Ocean Colour Algorithms

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This session on in-water algorithms will trace the history of the development of algorithmic methods applied to Ocean Colour data starting with the very first algorithms applied to global datasets obtained from the CZCS sensor.

We will outline the evolution of algorithm development as our knowledge (and data!) on the optical properties of both open-ocean and coastal waters have improved over the last three decades. Additionally we will examine the mathematical and statistical approaches (neural networks, non-linear optimisation, spectral un-mixing, principal component analysis etc.) that have been explored to make best use in using the radiometric quantities measured by the sensors in retrieving the relevant geophysical quantities of interest.

Specific attention will be placed on emphasising the complexities of applying such methods in coastal regions, and considerations will be made on the limitations and uncertainties that need to be understood.

Furthermore we will analyse the parallel progress of both the empirical and semi-analytical method, and consider the merits and deficiencies of each of these, providing a clear understanding of the difference between these methods and their practical application in the operational processing of data (see flowchart below).

Complimentary to this we will specifically consider the results from an intensive round robin inter-comparison of different semi-analytical methods (performed by the IOCCG).

In considering all of these various aspects of different available algorithms we will underline which algorithms have been considered for routine processing by the major space agencies (and why).

Continuing we shall address the relative benefit of using standard global coverage products compared to regional algorithms and visa versa, and explore various alternatives for the implementation of regional algorithms. Here we will investigate the “minimum requirements” for the implementation of such regional algorithms (i.e. required datasets, “Level” of satellite data required, computing requirements).

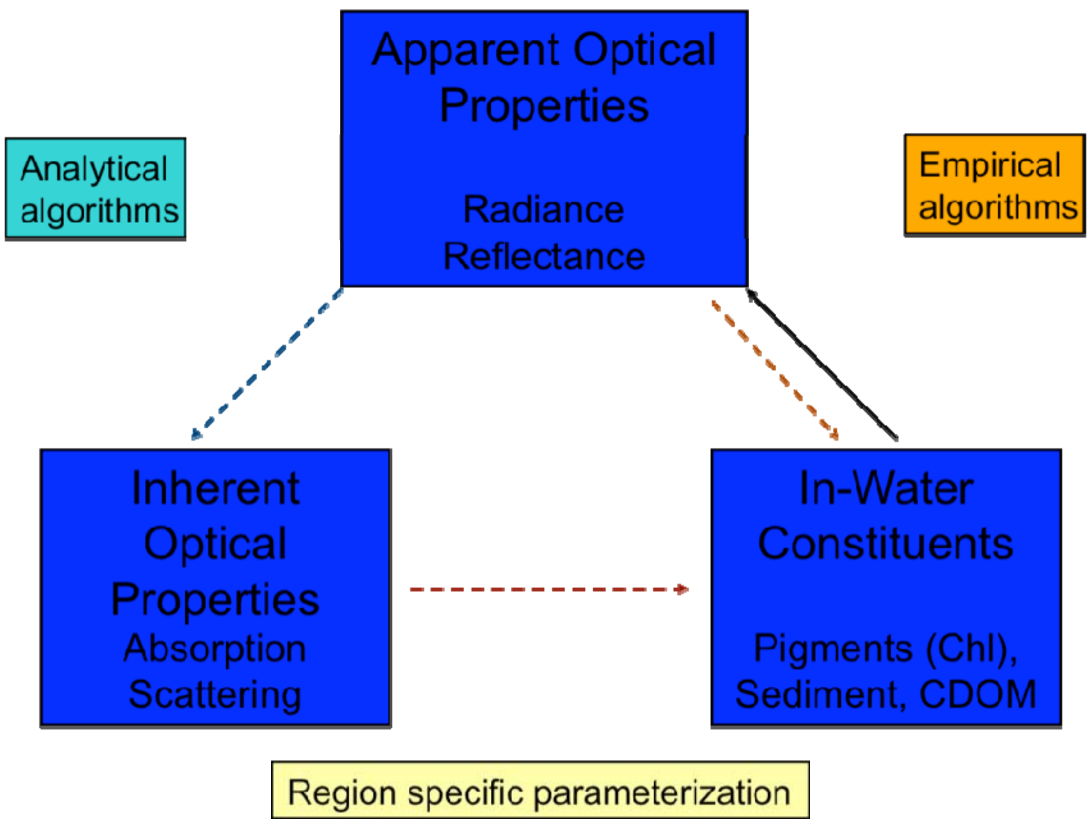
Finally we will make some considerations on the future direction for research on these topics. And deal with any real world examples/questions that participants may have and want to address.

