Revisiting the Earth's sea-level and energy budgets from 1961 to 2008

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[1] We review the sea-level and energy budgets together from 1961, using recent and updated estimates of all terms. From 1972 to 2008, the observed sea-level rise (1.8 ± 0.2 mm yr^{-1} from tide gauges alone and 2.1 ± 0.2 mm yr^{-1} from a combination of tide gauges and altimeter observations) agrees well with the sum of contributions (1.8 ± 0.4 mm yr^{-1}) in magnitude and with both having similar increases in the rate of rise during the period. The largest contributions come from ocean thermal expansion (0.8 mm yr^{-1}) and the melting of glaciers and ice caps (0.7 mm yr^{-1}), with Greenland and Antarctica contributing about 0.4 mm yr^{-1}. The cryospheric contributions increase through the period (particularly in the 1990s) but the thermosteric contribution increases less rapidly. We include an improved estimate of aquifer depletion (0.3 mm yr^{-1}), partially offsetting the retention of water in dams and giving a total terrestrial storage contribution of -0.1 mm yr^{-1}. Ocean warming (90% of the total of the Earth's energy increase) continues through to the end of the record, in agreement with continued greenhouse gas forcing. The aerosol forcing, inferred as a residual in the atmospheric energy balance, is estimated as -0.8 ± 0.4 W m^{-2} for the 1980s and early 1990s. It increases in the late 1990s, as is required for consistency with little surface warming over the last decade. This increase is likely at least partially related to substantial increases in aerosol emissions from developing nations and moderate volcanic activity. **Citation:** Church, J. A., N. J. White, L. F. Konikow, C. M. Domingues, J. G. Cogley, E. Rignot, J. M. Gregory, M. R. van den Broeke, A. J. Monaghan, and I. Velicogna (2011), Revisiting the Earth's sea-level and energy budgets from 1961 to 2008, *Geophys. Res. Lett.*, *38*, L18601, doi:10.1029/2011GL048794.

1. Introduction

[2] Sea-level rise is a high-profile and important aspect of climate change. However, in the last two Intergovernmental Panel on Climate Change (IPCC) assessments, the sum of observed contributions to sea-level rise has consistently been less than the observed rise over multi-decadal periods, thus reducing confidence in the sea-level projections. *Domingues et al.* [2008], and more recently *Moore et al.* [2011], made significant progress in closing the sea-level budget from 1961 to 2003. However, to do so, they had to estimate multi-decadal trends for the ice sheets, rather than use observed or calculated time series, and as a result they failed to reproduce the observed decadal variability in sea levels.

[3] Closing the sea-level budget requires accurate estimates of ocean thermal expansion and the related ocean heat-content change, by far the largest storage of heat in the climate system [*Bindoff et al.*, 2007]. Despite the Earth's energy budget being one of the most fundamental aspects of the climate system there have been failures to adequately resolve the energy budget for recent years [*Trenberth*, 2010; *Trenberth and Fasullo*, 2010].

[4] Clearly, the Earth's sea-level and energy budgets are closely related and must be solved in a consistent manner. We therefore consider them together, using new and updated estimates of all terms for the past five decades. By updating the time series of sea-level rise and its contributions, including a new estimate of groundwater depletion, we find an improved closure of the sea-level budget from 1972 to the present, both in the mean trends from 1972 to 2008, and also the variability. We also use these estimates to look at the implications for the energy budget calculation of *Murphy et al.* [2009].

2. The Components of Sea-Level Change and Earth's Energy Storage

[5] Time series from 1961 to 2008 of all of the contributions to the sea-level and energy budgets are given in Figures 1–3. Because of the uncertainty affecting estimates of the contributions during the 1960s, linear trends in the sea-level budget (Table 1) are given for 1972 to 2008 and 1993 to 2008. Similarly, integrals of components of the energy budget from 1972 to 2008 and 1993 to 2008 are shown in Table 2.

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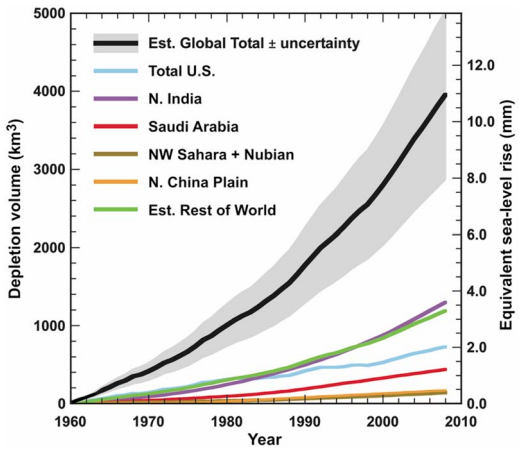

Figure 1. Cumulative net groundwater depletion, 1961–2008.

