IOCCG
International Ocean-Colour Coordinating Group

IOCCG Summer Lecture Series

"Frontiers in Ocean Optics and Ocean Colour Science"

http://www.ioccg.org/training/SLS_2016.html

OOV/LOV, Villefranche-sur-Mer, France, 18 -31 July 2016

Specific supports are acknowledged for the 2016 edition,
in addition to regular annual support from all IOCCG contributing agencies

International Ocean-Colour Coordinating Group

Table of Contents

1 INTRODUCTION

The Villefranche Oceanological Observatory (OOV) and the Laboratoire d'Océanographie de Villefranche (LOV), located in Villefranche-sur-Mer, France, hosted the third IOCCG Summer Lecture Series (SLS), 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, delivered by 17 distinguished lecturers on the fundamentals of ocean optics as well as cutting edge research *(see Appendix 1: List of teaching staff)*. The overarching objective was to focus on current critical issues in ocean colour science

A total of 22 students from 15 different countries of residence were selected from more than 140 excellent applications from around the world (*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 general motivation. The majority of the trainees were PhD students and post-doctoral students, along with several young early career researcher scientists. The participants came from a broad range of backgrounds, but all had experience in some aspect of ocean colour remote sensing.

2 COURSE ORGANIZATION

The SLS2016 brought together remote sensing specialists from various fields of ocean colour so the course content covered a wide range of topics based on theory, practical sessions and specific applications. The format of the Summer Lecture Series included a series of lectures as well as hands-on practical sessions and open group discussion sessions on pre-arranged topics to allow interaction between the students and lecturers.

The course was opened with a welcoming address by the OOV Director, Dr. Anne Corval. This was followed by a summary of IOCCG activities and a review of the course organization by Dr. David Antoine (local organizer and past IOCCG Chair). After this session the students all introduced themselves and gave a brief presentation on their current area of research (5 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 and share their work and passion.

The first week of the Summer Lecture Series covered theoretical aspects of ocean colour remote sensing including the concept of inherent and apparent optical properties (IOPs and AOPs) of ocean waters, optics of marine particles and ocean scattering, to ensure that all students had the appropriate background to benefit from the second week of lectures. The first week also included a practical AC lab to understand absorption, scattering and the colour of the ocean. During these practical sessions students learned how to calibrate the AC instrument, and how to measure CDOM, particulate absorption and attenuation, which helped them to understand how to collect high-quality *in situ* data and how to interpret the measurements. At the end of the week students were also given and introduction to, and an opportunity to use, the HydroLight radiative transfer model.

The second week of the course included a discussion of the AC-lab results, an introduction to Matlab code for semi analytical inversion, as well as lectures on uncertainties, atmospheric correction, ocean colour remote sensing in shallow and turbid waters, BCG modelling and a practical session on Giovanni. Students also enjoyed a lecture on the history of Villefrance and the LOV lab by Prof. Louis Legendre (*see Appendix 3 - Course Schedule* for full details).

In order for students to be able to prepare for the course, a synopsis of all the lectures and suggestions for further reading was sent in advance to all participants (*see Appendix 4- Course synopsis*). The overall objective of the SLS was to provide opportunities for students to improve their skills and knowledge, which they could then apply to their current and future research.

Group picture of students taken in the classroom after they received their SLS2016 participation certificates.

In addition to the group discussion session, the students were also able to network with the experts in the field on a one-to-one basis to discuss and refine aspects of their own research (including logistical and data issues) which most students found immensely helpful. Many students noted that one of the most important parts of the SLS was being able to make connections with some of the best researchers in the field of ocean optics. Lunch and coffee breaks were also an opportunity for students to talk with the lecturers, since most of the lecturers attended their colleagues' lectures. The social events (welcome cocktail and dinner) were additional opportunities for interactions amongst lecturers and students.

Students from the 2016 IOCCG Summer Lecture Series

3 COURSE EVALUATION

Students were given a questionnaire at the end of the course to report on their views on various aspects of the lecturers' performance and on aspects of the practical course organization. The conclusion for the 2016 Summer Lecture Series was that the students learned a lot and that they were very satisfied with the content of the lectures. The sense of community that arose from the lecture series allowed students to build meaningful relationships with other students as well as the lecturers. Most students indicated that they will benefit immediately from the lecture series in terms of their current research and will definitely recommend the course to colleagues. They were also extremely satisfied with the practical organization and with the support from the local staff. Overall the 2016 SLS was a highly valuable and special experience and one that will be carried throughout the students' scientific journey.

4 CONCLUSION

The 2016 IOCCG summer lecture series was very well received by all the students, and the event was considered an outstanding success. Many noted that the IOCCG summer lecture series was a life-changing experience that allowed students to create bonds that will last throughout their entire careers.

All presentations were audio and video recorded and these recordings, as well as all PowerPoint presentations, are available online via the IOCCG website at:
http://www.ioccg.org/training/lectures.html#SLS2016

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5 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 2016 Summer Lecture Series was sponsored and organised by the IOCCG and with additional specific financial support from the following institutions and agencies:

- Villefranche Observatoire (OOV)
- Centre National de la Recherche Scientifique (CNRS/INSU)
- Laboratoire d'Océanographie de Villefranche (LOV)
- GIS COOC (Groupement d'Intérêt Scientifique - COlour of the OCean)
- Scientific Committee on Oceanic Research (SCOR)
- US Ocean Carbon & Biogeochemistry Program (OCB)
- All the IOCCG funding agencies

The organizing team would like to thank the following key people for their help in the organization and their support during the course:

- David Antoine for motivating, orchestrating and overseeing the 2016 SLS, including developing the agenda and selecting the invited lecturers.
- Venetia Stuart, IOCCG executive scientist, for the overall organisation and coordination and managing the overall budget and financial support for 6 lecturers.
- Elisabeth Gross, Scientific Committee for Oceanic Research (SCOR), for management of applications.
- The IOCCG Selections Committee for their help in rating and selecting students
- Anne Corval, Director, OOV, for hosting the SLS2016 at the Villefranche observatory
- Antoine Sciandra, Director, LOV, for the support of LOV
- Joana Betencourt, EUMETSAT, for management of EMETSAT financial support to 5 students
- Heather Benway and Mary Zawoysky, Ocean Carbon & Biogeochemistry Program, for management of OCB financial support to 3 students and 2 lecturers
- Cédric Darbon, for all aspects of logistical assistance on site
- Corinne Poutier, LOV secretariat, for management of financial support to 12 students
- Véronique Gourbaud, management of OOV accommodation for students
- The staff of the OOV restaurant and the staff in charge the OOV accommodation and housekeeping
- The OOV IT team

