International Ocean Colour Science Meeting 2017 | Advancing Global Ocean Colour Observations

Proceedings of the

2017 International Ocean Colour Science Meeting (IOCS-2017)

Feira International de Lisboa (FIL) Conference Centre

Lisbon, Portugal

15 - 18 May 2017

Convened by the International Ocean Colour Coordinating Group (IOCCG)
Sponsored by EUMETSAT, ESA, the European Commission, NASA,
Thales Alenia Space, Airbus, and IPMA

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1. Introduction

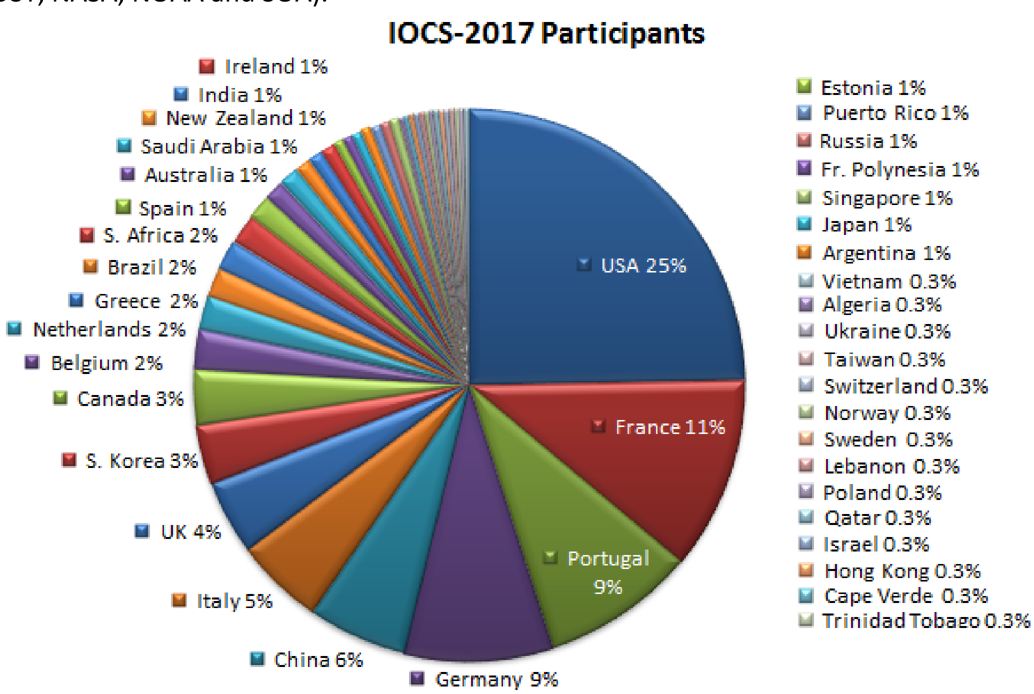
1.1 Background

The third International Ocean Colour Science (IOCS) meeting took place from 15 to 18 May 2017 in Lisbon, Portugal, convened by the International Ocean Colour Coordinating Group (IOCCG) in partnership with, and thanks to sponsorship from, EUMETSAT, ESA, the European Commission, NASA, Thales Alenia Space and Airbus, and with local support from the Instituto Português do Mar e da Atmosfera (IPMA). IOCCG gratefully acknowledges the support from all meeting sponsors. The meeting was followed by two training events: a Copernicus marine data stream training event and a SeaDAS training event

With the overarching theme of IOCS-2017 "*Exploring New Capabilities for Global Ocean Colour Observations*", the meeting served as a venue for the ocean colour community to discuss the state of the art in ocean colour remote sensing, and communicate their views, ideas and concerns to the space agencies, thus building and reinforcing the voice of the global ocean colour community and also helping IOCCG in its oversight role with respect to high-level discussions with space agencies.

1.2 Participants

A total of 344 researchers from 41 different countries participated in the four-day meeting, including ocean colour research scientists from around the world, as well as representatives from all the major space agencies with an interest in ocean-colour radiometry (CNES, CONAE, CSA, ESA, EUMETSAT, ISRO, JAXA, KIOST, NASA, NOAA and SOA).



The IOCS meeting was an excellent venue for networking but also helped to facilitate direct communication between the ocean colour research community and program managers and representatives from international space agencies. All the agencies were very interested to hear the advice from the scientific community in order to advance the science of satellite ocean colour remote sensing.

1.3 IOCS-2017 Meeting Programme

The IOCS-2017 plenary programme included seven invited keynote lectures as well as agency presentations and special sessions on the Copernicus Programme, VIIRS and NASA OCRT meeting, although IOCS-2017 did not focus solely on presentations: nine breakout workshops complemented the plenary sessions allowing participants to discuss current critical challenges and provide community feedback to the agencies. In addition, there were three poster sessions and a Q &A session where the ocean colour community could directly address space agency representatives. After the daily sessions, participants were invited to meet informally and continue their discussions at an ice breaker event on Monday evening, sponsored by Thales Alenia, and a dinner on Wednesday evening, sponsored by EUEMTSAT and ESA. Details of the meeting agenda can be viewed here. All presentations can be viewed at: http://iocs.ioccg.org/programme/conference-materials/ and poster abstracts can be viewed at: http://iocs.ioccg.org/wp-content/uploads/2017/05/abstracts-iocs-2017-all-10may2017.pdf

1.4 Opening Session

Stewart Bernard (past IOCCG Chair) opened the meeting and warmly welcomed participants to Lisbon. He extended apologies from Cara Wilson, IOCCG Chair, who had unfortunate travel delays. Stewart thanked the meeting sponsors for their support and noted that there was a lot of community interest in the IOCS meetings, which were gathering momentum.

Craig Donlon (ESA/ESTEC) welcomed participants on behalf of Josef Aschbacher (ESA Director of Earth Observation Programmes). Copernicus is the core programme for oceanography and ocean colour and ESA is working together with the European Commission and EUMETSAT to deliver applications and services to ensure users get what they need. Science is at the core of what ESA does: scientific results are packaged and delivered in an operational and robust manner to answer serious questions (e.g., climate change). This meeting is one example of the excellent collaborative nature of the Copernicus Programme – Craig encouraged participants to use this meeting to network and to get a better understanding of ocean colour.

Alain Ratier (EUMETSAT) thanked the Ministry of the Sea of Portugal and IPMA for hosting the meeting and welcomed the best ocean colour scientists in the world to Portugal, home of the famous Portuguese explorers. The Copernicus Programme has brought ocean colour into the operational era, but this is also based on the success of past missions. EUMETSAT will work with users for improved calibration, atmospheric correction and validation of products using fiducial reference measurements etc. so this will continue to be a long term relationship. Science meetings such as this are very valuable for propagating best practises across oceans to achieve the consistency of products and produce multi-mission datasets. EUMETSAT is looking forward to receiving recommendations from participants that they can take on board to better serve the community.

Lastly, Miguel Miranda (Director General of IMPA, and representing the Portuguese Minister of the Sea), welcomed participants to Lisbon. The Minister of the Sea is deeply interested in any research that can clarify phytoplankton dynamics, primary production and other processes in coastal areas that are critical for the Portuguese economy and long term sustainability. The facts of climate change are not clear, but things are changing fast, and the ability to use space-based techniques can help contribute to understanding these processes which are critical for the future of the blue economy.

2. Agency Reports

The meeting programme included reports from international space agencies on the status of their ocean-colour programmes, as well as sessions on the Copernicus Programme (EC, ESA and EUMETSAT), NOAA (science, research and applications from VIIRS) and the NASA Ocean Color Research Team (OCRT) meeting. A brief summary of these presentations is given below.

2.1 Copernicus Session (EC, ESA and EUMETSAT)

2.1.1 Introduction to the Copernicus Programme

Richard Gilmore (European Commission) introduced the Copernicus Programme, a cornerstone of the European Union´s efforts to monitor the Earth, its environment and ecosystems using Earth Observation. Six services (e.g., Copernicus Marine Environment Monitoring Service, CMEMS) use Earth observation data to deliver products that can be readily accessed and used. ESA designs and launches the satellites and EUMETSAT helps with the operations of the marine component of Sentinel-3, while the Copernicus *in situ* component provides *in situ* data access internally to Copernicus services. All the operational services are supported by a significant research programme. The Sentinel-3A mission (soon to be joined by Sentinel-3B) carries the OLCI instrument, designed for both ocean and land acquisition, and operated by EUMETSAT. OLCI builds on MERIS heritage (21 spectral bands, better S/N, on-board processing, 5 cameras, sun-glint attenuation) and complements other ocean colour missions such as SeaWiFS, MODIS and VIIRS. All data is provided on a full, free and open access basis.

2.1.2 Sentinel-2 and status of Sentinel-3B

Craig Donlon (ESA) provided an overview of the Sentinel-2 and -3 missions. Sentinel-2 consists of two identical spacecraft (A and B) operating in twin configuration, each carrying a Multi-Spectral Instrument (MSI) push-broom imager with 13 spectral bands (VIS, NIR & SWIR), at 10, 20 and 60 m spatial resolution with a 5 day revisit at the Equator (with 2 satellites). The bands are optimized for accurate atmospheric correction and vegetation monitoring but clearly have huge potential for marine applications. The S-2A mission is responding to user needs and evolving to meet those needs (e.g., pilot project to include L2A products for systematic production over Europe). Fiducial Reference Measurements (FRM) are required to determine the on-orbit uncertainty characteristics of satellite measurements via independent validation activities. Several workshops and a radiometer inter-comparison have taken place. Sentinel-3B launch is planned at the end of 2017. A new orbit phasing of S-3A and S-3B to 140° will optimise altimeter ground tracks, with limited impact on the optical mission. Tandem mission (flying S-3B 30 seconds behind S-3A during commissioning) has also been approved by the EC.

2.1.3 Copernicus Sentinel-3 Mission

Ewa Kwiatkowska (EUMETSAT) reported on ocean colour radiometry from the Copernicus Sentinel-3 missions: S-3A is on orbit, S-3B is launching soon, and S-3C and –D are being developed. OLCI L1B products were released to the public on 20 Oct 2016, and L2 data will be released in June this year. Limitations of L1 OLCI products are being addressed, and implementation of System Vicarious Calibration (SVC) will reduce biases for L2 products. The Sentinel-3 Validation Team provides independent validation evidence on the quality of OLCI products. Full reprocessing of S-3A OLCI will take place by the end of 2017.

2.1.4 Colour, Climate, Carbon and Copernicus

Shubha Sathyendranath (PML) provided an overview of the ESA Ocean Colour Climate Change Initiative (OC-CCI), which is providing a merged time series of ocean colour products from SeaWiFS, MODIS-A, MERIS, and VIIRS sensors, including uncertainty estimates on a per-pixel basis. The Sentinel-3 series of ocean-colour sensors (OLCI) will provide consistency with MERIS, as well as continuity, improved coverage (at least two sensors in orbit at the same time) and better spectral resolution. *In situ* validation programmes must keep pace with the additional products produced by OC-CCI.

2.1.5 Sentinel applications: fisheries and aquaculture

Vanda Brotas (University of Lisbon) spoke on fisheries and aquaculture applications of the Sentinel missions. The ongoing use of Earth observation to support fisheries includes prediction of Potential Fishing Zones (PFZs), improving fish sustainability and protection of fish stocks (SST, OC, winds, currents, and modelling), and ship detection using (Sentinel-1 and-2). Ocean fronts are areas of increased productivity, which can be quantified using remote sensing (e.g., composite frontal maps). Ecological indicators can also be derived from remote sensing (i.e., initiation, amplitude, timing and duration of the spring bloom) which can be related, for example, to sardine catch in the Gulf of Guinea. Satellite data can also be used to provide NRT alerts for potential HABs affecting Aquaculture units, and can help support aquaculture management.

2.1.6 Sentinel applications: monitoring harmful algal blooms

Blake Schaeffer (US Environmental Protection Agency) expanded on harmful algal bloom research related to Sentinel-2 and -3 science and applications, including atmospheric correction challenges. Case studies from oceans, estuaries, inland lakes and reservoirs were presented. Satellite data has been used to identify U.S. waterbodies which present potential risk of cyanobacterial blooms (impact on recreational activities and drinking water).

2.1.7 Sentinel applications: monitoring water quality in Africa

Mark Matthews (CyanoLakes) demonstrated a public information service for cyanobacteria blooms in South Africa. CyanoLakes is a company that provides commercial services which assist in the management of aquatic ecosystems by providing real-time information and forecasts on cyanobacteria blooms and water pollution using Earth observation satellite remote sensing technology. Cyanobacteria occur in most of the world's freshwaters due to increasing pollution and rising temperatures. They pose a health threat to recreational water users from various chronic and acute health effects. Cyanobacteria produce lethal toxins that have been linked to cancer and neurodegenerative diseases. CyanoLakes services offer the following benefits:

- prevent, detect and manage health risks
- improve the health and safety of users
- enhance routine monitoring and reporting

- reduce long-term monitoring costs
- improve management strategies
- improve decision making
- compliment potable water treatment systems
- achieve compliance with legislation

CyanoLakes provide solutions that incorporate local and international guidelines to inform decision makers and the general public about water safety. CyanoLakes uses the most advanced methods with the Copernicus OLCI and Envisat MERIS sensors to detect cyanobacteria using the Maximum Peak Height Algorithm. The MPH algorithm separates between algae and cyanobacteria allowing risk levels to be determined. The Earth Observation National Eutrophication Monitoring Program (EONEMP) project is funded by the Water Research Commission of South Africa to provide a public information service for 102 water bodies in the Republic of South Africa. The goal of EONEMP is to improve the monitoring of the health risk from cyanobacteria and eutrophication in a large number of South Africa's water bodies through disseminating timely and accurate information, and to integrate the information into the national monitoring database. The EONEMP application can be accessed at http://eonemp.cyanolakes.com.

2.1.8 Sentinel OCR data access and dissemination

Susanne Mecklenburg (ESA Sentinel-3 Mission Manager) informed participants about the various Sentinel data products, as well as access and dissemination of the data. A wide variety of Sentinel data over the oceans is available through ESA and EUMETSAT's data dissemination systems. Sentinel products are available in NRT (Near Real time), STC (Short Time Critical) and NTC (Non time Critical - within 2-3 days). All Sentinel-3 Level-1 data have been released, and Level-2 OLCI and SLSTR sample data products are planned for release in June 2017. Launch of Sentinel-3B is foreseen for end of 2017 (TBC). Sentinel data can be accessed through the ESA Sentinel Data Hub, the Copernicus Services Hub, and the Collaborative Hub as well as through the EUMETSAT Earth Observation Portal, CODA, Data Centre, and via EUMETCast. A variety of tools are available to visualise and process Sentinel-3 marine data.

2.1.9 Activities and plans for Cal/Val of Sentinel OCR

Ewa Kwiatkowska (EUMETSAT) reported on the broad topic of Sentinel Cal/Val activities which aims to fulfill the mission requirements and ensure traceability to mission requirements. Sentinel-3 OLCI cal/val activities are based on a joint ESA and EUMETSAT Cal/Val Plan. The Sentinel-3 Mission Performance Framework includes quality working groups, the Mission Performance Centre, the Sentinel-3 Validation Team and a wide range of in-house mission performance activities. Ongoing Cal/Val activities are undertaken to understand and model instrument behaviour and validate L1 products, and to validate and improve L2 products.

2.2 CNES (Centre National d'Etudes Spatiales, France)

Anne Lifermann presented CNES support to ocean colour science, highlighting the actions conducted by CNES in the field of ocean colour. CNES has been a strong supporter of ocean colour both at the Agency level (IOCCG membership, supporting IOCCG Summer Lecture Series, co-operations, studies, calibration activities e.g., Boussole, Bio-Argo, and development of applications) and through support of scientific laboratories.

2.3 CSA (Canadian Space Agency)

Martin Bergeron presented the Canadian Space Agency report on ocean colour activities. Given Canada's extensive coastlines and inland water bodies, momentum has been building for an opportunity to deliver weekly 100 m hyperspectral coastal and inland water imagery to meet the needs of the Canadian Government and research community, with additional capacity for international partners. An airborne demonstrator is being finalized and bread-boarding activities have been initiated. A summary of the activities of the Canadian water colour community was also presented.

