4th IOCCG Summer Lecture Series
"Frontiers in Ocean Optics and Ocean Colour Science"

Villefranche-sur-Mer, France, 25th June –6th July 2018

http://ioccg.org/what-we-do/training-and-education/ioccg-sls-2018/

In addition to recurrent support from all IOCCG contributing agencies, specific additional contributions are acknowledged for the 2018 edition, from the following agencies and institutions:

IOCCG
International Ocean-Colour Coordinating Group

Table of contents

1 Introduction

The Institut de la Mer de Villefranche (IMEV[1]) and the Laboratoire d'Océanographie de Villefranche (LOV), located in Villefranche-sur-Mer, France, hosted the fourth edition of the International Ocean Colour Coordinating Group (IOCCG) Summer Lecture Series (SLS).

The IOCCG-SLS is dedicated to high-level training in the fundamentals of ocean optics, bio-optics and ocean colour remote sensing.[2]

This was a 2-week intensive course, delivered by 13 renowned lecturers on cutting edge research. *(See Appendix 1: List of teaching staff*). The main objective was to focus on current critical issues in ocean colour science.

22 students from 13 different countries were selected from a total of 132 applications (*see Appendix 2: List of Selected Students*).

The selection of candidates was based on their motivation letter, knowledge of remote sensing, current area of research, previous training opportunities, and potential to apply the knowledge and skills that they would gain with the SLS to their future research and/or teaching.

The majority of the trainees were PhD students and post-docs, and also early career researchers wanting to gain more experience in the field of ocean colour. The participants came from a broad range of backgrounds, but were all familiar with at least some domains of bio-optics and ocean colour science and had a solid understanding of ocean colour remote sensing.

2 Course Organization

The first week of the SLS was dedicated to fundamentals in optics, bio-optics and ocean colour science, and also included hands-on practical sessions, in order to make sure that all students would be capable of benefiting from the second week of lectures, which was on different aspects of ocean colour remote sensing, inversion techniques, and applications (*see programme in Appendix 3 and lecture synopses in Appendix 4*).

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.

At the beginning of the SLS, the IMEV Director, Anne Corval, gave a welcoming address. Then the course coordinator, David Antoine, presented a summary of IOCCG activities and a review of the course organization. The students followed by each introducing themselves with a brief presentation on their current area of research.

This was an opportunity to get acquainted with the participants' academic backgrounds, their current positions and their activities and experience.

Then the programme unfolded as described in *Appendix 3*.

As was done for the first three editions, all lectures were audio and video recorded. They are available at: http://ioccg.org/what-we-do/training-and-education/ioccg-sls-2018/ or directly from:

http://video.upmc.fr/liste_films_collec.php?collec=S_IOCCG_2018

[1] Formerly known as the "Observatoire Océanologique de Villefranche", OOV
[2] http://ioccg.org/what-we-do/training-and-education/ioccg-sls-2018/

Students at work during the AC-lab practicals (left) and during the Copernicus practical in the conference room (right)

Lectures’ slots included time for interactions between the students and lecturers. Most of the lecturers attended their colleagues’ lectures. 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 answers to their questions. The social events (welcome cocktail and dinner) were additional opportunities of interactions among lecturers and students.

The Saturday afternoon and Sunday at the end of the first week was free time for students, so they had an opportunity to visit Villefranche and its surroundings.

Group picture (students and lecturers) taken in front of the Villefranche laboratory.

Students visiting Monaco…. *… and the "Lazaret" cave and museum in Nice*

3 Course Evaluation

A feedback/evaluation form was distributed to all students at the end of the lecture series. The forms were returned within the two weeks following the end of the SLS. They have been handed over to the IOCCG executive committee.

This is an opportunity for students to share their views on various aspects of the lecturers' performance and on practical aspects of the course organization. It is also an opportunity for organisers to improve what may need to be improved for subsequent editions.

From this feedback received so far, it looks like the IOCCG SLS2018 was well received by all students and lecturers, and the event was a great success.

4 Some reflexions after having carried out four IOCCG SLS

The IOCCG SLS2018 was the 4th edition, the first one having been held in 2012.

Things that have improved since the first edition:

- The flow of lectures along the two weeks of the SLS is now much better organised, with a logical succession of topics.

Things that stayed unchanged:

- Always hosted at IMEV/LOV since the first edition
- Practical organisation and student accommodation was essentially the same for the 4 editions

Things to consider for improvements for future editions:

- Gender balance for lecturers
- Time for discussion. Maybe we still need to include a few more "empty" slots for this. The effective way to do this, however, is generally to ask students to do a bit of homework and to report on it, so that the discussion is concrete enough. Otherwise, non-specific discussion sessions very often fall short.
- Student accommodation: Contrary to expectation, the new building dedicated to students and visitors' accommodation was not ready for use by the SLS in July 2018. The building is now

completed and the inauguration was held, so it will now definitely be available for the SLS 2020, if this 5th edition indeed is organised in Villefranche.

- Procurement of instruments for the practicals: it has always proven difficult to procure enough instruments for the hands-on sessions (the Villefranche lab no longer has the appropriate instruments for this). We wonder whether a specific loan agreement with a manufacturer could be put in place for future editions, under the auspices of the IOCCG.
- Interaction with LOV staff: there is a need to have more LOV researchers giving lectures. A general presentation about the research carried out at LOV could also be delivered in the introductory session in future training courses.

