

## A major problem with the Resplandy et al. ocean heat uptake paper

On November 1st there was extensive coverage in the mainstream media<sup>1</sup> and online<sup>2</sup> of a paper just published in the prestigious journal *Nature*. The article,<sup>3</sup> by Laure Resplandy of Princeton University, Ralph Keeling of the Scripps Institute of Oceanography and eight other authors, used a novel method to estimate heat uptake by the ocean over the period 1991–2016 and came up with an atypically high value.<sup>4</sup> The press release<sup>5</sup> accompanying the Resplandy et al. paper was entitled "Earth's oceans have absorbed 60 percent more heat per year than previously thought",<sup>6</sup> and said that this suggested that Earth is more sensitive to fossil-fuel emissions than previously thought.

I was asked for my thoughts on the Resplandy paper as soon as it obtained media coverage. Most commentators appear to have been content to rely on what was said in the press release. However, being a scientist, I thought it appropriate to read the paper itself, and if possible look at its data, before forming a view.

### ***Trend estimates***

The method used by Resplandy et al. was novel, and certainly worthy of publication. The authors start with observed changes in 'atmospheric potential oxygen' ( $\Delta\text{APO}_{\text{OBS}}$ ).<sup>7</sup> In their model, one component of this change ( $\Delta\text{APO}_{\text{Climate}}$ ) is due to warming of the oceans, and they derived an estimate of its value by calculating values for the other components.<sup>8</sup> A simple conversion factor then allows them to convert the trend in  $\Delta\text{APO}_{\text{Climate}}$  into an estimate of ocean heat uptake (the trend in ocean heat content).

On page 1 they say:

*From equation (1), we thereby find that  $\Delta\text{APO}_{\text{Climate}} = 23.20 \pm 12.20$  per meg, corresponding to a least squares linear trend of  $+1.16 \pm 0.15$  per meg per year<sup>9</sup>*

A quick bit of mental arithmetic indicated that a change of 23.2 between 1991 and 2016 represented an annual rate of approximately 0.9, well below their 1.16 value. As that seemed surprising, I extracted the annual  $\Delta\text{APO}$  best-estimate values and uncertainties from the paper's Extended Data Table 4<sup>10</sup> and computed the 1991–2016 least squares linear fit trend in the  $\Delta\text{APO}_{\text{Climate}}$  values. The trend was 0.88, not 1.16, per meg per year, implying an ocean heat uptake estimate of 10.1 ZJ per year,<sup>11</sup> well below the estimate in the paper of 13.3 ZJ per year.<sup>12</sup>

Resplandy et al. derive  $\Delta\text{APO}_{\text{Climate}}$  from estimates of  $\Delta\text{APO}_{\text{OBS}}$  and of its other components,  $\Delta\text{APO}_{\text{FF}}$ ,  $\Delta\text{APO}_{\text{Cant}}$ , and  $\Delta\text{APO}_{\text{AtmD}}$ , using – rearranging their equation (1):

$$\Delta\text{APO}_{\text{Climate}} = \Delta\text{APO}_{\text{OBS}} - \Delta\text{APO}_{\text{FF}} - \Delta\text{APO}_{\text{Cant}} - \Delta\text{APO}_{\text{AtmD}}$$

I derived the same best estimate trend when I allowed for uncertainty in each of the components of  $\Delta\text{APO}_{\text{OBS}}$ , in the way that Resplandy et al.'s Methods description appears to indicate,<sup>13</sup> so my simple initial method of trend estimation does not explain the discrepancy.

Figure 1 shows how my 0.88 per meg per year linear fit trend (blue line) and Resplandy et al.'s 1.16 per meg per year trend (red line) compare with the underlying  $\Delta\text{APO}_{\text{Climate}}$  data values.

