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An imperative for climate change planning: tracking Earth's global energy

Kevin E Trenberth

Planned adaptation to climate change requires information about what is happening and why. While a long-term trend is for global warming, short-term periods of cooling can occur and have physical causes associated with natural variability. However, such natural variability means that energy is rearranged or changed within the climate system, and should be traceable. An assessment is given of our ability to track changes in reservoirs and flows of energy within the climate system. Arguments are given that developing the ability to do this is important, as it affects interpretations of global and especially regional climate change, and prospects for the future.

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Introduction

The global mean temperature in 2008 was the lowest since about 2000 (Figure 1). Given that there is continual heating of the planet, referred to as radiative forcing, by accelerating increases of carbon dioxide (Figure 1) and other greenhouses due to human activities, why is the temperature not continuing to go up? The stock answer is that natural variability plays a key role [1] and there was a major La Niña event early in 2008 that led to the month of January having the lowest anomaly in global temperature since 2000. While this is true, it is an incomplete explanation. In particular, what are the physical processes? From an energy standpoint, there should be an explanation that accounts for where the radiative forcing has gone. Was it compensated for temporarily by changes in clouds or aerosols, or other changes in atmospheric circulation that allowed more radiation to escape to space? Was it because a lot of heat went into melting Arctic sea ice or parts of Greenland and Antarctica, and other glaciers? Was it because the heat was buried in the ocean and sequestered, perhaps well below the surface? Was it because the La Niña led to a change in tropical ocean currents and rearranged the configuration of ocean heat? Perhaps all of these things are going on? But surely we have an adequate system to track whether this is the case or not, do we not?

Well, it seems that the answer is no, we do not. But we should! Given that global warming is unequivocally happening [2•] and there has so far been a failure to outline, let alone implement, global plans to mitigate the warming, then adapting to the climate change is an imperative. We will of course adapt to climate change. The question is the extent to which the adaptation is planned and orderly with minimal disruption and loss of life, or whether it is unplanned? To plan for and cope with effects of climate change requires information on what is happening and why, whether observed changes are likely to continue or are a transient, how they affect regional climates and the possible impacts. Further, to the extent that the global community is able to reduce greenhouse gas emissions and mitigate the climate change, then information is required on how effective it is. This article addresses vital information needs to help understand climate change.

It is not a sufficient explanation to say that a cool year is due to natural variability. Similarly, common arguments of skeptics that the late 20th century warming is a recovery from the Little Ice Age or has other natural origins are inadequate, as they do not provide the physical mechanisms involved. There must be a physical explanation, whether natural or anthropogenic. If surface warming occurs while the deep ocean becomes cooler, then we should be able to see the evidence. It may be that there are insufficient data to prove one way or the other, as is often the case in the deep past. However, since 1979 there have been instruments in space tracking the total solar irradiance (TSI) [3,4], and so we know it is not the sun that has brought about warming in the past 30 years [5]. Hence a key issue is the extent to which we can track energy in the climate system.

The global energy budget

A series of recent studies provides new assessments and analyses of the flows of energy through the climate system. Studies include not only the annual mean but

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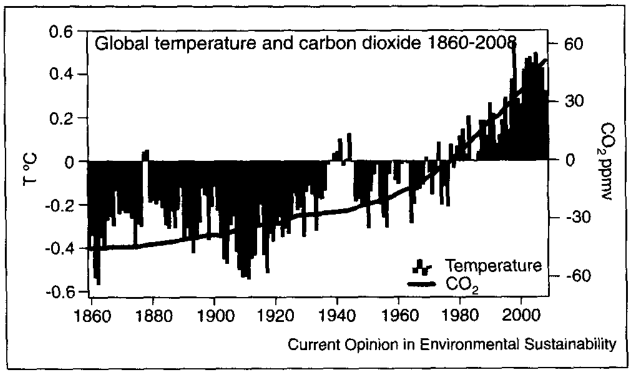
[1] Sponsored by the National Science Foundation.