2.1. Changes in the Terrestrial Storage of Water

[6] Previous studies of sea-level change lacked robust estimates of groundwater depletion. We use results from a recent study of *Konikow* [2011]. Data on the long-term net depletion of groundwater (the net reduction in the volume of water stored in the subsurface saturated zone), computed directly on a volumetric basis, are most widely available in the United States, but generally sparse or unavailable elsewhere. Depletion volumes and rates in the U.S.A. [*Konikow*, 2011] (Figure 1) were calculated using comprehensive calibrated groundwater simulation models, analytical approaches [e.g., *Konikow and Neuzil*, 2007], and/or groundwater budget analyses applied to 41 separate aquifer systems or geographic subareas of aquifer systems.

[7] Global depletion is calculated where direct estimates are available (Figure 1 and Table S1 in the auxiliary material), and estimated for unmeasured areas outside of the U.S.A. by correlations with global pumpage estimates.[1] In the U.S.A., total groundwater withdrawals in 2000 were 115 km^3 [*Hutson et al.*, 2004], and the total depletion that year was 17.7 km^3, or 15.4% of withdrawals. The total global withdrawals that year [*Margat and Custodio*, 2004; *Shah et al.*, 2007] were 800 km^3. Assuming that the global depletion represents about the same fraction of global withdrawals as in the U.S.A., then global depletion would be approximately 123 km^3. Data from the U.S.A. and several aquifer systems outside the U.S.A. indicate a net depletion in 2000 of 86 km^3, so the unaccounted depletion in the rest of the world would be 37 km^3 —30% of the total and slightly more than twice that in the U.S.A. The temporal rate of depletion from 1960–2008 was estimated in 46 separate areas by computations from calibrated simulation models or by correlation with pumpage records or water-level records. The average time rate was then applied (assuming a constant value) to the uncounted depletion in the rest of the world, yielding the rates shown in Figure 1. The uncertainty in each approach was estimated, and the weighted average indicated that the uncertainty in the global estimate is ±27%.

[8] *Konikow*'s [2011] calculations indicate that during 1961–2008, groundwater was depleted by 727 km^3 in the U.S.A. (averaging 15.2 km^3 yr^{-1}), equivalent to a global sea-level rise of 2.0 mm in the 48-year period. Global groundwater depletion during 1961–2008 was 3,960 km^3, and the rate of depletion averaged 82 ± 22 km^3 yr^{-1} (0.23 ± 0.06 mm yr^{-1}) during the 48-year period. The depletion rate was increasing and was 122 km^3 yr^{-1} (0.34 mm yr^{-1}) during 2000 and 140 km^3 yr^{-1} (0.39 mm yr^{-1}) during 2008, which can account for 12% of the reported recent rate of sea-level

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048794.

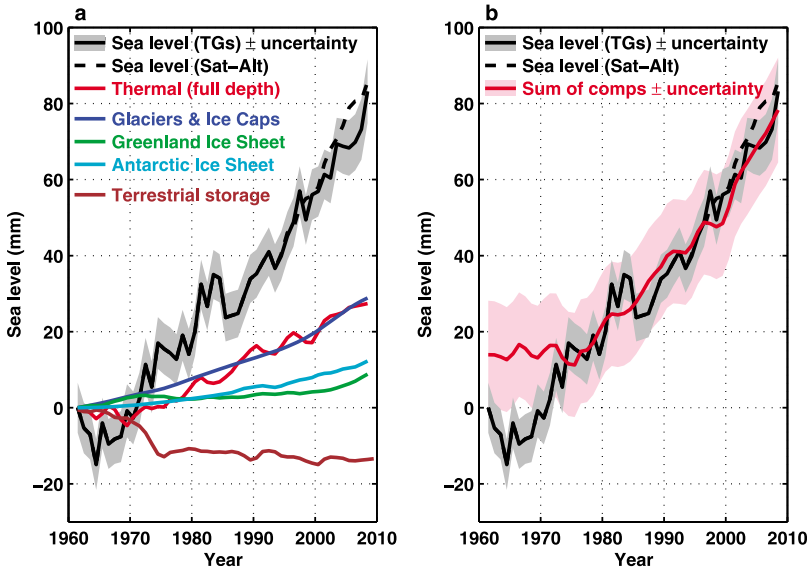

Figure 2. The global sea-level budget from 1961 to 2008. (a) The observed sea level using coastal and island tide gauges (solid black line with grey shading indicating the estimated uncertainty) and using TOPEX/Poseidon/Jason-1&2 satellite altimeter data (dashed black line). The two estimates have been matched at the start of the altimeter record in 1993. Also shown are the various components as described in the text. (b) The observed sea level and the sum of components. The estimated uncertainties (consistent with Table 1) are indicated by the shading. The two time series are plotted such that they have the same average over 1972 to 2008.

