CHAPTER 04

SATELLITE OCEAN COLOUR SENSORS

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1. Introduction

The 70% of the earth's surface is covered by the ocean and the life inhabiting the oceans play an important role in shaping the earth's climate. Phytoplankton, also known as microalgae, are the single celled, autotrophic components of the plankton community and a key part of oceans, seas and freshwater basin ecosystems. They are significant factor in the ocean carbon cycle and, hence, important in all pathways of carbon in the ocean. Phytoplankton contain chlorophyll pigments for photosynthesis, similar to terrestrial plants and require sunlight in order to live and grow. Most of them are buoyant and float in the upper part of the ocean, where plenty of sunlight is available. They also require inorganic nutrients such as nitrates, phosphates, and sulphur which they convert into proteins, fats, and carbohydrates. In a balanced ecosystem, phytoplankton are the base of the food web and provide food for a wide range of sea creatures (NOAA). The measurement of phytoplankton can be indexed as chlorophyll concentration and is important as they are fundamental to understanding how the marine ecosystem responds to climate variability and climate change.

In open ocean waters, the ocean colour is predominantly driven by the phytoplankton concentration and ocean colour remote sensing has been used to estimate the amount of chlorophyll-a, the primary light-absorbing pigment in all phytoplankton. The marine ecosystem captures the visible part of the solar spectrum (400nm - 700nm) for photosynthesis with the help of the pigment molecules (principally chlorophyll) contained in phytoplankton. As they absorb and scatter light from the sun, phytoplankton exert a profound influence on the submarine light field, including the flux upwards across the water surface. As their concentration increases, the colour of the ocean changes from blue to green. Such shifts in ocean colour and the abundance of phytoplankton (chlorophyll concentration) can be mapped by measuring the light reflecting from the sea with optical sensors on-board earth-orbiting satellites. The technique is called ocean-colour radiometry or ocean colour remote sensing, and has proved to be one of the most fruitful of remote-sensing technologies.

For the last few decades, satellite data was used to estimate large-scale patterns of chlorophyll and to model primary productivity across the global ocean from daily to inter-annual timescales. Such global estimates of chlorophyll and primary productivity have been integrated into climate models illustrating the feedback between ocean life and global climate processes (Dierssen *et al.*, 2013). The applications of ocean colour remote sensing are extensive, varied, and fundamental to understand and monitor the global ecosystem. They are being used for monitoring of harmful algal blooms, critical coastal habitats, eutrophication processes, oil spills, and a variety of hazards in the coastal zone. Major applications of ocean colour data are as follows (Ocean Optics Web Book).

- Mapping of chlorophyll concentrations
- Measurement of inherent optical properties such as absorption and backscatter
- Determination of phytoplankton physiology, phenology, and functional groups
- Studies of ocean carbon fixation and cycling
- Monitoring of ecosystem changes resulting from climate change
- Fisheries management
- Mapping of coral reefs, sea grass beds, and kelp forests
- Mapping of shallow-water bathymetry and bottom type for military operations
- Monitoring of water quality for recreation
- Detection of harmful algal blooms and pollution events

2. Ocean Colour sensors

Ocean colour (OC) is an oceanic Essential Climate Variable (ECV), which is used by climate modellers and researchers. Remote sensing of ocean colour from space began in 1978 with the successful launch of NASA's Coastal Zone Color Scanner (CZCS) and it was a milestone in the history of satellite ocean colour remote sensing. Since then, more than twenty ocean colour satellite sensors have been launched *viz.* MOS, OCTS, POLDER, SeaWiFS, OCI, OCM, OSMI, MERIS, CMODIS, COCTS CZI, OSMI, GLI, POLDER-2, MODIS_AQUA, MISR, POLDER-3, MERSI, HICO, OCM-2, GOCI and VIIRS (www.ioccg.org/sensors_ioccg.html). More ocean colour sensors are planned over the next decade by various space agencies. These sensors capture continuous global ocean colour data (e.g. chlorophyll concentration, primary production), which provide significant benefits for research in areas such as biological oceanography and climate change studies. According to the current framework for ocean colour remote sensing, the satellite sensor first measures the intensity of the upward spectral radiation at the top-of-atmosphere (TOA). The varying intensities are then used to retrieve the water-leaving radiance after atmospheric correction, leading to the further retrieval of the optically active marine components (e.g. phytoplankton, minerals and coloured dissolved organic matter). The characteristics of past, current and scheduled ocean colour sensors are furnished in Table 1, Table 2 and Table 3 respectively. Among them, a short description on CZCS, SeaWiFS, MODIS, MERIS and OCM are briefly explained in the following sub-sections.

