1933 have little influence on the regression). After ~1970, C_{I} estimates become increasingly dominant, and annual averages approach 0.5. In this artificial example, the changing blended mean and the C versus year regression are both entirely attributable to bias. However, the fitted regression slope (-0.003 mg chlorophyll yr^{-1} or ~0.5% yr^{-1}) is a very significant fraction of the ~1% yr^{-1} trends reported by Boyce *et al.*[1].

I stress that my argument is not a denial of any long-term change, but only that the trends described by Boyce *et al.*[1] include an important negative bias that should be removed to improve the estimation of underlying real changes. One way to do this is to rescale individual C_{T} such that the expected value of the 'new' estimate C_{T}' equals local $E(C_{\mathrm{I}})$. Boyce *et al.* could globally apply $C_{\mathrm{T}}' = 0.66\ (C_{\mathrm{T}})^{0.926}$ (adapted from equation (3)) and then repeat their analysis, substituting C_{T}' for C_{T}. A more complex approach could apply region- and level-optimized Secchi-to-C_{T}' functions. Either approach is a more convincing filter than the examination of residuals from original fit used by Boyce *et al.*[1], because their original fit included any bias as part of its total temporal trend.

METHODS

Log-scale to linear-scale transformation. If $E(\log C_{\mathrm{T}}) = a + b(\log E(C_{\mathrm{I}}))$, then $E(C_{\mathrm{T}}) \approx 10^a \times E(C_{\mathrm{I}})^b$, where 10^a is the multiplicative slope at $C_{\mathrm{I}} = 1.0$ (>1 if $a > 0$), and b describes curvature (>1 = concave up, <1 = concave down).
Temporal bias of blended 'constant chlorophyll' time series. C_{T} and C_{I} estimates for a single 'real' chlorophyll concentration were replicated from a point (blue stars in Fig. 1a, b) on the C_{T} versus C_{I} regression line located near the centroid. These artificial data were distributed across the years 1899–2008 to match frequency histograms from figure 1a in ref. 1. Note that data are constant within type across years, but differ by their expected values at this point ($C_{\mathrm{T}} = 0.716$, $C_{\mathrm{I}} = 0.5$). The resulting time series was summarized in two ways (Fig. 1c): data were averaged within year to produce a time series of blended means (circles in Fig. 1c) and a C versus year linear regression was calculated using the individual data estimates (line in Fig. 1c).

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Received 1 October 2010; accepted 1 February 2011.

1. Boyce, D. G., Lewis, M. R. & Worm, B. Global phytoplankton decline over the past century. *Nature* **466,** 591–596 (2010).
2. Siegel, D. A. & Franz, B. A. Century of phytoplankton change. *Nature* **466,** 569–571 (2010).
3. Falkowski, P. & Wilson, C. Phytoplankton productivity in the North Pacific ocean since 1900 and implications for absorption of anthropogenic CO_2. *Nature* **358,** 741–743 (1992).

Competing financial interests: declared none.

doi:10.1038/nature09951

A measured look at ocean chlorophyll trends

ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm *Nature* **466,** 591–596 (2010)

Identifying major changes in global ecosystem properties is essential to improve our understanding of biological responses to climate forcing and exploitation. Recently, Boyce *et al.*[1] reported an alarming, century-long decline in marine phytoplankton biomass of 1% per year, which would imply major changes in ocean circulation, ecosystem processes and biogeochemical cycling over the period and have significant implications for management of marine fisheries. Closer examination reveals that time-dependent changes in sampling methodology combined with a consistent bias in the relationship between *in situ* and transparency-derived chlorophyll (Chl) measurements generate a spurious trend in the synthesis of phytoplankton estimates used by Boyce *et al.*[1]. Our results indicate that much, if not all, of the century-long decline reported by Boyce *et al.*[1] is attributable to this temporal sampling bias and not to a global decrease in phytoplankton biomass.

