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Supplementary material

This material contains an extended discussion of the energetics (Sec. 2) and tables containing data in support of the Figures.

Notes on Sec. 2

Earth’s climate system is highly complex, but for the purpose of answering rather general questions based on conservation of energy it may be described as follows. It lies between two concentric spheres, an outer one that surrounds the whole system at an altitude of 20 km and an inner one that is beneath the deepest ocean (11 km). It may be divided into four broadly homogeneous components, the atmosphere (A), the land and shelves (L), the upper ocean (O), and the deep ocean (O′), shown schematically in Figure S-1. (Figures and Tables in this Material are designated S-1, S-2, etc.) The average ocean depth is 3800 m.

The principle of conservation of energy provides a strong connection between the energy fluxes through the two spheres and the rate of change of total energy within the CS. The connection reveals a remarkably high correlation between the variations of solar irradiance and the upper ocean heat content on annual to decadal time scales ([1], Chap. 13; [8]). To appreciate this correlation we must spell out the principle as it applies to the whole CS:

(S-1)

where the two area (A) integrals cover the two enclosing spheres and the energy fluxes F_{TOA} and F_{geo} are respectively the net radiative and the geothermal fluxes in $\mathrm{W/m^2}$, both defined as positive inward. The four volume (V) integrals represent the total internal energy of the four components described above.

Three of the volume integrals may be dropped in a first look at the problem. As Pielke [2] points out, in regard to the volume integral, the thermal reservoir of the ocean is much larger than that of the atmosphere and of the land and that other heat reservoirs such as sea and continental ice are inconsequential. The Intergovernmental Panel on Climate Change (IPCC) report [9] agrees; it states that the oceans are the dominant portion of the global energy budget of the earth’s climate system, accounting for more than 90% of the total. For example, the atmosphere’s heat capacity is equivalent to that of about 2.4 m of sea water [10]. While these are true, it is the rate of change of the energy content that concerns us, so that some care must be taken.

The land is less easily dismissed than the atmosphere. It has a large heat capacity but only a thin layer has much time dependence because of the small rate of heat diffusion into the ground. Yet less easily dismissed is the deep ocean O′, which stores a substantial amount of thermal energy on long time scales, but our distinction between O and O′ rules out O′ by definition, namely, O is that part of the ocean that has an appreciable time dependence on the annual-to-decadal scale. The depth of O is subject to various estimates, as discussed in Sec. 3.

Under the assumption that the three terms are negligible, Eq. (1) reduces to

(S-2)

where H_O is the heat content of O. A further assumption is made here, namely, that the kinetic energy of O is negligible; see [1], pp. 204-206.

Let's now consider the flux integrals. The geothermal contribution is constant, but cannot be ignored because it contributes directly. The flux into the ocean and trenches averages 101 ± 2.2 $\mathrm{mW/m^2}$ and that into the land and shelves averages 65 ± 1.6 $\mathrm{mW/m^2}$ (globally averaged, 87 ± 2.0 $\mathrm{mW/m^2}$) [11]. Some fraction of the entire 87 $\mathrm{mW/m^2}$, called F_g, contributes to dH_O/dt. The land and shelves component, measured at the surface, heats the atmosphere and is disposed of the same way as the radiative input is (some out the top as part of F_{rad}, some to O). The ocean floor component, measured at the ocean floor, heats both O and O′. It is possible, therefore, that as little as 30 $\mathrm{mW/m^2}$ contributes to O.

F_{TOA}, which is the net radiative flux at the outer surface, called top-of-atmosphere (TOA), has two sources, solar and terrestrial. It will be taken here as a measured quantity. The net inward solar part is 70% of the incident solar flux; of this, roughly 28% is absorbed by the atmosphere and 72% by the surface. Of the latter, 71% is incident upon O and 29% upon L. Therefore (0.72)*(0.71) = 51% of the absorbed solar contributes directly to dH_O/dt. Although the other 49% absorbed by A and L is largely reradiated as the (negative) terrestrial contribution to F_{TOA}, it contributes indirectly through coupling to L and A and, in principle, carries some additional time delay. The outgoing thermal radiation from A, L, and O originates primarily in A and is therefore only indirectly associated with dH_O/dt. These statements are qualitative and refer to global averages.