2.1 CZCS

The Coastal Zone Colour Scanner (CZCS) was the first instrument devoted to the measurement of ocean colour. The CZCS was a multi-channel scanning radiometer aboard the Nimbus 7 satellite, launched on 24 October 1978, and became operational on 2 November 1978. Though it was an experimental mission intended to last only one year, the sensor continued to generate valuable time-series data over selected test sites until 22 June 1986. The sensor resolution was 800m with six channels. The mission was success providing many lessons to the science community regarding calibration, validation and atmospheric corrections of an ocean colour remote sensing system. CZCS laid the foundations for

Table 1. Historical Ocean-Colour Sensors (Source: IOCCG)

SENSOR / DATA SOURCE	AGENCY	SATELLITE	OPERATING DATES	SWATH (KM)	SPATIAL RESOLUTION (M)	# OF BANDS	SPECTRAL COVERAGE (NM)	ORBIT
CZCS	NASA (USA)	Nimbus-7 (USA)	24/10/78 - 22/6/86	1556	825	6	433-12500	Polar
CMODIS	CNSA (China)	SZ-3 (China)	25/3/02 - 15/9/02	650-700	400	34	403-12,500	Polar
COCTS CZI	SOA (China)	HY-1A (China)	15/5/02 - 1/4/04	1400 500	1100 250	10 4	402-12,500 420-890	Polar
GLI	NASDA (Japan)	ADEOS-II (Japan)	14/12/02 - 24/10/03	1600	250/1000	36	375-12,500	Polar
HICO	ONR, DOD and NASA	JEM-EF Int. Space Stn.	18/09/09 - 4/12/14	50 km Selected coastal scenes	100	124	380 - 1000	51.6o, 15.8 orbits p/d
MERIS	ESA (Europe)	ENVISAT (Europe)	1/3/02 - 9/5/12	1150	300/1200	15	412-1050	Polar
MOS	DLR (Germany)	IRS P3 (India)	21/3/96 - 31/5/04	200	500	18	408-1600	Polar
OCI	NEC (Japan)	ROCSAT-1 (Taiwan)	27/01/99 - 16/6/04	690	825	6	433-12,500	Polar
OCM	ISRO (India)	IRS-P4 (India)	26/5/99 - 8/8/10	1420	360/4000	8	402-885	Polar
OCTS	NASDA (Japan)	ADEOS (Japan)	17/8/96 - 29/6/97	1400	700	12	402-12,500	Polar
OSMI	KARI (Korea)	KOMPSAT-1 / Arirang-1 (Korea)	20/12/99 - 31/1/08	800	850	6	400-900	Polar
POLDER	CNES (France)	ADEOS (Japan)	17/8/96 - 29/6/97	2400	6 km	9	443-910	Polar
POLDER-2	CNES (France)	ADEOS-II (Japan)	14/12/02 - 24/10/03	2400	6000	9	443-910	Polar
POLDER-3	CNES (France)	Parasol	Dec 2004 - Dec 2013	2100	6000	9	443-1020	Polar
SeaWiFS	NASA (USA)	OrbView-2 (USA)	01/08/97 - 14/02/11	2806	1100	8	402-885	Polar

Table 2. Current Ocean-Colour Sensors (Source : IOCCG)