6 Appendix 1 - List of teaching staff

- Curtis Mobley (Sequoia Scientific Inc. WA, USA)
- John Hedley (Environmental Computer Science Ltd, Tiverton, Devon, UK)
- Emmanuel Boss (University of Maine, USA)
- Collin Roesler (Bowdoin University, USA)
- Dariusz Stramski (Scripps Institution of Oceanography, USA),
- Hervé Claustre (LOV Villefranche, France)
- Stéphanie Dutkiewicz (MIT, USA)
- Heidi Dierssen (University of Connecticut, USA)
- Julia Uitz (LOV, Villefranche sur mer, France)
- Mike Twardowski (Harbor Branch Oceanographic Institute, Florida Atlantic University, USA)
- James Acker (Adnet Inc., NASA Goddard Earth Sciences Data & Information Services Center, USA)
- Zhongping Lee (University of Massachusetts at Boston, MA, USA)
- Agnieszka Bialek (National Physical Laboratory, UK)
- Kevin Ruddick (RBINS, Belgium)
- Quinten Vanhellemont (RBINS, Belgium)
- Cedric Jamet (MREN/ELICO, Wimereaux, France)
- Louis Legendre (LOV, Villefranche, France)

7 Appendix 2 - List of Selected Students

First Name	Last Name	Institute
Marie	Barbieux	Laboratoire d'Océanographie de Villefranche-sur-Mer, France
Nariane	Bernardo	São Paulo State University, Brazil
Henry	Bittig	Laboratoire d'Océanographie de Villefranche-sur-Mer, France
Ilaria	Cazzaniga	Institute for electromagnetic sensing of the environment (IREA - CNR) and Università degli studi di Milano-Bicocc, Italy
Liesbeth	De Keukelaere	Flemish Institute of Technological Research, VITO, Belgium
David	Flanagan	College of Charleston, USA
John	Gittings	King Abdullah Univ of Science and Technology, Saudi Arabia
Dmitry	Glukhovets	Moscow Institute of Physics and Technology and Ocean Optics Laboratory, SIO RAS, Russia
Juan Ignacio	Gossn	Instituto de Astronomía y Física del Espacio (IAFE-CONICET/UBA), Argentina
Andrea	Hilborn	University of Victoria, SPECTRAL Lab, Canada
Tin	Hoang Cong	Curtin University of Technology, Australia
Priscila	Lange	Oxford Univ, Dept of Earth Sciences, UK
Boram	Lee	Korean Institute of Science and Technology, Korea
Joan	Llort Jordi	University of Tasmania, Australia
James	Nyaga	Regional Centre for Mapping of Resources for Development, Kenya
Carina	Poulin	University of Sherbrooke, Canada
Anna	Raczkowska	Institute of Oceanology Polish Academy of Sciences, Poland
Deanesh	Ramsewak	University of Trinidad and Tobago, Trinidad & Tobago
Charlotte	Robinson	Climate Change Cluster, University of Sydney, Australia
Michael	Sayers	Michigan Technological University, USA
Zhehai	Shang	School For the Environment, University of Massachusetts, USA
Larissa	Valerio	James Cook University, Australia

8 Appendix 3 - Course Schedule

Third IOCCG Summer Lecture Series 18 - 29 July 2016, Observatoire Océanologique de Villefranche-sur-Mer, France		
Date	**Subject**	**Lecturers**
Sunday 17 July 2016	Participants arrive in Villefranche-sur-Mer	
Monday 18 July 2016		
09h00 - 09h10	Welcome address	Anne Corval, OOV Director
09h10 - 09h40	Overview of course content, logistical information, introduction to IOCCG	David Antoine, lectures coordinator
09h40 - 10h40	Brief student presentations (~5 min each) - (11 students)	Students
10h40 - 11h15	Coffee Break	
11h15 - 12h15	Brief student presentations (~5 min each) - (11 students)	Students
12h30 - 14h00	Lunch break	
14h00 - 15h30	Fundamentals of the light / matter interaction	Dariusz Stramski
15h30 - 16h00	Coffee Break	
16h00 - 17h30	IOPs of ocean waters, fundamentals	ZhongPing Lee
Tuesday 19 July 2016		
09h00 - 10h30	Radiometry and apparent optical properties (AOPs), fundamentals	Curtis Mobley
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: playing with light	Emmanuel Boss
12h30 - 14h00	Lunch break	
14h00 - 15h30	inversion of inherent optical properties (IOPs) from remote sensing	ZhongPing Lee
15h30 - 16h00	Coffee Break	
16h00 - 17h30	IOPs applications	ZhongPing Lee
WELCOME DRINK 6pm		
Wednesday 20 July 2016		
09h00 - 10h30	Optics of marine particles (1)	Dariusz Stramski
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Optics of marine particles (2)	Dariusz Stramski
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical: AC-lab	Emmanuel Boss / Collin Roesler
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Practical: AC-lab	Emmanuel Boss / Collin Roesler
Thursday 21 July 2016		
09h00 - 10h30	introduction to Hydrolight	Curtis Mobley
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical Session - HydroLight Lab 1	Curtis Mobley / John Hedley
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical Session - HydroLight Lab 2	Curtis Mobley / John Hedley
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Bio-optical modeling of IOPs, including phytopalnkton functional types (PFTs)	Collin Roesler
Friday 22 July 2016		
09h00 - 10h30	Ocean Scattering (1)	Mike Twardowski
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Ocean Scattering (2)	Mike Twardowski
12h30 - 13h45	Lunch break	
13h45 - 15h45	Practical: AC-lab	Emmanuel Boss / Collin Roesler
15h45 - 16h00	Coffee Break	
16h00 - 17h30	Practical: AC-lab	Emmanuel Boss / Collin Roesler

Saturday 23 July 2016		
09h00 - 10h30	Discussion of AC-lab results	Emmanuel Boss / Collin Roesler
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Complementarity of satellite OCR and in situ measurements: towards integrated observation systems	Hervé Claustre
12h30 - 14h00	Lunch break	
Afternoon	FREE	
Sunday 24 July 2016		
FREE		

Third IOCCG Summer Lecture Series
18 - 31 July 2016, Villefranche-sur-Mer, France

