Chapter 5.2 Phytoplankton and Primary Productivity Baselines/IPCC Assessment Of Potential Future Impact

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5.2 Phytoplankton and Primary Productivity Baselines/IPCC Assessment Of Potential Future Impact

5.2.1 Summary and Key Messages

This Chapter covers the distribution of chlorophyll contained in phytoplankton in the surface waters of the world's ocean, quantified at high resolution in time and space using satellite observations. This product is derived from the Ocean-Colour Climate Change Initiative (OC-CCI) of the European Space Agency. Spanning some fifteen years (1998 – 2012), the fields provide the baseline for the current status and inter-annual variability in phytoplankton, which is at the base of the upper-ocean food chain and serves as food for other organisms in marine food webs. To illustrate some of the applications of the data, test products have been generated of marine primary production at the global scale and monthly resolution, for each of the years in the time-series. The dynamics of phytoplankton at the seasonal scale are also analysed, to extract indicators of phenology. The distribution of phytoplankton is strongly coupled to environmental variables, such that they can serve as sentinels of ecosystem response to environmental variability. This dataset is a rich resource for studying seasonal and inter-annual variations of phytoplankton in the open ocean and forms the foundation for a time-series that, if continued without interruption, should allow the identification of climate-change-related trends. The additional test products of primary production and phenological indicators demonstrate the usefulness of the chlorophyll-a dataset in understanding the marine carbon cycle and the timing of major biological oceanographic events, and which have profound impact on the health of marine ecosystems.

Key Messages

- Phytoplankton are critically important in the global carbon cycle and ocean ecosystems;
- Phytoplankton concentration can be assessed via satellite measurement of ocean colour that can be used to estimate chlorophyll concentration;
- Time-series of satellite-derived phytoplankton biomass is long enough to be used as a baseline for assessing phytoplankton status;
- Time-series information that are essential to see changes in phytoplankton activity in a changing climate are currently being developed;
- Phytoplankton biomass and primary production are sensitive indicators of environmental change at both regional and global levels;
- As phytoplankton is at the base of the marine food web, changes in phytoplankton and primary production have impacts on higher trophic levels; and
- Space-based ocean-colour radiometry is a cost-effective and reliable technique to monitor phytoplankton, a key element of the marine food web and carbon cycle.

5.2.2 Main Findings, Discussion and Conclusions

Chlorophyll-a is an important pigment contained in all plants. Measurements of chlorophyll-a concentration are key to understanding the distribution and abundance of phytoplankton in the global oceans. These microscopic organisms are responsible for half of the net photosynthetic primary production on the planet, supporting marine food-webs across the oceans and playing a key role in the global carbon cycle.

Primary production is the mass of carbon fixed into organic matter, through photosynthesis, per unit volume of seawater, over a given period of time. These values are typically integrated over the water column to obtain estimates of production per unit surface area. Units for the integrated product are mgC m^{-2} d^{-1}. It is an important quantity to measure, as phytoplankton are the foundation of the marine food web and changes in their distribution and abundance can have a dramatic influence on processes such as carbon export to the deep ocean and sediments, maintenance of fish stocks and marine ecosystem health.

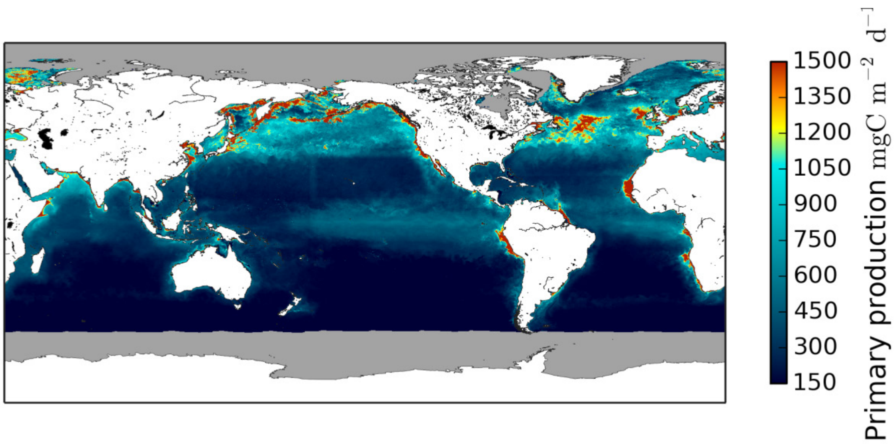
Phytoplankton respond to changes in a number of environmental conditions and so can act as sentinels of ecosystem change. To study changes in phytoplankton concentration on a global scale, remote-sensing platforms are ideal, due to their high temporal and spatial coverage. Such measurements allow us to quantify the phytoplankton phenology (seasonal dynamics, including timing and magnitude of growth) across the ocean.