Figure 1



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Time series of annual global mean temperature departures for 1861–2008 from a 1961–1990 mean (bars), left scale, and the annual mean carbon dioxide from Mauna Loa after 1957 linked to values from bubbles of air in ice cores before then. The zero value for 1961–1990 for temperature corresponds to 14 °C and for carbon dioxide 334 parts per million by volume (ppmv). Updated from Karl and Trenberth [16], original data from HADCRUv3 http://www.cru.uea.ac.uk/cru/data/temperature/#datdow, and http://www.esrl.noaa.gov/gmd/ccgg/trends/.

also the annual cycle, the energy distribution with latitude and the consequential meridional energy transports by the atmosphere and oceans, the seasonal uptake and release of energy by the oceans, and an assessment of the current state of the Earth's radiative balance. The global flows of energy are depicted schematically in Figure 2 [6••]. The Clouds and the Earth's Radiant Energy System (CERES) measurements from March 2000 to 2005 were used at top of atmosphere (TOA) but adjusted to an estimated imbalance from the enhanced greenhouse effect of 0.9 ± 0.5 W m^{-2} (with 90% confidence limits) [7•].

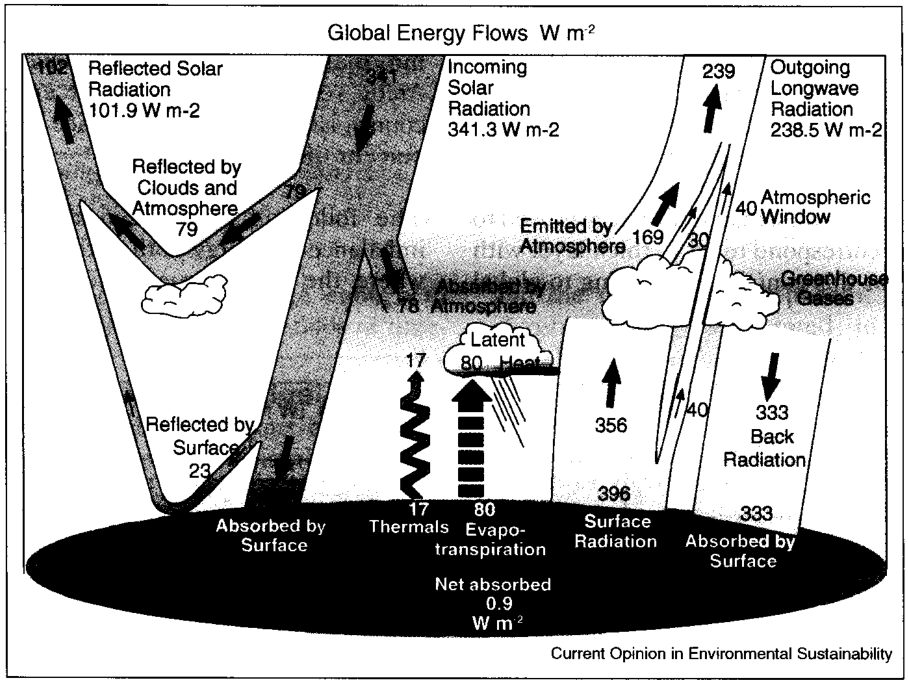
In Figure 2, there is firstly an accounting for the incoming absorbed solar radiation (ASR) and the outgoing longwave radiation (OLR) at TOA. Secondly, there is a separate accounting for the energy fluxes at the surface, and the difference is what goes on in the atmosphere. Measurements from satellite of albedo determine the reflected solar radiation and constrain the sum of the solar energy absorbed by atmosphere and surface. The sensible heat flux is reasonably well established within ± 10% from atmospheric analyses. Global changes in storage of water vapor and atmospheric moisture are very small and thus global evaporation closely matches precipitation and determines the surface latent heat flux [8]. Longwave (infrared) radiation is emitted at the surface of the Earth and, while large, is reasonably well established. It is compensated for by a very large back radiation from clouds and greenhouse gas emissions by the atmosphere, such that the net loss of energy by radiation at the surface is smaller than the evaporative cooling. The largest uncertainty is assigned [6••] to the downward longwave radiation in association with clouds and atmospheric temperature and moisture structure.

