Remote Sensing of Phytoplankton Pigments

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The use of remote sensing satellite data to determine chlorophyll concentrations, and thus primary production in the ocean and coastal waters, is a relatively new tool in oceanography. Remote sensing is a sought after method for primary production monitoring as it can increase spatial and temporal resolution of the primary production data (Hyde et al. 2007, Hyde et al. 2008). Because this method is so new, however, much of the work done in this area over the past few years has been to validate the satellite measurements, find sources of error, and inter-compare satellites, rather than directly use them.

Chlorophyll measurements using satellite sensors are done through the measurement of ocean color. Ocean color is the spectral composition of the visible light field that reflects off the ocean (McClain 2003). Differences in the wavelengths of the reflected visible light can be detected by space borne ocean color instruments with sensors designed to receive different wavebands (Bailey and Werdell 2006). The color of the ocean depends on several factors including substances dissolved and suspended in the water column, such as phytoplankton (McClain 2003). A clear open ocean looks blue because water absorbs at the near-infrared wavelengths and then scatters blue wavelengths (McClain 2003). As phytoplankton grow in the water column, green begins to be the dominant wavelength reflected (McClain 2003). Thus, the ocean color turns from blue to green with increased growth of phytoplankton (McClain 2003) and the wavelengths emitted follow this shift. The two main satellite sensors used to monitor ocean color are the Sea-viewing Wide Field-of-View (SeaWiFS) sensor and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Werdell et al. 2003; Kutser 2004; Bailey and Werdell 2006; Zhang et al. 2006; Gregg & Casey 2007; Melin et al. 2007). Spatial resolution for ocean color satellites is between 250m (MODIS) to 1km (SeaWiFS) (Bailey and Werdell 2006, Kutser 2004) with near daily coverage of the ocean (Zhang et al. 2006).

The current emphasis for research involving this remote sensing data is the comparison of remote sensing data to in situ data as well as comparisons between sensors (e.g. Werdell et al. 2003; Bailey and Werdell 2006; Hyde et al. 2007; Melin et al. 2007). The comparison with in situ data is necessary to ensure that sources of error due to the satellites are corrected for in order to get an accurate picture for what is going on in the water (Bailey and Werdell 2006; Hyde et al. 2008). In order to make this comparison, however, it is necessary to have high quality in situ data to have an accurate reference for the satellite data (Bailey and Werdell 2006; Hyde et al. 2008) which can often be a limiting factor (Zhang et al. 2006). With a solid reference, from the in situ data, not only can satellites be validated, but areas and magnitude of uncertainty can be determined (Melin et al. 2007).

From these comparisons several sources of error in chlorophyll measurements have been found. The primary sources of error include atmospheric errors due to the presence of aerosols (Hyde et al. 2007; Melin et al. 2007) and the presence of other reflective constituents in the water column such as Colored Dissolved Organic Matter (CDOM) and suspended sediments (McClain 2003; Hyde et al. 2007; Melin et al. 2007). Corrections can then be done to account for atmospheric errors by applying at atmospheric correction scheme (Melin et al. 2007) or modifying the existing one (Hyde et
al. 2007). Corrections for CDOM and suspended sediments involve re-working bio-
optical algorithms such that they are better tuned to the water in the region to depict
solely the chlorophyll in the water (Melin et al. 2007).

The errors associated with remote sensing data, however, are regionally specific.
In particular, areas of high latitude, such as the Arctic Ocean (Cota et al. 2004), and
coastal areas (Hyde et al. 2007; Hyde et al. 2008) are areas that need to be treated
differently from the rest of the global ocean. One reason for this is that the global
chlorophyll algorithms to calculate chlorophyll concentration are derived from bio-optical
observations in relatively oligotrophic waters open ocean waters at lower latitudes (Cota
et al. 2004). In coastal areas, satellites tend to overestimate the amount of chlorophyll in
the water (Zhang et al. 2006; Gregg & Casey 2007; Hyde et al. 2007). The reason for
this overestimation stems from water being much more turbid along the coast with more
suspended sediments (Hyde et al. 2008, Hyde et al, 2007). In the Arctic, times and
areas of low chlorophyll concentration are overestimated, while high chlorophyll
concentrations are underestimated (Cota et al. 2004). With this in mind it is important to
regionally compare satellite and in situ data as errors can be regionally specific.

Another large area of this remote sensing research are comparisons between
different satellite sensors. It is important to compare these two types of sensors to
ensure that they match as the SeaWiFS sensor is an older sensor that will soon phase
out (Zhang et al. 2006; Melin et al. 2007). Thus, this comparison is necessary in order to
ensure the continuity between these two sensor’s datasets (Zhang et al. 2006; Melin et
al. 2007). Additionally, the method of this comparison can be used to compare new
future sensors such as the National Polar-Orbiting Operational Environmental Satellite
System (NPOESS) (Zhang et al. 2006). In general, studies have found that satellite data
line up fairly well with each other (Zhang et al. 2006; Melin et al. 2007).