Background Reading

In preparation for the course, it is suggested that participants consult the following, freely available, IOCCG reports (a more detailed bibliography, on specific topics, will be provided during the course),

Working group on Ocean Colour in Case 2 Waters (Chaired by Shubha Sathyendranath):
IOCCG Report 3 (2000). *Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters* (http://www.ioccg.org/reports/report3.pdf)

Working group on Ocean Colour Algorithms (Chaired by ZhongPing Lee):
IOCCG Report 5 (2006). *Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications.* (http://www.ioccg.org/reports/report5.pdf)



Lecture on Inherent Optical Properties

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Objectives

This lecture is designed to provide an overview of the fundamentals of Inherent Optical Properties (IOPs), its relationship with AOPs, algorithms to invert IOPs from AOPs, as well as applications of IOPs.

Topics

Lecture 1: Fundamentals of IOPs and IOP-AOP relationships

Lecture 2: Algorithms to invert IOPs

Lecture 3: Applications of IOPs

Approach

I will give focused lectures along with hands-on practices. Advanced reading materials will be handed out to broaden knowledge.

Radiative Transfer Theory Applied to Problems in Optical Oceanography

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Lecture 1. Hyperspectral remote sensing of optically shallow waters. I'll give an of overview of the problem, what information people need in shallow waters, and what differences there are with deep water.

Lecture 2. Atmospheric correction for shallow waters. I'll talk about why atmos correction for deep case 1 water doesn't work for shallow water, and what techniques are used for shallow waters.

Lecture 3. Techniques for inverting spectra: I'll talk about semi-analytic and spectrum matching techniques for retrieving bathymetry, bottom type, and water IOPs, with the emphasis on bathymetry and error analysis.

Lecture 4. Ecosystem modeling. I'll talk about improvements to ocean ecosystem models when more accurate light calculations are used.

Lecture 5. More Ecosystem modeling. I guess I'll finish up Lecture 4.

HydroLight training. 5 lectures and labs. All sorts of things from an overview of the software, to demonstration runs, to students running H on their own computers

In Situ Optical Radiometric Measurements and Products

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Lecture 1: Above- & In-Water Radiometry (Methods & Calibration Requirements)

In situ optical radiometric measurements have direct application in the development and assessment of: *i*. theoretical models describing extinction of light in seawater; and *ii*. empirical algorithms linking the seawater apparent optical properties to the optically significant constituents expressed through their inherent optical properties or concentrations. In addition, *in situ* radiometric data are essential for the vicarious calibration of space sensors and the validation of remote sensing products. The most accurate input data is always the most desirable for any bio-optical modeling and calibration or validation activity. However, accuracy requirements impact methodological and instrumental investment which should be weighed against the specific need for each application.
The lecture, after a brief introduction to radiometric concepts and terminology, addresses the fundamentals of above- and in-water field radiometry. This includes a review of instruments, measurement methods and data analysis.

Additional elements addressed in the lecture include an overview of calibration requirements and methods for ocean color field radiometry. These latter include an introduction to absolute radiometric calibration of radiance and irradiance sensors, determination of the geometric response of cosine collectors, characterization of immersion factors for in-water sensors.

Finally, inter-comparisons of radiometric products derived from different measuring systems and methods are used to discuss individual performances.

Lecture 2: In Situ Radiometric Products (uncertainty analysis and applications)

Data products from in–water radiometric measurements generally include spectral values of: irradiance reflectance, remote sensing reflectance, normalized water–leaving radiance, diffuse attenuation coefficient and the so called Q-factor. Data products from above–water radiometric measurements are generally restricted to the normalized water–leaving radiance and the remote sensing reflectance.
By restricting the analysis to the normalized water-leaving radiance, the lecture addresses the various sources of uncertainties affecting *in situ* radiometric measurements (e.g., accuracy of absolute calibration, superstructure perturbations, changes in illumination conditions, wave effects and self-shading for in-water methods only). Emphasis is placed in the evaluation of

methods allowing for the minimization of the various perturbing effects and additionally in the quantification of contributions of these latter to uncertainty budgets.

