International Ocean Colour Science Meeting 2015 | Advancing Global Ocean Colour Observations

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International Ocean Colour Coordinating Group (IOCCG) www.ioccg.org

Stewart Bernard, IOCCG Chairman (sbernard@csir.co.za)

Venetia Stuart, Scientific Coordinator (vstuart@ioccg.org)

Table of Contents

1. Introduction

1.1 IOCS Meeting Rationale

Following the success and momentum arising from the first International Ocean Colour Science (IOCS) meeting held Darmstadt, Germany (6-8 May 2013), the International Ocean Colour Coordinating Group (IOCCG) resolved to hold a second such meeting in San Francisco, USA. Amongst the many outcomes from the milestone IOCS-2013 meeting was (i) the establishment of a permanent IOCCG Task Force on Ocean Colour Satellite Sensor Calibration, (ii) a follow-up workshop on Phytoplankton Functional Types, and (ii) a workshop on Ocean Optics Protocols, as well as (iv) numerous recommendations to the space agencies from the splinter sessions. The overall goal of the IOCS meetings is to bring together ocean colour research scientists and space agency representatives from around the world to help build a strong global ocean colour user community by collectively addressing common issues and goals, and also to promote international linkages among the different communities. Furthermore, these meetings provide a forum (breakout sessions) for discussion on various topics, and indirectly allow more people from the ocean colour community to be involved in IOCCG activities than is feasible through IOCCG Committee meetings and working groups alone. In doing so, the IOCS meetings help the IOCCG in its oversight role and also act to reinforce the voice of the ocean colour community when it comes to high-level discussions with space agencies.

This is the beginning of a new era for ocean colour radiometry with many space agencies planning to launch more complex and highly sophisticated ocean-colour sensors with potential for many new applications. For this reason, the overarching theme of IOCS-2015 was "*Applications of Ocean Colour from Climate to Water Quality*".

1.2 Organisation and Structure of IOCS-2015

The second IOCS meeting was convened by the IOCCG and was held in San Francisco, USA from 15-18 June 2015, with NASA and NOAA as the primary sponsors of the meeting. Additional sponsorship was obtained from ESA, EUMETSAT, CNES, SCOR and the Gordon & Betty Moore Foundation. All organisational aspects of the meeting were competently arranged by the IOCS-2015 meeting manager, Liz Gross, with the help of an Organizing Committee (6 members from NASA, NOAA and IOCCG) via regular telephone conferences, while the Scientific Planning Committee (17 members) provided advice on developing the scientific program and the selection of the keynote speakers as well as the breakout sessions. In total, 260 scientists from 29 different countries participated in the four-day meeting, including representatives from all the major space agencies with an interest in ocean-colour radiometry (CNES, CSA, ESA, EUMETSAT, INPE, ISRO, JAXA, KIOST, NASA, NOAA and SOA). The IOCS meeting thus helped to bring together both the users and the providers of ocean-colour data for in depth discussions of detailed requirements for ocean-colour products and services.

The format of the IOCS-2015 meeting included eleven agency presentations, seven invited keynote talks, ten breakout splinter sessions (three parallel sessions on two days, and four on the last day), two poster sessions, the NASA Ocean Color Research Team (OCRT) meeting, a SeaDAS/BEAM workshop, a "Visions & Hallucinations" session plus a panel discussion. The full meeting agenda plus all the poster abstracts can be accessed via the IOCS website at http://iocs.ioccg.org/. All presentations given during the meeting can be viewed at http://iocs.ioccg.org/program/iocs-2015-presentations/.

The meeting was opened by the IOCCG Chair, Stewart Bernard (CSIR, South Africa) who warmly welcomed participants and thanked them for travelling to San Francisco. From an IOCCG perspective the strong community engagement was very encouraging and welcome. He noted that the IOCCG provides a voice for the ocean colour community and the IOCS meeting provides a forum for community dialogue with the space agencies.

The "Visions and & Hallucinations" icebreaker event was held on Tuesday evening and was sponsored by the Gordon & Moore Foundation. This was a new event for IOCS, and was based on the TED (Technology, Entertainment, Design) talks concept, in which three scientists briefly outlined innovative and provocative capabilities in the field of ocean colour science. Emmanuel Boss (University of Maine, USA) gave a presentation on "Using your phone as an optical sensor", Paula Bontempi (NASA HQ) presented "2015: A Zooplankton Odyssey" and Stewart Bernard (CSIR, South Africa) presented "1000 Sailing Robots: Swarm Sensing with Low Cost Autonomous Yachts". The talks were highly entertaining and even somewhat feasible! The following evening participants were treated to an IOCS mixer at St. Francis Yacht Club with spectacular views of the Golden Gate Bridge, Alcatraz and the Marin Headlands, which was most enjoyable and convivial.

The overall feedback from the meeting has been extremely positive. The IOCCG expresses their sincere gratitude to all the meeting sponsors as well as the organising and scientific committees and the chairs of the various breakout sessions, for helping to make the meeting such a success.

2. Agency Reports

Program managers from various space agencies with an interest in ocean-colour remote sensing were invited to update the community on the status of ocean-colour programs at their respective agencies. Brief summaries of these presentations are given below.

2.1 NASA (USA)

Paula Bontempi provided a brief update on the historical, present and future NASA missions. Several EO missions have been launched, or would be launched in the near future, including the Pre-Aerosol, Cloud, ocean Ecosystem (PACE) mission, scheduled for launch in 2022. There is also a fairly large EO fleet of existing missions that are still operational and which undergo periodic reviews to justify why they need to continue EO. Continued observations are critical and NASA is dedicated to this. In addition, the International Space Station (ISS) has several Earth science instruments that have many advantages, including rapid, low-cost development, which complement global Earth observations.

The PACE mission is an ocean colour, aerosol, and cloud mission with a primary science objective of understanding and quantifying global ocean biogeochemical cycling and ecosystem function in response to anthropogenic and natural environmental variability and change. In addition the mission will extend key Earth system data records on global ocean ecology, biogeochemistry, clouds, and aerosols (using an expanded ocean colour sensor likely to be hyperspectral) and will also help to understand and resolve/quantify the role of aerosols and clouds in physical climate (the largest uncertainty). PACE will facilitate and advance research into plankton stocks and diversity (i.e., characterize phytoplankton functional groups, particle size distributions, and dominant species), ocean carbon, human impacts (water quality) and help to understand change and forecast futures. Feedback on the PACE mission was welcomed.

2.2 NOAA (USA)

Paul DiGiacomo reported on NOAA ocean-colour activities and provided an overview of various projects. These included the use of NRT ocean colour data for improved air-sea fluxes, the use of neural network techniques for gap-filling of satellite ocean colour observations for use in numerical ocean modeling, and the new VIIRS ocean colour product (satellite-derived Kd(PAR) data). In addition, NMFS was examining HABs and mortality events in southern right whale calves, as well as the use of a satellite derived bottom-up approach to determine fisheries production potential and exploitation for various ecosystem components. NOAA also provides NRT cruise support as well as harmful algal bloom bulletins delivered once or twice per week, including the weekly Lake Eerie HAB bulletin. NOAA is also developing VIIRS ocean colour products for coral reef ecosystem managers.

UNH and NESDIS are developing methods to predict PFTs using habitat models. Other studies have examined the evolution of sediment plumes in the upper Chesapeake Bay. The NOAA Ocean Colour Team has been developing/building the capability for the end-to-end satellite ocean colour data processing plus a capability for on-orbit instrument calibration. Examples were given of a new NIR ocean reflectance correction algorithm and a new de-striping algorithm for improved satellite-derived ocean colour product imagery. To meet requirements from all users (operational, science research, modelling etc.) NOAA will be producing VIIRS ocean colour products in two data streams: Near-Real-Time (NRT) ocean colour data processing (12-24 hours) and science quality ocean colour data processing (1-2 weeks delay).

2.3 EUMETSAT (Europe)

Ewa Kwiatkowska reported on EUMETSAT ocean-colour services. EUMETSAT is an operational satellite data provider and operator of the Sentinel-3 Marine Centre of the EC Copernicus programme. EUMETSAT activities in support of EC Copernicus include operation of satellites (Sentinel-3, Jason-3, Sentinel-6 / Jason-CS) and delivery of operational marine data and support services. For the Sentinel-3 mission marine L2 products disseminated from the EUMETSAT Marine Centre will include OLCI ocean colour products (FR 300m/RR 1200m), SLSTR Sea Surface Temperature and SRAL Sea Surface Topography. Global L1 products will be disseminated by both ESA and EUMETSAT. Expected launch of Sentinel-3A is 31 October 2015, with Sentinel-3B in 2017.

A Sentinel-3 Validation Team for ocean colour was jointly established by ESA and EUMETSAT. The team will provide independent validation evidence to support OLCI Cal/Val and will coordinate on field instrument calibrations, measurement round-robins, protocols and standardization. There will be three means of S3 data dissemination from EUMETSAT: (i) EUMETCast (the main method of disseminating NRT data via telecommunication satellites and via high speed terrestrial internet networks), (ii) Online Data Access (ODA) – a rolling archive of one month of data supporting ftp/http, and (iii) the EUMETSAT data center (complete historical archive of all EUMETSAT data including S3 data). EUMETCast satellite is currently only available over Europe with a possibility for EUMETCast-Africa. EUMETCast terrestrial is planned for NRT data dissemination outside of Europe. Sentinel-3A commissioning phase will last 5 months and will have a commissioning mid-term check point after which some data subsets are planned to be available to authorised users (S3 Validation Team). After the commissioning phase, there will be a gradual verification/validation of L2 data products up to the official release and full operational data provision as soon as feasible.

2.4 ESA (Europe)

Philippe Goryl reported on ocean-colour activities at ESA. The Earth Observation Satellites program at ESA is composed of three main and complementary elements, insuring a comprehensive system for Earth Observation: starting in the seventies with Meteosat, the Meteorological program is driven mainly by Weather forecasting and climate monitoring needs. These missions developed in partnership with EUMETSAT include MetOp , MSG and MTG satellites. It is complemented by the operational Sentinel missions, driven by user needs, which contribute to the European Copernicus initiative. These satellite developed in partnership with the EC include a SAR C-Band (S1), high resolution optical mission (S2), optical and infra-red medium resolution radiometer (S3), atmospheric composition monitoring capability (S4, S5) and an altimeter mission (S6). Finally the Earth Explorer missions, driven by scientific needs, aim at a better understanding of how the ocean, atmosphere hydrosphere, cryosphere and Earth's interior operate and interact as part of an interconnected system.

Part of the EO program, the first ESA ocean colour sensor- MERIS- on board ENVISAT was launched in 2002. ENVISAT ended its operation in 2012, making 10 year data set of high quality. The MERIS archive is now being reprocessed for the 4th time with the objective of aligning with the future Sentinel-3 OLCI in terms of products and format. In addition, the radiometric calibration will be updated and several Level 2 parameters will be improved (classification, Bright Pixel Atmospheric Correction, aerosol models, pressure, gaseous absorption). The products will be delivered with uncertainties per pixel. The global data set will be reprocessed at Full (FR) and Reduced Resolution (RR). The reprocessed data set should be available before mid-2016. The tools and the processing environment (including source code) – ODESA – will be updated accordingly.

The continuity of ocean colour measurements will be ensured with the launch of OLCI on board Sentinel-3A in late 2015. OLCI is similar to MERIS with several improvements, including: more spectral bands, broader swath, reduced glint area and improved straylight. The images will be acquired globally and processed systematically in Near Real Time at both resolutions – FR and RR. The data follow the Copernicus data policy which guarantees a free access for all users. Full mission performance will be achieved with two satellite in orbit (S3A and S3B) allowing a global coverage in less than 2 days. S3B should be launched late 2016 or early 2017. The Copernicus program will ensure continuity in ocean colour measurements for the next 20 years or more. In addition, the combined used of Sentinel-3 with the high resolution sensor on board Sentinel-2 (launch date 23 June 2015) will offer unprecedented water quality observing capabilities for coastal and inland waters.

