

# Does blending of chlorophyll data bias temporal trend?

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

Phytoplankton account for about half of global and nearly all of marine primary productivity; consequently, any widespread drop in phytoplankton biomass would almost certainly have severe ecological consequences. Boyce *et al.*<sup>1</sup> have reported strong (~1% per year) and sustained declines in marine phytoplankton biomass at local, regional and global scales. However, I suggest that some or much of their reported declines are attributable to bias between the two data types used by Boyce *et al.*<sup>1</sup>. Although real changes may have occurred, their proper quantification requires removal of the bias component.

To obtain a larger and longer data set, Boyce *et al.*<sup>1</sup> pooled estimates of local chlorophyll concentration derived from two very different sets of measurements: water transparency-based estimates of chlorophyll concentration  $C_T$ , and direct measurements of chlorophyll,  $C_I$ , from *in situ* profiles. In the former case, Secchi depth<sup>2</sup> ( $D$ ) is converted to  $C_T$  by global application of a previously published<sup>3</sup> fit,  $C_T = 457 D^{-2.37}$ . Blending of data types can introduce error unless their expected values  $E(C_T)$  and  $E(C_I)$  are the same at corresponding locations and times. To test their similarity, Boyce *et al.*<sup>1</sup> compared a large number of space- and time-matched  $C_I$  and  $C_T$  estimates. They show (supplementary figure 2 in ref. 1, reproduced here as Fig. 1a) that, across very large total ranges,  $\log C_I$  and  $\log C_T$  are strongly correlated ( $r^2 \approx 0.6$ ) and that expected values fit the equation

$$E(\log C_T) = 0.18 + (1.08 \pm 0.016) E(\log C_I) \quad (1)$$

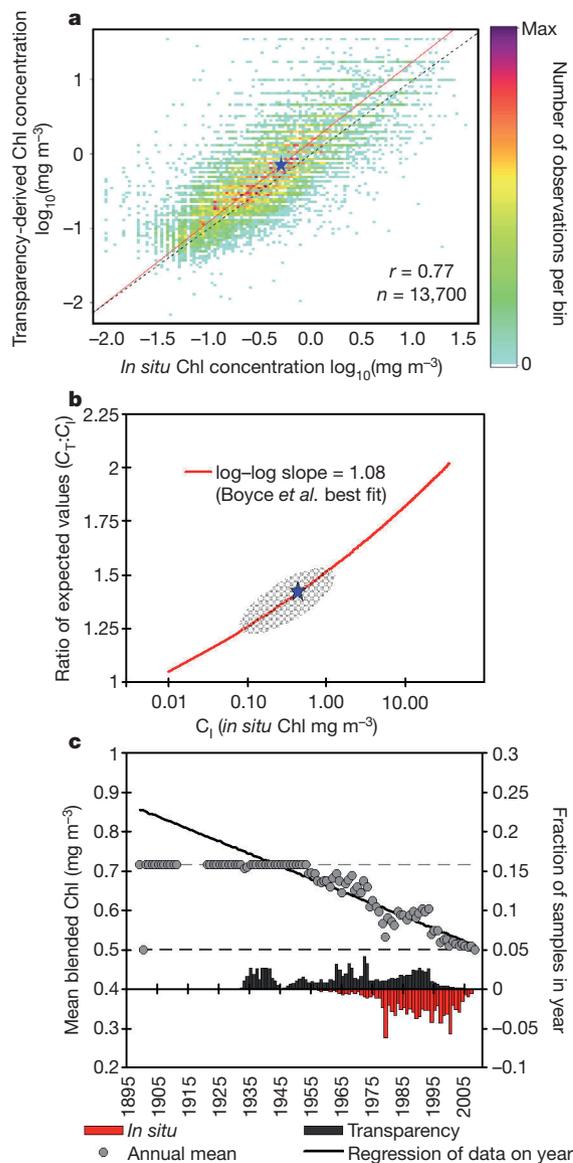
Boyce *et al.*<sup>1</sup> reported that the  $C_I$  versus  $C_T$  relationship has ‘linear scaling’ with slope near 1.0, and assumed that  $C_T$  and  $C_I$  estimates were similar enough to combine without further treatment. But quantification of interannual variability (perhaps factor of 2–3 range) is likely to be more sensitive to bias (perhaps factor of 1.2–1.5, see later) than are the very strong (factor of 10–100) regional and seasonal signals that dominate total variance. When equation (1) is back-transformed to linear scale (Methods), the resulting equations are power law with slopes very different from 1.0 (after the back transformation, it is the exponent, not the slope, that is ~1.0):