2.4 JAXA (Japan Aerospace Exploration Agency)

Hiroshi Murakami (Earth Observation Research Center, JAXA) provided an update on the Global Change Observation Mission for Climate (GCOM-C) carrying the Second-generation Global Imager (SGLI). The mission is planned for launch in 2017 at an 800-km altitude, sun-synchronous orbit at a descending local time of 10:30AM. SGLI has middle spatial resolution (250 m to 1000 m), 1150-1400 km swath, 19 bands from near-UV (380 nm) to thermal infrared (TIR) (12 μm) wavelengths including polarization slant-view (+45 degrees or -45 degrees along track) red and near infrared channels. The 250-m resolution will enhance observation capability over land and coastal areas, and the polarization and multidirectional observations will improve retrievals of aerosols and canopy structure over land. On-board calibrations, solar (with diffuser), lamp, lunar (by pitch maneuver), deep-space and black-body (for TIR) will help to make the climate-quality data products.

SGLI proto-flight tests including spectral response, gain, linearity, SNR, alignment, MTF, stray light, polarization sensitivity, and their modeling have been finished until 2016. Satellite integration and operation simulation tests will be finished until summer 2017. After the launch, we will have a three-month commissioning phase for function and parameter evaluation, and a following nine-month initial Cal/Val phase for preparing the public data release at one-year after the launch. The observation data product has been developed by JAXA and GCOM-C Principal Investigators (PIs) which has been firstly organized in summer 2009. The at-launch version algorithms have been implemented in the operation system in Feb. 2017.

The GCOM-C ocean-colour products will be calibrated and validated through *in-situ* measurements, and vicarious and cross calibrations in cooperation with the on-board calibrations. *In-situ* bio-optical data will be obtained by Cal/Val-dedicated and regular cruises under the collaboration with the universities and institutes (mainly PIs). International collaboration is essential to validate the products, improve algorithms, and expand effective applications in various bio-optical conditions in various locations and seasons.

2.5 NOAA Ocean Colour Session (USA)

The NOAA ocean colour session began with a welcome and introduction by Paul DiGiacomo. Menghua Wang then gave an overview and status update of the activities of the NOAA Ocean Color group with an emphasis on ocean colour from VIIRS-SNPP. He explained NOAA's capability of implementing an "end-to-end" approach for ocean colour. Using the Multi-Sensor Level-1 to Level-2 ocean colour data processing system (MSL12), eight standard global products are currently being generated from VIIRS-SNPP, including normalized water-leaving radiances at VIIRS 5 bands, i.e., 410, 443, 486, 551, and 671 nm; chlorophyll-a; diffuse attenuation coefficient at 490 nm; and attenuation coefficient at the photosynthetically available radiation (PAR). The suite of products is produced on a near-real time basis for users who require low latency and on a delayed-mode basis for production of science quality data for users who require high accuracy and consistency data with about a 2-week lag in latency. VIIRS has shown to be a very good sensor and ocean colour products are very good quality. The second full mission-long ocean colour data reprocessing is currently underway and will be released with several new global products, including a Quality Assessment Score (QA Score), two types of chlorophyll-a anomaly products and normalized water-leaving radiance at I-1 band (638 nm).

Next, Karlis Mikelsons demonstrated OCView (https://www.star.nesdis.noaa.gov/sod/mecb/color/), the intuitive and easy to use viewing tool. With OCView, one can view many data products from several sensors, including the full mission of VIIRS-SNPP, overlay true colour and granule boundaries, view estimates of pixel values, zoom and scroll to desired scene and share images online by pointing to the responsive URL address and offers a convenient way to download VIIRS Level-2 ocean colour files from NOAA CoastWatch/OceanWatch, the primary distributor.

The third presentation was by Veronica Lance who described the NOAA CoastWatch/OceanWatch Program (CoastWatch.NOAA.gov) which is the repository and distributor of ocean satellite data on behalf of NOAA Center for Satellite Applications and Research and also distributor of non-NOAA data such as OLCI Sentinel-3. Some useful data discovery tools such as the space and time search tool were described and some examples of global and regional L2 and L3 mapped products were shown.

The final presentation was from Cara Wilson who discussed types of satellite data products required by users which include long-term time series, not only near-real time. She gave several examples of how NOAA National Marine Fisheries Service people are using satellite data in support of NOAA missions along with other ocean colour user examples. Wilson runs an annual satellite data training class targeted to NOAA researchers who are subject matter experts but are not experts at using satellite data. Paul

DiGiacomo concluded with comments that the NOAA ocean color team has done excellent work and VIIRS ocean colour (and other products) are available through NOAA CoastWatch/OceanWatch.

2.6 KIOST (Korea Institute of Ocean Science &Technology)

Seongick Cho reported on the Korean geostationary ocean colour missions: GOCI and GOCI-II, on behalf of Young-Je Park, Hee-Jeong Han and other members of the Korea Ocean Satellite Center (KOSC). The Geostationary Ocean Color Imager (GOCI), the first ever ocean colour instrument operated on geostationary orbit, is providing eight ocean colour images a day (multi-band radiances at the visible to NIR spectral wavelengths) with a 0.5 km resolution for the North East Asian Seas since July, 2010.

Last year was one of the hottest summers on record, which caused massive mortality of fish and abalone in the sea farms. At the same time low salinity water arrived in the coastal waters of South Korea due to discharge of a huge amount of fresh water into the East China Sea from the Yantze River, caused by heavy rain in the catchment area. The low salinity water mass is one of the main concerns for local aquaculture management. Such low salinity waters could be identified in the GOCI imagery, thus useful for early warning.

In early 2015, an extensive bloom of *Sargassum honeri* floating algae was observed in the East China Sea and again this year a similar scale of *Sargassum* blooms was observed. Distribution of the floating *Sargassum* from GOCI imagery is well accepted by local authorities handling the issue.

Many phenomena on the sea surface and in the atmosphere can also be seen using GOCI, including sea ice, floating algae, dust aerosols, etc. Sea fog is recognized as an important safety issue in harbors and airports in Korea. KOSC is investigating sea fog algorithms aimed at incorporating GOCI-based imagery as a part of an existing warning system.

From late May to early June in 2016, a comprehensive field campaign took place in Korean waters with scientists from USA and Canada to investigate scientific applications of geostationary ocean colour observations, and to collect sea truth data for matchup with GOCI. The data from the joint campaign are currently being analyzed and shared amongst participants.

The South Korean bulk carrier Stellar Daisy sank off the coast of Uruguay *en route* from Brazil to China on 31 March, 2017. KOSC has been looking into high resolution and SAR satellite images around the scene, searching for an unfound lifeboat in response to a plea from families of missing people.

In the meantime, the follow-on sensor, GOCI-II, is being built with a scheduled launch in 2019. The sensor has been assembled and tests are in progress. KOSC is also in charge of developing a ground processing system for GOCI-II, perhaps taking advantage of recent computer technology. KOSC is preparing for next phase of application-oriented research using ocean satellite data from multiple sources as well as GOCI-II data.

2.7 CONAE (Comisión Nacional de Actividades Espaciales, Argentina)

Sandra Torrusio presented the CONAE missions, projects and initiatives for coasts and oceans. The Argentinean Space Agency, CONAE, had two operative Earth Observation satellite missions in cooperation with NASA: SAC-C dedicated to land and water applications (2000-2013), and SAC-D/ Aquarius (2011-2015) focused on the ocean (sea surface salinity, sea ice concentration, wind speed, water precipitation). Different examples of the applications of these data and products, and their access were shown. Currently, the CONAE is developing the SABIA-Mar Mission for ocean colour estimation (2021). This is a collaborative project with Brazil in order to provide data and products for the regional and international community, considering the scientific and operative aspects. The main instruments on board the platform will be two cameras: one in the visible and near infrared, and one in the SWIR range of the spectrum. The revisit will be two days and the spatial resolution of 200m for a regional scenario (South America) and 800m for the global one. Water leaving radiance, Chlorophyll-a estimation, turbidity and PAR are the mandatory products to be generated along life of the mission. Also, a secondary instrument will be included, a thermal camera for SST estimation, with a pixel around 400m for the regional scenario. New areas beyond South America can be planned in the frame of collaborative projects.

A summary of Pampa Azul national initiative was presented. This initiative is coordinated by Ministry of Science with the participation of several ministries and institutions. The main goals are: to deepen the scientific knowledge as the base of the policies of conservation and management of the natural resources; to promote technological innovations applicable to the sustainable exploitation of natural resources and to the development of industries related to the sea; strengthen the maritime conscience of the society; and to support the scientific presence of our country in the South Atlantic. Finally, different examples of operative applications carried out by CONAE in cooperation with several institutions were presented, such as oil spill monitoring, fishery support, coastal studies, vessel traffic, among others.

2.8 ISRO (Indian Space Research Organisation)

Prakash Chauhan introduced the Earth observation program of the Indian Space Research Organisation (ISRO), driven by applications of remote sensing technology for societal benefits. Earth observation (EO) data based services in India has evolved through investment in research and development of space-based geophysical products and subsequent methodology development for applications such as potential fisheries forecast (PFZ), algal bloom detection, inland fisheries, crop area assessment, mapping of forest cover area, watershed development, atmosphere and meteorology etc. Some of these services are now operational through institute oriented frameworks and are now being implemented by stake holders such as the Ministry of Earth Sciences (MoES), Ministry of Agriculture, Water Resources Ministry etc. To sustain these EO based services ISRO is ensuring continuity of space-based observations and also planning advance sensors for improved observations.

ISRO has invested strongly in the broad field of ocean colour remote sensing observations using air-borne, space and in-situ observations. Space based high resolution (~360m spatial resolution) ocean colour observations were started using OCEANSAT-1 OCM data from 1999, followed by OCEANSAT-2 OCM launched in 2009, the data of which is still currently available. OCM data is being used for developing ocean colour products such as chlorophyll-a concentration, diffuse attenuation coefficient, suspended matter concentration and aerosol optical depth at 865 nm. Applications such as *Noctiluca* bloom detection in the Arabian Sea, detection of enhanced primary production after major cyclones in the Bay of Bengal, potential fishing zone (PFZs) advisory for all maritime states of India, and suspended load estimation in estuaries and harbours are being regularly done using OCM data in India. OCM observations are also used in sediment transport models to understanding sediment fluxes in gulf of Kachchh and for other coastal regions in India. New research projects have been initiated by ISRO to develop newer ocean colour products such as phytoplankton functional type (PFTs), phytoplankton carbon, primary, new & export production, and PAR using OCM data. The Space Applications Centre, Ahmedabad and the National Remote Sensing Agency (NRSC), Hyderabad are also engaged in collecting in situ ocean colour data on AOP and IOPs in the Arabian Sea and Bay of Bengal.

In the year 2015-16 ISRO and JPL/NASA collectively acquired AVIRIS-NG hyperspectral data over many coastal and inland-water bodies over Indian sites. Currently this data is being used for hyperspectral algorithm development for algal bloom detection, macroalgae identification, bathymetry extraction etc. ISRO is currently involved in the development of the next generation ocean colour sensor called, OCM-3 which will be launched in the 2018-19 timeframe on-board the OCEANSAT-3 satellite. OCM-3 will have 13 spectral channels with additional channels in SWIR for turbid water atmospheric correction and a fluorescence band triplet. The ocean colour observations will be collocated with SST data using a SSTM sensor having two bands in 10-12-micron region of the electromagnetic spectrum.

2.9 Second Institute of Oceanography, State Oceanic Administration (SOA, China)

Zhihua Mao provided an update of the Chinese ocean colour satellite missions, in conjunction with Delu Pan and Xianqiang He. China launched their first ocean colour satellite (HY-1A) on 15 May 2002 and the second (HY-1B) on 11 April 2007. Both satellites carry two payloads: the Chinese Ocean Color and Temperature Scanner (COCTS) and the Coastal Zone Imager (CZI). COCTS has eight visible bands for ocean colour remote sensing and two infrared bands for sea surface temperature. Two new ocean colour satellites (HY-1C and HY-1D), the morning- and afternoon-satellite, will be launched in 2018. Both are identical satellites carrying COCTS and CZI instruments together with a new payload equipped with two ultra-violet bands. The status of the two satellites was presented, together with an introduction of a new data processing system for HY-1C/1D.

2.10 NASA Ocean Color Research Team Meeting (OCRT)

Paula Bontempi opened the NASA Ocean Color Research Team (OCRT) meeting providing an update on the state of the NASA Ocean Biology and Biogeochemistry (OBB) Program. She provided an overview of the Earth Science Division Budget, and discussed agency and program advanced planning, including the Decadal Survey for Earth Science and Applications from Space published in 2007. She provided a brief summary of the recent selections the OBB program has done, as well as current and upcoming opportunities through the NASA Research Opportunities in Space and Earth Sciences (ROSES), which is released on an annual basis every February (http://nspires.nasaprs.com/). She concluded her presentation by encouraging the community to be involved and provide feedback on the current and upcoming projects OBB will be developing, as well as the direction of the Program through the Advance Plan.

Next, Heidi Dierssen from the University of Connecticut informed the audience on the status of the Ocean Biology and Biogeochemistry Advanced Plan. The Plan is an effort to revisit, evolve, and revise the 2007 NASA Ocean Biology and Biogeochemistry Program's Advanced Plan entitled "Earth's Living Ocean: the Unseen World" (https://oceancolor.gsfc.nasa.gov/docs/technical/obb_report_5.12.2008.pdf). The draft Advance Plan version covers the next decade (2017-2027) of community research and technology ideas. The document, which has been assembled by volunteer efforts of a dedicated Working Group over the past two years, was released for community input on 18 May 2017. The draft Advance Plan (2017-2027) can be found at the NASA Carbon Cycle and Ecosystems Focus Area web page under the NASA Ocean Biology and Biogeochemistry program heading: (https://cce.nasa.gov/ocean_biology_biogeochemistry/announce_20170523.html). The plan is open to comments until 15 August 2017.

After a short break, Bryan Franz from NASA GSFC gave an overview of the NASA Ocean Biology Processing Group (OBPG). The OBPG is currently supporting calibration, validation, software development, (re)processing, and distribution for a multitude of NASA and international Earth Observing satellite missions and sensors, the majority focused on ocean colour data. In terms of reprocessing, all supported global missions, with the exception of MERIS, are now at version R2014.0, which includes updates to instrument and vicarious calibrations, updates to standard algorithms (e.g., OCI Chlorophyll), expansion of standard products to include a suite of inherent optical properties (GIOP), and a switch to NetCDF4 file formats (Level-2 and Level-3 data). He reported that a Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua Reprocessing (version 2014.1) will be coming soon. He showed a variety of matchups for different variables, which includes data that are available through the SeaWiFS Bio-optical Archive and Storage System (SeaBASS - https://seabass.gsfc.nasa.gov). In addition, he spent some time detailing the long-term (19-year) chlorophyll record, which is assembled from multiple satellite missions; the missions are consistently processed so that the long-term record is coherent. Part of the presentation was also devoted to the MODIS/Aqua calibration update, and the support that is given to other missions such as the Geostationary Ocean Color Imager (GOCI), Sentinel-2, Sentinel-3 Ocean Land Colour Instrument (OLCI), and the Hyperspectral Imager for the Coastal Ocean (HICO).

Chris Proctor, SeaWiFS Bio-Optical Archive and Storage System (SeaBASS) lead within NASA's OBPG, provided updates on SeaBASS, the OBB Field Support Group and High Performance Liquid Chromatography (HPLC) pigment analysis activities. These updates included information on recent protocols that have been developed, the Phytoplankton Taxonomy Working Group, and recently archived data and website changes within SeaBASS.

