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Estimating global chlorophyll changes over the past century

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ABSTRACT

Marine phytoplankton account for approximately half of the production of organic matter on earth, support virtually all marine ecosystems, constrain fisheries yields, and influence climate and weather. Despite this importance, long-term trajectories of phytoplankton abundance or biomass are difficult to estimate, and the extent of changes is unresolved. Here, we use a new, publicly-available database of historical shipboard oceanographic measurements to estimate long-term changes in chlorophyll concentration (Chl; a widely used proxy for phytoplankton biomass) from 1890 to 2010. This work builds upon an earlier analysis (Boyce et al., 2010) by taking published criticisms into account, and by using recalibrated data, and novel analysis methods. Rates of long-term chlorophyll change were estimated using generalized additive models within a multi-model inference framework, and *post hoc* sensitivity analyses were undertaken to test the robustness of results. Our analysis revealed statistically significant Chl declines over 62% of the global ocean surface area where data were present, and in 8 of 11 large ocean regions. While Chl increases have occurred in many locations, weighted syntheses of local- and regional-scale estimates confirmed that average chlorophyll concentrations have declined across the majority of the global ocean area over the past century. Sensitivity analyses indicate that these changes do not arise from any bias between data types, nor do they depend upon the method of spatial or temporal aggregation, nor the use of a particular statistical model. The wider consequences of this long-term decline of marine phytoplankton are presently unresolved, but will need to be considered in future studies of marine ecosystem structure, geochemical cycling, and fishery yields.

1. Introduction

Despite accounting for only 0.2% of global producer biomass, marine phytoplankton account for 46% of annual primary production (Field et al., 1998). Changes in marine phytoplankton biomass or productivity may lead to corresponding changes in geochemical cycles (Redfield, 1958), climate and weather (Murtugudde et al., 2002), fisheries landings (Chassot et al., 2010; Ryther, 1969), and the structure and dynamics of marine ecosystems (Chavez et al., 2003; Richardson and Schoeman, 2004). Although there is mounting evidence that marine phytoplankton concentration is changing at the scale of ocean basins and possibly globally, there is considerable debate regarding the direction and magnitude of change (Antoine et al., 2005; Behrenfeld et al., 2006; Boyce et al., 2010; Falkowski and Wilson, 1992; Gregg and Conkright, 2002; Gregg et al., 2005; Mackas, 2011; McQuatters-Gollop et al., 2011; Rykaczewski and Dunne, 2011; Venrick et al., 1987). This uncertainty likely results in part from the lack of consistent, long-term time series of estimates of phytoplankton concentration.

Changes in phytoplankton concentration have been inferred from measurements of upper ocean chlorophyll concentration (Chl; mg m^{-3}; Venrick et al., 1987), transparency (Falkowski and Wilson, 1992), visual estimates of ocean colour (Reid et al., 1998; Wernand and van Der Woerd, 2010), and remotely-sensed water-leaving radiances (Antoine et al., 2005; Behrenfeld et al., 2006; Gregg and Conkright, 2002). Recent trends estimated primarily from satellite data (<30 years) are strongly driven by transient climate fluctuations (Behrenfeld et al., 2006; Boyce et al., 2010; Chavez et al., 2011; Martinez et al., 2009), and longer series are required to resolve long-term trends (Beaulieu et al., 2013; Henson et al., 2010). To overcome this limitation, several studies have combined indices of phytoplankton concentration sampled over

Abbreviations: Chl_T, transparency-derived chlorophyll values; Chl_I, in situ-derived chlorophyll values; Z_D, Secchi depth; FU, Forel-Ule; OGCM, ocean general circulation model; GAM, generalized additive model.

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different time periods and from different observational platforms (Antoine et al., 2005; Boyce et al., 2010; Gregg and Conkright, 2002; Gregg et al., 2003; Raitsos et al., 2005; Saulquin et al., 2013). One such study combined shipboard measurements of ocean transparency and in situ Chl and concluded that average surface Chl had declined globally over the past century (Boyce et al., 2010). These findings were questioned by others, primarily because of contrasting results from other proxies in some regions (McQuatters-Gollop et al., 2011), and possible calibration issues arising from the merging of two independent time series (Boyce et al., 2011; Mackas, 2011; Rykaczewski and Dunne, 2011). These criticisms were addressed in a follow-up study where time series were calibrated against each other, and their accuracy was compared against more recent satellite-derived measurements of surface Chl (Boyce et al., 2012). This procedure removed any potential bias introduced by merging of data types, and correlated strongly ($r = 0.81$; ranged major axis slope = 1) with the independently derived satellite record. In constructing this database we also introduced a range of methodological advancements and sensitivity analyses, which demonstrated the accuracy of the Chl measurements. Here, we use this larger, and expanded database of Chl measurements (Boyce et al., 2012) combined with newly developed analysis methods and robustness checks to provide new estimates of long-term changes in global upper ocean Chl over the last century.

