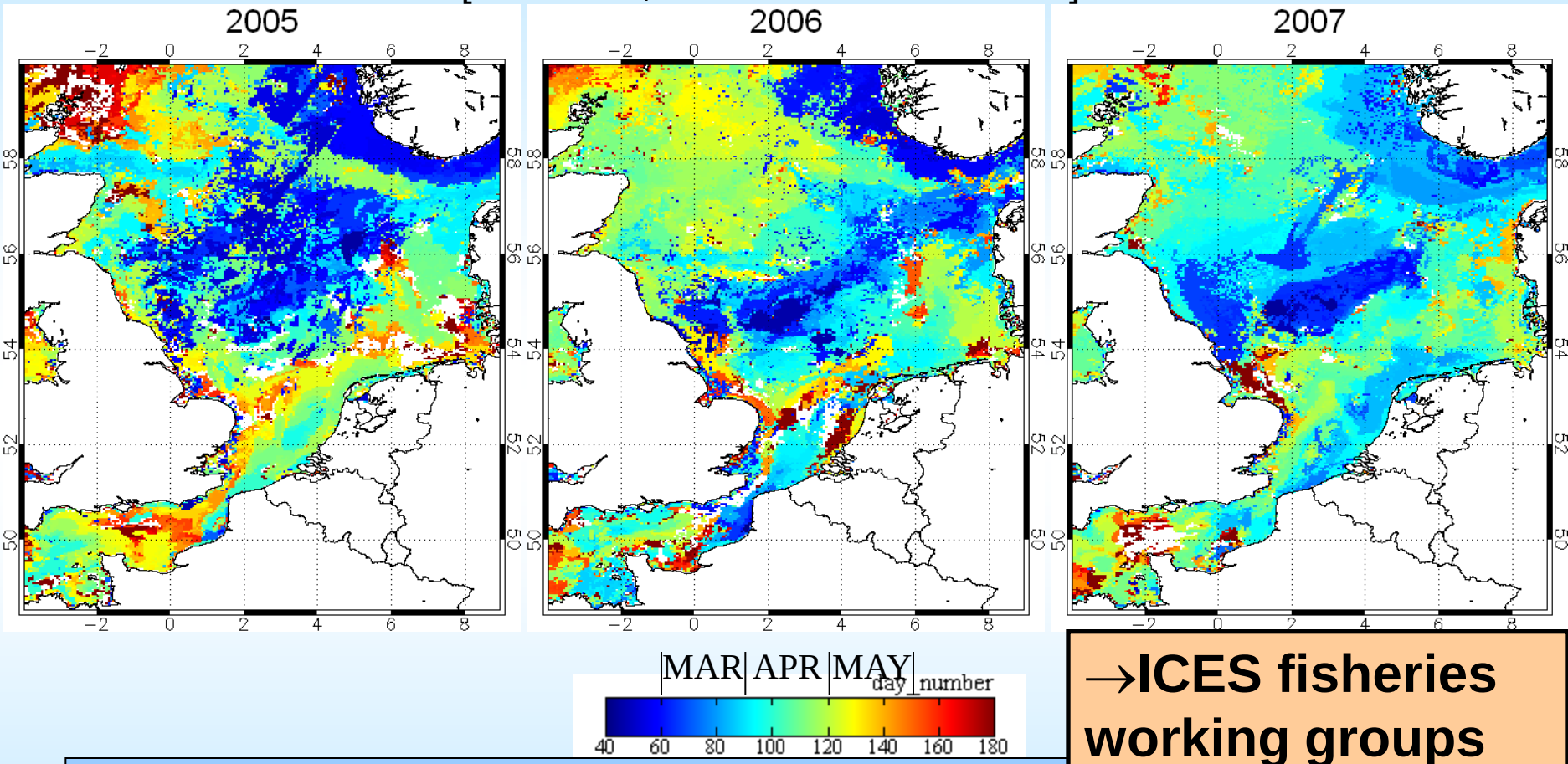
2. CHL for validation



[Lacroix et al, 2007]

App #4: Algal bloom timing in the North Sea

[Park et al, Int. J. Rem Sens. 2011]



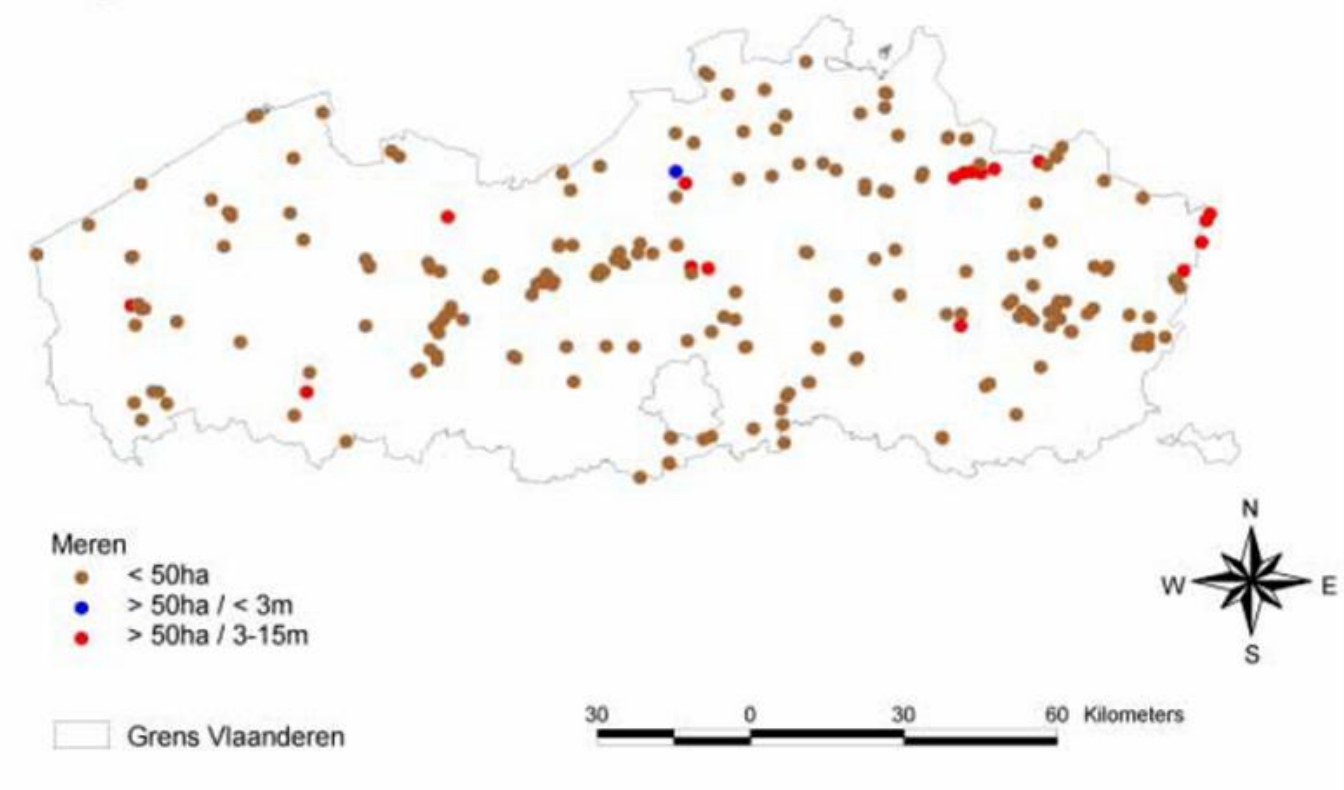
→ICES fisheries working groups

1. Early blooms in Norwegian coastal current, central North Sea
2. Late blooms in turbid water in east UK coast, German bight, western channel

=>Significant spatial and interannual variabilities in the North Sea

App#5: Inland water monitoring

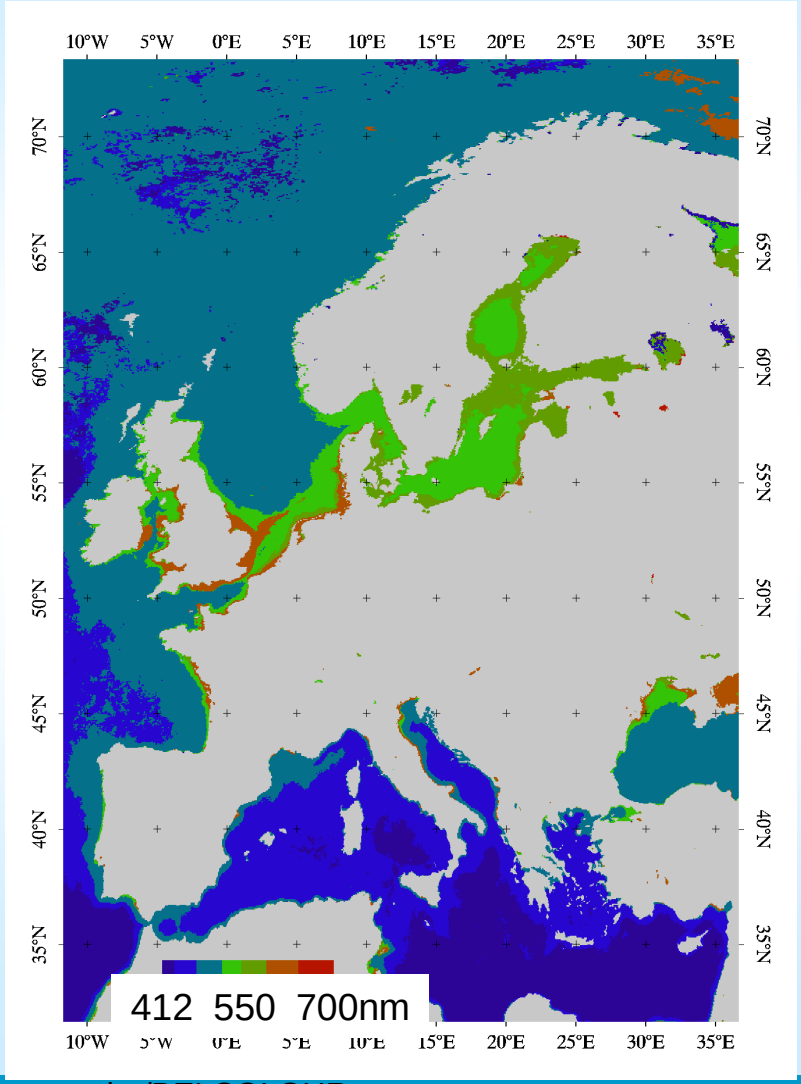
- **Review of Water Framework Directive reqts [VITO/BELCOLOUR report]**



[Map from http://www.ciwvlaanderen.be/]

App #6: Underwater light climate (fish genetics)

[Larmuseau et al, Molecular Ecology, 2009]



- **Wavelength of maximally transmitted light (WMTL) from MODIS data of 2007**
- **Light climate influences fish evolution (vision)?**

Future perspectives:

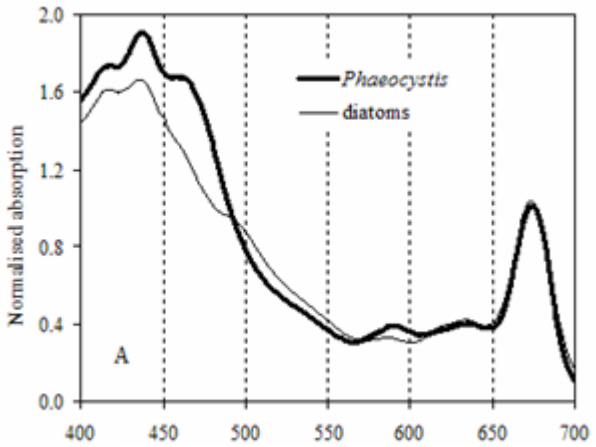
Use of optical remote sensing data of light climate for applications in habitat adaptation of visual predators … evolution studies??

Science results (selected)

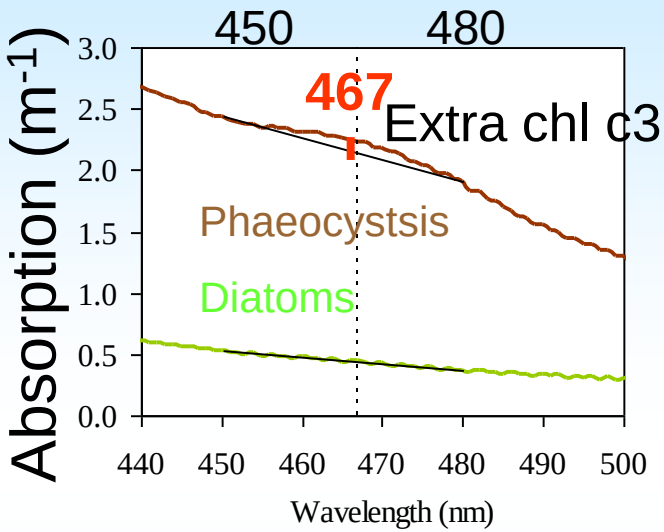
Detection of *Phaeocystis globosa*

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

Normalised absorption



Wavelength (nm)



