Their final critique is that we did not comment on deficiencies in greenhouse gas accounting rules that were exposed by our analysis. This would be a fair point if the object of the article was to explore the strengths and weakness of relevant accounting frameworks. However, it was not — it was to illustrate the relevance of the different types of policy institutions to forest-related LCA.

The real issue of substance in their Correspondence is the assertion that our analysis is deficient because we assume the effects of policy institutions on emissions rather than empirically analysing them. The point of difference is best illustrated with a hypothetical case involving a cessation of forest harvesting, which displaces production to a sector covered by a capped emissions trading scheme (ETS).

Our position is that, in a CLCA concerned only with net emission outcomes, it is sufficient to assume the ETS functions as intended, meaning the change in forest management should have no effect on the net emissions under the scheme. After harvesting stops, and production and emissions in the capped sector increase, the operation of the ETS should ensure the emission increase is fully offset by reductions elsewhere. Cowie *et al.* argue this is wrong because the effects on emissions should be based on empirical analysis.

The difference in perspectives is, in our view, a product of different method preferences. Cowie *et al.* favour attributional life-cycle assessment (ALCA), which assigns emissions to relevant products and systems using data on average physical flows of materials and energy[1–7]. Because ALCA is backward looking — as it provides a historical estimate of average emissions from a process or technology — it is inappropriate to assume effects without empirical evidence. An ALCA on our hypothetical case would also exclude the effects of the ETS because the focus would be on how to apportion emissions to the wood and non-wood production systems.

We believe CLCAs are preferable for public policy-making[8–10]. In CLCA, the objective is to assess how emissions are likely to change in response to a decision; here, the change in emissions triggered by the change in forest management practices[1,3,8–12].

CLCA's future orientation means that assumptions must be made about a number of variables, including policy institutions. Historical data are relevant only to the extent that they provide a reasonable basis for projecting the change in emissions from the relevant management decision.

Consistent with this, a CLCA on the hypothetical change in forest management would have to consider the ETS because it is designed to shape emissions outcomes by changing incentives at the margin[1,8,9]. It should ensure that the increase in emissions within the boundaries of the scheme are fully offset. When Cowie *et al.* say that, according to our approach, "any renewable option could be disregarded as non-beneficial," they allude to this point. Only, it is not that the alternative renewable options are 'non-beneficial', it is that the policy institution is the driver of the emission outcome.

Of course, alternative assumptions could plausibly be made about the effects of the ETS but they would still be assumptions. Cowie and colleagues' argument that it is inappropriate to simply assume the effects of policy institutions in a CLCA is the equivalent of telling an economic forecaster they cannot make assumptions about how economic policy might change in the future. An inevitable aspect of all activities involving forward-looking projections is that assumptions must be made about what the future holds. ❐

References

1. Weidema, B. *Market Information in Life Cycle Assessment* (Danish Environmental Protection Agency, 2003).
2. Milà i Canals, L. *et al.* Key elements in a framework for land use impact assessment within LCA. *Int. J. Life Cycle Assess.* **12,** 5–15 (2007).
3. Finnveden, G. *et al.* Recent developments in life cycle assessment. *J. Environ. Manage.* **91,** 1–21 (2009).
4. Helin, T., Sokka, L., Soimakallio, S., Pingoud, K. & Pajula, T. Approaches for inclusion of forest carbon cycle in life cycle assessment — a review. *GCB Bioenergy* **5,** 475–486 (2013).
5. Marland, G. & Schlamadinger, B. Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. *Biomass Bioenergy* **13,** 389–397 (1997).
6. Ximenes, F., George, B., Cowie, A., Williams, J. & Kelly, G. Greenhouse gas balance of native forests in New South Wales, Australia. *Forests* **3,** 653–683 (2012).
7. Lamers, P., Junginger, M., Dymond, C. C. & Faaij, A. Damaged forests provide an opportunity to mitigate climate change. *GCB Bioenergy* **6,** 44–60 (2014).
8. Ekvall, T. & Weidema, B. System boundaries and input data in consequential life cycle inventory analysis. *Int. J. Life Cycle Assess.* **9,** 161–171 (2004).
9. Bento, A. & Klotz, R. Climate policy decisions require policy-based lifecycle analysis. *Environ. Sci. Technol.* **48,** 5379–5387 (2014).
10. Plevin, R., Delucchi, M. & Creutzig, F. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *J. Ind. Ecol.* **18,** 73–83 (2014).
11. Weidema, B., Frees, N. & Nielsen, A.-M. Marginal production technologies for life cycle inventories. *Int J. Life Cycle Assess.* **4,** 48–56 (1999).
12. Earles J. & Halog, A. Consequential life cycle assessment: a review. *Int J. Life Cycle Assess.* **16,** 445–453 (2011).