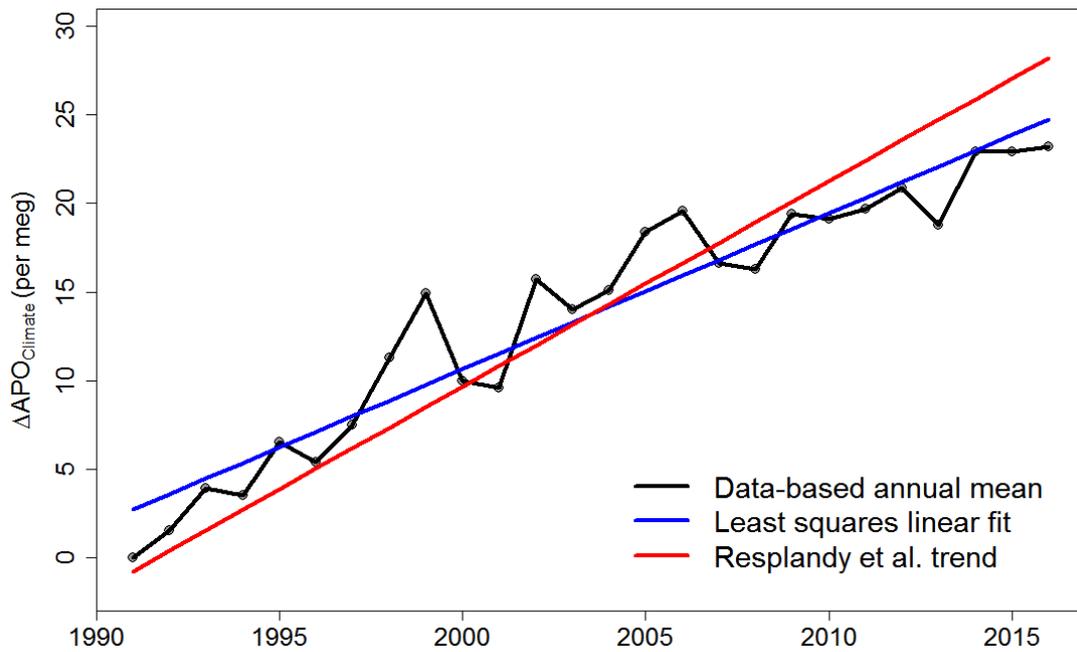


Figure 1.  $\Delta\text{APO}_{\text{Climate}}$  data values (black), the least squares linear fit (blue line) to them, and the linear trend per Resplandy et al. (red line)

Assuming I am right that Resplandy et al. have miscalculated the trend in  $\Delta\text{APO}_{\text{Climate}}$ , and hence the trend in ocean heat content (OHC), implied by their data, the corrected OHC trend estimate for 1991–2016 (Figure 2: lower horizontal red line) is about average compared with the other estimates they showed, and below the average for 1993–2016.

