IOCCG
International Ocean-Colour Coordinating Group

IOCCG Summer Lecture Series 2014

Frontiers in Ocean Optics and Ocean Colour Science
Villefranche-sur-Mer, France

21 July to 2 August 2014

Specific support is acknowledged for the 2014 training session, in addition to the regular annual support from all IOCCG contributing agencies.

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INTRODUCTION

The Laboratoire d'Océanographie de Villefranche (LOV), located in Villefranche-sur-Mer, France, hosted the second IOCCG Summer Lecture Series, dedicated to high-level training in the fundamentals of ocean optics, bio-optics and ocean colour remote sensing. This was a 2-week intensive course that took place from 21 July to 2 August 2014.

A total of 12 renowned lecturers were invited to provide lectures on cutting edge research, focusing on current critical issues in ocean colour science (See Appendix 1: List of teaching staff): 24 students from 13 different countries were selected from a total of 140 excellent applications received (see Appendix 2: List of Selected Students). The selection of candidates was based on their knowledge of remote sensing, current area of research, the potential to apply the knowledge and skills to future research and their motivation. The majority of the trainees were PhD students and post-docs, with several young early career researchers wanting to gain more experience in the field of ocean colour. The students had diverse backgrounds and expertise, but all were familiar with at least some domains of ocean optics and/or ocean colour remote sensing. Several students received scholarships from the US Ocean Carbon & Biogeochemistry (OCB) program and from the Scientific Committee on Oceanic Research (SCOR) to attend the course, which is gratefully acknowledged.

IOCCG Summer Lecture Series training course participants, lecturers (not all) and organizers.

COURSE ORGANIZATION

The training course focused on the current critical issues in ocean colour science. It brought together specialists from various fields of ocean colour. Consequently, the course content dealt with many oceanographic questions (see Appendix 3 - Course Content). The objective was to provide opportunities for students to improve their skills and knowledge which they could then apply to their current and future research.

Students were given ample opportunity to interact with other students and with the invited lecturers for in-depth discussions on various pre-selected topics, as well as on their own scientific research. This lecture series gave students a possibility to refine their research subjects and to be aware of current research in ocean optics. It also helped them to choose a future direction or field for their research, based on a better understanding of the background, results already achieved, and issues still pending.

The format of the Summer Lecture Series was an intensive 2-week course that included a series of lectures, practical sessions and open discussion sessions (see Appendix 4 - Course schedule). In order for students to be able to prepare for the course, a synopsis of all the lectures and suggestions for further reading were sent in advance to all participants (see Appendix 5 - Course synopsis).

The course was opened with a welcoming address by the OOV director Gabriel Gorsky. Next, David Antoine (local organizer and former IOCCG Chair) presented a summary of IOCCG activities and a review of the course organization. The students each introduced themselves and gave a brief presentation on their current area of research (5-10 minutes). This was an opportunity to get acquainted with the participants' academic backgrounds, their current positions and their experiences. It was also a chance for the students to make contacts and discuss ideas with people with similar interests.

The Lecture room

The lecture sessions covered a wide range of topics of ocean colour based on the theory, practice and specific applications. The first week covered the theoretical basis including the concept of inherent optical properties (IOP) of ocean waters, ocean colour algorithms and their associated errors and uncertainties, hyperspectral remote sensing of optically shallow waters, and the aims and challenges of *in situ* measurements. Midweek, there was a group discussion session; the students could ask questions and discuss different subjects. At the end of the week students had the opportunity to use the HydroLight radiative transfer model.

The second week of the course included practical sessions during which students were trained on various image processing and application software. Some of the software was freely available from space agencies and other organizations. The students also were trained to use a number of Matlab routines. These sessions were helpful to understand some concepts and information on how models work. The course also contained practical sessions with AC-meters, during which students learned how to calibrate the instrument, and how to measure CDOM and particulate absorption and attenuation. This practical session was important to help understand *in situ* data and how to get a quality measurement. More details on lectures and practical lessons are presented in the Course Synopsis (Appendix 5).
The last discussion session was dedicated to the definition of Case 1 and Case 2 waters.


IOCCG Summer Lecture Series 2014 - welcome cocktail and group dinner.

The discussion sessions allowed interaction between the students and lecturers. Most of the lecturers attended their colleagues' lectures. This provided additional opportunity for discussions, which the students found most enlightening. Lunch and coffee breaks were also an opportunity for students to talk with the lecturers and get answers to their questions. Now students know where to start looking for information and who can help them to get answer to their questions. The social events (welcome cocktail and dinner) were additional opportunities of interactions among lecturers and students.

COURSE EVALUATION

At the end of the course, students were given a questionnaire to provide IOCCG with feedback on various aspects of the lecturers' performance and of the practical organization. Overall, the students found the 2014 Summer Lecture Series a valuable learning experience and an excellent opportunity to meet both the leading scientists as well as the diverse group of students from different countries and cultures. They content of the lectures met or exceeded their expectations and in all cases the course was highly beneficial for their current research, and they will certainly recommend the course to colleagues. The 2 week duration of the course was considered just right, all the students highlighted the good practical organization and local staff support. All in all they thought it was a privilege to be able to attend the course.