SENSOR / DATA LINK	AGENCY	SATELLITE	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	BANDS	SPECTRAL COVERAGE (NM)	SPECTRAL RESPONSE FUNCTION	ORBIT
COCTS CZI	SOA (China)	HY-1B	11 April 2007	3000 500	1100 250	10 4	402 - 885 433 - 695		Polar
GOCI	KARI/KIOST (South Korea)	COMS	26 June 2010	2500	500	8	400 - 865		Geostationary
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	4 May 2002	2330	250/500/1000	36	405-14,385	SRF-link	Polar
MODIS-Terra	NASA (USA)	Terra (EOS-AM1)	18 Dec 1999	2330	250/500/1000	36	405-14,385	SRF-link	Polar
OCM-2	ISRO (India)	Oceansat-2 (India)	23 Sept 2009	1420	360/4000	8	400 - 900		Polar
OLCI	ESA/ EUMETSAT	Sentinel 3A	16 Feb 2016	1270	300/1200	21	400 - 1020	SRF-link	Polar
VIIRS	NOAA (USA)	Suomi NPP	28 Oct 2011	3000	375 / 750	22	402 - 11,800	SRF-link	Polar
VIIRS	NOAA/NASA (USA)	JPSS-1	18 Nov 2017	3000	370 / 740	22	402 - 11,800	SRF-link	Polar

Table 3. Scheduled Ocean-Colour Sensors (Source : IOCCG)

SATELLITE	AGENCY	SENSOR / DATA LINK	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	# OF BANDS	SPECTRAL COVERAGE (NM)	ORBIT
HY-1C/D (China)	CNSA (China)	COCTS CZI	2018	3000 950	1100 250	10 4	402 - 12,500 433 -885	Polar
GCOM-C	JAXA (Japan)	SGLI	Dec 2017	1150 - 1400	250/1000	19	375 - 12,500	Polar
HY-1E/F (China)	CNSA (China)	CZI	2021	2900 1000	1100 250	10 4	402 - 12,500 433 - 885	Polar
EnMAP	DLR (Germany)	HSI	2019	30	30	242	420 - 2450	Polar
OCEANSAT-3	ISRO (India)	OCM-3	2018-2019	1400	360 / 1	13	400 - 1,010	Polar
Sentinel-3B	ESA/ EUMETSAT	OLCI	2018	1265	260	21	390 - 1040	Polar
SABIA-MAR	CONAE	Multi-spectral Optical Camera	Sept 2021	200/2200	200/1100	16	380 - 11,800	Polar
GeoKompsat 2B	KARI/KIOST (South Korea)	GOCI-II	March 2019	1200 x 1500 TBD	250/1000	13	412 - 1240 TBD	Geostationary
PACE	NASA	OCI	2022/2023	2000	1000	hyperspectral (5 nm from 350 to 890 nm + 6 in NIR-SWIR)	350-2250 nm	Polar
GISAT-1	ISRO (India)	HYSI-VNIR	*(planned)	250	320	60	400-870	Geostationary (35,786 km) at 93.5°E
ACE	NASA	OES	>2020	TBD	1000	26	350-2135	Polar
GEO-CAPE	NASA	Coastal Ocean Color Imaging Spec (Name TBD)	>2022	TBD	250 - 375	155 TBD	340-2160	Geostationary
HyspIRI	NASA	VSWIR instrument	>2022	145	60	10 nm contiguous bands	380 - 2500	LEO, Sun Sync.

subsequent satellite ocean colour sensors, and formed a cornerstone for international efforts to understand the ocean's role in the carbon cycle. It also provided oceanographers with new insights into the biological and chemical properties of ocean water masses.

2.2 SeaWiFS

Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) was the only scientific instrument on GeoEye's OrbView-2 (AKA SeaStar) satellite, and was a follow-on experiment to the CZCS. The satellite was launched 1 August 1997, SeaWiFS began scientific operations on 18 September 1997. The spacecraft occupied a sun-synchronous orbit at an altitude of 705 km with an equatorial crossing time at 12 pm. The sensor resolution was 1.1 km in Local Area Coverage (LAC) and 4.5 km Global Area Coverage (GAC). The instrument was specifically designed to monitor ocean colour characteristics such as chlorophyll-a concentration and water clarity. During its operational period, the spacecraft telemetry became invalid due to failure of GPS, SeaWiFS interface and battery. As a result, there are gaps in data collection during 1 January 2008- 12 April 2008. In order to make data available at same accuracy, the spacecraft orbit altitude changed from 705 to 690 km. Unfortunately, the sensor failed its operation on 14 December 2010.