Antonio Mannino (NASA GSFC) discussed the status of the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission; the PACE mission is fully supported in FY17, and is moving forward as scheduled for FY17. He detailed some of the benefits of the mission, such as the high spatial resolution and the Ocean Color Instrument (OCI), and described some challenges and solution for accomplishing heritage and advanced science with PACE, specifically for ocean colour, clouds and aerosol science. His presentation was followed by that of Emmanuel Boss (University of Maine) who, as the PACE Science Team (SL) Lead, updated the community on the status of the PACE ST. The ST was selected in 2014 and is slated to complete its research at the end of calendar 2017.

Updates on NASA Earth Venture Suborbital-2 activities followed the PACE presentations. Michael Behrenfeld from Oregon State University provided a status report on the Earth Venture Suborbital - 2: North Atlantic Aerosols and Marine Ecosystems Study (NAAMES - https://naames.larc.nasa.gov) project, which is currently preparing for the third cruise in the North Atlantic, slated to take place in September 2017. NAAMES aims at understanding what are the primary ecological and physical interactions governing the annual plankton cycle in the North Atlantic, and its secondary variability, and what properties of plankton assemblages are most important in understanding remote marine aerosols and boundary layer clouds over the annual cycle. Some results from the first two campaigns were shown, which took place during November-December 2015, and May-June 2016.

Alex Gilerson (City College of NY) provided results from the Ship-Aircraft Bio-Optical Research (SABOR) project from July-August 2014. He specifically focused on airborne and shipborne polarimetric measurements taken over open ocean and coastal waters, discussing the relationships between the degree of linear polarization and the attenuation/absorption ratio, which provides additional capabilities for the retrieval of water parameters. In addition, he stressed the sensitivity of top of atmosphere polarization signals to changing water conditions, which are particularly important near the coast.

The final presentation of the OCRT was provided by Zhongping Lee (University of Massachusetts-Boston) on quality assuring satellite remote sensing reflectance spectra and its impact on long-term observations. Dr. Lee stressed the importance of having good quality remote sensing reflectance (Rrs) for deriving all other variables of interest from ocean colour data. He developed a new quality assurance (QA) system from a large collection of high quality in situ hyperspectral (Rrs) data sets. This QA system can be used to objectively evaluate the quality of an individual Rrs spectrum.

3. Keynote Addresses

A total of seven keynote speakers were invited to give presentations throughout the four-day IOCS meeting. All their presentations can be downloaded from the IOCS meeting website at:
http://iocs.ioccg.org/programme/conference-materials/

3.1 Keynote 1: -Paula Bontempi (NASA HQ, USA)

Imaging Earth's Ocean Gardens

Dr. Paula Bontempi has been a biological oceanographer for 25 years. She began her career as a research intern at the New England Aquarium as an undergraduate at Boston College, later entering the fields of phytoplankton taxonomy and physiology in the Department of Oceanography at Texas A&M University. Research on phytoplankton taxa and coupled physical and biological drivers of global and regional phytoplankton spatial patterns led to interests in marine bio-optics and ocean colour remote sensing (mostly because she was certain ocean colour remote sensing didn't work). She graduated from the University of Rhode Island's Graduate School of Oceanography in 2001 with a Ph.D., spending time during her studies as a research fellow at the SACLANT Lab in La Spezia, Italy, taking the famous Friday Harbor Optical Oceanography course, and as a summer intern at NASA's Goddard Space Flight Center. She moved from the faculty at the University of Southern Mississippi's Department of Marine Science to NASA Headquarters in 2003. She is currently the program manager for Ocean Biology and Biogeochemistry at NASA Headquarters, as well as the Lead for NASA's Carbon Cycle and Ecosystems Focus Area and the agency's Carbon Cycle Science research. She is Program Scientist for MODIS-Terra and Aqua, Suomi NPP, PACE, NAAMES (EV-S), HICO, CORAL (EV-S), and the former SeaWiFS mission. She has been honored to be invited to teach the Earth Science module of NASA's astronaut training class every three years. Her favorite job is being a mother, ice skating, roller skating, and skateboarding with her son (and is thankful that the 10-year olds at the skate parks take pity on her). She is glad to put some organic chemistry to use frequently building exploding volcanoes in her kitchen with her son.

The advent of satellite oceanography in the late 1970's allowed Earth scientists to have a wide-angle lens with which to view the vast expanses of life near the ocean's surface. Complementing ship-based snapshots of the ocean's biology and chemistry, satellites provided an ability to have a global, long-term view of the ocean from space. The Earth's aquatic realm is immense, and prior to satellite observations the oceans remained critically under-sampled in time and space. Methods that improve the temporal and spatial coverage offset this problem and infallibly lead to major leaps in our understanding of the oceans. The partnership between in-water (e.g., ship, mooring, drifter) and satellite ocean sampling is essential and must, at a minimum, persist so we can understand and protect our home planet. Such measurements are particularly critical during the current era of varying and rapidly changing climate. Explosive growth of human populations along coastal margins places increasing pressure on dynamic coastal and aquatic ecosystems, modifying natural processes and, in many cases, putting life, health, and property at risk from hazards inherent to the ocean.

Ocean colour remote sensing began with the launch of the Coastal Zone Color Scanner (CZCS) proof-of-concept mission in 1978. What have CZCS and other ocean colour data revealed? To start, we have confirmed that a close coupling exists between ocean climate and primary production. We know that the biologically productive ocean is extremely sensitive to vertical mixing. We have also verified the general Sverdrup/Riley concepts: that the combination of vertical mixing and light in a water column has major effects on the seasonal and temporal appearance of phytoplankton in the ocean. Satellite data of the ocean also allow ready identification of ocean and coastal fronts, which are key sites of high productivity and support tremendous upper trophic level biomass. Global ocean satellite data have also improved our understanding of important interactive relationships between coastal (e.g. squirts, jets, eddies) and oceanic waters, revealing a far greater influence of coastal processes on global ocean basins than anticipated. A global ocean view has additionally enabled previously unattainable synoptic estimates of primary production that can be resolved seasonally and decadally.

In mid-September of 2007, the ocean research community achieved a major milestone as NASA and industry partners marked the collection of ten uninterrupted years of global Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite ocean colour data. Discovery and confirmation of oceanographic phenomena from ocean colour continued with SeaWiFS, and included the impact of sunlight absorption by phytoplankton on the heat budget of the ocean, and elucidation of the linkage between biological production, associated carbon fixation, and climate. These findings and others concerning light penetration, photosynthesis, and phytoplankton growth within the oceans confirmed ideas that were established long before satellites existed. However, the use of satellites grounded these theories concerning the ocean biosphere and placed these theories within the context of Earth's global ecology.

The ten-year time series of SeaWiFS data allows researchers to take the pulse of Earth's living oceans on a global scale in near-real time. Ten years beyond that and with a range of international ocean colour missions and sensors, we now find ourselves standing on the threshold of possible breakthroughs in ocean biological and chemical sciences. Critical to this progress have been advances in our understanding of ocean circulation and cryospheric science aided by additional satellite observations. These data streams support research needs as well as applications (internationally) with regard to defense, fisheries management, environmental and water quality, shipping, and recreation.

The decade of global, research-quality satellite ocean colour data is a significant achievement and rightly celebrated. However, as a community devoted to the stewardship of Earth, we must emphasize the need for a sustained, long-term commitment to continuous, global, research quality colourimetric observations. Despite the profound advances already achieved in understanding our ocean gardens, much of the global ocean remains unexplored and its ecology a mystery. We have a responsibility to continue today's minimum set of key climate observations of ocean biology and chemistry. There is also a clear path to move international ocean colour remote sensing well beyond current capabilities and begin exploring new questions and enabling new discoveries regarding our ocean gardens. The past three decades have given us only a brief glimpse of a constantly changing Earth system in which natural and human factors interplay. We know that ocean ecosystems and their biogeochemical cycles are extremely complex. It is therefore incumbent upon us to inspire and support the next generation of satellites and Earth scientists. Discoveries await in Earth's living oceans. Our path may lead to insights on global change, some perhaps we have not yet considered. However, the time series of satellite ocean colour data to provide the basis of future exploration and enable both these discoveries and climate research is not guaranteed.

To gain insight in to climate variability and change, one requirement is a continuous time series of observations to estimate ocean properties such as phytoplankton chlorophyll a with the radiometric accuracy of SeaWiFS or better. Describing and quantifying new properties of ocean biology and chemistry from satellites allows developments in basic research, such as the mechanistic understanding of phytoplankton physiology, habitat health, and carbon fluxes, to move from the laboratory to the global context of Earth's biosphere. These advances require an evolution in satellite instruments and missions beyond traditional measurements that enable scientific discovery. And it is here that the challenge lies; to ensure that developments in ocean colour remote sensing match the rapid pace of scientific research. Without global ocean colour satellite data, humanity loses its capacity to take Earth's pulse and to explore its unseen world. It is our duty to provide a long-term surveillance system for the Earth, not only to understand and monitor the Earth's changing climate, but to enable the next generations of students to make new discoveries in our ocean gardens as well as explore similar features on other planets.

3.2 Keynote 2: Michael Behrenfeld (Oregon State University, USA)

Dawn of Satellite Lidar in Oceanography

Dr. Michael Behrenfeld did his undergraduate studies in Biology at Eastern Washington University. He then completed a Master's degree in Biochemistry, Statistics, and Environmental Studies and a Ph.D in Bio-optical Oceanography, both at Oregon State University. He then took a post-doctoral position with Dr. Paul Falkowski at Brookhaven National Laboratory in New York and simultaneously taught as an Adjunct Professor at Long Island University, Southampton NY. From there, he worked briefly as an Assistant Professor at Rutgers University in New Jersey before taking a civil servant position at the NASA Goddard Space Flight Center. In 2005, he moved back to his native Pacific Northwest as a Professor in the Department of Botany and Plant Pathology at Oregon State University, where he remains today. Dr. Behrenfeld's scientific interests range from subcellular processes to global scale phenomena. His recent work has focused on the photophysiological signatures of iron stress in phytoplankton, alternative pathways and fates of photosynthate, global expressions of photoacclimation in phytoplankton, phytoplankton blooms, and the use of active lidar sensors for studying plankton ecology. –

Satellite ocean colour measurements have revolutionized our understanding of global ocean ecosystems. However, the passive ocean colour approach has inherent limitations regarding observing conditions for valid retrievals, atmospheric corrections, interpretation of the retrieved ocean signal, and information content on plankton vertical structure. Active lidar measurements address these issues and can provide an excellent observational complement to the passive ocean colour record. While airborne lidar systems have been used for decades to probe ocean ecosystems, only recently have lidar measurements been made from space. The focus of these measurements has been to study atmospheric properties, but they have unintentionally provided a critical 'proof of concept' that quantitative plankton properties can also be retrieved. The satellite lidar era in oceanography has arrived. Now it is time to imagine how much more we can learn with a space lidar actually built for ocean investigations.

3.3 Keynote 3: Kevin Ruddick (Royal Belgian Institute of Natural Sciences, RBINS)

High resolution (1-30m) Optical Remote Sensing of Processes in Coastal and Inland Waters - New Opportunities

Kevin started his studies with a Bachelor's in Mathematics, moving through Masters in Computational Fluid Dynamics and in Marine Modelling to a PhD in Physical Oceanography and Hydrodynamic Modelling. The turning point occurred in 1996 when NASA was preparing to launch SeaWiFS and make the data freely available. Kevin was lucky to get a small project to start in Ocean Colour Remote Sensing. He learned about atmospheric correction by reading papers and the SeaDAS processing source code, and contributed to improving the SeaDAS/SeaWiFS atmospheric correction over turbid waters. Since then he has followed with amazement the incredible progress in both satellite hardware and data processing algorithms, specialising in satellite data algorithms, validation and exploitation for turbid waters. His team now works with a wide range of optical missions, validating and exploiting the mainstream polar-orbiting ocean colour missions, but also extracting information on water constituents from other missions, including geostationary meteorological satellites and high resolution land remote sensing missions.

The advent of satellite optical sensors providing very high spatial resolution data at low or no cost opens up important new applications for coastal and inland waters. High quality Landsat-8 and Sentinel-2 data are now available globally and free of charge at 10-30m resolution. Worldview and Pléiades provide on demand even higher resolution data, down to 1-2m multispectral or even less for panchromatic data. These missions, although designed for terrestrial applications, reveal features and processes in coastal and inland waters worldwide that have been hitherto accessible only to expensive airborne missions.

Emerging applications include the assessment of sediment transport associated with offshore constructions; detection of patchy distributions of algae and floating vegetation; water quality in estuaries, ports and inland waters; small scale discharges; detection of large marine animals; impact of ships; sub pixel scale effects in medium resolution imagery, etc. These applications go beyond the usual scientific research interest since many environmental disasters occurring anywhere in the world could now be seen by ordinary citizens at no cost.

The exploitation of such data also brings new algorithmic challenges and opportunities including: the use of SWIR bands for atmospheric correction; the challenge of lower signal:noise specifications and possible spatial binning techniques; the exploitation of extremely high resolution panchromatic bands; the assessment of the impact of sub-pixel scale effects for medium resolution ocean colour missions; the need to remove/filter sunglint and surface wave effects; the possibility to resolve patchy distributions (suspended matter, surface foam, algal blooms, floating vegetation, etc.); problems of data contamination by cloud and object shadows; validation of narrow swath sensors; processing of data from unusual detector arrangements with possible timing and viewing angle differences; multi-resolution data; and the quantification of limitations on algorithms for retrieval of suspended particulate matter and chlorophyll a concentrations and other parameters when using suboptimal spectral band sets. In this presentation, the state of the art of high resolution remote sensing for coastal and inland waters was reviewed and the many emerging algorithmic opportunities and challenges were outlined using examples from Landsat-8, Sentinel-2 and Pléiades.

3.4 Keynote 4: Heidi M. Sosik (Woods Hole Oceanographic Institution, USA)

Resetting the Baseline for Phytoplankton *In Situ* Measurements: Can we Routinely Measure Phytoplankton Diversity and Size?

Dr. Heidi Sosik is a biological oceanographer and phytoplankton ecologist. She holds Bachelor and Master of Science degrees in Civil Engineering from the Massachusetts Institute of Technology and a PhD in Oceanography from Scripps Institution of Oceanography at the University of California, San Diego. She is currently a Senior Scientist in the Biology Department at Woods Hole Oceanographic Institution (WHOI). Dr. Sosik's honors include a Presidential Early Career Award for Scientists and Engineers in 1996 and WHOI's Senior Scientist Leadership Prize in 2013. She currently serves as Director of the Center for Ocean, Marine, and Seafloor Observing Systems (COSMOS) and Chief Scientist of the Martha's Vineyard Coastal Observatory (MVCO). Sosik is active in many national and international roles including Associate Editor for leading journals and service on strategic planning and scientific steering committees.

Dr. Sosik's research spans phytoplankton ecology and physiology, optical oceanography and ocean remote sensing, modeling, and instrument development. In recent years, she and co-workers have developed automated underwater cell analyzers that dramatically enhance our ability to study microscopic organisms that fuel ocean food chains and sometimes produce harmful algal blooms. Now in commercial production, "Imaging FlowCytobot" is a robotic underwater microscope that counts photosynthetic single-cells in the water and photographs them. The images and associated data are analyzed with customized software to automatically classify the plankton into taxonomic groups.

The introduction of underway and submersible fluorometers in the 1960s and 1970s had an enormous and enduring impact on the *in situ* study of phytoplankton in aquatic systems. While these tools are beautifully suited for rapid assessment of spatio-temporal patterns in biomass proxies, they provide little to no information about critical biological details related to taxonomic and morphological diversity in plankton communities. We know this level of biological diversity is high and important for determining optical and biogeochemical impacts. Can we reset our observational baseline to go beyond chlorophyll observations? Will we look back on this decade as the one that set the stage for a new era of routine *in situ* observations of plankton diversity? This talk provided a perspective on the status, prospects, and challenges in this field, with a focus on cytometric and imaging approaches that enable automated analysis of large numbers individual microbes.