CONCLUSION

The objectives of the 2014 IOCCG summer lecture series were reached and the event was an outstanding success. The atmosphere among participants was very good and may lead to future collaboration between students and lecturers. All presentations have been made available to the participants and are also available on the IOCCG website at:
http://www.ioccg.org/training/lectures.html.

Since the number of students was limited by the accommodation capabilities at LOV (also to maintain a group of a reasonable size), arrangements were made for all the lectures to be video and audio recorded. These will be made available online, as was done for the 2012 lecture series. The videos of the 2012 lectures have been downloaded many thousands of times by students from around the world. The recorded lectures from the 2014 Summer Lecture Series will add to this valuable training resource, which will allow a much larger audience to benefit from the lectures.

ACKNOWLEDGEMENTS

The IOCCG thanks all the lecturers and students for their contributions and cooperation, for their enthusiastic knowledge sharing, and for their time during the course. We are grateful to the contributions from all our sponsors, and to all organizations for providing and managing financial support for the participants. They made this training course possible. The 2014 Summer Lecture Series was sponsored and organised by the IOCCG and with additional specific financial support from the following institutions and agencies:

- Villefranche Observatory (OOV)
- Centre National de la Recherche Scientifique (CNRS/INSU)
- Centre National d'Etudes Spatiales (CNES)
- Laboratoire d'Océanographie de Villefranche (LOV)
- GIS COOC (Groupement d'Intérêt Scientifique - COlour of the OCean)
- Université Pierre et Marie Curie (UPMC)
- National Aeronautics and Space administration of the USA (NASA)
- National Oceanic and Atmospheric Administration of the USA (NOAA)
- Scientific Committee on Oceanic Research (SCOR)
- US Ocean Carbon & Biogeochemistry Program (OCB)

The organizing team would like to thank all the OOV/LOV staff for their help in the organization and their support during the course.

Appendix 1 - List of teaching staff

Name	Institute	E-mail
Emmanuel Boss	University of Maine, USA	emmanuel.boss@maine.edu
Roland Doerffer	Helmholtz Center Geesthacht, Germany	roland.doerffer@hzg.de
Stephanie Henson	National Oceanography Centre, UK	S.Henson@noc.soton.ac.uk
Mati Kahru	Scripps Institution of Oceanography, USA	mkahru@ucsd.edu
Zhongping Lee	University of Massachusetts at Boston, USA	zhongping.lee@umb.edu
Marlon Lewis	Dalhousie University, Halifax, Canada	marlon.lewis@dal.ca
Curtis Mobley	Sequoia Scientific Inc. WA, USA	curtis.mobley@sequoiasci.com
Collin Roesler	Bowdoin University, USA	croesler@bowdoin.edu
Kevin Ruddick	Royal Belgian Institute of Natural Sciences, Belgium	K.Ruddick@mumm.ac.be
Dave Siegel	University of California, Santa Barbara, USA	davey@eri.ucsb.edu
Dariusz Stramski	Scripps Institution of Oceanography, USA	dstramski@ucsd.edu
Menghua Wang	NOAA/NESDIS/STAR, USA	menghua.wang@noaa.gov

Appendix 2 - List of Selected Students

Name	Institute	E-mail
James Allen	University of California, Santa Barbara, USA	james.allen@ucsb.edu
Emma Bone	University of Cape Town, South Africa	emmalewisbone@gmail.com
Isabel Caballero de Frutos	Instituto de Ciencias Marinas de Andalucía, Spain	isabel.caballero@uca.es
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Hongyan Xi	Helmholtz-Zentrum Geesthacht, Germany	hongyan.xi@hzg.de
Laura Maria Zoffoli	INPE, Brazil	mlzoffoli@gmail.com

Appendix 3 - Course Content

- Inherent Optical Properties (inversion and applications in coastal and open ocean waters).
- Errors and uncertainties in ocean colour remote sensing (emphasis on inverse modelling).
- Radiative transfer in the ocean: shallow water remote sensing and HydroLight training.
- Atmospheric correction of ocean colour remote sensing observations.
- Advanced ocean colour remote sensing products for ocean carbon cycle and biogeochemistry.
- Optics from autonomous platforms: linking IOPs to biogeochemistry and remotely sensed ocean colour (including hands-on exercises).
- Phytoplankton variability and climate change.
- Retrieving phytoplankton biomass and functional groups.
- *In situ* measurements.
- Ocean colour remote sensing in turbid coastal waters.
- Optics of marine particles (phytoplankton, minerogenic particles, colloids, bubbles).