$$E(C_T) = 1.51 (C_I)^{1.08} \quad (2)$$

and/or

$$E(C_I) = 0.66 (C_T)^{0.926} \quad (3)$$

A key consequence is that  $E(C_T)$  is larger than  $E(C_I)$  throughout the range of observations (Fig. 1b). The positive bias of  $C_T$  relative to  $C_I$  is 25–50% for  $C_I$  between 0.1–1.0 (most of the data). Because the exponent is >1, bias increases at higher chlorophyll concentrations. The difference of expected values can interact with the long-term trend in a mix of samples (mostly  $C_T$  early, mostly  $C_I$  later, Fig. 1c and figure 1a in ref. 1) to cause a trend in the blended mean that confounds/adds to any real temporal change of chlorophyll concentration. To isolate and illustrate this biased trend, I use an artificial ‘constant chlorophyll’ blended time series (Methods) in which  $C_T$  and  $C_I$  are time invariant, and the only time dependence is the amount of each data type per year (taken from figure 1 in ref. 1). Figure 1c shows within-year averages, plus the linear regression of all data on year. Years before 1965 are strongly dominated by  $C_T$  and have annual averages of ~0.7 (due to small  $n$ , years before



**Figure 1 | Evidence for bias between the transparency-based and in-situ estimates of chlorophyll concentration used by Boyce *et al.*<sup>1</sup>.** a, Log-log scatterplot of space- and time-matched transparency-based ( $C_T$ ) and *in situ* ( $C_I$ ) estimates of chlorophyll (Chl) concentration. Pixel colour indicates data density. Red line is the log-log Model II fit. Black line is  $C_T = C_I$ . Reproduced with permission from Boyce *et al.*<sup>1</sup>. b, Ratio of  $E(C_T):E(C_I)$  versus log-scale  $C_I$ , showing that  $C_T$  has positive bias throughout the range of observations. Red line is from the log-log fit. Shaded ellipse shows the range containing most observations. Blue star marks the  $C_T = 0.716$ ,  $C_I = 0.5$  pair used in the temporal bias calculation in c. c, Temporal bias of a ‘constant chlorophyll’ blended time series caused by interaction between ( $E(C_T) > E(C_I)$ ) and trends in the mixture of data source types. Dashed lines show the values for all individual data points (either  $C_I$  or  $C_T$ ). Red and black column graphs (from figure 1a in ref. 1) show relative abundance of  $C_I$  and  $C_T$  per year. Circles are annual blended means. Black line is the linear trend of all data versus year.

1933 have little influence on the regression). After  $\sim 1970$ ,  $C_T$  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 ( $-0.003 \text{ mg chlorophyll yr}^{-1}$  or  $\sim 0.5\% \text{ yr}^{-1}$ ) is a very significant fraction of the  $\sim 1\% \text{ yr}^{-1}$  trends reported by Boyce *et al.*<sup>1</sup>

I stress that my argument is not a denial of any long-term change, but only that the trends described by Boyce *et al.*<sup>1</sup> 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  $E(C_T)$ . Boyce *et al.* could globally apply  $C_T' = 0.66 (C_T)^{0.926}$  (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.*<sup>1</sup>, because their original fit included any bias as part of its total temporal trend.

