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Indications of positive feedback in climate change due to a reduction in Northern Hemisphere biomass uptake of atmospheric carbon dioxide

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Introduction

Measurements of atmospheric carbon dioxide (CO_2) concentration have been made at the Mauna Loa Observatory in Hawaii since 1958. Due to its mid-ocean isolation and its location near the equator, the Observatory is regarded as providing the most representative single and continuous record of mean concentration of CO_2 for the whole planet. The observed upward trend in the time-series plot is the well-known Keeling curve (Keeling, 2008) which is often credited with being the fundamental evidence that has led scientists, pressure groups, civic society and politicians to take increasing CO_2 and its attendant climate change increasingly seriously.

From the earliest records it was recognised that there is a significant intra-annual fluctuation in CO_2 concentration which is widely assumed (Keeling and Whorf, 2004) to be caused by the differential uptake of CO_2 by the much larger landmass, and therefore biomass, of the Northern Hemisphere during its summer period, compared with the equivalent uptake during the Southern Hemisphere summer. This behaviour is evident in the weekly atmospheric CO_2 data (Figure 1) from the Mauna Loa observatory from 1958 to 2015 (Scripps Institution of Oceanography, 2015). The drop in CO_2 concentration is typically of 4 months' duration (equivalent to 0.33 of a year), between May and September each year, followed by a lengthier and greater rise during the Northern Hemisphere autumn, winter and early spring. This paper explores the behaviour of the drop over the past 57 years, which gives an indication as to how the planetary biosphere is reacting to various impacts including climate change itself.

The reaction of the planetary biosphere is important because it provides the only mechanism for taking man-made CO_2 back out of the atmosphere and locking it up, or sequestering it. Over geological time periods CO_2 has been absorbed from the atmosphere, or from its dissolved form in the oceans, into plants and animals which have then been turned into chalk, limestone, coal, lignite, oil and natural gas. This process con-

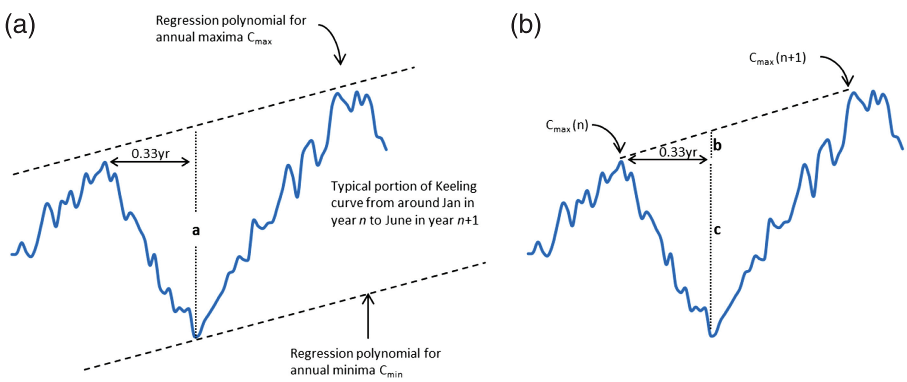

Figure 1. (a) Intra-annual drop in year n corresponds to the line labelled 'a', the difference between regression values C_{max}(n + 0.33) and C_{min}(n); (b) Intra-annual drop in year n corresponds with the line 'b + c' where b = (C_{max}(n + 1) – C_{max}(n))/3 and c is taken from observed data.

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tinues, and CO_2 is currently being absorbed by natural vegetation which then locks carbon, for example, into tree trunks or feeds carbon-based compounds down into roots and soil. Additionally, dead plant material can be stored long-term under the anaerobic conditions which prevail in peat deposits or in sediments in rivers, lakes or seas. Dying oceanic plankton also carry significant amounts of carbon in their exoskeletons as they settle and accumulate on ocean floors.