More generally, the “bicolour” aspect of the SLS, which covers both marine optics/bio-optics and satellite ocean colour science, might be an issue for some students who have an interest in either of these domains but not in both. Discussions have been on going about splitting the SLS into two successive sessions, with different groups of students. No easy practical way of doing this has been found while keeping the budget at a reasonable level and the burden on the volunteer lecturers..

5 Acknowledgments

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 2018 Summer Lecture Series was sponsored and organised by the IOCCG with additional specific financial support from the following institutions and agencies:

- CNES (Centre National d’Etudes Spatiales, France)
- EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)
- GIS-COOC (French *Groupement d’intérêt scientifique couleur de l’océan*)
- IMEV (Institut de la Mer, de Villefranche)
- LOV (Laboratoire d’Océanographie de Villefranche)
- NOAA (National Oceanic and Atmospheric Administration, USA)
- OCB (Ocean Carbon & Biogeochemistry Program, USA)
- SCOR (Scientific Committee on Oceanic Research)

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

- Venetia Stuart, IOCCG executive scientist, for the overall organisation and budget preparation
- Elisabeth Gross, Scientific Committee for Oceanic Research (SCOR), for management of applications and help in selecting students
- The IOCCG committee for help in selecting students (http://www.ioccg.org/about/members.html)
- Anne Corval, Director, IMEV, for hosting the SLS2018 at the Villefranche observatory
- Antoine Sciandra, Director, LOV, for the support of LOV
- Charlotte Thomin, for all aspects of logistical assistance on site
- Corinne Poutier, LOV secretariat, for management of financial support to students
- Véronique Gourbaud, management of IMEV accommodation for students
- The staff of the IMEV restaurant and the staff in charge the IMEV accommodation and housekeeping

- The IMEV IT team
- La Trinquette's team, thanks for the dinner

6 Appendix 1 - List of teaching staff

- David Antoine (Curtin University, Perth, Australia) – **Course Coordinator**
- Emmanuel Boss (University of Maine, USA)
- Zhongping Lee (University of Massachusetts at Boston, MA, USA)
- Kevin Ruddick (Royal Belgian Institute of Natural Sciences, Belgium)
- Dariusz Stramski (Scripps Institution of Oceanography, USA)
- John Hedley (Environmental Computer Science Ltd, Tiverton, Devon, UK)
- Jeffrey Polovina (NOAA Fisheries, Honolulu)
- Matt Slivkoff (Curtin University, Perth)
- Mike Twardowski (Harbor Branch Oceanographic Institute, Florida Atlantic University, USA)
- Hayley Evers-King (Plymouth Marine Laboratory, UK)
- Quinten Vanhellemont (Royal Belgian Institute of Natural Sciences, Belgium)
- Griet Neukermans (Laboratoire d'Océanographie de Villefranche, France)
- Louis Legendre (Professor Emeritus UPMC, Laboratoire d'Océanographie de Villefranche, France)

7 Appendix 2 - List of Selected Students

- Christiana Ade – University of California at Merced, USA
- Falilu Adekunbi – University of Lagos, Nigeria
- Derya Akkaynak – Princeton University, United States, and University of Haifa, Israel
- Ave Ansper – Tartu Observatory, Estonia
- Katarzyna Draganska-Deja – Institute of Oceanology of the Polish Academy of Science, Poland
- Frieda Geldenhuys – Council for Scientific and Industrial Research (CSIR), South Africa
- Maria Fernanda Giannini – University of Victoria, Canada
- Hanna Kauko – Norwegian Polar Institute, Norway
- Srinivas Kolluru – Indian Institute of Technology Bombay, India
- Héloïse Lavigne – Royal Belgium Institute of Natural Sciences (RBINS), Belgium
- Juan Li – Takuvik, Université Laval, Canada
- Jing Li – Nanjing Institute of Geography and Limnology, Chinese Academy of Science, China
- Raisha Lovindeer – University of California, Irvine, United States
- Thais Medeiros – CSIRO, Australia and Federal University of Rio de Janeiro, Brazil
- Guillaume Morin – Institut de la Mer de Villefranche, France,
- Vasileios Pefanis – Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany
- Sornsiri Phongphattarawat – University of Oxford, United Kingdom
- Geneviève Potvin – Université de Sherbrooke, Canada
- Stephen Sagar – Geoscience Australia, Australia
- Louis Terrats – Institut de la Mer de Villefranche – Marine optics group, France
- Xiaohui Zhu – Boston University, United States