ESA shall continue to deliver R&D that pioneers new satellite technologies, geophysical algorithms, products and applications of ocean colour working in partnership with the EC, EUMETSAT and the other international community. This is done in particular in the framework of Climate Change Initiative Program (CCI) which aims at producing an uncertainty-characterised, inter-sensor bias-corrected, merged time series of ocean-colour products for climate research, or in the framework of the Scientific Exploitation of Operational Mission Program (SEOM) where activities and algorithms can be developed, tested, publically presented and discussed through dedicated workshop and user consultation meetings.

Finally, following the QA4EO process, ESA is initiating several projects aimed at establishing and maintaining SI traceability for Fiducial Reference Measurements (FRM). One ocean colour project will start at the end of 2015 – FRM4SOC. The objective of the project will be achieved through the development, implementation and reporting of instrument laboratory and field inter-comparison experiments for FRM radiometers, supporting measurements, protocols, and dedicated international coordination activities. The participation of National Metrology Institution(s) is mandatory to achieve credible success in this project. A workshop where the results will be analysed and synthesized shall conclude the activity. In addition, a study will be done to better define what is required in terms of infrastructure for vicarious calibration and validation for Europe for the next 20 years.

2.5 KIOST (South Korea)

YoungJe Park (KIOST, Korea) provided an update on the GOCI-I & II missions. GOCI is the first ocean-colour sensor in a geostationary orbit, and was successfully launched in June 2010. The Korea Institute of Ocean Science and Technology (KIOST) provide global leadership in advanced marine sciences and technology while the Korea Ocean Satellite Center (KOSC) is in charge of GOCI operations including mission development, Cal/Val, applications, and research. The GOCI radiometric gain evolution from 2011 to 2014 is ~0.45% indicating that GOCI is still very stable five years after launch.

The GOCI Data Processing Software (GDPS) was updated last year and can be downloaded from the KOSC website. Near real-time data service is provided to over 20 organizations. KOSC responds to reported issues such as HABs, floating green algae, brown algae, yellow dust, dredging/dumping activities, sea fog etc. Recently, GOCI imagery was used to identify the spatial coverage of the massive outbreak of the harmful algae *C. polykrikoides*, which was difficult to observe with *in situ* observations. Similarly GOCI data was used to map the distribution of patches of patches of *Sargassum horneri.*

The GOCI-II mission will have an observation interval of 10 times per day with 250-300m resolution (Local Area Mode). In addition, there will be full disc coverage once per day at 1-km resolution. The GOCI-II instrument will have 12 VIS/NIR spectral bands plus one wideband and the mission is scheduled to be launched in 2019.

2.6 JAXA (Japan)

Hiroshi Murakami (JAXA/EORC) reported on JAXA's Earth observation satellite missions and GCOM-C/SGLI development status. Mission targets of GCOM-C include research on climate system, carbon cycle and radiative forcing using a series of satellites (GCOM-C, C2 and C3).

The SGLI sensor will have 250-m resolution to detect finer structures in the coastal area such as river outflow, regional blooms, small currents and red tides and will also have along-track slant-view polarization observation to improve the land and coastal monitoring, and aerosol estimation. Furthermore, it will have on-orbit calibration functions, such as solar diffuser, lamp, and monthly moon observation. Development of the SGLI instrument, retrieval algorithms, ground system, and Cal/Val planning are being conducted toward the launch of SGLI in Japanese Fiscal Year 2016. SGLI manufacturing and characterization, algorithms and ground processing system, and post-launch Cal/Val planning are being conducted by JAXA and the GCOM-C PI team. The next research announcement will be released in summer 2015.

2.7 CNES (France)

Mariana Lévy reported on CNES ocean programs as well as the proposed geostationary ocean colour mission, GEO-OCAPI. Ocean sciences are one of the major interests of CNES Earth observation programs. They support a strong scientific community through dedicated research funding as well as large scope projects such as Copernicus Marine Service, Mercator-Ocean, Bio-Argo, Boussole, GIS-COOC etc. CNES satellite missions are operated through different frameworks, either ESA/EUMETSAT or multilateral cooperation e.g., U.S., China, India. CNES is involved at all levels in the Sentinel-3 Copernicus Program including the space component, core services and science support. In addition, CNES has a strong involvement in altimetry and significant involvement in other ocean variable measurement (e.g., salinity, SMOS).

Phase 0 of the GEO-OCAPI (Ocean Color Advanced Permanent Imager) has been successfully conducted, and Phase A has just started (to support a proposal to ESA Earth Explorer 9 Announcement of Opportunity). The instrument will have between 12 and 18 spectral bands, with a signal-to-noise ratio <400, and spectral resolution from 10 to 40 nm. Ground spatial resolution will be 500 meters and larger for open ocean (Case-1 waters) and 100-250m meters for the coastal ocean (Case-2 waters). Revisit frequency is the main design driver, from ½ to 1 hour (diurnal) with a daily composite (mosaïc) after clouds/glitter correction. Geo-OCAPI will represent the next generation ocean colour mission complementing low orbit observation with very high temporal resolution, high spatial resolution of 100/500 m, 12-18 spectral channels, with a swath of 1000 km compatible with LEO dat. The proposed launch of the mission is 2020/2021. This program strongly depends on the development of critical technologies and international cooperation.

2.8 INPE (Brazil)

Milton Kampel reported on activities at INPE, the main civilian organization for space research in Brazil which contributes to big national challenges. INPE is developing EO scientific and data collection satellites as well as ground systems. They also carry out data analysis and modelling. Several examples of Earth observation applications over land and the ocean were presented (e.g., deforestation, algal blooms, oil spills etc.).

INPE is also involved in a bilateral agreement with CONAE (Argentina) to design, launch and operate an ocean colour mission called SABIA-MAR. There will be two satellites flying as a constellation with shared responsibilities between INPE/AEB and CONAE. Two planned mission scenarios have been defined: a global scenario and a coastal scenario, which could be increased depending on availability of resources.

The ocean colour mission will provide 200 m spatial resolution and 1-day revisit time for the coastal scenario and 800 m spatial resolution with 1-day revisit time for the global scenario, with an ancillary payload for atmospheric correction. A secondary mission objective is to provide SST at 400 m resolution, 1-day revisit time for both scenarios. Each satellite will have a 4 year mission lifetime. The first satellite is scheduled to be launched at the end of 2018, with the second one launched in 2019. Data access will be open, relying on the ground receiving stations in South America, so they may not have the capacity to acquire the coastal zone data at 200m on a global basis (only under request).

2.9 CSA (Canada)

Martin Bergeron reported on the Canadian Space Agency (CSA) which primarily supports the Canadian ocean colour community through its Earth Observation Application and Utilization (EOAU) programs. For more than 10 years now, near $20M CAD of investment has been provided for operationally-focused science supporting Government of Canada Departments mandates relevant to marine, coastal and inland waters. Support has also been provided to data access initiatives such as the ESA/MERIS near real time acquisition infrastructure and, since decommission, with Natural Resources Canada (NRCan) ESA/MERIS data archives facilities. Recognizing the importance of ocean colour data for Canada, the CSA has initiated discussions regarding the access to Sentinel-3 data and is supporting preparatory validation activities. The CSA acknowledges the need for International coordination through its participation in IOCCG and Blue Planet – the over-arching Marine Task within the Group on Earth Observation (GEO).

CSA has no capacity of its own in ocean colour remote-sensing. Its primary Earth Observation platform is RADARSAT-2 and the upcoming RADARSAT Constellation (RCM) which provides a broad array of applications and services over the marine domain. While not ocean colour missions, CSA also collaborates in international missions relevant to water such as SMAP and SWOT. CSA has recently started looking into potential initiatives relevant to water colour remote-sensing with mission concept studies such as WaterSat and the Canadian Hyperspectral Mission (CHM). These two prospective missions are driven by Canadian users' desire for high spatial resolution hyperspectral data with frequent revisit time, either of which could contribute to coastal and inland water colour science, water management and monitoring activities.

A new Canadian Network, NetColor, aims to federate and coordinate ocean colour activities within Canada within academia, the private sector, and the Government coast-to-coast. NetColor aims to develop a critical mass of scientists to influence and advise the CSA on specific thematic needs and requirements.

2.10 SOA (China)

Zhihua Mao presented China's advances in satellite remote sensing, with the launch of many different satellites missions over the past few years. Amongst them are four satellite missions related to remote sensing of ocean colour, including the ocean observation satellites (HaiYang, HY series), the meteorological satellites (FengYun, FY series), environment and disaster monitoring satellites (HJ series), and the Chinese spacecraft (SZ series). The State Oceanic Administration (SOA) is responsible for the HY satellites, which are ocean colour satellites. The first satellite in this series (HY-1A) was launched on 15 May 2002, while the second (HY-1B) was launched 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 bands similar to SeaWiFS plus two infrared bands to measure sea surface temperature. The HY-1B satellite is still operational.

The HY-2 satellite series represents ocean dynamic satellites, with the first satellite (HY-2A) launched on 16 August 2011. The HY-2A mission carries three microwave payloads including a scatterometer, an altimeter plus a radiometer. Satellite data from the HY, FY and HJ missions can be downloaded free of charge by approved applicants.

China plans to launch many satellites over the next ten years including another two ocean colour satellites (HY-1C and HY-1D) which will be launched in 2017 (morning and afternoon satellites). HY-1C and HY-1D are identical satellites, similar in design to HY-1B, but carrying a new payload equipped with two ultra-violet bands and an on-board radiance calibration system. Continuing this series, the HY-1E and HY-1F morning and afternoon satellites are scheduled to be launched around 2020.

2.11 ISRO (India)

Prakash Chauhan reported on the Earth observation program of ISRO, which is driven by the application of remote sensing technology for societal benefits. Earth observation data based services in India has evolved through investments done in research and development for space based geophysical products development and subsequent methodology development for applications like 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 such as Ministry of Earth Sciences, 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 observations using both space based and *in situ* observations. Space based, high resolution (~360m spatial resolution) ocean colour observations were started with OCEANSAT-1 OCM in 1999, which was followed by OCEANSAT-2 OCM launched in 2009. The OCM data was used for developing ocean colour products such as chlorophyll-a concentration, diffuse attenuation coefficient, suspended matter concentration and aerosol optical depth at 865nm. OCEANSAT-2 OCM data is acquired in two modes, i) Local Area coverage (LAC) at 360 m spatial resolution using a ground station at Hyderabad, India and ii) Global Area coverage (GAC) mode at 1-km spatial resolution through on-board recording mechanism and subsequent down link. After the initial Cal/Val experimentation using vicarious and lunar calibration, OCM-2 products were fine tuned for better quality. Applications such as *Notiluca* bloom detection in the Arabian Sea, detection of enhanced primary production after major cyclones, potential fishing zone (PFZs) advisory, 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 understand sediment fluxes in the 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 POC, DOC and phytoplankton carbon, primary, new and export production, and PAR using OCM data. The Space Applications Centre (Ahmedabad) and 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. ISRO's future ocean colour sensor will be OCM-3 which will be launched in the 2017-18 timeframe on-board 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. Ocean colour observations will be co-located with SST data using a SSTM sensor having two bands in 10-12 micron region of electromagnetic 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/program/iocs-2015-presentations/.