Currently around half of man-made emitted CO_2 remains in the atmosphere, while the other half is absorbed by the ocean and vegetation. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) provides a good summary of how it is expected that ecosystems may respond to future climate change. It is generally thought that they will dampen climate change by becoming more active, or productive, due to CO_2 fertilisation and higher temperatures. However, this net carbon exchange of terrestrial ecosystems is expected to contribute increasing sequestration only up until around 2030, when it may well peak. Thereafter, ecosystems could become damaged, due to their inability to respond to the rapidity and extent of the changing climate, their productivity could begin to decline and, indeed, they could become net carbon emitters towards the end of the twenty-first century. This outcome would be potentially very serious as the planet itself would then be contributing CO_2 and further adding to the continuing man-made CO_2 emissions in the atmosphere. This is when there is a risk of such positive feedback creating runaway climate change.

However, there are many unknowns, and ecosystems could respond in nonlinear ways and could indeed experience more rapid transitions, or even collapses, to lower biomass and productivity states. This paper explores evidence from analysis of the Keeling curve that the Northern Hemisphere biosphere may already have peaked in its ability to sequester CO_2.

Time series analysis

It is well understood that continuing man-made emissions to the atmosphere (US Department of Energy, 2015) are steadily increasing the underlying CO_2 concentrations in the Earth's atmosphere, and that the intra-annual fluctuation, driven by biomass, is entirely independent. This allows, as a first order approximation, analysis of the trend in intra-annual CO_2 drop to provide an indication of the absolute and relative activity of Northern Hemisphere bioaccumulation. There are two ways to estimate the trend in intra-annual drop: regression of annual maxima/minima (Figure 1(a)) or estimation of difference, followed by regression (Figure 1(b)).

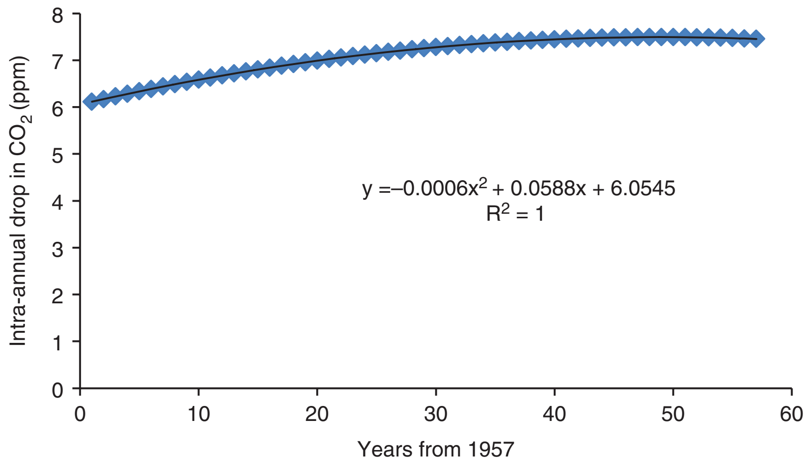

Figure 2. Magnitude of the intra-annual drop in CO_2 derived from regression forecasts of C_{min} and C_{max} with a timeshift of 0.33 years. The peak occurs at n = 49, or year 2006.