8 Appendix 3 - Course Schedule

Fourth IOCCG Summer Lecture Series 25 June -7 July 2018, Observatoire Océanologique de Villefranche-sur-Mer, France WEEK #1		
Date	**Subject**	**Lecturers**
Sunday 24 June 2018	Participants arrive in Villefranche-sur-Mer	
Monday 25 June 2018		
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	Ocean research in Villefranche: An amazing (hi)story	Louis Legendre
Tuesday 26 June 2018		
09h00 - 10h30	IOPs of ocean waters, fundamentals	ZhongPing Lee
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Radiometry and apparent optical properties (AOPs), fundamentals	David Antoine
12h30 - 14h00	Lunch break	
14h00 - 15h30	inversion of inherent optical properties (IOPs) from remote sensing	ZhongPing Lee
15h30 - 16h00	Coffee Break	
16h00 - 17h30	IOP applications	ZhongPing Lee
WELCOME DRINK 6pm (tentative, to be confirmed)		
Wednesday 27 June 2018		
09h00 - 10h30	Practical: AC-lab (1/4)	Mike Twardowski / Matt Slivkoff
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: AC-lab (2/4)	Mike Twardowski / Matt Slivkoff
12h30 - 14h00	Lunch break	
14h00 - 15h30	Science and applications of Secchi disk depth	ZhongPing Lee
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Optics of marine particles (1/2)	Dariusz Stramski

IOCCG

International Ocean-Colour Coordinating Group

Thursday 28 June 2018		
09h00 - 10h30	Optics of marine particles (2/2)	Dariusz Stramski
10h30 - 11h00	Coffee Break	
11h00 - 12h30	introduction to Hydrolight	John Hedley
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical Session - HydroLight Lab	John Hedley
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Scientific Research and Discovery: Process, Consequences and Practice	Louis Legendre
Friday 29 June 2018		
09h00 - 10h30	Ocean Scattering (1/2)	Mike Twardowski
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Ocean Scattering (2/2)	Mike Twardowski
12h30 - 13h45	Lunch break	
13h45 - 15h45	Practical: AC-lab (3/4)	Mike Twardowski / Matt Slivkoff
15h45 - 16h00	Coffee Break	
16h00 - 17h30	Free time	
Saturday 30 June 2018		
09h00 - 10h30	Past, present and future of satellite OCR	David Antoine
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: AC-lab (4/4)	Mike Twardowski / Matt Slivkoff
12h30 - 14h00	Lunch break	
Afternoon	FREE	
Sunday 1 July 2018		
FREE		

IOCCG

International Ocean-Colour Coordinating Group

Fourth IOCCG Summer Lecture Series
25 June -7 July 2018, Observatoire Océanologique de Villefranche-sur-Mer, France
WEEK #2

Date	Subject	Lecturers
Monday 2 July 2018		
09h00 - 10h30	Practical: playing with light	Emmanuel Boss, Matt Slivkoff
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Shallow water remote sensing	John Hedley
12h30 - 14h00	Lunch break	
14h00 - 15h30	The three dimensional light environment in coral reefs and seagrass ecosystems	John Hedley
15h30 - 16h00	Coffee Break	
16h00 - 17h30	From IOPs to BGC qantities (1/2)	Emmanuel Boss
Tuesday 3 July 2018		
09h00 - 10h30	From IOPs to BGC qantities (2/2)	Emmanuel Boss
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Radiometry, apparent optical properties, measurements & uncertainties	Matt Slivkoff
12h30 - 14h00	Lunch break	
14h00 - 15h00	How to be part of our scientific community?	Emmanuel Boss
15h00 - 15h30	Discussion session (ALL)	All
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Ocean color in support of fisheries and protected species research	Jeffrey Polovina
Wednesday 4 July 2018		
09h00 - 10h30	Atmospheric corrections (1/2)	David Antoine
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Atmospheric corrections (2/2)	David Antoine
12h30 - 14h00	Lunch break	
14h00 - 15h30	OC remote sensing in tubid waters (1/2)	Kevin Ruddick & Quinten Van Hellemont
15h30 - 16h00	Coffee Break	
16h00 - 17h30	OC remote sensing in tubid waters (2/2)	Kevin Ruddick & Quinten Van Hellemont
GROUP DINNER 7pm		

IOCCG
International Ocean-Colour Coordinating Group

Thursday 5 July 2018		
09h00 - 10h30	Practical: OC remote sensing in tubid waters	Kevin Ruddick & Quinten Van Hellemont
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Coccolithophores: optical properties and biogeochemistry	Griet Neukermans
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical on Copernicus datasets	Hayley Evers-King
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Practical on Copernicus datasets	Hayley Evers-King
Friday 6 July 2018		
09h00 - 10h30	Students present their work from the practicals	Kevin Ruddick, Quinten Van Hellemont and Hayley Evers-King
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Students present their work from the practicals	Kevin Ruddick, Quinten Van Hellemont and Hayley Evers-King
12h30 - 14h00	Lunch break	
14h00 - 15h30	Harmful Algal Blooms: Challenges and opportunities for remote sensing (1/2)	Hayley Evers-King
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Harmful Algal Blooms: Challenges and opportunities for remote sensing (2/2)	Hayley Evers-King
17h30 - 18h00	Closure, concluding remarks	David Antoine
	CLOSURE - 4th SUMMER LECTURE SERIES	

9 Appendix 4 - Lectures Synopses (lecturers alphabetic order)

9.1 David Antoine - Curtin University, Perth, Australia

Lecture 1 :"Radiometry and apparent optical properties (AOPs), fundamentals", Tuesday 26th June, 11am.
Topics covered:
The "inherent optical properties" (IOPs) will have been defined by Zhongping Lee's lecture just before this one.
Here we will define the radiometric quantities, namely the radiance and various irradiances, which describe the light field within the water, and from which the "Apparent optical properties" (AOPs) can be derived (reflectances, diffuse attenuation coefficients etc..).
This lecture will review the radiometric variables and most commonly used AOPs in optical oceanography and ocean colour remote sensing, how they relate to the IOPs and will also illustrate how they vary in the natural environment and how we measure them.
More details on the measurement of these radiometric quantities and the associated protocols and measurement uncertainties will be covered by Matt Slivkoff's lecture on 3rd July, 11am.

