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Ocean heat content and Earth's radiation imbalance. II. Relation to climate shifts

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ABSTRACT

In an earlier study of ocean heat content (OHC) we showed that Earth's empirically implied radiation imbalance has undergone abrupt changes. Other studies have identified additional such climate shifts since 1950. The shifts can be correlated with features in recently updated OHC data. The implied radiation imbalance may possibly alternate in sign at dates close to the climate shifts. The most recent shifts occurred during 2001–2002 and 2008–2009. The implied radiation imbalance between these dates, in the direction of ocean heat loss, was -0.03 ± 0.06 W/m^2, with a possible systematic error of $[-0.00, +0.09]$ W/m^2.

1. Introduction

There has been considerable interest in whether Earth has been warming or cooling in recent years. Many studies show that the globally averaged surface temperature has been "flat" or decreasing since 1998. For example, in a recent study Kaufmann et al. [1] state "…global surface temperatures did not rise between 1998 and 2008". Using surface temperature as the best indicator of warming has been questioned by Pielke [2,3], who says "Unlike temperature at some specific depth in the ocean or height in the atmosphere, where there is a time lag in its response to radiative forcing, no time lags are associated with heat changes, since the actual amount of heat present at any time is accounted for. Moreover, because the surface temperature is a massless two-dimensional global field while heat content involves mass, the use of surface temperature as a monitor of climate change is not accurate for evaluating heat storage changes" [3]. In our treatment, this takes the following form: ocean heat content (OHC) has a direct relationship to Earth's radiation budget, whereas surface temperature does not. In paper [4] we quantified this relationship and tentatively identified three recent abrupt changes in the implied radiation imbalance. We argued that each of these changes was correlated with a *climate shift* (CS) that had been identified independently.

Abrupt shifts in Earth's climate system are common. A major point of this Letter is that these shifts should be acknowledged in the analysis of climate data such as OHC. Among the first to characterize a CS was Trenberth [5], who reported a "different regime after 1976". Ebbesmeyer et al. [6] documented the many aspects of this 1970s CS in a study of 40 multidisciplinary variables. Swanson and Tsonis [7], in a study of four northern hemispheric climate indices, report "synchronization peaking" showing five CS since 1900. Douglass [8] in a study of a more global set of climate indices showed that since 1870 at least 18 such CS have occurred, the most recent in 1976–1977, 1984–1987, and 2001–2002. Thus climate shifts appear to be an essential feature of Earth's climate system, and, as we shall show here, studies of OHC can be used to confirm and detect them. Since publication of paper [4], OHC data have been updated through the third quarter of 2011. We examine these data with specific attention to the CS occurring since 1955.

In Section 2 the data and methods used in this Letter are described. Section 3 presents the analysis of the data; Section 4 is a discussion of the results.

2. Data and methods

The principal OHC data set used in this study is an update [9] of that of Levitus et al. [10]. These data consist of quarterly values of OHC measured to a depth of 700 m summed over the world's oceans. Standard error (SE) is included and the set runs from the first quarter of 1955 to the third quarter of 2011. See Fig. 1. Changes and improvements to the basic data since 2009 are threefold (paraphrased from the NODC web site): (1) Substantial quality control has been carried out by the Argo community on the profiling floats, mainly to correct pressure offsets, and a substantial amount of data for recent years has been added to the analysis. (2) Corrections and changes in the base climatology were formally completed with additional data and quality control. (3) Changes due to revised XBT bias calculations were made; this is an ongoing process, but recalculations will mostly affect the most recent years.

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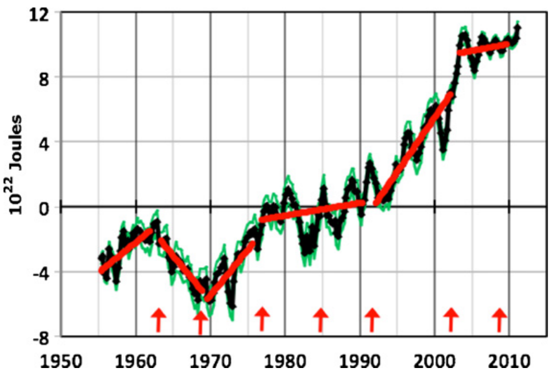

Fig. 1. Ocean heat content from NODC (see Section 2). Red arrows are the dates of seven climate shifts (CS) reported by Douglass [8,12]. These seven CS define seven time segments. The one standard deviation uncertainties are shown by the green curves. The solid red lines are the slopes for the seven time segments. Values of the slopes and the implied radiation imbalance are given in Table 1 and are plotted in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

While there are several other determinations of OHC covering earlier periods, as described in paper [4], we concentrate on this updated set because it is reproducible; quality control and underlying climatologies are readily available along with methodology and necessary auxiliary information (land masks, etc.). Anyone can, and some have, exactly reproduced these results. It also makes use of the "assumption of zero anomaly" method of infill for regions of missing data, which tends to underestimate changes but does not introduce spurious signals as do other infill options. Finally, the data are subjected to extensive quality control procedures. We are indebted to T. Boyer for supplying the description on which this paragraph is based.