## METHODS

**Log-scale to linear-scale transformation.** If  $E(\log C_T) = a + b(\log E(C_T))$ , then  $E(C_T) \approx 10^a \times E(C_T)^b$ , where  $10^a$  is the multiplicative slope at  $C_T = 1.0$  ( $>1$  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 ( $C_T = 0.716$ ,  $C_I = 0.5$ ). 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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# A measured look at ocean chlorophyll trends

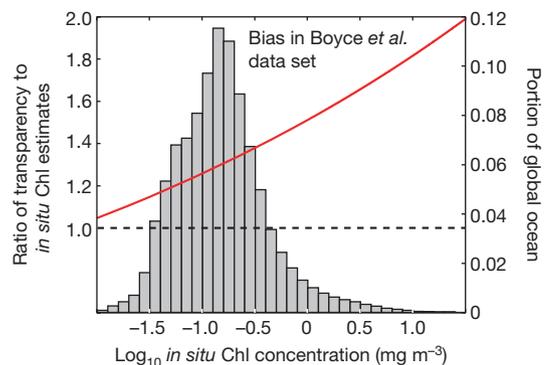
ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm *Nature* **466**, 591–596 (2010)

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.*<sup>1</sup> 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.*<sup>1</sup>. Our results indicate that much, if not all, of the century-long decline reported by Boyce *et al.*<sup>1</sup> 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<sup>2</sup>. 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<sup>3</sup>. The equation applied by Boyce *et al.*<sup>1</sup> to convert from transparency (Secchi-disk measurements) to Chl consistently overestimates Chl concentrations compared to *in situ* measurements ( $\log_{10} \text{Chl}_{\text{transparency}} = 0.18 + 1.08 \times (\log_{10} \text{Chl}_{\text{in-situ}})$ ; see supplementary figure 2a in ref. 1). The regression equation Boyce *et al.*<sup>1</sup> 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.*<sup>1</sup> contains a long-term trend in sampling instrumentation (with the portion of estimates

derived from transparency gradually dropping from  $\sim 100\%$  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.*<sup>1</sup> 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<sup>4</sup>). 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.*<sup>1</sup> (number of unique



**Figure 1 | Bias between transparency and *in situ* estimates of Chl in the blended data set of Boyce *et al.*<sup>1</sup>.** 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.*<sup>1</sup>. The histogram (grey bars and right axis) shows the approximate global distribution of Chl concentrations<sup>4</sup> in the surface ocean.

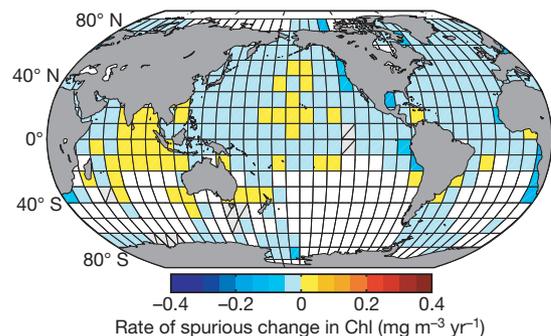
measurements = 451,887). For Chl measurements estimated by transparency, we included the bias in our synthetic data set according to the regression equation used by Boyce *et al.*<sup>1</sup> relating *in situ* and transparency estimates of Chl. This allows independent assessment of the trend in the blended data set that was introduced by century-long changes in sampling instrumentation. We binned the synthetic Chl record into  $10^\circ \times 10^\circ$  ocean cells<sup>1</sup> 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  $-0.007 \text{ mg m}^{-3} \text{ yr}^{-1}$ , indicating that sampling biases induce a long-term trend similar in magnitude and spatial distribution to the  $1\% \text{ yr}^{-1}$  decline in Chl reported by Boyce *et al.*<sup>1</sup>

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.*<sup>1</sup> 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.

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**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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## Is there a decline in marine phytoplankton?