The data presented here provides a global record of phytoplankton chlorophyll-a and the derived products of primary production and phytoplankton phenology. Together, these products allow an insight into the current variability in phytoplankton biomass across the globe and provide a time-series from 1998 to 2012 that will allow observations of the response of phytoplankton to climate variability on a global scale.

Findings

The results are a digital time series of chlorophyll fields at the global scale, with a spatial resolution of ~4x4 km and a temporal resolution of one day (available at www.esa-oceancolour-cci.org/). This dataset constitutes a rich data archive for studying seasonal and inter-annual variations in this biological field in the open ocean. The length of the time-series is insufficient for isolating potential trends related to climate change from climate variability. Because the ocean is subject to decadal-scale oscillations, the time series has to be extended to at least three or four decades, before climate-change-related trends can be identified, highlighting the importance of maintaining and building on this climate-quality dataset for many decades into the future.

Figure 5.1. An example of primary production (for May 2004) computed using the OC-CCI chlorophyll fields. The image shows high production in coastal and equatorial upwelling areas, and in the North Atlantic, associated with Spring bloom). These features vary seasonally and interannually.



The fields of chlorophyll concentration were combined with additional information to generate maps of primary production. The results are digital, monthly maps at ~ 9 x 9 km resolution. An example (May 2004) is shown in Figure 5.1. This is a test product, which has not been validated. It was generated to demonstrate one of the important applications of satellite-derived chlorophyll fields. An integrated annual production estimate was made for each complete year of data and the results, around 42Gt C yr$^{-1,}$ are comparable to previous estimates, as shown in Table 5.1.

The chlorophyll data have also been used to compute indicators of phytoplankton phenology for the years 1998 – 2011. The results are provided as digital fields at one-degree resolution. They are useful to study not only whether the chlorophyll concentrations in different parts of the world ocean are changing, but also to examine whether the timings of the major events in the phytoplankton calendar are changing.

The length of the time series of these products is not sufficient to detect changes that are significant in a climate-change context. The value of the results lies in providing a baseline, more than a decade long, of data, against

Table 5.1 Comparison of global annual marine primary production estimates

Source	Annual PP estimate for the global ocean
Longhurst et al. (1995)	44.7 – 50.2 Gt C yr^{-1}
Antoine et al. (1996)	36.5 – 45.6 GtC yr^{-1}
Field et al. (1998)	48.5 Gt C yr^{-1}
Geider et al. (2001)	48.3 Gt C yr^{-1}
Behrenfeld et al. (2005)	60 – 67 Gt C yr^{-1}
Westberry et al. (2008)	52 Gt C yr^{-1}
Moore et al. (2001)	45.2 Gt C yr^{-1}
Uitz et al. (2010)	45.6 Gt C yr^{-1}
TWAP test product	40.7 – 44.1 Gt C yr^{-1}

which future data can be compared for any potential evidence of change. Note that for this goal to be feasible, it is important to maintain the time-series without break and with consistent methods, for many decades into the future.

