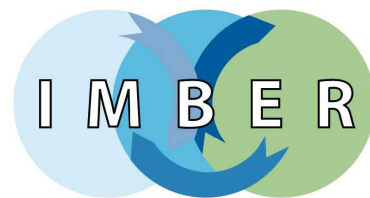


Time of emergence of trends in ocean biogeochemistry

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This is a time of change. The steady increase of anthropogenic CO₂ emissions leads to a rise in global temperatures and pushes the oceans towards acidification and, potentially, deoxygenation (Bopp et al. 2013; Cocco et al. 2013). One way to quantify these changes is to estimate the magnitude of a trend. Another relevant characteristic is the time period needed for the trend signal to first be detected. The latter has important implications for society, as it sets the pace for adaption and mitigation measures. However, it is not always clear if an observed trend is representative of the long-term evolution of the climate-carbon system, or if it is just an imprint of short-term fluctuations attributable to natural variability; an illustrative example is the current debate about the "hiatus".

The detection of forced trends in biogeochemical cycles and ecosystems is challenging. This is particularly so in the ocean, where observations are scarce and limited in either time or space. A major issue is the presence of natural variability related to, e.g., volcanic eruptions (Frölicher et al. 2011) or climate modes such as the North Atlantic Oscillation (Keller et al. 2012) or El Niño-Southern Oscillation (ENSO; Keller et al. in prep). This variability has the potential to enhance or mask trends over decadal timescales. Successful detection of trend signals is thus a signal-to-noise (S/N) issue, i.e., the signal has to be of a magnitude that enduringly exceeds the envelope of background variability. One possible measure to estimate this is the time of emergence (ToE; Hawkins and Sutton, 2012) of a signal, that is, the time at which the S/N ratio exceeds a certain threshold. Thus, ToE is indicative of the time required for the anthropogenic trend to leave the variability band. This must not be confused with the period required to detect this trend in observational or model data.

ToE and related methods have been applied in a number of model studies focusing on ocean acidification indicators such as pH, surface total alkalinity or the saturation state of aragonite (Ilyina et al. 2009; Ilyina and Zeebe, 2012; Friedrich et al. 2012; Mora et al. 2013; Hauri et al. 2013). The implementation of ToE differs between studies; a common approach is the comparison of modelled noise (usually the standard deviation of an unforced control simulation) and observed or modelled trends. Note that the choice of datasets and the definition of thresholds have implications for the robustness of results (see Mora et al. (2013) and the corresponding comment by Hawkins et al. (2014)).

In a recent study (Keller et al. 2014), we use a model ensemble of 17 MSMs to investigate the ToE of trends in surface ocean biogeochemistry. For maximum comparability with the available observations, we focus on three frequently measured carbon cycle variables, dissolved inorganic carbon (DIC), pCO₂ and pH, and sea-surface temperature (SST) on the local (grid cell) scale. We use historical simulations covering the years 1870-1999 with annual resolution. ToE is defined as:

$$\text{ToE} = (2 \times N) / S$$

where S is the trend and N a measure of variability. S and N are defined as the linear trend (per year) over the period 1970-1999 and the standard deviation of the (detrended) years 1870-1999, respectively. See Fig. 14 for an illustration.

Fig. 15 shows the ensemble mean ToE patterns of DIC, pCO₂, pH and SST, all variables at the surface. We find that trend signals in the three carbon cycle variables emerge on much shorter timescales than the physical climate variable SST. The ToE pattern of SST is very noisy, varying typically between 45 and 90 years (yr). The exceptions are areas around the equator in the Atlantic, Indian and western Pacific Oceans, that have values of approximately 35 yr. A large coherent area with ToE > 80 yr in the (eastern) equatorial Pacific can be attributed to high levels of variability linked to ENSO. The linear trend in DIC appears in large parts of the global oceans after approximately 10–30 yr; higher values are found at high latitudes, especially in the Arctic Ocean (≈ 50 yr), and localized in the equatorial Pacific (up to ≈ 70 yr). ToE of pCO₂ and pH show a very similar pattern. However, the trends emerge much faster for pCO₂ and pH than for DIC: after ≈ 12 yr for the majority of the global ocean area, 14–18 yr in the Arctic Ocean and ≈ 20 yr in the equatorial Pacific. A likely reason for these different timescales of DIC and pH/pCO₂ are nonlinear processes in ocean chemistry described by the buffer factor (or Revelle factor; Revelle and Suess, 1957), which result in increases of pCO₂ of approximately 10 times the magnitude of the corresponding relative increases in DIC. In contrast to DIC, relatively high ToE values are found for both pCO₂ and pH in the Southern Ocean and in the upwelling region off Peru and Chile (in both regions, localized > 30 yr).