Absorption algorithm

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

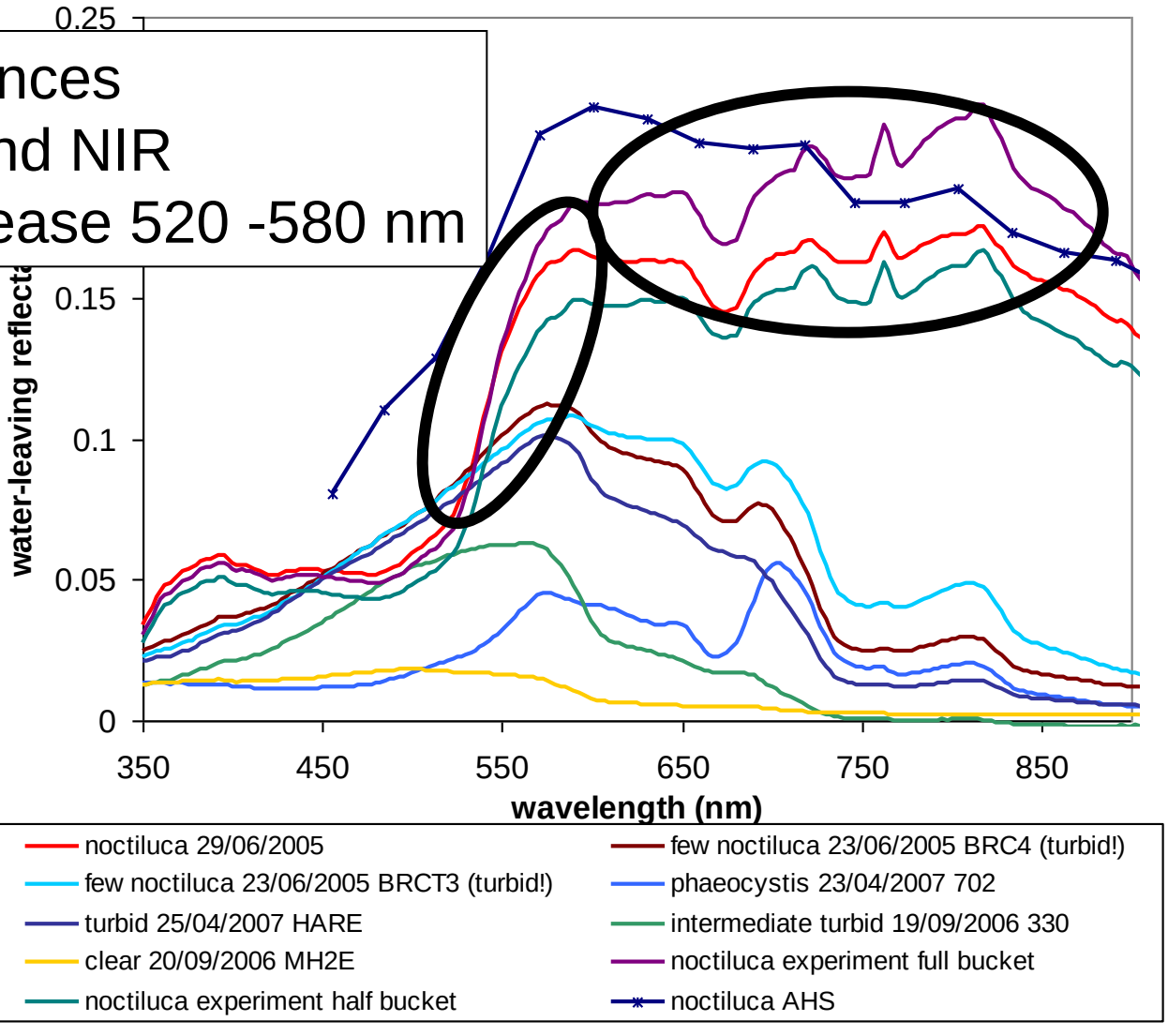
Reflectance algorithm

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

Detection of *Noctiluca scintillans*

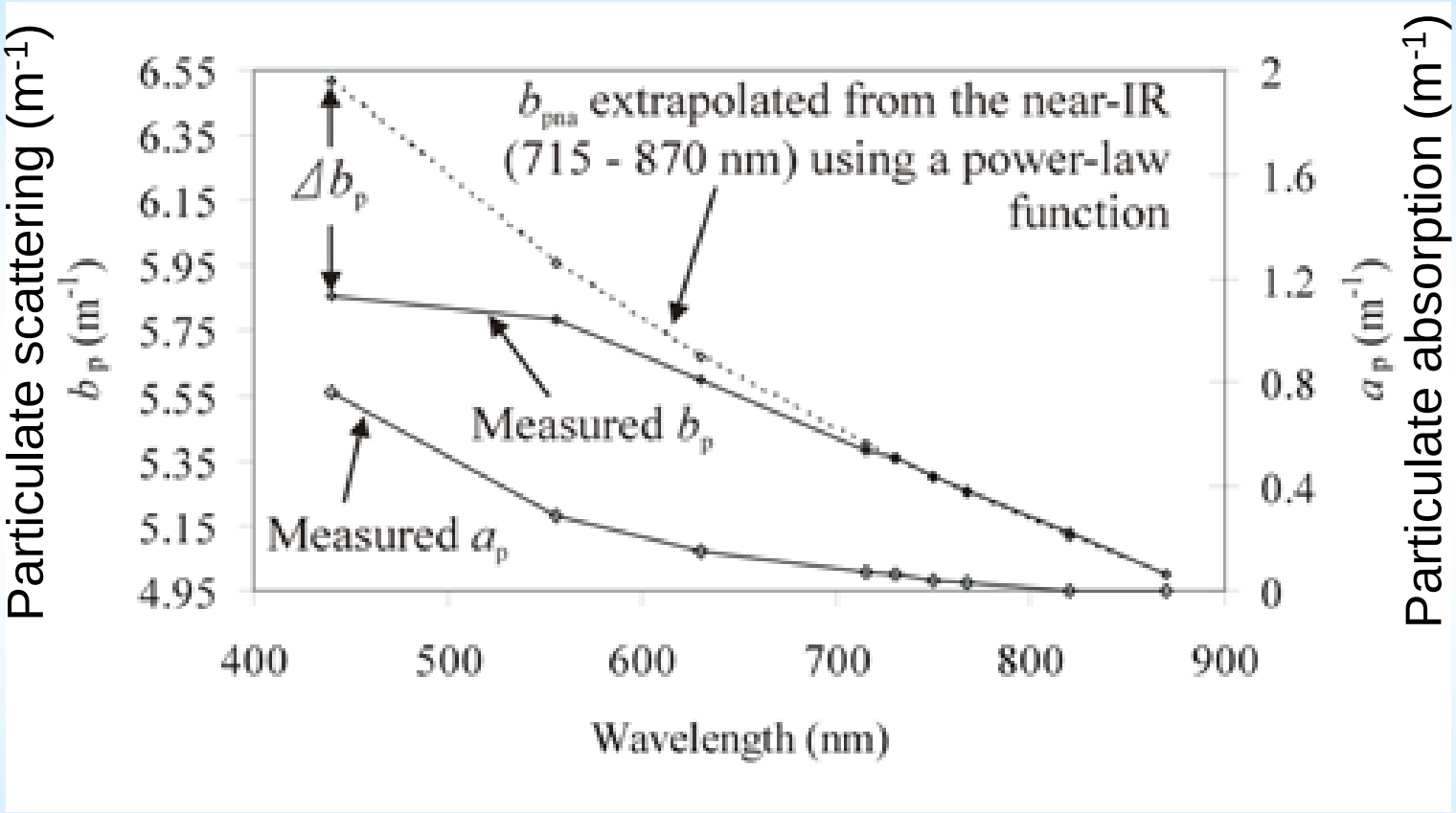
[Van Mol et al, EARSEL eProceedings, 2007]

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



Spectral variation of scattering from near infrared to visible

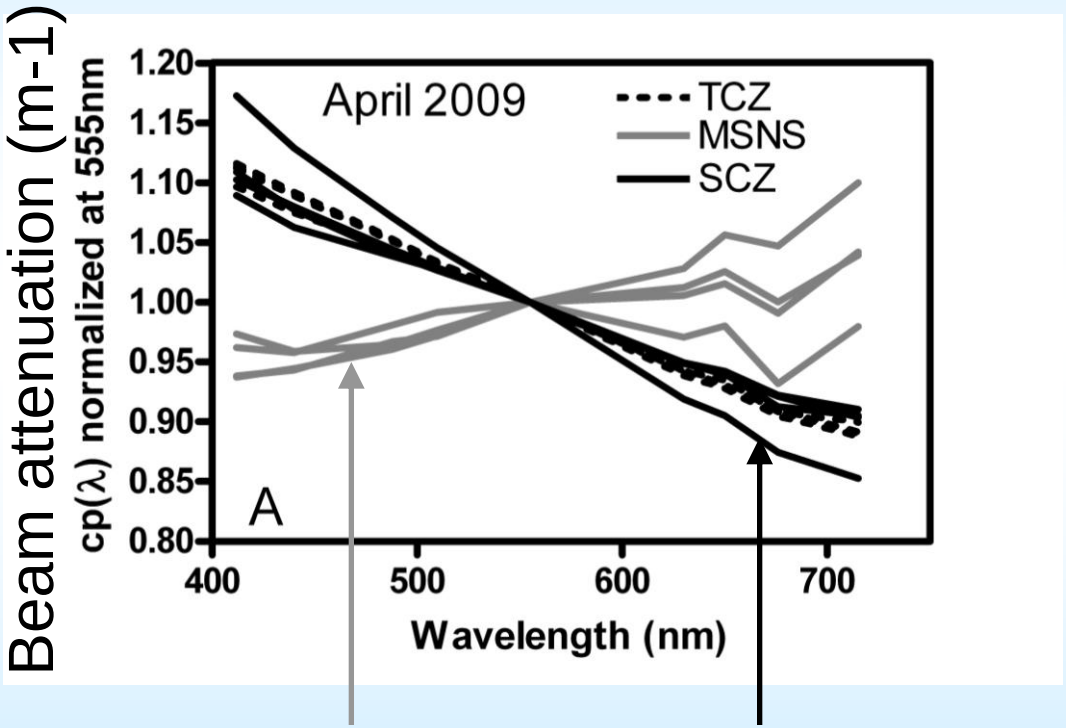
[Doxaran et al, Limnology and Oceanology, 2009]



- The relation between Δb_p and a_p is function of particle size dist.
- Next step: similar analysis for backscatter (with new instrument) …

Spectal variation of particulate scattering

[Astoreca et al, submitted to Continental Shelf Research, 2011]



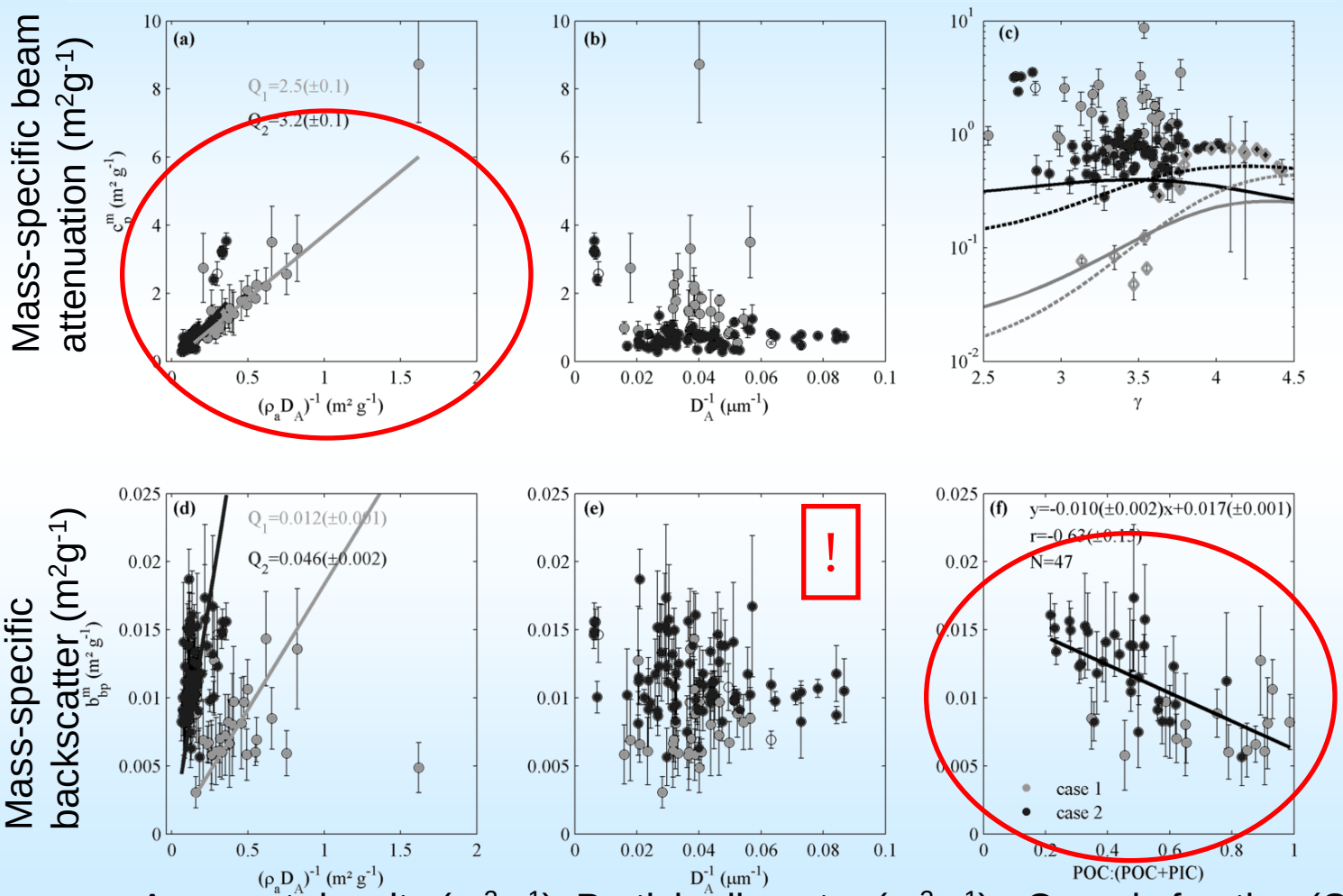
- Spectral variation depends on particle type and size
- Phytoplankton ~7µm give anomalous positive slope
- In situ measurements confirmed by lab experiments and Mie theory simulations

"Algal bloom" spectrum

"Normal" spectrum

Mass-specific Particulate beam attenuation (c_p) and backscatter (b_{bp})

[Neukermans et al, submitted to Limnology and Oceanography, 2011]



Apparent density (m^2g^{-1}) Particle diameter (m^2g^{-1}) Organic fraction (Carbon)

Regions:

S. North Sea (BE/UK/FR/NL)

Channel (FR/EN)

Atlantic (FR/SP)

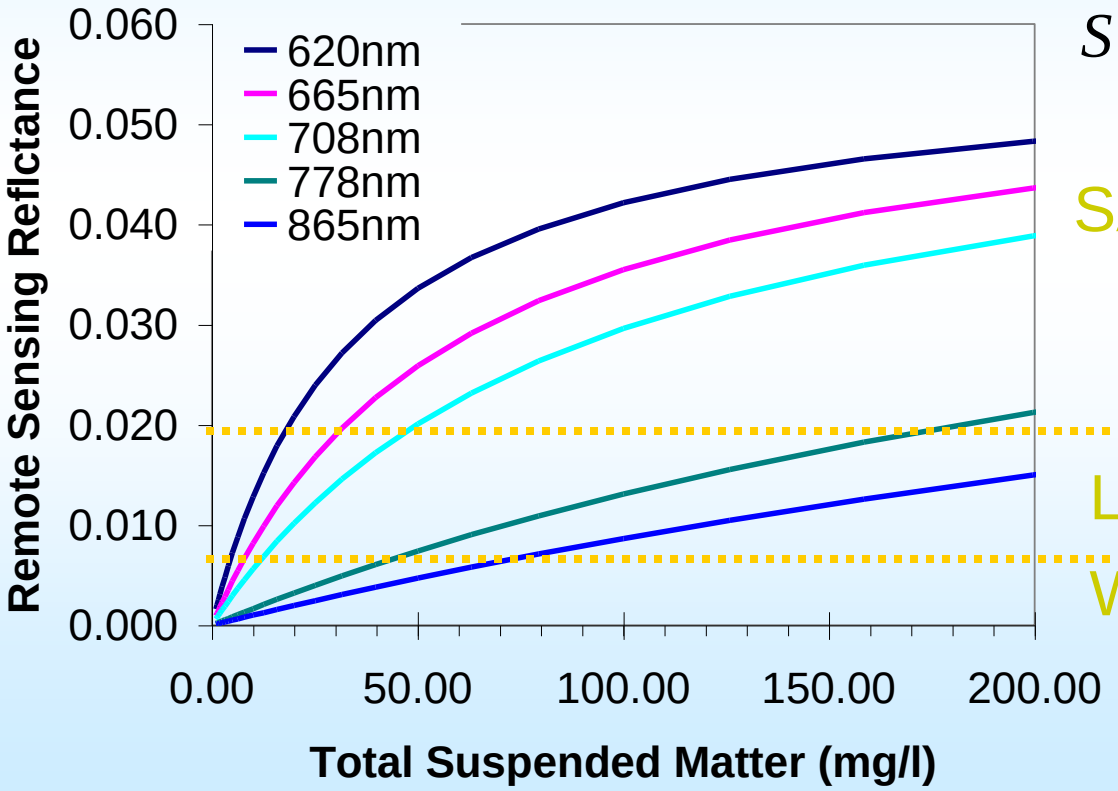
Ligurian (IT/FR)

Fr. Guyana

One band TSM retrieval algorithms

[Nechad et al, Rem. Sens Env., 2010]

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



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

SATURATION

LINEAR (optimal)

WEAK SIGNAL

Dissolved CO_2

[Borges et al, ESA Living Planet Proceedings, 2010]