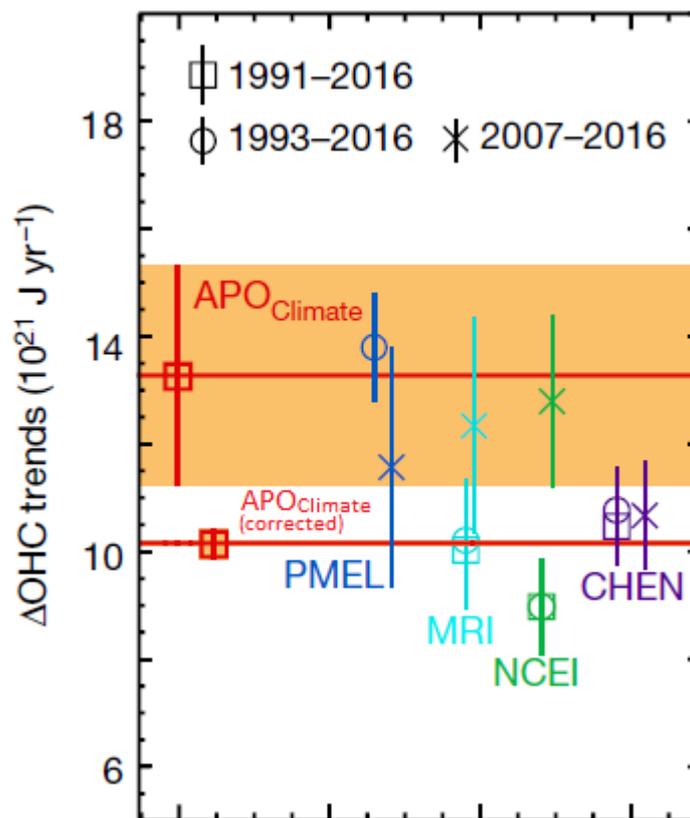


Figure 2. An adaptation of Figure 1b from Resplandy et al. with the corrected estimate for the  $\text{APO}_{\text{Climate}}$  derived  $\Delta\text{OHC}$  trend added (lower horizontal red line; no error bar is shown)

I wanted to make sure that I had not overlooked something in my calculations, so later on November 1st I emailed Laure Resplandy querying the  $\Delta\text{APO}_{\text{Climate}}$  trend figure in her paper and asking for her to look into the difference in our trend estimates as a matter of urgency, explaining that in view of the media coverage of the paper I was contemplating web-publishing a comment on it within a matter of days. To date I have had no substantive response from her, despite subsequently sending a further email containing the key analysis sections from a draft of this article.

How might Laure Resplandy<sup>14</sup> have miscalculated the  $\Delta\text{APO}_{\text{Climate}}$  trend as 1.16 per meg per year? One possibility is that the computer code for the trend computation somehow only deducted  $\Delta\text{APO}_{\text{FF}}$  and  $\Delta\text{APO}_{\text{Cant}}$  from  $\Delta\text{APO}_{\text{OBS}}$  when computing the 1991–2016 trend, thereby in fact obtaining the trend for  $\{\Delta\text{APO}_{\text{Climate}} + \Delta\text{APO}_{\text{AtmD}}\}$ , which is 1.16 per meg per year.<sup>15</sup>

## ***Uncertainty analysis***

I now turn to the uncertainty analysis in the paper.<sup>16</sup> Strangely, the Resplandy et al. paper has two different values for the uncertainty in the results. On page 1 they give the  $\Delta\text{APO}_{\text{Climate}}$  trend (in per meg per year) as  $1.16 \pm 0.15$ . But on page 2 they say it is  $1.16 \pm 0.18$ . In the Methods section they go back to  $1.16 \pm 0.15$ . Probably the  $\pm 0.18$  figure is a typographical error.<sup>17</sup>

More importantly, it seems to me that uncertainty in the  $\Delta\text{APO}_{\text{Climate}}$  trend, and hence in the ocean heat uptake estimate, is greatly underestimated in Resplandy et al., because of two aspects of the way that they have treated trend and scale uncertainties affecting  $\Delta\text{APO}_{\text{OBS}}$ . First, they appear to have treated corrosion, leakage and desorption errors in  $\Delta\text{APO}_{\text{OBS}}$  as fixed errors that have the same influence each year.<sup>18</sup> But these are annual trend errors, so their influence is proportional to the number of years elapsed since the 1991 base year.<sup>19</sup> Secondly, they appear to have treated both these trend errors and the scale systematic error in  $\Delta\text{APO}_{\text{OBS}}$  as uncorrelated between years.<sup>20</sup> However, each year's error from each of these sources is simply a multiple of a single random trend or scale systematic error, and is therefore perfectly correlated with the same type of error in all other years.

On a corrected basis, I calculate the  $\Delta\text{APO}_{\text{Climate}}$  trend uncertainty as  $\pm 0.56$  per meg  $\text{yr}^{-1}$ , more than three times as large as the  $\pm 0.15$  or  $\pm 0.18$  per meg  $\text{yr}^{-1}$  values in the paper.<sup>21</sup> This means that, while Resplandy et al.'s novel method of estimating ocean heat uptake is useful in providing an independent check on the reasonableness of estimates derived from *in situ* temperature measurements, the estimates their method provides are much more uncertain than *in situ* measurement-based estimates, and are consistent with all of them.