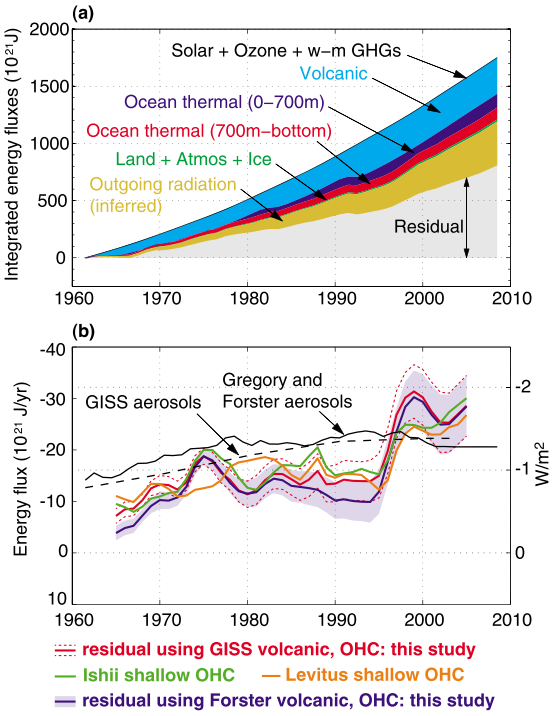

Figure 3. The Earth's energy budget from 1961 through 2008. (a) The top line indicates the integrated radiative forcing from well-mixed greenhouse gases, ozone and solar changes. This radiative forcing is offset by the cooling due to stratospheric aerosols from volcanic eruptions (cyan), the warming of the upper (0 to 700 m) ocean (blue), the deep ocean (red) and energy absorbed in the melting of ice and warming the atmosphere and the land (green), and the change in outgoing radiation inferred from temperature change (brown). The integrated aerosol (and other) forcing is estimated as a residual (grey). (b) The inferred global averaged aerosol radiative cooling (red) is calculated for three different values of λ [1.25 W m^{-2} K^{-1} (solid) and 0.75 W m^{-2} K^{-1} and 1.75 W m^{-2} K^{-1} (dashed)]. The aerosol coolings for the central value of λ are also given for the *Ishii and Kimoto* [2009] and *Levitus et al.* [2009] heat content estimates (green and orange respectively). The equivalent results for the *Gregory and Forster* [2008] volcanic forcing and the present heat content estimates are shown by the blue line and shading. Results from previous aerosol forcing estimates of *Gregory and Forster* [2008] and GISS forcing are shown in black solid and dashed respectively.

rise of 3.2 mm yr^{-1}, estimated from satellite altimeter data [*Church and White*, 2011].

[9] The method used by *Konikow* [2011] contrasts with the approach followed by *Wada et al.* [2010], who estimated depletion indirectly from the difference between global-model based estimates of natural recharge and indirect estimates of withdrawal fluxes. Their approach assumes that depletion equals the difference between natural recharge and (anthropogenic) withdrawals, and may inadequately account for surface water-groundwater interactions, artificial recharge, and the fact that withdrawals are also compensated by reductions in natural discharge and increases in recharge, as described by *Theis* [1940]. Consequently, the *Wada et al.* [2010] estimates are almost a factor of two larger than the Konikow estimates used here.

[10] The retention of water in man-made reservoirs, with associated seepage into the surrounding soil [*Chao et al.*, 2008], reduced sea level by around 30 mm from 1900 to 2008, mostly after 1950 (slightly over 0.5 mm yr^{-1}; no error bars are given and we assign an uncertainty of 30% based on the difference between the nominal and actual reservoir

Table 1. The Sea-Level Budget[a]

Component	1972 → 2008	1993 → 2008
Total s.l. (t.g. only)	**1.83 ± 0.18**[b]	**2.61 ± 0.55**
Total s.l. (t.g. + sat)	**2.10 ± 0.16**	**3.22 ± 0.41**
Shallow thermal (0–700m)	0.63 ± 0.09	0.71 ± 0.31
Deep thermal (700–3000m)	0.07 ± 0.10	0.07 ± 0.10
Abyssal thermal (3000m-bottom)	0.10 ± 0.06	0.10 ± 0.06
Total thermal (full depth)	**0.80 ± 0.15**	**0.88 ± 0.33**
Glaciers & Ice Caps	0.67 ± 0.03	0.99 ± 0.04
Greenland Ice Sheet	0.12 ± 0.17	0.31 ± 0.17
Antarctic Ice Sheet	0.30 ± 0.20	0.43 ± 0.20
Land ice (G&IC, GIS, AIS)	**1.09 ± 0.26**	**1.73 ± 0.27**
Thermal (full depth) + Land ice	**1.89 ± 0.30**	**2.61 ± 0.42**
Dam retention	−0.44 ± 0.15	−0.30 ± 0.15
Groundwater depletion	0.26 ± 0.07	0.35 ± 0.07
Natural terrestrial storage	0.07 ± 0.10	−0.14 ± 0.10
Total terrestrial storage	**−0.11 ± 0.19**	**−0.08 ± 0.19**
Total mass contributions	**0.98 ± 0.33**	**1.66 ± 0.33**
Total thermal + Mass	**1.78 ± 0.36**	**2.54 ± 0.46**
Residual (t.g. only)	**0.05 ± 0.40**	**0.08 ± 0.72**
Residual (t.g. + sat)	**0.32 ± 0.39**	**0.69 ± 0.62**

