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[1], Mackas[2], Rykaczewski and Dunne[3], and McQuatters *et al.*[7] 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[4,5], 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)[5].

Mackas[2] and Rykaczewski and Dunne[3] 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[3] 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[6]. There are two ways to avoid this problem. First, simulated values can be computed using model I regression as Rykaczewski and Dunne[3] 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[3] have done. Alternatively, simulated values can be computed using model II regression with the appropriate parameters of our fitted model[1]. 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[1] 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[3] 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.*[7] 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.*[7]) did not affect the direction of change in any of the Atlantic regions.

Furthermore, McQuatters *et al.*[7] 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.*[7] mention, the CPR retains the largest phytoplankton cells (>270 μm), and the vast majority of phytoplankton cells—which are much smaller—are not sampled quantitatively[8]. 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[9].

McQuatters *et al.*[7] 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[1] and others'[10–13] 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[5,9,14]. 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[7,15], 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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