Further element considered in the lecture is the application of *in situ* radiometric data to the assessment of satellite primary products (i.e., the normalized water leaving radiance determined from top-of-atmosphere radiance corrected for the atmospheric perturbations). Focus is placed on the use of *in situ* data to evaluate differences in cross-mission products (i.e., normalized water leaving radiance from SeaWiFS, MODIS-A, MODIS-T and MERIS), variations in space system performance with time and intra-annual changes in accuracy.

Suggested reading: G. Zibordi and K.J. Voss. Field Radiometry and Ocean Color Remote Sensing. In *Oceanography from Space*, *revisited.* V. Barale, J.F.R. Gower and L. Alberotanza Eds., Springer, Dordrecht, pp. 365-398, 2010.

In Situ Measurements

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Lecture 1. In situ Measurements (1). Saturday, 0900-1030 h.

Starting from a base in the radiative transfer equation, the fundamental measurement of the underwater radiance field will be introduced. Historical observations will be traced through two recent developments. These measurements will be used to introduce (or re-introduce) various integrated radiometric quantities: the planar and scalar irradiances, the average cosines, and reflectances. Variations in the radiance distribution along a path (say in the vertical) brings together consideration of the fundamental inherent optical properties, the absorption coefficient and volume scattering function, as well as the beam and diffuse attenuation coefficients and scattering coefficients over various solid angles. Modern methods for the independent measurement of these quantities will be presented and discussed. Attempts at optical closure field experiments will be presented.

Lecture 2. In situ Measurements (2). Monday, 1100-1230

A brief review of the instrument concepts introduced in the first lecture will be followed by a discussion of some new and novel platforms for the measurement of underwater optics. Emphasis will be on autonomous measurement systems: moored platforms, autonomous underwater and surface vehicles, gliders, surface drifters, profiling floats, and animal tags. The lecture will finish with a discussion of two ancient optical measurement devices, and the surprising utility of these for solving modern problems in biological oceanography.

Background reading to be completed prior to lecture: Ocean Optics Web Book.

http://www.oceanopticsbook.info/view/introduction/overview

Errors and Uncertainties in Ocean Colour Remote Sensing

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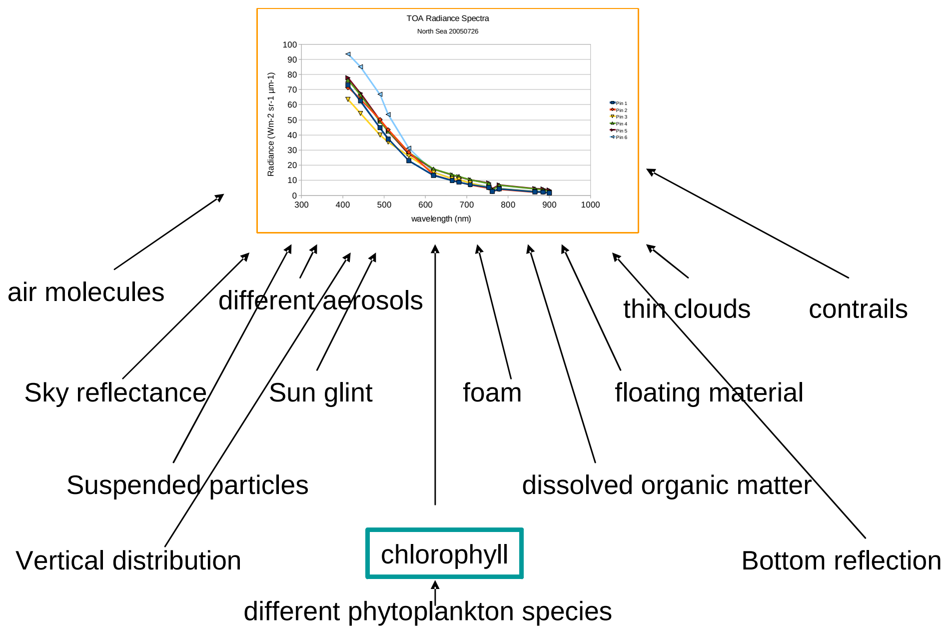
One of the main questions you will be asked as a remote sensing expert is: how reliable and good are information, which we derive from remotely sensed ocean colour data? Can we trust them? What is the error or uncertainty range of these data?