The present-day climate is changing mainly in response to human-induced changes in the composition of the atmosphere as increases in greenhouse gases promote warming, while changes in aerosols can increase or diminish this warming regionally depending on the nature of the aerosols and their interactions with clouds. The current radiative imbalance at the TOA has increased from a very small imbalance only 40 years ago when carbon dioxide increases and radiative forcing were less than half of those today. The excess in heat does several things. (i) It warms the planet, increasing temperatures that in turn increase the radiation back to space. (ii) It melts snow and ice on land, and sea ice, and melting of land ice contributes to eustatic sea level rise at a rate of about 1.2 ± 0.4 mm yr^{-1} from 1993 to 2003 [2•]. (iii) It goes into the ocean and increases ocean heat content, contributing to what is called thermosteric sea level rise, at a rate of 1.6 ± 0.5 mm yr^{-1} for 1993–2003 [2•]. (iv) It goes into changes in evaporation and the hydrological cycle that, in turn, alter atmospheric heating and clouds. As clouds have both a greenhouse effect and reflect solar radiation, they can both heat or cool the Earth radiatively—which of these dominates in a given region depends upon the cloud properties (e.g. coverage, height and thickness). Generally there is large cancellation, but averaged globally, it is the radiative cooling effect of clouds that dominates. For example, strong cancellation occurs in deep convective clouds that have cold cloud tops (relevant for how much clouds emit toward space) and are bright [9]. Shallow low-level cloud decks, such as stratocumulus, on the contrary, are bright but relatively warm, and thus mostly act to cool the planet. An exception is in the Polar Regions in winter [10].

From 1993 to 2003 there is a reasonable accounting for both the energy imbalance and the sea level rise [2•] (SLR). About 60% of the SLR came from ocean warming and expansion and 40% from melting land ice. A key issue emerging is where has the energy gone since then? Presuming that there is a current radiative imbalance at the top-of-the-atmosphere of about 0.9 W m^{-2}, then this is 1.45×10^{22} J/yr integrated globally. At the same time since 2003, SLR has slowed somewhat (Figure 3) and averages about 2.5 mm/yr from 2003 to early 2008 [11]. If all of the energy were used to melt sea ice, land ice, or warm the ocean, what would it do to sea level rise? Trenberth and Fasullo [12] detail this as follows.

A 1 mm eustatic rise in sea level requires melting of 360 Gt of ice [13•] that takes 1.2×10^{22} J. Because the ice is cold, warming of the melted waters to ambient temperatures can account for perhaps another 12.5% of the energy (total 1.35×10^{20} J). Sea level rise from thermal expansion depends greatly on where the heat is deposited as the coefficient of thermal expansion varies with temperature and pressure. The warming required to produce 1 mm SLR if the heat is deposited in the top

Figure 2



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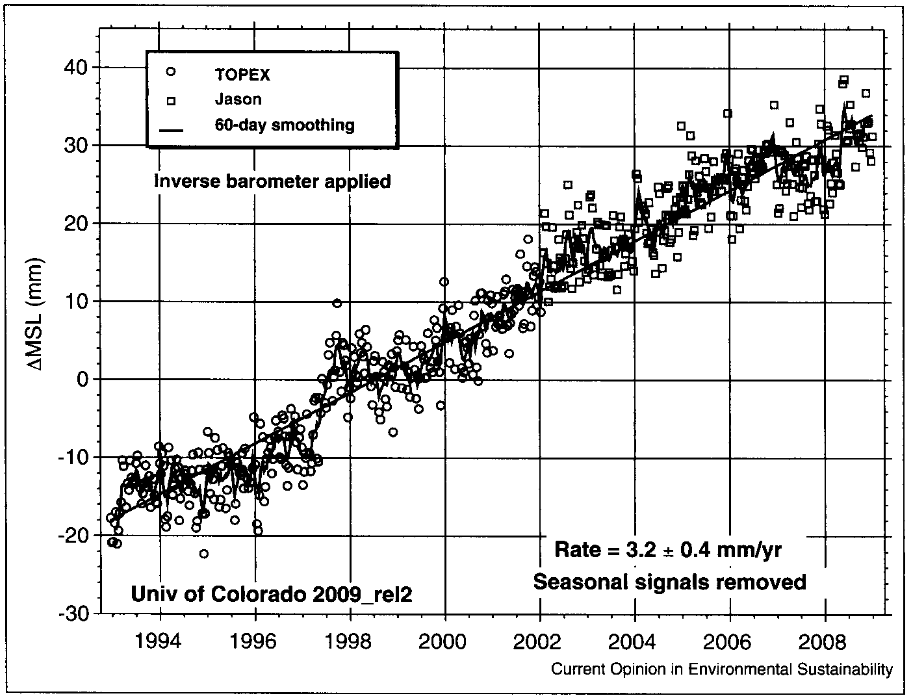
The global annual mean Earth's energy budget for the March 2000–May 2004 period in W m^{-2}. The broad arrows indicate the schematic flow of energy in proportion to their importance. From Trenberth *et al.* [6••].