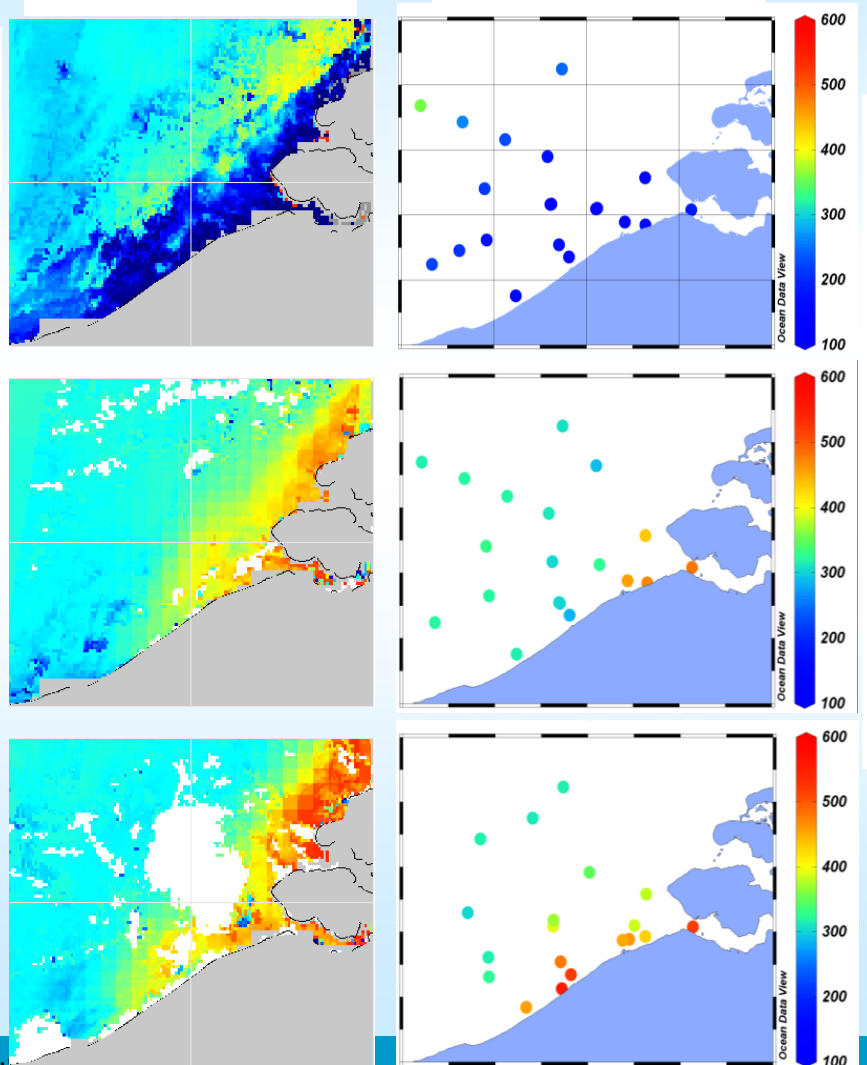
Estimated pCO_2@10 °C

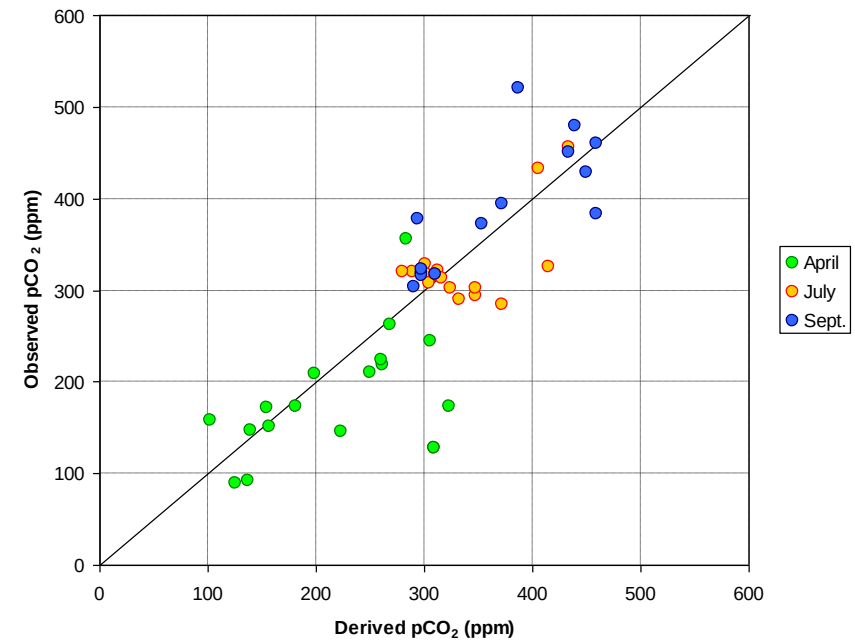
In situ pCO_2@10 °C

Apr 2007

Jul 2007

Sep 2007





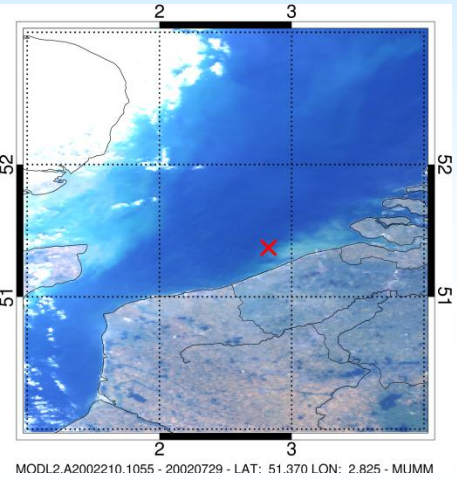
pCO2 algorithm has input:

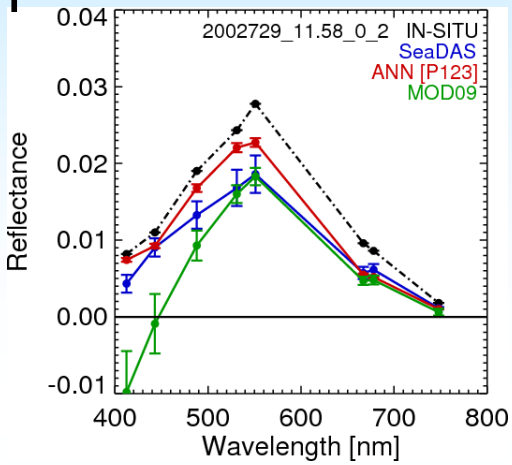
- hydrodynamic model salinity
- satellite Chlorophyll

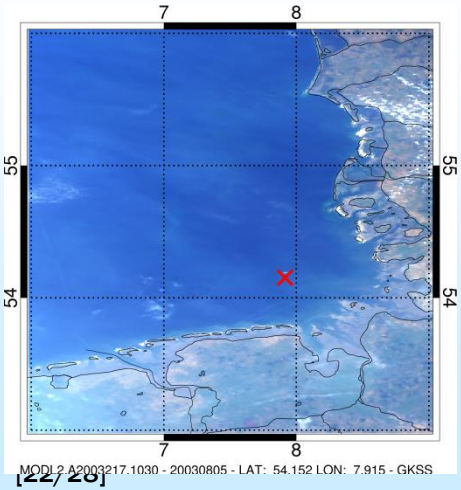
Atmospheric correction inter-comparison

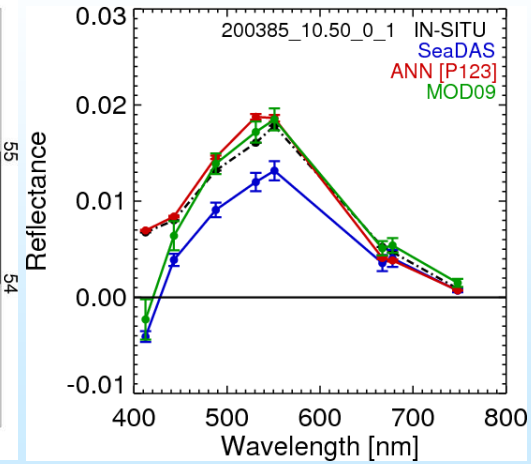
[Schroeder et al, in prep]

2 examples

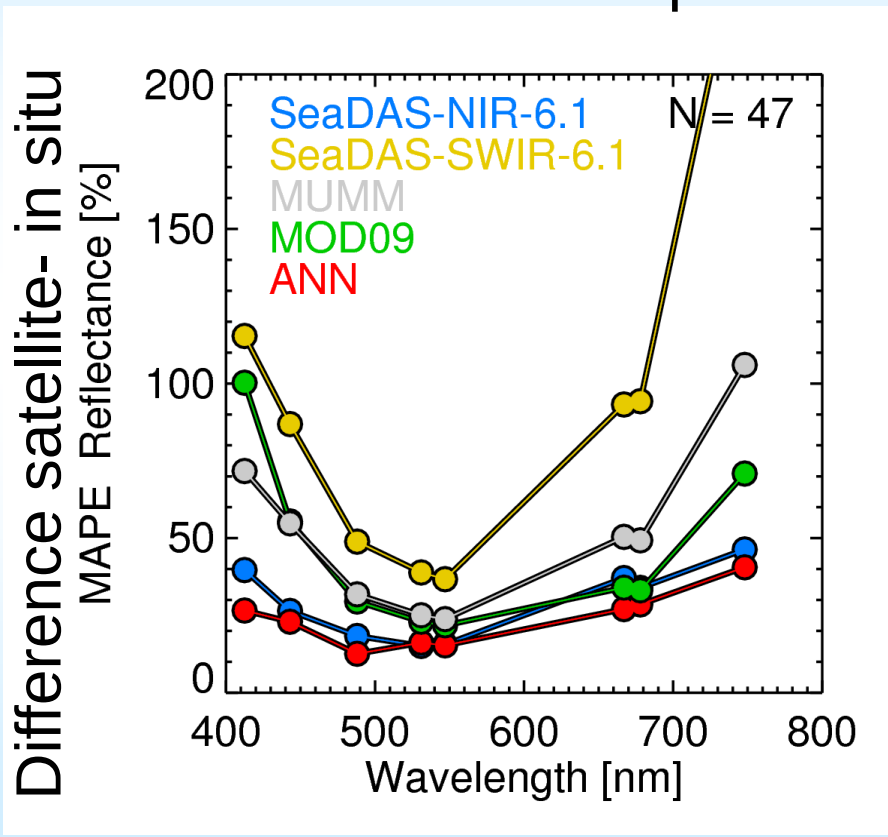








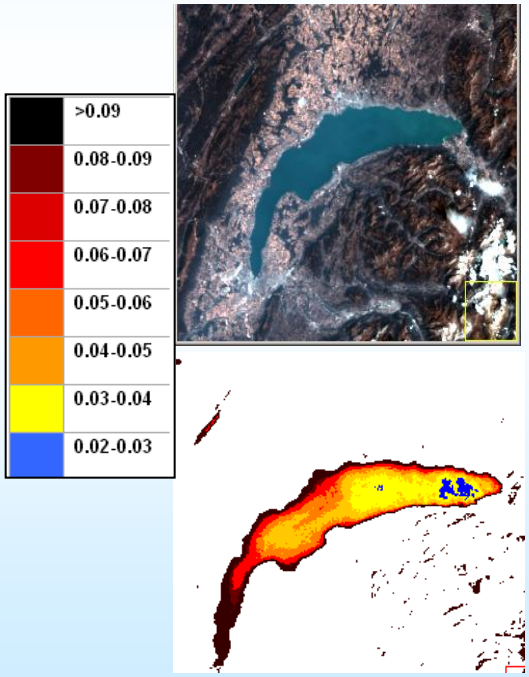
All 47 matchups



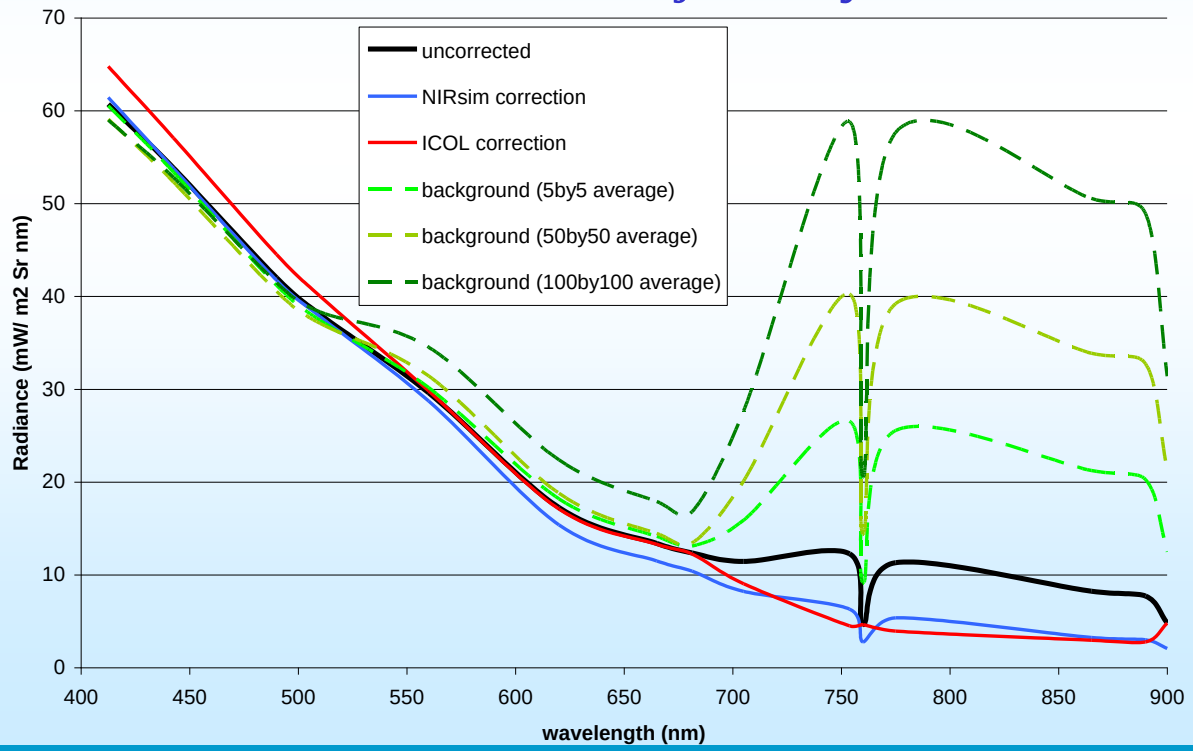
Adjacency detection and correction with the NIR similarity spectrum: application to airborne and MERIS data

[Sterckx et al, Int. J. Rem. Sens, in press]