For some types of phytoplankton blooms, however, these parameters of satellite
remote sensing are still inadequate. In the case of cyanobacteria blooms, the blooms
appear more like shallow water or terrestrial habitats to a sensor than open water or
coastal habitats in terms of intensity of signal (Kutser 2004). Additionally, these blooms
are so patchy with such fine spatial phenomena that they are not accurately seen by
other satellite remote sensors (Kutser 2004). Thus, an alternative technology is needed
in order to monitor areas such as the Gulf of Finland which are dominated by these
blooms (Kutser 2004). The solution in this case is the use of Hyperion, a hyperspectral
sensor in space, not designed for the water environment, with a 30m spatial resolution
(Kutser 2004). This example highlights again the need for regional specific analysis of
remote sensing effectiveness and accuracy.

Additionally, there is still some dispute as to the accuracy of the satellite data
even with these corrections. The main assertion is that data collection by remote
sensors is necessarily done during times of higher production (Gregg and Casey 2007).
One example of this is that sensors are only able to collect data on days when clouds
are not present. Thus, there is a bias towards data collection on high production days
(Gregg and Casey 2007). If these days are then integrated over the course of a month
or a year the overestimation compounds (Gregg and Casey 2007). Though multiple
satellites can increase the frequency of sampling of an area, they are still not able to
sensor during these cloudy periods. The biggest issue, however, is the exclusion of high
solar zenith angles (greater than 75 degrees) from processing algorithms (Gregg and
Casey 2007). This leads to an overestimate of chlorophyll data in higher latitudes
(Gregg and Casey 2007). Thus, it appears that there is still more work to be done in examining these sensors before they can be exclusively used for primary production sampling.

In summary, remote sensing of chlorophyll will be important to future primary production monitoring as it will increase spatial and temporal coverage. There is still much to be done, however, until this will be a viable method to be exclusively used for this type of censusing. Important things to consider in this process are regional specific sources of error and phytoplankton specific sources of error. Additionally, it is necessary to examine the compatibility of satellite sensors to ensure continued continuity of data collection as well as to increase temporal resolution.

As primary production is very dynamic in both spatial and temporal scales, I feel that remote sensing will be a key resource for more complete, accurate censusing in the future. Traditional water monitoring is labor intensive, only sample at very specific locations, and with large time periods between sampling. Continuous monitoring buoys help to solve the temporal resolution issue, but are still anchored at a specific location. Ship board flow-through systems are able to get a more continuous spatial look, but only at the small strip through which the boat passes. Thus, none of our traditional measures are adequate to capture the complete spatial and temporal scale of phytoplankton dynamics of a system. For example, a study found that satellites can increase temporal resolution eight-fold and spatial coverage from 2 m² to more than 2600m² over the in situ data (Hyde et al. 2008). It is for this reason, that I feel that satellite remote sensing will be the future of primary production monitoring and as such its inter-calibration will become an even larger part of the field.
Literature Cited


In this paper, Cota et al. examines the issue that global algorithms to calculate primary production in the oceans do not always provide accurate data for higher latitudes, such as the Arctic Ocean. It has been found that in the case of the Arctic Ocean low chlorophyll concentrations are often overestimated by the global algorithms and higher chlorophyll concentrations are underestimated almost two-fold. They explain that the reason for this is that global algorithms are derived primarily from observations in areas of lower latitudes. The purpose of this research was to derive a function whereby the existing SeaWiFS data could be converted into more accurate chlorophyll measurements for the Arctic Ocean. To do this they examined in situ data for the region and created a linear function to convert the data. This paper provides a very intelligent solution to an issue that spans more regions that just the artic. Instead of entirely reprocessing the data for the Arctic regions which would be very time and computationally intensive, they found a simple solution. This simple solution then can be translated to other regions that are facing the same issue.


Contrary to the common sentiment regarding satellite remote sensing of chlorophyll, Gregg and Casey assert that ocean color sensors such as MODIS and SeaWiFS do not provide accurate global coverage. These biases affect global and regional mean chlorophyll as well as regional interannual variation and global seasonal variation. The sources of biases, or errors, in the data are due to several factors such as clouds and aerosols. In the case of clouds, because satellites can not sampling accurately during cloudy periods, they necessarily must sample on sunny days. As sunny days have higher productivity than cloudy ones, satellites inherently sample during higher production periods. But the primary source of error is due to the exclusion of high solar zenith angles (i.e. greater than 75 degrees) from their processing algorithms. Because this solar zenith angle is excluded, there are data gaps in the areas with this angle of sun light such as the high latitudes. This exclusion will affect broader global averages as only lower latitude measurements are included. This paper brings to light the fact that we need to be very critical about the satellite data, when it is taking data, patterns in data collection gaps before we use it as a substitution for in situ measurements.