Figure 3



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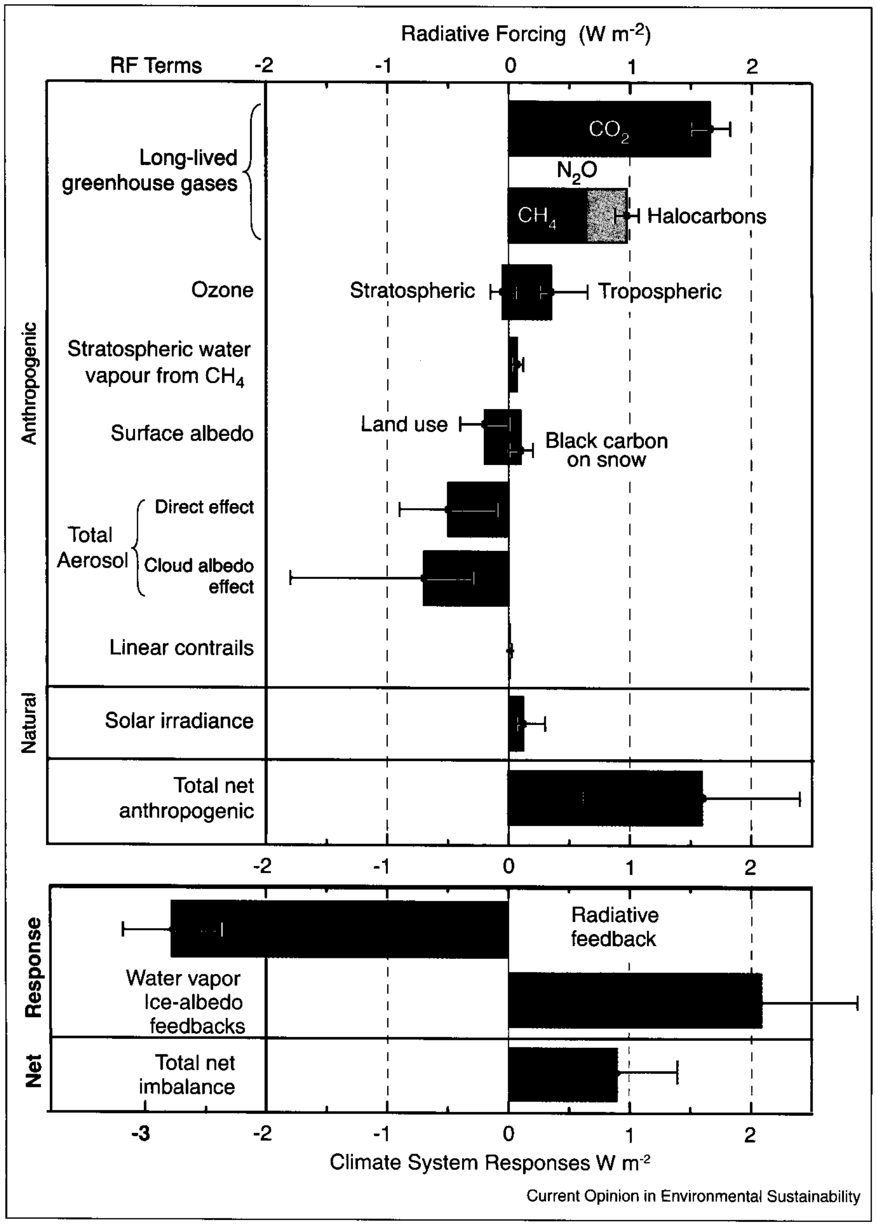
Global sea level since August 1992. The TOPEX/Poseidon satellite mission provided observations of sea level change from 1992 until 2005. Jason-1, launched in late 2001 continues this record by providing an estimate of global mean sea level every 10 days with an uncertainty of 3–4 mm. The seasonal cycle has been removed and an atmospheric pressure correction has been applied. http://sealevel.colorado.edu/ courtesy Steve Nerem (reproduced with permission).