Date	**Subject**	**Lecturers**
Monday 25 July 2016		
09h00 - 10h30	Matlab code for semi analytical inversion	Collin Roesler
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Bio-optical modeling of single and multi-channel fluorescence	Collin Roesler
12h30 - 14h00	Lunch break	
14h00 - 14h30	The history of the Villefranche Observatory	Louis Legendre
14h30 - 15h30	Discussion session	
15h30 - 16h00	Coffee Break	
16h00 - 17h30	The three dimensional light environment in coral reefs and seagrass	John Hedley
Tuesday 26 July 2016		
09h00 - 10h30	Radiometry, apparent optical properties, measurements & uncertainties (1)	Agnieska Bialek
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Radiometry, apparent optical properties, measurements & uncertainties (2)	Agnieska Bialek
12h30 - 14h00	Lunch break	
14h00 - 15h00	Discussion session (ALL)	All
15h00 - 15h30	Satellite ocean color retrieval of phytoplankton functional types in the open ocean, part I	Julia Uitz
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Satellite ocean color retrieval of phytoplankton functional types in the open ocean, part II	Julia Uitz
Wednesday 27 July 2016		
09h00 - 10h30	Atmospheric corrections (1)	Cédric Jamet
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Atmospheric corrections (2)	Cédric Jamet
12h30 - 14h00	Lunch break	
14h00 - 15h30	OC remote sensing in tubid waters (1)	Kevin Ruddick & Quinten Van Hellemont
15h30 - 16h00	Coffee Break	
16h00 - 17h30	OC remote sensing in tubid waters (2)	Kevin Ruddick & Quinten Van Hellemont
GROUP DINNER 7pm		
Thursday 28 July 2016		
09h00 - 10h30	Practical: OC remote sensing in tubid waters	Kevin Ruddick & Quinten Van Hellemont
10h30 - 11h00	Coffee Break	
11h00 - 12h30	OCR & global biogeochemical modelling (1)	Stephanie Dutkiewicz
12h30 - 14h00	Lunch break	
14h00 - 15h30	Shallow-water remote sensing (1)	Heidi Dierssen
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Shallow-water remote sensing (2)	Heidi Dierssen
Friday 29 July 2016		
09h00 - 10h30	OCR & global biogeochemical modelling (2)	Stephanie Dutkiewicz
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Improved ocean ecosystem predictions through improved light calculations.	Curtis Mobley
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practicals: giovanni (1)	James Acker
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Practicals: giovanni (2)	James Acker
17h30 - 18h00	"Historical" tour of the Villefranche remote sensing lab: field instruments of the 1960s and 1970s	David Antoine
	CLOSURE - 3rd SUMMER LECTURE SERIES	

9 Appendix 4 - Lectures Synopses

9.1 James Acker: Adnet Inc., NASA Goddard Earth Sciences Data and Information Services Center, Greenbelt, Maryland 20771 USA

Syllabus for Giovanni Practicals – IOCCG Summer Lecture Series 2016

I. Introduction to Giovanni
   A. Short History
   B. What's Available (Data)
   C. Basic Operations (Maps, Time-Series, X-Y Scatter Plot, Animation, Hovmöller plots)

II. Example Problem 1
   A. Characterize the Peru Upwelling Zone
   B. Plot Maps
   C. Plot Time-Series
   D. Plot X-Y Scatter Plots

III. Review of Research (Selected Papers)

IV. Example Problem 2
   A. El Nino and La Nina in the Equatorial Pacific Upwelling Zone
   B. Plot Maps
   C. Plot Time-Series
   D. Discovery – what other data types (not just oceanographic) would be interesting to use?

V. Discovery Problem
   A. Students will use Giovanni collaboratively to investigate winter upwelling in the South China Sea. Goal: Characterize the differences in chlorophyll concentration and SST over the full seasonal cycle, determine when and where enhanced production occurs, and posit causes for the observed pattern. Utilize other data sets to investigate the posited causes.

9.2 Agnieszka Bialek: National Physical Laboratory, Teddington, UK

General Topic: Radiometry, apparent optical properties, measurements & uncertainties

The lectures will focus on SI – traceability in radiometric measurements, followed by a basis of uncertainty evaluation for them. Radiometry metrology, with examples of absolute radiometric calibration, will be presented and its application to apparent optical properties measurement.

Lecture 1: Introduction to traceable radiometric measurements
A concept of SI (International System of Units) and traceability chain for radiometric scales will be explained in the context of apparent optical properties measurements. Typical absolute radiometric calibration sources and measurements for irradiance and radiance will be discussed in more details. Few other significant instrument characteristic influencing the measurements in situ will be discussed.

Lecture 2: Induction to uncertainty evaluation
Definition of the basic terms and measurements uncertainty evaluation theory will be accompanied with an example of uncertainty evaluation for a conventional instrument. The aim here, is to clarify the terminology and provide a simple case of uncertainty propagation. The lecture will finish with introduction to Monte Carlo Method application for uncertainty evaluation.

References:
B. Carol Johnson, Howard Yoon, Joseph P. Rice and Albert C. Parr, *Principles of Optical Radiometry and Measurement Uncertainty*, In G. Zibordi et.al. (Ed) *Optical Radiometry for Ocean Climate Measurements*, Experimental Methods in the Physical Sciences, Volume 47, Academic Press, 2014 p 14-62
G. Zibordi and K.J. Voss, *In situ Optical Radiometry in the Visible and Near Infrared*, In G. Zibordi et.al. (Ed) *Optical Radiometry for Ocean Climate Measurements*, Experimental Methods in the Physical Sciences, Volume 47, Academic Press, 2014, p 248-295
BIPM, IEC, ISO IFCC, and IUPAP IUPAC, 2008, *Evaluation of measurement data - Guide to the expression of uncertainty in measurement* (GUM 1995 with minor corrections), JCGM 100: 2008, http://www.bipm.org/en/publications/guides/gum.html

BIPM, IEC, ISO IFCC, and IUPAP IUPAC, 2008, *Evaluation of measurement data – Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method*, JCGM 101:2008, http://www.bipm.org/en/publications/guides/gum.html

9.3 Hervé Claustre: Laboratoire d'Océanographie de Villefranche, Villefranche-sur-mer , FRANCE

General Topic: Complementarity of satellite ocean colour radiometry and *in situ* measurements: towards integrated observation systems.

This lecture will emphasize the complementarity between ocean color remote sensing and *in situ* data acquisition. In particular, it will highlight how new types of autonomous platforms (e.g., floats, gliders, instrumented mammals), which are dramatically increasing the spatio-temporal resolution of *in situ* measurements, nicely complement the satellite signal into the ocean interior. The lecture will address the strengths and limitations of both types of acquisition and will present on-going research to develop synergies between them toward the development of a global, three-dimensional view of key biogeochemical variables. These developments represent a prerequisite to progressively design and implement a future global integrated observation system for biogeochemistry and ecosystems.