## ***Effect on climate sensitivity and carbon budgets***

Resplandy et al. point out that a larger increase in ocean heat content (a higher ocean heat uptake) would affect estimated equilibrium climate sensitivity. That is true where such sensitivity estimates are derived from observationally-based analysis of the Earth's energy budget. However, after correction, the Resplandy et al. results do not suggest a larger increase in ocean heat content than previously thought. In fact, using the corrected Resplandy et al. estimate of the change in ocean heat content over the relevant period (2007–2016) in the recent [Lewis and Curry \(2018\)](#)<sup>22</sup> energy budget study would slightly lower its main estimate of equilibrium climate sensitivity. Moreover, a larger estimated increase in ocean heat content would principally affect the upper uncertainty bound of the equilibrium climate sensitivity estimate. Contrary to what Resplandy et al. claim, the lower bound would be little affected and would remain well below  $1.5^\circ\text{C}$ ,<sup>23</sup> providing no support for increasing the lower bound of the IPCC's range for equilibrium climate sensitivity to  $2.0^\circ\text{C}$ .

Resplandy et al. also make the bizarre claim that increasing the lower bound of the IPCC's equilibrium climate sensitivity range from  $1.5^\circ\text{C}$  to  $2.0^\circ\text{C}$  would have the effect of "reducing maximum allowable cumulative  $\text{CO}_2$  emissions by 25% to stay within the  $2^\circ\text{C}$  global warming

target". In fact, that cumulative carbon emissions budget is very largely determined by a combination of carbon-cycle characteristics and the transient climate response.<sup>24</sup> Observational estimates of the transient climate response are unaffected by the level of ocean heat uptake. Therefore, increasing the lower bound of the equilibrium climate sensitivity range would have little or no impact on the cumulative carbon emissions budget to stay within 2°C global warming.

## **Conclusions**

The findings of the Resplandy et al paper were peer reviewed and published in the world's premier scientific journal and were given wide coverage in the English-speaking media. Despite this, a quick review of the first page of the paper was sufficient to raise doubts as to the accuracy of its results. Just a few hours of analysis and calculations, based only on published information, was sufficient to uncover apparently serious (but surely inadvertent) errors in the underlying calculations.

Moreover, even if the paper's results had been correct, they would not have justified its findings regarding an increase to 2.0°C in the lower bound of the equilibrium climate sensitivity range and a 25% reduction in the carbon budget for 2°C global warming.

Because of the wide dissemination of the paper's results, it is extremely important that these errors are acknowledged by the authors without delay and then corrected.

Of course, it is also very important that the media outlets that unquestioningly trumpeted the paper's findings now correct the record too.

But perhaps that is too much to hope for.

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<sup>1</sup> Examples are:

<https://www.bbc.co.uk/news/science-environment-46046067>

<https://www.nytimes.com/2018/10/31/climate/ocean-temperatures-hotter.html>

<https://www.washingtonpost.com/energy-environment/2018/10/31/startling-new-research-finds-large-buildup-heat-oceans-suggesting-faster-rate-global-warming/>

<https://www.scientificamerican.com/article/the-oceans-are-heating-up-faster-than-expected/>

<https://edition.cnn.com/2018/11/01/australia/ocean-warming-report-intl/index.html>

<http://www.latimes.com/science/sciencenow/la-sci-sn-oceans-study-climate-change-20181031-story.html>

<https://www.usatoday.com/story/news/nation-now/2018/11/01/oceans-more-heat-study-global-warming-climate-change-nature/1843074002/>

<https://www.independent.co.uk/environment/climate-change-global-warming-ocean-temperature-heat-fossil-fuels-science-research-a8612796.html>

<sup>2</sup> Examples are:

<http://www.realclimate.org/index.php/archives/2018/11/unforced-variations-nov-2018/>

<https://wattsupwiththat.com/2018/11/02/friday-funny-at-long-last-kevin-trenberths-missing-heat-may-have-been-found-repeat-may-have-been/>

<https://bskiesresearch.wordpress.com/2018/11/01/that-new-ocean-heat-content-estimate/>