3.5 Keynote 5: Ana Dogliotti (IAFE (CONICET/UBA), Argentina)

Research and applications of ocean colour radiometry in the very turbid waters of the Río de la Plata river (Argentina)

Dr. Ana Dogliotti is head of the Marine Division of the Quantitative Remote Sensing Group at the Institute of Astronomy and Space Physics (IAFE) in Buenos Aires, Argentina. She received a Ph.D. in biology from the University of Buenos Aires in 2007, where she used satellite ocean colour data to study phytoplankton ecology and distribution in the Argentinean Sea. After getting her PhD she worked as a postdoctoral researcher at the Río Grande Federal University (FURG) in Brazil in 2008 and at the Royal Belgian Institute of Natural Science (RBINS) in Belgium in 2011 where she specialized in optically complex turbid waters. Since 2012 she is researcher at the National Research Council for Sciences (CONICET) in Argentina and is currently the coordinator of the ANTARES Network, an integrated Latin American network that focuses in the study of long-term changes in coastal ecosystems sites using in situ and remote sing data. Her research interests are developing algorithms and applications using ocean colour technologies for water quality monitoring and assessment in lakes, estuaries, and oceans. She carries on activities like satellite products validation (using field-based optical instruments and satellite remote sensing data), evaluation of atmospheric correction algorithms and development of bio-optical algorithms to evaluate and improve satellite-derived products in the Argentine Sea and particularly in the optically complex turbid waters of Río de la Plata in Argentina. She is actively involved in ocean colour satellite missions like Sentinel-3 as a member of the S3 Validation Team and is also part of the Scientific Team of the future Argentine-Brazilian Ocean Color Satellite Mission SABIA/MAR.

Retrieving information from ocean colour radiometry in very turbid waters is highly challenging. In particular the Río de la Plata (RdP) river, the widest river in the world located in the eastern coast of South America at approximately 35°S, carries high amounts of suspended particulates which are mainly provided by the Bermejo River, considered one of the most turbid rivers in the world. Very high concentrations of suspended particulate matter (SPM) have been reported ranging from 100 - 300 g m^{-3} with extreme concentrations of ~1,000 g m^{-3}. Interest in retrieving water constituents using remote sensing is mainly motivated by the environmental and economic importance of this estuary, especially for the countries on its shores, Argentina and Uruguay.

One of the first studies performed using remote sensing data in the turbid waters of RdP was a qualitatively evaluation of the atmospheric correction algorithm. However, at that time a direct validation of satellite-derived estimates could not be performed due to lack of *in situ* reflectance measurements. After experience gained in different renowned institutions and in collaboration with the Argentine National Space Agency and the University of Buenos Aires, field campaigns have been performed and the first bio-optical data has been collected in this region allowing a first evaluation of atmospheric correction algorithms. Since then, strong efforts have been put into collecting field measurements and in acquiring new instruments to improve our knowledge of this complex and interesting system. Given the high amount of suspended particulate matter that the RdP exports to the adjacent shelf waters, directly affecting phytoplankton productivity, nutrient dynamics and transport of pollutants, the focus has been put on retrieving SPM and, in particular, turbidity, an optical property more related to reflectance than SPM. A general algorithm to retrieve turbidity from ocean colour data has been proposed and used to analyze 15 years of MODIS-derived turbidity maps. The seasonal and inter-annual variability of turbidity and its relation with Oceanic Nino Index (ONI) and the water discharge of RdP tributaries were assessed.

Given the high amount of sediments, the availability of light is significantly reduced, not ideal conditions for phytoplankton to grow, however intense blooms have been detected in the estuary, like *Microcystis* sp. blooms in November 2012 in Buenos Aires and in February 2015 along Montevideo coasts. However, retrieving chlorophyll concentration in very turbid waters is highly challenging.

More recently, at the beginning of 2016, the city of Buenos Aires suffered a large invasion of floating aquatic Hyacinths (*Eichhornia crassipes*) which could be observed by different ocean colour sensors and for which a floating vegetation index, adapted for turbid waters, has been developed and applied to detect and quantify them.

This presentation drew on experiences gathered throughout the early and present stage of Ana's research in these extreme and optically-complex waters, which has been possible thanks to the support of different institutions and successful collaborations with researchers from different parts of the world.

3.6 Keynote 6: Ronghua Ma (Chinese Academy of Sciences)

Lake Colour/Environment Remote Sensing in China

Prof. Ronghua Ma is the co-head of the Lake Environment Remote Sensing group at the Division of Geographic Information Science (DGIS) and the Lake and Watershed Data Center (LWDC), Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. He has lead a number of important national and international projects on the use of satellite data to monitor lake environment change, with a particular focus on developing new approaches to identifying phytoplankton concentrations, optical conditions and trophic status. These were developed for aquatic ecosystems with complex aquatic and atmospheric conditions and have been used by both researchers and regulatory agencies. He has developed a number of widely used algorithms for the detection of cyanobacteria blooms and optical depths. He designed and manages the in-situ experimental platform for Lake Taihu, obtaining continuous above/under-water surface measurements, as well as an indoor experimental platform to observe dynamics in the vertical distribution of phytoplankton and particulate matter under different conditions. His research and development activities has resulted hundreds of peer-reviewed cooperative papers/books in English/Chinese, and tens of patents. These developments have been used in a Provincial early warning scheme for algal bloom monitoring by remote sensing of Lake Taihu, Lake Chaohu, Lake Hongze, major water resources in the middle and lower reaches of the Yangtze River. Prof. Ma *earned major awards by the Jiangsu Provincial Government in 2008 and in 2012 and by Chinese Academy of Sciences in 2015 for his pioneering work on the lake cyanobacterial bloom monitoring.*

Over the last half century, dramatic changes occurred to China's 2928 lakes (>1 km2 in size), where 243 lakes vanished, 60 new lakes appeared, 254 lakes were downgraded in class, and 98 lakes were upgraded in class. These observed changes are geographically unbalanced. Limited environmental data suggested that such unbalanced changes might be primarily attributed to climate change in North China and human activities in South China, respectively. With the rapid economic development across China especially in eastern China since the 1980s, the environmental issue is being paid more and more attention by public and government. The accelerated nitrogen (N) and phosphorus (P) loadings from the watershed are converged to lakes/reservoirs/coastal waters, which lead to water eutrophication and then to trigger algal blooms. The effective control and management is necessary especially for the human-used waters because of the blooms causing fish and shrimp to death and endangering human health. Prior to the control and management, it is necessary to acquire algal blooms covering area, pigment concentration or algal biomass for both of the real-time monitoring and early warning. Satellite remote sensing is an effective way to monitor water quality because of large area covering, real-time monitoring and frequent and timing revisit.

Almost all types of lake waters in five lake-regions in China, from Tibet Autonomous Region in the west to Heilongjiang province in the east, from Inner Mongolia Autonomous Region in the north to Hainan province in south, and from the mountain to the plain, from the hyper-eutrophic to the oligotrophic, from the turbid to the clear, are measured to not only obtain apparent optical properties (AOP: R_{rs}, E_u/E_d, L_u/L_d, k_d, k_u, k_L) but also inherent optical properties (IOP: a_{ph}, a_d, a_g, b_b). Some parameter ranges for their mathematical functions/models were statistically determined from almost all literatures in Chinese and English. Some new indices for blooms, chlorophyll-a, phycocyanin, suspended particulate matter, such as BNDI (Baseline Normalized Difference Index, BNDBI (Baseline Normalized Difference Bloom Index), PCI (PhyCocyanin Index), NGRDI (Normalized Green-Red Difference Index), CMI (Cyanobacteria and Macrophytes Index) by MODIS, MERIS were mentioned. Additionally, the distribution type/function of lake chlorophyll-a in vertical were also given to estimate the total phytoplankton biomass and to present the spatio-temporal distribution during 2003 to 2013 in Lake Chaohu by MODIS imageries. An algorithm of APA (Algae Pixel-growing Algorithm) is presented to improve the algal blooming area precision, which aims to decompose algal bloom coverage to sub-pixel level.

A model/software integrating cyanobacteria growing, water dynamic and nutrient distribution model. And a software for the lake cyanobacterial blooms monitoring by MODIS were presented, and then a long characteristics of algal blooms, respectively, in Lake Taihu during 2001 to 2016 and Lake Chaohu during 2000-2013, were presented. Finally, a FTP (Field Test Platform) in Lake Taihu for lake colour remote sensing, integrating instruments from the air to the underwater including a HeadWall HyperSpec® VNIR (400-1000nm), a RAMSES Underwater Hyperspectral (RAMSES-ARC/ACC-UV/VIS), a HS-6P, a Flow velocity and direction instrument, and an on-line water quality monitoring system/Cyclops-7 Submersible Sensors (including chl-a, turbidity, water temperature, DO, conductivity, blue-green algae, etc.)

3.7 Keynote 7: Paul DiGiacomo (NOAA/NESDIS, USA)-

Continuity of Ocean Colour Radiometry Data: Operations = Research + Applications + Services + Users

Dr. Paul M. DiGiacomo is Chief of the Satellite Oceanography and Climatology Division in the NOAA/NESDIS Center for Satellite Applications and Research (STAR). He also serves as the NOAA CoastWatch/OceanWatch Program Manager, and is Manager of the Marine Optical BuoY (MOBY) Project. Prior to joining NOAA in 2006, Paul served as Supervisor of the Earth Missions Concepts Group at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, CA, as well as the Discipline Program Manager of the Carbon Cycle and Ecosystems Program Office at JPL. Paul is a biological oceanographer specializing in remote sensing of coastal regions, particularly for water quality applications. He has a B.S. from Penn State University and a Ph.D. from UCLA, both in Biology, and subsequently was a National Research Council (NRC) Resident Research Associate at JPL. Paul is active in a number of inter/national ocean observing, research and application working groups. He serves as Co-Chair of the Group on Earth Observations (GEO) Blue Planet Initiative and likewise the GEO AquaWatch Water Quality Initiative. Paul also serves as Co-Chair of the Ocean Colour Radiometry-Virtual Constellation for the Committee on Earth Observation Satellites, as NOAA Representative to the International Ocean Colour Coordinating Group (IOCCG), as lead for NOAA's JPSS Ocean Environmental Data Records Team, and is a member of the European Space Agency's Sentinel-3 Validation Team.

Space-based ocean measurements are becoming increasingly mature and transitioning into routine and sustained operations. In particular, several space agencies are now, or will soon be, flying ocean colour radiometry (OCR) sensors, and some have multi-satellite mission programs stretching out for decades based on a standard sensor (e.g.,VIIRS on JPSS series, OLCI on Sentinel-3 series). These operational OCR data need to support a broad spectrum of users and their needs. This includes users traditionally considered to be strictly research-oriented as well as supporting applications and services on time-scales ranging from near-real time (NRT) to climate. In this context there are "upstream" (i.e., data provider) as well as "downstream" (intermediate and end-users) challenges and opportunities; these are scientific and technical as well as programmatic and social/behavioral in nature. This keynote will address these issues and identify approaches to better enable and support these communities and help ensure continuity and effective utilization of high quality and fit-for-purpose OCR data products.

There is a prevailing perception that operational satellite missions, and the associated data generated by operational agencies, can only support NRT applications, and that quality is not a primary driver for operational data. This is simply a fallacy. Operational missions must provide routine and sustained (= operational) data of the highest possible quality, supporting both research and user-driven applications and services, on time-scales spanning from NRT to climate, unequivocally underpinned by fundamentally strong science. In this context, operational missions need to implement and maintain integral supporting space-based and ground system infrastructure and associated scientific and technical activities, e.g., extensive pre-launch characterization, calibration/validation, on-orbit maneuvers, and life of mission reprocessing to ensure the resulting data are fit for all users and their needs, not just for NRT purposes. Innovations have and will result from these operational missions as well as from complementary research and development (R&D) missions which are also essential. These R&D missions provide new and improved measurement capabilities, novel approaches, and key discoveries that facilitate synergistic development and will ultimately infuse, benefit and transition into operations.

While innovation will always be an essential need and driver of new and improved capabilities, satellite ocean colour is no longer a “start-up” enterprise. The generation of standard, fit-for-purpose data products has become routine and mature enough to be utilized far beyond the research community that developed them. Even so, usage of OCR data and derived products in routine applications is not as widespread and commonplace as it should be. Several reasons likely contribute to this situation and operational agencies in particular must work to rectify it. One need is to work toward a more mission-agnostic measurement-based approach. Users do not care about specific missions per se, they want accurate, consistent and fit-for-purpose data and derived products, particularly those merging (NB: choose your preferred term here!) multi-sensor satellite as well as in situ data to increase coverage and mitigate data drop-outs (clouds et al.). Routine and sustained assimilation of OCR data in forecast and prediction systems for biological, biogeochemical and physical applications and services is also a crucial yet still under-developed need and opportunity. Finally, there needs to be greater focus by data providers on the overarching, end-to-end value chain, moving from OCR observations and data to derived products and information that provide actionable knowledge for users.

4. Breakout Session Reports

A total of 9 breakout workshops (3 parallel sessions at one time) covering a wide range of topics was conducted at the IOCS-2017 meeting as follows:

- ***Monday 15 May 2017 (Breakout Workshops 1 – 3)***
    - **Breakout 1:** Quantifying the benefits and challenges of hyperspectral remote sensing: Looking towards the future of space-borne radiometry
    - **Breakout 2:** *Trichodesmium* detection from space and ecological role in the ocean: A review of the state of science, challenges and ways forward
    - **Breakout 3:** Ocean colour vicarious calibration: Community requirements for future Infrastructure

- ***Tuesday 16 May 2017 (Breakout Sessions 4 – 6)***
    - **Breakout 4:** Remote sensing of inland and coastal waters: Current status, challenges, research priorities, and end-user engagement
    - **Breakout 5:** Ocean colour algorithms and models for Southern Ocean pigments and primary production
    - **Breakout 6:** Active remote sensing for ocean colour

- ***Wednesday 17 May 2017 (Breakout Sessions 7 – 9)***
    - **Breakout 7:** Multi-water algorithms and algorithm performance assessment
    - **Breakout 8:** Advances in protocols for water-leaving radiance and related parameters
    - **Breakout 9:** Carbon from ocean colour radiometry

A summary report from each of these breakout workshops is given below, highlighting the community consensus on key issues addressed by each workshop, and including advice for the space agencies. This type of feedback will help to improve communication between the scientific research community and the space agencies by focusing on the value and impact of new research avenues.

4.1 Breakout 1: Quantifying the benefits and challenges of hyperspectral remote sensing: Looking towards the future of space-borne radiometry

Co-chairs: Ryan Vandermeulen (SSAI/NASA), Kevin Turpie (UMBC/NASA), Astrid Bracher (Alfred Wegener Institute), Susanne Craig (Dalhousie U.), Cecile Rousseaux (USRA/NASA)

The future of space-borne hyperspectral radiometry will enable unprecedented synoptic measurements of the ocean and atmosphere that have potential to resolve benthic substrate types, improve atmospheric correction, characterize and quantify specific aerosols, enhance bio-optical retrievals, gauge coral reef health, and distinguish phytoplankton functional types (PFTs) on global scales. Each new "product" offered by hyperspectral measurements opens up new research questions and sheds light on oceanographic processes that were previously obscured by a lack of spectral band coverage. The purpose of this breakout session was to initiate discussions on the collective *challenges* and knowledge gaps in the field of hyperspectral remote sensing as well as facilitate a critical discussion on the mitigation of these challenges into the future. The session was divided in three sets of talks and subsequent moderated community discussions addressing: 1) ocean algorithm development, 2) atmospheric correction, and 3) sensor design considerations.