3.1 Keynote 1 - Marina Lévy (University Pierre et Marie Curie, France):

Physical and Biogeochemical Modeling at the Sub-Mesoscale

Marina Lévy is head of the Bio-Physical Interactions group at the Oceanography and Climatology Department (LOCEAN) of University Pierre et Marie Curie (UPMC), in Paris, France. After graduating from the French Ecole Polytechnique, she prepared her PhD thesis on the oceanic carbon cycle in the Mediterranean Sea at UPMC. In 1998, she worked under a post-doctoral fellow-ship at the Lamont-Doherty Earth Observatory of Columbia University, New-York, and obtained, in 1999, a permanent position at CNRS. Her research interests are the study of the interactions between ocean physics, biogeochemistry, plankton, marine ecosystems and ecology, with a particular focus on the role of ocean turbulence, and with the final goal of being able to make better predictions for the future. Her approach combines numerical modeling, use of multi-satellite data and field observations. She was awarded the CNRS bronze medal in 2004 for her pioneering work on the interactions between sub-mesoscale physics and phytoplankton productivity..

Ocean colour imagery reveals ubiquitous, beautiful sub-mesoscale (1 – 10 km) features in the distribution of phytoplankton at the sea-surface. Frequently mesocale (~100 km) and sub-mesoscale

Chlorophyll and SST patterns coincide, and there is often synergy with other satellite products e.g., Chlorophyll and altimetry. The questions raised by these observations include what are the drivers of this variability, does it induce inter-annual variability of the bloom, does it increase the ability of phytoplankton co-exist and what is its contribution to biogeochemical (N, C, O) budgets? This presentation addressed these questions and showed how high-resolution bio-physical models can be used to tackle them.

The drivers of this variability include stirring (geostrophic velocity), vertical velocities and stratification. Regarding inter-annual variability of phytoplankton blooms, models have revealed that 50% of the variability in bloom amplitude is due to meso/sub-mesocales. Models have also revealed that there is more ability for phytoplankton to coexist at sub-mesoscale fronts, and less ability for co-existence in the core of mesoscale eddies.

Concluding remarks noted that sub-mesoscale variability of Chlorophyll is widespread in ocean colour observations but this variability has long been neglected in both models and data analysis. Understanding the implications requires synergetic use of different satellite products, *in situ* observations and models. There is a need for high time and space resolution in both satellite products and models. Geostationary ocean colour missions such as GOCI and the future GEO-OCAPI and GEOCAPE, as well as high resolution altimetry e.g., SWOT, have a lot of potential in the future.

3.2 Keynote 2 – Stuart Phinn (University of Queensland, Australia)

Collaborative Earth-Observation Infrastructure for Coastal and Coral Reef Monitoring and Management

Stuart Phinn's research interests are in measuring and monitoring environmental changes using earth observation data and publishing/sharing ecosystem data. He is a professor of Geography at the University of Queensland where he teaches remote sensing and he has established and co-directs the Biophysical Remote Sensing Research Group, Joint Remote Sensing Research Program and Australian Earth Observation Coordination Group. Most recently he was the founding director of Australia's Terrestrial Ecosystem Research Network and its Associate Science Director. He received his PhD from the University of California – Santa Barbara/San Diego State University in 1997. The majority of his work uses images collected from satellite and aircraft, in combination with field measurements, to map and monitor the Earth's environments and how they are changing over time. A large part of this is in coastal and marine environments with C. Roelfsema. This work is done in collaboration with other environmental scientists, government environmental management agencies, NGO's and private companies. He publishes extensively with his collaborators, and currently has 153 papers in refereed international journals, 1 book, and 11 book chapters. A large part of this work also involves training the next generation of scientists and managers who effectively use remote sensing, and has graduated 36 PhD students. A growing part of this work *now focuses on national coordination of Earth observation activities and the collection, publishing and sharing of ecosystem data.*

Knowledge gained from establishing and attempting to sustain national and international ecosystem science monitoring and research programs are critical to reflect on. Lessons learnt from these longer term, often 5- 10 year projects, enable others to learn not to make the same mistakes. This knowledge is also critical for establishing and sustaining long-term coastal and oceanic observing networks for research, monitoring, modelling and management. Development and delivery of Ocean Colour applications and products falls in this area, specifically for scientific, monitoring and management. In this context “long-term” refers to sustained regular measurements over at least a decade, and “coordinated” refers to a group of individuals or organisations acting together to achieve a common set of goals for the good of everyone. A number of these coordinated, long-term networks, with EO capabilities at their cores, already operate in different areas of the world, and are used for production and validation of ocean colour and other coastal satellite image based products. Although oceanic observing is highly coordinated, coastal observing, and its links to terrestrial and oceanic observational networks is often not as well developed.

This presentation draws on experiences from a number of terrestrial and marine observational systems in Australia, ranging from public involvement in community based systems or citizen science, through to coordinated regional, state and national programs, including the Integrated Marine Observing Systems (www.imos.org.au) and the Terrestrial Ecosystem Research Network (www.tern.org.au). Both of these networks were formed over a 5-8 year period and the lessons learnt in these processes and ongoing operations are pertinent to any form of coordinated observational science, especially those linked to satellite monitoring capabilities.

To establish programs such as these, and to ensure they are used, a key principle is linking EO data to field or ship based measurements and to provide information that the relevant people can access, understand and trust. This is a basic premise underlying calibration/validation globally, and interestingly, effective collaboration and science. This all works fine if you are one group and have a common goal, however that is not the case when building national or international networks from separate groups and discipline areas to collect and share data for a range of purposes. The approaches used in Australia’s TERN and IMOS were derived explicitly to address these challenges and to enable rapid, but sound development of their networks in inclusive national systems. The results are a functioning national network of data collection, publishing and sharing capabilities. However, these were not established without making mistakes and learning from them.

What worked in establishing the networks were: recognising existing data collection networks and approaches; establishing expectations from all participants; engaging across all sections of science community; acknowledging mistakes openly and building on them; recognising the need for cultural changes in sharing data; and shared progression and development of knowledge.

What did not work was: directly imposing new data collection, processing and distribution guidelines; excessive reporting; progress without consultation and discussion; not recognising disciplines and inter-disciplinary; limited time for evaluation and critiques; accepting the current situation without constructive criticism, not developing shared goals, and accommodating “excessive egos” and “rock star” scientists.

Collectively, these are new approaches to conducting science and enabling it to be used where it should be (all levels of decision making) and sustained long term and to build future generations. Lead to major change in how we do and will do science in Australia – for EO, lead to the AEOCCG, for science as a whole lead to National Marine Science Plan and the Long Term Plan for Ecosystem Science.

3.3 Keynote 3 – Sung Yong Kim (Korea Advanced Institute of Science and Technology, KAIST)

Research and Applications Using Submesoscale GOCI Data

Sung Yong Kim is an Assistant Professor in the School of Mechanical Aerospace Systems Engineering at Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Republic of Korea and the director of the Environmental Fluid Mechanics Laboratory at KAIST. He received B.S. degree in Naval Architecture and Ocean Engineering from Seoul National University, Seoul, Republic of Korea, in 1999 and Ph.D. degree in Applied Ocean Science from Scripps Institution of Oceanography, La Jolla, USA, in 2009. His present research interests are in the areas of coastal circulation, sub-mesoscale processes, statistical and dynamical data analysis, environmental parameterization, and operational coastal ocean observing system. He has served as a member of Technical Committee (MONITOR) in the North Pacific Marine Science Organization (PICES) since 2014. He is the recipient of the Young Frontier Research Scientists Award in the Korean Academy of Science and Technology in 2013 and the Young Scientist Award in the Korean Society of Oceanography in 2014.

The talk presented examples of oceanic sub-mesoscale studies using geostationary ocean color imagery (GOCI) maps. Sub-mesoscale features in the ocean, observed as eddies, fronts, and filaments, are identified with the O(1) Rossby number and a horizontal spatial scale smaller than the first baroclinic Rossby deformation radius. Thus, studies of sub-mesoscale processes demand the high-resolution observations of less than a temporal scale of one hour and a spatial scale of O(1) km, which can be beyond the temporal and spatial resolutions that present-day satellite sensors can resolve. However, the GOCI maps with resolutions of one hour in time and 0.5 km in space have high potential to support sub-mesoscale studies. Sub-mesoscale process studies have benefited from primarily idealized numerical models and theoretical frameworks because they require the use of high resolution observations of less than one hour in time and O(1-10) km in space. In this talk, several aspects of the scientific use of GOCI maps to investigate oceanic sub-mesoscale processes were highlighted.

3.4 Keynote 4 – Daniel Odermatt (Odermatt & Brockmann GmbH, Switzerland)

The Future of Water Quality from Space

Daniel Odermatt is an expert in Earth Observation and on aquatic applications. He is the managing director of Odermatt & Brockmann GmbH in Zurich, Switzerland, and a scientific collaborator at the Swiss Federal Institute for Aquatic Science and Technology (Eawag). After completion of his PhD thesis on Spaceborne Inland Water Quality Monitoring at the University of Zurich in 2011, he assessed the benefits of Copernicus downstream services for authorities in Switzerland as head of the Swiss National Point of Contact for Satellite Images. He moved to a position as remote sensing expert at Brockmann Consult GmbH in Germany, funded by the European Marie Curie Industry Academy Partnership Program. He developed the scientific design, supervised the implementation and validated the first complete MERIS inland water quality product archive for several hundred lakes worldwide, which became available in early 2015 from Brockmann Consult on behalf of the European Space Agency. His ambitions are to contrast and structure the exorbitance of study-specific algorithms for optically complex waters developed in recent years, to advance suitable methods to operational applications, to improve the robustness of these applications and to foster their use in environmental monitoring programs and other surveys.

The growing observational capabilities for remotely sensing coastal and inland water quality go in hand with an increasing demand for water quality information in many parts of the world. This demand arises from various user groups, concerns global to regional scales, and is shaped by individual technical and legal requirements. Remote sensing has some undisputable assets in this view, and is thus often cited in the context of unsealed future prospects by potential users. Limitations however arise from a range of current operative work practices on both producer and user side, and they effectively prevent the usage of remotely sensed water quality information in operational environmental assessment programmes to date. With data continuity provided for in the future, it is time to reconsider the ways how remotely sensed water quality information is derived and used.

Bio-optical models and inversion algorithm concepts for coastal and inland waters became available as early as in the 1990s, but no standard retrieval methodology emerged due the often-quoted optical complexity of these waters. Consequently, water quality retrieval applications in a quasi-operational manner as enabled by MERIS led to a growing variety of site-specific band ratio algorithms. Hence the observational capabilities grew, at the cost of a methodology complex that resulted from the waters' unsolved optical complexity. In order to establish consistent work practises for the future, standard procedures for algorithm selection, parameterization and validation must be defined, and persisting methodological gaps must be identified. Fundamental issues like the understanding of inherent optical properties and their relationship to derived concentrations, water stratification effects, the identification of particular water types or error quantification require more attention again, and algorithms that provide for the corresponding information must be made available to a wider audience.

Apart from these methodological challenges, new strategies are needed to establish crosscutting activities with water quality managers, hydrodynamic modellers and other stakeholders. The most recent GEO Water Quality Summit (Geneva, April 2015) attracted an unprecedented number of such stakeholders, and confirmed the growing interest in remotely sensed water quality. The Community of Practice initiated at the summit aims to develop a synoptic multi-scale monitoring service using water quality information from all available sources. Beyond the methodological challenges this poses, it requires clarification of the division of labour between public and private players as well as developed and developing countries, of strategic data ownership and public environmental data access, of quality standards and legal relevance, and financing. Therefore, this community effort will potentially provide for a framework that enables an optimal uptake of remotely sensed water quality information in operational environmental assessment programmes in the future.