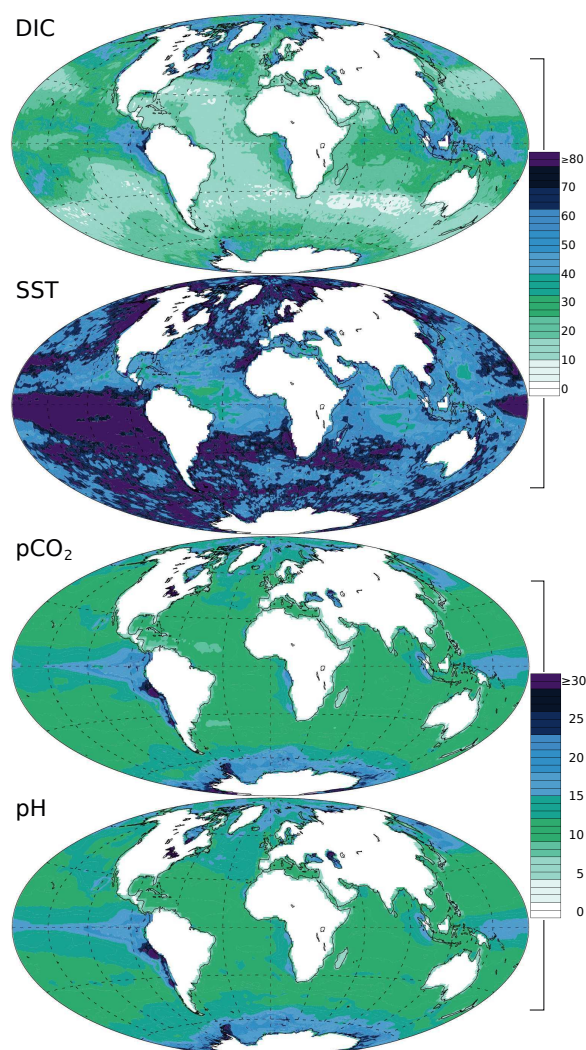


Figure 15. Ensemble mean ToE (years) of DIC, SST, pCO₂, and total pH - all variables at the surface level. Note the different scales for DIC/SST and pCO₂/pH. The trend signal is detectable much earlier on the grid cell scale for pCO₂ and pH than for SST and DIC.

We find that, in general, the standard deviation is of greater importance in determining ToE than the strength of the linear trend. In areas with high natural variability, even strong trends in both the physical climate and carbon cycle system are masked by variability over decadal timescales. This explains inconsistencies in trends based on time series of insufficient length and illustrates the necessity for long-term observations. Considering the changes since the beginning of industrialization, the rapid emergence of trend signals implies that anthropogenic trends in the surface ocean carbon cycle are already detectable in large parts of the global oceans. This finding is even more relevant as the highest rates of ocean acidification are measured (Bates, 2012; Dore et al. 2009) and modelled (Resplandy et al. 2013) in subsurface waters. A further finding of the study is that, in contrast to the trend, standard deviation is affected by the seasonal cycle. This has important implications for the use of scarce observations. In some parts of the global oceans, there are hints that statements based on irregularly sampled seasonal data are representative for the whole year. In large areas however, especially in the high latitudes, intra-annual variability could interfere with such a generalization.

The study clearly illustrates the need for more long-term measurements with sufficient seasonal data coverage. In particular, global data sets describing the space-time variability of biogeochemical variables over adequate timescales are largely absent. DIC is a very important variable and crucial for our understanding of biogeochemical processes. Solely for the detection of anthropogenic trends, however, $p\text{CO}_2$ and pH seem to be a better choice. Further, not only observations are necessary for the correct detection of trends. Independent data sets are also key for the realistic forcing and evaluation of climate models which are, due to the current scarcity of observations, the measure of choice for many research questions.

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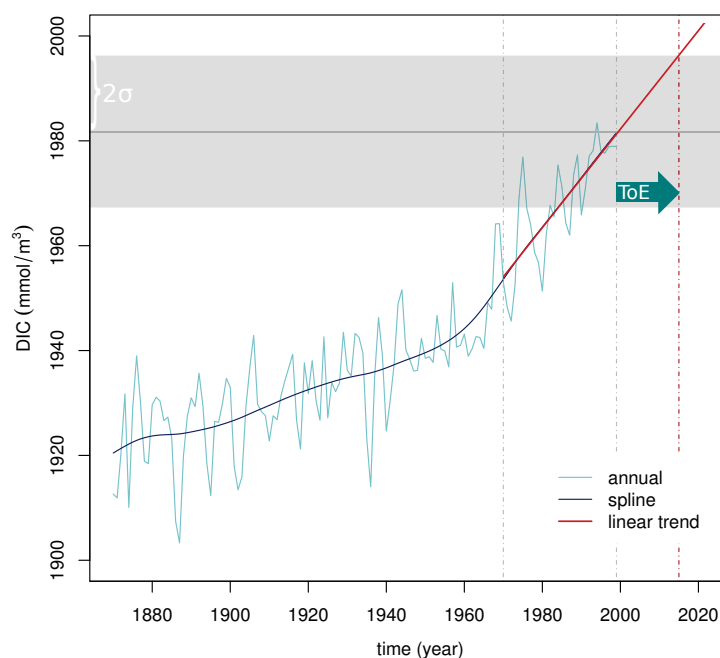


Figure 14. An illustration of ToE based on the model CESM1: Annual time series (light blue), corresponding smoothing spline (dark blue), and linear trend (red) of DIC at 22°N, 158°W. The grey bar represents two times the standard deviation of the detrended time series (i.e., annual-spline). The linear trend is based on the years 1970–1999 of annual resolution, as indicated by the grey vertical lines. The intersection of the red vertical line and the upper border of the grey bar ($x = 2015$) shows when the trend leaves the envelope of background variability and, from then on, is detectable. Consequently, the ToE at this location is 16 years (2015–1999).