2.3 MODIS

MODerate- resolution Imaging Spectroradiometer (MODIS) are the series of EOS sensors launched by NASA on TERRA (December 1999) and AQUA (May 2002) satellites. MODIS is one of the most successful sensor in the ocean colour series and it is operational till date. Unlike SeaWiFS, MODIS records SST also with a spatial resolution of 1.1 km. The instruments capture data in 36 spectral bands ranging in wavelength from 0.4 µm to 14.4µm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km). The instrument image the entire Earth every 1 to 2 days. They are designed to provide measurements in large-scale global dynamics including changes in Earth's cloud cover, radiation budget and processes occurring in the oceans, on land, and in the lower atmosphere. MODIS is succeeded by the VIIRS instrument onboard the Suomi NPP satellite launched in 2011 and future Joint Polar Satellite System (JPSS) satellites (http://modis.gsfc.nasa.gov).

2.4 Ocean Colour Monitor (OCM) and OCM-2

Ocean Colour Monitor (OCM) and OCM-2 on board OCEANSAT-1 and OCEANSAT-2 respectively were launched by the Indian Space Research Organisation (ISRO) and designed to map the ocean colour, especially in Indian waters. OCM was the first satellite sensor employed for oceanographic studies in the Indian waters. The OCM sensor was launched on 26 May 1999 and it operated successfully till August 2010. OCM-2, the successor of OCM launched on 23 September 2009, and is currently operational. In OCM, the sensor is a solid state camera which collects data on atmospheric aerosols, suspended sediments and chlorophyll concentration, detect and monitor phytoplankton blooms. It operates in eight spectral bands. OCM provides a spatial resolution of 350 meters and a swath of 1420 km, and capable of covering the whole country every two days. The main applications are measurement of chlorophyll, detection of algal blooms, identification of potential fishery zones, delineation of ocean currents and eddies, observation of pollution and sediment inputs into the coastal zone and their impact on marine food, *etc.* (ISRO, 1999).

2.5 MERIS

Medium Resolution Imaging Spectrometer (MERIS) was launched in March 2002 and one of the main instruments on-board the European Space Agency (ESA)'s ENVISAT platform. The MERIS instrument was a moderate resolution wide field-of-view push-broom imaging spectro-radiometer capable of sensing in the 390 nm to 1040 nm spectral range. The instrument had a swath width of 1150 meters, providing a global coverage every 3 days at 300 m resolution. The primary objective of MERIS was to observe the colour of the ocean, both in the open ocean (clear or Case I waters) and in coastal zones (turbid or Case II waters). These observations were used to derive estimates of the concentration of chlorophyll and sediments in suspension in the water. In addition, this instrument was useful to monitor the evolution of terrestrial environments, such as the fraction of the solar radiation effectively used by plants in the process of photosynthesis, amongst many others applications (LAADS-DAAC). ESA formally announced the end of ENVISAT's mission on 9 May 2012.

3. Ocean Colour Climate Change Initiative (OC-CCI)

The European Space Agency (ESA) initiated Climate Change Initiatives (CCI) for all Essential Climate Variables (ECV). The Ocean Colour CCI (OC-CCI) is the one of them that related to a 'living' variable and having the goal of providing stable, long-term, satellite-based ECV data products. They utilise data archives of from ESA's MERIS and NASA's SeaWiFS, MODIS and possibly CZCS (after careful evaluation) sensors. The OCCCI presents an integrated approach by setting up a global database of in situ measurements and by inter-comparing OC-CCI products with pre-cursor datasets. The availability of *in-situ* databases is fundamental for the validation of satellite derived ocean colour products. A global distribution *in-situ* database was assembled, from several pre-existing datasets, with data spanning between 1997 and 2016 (OC-CCI web).

The OC-CCI project aims to:

- Develop and validate algorithms to meet the Ocean Colour ECV requirements for consistent, stable, error-characterized global satellite data products from multi-sensor data archives.

- Produce and validate, within an R&D context, the most complete and consistent possible time series of multi-sensor global satellite data products for climate research and modelling.
- Optimize the impact of MERIS data on climate data records.
- Generate complete specifications for an operational production system.
- Strengthen inter-disciplinary cooperation between international Earth observation, climate research and modelling communities, in pursuit of scientific excellence.