700 m of the ocean can take from 50 to 75 × 10^{20} J, or ~110 × 10^{20} J if deposited below 700 m depth [14]. Thus melting ice is a factor of 40–70 times more effective than thermal expansion in raising sea level when heat is deposited in upper 700 m, or the factor is ~90 when heat is deposited below 700 m depth. Hence 0.9 W m^{-2} integrated globally is a sea level equivalent (SLE) of ~107 mm from land ice melt or 1.3–2.7 mm from thermosteric ocean expansion. If instead this energy is used to melt sea ice, it would correspond to a 1 m thick layer with area 42 × 10^6 km^2, but this contributes nothing to global sea level rise. The average Arctic sea ice extent for 1979–2000 is 7.0 × 10^6 km^2. Hence, given the modest sea level rise observed, it is clear that the energy has not all gone into melting land ice, and nor has it gone into melting Arctic sea ice as there is not enough. The reason, of course, is that the vulnerable ice covers only a very small percent of the Earth.

The following briefly considers the current average imbalance in energy both at the TOA and at the surface, where the energy goes, and how it varies in time to

Figure 4



The top part of the figure is the radiative forcing from IPCC [1] with the agents of change in left column and radiative forcing W m^{-2} with 90% confidence limits. The lower part shows estimates of the main negative radiative feedback, the water vapor, ice-albedo and other feedbacks, and the net radiative imbalance. Error bars for the latter are based on Fasullo and Trenberth [7•] and others are approximate.

Table 1

For the 2004–mid-2008 period a rough estimate is made of contributions to energy (10^{20} J/yr) and corresponding sea level equivalent (SLE) change (mm/yr) that balance net radiation changes (the 'observed') from human influences

2004–2008	Land	Arctic sea ice	Ice sheets	Total land ice	Ocean	Sun	'Observed'	Residual
Energy 10^{20} J/yr	2	1	1.4	2–3	20–95	16	145	30–100
SLE mm/yr	0	0	1.0	2.0	0.4–1.2		2.5	0

Contributions from storage of heat in land and ocean, melting of ice, the change in the TSI, and the likely residual allowing for errors bars of 1 standard deviation.

examine whether there are variations large enough to offset the imbalance entirely for certain periods of time.

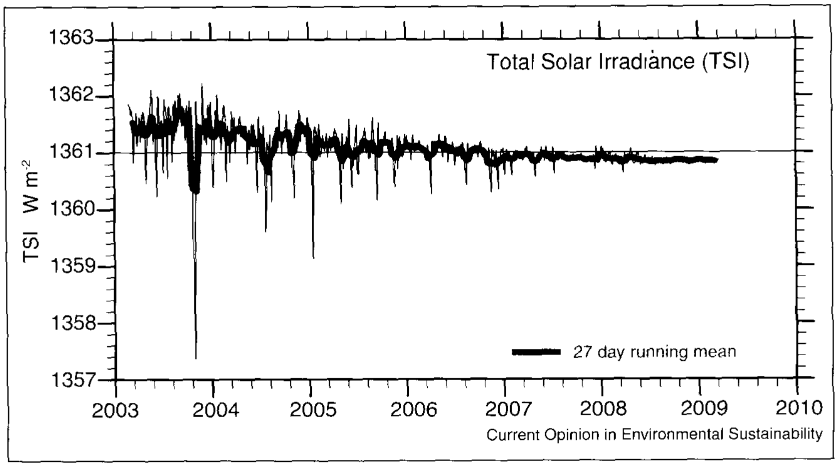
Changes in the global energy budget

We cannot track energy in absolute terms because the accuracy of several measurements is simply not good enough. This includes the TSI [4] and the Earth's TOA energy budget [6••,7•,15]. But the stability and precision of the measurements may provide confidence in variability over time as long as continuity is assured, in particular through adequate overlap between calibrated observations from different instruments on new spacecraft as one set of observations ceases and another takes over. In other words, changes from one year to the next may still be accountable.