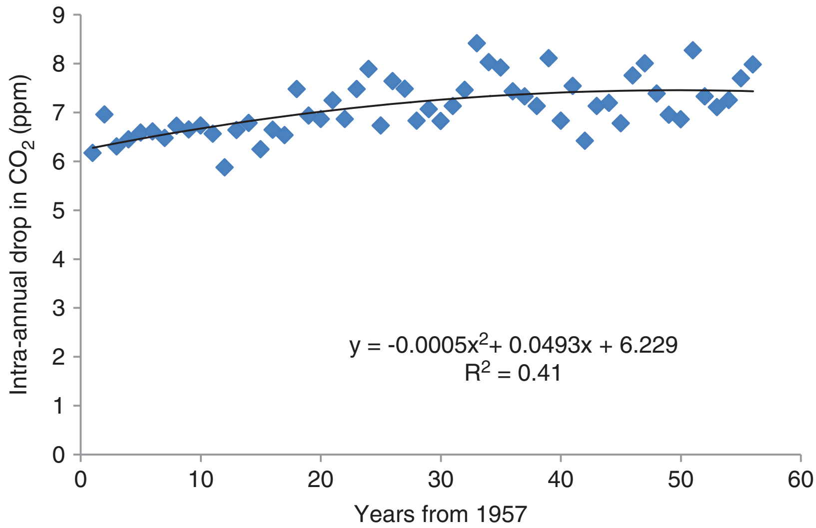

Figure 3. Magnitude of the intra-annual drop, derived directly from Mauna Loa observations, allowing 1/3 time adjustment between years. The peak on the quadratic regression curve occurs at n = 49, or year 2006.

Regression of annual maxima/minima

A polynomial regression can be performed through the annual minima of CO_2 taken from the Mauna Loa data, available from 1958 to 2015. The following equation can be used to calculate CO_2 values in parts per million:

$$CO_{2(min)}(n) = 0.0128n^2 + 0.7467n + 310.77$$

where n is year from 1957 and the square of the correlation coefficient $R^2 = 0.9992$.

Similarly, a polynomial regression can be derived for the annual maxima, resulting in the following equation:

$$CO_{2(max)}(n) = 0.0122n^2 + 0.7974n + 316.56$$

where n is year from 1957 and $R^2 = 0.9991$.

The difference can then be calculated between the regression prediction of the minimum in calendar year n and the concentration at year = n + 0.33 on the regression line for the annual maxima (Figure 1(a)). The resulting differences, by year, can then be plotted (Figure 2).

Estimation of difference, followed by regression

The difference between the maximum in calendar year n and the immediately following minimum in the same year can be directly derived for the weekly Mauna Loa dataset (Scripps Institution of Oceanography, 2015). This difference can then be augmented by addition of one-third of the assumed linear increase from the maximum in year n to the maximum in year n + 1 (Figure 1(b)). The resulting differences are plotted in Figure 3.

Analysis

It is, of course, not surprising that very similar results are obtained by both analytical methods. It appears that the absolute intra-annual drop in CO_2 increased a little until a peak was reached in 2006, followed thereafter by a small reduction. Further analy-

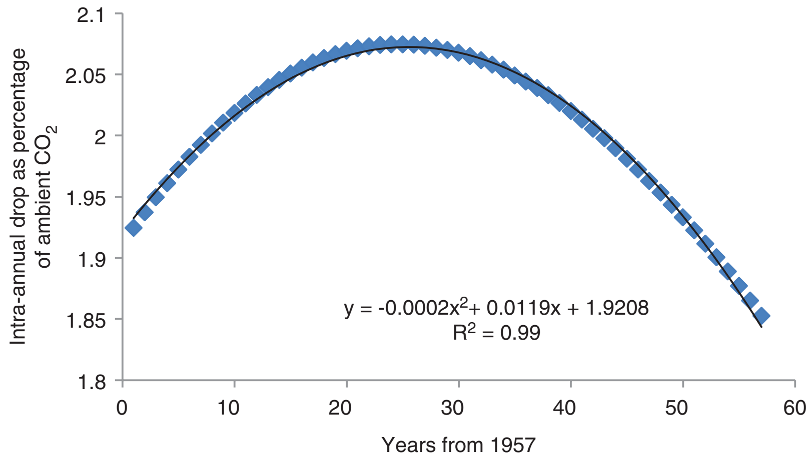

Figure 4. Percentage drop derived from Figure 2. The peak occurs at year 1982.