Discussion and Conclusions

Chlorophyll-a

By rigorously combining data from multiple sensors and providing uncertainty estimates on a pixel-by-pixel basis, the OC-CCI project has generated a climate-quality data record of phytoplankton chlorophyll-a. As the chlorophyll-a estimates are derived from remote-sensing measurements of ocean colour, most of the signal is from the first optical depth, with the consequence that they do not capture the full water-column chlorophyll in regions where the vertical structure in chlorophyll is pronounced, and where a deep chlorophyll maximum is present. The algorithm used in this work was designed for open ocean (Case 1) waters, and should be used in coastal (Case 2) waters only with caution. The product is *likely* to be less accurate in lakes and coastal regions. The OC-CCI product is still being developed and there are plans to update and refine the product over the next three years.

Primary Production

Small gaps in the primary-production estimates arise due to cloud cover, which introduced gaps in chlorophyll data, and larger gaps due to a number of months for which data on light at the sea surface was unavailable from NASA.

The method used here accounts for variability in primary production due to variations in chlorophyll concentration and available light. It does not account for year-to-year variations in the model parameters due to changes in environmental conditions. It would be desirable to develop validated methods for estimating photosynthesis parameters from space.

Phenological Indicators

The initial parameter estimation function used in this work did not perform very well in areas where the data values were low, and contained high relative variability. This is somewhat alleviated by the use of a smoothing function (Hann Window) on the data (only for the estimation of the initial parameters), with the main algorithm being run on the unsmoothed data. But the goodness-of-fit field provides a measure of how well the algorithm performed in reproducing the observed fields. Note that for the magnitudes of the peak values, the associated uncertainties are the same as the uncertainties in the chlorophyll fields themselves. For the timing of the events, the uncertainties are associated with gaps in the data; however these were minimised as much as possible by using OC-CCI data (through merging data from multiple sensors).

Coral spawning observations

Recommendations

Of the three satellite sensors used to generate the time series of products presented here, only MODIS-Aqua sensor of NASA is still operational (MODIS stands for Moderate Resolution Imaging Spectroradiometer). To identify long-term trends in the products presented here, which might be occurring in a changing climate, it is essential that the times series remain unbroken and continue into the future for many years. This would require that the MODIS-Aqua sensor continue to function at least until the launch of ESA's ocean-colour sensor OLCI (Ocean and Land Colour Instrument) on Sentinel-3. The longer the overlap between sensors, the better the cross-sensor calibration and bias correction that can be performed. Given that MODIS-Aqua sensor is now performing well past its design life span, the situation is precarious at present. It is recommended that at least two ocean-colour sensors are in orbit at any given time in the future, to avoid potential difficulties in achieving a seamless merging of the various missions. The possibility of incorporating data from other satellite sensors, such as VIIRS (Visible Infrared Imaging Radiometer Suite), into the time series should also be explored.

5.2.3 Notes on Methods

Chlorophyll-a

The chlorophyll-a product is Version-1 of the products generated by the OC-CCI. In the OC-CCI processing chain, water-leaving reflectances at multiple wavebands in the visible are derived from MERIS (Medium Resolution Imaging Spectrometer), MODIS and SeaWiFS (Sea-viewing Wide Field-of-view Sensor) sensors after atmospheric correction. The atmospheric correction algorithms that were used with each sensor were the ones that performed best in an inter-comparison that was undertaken as part of the OC-CCI Project. A band-shifting algorithm was then applied to the data, to bring the data from all sensors to a common set of wavebands, corresponding to SeaWiFS. The data from MERIS and MODIS were then compared with SeaWiFS data when overlapping data were available for each pair, to establish and correct for inter-sensor bias, if any, at each pixel. Water-leaving reflectances from the three sensors were then merged for each of the wavebands. The calculation of chlorophyll-a concentration was then performed using the empirical NASA OC4v6 algorithm, with the water-leaving reflectances at four wavelengths as input. This algorithm was also one of the best performing of in-water algorithms that were compared in the project. The units for the chlorophyll-a product are mg m^{-3} and it is provided at daily temporal resolution with a spatial resolution of ≈ 4 km/pixel. The coverage of the product is global and the data are currently available from September 1997 to December 2012. The chlorophyll products were validated by comparing the products against in situ observations, and the results of the validation were used to generate root-mean-square differences and bias in the product, for every pixel. For further details, please refer to the OC-CCI Product User Guide (http://www.esa-oceancolour-cci.org/?q=webfm_send/318).