Adjacency detection



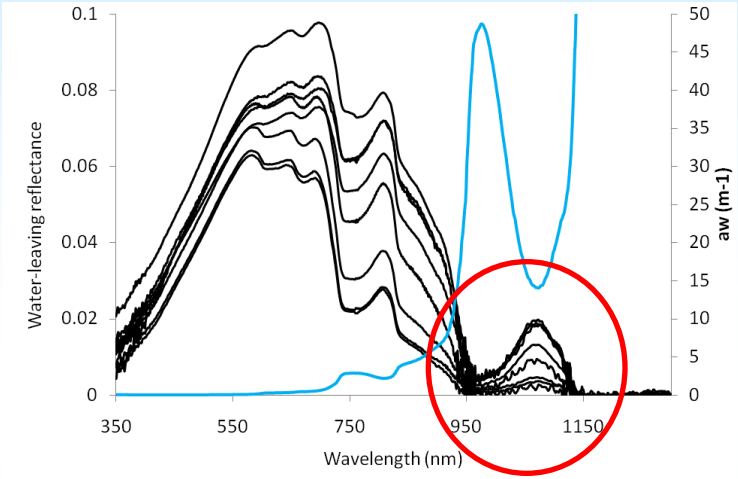
Adjacency correction

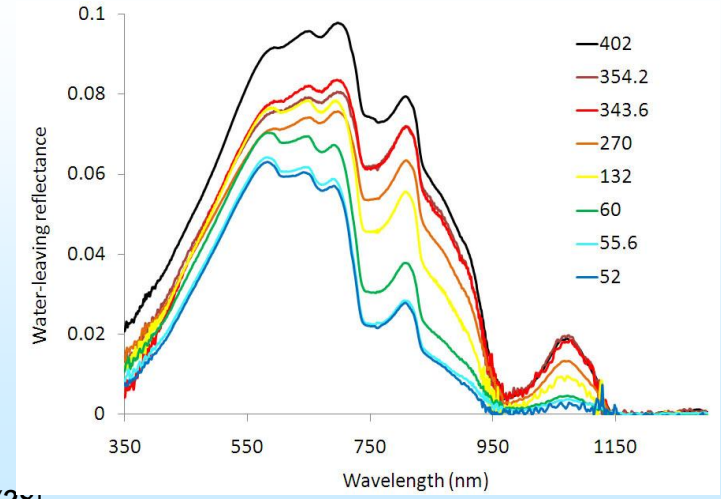


In situ evidence of non-zero SWIR reflectance in the Scheldt [Knaeps et al, submitted to Rem. Sens. Env]

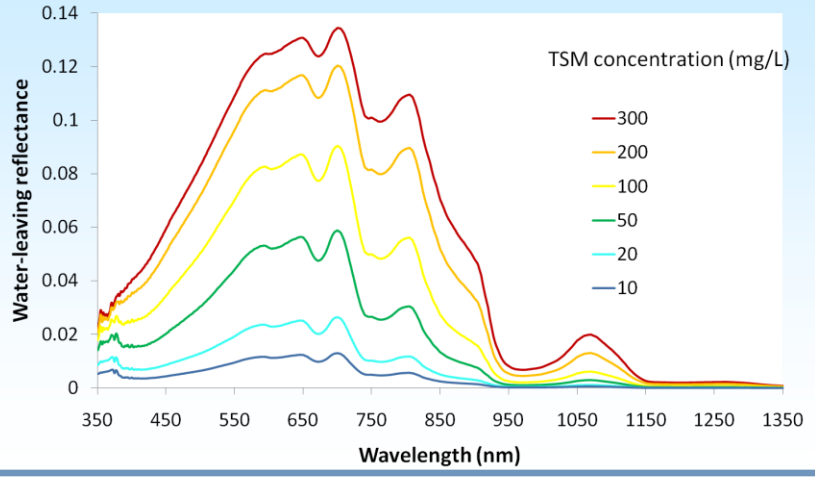
ASD water reflectance

Pure water absorption coefficient (Pope & Fry, 1997; Kou *et al.*, 1993)

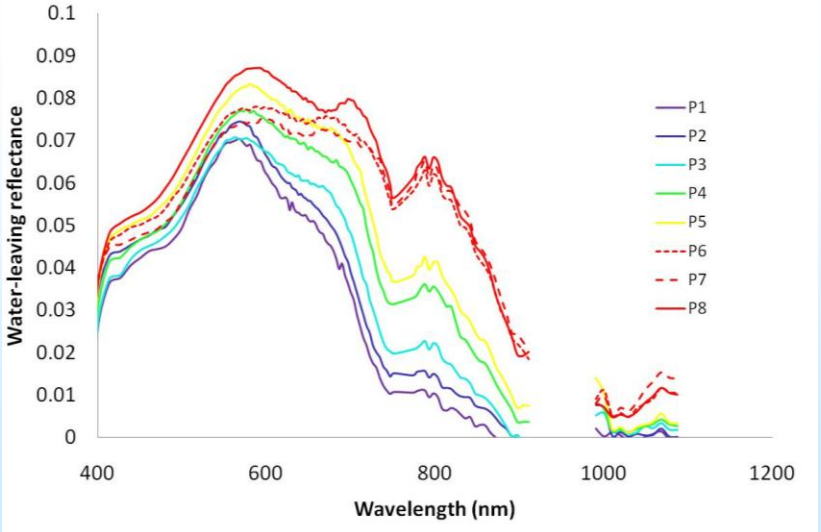




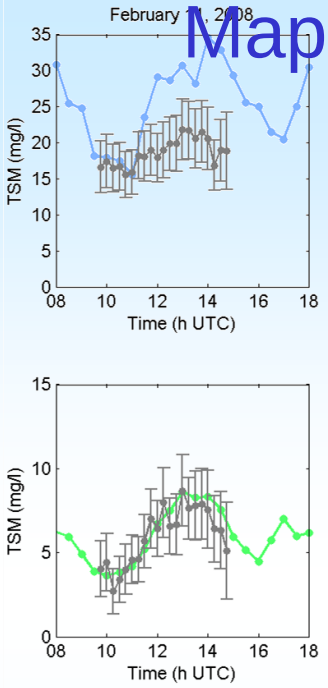
Simulated water reflectance with Hydrolight

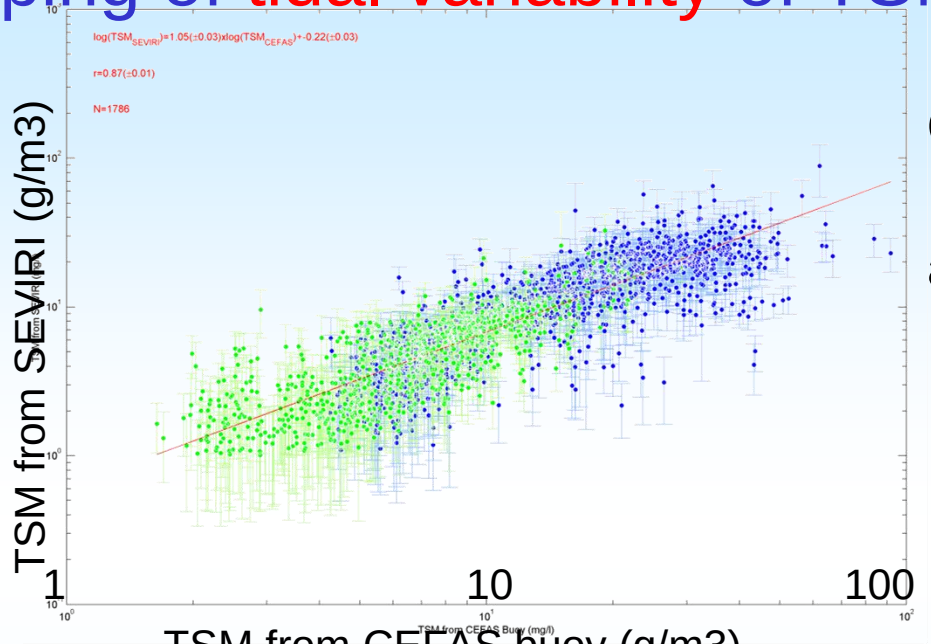


APEX water reflectance



Mapping of tidal variability of TSM by SEVIRI



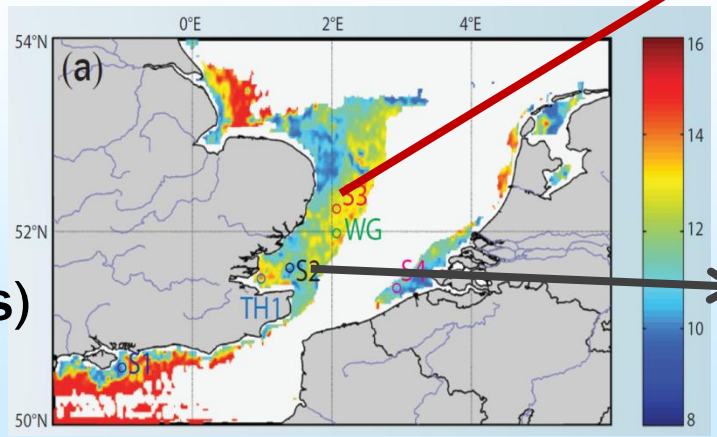


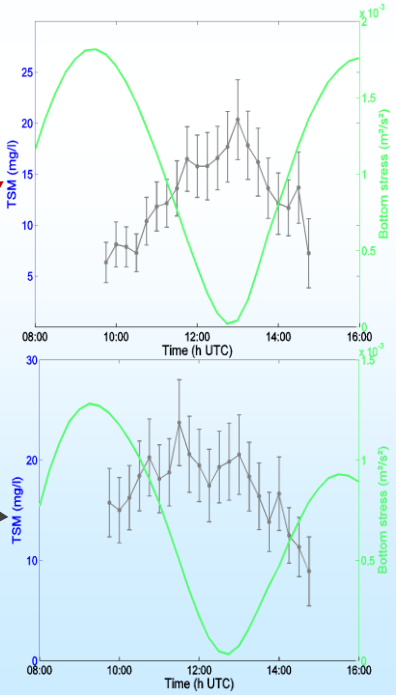
TSM from CEFAS buoy (g/m3)

[Neukermans, in prep.]

Good overall correlation between SEVIRI TSM and CEFAS SB TSM, but large deviations occur.

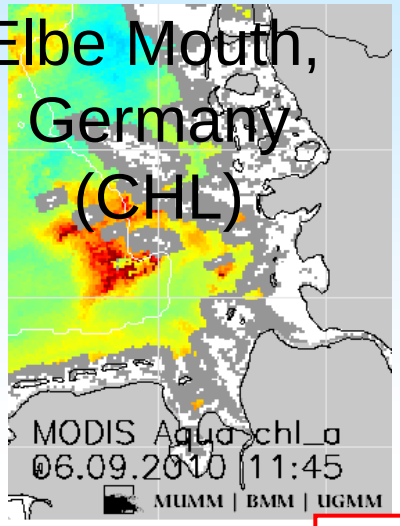
TSM mainly driven by tidal resuspension with max(TSM) occurring about 3h after max(BottomStress)



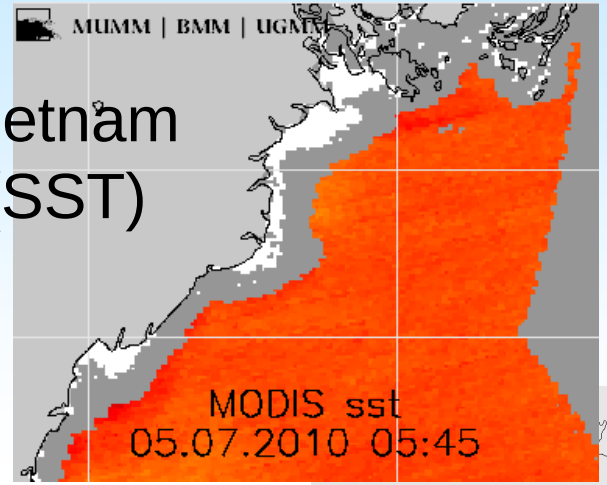


Automation of image processing [Vanhellemont, in prep]

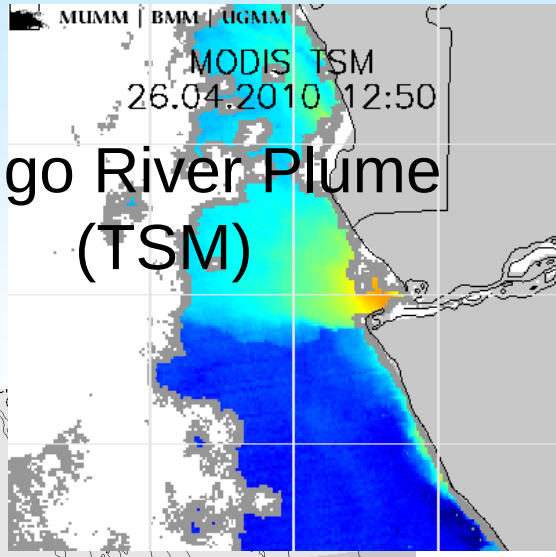
Elbe Mouth, Germany (CHL)



Vietnam (SST)

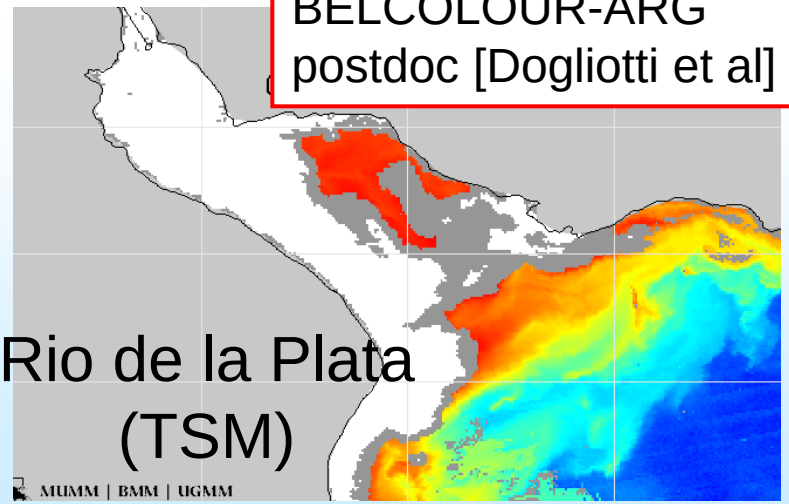


Congo River Plume (TSM)

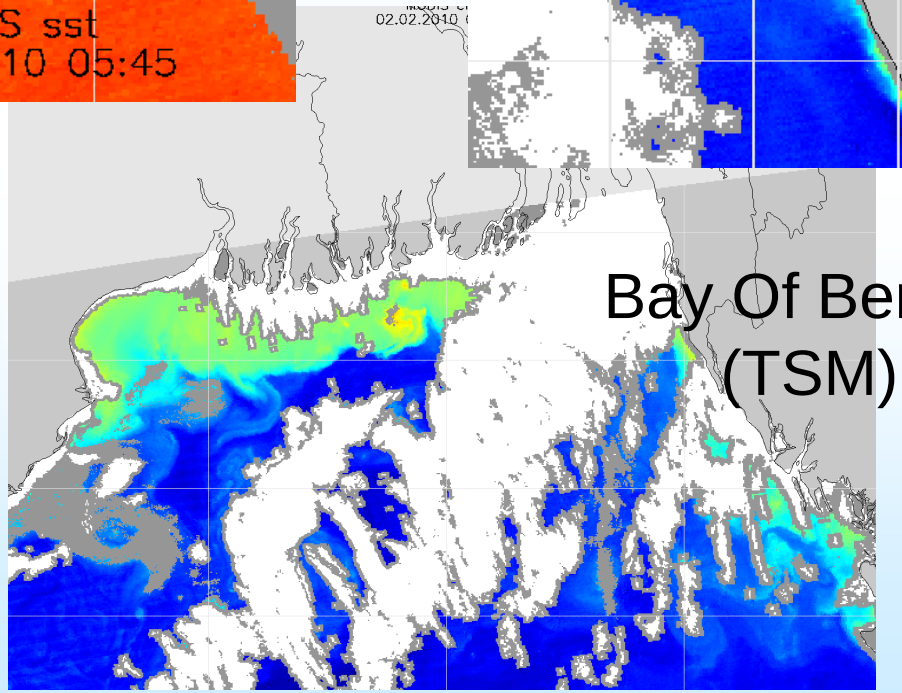


BELCOLOUR-ARG postdoc [Dogliotti et al]