Appendix 4 - Course Schedule

Second IOCCG Summer Lecture Series 21 July - 2 August 2014, Villefranche-sur-Mer, France		
Date	**Subject**	**Lecturers**
Sunday 20 July 2014	Participants arrive in Villefranche-sur-Mer	
Monday 21 July 2014		
09h00 - 09h10	Welcome address	LOV/OOV Directors
09h10 - 09h40	Overview of course content, logistical information, introduction to IOCCG	David Antoine
09h40 - 09h50	Personal introductions	
09h50 - 10h30	Brief student presentations (~5-7 min each) - (6 students)	Students
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Brief student presentations (~5-7 min each) - (13 students)	Students
12h30 - 14h00	Lunch break	
14h00 - 14h30	Brief student presentations (~5-7 min each) - (5 students)	Students
14h30 - 15h30	The Science of Ocean Colour - a film by Roland Doerffer (46 min.)	
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Inherent Optical Properties of ocean waters	Zhongping Lee
Tuesday 22 July 2014		
09h00 - 10h30	(1) Improved ocean ecosystem predictions through improved light calculations	Curtis Mobley
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Inversion of Inherent Optical Properties from remote sensing	Zhongping Lee
12h30 - 14h00	Lunch break	
14h00 - 15h30	(2) Issues related to airborne hyperspectral remote sensing	Curtis Mobley
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Ocean colour remote sensing in turbid coastal waters (1)	Kevin Ruddick
Wednesday 23 July 2014		
09h00 - 10h30	Atmospheric correction of ocean colour RS observations (1)	Menghua Wang
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Phytoplankton variability and climate change (1)	Stephanie Henson
12h30 - 14h00	Lunch break	
14h00 - 15h30	(3) Spectrum-matching techniques for inversion of remote-sensing reflectance	Curtis Mobley
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Atmospheric correction of ocean colour RS observations (2)	Menghua Wang
Thursday 24 July 2014		
09h00 - 10h30	Ocean colour remote sensing in turbid coastal waters (2)	Kevin Ruddick
10h30 - 11h00	Coffee Break	
11h00 - 12h30	IOP Applications	Zhongping Lee
12h30 - 14h00	Lunch break	
14h00 - 15h30	Phytoplankton variability and climate change (2)	Stephanie Henson
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Group discussion session	Antoine, Wang, Henson, Lee, Ruddick, Mobley, Lewis
Friday 25 July 2014		
09h00 - 10h30	Atmospheric correction of ocean colour RS observations (3)	Menghua Wang
10h30 - 11h00	Coffee Break	
11h00 - 12h30	In situ measurements (1)	Marlon Lewis
12h30 - 13h45	Lunch break	
13h45 - 15h45	Practical session using Giovanni (seasonal/interannual variability)	Stephanie Henson
15h45 - 16h00	Coffee Break	
16h00 - 17h30	(4) Introduction to HydroLight	Curtis Mobley
Saturday 26 July 2014		
09h00 - 10h30	In situ measurements (2)	Marlon Lewis
10h30 - 11h00	Coffee Break	
11h00 - 12h30	(5) Practical Session - HydroLight Lab 1	Curtis Mobley
12h30 - 14h00	Lunch break	
14h00 - 15h30	(6) Practical Session - HydroLight Lab 2	Curtis Mobley
15h30 -	FREE	
Sunday 27 July 2014		
FREE		

Second IOCCG Summer Lecture Series
21 July - 2 August 2014, Villefranche-sur-Mer, France

Date	Subject	Lecturers
Monday 28 July 2014		
09h00 - 10h30	Bio-optical modeling of Inherent Optical Properties (including PFT approaches)	Collin Roesler
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Errors and uncertainties in ocean colour remote sensing (1)	Roland Doerffer
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical: Playing with light: (absorption scattering, fluorescence and polarization)	Emmanuel Boss
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Errors and uncertainties in ocean colour remote sensing (2)	Roland Doerffer
Tuesday 29 July 2014		
09h00 - 10h30	Practical: Errors and uncertainties in ocean colour remote sensing	Roland Doerffer
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical contd: Errors and uncertainties in ocean colour remote sensing	Roland Doerffer
12h30 - 14h00	Lunch break	
14h00 - 15h30	AC-meter practical: learn how it operates, calibrate and CDOM	Emmanuel Boss, Collin Roesler
15h30 - 16h00	Coffee Break	
16h00 - 17h30	AC-meter practical: learn how it operates, calibrate and CDOM	Emmanuel Boss, Collin Roesler
Wednesday 30 July 2014		
09h00 - 10h30	Practical: Matlab code for semi-analytic inversion (non-linear and linear matrix inversion)	Collin Roesler
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Optics of marine particles (1)	Dariusz Stramski
12h30 - 14h00	Lunch break	
14h00 - 15h30	AC-meter practical: particulate absorption and attenuation	Emmanuel Boss, Collin Roesler
15h30 - 16h00	Coffee Break	
16h00 - 17h30	AC-meter practical: particulate absorption and attenuation	Emmanuel Boss, Collin Roesler
Thursday 31 July 2014		
09h00 - 10h30	Dynamics of open ocean CDOM	Dave Siegel
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Optics of marine particles (2)	Dariusz Stramski
12h30 - 14h00	Lunch break	
14h00 - 15h30	Linking between IOP and biogeochemistry and/or Scattering measurement & theory	Emmanuel Boss
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Discussion of the AC lab results	Emmanuel Boss, Collin Roesler
Friday 1 August 2014		
09h00 - 10h30	Alternative interpretations of regional and global trends in ocean colour observations	Dave Siegel
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: Validation of satellite ocean colour data	Mati Kahru
12h30 - 14h00	Lunch break	
14h00 - 15h30	Bio-optical modeling of single and multichannel fluorescence	Collin Roesler
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Group discussion session	Antoine, Siegel, Stramski, Mobley, Kahru, Roesler
Saturday 2 August 2014		
09h00 - 10h30	Constraining the global carbon cycle from satellite observation	Dave Siegel
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: Detecting change in satellite time series.	Mati Kahru
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical: Detecting change in satellite time series.	Mati Kahru
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Disucssion session and conclusion of 2014 Summer Lecture Series	All

CLOSURE - 2nd SUMMER LECTURE SERIES

Appendix 5 - Course Synopsis

Zhongping Lee: Lectures on Inherent Optical Properties

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.