<https://andthentheresphysics.wordpress.com/2018/11/03/new-ocean-heat-content-analysis/>

[https://twitter.com/Knutti\\_ETH/status/1057960390502608901](https://twitter.com/Knutti_ETH/status/1057960390502608901)

<sup>3</sup> L. Resplandy, R. F. Keeling, Y. Eddebbar, M. K. Brooks, R. Wang, L. Bopp, M. C. Long, J. P. Dunne, W. Koeve & A. Oschlies, 2018: Quantification of ocean heat uptake from changes in atmospheric O<sub>2</sub> and CO<sub>2</sub> composition. *Nature*, 563, 105-108. <https://doi.org/10.1038/s41586-018-0651-8> ("Resplandy et al.")

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- <sup>4</sup> A value of 13.3 zetta Joules (ZJ) per year, or 0.83 Watts per square metre of the Earth's surface. ZJ is the symbol for zetta Joules; 1 ZJ =  $10^{21}$  J. 1 ZJ per year = 0.0621 Watts per square metre ( $\text{W}/\text{m}^2$  or  $\text{Wm}^{-2}$ ) of the Earth's surface.
- <sup>5</sup> <http://web.archive.org/web/20181103021900/https://www.princeton.edu/news/2018/11/01/earths-oceans-have-absorbed-60-percent-more-heat-year-previously-thought>
- <sup>6</sup> However that is in comparison with an IPCC estimate for 1993–2010; estimates for 1991–2016 are higher.
- <sup>7</sup>  $\Delta\text{APO}$  is the change in 'atmospheric potential oxygen', the overall level of which has been observationally measured since 1991 ( $\Delta\text{APO}_{\text{OBS}}$ ). It is the sum of the atmospheric concentrations of  $\text{O}_2$  and of  $\text{CO}_2$  weighted respectively  $1\times$  and  $1.1\times$ .
- <sup>8</sup> The authors break the observed change in  $\Delta\text{APO}_{\text{OBS}}$  into four components,  $\Delta\text{APO}_{\text{FF}}$ ,  $\Delta\text{APO}_{\text{Cant}}$ ,  $\Delta\text{APO}_{\text{AtmD}}$  and  $\Delta\text{APO}_{\text{Climate}}$ , deriving the last component (which is related to ocean warming) by deducting estimates of the other three components from  $\Delta\text{APO}_{\text{OBS}}$ .  $\Delta\text{APO}_{\text{FF}}$  is the decrease in APO caused by industrial processes (fossil-fuel burning and cement production).  $\Delta\text{APO}_{\text{Cant}}$  accounts for the oceanic uptake of excess anthropogenic atmospheric  $\text{CO}_2$ .  $\Delta\text{APO}_{\text{AtmD}}$  accounts for air–sea exchanges driven by ocean fertilization from anthropogenic aerosol deposition.
- <sup>9</sup> 1 per meg literally means 1 part per million (1 ppm), however 'per meg' and 'ppm' are defined differently in relation to atmospheric concentrations and are not identical units.
- <sup>10</sup> The same data is available in Excel format from a link on Nature's website, as "[Source Data Fig. 2](#)".
- <sup>11</sup> Dividing by their conversion factor of  $0.087 \pm 0.003$  per meg per ZJ. ZJ is the symbol for zetta Joules; 1 ZJ =  $10^{21}$  Joules.
- <sup>12</sup> I used ordinary least squares (OLS) regression with an intercept. That is the standard form of least squares regression for estimating a trend. Resplandy et al. show all APO variables as changes from a baseline of zero in 1991, but that is an arbitrary choice and would not justify forcing the regression fit to be zero in 1991 (by not using an intercept term). Doing so would not in any event raise the  $\Delta\text{APO}_{\text{Climate}}$  estimated trend to the level given by Resplandy et al.