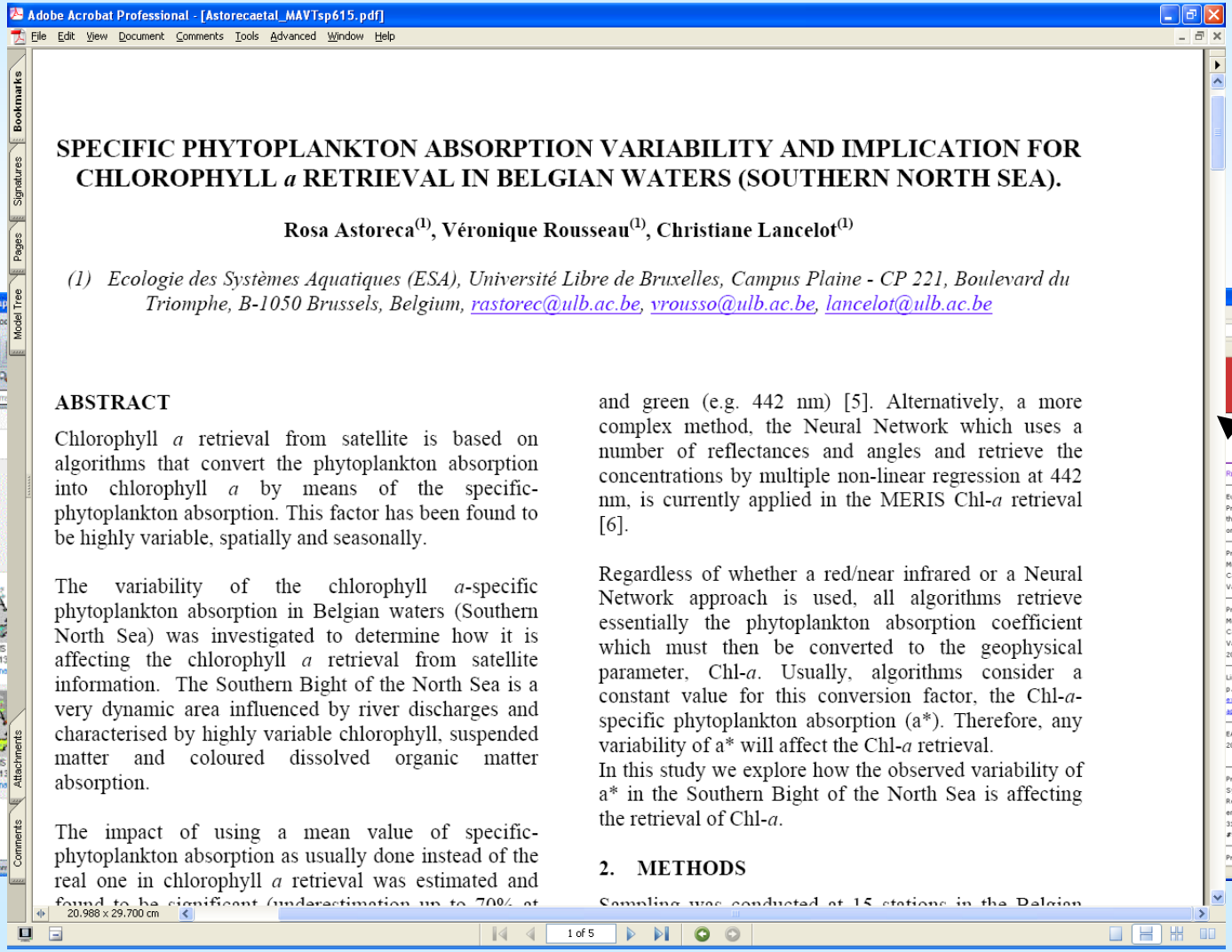
Rio de la Plata (TSM)



Bay Of Bengal (TSM)



Web site publications and products



Conclusions

- BELCOLOUR-2 is the research behind current/future applications of marine
- Project
  research
  exploita
  detectio

  ffects,
  es
  QC, etc.)

BELCOLOUR has established expertise and strong internal and external collaborations

- Will future be fragmented?
- What happens to the researchers?

- Publications (includes RECOLOUR spin-off):
  - 19 peer-reviewed accepted/published (inc. 5 external collaborations)
  - 3 peer-review submitted
  - 7 peer-review drafted

  Our heritage
  - 13 other publications, conference proceedings
  - ~10 international conference presentations/year
- Training:
  - 1 Masters course (RUG/VUB), 6 Masters theses, 2 Phd theses

Reserve slides

Applications

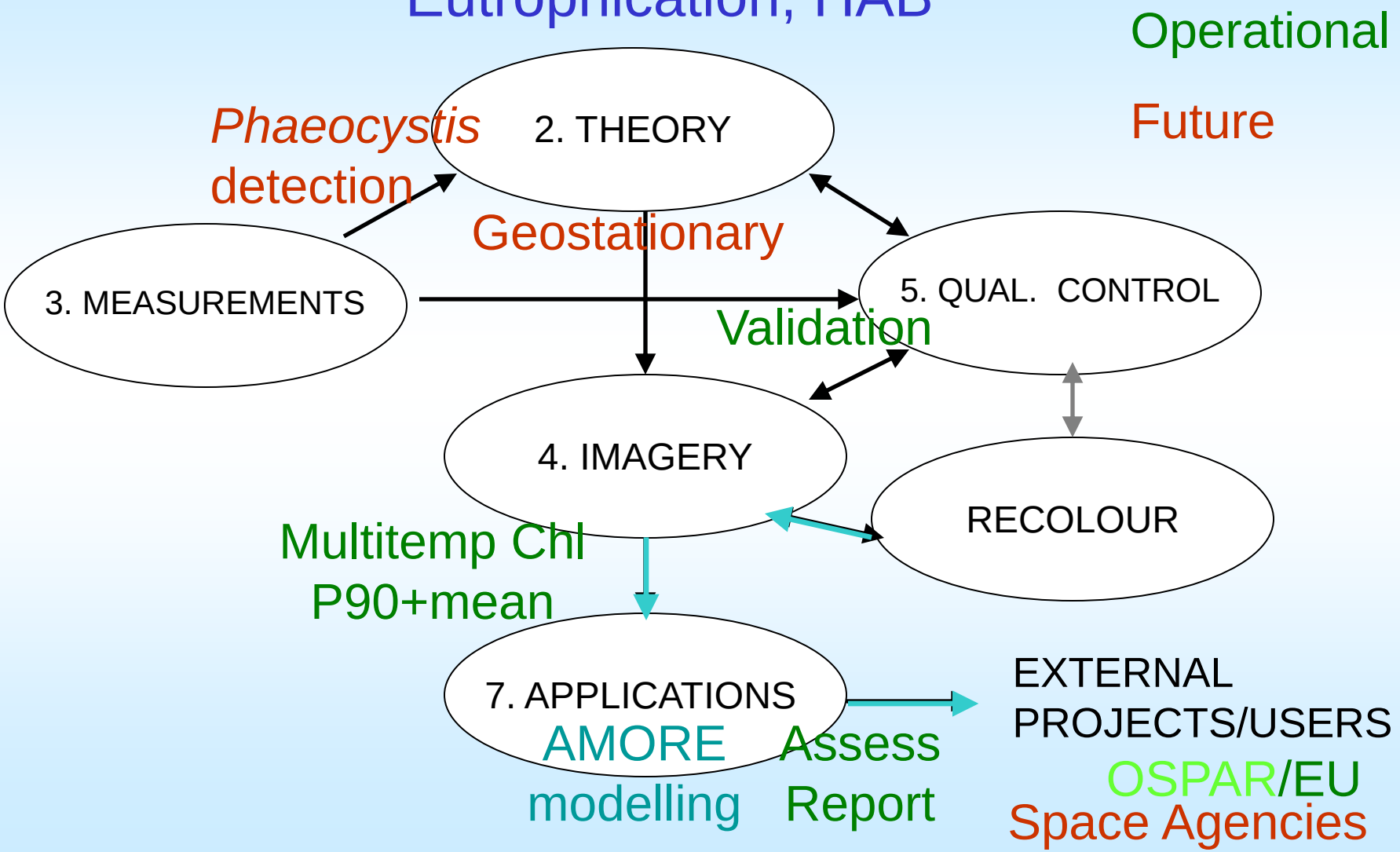
- **Research leads to use of optical remote sensing for:**
  - **Marine science support (e.g. NRT for cruise ships, multitemporal composites, time series extraction via web site)**
  - **Ecosystem functioning, aquaculture and fisheries (e.g. primary production maps, algae bloom timing, monthly CHL)**
  - **Eutrophication (OSPAR/WFD) via forcing/validation of ecosystem modelling (AMORE-3) and optimising sampling**
  - **Sediment transport support via initialisation/validation of models**
  - **HAB group support (Marcoast, ICES, AMORE-3)**
  - **pCO_2 and CO_2 fluxes**
  - **Inland waters**

Atmospheric correction inter-comparison

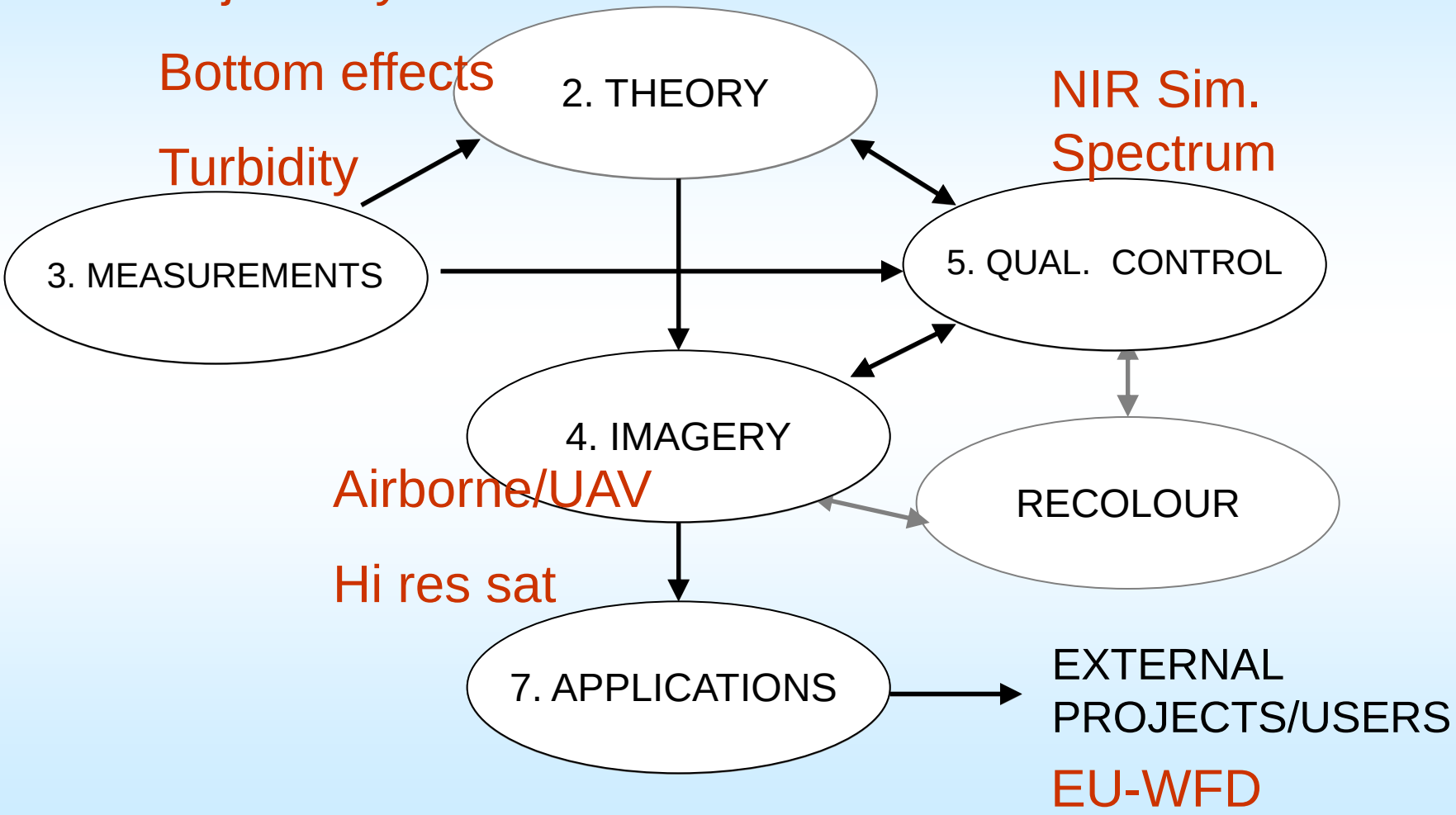
[Schroeder, in prep]

- Validation completed incorporating MUMM's reflectance data base until end of 2008
- Five algorithms compared (MUMM, NIR-6.1, SWIR-6.1, MOD09, ANN)
- SeaDAS 6.1 standard atmospheric correction significantly improved compared to v5.4 (major changes introduced with v6.0)
- Results indicate overall best performance of ANN algorithm at all time differences ±30, ±60, ± 120, ±180 min to satellite over pass
- Peer reviewed publication in preparation (Optics Express)

Project structure e.g. 1/2: OSPAR, Eutrophication, HAB

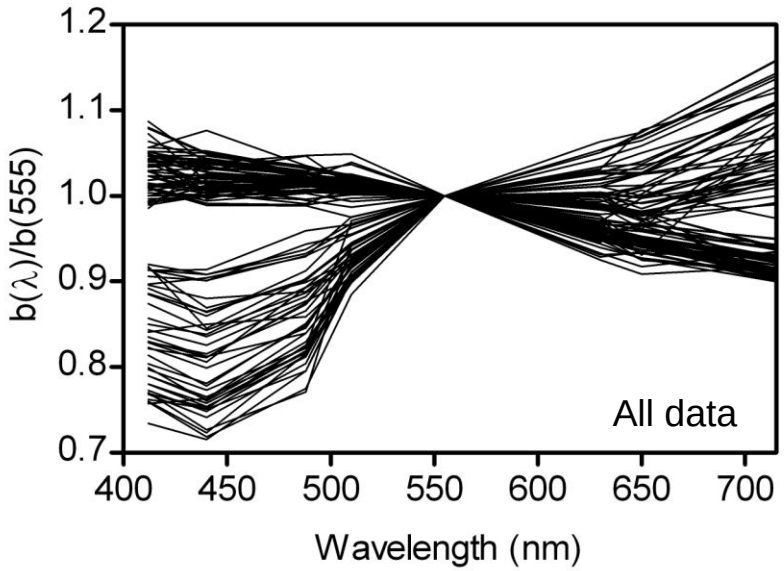


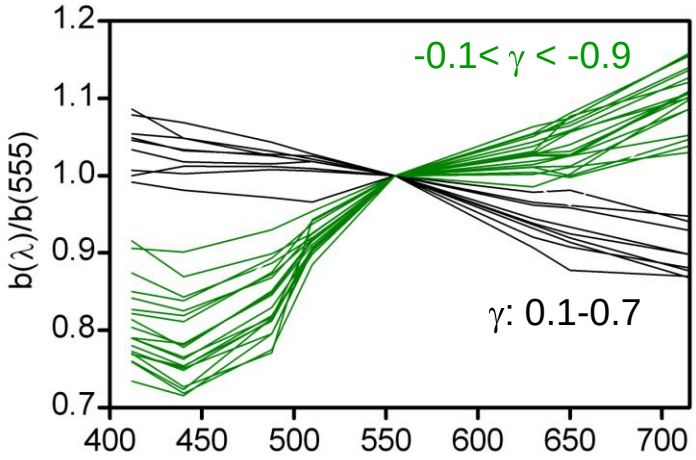
Project structure e.g. 2/2 Inland Waters

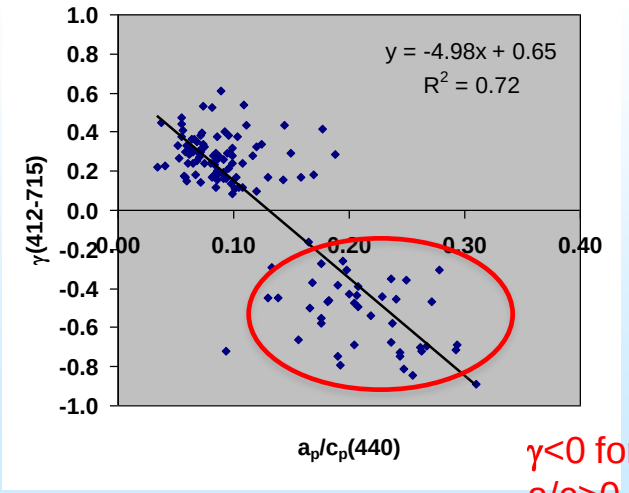


Spectral variations of scattering: Do phytoplankton blooms play a role? [Astoreca et al.]

