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GLOBAL STATUS OF REMOTE SENSING OF PHYTOPLANKTON

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ABSTRACT

The color of the ocean as measured by the space-borne sensors contains the quantitative information on phytoplankton pigments, especially chlorophyll. In this paper we have reviewed principle of ocean color remote sensing. The concept of spectral, spatial, temporal and radiometric resolutions are first described followed by a discussion on present status of ocean color sensors. A brief account on various applications of remotely sensed ocean color information is presented with the examples from several sensors and region. In the open ocean, the techniques for measuring chlorophyll is almost established, where as in coastal waters the retrieval of ocean color information becomes complicated because of the interference of suspended sediments. Ocean color images are found useful to trace the mesoscale dynamics. Remotely sensed phytoplankton are also found useful to understand Carbon at basin as well as global scale. The paper concludes with comment on future of ocean color remote sensing and recommendations for promotion of ocean color science in Southeast Asia.

1.0 Introduction

The phytoplanktons are the floating microscopic plant population found in the ocean. They contribute over 25% of the total vegetation of the planet. They are often referred as primary producers as they produce organic substances from carbon dioxide and water within the cell, utilizing the sun light by photosynthesis, and make the base of food chain which support either directly or indirectly, the entire animal population of the ocean. Chlorophyll is the principal plant pigment of phytoplankton, acts as an agent in the photosynthetic process. Phytoplankton also plays an important role in maintaining balance of atmospheric carbon dioxide. Phytoplankton distribution depends on certain physical oceanographic set-up; thus they manifest dynamic oceanographic phenomena of the ocean through their distribution. Hence they are often considered as the tracers for upper ocean dynamics. Realizing their importance in ocean ecosystem, measurement of phytoplankton biomass has drawn considerable attention of oceanographers during last half of the present century. Because of its photosynthetic function, chlorophyll is considered, as an indicator of oceanic plant biomass and productivity and it is one of the most frequently measured biochemical parameters in oceanographic investigations. Although conventional ship measurements provide accurate estimates of chlorophyll pigment, vastness of the oceans does not allow us to get the information about its spatial and temporal variability ,in the oceans. Hence during the 1970s remote Sensing had evolved as the preferred technology for phytoplankton study that can provide the synoptic information from the upper ocean. Since remote sensing of phytoplankton pigments is based on the optical properties or color of the constituents of seawater, it is often referred as ocean color remote sensing. Satellite remote sensing of ocean color is already established as a dependable tool to provide estimates of phytoplankton stock both on global and regional scale. With recent launching of new ocean color sensors remote sensing of phytoplankton has got increased attention of oceanographers round the World.

In this paper, first the principle of ocean color remote sensing is reviewed providing different correction techniques involved with remotely sensed ocean color data processing and interpretation. We then discuss characteristics of ocean color sensors, which include spectral, spatial, temporal and radiometric sampling aspects. This is followed by a brief account on present status of ocean color sensors. In the following section various applications of remotely sensed phytoplankton pigment concentration are reviewed with the help of relevant examples. The paper concludes with a look forward to the advances in the field of ocean color remote sensing and finally with a few recommendations for promotion of ocean color of remote sensing in Southeast Asia. We have also provided a brief list of literature on the subject for more comprehensive information

2.0 Principles of ocean color remote sensing

Ocean color remote sensing is based on the concept that particulate and dissolved substances suspended in the upper ocean interact with the incident sun light. Such interaction could either be absorption of light by substances such as phytoplankton pigments and dissolved organic matter or scattering of light by substances like inorganic suspended sediments. As water molecules scatter light similar to the way that atmosphere scatter light, where concentration of particulate matter and dissolved substances are negligible, ocean appears deep blue in color. The scattering and absorption processes alter this color. Chlorophyll, the photosynthetic pigment found in phytoplankton, absorbs strongly in the red and blue region of the visible light spectrum (Figure 1) and reflects in the green. As the concentration of phytoplankton increases, the color of the water appears increasingly green. The absorption of light by chlorophyll can be quantified to determine the concentration of chlorophyll in water allowing estimation of phytoplankton abundance in a given area. However, the relationship between light absorption and chlorophyll concentration leads to complication by the presence of light scattering inorganic particulate matter in the water. Concentration of such particulate matter is generally high in coastal waters. That makes the water color near the coast green to brown or reddish brown. Even though chlorophyll pigment present in high concentration in water near the coast, the presence of fluvial suspended load makes it difficult to extract the amount of light absorption solely attributable to chlorophyll. In order to differentiate the oceanic water where the phytoplankton is the major water constituents, from that of the coastal waters where the non-chlorophyll particulate matter is abundant, they are often respectively categorized as “case 1” and “case 2” waters in scientific literature. Besides, cocolithophores, a type of phytoplankton which form hard mineral shells that scatter light very effectively can make the ocean color milky white.

However measurement of pigment concentration from the remotely sensed signals received at a space-borne ocean color sensor involves correction from the noises inherent in the signals because of interference by atmospheric as well as under water optical process.

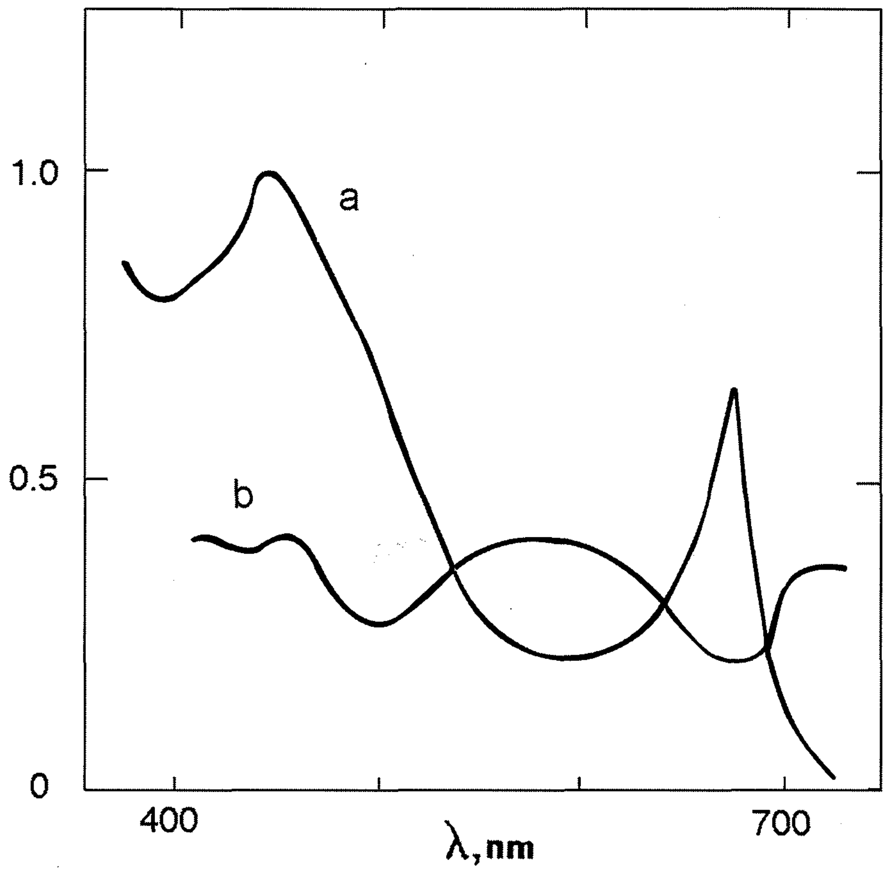


Figure 1: Spectral variation absorption (a) and backscattering (b) due to chlorophyll pigment.