Lecture 1: Fundamentals of IOPs and IOP-AOP relationships

Definition of absorption and (back) scattering coefficients
Typical values and spectra of absorption, (back) scattering, and volume scattering function
Theoretical bases between AOP (in particular Rrs) and IOPs and their simplified expressions

Lecture 2: Algorithms to invert IOPs

Empirical algorithms
Bottom-up semi-analytical algorithms
Top-down algebraic/semi-analytical algorithms

Lecture 3: Applications of IOPs

Waters quality assessment
Phytoplankton blooms
Light field
Primary production

Approach:

I will give focused lectures along with hands-on practices. Students are expected to bring their own laptop computers with MS Excel (including the add-in Solver) installed. Reading materials will be handed out to broaden knowledge.

Curtis Mobley: Radiative Transfer Theory Applied to Problems in Optical Oceanography

Much of the background material for the lecture series can be found on the Ocean Optics Web Book at http://www.oceanopticsbook.info/. Students are encouraged to read over the various pages, especially those on the definitions of radiometric variables, IOPs, AOPs, and remote sensing.

Lecture 1: Improved ocean ecosystem predictions through improved light calculations

I will review the current state of light models used to compute water heating and biological primary production in coupled hydrodynamical-biological-optical ocean ecosystem models. I will then show how radiative transfer codes can be made to run extremely fast, which allows them to be used in ecosystem models, which are severely constrained by computer resources. I will show differences in predicted ecosystem development when simple approximate vs accurate numerical light models are used in ecosystem models.
Reference:
Mobley (2011). Fast light calculations for ocean ecosystem and inverse models. *Optics Express* 19(20), 18927-18944.

Lecture 2: Issues related to airborne hyperspectral remote sensing

The emphasis is on 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. I will discuss atmospheric correction for shallow and coastal Case 2 waters, as is needed for remote sensing to retrieve bathymetry and bottom classification. I'll review why atmospheric correction as typically used for deep, open ocean, Case 1 (black pixel techniques) water doesn't work for shallow water, and what techniques are often used for shallow waters (empirical line fits and radiative transfer methods).
References:
www.oceanopticsbook.info/view/remote_sensing/the_atmospheric_correction_problem
www.oceanopticsbook.info/view/remote_sensing/level_2/atmospheric_correction_empirical_line_fits
www.oceanopticsbook.info/view/remote_sensing/level_2/atmospheric_correction_radiative_transfer_modeling

Lecture 3: Spectrum-matching techniques for inversion of remote-sensing reflectance

I'll talk about both semi-analytic and data-base spectrum matching techniques for retrieving bathymetry, bottom type, and water IOPs. Techniques for error estimation will be shown.
References:
Lee et al (1998). Hyperspectral remote sensing for shallow waters. I. A semianalytical model, *Appl Optics* 37(27), 6329-6338

Lee et al. (1999). Hyperspectral remote sensing for shallow waters. II. Deriving bottom depths and water properties by optimization, *Appl Optics* 38(18), 3831-3843

Mobley et al. (2005). Interpretation of hyperspectral remote-sensing imagery by spectrum matching and look-up tables. *Appl. Optics* 44(17), 3576-3592.

Dekker et al. 2011. Intercomparison of shallow water bathymetry, hydro-optics, and benthos mapping techniques is Australia and Caribbean coastal environments. *Limnol. Oceanog. Methods* 9, 396-425.

Lecture 4: Introduction to HydroLight

I will discuss what the HydroLight radiative transfer model is and is not, how it is used, and what are its inputs and outputs. I will show how to run the code and examine its outputs. Students will be given a CD with an executable version of HydroLight to install on their laptops.
Note: The student version of HydroLight runs only on computers with some version of the Microsoft Windows operating system (and with a CD reader for installation). Students with Apple computers can team up with someone who has a Windows computer.
Reference:
www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/hydrolight

HydroLight training lab 1. Simple simulations using HydroLight.
Students will run HydroLight on their laptops for various simple simulations such as using standard bio-optical models for Case 1 water and shallow water with a given bottom type.
References:
HydroLight 5.2 Users' Guide and *HydroLight 5.2 Technical Documentation*. These can be downloaded at
http://www.oceanopticsbook.info/view/references/publications
Additional information can be downloaded at under "Software and Downloads" at
http://www.sequoiasci.com/product/hydrolight/ (requires registration on the website)

HydroLight training lab 2. Advanced simulations using HydroLight.
Students continue to run HydroLight for more advanced simulations, such as reading in their own data files for IOPs, sky irradiances, or bottom reflectances, and for simulating complex Case 2 waters.

Week 2: Interested students can continue to run HydroLight and obtain help from me as needed.

Kevin Ruddick: Ocean Colour Remote Sensing in turbid coastal waters

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.