Suggested reading:
IOCCG Report 11 (IOCCG 2011), Bio-Optical Sensors on Argo floats. Claustre, H. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 11, IOCCG, Dartmouth, Canada. http://www.ioccg.org/reports/IOCCG_Report11.pdf

Sauzede, R., H. Claustre, J. Uitz , C. Jamet, G. Dall'Olmo, F. D'Ortenzio, B. Gentili , A. Poteau and C. Schmechtig (2016). A neural network-based method for merging ocean color and Argo data to extend surface bio-optical properties to depth: Retrieval of the particulate backscattering coefficient. Journal of Geophysical Research, 121, doi:10.1002/2015JC011408. http://omtab.obs-vlfr.fr/fichiers_PDF/Sauzede_et_al_JGR_2016.pdf

9.4 Heidi Dierssen: Professor. Marine Sciences. University of Connecticut, CT, USA

General Topic: Remote sensing in shallow waters

Optically shallow water occurs when the spectral properties of the seafloor or "benthos" have a measurable influence on the remote sensing reflectance signal. For white sandy bottoms, the bottom serves to reflect a large fraction of visible photons in a backward direction and the sea surface reflectance can be enhanced across all visible wavelengths. For photosynthetically active benthos (seagrass, benthic algae, corals, etc..), photons are highly absorbed in certain wavelengths used for photosynthesis and highly scattered in others like the far red edge and the resulting sea surface spectral reflectance can appear darker or brighter depending on the wavelength. However, the measurable influence of benthic reflectance on the upwelling light field at the sea surface also depends on the optical

properties of the water column and the water depth. This is a coupled radiative transfer problem and methods to retrieve seafloor properties from remote sensing imagery must consider all three of these aspects: 1) benthic reflectance; 2) water column properties; and 3) water depth.
In the following lectures, I will be introducing you to the basic concepts involved in optically shallow remote sensing and providing some practical methods for how to retrieve and validate derived benthic products. Unfortunately, we won't be able to cover everything in detail, but the references below should provide much more information on these topics.

Lecture 1: What is benthic reflectance and how is it measured?

1. What is benthic reflectance? How does it vary for different benthic constituents?
2. How is it measured?
    - Underwater
        - Plaque method
        - Eu/Ed probe
    - Laboratory
        - Issues with air-water interface
        - Biofilms, etc..
    - Specular Reflection
    - Bi-directional Reflectance Distribution Function (BRDF)
3. Propagating Benthic R to sea surface
    - Influence of water column properties
    - Influence of water depth

Lecture 2: Retrieving benthic reflectance from remote sensing imagery from different platforms.

1. General Methods
    - Look-up tables
    - Inversion models
    - Enhancements to these approaches
2. Sensors requirements
    - What can be done with limited multi-channel sensors (Landsat, Worldview, etc..)?
    - What can be done with hyperspectral imagery?
        - airborne platforms
        - satellites (signal:noise issues)

3. Validation of imagery
    - Challenges and recommended approaches

References

Overview Papers

Dekker AG, Phinn SR, Anstee J, Bissett P, Brando VE, Casey B, Fearns P, Hedley J, Klonowski W, Lee ZP, others (2011) Intercomparison of shallow water bathymetry, hydro-optics, and benthos mapping techniques in Australian and Caribbean coastal environments. Limnol Ocean Methods 9:396–425

Hedley JD, Roelfsema CM, Chollett I, Harborne AR, Heron SF, Weeks S, Skirving WJ, Strong AE, Eakin CM, Christensen TR, others (2016) Remote sensing of coral reefs for monitoring and management: A review. Remote Sens 8:118

Other Selected Papers

Andrefouet S, Payri C, Hochberg EJ, Hu C, Atkinson MJ, Muller-Karger FE (2004) Use of in situ and airborne reflectance for scaling-up spectral discrimination of coral reef macroalgae from species to communities. Mar Ecol-Prog Ser 283:161

Dierssen HM, Zimmerman RC, Drake LA, Burdige DJ (2009) Potential export of unattached benthic macroalgae to the deep sea through wind-driven Langmuir circulation. Geophys Res Lett 36:L04602

Hedley J, Russell B, Randolph K, Dierssen H (2016) A physics-based method for the remote sensing of seagrasses. Remote Sens Environ 174:134–147

Hochberg EJ, Atkinson MJ, Andréfouët S (2003) Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. Remote Sens Environ 85:159–173

Mumby PJ, Skirving W, Strong AE, Hardy JT, LeDrew EF, Hochberg EJ, Stumpf RP, David LT (2004) Remote sensing

of coral reefs and their physical environment. Mar Pollut Bull 48:219–228
Dierssen HM, Zimmerman RC, Drake LA, Burdige DJ (2009) Potential export of unattached benthic macroalgae to the deep sea through wind-driven Langmuir circulation. Geophys Res Lett 36:L04602
Hedley J, Russell B, Randolph K, Dierssen H (2016) A physics-based method for the remote sensing of seagrasses. Remote Sens Environ 174:134–147
Hochberg EJ, Atkinson MJ, Andréfouėt S (2003) Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. Remote Sens Environ 85:159–173
Mumby PJ, Skirving W, Strong AE, Hardy JT, LeDrew EF, Hochberg EJ, Stumpf RP, David LT (2004) Remote sensing of coral reefs and their physical environment. Mar Pollut Bull 48:219–228

9.5 Stephanie Dutkiewicz: Principal Research Scientist, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA

General Topic: Ocean Colour and Biogeochemical/Ecosystem Models

The purpose of these lectures is to allow the students to feel comfortable with the concept of numerical modelling, provide them with an awareness of the types and availability of different numerical model outputs, and an understanding of how numerical models output may be able to aid them in their research. A variety of examples will in themselves be useful into understanding various optically interesting processes in the ocean, as well as climate change and trend analysis.

Lecture 1: Ocean Colour and Biogeochemical/Ecosystem Models (Thursday 28th July)
This lecture will highlight how numerical models can enhance the use of ocean colour products; models "filling in" for missing data, helping understand feature seen in ocean colour, and how the two tools can together help understand phenomena beyond what each one could individually accomplish. I will first provide a brief introduction to numerical models, and how ocean colour products are used to evaluate model output. We will consider the different types of models (e.g. regional, global, climate, data assimilation) and the uses/misuses of each, and include a short description of data assimilation methods and ocean colour relevant reanalysis products. The bulk of the lecture will emphasis the synergist use of models and ocean colour products, with examples from process studies, ecosystem monitoring, and climate change analysis.

References:

- Follows, M.J. and S. Dutkiewicz, 2011: Modeling diverse communities of marine microbes. *Annual Reviews of Marine Science*, 3, 427-451.
- Henson, S.A., J.L. Sarmiento, J.P. Dunne, L. Bopp, I. Lima, S.C. Doney, J. John, and C. Beaulieu (2010). Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences*, 7, 621-640, doi:10.5194/bg-7-621-2010.
- Gregg, W.W. (2008). Assimilation of SeaWiFS ocean chlorophyll data into a three-dimensional global ocean model. *Journal of Marine Systems*, 69, 205-225.

Lecture 2: **Better Linkages between Numerical Model Output and Optical/Ocean Colour Products** (Friday 29 July)

The base currency of most biogeochemical models is carbon. On the other hand, ocean optical measurements provide IOPs and ocean colour provides reflectance. How can we reconcile the mismatches between the outputs of these different tools for improving the study of the ocean ecosystems and biogeochemistry? There are great strides being made in determining phytoplankton functional types, diversity, and carbon pools in the ocean from ocean colour. We will first discuss how numerical models can use these newer datasets. This lecture will then highlight how recent advances in numerical models are linking more directly to ocean optics and ocean colour through explicitly including IOPS and/or radiative transfer models. We will see how these advances lead models to have increased datasets with which to evaluate (and potentially assimilate), can improve the model representation of ecosystems and ocean physics, and how such models can provide laboratories for exploring uncertainties in ocean colour products and algorithms, as well as ocean colour climate trends.