3.5 Keynote 5 – Marcel Babin (Université Laval, Canada)

Impact of Climate Change on Polar Ecology

Marcel Babin is the Research Director, Takuvik Joint International Laboratory, Université Laval (Canada) and Centre National de la Recherche Scientifique (CNRS, France). He is an oceanographer with expertise in the areas of light propagation and light-matter interactions in the ocean. His research interests cover the study of fundamental light-driven processes in the ocean, variations in ocean primary production, monitoring of light-driven carbon fluxes from space using ocean colour remote sensing, and modelling of light-driven ocean processes and ecosystem interactions. While remote sensing and the related technical developments are central to his research program, his scientific objectives are motivated by fundamental questions on the impact of climate change on marine ecosystems, particularly the sensitive Arctic ecosystems.

Climate change is the most pronounced in the Arctic where air and seawater temperature is increasing twice as fast as elsewhere. The main observed impacts on the Arctic Ocean include a decrease by 40% since 1979 in the extent of the September icepack, and an increase in freshwater water runoff which, combined with modifications in the ocean circulation, increases vertical stratification. It has been hypothesized that these and other changes will reshape the functioning of marine ecosystems and trophic interactions. While primary production may increase at the highest latitudes where the spring bloom is expected to occur ever earlier, and to become more intense, it may decrease in the productive Bering and Nordic Seas where strengthened stratification will prevent vertical mixing and favour the prevalence of deep-chlorophyll maxima under an oligotrophic surface layer. Additionally, phytoplankton fall blooms may become more common because of intensifying air-sea interactions. In this presentation, I will show a series of results recently obtained using ocean color remote sensing, that substantiates all these predictions. I will also discuss the current limitations in the use of ocean color remote sensing in the Arctic to monitor phytoplankton biomass and primary production, and possible alternative approaches.

3.6 Keynote 6 – Cara Wilson (NOAA/NMFS/SWFSC, USA)-

Remote Sensing and Fisheries

Cara Wilson is a satellite oceanographer for the Environmental Research Division (ERD) at NOAA's Southwest Fisheries Science Center in Monterey CA and is the PI of the West Coast node of NOAA's CoastWatch program which is housed at ERD. Her research interests are in using satellite data to examine bio-physical coupling in the surface ocean, with a particular focus on determining the biological and physical causes of the large chlorophyll blooms that often develop in late summer in the oligotrophic Pacific near 30°N. She received a Ph.D. in oceanography from Oregon State University in 1997, where she examined the physical dynamics of hydrothermal plumes. After getting her PhD she worked as the InterRidge Coordinator at the University Pierre et Marie Curie in Paris, France. Her introduction to remote sensing came with a post-doc at NASA's Goddard Space Flight Center which involved analyzing TOPEX and SeaWiFS data. She joined NOAA in 2002 and is currently a member of NOAA's ocean color working group, the IOCCG (International Ocean Colour Coordinating Group), and the International Affairs committee of PORSEC (Pan Ocean Remote Sensing Conference). In 2011 she served on the National Research Council's Committee on Assessing Requirements for Sustained Ocean Color Research and Operations. In her free time she leads Sierra Club service trips.

To most people the term "fisheries" evokes images of salty fishermen battling the elements to catch fish, however the term encompasses more than just the harvesting of fish. Fisheries involve not just commercial fish stocks, but all living marine resources (LMRs), including marine mammal, sea turtles and invertebrates. Additionally there are three distinct aspects of fisheries: harvesting, assessment, and management/conservation, all of which have different goals. Here I will discuss the role that ocean color data plays in all three of these aspects of fisheries. Ocean color data is used to optimize the catch per unit effort (CPUE), by helping direct fisherman to schools of fish and thereby save time and fuel costs. While clearly ocean color sensors cannot detect fish, areas of higher chlorophyll, and chlorophyll fronts, can pinpoint areas where fish are more likely to congregate. There are international differences in how fish advisories are generated and disseminated, as national agencies serve different constituencies. In some countries, notably India and Japan, the national fisheries agencies are actively involved with using satellite data to help increase the efficiency of their fishing fleets. In the US fish advisories are a commercial enterprise, and are not generated by government agencies. Ocean color data is not yet widely used in stock assessment, simply because stock assessment models do not incorporate environmental data of any kind. However there has been a recent move towards an ecosystem-based management of fisheries which has given new impetus to better understand the environmental factors influencing fish stock dynamics, and to try to include environmental variability as an integral part of the assessment process. Ocean color data plays an important role in characterizing and monitoring the habitat that influences living marine resources, information which is which is needed for conservation and management. While near-real time ocean color data is needed for optimizing CPUE, stock assessment, management and conservation applications require long time series of climate-quality data records.

3.7 Keynote 7 – Kenneth J. Voss (University of Miami, USA)-

In Situ Sensors (MOBY Past, Current and Future)

Dr. Kenneth Voss is a Professor in the Physics Department at the University of Miami. His specialty is Ocean and Atmospheric Optics. He received his Ph. D. in Physics at Texas A&M University (1984), where he built an instrument to measure the polarized light scattering in seawater with Dr. Ed Fry. His post-doctoral experience was at Scripps Institution of Oceanography (SIO), with Mr. Ros Austin at the Visibility Laboratory. Here he worked on developing instrumentation to measure different aspects of the in-water light field. After the post-doctoral experience he continued at the Visibility Laboratory and the Institute of Marine Resources at SIO until moving to a faculty position at the University of Miami (1989). Since arriving at Miami he has been involved with remote sensing, through the SeaWiFS and MODIS projects, along with in-water, atmospheric optics, and instrumentation. In 2003 he was elected Fellow to the Optical Society of America. He is currently the PI for the MOBY project.

The Marine Optical BuoY has been deployed off of the island of Lanai for over 17 years, providing high quality hyperspectral water leaving radiance data for use in vicariously calibrating ocean color satellite instruments. This site was chosen as it met many of the requirements for vicarious calibration of ocean color satellites. The original system, now over 18 years old, has performed very well over the years; however, as with all systems, the components are getting old and tired, and there have been many advances in optics and electronics since the system was designed in the early 1990's. With the advances in mind, and to correct some deficiencies due to aging, we are currently in the midst of building a "refreshed" optical and electronic system for MOBY. Some of the features of the new system are: better spectral imaging for reduced straylight, simultaneous measurements to allow greater precision and reduce the influence of environmental instability, more accurate measurement of auxiliary data such as buoy tilt/roll and relative instrument heading. I will be presenting some of the historical data, showing the stability of the instrument over many years and some of the initial characterization data on the new MOBY-Refresh instrument.

4. Breakout Session Reports

A total of 10 breakout sessions covering a wide range of topics were conducted at the IOCS meeting in several parallel sessions as follows:

- ***Tuesday 16 June 2015 (Breakout Sessions 1 – 3)***
    - **Breakout 1:** Remote Sensing of Phytoplankton Composition – Possibilities, Applications and Future Needs
    - **Breakout 2:** Benefits and Challenges of Geostationary Ocean Colour Remote Sensing – Science and Applications
    - **Breakout 3:** Understanding and Estimating Uncertainty in Ocean Colour Remote Sensing Data and Derived Products

- ***Wednesday 17 May 2015 (Breakout Sessions 4 – 6)***
    - **Breakout 4:** Tools to Harness the Potential of Earth Observations for Water Quality Reporting and Management
    - **Breakout 5:** Ocean Colour Remote Sensing in High Latitude Areas
    - **Breakout 6:** New Applications Using Very High Resolution Satellite Ocean Colour Data

- ***Thursday 18 May 2015 (Breakout Sessions 7 – 10)***
    - **Breakout 7:** Joint Hyperspectral Remote Sensing Breakout Meeting
    - **Breakout 8:** Ecosystems and Climate Change Applications
    - **Breakout 9:** Satellite Instrument Pre- and Post-Launch Calibration
    - **Breakout 10:** Joint use of Bio-Argo and Ocean Colour

A summary report from each of these breakout sessions is given below, highlighting the key points from each session. Many also include recommendations for the space agencies.

4.1 Breakout 1: Remote Sensing of Phytoplankton Composition – Possibilities, Applications and Future Needs

Co-Chairs: Colleen Mouw (Michigan Technological University, USA), Astrid Bracher (Alfred Wegener Institute, Germany), Nick Hardman-Mountford (CSIRO, Australia)

The motivation for this breakout session was to broaden the discussion beyond the algorithm phytoplankton functional type (PFT) developers themselves to understand:

1) How current satellite phytoplankton composition products are and could be used in modeling (climate, ecosystem, optical) activities and ecosystem and fisheries management?

2) What *in situ* observational needs and opportunities are required to support forthcoming satellite capabilities leading to expanded satellite phytoplankton composition algorithm approaches and products?

Currently, many of the phytoplankton functional type retrieval approaches are globally focused. This suits global modelers particularly interested in climate related science questions. However, the majority of other users have a local interest. Talks were presented from both scales covering use of PFT products in model verification, fisheries and aquaculture management. In all cases, improved communication of algorithm uncertainty, strengths and limitations with each end use in mind were articulated as being highly valuable. To ensure widening the application of satellite PFT products, ongoing discussion with a wide user community is encouraged. This will be most easily facilitated at broad audience meetings where a variety of communities converge.

To date, the majority of the existing PFT satellite retrieval approaches have utilized high precision liquid chromatography (HPLC) pigment relationships with taxonomic groups or size classes in developing relationships and validation. In considering expanding satellite sensor capability into the future, there is a need to begin to define coordinated efforts for *in situ* datasets to ensure the full impact of the planned capability is realized. Recommendations from the breakout discussion included:

- Selecting specific unified datasets that include coincident apparent and inherent optical properties, and phytoplankton composition that all algorithm developers utilize to improve the ability to intercompare validation metrics.
- At minimum, ensure HPLC pigments are observed. Consider the addition of particle imaging and genomics capability if possible.
- Begin to explore how genomics information may be able to support PFT determination.
- Utilizing existing time series sites rich in phytoplankton composition information.
- Add additional phytoplankton composition observational capability to these time series sites.
- Ensuring inter-calibration and standardization of measurements advancing the knowledge of phytoplankton composition *in situ.*

As a starting place, an initial gap analysis table (below) was outlined based on discussion points from the breakout session.