[a]Linear trends in mm yr^{-1} (with one standard deviation error estimates) are shown for the sea-level time series from the reconstructed tide-gauge data (t.g.) and from joining the altimeter data to the reconstructed data in 1993 (t.g. + sat) and for each term in the sea-level budget for two separate time intervals. Uncertainty estimates for the sea level, shallow thermal expansion and the ground water depletion are from our analysis and all other uncertainty estimates are from the relevant publications as cited in the text.

[b]Bold numbers indicate sum of other rows, as indicated in first column.

Table 2. The Earth's Heat Budget[a]

Component	1972–2008	1993–2008
Shallow ocean (0–700m)	112.6	45.9
Deep ocean (700–3000m)	49.7	20.7
Abyssal ocean (3000m-bottom)	30.7	12.8
Total ocean storage	**193.0**[b]	**79.4**
Glaciers (Latent only)	3.0	1.7
Antarctica (Latent only)	1.4	0.8
Greenland (Latent only)	0.7	0.6
Sea ice	2.5	1.0
Continents	4.7	2.0
Atmosphere	2.0	1.2
Total other storage	**14.2**	**7.3**
Total storage	**207.2**	**86.7**
Solar + Ozone + well-mixed GHGs	**1461.7**	**709.6**
Energy consumption	13.0	6.5
Volcanic (GISS)	−207.8	−14.6
Outgoing radiation	−343.4	−199.3
Total forcing	**923.6**	**502.2**
Total forcing - Total storage	**716.4**	**415.5**

[a]The integrated changes in the heat storage and the radiative forcing are in units of 10^{+21} J. The total forcing minus the total storage is the amount of energy that must be balanced by the aerosol cooling (or other climate forcing).

[b]Bold numbers indicate sum of other rows, as indicated in first column.

capacity and that the reservoirs are assumed to be 85% full). Natural exchanges with terrestrial reservoirs average out to near-zero over multi-decadal time periods [*Ngo-Duc et al.*, 2005; *Milly and Shmakin*, 2002] but can have larger rates over shorter periods. The total terrestrial storage term partially offsets other contributions to sea-level rise (Figure 2a).

2.2. Ocean Changes

[11] For 1961 to 2008, upper (0–700 m) ocean thermosteric sea level and heat content were updated from *Domingues et al.* [2008]. Ocean temperature profiles (1960–2004) are from the ENACT/ENSEMBLES version 3b (EN3b) data base [*Ingleby and Huddleston*, 2007] for bottles, Conductivity-Temperature-Depth (CTDs) and eXpendable BathyThermographs (XBTs). To minimise biases in XBT data [*Gouretski and Koltermann*, 2007], we use a time-dependent (but depth constant) fall-rate correction [*Wijffels et al.*, 2008]. To complement the above EN3b data selection, we use the most recent version of quality-controlled Argo data (2000–2008), corrected for pressure biases [*Barker et al.*, 2011].

[12] Thermal expansion and heat content estimates of the upper 700 m of the global ocean fall by about 7 mm and 40×10^{21} J from 1961 to 1969 and then rise steadily, oscillating (less than 5 mm and 30×10^{21} J) around the long-term trends, contributing almost 18 mm and 124×10^{21} J by 2008, with respect to 1961. Because of a lack of data, we use a linear trend for the deep-ocean contribution. For the depth range 700–3000 m for 1955 to 2003, the trends are 0.07 ± 0.1 mm yr^{-1} and 1×10^{21} J yr^{-1} [*Levitus et al.*, 2005; *Antonov et al.*, 2005], but these estimates may be biased low because of inadequate deep-ocean sampling, particularly in the early part of the record. Below 3000 m and since the 1980s, the trends are 0.09 ± 0.06 mm yr^{-1} and 1×10^{21} J yr^{-1} [*Purkey and Johnson*, 2010]. There are few long-term observations to indicate if this is a recent or a longer-term trend. Either way, it would contribute less than 5 mm to sea level since 1961 and we use this trend for the full period. The full-depth thermal expansion is about 25 mm over 1961–2008 (Figure 2a; 0.8 ± 0.1 mm yr^{-1} since 1972).