2.1 Atmospheric correction

Remote sensing of the sea using visible wavelengths relies on the sunlight, which is backscattered from the sea to convey information about the optically active constituents of the seawater including phytoplankton pigments. In a typical scenario of ocean color remote sensing various optical paths of light particles (photon) between the ocean surface and remote sensors are illustrated in the Figure 2. Up to 80% or more of the light reaching at the sensor is atmospheric path radiance backscattered by molecular or aerosol particles in the atmosphere (ray C). In addition, not all the water leaving radiance reach the sensor since some of it absorbed or scattered (ray D) within the atmospheric column. To quantify the upwelling radiance for estimation of water constituents it is necessary to remove the undesirable signals received from the atmosphere. This is called atmospheric correction. Most recent standard procedures (Gordon and Wang 1994) are available for carrying out such correction on satellite derived image. Once the radiance signal has been corrected for atmospheric interference, the signal is then corrected for the solar zenith angle to derive normalized water-leaving radiance. Normalized water leaving radiance is subsequently used in algorithms meant for different water constituents for deriving the desired parameters.

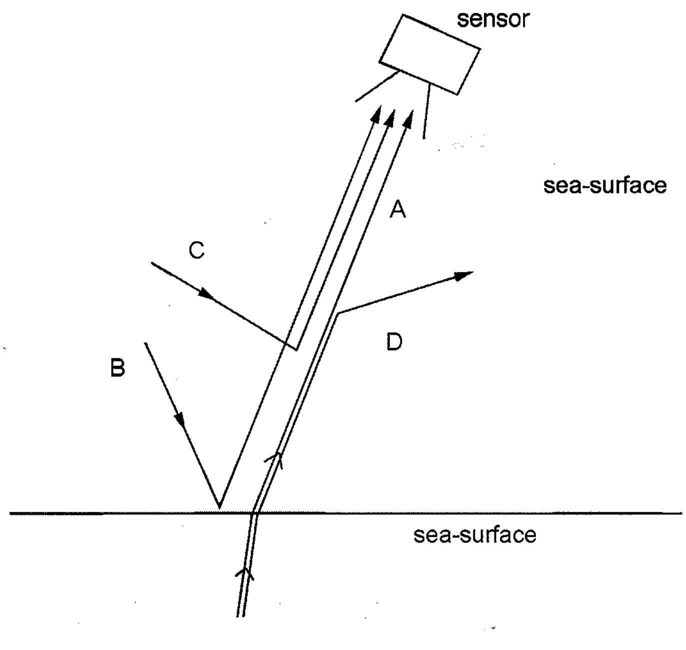


Figure 2: Light paths reaching an ocean colour sensor (A) leaving the water within the field of view; (B) reflected from the surface; (C) scattered by the atmosphere into the field of view; and (D) scattered aot of the field of view.

2.2 The underwater light field

Figure 3 illustrates the various components, which control the underwater light field in the upper ocean. These components determine the magnitude and spectral distribution of light leaving the sea, and ultimately define its apparent color. Photons from the sun reach the sea surface directly or are scattered in the atmosphere to reach the sea as skylight. They are refracted as they pass through the sea surface and then scattered or absorbed as they interact with the water and different constituents of water. The behavior of photons satisfies the probabilities, which can be expressed in term of inherent optical properties of seawater. The major optical properties are absorption coefficient, and the volume scattering function, which describes the directional distribution of the scattered light. Both of these vary with wavelength.

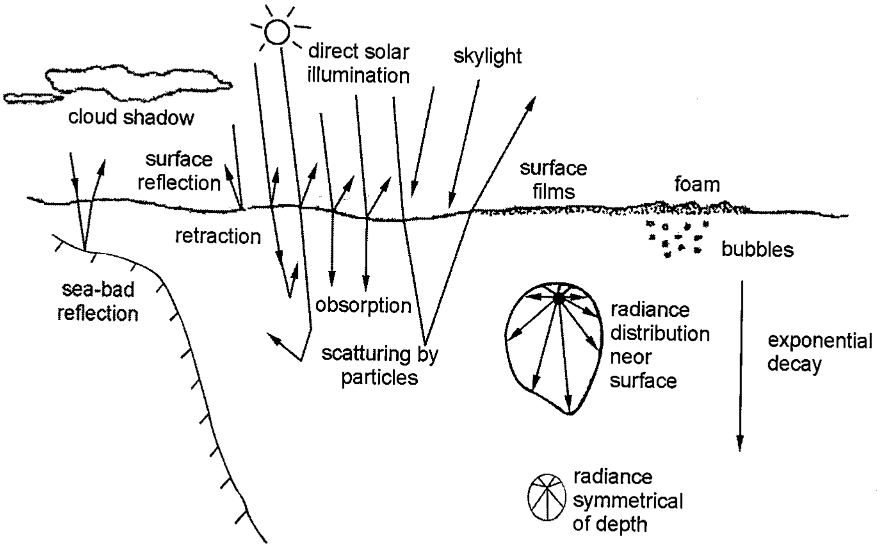


Figure 3: Different components, which control the incoming and outgoing light from the upper ocean.

The ratio of upward and downward irradiance is known as the subsurface irradiance reflectance ratio (R). Spectral variation of R (λ) depends on the ratio of backscatter and absorption coefficient. R (λ) varies in a complex way with changes in water constituents and it can be decomposed into ratio of backscatter and absorption coefficients attributed to different water constituents such as pigment, suspended matter etc. It is the ultimate goal of ocean color remote sensing to measure R (λ) in sufficient spectral detail that the concentration of chlorophyll, of the suspended sediment and the yellow substance can be determined with an acceptable level of accuracy. Theoretically it should be possible to distinguish between different species of phytoplankton if their pigment characteristics are sufficiently distinct. The response of R to different seawater compositions has been modeled, but in practice it is difficult to invert ocean color data to recover such information if more than one constituent is present. Hence ocean waters are classified under "case 1" and "case 2" categories. Case 1 waters mostly belong to oceanic region and dominated my phytoplankton. This category of waters has provided most success in calibration of the ocean color. This is because the strong absorption in the blue part of the spectrum by the chlorophyll a pigment ensures a good correlation between chlorophyll concentration and the ratio of R at 550 nm (green) and 440 nm (blue) as shown in Figure 4. Chlorophyll algorithm is developed using empirical relationship between in situ measurements of chlorophyll and ocean color signal at the sample locations. The same relationship is implemented for the entire image for pigment retrieval. However in case 2 waters, reliable calibration algorithms are yet to be developed (for global application), except in the limited case of sampling site specific models based on coincident in situ data.

Recently it has been suggested that oceans should be partitioned in to various oceanographic provinces based on regional absorption characteristics of phytoplankton pigments Such characteristics could then be used to improve algorithms for enhancement in accuracy of phytoplankton pigment estimates.