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COMMENTARY:

El Niño and a record CO_2 rise

Richard A. Betts, Chris D. Jones, Jeff R. Knight, Ralph F. Keeling and John J. Kennedy

The recent El Niño event has elevated the rise in CO_2 concentration this year. Here, using emissions, sea surface temperature data and a climate model, we forecast that the CO_2 concentration at Mauna Loa will for the first time remain above 400 ppm all year, and hence for our lifetimes.

The long-term rise in atmospheric CO_2 concentration, approximately 2.1 ppm yr^{-1} over the past decade, is caused by anthropogenic emissions arising from fossil fuel burning, deforestation and cement production[1,2]. The annual growth rate, however, varies considerably as a result of climate variability affecting the relative strength of land and ocean carbon sources and sinks. The annual growth rate measured at Mauna Loa, Hawaii[3,4] is correlated with the El Niño–Southern Oscillation (ENSO), with more rapid growth associated with El Niño events[5–9] through drying of tropical land regions and forest fires. To test the predictive value of this relationship, we present a forecast, made in October 2015, of the CO_2

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concentrations throughout 2016 based on the relationship, and verify against observations available so far. We predict the monthly mean CO_2 concentration at Mauna Loa to remain above 400 ppm even in its annual minimum in September, which would not have been expected without the 2015–2016 El Niño.

The annual mean Mauna Loa CO_2 concentration for 2015 was 400.9 ppm (ref. 3), making 2015 the first year with an annual mean above 400 ppm. The annual growth rate between 2014 and 2015 was 2.27 ppm. The largest annual mean growth rate on record is 2.9 ppm yr^{-1} in 1997–1998 (Fig. 1a), the period of a large El Niño event (Fig. 1b), during which the November–January sea surface temperature (SST) anomaly in the Niño 3.4 region (5° N–5° S, 170° W–120° W) of the equatorial Pacific was 2.38 ± 0.30 °C (ref. 10).

Historically there have been markedly large annual CO_2 growth rates in El Niño years (Fig. 1), probably due to warming and drying of tropical land areas resulting in reduced carbon uptake by vegetation growth, increased carbon release by fire and drought-induced tree mortality. In 1997, dry conditions in Indonesia and Malaysia allowed human-ignited fires to escape control and ignite carbon-rich peatlands, which continued to burn for some months. An estimated 0.81 to 2.57 GtC were emitted to the atmosphere as a result[11], equivalent to 13–40% of global annual mean carbon emissions from fossil fuels at that time and hence a substantial contribution to the anomalously large CO_2 growth rate that year[12]. During La Niña events, when the equatorial Pacific is colder than average, the annual CO_2 growth rate is slower.

The recent El Niño, now in its declining phase, was comparable with the 1997–1998 event in some respects. Although maximum SSTs were cooler in the eastern tropical Pacific, the Niño 3.4 index was 2.6 ± 0.30 °C over November 2015 to January 2016 (larger than November 1997 to January 1998) and most tropical land regions were again anomalously dry. Once again, drought conditions allowed human-caused fires in Indonesia to burn large areas. Estimates for 2015 suggest that the total greenhouse gas emissions from these fires is equivalent to 0.4 GtC, with large uncertainty — less than those in 1997[13], but still larger than for non-El Niño years.

A multiple linear regression (Equation 1; Fig. 2) has previously been used[8,9] to reconstruct the annual CO_2 growth rate (ΔCO_2) on the basis of anthropogenic emissions (ε) and the SST anomaly (N) in the relevant region of the Pacific over the preceding April to March.