Ac9 particle scattering



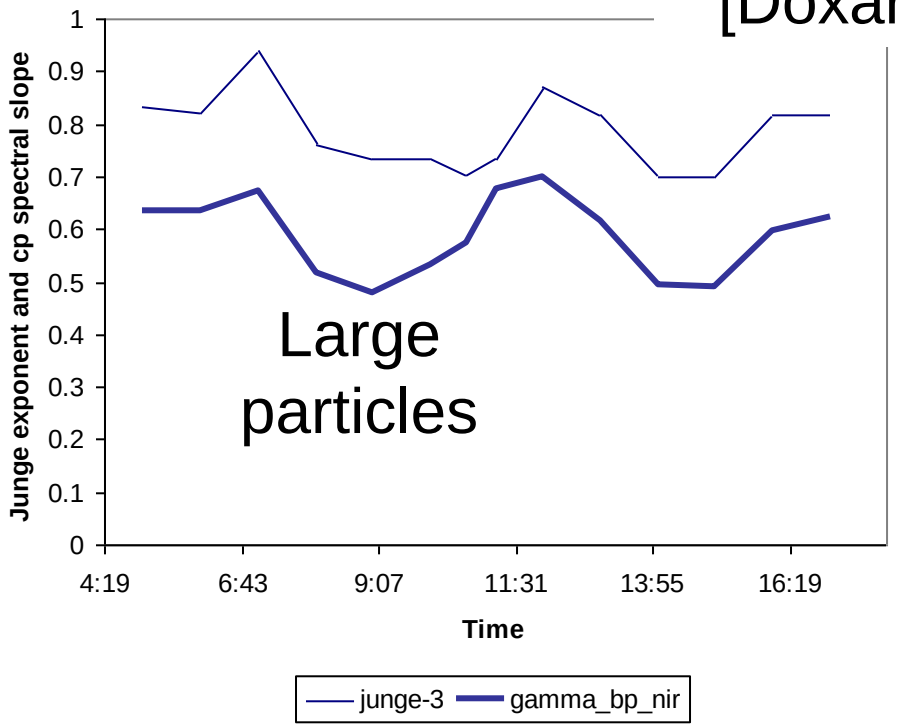


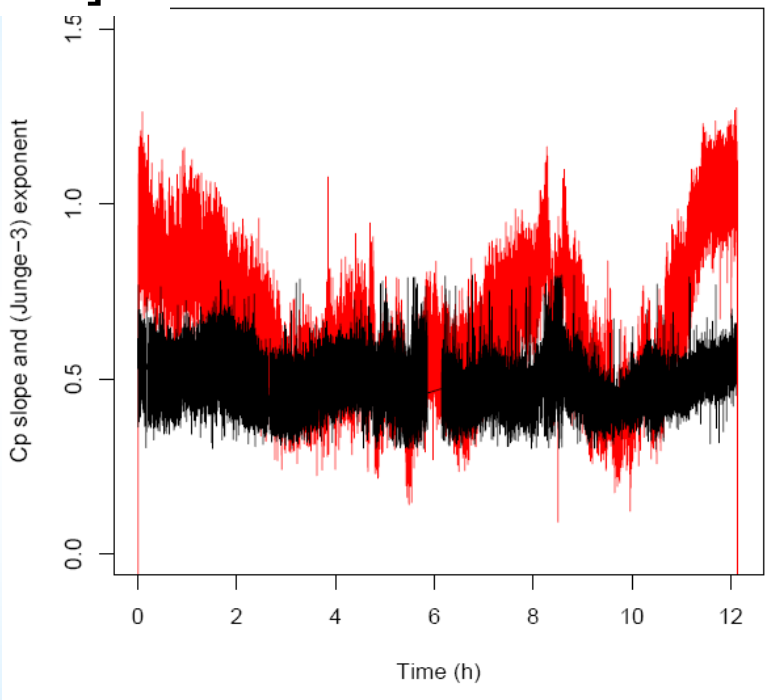


γ<0 for a/c>0.14

Particulate attenuation spectral slope vs. Particle Size Distribution (Junge exponent – 3)

[Doxaran et al]





Tidal variations over mudbanks (Belgian coast – July 2007)

Tidal variations at Scheldt river mouth (Belgian coast – September 2009)

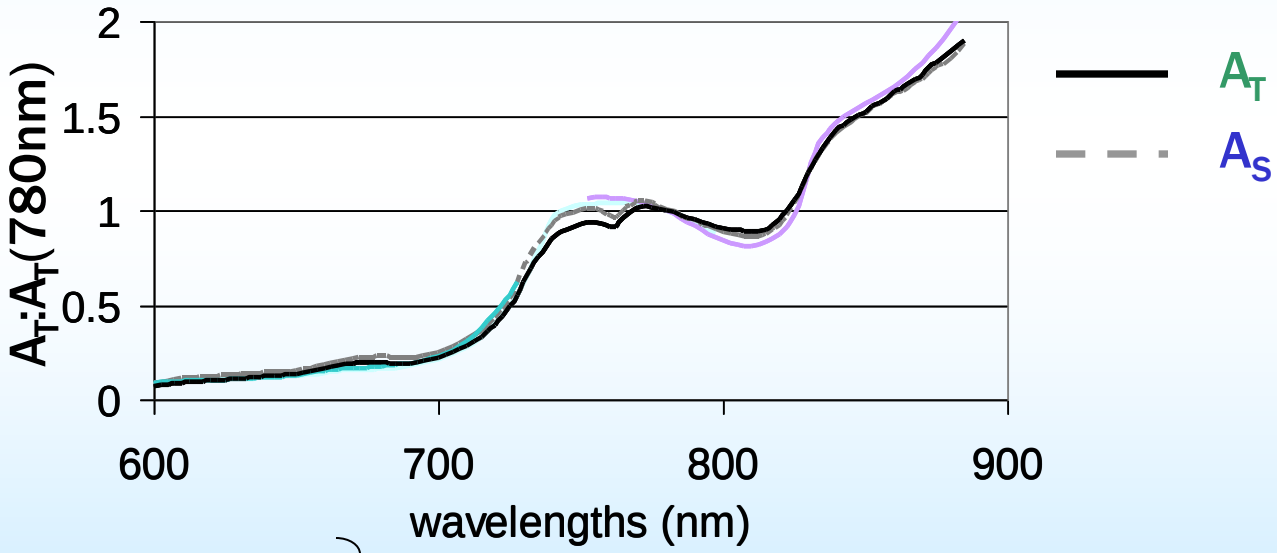
data in process

Generic one-band TSM and turbidity algos (hyperspectral calibration)

[Nechad et al, 2009]

- **T-calibrated algorithm:**

$$T = \frac{A_T \rho_w}{1 - \rho_w / C} + B \qquad A_T = \frac{a_{np}}{\gamma b^*_{bT}}$$

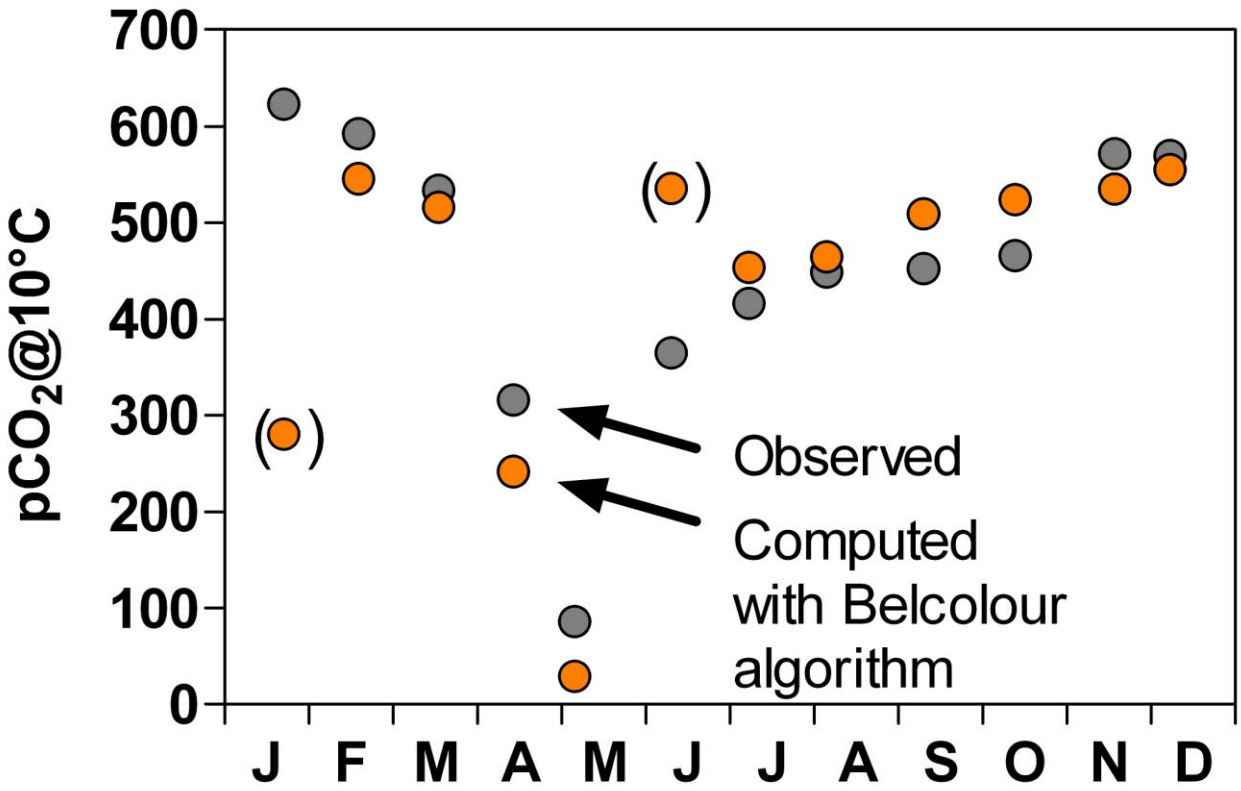


a_w [Pope & Fry 1997]
a_w [Buiteveld 1994]
a_w [Kou *et al*1993]

} Laboratory pure water absorption measurements

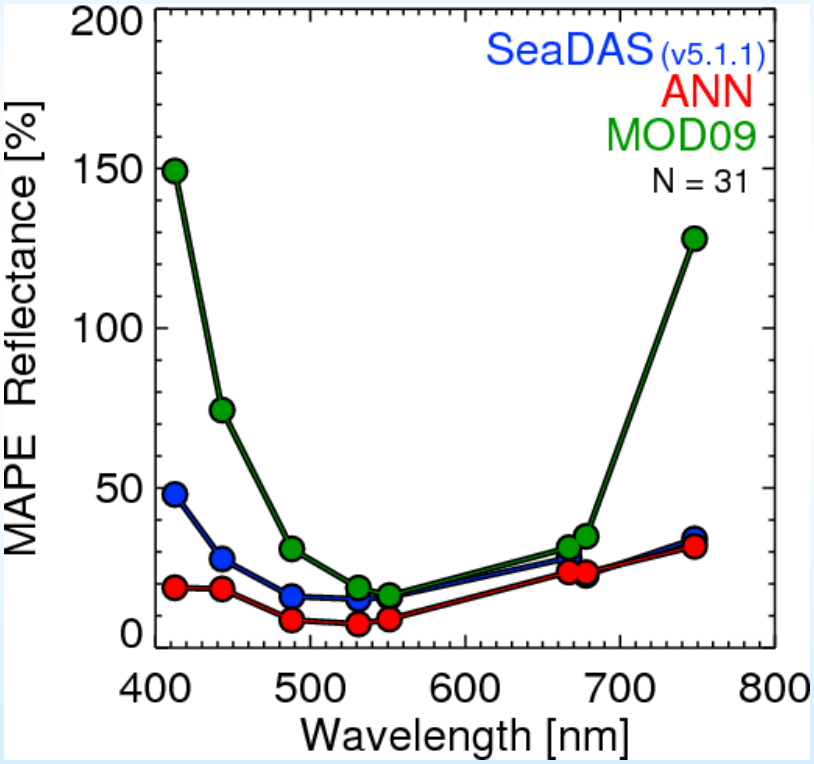
Comparison of observations from a totally independent data-set (Luctor) at the mouth of the Scheldt and values computed with the algorithm (pCO_2@10°C = f(SSS; Chla) based on the 2008 Belcolour data-set shows the ability to reconstitute a full annual cycle of pCO_2. The two outsiders are due to SSS value outside range of algorithm application, and suspicious input value (Chla value)

[Borges et al]



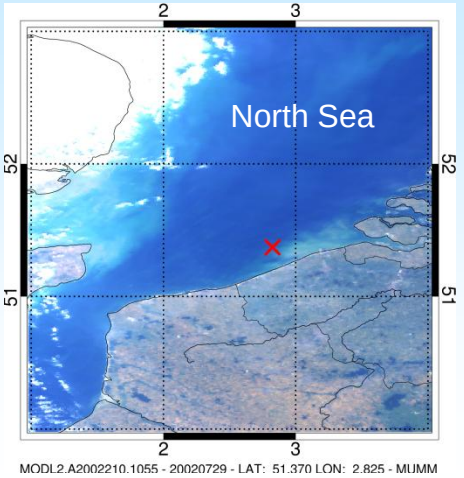
Atmospheric correction inter-comparison

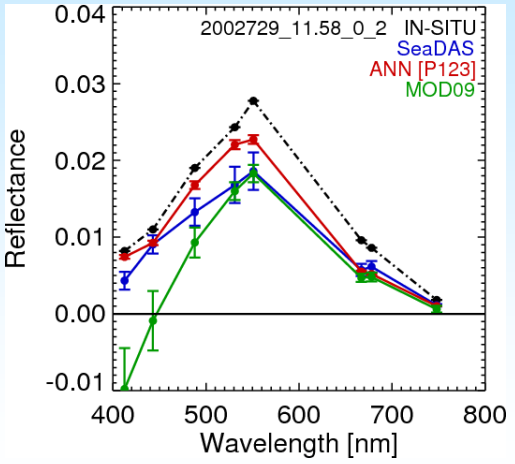
[Schroeder et al]