Suggested readings:
-Essentially everything can be found 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
-And obviously, if you have more appetite: Mobley CD, 1994. Light and Water: Radiative Transfer in Natural Waters, Academic press.
Also:
-Morel, A. and R.C. Smith (1982) Terminology and units in optical oceanography, Marine Geodesy, 5, 335-349.
-Remote Sensing of Coastal Aquatic Environments, Technologies, Techniques and Applications. Editors: Miller, Richard L., Del Castillo, Carlos E., McKee, Brent A. (Eds). Kluwer Publishing.
A number of chapters in this book are relevant here

Lecture 2 : "Past, present and future of satellite OCR"
Friday 29 th June, 1:45pm.
Topics covered:
This lecture will:
- Remind some basics about how ocean colour sensors work.
- Give a historical review of the steps taken towards developing the present day capability, and what the future of passive Ocean Colour Radiometry is made of
- Present complementary solutions to low-Earth orbit passive OCR that have already started to be developed, including sensors on geostationary orbits, polarimeters, and satellite-borne Lidars, and give an overview of the scientific and technical challenges behind developing these new capabilities
Suggested readings:
- Acker J., 2015, "The color of the atmosphere with the ocean below: a history of NASA's ocean color missions". CreateSpace Independent Publishing Platform, USA ©2015, ISBN:1507699220 9781507699225
- Loisel H, L. Duforet, D. Dessailly, M. Chami, and P. Dubuisson, 2008. Investigation of the variations in the water leaving polarized reflectance from the POLDER satellite data over two biogeochemical contrasted

oceanic areas," Opt. Express 16(17), 12905–12918.
- Hostetler, CA, et al., 2018. Spaceborne Lidar in the Study of Marine Systems. Annu. Rev. Mar. Sci. 2018. 10:121–47. https://doi.org/10.1146/annurev-marine-121916-063335
- Choi, JK, et al., 2012, GOCI, the world's first geostationary ocean color observation satellite, for the monitoring of temporal variability in coastal water turbidity, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C09004, doi:10.1029/2012JC008046
- IOCCG (2012). Ocean-Colour Observations from a Geostationary Orbit. Antoine, D. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 12, IOCCG, Dartmouth, Canada.

Lecture 3 :"Atmospheric corrections, 1/2"
Wednesday 4 th July, 9am and 11am.
Topics covered:
As far as satellite ocean colour is concerned "Atmospheric correction" refers to the process by which most of the recorded signal (~90-95%) has to be estimated before being subtracted so as to access to the remaining part (5-10%), which is the marine signal of interest. The quality (accuracy) of this process is therefore crucial for successful retrieval of the marine reflectances, hence of any product derived from these reflectances.
The lecture will address:
- The accuracy requirements for atmospheric correction of satellite OCR. What an algorithm has to achieve to be qualified for OCR atmospheric correction?
- What the total signal measured by the sensor is made of, and how the various contributions vary spectrally
- Some basic principles of OCR atmospheric corrections
- How OCR atmospheric correction can be performed under simplified assumptions in a number of situations
- How most modern OCR atmospheric correction schemes work
- Alternative approaches to the "aerosol-model-based" schemes
- Under which conditions modern OCR atmospheric correction schemes still fail
- Current issues (turbid waters, absorbing aerosols, high spatial resolution sensors)
Suggested readings:
- Gordon, H. R. (1997), Atmospheric correction of ocean color imagery in the Earth observing system era, J. Geophys. Res., 102, 17081-17106.
- Antoine, D. and A. Morel (1999), A multiple scattering algorithm for atmospheric correction of remotely-sensed ocean colour (MERIS instrument) : principle and implementation for atmospheres carrying various aerosols including absorbing ones, Int. J. Remote Sensing, 20, 1875-1916.
- 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.
- IOCCG (2012). Mission Requirements for Future Ocean-Colour Sensors. McClain, C. R. and Meister, G. (eds.), Reports of the International Ocean-Colour Coordinating Group, No. 13, IOCCG, Dartmouth, Canada.

9.2 Emmanuel Boss - University of Maine, USA

Practical: playing with light

In this hands-on lab we will remind ourselves about properties of light when encountering matter (reflection, refraction, diffraction, absorption, fluorescence) and encounter some components used in our instrumentation (lenses, polarizers, diffraction grating). Students will divide into small groups and will migrate through the stations where written material will provide guiding questions will provide instruction and provide the relevance of the station in our science. Faculty will be on hand to discuss material further.