2.3. Glaciers and Ice Caps

[13] The contributions from Glaciers and Ice Caps (G&IC) were updated from *Cogley* [2009] by interpolation of direct (in-situ) and geodetic (based on repeated mapping and leading to larger estimates than previous results) measurements of mass balance for the entire glacierized area outside the Greenland Ice Sheet (GIS) and Antarctica [*Cogley*, 2009]. The contributions from glaciers around the Antarctic Ice Sheet (AIS), where measurements are few, were obtained by upscaling [*Cogley*, 2009]. The G&IC contributions, with pentadal resolution from 1951–2008, are interpolated to yearly values. G&IC melting contributed over 30 mm for the full period and increased in the mid 1970s and the late 1990s. Comparatively little energy is required to melt this quantity of glacial ice (4×10^{21} J).

2.4. Greenland and Antarctica

[14] We use an improved estimate of the GIS contribution defined by the ice discharge minus the surface mass balance [*Rignot et al.*, 2008, 2011; *van den Broeke et al.*, 2009]. It is positive from 1961 to the early 1970s, then essentially zero until the 1990s when it becomes positive once more and contributes to sea-level at a rate similar to ocean thermal expansion.

[15] The mass balance of the AIS is less well constrained and remains controversial (for example, see *Velicogna* [2009] versus *Zwally and Giovinetto* [2011]). We use the estimates of *Rignot et al.* [2011] which are based on atmospheric climate models constrained by re-analysis data and ice discharge estimates from 1980. The latter are derived from velocities determined from satellite synthetic aperture radar data and ice thickness, mostly from radar echo sounding. The Antarctic contribution increases through the 1990s and is consistent with GRACE gravity data since 2003 [*Velicogna*, 2009]. Prior to 1980, we assume a value of 0.1 mm yr^{-1} in 1950 (based on the work by *Lemke et al.* [2007, p. 365]) and then interpolate to yearly values. The 1950 value is not well determined and could be in the range from zero to perhaps as much as 0.4 mm yr^{-1}; the value chosen here is also consistent with the IPCC Fourth Assessment Report (AR4) estimates. Using either zero or 0.2 mm yr^{-1} in 1950 would alter the integrated sea-level change from 1950 to the end of the record by less than 2 mm. The AIS contributes slightly more than Greenland over the full period. Melting of the Greenland and Antarctic ice over 1972 to 2008 requires about 2×10^{21} J and melting of sea ice [*Levitus et al.*, 2005] a similar amount.

[16] Note that from 2004 to the end of the record, the ice sheets contribute to sea level at a combined rate of 1.3 ± 0.4 mm yr^{-1}, approaching the estimated combined rate from upper ocean thermal expansion and the melting of G&ICs.

2.5. Other Contributions

[17] Changes in atmospheric water content [*Trenberth et al.*, 2005] and the melting of sea ice and ice shelves [*Shepherd et al.*, 2010] make insignificant contributions to sea level change. The additional heat storage in the atmosphere is computed from the mass of the atmosphere (5.3×10^{18} kg) [*Gill*, 1982] and the heat capacity C_p of 1000 J kg^{-1} K^{-1}. This amounts to 2.0×10^{21} J since 1972. *Huang* [2006] estimates the additional heat stored in the ground from 1950 to 2000 as 6.7×10^{21} J and we assume this increase to be linear. The geothermal heat flux of 0.087 W m^{-2} [1.4×10^{21} J yr^{-1}; *Pollack et al.*, 1993] is not included in the budget as this remains relatively constant over time and is not a component of the perturbations to the energy budget since preindustrial times that we focus on here. For comparison, we do include the anthropogenic consumption of energy using a 1980–2006 estimate from the US Energy Information Administration (http://www.eia.gov/pub/international/iealf/tablee1.xls), linearly extrapolated to 1972 and 2008. Although increasing rapidly, this term (0.4×10^{21} J yr^{-1}, less than 0.01 W m^{-2}) is more than 100 times smaller than the forcing from greenhouse gases and more than an order of magnitude less than the energy required for the observed heat storage increases.

3. Observed Sea-Level Rise and the Sea-Level Budget

[18] We use an estimate of global averaged sea level from *Church and White* [2011]. From 1993 to 2009, they estimated global-averaged sea level with satellite altimeter data using standard techniques. For the period from 1961, they 'reconstructed' sea level using coastal and island tide gauges

and empirical orthogonal functions of sea level calculated with satellite altimeter data. *Fiedler and Conrad* [2010] indicate that there can be an important impact on tide-gauge data from terrestrial loading and gravitational changes resulting from dam storage. However, for the large number of tide gauges used here (over 200), we estimate the impact of this correction (which we include) on global mean sea level is only about 0.05 mm yr^{-1}. Similar corrections for changes in the cryosphere are smaller, at least until recently. The satellite and the in situ sea-level time series have also been corrected for glacial isostatic adjustment [*Davis and Mitrovica*, 1996; M. Tamisiea, personal communication, 2004] so that the sea-level estimates are a measure of changes in ocean volume.