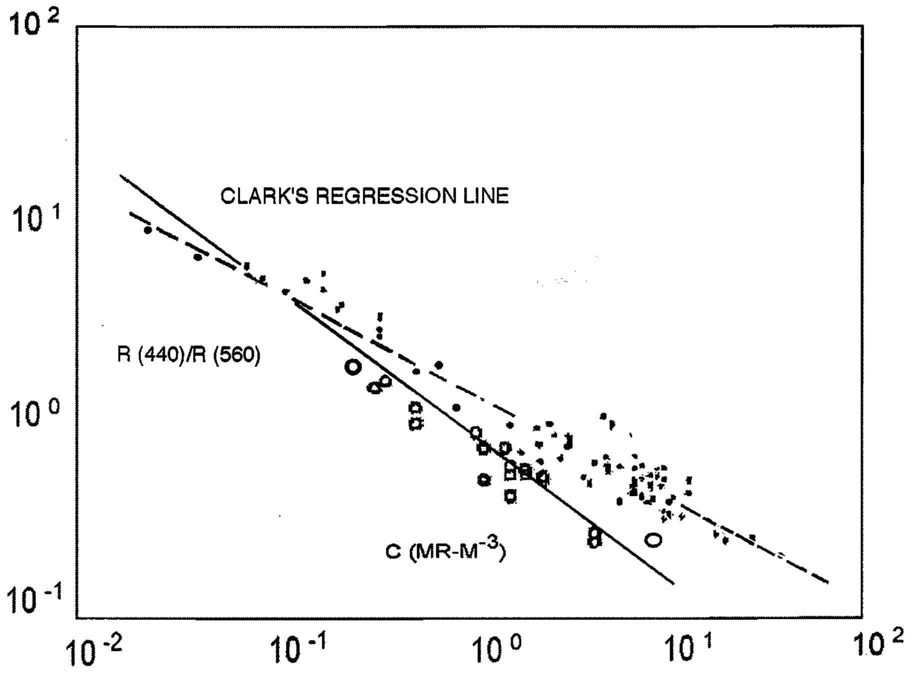


Figure 4: Correlationship between reflectance (R) ratio, R(441)/R(560), and chlorophyll pigment concentration (Gordon and Morel, 1983).

2.3 Other possible problems

When analyzing image data one has to ensure the image to be reasonably cloud free and also avoidance of the artifacts due to undesirable sea surface effect or sun glint effect as they can affect the radiance field in the area of interest. Besides sea foams, bubbles can also distort pigment estimates significantly. Moreover thick clouds also sometimes causes sensor overshooting. One has also to be careful while working with the images from shallow sea, because the variation of depth in shallow waters may cause changes in the ocean color.

3.0 Characteristics of Ocean color sensors

Remote sensors are mounted on a satellite vehicle and satellite should provide certain necessary facilities such as power supply, thermal control, aspect control and data handling system, for successful operation of the sensor in the orbit. Some of the important characteristics of ocean color sensors are presented in Table 1. They are mostly dependent on the orbital characteristics of the sensor/satellite. The type of orbit chosen for a satellite controls the spatial and temporal Earth coverage. Ocean color sensors are usually launched on polar-orbiting and sun synchronous satellites, which are different from the geostationary satellites, used for meteorological data collection. It takes about 100 minutes for a polar orbiting satellite to complete a sun-synchronous orbit. The usual local time of descending node is around noon for any location along the orbital path. So all ocean color images provide the noon time coverage of any given area. Some important characteristics of the ocean color sensors are discussed below to give an idea about their relevance in ocean color remote sensing. Such characteristics of all known historical, existing, and scheduled ocean color sensors are presented in Table 2.

3.1 Spectral resolution

The electromagnetic spectrum within the spectral range of 200 nm and 1m (Figure 5) is relevant for various ocean remote sensing applications. For ocean color study visible and near infrared spectral region (400-700 nm) is relevant. However, not the entire visible and near-IR part is useful. The atmosphere, including air, water vapor and aerosols present in the atmosphere absorb most radiation at certain wavelengths within the visible and near-IR part of the spectrum. This leaves only limited wavelengths, known as "atmospheric window", for inclusions in remote sensing channels of an ocean color sensor. The choice of channels is also governed by the application for which the sensors are developed. Some of the ocean color sensors include the thermal IR region (>900 nm) for simultaneous observation of sea surface temperature. Table 3 presents spectral characteristics of CZCS (Coastal Zone Color Scanner), OCTS (Ocean Color and Temperature Scanner) and SeaWiFS (Sea-viewing Wide Field-of-view Sensor). The CZCS and the OCTS were having both visible and thermal IR bands, however SeaWiFS is totally dedicated for ocean color measurements. The spectral channels with near-IR bands (at >700 nm) are meant for measuring aerosol radiance for atmospheric correction on the ocean color image.

Sensor Parameter	**Range**	**Resolution (Smallest discernible element)**	**Spacing of smallest discernible element**
Spectral	Wavelength Coverage	Spectral bandwidth of Individual band	Spectral sampling frequency
Spatial	Total field of view for one image acquisition	Ground sampled distance, or instantaneous field of view	Spatial sampling frequency
Temporal	Time during which sensor can acquire image over a given location e.g. any time of day or just one time	Duration of acquisition time, integration, dwell or exposure time	Frequency with which image of feature can be acquired e.g. any day or only certain day
Radiometric	Dynamic range of radiance input	Noise equivalent reflectance difference	Always adjacent and determined by quantization

Table 1: Some important characteristics of ocean color remote sensors.

Satellite	Nimbus7 (USA)	ADEOS (Japan)	IRS P3 (India)	Priroda (Russia)	OrbView-2 (USA)	EOS AM-1 (USA)	IRS-P4 (India)	ROCSAT-1 (Taiwan)	ADEOS-2 (Japan)	ENVISAT-1 (Europe)	KOMPSAT (Korea)
Sensors	CZCS •	OCTS/ POLDER •	MOS ••	MOS ••	SeaWiFS ••	MODIS MISR •••	OCM •••	OCI •••	GLI/ S-GLI/ POLDER-2 •••	MERIS •••	OSMI •••
Operation Date / Schedule	Oct.78- June 86	Aug.96- July97	Mar.96-	Apr. 96	Aug.97	June98	Nov.98	Apr.99	June 2000	Dec.99	Aug.99
Swath (km)	1556	1400/ 2400	200	85	2806	2330/ 360	1420	690	1600 1600/ 2400	1150	800
Resolution (m)	825	700/ 6000	500	650	1100	1000/ 250	360	825	250/1000 750/ 6000	300/ 1200	850
Number of Spectral Bands	6	12/ 9	18	17	8	36/ 4	8	6	36 11/9	15	6
Spectral Coverage (nm)	433-12500	402-12500/ 443-910	408-1600	408-1010	402-885	405-14385 446-867	402-885	433-12500	375-12500 412-865 443-910	412-1050	400-900

• Historic   •• Existing   •••Scheduled

Table 2: Some important characteristics of ocean color remote sensing sensors.

3.2 Spatial resolution

The design of the sensor decides the angle of view from which the signal is received by the sensor at any one instant. This is called the instantaneous field of view (IFOV) or spatial resolution of the sensor. Spatial resolution of ocean color sensors have a resolution of around 1000m (Table 2), except the sensors such as POLDER (Polarization and Directionality of the Earth's Reflectance) which consist of an area array camera operating in snapshot mode covering a field of view of 6000 meters. The design of such sensors are altogether different from the conventional ocean color sensors. To produce an image of wide coverage around the Globe on each satellite orbit, the sensors are so designed to scan across the satellite tracking directions. For polar orbits the scan timing is arranged so that subsequent scans occur after the satellite has traveled a distance approximately equal to the IFOV projection on the satellite subtrack. The scanner samples at a rate so that the subsequent IFOVS just overlap along the scan direction and there are typically 2000 to 4000 samples along a scan line. In this way the whole area within a wide swath is efficiently sampled. The swath covered by a ocean color sensors are mostly more than1500 km, however, for the purpose of localized coastal data a few sensors have narrower swath width (Table 2).

