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Comment

Reply to "Comment on 'Ocean heat content and Earth's radiation imbalance. II. Relation to climate shifts'" by Nuccitelli et al.

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Nuccitelli, Way, Painting, Church and Cook [1] comment on our Letter "Ocean heat content and Earth's radiation imbalance. II. Relation to climate shifts" [2]. Their criticism is unwarranted on at least three essential grounds. (1) It is based on a misunderstanding of the climate shift concept, which is central to our Letter; (2) in making its claim of incompleteness because of neglect of the deeper ocean heat content, it ignores our statement of possible error and introduces incompatible data; (3) it over-interprets our comments about CO_2 forcing. We expand on these points.

(1) *Climate shifts*. A major point of our Letter [2] was that any study of ocean heat content (OHC) must recognize that the global climate system undergoes abrupt changes in regime or climate shifts that have been widely reported in other investigations (see Refs. [5–8] of [2]) and that OHC slopes evaluated across climate shifts are meaningless. Our principal result, important for the discussion in this reply, is that during a 2001–2002 climate shift the OHC slope changed abruptly from a positive value to a value close to zero. There is a tendency in the literature to mistrust any trend analysis involving periods shorter than decadal. This tendency is based on model evaluations, which play no part in the present case.

Nuccitelli et al. mistakenly and repeatedly refer to "climate shift periods". Climate shifts [3] are much shorter in duration (one or two years) than the duration of OHC trends (several years) and thus can be identified. They consider linear trends over decadal (or greater) time intervals, where such trends are meaningless because climate shifts interrupt near-linear behavior. This is especially true since the data used in [1] are pentadal, 5-year averages, which automatically damp out the sharp changes in OHC at climate shifts.

(2) *Data and the deeper ocean*. Nuccitelli et al. introduce a data set different from ours. There are actually three OHC data sets of interest: two corresponding to 0–700 meters depth and one corresponding to 0–2000 meters depth [4]. For 0–700 meters, one set is at high temporal resolution with four quarterly data values per year. We label this set OHC700_quart. There is no similar complete set for 2000 m. For both 0–700 and 0–2000, there are low temporal resolution sets that come from five-year (pentadal) moving averages with data values given at yearly intervals. We call these OHC700_pent and OHC2000_pent. All three sets are plotted in Fig. 1 from 1970 to the present. Also shown as red arrows are two of the climate shifts listed in [2]: CS5, 1991 and CS6, 2001–2002.

Concerning the disparity between our results and theirs, Nuccitelli et al. state "Our 0–700 meter results differ from that of DK12 over the 2002–2008 period because we use pentadal data whereas DK12 use quarterly data. This result highlights the fact that the DK12 conclusions are the result of their focus on short-term noise". We categorically reject the characterization of the quarterly data as "noise". It may be well to avoid comparing short-term data sets with model calculations, but we are here dealing only with data in the context of climate shifts which themselves are based on observations. We can equally well criticize the use by Nuccitelli et al. of five-year-averaged data, since the moving average "smears out" any phenomena related to the abrupt climate shifts.

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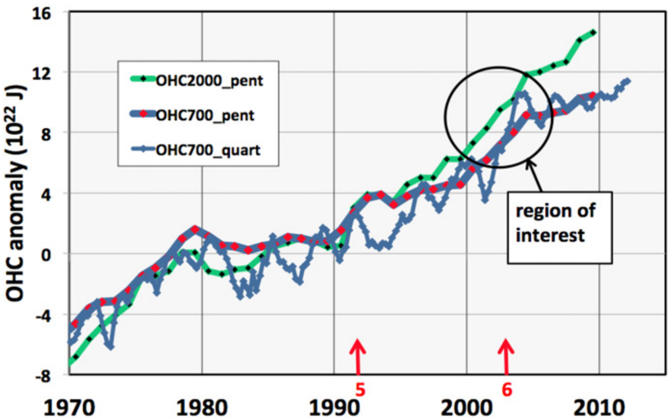

Fig. 1. Ocean heat content data available [4], two for depths 0–700 m and one for depths 0–2000 m, at different time resolutions (see figure legend and text). Arrows denote times of two climate shifts. (For interpretation of the references to color, the reader is referred to the web version of this Letter.)

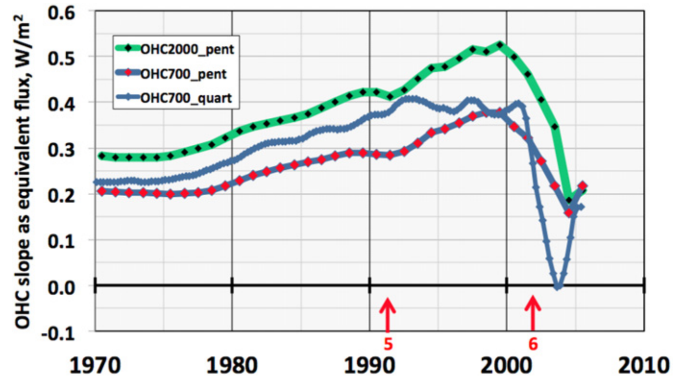

Fig. 2. Trends in the data of Fig. 1 expressed as equivalent flux. All symbols and lines correspond to those in Fig. 1.