[19] The reconstructed sea level falls more than 10 mm from 1961 to 1966 and then rises to the end of the record with small oscillations of about 5 mm partly related to volcanic eruptions [*Domingues et al.*, 2008]. The greater rate of rise after 1993 in the tide-gauge data is confirmed by satellite altimeter observations. The reconstructed sea level mostly agrees with the more accurate satellite data within uncertainty limits and over the satellite record the total rise is almost identical but the linear trend for the tide gauges over the 1993–2008 period is smaller (by about 20%).

[20] The sum of the contributions agrees well with the observed rate of sea-level rise, and certainly within error bars (Figure 2b and Table 1) from 1972. Error estimates (Table 1) come from weighted least-squares estimates of the trends for observed sea level and upper-ocean thermal expansion, and for the remaining time series from uncertainty estimates provided by the originators of the data sets (where given). Thermal expansion contributes about 40% of the observed rise since 1972, the proportion decreasing as the ice contributions increase. The sum of the glacier and thermosteric contributions explains approximately 75% of the observed rise since 1972. It is also clear that both the Greenland and Antarctic ice sheets are an important component in closing the sea-level budget, particularly since 1993, as found for example by *Cazenave and Llovel* [2010]. The larger differences between the sum of contributions and the observed sea-level change occur in the 1960s when sea level, thermal expansion and terrestrial storage estimates fall but the poorly constrained cryospheric contributions are positive. This poorer agreement may be a result of the poorer ocean (the number of ocean observations increased significantly in the early 1970s) and cryospheric data coverage in the 1960s. As a result, it is likely we cannot adequately resolve the response to and the recovery from the 1963 volcanic eruption of Mount Agung. The response of the climate system to volcanic eruptions in the 1980s and 1990s is likely to be better observed but perhaps still incompletely resolved.

[21] From 1993, the sum of contributions is not significantly different to the observed rise but the linear trend in the altimeter observations is larger. A larger terrestrial storage component, as inferred by *Wada et al.* [2010], would reduce these differences. Note that similar sea-level budget closures for 1955 to 2005 [e.g., *Moore et al.*, 2011] and 1993 to 2007 [e.g., *Cazenave and Llovel*, 2010] have recently been obtained using slightly different contributions from those estimated here. A significant issue remains the identification of systematic errors in the observational data base. For example, the IPCC AR4 sea-level budget for 1993–2003 [*Bindoff et al.*, 2007] has an upper-ocean thermosteric sea-level rise of 1.6 mm yr^{-1}. This is about twice the current estimates (Table 1), inconsistent with ocean warming estimated using XBT data corrected for fall-rate errors [*Wijffels et al.*, 2008].

4. Implications for the Earth's Energy Budget

[22] We follow the approach of *Murphy et al.* [2009] to examine the Earth's energy balance. We use updates of radiative forcing (F) from well-mixed greenhouse gases and fluctuations in solar radiation [*Gregory and Forster*, 2008] (with the stratospheric ozone scaled as by *Murphy et al.* [2009]) and volcanic aerosols from the Goddard Institute for Space Studies (GISS) [*Sato et al.*, 1993], updated at http://data.giss.nasa.gov/modelforce/RadF.txt, and *Gregory and Forster* [2008]. Integrated from 1961 through to the end of 2008, well-mixed greenhouse gases, ozone and solar forcing would result in the storage of $1{,}735 \times 10^{21}$ J of additional heat in the Earth's system if it were all retained (Figure 3). However, as discussed in section 2, only 250×10^{21} J (234 from 1961–2008, 207 from 1972–2008) of the forcing is stored in the Earth system (Figure 3a and Table 2), over 90% in the ocean with minor storage in the atmosphere and the solid earth and consumption in the melting of ice. Negative radiative forcing from volcanic aerosols offset about 320×10^{21} J (317 for *GISS*, 398 for *Gregory and Forster* [2008]) of the greenhouse gas forcing. The remaining portion (1200×10^{21} J; 1190 for the whole period, 1060 for 1972–2008) must be balanced by the sum of reflection of solar radiation by tropospheric aerosols and increased radiation from a warming Earth.