The OHC data are three-month averages reported quarterly. To remove seasonal effects, we made a four-point running average of reported data. The standard deviation (SD) of this average is taken as $SE/n^{1/2}$, where $n = 4$.

OHC data are expressed in units of 10^{22} J (10 ZJ). To relate OHC to radiative imbalance, one uses [4,11]

$$F_{TOA} + F_{geo} = 0.62\left[d(\mathrm{OHC})/dt\right], \tag{1}$$

where F_{TOA} is the radiative imbalance at the top of the atmosphere (inward), F_{geo} is Earth's geothermal output of 0.087 W/m^2, both in units of W/m^2, and time is in years (see paper [4]). The factor 0.62 is a result of converting 10^{22} J/yr to watts and dividing by Earth's area to obtain the flux. Using 700-m OHC data in Eq. (1) involves the assumption that other sources of rates of change of climate system heat content such as those of the atmosphere and the deep ocean are negligible. This assumption is discussed in the supplementary material of paper [4] and in Section 4 below.

In previous studies [4,8,12,13] seven climate shifts are reported to have occurred during 1964–1966, 1968–1969, 1976–1977, 1984–1987, 1991, 2001–2002 and 2008–2009. The last comes from observations of changes in an El Niño index reported in [13]. See Table 1. Red arrows in Figs. 1 and 2 correspond to these dates.

3. Results

Fig. 1 shows the OHC data (4-point averages) and their uncertainty range. Almost all prior analyses of such OHC data fail to recognize the possible influence of climate shifts, in that smooth curves, such as straight lines, are used to characterize extensive blocks of the data series. In our analysis, lines of constant slope were fit to each segment between the climate shifts. The ends of the segments were stopped several data points from the climate shifts, whose positions were used as input. The values of the slopes are given in Table 1. Also given in the table and plotted in Fig. 2 are the values of radiation imbalance calculated from Eq. (1). The plot shows that the implied radiation imbalance alternates between positive and negative values. With regard to the 1984–1987 climate shift, the data are too noisy to determine whether there was a change in slope.

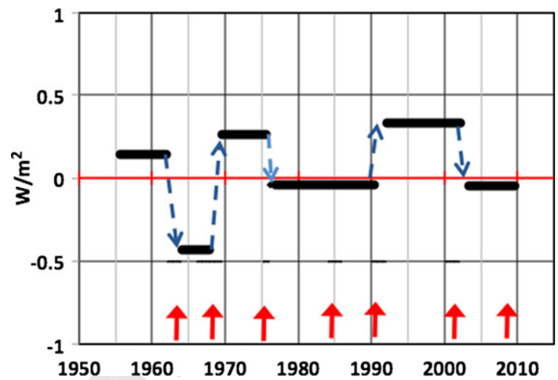

Fig. 2. Plot of implied radiation imbalance *vs.* date. The plot shows value alternating about 0. The radiation imbalance is never greater than 0.5 W/m^2. (For interpretation of the references to in this figure, the reader is referred to the web version of this Letter.)

4. Discussion

4.1. Response time

Douglass and Knox [4] have commented on the response time. We summarize. The global energy balance approach of this Letter attempts to account for all of the energy of the climate system on an annual to decadal basis. Data uncertainties prevent an assessment of long-term heat storage. The time delay between the variations in the flux F_{TOA} and the changes in the ocean heat content appears to be zero, or at most one month, which is more or less in agreement with Pielke [3,4]. That the time of the maximum of annual variation of the measured (CERES) flux and that of the inferred (Argo) flux agree confirms this. As discussed in the Supplementary Material of paper [4], much (49%) of the un-reflected incoming solar flux heats the land and atmosphere. The observed lack of time delay between the solar signal and the rate of change of OHC implies that this energy either shows up rapidly in the ocean or exits as long-wave radiation and is thereby accounted for as part of F_{TOA}. Here "rapidly" refers to processes occurring on a monthly, or shorter, time scale.