Factors, which determine top of atmosphere reflection spectra, from which try to retrieve e.g. the chlorophyll concentration

In this section of the IOCCG training course, which consists of 3 lectures and exercises, we will look into this problem.

Lectures

The first lecture will be dedicated to the sources of uncertainties. We have to consider that our observation are the reflectivity in a number of spectral bands, which are measured at the top of atmosphere (TOA) or, in case of an aircraft platform, in a certain height above the water. We try nothing less than to isolate, retrieve and quantify a small effect on these spectra, which is caused by absorption and scattering of e.g. of phytoplankton, from a large number of other effects, of which in particular the atmosphere dominates the TOA spectrum. Problems of this kind may induce large uncertainties. In some cases it might be even impossible to retrieve reliable information of the ocean from remotely sensed reflectance spectra. Thus, one important area of ocean colour research is to analyse sources of uncertainties, to develop methods to quantify uncertainties and finally to find way to reduce uncertainties.

In this lecture we will consider

- Natural factors, which determine uncertainties, and their variability
- Uncertainties, which are induced by reducing the manifold of factors to a few dominant

- Errors caused by spaceborne or airborne instruments: calibration, ageing, noise
- Errors caused by in situ measurements, sampling and procedures
- Problem of comparing in situ with space borne observations

In the second lecture we look into procedures, how to determine uncertainties:

- How to quantify uncertainties: scatter, bias, robustness, stability
- Validation procedures and strategies
- Testing of algorithms
- Round robin exercises
- Sensitivity studies
- Determination of uncertainties on a pixel by pixel bases
- flagging

The third lecture will finally discuss the results of our exercises and will be dedicated to the question, how to reduce uncertainties. This is a wide field, where a lot of research is still needed, and it offers themes for your future work.

- Detection of spectra / pixels, which are out of scope of the algorithm
- Masking of clouds and cloud shadows
- Use of additional information
- Pre-classification of water types and use of dedicated algorithms
- How to produce maps from satellite data, which include information about uncertainties.

Exercises

Beside the lectures and discussions, we have 3 hours for exercises concerning uncertainties. Here we will look into the information content of reflectance spectra and compare this with the information, we want to derive. We will also look into in situ data and determine uncertainties when comparing the optical properties with concentrations. Another exercise is dedicated to the uncertainties caused by the vertical distribution of water constituents. Finally we will determine the uncertainty when retrieving IOPs from reflectance spectra of different mixtures of water constituents.

Important:

For the exercises we will use pre-prepared software modules written in Scilab, a freely available programming system, which is similar to Matlab. You can download Scilab from www.scilab.org, version 5.3.3.

You have to use your own laptop computer, since no other computers will be available for the course. If you do not have a laptop available, please cooperate with your neighbour in the course.

High-Resolution Hyperspectral Ocean Colour Remtoe Sensing in Coastal Areas

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Part 1 covers the nature of hyperspectral imaging and the history of the development including airborne systems AVIRIS, PHILLS and the new PRISM, and the spaceborne HICO instrument on the International Space Station (http://hico.coas.oregonstate.edu). Calibration and characterization of the sensors and on-orbit calibration is also covered.

Part 2 covers the algorithms and processing of the data to produce ocean products including atmospheric correction, algorithms for both optically shallow (e.g. coral reefs) and optically deep (e.g. river plume) coastal environments. Example applications using airborne hyperspectral and HICO data are presented.

Corson, M. and C. O. Davis, 2011, “The Hyperspectral Imager for the Coastal Ocean (HICO) provides a new view of the Coastal Ocean from the International Space Station,” AGU EOS, V. 92(19): 161-162.

Davis, C. O., J. Bowles, R. A. leathers, D. Korwan, T. V. Downes, W. A. Snyder, W. J. Rhea, W. Chen, J. Fisher, W. P. Bissett and R. A. Reisse, 2002, Ocean PHILLS hyperspectral imager: design, characterization, and calibration, Optics Express, 10(4): 210-221.

Davis, C. O., K. L. Carder, B-C Gao, Z. P Lee and W. P. Bissett, 2006, The Development of Imaging Spectrometry of the Coastal Ocean, IEEE Proceedings of the International Geoscience and Remote Sensing Symposium, V. 4: 1982-1985.