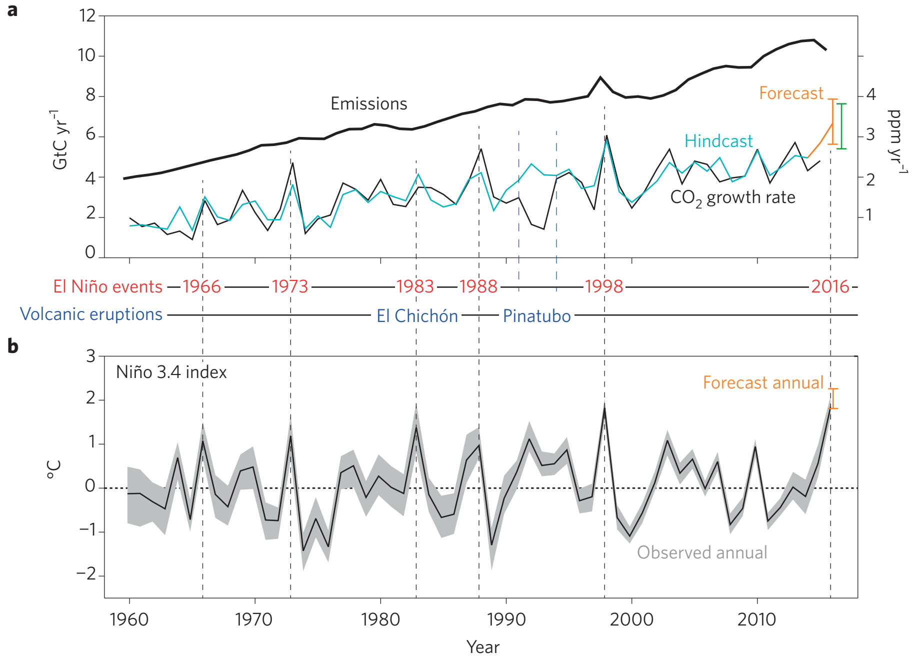

Figure 1 | Identifying, testing and forecasting the relationship between Niño 3.4 SST anomalies and Mauna Loa CO_2 growth rates. **a**, Anthropogenic CO_2 emissions (thick black line); CO_2 growth rate from observations (thin black line), reconstructed from regression against emissions and Niño 3.4 anomaly before 2015 (blue line) and forecast for 2016 using the forecast annual mean SST as of October 2015 (orange line and bar) and observed annual mean SST as of April 2016 (green bar). **b**, Annual (April to March) mean SST anomalies in the Niño 3.4 region from the HadSST3 ensemble of homogenized observations (grey shading) and its median (black line), with the forecast final annual mean from HadSST3 observations from 1st April to 31st October combined with GloSea5 forecast SSTs for 1st November 2015 to 30th March 2016 (orange bar). See Supplementary Information for more details.

$$\Delta CO_2 = \alpha_1 + \alpha_2 N + \alpha_3 \varepsilon \qquad (1)$$

This provides an opportunity to test the predictability of atmospheric CO_2 using understanding and forecast capability from two components of the Earth system, the carbon cycle and the oceans. The CO_2 concentration for a calendar year can be predicted from observed SSTs, and the forecast period can potentially be extended further into the future as SSTs are predictable several months in advance using coupled ocean–atmosphere climate models. To test this, we present a prediction of the annual CO_2 growth rate and annual maximum and minimum concentrations for 2016. We use observed SSTs between 1st April and 30th September 2015[10] and simulated SSTs from the GloSea5 global seasonal forecasting system for 1st October 2015 to 31st March 2016[14]. We apply the resulting annual mean Niño 3.4 SST anomaly of 2.02 ± 0.23 °C in Equation 1 to forecast the annual mean rise in CO_2 in 2016, and hence the average CO_2 concentration for the year. The use of previously forecast SSTs for the last 6 months provides a test of predictability of the CO_2 concentration further ahead of time and throughout a whole calendar year. We also forecast the annual maximum and minimum monthly CO_2 concentration, by assuming that the seasonal cycle is of the same shape and amplitude as the previous five years and applying this to the predicted annual mean.