Part 1: Hyperspectral algorithm development

Talk 1: Astrid Bracher (AWI) - Scientific Roadmap for Phytoplankton Diversity from Ocean Colour
Talk 2: Heidi Dierssen (U. Conn) - Out-of-the-Box Applications for Hyperspectral Remote Sensing

Discussion 1: Common challenges related to the utilization of hyperspectral data vary across sub-disciplines and users. From a management perspective, there are challenges associated with creating viable end user requirements without the availability of established and vetted hyperspectral data products. Future work is required in order to fully catalogue metrics of performance when using hyperspectral data, including a characterization of the implications associated with a lack of spectral band coverage and radiometric sensitivity, and robust error estimates from higher order products, such as PFTs. Much work has been done in the way of algorithm development using band ratio, semi-analytical, and inversion (PhytoDOAS) techniques, but there are many applications using hyperspectral data that may be uncovered by further exploiting statistical techniques and machine learning. In addition, *in situ* instrumentation advances including hyperspectral backscatter measurements, compact flow cytometry and microscopy, permissive optical sensors designed for turbid waters, and a global network of hyperspectral validation platforms across varying water types would help develop the theoretical background for inversions and further parameterize radiative transfer models. Discussions highlighted the need to establish a framework for clear traceability of errors, increase the utilization of current hyperspectral satellite data as a test bed (SCIAMACHY, HICO, etc.), improve communication between data providers and users, and continue to mature the development and curation of hyperspectral optical databases and products (e.g. PFTs) for use in algorithm development.

Part 2: Atmospheric correction of hyperspectral data

Talk 1: François Steinmetz (HYGEOS) – New approaches to Atmospheric correction
Talk 2: Amir Ibrahim (USRA/NASA) – Atmospheric correction of HICO

Discussion 2: One of the main challenges associated with atmospheric correction (AC) of hyperspectral ocean colour data is to compensate for absorbing gases (e.g. water vapor, oxygen, ozone, and nitrogen dioxide) as well as inelastic scattering processes (e.g. Raman scattering), which have the potential to significantly impact the quality of ocean colour returns if not properly characterized. There is still room for growth and maturity in hyperspectral AC, such as through targeted spectral sub-sampling (1 nm or less) of specific regions, increasing parameterization of ocean-atmosphere models, developing varying AC methods for different regions (e.g. high solar zenith angles), or adopting a decision-tree approach to AC as an alternative to full inversions. The feasibility and advantages of extending measurements into the UV was discussed, including the detection of NO_2 absorption peak, and using UV bands as a ground point to help constrain NIR-band aerosol model selection from over correcting (UV water leaving radiance should never be negative). Ocean applications of extending measurements in to the UV include the possible detection of Mycosporine-like amino acids to help distinguish PFTs, as well as better CDOM estimates. Challenges associated with moving into the UV include high uncertainty in solar irradiance in the UV, as well as weak calibration sources. Discussions highlighted the need for ocean scientists to engage more with atmospheric scientists, and potentially abandon a "one-size-fits-all" approach to AC.

Part 3: Hyperspectral feasibility and sensor design considerations

Talk 1: Arnold Dekker (CSIRO) - Feasibility Study for an Aquatic Ecosystems Imaging Spectrometer

Discussion 3: There is a perpetual competition between the spectral, spatial, temporal, and radiometric performance of a sensor that must be considered when designing a mission (so that sufficient photons are collected). The priority of each design component has an impact on science, as well as the cost of a mission, and will change depending on end-user requirements. For coastal and inland applications, there is a strong need to prioritize the spatial resolution in tandem with the spectral resolution in order to inclusively characterize changes in more aquatic environments across global scales. However, sufficient temporal resolution is also required to characterize diurnal/tidal processes as well as reduce sampling bias, and the Signal-to-Noise Ratio (SNR) of the instrument must be sufficient to provide quality data returns. Overall, there is a distinct advantage in shifting this weight to support higher spectral resolution, as more spectral channels can help fully characterize changes in reflectance across multiple water types and varying concentrations of water constituents. However, in order to support a consistent and reliable product, there is a clear need for collection of high quality *in situ* data, as well as on-board lunar calibrations to help characterize channel degradation over time. Discussions among managers highlighted the need to create more mature end-user requirements to help drive sensor design, which, in turn, may require an investment in the science and the creative exploitation of hyperspectral data capabilities (e.g. machine learning).

4.2 Breakout 2: *Trichodesmium* detection from space and ecological role in the ocean: A review of the state of science, challenges and ways forward

Co-Chairs: Ajit Subramaniam (Columbia University), Cécile Dupouy (IRD, France), Lachlan McKinna (NASA GSFC)

Trichodesmium is a colonial cyanobacterium that is capable of fixing atmospheric dinitrogen. The new nitrogen that enters the marine ecosystem through autotrophic nitrogen fixation contributes towards the sequestration of atmospheric carbon dioxide. *Trichodesmium* can be considered a "charismatic microbe" for remote sensing in that it is one of the few microbes that can be seen distinctly from space. Blooms of this organism can cover thousands of square kilometers and have been documented in ocean colour satellite and space shuttle imagery.

But despite the fact that these blooms can be anecdotally seen in true colour images, this charismatic microbe is also enigmatic and attempts to develop algorithms for detecting and quantifying this organism on a routine basis globally have been challenging. Over the past three decades, the optical properties of this organism have been studied and several different optical models have been developed for detecting blooms and sub-bloom concentrations of *Trichodesmium,* however, this problem remains unresolved.

A breakout workshop on Remote Sensing of *Trichodesmium* was organized at the International Ocean Colour Science Meeting held in Lisbon, Portugal in May 2017. The objective of this workshop was to take stock of the current state of science for remote sensing of this organism, identify the challenges, develop a community consensus on ways forward. The contributions and exchange of information between two related communities – biogeochemical modelers and the freshwater cyanobacterial remote sensing experts were explicitly sought. Ajit Subramaniam introduced the problem, providing a historical perspective as well as framing the discussion that followed.

The modeling perspective was presented by Stephanie Dutkiewicz who provided the ecological context for nitrogen fixation, explained how her group represented nitrogen fixation in general and *Trichodesmium* in particular in the model. She emphasized that it was important to recognize both that *Trichodesmium* was not the only diazotroph in the model and that different diazotrophs were represented with different traits and thus showed slightly different global distributions. Although *Trichodesmium* is the best known and best studied marine nitrogen fixer, there are other diazotrophs that could be more important at least on a regional basis. She also emphasized the sparseness of validation data for biogeochemical models and thus the importance of robust methods to detect and map global distributions of *Trichodesmium*, both to improve our understanding of the nitrogen and carbon cycles but also to validate the assumptions about the traits made in the model.

Sara Rivero-Calle presented the global distribution of *Trichodesmium*. Although this organism is thought to be found only in tropical and subtropical waters, she made a convincing case that temperature was probably not a good discriminant, having found this organism in colder waters. She pointed out that the distributions were often very patchy, causing a major challenge for both remote sensing as well as ground truthing of this organism. She also pointed out that much of the work on remote sensing of this organism focused on bloom conditions but that it was biogeochemically significant even at much lower sub-bloom concentrations and that these populations were not accounted for in satellite based estimates. In subsequent discussion, the challenges of sampling of this organism were brought out. Sampling biases included discarding replicates for biomass and bio-optical measurements that contain *Trichodesmium* because even a single colony can cause large variability, particularly in oligotrophic waters. In addition, the difficulties of sampling in slicks was also discussed. It was pointed out that even in a slick, *Trichodesmium* only contributed to a proportion of the total chlorophyll or carbon and we don't have a good understanding of how this proportion changes. As noted in the recommendations below, the discussions pointed to the need for community consensus on best practices for validation of algorithms. For example, models often use carbon biomass as a currency but bulk measurements of particulate organic carbon were very challenging when *Trichodesmium* was present on the filters.

Cecile Dupouy presented her work on the inherent optical properties of *Trichodesmium*. As a colonial organism with gas vesicles, *Trichodesmium* has unique optical properties that collectively should make it easier to distinguish it from other phytoplankton but also presents challenges for measuring and scaling from laboratory measurements to field applications. For example, the absorption spectra of isolated colonies have a unique shape but this is almost never encountered in field samples except for the high absorption due to Mycosporin like Amino Acids (MAAs) in the ultraviolet part of the spectrum. Cecile also pointed out the challenges of patchiness – apart from the spatial patchiness issue, she said that *Trichodesmium* can also be temporally patchy where it appears at the surface in the morning but gets mixed down later in the day due to diurnal winds or migration behavior. Thus the overpass time of the sensor could also make a difference to what was being detected and this also presents additional challenges for validation of algorithms. She presented the details of her work in the waters around New Caledonia including results from a recent cruise where an 8-fold variation in near surface concentrations were found in a 24 hour period.

In the general discussion that followed, the mismatch between the biogeochemical definition of Phytoplankton Functional Types (PFTs) and optical definitions of PFTs was pointed out. While *Trichodesmium* is important biogeochemically as a nitrogen fixer, it does not fit into any of the commonly accepted optical definitions of PFTs. As a colonial organism, its size is more in line with larger diatoms and dinoflagellates. However, its pigment complement is that of cyanobacteria. It was also pointed out that HPLC techniques commonly used for PFT definitions do not work well for *Trichodesmium* since HPLC does not measurement the phycobilipigments found in this organism.

Lachlan McKinna presented the current state of satellite remote sensing algorithms for *Trichodesmium.* He reiterated the challenges of validating algorithms, pointing out both the problems of patchiness in the horizontal but also in the vertical plane – surface slick are often found just in the upper several centimeters and volumetric expressions of concentration may not be relevant. He said that in-water radiometers could completely miss the optical effects of surface slicks, reiterating the importance of proper above water remote sensing reflectance measurements but at the same time pointed to the challenges of making such measurements without disturbing the waters with the slicks. He suggested that the community consider areal estimates of abundance for slicks. The importance of spectral and spatial resolution of satellite sensors was emphasized. He showed how information was lost due to spatial averaging when the resolution decreased from 30 m to 1 km to 4 km. He pointed out that a lot of the algorithms that used temporally binned 4 km or 9 km level 3 data would not be able to resolve *Trichodesmium*. He also presented the current work being done on hyperspectral approaches to atmospheric correction on behalf of Amir Ibrahim who was not able to attend the meeting. An important take home message was that while hyperspectral remote sensing approaches detecting and quantifying *Trichodesmium* were critical, these also present challenges for atmospheric correction due to atmospheric absorption features in parts of the spectrum that may be unique to this organism. Surface slicks of *Trichodesmium* also exhibit very strong water-leaving radiance in the near-infrared, similar to land vegetation, and the contemporary “black pixel assumption” used for atmospheric correction cannot be applied in this case. Additional challenges for atmospheric correction that need to be dealt with for unambiguous detection of *Trichodesmium* include dust plumes and thin clouds.

Ronghua Ma presented very exciting results of the work being done in detection, modeling, and prediction of cyanobacterial blooms in fresh water lakes such as Lake Taihu in China. His group has developed a Phycocyanin Index (PCI) that allowed them to map the cyanobacterial blooms. He said that this index was not as sensitive to atmospheric correction issues such as thin clouds and aerosols or in-water interference by Coloured Dissolved Organic Matter. But he pointed out that vertical distributions were still a challenge and required sophisticated in-water instrumentation and a cabled observatory for validation.

Recommendations

In situ/modelling

Needs for a common understanding in the community as to what appropriate measurement techniques and units are for validation:

1) Need to understand the effects of fractal behavior of slicks by synoptically sampling from the sub-meter to the 1-km scales;
2) Need for hyperspectral above-water reflectance data for both validating tricho algorithms but also to improve the atmospheric correction techniques;
3) Need to determine appropriate ground-truthing measurements:
    a. tricho counts along with bio-optical measurements in slicks and in bulk water to separate the effects of tricho from background,
    b. standard techniques to measure phycoerythrin concentrations.

New sensors and satellites

1) Need to have an appropriate operational (i.e. not a scene-by-scene approach) atmospheric correction for surface slicks, appropriate spectral bands to resolve phycoerythrin and spatial resolution to detect slicks

2) Geostationary satellites could resolve temporal variations of biomass and this maybe the key for models

3) It is important to point out that with the exception of the spectral band requirement (because phycoerythrin-rich marine cyanobacteria will have a different absorption and inelastic scattering/fluorescence properties than freshwater phycocyanin rich cyanobacteria), the other requirements are valid for freshwater lake cyanobacteria as well. Detecting and understanding the dynamics of freshwater cyanobacterial blooms have tremendous economic and human health implications.

Acknowledgements
We wish to thank the IOCCG for hosting this breakout session on *Trichodesmium* remote sensing and the attendees who contributed to the valuable discussion. We also wish to extend our gratitude to Prof. Chuanmin Hu and Prof. Tiit Kutser who contributed material to the workshop and provided valuable in-depth advice on the topic.

4.3 Breakout 3: Ocean Colour Vicarious Calibration: Community Requirements for Future Infrastructures

Co-Chairs: Constant Mazeran (Solvo), Christophe Lerebourg (ACRI), Sean Bailey (NASA/GSFC)

Goal and Programme of the Workshop

System Vicarious Calibration (SVC) is recognized as a crucial component of all ocean colour (OC) missions to achieve global, climate quality, Ocean Colour Radiometry (OCR). The purpose of the IOCS workshop was to specifically review the requirements of future SVC infrastructures that shall support recent and future OC missions like ESA/Sentinel-3 and NASA/PACE. It was organised as a forum open to the OC community to ensure consensus, international harmonization and rationalization of efforts in the next decades. The meeting was built upon three activities initiated by the Space agencies after the first IOCS meeting of 2013, and summarized at the beginning of the breakout session:

- The NASA/ROSES call of 2014 addressing SVC for PACE;
- The ESA/FRM4SOC project started in 2016, which has organized in February 2017 a workshop on "Options for future European Satellite OCR Vicarious Adjustment Infrastructure for the Sentinel-3/OLCI and Sentinel-2/MSI series";
- The on-going EUMETSAT project on "Requirements for Copernicus Ocean Colour Vicarious Calibration Infrastructure", a European Commission Copernicus study.

This short introduction was followed by a quick status of four main SVC instrumental concepts, under operation or development:

- The HYPERNAV concept (presented by Andrew Barnard, Sea-Bird Scientific);
- The HARPOONS concept (presented by Sean Bailey on behalf of Carlos Del Castillo, NASA/GSFC);
- The MOBY-NET concept (presented by Ken Voss, University of Miami);
- The BOUSSOLE concept (presented by David Antoine, CNRS-LOV & Curtin University).

Then, most part of this workshop was a community discussion to review and justify the requirements of these infrastructures. It was guided by some of the most important items covered in the EUMETSAT requirement document (sent in advance to the participants) and encompassing the SVC process, the field infrastructure, the data processing and the operational aspects. Conclusions of this discussion are briefly reported hereafter.

Recommendations and key messages

Justification of SVC – An essential justification for implementing a SVC relies on the necessary combination of multiple space missions to conduct climate change studies, with a harmonization and a traceability of the radiometric calibration over long-term data records. It was agreed that the SVC is today only justified for open-ocean clear-waters, where the required uncertainty of 5% in OCR (blue bands) is demonstrated (for the other bands, the uncertainty is spectrally correlated when using a Gordon & Wang atmospheric correction). Participants also discussed how to illustrate this need for a SVC, through a self-explanatory image intended to decision-makers; various ideas were suggested, such as a validation plot against *in situ* data with and without applying SVC gains; multi-mission time-series without applying SVC gains; preliminary results of OLCI without applying SVC gains, showing biases with respect to VIIRS and MODIS.

Requirements through uncertainty – The rationale for defining requirements through the end-to-end uncertainty budget of the SVC gains, as done in the EUMETSAT document, was fully accepted. It was also acknowledged, though, that the quantification of required uncertainties of all sub-components of the SVC process is not always feasible. In this respect, it was recommended to write definitive numbers in public documents when they cannot be perfectly justified. For instance, the detailed uncertainty budget provided in the Excel companion file of the EUMETSAT report should be clearly presented as guidance. Using a relaxed terminology was discussed (*e.g.* "target requirement"); however the overall uncertainty of SVC gains should be considered as a strict requirement, considering that differences as small as 0.3% in the gain value induce a bias of 5% in OCR for the 'blue/green' spectral region. The difficulty to rigorously justify a requirement on the OCR stability was also acknowledged, although 1% per decade (blue bands) seems a reasonable upper limit. Uncertainty of the models used in the SVC process (in particular the atmospheric correction) was questioned: it was recommended to take into account this uncertainty in the choice of the SVC site (*e.g.* to minimize the effects of the atmosphere), but not further in the computation of vicarious gains, by principle of the SVC (sensor + algorithm).