We cannot address time delays for those parts of F_{TOA} that are indirectly coupled to dH_O/dt without a specific model of the interactions among the components of the CS. However, as is known [8, 12, 13], and as is seen in the text, there is almost no effective time delay on an annual scale, from which we conclude that either the time constants for energy transfer among O, L, and

A are short compared with one year or that negligible overall transfer takes place. The latter is inconsistent with the magnitude of transfer actually seen to occur.

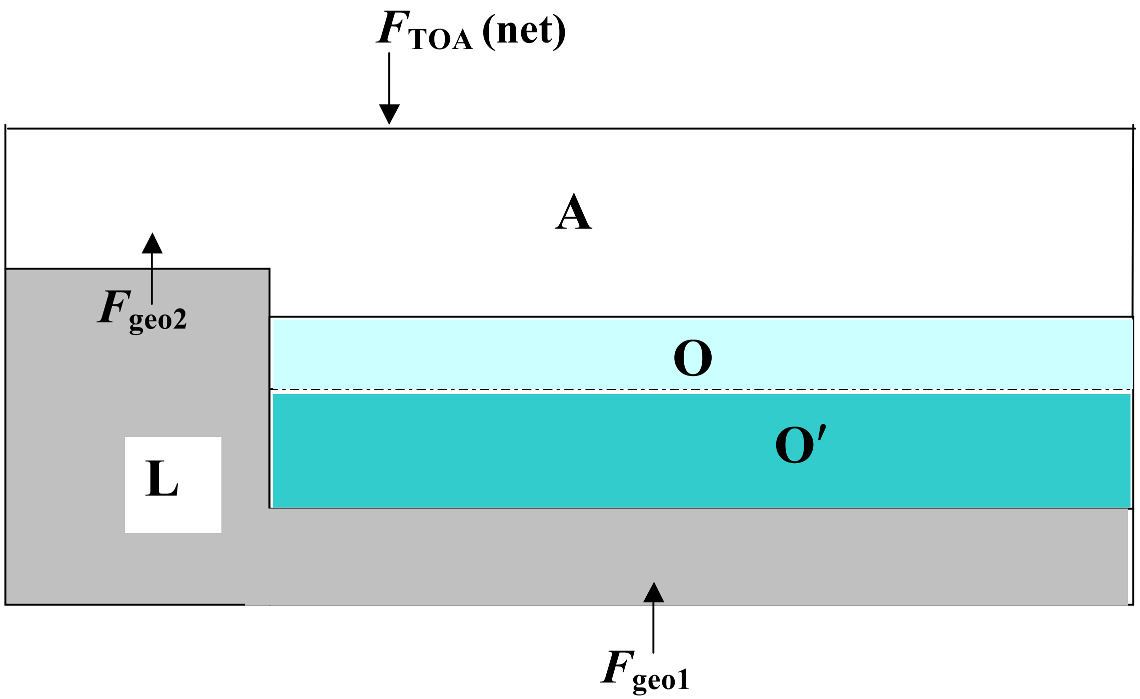
Working with global averages, we may divide each term of Eq. (S-2) by the area of Earth, since this is negligibly different from the area of the outer and inner spherical surfaces being considered. Thus

. (S-3)

In the literature one generally finds the total ocean heat content expressed in units of 10^{22} J = 10 ZJ and time scales in years. When dH_O/dt is evaluated in these units, we have, in W/m^2,

. (S-4)

Figure S-1. Schematic of the climate system and its four homogeneous components as related to overall energetics. A = atmosphere, L = land, O = upper ocean whose energy content is variable on short time scales, O′ = deeper ocean with constant or slowly varying energy content. The varying total energy input, given by the sum of the three fluxes shown with arrows, causes variations in the energy content of O (light blue shading), as discussed in the text. F_{geo1} and F_{geo2} are the partitions of F_{g} discussed qualitatively at the end of Sec. 2.