References:

Baird, M., N. Cherukuru, E. Jones et al. (2016). Remote-sensing reflectance and true colour produced by a coupled hydrodynamic, optical, sediment, biogeochemical model of the Great Barrier Reef, Australia: Comparison with satellite data. *Environmental Modelling and Software*, 78, 79-96

Dutkiewicz, S., A.E. Hickman, O. Jahn, W.W. Gregg, C.B. Mouw, and M.J. Follows (2015): Capturing optically important constituents and properties in a marine biogeochemical and ecosystem model. *Biogeoscience*, 12, 4447-4481 doi:10.5194/bg-12-4447-2015

Fujii, M., E. Boss, and F. Chai (2007): The value of adding optics to ecosystem models: a case study. *Biogeosciences* 4, 1585-1631.\

9.6 John Hedley: Director, Environmental Computer Science Ltd., UK

General Topic: The three dimensional light environment in coral reefs and seagrass ecosystems.

Radiative transfer modelling for shallow water remote sensing typically assumes the benthos can be treated as a flat homogenous reflecting surface. However many environments such as seagrasses or coral reefs are structurally complex, their reflectance when viewed from above includes contributions of vertical structure, shadows and inter-reflections. In addition, to properly understand the photobiology of these environments it is necessary to understand how the light at the bottom of the water column propagates into the benthic canopy to reach the photosynthetic tissues.

In this lecture we will develop an understanding of the three-dimensional light environment in shallow waters, and the factors that should be borne in mind when working on remote sensing or photobiology in these environments. The lecture will use results and visualisations from a three-dimensional radiative transfer model to illustrate the points made. The discussion is especially relevant to high spatial resolution remote sensing with pixels < 10 m (WorldView, Pleiades, Sentinel 2), and we will also consider sun-glint correction of this kind of imagery.

References

Hedley J. D. (2008) A three-dimensional radiative transfer model for shallow water environments. Optics Express 16: 21887-21902.

Kay S., Hedley J. D., Lavender S. (2009) Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths. Remote Sensing 1, 697-730.

Hedley J. D., McMahon K., Fearns P. (2014) Seagrass canopy photosynthetic response is a function of canopy density and light environment: A model for Amphibolis griffithi. PloS ONE 9(10): e111454.

Anthony K. R. N., Hoogenboom, M.O., Connolly S. R. (2005) Adaptive variation in coral geometry and the optimization of internal colony light climates. Functional Ecology 19: 17-26.

9.7 Cedric Jamet: MREN/ELICO, Wimereux, France

General Topic: Atmospheric correction of ocean color satellite images

This lecture aims at presenting the definition of the atmospheric correction and its current state and issues. The signal measured by the satellite sensor is the sum of several contributions, mainly from the atmosphere. But in ocean color, we are only interested in the light back-scattered by the ocean, which is related to the inherent optical properties of seawaters and biogeochemical parameters. So the goal of the atmospheric correction is to remove the atmospheric contribution to the signal measured by the satellite sensor. The definition of the different contributions will be provided and methods to remove the atmospheric contributions will be presented for the open and coastal waters.

1. Introduction: Brief History - What is atmospheric correction and why it's important
2. Radiometry and optical properties: Basic radiometric quantities, Apparent optical properties, Inherent Optical properties
3. Atmospheric correction: Definition of the equation, Definition of the different terms
4. Sun-glint correction
5. Whitecaps correction
6. Rayleigh correction
7. Aerosol correction: Optical properties of the atmosphere, Molecular absorption and scattering, Aerosol properties and models
8. Overview of various approaches: Open ocean waters, Coastal waters
9. Validation of atmospheric correction
10. Other issues: Absorbing aerosols, CDOM dominated waters, Adjacency effects

References
Bailey, S.W., & Werdell, P. J. (2006). A multi-sensor approach for the on-orbit validation of ocean color satellite data products. Remote Sensing of Environment, 102, 12–23.
Frouin, R., Schwindling, M., & Deschamps, P. -Y. (1996). Spectral reflectance of sea foam in the visible and near-infrared: In situ measurements and remote sensing implications. Journal of Geophysical Research, 101, 14361–14371.
Gordon, H. R., & Wang, M. (1994). Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preminilary algorithm. Applied Optics, 33, 443–452.
Gordon, H. R. (1997). Atmospheric correction of ocean color imagery in the Earth Observing system era. Journal of Geophysical Research, 102, 17081–17106.
IOCCG (2010). Atmospheric Correction for Remotely-Sensed Ocean-Colour Products. Wang, M. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 10, IOCCG, Dartmouth, Canada.
Van de Hulst, H. C. (1980), “Multiple Light Scattering,” Academic Press, New York, 739pp.

9.8 Zhongping Lee: University of Massachusetts Boston, Boston, USA

General Topic: Inherent Optical Properties, its inversion and applications

Lecture 1: IOPs of Ocean Waters, Fundamentals (Mon 18 July)

This lecture will cover the definition of the inherent optical properties (IOPs), which include absorption coefficient, scattering coefficient, and the volume scattering function. This lecture will also introduce and discuss the common/basic components of oceanic IOPs, such as pure (sea)water, phytoplankton, CDOM, sediments. It will cover their values and their ways of spectral variations.

References:
Pope and Fry, 1997, "Absorption spectrum ~380–700 nm of pure water. II. Integrating cavity measurements", Appl. Opt., Vol. 36.
Bricaud et al, 1995, "Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization", JGR, Vol. 100.
Stramski et al 2001, "Modeling the inherent optical properties of the ocean based on the detailed composition of the

planktonic community", Appl. Opt., Vol. 40.
Lee et al 2015, "Hyperspectral absorption coefficient of "pure" seawater in the range of 350–550 nm inverted from remote sensing reflectance", Appl. Opt., Vol. 54.

Lecture 2: Inversion of IOPs from Rrs (Tues 19 July)

Historically Rrs inversion was focused on chlorophyll. This lecture will introduce why it is also, if not more, important to invert IOPs from Rrs; and further introduce/discuss a few approaches commonly adopted by the community. It will focus on analytical or semi-analytical approaches, as those will require an understanding of the IOP-AOP relationships and bio-optical relationships. Hands-on practice with Excel will also be played during the lecture. **Students are required to install the Solver Add-in within Excel** (see https://support.office.com/en-us/article/Load-the-Solver-Add-in-612926fc-d53b-46b4-872c-e24772f078ca).

References:

Morel, 1980, "In-water and remote measurements of ocean color", Boundary-Layer Meteorology, Vol. 18, 177-201.
Lee et al 2002, " Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters", Appl. Opt., Vol. 41.
Wang et al., 2005, "Uncertainties of inherent optical properties obtained from semianalytical inversions of ocean color", Appl. Opt., Vol. 44.
Werdell et al., 2013, "Generalized ocean color inversion model for retrieving marine inherent optical properties", Appl. Opt., Vol. 52.