Sensor	CZCS	OCTS	SeaWiFS
Wavebands(nm)			
1	433-453	402-422	402-422
2	510-530	433-453	433-453
3	540-560	480-500	480-500
4	660-680	510-530	500-520
5	700-800	555-575	545-565
6	10,500-12,500	655-675	660-680
7		745-785	745-785
8		845-885	845-885
9		3.55-3.85 micron	
10		8.25-8.75 micron	
11		10.3-11.3	
12		11.5-12.5	

Table 3: Spectral bands of CZCS, OCTS and SeaWiFS

3.3 Temporal resolution

Increased swath width brings down the time interval for the sensor to cover the whole earth, which is also known as temporal resolution. Usual temporal resolution of most of the ocean color sensors is 2 days for the whole Earth and at middle to high latitudes once a day. However, practically cloud cover limits actual imaging of the entire ocean surface to approximately every eight days, which means that at least one cloud-free view of any area on the ocean surface can be obtained in an eight-day period. Coverage along the equator may be slightly degraded due to instrument tilt to avoid sun glint effect.

3.4 Radiometric resolution

The ocean color information measured by a sensor are generated as voltage or frequency signal corresponding to the measurements being made. The analogue form of the information are then converted into digital signal for transmission from the satellite to a receiving station at the earth. The digital signal should be noise-free for retrieval and necessary image processing. Monitoring of transmission of noise-free signal is achieved by running a standard voltage ramp through the system periodically. The digital encoding of remotely sensed images facilitate their storage, dissemination and analysis and enhancement by image processing computer. In binary coding, n bits of information are required to represent a whole number in the range 0 to 2^{n-1}. This is known as quantization level or radiometric resolution. Usually the sensitivity of ocean color sensors requires a 10-bit digitization (that is 0 to 1023).

4.0 Status of ocean color sensors

The CZCS launched in October 1978, on-board the Nimbus7 satellite, one of a series of experimental satellites of NASA, was the first space-borne ocean color sensor. Although originally designed to record data from coastal waters in mid-latitudes with moderate to high pigment concentration, CZCS had proven to be useful for a dynamic range of waters and could even resolve the pigment gradients in oligotrophic oceanic waters. However, being an experimental rather than operational sensor, CZCS was neither always switched on, nor was there a continuous archiving of data for local as well as global coverage. Nonetheless, the satellite had long over-lived its originally designed life and it was operational till June 1986 spreading over almost eight years after its launch. Presently an impressive archive of data is available for analysis and oceanographic interpretation at the Goddard Space Flight Center (GSFC) of NASA and the data are open for users along with data processing software to work on the historical CZCS image. There was a time lag of almost one decade before the next ocean color sensor the OCTS was launched, in August 1996 on-board the ADEOS satellite by National Space Development Agency (NASDA) of Japan. Unfortunately the satellite had gone out of operation from June 30, 1997 due to malfunctioning of the ADEOS satellite, after successful operation for about nine months. The OCTS was meant for receiving both ocean color and SST data. Despite its short life span, the data quality has been found to be very useful for many ocean color investigations and complimentary study along with SST, in seas around Japan and elsewhere. Earth Observation Research Center (EORC) of NASDA is still working on OCTS data to improve the processing algorithm with updated calibration. Presently data processing using version 4 calibration parameters is under progress.

There was also another ocean color sensor the POLDER developed by CNES, France that had been launched on the ADEOS satellite along with the OCTS. As it can be notices from the Table 2, the POLDER is a wide-field-of view (2400 km swath), moderate resolution (6×7 km^2 at nadir) multi-spectral imaging radiometer designed to collect global and repetitive observations of the solar radiation reflected by Earth-atmosphere-ocean system. It is highly useful for ocean color application. However, despite coincidence of two ocean color sensors on one platform, it has not yet been utilized much by the oceanographic community in the field of ocean color, mainly due to coarse resolution as well as lack of experience to work with such a unique ocean color sensor. However, CNES encourages scientists to carry out research on the POLDER data by providing data as well as image processing software.

The SeaWiFS, an eight-channel visible radiometer was launched by Orbital Science Corporation of U.S.A onboard the OrbView-2 (formerly "SeaStar") satellite in August 1997. It is considered to be the follow-on mission to the CZCS and predecessor to several ocean color sensors scheduled for deployment in the years 1998-2003. The SeaWiFS mission is a public private partnership between NRSA and the Orbital Science Corporation. Although the SeaWiFS spacecraft and data belong to the Orbital Science Corporation, NASA has purchased the rights to use data for scientific purpose. There are many High Resolution Picture Transmission (HRPT) data receiving stations located at various locations around World to collect the data from the local region. For South East Asian region there are around eight HRPT data receiving stations (Taiwan 4, China 3, and South Korea 1) apart from five stations at Japan which covers the seas around Japan and part of SE Asian region. One of the primary goals of the SeaWiFS mission is to achieve accuracy in chlorophyll *a* estimation within 35% over the range 0.05-50.0 mg m^{-3}. Ocean color scientists have been working on the SeaWiFS data at several places around the World and it has been proved to be an extremely successful ocean color mission, moreover an improvement to CZCS mission by having better spectral bands for atmospheric correction (Table 3). The improved atmospheric correction particularly aids estimation of chlorophyll in coastal region. Significantly the SeaWiFS has a spectral channel at violet wavelength (412 nm) which can be of immense use for coastal study besides oceanic chlorophyll *a* measurement. With the help of violet spectral band, concentration of the yellow substances, that is a characteristic of coastal water, can be estimated. After carrying out initial processing of the SeaWiFS data for seven months (February-August 1998), recently (since September 1998) SeaWiFS project has switched over to improved algorithms for reprocessing of the all images. These improvements include the modification in chlorophyll algorithm. Recent modification method is expected to produce more near-accurate estimates of chlorophyll *a* especially in the coastal waters. All SeaWiFS data are available from the Goddard Distributed Active Archive Center (DAAC) in Hierarchical Data Format (HDF). HDF is a "self describing" data format, that contains all the pertinent information necessary to examine data in a file, within one file. The SeaWiFS data are recorded in two forms: 1) 1 km resolution LAC (Local Area Coverage) data, 2) 5 km resolution GAC (Global Area Coverage) data. The GAC data are used for production of global dataset. Both GAC and LAC SeaWiFS data are processes from raw radiance to three levels (Level 1A, Level 2, and Level 3) at SeaWiFS Project and then transmitted to the Goddard DAAC for archiving and retrieval. The SeaWiFS data were available to the public without restriction initially for a few months (till March 11, 1998) after launching of

SeaWiFS. Following March 11 1998, the data are available only for scientific research to authorized users who have registered with the SeaWiFS project. Interested researchers have to be accepted by SeaWiFS Project as an authorized user. However this arrangement is restricted only for scientific users. For commercial application one has to contact the Orbital Science Corporation and buy the necessary data. Besides the German Modular Optoelectric Scanner (MOS) sensor was launched in 1996 aboard an experimental satellite the IRS-P3 of the Indian Space Research Organization (ISRO). Data from European coastal waters and part of the Arabian Sea are now available to the researchers. This sensor has also been found useful for coastal studies with specific sensors and also its high resolution data. There is also an identical MOS sensor on the Priroda satellite of Russia. This sensor has a smaller swath, lower resolution and less coverage than the one on the IRS-P3 (Table 2). However it's current status is not known.