4.2. Climate shifts and nature of the phase-locked states

In numerous studies climate shifts are inferred from the study of a single climate observable. See references in Knox and Douglass [11]. An innovative way to identify Climate Shifts using networks of many climate indices was introduced by Swanson and Tsonis [7]. Their method can be thought of as a particular quantitative "teleconnections" scheme. They reported five climate shifts after 1900 using four northern hemispheric indices (Niño; Pacific Decadal Oscillation, PDO; North Atlantic Oscillation, NAO; North Pacific Index, NPI). Douglass [8] extended the Swanson and Tsonis scheme in a number of ways. Using a more global set of indices (*Niño3.4*, north and south Pacific indices and Atlantic Multidecadal Oscillation, AMO) he reported eighteen climate shifts since 1880. In a later paper [13] he studied the Pacific sea surface temperatures in greater detail and found that the data contained two components: N_L, a signal that exhibits the familiar El Niño/La Niña phenomenon,

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Table 1
Summary of climate shifts (CS) and properties of intervening segments. As mentioned in Section 4.3, a deep-ocean-related systematic error of −0.00, +0.09 W/m^2 is associated with these values in addition to the quoted random errors.

Date of CS [12,13]	Segment [8]	Slope = d(OHC)/dt (the uncertainty is determined by the SD values of OHC)	Implied flux imbalance = 0.62d(OHC)/dt − 0.087
		10^{22} J/yr	W/m^2
	Prior to 5	0.37 ± 0.20	0.14 ± 0.12
1964–1966			
	5 February 1963–December 1966	-0.55 ± 0.20	-0.43 ± 0.12
1968–1969			
	6 August 1969–January 1975	0.56 ± 0.20	0.26 ± 0.12
1976–1977			
	7 January 1975–June 1984	0.077 ± 0.15	-0.039 ± 0.090
1984–1987			
	8 September 1985–December 1990		
1991			
	9 June 1991–January 1999	0.67 ± 0.10	0.33 ± 0.06
2001–2002			
	10 June 2001–March 2008	0.086 ± 0.10	-0.034 ± 0.06
2008–2009			

and N_H, a signal of one-year period. Analysis showed the existence of an annual solar forcing F_S and that N_H is phase locked directly to F_S while N_L is frequently phase locked to the second or third subharmonic of F_S. At least ten distinct subharmonic time segments of N_L since 1870 were found. The beginning or end dates of these segments have a near one-to-one correspondence with the abrupt climate changes reported by Douglass [8].

4.3. Comparison with other studies

Again we emphasize the importance of recognizing climate shifts. In particular, it is unsound to calculate a slope across a climate shift. The paper of Lyman et al. [14] is a case in point. These authors reported a radiative imbalance of 0.63 ± 0.28 W/m^2 over the period 1993–2008. This was based on an oversimplified interpretation of the data. The OHC data they considered has a steep slope from 1993 to about 2001–2002, after which there is, in their words, a "flattening", which is identified in the present Letter as the result of the climate shift of 2001–2002. Thus, their estimate of radiation imbalance has little meaning because their slope spans the associated discontinuity.

In paper [4] we studied Argo OHC data in the period after the 2001–2002 climate shift and concluded that the radiation imbalance was negative with an uncertainty that included zero, in agreement with [3] and this study. Contrary to Lyman et al.'s interpretation of OHC data, we therefore found that there was no present empirically implied radiation imbalance and subsequently [11] found no observational justification for an accumulation of the "missing energy" proposed by Trenberth and Fasullo [15] on the basis of model calculations (Hansen et al. [16]). The expected amount of such an accumulation has recently been reduced considerably in a new model-based analysis by Hansen et al. [17].

von Schuckmann and Le Traon [18] considered Argo OHC data covering 0–2000 meters for the period 2005–2010, finding a slope of 0.55 ± 0.1 W/m^2 referenced to the area of the oceans. This becomes 0.38 ± 0.07 W/m^2 when referenced to the area of whole Earth, 29% less than an earlier value given by von Schuckmann et al. [19]. This value, however, is based upon the OHC time segment beginning in 2005. Calculating the OHC slope of the latest NODC data used in this study from 2005 to the present (third quarter of 2011), one obtains a slope of 0.247 ± 0.087 J/yr, whose equivalent flux is 0.170 ± 0.054 W/m^2, which nearly overlaps the NODC values (Table 1, segment 10) given the uncertainties. Thus, the von Schuckmann value of slope may differ in magnitude from those reported here because of the absence of data prior to 2005. The same comment applies to the recent paper by Loeb et al. [20]. Purkey and Johnson [21], in a recent deep-ocean analysis based upon a variety of time periods generally in the 1990s and 2000s, suggest that the deeper ocean contributes on the order of 0.09 W/m^2. To account for this we suggest that a systematic error of −0.0 to +0.09 W/m^2 be attributed to all the flux values.