One advantage of turbid waters is that the water is brighter than oceanic waters and the stringent signal:noise requirements of dedicated ocean colour sensors can be relaxed for some applications. This facilitates the use of many other optical remote sensors designed for land applications. In particular, the new Landsat-8 sensor has much improved signal:noise with respect to previous Landsat missions and the data, which is freely available from USGS, is suitable for quantification of suspended particulate matter in turbid waters. At such high resolution (30m) the impact of human activities (ports, offshore constructions, ships, etc.) is much clearer. The processing and exploitation of such very high resolution data will be described.

Requirements for the lectures

- A basic knowledge of the definitions of optical properties (scattering, absorption, attenuation) and from other lectures from this IOCCG summer school, particularly those of Zhongping Lee and Curtis Mobley.
- Excel installed on a portable PC (at least per two students).

Suitable background reading

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

Menghua Wang: Atmospheric Correction of Ocean Color RS Observations

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, VIIRS, and the first geostationary ocean color sensor GOCI 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 NIR radiance modeling
    - The SWIR-based atmospheric correction
- Examples from MODIS-Aqua, VIIRS, and GOCI 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. Some recent research results

9. Summary

<u>Some Useful References</u>

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)

Stephanie Henson: Using satellite ocean colour data to investigate variability and climate change effects in phytoplankton

My lectures will discuss how satellite ocean colour data can be applied to research questions concerning variability in phytoplankton. We will cover some of the types of variability observable by satellite ocean colour data: spatial, seasonal, interannual and decadal. We will also consider how long-term trends and possible climate change effects can be studied, particularly in combination with other data sources (e.g. SST, wind) and biogeochemical models. I will also discuss why this variability is important to understand and how it can give us a window into understanding how atmospheric and physical processes influence phytoplankton populations. Finally we will learn about some simple techniques for analysing satellite ocean colour time series data. These lessons will be applied in the subsequent practical session, where we will use a simple online tool to visualise time series data. This will be followed by more in-depth analysis using pre-prepared scripts. There will be the opportunity for you to work with data from your own study region and/or to address your particular research question.

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 (Wifi enabled), 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.

Background Reading

- Follows, M., and S. Dutkiewicz (2002), Meteorological modulation of the North Atlantic spring bloom, *Deep Sea Research Part II*, *49*(1-3), 321-344.
- 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.
- Martinez, E. et al. (2009), Climate-driven basin-scale decadal oscillations of oceanic phytoplankton, *Science*, *326*, 1253-1256.
- Siegel, D. A. et al. (2002), The North Atlantic spring phytoplankton bloom and Sverdrup's critical depth hypothesis, *Science*, *296*(5568), 730-733.

Marlon R. Lewis: In Situ Measurements

Lecture 1: In situ Measurements (1)

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)

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

Collin Roesler

Lecture 1: Bio-optical modeling of Inherent Optical Properties including PFT approaches

This class will focus on retrieving the inherent optical properties (IOPs) from semi-analytic ocean color inversion using both non-linear regression and linear singular value decomposition approaches. In addition to retrieving the total absorption and backscattering coefficients, approaches for separating the IOPs into those that provide information on phytoplankton functional types are included. The lecture will be supported by a practical session dedicated to providing students with an understanding of how the forward radiative transfer model is incorporated into the non-linear and linearized semi-analytical inversion models.

Suggested Readings :

Roesler, C. S., and M. J. Perry. 1995. In situ phytoplankton absorption, fluorescence emission, and particulate backscattering spectra determined from reflectance. Journal of Geophysical Research 100: 13,279:13,295.

Z. P. Lee, K. L. Carder, T. G. Peacock, C. O. Davis, and J. L. Mueller (1996). Method to derive ocean absorption coefficients from remote-sensing reflectance. *Appl. Opt.* 35(3): 453-462.

Hoge, F. E.*, and* P. E. Lyon *(*1996*),* Satellite retrieval of inherent optical properties by linear matrix inversion of oceanic radiance models: An analysis of model and radiance measurement errors*,* J. Geophys. Res.*,* 101*(*C7*),* 16631–16648*, doi:*10.1029/96JC01414

Garver, S.A. and Siegel, D.A. (1997). Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation: 1. Time series from the Sargasso Sea. Journal of Geophysical Research 102: doi: 10.1029/96JC03243. issn: 0148-0227.

ÁM Ciotti, JJ Cullen, MR Lewis. 1999. A semi-analytical model of the influence of phytoplankton community structure on the relationship between light attenuation and ocean color. J. Geophys. Res. 104(C1): 1559-1578.

Maritorena, S., D.A. Siegel and A.R. Peterson, 2002: Optimization of a semianalytical ocean color model for global-scale applications. Applied Optics-LP, 41, 2705-2714.

Roesler, C. S., and E. Boss. 2003. Spectral beam attenuation coefficient retrieved from ocean color inversion. Geophys. Res. Lett., 30(9), 1468-1472, doi:10.1029/2002GL016185

IOCCG. 2006. Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications. Lee, Z.-P. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 5, IOCCG, Dartmouth, Canada.