[23] The rate of storage of heat by the climate system equals the net heat flux into the climate system $N = F - \lambda\Delta T$, where F is the radiative forcing, ΔT is the global averaged temperature change and the climate feedback parameter λ is assumed constant over this period (but see discussion below). This parameter is inversely related to climate sensitivity to a doubling of carbon dioxide, $\Delta T_{eq} = 3.7\ \mathrm{W\ m^{-2}}/\lambda$. *Murphy et al.* [2009] used a regression of $N - F$, with N determined from satellite radiative flux data from the ERBE and CERES missions, against the global averaged temperature change ΔT to make an observational estimate of the climate feedback parameter. The regression is subject to a large systematic uncertainty; here we use the central value for the regression slope $\lambda = 1.25 \pm 0.5\ \mathrm{W\ m^{-2}\ K^{-1}}$ [*Murphy et al.*, 2009]. This value, combined with global surface temperature observations (HadCRUT3: file hadcrut3gl.txt downloaded from http://www.cru.uea.ac.uk/cru/data/temperature/ on 09-Jul-2010), results in a time-integral of the climate radiative response $\lambda\Delta T$ of 384×10^{21} J from 1961 to 2008. Following *Murphy et al.* [2009], the time-integrated cooling due to tropospheric aerosol (and any unidentified forcings) is inferred as the time-integral of the other forcings (well-mixed greenhouse gas, solar and volcanic) minus the sum of the heat storage and the time-integrated climate radiative response, and amounts to 800×10^{21} J (Figure 3a and Table 2) [716 for 1972–2008, 815 for 1961–2008].

[24] Expressed as a flux, the inferred aerosol forcing for the GISS volcanic forcing and the central value of the climate parameter changes from about $-0.5\ \mathrm{W\ m^{-2}}$ in the 1960s to $-1.2\ \mathrm{W\ m^{-2}}$ in the mid 1970s and then averages about $-0.9\ \mathrm{W\ m^{-2}}$ to the mid 1990s (Figure 3b). The

increasing aerosol forcing prior to the mid 1970s may be related to increased industrial aerosol emissions from coal burning, with the small decrease from the mid 1970s to the mid 1990s possibly related to the introduction of sulphur-emission capture technology used successfully to reduce the impacts of acid rain. In the early 1990s, the inferred aerosol forcing for the range of climate feedback parameters ranges from -0.7 W m^{-2} to -1.1 W m^{-2} for the GISS volcanic forcing and from -0.4 W m^{-2} to -0.9 W m^{-2} for the *Gregory and Forster* [2008] volcanic forcing. These results imply a central estimate of -0.8 ± 0.4 W m^{-2} for the 1980s and early 1990s. The inferred negative aerosol forcing is smaller (but not significantly so) than the estimates from *Gregory and Forster* [2008] of -1.3 W m^{-2}, *Hansen et al.* [2005] of -1.2 W m^{-2} (http://data.giss.nasa.gov/modelforce/) and *Murphy et al.* [2009] of -1.1 ± 0.4 W m^{-2} but larger than the estimate of the direct forcing of -0.3 ± 0.2 W m^{-2} of *Myhre* [2009]. The magnitude of the inferred aerosol forcing increases in the late 1990s and early 2000s to more than -1.5 W m^{-2} (Figure 3b) by the end of the record.

[25] *Murphy et al.* [2009] argued that a similar increase in their slightly shorter time series was most likely due to uncertainties in ocean heat storage rather than changes in aerosol or cloud forcing. The estimated statistical uncertainties of ocean heat content estimates are less than the observed increase, but the remaining systematic uncertainties in ocean heat-content changes are difficult to quantify and are the subject of ongoing research. The 1997/98 *El Niño* event is likely to affect ocean heat storage. It is possible that part of the dip in heat storage (and thermal expansion, Figure 2a) in our time series in 1998 is a result of unresolved XBT biases and/or sampling issues during the 1997/98 *El Niño* event. This fall is less prominent in the *Ishii and Kimoto* [2009] and *Levitus et al.* [2009] (http://www.nodc.noaa.gov/OC5/indprod.html) ocean heat-content estimates. However, when these alternative ocean heat-content estimates are used, a similar (but not as abrupt) increase is found in the inferred aerosol forcing (Figure 3b). From 2002 to the end of the record, our estimate of the rate of ocean heat-content increase is about 0.4 W m^{-2} (averaged over the whole globe), similar to the more accurate Argo-derived estimate for 2005 to 2010 of 0.55 ± 0.1 W m^{-2} over the ocean [*von Schuckmann and Le Traon*, 2011] but mostly larger than other Argo estimates [*Llovel et al.*, 2010].

[26] For the inferred increase in aerosol cooling to be an artefact of inaccurate heat content estimates after 2000, more than 0.6 W m^{-2} over the globe (0.8 W m^{-2} into the ocean) of additional ocean heat storage is required. This would mean more than doubling our estimates and the Argo estimate of *von Schuckmann and Le Traon* [2011] of upper-ocean warming (with even larger increases for the other smaller Argo estimates, see *Llovel et al.* [2010]). The sea-level budget can also be used to constrain the heat budget. If the additional global average heat flux was stored in the ocean it would imply more than an additional 1 to 1.3 mm yr^{-1} global averaged thermosteric sea-level rise from 2000, and the sum of contributions to sea-level rise would be larger than the sea-level rise measured by altimeters from 2000 to 2008.