Apart from these active sensors there are several ocean color sensors are in pipeline to be deployed in the years 1998-2003 (Table 2). Significant of them are the Global Imager (GLI) scheduled to be launched on the ADEOS-2 satellite in June 2000. Fifteen spectral bands of this sensor will be dedicated to ocean color. There are also two ocean color sensors the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging Spectroradiometer (MISR) to be launched by NASA on the EOS AM-1 satellite. The MODIS will be receiving data at 36 spectral bands of visible and infrared region and 9 of those will be available for ocean color application. The MODIS ocean color products will be suitable to study phycobiliproteins, florescence, cocolithophores, chlorophyll and PAR (Photosynthetically Active Radiation). The data policy has been formulated for users to have free accessibility of data. The Medium Resolution Imaging Spectroradiometer (MERIS) is scheduled to be launched by the European Space Agency (ESA) onboard the ENVISAT-1 satellite. The primary goal of this sensor is bio-optical oceanography including estimation of pigments, yellow substances and suspended matter that would make it useful for both oceanic and coastal studies. Besides, India, Taiwan and Korea are scheduled to launch ocean color sensors. Indian Ocean color sensor, the Ocean Color Monitor (OCM) will be launched on Oceansat/IRS-P4 (India). The Taiwanese Ocean Color Imager (OCI) and the Korean Ocean Scanning Multispectral Imager (OSMI) are scheduled to be launched respectively on the ROCSAT-1 and the Korea multi-purpose satellite (KOMPSAT).

Cloud is the major limitation encountered by the investigators in the field of ocean color remote sensing. Cloudiness prevents deriving chlorophyll a concentration over about 60 percent of the ocean on a daily basis excluding that already lost due to high Sun glint. Hence launching of the above ocean color sensors by different countries within rather a short duration of five years is undoubtedly a welcome development as it would increase sampling frequency of ocean color data. It would further provide a unique opportunity to the satellite oceanographers to plan studies on large and meso-scale oceanographic processes in different part of the World Ocean. It would specifically help to study plankton processes, which vary rapidly over time and space. Finally these intensive research activities may lead to large scale operationalization of ocean color data.

5.0 Application of remotely sensed phytoplankton pigment concentration

Phytoplankton load, as revealed by ocean color can be attributed to mainly plant pigment, chlorophyll *a*. The CZCS-derived phytoplankton estimates are combination of both chlorophyll *a* and its covarying pigment, phaeopigment concentrations. As an improvement over CZCS it has been possible to derive concentration of only chlorophyll *a* from the recent sensors such as OCTS and SeaWiFS by adopting improved algorithms. With launching of MODIS it will be possible to measure chlorophyll fluorescence, thus better estimates of chlorophyll *a*.

5.1 Phytoplankton distribution as tracer to a dynamic ocean

Distribution of phytoplankton pigments can be used to trace oceanographic features such as currents, jets and plumes. An example of CZCS-derived phytoplankton pigment image for the northeastern coast of United States (Plate 1) reveals the high pigment concentrations along the coast and influence of Gulf Stream. The upper part of the color bar with violet color shows lowest pigment concentration and red color indicates highest level at the lower part of the bar. Several large Gulf Stream Warm Core Rings, prominent features of this western boundary currents, can be marked on this image with ring-shaped water pockets with very low level of phytoplankton pigment concentration. Higher productivity areas can also be marked near the Chesapeake and Delaware Bays on this image. Plate 2 shows an OCTS derived chlorophyll *a* imagery covering seas near Malaysia on June 13, 1997. Highly pigmented waters can be noticed near to coast however oceanic waters with very low level of chlorophyll *a* concentration. Plate 3 shows a series of six chlorophyll *a* images derived from SeaWiFS images covering the Kuroshio-Oyashio frontal area along east coast of Japan spreading over entire winter season (mid-December to mid-March). The images depict development of phytoplankton bloom during summer under the influence of the Kuroshio-Oyashio currents.

5.2 Phytoplankton as indicator of ocean production

Chlorophyll *a* concentration is a key input to the primary production taking place in ocean water. Moreover, since phytoplankton are the first link in the pelagic food chain, the success of most oceanic life is dependent on the success of phytoplankton. Since many countries are dependent on fish for food and commerce, the health and economies of many people especially in the developing World are also dependent on this first link. Therefore, understanding the process that affects phytoplankton is of importance from economic and conservational point of view. Phytoplankton distribution is controlled by the physical oceanographic processes. Their feeders such as zooplankton and fishes depend on them for food. Hence information on phytoplankton distribution in the context of their physical set up, are considered to be an important information to study the biological resource variability including those belong to higher trophic levels, over local and regional scale. The frontal areas such as Gulf Stream (Plate 1) and Kuroshio (Plate3) provide favorable habitat for pelagic fishes to congregate both due to favorable temperature gradient and food availability. The Gulf Stream area near Chesapeake and Delaware Bays (Plate 1) is a well known highly productive area and was well known for its Grand Banks cod fishery. However, in the recent decades there has been a total collapse of the cod fishery due to overfishing.