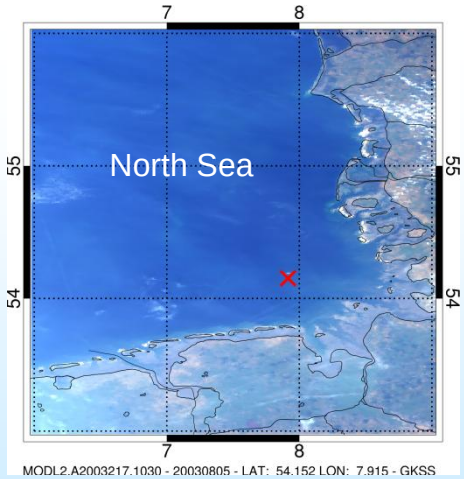
(MAPE=Mean Absolute Percentage Error)

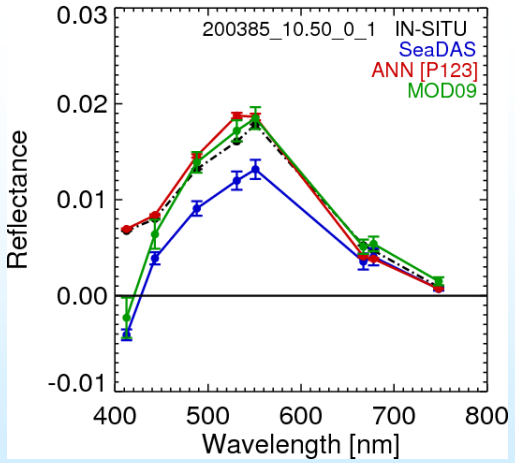
29.07.2002





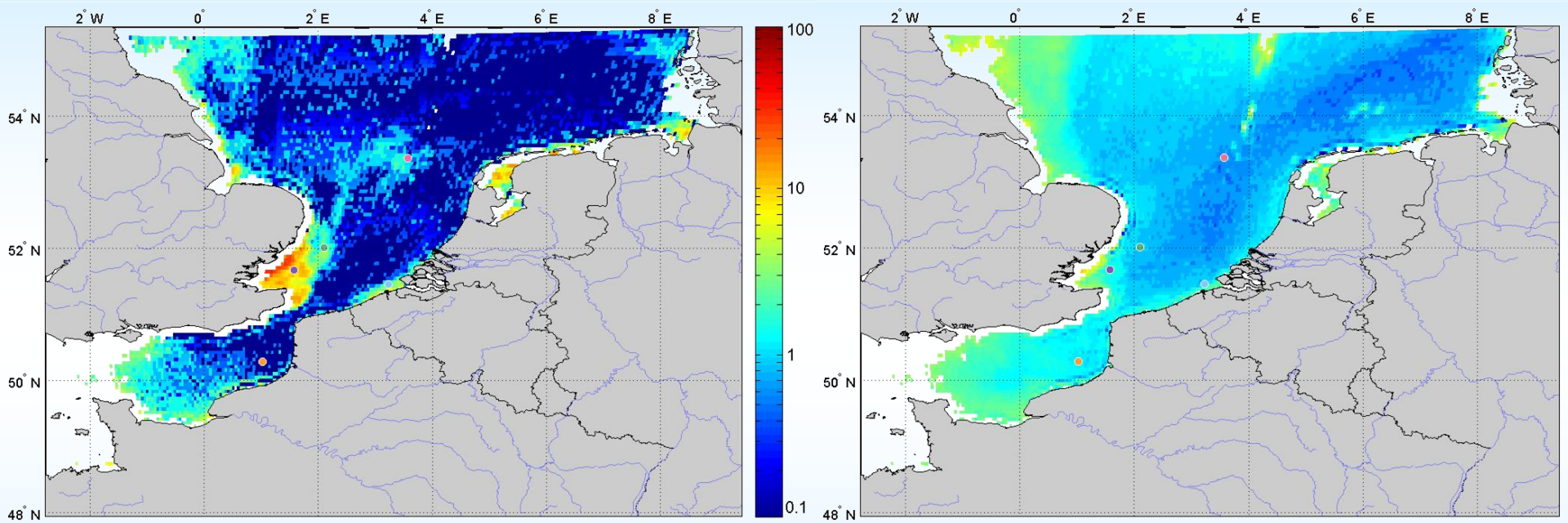
05.08.2003





TSM mapping and uncertainty (SEVIRI)

TSM (mg/l) [Neukermans et al, 2009] **ΔTSM (mg/l)**

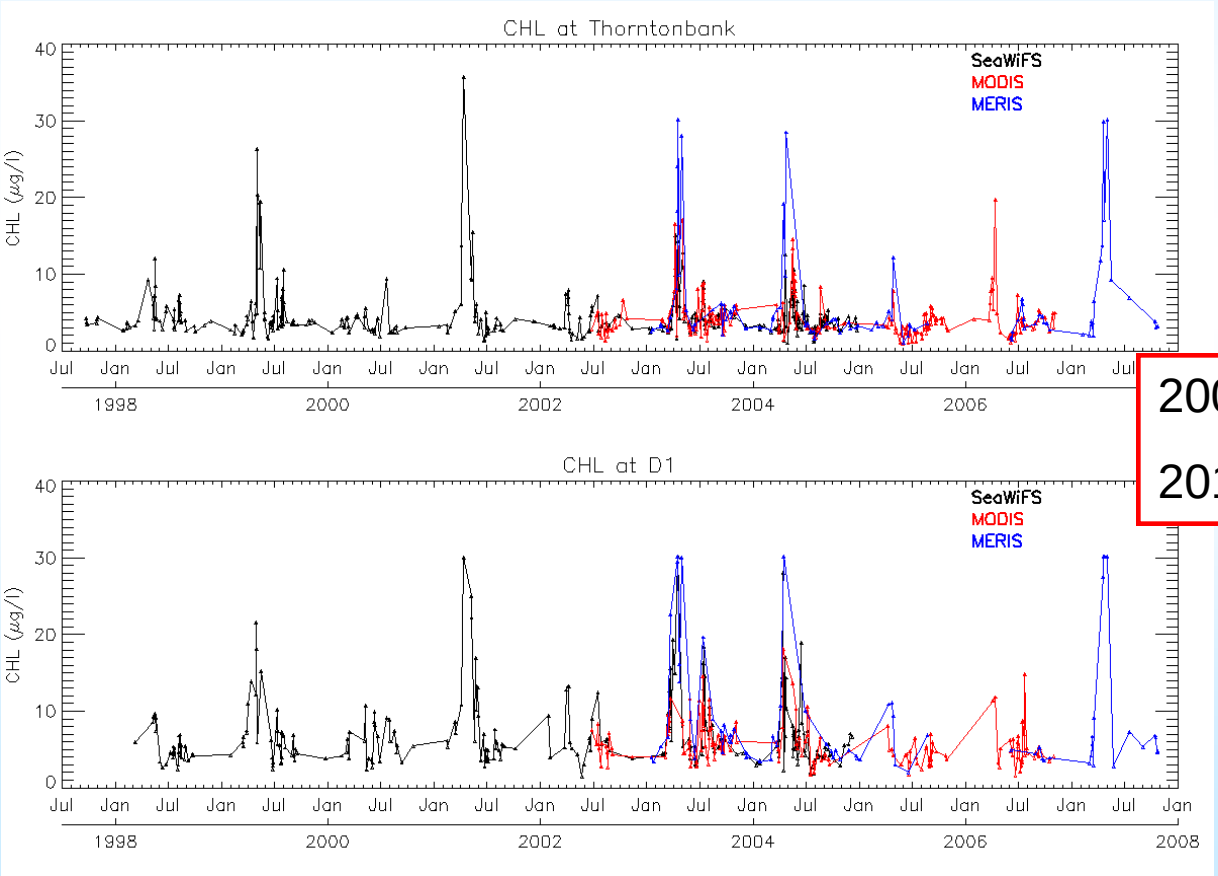


June 29th 2006 at 13:00 UTC

$$\Delta TSM = \frac{AC\Delta\rho_w^{(0.6)}}{(C-\rho_w^{(0.6)})^2}$$

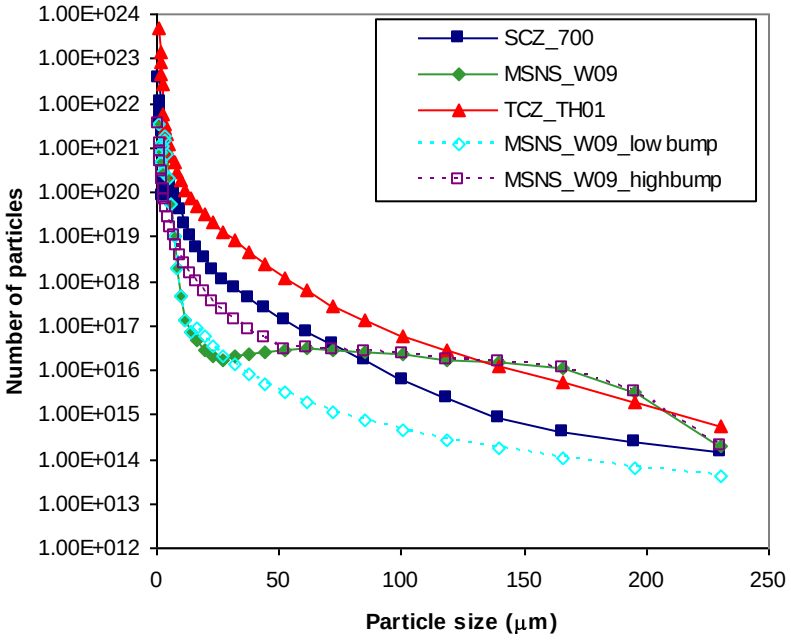
App #5: Aquaculture support

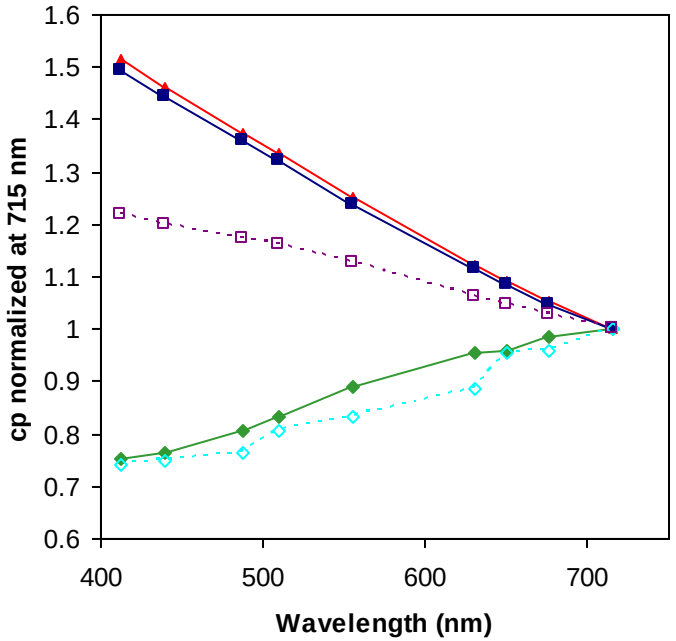
- **CHL, TSM and SST time series extracted from BC archive for ILVO (mussel production in Belgian waters)**



2008 original

2010 updated





• Particle size distributions (PSDs) observed in the Southern North Sea show a power-law 'flat' distribution in the TCZ and SCZ while a bimodal distribution with peaks at 7 and 200 μm is observed in the MSNS.

[Astoreca et al, submitted]

• Mie computations were used to explain the occurrence of the c_p spectral negative slopes. The observed PSDs were used as inputs.
• Results show that c_p follows a power-law shape with positive γ_{cp} in the SCZ and TCZ.
• a negative γ_{cp} is obtained for the MSNS with absorbing particles
• when modifying the PSD of the MSNS by removing the peak at 7 μm, the result is a positive γ_{cp} as in the TCZ.
• when removing the peak at 200 μm from the MSNS PSD, the result is a negative γ_{cp}

=> the negative γ_{cp} results from the bloom of phytoplankton particles of size 7 μm.

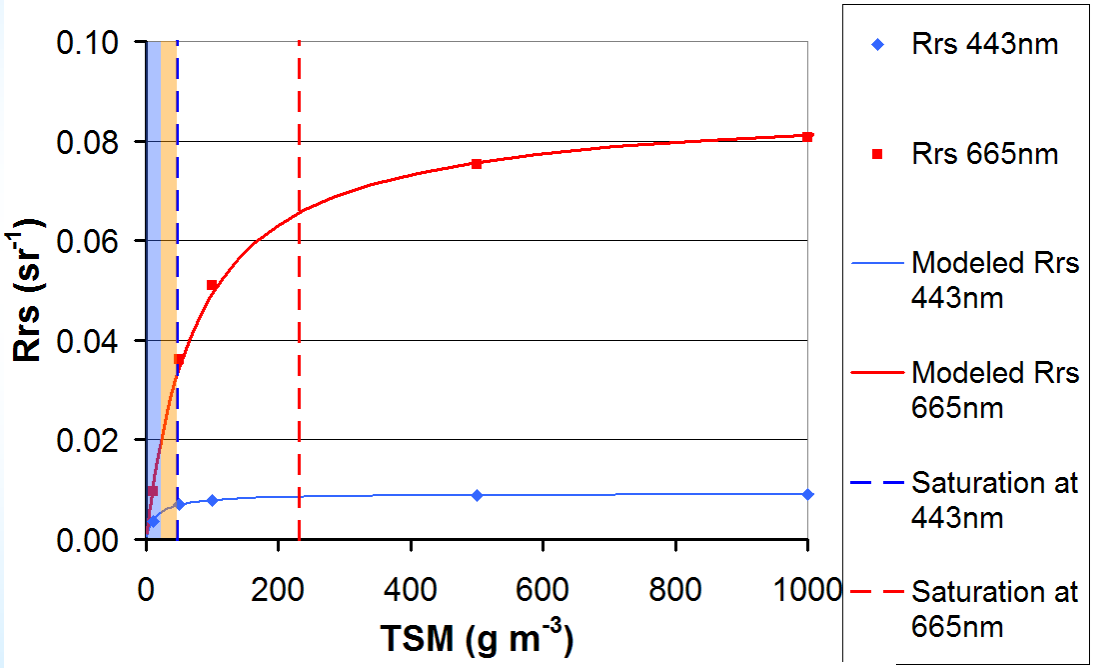
Is there a general algorithm for TSM estimation from satellites?