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

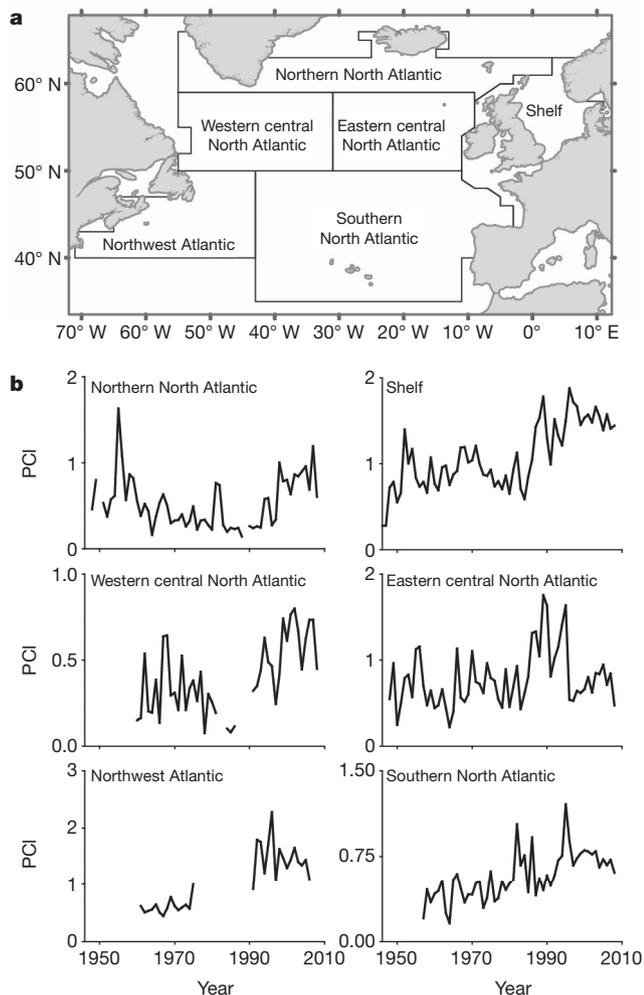
Phytoplankton account for approximately 50% of global primary production, form the trophic base of nearly all marine ecosystems, are fundamental in trophic energy transfer and have key roles in climate regulation, carbon sequestration and oxygen production. Boyce *et al.*<sup>1</sup> compiled a chlorophyll 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<sup>2</sup>, however, show an increase in an index of chlorophyll (Phytoplankton Colour Index) in both the Northeast and Northwest Atlantic basins<sup>3–7</sup> (Fig. 1), and other long-term time series, including the Hawaii Ocean Time-series (HOT)<sup>8</sup>, the Bermuda Atlantic Time Series (BATS)<sup>8</sup> and the California Cooperative Oceanic Fisheries Investigations (CalCOFI)<sup>9</sup> also indicate increased phytoplankton biomass over the last 20–50 years. These findings, which were not discussed by Boyce *et al.*<sup>1</sup>, 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<sup>10</sup>. Although the CPR's mesh size is  $270 \mu\text{m}$ , the device consistently collects small cells—such as coccolithophores—on the silk<sup>10</sup>; with recent work indicating that the relative contribution of smaller size fractions to the PCI is increasing in some regions<sup>11</sup>. 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<sup>6,7</sup> satellite sensor and, in contrast to the findings of Boyce *et al.*<sup>1</sup>, shows an increase in phytoplankton biomass throughout much of the North Atlantic (Fig. 1).

For the first 50 years of the Boyce *et al.*<sup>1</sup> 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.*<sup>1</sup> does not take into account the fact that the relationship between Secchi depth visibility and chlorophyll concentration may not be spatially or temporally uniform<sup>12</sup>, and may therefore be biased. Boyce *et al.*<sup>1</sup> 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

# BRIEF COMMUNICATIONS ARISING



**Figure 1 | Results from the CPR survey show increased phytoplankton in most regions of the North Atlantic.** **a**, Sub-regions, based on CPR Standard Areas, used to illustrate long-term regional variability of phytoplankton trends. **b**, Trends in the PCI in the North Atlantic from 1946–2008. Only years with >7 months of data were used in trend calculation. The reduction in the PCI after 1995 in the eastern central North Atlantic is attributed to changes in the strength and extent of the subpolar gyre<sup>15</sup>.

relationship is debatable for another reason: everywhere, even in oligotrophic ocean regions, Secchi disk visibility is influenced by non-living suspended particles and by ‘gilvin’ (dissolved organic matter), not only by phytoplankton-containing pigments—of which chlorophyll is only one. The high chlorophyll values at the beginning of the time series in figure 4a in ref. 1 are derived mostly from Secchi observations. If these are excluded, the trend in the chlorophyll index changes to positive in the North Atlantic, Equatorial Atlantic, South Atlantic, North Pacific and South Pacific. These post-1980 trends are consistent with results from other sustained monitoring programmes such as HOT<sup>8</sup>, BATS<sup>8</sup> and CalCOFI<sup>9</sup>, as well as the CPR survey. The increasing trend in chlorophyll in the 1980s for the North Atlantic is also clear in the satellite observation records cited by Boyce *et al.*<sup>1</sup> (see figure 2 in ref. 13 and figure 7 in ref. 14).