Lecture 3: Applications of IOPs (Tue 19 July).

This lecture introduces examples of IOPs applications in environmental and ocean biogeochemistry studies. This includes water quality monitoring, light field predictions, as well as estimation of primary production. In the past, many of such applications use remotely sensed chlorophyll concentration; here the reasons and potentially advantages of using IOPs are also discussed.

References:

Lee et al 1996, "Estimating primary production at depth from remote sensing", Appl. Opt., Vol. 35.
Arnone et al 2004, "Water mass classification", Oceanography, June 2004.
Craig, et al 2006, "Use of hyperspectral remote sensing reflectance for detection and assessment of the harmful alga, Karenia brevis", Appl. Opt., Vol. 45.
Cannizzaro et al "Detection of Karenia brevis blooms on the west Florida shelf using in situ backscattering and fluorescence data", Harmful Algae, Vol. 8, 898-909.
Shang et al., 2012 "Phytoplankton bloom during the northeast monsoon in the Luzon Strait bordering the Kuroshio", RSE, 124, 38-48.
Lee et al., 2015, "Secchi disk depth: A new theory and mechanistic model for underwater visibility", RSE, Vol. 169.**Curtiss Mobley:** Senior Scientist and Vice President for Science, Sequoia Scientific, Inc., WA , USA

9.9 Curtiss Mobley: Vice President for Science, Sequoia Scientific, Inc., WA , USA

General Topic: 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. The text *Light and Water* by Mobley also covers much of the material discussed in the lectures. This book will be distributed on CD, but it can also be downloaded from the references page of the Ocean Optics Web Book.

Mobley Lecture 1: Radiometry and AOPs (Tues 19 July)

The inherent optical properties (IOPs; previous lecture by Zhongping Lee) describe the absorbing and scattering properties of the water. Radiometric variables, namely the radiance and various irradiances, describe the light field within the water. Apparent optical properties (AOPs) give approximate descriptions of the water optical properties using easily measured (compared to IOPs) radiometric variables. This lecture first reviews the radiometric variables used in optical oceanography, ocean color remote sensing, and ocean ecosystem modeling. The most commonly used AOPs are then reviewed. These include reflectances (irradiance reflectance, remote-sensing reflectance), which are ratios of radiometric variables, and diffuse attenuation functions ("K functions"), which are normalized depth derivatives of radiometric variables.

References:
The level-one pages in the Light and Radiometry chapter of the Ocean Optics Web Book at
www.oceanopticsbook.info/view/light_and_radiometry
The pages on AOPs, reflectances, and K functions beginning at
www.oceanopticsbook.info/view/overview_of_optical_oceanography/apparent_optical_properties

Mobley Lecture 2: **Introduction to HydroLight** (Thurs 21 July)

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 current 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 (Mobley and Hedley): **Simple Simulations Using HydroLight** (Thurs 21 July).
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 5.3 Users' Guide and *HydroLight 5.3 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 (Mobley and Hedley): **Advanced Simulations Using HydroLight.** (Thurs 21 July).
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 Mobley and Hedley as needed.

Mobley Lecture 3: **Improved Ocean Ecosystem Predictions through Improved Light Calculations** (Monday 25 July).

This lecture first reviews 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.

References:

Mobley (2011). Fast light calculations for ocean ecosystem and inverse models. *Optics Express* 19(20), 18927-18944.

Mobley, Chai, Xiu, and Sundman (2015). Impact of improved light calculations on predicted phytoplankton growth and heating in an idealized upwelling-downwelling channel geometry. *J. Geophys. Res: Oceans* 120, doi:10.1002/2014JC010588.

9.10 Collin Roesler: Dept. of Earth and Oceanographic Science, Bowdoin College, Brunswick, Maine USA

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.

Lee, Z.P., 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.

Ciotti, A.M., J.J. Cullen, M.R. 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

Roesler, C.S., S.M. Etheridge, and G.C. Pitcher. 2003. Application of an ocean color algal taxa detection model to red tides in the Southern Benguela. In *Proceedings of the Xth International Conference on Harmful Algae*. Florida Fish and Wildlife Conservation Commission and Intergovernmental Oceanographic Commission of UNESCO, St. Petersburg, FL, USA.

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
Franz, B. A., and P.J. Werdell. 2010. A generalized framework for modeling of inherent optical properties in ocean remote sensing applications. *Proceedings of Ocean Optics, Anchorage, Alaska*, *27*.

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.
Yentsch, C.S., and D.A. Phinney. 1985. Spectral fluorescence: an ataxonomic tool for studying the structure of phytoplankton populations. *Journal of Plankton Research*, *7*(5): 617-632.
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.
MacIntyre, H.L., E. Lawrenz, and T.L. Richardson. 2010. Taxonomic discrimination of phytoplankton by spectral fluorescence. In *Chlorophyll a fluorescence in aquatic sciences: methods and applications* (pp. 129-169). Springer Netherlands.
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.

9.11 Kevin Ruddick: Royal Belgian Institute of Natural Sciences (RBINS), Belgium

General Topic: 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).
- ACOLITE atmospheric correction software for Landsat-8 and Sentinel-2. This program uses an IDL run-time license that is bundled (self-installs for free). Software and documentation can be found at: https://odnature.naturalsciences.be/remsem/software-and-data/acolite. If there are installation questions they can be posted on the ACOLITE forum or we can fix them on arrival.

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

9.12 Dariusz Stramski: Professor of Oceanography, Scripps Institution of Oceanography, University of California San Diego

General Topics: Fundamentals of Light-Matter Interactions and Optics of Marine Particles

This series of three lectures will provide an overview of fundamentals in the following topical areas:

(1) The nature of light and fundamentals of light-matter interactions: characteristics of electromagnetic radiation (dual wave-particle nature, energy, speed, frequency, wavelength, polarization), mechanisms of emission, absorption, and scattering of electromagnetic radiation;
(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 (Monday July 18): Topics 1 through 4

Comprehensive references:

Johnsen, S. 2012. *The Optics of Life, A Biologist's Guide to Light in Nature*. Princeton University Press.

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.2

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.

Lectures 3 & 4 (Wednesday July 20): 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.

9.13 Julia Uitz: Laboratoire d'Océanographie de Villefranche (LOV), France

General Topic: Satellite ocean color retrieval of phytoplankton functional types in the open ocean

Synopsis

The last decades have seen major advances in the satellite remote sensing of biogeochemical products beyond chlorophyll concentration. Among those products, phytoplankton community composition has received strong interest because of its critical role in biogeochemical cycling, carbon fluxes in particular. This lecture will seek to give an overview of existing approaches to retrieving phytoplankton functional types (PFTs) from satellite ocean color observations and, importantly, to provide insights into the strengths and weaknesses of these approaches. We will also discuss needs and opportunities for future research in PFT algorithms.