- <sup>13</sup> I took a large number of sets of samples for each of the years 1991 to 2016 from the applicable error distributions of  $\Delta\text{APO}_{\text{OBS}}$ ,  $\Delta\text{APO}_{\text{FF}}$ ,  $\Delta\text{APO}_{\text{Cant}}$ , and  $\Delta\text{APO}_{\text{AtmD}}$  given in Extended Data Table 4, and calculated all the corresponding sample values of  $\Delta\text{APO}_{\text{Climate}}$  using equation (1). I then computed the ordinary least squares linear trend for each set of 1991–2016 sampled values of  $\Delta\text{APO}_{\text{Climate}}$ , and calculated the mean and standard deviation of the trends.
- <sup>14</sup> Laure Resplandy was responsible for directing the analysis of the datasets and models.
- <sup>15</sup> This fact was spotted by Frank Bosse, with whom I discussed the apparent error in the Resplandy et al.  $\Delta\text{APO}_{\text{Climate}}$  trend.
- <sup>16</sup> All uncertainty values in the paper are  $\pm 1$  sigma (1 standard deviation). Errors are presumably assumed to be Normally distributed, as no other distributions are specified.
- <sup>17</sup> The statement in their Methods that " $\Delta\text{Cant}'$  cannot be derived from observations and was estimated at  $0.05 \text{ Pg C yr}^{-1}$ , equivalent to a trend of  $+0.2$  per meg $^{-1}$ , using model simulations" is presumably also a typographical error. The correct value appears to be  $+0.12$  per meg  $\text{yr}^{-1}$ , as stated elsewhere in Methods and in Extended Data Table 3.
- <sup>18</sup> On that basis, I can replicate the Extended Data Table 4  $\Delta\text{APO}_{\text{OBS}}$  uncertainty time series values within  $\pm 0.1$ . Note that all the values in that table, although given to two decimal places, appear to be rounded to one decimal place.
- <sup>19</sup> The overall uncertainties given in Table 3 in Resplandy et al.'s source paper for its errors in  $\Delta\text{APO}_{\text{OBS}}$  support my analysis.
- <sup>20</sup> When using the Resplandy et al. Extended Data Table 4  $\Delta\text{APO}_{\text{Climate}}$  total uncertainty time series and assuming that each year's errors are independent, despite the trend and scale systematic errors being their largest component, the estimated  $\Delta\text{APO}_{\text{Climate}}$  uncertainty reduces to between  $\pm 0.20$  and  $\pm 0.21$  per meg  $\text{yr}^{-1}$ . That is still slightly higher than the  $\pm 0.15$  and  $\pm 0.18$  per meg  $\text{yr}^{-1}$  values given in the paper. The reason for the small remaining difference is unclear.
- <sup>21</sup> It seems likely that the same non-independence over time issue largely or wholly applies to errors in  $\Delta\text{APO}_{\text{Cant}}$ ,  $\Delta\text{APO}_{\text{AtmD}}$  and probably  $\Delta\text{APO}_{\text{FF}}$ . If the errors in  $\Delta\text{APO}_{\text{Cant}}$  and  $\Delta\text{APO}_{\text{AtmD}}$  (but not in  $\Delta\text{APO}_{\text{FF}}$ )

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were also treated as perfectly correlated between years, the  $\Delta\text{APO}_{\text{Climate}}$  trend uncertainty would be  $\pm 0.60$  per  $\text{meg yr}^{-1}$ .

<sup>22</sup> Lewis, N., and Curry, J., 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *J. Climate*, **31**(15), 6051-6071.

<sup>23</sup> Even if the 2007–2016 ocean heat uptake estimate used in Lewis and Curry (2018) were increased by  $3 \text{ ZJ yr}^{-1}$  to match Resplandy et al.'s (incorrect) estimate for 1991–2016, the  $1.05^\circ\text{C}$  5% lower bound of its HadCRUT4v5-based estimate of effective/equilibrium climate sensitivity would only increase to  $1.15^\circ\text{C}$ . Moreover, Resplandy et al.'s  $\Delta\text{APO}_{\text{Climate}}$  data imply have a lower ocean heat uptake estimate for 2007–2016 than they do for 1991–2016.

<sup>24</sup> See the IPCC's 2018 [Special Report on Global Warming of 1.5°C](#)