A great book on the subject:
Clouds in a glass of beer, by Craig F. Bohren, Dover, 2001

From IOPs to BGC quantities (2 lectures)

While many of us are excited about measurements of IOPs to predict the sub-surface light-field a larger group is interested in using IOPs as proxies for bio-geochemical quantities. In these two lectures, I will survey the applications spanning from dissolved to particulate materials and from phytoplankton to sediments. I will cover proxies of 'extensive' variables (e.g. concentrations of particulate and dissolved substances) as well as 'intensive' variables (composition, size, packaging (aggregation) and shape). Using examples from a variety of papers I will show the richness of applications as well as the limitation of using IOPs as proxies. I will present work that is still controversial to showcase to the students how much more is left to be done!

There are way too many papers on the subject and I cannot do justice to all…

How to be part of our scientific community?

In this lecture I will present and then open a discussion among students and faculty about aspects of science we seldom discuss with students, those that are associated with our relationships within our community. I recently wrote a short paper about it and I recommend the students read it before the lecture.

Boss, E. 2018. Advice for young scientists on fruitful membership in the scientific community. Oceanography 31(2), https://doi.org/10.5670/ oceanog.2018.203.
Can be downloaded also from: https://tos.org/oceanography/assets/docs/31-2_boss2.pdf or http://misclab.umeoce.maine.edu/documents/Boss2018.pdf)

9.3 Hayley Evers-King – Plymouth Marine Laboratory, UK

1. Accessing and working with Copernicus Marine data

Lecture and practical content:

This session will provide an overview of the marine data available from Copernicus, with a particular focus on Sentinel 3 and OLCI. Resources for user support will be discussed. During the practical session, participants will be provided with a variety of programming tools to support their use of this data in python and SNAP. There will also be opportunity to discuss the use of this data in their own research workflows.

Recommended reading/software to install:

SNAP
The European Space Agency (ESA) have developed a series of toolboxes for working with data from the Sentinel satellites. These can be downloaded from the Sentinel Toolbox Exploitation Platform (STEP). The toolboxes share a common architecture called the Sentinel Application Platform (SNAP).

SNAP builds on the legacy of the VISAT BEAM software developed for use with data from the ENVISAT satellite. Key functionalities of SNAP include:

- Image display and navigation
- Layer management to view and manipulate multiple product layers as well as images from
- WMS servers/ESRI shape files.
- Subsetting and exporting to different file formats including:
- Plots and statistics for defined regions of interest.
- Mask definition and display (pre or self defined)
- Band arithmetic (to apply mathematical expressions to products.
- Graph Processing Framework (GPF): for creating user-defined processing chains
- Supports numerous sensors beyond the Sentinels (Including MERIS, MODIS, Landsat8)
- Reprojection and ortho-rectification to a variety of map projections,
- Geo-coding and rectification using ground control point
- Multithreading and Multi-core processor support

This is the key piece of software we will use during this course. SeaDAS (developed by NASA) also has a similar graphical user interface to SNAP.

SNAP is available for Windows, Mac and UNIX systems. To download and install, first visit this page and select the download of the Sentinel Toolboxes suitable for your operating system.
Open the downloaded file and follow the installation instructions. You can opt to only install the toolboxes you want. For this course you will only need the Sentinel 3 toolbox, but you may wish to install all. If you wish to install other toolboxes after the initial installation you can follow the guidelines here to install from within SNAP.

Once installed, open the software by clicking on the icon in your relevant install location (e.g. in 'All Programs' in Windows, 'Applications' in Mac, or the equivalent dependent on your UNIX system. You can also open from the command line, information on the SNAP command line interfaces is here.

We recommend you update all the plugins once installed. You can do this from the top menu under Help>Check for updates.

For use of python code we recommend participants install the anaconda 2.7 distribution, as well as the basemap and netcdf libraries.

2. Harmful Algal Blooms – Challenges and opportunities for optics and remote sensing

Harmful algal blooms can have huge impacts on our social and economic interactions with the marine environment. Although often natural, these blooms can have substantial impacts on marine ecosystems as well. Optics and remote sensing can play several key roles in helping us to understand, monitor, and predict HABs and their impacts. Measuring HABs using optical techniques presents a number of challenges. They frequently occur in optically complex, coastal regions, leading to associated complications in both in situ and remote sensing measurement and data processing. However, these blooms also present opportunities for the development of novel algorithm approaches for quantifying high biomass, identifying particular species and their characteristics, and using multiple sources of oceanographic data synthetically to build predictive models of their diverse impacts.