First time above 400 ppm all year

Using the regression, we forecast an annual mean CO_2 growth rate of 3.15 ± 0.53 ppm yr^{-1} between 2015 and 2016 (Fig. 1a). This will be the highest annual growth rate on record, and implies an annual mean CO_2 concentration at Mauna Loa of 404.45 ± 0.53 ppm. For comparison, persistence of the last decade's mean growth rate of 2.1 ± 0.1 ppm yr^{-1} from the 2015 value of 400.9 ppm would have suggested a concentration of 402.9–403.1 ppm. The processes related to the El Niño are therefore estimated to contribute approximately

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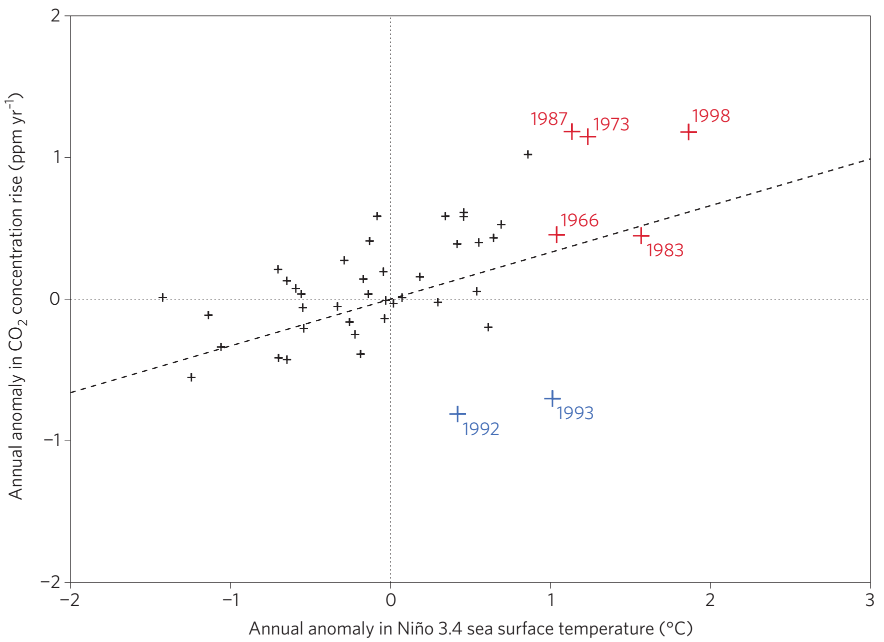

Figure 2 | CO_2 growth rate (minus anthropogenic emissions component) versus Niño 3.4 anomaly[9]. Red crosses show El Niño years and blue crosses show years affected by the Mount Pinatubo eruption, which led to a temporary global cooling.

an additional 1 ppm to this year's CO_2 growth rate.

A point of interest is the passing of 400 ppm in the Mauna Loa record. Although there is nothing physically significant about this concentration, it has recently become an iconic milestone in popular discourse regarding the ongoing rise in atmospheric CO_2 (for example, ref. 15). In the last two years, CO_2 has fluctuated around 400 ppm through the annual cycle, which has amplitude of approximately 6–7 ppm at Mauna Loa. 2014 was the first year that monthly CO_2 concentrations rose above 400 ppm, and in 2015 the annual mean concentration has passed 400 ppm for the first time, but the monthly mean concentration fell back below 400 ppm for three months at the end of the boreal summer, reaching a monthly mean of 397.50 ppm in September. Adding the recent mean growth rate of 2.1 ppm yr^{-1} to this value would suggest a 2016 September concentration of 399.60 ppm. However, on the basis of the observed and forecast Niño 3.4 SSTs as of November 2015, we predict a Mauna Loa CO_2 concentration in September 2016 of 401.48 ± 0.53 ppm (Fig. 3).

Could daily CO_2 concentrations fall below 400 ppm? In 2015, the lowest daily value at Mauna Loa was 396.23 ppm (see Supplementary Information), that is 1.27 ppm below the September mean. Assuming stationarity in the distribution of daily values around the monthly mean, the lowest daily CO_2 concentration at Mauna Loa could be between 399.45 and 401.05 ppm. Therefore the daily values will be most likely to stay above 400 ppm, although values slightly below remain a small possibility.