Gao, B-C, M. J. Montes, C. O. Davis, and A. F.H. Goetz, 2009, Atmospheric correction algorithms for hyperspectral remote sensing data of land and ocean, Remote Sensing of Environment, doi:10.1016/j.rse.2007.12.015

Lee, Z-P, B. Casey, R. Arnone, A. Weidemann1, R. Parsons, M. J. Montes, Bo-Cai Gao, W. Goode, C. O. Davis, J. Dye, 2007, Water and bottom properties of a coastal environment derived from Hyperion data measured from the EO-1 spacecraft platform, J. Appl. Remote Sensing, V. 1 (011502): 1-16.

R. L. Lucke, M. Corson, N. R. McGlothlin, S. D. Butcher, D. L. Wood, D. R. Korwan, R.-R. Li, W. A. Snyder, C. O. Davis, and D. T. Chen, 2011, “The Hyperspectral Imager for the Coastal Ocean (HICO): Instrument Description and First Images,” Applied Optics, V. 50 (11): 1501-1516 doi:10.1364/AO.50.001501

Mobley, C. D., L. K. Sundman, C. O. Davis, T. V. Downes, R. A. Leathers, M. J. Montes and J. H. Bowles, W. P. Bissett, D. D. R. Kohler, R. P. Reid, E. M. Louchard and A. Gleason, 2005, Interpretation of hyperspectral remote-sensing imagery via spectrum matching and look-up tables, Applied Optics, 44(17): 3576-3592.

Atmospheric Correction of Ocean Color Remote Sensing Observations

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This lecture will provide an overview of atmospheric correction approaches for remote sensing of water properties for open oceans and coastal waters. Beginning with definitions of some basic parameters for describing ocean and atmosphere properties, the radiative transfer equation (RTE) for ocean-atmosphere system will be introduced and discussed. Various methods for solving RTE, in particular, the successive-order-of-scattering method will be described. We examine various radiance contribution terms in atmospheric correction, i.e., Rayleigh scattering radiance, aerosol radiance (including Rayleigh-aerosol interaction), whitecap radiance, sun glint, and water-leaving radiance. Atmospheric correction algorithms using the near-infrared (NIR) and shortwave infrared (SWIR) bands will be described in detail, as well as some examples from MODIS-Aqua measurements. The standard NIR atmospheric correction algorithm has been used for deriving accurate ocean color products over open oceans for various satellite ocean color sensors, e.g., OCTS, SeaWiFS, MODIS, MERIS, VIIRS, etc. Some specific issues of atmospheric correction algorithm over coastal and inland waters, e.g., highly turbid and complex waters, strongly absorbing aerosols, will also be discussed. The outline of the lectures is provided below.

Outline of the Lectures

1. Introduction
   - Brief history
   - Basic concept of ocean color measurements
   - Why need atmospheric correction

2. Radiometry and optical properties
   - Basic radiometric quantities
   - Apparent optical properties (AOPs)
   - Inherent optical properties (IOPs)

3. Optical properties of the atmosphere
   - Molecular absorption and scattering
   - Aerosol properties and models
     - Non- and weakly absorbing aerosols
     - Strongly absorbing aerosols (dust, smoke, etc.)

4. Radiative Transfer
   - Radiative Transfer Equation (RTE)
   - Various approaches for solving RTE
   - Successive-order-of-scattering method
   - Single-scattering approximation
   - Sea surface effects
   - Atmospheric diffuse transmittance

- Normalized water-leaving radiance

5. Atmospheric Correction
   - Define reflectance and examine the various terms
   - Single-scattering approximation
   - Aerosol multiple-scattering effects
   - Open ocean cases: using NIR bands for atmospheric correction
   - Coastal and inland waters
     - Brief overviews of various approaches
     - The SWIR-based atmospheric correction
   - Examples from MODIS-Aqua measurements

6. Addressing the strongly-absorbing aerosol issue
   - The issue of the strongly-absorbing aerosols
   - Some approaches for dealing with absorbing aerosols
   - Examples of atmospheric correction for dust aerosols using MODIS-Aqua and CALIPSO data

7. Requirements for future ocean color satellite sensors

8. Summary

Some Useful References

Chandrasekhar, S. (1950), "Radiative Transfer," Oxford University Press, Oxford, 393 pp.