Meehl et al. [22] show that decadal "hiatuses" are consistent with model predictions of an otherwise constantly rising average Earth temperature. The hiatus coinciding with the past decade is traced to a possible connection with La Niña in the models. This Letter incorrectly states that 1 W/m^2 is an observed radiative imbalance, which it is not, as it is based on model computations (see [11]). The use of the word "hiatus" is obviously based on the assumption that the temperature is always expected to increase.

Is the recent value of flux imbalance -0.034 ± 0.06 W/m^2 consistent with what is expected from various climate forcings? The change in total solar irradiation (TSI) from 2003 to 2010 is −0.49 W/m^2 [23]. When averaged over the surface (a factor of 1/4) and assuming an albedo of 0.70, this represents a solar forcing of −0.086 W/m^2. The geothermal flux is +0.087 W/m^2 [4,24], so that TSI and geothermal contributions just about cancel each other. For this same period, CO_2 increases from 375.8 to 389.8 ppm [25]. Using $\Delta F = 5.35 * \ln(C/C_0)$, the predicted no-feedback CO_2 forcing is 0.196 W/m^2, compared with -0.034 ± 0.06 W/m^2, well outside the uncertainty in the observations. Therefore, the CO_2 forcing feedback would have to be negative to obtain agreement, whereas the models apparently have positive feedback.

All of the OHC-derived (empirical) radiation imbalance values are smaller than the model values quoted by Trenberth and Fasullo and the new model-based value (0.59 W/m^2) of Hansen et al. [17]. Indeed, in our analysis the OHC component of the implied imbalance is sufficiently small that the geothermal contribution is significant and may determine its sign.

Since 2002 the implied radiation imbalance is close to zero. The "pause" or "hiatus" in OHC on which this is based has been recognized numerous times in the recent literature, but its implications for the concept of "missing energy" and the theoretical predictions of radiation imbalance have almost never been brought out. See the discussion by Knox and Douglass [11].

Acknowledgement

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Figure 1

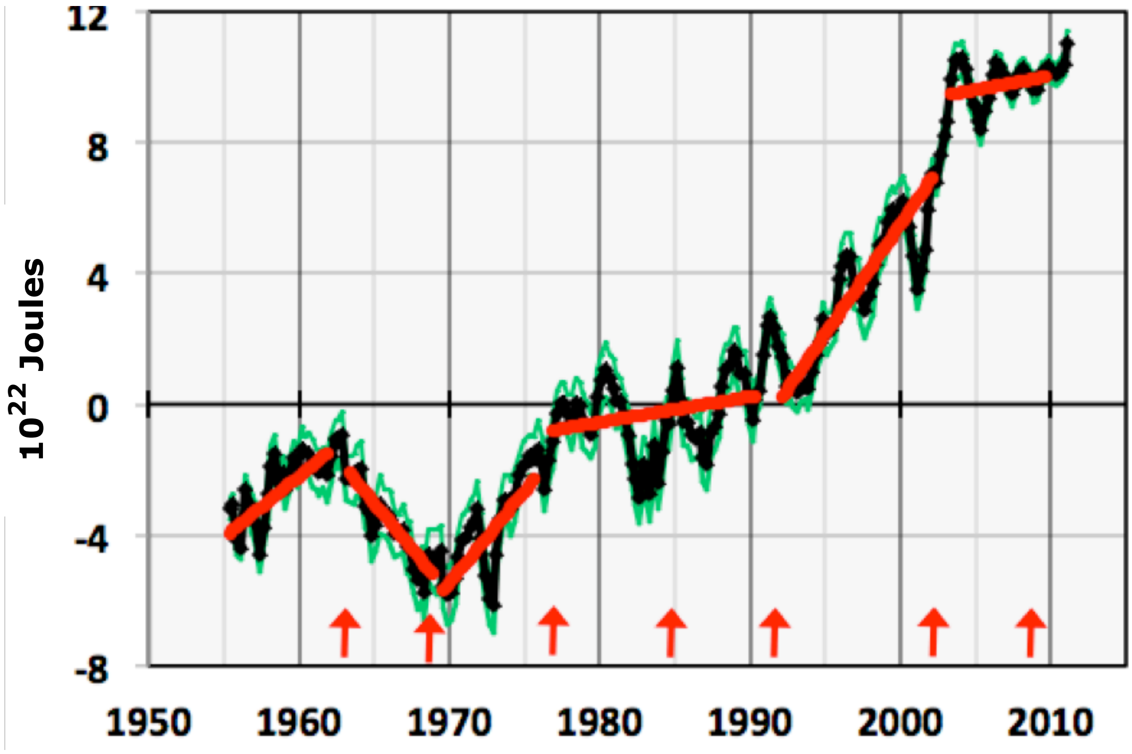

Figure 2