Gap Analysis

	Existing	Desired (10-15 years)	Needed
In situ Observations	• Reasonable global distribution of HPLC pigments. Some pigment time series • Few time series of particle imaging • Rapidly growing genomic capabilities • Little synergy between observational types	• Broad global distribution and many time series sites of coordinated pigment, particle imaging and genomic observations • Expanding platforms for phytoplankton observing	• Coordination of existing time series sites with AOPs, IOPs, and phytoplankton composition • Investment in additional phytoplankton composition observations • Development of unified protocols and data repository for various types of phytoplankton composition observations
Algorithm Strengths/ Limitations	• Primarily global • Rooted mostly in multispectral resolution • Broad similarities but many divergent details	• Hyperspectral exploitation resulting in greater discrimination of functional types • Reduced uncertainty due to improved sensor capability and reduced input product uncertainty • Identification of 'standard' PFT products for various applications	• Coordinated use of identical independent datasets in development and validation across all algorithms. • Exploitation of current hyperspectral satellite data as synergistic use to multispectral satellite data
Meeting Users Needs	• Some comparisons to global models • Limited regional implementation for fisheries management	• Clear communication of limitations and uncertainties • Summarize range of algorithm options based on intended use and uncertainty requirements	• Enhanced efforts of algorithm development on regional scale surrounding prioritized areas of user needs

4.2 Breakout 2: Benefits and Challenges of Geostationary Ocean Colour Remote Sensing – Science and Applications

Co-Chairs: Antonio Mannino (NASA GSFC) and Maria Tzortziou (CCNY)

Ocean colour (OC) remote sensing from geostationary orbit (Geo) provides the capability of high temporal resolution measurements (e.g., <hourly) and improved cloud-free coverage that can revolutionize the scientific application and societal value of OC data from space. This capability is necessary to study coastal waters where the physical, biological and chemical processes react on short time scales, and apply observations to monitor coastal water quality indicators, detect and track coastal hazards, and improve assimilation of satellite data into operational models. Because phytoplankton blooms and community composition evolve on time scales of hours to days, Geo OC observations spanning from inland waters, rivers, estuaries to the open ocean would improve our quantitation of phytoplankton dynamics and global carbon cycling. The Korean GOCI sensor is the only OC instrument to operate in Geo. Its success has spawned a follow-on mission by the Koreans called GOCI-II. Other geostationary OC missions are in planning stages including NASA's GEO-CAPE, the European OCAPI, and others. Despite the advances made with GOCI data, much remains to be resolved to fully utilize OC data from Geo. The objectives of this breakout session were to discuss (1) the unique science and applications value of OC observations from a geo-orbit; (2) the advantages of geostationary OC in combination with OC from polar orbiting sensors and the minimum set of requirements to achieve a quasi-global geostationary OC constellation; (3) key issues to resolve for successful application of geostationary OC data including atmospheric correction, sun-earth-sensor geometry, BRDF, sensor pointing stability, etc., and (4) the processes and new products possible from geostationary orbit including the challenges in reducing uncertainties to take full advantage of the high temporal resolution.

Geostationary (or geosynchronous) ocean colour observations offer several advantages over low-earth observations (LEO) to study processes in coastal and inland waters as well as the dynamics of the open ocean. These advantages include higher temporal resolution, which is on the order of hourly to sub-hourly repeat observations. Such high frequency observations permit (1) rate process measurements such as quantifying changing stocks of carbon pools and improvement of primary productivity model results and (2) tracking of hazards such as harmful algal blooms and oil spills. Because cloud cover varies during the day, Geo can provide significantly better spatial coverage compared to LEO. For example, Ruddick et al. (2014) have shown that a polar orbiting sensor gives approximately 110 observation (cloud free) days per year in the Southern North Sea compared to about 200 days/year for the Geo. Moreover, the study showed that a Geo sensor with hourly acquisitions from 10:00 to 15:00 would result in 110 days/year when four or more images would be available during a single day, allowing to resolve diurnal processes. Geo also offers the capability to obtain higher signal-to-noise (SNR) by dwelling longer at any given location such as areas with low solar zenith angles (early or late period of the day and for high latitude regions).

Several challenges for successful implementation of Geo ocean colour missions were identified and discussed including: the need for new approaches to atmospheric correction, bidirectional reflectance distribution function (BRDF) correction, high sun and viewing zenith angles, and wave shadowing; the need to reduce algorithm uncertainties to be able to quantify diurnal changes; and instrument or platform issues such as pointing stability. The issues discussed for atmospheric correction included the limitations of the plane parallel ("flat earth") model currently used versus a spherical shell model that would need to be developed. Because of the diurnal variability in atmospheric nitrogen dioxide (NO_2)

and ozone, corrections for these trace gases will need to be implemented to prevent false variability in ocean colour observations. Absorbing aerosols are prevalent over populated inland and coastal waters. Correction for absorbing aerosols will require measurements of the single scattering albedo and aerosol layer height. Because the sun-sensor geometry varies throughout the day and with season, a BRDF correction scheme will be necessary. The high sun and viewing zenith angles contributes additional challenges to Geo ocean colour such as in strong sky/sun reflection across the air-sea interface at such high angles, marine BRDF, and lower signal at high solar zenith and view angles.

Recommendations were made on approaches to resolve some of these issues (1) perform sensitivity studies to examine the accuracy of retrievals at large sensor and solar zenith angles, (2) optimize NASA's OC aerosol models for coastal regions, (3) develop methods to detect different types of absorbing aerosols (mineral dust, black carbon, industrial pollutants, continental aerosols), (4) explore the possibility of using aerosol transport models such as GOCART to identify and correct for different types of aerosols, and (5) follow the expected improvements in atmospheric corrections algorithms, for example, developments by the NASA PACE science team. Instrument technical issues discussed that we will need to overcome in future Geo instruments include straylight, ghosting, solar calibration, lunar calibration, pixel-level spectral response functions, and pointing stability. The cost of Geo missions can be mitigated by hosting ocean colour instruments on commercial satellites as secondary payloads. In this manner, the space agencies would pay a hosting and data transmission fee and not the full cost of a dedicated spacecraft and launch vehicle. Several Geo instrument concepts are possible for relatively modest costs.

How we promote Geo OC missions was discussed. One suggestion was to emphasize the measurements that relate to coastal managers (socio-economic issues). These measurements included those related to fisheries, water quality (human health, beach closures), invasive species (ballast water). Other suggestions included other applications of Geo OC observations: tracking hazards such as HABs and oil spills, map and follow evolution of phytoplankton blooms, ecosystem health, improving models for forecasting and convolving Geo missions as part of a global observation system with LEO sensors. Synergies with LEO missions that were discussed include improved temporal resolution globally, enhanced global spatial coverage, improvements in global productivity measurements, on-orbit cross-calibration, and joint calibration/validation activities.

Updates on planned Geo OC missions were presented. GOCI-II will have greater capabilities than GOCI-I and will be launched in 2019. The European Geo-OCAPI mission is proceeding to Phase A in preparation for a proposal. The NASA GEO-CAPE mission is currently in pre-Phase A with engineering and science studies continuing to further develop this mission.

A recommendation from the breakout discussion was to form a new IOCCG working group on Geo that would (1) share information and ideas to promote a "quasi-global" Geo OC constellation, (2) compile and share field measurements and simulated Geo-relevant datasets, (3) coordination of field campaigns to resolve Geo challenges (e.g., GOCI validation cruises, Korean-U.S. campaign planned for 2016), and (4) foster international collaboration on Geo applications with GOCI-I and –II and other Geo sensors such as the meteorological satellites.

4.3 Breakout 3: Understanding and Estimating Uncertainty in Ocean Colour Remote Sensing Data and Derived Products

Co-Chairs:
Part I – Kevin Turpie (UMBC), Emanuel Boss (Univ of Maine),
Part II – Stéphane Maritorena (UCSB), Frédéric Mélin (EC-JRC),
Part III – Roland Doeffer (Helmholtz Zentrum Geesthacht), Jeremy Werdell (NASA/GSFC).

Estimates of uncertainty are vital to determine whether data support hypotheses, e.g., indicating whether a change or trend is significant. Assigning uncertainty also lets us know whether the information derived from the data is of sufficient quality to support decision-making. Despite the necessity of quantifying uncertainty, most ocean colour products have been distributed without associated uncertainty estimates, or with indicators only partially describing uncertainty. The planned availability of uncertainty products should help: improve user confidence in remote sensing data; define the range of possible applications of data products; support data assimilation in ecological and climate models; or support trend analysis in climate research.

Status
There is general agreement that current comparisons between satellite and in situ measurements are insufficient to determine uncertainty for satellite data products. The sampling is too limited to account for all conditions under which satellite measurements are taken. Ship-based measurements cannot provide the necessary time and space coverage. Buoys or fixed platforms greatly improve temporal coverage, but there are only a few of them and they are at fixed locations. However, sampling for surface radiometry is greatly improved through measurement networks, such as AERONET-OC, although it is in predominantly coastal waters. Floats may be able to provide even better space and time coverage in the future for some IOPs and AOPs. For instance, Bio-Argo floats could improve the sample for other data products that are derived from ocean color (e.g., various bio-optical and environmental parameters).

There is also a clear need to define an unambiguous language for communicating uncertainty. Very few members of the community use, or are even aware of, international standards for uncertainty estimation methods and terminology. A common terminological and methodological framework is critical to develop requirements based on user needs and to convey the meaning of uncertainty products to data users. This is also required for negotiating and resolving any apparent conflicting needs.

In general, the ocean colour community is still in a mode of exploration regarding estimation of uncertainty in satellite data products. There is a wide range of activities, but no clear direction nor a consensus yet on either methodology or metrics. Instead, investigators have offered multiple methods for producing spatially-resolved uncertainty estimates, each based on different assumptions, and covering different facets of the uncertainty budget. Example techniques reviewed during IOCS are as follows:

i) **Class-Based Approach** – stratifies uncertainties based on satellite matchups with in situ measurements sorted by water types, which can be identified by spectral characteristics. This approach is currently used for generating chlorophyll product uncertainties in NASA's MEaSUREs program, and for all products distributed by the ESA Ocean-Colour Climate Change Initiative.

ii) **Machine Learning** – Includes techniques, such as Neural Networks, that use in situ and satellite data to directly build relationships between satellite radiometry and derived products and their uncertainty. The Bayesian method also applies Bayesian statistics to in-water retrievals and an a priori uncertainty model based on in situ measurements to obtain uncertainty in surface radiometry and derived products.

iii) **Uncertainty Propagation** – Takes measured or modeled uncertainty for the TOA sensor, or any other quantity intervening as input to the algorithms, and propagates these through remote sensing algorithms to estimate satellite data uncertainty for surface radiometry, and eventually derived products. Such an approach is being implemented by ESA for the upcoming OLCI and MERIS reprocessing, while NASA is developing a similar approach for its suite of data products.

iv) **Algorithm-Based Method** – Compares results of two algorithms, where one is known to have a much smaller uncertainty under given known conditions.

v) **Colocation Approach** – Compares results from two different sensors that are measuring, ideally nearly simultaneously, the same quantity at the same location. The approach assumes that either the data from one sensor has much lower uncertainty than the one being assessed or there is no significant correlation between product errors, which would exaggerate agreement.

However, it would be useful to evaluate the summation of all sources of error in the validation process to verify uncertainty, however it is derived, including: satellite algorithm uncertainty, ii) the in situ measurement uncertainty, and iii) the uncertainty attributed to sampling discrepancies between the satellite-derived quantities and the validation measurements. Sums of these various uncertainty sources could be compared with validation uncertainty to verify methods of estimation or support "closure" studies.

Recommendations

1) It is recommended that the IOCCG establish a permanent group on uncertainty to coordinate and reinforce a dialog between data product users and developers, facilitated through common language and practice (i.e., a framework of terminology, methodology and metrics) based on international standards.

2) As part of that dialog, it is recommended that the community engage in more discussion regarding temporal and spatial variability in uncertainty, the meaning and communication of data bias (as a representation of systematic error), and how these concepts can be used.

3) It is also recommended that the community leverage off of uncertainty studies conducted in other fields. Closure studies common to atmospheric sciences were given as an example. It is recommended that field data used for matchup should have passed at least a rudimentary in-situ closure procedure (e.g. compared to an independent instrument or biogeochemical measurement).

4) As the space agencies are looking at propagating uncertainties from at-sensor radiometry to Rrs uncertainties, additional exploration of propagating Rrs uncertainties into bio-optical algorithms is recommended. Likewise, further exploration of propagating in situ measurement uncertainties into bio-optical algorithms is also recommended.

5) Developers of propagation of uncertainty approaches should work to include the inherent algorithm uncertainty (i.e., uncertainties stemming from the “imperfect algorithm error”). Algorithms necessarily cannot account for all variation, and the resulting uncertainty can be comparable to the uncertainty that is propagated from algorithm input.