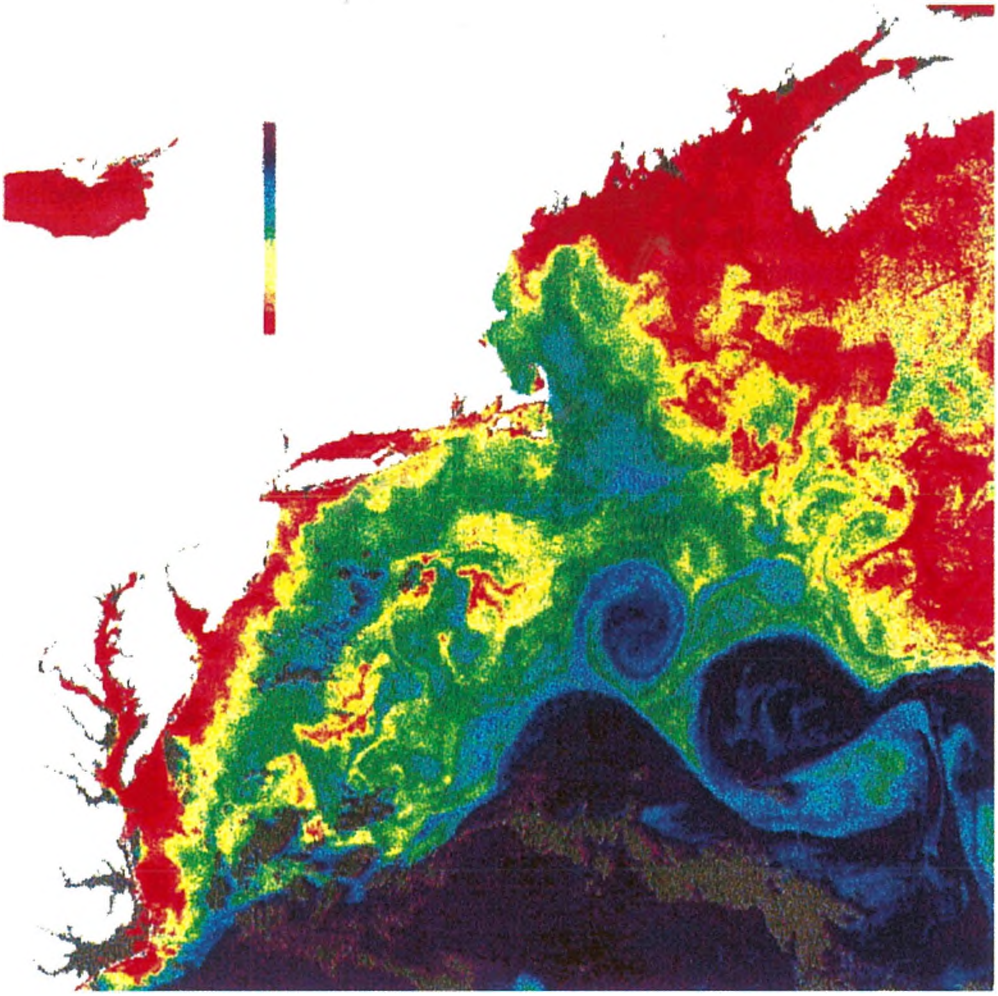


Plate 1: A daily CZCS phytoplankton pigment product covering coastal waters along northeastern coast of the United States shows the high pigment concentration along the coast and influence of the Gulf Stream.

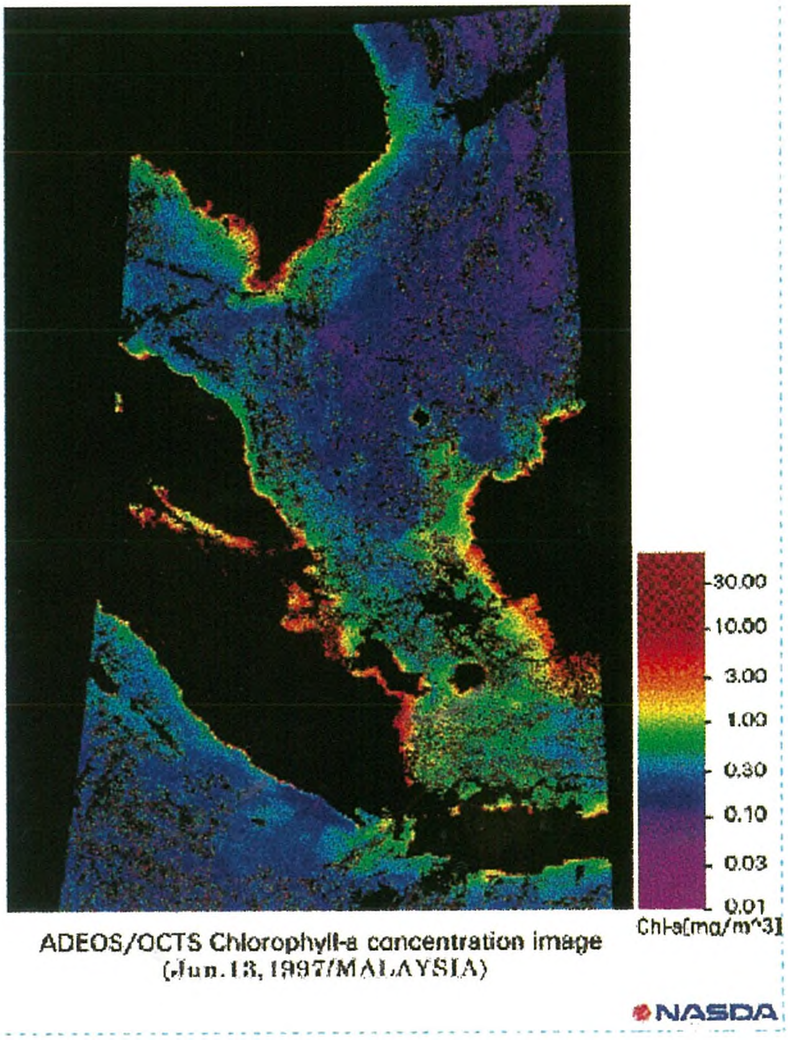
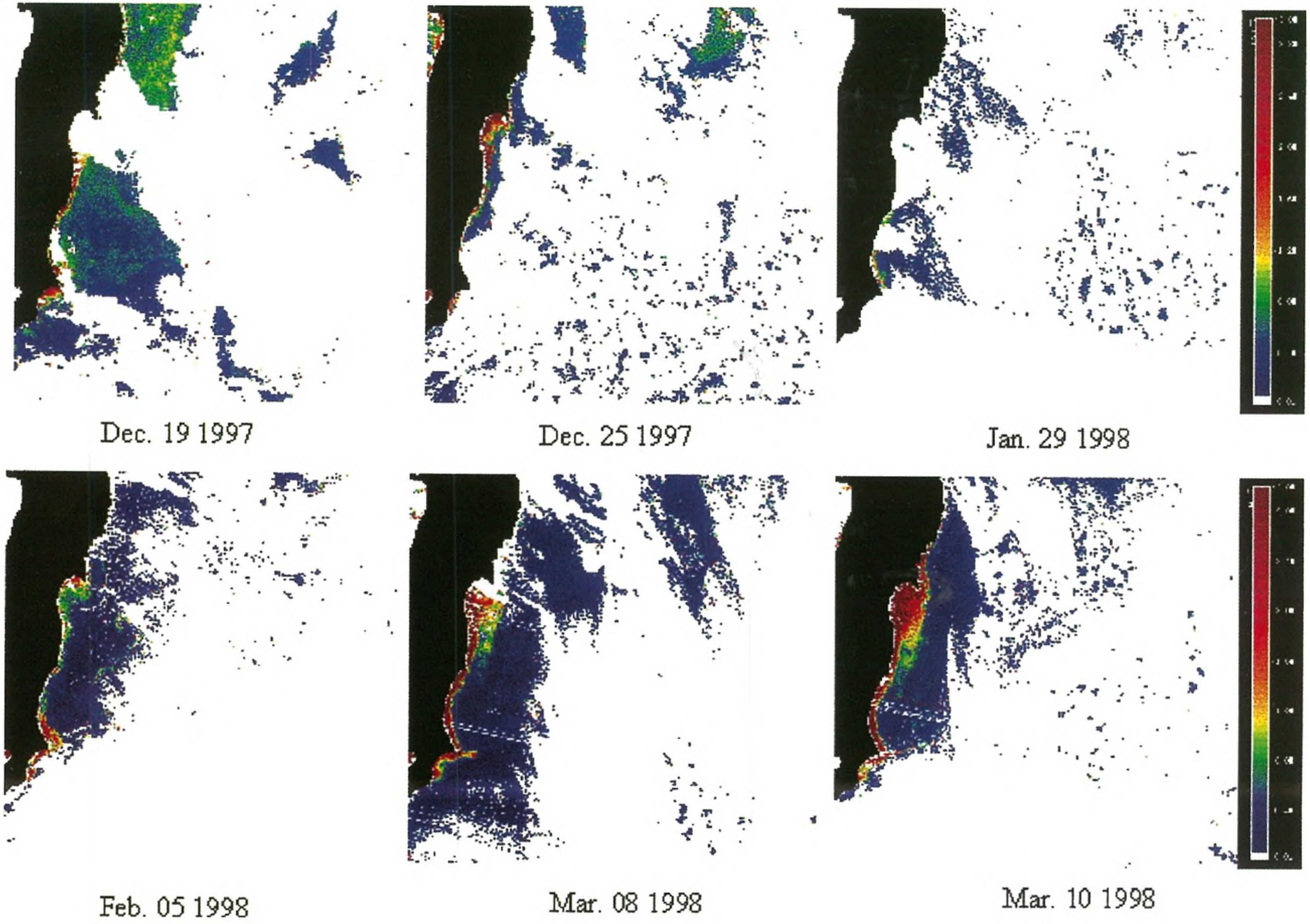


Plate 2: OCTS chlorophyll-a product of the seas near Malaysia shows highly pigmented waters along the coast and oceanic waters with very low pigment concentration.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Dec. 25 1997

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Plate 3: SeaWiFS derived chlorophyll-a distribution at the Kuroshio-Oyashio frontal region.