Aerosol characterization – All the participants agreed with the need to well characterize the atmosphere over the SVC site, in particular for the aerosols. Understanding their impacts on the signal measured at top of the atmosphere (TOA) is essential to ensure the applicability of the SVC established at a given site to other regions. Furthermore, if the aerosol measurements are not included in the computation of SVC gains, they remain still important in the screening process; this also justifies the need for their characterization and regular monitoring at the SVC site.

Detailed review of technical requirements – The format of the workshop did not allow a detailed discussion on the specific technical requirements. These are expressed in the literature and, notably, in the EUMETSAT draft report sent to the participants. The whole OC community is strongly invited to give feedbacks on this public report before July 1st, 2017 by contacting Constant Mazeran (constant.mazeran@solvo.fr) or Ewa Kwiatkowska (ewa.kwiatkowska@eumetsat.int).

Operational aspect – Participants insisted on the human aspects necessary for ensuring an operational SVC service. Maintaining the expertise over the long term should be a priority of any SVC programme.

International collaboration and short-term future for SVC – On the NASA side, the follow-up of the ROSES project, ending in September 2017, remains unknown at the date of the workshop. On the European side, EUMETSAT is planning to open an ITT in the course of 2017 for defining a first design of the SVC infrastructure within the Copernicus programme. IOCCG has created a new working group on SVC, which will contribute to international collaborations; participants agreed that the monograph in preparation should recommend the agencies to further fund the required development of SVC infrastructures.

***Main concluding message to the Space Agencies* –** Participants of the workshop have agreed on the following statement: "*Main priority for operational SVC is to ensure sustainable resources (staff, knowledge and infrastructure) to build long-term data series over multi-mission lifetime"*.

4.4 Breakout 4: Remote Sensing of Inland and Coastal Waters

Co-Chairs: Wes Moses (NRL), Carsten Brockmann (Brockmann Consult), Andrew Tyler (Univ. of Stirling), Quinten Vanhellemont (RBINS, Belgium), Nima Pahlevan (NASA GSFC), Steve Greb (DNR, Wisconsin), Paul DiGiacomo (NOAA)

Rapporteurs: *Henry Houskeeper (UC Santa Cruz), Andrea Hilborn (Univ. of Victoria), Christiana Ade (NCSU), Brice Grunert (Mich. Tech. Univ.), Jeremy Kravitz (Univ. of Cape Town)*

Context

Remote sensing of inland and coastal waters is more complicated than that of open ocean waters due to the complexity of specific inherent optical properties of the water and the overlying atmosphere, which make it very challenging to derive water-leaving radiances and develop bio-optical algorithms that can perform consistently well in retrieving biophysical parameters. The smaller spatial extent, optical complexity, and temporal dynamism of inland and coastal waters often make the spatial, spectral, and temporal resolutions of current sensors inadequate for monitoring water quality. At the global scale, these challenges are compounded further by inconsistencies in the acquisition, processing, and quality control of *in situ* and satellite data. Nevertheless, in spite of these and other challenges, there is an urgent need for reliable remote sensing techniques to operationally monitor these important aquatic resources and a number of projects have made significant progress in this area. This workshop provided a forum to discuss the challenges, report the progresses made, and identify research priorities for operational remote sensing of inland and coastal waters.

Details

The session was composed of presentations and discussions around four aspects of remote sensing of inland and coastal waters

***(i) Atmospheric Correction** -What are the current challenges in atmospheric correction of inland and coastal waters and what advances are needed in algorithm development/validation?* (Nima Pahlevan)

The talk addressed current capabilities and challenges in validating aerosol retrievals and using appropriate aerosol models, the significance of trace gas contribution to the remote sensing signal over waters near industrialized cities, the impact of target geometry and surrounding topography on adjacency effects in remote sensing data regardless of the spatial characteristics of the sensor, the role of sensor design and illumination/viewing geometry on sun glint effects, and the impact of calibration uncertainties on the errors in the retrieved remote sensing reflectance.

The following recommendations were suggested in the discussion that followed:

- Identify potential new validation sites and set up hyperspectral AERONET/AERONET-OC stations in other coastal and inland water bodies;
- Encourage researchers to collect optical properties of aerosols/trace gases together with bio-optical data and share the data on public databases such as SeaBASS and Limnades;

- Apply spectral unmixing approaches to correct for adjacency effects from adjacent land/ice;
- Explore glint mitigation strategies such as tilting the sensor or shifting the orbits to maximize the utility of satellite observations; also explore beneficial uses of sun-glint signal.

(ii) Bio-Optical Modeling -*Considering the extreme and widely varying bio-optical properties of inland and coastal waters, what is the best approach for developing operational algorithms?* (Tim Moore – Univ. of New Hampshire and Evangelos Spyrakos -Univ. of Stirling)

The presentations addressed extreme bio-optical conditions encountered in inland and coastal waters, wide spatio-temporal variations in bio-optical properties within and across water bodies, difficulties in collecting good *in situ* data in waters with extreme conditions, classification of optical water types based on bio-optical properties, and application of water-type-specific blended algorithms for retrieving biophysical parameters.

The following are some of the points raised in the discussion that followed:

- Algorithms should be developed globally but applied locally, i.e., the approach should be able to handle the level of variations observed globally but should be applied with localized adjustments depending on the particular water body of interest, for example using Optical Water Type classification and developing ensemble approaches;
- There is a need for more *in situ* data to evaluate the performance of global algorithms in local water bodies;
- More support is needed from the community to make *in situ* data easily available and accessible for evaluating atmospheric correction and bio-optical algorithms; data sharing and data publication should be encouraged;
- There is a need for standardization of procedures for *in situ* data collection in inland waters, but extreme conditions pose challenges to adoption of a uniform protocol;
- Measurements of mass-specific Inherent Optical Properties (sIOPs) are critical for algorithm development.

(iii) Sensor Characteristics - *What are the desired sensor characteristics for remote sensing of inland and coastal waters?* (Wes Moses)

The presentation addressed four aspects of sensor characteristics: (a) spatial resolution, (b) spectral resolution, (c) Signal-to-Noise Ratio (SNR), and (d) temporal resolution. The following were the main take-away points: a spatial resolution finer than 200 m is required to capture spatial variability of bio-optical properties in coastal waters; small inland water bodies require a finer resolution; a spectral resolution of 5 nm would be ideal; there is a trade-off amongst spatial resolution, spectral resolution, and SNR, which must be evaluated in terms of its effect on retrieval accuracies when deciding on these characteristics for a mission; the required temporal resolution largely depends on the application and the particular water body.

The discussion that followed also covered issues related to data product consistency and continuity. The following are some of the points raised in the discussion:

- Spatial resolution takes precedence over the other characteristics because pixel purity is very important for inland and near-shore waters;

- While there is always a desire for finer spatial resolutions, quantitative studies evaluating the impact of various spatial resolutions on retrievals are needed in order to establish reasonable limits on desired spatial resolution;
- Spectrally convolve hyperspectral data from future missions to generate legacy multispectral data products;
- Promote consistency in pre- and post-launch sensor calibration across multiple missions and multiple space agencies to enable robust blending of data products from a constellation of satellites.

(iv) End-User Engagement - *What are the challenges and technological gaps in operational product generation, validation, data dissemination, capacity building, citizen education, and user engagement for operational monitoring of inland and coastal waters?* (Carsten Brockmann and Steve Greb).

Carsten provided a brief description of the Copernicus Inland Water Service, which provides the following inland water products globally: surface temperature, reflectance, turbidity, and trophic state using data from MERIS, OLCI (Sentinel-3) and MSI (Sentinel-2). Steve introduced the GEO AquaWatch working group, whose mission is to improve water quality in coastal and inland waters through effective monitoring, management, and decision making.

The following are some of the points mentioned in the discussion that followed:

- Developing countries have a greater need for operational monitoring of water quality; the capability exists to deliver water quality products for these regions, but validation of the products is a challenge due to scarcity of *in situ* data;
- The science community needs to better understand the needs of the management community and needs to showcase what products can be provided. The level of uncertainty that can be accepted needs to be better defined;
- Building trust with the management community will require documented protocols, validation efforts and rigorous QA/QC . Establishment of an international group to address these issues is encouraged, which could be a future task for AquaWatch;
- Citizen science measures should be encouraged for generating *in situ* data for product validation (such measures have been successful in Brazil and Peru).

4.5 Breakout 5: Ocean colour algorithms and models for Southern Ocean

Co-Chairs: Maria Vernet (Scripps Institution of Oceanography), Mati Kahru (Scripps Institution of Oceanography), and David Antoine (Curtin University, Australia).

Goal: *To define current understanding, new data that may be coming on line, role of new technologies, and concepts for better international cooperation for observations, data sharing, algorithm development and implementation of alternative algorithms in satellite data processing for the Southern Ocean.*

One sentence: "Is the Southern Ocean different from the others? Combining active and passive remote sensing, BGC floats and models towards quantifying SO carbon sources and sinks and their decadal changes".

Key Questions discussed during the workshop

Introduction - Defined as the area south of the subtropical convergence that can reach as far north as ~35^{o}N in the South Pacific, close to the Chilean coast, and in the South Atlantic, at the Argentina-Brazil-Uruguay coasts, this area includes more than 30% of the world's oceans. From 35^{o}S to 75^{o}S at Antarctica's continental coast, there is a complex series of fronts, a large gradient in air and ocean temperatures, sun angle and day length resulting in a complex environment. Alternatively, the polar regions of the Southern Ocean have been defined as south of the Polar Front or south of 60^{o}S. This region is characterized by the largest current on Earth, the Antarctic Circumpolar Current, circulating around the continent, powered by the westerly winds and subject to a series of low pressure systems, between 5 or 6 circulating around the continent. Sea ice covers a large proportion of ocean water around the continent, with maximum extent in August, and minimum in February/March. The combination of sea ice, high solar zenith angles, and darkness or near darkness for a significant portion of the year provides an environment challenging to satellite ocean colour retrievals.

Goal - The major interest is to constrain the carbon cycle in the Southern Ocean region, in particular south of 55°S or south of the Polar Front. For that purpose an **accurate top of atmosphere ocean surface reflectance spectrum at high solar angles** is needed.

For the carbon cycle, possible areas of improvement were identified as:

- Better interpretation of the particulate backscattering (b_{bp}) signal
- More on the b_{bp} *vs*. POC relationships
- More accurate and more extended data on phytoplankton biomass (chlorophyll *a*, carbon)
- Modeling of Phytoplankton Net Primary Production (NPP) and phytoplankton growth, both chlorophyll- and carbon-based
- Determination of Net Community Production defined as (NPP - Respiration)
- Determination of Carbon Flux out of the Euphotic Zone / Upper Mixed Layer
- Determination of particulate inorganic carbon, i.e. calcite in coccolithophorids
- Determination of gas exchange with atmosphere (CO_2, O_2).

In this context, a series of questions were discussed:

1. ***The first order limitation is estimation of phytoplankton abundance and distribution from space during winter months and periods of high solar zenith angles.***
   Results from CALIOPE and other future laser sensors from space (LIDARs) open up a new opportunity for determination of phytoplankton abundance year-round. Therefore, development and launching of ocean-dedicated space LIDARs, e.g. MESCAL is supported. In addition, passive ocean colour sensors can improve their coverage or the quality of their derived products through:
   a) Improved atmospheric corrections, e.g. application of POLYMER or other improvements (e.g. spherical geometry)
   b) Better determination of flags in NASA algorithms in the presence of sea ice, edge effects, cloudiness, and sea state.
   c) Better understanding of the effect of bubbles on the reflectance spectrum
   d) An increase in year-round field measurements is also needed: Profiling floats (BGC Argo floats, with biogeochemical sensors), optical sensors added to existing moorings in South Pacific and South Atlantic (Ocean Observatory Initiative, OOII).

2. ***Discrepancies among Southern Ocean algorithms (NASA's global algorithms)*** - The great variability in results with respect to the accuracy of chlorophyll (chlor_a) determination using either NASA's OC4 or OCI (i.e., band ratio or band difference algorithms) needs to be understood. More research is needed in:
   a) Determination of causes in these differences: regional, seasonal, Fe availability, etc.
   b) As above, year round measurements with BGC Argo floats or similar
   c) Improve white cap correction: In NASA algorithm white caps are included as aerosols for winds >10 m/s. Given winds in the Southern Ocean are usually higher than this threshold, a better correction would improve accuracy.

3. ***Southern Ocean Algorithm development -*** Are the data sets available to calibrate/validate reflectance spectrum/fluorescence signals? Limitations to date include the fact that most of the data available is from summer months, the sampling is usually targeted, not covering large areas and different oceanic domains, resulting in low data density compared to other regions. Recommendations to overcome these limitations:
   a) Start deployment of optical sensors in "GO" Ships;
   b) Increase availability of optical variables with vertical resolution (e.g. BGC Argo floats);
   c) Use of imaging flow cytometry on ships and moorings to obtain phytoplankton composition and size with automated systems;
   d) Establishing a SIMBIOS-type optical van that can be deployed on ships of opportunity;
   e) Add above-water radiometry in future projects;
   f) Better determination of phytoplankton carbon (C_{phyto}) to improve Carbon:Chlorophyll ratios used in models;
   g) Increase Calcite estimation at and north of the Polar Front region;

h) Larger accessibility to data by collecting all in-situ data and submitting to SeaBASS or, alternatively, creation of a Southern Ocean database;
i) Hyper-spectral backscattering sensor to understand differences between SO and northern latitude;
j) LIDARs, again (space and on board ships);
k) Autonomous Vehicles (Gliders, AUV, etc.) in addition to field data from cruises outfitted with optical sensors to extend areal and temporal coverage and understand optical variables during transition periods;
l) SO Modeling is essential for this low-sampled region in order to i) improve sampling and ii) complete spatial and temporal coverage;
m) Better international coordination of data integration and analysis.

4. ***International community plans for future field campaigns to advance our understanding of Southern Ocean carbon cycle using satellite ocean colour and other observations.***

a) Urge all owners of ocean colour related in situ data to submit their data to SeaBASS;
b) Creation of a SO ocean colour community;
c) Share within the community a list of recent and future field campaigns to make optical measurements, e.g.,
   - ACE (2016-2017 Antarctic Circumpolar Experiment, International) organized by the Swiss Polar Institute (Principal Investigators, D. Antoine & S. Thomalla & S. Hooker).
   - ICESSOC (International Coordinated Experiment of the Southern Ocean Carbon Cycle, USA), B.G. Mitchell, Scripps Institution of Oceanography;
   - SOCLIM (2016 Kerguelen, France), A. Bricaud, France;
   - CSIR cruises on board R/V Agulhas (2018, South Africa), S. Thomalla, South Africa;
   - SOCCOM (80 floats with bio-optics, NSF/NASA), E. Boss, U. of Maine, USA;
d) Improve coordination within national agencies, (e.g. in USA better coordination between NASA, NSF and NOAA) and between nations for ships, aircraft and *in situ* autonomous systems;
e) International effort, perhaps joint between IOCCG and SCAR, to define an international 10-year plan for robust constraints on NCP for the S. Ocean

5. ***Improving the understanding of relationships between surface satellite observations and organic carbon export.***

Carbon available for export can be quantified from the Net Community Production (NCP), defined as Net Primary Production – Community Respiration. To date, NCP estimated from Ocean colour does not agree with estimates based on atmospheric gases unless the SPG-ANT correction is employed (Nevison et al. 2012). The EXPORTS project does not cover high-latitude ecosystems, i.e. the Southern Ocean. The following recommendations were proposed:

a) Explore the potential of greater geographic distribution and temporal sampling of atmospheric gas sampling of O_2 and N_2O for constraining S. Ocean NCP;

b) Update the Schlitzer-type approach to massive inverse model of existing hydrographic data to infer export and NCP;
c) Implement additional measurements of Ar/O_2 on ships as a routine observation;
d) Need better quantitative understanding of role of iron, mixing and light as regulators of NPP and NCP;
e) Field data on gas exchange in relation to NPP is needed to corroborate existing models.