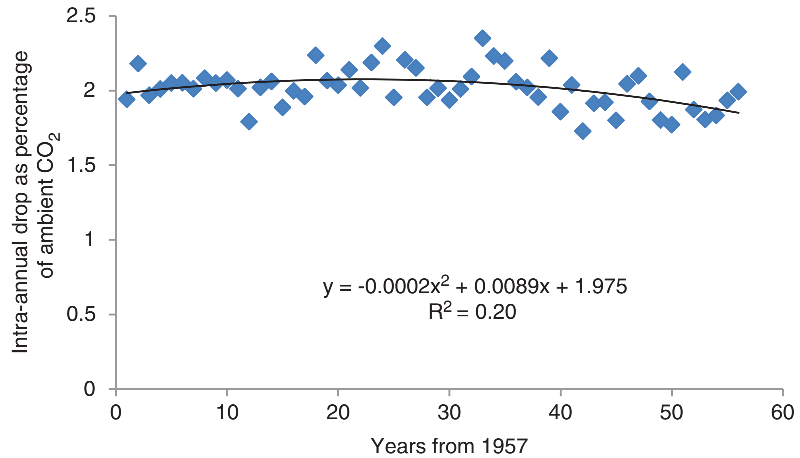

Figure 5. Percentage drop derived from Figure 3. The peak occurs at year 1979.

sis of the residuals from Figure 3 does not reveal any significant autocorrelation, which suggests that the quadratic regression, or curve-fitting, provides a good model.

There is, however, a visually evident, and statistically significant, increase in the absolute value of the residuals in Figure 3 over time; a moving decadal standard deviation of the residuals has an R^2 value of 0.84 (highly significant at $P < 0.001$). This is in line with the evidence (Hansen *et al.*, 2012) that the variability of weather has increased over the past decades, which could, in turn, potentially drive an increased variability in Northern Hemisphere bioaccumulation.

It has been reported (IPCC, 2007) that global ecosystem productivity increased by 6% in the period 1982–1999. As an independent comparison, Figures 2 and 3 suggest that Northern Hemisphere biomass uptake increased by 4% over the same period. Mauna Loa data indicate that the CO_2 concentration in the atmosphere increased by around 8% over the same period. So, over that period, ecosystem carbon uptake was not keeping pace with rising CO_2 levels. In contrast, the respective values for another 17-year period, 1960–1977, are 11.3 and 5.4%, which suggests that uptake was increasing faster than CO_2 in the atmosphere. This is further evidenced by Figures 4 and 5, which show the intra-annual drop – as a percentage of contemporaneous atmospheric CO_2 – follows a relatively more pronounced curve than that found in Figures 2 and 3 and peaks even earlier, at around 1980.

This analysis could be reasonably challenged on two grounds:

(i) Firstly, the intra-annual drop has possibly not retained a constant duration of one-third of a year over the period. Detailed scrutiny suggests that at the start of the Mauna Loa record the average duration was, indeed, around 17.8 weeks, although this had maybe extended to 19 weeks by 2014 (but $R^2 = 0.03$, so this is not statistically significant). This relationship is not strongly evidenced but is in accordance, for example, with Jeong *et al.* (2011) who suggest that the Northern Hemisphere (>30°N) growing season has extended by about 8 days over the past 23 years. However, conducting exactly the same analysis, assuming an appropriately increasing duration, hardly changes the nature of Figure 2 at all, with the peak remaining at year 2006.

(ii) Secondly, although a high degree of quality control is applied to Mauna Loa data (Scripps Institution of Oceanography, 2015), any environmental time series can be sensitive to extreme outliers, especially when analysing for maximum and minimum values each year. So it is worth re-analysing the data using a form of quantile regression: in this case the second highest and second lowest (effectively the 5th and 95th percentile) values for each year were also passed through the same analysis. The result is very similar to Figure 3 ($R^2 = 0.46$), although the peak shifts slightly earlier to year 2000.

Discussion

A major concern associated with man-made climate change is the risk that positive feedback begins to worsen the already rapid rise of atmospheric CO_2. Positive feedback would result from climate change causing perturbations to natural systems, which cause them either to release additional CO_2 into the atmosphere or to reduce the rate at which they absorb CO_2 from the atmosphere. This could come about in several ways, including a reduction in the efficiency of uptake by biomass possibly brought on by excessive heat, drought, floods and storms, pests/diseases and species extinctions.