Recommended reading:

Schofield, O. , Grzymski, J. , Bissett, W. P., Kirkpatrick, G. J., Millie, D. F., Moline, M. and Roesler, C. S. (1999), OPTICAL MONITORING AND FORECASTING SYSTEMS FOR HARMFUL ALGAL BLOOMS: POSSIBILITY OR PIPE DREAM?. Journal of Phycology, 35: 1477-1496. doi:10.1046/j.1529-8817.1999.3561477.x

Hallegraeff, G. M. (2010), OCEAN CLIMATE CHANGE, PHYTOPLANKTON COMMUNITY RESPONSES, AND HARMFUL ALGAL BLOOMS: A FORMIDABLE PREDICTIVE CHALLENGE. Journal of Phycology, 46: 220-235. doi:10.1111/j.1529-8817.2010.00815.x

Richard P. Stumpf (2012) Applications of Satellite Ocean Color Sensors for Monitoring and Predicting Harmful Algal Blooms, Human and Ecological Risk Assessment: An International Journal,7:5, 1363-1368, DOI: 10.1080/20018091095050
https://www.researchgate.net/profile/Clarissa_Anderson/publication/323497462_Designing_an_observing_system_for_early_detection_of_harmful_algal_blooms/links/5a985693aca27214056d48ac/Designing-an-observing-system-for-early-detection-of-harmful-algal-blooms.pdf#page=118

https://books.google.co.uk/books?hl=en&lr=&id=tppYDwAAQBAJ&oi=fnd&pg=PA338&dq=Harmful+algal+blooms+satellite+data&ots=SJRBrXadOz&sig=7hsZkepF4ClgBetzN6Pah-WYQAY#v=onepage&q=Harmful%20algal%20blooms%20satellite%20data&f=false

9.4 John Hedley, Numerical Optics Ltd., UK.
Introduction to HydroLight (Thursday 28 June 11.00-12.30)

Numerical modelling of the propagation of light in water and the resulting remote sensing reflectance is an essential component of studies in ocean optics. This lecture will introduce the HydroLight radiative transfer model. The inputs, outputs, functions and limitations of HydroLight will be reviewed. The underlying solution method used in HydroLight will be discussed in the context of other solution methods, such as Monte-Carlo models. The importance of accurate light calculations in ecosystem models will also be discussed.
References:

www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/hydrolight

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.

Practical Session - HydroLight Lab

Thursday 28 June 14.00-15.30
Students will be given an executable version of HydroLight to install on their laptops (MS Windows or Mac). The students can then run HydroLight on a series of suggested exercises designed to consolidate their understanding of hydrological optics and how AOPs depend on IOPs. Various simulations can be run, using standard bio-optical models for Case 1 waters, Case 2 waters or shallow waters with a given bottom type. Students with experience of HydroLight can also use this opportunity to raise any specific questions they may have. HydroLight can continue to be used after this session and I will be available until Wednesday the 4th to answer any further questions.

References:
HydroLight 5.3 Users' Guide and *HydroLight 5.3 Technical Documentation*. These can be downloaded at http://www.oceanopticsbook.info/view/references/publications

Shallow water remote sensing

This lecture will discuss marine remote sensing applications that depend on the visibility of the bottom, such deriving bathymetry or benthic mapping of coral reefs and seagrasses with high spatial resolution imagery (pixels < 30 m). A wide range of techniques have been applied to these objectives, from fully empirical to those based on radiative transfer models, however many of the challenges and limitations are common to all approaches. Benthic complexity, surface glint, spatial variability in IOPs all contribute to the challenge of deriving meaningful information. In this lecture I will discuss some of these issues, and give an overview of some of the practical methods used to address these and the limitations of the methods. I will also discuss how uncertainty propagation can be used to give an indication of when these limitations are approached.

References:

Hedley JD. Roelfsema CM, Chollett I, Harborne AR, Heron SF, Weeks S, Skirving WJ, Strong AE, Eakin CM, Christensen TRL, Ticzon V, Bejerano S, Mumby PJ (2016) Remote sensing of coral reefs for monitoring and management: A review. Remote Sensing 8: 118-157.

Zoffoli ML, Frouin R, Kampel M. (2014) Water column correction for coral reef studies by remote sensing. Sensors 14, 16881–16931.

Dekker A, Phinn S, Lyons M, Roelfsema C, Anstee J, Bissett P, Brando V, Cleveland J, Fearns P, Hedley JD, Klonowski W, Lee Z, Lynch M, Mobley C (2011) Intercomparison of methods for physics-based shallow water remote sensing. Limnology and Oceanography Methods 9: 396-425.

Kay S, Hedley JD, 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.

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.

References:

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

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.

Mobley C. D., Sundman L. K. (2003) Effects of optically shallow bottoms on upwelling radiances: Inhomogeneous and sloping bottoms. Limnology and Oceanography 48: 329-336.

9.5 Zhongping Lee, University of Massachusetts Boston, USA

Lecture 1: Basics of IOPs

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 R_{rs}**

Historically R_{rs} inversion was focused on chlorophyll. This lecture will introduce why it is also, if not more, important to invert IOPs from R_{rs}; 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 carried out during the lecture.

Students are required to install the Solver Add-in within Excel (**After open an Excel file, click File -> Options -> Add-ins -> Solver Add-in -> Go -> OK**)

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**

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 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.
Zoffoli, M.L., et al., 2017, "Estimation of Transmittance of Solar Radiation in the Visible Domain Based on Remote Sensing: Evaluation of Models Using In Situ Data". JGR-Oceans, 122, 9176-9188

Lecture 4: **Science of Secchi disk depth**

Secchi disk depth is an easy and intuitive measurement of water clarity (or transparency), where such measurements have been carried out in oceans and lakes for >150 years, with roughly a million data available. This lecture covers the interpretation of such subjective measurements and the relationships between Secchi disk depth and other optical or biological properties, such as euphotic zone depth or chlorophyll concentration.