References for Supplementary material

Numbers/references are identical to those in the main text.

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Table S-1. Ocean heat content (H_O), from various sources as discussed in Sec. 4, and F_{TOA} from CERES

Domingues	Domingues		CERES	CERES	CERES		ARGO	ARGO	ARGO
year	H_O $(10^{22}$ J)		month	year	Net (W/m^2)		month	year	OHC $(10^{22}$ J)
1950.5	**–6.3**		mar	2000	**6.425**		jul	2003	**–0.867**
1951.5	**1.8**		apr		**1.951**		aug		**–3.165**
1952.5	**–4.3**		may		**–5.451**		sep		**–4.183**
1953.5	**–4.3**		jun		**–9.676**		oct		**–3.194**
1954.5	**2.1**		jul		**–8.167**		nov		**0.191**
1955.5	**–1**		aug		**–4.720**		dec		**0.243**
1956.5	**1**		sep		**–1.178**		jan	2004	**–0.334**
1957.5	**–0.1**		oct		**1.635**		feb		**1.334**
1958.5	**10.6**		nov		**4.264**		mar		**3.463**
1959.5	**0.7**		dec		**6.225**		apr		**3.896**
1960.5	**1**		jan	2001	**9.629**		may		**3.306**
1961.5	**0**		feb		**8.715**		jun		**2.857**
1962.5	**3.7**		mar		**7.595**		jul		**–0.652**
1963.5	**1.3**		apr		**1.552**		aug		**–1.615**
1964.5	**–1.4**		may		**–5.728**		sep		**–1.993**
1965.5	**–2.3**		jun		**–8.426**		oct		**–3.164**
1966.5	**3.2**		jul		**–8.089**		nov		**–3.581**
1967.5	**2.1**		aug		**–5.471**		dec		**–2.418**
1968.5	**–2.3**		sep		**0.066**		jan	2005	**–1.515**
1969.5	**–3**		oct		**1.584**		feb		**1.819**
1970.5	**–2.3**		nov		**4.737**		mar		**1.836**
1971.5	**1.8**		dec		**6.009**		apr		**1.889**
1972.5	**–0.1**		jan	2002	**8.508**		may		**1.775**
1973.5	**0.5**		feb		**8.920**		jun		**–1.316**

1974.5	**0.3**		mar		**7.475**		jul		**–3.785**
1975.5	**–0.3**		apr		**1.291**		aug		**–3.968**
1976.5	**–2.3**		may		**–5.103**		sep		**–2.887**
1977.5	**2.4**		jun		**–9.641**		oct		**–2.109**
1978.5	**0**		jul		**–9.444**		nov		**–2.846**
1979.5	**0.5**		aug		**–6.183**		dec		**1.604**
1980.5	**7.4**		sep		**–1.222**		jan	2006	**1.682**
1981.5	**3**		oct		**2.691**		feb		**1.722**
1982.5	**3**		nov		**4.381**		mar		**2.502**
1983.5	**3.9**		dec		**6.333**		apr		**1.755**
1984.5	**3.3**		jan	2003	**7.975**		may		**2.090**
1985.5	**1.7**		feb		**9.120**		jun		**1.570**
1986.5	**4.9**		mar		**6.989**		jul		**–2.162**
1987.5	**6.1**		apr		**1.974**		aug		**–3.420**
1988.5	**7.3**		may		**–5.697**		sep		**–3.344**
1989.5	**9.2**		jun		**–8.929**		oct		**–2.117**
1990.5	**7.1**		jul		**–8.340**		nov		**–2.482**
1991.5	**8.5**		aug		**–4.313**		dec		**–0.650**
1992.5	**6**		sep		**–0.725**		jan	2007	**–0.691**
1993.5	**7.7**		oct		**2.049**		feb		**0.087**
1994.5	**8.6**		nov		**4.440**		mar		**0.612**
1995.5	**8.2**		dec		**6.047**		apr		**0.393**
1996.5	**11.2**		jan	2004	**9.117**		may		**0.162**
1997.5	**11.6**		feb		**9.721**		jun		**–1.586**
1998.5	**7.9**		mar		**5.973**		jul		**–1.642**
1999.5	**7.8**		apr		**2.840**		aug		**–5.994**
2000.5	**9.1**		may		**–5.952**		sep		**–4.272**
2001.5	**10.4**		jun		**–9.928**		oct		**–3.422**
2002.5	**13.5**		jul		**–7.360**		nov		**0.003**
2003.5	**11.8**		aug		**–4.507**		dec		**–0.204**
			sep		**-0.207**		jan	2008	**0.742**