[27] A potential alternative explanation for the significant change in aerosol loading is that λ changes over time and/or when the relative strengths of greenhouse-gas forcing and volcanic forcing change. The volcanic forcing decreased to near zero after 2000. A value of λ at the lower end of the range (0.75 W m^{-2} K^{-1}; climate sensitivity of 4.9°C) implies an aerosol forcing closer to but still smaller than the *Gregory and Forster* [2008] estimate prior to the late 1990s and an even larger aerosol forcing after 2000 (Figure 3b). In contrast, a value of λ at the upper end of the range (1.75 W m^{-2} K^{-1}; climate sensitivity of 2.1°C) implies a significantly smaller aerosol forcing prior to the late 1990s but an aerosol forcing similar to Gregory and Forster after 2000 (Figure 3b). For variations in λ to explain the apparent increase in aerosol forcing, λ would need to change from a value below the uncertainty limits (equivalent to a climate sensitivity of greater than 4.5°C) to a value near the upper bound of the uncertainty limits (equivalent to a climate sensitivity of about 2°C). Such an explanation would seem unlikely. Volcanic forcing is uncertain, particularly prior to the satellite record, and would contribute to increased uncertainty of the inferred aerosol forcing prior to 2000.

5. Inferences from the Budgets

[28] The budget calculations imply that the rapidly increasing surface temperatures from the mid 1970s to the mid 1990s are consistent with the increasing greenhouse gas concentrations and the steady to slightly weaker negative forcing from anthropogenic aerosols. The subsequent increase in the inferred negative aerosol (or some unidentified) forcing in the 2000s appears to be robust with respect to uncertainty in ocean heat-content estimates and the moderate variation in the values of λ, given that for the last part of the record the volcanic forcing used in the calculations is essentially zero. This more negative aerosol (or other) forcing is required for energy balance, as there was little surface warming over the last decade even though greenhouse gas concentrations continued to increase (with a small decrease in solar input) and the ocean continued to warm and sea level continued to rise.

[29] There are several potential contributions to the increased negative forcing. Firstly, decreases in stratospheric water vapour, which we have not taken into account, give a negative forcing and could explain 0.1–0.2 W m^{-2} of this inferred change [*Solomon et al.*, 2010]. The almost doubling of fossil fuel use in developing nations [*Le Quéré et al.*, 2009] and inadequate control of sulphur emissions since the early 2000s, particularly in China, would lead to a more negative aerosol forcing [*Kaufmann et al.*, 2011]. Indeed, increases in sulphur emissions from developing nations, particularly in south and east Asia since 2000 [*Streets et al.*, 2009; *Lu et al.*, 2010], and a large pulse of organic carbon emissions in south-east Asia in 1997–1998 [*Streets et al.*, 2009] from forest fires have been documented. Recent in situ and satellite observations suggest that seasonally these aerosols are carried increasingly into the upper troposphere and lower stratosphere by deep convection [*Hofmann et al.*, 2009; *Vernier et al.*, 2011a]. At the Mauna Loa Observatory, the increase in 15.8–33 km aerosol backscatter over 2000–2009 is an increased negative radiative forcing of about -0.15 W m^{-2} over the decade [*Hofmann et al.*, 2009]. *Vernier et al.* [2011b] have also demonstrated that a series of moderate volcanic eruptions have increased stratospheric aerosol loading (not included in our forcing time series) at heights greater than 20 km since 2002. *Solomon et al.* [2011] have recently estimated an increased negative stratospheric

forcing since 2006 of −0.1 W m^{-2}, resulting in a total value of −0.2 W m^{-2} in 2009.

[30] The closure of the sea-level budget as an evolving time series since 1972 is an important step and adequate closure of the sea-level and energy budgets simultaneously allows more rigorous testing of individual component models for projecting climate change and sea-level rise. The failure to explain the fall in sea-level change during the 1960s may be a result of the poorer data coverage in the 1960s and thus an inability to adequately resolve the response to and the recovery from the 1963 volcanic eruption of Mount Agung in the observations. The response of the ocean to later volcanic eruptions is likely to be better, but perhaps still incompletely, resolved. Consistent with this idea, climate model simulations indicate larger falls in ocean heat content following volcanic eruptions than estimated from observations [*Domingues et al.*, 2008].

[31] Immediate priorities include improving the quality control and completeness of historical ocean data (to the extent possible); extending the budgets to the full 20th century, and for the most recent period using improved and different (Argo [e.g., *von Schuckmann and Le Traon*, 2011] and GRACE [e.g., *Leuliette and Miller*, 2009]) observations; testing whether or not model simulations of individual terms sum to be consistent with the observed sea-level and energy time series; up-to-date time series of all climate forcings, including anthropogenic and volcanic aerosols; understanding the regional distribution of sea-level rise, including the impact of geophysical, gravitational and Earth-rotational changes caused by the redistribution of mass [*Mitrovica et al.*, 2001]; and using the observations to constrain future projections.

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