6) In general, it is recommended that more work be done to compare and understand the pros and cons of the various methods that are being developed for the evaluation of uncertainties associated with ocean colour products.

7) It is recommended that the community further explore propagating uncertainties from Level-2 scenes to Level-3 composites. What uncertainties should be produced? Do they mean what we think they mean? As Level-3 composites are central to forming regional and global time series, which are used in climatological research, we also need to better understand how trends are affected by all upstream sources of uncertainty.

4.4 Breakout 4: Tools to Harness the Potential of Earth Observations for Water Quality Reporting and Management

Co-Chairs: Blake Schaeffer (EPA/Office of Research and Development) and Vittorio Brando (Italian National Research Council, CNR)

Earth observation technology has the potential to accelerate the engagement of communities and managers in the implementation and performance of best management practices. Satellite technology has proven useful in coastal waters, estuaries, lakes, and reservoirs, which are relevant to water quality managers. However, the delivery and communication of management relevant water quality information from earth observation data is typically limited between the scientific community and water quality managers. This session was designed to bridge the scientific and management communities.

The session was divided in two sets of talks addressing the "data deliver/user needs" trade-off, each followed by a moderated community discussion.

Two talks introduced the first part focused on the "data delivery":

- Uses and challenges of earth observation data for inland water quality: a GloboLakes perspective, by Evangelos Spyrakos (U. Stirling)
- Earth observation in support of reporting to European legislation on surface water quality; technical offers and uptake by users, by Carsten Brockmann (Brockmann Consult GmbH)

The discussion after these talks was primed by the following questions:

- How can we overcome barriers to sharing in situ calibration and validation data?
- How do we see the field of water quality earth observation advancing in the next 5 years?
- What level of accuracy is needed for the monitoring of lake water quality?
- How mature are the current in-water and atmospheric correction algorithms over inland and near-shore waters?
- Remote sensing derived products and indicators required for reporting are different. Can we develop a strategy to foster communication between EO scientists and users? How can we technically support this dialogue?

Three talks in the second part of the session focused on "user needs":

- Development of a GEO global water quality monitoring and forecasting service, by Steve Greb (Wisconsin Dept. Natural Resources)
- Water quality assessment frameworks for the 21st Century. Connecting the dots and adapting to change, by Tod Dabolt (EPA/Office of Water)
- Changing the global water quality conversation: from Earth observation to action, by Francis Gassert (World Resources Institute)

The discussion after these talks was primed by the following questions:

- How to build and maintain user confidence in and encourage uptake of EO data?
- How can resource scarce monitoring programs leverage the onslaught of new data and

assessment methods?

- What are potential policy barriers and or ways policy can encourage the adoption of new methods that leverage sensor data?
- What are some opportunities to better leverage citizen science with regards to leveraging remote sensing data for water quality and what should the states and federal roles be?
- Remote sensing derived products and indicators required for reporting are different. Can we develop a strategy to foster communication between EO scientists and users? How can we technically support this dialogue?

Based on the discussions, recommendations were drawn at three different levels:

1) End users

Many researchers assume the end user has a specific set of needs in both data products and accuracy requirements. Typically, but not always, research projects are conceptualized, developed and underway prior to end user engagement. There are usually differences between scientist expectations and end user needs. End users expressed the need to rationalize a story that could be understood and didn't always require detailed reporting accuracies. It is recommended that end users provide examples of when less accurate data is better than no data. This will start a dialogue to manage expectations of both the end users and the researchers. End users have different levels of monitoring and reporting needs that may be flexible depending on the fit for purpose circumstances. Accuracy is relative and expectations of accuracy will change as research progresses. Finally, continued training and enhanced engagement with end users are recommended.

2) Science community

There is a need to explore the trade-off between data quality and user needs, in particular to address issues such as usability vs. accuracy and validity, as well as establishing the requirement on accuracy on global and local scales. A framework is needed to understand "When is good enough good enough?", and to assess the level of maturity of data and products to transition from research to operational services.

3) Space agencies

There is a significant growing demand from water quality managers, numerous government agencies, NGOs, and the research community for spatial resolution able to resolve coastal and inland water bodies. Currently the community is testing a new class of observation capability repurposing Landsat 8 for aquatic applications. The Landsat Operational Land Imager may be considered adequate for ocean colour retrievals and water clarity mapping due to its radiometric resolution and calibration accuracy [Pahlevan et al., 2014; Vanhellemont and Ruddick, 2014; Franz et al., 2015]. We expect that with the successful launch of Sentinel 2A and forthcoming launch of Sentinel 2B the temporal resolution will increase almost reaching those normally associated with ocean colour missions [Hestir et al., 2015; Mouw et al., 2015]. Combined with radiometric resolution similar to ocean colour missions, these developments may offer an opportunity to also describe the temporal evolution of water quality processes at the scale needed for environmental reporting and applications. Future sensors such as the Landsat and Sentinel 2 series should incorporate additional narrow spectral channels to enable accurate observations of chlorophyll and cyanobacterial pigments concentrations.

4.5 Breakout 5: Ocean Colour Remote Sensing in High Latitude Areas

Co-Chairs: Emmanuel Devred (U. Laval), Maria Tzortziou (CUNY), Toru Hirawake (Hokkaido University), Antonio Mannino (NASA GSFC), Rick Reynolds (Scripps)

In the context of global warming, polar marine environments sustain the most dramatic impact as exemplified by the receding of summer sea-ice cover. The remoteness and harsh environment of high latitude areas hampers traditional oceanographic sampling. Satellite remote sensing is an essential tool to resolve the spatial and temporal scales required for monitoring changes. However, remote sensing at high latitudes encounters unique challenges such as sea-ice cover, seasonal darkness, low sun elevation, frequent cloud cover and fog, specific bio-optical properties, and high concentrations of bubbles from wind-induced breaking waves. In addition, issues relative to coastal areas, such as very turbid and highly dynamic waters, occur widely.

Strong interest in the use of remote sensing in polar seas by the community has triggered the writing of an IOCCG report on the issue and the organization of a breakout session during the 2015-IOCS conference that provided an opportunity for further exchange of ideas and extended dialogue on future directions and strategies for carrying out state-of-the-art research using ocean colour remote sensing in high latitude areas. The breakout session was organized into two parts, the first part devoted to the current state-of-the-art in regards to algorithms and data processing, and the second one to future needs and field campaigns.

Atmospheric corrections at high latitudes are subject to issues related to low sun angles, contamination of the signal by sea-ice (ice-edge and drifting ice), in addition to usual challenges present in coastal environments (high particle concentration and turbidity). Some studies have been performed to account for the curvature of the earth and for flagging water pixels contaminated by sea-ice, but these findings have yet to be implemented in current processing software. New approaches on atmospheric correction that might be more appropriate for high latitude areas are being explored, including use of simultaneous atmosphere/ocean retrievals based on radiative transfer models for the coupled atmosphere/ocean system. Some new approaches are also being developed to correct for sea-ice contamination (e.g., 3D radiative transfer code with polarization, use of NIR spectral information). Development of bio-optical models needs to account for the peculiar properties of polar phytoplankton (i.e., low light adaption and strong packaging effects). There is a large contrast in the absorption budget between the Arctic Ocean (CDOM dominated) and the Southern Ocean (phytoplankton dominated). During the breakout session, examples were shown that suggest semi-analytical approaches to estimate IOPs improve the accuracy of prediction for certain products compared to classical band-ratio methods. A need to establish constituent-IOP relationships has been pointed out for the estimation of biogeochemical stocks. Finally, direct use of phytoplankton absorption to estimate net primary production was recommended given the poor performance of current chlorophyll-a algorithms. The deep chlorophyll-a maximum (DCM) can represent up to 30% of the column-integrated primary production and needs to be locally accounted for in model estimates; for example, statistical approaches that relate surface chlorophyll-a concentration to vertical distribution of phytoplankton have been successfully used to infer column-integrated PP in the Arctic Ocean. Under-ice blooms may also represent an important fraction of the annual primary production in polar seas, but this question remains to be addressed. High latitude seas also host the largest blooms of calcifiers and therefore contribute significantly to the PIC cycle. To address these topics and resolve the highly dynamic processes and strong bio-optical complexity of high latitude coastal waters, a recommendation is to use remote sensing observations (airborne or satellite platforms) at higher spatial resolution (<100 m).

The second part of the session was dedicated to field campaigns aiming at characterizing the bio-optical environment, developing an archive for validation activities (i.e., satellite – *in situ* matchups) and the understanding of processes (e.g., biogeochemical cycles). Cloudiness and fog as well as the polar night represent challenges to obtain a large database of satellite-*in situ* matchups. It was also noted that as soon as October, ocean colour data are not collected by visible sensors due to very low sun angles even if the water is still open. Possible actions to increase the number of remote sensing observations over polar seas include: the use of geosynchronous satellites with inclined orbit (or other orbits permitting longer integration times in polar seas such as elliptical), Lidar technology and other means of measurements to complement ocean colour remote sensing (airborne radiometers, gliders, drones, unmanned autonomous vehicles). A rapid action to increase the annual period of observation would be to increase the sun angle threshold (to 75^{o} instead of 70^{o} currently used) in processing software. In addition to a limited number of matchups and *in situ* observations, there is a persistent bias in sampling toward the summer and the western part of Arctic Ocean, whereas the Southern Ocean has a regional bias primarily because of logistical constraints. The Arctic Ocean basin and the Russians seas were two identified areas that required a sampling effort. Deployment and localisation of autonomous underwater vehicles (e.g., gliders and Argo floats) remains problematic due to the extreme conditions. Two large oceanographic field campaigns that focus on high latitude seas are currently under consideration for implementation by NASA's Ocean Biology and Biogeochemistry program): Arctic-COLORS: Arctic Coastal Land Ocean interactions (Notional Timeline: Phase I to start in 2017) and ICESOCC: Scoping for Interdisciplinary Coordinated Experiment of the Southern Ocean Carbon Cycle (Notional Timeline: Field Campaign to start in 2019). Currently, Canada, through Laval University, is leading an initiative to study phytoplankton edge blooms (ice camp and research cruises spread over 2015-2016 in the Baffin Bay). There are also a number of smaller initiatives that could significantly contribute to an Arctic database (e.g., Tara circum-Arctic expedition, ArcticNet annual field campaign in the Beaufort Sea and Canadian Archipelago).

During the session it was acknowledged that a number of challenges specific to polar seas exist but are not insurmountable, in fact some are being tackled (e.g., contamination by sea-ice). Ocean colour remote sensing remains an essential tool to study remote polar regions, however a larger database of observations is needed with a better regional representation than what currently exists. A number of upcoming field campaigns will help address these challenges.

4.6 Breakout 6: New Applications Using Very High Resolution Satellite Ocean Colour Data

Co-Chairs: Kevin Ruddick (RBINS), Quinten Vanhellemont (RBINS), Stewart Bernard (CSIR, South Africa), Chuanmin Hu (Univ. South Florida), Antoine Mangin (ACRI-ST), Nima Pahlevan (NASA GSFC).

The advent of satellite optical sensors providing very high spatial resolution data (<100m) at low or no cost opens up important new applications for coastal and inland waters. High quality Landsat-8 data is now available globally and free of charge at 30m resolution (15m panchromatic) and similar data is expected from Sentinel 2/MSI (10m-60m, launch expected 2015). Worldview and Pléiades provide on demand even higher resolution multispectral data, down to 1-2m and even less for panchromatic. The application potential is particularly high considering that most impacts of human activities are better visible at these smaller length scales. However, all such high spatial resolution missions, except the experimental HICO mission, have been designed for land remote sensing applications according to system requirements that are significantly inferior in other respects (spectral bands, signal-to-noise) to those of ocean colour missions.