Primary Production

Primary Production was estimated using a primary-production model (Platt and Sathyendranath 1988; Longhurst et al. 1995; Platt et al. 1995; Sathyendranath et al. 1995), a combination of remotely-sensed chlorophyll and light data, and information derived from ship-based in situ measurements on some model parameters. In validation exercises (comparison with field measurements of primary production), the model compared favourably with respect to other models (Friedrichs et al. 2009, Saba et al. 2010, 2011). For the computations, the model parameters, related to photosynthetic response to available light, and to vertical structure in chlorophyll concentration, were organised according to season into ecological provinces, as in Longhurst et al. (1995), with smoothing applied across boundaries of provinces. The product is provided at the global scale with a spatial resolution of 9 km and a temporal resolution of one month. The estimate of primary production given is the integral through the water column. Each biogeochemical province was assigned five parameters, which varied with the four seasons. Two of these were parameters defining the phytoplankton photophysiology: maximum photosynthetic rate per unit chlorophyll concentration at high light levels (P_m^B), and the rate of change of production with light availability, when light levels are low (α^B); three parameters were related to the vertical distribution of chlorophyll: the depth of maximum chlorophyll concentration (Z_m), the thickness of the subsurface peak in chlorophyll concentration (σ) and the ratio of the peak chlorophyll concentration to the background chlorophyll concentration (ρ). Parameters were smoothed across province boundaries to allow a transition zone between provinces.

The chlorophyll profile parameters were used in conjunction with the remotely-sensed chlorophyll data from the OC-CCI project, to create chlorophyll profiles for each 9 km pixel. Average sea-surface irradiance (Photosynthetically-Active Radiation) for each month and for each location was obtained from NASA and was used to scale the results of a spectral clear-sky model to allow input of spectrally-resolved irradiance into the primary-production model. The propagation of spectral light to various depths in the water column accounted for attenuation by water, phytoplankton and other coloured substances. The profile of light was then combined with the vertical profile of chlorophyll and photosynthetic parameters to obtain estimates of depth-resolved primary production. The calculations were repeated for hourly time steps during the day. The results were then integrated over time and depth to yield total primary production per unit area.

Phenology Indicators

Phytoplankton phenology describes the timings of major events in the annual cycle of phytoplankton. This builds on Platt and Sathyendranath (2008) and Racault et al. (2012). In this work, indicators associated with two major peaks of phytoplankton (nominally in Spring and Fall) were identified from the satellite data. The phenology indicators (timing and magnitude at peak of the two blooms and the duration of the blooms) were estimated through the fitting of an equation, constructed from two Gaussian peaks and a sloping baseline chlorophyll concentration, to the chlorophyll time-series for each year, resolved at five-day intervals. The time-series used is a five-day composite of the daily chlorophyll data that has been binned to a 1° spatial resolution. The reason for the change in spatial resolution is the high processing time otherwise required, as well as the need to create time series with minimal gaps in the data.

To fit the double Gaussian equation, an initial guess of the parameters was provided to a sequential least squares minimisation function. The initial guesses for the chlorophyll-baseline parameters were calculated using the lowest 10% of data values. The mean of these points was used to set the initial guess for B_0 (background biomass) and the gradient initial guess was set as the gradient between the first ten and last ten points (from within the lowest 10% sub-set). To identify the two Gaussian peaks, the largest peaks in the data were identified by their area, where each peak is defined as a maximum with adjacent minimum. The initial guess for the peak width parameter (sigma) is then calculated for each of these two peaks, using the distance in time between the two neighbouring minima. The initial peak amplitudes are simply the chlorophyll values at each of the two peaks. To avoid the possibility that the minimisation function would merge multiple peaks into one broad peak, some bounds were introduced to limit the width of the fitted Gaussians.

This product also has a global coverage. The root mean square differences (RMSD) of the fit at each pixel alongside the phenology indicators as a metric of the quality of the fitting procedure was provided.

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