The normal flow of energy through the climate system (Figure 2) is $\sim$122 PW = Petawatts (10^{15} W); equivalent to 239 W m^{-2} globally. Human activities contribute directly to local warming through burning of fossil fuels, thereby adding heat, estimated globally to be about 4×10^{20} J/yr ($\sim$0.028 W m^{-2}) or 1/9,000th (0.01%) of the flow through the climate system [16,17]. Radiative forcing [2•] from increased greenhouse gases (Figure 4) is estimated to be $\sim$3.0 W m^{-2} or 1.3% of the flow or energy, and the total net anthropogenic radiative forcing once aerosol cooling is factored in is estimated to be $\sim$1.6 W m^{-2} (0.7%), close to that from carbon dioxide alone (Figure 4). The imbalance at the top-of-the-atmosphere (TOA) would increase to be $\sim$1.5% ($\sim$3.6 W m^{-2}) once water vapor and ice-albedo feedbacks are included. However, the observed surface warming [2•] of 0.75 °C if added to the radiative equilibrium temperature of the planet would result in a compensating increase in longwave radiation of 2.8 W m^{-2} (Figure 4) (although this does not translate into OLR). The net imbalance is estimated to be $\sim$0.5 PW (0.9 W m^{-2}, 0.4%) owing to the responses of the climate system (Figure 4). These values are small enough to yet be directly measured from space, but their consequences can be seen and measured, at least in principle.Table 1 summarizes arguments given in the following as to where this energy may have gone after 2003.

The sun has progressed from an active part of the sunspot cycle in 2003 to a very quiet phase in 2008 (Figure 5). The net change is a decrease in TSI of $\sim$0.5 W m^{-2}. However, in terms of the incoming radiation, this is reduced by a factor of 4 (the ratio of the Earth's surface to its cross-section) and another 30% which is reflected, to give

Figure 5



Daily total solar irradiance from the total irradiance monitor (TIM) instrument on the solar radiation and climate experiment (SORCE), along with a 27-day running mean in red. http://lasp.colorado.edu/sorce/index.htm (data courtesy Laboratory for Atmospheric and Space Physics, U Colorado).

~0.1 W m^{-2} reduction in ASR. This is quite small compared with human effects, although it would add up if continued for many decades.

The atmosphere has limited heat capacity corresponding globally to that of only a 3.5 m layer of the ocean [18]. If post-1980 surface warming [2•] of 0.2 K/yr applies to the whole atmosphere, it corresponds to 1×10^{20} J/yr. Reliable CERES data are not yet available beyond 2005 to assess whether or not the energy imbalance at the TOA has changed.

Cloud cover: A simple interpretation of Figure 2 suggests that a 1% increase in cloud cover could increase reflection of solar radiation by ~0.8 W m^{-2}, enough to offset global warming from greenhouse gases. This does not account for the greenhouse effect of the same clouds, but it suggests an order of magnitude of the effect. In Polar Regions cloud is often confused with surface snow or ice and thus changes in cloud are best known for 60°N to 60°S. From 2001 through 2005 a comparison of the cloud amount from MODIS with CERES net radiation for monthly anomalies gives a statistically significant relation (correlation −0.32), suggesting that a 1% increase in cloud results in −0.5 W m^{-2} net radiation. However, anomalies in cloud exceeding 0.5% seldom last six months although fluctuations of ±1% occur in the High Resolution Infrared Radiometer Sounder (HIRS) cloud observations from 1979 through 2001 [19].

Aerosols: The importance of human-induced aerosol forcing has increased over time [2•,20]. Overall direct and indirect effect values are uncertain (Figure 4) but radiative forcing averages ~−1.2 W m^{-2}. Seasonal and short-term changes in optical depth of aerosols are evident [21] from 2000 to 2007 but trends are not apparent. Variations in aerosols mainly come from volcanic eruptions, such as Mount Pinatubo in 1991 that had substantial effects (several W m^{-2} globally) for over a year [22] but no recent volcanic events of consequence have occurred.

Land has a specific heat that is roughly a factor of 4.5 less than that of sea water (for moist land the factor is probably closer to 2). Moreover, heat penetration into land is limited by the low thermal conductivity of the land surface; as a result only the top few meters of the land typically play an active role in heat storage and release. Borehole evidence suggests a warming of 2×10^{20} J/yr in land [23].

Ice sheets over Antarctica and Greenland have a large mass but, like land, the penetration of heat occurs primarily through conduction so that the mass experiencing temperature changes from year to year is small. Unlike land, however, ice caps and ice sheets melt, altering sea level albeit slowly. Evidence is strong that melting of the major ice sheets has accelerated this century in Antarctica [24•] and Greenland [13•] especially from 2003 to January 2008, where the contribution to sea level could be 1.0 mm/yr, coming roughly equally from both ice sheets, and hence 1.35×10^{20} J/yr.

Sea ice is important where it forms. Record losses of Arctic sea ice of about 10^6 km^2 occurred in summer of 2007 relative to the previous lowest year [25], although the thickness and volume of the ice is quite uncertain. To melt 10^6 km^2 of ice 1 m thick and raise the temperature of the water by 10 °C requires 3.4×10^{20} J, or globally 0.02 W m^{-2}. For 2004–2008 this is about 0.9×10^{20} J/yr.