Suggested readings

IOCCG Working Group (2014). Report Number 15, Phytoplankton Functional Types from Space, Edited by S.

Sathyendranath. http://www.ioccg.org/reports/IOCCG_Report_15_2014.pdf.

Nair A., S. Sathyendranath, T. Platt, J. Morales. V. Stuart, M.-H. Forget, E. Devred, H. Bouman (2008). Remote sensing of phytoplankton functional types. Remote Sensing of Environment, 112(8), 3366-3375. http://dx.doi.org/10.1016/j.rse.2008.01.021.

More references available on demand (julia.uitz@obs-vlfr.fr).

9.14 Prof. Mike Twardowski: Harbor Branch Oceanographic Institute, Ft. Pierce, Florida, USA

General Topic: Ocean Scattering

These lectures will provide more detail on the Inherent Optical Property of Scattering, ranging from theory, to measurement and closure, to interpretation in terms of ocean biogeochemistry. Background material for the lectures can be found in section 3.8 of Mobley (1994) *Light and Water*, and in Ch. 4 of Kirk (1994) *Light and Photosynthesis in Aquatic Ecosystems.*

Lecture 1: Scattering background

Theory, definitions, and sources of scattering in water will be reviewed in this lecture. Angular, spectral, and polarization properties of scattering will be discussed. A detailed examination of aspects involved in measuring scattering will be provided, including technological considerations.

Lecture 2: Interpretation of scattering

Distributions, variability, and closure for scattering properties will be discussed. State-of-the-art knowledge in the volume scattering function and the relation of scattering to ocean biogeochemical properties will be presented. Various applications for scattering will be briefly touched on, including passive and active remote sensing, particle field characterization, and imaging. The lecture will conclude with a discussion of current issues and gaps in our understanding of ocean scattering.

References:

Stramski, D., and Kiefer, D. A. 1991. Light scattering by microorganisms in the open ocean. *Progress in Oceanography*, 28, 343–383.

Stramski, D. E. Boss, D. Bogucki, and K. Voss. 2004. The role of seawater constituents in light backscattering in the ocean. *Progress in Oceanography*, 61:27–56.

Sullivan, J., M. Twardowski, J.R.V. Zaneveld, and C. Moore. 2013. Measuring optical backscattering in water, *In*: A. Kokhanovsky (Ed), *Light Scattering Reviews 7: Radiative Transfer and Optical Properties of Atmosphere and Underlying Surface*, Springer Praxis Books, DOI 10.1007/978-3-642-21907-8_6, pp. 189-224.

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in Case I and Case II waters. *Journal of Geophysical Research*, 106(C7):14,129-14,142.

Twardowski, M.S., H. Claustre, S.A. Freeman, D. Stramski, and Y. Huot. 2007. Optical backscattering properties of the "clearest" natural waters. *Biogeosciences*, 4, 1041–1058, www.biogeosciences.net/4/1041/2007/.

Twardowski, M., X. Zhang, S. Vagle, J. Sullivan, S. Freeman, H. Czerski, Y. You, L. Bi, and G. Kattawar. 2012. The optical volume scattering function in a surf zone inverted to derive sediment and bubble particle subpopulations, *Journal of Geophysical*

9.15 Emmanuel Boss: University of Maine, School of Marine Sciences, ME, USA

General Topic: Practical: AC-lab

Teachable Optics

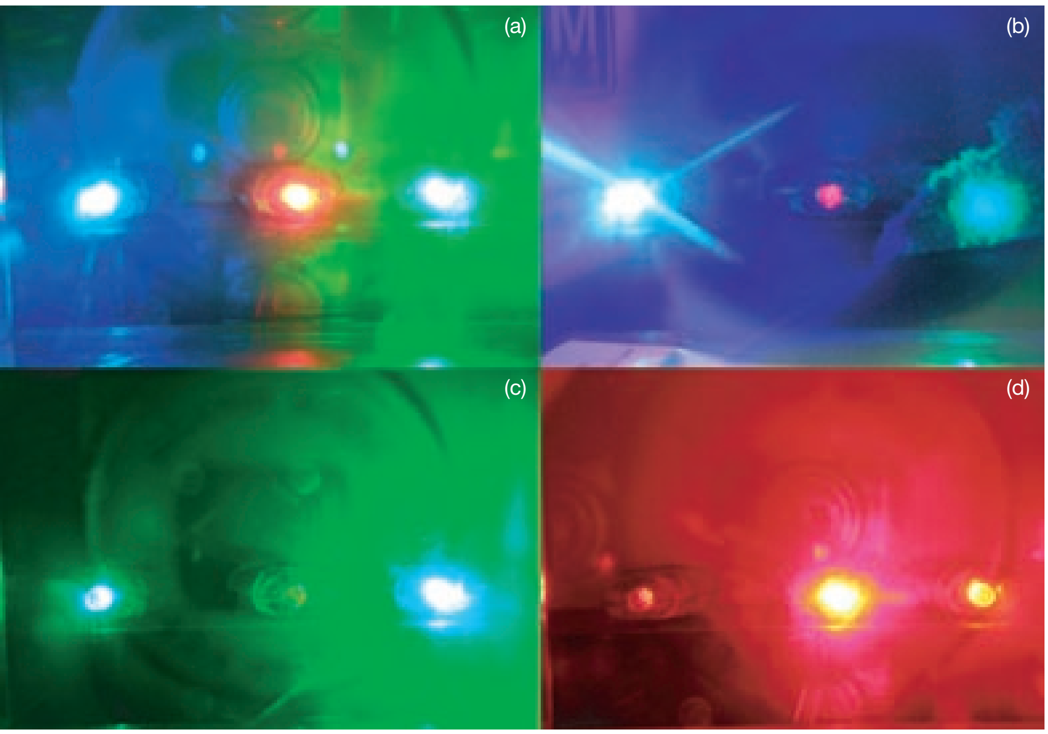
[Absorption, Scattering and the Color of the Ocean]

Emmanuel Boss

As an optical oceanographer, I study the interaction of light with ocean water to learn more about materials in the water column. Throughout my career, I have had the opportunity to teach the principles of optics to students at many levels, spanning from kindergarteners to graduate students. I would like to share a series of simple activities that I have used with all levels of learners to introduce the concepts of absorption and scattering and how they affect our perception of the environment.

[What You'll Need]

- ✓ 3 colored LEDs (e.g., light-up key chains from a hardware store)
- ✓ 1 laser pointer
- ✓ 4 clear plastic glasses
- ✓ Food coloring – 3 colors
- ✓ Maalox (or milk)
- ✓ Colored paper
- ✓ Printout of a "true color" satellite ocean color image (see, for example, images and resources at: http://oceancolor.gsfc.nasa.gov/SeaWiFS/TEACHERS/).