5.3 Coastal pollution:

The phytoplankton shows where coastal pollutants degrade the ocean ecosystem and prevent or alter the plant growth. They can further show subtle changes in phytoplankton distribution as a result of change in SST and salinity. Since phytoplankton depend upon specific oceanographic conditions for growth, they frequently become the first indicators of a change in their environment. Since most of the polluted regions belong to coastal waters, it is necessary to develop appropriate models/algorithms to successfully implement them on ocean color images to derive the desired information. With the specific spectral bands on SeaWiFS and the forthcoming sensors meant for coastal water studies it would be possible to assess the influence of coastal pollution on coastal ecosystem.

5.4 Carbon cycle and global climate study

Through photosynthesis, phytoplankton affects the Earth's climate by absorbing a significant portion of the World's carbon dioxide. When phytoplankton die, if their carbon is not consumed by other living creatures, it sinks to the ocean floor and eventually emitted back into the atmosphere again through volcanism; part of this process known as the carbon cycle (Figure 6). The carbon cycle has drawn considerable attention of the scientists in view of its effect on global climate. Before the industrial Revolution, the level of atmospheric carbon dioxide had remained nearly stable for thousands of years.

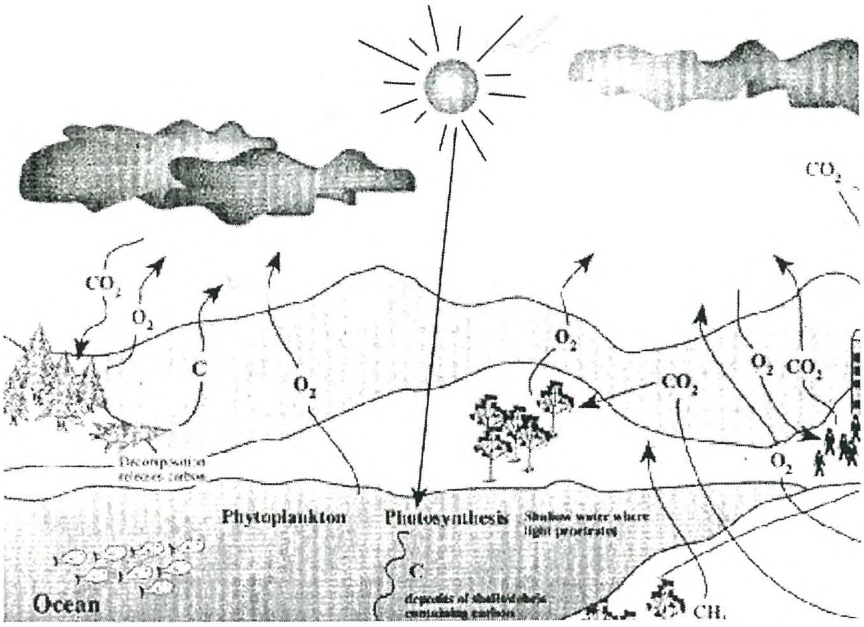

Figure 6: Pictorial depiction of the Carbon Cycle

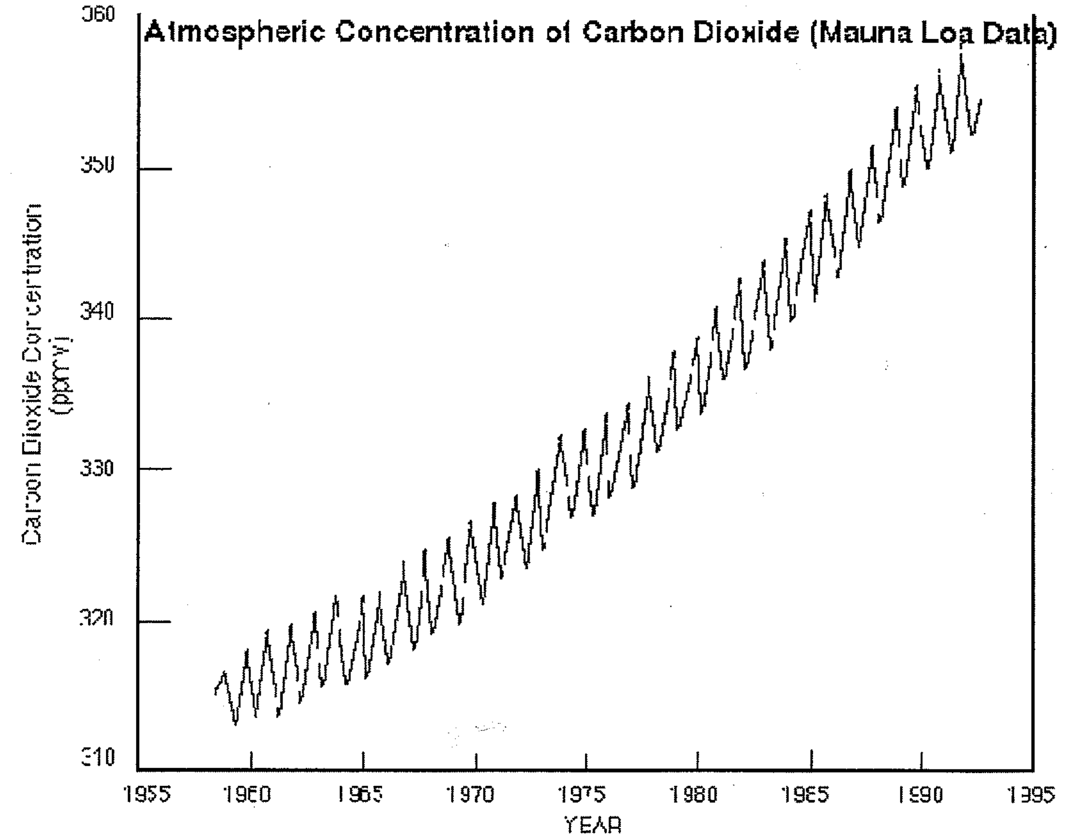

Figure 7: Increase in atmospheric carbon dioxide during 1965-1995

Since human beings developed a fossil fuel based global economy and life style, the amount of atmospheric carbon dioxide has increased dramatically as evident from the Fig.7. This increase means that less long-wavelength energy (temperature) emitted from the earth can escape to space. It is now being predicted if such trend continues this can lead to global warming. Primary production process in ocean can provide insight to carbon cycle and global climate. Ocean color or phytoplankton information is considered to be a good indicator to primary production, hence they can aid in monitoring the change in global climate and to assess how does such a change affects the living system.