[Nechad, in prep]

- Hydrolight simulations
- Non linear regression (NLR) analysis to fit $(Rrs//TSM)_{SIOP,GEO}$
  (1) $Rrs = G\,TSM / (A - TSM/C)$
- using (1), parameterise:
  - Saturation
  - Sensitivity
  - Uncertainties due to SIOPs and sun/viewing geometry

Wavelengths (nm)	TSM ranges (g m^{-3})
412-560nm	0-10
620-665nm	10-30
682-705nm	30-100
775nm	100-500
865-900nm	500-1500

Rrs (sr^{-1}) at bands 665 and 443 nm vs TSM (g m^{-3}), generated from Hydrolight for a_{NAP}*=0.04 m^2g^{-1}, S_{NAP}=0.012 nm^{-1}, b_{bp}*=0.012 m^2g^{-1} and γ=0.5, CHL=1 mg m^{-3}. The sun zenith angle is 0°



High Rrs (443nm) sensitivity up to 20 g m^{-3}
High Rrs (665nm) sensitivity up to 46 g m^{-3}

Development and validation of a primary production algorithm for coastal waters of the Southern North Sea [Rousseau et al, in prep]

$$PP = Chla * P^B_{\max} * \int_{t=sunrise}^{t=sunset} \int_{z=0}^{z=d} 1-(e^{\frac{(-\alpha^B * E_{t,z})}{P^B_{\max}}}) * dt\,dz$$

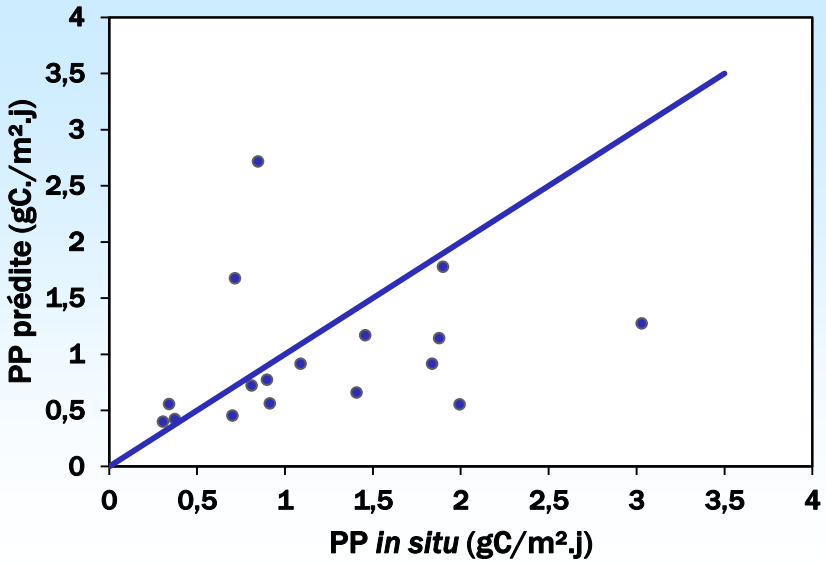
$$P^B_{\max} = 0{,}463 * T + 4{,}037 * [PO_4] - 2{,}103$$

$$\alpha^B = 0{,}017 + 0{,}003 * P^B_{\max}$$

$$E_z = E_0 * e^{-K_d(PAR)*z}$$

$$\ln(K_d(PAR)) = 0{,}454 * \ln([MES]) + 0{,}157 * \ln([Chla]) - 6{,}191 * \ln(sal) + 19{,}995$$

PP algo performance [Rousseau et al, in prep]



Relative errors

Average	Min	Max
51%	7%	220%

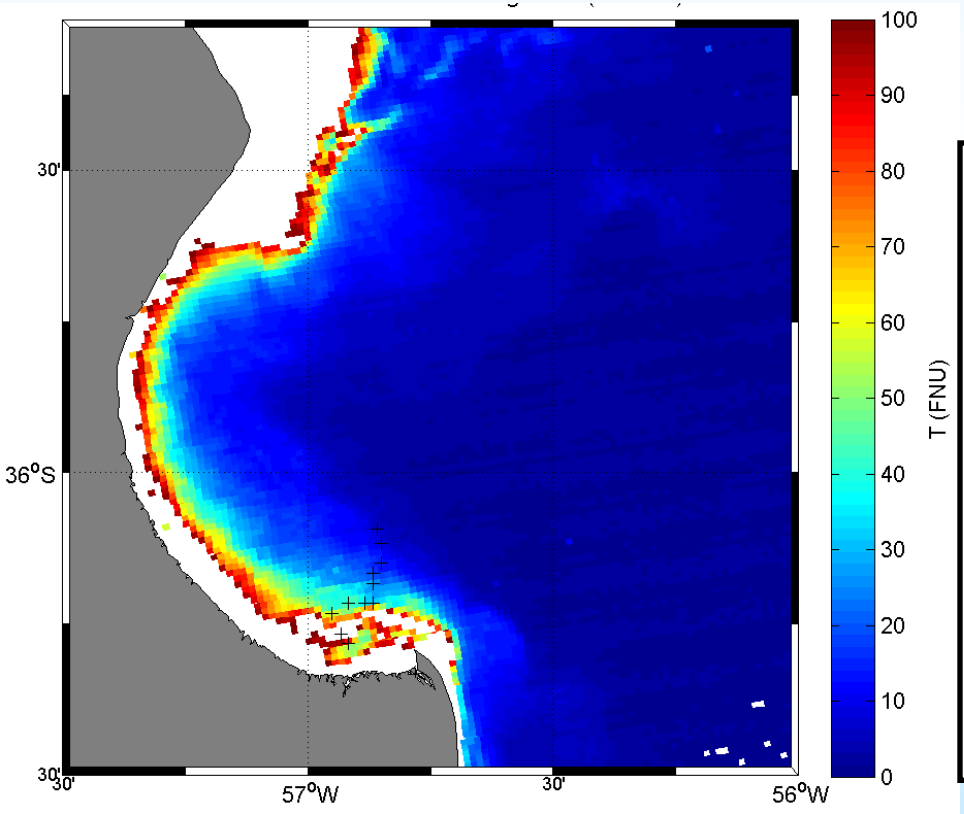
- Regional algorithm based on specific data
- Hyp: PBmax, αB and Kd(PAR) are constant along the day; Salinity > 31

- Good predictive models for PBmax, αB and Kd(PAR) → Good for PP
  But need to improve the description of PBmax
- GPP vs NPP : respiration taken into account : coupling with 3D-MIRO model
- Climatology vs In situ measurements of Et (satellite) and z (3D-model)

App #8: La Plata: TSM and Turbidity maps (BELCOLOUR-ARG)

[Dogliotti, in prep]

- A band-difference TSM and turbidity algorithm was developed based on Nechad et al. (2009/10) one-band algorithm.
- Good results were obtained for low Turbidity (<100 NFU)



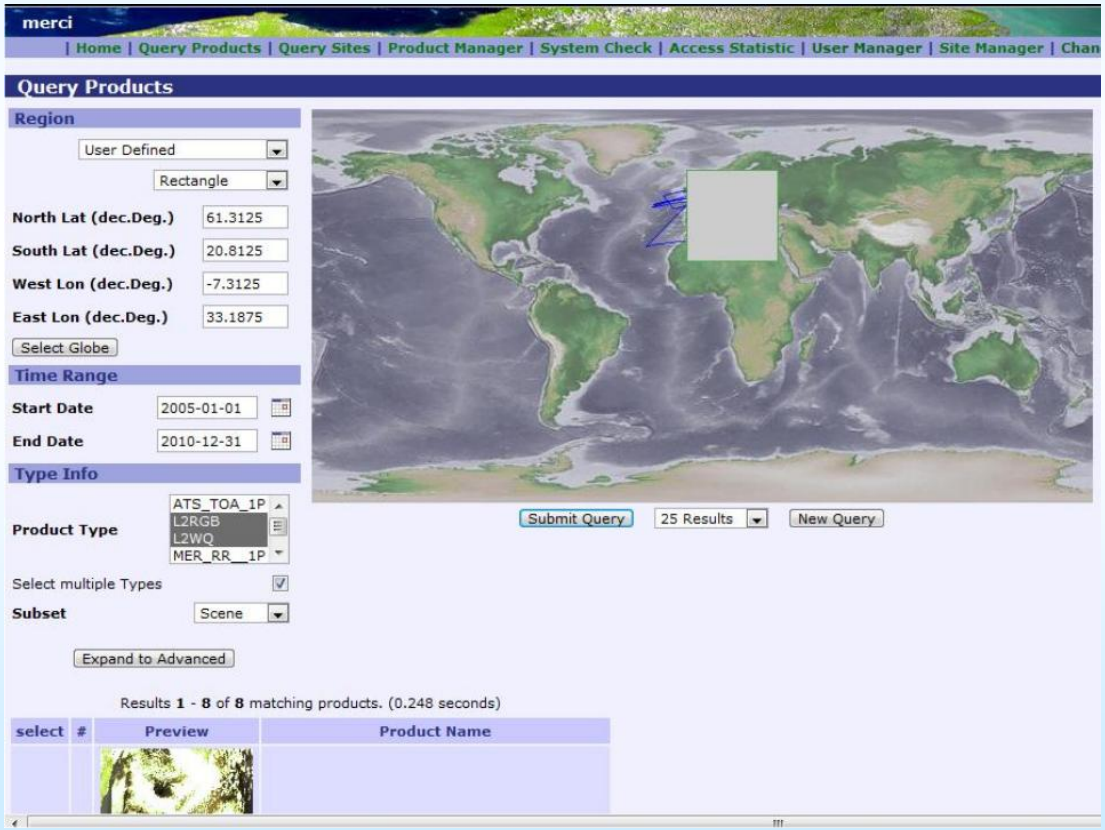
Future perspectives:

- Improve atmospheric correction algorithm to apply one-band TSM algorithms

- Start collecting *in situ* radiometric measurements

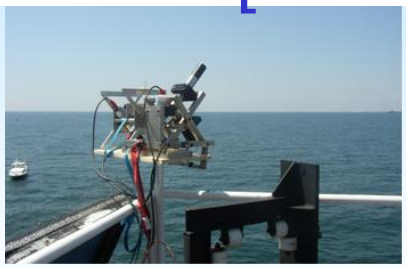
Reorganisation of image archive (in progress)

- **BELCOLOUR image archive was just graphics images … reorganising to give time series, digital data downloads**

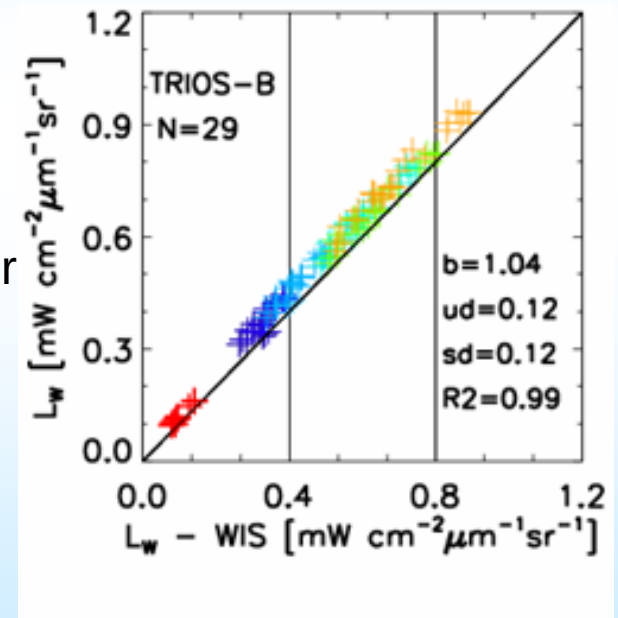


[J-R. Diouf]

Water-leaving radiance protocol intercomparison on AAOT [Zibordi et al, in prep]



MUMM abovewater system



Also VITO/MUMM comparison (Sint Anna pontoon)

JRC underwater system

Automation of image processing (1/2)

[Vanhellemont, in prep]

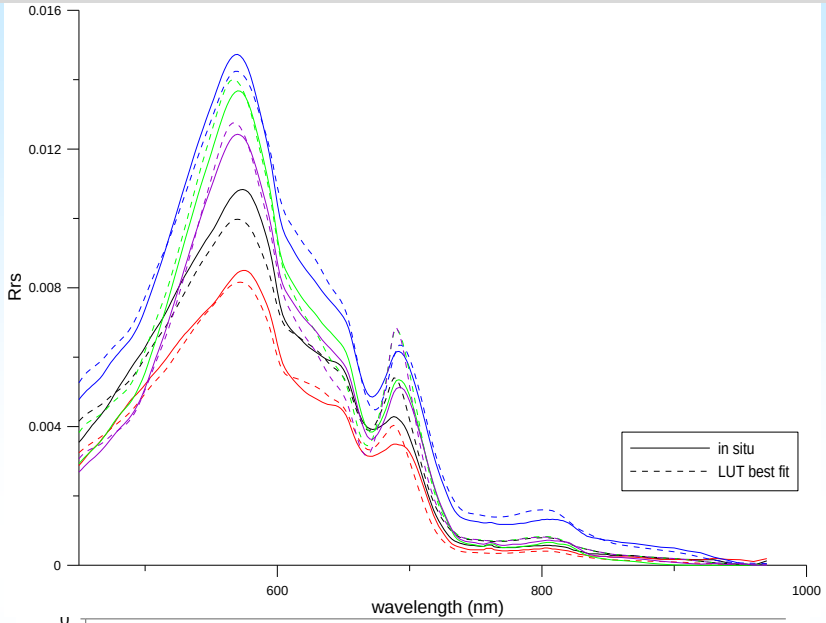
- Flexible software to process satellite imagery
  - New region: 4 bounding coordinates
  - MODIS/SeaWiFS
  - MERIS RR and FR
  - Custom products easily implemented (TSM, Kd)
- Outputs
  - gridded scenes (NetCDF/png)
  - daily and multitemporal binning
  - time-series
- Fast
  - processing 8 years of MODIS data for SNS: 20 minutes
  - extraction of time-series, mean maps: matter of seconds

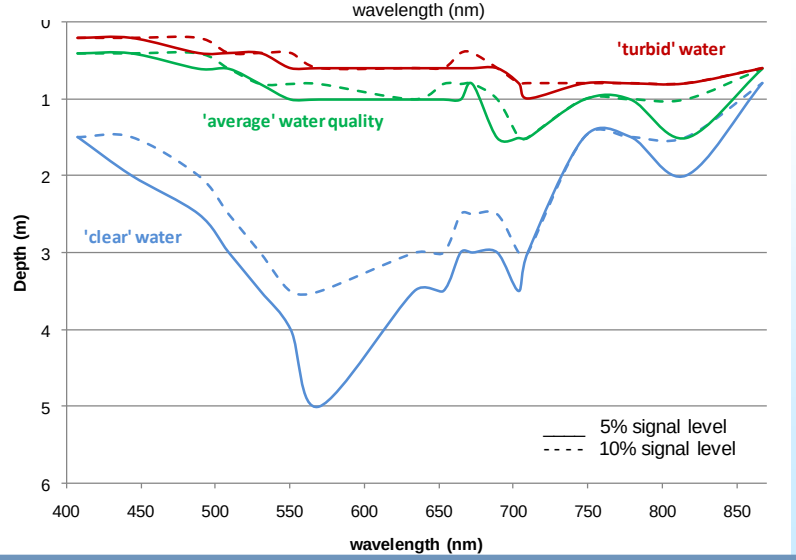
Effect of bottom substrate on water leaving reflectance and water quality retrieval

Tote Carolien, Sterckx Sindy, Knaeps Els, Raymaekers Dries

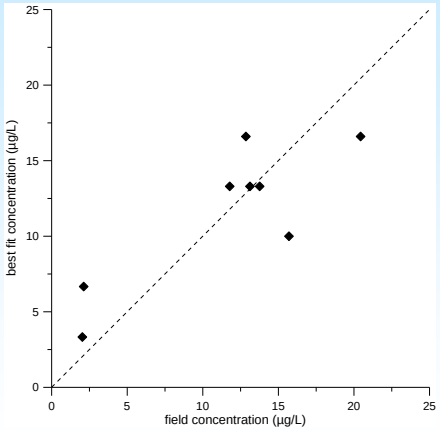
n Day
Oudenburg, 25th May 2011

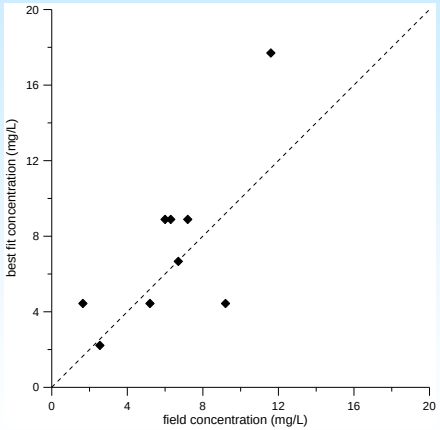
Ecolight simulations: look-up-table





WQ based on *in situ* Rw measurements





WQ based on CASI image