Kostadinov, T.S., D.A. Siegel, and S. Maritorena. 2009: Retrieval of the particle size distribution from satellite ocean color observations. Journal of Geophysical Research – Oceans, 114, C09015, doi:10.1029/2009JC005303

Lecture 2: Bio-optical modeling of single and multichannel fluorescence

This course will focus on retrieval of phytoplankton biomass and pigment-based taxonomy from single and multichannel fluorescence with attention to issues surrounding remote platform deployments. Issues of variability in fluorescence yield, non-photochemical quenching and biofouling will be addressed.

Suggested Readings:

Falkowski, P., and D. A. Kiefer. 1985. Chlorophyll a fluorescence in phytoplankton: relationship to photosynthesis and biomass. Journal of Plankton Research **7:** 715-731.

Proctor, C. W., and C. S. Roesler. 2010. New insights on obtaining phytoplankton concentration and composition from in situ multispectral Chlorophyll fluorescence. Limnology and Oceanography: Methods **8:** 695-708.

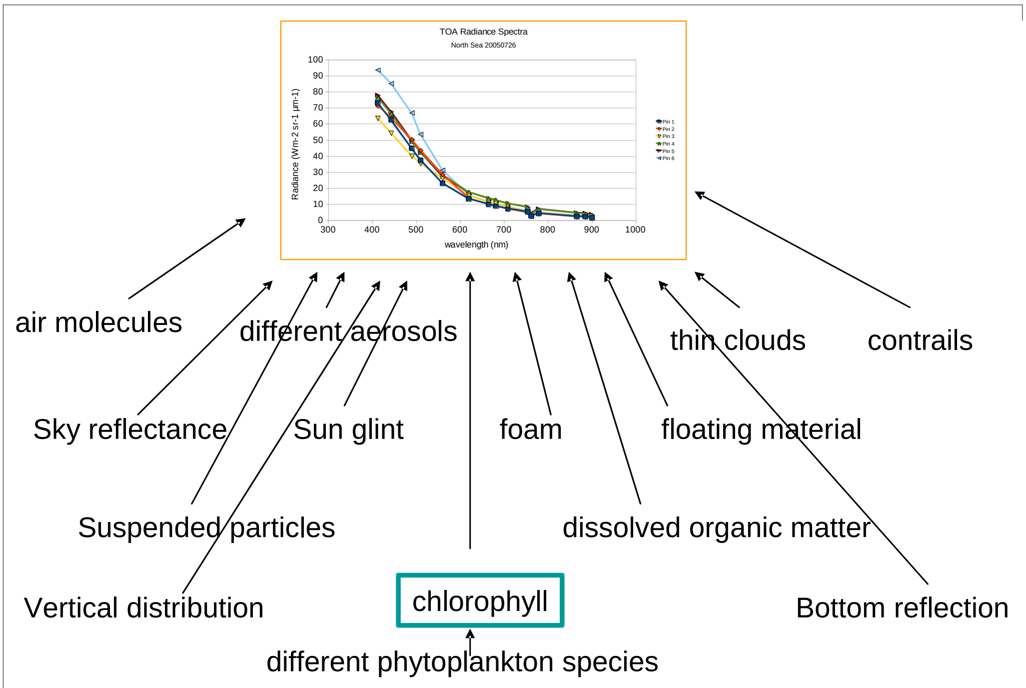
Sackmann, B., M. Perry, and C. Eriksen. 2008. Seaglider observations of variability in daytime fluorescence quenching of chlorophyll-a in Northeastern Pacific coastal waters. Biogeosciences Discussions **5**.

Huot, Y., and M. Babin. 2011. Overview of Fluorescence Protocols: Theory, Basic Concepts, and Practice, p. 31-74. *In* D. J. Suggett [ed.], Chlorophyll Fluorescence in Aquatic Sciences: Methods and Applications. Developments in Applied Phycology. Springer.

Roesler, C. S., and A. H. Barnard. 2013. Optical proxy for phytoplankton biomass in the absence of photophysiology: Rethinking the absorption line height. Methods in Oceanography **7:** 79-94.

Roland Doerffer: Errors and uncertainties in ocean colour remote sensing

One of the main questions you will be asked as a remote sensing expert is: how reliable and good is the information, which you derive from remotely sensed ocean colour data? Can we trust them? What is the error or uncertainty range of these data?
We have to face the problem that in many cases more factors determine the radiance spectrum at top of atmosphere than we can retrieve from the spectra. Furthermore we have masking and saturation effects and ambiguities and other problems. Thus, the question of error and uncertainty cannot easily be answered.



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 hours of lectures and 3 hours of exercises, we will look into this problem and discuss solutions.

Lectures

In ocean colour remote sensing we try nothing less than to retrieve and quantify a small effect on top of atmosphere radiance spectra, which is caused by absorption and scattering of e.g. phytoplankton in the ocean, and isolate it 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 even be impossible to retrieve reliable information of the ocean and in particular of coastal waters from remotely sensed reflectance spectra. Thus, one important area of ocean colour research is to analyse sources of uncertainties, to detect cases when an algorithm fails, to develop methods to quantify uncertainties and finally to find ways to reduce them.
The first lecture will be dedicated to the sources of uncertainties.