The optical properties of natural seawater are dependent on the concentrations of three main constituents: phytoplankton and other organic particles, inorganic mineral particles and coloured dissolved organic matter[2]. Variations in both the optical properties and relative abundance of these constituents prevent application of a single equation to accurately estimate phytoplankton concentration from ocean transparency for the global ocean[3]. The equation applied by Boyce *et al.*[1] to convert from transparency (Secchi-disk measurements) to Chl consistently overestimates Chl concentrations compared to *in situ* measurements ($\log_{10} \mathrm{Chl}_{\mathrm{transparency}} = 0.18 + 1.08 \times (\log_{10} \mathrm{Chl}_{\text{in-situ}})$; see supplementary figure 2a in ref. 1). The regression equation Boyce *et al.*[1] use between the two methods of measurement indicates that the bias is greater for increasing Chl concentrations. This overestimate of Chl ranges from about 5% at low concentrations to >100% at higher concentrations (Fig. 1). Given the approximate global distribution of Chl concentrations, the median bias between the two sampling methods is about 35%. Because the blended Chl database used by Boyce *et al.*[1] contains a long-term trend in sampling instrumentation (with the portion of estimates derived from transparency gradually dropping from ~100% before 1955 to <15% after 1995; see figure 1a in ref. 1), a spurious, long-term decline in estimated Chl is introduced over the length of the data set.

To examine whether the trends reported by Boyce *et al.*[1] could be attributed to biases introduced by these changes in sampling instrumentation, we generated a synthetic data set of global Chl with no time-dependent trend in the underlying Chl concentration (1997–2009 monthly climatology of 9-km SeaWiFS Chl[4]). We then 'sampled' this Chl climatology according to the measurement efforts (instrumentation, location and time of year) recorded in the publicly available data sets used by Boyce *et al.*[1] (number of unique

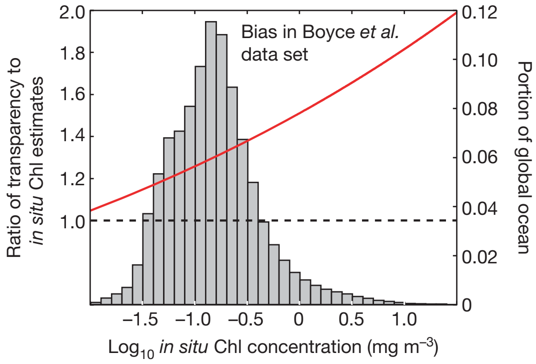

Figure 1 | Bias between transparency and *in situ* estimates of Chl in the blended data set of Boyce *et al.*[1]. When the bias is re-plotted with reference to the ratio between the transparency estimates and *in situ* estimates, the overestimate of the transparency method is apparent (red line and left axis). The dotted line is the 1-to-1 relationship assumed by Boyce *et al.*[1]. The histogram (grey bars and right axis) shows the approximate global distribution of Chl concentrations[4] in the surface ocean.

measurements = 451,887). For Chl measurements estimated by transparency, we included the bias in our synthetic data set according to the regression equation used by Boyce *et al.*[1] relating *in situ* and transparency estimates of Chl. This allows independent assessment of the trend in the blended data set that was introduced by century-long changes in sampling instrumentation. We binned the synthetic Chl record into 10° × 10° ocean cells[1] and estimated the mean instantaneous rate of Chl change to generate a map of the spurious, local scale trends in Chl resulting from sampling bias (Fig. 2). This map resembles figure 2a in ref. 1, with 81% of the cells showing a decline in Chl and the largest spatial areas of decline in the North Pacific, North Atlantic and Arctic Oceans. The Indian Ocean is the only broad region in which the number of transparency measurements relative to *in situ* measurements has increased over time, inducing a positive bias in the regional Chl trend. The globally averaged rate of Chl decline in our synthetic data set was $-0.007\ \mathrm{mg\,m^{-3}\,yr^{-1}}$, indicating that sampling biases induce a long-term trend similar in magnitude and spatial distribution to the 1% yr^{-1} decline in Chl reported by Boyce *et al.*[1].

Investigation of large-scale and long-term changes in biogeochemical cycling, physical climate properties and the condition of the world's ecosystems is of increasing importance as we are faced with the challenges of detection, attribution and adaptation in the face of anthropogenic global change. Boyce *et al.*[1] should be commended for their effort to address this critical issue, but the long-term decline in global Chl they report is probably an artefact of sampling methodology. This dialogue emphasizes the need for ongoing observations of marine ecosystems and prudent examination of historical data sets.