Two vital issues are to be addressed in context of phytoplankton: 1. How does a change in phytoplankton (due to natural or artificial reason) affect global climate? 2. How does such a change affect the ocean's food supply? The first step towards answering these questions are: 1) estimating the level of primary production in the ocean with accepted level of accuracy, 2) finding out how variable (both spatially and temporally) is productivity and finally 3) determining if is there a long term trend. All of these questions can be answered through ocean color remote sensing if we have a reliable technique to achieve desired accuracy. Plate 4 shows the global ocean phytoplankton biomass within the upper layers of biomass from the CZCS. While this is an annual product, with the existing SeaWiFS and forthcoming ocean color sensors, it would be possible to provide comparable global coverage on a weekly to monthly

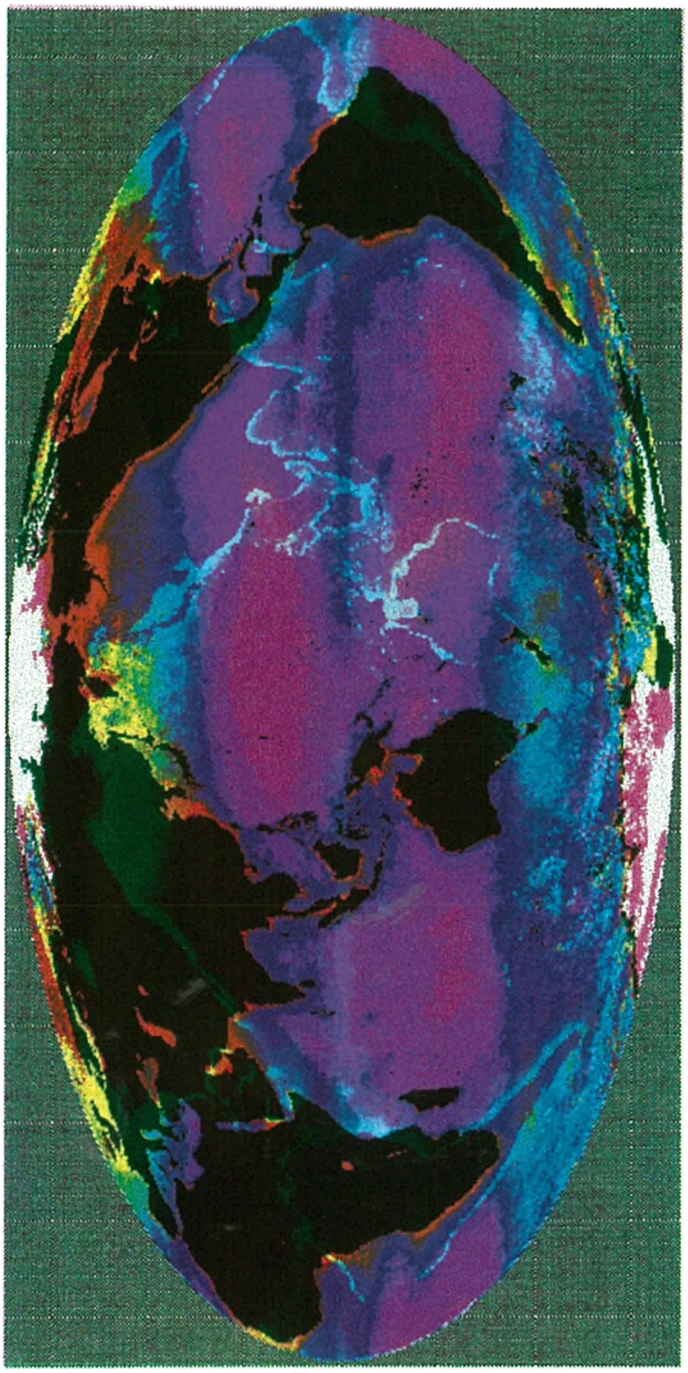

Plate 4: Global ocean phytoplankton biomass as revealed from annual CZCS binned product.

basis to enable scientists to study large-scale changes in marine ecosystems over weeks and decades. Currently scientists are exploring both statistical and semi-analytical models to estimate productivity using bio-geographical quantities such as phytoplankton pigments, SST, light levels etc, measurable using satellite remote sensing. Statistical models involve developing statistical relationships between satellite derived ocean color with primary productivity. This technique is found quite reliable for assessment of long-term, regional trends and estimating global productivity. In case of the semi-analytical mathematical models, physical processes are integrated into algorithms and they are most useful in calculating primary productivity for more over localized region.

6.0 Prospects of ocean color remote sensing in coming decade

During next five years there is an encouraging schedule for launching of ocean color sensors by the countries representing almost all regions of World. Assemblage of ocean color satellite systems through international efforts would lead to continuous global coverage of the World Ocean. However, it is a challenge before scientific community to achieve inter-calibration of the sensors and validate the data from different satellites for producing standard outputs. Moreover the envisaged missions provide a unique opportunity for development of techniques and methodology and refinement of the existing ones for successfully recovering ocean color information from satellite data. It would also lead to advances in the application of ocean color remote sensing to address problems related to local, regional and global ocean processes. Especially the coastal waters classified under “case 2” category, are expected to draw increased attention of the investigators as many of the countries located along the coastline are interested in assessing coastal oceanographic processes.

In the context of Southeast Asia, where most of the countries are surrounded by ocean and exposed to global climatic phenomena such as El Nino, remotely sensed phytoplankton pigment information could be an efficient tool for understanding and assessment of the impact of such phenomena on marine ecosystem. Besides most of the Southeast Asian countries have interest in development and management of their coastal region for commercial activities such as fishing and coastal aquaculture, hence they need efficient sustainable management strategy to protect the coastal environment from further degradation. Ocean color information can help immensely to aid in such efforts. In view of anticipated launching of a number of ocean color sensors in the coming years, especially three sensors by the nearby countries, there is a major scope for the scientists from this region to undertake research programs related to ocean color remote sensing in their respective areas of interest. Joint efforts by scientific community from this region and those from the countries already exposed to ocean color remote sensing technology can help development of appropriate techniques and methods to address the research and application needs of Southeast Asia.

7.0 Conclusions and recommendations

In this status paper we have tried to present the principle of phytoplankton remote sensing, characteristics of the ocean color sensor systems and various applications of the remotely sensed phytoplankton pigment data in a simple language, without citing equations, so that it would be easier to appreciate for the resource scientists, especially those who are new to remote sensing technology. We have attempted to clarify the potential and limitations involved with the technology, so that the prospective users can appreciate such aspects. In addition we have touched upon a few important images to depict capability of remote sensing technique in understanding ocean process and ecosystem.

In our recommendations we would urge the scientific community in the fields, relevant to ocean color remote sensing, to evolve a program for technical collaboration with their counterparts in the countries where they have been exposed to ocean color remote sensing, especially in nearby countries in Asia. It appears more relevant in view of scheduled launching of ocean color sensors by four countries near to the region (Japan, Korea, Taiwan, and India). To start with, a forum such as joint working group of scientists and technocrats can be formed for frequent interaction between them and identifying areas of common interest. Scientists from the countries those who are involved in development of ocean color sensors and techniques for application of remotely sensed data can provide the data and share their experience with their colleagues from Southeast Asian countries. Moreover it is also very important on the part of these countries to generate more trained manpower in this field to meet the research interests of the respective countries in this emerging field of science.

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EORC Home page (http://www.eorc.nasda.go.jp/ADEOS)