At higher northern latitudes, the seasonal cycle of CO_2 is of larger amplitude due to a stronger influence of the nearby large land masses and their seasonal vegetation cover. Therefore CO_2 concentrations below 400 ppm are expected in late summer this year and a few subsequent years (see Supplementary Information). However, as the global and local mean concentrations continue to rise, even these locations will soon pass the 400 ppm threshold.

Our forecast, valid from October 2015, is verifiable by comparison with the two independent routine measurements of CO_2 concentrations at Mauna Loa[3,4]. The forecast will be considered a success if the 2016 annual mean CO_2 concentration is measured as between 403.92 and 404.98 ppm. It is important to note that growth rate anomalies of 0.6 ppm yr^{-1} above the emissions-based rate still occurred in a year with small positive Niño 3.4 anomaly and even in a year with a small negative anomaly (Fig. 2). Therefore the 2015–2016 growth rate would need to be greater than 2.7 ppm yr^{-1} in order for the forecast to be convincingly distinguishable from what could be expected from the trend plus variability unrelated to ENSO. Concentrations of 403.6 ppm or below could have been expected without knowledge of the El Niño. Concentrations higher than the upper end of our uncertainty range may indicate unexpected non-linearities in the relationship. Indeed, as the forecast relies on extrapolating an empirical relationship outside of its calibration range, this comparison could provide important new data in developing understanding.

Our method predicted an annual maximum monthly mean of 407.57 ± 0.53 ppm in May; and 406.70 ± 0.53 ppm for April. The observed CO_2 concentration for April was 407.57 ppm so the method slightly underestimated the concentration for that month, although this was not the case in the first three months of the year (Fig. 3b). The concentration in April 2015 was 403.45 ppm, but although the 4.12 ppm increase over the 12 months to April 2016 is a clear indicator of a large annual growth rate this year, it may not be representative of the precise annual mean value. Data available at the time of going to press indicate that the mean concentration in May 2016 is similar to that in April.

The observed annual mean Niño 3.4 anomaly of 1.85 ± 0.20 °C (range: 1.61–2.09) was smaller than the combined hindcast and forecast of 2.02 ± 0.23 °C (range: 1.81–2.26) but with a good overlap of the range. Using this in Equation 1 provides an updated growth rate forecast of 3.08 ppm yr^{-1} (Fig.1a, green bar), 0.1 ppm yr^{-1} smaller than our original forecast, suggesting an annual mean CO_2 concentration of 404.39 ± 0.53 ppm with maximum and minimum values also 0.1 ppm lower than the original forecast. This update, obtained with hindsight, therefore results in only a comparatively small change.

Natural versus anthropogenic effects

An important point is that the record annual rise in annual mean CO_2 concentration is expected despite the estimate of a small fall in documented global CO_2 emissions in 2015 compared to 2014[16]. The 2016 growth rate is forecast to be larger than recent years because of the effect of the current El Niño. It is also forecast to be larger than that following the previous large El Niño in 1997–1998, mainly because anthropogenic emissions have themselves risen since that time — 10.3 GtC in 2015, compared to 8.2 GtC in 1997. The El Niño contribution itself may not be entirely free of anthropogenic influence — with additional emissions from forest fires, set as part of forest clearance[17]. Indonesian fires, attributable to human action, could

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contribute approximately 0.2 ppm of the El Niño-related additional 1 ppm CO_2 rise. Therefore there may be scope to reduce the anomalously high growth rate in El Niño years, by around 20%, by eliminating the use of fire for forest clearance in this region. Quantifying this direct anthropogenic contribution to the El Niño-related emissions with confidence would be challenging, but we suggest it would be an important avenue for future research with clear implications for understanding a potential contribution to climate change mitigation.