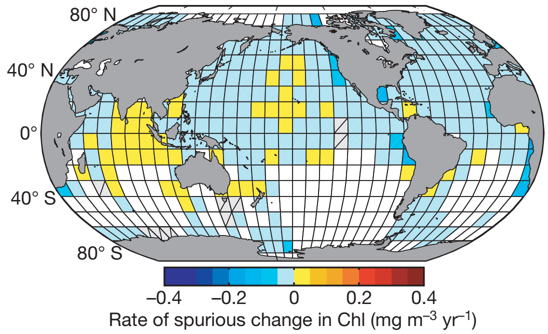

Figure 2 | Spurious trends in the blended Chl database introduced by time-dependent changes in sampling instrumentation. Regions in which the time period of sampling spanned <15 years (white cells) were excluded from the analysis, and areas in which changes in Chl sampling instrumentation introduced no bias are marked with a diagonal.

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Received 16 October 2010; accepted 1 February 2011.

1. Boyce, D. G., Lewis, M. R. & Worm, B. Global phytoplankton decline over the past century. *Nature* **466**, 591–596 (2010).
2. Sathyendranath, S., Prieur, L. & Morel, A. A 3-component model of ocean color and its application to remote-sensing of phytoplankton pigments in coastal waters. *Int. J. Remote Sens.* **10**, 1373–1394 (1989).
3. Morel, A. & Prieur, L. Analysis of variations in ocean color. *Limnol. Oceanogr.* **22**, 709–722 (1977).
4. McClain, C. R. *et al.* Science quality SeaWiFS data for global biosphere research. *Sea Technol.* **39**, 10–16 (1998).

Competing financial interests: declared none.

doi:10.1038/nature09952

Is there a decline in marine phytoplankton?

ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm *Nature* **466,** 591–596 (2010)

Phytoplankton account for approximately 50% of global primary production, form the trophic base of nearly all marine ecosystems, are fundamental in trophic energy transfer and have key roles in climate regulation, carbon sequestration and oxygen production. Boyce *et al.*[1] compiled a chlorophyll index by combining *in situ* chlorophyll and Secchi disk depth measurements that spanned a more than 100-year time period and showed a decrease in marine phytoplankton biomass of approximately 1% of the global median per year over the past century. Eight decades of data on phytoplankton biomass collected in the North Atlantic by the Continuous Plankton Recorder (CPR) survey[2], however, show an increase in an index of chlorophyll (Phytoplankton Colour Index) in both the Northeast and Northwest Atlantic basins[3–7] (Fig. 1), and other long-term time series, including the Hawaii Ocean Time-series (HOT)[8], the Bermuda Atlantic Time Series (BATS)[8] and the California Cooperative Oceanic Fisheries Investigations (CalCOFI)[9] also indicate increased phytoplankton biomass over the last 20–50 years. These findings, which were not discussed by Boyce *et al.*[1], are not in accordance with their conclusions and illustrate the importance of using consistent observations when estimating long-term trends.

Since 1931 more than 5 million nautical miles of ocean have been sampled by ships of opportunity towing the CPR and more than 250,000 phyto- and zooplankton samples, including the Phytoplankton Colour Index (PCI), analysed using a virtually unchanged methodology[10]. Although the CPR's mesh size is 270 μm, the device consistently collects small cells—such as coccolithophores—on the silk[10]; with recent work indicating that the relative contribution of smaller size fractions to the PCI is increasing in some regions[11]. The PCI also accounts for fragile, broken and fragmented cells that contribute to phytoplankton biomass but are not morphologically identifiable. PCI has repeatedly been successfully intercalibrated with measurements of chlorophyll from the SeaWiFS[6,7] satellite sensor and, in contrast to the findings of Boyce *et al.*[1], shows an increase in phytoplankton biomass throughout much of the North Atlantic (Fig. 1).

For the first 50 years of the Boyce *et al.*[1] time series, the majority of the chlorophyll estimates were derived from Secchi measurements; later, chlorophyll sampling became a standard oceanographic procedure and after 1980 most of the data were from *in situ* chlorophyll measurements. The 'mixed' data set of Boyce *et al.*[1] does not take into account the fact that the relationship between Secchi depth visibility and chlorophyll concentration may not be spatially or temporally uniform[12], and may therefore be biased. Boyce *et al.*[1] use chlorophyll measurements (and presumably Secchi depth readings, although this is unclear) from the top 20 m of the water column. This coincides well with the CPR sampling depth, but does not take into account the high levels of chlorophyll found in the deep chlorophyll maximum. The Secchi–chlorophyll