References:

Preisendorfer, R.W., 1986, "Secchi disk science: Visual optics of natural waters," L&O, Vol 31, 909-926.
Lee et al., 2015, "Secchi disk depth: A new theory and mechanistic model for underwater visibility", RSE, Vol. 169.
Lee et al., 2018, "Resolving the long-standing puzzles about the observed Secchi depth relationships ", L&O, accepted.

9.6 Louis Legendre, Emeritus Professor, Sorbonne Université, France

Ocean research in Villefranche: An amazing (hi)story (Monday 25 June 2018)

The fourth IOCCG Summer Lecture Series is held at the Observatoire Océanologique de Villefranche-sur-Mer (corresponding English name: Freetown-by-the-Sea), which is housed in historical buildings of a former military port. The lecture answers such questions as: Why is there an oceanographic institute in Villefranche-sur-Mer? Why did Russian scientists create that institute in 1885? Why was a major military port in Villefranche-sur-Mer? Why was Villefranche-sur-Mer created more than 700 years ago? In order to answer these questions, the lecture examines various aspects that include the maritime territory of France and the organisation of French marine research, the unique site and improbable history of Villefranche-sur-Mer, the transformation of facilities of a military port into a reputed research institute, and the succession of Russian and French scientists in Villefranche over almost 140 years.

Relevant websites:

https://en.wikipedia.org/wiki/Villefranche-sur-Mer

http://www.lifeinriviera.com/guide/villefranche-sur-mer/history/

Scientific Research and Discovery: Process, Consequences and Practice (28 June 2018)

Scientific research and discovery are examined in terms of process, consequences and practical aspects. The topics examined during the lecture include: the processes of scientific research and discovery, the nature of scientific creativity, the writing of scientific paper, and scientific research as a career. The lecture is based on the book Scientific Research and Discovery: Process, Consequences and Practice (Legendre, Louis, 2004, Book 16, Excellence in Ecology, International Ecology Institute, Oldendorf-Luhe), of which an abridged electronic edition is available, free of charge, at: http://www.int-res.com/book-series/excellence-in-ecology-books/ee16/

9.7 Griet Neukermans, Laboratoire d'Océanographie de Villefranche, France

Coccolithophores: Optical Properties and Biogeochemistry

Coccolithophores are a group of phytoplankton (Class: Prymnesiophyceae) distinctive by their production of calcite plates, called coccoliths, which surround the cell. Coccolithophores come in a wide variety of sizes and shapes, and are important contributors to pelagic calcium carbonate production. They are found throughout the global ocean and sometimes form spectacular blooms, which colour the ocean bright milky-turquoise. This class will cover the optical properties and biogeochemical roles of coccolithophores. More specifically:

(i) their light scattering and absorption properties,
(ii) their detection from ocean colour satellites,
(iii) their diversity, distribution, and bloom formation,
(iv) their role in the ocean carbon cycle; in the biological carbon pump as well as in the carbonate counter pump, and finally
(v) their response to climate change.

Suggested reading:

1) *Balch, 2018: https://www.annualreviews.org/doi/10.1146/annurev-marine-121916-063319*

2) *Monteiro et al., 2016: http://advances.sciencemag.org/content/2/7/e1501822*

3) *Rost and Riebesell, 2004. http://epic-reports.awi.de/11394/1/Ros2004a.pdf*

4) *Tyrrell and Young, 2009. Encyclopedia of Ocean Sciences. https://www.sciencedirect.com/science/article/pii/B9780123744739006627*

5) *Thierstein and Young, 2004. Coccolithophores: From molecular processes to Global Impact. https://www.springer.com/gp/book/9783540219286*

9.8 Jeffrey Polovina, Scientist Emeritus, Pacific Islands Fisheries Science Center, NOAA, USA

Ocean Color in Support of Fisheries and Protected Species Research

Satellite remotely-sensed ocean color data, in particular surface chlorophyll, contribute to fisheries and protect species research and management in a variety of ways. The data are used to describe and monitor ocean features such as fronts, eddies, and upwelling that define the forage habitats of many animals. Given the global spatial and regular temporal resolution, surface chlorophyll data together with other satellite measurements are often used together with electronic tagging data to describe the dynamic oceanographic habitat of animals and subsequently serve as input in dynamic ocean habitat models. Surface chlorophyll data are also ideally suited to define and monitor the spatial and temporal dynamics of biomes that may characterize ecosystems. Examples of a suite of applications of ocean color used in fisheries and protected species research will be presented.

Three suggested background papers are:

Chassot, E., S. Bonhommeau, G. Reygondeau, K. Nieto, J. J. Polovina, M. Hunt, N. K. Dulvy, H. Demarcq. 2011. Satellite remote sensing for an ecosystem approach to fisheries. ICES Journal of Mar. Sci.;doi:10.1093

Polovina J. J., E. A, Howell, M Abecassis. 2008. The ocean's least productive waters are expanding. Geophys. Res. Lett., 35, L03618, doi:10.1029/2007GL031745.

Polovina, J.J., Howell, E.A., Kobayashi, D.R. and Seki, M.P., 2017. The Transition Zone Chlorophyll Front updated: Advances from a decade of research. Progress in Oceanography, 150, pp.79-85.