4.6 Breakout 6: Use of active remote sensing for ocean colour

Co-Chairs: James Churnside (NOAA), Chris Hostetler (NASA), Cédric Jamet (LOG/ULCO)

Active remote sensing of global ocean plankton properties (such as satellite-based lidar) presents an unprecedented new opportunity for overcoming some of the major limitations of passive ocean colour data that have challenged the community for decades. Passive remote sensing of ocean colour observations have revolutionized our understanding of global plankton ecosystems and provide multi-spectral retrievals at many advantages: multiple wavelength bands, good spatial resolution (300-1000 meters) and on high repetitive cycles (~2 days). However, the ocean colour signal is limited to the very near surface layer, provides no information on plankton vertical structure, is extremely limited in polar regions, suffers from cloud cover and absorbing aerosols, and provides no information on day-night changes in plankton properties. Satellite active remote sensing can address some of these challenges and would provide an exceptional complement to passive observations.

For instance, Lidar (Light detection and ranging) can provide ocean retrievals under thin clouds, between holes in broken clouds, and throughout the polar annual cycle. Lidar measurements can also retrieve plankton vertical structure and information on day-night changes. Lidar technology has rapidly matured through field deployments of multiple airborne sensors, making transition to an ocean-optimized satellite system foreseeable in the next generation of missions.

On the other side, SAR (Synthetic Aperture Radar) technique has been shown to help determining phytoplankton blooms and oil sticks using the modification of the roughness of the sea surface. SAR is able to provide patterns of mesoscale and sub-mesoscale ocean surface signatures. The image contrasts are associated with the ocean surface roughness, variations linked to changes in the near-surface winds, waves, and currents as well as the presence of surface contaminants. Space-borne SAR sensors provide images since the mid-1980s at a high spatial resolution (5-30 meters).

The goal of the breakout session is to present the basics of active remote sensing, provide examples of successes in the field and from airborne and satellite active sensors (with a focus on lidar technique), and to discuss potential avenues for further advances for ocean applications.

Four key questions

1. How to get a 3D observation of the ocean colour?
2. What is the technology currently available?
3. How can active measurements be used to validate and improve passive ocean colour retrieval algorithms?
4. How to link active measurements to ocean colour parameters?

The session included three talks followed by a general discussion:

(i) Introduction to the session and presentation of SAR technique (Cédric Jamet)
(ii) Airborne ocean profiling lidar (James Churnside)
(iii) Space-borne ocean lidar (Chris Hostetler)
The session was attended by thirty-five participants. A strong support of the community was shown during the session for the development of an oceanic profiling lidar from space, as the participants recognized the diverse benefits of this technology. However, as the ocean colour community is not used to this kind of remote sensing technique, three main activities have been proposed:

- ***Tool development***
  - Simulation of passive/active data (modelling statistical analysis, ..)
  - Data distribution/user friendly format
  - Develop user community
- ***Needed investments***
  - Near-future lidar mission, e.g. MESCAL
  - Airborne prototype instruments
  - Next-generation satellite technology, e.g. Blue lasers
- ***Investigations***
  - beam C retrieval
  - Separation of CDOM from pigment absorption
  - Particle size distribution
  - Others

The **main recommendation of the breakout session concerns the next space lidar** through the MESCAL NASA/CNES (possible) mission. There is an enthusiasm for this possible mission. The new lidar instrument developed at NASA, High Spatial Resolution Lidar (HSRL), is recognized as very valuable for being able to collect vertical profile of the diffuse attenuation coefficient and the particulate back-scattering parameter. The participants recognize that any space-based oceanographic lidar will provide valuable new insights, but strongly support the **enhanced version of MESCAL** as the scenario that is the most interesting for doing new science (**Lidar at 355 and 532 nm, fluorescence sensor, 3-m vertical resolution**). This enhanced version will enable a 3-dimensional reconstruction of global ocean ecosystems by combining the lidar products with advanced ocean colour data (such as PACE) and Bio-Argo global data.

4.7 Breakout 7: Multi-water algorithms and algorithm performance assessment

Co-Chairs: Ewa Kwiatkowska (EUMETSAT), Bridget Seegers (NASA/USRA), Carsten Brockmann (Brockmann Consult), Tim Moore (Uni. New Hampshire), Blake Schaffer (US-EPA), Susanne Craig (Dalhousie University)

Part 1 - Multi-water algorithms

The multi-water part of the breakout workshop sought community recommendations towards demonstration products that can deliver accurate transitions across open ocean, coastal and inland waters. There are many challenges facing the quality and fitness for purpose of operational products which straddle different water types. This reduces the user uptake because ocean colour data are difficult to understand by non-expert users. The breadth of the issues had been described at the preceding breakout workshop on “Remote sensing of inland and coastal waters”. The goal of the current session was to define a roadmap for demonstration products. In the introductory part, the workshop focused on the definition of user requirements for blended multi-water products and on the overview of atmospheric corrections and bio-optical algorithms for open ocean, coastal and inland water transitions. The follow-on discussion focused on recommending a way forward to the agencies to advance the state-of-the-art and harness existing competencies in the community.

Ocean colour has a substantial and growing operational and scientific user community (presentation: Stewart Bernard). For multi-waters, there is currently a variety of product options, processing tools or alternative sets of products, which often give widely varying magnitudes of values. Non-specialist users require simple, ready-to-go products, yet of utmost quality. The quality of products impacts follow-on applications and information services, and it is critical. Ocean colour uptake can be improved if expert decisions on best algorithm selection are incorporated upfront into the products.

Atmospheric correction is a huge problem in coastal and inland waters (presentation: Menghua Wang). The difficulties include turbid water surface boundary, absorbing aerosols, land adjacency effects, shallow water effects, and atmospheric gases from land emissions. These issues could be addressed with high-SNR SWIR bands, UV bands, multi-angle polarimetry, aerosol vertical profiles (O_2 absorption bands for higher AOTs), realistic absorbing aerosol models, use of ancillary data, and advanced RT modelling. New robust multi-spectral optimization algorithms, like POLYMER, could be treated as a first guess. Relative spatial stability of atmospheric conditions could be explicitly utilized in view of highly varying underlying coastal/inland surface.

Optical water type classification and blending approaches have shown skill in describing global ocean, coastal and inland waters and water transitions (presentations: Daniel Odermatt, Thomas Jackson). However, the fundamental issue impeding the progress is lack of in situ measurements to describe the true extent of water types. At the current stage, these methods are mature to be trialled for demonstration multi-water chlorophyll products. Additional development and in situ data are required for multi-water SPM and CDOM. The methods use complete ocean colour spectrum, including red and NIR bands. Application of spatio-temporal variability could be useful. The water type definitions should relate to ecologically significant types, which are of major interest to users.

Highest priority challenge / aim / ambition was defined as: Meeting needs of non-expert users where the highest interest is in coastal and inland waters, and transitions from open seas. Accurate atmospheric correction and seamless multi-water products are a prerequisite for reaping the benefits of the new sensors and providing reliable user services.

Multi-water algorithm recommendations

There were two major session recommendations to the space agencies:

1) **Develop an atmospheric correction prototype processor for coastal and inland waters**

It was recommended to set-up a funded OCR-VC working group with specific deliverables. The working group should enable active collaboration among atmospheric correction experts who would advance science, explore new ideas, and utilize sensor specific capabilities (this is NOT an algorithm shoot-out!). To accelerate, the development should be based on an existing framework. As an example, SeaDAS provides such existing community framework/sand-box. The prototype development is expected for missions of participating OCR-VC agencies (e.g. OLCI, S2, VIIRS,...). The timeframe for the initial deliverable would be 2 years.

2) **Develop a prototype processor that will deliver accurate transitions between open ocean, coastal waters and inland waters**

Similarly to Recommendation 1, it was advocated for OCR-VC agencies to set-up a funded working group with specific deliverables. The group should establish active collaboration among algorithm/in-situ/IT experts and hands-on development using existing and new ideas and specific sensor capabilities. The implementation within a joint community framework/sand-box was firmly recommended, where such existing example is SeaDAS. The prototype development is expected for missions of participating OCR-VC agencies (e.g. OLCI, S2, VIIRS,...). The timeframe for the initial deliverable would be 2 years.

Part 2 - Algorithm performance assessment

The number of ocean colour algorithms available to the community has increased in recent years, along with the need for more highly-tuned algorithms to inform models, decision support, and management. The ocean colour community has generally relied on a finite set of statistical tools for algorithm assessment, which limits the ability to compare algorithms with minor differences. The session accumulated input and recommendations on developing an objective classification system for algorithm performance and how to best inspire the community to make changes to assessment approaches.

A pair of presentations made it clear that the current reliance on error metrics such as r^2 and root mean square error (RMSE) is not ideal for a robust assessment of algorithm performance, making it difficult to accurately compare algorithms or measure algorithm performance improvement. The metrics selected should assess bias, variability/precision, and accuracy (bias + variability) and be less sensitive to outliers than error metrics. The choice of which statistic to use for these may depend on other conditions including water type, seasonality, geography, sediment concentrations. Currently, many algorithm assessments are based on match-ups, but this not enough to fully assess algorithm performance and there is a need to have metrics explicitly on spatial and temporal patterns (transects, time series, seasonal). There is also a need to acknowledge the heavy sampling bias when using match-ups both seasonally and spatially. It was demonstrated that it can also be useful to consider water class and blending when assessing algorithms. When using multiple metrics it is important to not use redundant metrics. Tools such as star plots and numeric ranking may help with decision making and algorithms selection when multiple metrics are used.

A key point summary of the talks included that assessment of algorithm performance should be done through multi-metric approach rather than relying on a single measure of performance. The multi-metric assessment is applicable (and required) for both atmospheric correction and in-water algorithms. It is important to consider the questions trying to be answered and keep in mind what is important for the end users (number of retrievals, unbiased results, minimal error, IOPs?). Techniques such as bootstrapping can allow insight into the robustness of results and the sensitivity to sample selection.

Algorithm assessment recommendations

Recommendations for advancing algorithm performance assessment in the community were discussed.

1) **Develop community guidance on the standardization of statistical metrics to assess algorithm performance in water and on satellite data.** Including defining a core set of statistical metrics, with agreement on their meaning. Then, establish guidelines on the conditions and appropriateness for use, which may be research question dependent. The suggested approach to developing the guidance was to identify appropriate literature to develop understanding in approaches and identify gaps, which in turn will guide publishing of new papers that build on that collection of work.

2) **Develop a strategy to inform the community of best practices for performance assessment of algorithms.** The recommended approach would be to create a website providing best practices and provide community training opportunities.

The website should host three sections: 1) The most up to date algorithm assessment literature 2) A library of code/packages to ease the implementation of more robust algorithm assessment. Along with guidance about which metrics are valid and appropriate skill metrics, which is research question dependent. 3) Provide a common data set to run algorithm to give first look at how it compares to the community set of algorithms.

The community training opportunities in more rigorous statistical approaches would include algorithm performance assessment workshops at conference, young scientist training workshops, lectures, and other training opportunities.

4.8 Breakout 8: Protocols for Water leaving Radiance and Remote Sensing Reflectance

Co-Chairs: Kenneth Voss (University of Miami), Giuseppe Zibordi (EU JRC) Kevin Ruddick (RBINS, Belgium) and Zhongping Lee (University of Massachusetts)

The purpose of this breakout workshop was to review the current NASA protocols for above-water and in-water derivation of the water leaving radiance, normalized water leaving radiance, and the remote sensing reflectance. The session was broken into two parts, above water and in-water protocols.

The first part was above-water measurements, with a short introduction on the NASA protocol for this measurement, and an overview of what people are currently doing in the field. It was clear that there is much variation in how people are making this measurement, some variations are based on more recent papers and some are based on practical considerations. During the discussion we talked about instrument characteristics, documentation required during measurements, and measurement angles relative to the sun and nadir. The critical factor in these is the reflectance of the surface.

Results of the discussion

- Some agreement that the protocols should specify preferred angles, with the reasoning behind the choice, so users will be able to know what they lose when operating in a different fashion (which will happen anyway).
- Documentation needs to be complete and include pictures of the sky and sea surface during the measurement and include the integration time used.
- A somewhat detailed conclusion was that the Mobley 1999 results for removing surface-reflected contribution appear better than the Mobley 2015 work when considering low the wind speed condition that generally characterize measurements. However the 1999 work used a model for sky radiance distribution that did not vary spectrally so does not have the spectral variation that exists. There have been or on going works that can/will improve on the characterization of this factor.
- The reflectance plaque (when used to determine downwelling irradiance) should be carefully calibrated and documented.
- There should be an experiment (may have data already) to compare irradiance measurements taken with a reflectance plaque and that with a calibrated irradiance collector.
- The measurements during non-ideal conditions, which is common during field experiments, should be well documented in view of ranking their applicability.
- Spectral calibrations need to be carefully done on all instruments.

The second part of the workshop dealt with the in-water measurements, and the main issue with the existing protocols is that the current best practices (slow-drop, multi-cast, and sky blocked methods) are not described and need to be detailed.

Recommendations from the in-water measurements session (beyond describing these methods):

- The protocols should discuss the number of samples per depth, but also the time over which the samples were taken
- The protocols should also discuss strategies for alternative platforms (floats, gliders, etc.).
- There was some consensus that the Es collector should not be gimbaled, but results should be filtered to eliminate tilts greater than 5 degrees, and even this may be too large for low sun elevations.
- Care should be taken to eliminate all shadowing as much as possible, and calculations should be performed on specific instrument self-shadowing.
- The depth range and methods used for calculating the diffuse upwelling attenuation coefficient should be refined in view of proposing objective schemes.

Finally, there were some topics that were common to both types of measurements:

- Users should carefully consider and document the measurement uncertainties for their specific case. The protocols should include some information to help with this.
- SeaBASS (the most commonly used database) should add a flag to indicate whether data is validation quality, or had been compromised in some way to make it useful, but not of sufficient quality for validation.
- Finally, the important issue of BRDF corrections, to get “exact” values was not discussed, but is extremely important.

Also briefly discussed was the hybrid scheme or the Skylight-Blocked Approach (SBA), but no community-wide “protocols” yet. Overall the discussion in the session was very productive.

4.9 Breakout 9: Carbon From Ocean Colour

Session Chairs: Shubha Sathyendranath (PML) and François Montagner (EUMETSAT)

The meeting was well attended. Though a roll call was not taken at the session, over 140 participants had registered for the session. The meeting began with a short presentation by F. Montagner, who introduced the main goals of the breakout session:

Goal 1: Assess the performance and limitations of the current Particulate Organic Carbon (POC) and Particulate Inorganic Carbon (PIC) products. The session will recommend approaches towards validation of these products and towards consistent implementation of these algorithms in global operational processing systems across missions.

Goal 2: Liaise with the modellers to understand the requirements for further carbon products, including chlorophyll carbon ratio and Dissolved Organic Carbon (DOC).

This was followed by four short presentations from the invited speakers. Hayley Evers-King (UK) provided an overview of comparisons of algorithms for Particulate Organic Carbon (POC) and Phytoplankton Carbon (PC) that had been undertaken within the "Pools of Carbon in the Ocean (POCO)" project supported by ESA. The analysis showed that, in general, POC algorithms for the open ocean were mature and ready for operational implementation. The comparison of PC algorithms was more difficult, and had to be limited to pico-plankton, because of the nature of the in situ data available for the comparison. Algorithm selection had to take into account other considerations, in addition to performance against a validation dataset, such as the underlying assumptions and the availability of a theoretical basis to underpin empirical relationships used in algorithms. Further improvements to algorithms would require a concerted effort to enhance the in situ data base for use in algorithm development and validation. Algorithms are also available for estimation of PIC from ocean-colour data. PIC in the open ocean is dominated by calcifying organisms such as coccolithophores and foraminifera. It has an important role in the ocean carbonate system and in marine ecosystems. They are detectable from space due to their high back-scattering properties. A user survey undertaken as part of the POCO project showed high user interest in POC and PC. Uncertainty estimates are an important consideration for the users when selecting algorithms for their applications. Hayley presented an example of how uncertainty estimates can be generated using the methodology developed under the ESA OC-CCI.