2. Methods

2.1. Data

Due to the difficulty associated with direct enumeration of phytoplankton and in separating phytoplankton carbon from that contained in other living and detrital particles, the measured concentration of chlorophyll has been widely used as a first-order indicator of the abundance and biomass of oceanic phytoplankton. Despite variability in the phytoplankton Chl-to-carbon ratio (Geider, 1987; Saba et al., 2010), Chl is still the most practical and extensively used proxy of phytoplankton biomass over large spatial scales (Antoine et al., 2005; Behrenfeld et al., 2006; Gregg and Conkright, 2002; Gregg et al., 2005; Henson et al., 2010; Huot et al., 2007; Montes-Hugo et al., 2009; Raitsos et al., 2005; Reid et al., 1998).

We use a new and publicly-available database of integrated Chl values collected via shipboard sampling platforms from 1890 to 2010 (details in Boyce et al., 2012). The database is only briefly described here; full details of the data sources, temporal and geographic distribution, quality control and inter-calibration are given in Boyce et al. (2012). It consists of measurements of ocean transparency (derived from Secchi-depth measurements; Z_D) and colour (derived from the Forel-Ule color-matching scale; FU), which were both calibrated against a large and comprehensive database of quality-controlled in situ Chl measurements derived from spectrophotometric or fluorometric analyses of seawater. Since the calibration methods used to derive Chl values are sensitive to the optical properties of the seawater, all near-shore measurements (<20 m water depth or <1 km from the nearest coastline) were removed from the database on the assumption that these waters would likely contain significant concentrations of other optically active constituents, that confound the optical detection of phytoplankton Chl. Statistical techniques were used to identify erroneous measurements; these were corrected or removed from the database.

This database (details in Boyce et al., 2012) has been expanded and improved over a previous version (used by Boyce et al., 2010), in a variety of ways, including:

(1) The number of individual measurements, and the temporal and spatial coverage of the database has considerably increased, despite the use of more stringent quality control methods.
(2) Transparency values in the database were calibrated directly against a large number of quality-controlled in situ Chl measurements ($n = 12{,}841$); this is a large increase over the number of matchups used to calibrate globally distributed remotely sensed water-leaving radiance values from the Coastal Zone Colour Scanner (CZCS; $n = 60$) or the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; $n = 2, 853$; Evans and Gordon, 1994; O'Reilly et al., 2000), and ensures that our calibration equations accurately represent in situ Chl concentrations.
(3) A range of new statistical methods (*i.e.* spatial filters) were developed to identify potential outlying or implausible Chl measurements in the database, and to subsequently remove or correct them. A range of Chl depth interpolation methods were also explored to verify the assumption that the mean Chl over 20 m was the appropriate metric.
(4) Measurements in the database were subjected to a number of additional post-calibration analyses testing their quality, precision, and robustness (Boyce et al., 2012). This included testing their accuracy against widely used remote sensing estimates of Chl. These analyses indicated that the Chl values in this database are strongly correlated with Chl from SeaWiFS ($r = 0.81$; ranged major axis slope = 1) on log–log scales. The larger number of matchups and strong correspondence with remote sensing measurements attest to the improved quality of the integrated Chl database (see Boyce et al., 2012 for further details).

Prior to our trend analyses, sensitivity analyses were undertaken to ensure that merging in situ, color, and transparency-derived Chl measurements would not bias the results of subsequent trend analyses. These sensitivity analyses suggested that Chl trends derived from Forel-Ule ocean colour measurements were atypical. Changes in Forel-Ule ocean color determinations are not sensitive to small changes in Chl observed in oligotrophic (blue) waters (FU < 2) where the optical properties of pure water dominate, or in mesotrophic (green or brown) waters where other particles and dissolved substances are significant (FU > 10). Oligotrophic blue waters contain the lowest Chl concentrations globally and are widely distributed. Because the validity of these values could not be confirmed and to avoid any potential bias, we removed all FU-derived Chl values prior to the trend analysis. The resulting database used here (Table 1) contains 451,383 calibrated Chl values, is globally distributed, and spans over a century (1890–2010). Despite this, the measurements are sparse in many areas, particularly in the Southern hemisphere, and prior to 1950.

2.2. Statistical analyses

Inter-annual changes in average Chl are often small relative to the naturally-occurring variability. For instance, stochastic natural disturbances can drive large transient Chl changes over days to weeks (Hamme et al., 2010), intra-annual Chl variability can span several orders of magnitude in some locations, and inter-annual to decadal climate fluctuations can induce 20-fold changes in Chl over varying time intervals (Barber and Chavez, 1986). Detection of any long-term trends that may underlie this large variability requires powerful and flexible analysis tools. Hence, we estimated changes in Chl over time using generalized additive models (GAMs). GAMs are an extension of widely-used generalized linear models, but enable the estimation of both linear trends as well as non-monotonic responses, (*i.e.* seasonal cycles) within the same