With the current El Niño in decline and many models predicting a switch to La Niña conditions, the CO_2 growth rate can be expected to fall again next year. The record CO_2 growth rate this year will therefore be short-lived, and is too small in itself to induce a noticeable effect on climate. Nevertheless, it illustrates the two-way interactions between climate change and the carbon cycle, and the potential for feedbacks on anthropogenic climate change if this involves changes in temperature and precipitation affecting ecosystems. Loss of tropical forests plays a role in some Earth system model projections of enhanced CO_2 rise[18], although diverging model results currently leads to low confidence in specific changes in ENSO behaviour under climate change[19]. If the relationship between ENSO and CO_2 growth rate is robust enough to inform good forecasts of CO_2 concentrations, the ability to reproduce this may provide a useful benchmark for evaluating the emergent behaviour of Earth system models[20].

With the growth rate expected to reduce again after the El Niño, could the annual minimum CO_2 concentration fall back below 400 ppm again next year or further in the future? This is exceptionally unlikely. In the instrumental record that covers the last half-century, annual growth rate has always been positive as a result of ongoing anthropogenic emissions, and the amplitude of the seasonal cycle has not varied substantially. Both the annual mean and September minimum CO_2 concentrations have therefore increased year on year. This was the case even in years with large La Niña events or major volcanic eruptions that temporarily caused cooling and greater net uptake of CO_2 by the biosphere, resulting in smaller, but still positive growth (Fig. 1a). For example, in the large La Niña in 1999–2000, the growth rate remained above 1ppm yr^{-1}. Unless a very large volcanic eruption injects substantial quantities of aerosol into the stratosphere, we would expect concentrations continue to rise further above 400 ppm in the next few years.

In the longer term, a reduction in CO_2 concentration would require substantial and sustained cuts in anthropogenic emissions to near zero. Even the lowest emissions/concentrations scenario assessed in the IPCC Fifth Assessment Report projects CO_2 concentrations to remain above 400 ppm until 2150. This scenario, RCP2.6[21], is considered amongst the lowest credible emissions scenario, and relies on assumed development of 'negative emissions' methods whose potential is considered limited[22]. Indeed some argue that RCP2.6 is now beyond reach without radical changes in global society[23]. Hence our forecast supports the suggestion[24] that the Mauna Loa record will never again show CO_2 concentrations below the symbolic 400 ppm within our lifetimes. ❐