9.9 Kevin Ruddick & Quinten Vanhellemont, Royal Belgian Institute of Natural Sciences (RBINS), Belgium

Ocean Colour Remote Sensing in Turbid Waters

The use of ocean colour remote sensing data has increased dramatically over the last ten years, particularly for coastal and inland waters where impacts between the aquatic environment and human activities may be particularly intense. Many of these 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 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 waters. Firstly, atmospheric correction is more difficult 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 atmosphere and water 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 Excel-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, OLCI, VIIRS and hyperspectral sensors.

The atmospheric correction of high resolution (10-60m) satellite imagery from Landsat and Sentinel-2 over turbid waters will be explained, and demonstrated with a hands-on practical exercise using ACOLITE. During the practical, the students will download imagery for their study areas, perform the atmospheric correction using ACOLITE and discuss the results interactively.

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

Requirements for the lectures

- A basic knowledge of the definitions of optical properties (scattering, absorption, attenuation) from other lectures from this IOCCG summer school, particularly those of Emmanuel Boss.
- An ability to use basic functions of Excel.
- Students are encouraged to download ACOLITE and images of their interest prior to the lectures.

Suitable background reading

1) *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*
2) *https://odnature.naturalsciences.be/remsem/software-and-data/acolite*
3) *http://odnature.naturalsciences.be/remsem/acolite-forum/index.php*

9.10 Matthew Slivkoff, Curtin University, Australia

Radiometry, apparent optical properties, measurements and uncertainties.

This lecture re-caps the radiometric measurement fundamentals of radiance and irradiance and then describes the different design principles utilised in multispectral and hyperspectral radiometers.

Radiometric calibration uncertainties are discussed, in addition to uncertainties associated with practical oceanographic AOP deployment techniques and subsequent data analysis.

Some relevant reading materials are:

Mueller, J. L., et al. (2003). Instrument Specifications, Characterisation and Calibration. Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4. J. L. M. a. G. S. F. a. C. R. McClain. Greenbelt, Maryland, National Aeronautical and Space Administration. ***II:*** *1-57.*

Talone, M., et al. (2016). "Stray light effects in above-water remote-sensing reflectance from hyperspectral radiometers." Applied Optics ***55****(15): 3966-3977.*

Zaneveld, J. R., et al. (2001). "Influence of surface waves on measured and modeled irradiance profiles." Applied Optics ***40****(9): 1442-1449.*

D'Alimonte, D., et al. (2013). "Regression of in-water radiometric profile deata." Optics Express ***21****(23): 27707-27733.*

D'Alimonte, D., et al. (2018). "Effects of integration time on in-water radiometric profiles." Optics Express ***26****(5): 5908-5939.*

IOCCG
International Ocean-Colour Coordinating Group

9.11 Dariusz Stramski, Scripps Institution of Oceanography, U. California San Diego, USA.

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
   a. dual wave-particle nature of light
   b. properties of electromagnetic radiation (energy/Poynting vector, phase velocity, frequency, wavelength, electromagnetic spectrum, polarization, Stokes vector)
   c. wave-like phenomena: interference, reflection, refraction, diffraction
   d. mechanism of light emission and basic radiation laws (Planck, Stefan-Bolzmann & Wien's laws, solar radiation, Earth radiation)
   e. mechanism of absorption (internal energy of atoms and molecules, basic features of absorption by molecular water and pigments)
   f. mechanism of scattering (oscillating dipole, elastic and inelastic scattering, basic features of molecular and particle scattering)
2) Fundamentals of single-particle optics
   a. quantification of absorption and scattering properties of individual particles
   b. dependence of particle optical properties on physical and chemical characteristics of particles
   c. linkage between the single-particle and bulk optical properties of particle suspension
3) 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-biological interactions such as prey-predator interactions and viral infection
   d. mineral particles
   e. colloidal matter
   f. air bubbles
4) 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.

Lecture 1 (Monday June 25): Topical area 1: The nature of light and fundamentals of lightmatter interactions

Textbook references:

Hecht, E., Physics, Brooks/Cole Publishing Co, 1994.
Hecht, E., Optics, Addison-Wesley, 1998.
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 andExperimental Foundations. Academic Press.

Lectures 2& 3 (Wednesday June 27 and Thursday June 28): Topical areas 2, 3 & 4: Single particle optics; Optical properties of marine particles; Roles of particles in ocean optics

Examples of useful reading:

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

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

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.

Stramski, D., and A. Morel. 1990. Optical properties of photosynthetic picoplankton in different physiological states as affected by growth irradiance. Deep-Sea Res., 37, 245-266.

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

Mobley, C. D., and D. Stramski. 1997. Effects of microbial particles on oceanic optics: Methodology for radiative transfer modeling and example simulations. Limnol. Oceanogr., 42, 550-560.

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.

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.

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

Stramski, D., and S. B. Woźniak. 2005. On the role of colloidal particles in light scattering in the ocean. Limnol. Oceanogr., 50, 1581-1591

9.12 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 measurement of 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 Research, 117, C00H17, doi:10.1029/2011JC007347.