We consider a quantitative analysis of the three data sets. All of the slopes in [1] and [2] were expressed in terms of their relation to the top-of-atmosphere radiation imbalance through a conservation-of-energy relation [5]: the net input (radiation imbalance F_{TOA} at the top of the atmosphere plus geothermal input F_{GEO}) is equal to the rate of change of ocean heat content (OHC):

$$F_{TOA} + F_{GEO} = 0.62\, d(\mathrm{OHC})/dt. \tag{1}$$

F_{GEO} (0.087 W/m^2) [6] is a small but important source of heat from the center of the earth and is dropped temporarily but will be discussed below. In principle OHC should be augmented by the heat content of the land, atmosphere, and ice but their contributions are either small or slowly changing (see Fig. 1 and Table 1 of [1]). OHC is measured in units of 10^{22} J/year and the time in years. The factor 0.62 is a result of converting 10^{22} J/year to watts and dividing by Earth's area to obtain a flux. The assumed lower boundary of the closed atmosphere-ocean climate system is at a depth D that was 700 m in [2] and $D = 2000$ m in [1].

The three available data sets, OHC700_quart, OHC700_pent and OHC2000_pent are plotted in Fig. 1 from 1970 to the present. The focus of Nuccitelli et al. and this communication is the behavior of the OHC data before and after the climate shift of 2001–2002. From Eq. (1), our primary interest is in the slope of the OHC curves.

Is there a climate shift in the OHC data during 2001–2002? Nuccitelli et al. state "Contrary to the results in DK12, there is no significant decrease or flattening in total heat content during the past decade, as illustrated in Table 1". One sees in the plots of Fig. 1 of our Letter and in Fig. 1 of Nuccitelli et al. what appear to be abrupt changes of slope at 2001–2002 and at 2003, respectively, from a positive slope to a smaller slope.

Nuccitelli et al. calculate the average slope of OHC between various dates (1970, 1980, 1990, 2000 and 2002) and 2008, listed in their Table 1. To facilitate a comparison we also calculate these average slopes for every date after 1970 for the three data sets and show plots of the results in Fig. 2. The high resolution OHC700_quart, used by [2], shows a maximum at about 2001 followed by a minimum. On the other hand, in the case of the low resolution OHC700_pent and OHC2000_pent data, a maximum in slope occurs for both at about 1998, which is what one would expect because the 5-year averaging window would "reach" the climate shift 2½ years earlier. A minimum is observed in both OHC700_pent and OHC2000_pent at nearly the same date seen in OHC700_quart.

The OHC slopes of the three data sets before and after the climate shift of 2001–2002 were computed and are listed in Table 1. Before the climate shift the slope values are all positive: 0.67, 0.24 and 0.44, which are nearly the same within the uncertainties. After the climate shift the OHC slope of OHC700_quart has the value give by [2] while the low resolution data sets show a minimum but the values are not as low as that the high temporal resolution OHC700_quart. This result is expected because the 5-year window would replace a minimum by the average about that value, which would be larger. Thus, there is no conflict between the low resolution temporal data and the higher resolution data. They are consistent with each other.

Nuccitelli et al. claim that [2] ignore the contribution of 700–2000 m to OHC, thus underestimating trends. We did not ignore it, but explicitly stated its omission and included a large error bar (shown in the abstract of [2]). As mentioned earlier, from conservation of energy flux one must include the entire geosystem (land, ice, upper ocean and deep ocean) in equating its rate of change of energy content to the net flux. However, this contribution is small, as Table 1 of Nuccitelli et al. shows and does not change

Table 1
Measured rates of change of ocean heat content, expressed in terms of top-of-atmosphere flux imbalance in units of W/m^2.

	OHC700_quart	OHC700_pent	OHC2000_pent
Slope[a] between CS5 and CS6 (1991 to 1999)	0.67 ± 0.15 (from [2])	0.24 ± 0.20 (from data of Fig. 1)	0.44 ± 0.20 (from data of Fig. 1)
Date of max in Fig. 2	2000.875	1998.5[b]	1999.5[b]
Date of min in Fig. 2	2003.675	2004.5[c]	2004.5[c]
Slope[a] after CS6	0.09 ± 0.15 (from [2])	0.16 ± 0.10[d]	0.19 ± 0.10[d]

[a] Slopes are measured in units of equivalent flux (W/m^2). Slope $= 0.62 * [d(\mathrm{OHC})/dt]$.
[b] Range of 5-year average "reaches" climate shift CS6 about 2½ years earlier.
[c] This is also the date that the range of the 5-year average is after CS6.
[d] Slope and uncertainty from least squares. The 5-year average will "smear out" a sharp minimum and replace it with a larger value.

our conclusions. We note that our estimate of F_{GEO} is of the same magnitude and effectively cancels the deep ocean part of the contribution to F_{TOA} (see Eq. (1)).

(3) CO_2 *feedback*. Referring to the period 2003–2008 in [2], we computed the no-feedback CO_2 change in forcing due to an increased concentration, which was 0.196 W/m^2. The observed top-of-atmosphere radiative forcing as implied by the rate of change of OHC during the same period was -0.36 W/m^2. We then remarked that there must be negative feedback to the CO_2 forcing in order that it not contradict the observation. Nuccitelli et al. seem to have taken this factual remark as the principal point of our Letter, which it was not.

In sum, we show that the criticism of our results (change of slope in the implied F_{TOA} at the climate shift of 2001–2002) by Nuccitelli et al. is unwarranted because they used different data of less temporal resolution. A more careful analysis of this data shows, in fact, consistency and not conflict with our results.

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