The results presented here suggest that Northern Hemisphere biomass uptake has peaked and is now marginally diminishing. Such an event could have very serious implications by accelerating the rise of global atmospheric CO_2 and thereby further worsening climate change. The findings of this analysis build on earlier studies that have previously suggested the planetary biosphere to be more resilient than it might now appear. For example, although using a different technique and data for Mauna Loa only up until 2011, Groven *et al.* (2013) derive a similar scatter plot to that found in our current analysis (Figure 3) and then assume a linear upward trend. However, our analysis shows the R^2 value for an assumed linear trend (0.36) is less than the value for the polynomial shown (0.41); a F-statistic test indicates a significant ($P = 0.03$) difference between these values, with the curve, which peaks at year 2006, clearly being the better statistical fit.

Additionally, Ballantyne *et al.* (2012) suggest that global bio-uptake doubled between 1960 and 2010 and found no evidence that carbon uptake has started to diminish on a global scale, even though a temporary reduction was noted in the 1990s. Buermann *et al.* (2007) observe a decline in the amplitude of the Mauna Loa intra-annual fluctuation over a 10-year period from the early 1990s, and they attribute this to the severe droughts in North America; however, the authors suggest a return to more normal conditions after 2004.

Other studies have also demonstrated an absence of any evident reduction in biomass efficiency: Gloor *et al.* (2010) present evidence of a linear relationship between the rate of carbon uptake by land and ocean and the levels of ambient atmospheric CO_2; Poorter and Navas (2003) review numerous laboratory experiments and report that biomass uptake would be around 50% greater under a doubling of historical atmospheric CO_2 levels; Knorr (2009) finds an unchanging partition between atmospheric and sequestered carbon; while Raupach *et al.* (2008) find no implication that carbon sinks are weakening, although the rate of growth of uptake has fallen slightly behind the growth in emissions.

Conclusions

In summary, our analysis has provided evidence of the following:

(i) A possible extension of the duration of CO_2 uptake by bioaccumulation in the Northern Hemisphere summer (i.e. extended growing season).
(ii) An increase in the variability in the amount of CO_2 absorbed by Northern Hemisphere bio-accumulation each summer (i.e. possibly increased weather extremes).
(iii) A small decline in the ability of Northern Hemisphere bioaccumulation to absorb CO_2 from the atmosphere (i.e. possibly the onset of positive climate change feedback).

These findings are potentially worrying because of the implication that more extreme and more variable weather patterns may possibly be adversely impacting the planetary biosphere's ability to absorb CO_2 from the atmosphere. The conclusion that positive climate change feedback may just be beginning to be observable at a planetary scale should further encourage more research to arrive at firmer conclusions and should support yet more determined action to reduce man-made emissions with even greater urgency.

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Letters

Readers are encouraged to submit letters for possible publication. Letters can be submitted either electronically through the system used for articles, by email attachment to weather@wiley.com or by post, as shown on the Contents page. The Letters Editor reserves the right to edit any letter.

Soundtrack to a storm

John Turnpenny's (2016) evocative account of his ascent of Cairn Gorm last summer, and hasty escape from a thunderstorm, was beautifully written, scientifically accurate, and generally a pleasure to read. However, his personal soundtrack to the gathering storm, *Night on a Bare Mountain* by Modest Mussorgsky, was inspired by the supernatural rather than the meteorological. A more apt accompaniment would probably have been Richard Strauss's *Alpine Symphony*, which portrays a journey up a mountain, initially in the sunshine, with a spectacular aural depiction of a thunderstorm near the summit (Aplin and Williams, 2011). Furthermore, the peaceful closing sections of the piece, after the hasty retreat back down the mountain to safety, would be the perfect accompaniment to Turnpenny's post-hike tea and shortbread. Do other readers have favourite music to imagine when experiencing significant weather?

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