The objective of this breakout session was to identify:

1) Identify the new features and processes in coastal and inland waters that can now be studied with these high spatial resolution satellite sensors, together with the associated applications and users.
2) Identify the new challenges for data processing and outline possible new algorithmic approaches.

This breakout session was structured via short talks introducing each of the following emerging questions as a basis for group discussion:
1a. Who are the future users of such data?
1b. What new marine processes and features can be seen at 10m resolution? At 1m?
1c. What new processes and features can be detected in ports, estuaries and inland waters?
2a. What are the processing challenges ... and opportunities?
2b. What new algorithms will be required?

Firstly, the benefits of the higher spatial resolution are quite obvious for **regions of interest or features smaller than or close to the size of a typical moderate resolution (300-1000m) satellite pixel**. Examples include ports, estuaries and many inland waters as well as suspended sediment distributions/wakes caused by offshore constructions, ships, etc. In fact, the number of inland waters that can be monitored by remote sensing increases very dramatically as spatial resolution improves.

Secondly, the higher spatial resolution is valuable for improving **the spectral contrast of patchy features** such as certain algae blooms, water with sea-ice, corals, seagrass, etc. As an example, a patchy *Noctiluca* *scintillans* bloom is easily identifiable from spectral reflectance when fully resolved but may be undetectable when averaged with ambient water over a much larger pixel.

The talks and discussions identified the following **applications** of the new high spatial resolution data:

- the assessment of sediment transport and Environmental Impact Assessment associated with ports, offshore constructions, dredging and dumping operations, sand/gravel/ore extraction, etc.
- detection/identification of patchy distributions of phytoplankton (e.g. Phaeocystis), dinoflagellates (e.g. *Noctiluca scintillans*), macroalgae (e.g. Sargassum), etc.
- detection/identification of patchy distributions of benthic flora (e.g. seagrasses) and corals
- detection/identification of floating substances (e.g. foam and slicks) or objects (boats, containers)
- measurement of water constituents in patchy water/sea-ice and polynya environments
- monitoring of water quality in estuaries, ports and inland waters
- detection of small scale discharges
- detection of large marine animals
- opportunities for data/product assimilation with high resolution coastal/bio-optical models for enhanced nowcasting and forecasting
- support for processing of medium resolution ocean colour imagery, e.g. modelling of sub pixel scale sunglint and skyglint at a wavy sea surface
- support for validation of medium resolution ocean colour data, e.g. assessment of sub pixel scale spatial variability and possible pixel contamination by platforms, ships and other structures.

In many cases the satellite data is becoming competitive for applications which have been traditionally reserved to (or considered not cost effective for) airborne remote sensing.

The following **data processing challenges/opportunities** were also noted:

- the low signal-to-noise specification of sensors designed for land applications
- generally lower spectral resolution of the sensors coupled with the width of the bands to improve signal-to-noise at such high spatial resolution
- the lack of certain spectral bands typically used for ocean colour applications
- the interest in exploiting very broad spectral bands, such as the Landsat panchromatic band, to enhance the spatial resolution of narrower multispectral bands
- the need to deal with spatially resolved (or partially resolved) sea surface effects such as sunglint and Fresnel reflection from wind and swell waves.
- the relevantly greater importance of algorithms for cloud shadow detection and for correction of adjacency effects (for which the object causing adjacency may even be outside the image)
- the greater importance of good geo-referencing
- the greater difficulties of vicarious calibration and validation for sensors with longer revisit period

Finally **an important recommendation to the space agencies is that the ocean colour community be better represented at the formulation stage of these high spatial resolution missions** to ensure that suitable provision is made for optimal exploitation for aquatic applications. This is, in particular, important to fill the void in understanding of the global carbon cycle pertaining to coastal and estuarine environments. Specific future missions would include Landsat-10+ and Sentinel-2E+.

4.7 Breakout 7: Joint Hyperspectral Remote Sensing Breakout Meeting

Co-Chairs: **Part I - Kevin Turpie (UMBC GSFC), Cecile Rousseaux (USRA GSFC);**
Part II - Maria Tzortiou (CUNY), Emmanuel Boss (Univ of Maine);
Part III - Michelle Gierach (NASA JPL), Sherry Palacios (BAERI ARC)

Hyperspectral remote sensing is greatly anticipated to transform marine, coastal, estuarine, and inland aquatic research and resource management – accelerating efforts to understand and monitor synoptic and global ecological response to population growth and climate change. However, challenges remain regarding the operational infrastructure and resources needed to support future spaceborne missions. In this three-part meeting, we began by exploring these challenges and the progress made towards their resolution. In the second and third parts, we explored potential applications and needed science directed at shelf and open-ocean and coastal and inland waters, respectively. Presentations and discussions were focused on the following questions.

1) How will hyperspectral data help?

Accurate separation of in-water and benthic optical constituents supports science and applications for a variety of sub-disciplines. For water-column ecology, retrievals of phytoplankton functional types (PFT), light availability, and chlorophyll fluorescence can be better supported, as demonstrated using first-generation hyperspectral satellite sensors (SCIAMACHY and HICO) and airborne sensors. Determination of community composition and particle size distribution can also provide insight into primary and export production, improving our understanding of global carbon cycles. Knowledge of optical constituent properties will enable the early detection of conditions that are potentially hazardous to humans and detrimental to coastal and fresh water ecosystem services, e.g., harmful algal blooms, suspended sediment, and pollutants. Aquatic habitats, including coral reefs and submerged aquatic vegetation, could be globally surveyed and monitored and knowledge of key exchanges between terrestrial and aquatic environments through palustrine and riverine systems could be greatly improved.

2) What spatial and temporal scales are needed?

Spatial resolution depends highly on the subject of study (e.g., synoptic open ocean observations: ≦1000m; coastal blooms: ≦500m; coastal habitats: ≦60m; freshwater resources: ≦100m). Likewise is true for temporal sampling (e.g., synoptic open ocean observations: ≦ days; coastal blooms: = hours to days; coastal habitats and inland water resources: = days to months). To understand the interaction of all these processes in coastal regions will require a combination of remote sensing assets in LEO and GEO orbits, covering a range of spatial and temporal resolutions, coordinated with more complete *in situ* observations. For the USA, the planned PACE/ACE, GeoCAPE, and HyspIRI missions are expected to cover this range. It is highly recommended, therefore, that these missions be designed for optimum concurrency.

3) What are the common challenges?

Engineering – The downlink requirements needed to transmit hyperspectral data from satellite offers significant engineering challenges. Likewise, the volume of data received presents challenges associated with processing, distribution, and archiving. Possible engineering solutions to these challenges are not obvious.

The scientific need to extend hyperspectral observations into the UV underscores previously known engineering challenges including: i) difficulties in generating adequate power from calibration sources at wavelengths below 450 nm, ii) increased uncertainty of solar irradiance in the UV-Vis spectrum, especially at high spectral resolution, and iii) the need to monitor spectral response in a narrow band instrument on orbit. One suggestion, for example, was to reduce UV observations to a few wider bands centered on key wavelengths.

Algorithms – The quantitative case for hyperspectral over well optimized multi-spectral radiometry <u>needs to be explicitly demonstrated</u>, e.g., using a combination of radiative transfer and empirical studies for a relevant ranges of water types. This is also especially true for high value PFT applications. Such analyses are of considerable importance in elucidating the relative pay-off, from an application driven perspective, between radiometric sensitivity and dynamic range, spectral resolution, spatial/temporal value priorities and other sensor design criteria.

Coastal and Inland Waters – Many of the important science questions that will be better answered by hyperspectral remote sensing are focused on global observations of shelf, coastal or inland waters. This brings forward the enduring challenge of atmospheric correction in these regions. To support science near the sea's margins, operational atmospheric correction algorithms need to be developed that must deal with i) highly variable NO_2 concentrations, ii) absorbing aerosols, and iii) adjacency effects (near coast lines). Improved algorithms could also provide corrections for cirrus contamination and sun glint.

In addition, our knowledge of optical properties for coastal and inland waters is relatively poor. High constituent concentrations often impede our ability to make accurate *in situ* measurements of inherent optical properties with existing sensors. These environments will require focused research efforts and a new generation of *in situ* sensors capable of assessing key constituent optical properties (absorption, scattering, and fluorescence).

4) How do we coordinate and integrate common algorithm development efforts?

The community must first prioritize needs through a process of open dialog. Implementation of new product algorithms will be multi-staged, involving modeling, experimentation, validation, and peer-review. The review would evaluate an Algorithm Theoretical Basis Document (ATBD), or the equivalent, and experimental data products. Currently, the PACE, HyspIRI, and GeoCAPE missions have established a group to facilitate cross-mission dialog. However, more international collaboration and coordination is needed.

It was recommended that a group be established to identify applicable airborne hyperspectral datasets and to create a single website linking to sites distributing data. This group could also work to i) establish discussion with data owners/distributors and users; ii) availability of datasets, and iii) suggest standards for format, metadata and documentation. The group could also inter-compare datasets to determine applicability to algorithm development. The current PACE science team is working to collect *in situ* and synthetic hyperspectral data for algorithm development. Similarly, the HyspIRI team is also setting up a group to work with airborne data assets. It is recommended that these efforts also be open to the international development community. Hyperspectral data from space should also be utilized. Current (OMI, GOME) and historic (e.g. SCIAMACHY, HICO) data should be exploited to demonstrate the potential use of hyperspectral information. Results could be combined or compared with multispectral data results that often show higher spatial resolution and / or higher temporal resolution, but are limited to fewer and broader bands. Other sensors, such as CHRIS/Proba (ESA), or the soon to be launched EnMap (Germany), PRISMA (Italy), and HISUI (Japan) could also provide test beds for some ocean colour remote sensing applications.

5) What other data would be useful to accompany hyperspectral data?

Hyperspectral data provide an essential information source for ocean colour science. However, just as with multi-band imagery, additional space-based measurements and accurate bio-optical-physical models would greatly enhance the potential of hyperspectral data and provide further insight into marine and coastal terrestrial processes. Observations of O_3, NO_2, and meteorological data (e.g. winds speed and direction, pressure, relative humidity) are crucial for traditional atmospheric correction techniques. Sea Surface Temperature (SST), sea surface height (SSH), and sea surface salinity (SSS) could also improve the pace of progress towards new algorithms. Lidar data to determine vertical structure of key atmospheric and water constituents would be useful to understand sources of uncertainty. Investigations of optically complicated coastal and inland waters could be enhanced with interdisciplinary research efforts focused on key geographic locations or "natural laboratories". Validation and calibration data are critical, but are typically sparse and sampled unevenly. Cross mission measurement comparisons further inform validation and calibration efforts. Calibration data from the Moon or “stable” terrestrial targets are critical. Finally, it is essential to have a standard spectral library for specific absorption, backscatter for optical constituents of the water column and reflectance spectra for benthic and palustrine cover.

4.8 Breakout 8: Ecosystems and Climate Change Applications

Co-Chairs: Cara Wilson (NOAA/NMFS) and Paul DiGiacomo (NOAA/NESDIS)

To be updated soon.