- Natural factors, which determine uncertainties, and their variability
- Uncertainties, which are induced by reducing the manifold of factors to a few dominant ones
- 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 detect cases, which are out of scope of an algorithm, and how to determine uncertainties:

- How to quantify uncertainties: scatter, bias, robustness, stability
- Validation procedures and strategies
- Testing of algorithms
- Round robin exercises
- Sensitivity studies
- Detection of spectra / pixels, which are out of scope of the algorithm
- Determination of uncertainties on a pixel by pixel bases
- flagging

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

- Masking of clouds and cloud shadows
- Use of additional information
- Pre-classification of water types and use of algorithms, which are dedicated to different water types
- 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 it with the information, we want to derive. We will look into in situ data and determine uncertainties when comparing the optical properties with concentrations. 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 5.5

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.

Emmanuel Boss: Laboratory exercises

1. Playing with light

During this hands-on lab students will move between stations in which hands-on exercises will be set. Students will be asked to perform certain actions, but before performing the actions, will need to predict what is likely to happen. Once students perform the exercise they will need to explain why/how the observed reaction has happened.

- Transmission of light of different wavelengths in water with different food coloring.
- Beer-Lamber-Buguer's law: transmission of light as function of drops of food color and malox.
- Scattering of a laser beam in air, air+droplets, water and water+malox.
- Polarization: how is it affected by scattering by surfaces and by particles in water?
- Effects of index of refraction on light scattering. Index matching.
- Transmission across the air-water interface. Total internal reflection and Snell's cone.
- Playing with lenses, converging and diverging light beams.
- How does ocean color comes about? Role of scattering and absorption in the intensity and color of the water leaving radiance.
- Breaking visible light into its component: diffraction grating and prism. Looking at different light sources.
- Pin-hole optics.
- Fluorescence by different substances.

2. CDOM absorption lab

Learn to calibrate WETLabs AC sensor. Run 3 samples of CDOM using both a and c-sides of instrument. Process data and obtain exponent of CDOM spectra.

3. Particulate attenuation lab:

Calibrate and then measure absorption and attenuation of Med water sample using a WETLabs AC sensor. Run 0.2μm filtered Med water. Compare total and particulate (total-dissolved) beam attenuation and its spectral exponent.

4. Particulate absorption and scattering lab:
Process the previous day's data using different scattering corrections to compute a_pg, a_p and b_p. How important is the correction scheme and at what wavelengths? Fit a power law to b_p. How well does it fit the spectra? How does it compare with that of c_p (compare magnitude and exponents).
+ if time permits, **linking between IOPs and biogeochemistry**.

Dariusz Stramski: Optics of Marine Particles

This lecture will provide an overview of fundamentals in the following topical areas:

(1) Mechanisms of light absorption and scattering by particles;

(2) Quantification of absorption and scattering properties of individual particles;

(3) Dependence of particle optical properties on physical and chemical characteristics of particles;

(4) Linkage between the single-particle optical properties and bulk optical properties of particle suspension;

(5) Optical properties of various types of marine particles including:

(a) Inter- and intraspecies variability of phytoplankton optical properties;

(b) Optical properties of heterotrophic bacteria;

(c) Optical effects of interactions of biological particles such as prey-predator interactions and viral infection;

(d) Optical properties of minerogenic particles;

(e) Optical properties of air bubbles;

(6) Roles of various types of particles in ocean optics: from rudimentary approaches such as chlorophyll-based approach to higher-level approaches such as reductionist approach;

(7) Methodological aspects of the study of optical properties of marine particles.

Lecture 1: Topics 1 through 4

Useful reading:

Bricaud, A. and A. Morel. 1986. Light attenuation and scattering by phytoplanktonic cells: A theoretical modeling. Appl. Opt., 25, 571-580.

Morel, A. and A. Bricaud. 1981. Theoretical results concerning light absorption in a discrete medium and application to specific absorption by phytoplankton. Deep-Sea Res., 28, 1375-1393.

Morel, A. and A. Bricaud. 1986. Inherent optical properties of algal cells including picoplankton: Theoretical and experimental results, p. 521-555. In Photosynthetic picoplankton, Can. Bull. Fish. Aquat. Sci. 214.

Lecture 2: Topics 5 through 7

Useful reading:

Babin, M. and D. Stramski. 2004. Variations in the mass-specific absorption coefficient of mineral particles suspended in water. Limnol. Oceanogr., 49, 756-767.

Morel, A. and Y-H. Ahn. 1991. Optics of heterotrophic nanoflagellates and ciliates. A tentative assessment of their scattering role in oceanic waters compared to those of bacterial and algal cells. J. Mar. Res., 49, 177-202.

Stramski, D., A. Bricaud, and A. Morel. 2001. Modeling the inherent optical properties of the ocean based on the detailed composition of planktonic community. Appl. Opt., 40, 2929-2945.

Stramski, D., and D. A. Kiefer. 1991. Light scattering by microorganisms in the open ocean. Prog. Oceanogr., 28, 343-383.

Terrill, E. J., W. K. Melville, and D. Stramski. 2001. Bubble entrainment by breaking waves and their influence on optical scattering in the upper ocean. J. Geophys. Res., 106, 16815-16823.

Comprehensive references:

Woźniak, B. and J. Dera. 2007. Light Absorption in Sea Water. Springer.

Jonasz, M. and G. R. Fournier. 2007. Light Scattering by Particles in Water. Theoretical and Experimental Foundations. Academic Press.