			oct		**2.036**		feb		**4.926**
			nov		**4.901**		mar		**3.466**
			dec		**7.728**		apr		**4.837**
			jan	2005	**8.736**		may		**3.339**
			feb		**8.615**		jun		**0.967**
			mar		**7.210**				
			apr		**1.988**				
			may		**–3.631**				
			jun		**–9.083**				
			jul		**–8.982**				
			aug		**–5.188**				
			sep		**–0.431**				
			oct		**2.039**				

Table S-2. Properties of the top-of-atmosphere radiation balance during 2000-2008 as measured (CERES) and as implied by ocean heat content variation (Argo), compared with the principal forcing (solar eccentricity effect). F_{TOA} values are in W/m^2.

	CERES [24] **Mar 2000 to oct 2005**	**Argo [19]** **Jul 2003 to jun 2008**	**Solar eccentricity effect**	**Comment**
Mean of F_{TOA}	–0.303±0.187 Systematic error = 4.3 [22]. Adjust to mean of Argo in overlap period	–0.244±0.990 [includes –0.087 from interior heat of earth]	0	
Slope of F_{TOA}	–0.485 (W/m^2)/yr	0.001 ± large (end effects)		Solar is in decreasing part of 11 year cycle –0.055(W/m^2)/yr 2001 to 2007
peak-to-peak span of F_{TOA}	18.7 ±0.7 Depends on instrument calibration	17.3±2 Depends on instrument calibration and 0.62.	22.7 Depends on S_0; No uncertainty	All in phase. Max near January. CERES≈Argo;
Slope of peak-to-peak of F_{TOA}	–0.016 ±0.86 W/m^2/year Expect 0 from eccentricity effect	–1.16±3.19	0	CERES and ARGO consistent with zero

Table S-3. Summary of implied and measured values of F_{TOA}. Values in the fourth column that are derived from the third column are reduced by $F_g = 0.087$ W/m^2 because of the geothermal energy contribution.

Source	**Time period**	**dH_O/dt in flux units (W/m^2)**	**Implied or measured F_{TOA} (W/m^2)**	**Comment**
Levitus *et al*. [16]	1955–1998	+0.20	+0.113	0 to 3000m ΔH_O data
Levitus *et al*. [18]	1969-2003	0.198±0.03	0.111±0.03	
Levitus *et al*. [18]	2004-2007	0±0.03	–0.087±0.03	
IPCC [9] chap 5, page 387	1961–2003	+0.21±0.04	+0.123±0.04	0 to 3000m Based on [16]
Domingues et al. [14]	1961–2003	+0.23±0.04	+0.143±0.04	0 to 700m ΔH_O data
Domingues [15]; this paper	1960–1975	–0.06±0.11	–0.15±0.11	0 to 700m ΔH_O data
Domingues [15]; this paper	1975–2000	+0.24±0.07	+0.15±0.07	0 to 700m ΔH_O data
Argo [13]; this paper	2003.7–2008.5	–0.153±0.99	–0.240±0.99	0 to 750m ΔH_O data
CERES [24]; this paper	2000.5–2005.5		–0.303±0.19	Mean from Argo TOA matched 2003-2005
Hansen *et al.* [28]	value at 2003		+0.85±0.15	Model calculation
IPCC 2007, Fig SPM.2, page 5	value at 2005		+1.6 (0.6 to 2.4)	Differs from IPCC [9]
Argo [26]	2003–2008	–0.22±0.3	–0.31±0.2	