An inter-comparison analysis between OC-CCI chlorophyll-a product and satellite pre-cursor datasets was done with single missions and merged single mission products. Single mission datasets considered were SeaWiFS, MODIS-Aqua, MERIS and VIIRS; merged mission datasets were obtained from the GlobColour (GC) as well as the Making Earth Science Data Records for Use in Research Environments (MEaSUREs). OC-CCI product was found to be most similar to SeaWiFS record, and generally, the OC-CCI record was most similar to records derived from single mission than merged mission initiatives. Results suggest that CCI product is a more consistent dataset than other available merged mission initiatives (see Figure 1). In conclusion, climate related science, requires long term data records to provide robust results, OC-CCI product proves to be a worthy data record for climate research, as it combines multi-sensor OC observations to provide a > 15-year global error-characterized record. The

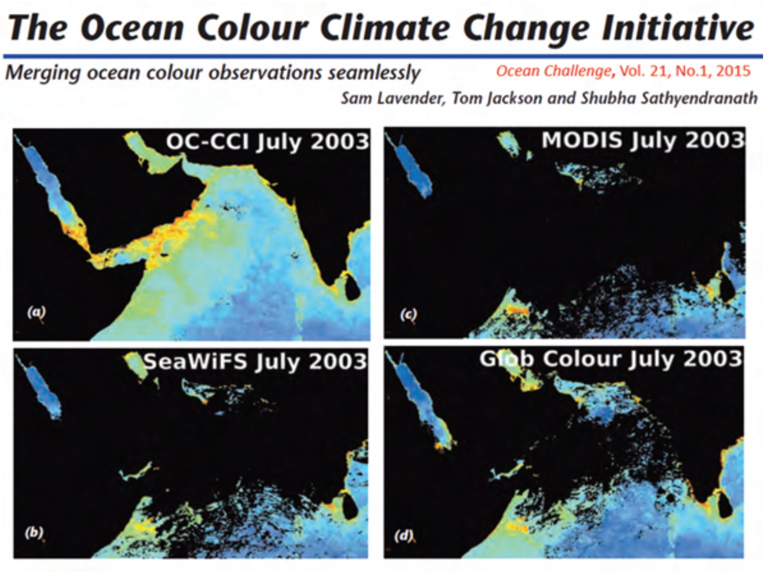

Fig. 1. Inter-comparison analysis between OC-CCI chlorophyll-a product with MODIS, SeaWiFS and GlobColour

data can be accessed by several options, including FTP and composite browser, is available in http://www.oceancolour.org/. A screen shot of the website is shown in Figure 2.

Fig. 2. screen shot of OC-CCI web portal

The OC-CCI project completed its third year with the release of version 3.1 product to the international science community following internal quality control and analysis. The project is maintained through the participation of the different consortium members: Plymouth Marine Laboratory (Science lead) (UK), Telespazio VEGA (UK), Brockmann Consult (Germany), Helmholtz-Zentrum Geesthacht (Germany), Joint Research Centre (EU), HYGEOS (France), Nansen Environmental and Remote Sensing Centre (Norway) and Foundation of the Faculty of Sciences of the University of Lisbon (Portugal) but enhanced with new CRG members (University of Reading) and user engagement (Sam Lavender through VEGA). In addition to European partners, OC-CCI has identified partners in the USA (National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, Naval Research Laboratory), Japan (Hokkaido University) and Canada (Bedford Institute of Oceanography). Additional international expertise is sought through interaction with the International Ocean Colour Coordination Group (IOCCG).

4. International Ocean-Colour Coordinating Group (IOCCG)

The IOCCG is an international Committee of experts with representatives from national space agencies as well as the ocean colour user community and was established in 1996. IOCCG promotes the application of remotely-sensed ocean-colour data through coordination, training, association between providers (space agencies) and users (scientists), advocacy and provision of expert advice. Objectives include developing consensus and synthesis at the world scale in the subject area of satellite ocean colour radiometry, establishing specialised scientific working groups to investigate various aspects of ocean-colour technology and its applications, and addressing continuity and consistency of ocean colour radiance datasets. The IOCCG also has a strong interest in capacity building, and conducts and sponsors advanced ocean colour training courses in various countries around the world (IOCCG). An overview and various activities of IOCCG are schematically represented in Figure 3.

Fig. 3. An overview and various activities of IOCCG (source: IOCCG)

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