[Light by three LEDs (blue, red and green) shone through a clear plastic vessel including (a) water, (b) water with several drops of blue food coloring, (c) water with several drops of green food coloring and (d) water with several drops of red food coloring. Notice how the transmission of light is modulated by the color of the medium. The color observed matches the wavelengths that are preferentially transmitted (i.e., least absorbed).]

Demonstrations: What determines the color we observe?

>> Ask students to observe a piece of colored paper and ask them what color it is.

Shine the three LEDs on the paper and ask them again what color they see. Then ask students about the color of the walls in their rooms at home and how it changes when the light is turned off at night.

[CONCLUSION] The color we perceive depends on the color of the illumination as well as the properties of the material observed (in this case, paper).

>> Fill four clear plastic glasses with water. Place several drops of different shades of food coloring (blue, green, red) into three of them and mix.

Shine the three colored LEDs through the glass with no color and ask the students if they can see all of them. Once they do, ask them which color LED will transmit best through the glass with the red food coloring (answer: the red).

Do the same with the other colors. (See figure at left.)

[CONCLUSION] The color we perceive depends on the properties of the medium. In particular, the color we observe is that which is not absorbed by the medium.

>> Next, shine a laser pointer at the wall or ceiling.

Ask the students if they can observe the beam (answer: no). Can they spot the place where the beam hits the wall? How

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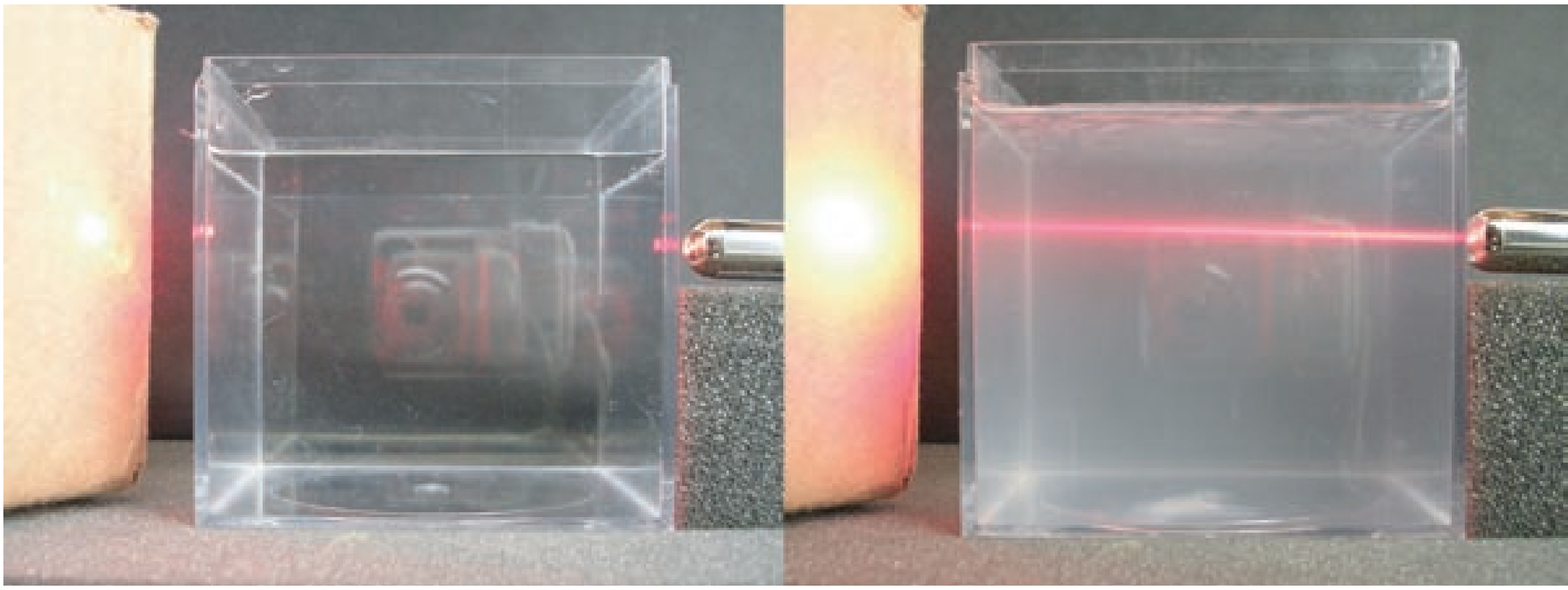

Laser pointer shone through a clear plastic vessel including (a) water and (b) water with several drops of Maalox. The beam is not observed in clear water due to little redirection of photons to our eyes while it is well observed when the water is turbid.

do their observations comport with what they see in science fiction movies, where bright beams often emanate from ray guns or UFOs (answer: movies are not always faithful to reality).

>> Now shine the laser through water (a long aquarium is best).

Can the students observe the beam? (They should not, unless the water is turbid or has many bubbles, or the laser is intense enough that molecular scattering is observable.) Add a few drops of Maalox to the water and mix. Can they observe the beam now? (Answer: yes, see figure above.)

[CONCLUSION] The light we perceive depends on the properties of the medium. In particular, the intensity depends on the scattering of light by the medium.

>> Add a few drops of Maalox to the colored water used earlier.

How does the color change? (Answer: it becomes more intense.)

>> In a clear glass of water, mix all the colors of food coloring.

What is the color observed? (Answer: black.) What does it mean? (Answer: No light is coming out of the cup; all the light ends up within it.) Now add Maalox. How does the color change? (Answer: it lightens up and looks brown, like adding milk into coffee.)

[CONCLUSION] The light and color we perceive depends on the properties of the medium. When we add milk to coffee, we don't change its color (spectra) but rather the amount of light coming back from the glass to our eyes.

Both scattering and absorption can affect color. Scattering by particles much larger then the wavelength affects the intensity of the scattered light but not its color (as demonstrated in the experiment with the Maalox). However, when scattering occurs from particles much smaller than light, it leads to changes in the color of the scattered light compared to the incident light. An example is the color of the sky; because scattering of light by small particles is inversely dependent on wavelength (it decreases as the inverse fourth power of wavelength), short-wavelength blue photons are scattered with higher probability than the longer wavelength red ones. Thus we observe a blue sky.

>> Show participants "true color" images of the ocean taken from satellites such as NASA's SeaWIFS.

Discuss the colors observed (green near the coast and at the equator, blue in the middle of the subtropical gyres). What may cause the variations in color? (Answer: tiny micron-sized algae called phytoplankton absorb blue and red photons near the coasts and equatorial zones, leaving only green photons to scatter back.)

Following these demonstrations, let the students experiment on their own with water, colors and light sources. They are likely to discover some phenomena you did not have time to discuss—for example, total internal reflection at the boundary between water and air, Snell's law, etc.

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[References and Resources]

>> For other hands-on demonstrations in the geosciences, take a look at Zbigniew Sorbjan's book, *Hands-on Meteorology: Stories, Theories, and Simple Experiments* (published in 1996 by the American Meteorological Society).