On the basis of the data from the CPR survey and the BATS programme, chlorophyll in the North Atlantic is shown to be increasing, especially after 1980. This increase is also seen in long-term time series from the North Pacific (HOT, CalCOFI). This considerable body of data contrasts with the results presented by Boyce *et al.*<sup>1</sup>; it indicates that there is no strong evidence for a marked decline in global marine phytoplankton.

## METHODS

CPR samples are collected by a high-speed plankton recorder (~9–23 knots) towed in the mixed surface layer of the ocean (~10 m depth); one sample represents 18 km of tow. Water passes through the recorder, and plankton are filtered by a slow moving silk band (mesh size 270 μm). A second layer of silk covers the first and both are reeled into a tank containing 4% formaldehyde. The PCI is based on a relative scale of greenness caused by accumulation of phytoplankton cells on the silk, and determined by reference to a standard colour chart<sup>10</sup>.

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Boyce *et al.* reply

REPLYING TO A. McQuatters-Gollop *et al.* *Nature* **472**, doi:10.1038/nature09950 (2011); D. L. Mackas *Nature* **472**, doi:10.1038/nature09951 (2011); R. R. Rykaczewski & J. P. Dunne *Nature* **472**, doi:10.1038/nature09952 (2011)

In their thoughtful responses to our article on global chlorophyll (Chl) trends<sup>1</sup>, Mackas<sup>2</sup>, Rykaczewski and Dunne<sup>3</sup>, and McQuatters *et al.*<sup>7</sup> suggest that some of the variation observed in our analysis may be explained by a possible bias, whereby transparency-derived chlorophyll ( $C_T$ ) measurements overestimate phytoplankton abundance relative to direct *in situ* chlorophyll ( $C_I$ ) measurements. Although we cannot entirely discount the possibility that changes in sampling methods may introduce fractional bias, extensive sensitivity analyses detailed below show that this is not responsible for the observed Chl declines. Furthermore, the accuracy of  $C_T$  as a proxy of surface Chl has been independently verified<sup>4,5</sup>, and indicates that  $C_T$  explains only 0.5–1.5% less of the variance in surface Chl than precision measurements of water-leaving radiance (remotely sensed ocean colour)<sup>5</sup>.

Mackas<sup>2</sup> and Rykaczewski and Dunne<sup>3</sup> suggest that a systematic bias between  $C_T$  and  $C_I$  combined with an unbalanced temporal sampling effort may have influenced the direction of Chl trends. However, several lines of evidence indicate that this is not the case. We adjusted  $C_T$  using the corrective algorithm suggested by Mackas (equations (2) and (3) in ref. 2) and re-estimated Chl trends. This improved the agreement between  $C_T$  and  $C_I$  ( $b = 0.98$ ;  $r^2 = 0.6$ ) and did not change the direction of Chl trends in any of the regions. The magnitude of change varied in some regions and the proportion of declining cells dropped from 59% to 53%; however, our original conclusions remained valid. In our paper we compared  $C_T$  and  $C_I$  using model II major axis regression, assuming error in both variables (supplementary figure 2a in ref. 1). However, the simulations performed by Rykaczewski and Dunne<sup>3</sup> use our model II regression parameters to predict simulated Chl values using model I ordinary least squares (OLS) regression, which is based on a different set of statistical assumptions and will therefore bias their analysis<sup>6</sup>. There are two ways to avoid this problem. First, simulated values can be computed using model I regression as Rykaczewski and Dunne<sup>3</sup> have done, but using parameters estimated from a model I regression of  $C_T$  and  $C_I$  matchups. Such model I analysis reveals that  $C_T$  values are lower on average than  $C_I$  ( $b = 0.83$ ;  $r^2 = 0.6$ ); hence the simulation should adjust  $C_T$  measurements downward rather than upward as Rykaczewski and Dunne<sup>3</sup> have done. Alternatively, simulated values can be computed using model II regression with the appropriate parameters of our fitted model<sup>1</sup>. The error introduced by application of an inappropriate model is further highlighted by the observation that the Chl trends simulated by Rykaczewski and Dunne (figure 2 in ref. 3) appear opposite to our results<sup>1</sup> across much of the ocean; for example, their simulated declines in coastal areas were not reproduced by our analyses (figure 2b in ref. 1). Furthermore, although Rykaczewski and Dunne<sup>3</sup> attribute Chl increases in the Indian Ocean to an increasing proportion of  $C_T$  measurements through time, we did not observe such a pattern in our database: like other regions, both Indian basins show a decreasing proportion of  $C_T$  and an increasing proportion of  $C_I$  measurements through time. By removing all Chl measurements collected in shelf regions (<200 m depth) the agreement between  $C_T$  and  $C_I$  was further improved ( $b = 1.016$ ,  $n = 11,329$  matchups). Re-fitting models to this filtered data set ( $n = 283,681$ ) did not alter the direction of trends in any of the regions examined, nor did it change the local trends, suggesting that the observed declines are robust. Lastly, our statistical models reproduced with high fidelity the well-known seasonal cycles of Chl in different regions and demonstrated clear coherence between Chl and leading climate indicators; this would not be expected if a systematic bias were confounding the data.