Jamie Shutler (UK) presented a comparison of algorithms for dissolved carbon (organic and inorganic) in the ocean. He introduced the importance of water and oceans within the carbon cycle, and briefly explained the oceanic organic and inorganic cycles, identifying DOC and Dissolved Inorganic Carbon (DIC) carbon pools. He then highlighted the need for sensor synergy (with reference to the Carbon Strategy Report of the Committee on Earth Observation Satellites, CEOS) and introduced DOC and its spectral absorption, briefly reviewed remote-sensing methods for estimating DOC in coastal waters (which typically rely on DOC-salinity relationships) and then focussed on how global DOC could be observed from satellites (mostly identifying new opportunities). He showed the alkalinity-salinity relationship and how this enables surface water DIC to be estimated (current methods and new opportunities for exploiting ocean colour). He concluded with some recommendations for operational exploitation and highlighted possible routes for future research focus and discussion (for both DOC and DIC).

A modeller's perspective (Validity and impact of satellite products) was provided by Cecile Rousseaux (USA). She identified the major pools and fluxes of carbon in the ocean, their interactions with land and atmosphere, as well as their vulnerability to climate change. Satellite ocean colour and ocean biogeochemical models are important because they provide global representations. Models are also able to investigate variables not currently available from satellites and to generate projections into the future. Satellite ocean-colour data are used to validate biogeochemical models; to improve model parameterisations and as an important source of data for models run in assimilation mode. Models can be used to fill gaps in satellite data that arise from inter-orbit gaps, insufficient light for detection at high latitudes, sun glint, clouds or high aerosols. Assimilation of surface chlorophyll in models can improve the model representation of a variety of variables, including carbon-related properties such as surface fugacity of carbon dioxide. She provided examples of comparisons of model carbon products and corresponding satellite products, such as POC, PIC and PC. When comparing satellite and model products, it is important to consider whether the two sets of products represent the same components of the ocean carbon pools. Differences as well as similarities between them provide insights into how the marine ecosystem functions, and how best to represent them in models. She recalled some of the recommendations that arose from the CLEO (Colour and Light in the ocean from Earth Observation) Workshop held in ESA in September 2016, which included the user requirements for additional carbon products (primary production, phytoplankton carbon, particulate and dissolved carbon). She stressed the importance of uncertainty estimates for satellite products, for use in validation of model products and for data assimilation.

Hubert Loisel (France) addressed the particular problems associated with satellite estimates of carbon pools in coastal waters. The coastal domain is varied and dynamic, and is known to be an important contributor to marine primary production, and to the supply and burial of organic carbon in the ocean. Because of the high temporal and special coverage provided by satellite remote sensing, and because of the many key variables that can be retrieved from ocean-colour data (including chlorophyll (Chl), suspended sediment matter, particulate organic carbon and dissolved organic carbon), satellite-based methods are important for studying the coastal systems. But there are many specific problems to be addressed: difficulties with atmospheric correction over coastal waters (SWIR/Polymer approaches offer improvement); bio-optical complexity that impacts algorithm accuracy; difficulty with observing vertical structure; and the need to account for the high spatial heterogeneity and temporal variability in the properties, when validating coastal products. Analyses over many regions have indicated that the OC5 algorithm works well for Chl retrieval in coastal waters, but a global validation exercise is needed to confirm this finding. Whereas algorithms to detect terrigenous DOC have been mostly regional and seasonal in scope, a recent study has shown that a more generalised approach based on spectral slope of absorption by coloured dissolved organic material may account for marine DOM. It was suggested that DOC could also be used to estimate pCO_2 when combined with other information such as SST, if such a result reported for lakes could be adapted to coastal waters. Recently, regional empirical algorithms have been developed to assess POC in coastal areas. Analytical approaches for estimating POC in coastal waters have also shown promising results. Optical classification-based algorithms offer a promising avenue for improved retrievals of carbon products in coastal waters, but such approaches require a very large dataset for their development. His recommendations included: a global Chl, POC, DOC, Inherent Optical Properties, Remote Sensing Reflectance data base for coastal areas; operational production by agencies of selected coastal products, such as suspended sediment matter and terrestrial DOC; further algorithm development and validation based on global inter-comparison of Chl (and this can be done quickly); development of optical class-based algorithms; more in situ measurements of vertical structure in carbon variables.

The discussions that followed the presentations focussed on the following seed questions:

- Where are the critical shortcomings and needs?
- What is ready for operational agencies to pick up?
- Algorithms development and validation: what actions are needed?
- What is needed from in situ observations?
- What are the priority directions?
- Where are your needs evolving?

The following community priorities were identified during the discussion:

- Top priority to improve the contents, coverage, consistency of *in situ* measurement databases
  - Apply standardised best practices and protocols to establish high quality in situ measurements as Fiducial Reference Measurements
  - Ongoing update of the IOCCG technical reports on protocols
  - Key carbon pools: phytoplankton carbon, POC, DOC, pCO2 (existing SOCAT dataset can be used for global validation of pCO2).
  - Developments needed to improve in situ estimates of phytoplankton carbon. Flow cytometric methods are promising (reference to H. Sosik's plenary talk)
  - Associated measurements: particle size distribution
  - Explore typology or optical classification-based algorithms and use for merging of products.
  - Spectrofluorometry for DOC assessment

It was recommended that Agencies implement relevant aspects in e.g., SeaBASS, FRM4SOC.

- Proposed Action to IOCCG: support the establishment of an IOCCG Task Force on Carbon
  - Potential leads: H. Sosik (TBC), C. Rousseaux, J. Shutler,

- Liaise with organic chemistry experts (L. Santoleri, C. Fichot) and non-OC remote sensing experts as needed
- Liaise with other relevant international groups e.g. CLIVAR, SOLAS, GEOTRACES
- Initial focus on (i) Disentangling the complexity of the optical <-> C relationship: Regional vs. Classification based approaches; (ii) Multiple vs. blended algorithms; (iii) Support and build on existing initiatives e.g., NASA and IOCCG protocols for carbon measurements; (iv) Global *in situ* database assembly; (v) Uncertainty estimates as per FRM standards (for in situ) and other approaches for satellite products.
- Additional Terms of Reference to be developed by the Community

• Recommendation to Agencies to implement quasi / pre operational RS products:
  - POC in Open ocean
  - Suspended Particulate Matter in Coastal waters
  - As "research" or "experimental" as needed
  - Carrying clear indication of uncertainty or at least fitness for purpose

• Recommendation to develop user engagement and training

• Importance of temporal resolution of satellite observations in coastal waters -> interest of geostationary mission with UV-VIS coverage

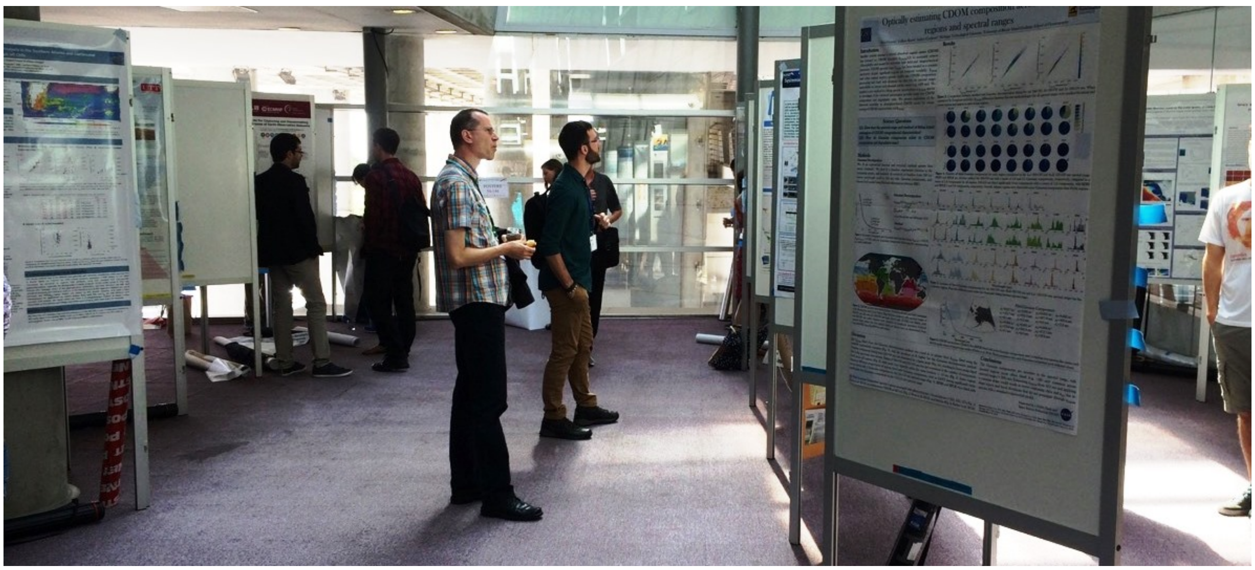
• Importance of vertical profile resolution
  - In situ e.g. BioArgo
  - Airborne lidar
  - Lidar on Satellite

• "Terrestrial" DOC in coastal / inland waters
  - Mature algorithms exist,
  - Regional or optical classification-based
  - Comparison / reconciliation of approaches needed.
  - Geostationary sensor could be very useful

The meeting was closed with a request from the chairs to the participants to please stay engaged as a community and keep carbon-related activities moving forward.

5. Poster Sessions

Attendees were able to interact with colleagues during three scientific poster sessions, which took place in the early evening on the first three days. A total of 237 posters were presented covering a wide range of topics. Poster abstracts can be viewed on the IOCS-2017 meeting website at: http://iocs.ioccg.org/wp-content/uploads/2017/05/abstracts-iocs-2017-all-10may2017.pdf. These poster sessions allowed researchers and young scientists to present their current research and receive useful feedback from other scientists working in the same field.



6. Q & A Session: Ocean Colour Community and Space Agencies

On the final day of the meeting, a Q & A session was held where the ocean colour community could address space agency representatives to ask insightful questions and communicate their views, ideas and concerns.

Blake Schaefer suggested that at the next IOCS meeting, agency updates should focus on quantifying how previous community recommendations have been implemented. Craig Donlon (ESA) observed that ESA has taken a great deal of recommendations on board, but it is a slow process. For example, ESA recently sourced the funds to address fiducial reference measurements, acting directly on the recommendations from the breakout session on System Vicarious Calibration from the IOCS-2013 meeting. Paul DiGiacomo (NOAA) confirmed NOAA's appreciation of community feedback, and informed participants about the interagency coordination work being carried out behind the scenes by the "Ocean Colour Radiometry-Virtual Constellation" (OCR-VC), under the auspices of CEOS (Committee on Earth observation Satellites), where many important topics are addressed at the inter-agency level. Paula Bontempi (NASA) also pointed out that the agencies have very different processes for implementing recommendations, so when making recommendations, the proponents should be as specific as possible, and the community should be ready to respond to follow-up solicitations, often at very short notice.

Ajit Subramaniam inquired about the process of taking the recommendations forward, from a community perspective, perhaps through a White Paper? Ewa Kwiatkowska (EUMETSAT) responded that different agencies have different methods of funding these recommendations, e.g., in Europe, ITTs are issued for certain projects. It is vital that the community defines its priorities i.e., what type of activities should be put forward, and what are the deliverables, bearing in mind that not everything can be implemented within the next few years. Prakash Chauhan (ISRO) also pointed out that feedback from the IOCCG and from international meetings such as IOCS has resulted in changes in their instrument design (the new OCM sensor now has 13 channels as opposed to 8). The IOCCG has done a commendable job in publishing the IOCCG reports, which the agencies take very seriously. Sandra

Torrusio (CONAE) also remarked on the strong contributions of the IOCCG reports for the definition of ocean colour missions and the importance of international cooperation in these projects.

Emmanuel Boss inquired whether it was possible to have one data center where products that are similar across agencies, carefully calibrated across platforms are stored (e.g., chlorophyll concentration). Craig Donlon (ESA) replied that, from an agency and programme perspective, it is very difficult to have a unique data center. A ground segment is an essential component of a satellite system. Political factors also come into play e.g., in Europe, the Copernicus Programme has its own data center. Multiple centers processing the data in slightly different ways can also help to highlight differences due to processing, quality control and stability, in order to gauge how well the data processing is working. Ewa Kwiatkowska (EUMETSAT) noted that, as a community, we have the capability to work on harmonized, seamless algorithms that can be used across sensors so that the products are similar across the different instruments. This meeting and the community recommendations are critical to help agencies achieve this kind of harmonisation across agencies and data providers.

Susanne Craig highlighted the need for “blue skies” research where the applications and socio-economic benefits are not immediately apparent. Paula Bontempi pointed out that NASA is very science orientated, with a drive to move ocean colour remote sensing well beyond current capabilities and begin exploring new science questions and enablie new discoveries. On the other hand, Martin Bergeron (CSA) noted that in a small country like Canada with limited resources, the societal benefits are critical in deciding what to fund, often in partnership with larger activities.

Another question from the audience addressed the issue of atmospheric correction and the need for a resource to understand which algorithm should be used for various data sets. Ewa Kwiatkowska remarked that the multi-water breakout session had discussed atmospheric correction in detail, and recommended that an atmospheric correction prototype processor for coastal and inland waters be developed, perhaps through a funded OCR-VC working group with specific deliverables. Furthermore, one of the IOCCG working groups is carrying out an inter-comparison of existing atmospheric correction algorithms. There was general agreement that updates of the various IOCCG working groups should be presented at the next IOCS meeting to keep the community informed.

Robert Frouin suggested that the agencies should come together to try to define an international mission in which assets, including expertise, are shared to provide what the users need. Stewart Bernard noted that agencies have very different processes and mandates, and are driven by different purposes and stakeholders. Collaboration at a spacecraft level only works on a modular basis because of how the space engineering industry works - there is a vast political landscape that is difficult to navigate. Carsten Brockman pointed out that there are examples of NOAA partnering with EUMETSAT in the operational aspects of the Initial Joint Polar System (IJPS). Several identical instruments are carried on both fleets of satellites to provide data continuity between EUMETSAT MetOp satellites and NOAA Polar Operational Satellites. This is the level of operationality where the ocean colour community has room to further improve. On the other hand, having the diversity of instruments from different agencies also helps to stimulate new ideas, technologies and products.

The IOCCG Chair, Cara Wilson, also requested feedback from the community about the IOCS meetings themselves. There was unanimous agreement that the format of breakout groups and discussion sessions was excellent, as it was important for participants to be able to discuss their ideas rather than just listen. A suggestion for the next meeting was to have a half-day session on a mature topic like chlorophyll retrievals – how to obtain a consistent chlorophyll, taking into account the diversity of instrument concepts (multi-sensor data fusion).

For IOCS-2017, the call for breakout workshops was open to the entire community, and any topic could be proposed. However, for the next IOCS meeting, the IOCCG Committee might provide some topics they would like to see addressed, and solicit interested chairs for these breakout sessions.

7. Social Programme

IOCS-2017 meeting participants were fortunate to be invited to two special social events, supported by meeting sponsors. An ice breaker event, sponsored by Thales Alenia, took place at the beautiful Pavilhão de Portugal overlooking the bay on the first evening. The Pavilion is a prestigious landmark building designed by Alvaro Siza to host Expo 98 – the world's largest trade fair. It has a remarkable sagging concrete roof weighing 1,400 tonnes and measuring 50 by 67 meters which appears to undulate like sail, keeping within the maritime theme of most of the district's architecture.

EUMETSAT and ESA hosted a dinner on Wednesday evening at the Pátio da Galé, where participants had the opportunity to mingle with the other conference delegates while tasting delicious Portuguese specialties and enjoying live fado music. The Pátio da Galé is located in the heart of Lisbon city center, in the west wing of the Terreiro do Paço (The Palace Square).