4.9 Breakout 9: Satellite Instrument Pre- and Post-Launch Calibration

Session Chair: Gerhard Meister (NASA, GSFC)

The session was well attended with about 50 attendees. The 11 speakers represented most space agencies involved in ocean color research: ESA, EUMETSAT, ISRO, KIOST, NASA, NOAA, SOA. Most agencies were represented in the IOCS 2013 calibration breakout session as well, the Chinese State Oceanic Administration (SOA) was the only new addition. The presentations provided an excellent overview of calibration activities of current (MODIS Aqua, OCM-2, GOCI, COTCS, and VIIRS) and recent (SeaWiFS, MERIS) ocean color sensors. The participation regarding future sensors was not quite as extensive. KIOST presented plans for GOCI-II. For the OLCI sensor on the Sentinel-3 mission (launch late in 2015), EUMETSAT presented possible modifications to the on-orbit solar diffuser characterization, but there was no update regarding the prelaunch characterization of OLCI (ESA presented on this in 2013). Neither JAXA (they presented in 2013, SGLI launch in 2017) nor the Brazilian/Argentinian space agencies (SABIA-MAR launch in 2018/2019) presented the calibration activities or plans regarding their sensors. For many of the future missions, an overloaded schedule prevented the calibration experts from attending, especially for those missions close to launch.

The first presentation by Fred Patt sparked an interesting discussion regarding calibration uncertainty. The SeaWiFS calibration is limited by the digitization of the data. Introducing an approach that considers changes of less than 1 count, the SeaWiFS long term trend of water leaving radiances at 555nm changed significantly enough to be of concern to the ocean color community. Throughout the session, it became clear that state of the art calibration uncertainty for long term trending of top-of-the-atmosphere radiances for most sensors is on the order of 0.1% of top-of-atmosphere radiances, at best. The interpretation of long term trends in ocean color products should consider the calibration uncertainty in any assessment.

Jack Xiong (NASA) presented the calibration efforts of the MODIS Calibration Support Team (MCST), focusing on the MODIS on the Aqua mission. One particular concern is the large degradation of the MODIS solar diffusers at the short wavelengths. MCST has started to use desert trending for those wavelengths to correct the solar diffuser trending. The calibration of MODIS is especially challenging due to a significant scan-angle dependence of the degradation.

Ludovic Burg (ACRI-ST) presented the calibration improvements of the 4th reprocessing of MERIS. The ‘pristine’ solar diffuser on MERIS (very limited exposure to solar radiation) has degraded by about 2% at the short wavelengths over the mission, about 10 times less than the MODIS Aqua solar diffuser. He showed that the prelaunch characterization of the MERIS solar diffuser did not fully explain the solar diffuser measurements on-orbit and described how an improved model will improve the accuracy.

Prakash Chaun (ISRO) presented the status of OCM-2. Lunar calibration, vicarious calibration, Rayleigh calibration and a relative adjustment to correct for striping have been used for calibration adjustments.

Seongick Cho (KIOST) presented on both GOCI and GOCI-II. The annual variation of the solar diffuser measurements of GOCI has been successfully modeled and will be published soon. Significant enhancements are planned for the calibration capabilities of GOCI-II: there will be an additional (pristine) solar diffuser, and lunar measurements will be made as well, although there are some limitations.

Xianging He (SOA) presented HY1B/COCTS calibration activities. The main challenges are the absence of an on-board calibration device and incomplete prelaunch characterization of the instrument polarization sensitivity. A crosscalibration to SeaWiFS is used for instrument calibration, and an approach has been developed to characterize the polarization sensitivity using on-orbit data.

Gene Eplee (SAIC) and Junqiang Sun (GST) reported on the VIIRS related calibration activities of NASA and NOAA, respectively. Both agencies adopted an approach of combining the lunar and solar diffuser measurements. The type of degradation of the VIIRS solar diffuser was discussed controversially after the talks. The NASA team has developed a correction to the lunar irradiance model (ROLO) to correct for libration angle dependencies in the VIIRS lunar data. Both teams reported significant improvements in the ocean color products after the application of the new calibration approaches.

Constant Mazeran (Solvo) presented challenges for the vicarious calibration for non-standard atmospheric correction algorithm. Standard NASA atmospheric correction algorithms use vicarious calibration approach with unique vicarious gain factors. For spectral matching atmospheric correction algorithms (e.g. POLYMER), the vicarious gains are not always unique. However, the derived ocean color products can be equally robust.

Ewa Kwiatkowska (EUMETSAT) reported on preparations for the OLCI (Sentinel-3) calibration. The feasibility of an on-orbit characterization of the BRDF of the solar diffuser with spacecraft yaw maneuvers is currently being evaluated. This approach could potentially reduce uncertainties due to the prelaunch characterization of the solar diffuser BRDF. Results will be presented to ESA and EUMETSAT teams and management.

4.10 Breakout 10: Joint use of Bio-Argo and Ocean Colour

Co-Chairs: Antoine Mangin (ACRI-ST) and Xiaogang Xing (OUC/Takuvik)

Context

The Bio-Argo is in operational status within Argo thanks to significant effort of the biogeochemical and bio-optical communities over the last years and following in particular recommendations of OceanObs 2009. The required Quality Control in Real Time of biogeochemical and bio-optical variables is presently being implemented within the Argo data management system and data delivery has started through Coriolis. After some regular QC and specific care about systematic error between floats, it is believed that Bio-Argo floats could become a new and important contributor to operational OCR for cross verification and validation. Also using Bio-Argo in complement in providing the full 3D picture gives an invaluable increase in the knowledge of oceanic biogeochemistry. As a consequence, the Bio-Argo community is willing to work on constructive collaboration with OCR actors.

Objectives

The breakout session on the "joint use of Bio-Argo and Ocean Colour and associated presentation was focused on :

1. Recent progress of the Bio-Argo technology and deployments (X. Xing, E. Boss)
2. Harmonised protocol for sampling and QC (A. Mangin and E. Organelli)
3. R&D works on blending EO data and Bio-Argo floats ; towards a 3D picture (R. Sauzède)
4. Near future of the Bio-Argo network (regional points of view developed by N. Hardman-Mountford for Indian Ocean and by M. Babin for Arctic)

To feed the discussion, four key questions have been addressed during this breakout session:

1. How do we ensure the link/complementarity between fiducial reference quality data requested for OCR and ongoing QC of float data?
2. How should be organized biogeochemical and bio-optical cruises with deployment of Bio-Argo floats?
3. What are the needs for cooperation between OCR and Bio-Argo ?
4. What are the criteria for optimization of Bio-Argo deployment (in complementarity with other observations means) ?

A synthesis of the answers is provided below.

1. How do we ensure link between fiducial reference quality data and ongoing QC of float data?

- Whenever possible the first floats deployment should be done next to Boussole or Moby for calibration (however practically delicate). This is, however, not mandatory as the radiometer and optical sensor have been initially calibrated in the same way that the sensors implemented on moorings.
- Deploy the float concomitantly to a CTD and optical casts allowing for reference measurements, including sampling for HPLC pigments and POC.

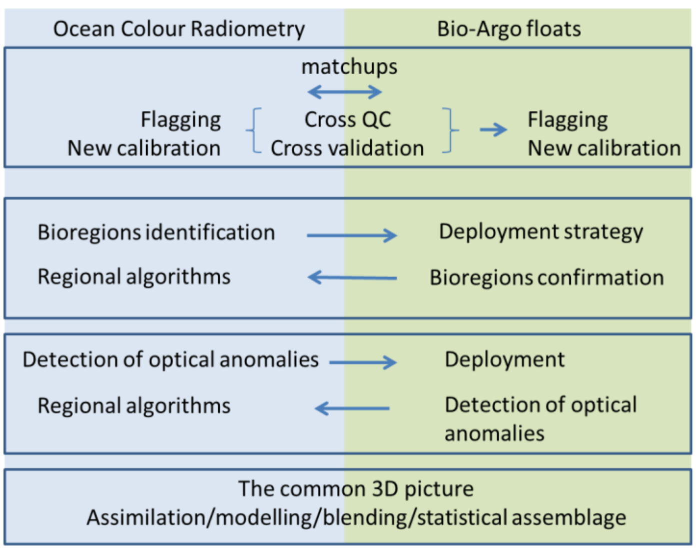
- Continuous analysis of float observations against remote sensing products over the whole life of the floats to :
    - determine if drift may have occurred and
    - "calibrate" the fluorometer to the satellite chlorophyll product.
- Monitoring of the dark signal at depth

2. How biogeochemical and bio optical cruises for deployment of Bio-Argo floats should be organized?

- International collaboration between cruises for coordination of opportunities/deployment and recovery of floats
- IOP and AOP measurement (3-5 days) from ship at a given location in parallel with calibration of Bio-Argo (or VAL-Argo) floats. Then float is launched to provide the temporal evolution.

3. What are the needs for cooperation between OCR and Bio-Argo ?

The complementarities between Ocean Colour Radiometry and Bio Argo floats have been discussed and are summarized on the following table. These complementarities range from mutual support to Quality Control and cross-validation, to exploitation (access to the 3D-picture and identification of regional bio-optical anomalies).



Complementarity between OCR and Bio-Argo

4. What are the criteria for optimization of bio-Argo deployment (in complementarity with other observations means) ?

There has been few discussion about this specific point. Optimization could be done by bio-regionalization and/or modelling of floats trajectories. In all cases, it depends on the final use (local studies on a specific biological system, assimilation into model, climate change, support to OCR…). The approach proposed some years ago (*see Claustre et al., OceanObs 2009*) might be a basis for designing the future network. Within few months, the community will be solicited to work on the design of a global Bio-Argo network as now expected by the Argo program.

Conclusions of Bio-Argo Breakout Session

Because there were four parallel breakout sessions, the number of attendees to the bio-Argo session was relatively low, but highly motivated. This has allowed very fruitful and direct discussions among participants who have shown and shared a high interest in exploiting complementarity between OCR and Bio-Argo. A general question is how to access to Bio-Argo data (there is a clear need for a centralized access (or information) point. The Bio-Argo community is willing to meet soon the Space agencies to build on a common strategy for deployment and harmonized use of both observation means.

5. Panel Discussion

Craig Donlon (ESA) led a panel discussion on "Future Directions of Ocean Colour Remote Sensing" along with panel members Stewart Bernard (IOCCG Chair), Paul DiGiacomo (NOAA) and Paula Bontempi (NASA HQ). The panel responded to several questions from the audience and also addressed a number of seed questions including "Operational ocean colour is about to become a reality for the next 20 years. How do we ensure more missions mean better science?" One of the key points is to ensure access to data from all the missions, including L0 and L1A data. This community must advocate strongly for access to lower level data. It was also recognised that new paradigms will emerge in future at the agency level, e.g., taking data to the users and working towards the next level of ground segments. We can also add value to ocean colour using complementary streams of data, with better integration with models at a wide range of scales allowing users to fill in gaps etc. It is important to ensure collaboration between "operational" and research applications underpinned by strong science. Satellite agencies should also have training in place to teach for example, synergistic use of satellite data. IOCCG can help at the lower level with training courses, resources for students etc. but the conveyance of services by agencies and the private sector is very important.

Regarding the seed questions "Better assimilation into better ecosystem models to deliver better biogeochemical and ecological forecasts" the ocean colour and biogeochemical community must choose the timescale of processes they wish to study – the technology is already there (e.g., Bio-Argo data) but good models must have good physics. It would be beneficial to bring in people from the modelling community to communicate with the physical oceanography community, which is why Marina Levy was invited to talk at IOCS-2015 and why the IOCCG is starting a new working group on modelling.

6. Poster Sessions

Two poster sessions were conducted during the course of the meeting (Tuesday and Wednesday afternoon). A total of 160 posters were presented in a wide range of topical areas (see http://iocs.ioccg.org/posters-abstracts/ for list of posters). Poster abstracts, listed in alphabetical order by author or by topical area, can be downloaded from the meeting website at: http://iocs.ioccg.org/abstracts/browse-approved-abstracts/. Many of the posters were voluntarily submitted to the open-access on-line library of scientific posters "eposters.net", where they can be viewed (see: http://www.eposters.net/sponsor/international-ocean-colour-science-meeting.