In this paper, Hyde et al. examines two potentially large sources of error in SeaWiFS remotely sensed chlorophyll a measurements namely atmospheric correction errors and colored dissolved organic matter (CDOM) in Massachusetts Bay. Both errors cause an overestimate of chlorophyll a concentration. In order to examine these errors the SeaWiFS data was compare to in situ data. It was found in the case of Massachusetts Bay that CDOM and the associated suspended sediments are not present owing to the sediment sink of Boston Harbor, the major freshwater source to the Bay. The
atmospheric correction errors could be corrected for using a localized empirical correction algorithm. The correction of this data is important as the use of this data will increase the sampling frequency and thereby the temporal resolution for primary production monitoring in the Bay. This is a key factor to consider in the monitoring of primary production as its growth has high temporal and spatial variability. The paper was well written and treaded the fine line between being too technically specific and glossing over too many details.


In this paper, Hyde et al. tackles the issue of the inadequacy of intermittently measured point locations to represent primary production in a highly variable coastal ecosystem. In the ecosystem examined, Massachusetts Bay, in situ data are only collected at two locations 17 times per year. The problem with this low spatial and temporal resolution is that samples can either miss phytoplankton blooms completely, or measure the large phytoplankton blooms but extrapolate them across a much larger area than they actually cover. There were two main objectives of this study, first, to use in situ measurements to regionally tune an existing satellite production model. The second objective was to apply this new regional satellite production model to characterize temporal and spatial primary production in Massachusetts Bay between 1998 to 2005. In order to ensure these matches were done appropriately a lot of care was taken to ensure that the satellite and in situ measurements were taken very close to one another temporally and spatially. The study found that satellite measurements could be used to estimate primary productivity through the region and increased temporal resolution eight-fold from the in situ measurements as well as increased the spatial coverage from 2 m² to more than 2600m². The paper is very interesting in that not only does it compare these two productivity estimation methods, but it also comments on the status of primary production in the area.


Cyanobacterial blooms previously have been unable to be quantitatively mapped using traditional methods due to their patchiness and subsurface vertical structure. Traditional methods highlighted in this paper include water sampling, flow-through sensors, and satellite remote sensing. Due to the patchiness of the bloom they often have a spatial scale of their phenomena that cannot be picked up by any of these sampling methods. In the case of water sampling, the samples are taken at discrete locations with so much space between, that abrupt spatial changes in the bloom are not observed. In the case of the flow-through sensors, though they do move through space, their swath is limited in width and they only follow the path of the boat. Satellites are able to cover the entire area of the bloom, but because the pixel size is so large (250m MODIS; 1km SeaWiFS), and thus the spatial resolution so coarse, much of the dynamics of the bloom are lost within pixels. Besides these issues, the subsurface vertical structure of cyanobacterial blooms provide additional compounding factors. Typical phytoplankton blooms only exist on the surface. Cyanobacteria, however, with their buoyancy control are able to exist in large concentrations below the sea surface. This is difficult to monitor by remote sensing as you are only really able to examine the very surface of the water. An alternative technology, Hyperion, has become available
and with its fine spatial resolution (30m) it is able to monitor these blooms. In this paper, Kutser examines the dynamics of a cyanobacteria bloom and what needs to be done in order to accurately monitor the bloom.


In this paper, Melin et al. compares two satellite sensors (SeaWiFS and MODIS) with each other as well as with field observation measurements in the northern Adriatic Sea. The satellite data were compared with field observations in order to highlight sources of error in the satellite data and correct them so they matched in situ, field measurements. One source of error examined was the impact of aerosol particles in the atmosphere. This error was removed through the use of an atmospheric correction. An additional source of error between the satellite data and field measurements are the presence of other scattering in water constituents. The issue here is that particles in the water column that are not phytoplankton can reflect light and be picked up by satellite sensors that will misinterpret them as phytoplankton. In order to remove this error bio-optical algorithms need to be applied. Melin et al. compared three different bio-optical algorithms at different wavelengths in order to select the algorithm that best fit the field measurements. Overall the paper concludes that it is necessary to do this verification and necessary to determine the level of uncertainties of the sensors in order to be able to use them in the place of field measurements.


In this paper, Zhang et al. calculated chlorophyll concentration of the Taiwan Strait and South China Sea using two satellite sensors, SeaWiFS and MODIS. The data from these sensors was validated using field measurements. It is important to compare satellite data with in situ measurements to ensure all errors are removed from the satellite data. This need, however, can be a limiting factor in the use of satellite data as in the case of these two locations it is only recently that reliable in situ measurements have been obtained. They found from their study that the data was comparable both between sensors and with the in situ data. The only area where this did not match up very well was along coastal waters. This was owed to the turbidity of the water column that adds an additional source of error and leads to an overestimate of chlorophyll by the satellite. This paper also highlights the importance of comparisons between these two satellites as SeaWiFS sensor is an older sensor than MODIS and will soon phase out. Therefore, to ensure continuity between these two datasets it is essential to know that their data are comparable. Additionally, the method of this comparison can be used to compare new future sensors such as the National Polar-Orbiting Operational Environmental Satellite System (NPOESS).