Van de Hulst, H. C. (1980), "Multiple Light Scattering," Academic Press, New York, 739pp.

Gordon, H. R. and A. Morel (1983), "Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery: A Review," Springer-Verlag, New York, 114pp.

Gordon, H. R. and M. Wang (1994), "Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm," *Appl. Opt.*, **33**, 443-452.

Gordon, H. R. (1997), "Atmospheric correction of ocean color imagery in the Earth Observing System era," *J. Geophys. Res.*, **102**, 17081-17106.

Wang, M. (2007), "Remote sensing of the ocean contributions from ultraviolet to near-infrared using the shortwave infrared bands: simulations," *Appl. Opt.*, **46**, 1535-1547.

IOCCG (2010), "Atmospheric Correction for Remotely-Sensed Ocean-Color Products," Wang, M. (ed.), *Reports of International Ocean-Color Coordinating Group*, No. 10, IOCCG, Dartmouth, Canada. (http://www.ioccg.org/reports_ioccg.html)

Ocean Colour and Climate Change

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Lecture 1: Model predictions of the response of ocean physical and biological processes to climate change

I will summarize the main physical changes predicted by global warming models for the rest of this century and how we expect those changes to impact both lower trophic and upper trophic level processes in the ocean. I will discuss empirical as well as ecosystem model approaches for predicting the biological response and examine how the model simulations compare with estimates of chlorophyll and primary production based on ocean color observations. A major emphasis of the discussion will be on interannual as well as intra and inter-model variability.

References:

Sarmiento, J. et al. (2004), Response of ocean ecosystems to climate warming, *Global Biogeochem. Cycles*, *18*(GB3003), doi:1029/2003GB002134.

Steinacher, M., F. Joos, T. Frölicher, L. Bopp, P. Cadule, S. Doney, M. Gehlen, B. Schneider, and J. Segschneider (2010), Projected 21st century decrease in marine productivity: a multi-model analysis, *Biogeosciences*, *7*, 979–1005.

Lecture 2: Detection of trends in ocean color data

I will briefly review recent studies attempting to use ocean color products to detect climate trends then examine how variability such as that identified by the model simulations affects our ability to detect long-term trends in the observations.

References:

Henson, S., J. Sarmiento, J. Dunne, L. Bopp, I. Lima, S. Doney, J. John, and C. Beaulieu (2010), Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity, *Biogeosciences*, *7*, 621–640.

Ocean Colour Remote Sensing in turbid coastal waters

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Royal Belgian Institute of Natural Sciences (RBINS),
B-1200 Brussels, Belgium

The use of ocean colour remote sensing data has increased dramatically over the last ten years, particularly for coastal waters where impacts between the marine environment and human activities may be particularly intense. Many of these coastal waters will be turbid because of high concentrations of suspended particulate matter caused by a variety of processes including high biomass algal blooms, sediment resuspension by wind/tide, river plumes, etc. Within these lectures on “Ocean Colour Remote Sensing in turbid coastal waters” the specific challenges and opportunities presented by turbid waters will be presented, where “turbid” is understood here to indicate waters with high particulate scattering.

There are two major additional difficulties for ocean colour remote sensing in turbid coastal waters. Firstly, atmospheric correction is more difficult in turbid waters because it is not possible to assume zero near infrared marine reflectance (“black pixel assumption”), thus complicating the decomposition of top of atmosphere measurements into atmospheric and marine reflectances. Secondly, the optical properties of non-algae particles, such as mineral particles from bottom resuspension or from river discharges, need to be considered in addition to algal particles. If the absorption and scattering of non-algae particles is significant compared to that of algal particles it may become difficult or even impossible to distinguish the optical properties of the algal particles. In such conditions the estimation of chlorophyll a may become severely degraded or suffer from a detection limit problem. In turbid waters both the atmospheric correction and the chlorophyll retrieval problems are highly dependent on the technical specification of the remote sensors being used, and in particular on the spectral band set. These two key issues will be explained in detail, via lectures and via simple computer-based exercises. The algorithmic approaches that can be used to deal with these problems will be outlined, based on the current state of the art and with reference to the capabilities of past, current and future ocean colour sensors such as SeaWiFS, MODIS, MERIS, GOCI and OLCI.