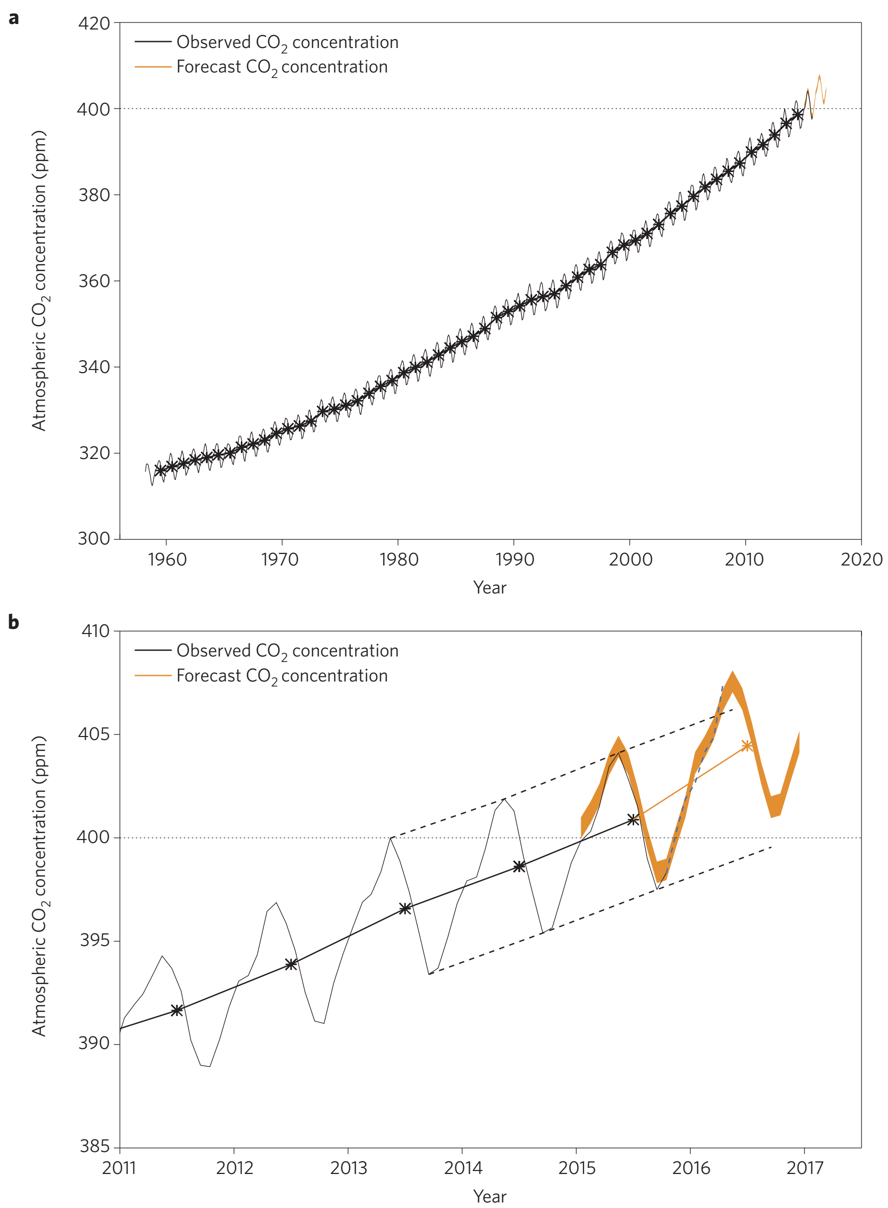

Figure 3 | Observed and forecast CO_2 concentrations at Mauna Loa. **a**, Monthly mean CO_2 concentrations, observed from 1957 to 2015 (black line) and hindcast/forecast for 2015 and 2016 (orange line). **b**, As in a but since 2010, also with observed and hindcast/forecast annual mean concentrations (black and orange stars and central solid lines) and the linear extrapolation of trends in annual maximum and minimum monthly values from previous years (dashed black lines) to indicate expected changes in the absence of El Niño. The width of the orange shading shows the uncertainty in hindcast/forecast CO_2 concentration, given as two standard devations from the mean.

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References

1. Ciais, P. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 6 (IPCC, Cambridge Univ. Press, 2013).
2. Le Quéré, C. *et al. Earth Syst. Sci. Data* **7,** 349–396 (2015).
3. Keeling, C. D. *et al.* in *A History of Atmospheric CO_2 and its Effects on Animals, Plants, and Ecosystems* (eds Ehleringer, J. R., Cerling, T. E. & Dearing, M. D.) Ch. 5 (Scripps Institution of Oceanography, 2001).
4. Thoning, K. W., Tans, P. P. & Komhyr, W. D. *J. Geophys. Res.* **94,** 8549–8565 (1989).
5. Bacastow, R. B. *Nature* **261,** 116–118 (1976).
6. Bacastow, R. B. *et al. Science* **210,** 66–68 (1980).
7. Keeling, C. D., Whorf, T. P., Whalen, M. & van der Plicht, J. *Nature* **375,** 666–670 (1995).
8. Jones, C. D., Collins, M., Cox, P. M. & Spall, S. A. *J. Clim.* **14,** 4113–4129 (2001).
9. Jones, C. D. & Cox, P. M. *Geophys. Res. Lett.* **32,** L14816 (2005).
10. Kennedy, J. J., Rayner, N. A., Smith, R. O., Saunby, M. & Parker, D. E. *J. Geophys. Res.* **116,** D14104 (2011).
11. Page, S. E. *et al. Nature* **420,** 61–65 (2002).
12. Langmann, B. & Heil, A. *Atmos. Chem. Phys.* **4,** 2145–2160 (2004).
13. *Global Fire Emissions Database* (Global Fire Data, accessed 27 May 2016); http://globalfiredata.org
14. MacLachlan, C. *et al. Q. J. R. Meteorol. Soc.* **141,** 1072–1084 (2014).
15. Howard, B. C. Northern hemisphere cracks 400 ppm CO_2 for whole month for first time. *National Geographic* (May 27 2014); http://go.nature.com/1spge8j
16. Jackson, R. B. *et al. Nature Clim. Change* **6,** 7–10 (2016).
17. Field, R. D., van der Werf, G. R. & Shen, S. S. P. *Nature Geosci.* **2,** 185–188 (2009).
18. Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. & Totterdell, I. J. *Nature* **408,** 184–187 (2000).
19. Collins, M. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 12 (IPCC, Cambridge Univ. Press, 2013).
20. Cox, P. M. *et al. Nature* **494,** 341–345 (2013).
21. van Vuuren, D. *et al. Climatic Change* **109,** 95–116 (2011).
22. Smith, P. *et al. Nature Clim. Change* **6,** 42–50 (2016).
23. Anderson, K. *Nature Geosci.* **8,** 898–900 (2015).
24. Keeling, R. F. Is this the last year below 400? *The Keeling Curve* (21 October 2015); http://go.nature.com/1X2gXc1