In a related comment, McQuatters *et al.*<sup>7</sup> claim that the removal of all  $C_T$  observations changes the trends to positive in the Atlantic and Pacific regions. We caution that comparing trends from  $C_T$  or  $C_I$  individually may be misleading, as the length of time series, spatial coverage and availability of data can be very different. However, estimating trends using only  $C_I$  measurements changed the Chl trend to positive in the South Atlantic ( $P = 0.10$ ; 73% of all measurements) and North Pacific ( $P < 0.05$ ; 26% of all measurements) regions only. Likewise, estimating trends since 1980 (as suggested by McQuatters *et al.*<sup>7</sup>) did not affect the direction of change in any of the Atlantic regions.

Furthermore, McQuatters *et al.*<sup>7</sup> present Continuous Plankton Recorder (CPR) colour index data indicating that phytoplankton abundance in the North Atlantic has increased rather than decreased, as we reported. However, there are important differences between the CPR data and those used in our analysis, which may explain some of the observed discrepancies. As McQuatters *et al.*<sup>7</sup> mention, the CPR retains the largest phytoplankton cells (>270  $\mu\text{m}$ ), and the vast majority of phytoplankton cells—which are much smaller—are not sampled quantitatively<sup>8</sup>. Thus a CPR-derived colour index may not be strictly comparable to direct Chl or transparency measurements. Additionally, the CPR data set almost exclusively contains measurements sampled north of 40° latitude (figure 1a in ref. 7) and many observations from inshore areas, which is contrary to our approach. The suggested phytoplankton increase across the Atlantic is also not supported by an independent analysis of *in situ* and satellite data collected over similar timescales<sup>9</sup>.

McQuatters *et al.*<sup>7</sup> also observe that some shorter-term (~20 yr) localized time series show increases rather than decreases in Chl. We do not dispute this but suggest that comparing such series to the longer-term (>50 yr), basin-scale trends we report may be misleading. Ours<sup>1</sup> and others<sup>10–13</sup> analyses demonstrate that large-scale, long-term data sets are needed to isolate low-frequency trends from the yearly to decadal fluctuations that are often driven by climate oscillations. Comparisons of ours and other long-term regional estimates indicate broad agreement<sup>5,9,14</sup>. Furthermore, as we included the cited BATS, HOTS and CalCOFI time series in our analysis, the important contributions that these data make are fully accounted for. As shown both in our paper (figure 2b in ref. 1), and in the CPR time series<sup>7,15</sup>, phytoplankton has increased in some areas and thus it should not be surprising that some time series reproduce this trend.

We welcome the critical suggestions offered by the authors and agree that the inter-calibration of different Chl measurement techniques is an ongoing and important topic. The above-mentioned requirement for long time series, the relatively low coverage of historic Chl measurements across the global oceans, and the multitude of available Chl measurement techniques necessitate the use of synthetic Chl time series for any global long-term analysis. Based on the extensive robustness analyses reported here and previously, we conclude that the observed global decline in Chl is independent of the data source used, and is not biased as a result of combining transparency and *in situ* data.

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# BRIEF COMMUNICATIONS ARISING

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