In addition to aspects of chlorophyll retrieval in turbid coastal waters, other relevant parameters will be discussed, including diffuse attenuation coefficient, euphotic depth, suspended particulate matter, etc. The links with applications in marine science and coastal zone management will be described.

<u>Requirements for the lectures</u>

- A basic knowledge of the definitions of optical properties (scattering, absorption, attenuation) from other lectures from this IOCCG summer school, particularly those of Mark Dowell, Zhongping Lee and Curtis Mobley.
- An ability to use basic functions of Excel.

<u>Suitable background reading</u>

IOCCG report #3 on “Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters”, available from http://www.ioccg.org/reports/report3.pdf

Harmful Algal Blooms: The Contrast with Other Algal Blooms

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Silver Spring, MD 20910, USA

1. What are harmful algal blooms (HABs)?
    - Contrast of HABs to functional groups
    - What must be known to detect HABs
        - Environment
        - Simple physiology and ecology
        - Ecological conditions
    - “operational” vs research considerations
    - Work exercise: A strategy to respond to reports of a HAB

2. Methods
    - Chlorophyll
    - Change detection
    - Analytical algorithms
    - Spectral shape (MCI, FLH, CI)
    - Other algorithms (brightness, empirical, etc.)
    - Ancillary data (SST, winds)
    - Ensemble methods
    - Work exercise: Case Study (to be provided)

3. Using satellite
    - Limitations defined by objective, method, species, environment
    - Satellite strengths and weakness
    - Algorithm failures
    - Atmospheric correction challenges
    - Work exercise: identify best method for a case study (to be provided)

4. Validation
    - Quantitative data vs qualitative data
    - False positives and false negatives
    - Field observations (ocean color, cells, toxins, impacts)
    - Work exercise: sampling strategy

5. Applications
    - Advisories
    - Forecasts
    - “Event response” (dead marine mammals, fish kills, bird kills, sickness)
    - Discussion of case studies

Suggested Reading

J. GOWER, S. KING, G. BORSTAD and L. BROWN (2005). Detection of intense plankton blooms using the 709 nm band of the MERIS imaging spectrometer International Journal of Remote Sensing 26(9): 2005–2012

Stumpf, R.P. and M.C. Tomlinson (2005) Remote sensing of harmful algal blooms. In: Miller, R.L., C.E. Del Castillo, and B.A. McKee, eds. *Remote Sensing of Coastal Aquatic Environments*. Springer, AH Dordrecht, The Netherlands, chapter 12, pp. 277-296.

Stumpf, R.P. (2006) Forecasting Harmful Algal Blooms: The Roles of Optical Oceanography and Remote Sensing. Material presented at Ocean Optics XVIII.

Wynne, T. T., Stumpf, R. P., Tomlinson, M. C., and Dyble, J. (2010). Characterizing a cyanobacterial bloom in western Lake Erie using satellite imagery and meteorological data. Limnol. Oceanogr., 55(5), 2025–2036

Ocean Colour Remote Sensing at High Latitudes

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New Arctic Frontier
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Ocean colour remote sensing has often been used to study polar seas, especially in Antarctica where the optical properties of the upper ocean are not as complex as they are in the Arctic (Comiso et al., 1990, Comiso et al., 1993, Sullivan et al., 1993, Arrigo et al., 1998, Stramski et al., 1999, Arrigo et al., 2008b). It was shown based on OC data that primary production in Antarctic waters has changed little over the last 14 years (Arrigo et al., 2008b). In contrast, the few studies that have been conducted to date in the Arctic Ocean suggest that pan-Arctic primary production, as well as photooxidation of coloured dissolved organic matter have been increasing (Belanger et al., 2006, Pabi et al., 2008, Arrigo et al., 2008a) as a consequence of receding perennial ice. The annual maximum phytoplankton biomass is now reached earlier in several Arctic seas (Kahru et al., 2010). As the extent of the seasonal ice zone increases (difference between the annual maximum and minimum extents), ice-edge blooms may play a heightened role (Perrette et al., 2011). The on-going changes within the context of accelerating climate change necessitate a vastly improved understanding of the polar ecosystems based on an intensive observation program. The use of ocean colour remote sensing in polar regions is, however, impeded by a number of difficulties and intrinsic limitations including:

- **The prevailing low solar elevations.** At high latitudes, the Sun zenith angle is often larger than the maximum (generally 70°) for which atmospheric correction algorithms have been developed based on plane-parallel radiative transfer calculations. Consequently, at high latitudes, a large fraction of the ocean surface is undocumented for a large part of the year even though primary production may be significant.
- **The impact of ice on remotely sensed reflectance.** Belanger et al (2007) and Wang & Shi (2009), used radiative transfer simulations to examine the effects of the sea ice adjacency and sub-pixel ice contamination on retrieved seawater reflectance and level-2 ocean products. They found significant impacts within the first several kilometres from the ice-edge and for concentrations of sub-pixel ice floes exceeding a few percent.
- **The deep chlorophyll maximum (DCM).** A DCM is very often observed both in the Antarctic and Arctic Oceans. In the Arctic Ocean, the freeze-thaw cycle of sea ice and the large export of freshwater to the ocean by large Arctic rivers create pronounced haline stratification within the surface layer. In post-bloom conditions, a deep-chlorophyll maximum is associated with such vertical stratification. Contrary to the DCM observed at lower latitudes (Cullen, 1982), the Arctic DCM often corresponds to a maximum in particulate carbon and primary production (Martin et al., 2010)**.** The statistical relationships between surface chlorophyll and

chlorophyll concentration at depth developed for lower latitudes (Morel & Berthon, 1989) are most probably not valid for the polar seas (Martin et al., 2010). Ignoring the vertical structure of the chlorophyll profile in the Arctic Ocean leads to significant errors in the estimation of the areal primary production (Pabi et al., 2008, Hill & Zimmerman, 2010).

- **The peculiar phytoplankton photosynthetic parameters.** The low irradiance and seawater temperature prevailing in polar seas are associated with unique bio-optical and photosynthetic parameters characteristic of extreme environments (Rey, 1991) that must be accounted for in primary production models. To date, only a few studies have attempted to do so in the Arctic Ocean (Arrigo et al., 2008b).
- **The optical complexity of seawater, especially over the Arctic shelves.** Because of the important freshwater inputs, the Arctic continental shelves, which occupy 50% of the area, are characterized by high concentrations of CDOM (Matsuoka et al., 2007, Belanger et al., 2008). Also, as a consequence of photoacclimation to low irradiances, phytoplankton cells often contain large amounts of pigments. The chlorophyll-specific absorption coefficient is therefore particularly low due to pronounced pigment packaging (Cota et al., 2003, Wang et al., 2005). Because of these optical peculiarities, standard ocean colour algorithms do not work in the Arctic Ocean (Cota et al., 2004, Matsuoka et al., 2007).
- **The persistence of clouds and fog.** High latitudes are known to present a heavy cloud cover. In addition, as soon as sea ice melts and open waters come in direct contact with the atmosphere, fog develops near the sea surface. These features limit the usage of ocean colour data.

This lecture will cover all of the topics mentioned above and will be organized into two parts (90’ each) as detailed below :

1. **Ocean colour remote sensing in polar seas**
    1. Ocean, sea ice and atmosphere in Arctic and Antarctic: relevant features
    2. Seawater optical properties
    3. Retrieval of ocean properties from ocean colour
        1. Atmospheric corrections
        2. Contamination of the signal by sea ice
        3. Retrieval of IOPs and AOPs, and biogeochemically relevant variables
    4. Availability of data as favoured by polar orbits and limited by elevated cloudiness
2. **Primary production estimates from OC in polar seas**

    1. General features of Arctic and Antarctic Oceans related to PP (phytoplankton species, annual cycle of PP, nutrients, DCM)
    2. PP models and their validation

3. Results from PP models

References

Arrigo KR, Van Dijken G, Pabi S, 2008a. Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters* **35**.

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Satellite-Detected Fluorescence

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This class will focus on retrieving information from the quantum yield of Sun-induced fluorescence using remote sensing. After reviewing the basic theory behind fluorescence emission in the cell and within the water column, we will examine the recent algorithms proposed to retrieve the quantum yield in open ocean waters. Finally, we will examine different proposed interpretations of the variability in the quantum in the ocean that were developed both from in situ measurements and from remote sensing.

Suggested reading

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