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Additional information

Supplementary information is available in the online version of the paper. Correspondence and requests for materials should be addressed to R.A.B.

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COMMENTARY:

Earth's surface water change over the past 30 years

Gennadii Donchyts, Fedor Baart, Hessel Winsemius, Noel Gorelick, Jaap Kwadijk and Nick van de Giesen

Earth's surface gained 115,000 km^2 of water and 173,000 km^2 of land over the past 30 years, including 20,135 km^2 of water and 33,700 km^2 of land in coastal areas. Here, we analyse the gains and losses through the Deltares Aqua Monitor — an open tool that detects land and water changes around the globe.

Changes from land to water and vice versa are extremely relevant as witnessed by many recent news items: the President of Kiribati declared that his people would need to move to new grounds to prevent them from dying from the effects of sea-level rise on the atoll[1]; the impoundment of the Three Gorges Dam in China is causing massive inundations, forcing about 1.3 million people to resettle[2]; new islands along the coast of Dubai are created to provide new secluded areas for leisure and residence for the wealthy; and finally, the Mississippi Delta is losing thousands of hectares of land per year due to soil subsidence and lack of sediments[3], further aggravated by sea-level rise.

The causality of appearing or disappearing water surfaces may strongly depend on the case-specific context. Although atolls, such as Kiribati, are under severe threat, the exact effects of sea-level rise on coastal erosion, globally, may strongly depend on biophysical interactions as well, particularly in coastal marshes[4], as atolls may increase accretion rates as sea-level rise progresses[5]. The impoundment of the Three Gorges Dam has resulted in a reduction in sediment concentrations in the downstream Yangtze River of about 70%. Unexpectedly, this reduction has not led to a retreat of the downstream submerged Yangtze River Delta so far[6], contrasting what happens in the Mississippi Delta.

These examples demonstrate that conversions — and the stories and reasons behind them — can vary widely and are often the result of compounding causes. Therefore, general conclusions cannot be drawn from a limited sample of case studies. Instead, planetary-scale monitoring is needed to understand (and disentangle) the causes of detected changes and their attribution to natural variability, climate change or man-made change. Until now, such monitoring and estimates of land–water conversions were not feasible.

The massive growth in satellite data has resulted in a severe demand in storage, computation and smart analytics to enable analysis of planetary-scale data. Until recently, such analyses were performed by highly specialized scientists and engineers, and on a case-by-case basis. New cloud platforms for large satellite data analysis, such as Google Earth Engine (http://earthengine.google.com), rapidly remove thresholds to use planetary-scale data[7,8]. These platforms provide access to a plethora of satellite information in three ways: (1) storage of satellite data in the cloud; (2) provision of computational resources; and (3) availability of analytical tools to process data into a clear end product.

The Deltares Aqua Monitor (http://aqua-monitor.deltares.nl) is the first global-scale tool that shows at 30-m resolution where water is converted to land and vice versa. With assistance from Google Earth Engine, it analyses satellite imagery from multiple Landsat missions, which observed Earth for more than three decades on the fly. The Aqua Monitor provides a much needed[9], fully planetary-scale view on

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