David Siegel

Talk 1: Chromophoric Dissolved Organic Matter (CDOM) in the Global Ocean

The lecture will present a review of what is known about the sources, sinks and distribution of chromophoric dissolved organic matter (CDOM) in the global ocean. CDOM is shown to be the dominate property contributing to light absorption from the ultraviolet into the blue-green. The relationship between CDOM and the concentration of dissolved organic carbon and CDOM fluorescence are explored. CDOM dynamics is addressed on a range of time scales from experimental time scales (days) to time scales relating to the meridional overturning circulation (millennia).

Nelson, N.B., & Siegel D.A., 2013: Global distribution and dynamics of chromophoric dissolved organic matter. *Annual Review of Marine Science*, **5**, 447-476

Talk 2: Bio-Optical Complexity and the Interpretation of Global Phytoplankton Dynamics from Satellite Ocean Color Observations

The lecture focuses on the bio-optical complexity hidden in the empirical satellite chlorophyll retrievals and suggests that incorrect conclusions can be drawn about global and regional scale changes by not considering the complex interplay of oceanic properties.The talk goes further to address the plastic nature of chlorophyll under light and nutrient stresses and whether chlorophyll concentration is an appropriate metric for understanding change in global phytoplankton populations.

Siegel, D.A., M.J. Behrenfeld, S. Maritorena, C.R. McClain, D. Antoine, S.W. Bailey, P.S. Bontempi, E.S. Boss, H.M. Dierssen, S.C. Doney, R.E. Eplee Jr., R.H. Evans, G.C. Feldman, E. Fields, B.A. Franz, N.A. Kuring, C. Mengelt, N.B. Nelson, F.S. Patt, W.D. Robinson, J.L. Sarmiento, C.M. Swan, P.J. Werdell, T.K. Westberry, J.G. Wilding, J.A. Yoder, 2013: Regional to Global Assessments of Phytoplankton Dynamics from the SeaWiFS Mission. *Remote Sensing of the Environment*, **135**, 77-91.

Talk 3: Assessment of Ocean Carbon Export From Satellite Data: New Approaches and a Plan for the Future

The biological carbon pump is thought to export anywhere from 5 to 12 Pg C each year from the surface ocean depth largely in the form of settling organic particles and its functioning is crucial for the global carbon cycle. Assessments of the global export flux have either been through the extrapolation of point measurements to global scales or the results of ocean system model experimentation. Satellites resolve relevant space and time scales providing guidance to the empirical extrapolation problem, but they do not quantify directly carbon export. Here, I introduce a mechanistic approach for assessing global carbon export linking satellite data with a food web model. The synthesis does an excellent job reproducing regional export flux observations and it reproduces the basic patterns of export spatially and seasonally. This approach provides many insights into future research on carbon export and ocean ecosystem trophic dynamics. Towards this future, the science plan for a NASA field campaign on assessing the state of the biological pump, EXport processes in the Ocean from RemoTe Sensing (EXPORTS), is presented.

Siegel, D.A., K.O. Buesseler, S.C. Doney, S.F. Sailley, M.J. Behrenfeld, P.W. Boyd, 2014: Global assessment of ocean carbon export by combining satellite observations and food-web models.

GlobalBiogeochem. Cycles, **28**, doi:10.1002/2013GB004743.

EXPORTS Writing Team, 2014: Export Processes in the Ocean from RemoTe Sensing (EXPORTS): A Science Plan for a NASA Field Campaign. Science plan, 104 pp.http://cce.nasa.gov/cce/ocean_exports_intro.htm

Mati Kahru: Practical session using WIM/WAM software package

The purpose of these practical tutorials is to provide students with practical knowledge and experience how to perform certain tasks using satellite data. A requirement is to have access to a Windows computer (laptop or desktop) that has been updated with Windows Update. Software and satellite data will be distributed during the course and are also available online. Links to the online tutorial instructions and software are provided here but both the instructions and software will be updated before the course. Software and data will be distributed on both DVD and USB memory sticks just before the course. The software can also be downloaded and installed from http://wimsoft.com/Course/wam.msi (use option Typical to install, license number is 9299798141).

Students are encouraged to install the software and read the currently available tutorial instructions (links below) but must keep in mind that both software and instructions will be updated before the course and they will need to install the updated software (after uninstalling the old version). Basics knowledge of the Windows command line prompt is required, i.e. how to open the Windows command window and issue commands.

Practical tutorial 1: Validation of satellite ocean colour data

Satellite measurements are typically very indirect measurements of the variables of interest and therefore have potentially large errors. We need to validate satellite measurements regionally and temporally and determine the approximate errors. I this exercise we will compare various levels of satellite data (Level-2, Level-3, Level-4) with various in situ data. We will also compare satellite data between various satellite sensors. Preliminary instructions are available at the link below but will be updated before the course: http://www.wimsoft.com/Course/4/Validation_2014.pdf

Practical tutorial 2: Detecting change in satellite time series

Time series of satellite data are a major tool to detect regional or global change. We will use various satellite data and evaluate the possibility of detecting various trends, e.g. in ice concentration, phytoplankton annual bloom magnitude and bloom timing, indices of particle size structure. Preliminary instructions are available at the link below but will be updated before the course: http://www.wimsoft.com/Course/4/Detection_of_change_2014.pdf