The ocean has the capacity to change heat storage and plays a strong role in the annual cycle and interannual variability [26]. Many analyses before about 2008 of ocean heat content are now obsolete as they did not account for errors in the fall rate of expendable bathythermographs (XBTs) [27,28]. For instance a recent reexamination of sea level rise from island and coastal tide gauge stations and ocean heat content used uncorrected values [29]. Ocean multivariate analyses are considered more reliable after the introduction of satellite altimetry in 1992 [30]. However, subsurface ocean measurements were inadequate in many areas before 2002; for instance little or no sampling over many parts of the southern oceans [30–33].

Moored arrays of buoys such as the TAO/TRITON array in the tropical Pacific have greatly helped ocean sampling and, beginning about 2000, ARGO floats have provided soundings of salinity and temperature from a depth of about 2000 m to the surface with increasing global coverage. Between 2003 and 2005 early estimates of ocean heat content suggested a downturn [34], while sea level continued to rise [35]. This inconsistency stemmed partly from ARGO float data problems that have supposedly been corrected or omitted [36]. Several new reanalyses have been made of the ocean heat content based upon corrected XBT fall rates and other adjustments to the basic data, which tend to remove a lot of decadal variability, but retain the overall rate of rise in heat content of 37×10^{20} J/yr, or for sea level 1.6 ± 0.2 mm/yr from 1961 to 2003 [28,37••,38,39]. Evidence suggests that warming of the southern oceans is real in spite of the data shortcomings [33]. Even so, since 2003 there appears to be a slowdown in the rise of ocean heat [11,40] although sampling was found to be inadequate [41] in the earlier ARGO data analysis [40].

Sea level: In 1992 new observations became available for the first time from the TOPEX/Poseidon satellite that measured global sea level to millimeter accuracy. This has continued with the Jason missions to give a wonderful global sea level record (Figure 3), which suggests an increase of ~3.2 mm yr^{-1} with a few short-term departures from a fairly linear trend. There was an increase above the trend line in 1997–1998 associated with the major 1997–1998 El Niño event, and a dip below the line in 2007–2008 with the recent La Niña. These fluctuations in sea level with El Niño come partly from changes in ocean heat content, but mainly arise from changes in ocean mass when water is evaporated from the ocean (as it loses heat) and is precipitated on land in the changing precipitation patterns [42]. From regressions [43], a 1.5 °C drop in Niño 3.4 SSTs for six months (as occurred from October 2007 to March 2008) would increase rainfall over land in the tropics (±25°) to such an extent as to lower sea level by 6.0 mm; hence the 2007–2008 La Niña (Figure 3) is likely responsible for the recent slowdown in sea level rise.

Estimated contributions to sea level from changes in storage of water on land in reservoirs and dams may account for −0.55 mm/yr sea level equivalent [44], but these are compensated for by ground water mining, urbanization, and deforestation effects. This obviously depends on the time frame, but the net sum of land effects is thought to be small [37••].

The eustatic sea level rise of about 1.2 mm/yr up to 2003 [2•] appears to have accelerated since then with new assessments from glaciers [45] of ~1 mm/yr and from the major ice sheets [13•,24•,37••], which also contribute ~1 mm/yr. However, the global freshwater flux and salinity are not well constrained by observations, and model synthesis results [14] depend on the deep ocean temperature trends that are also poorly constrained by observations. Changes in salinity affect density and thus contribute a small halosteric contribution to sea level rise [40].

For the mid-2003–2008 period, abundant data exist on changes in both ocean heat content from ARGO floats down to 900 m (and XBT data can be omitted) and ocean mass from Gravity Recovery and Climate Experiment (GRACE) gravity satellite measurements. Their sum should amount to the sea level from altimetry estimates from satellites, but substantial discrepancies between trends of ~2 mm/yr were found [40]. Part of this discrepancy can be accounted for by improved land–sea masks and better resolution in the GRACE measurements. One claim to resolve the discrepancies through increased contributions from melting land ice of 2 mm/yr for 2003–2008 is based on an alternative GRACE data analysis that includes a substantial Glacial Isostatic Adjustment [11]. Leuliette and Miller [41] also claim to have closed the sea level budget by increasing the ocean expansion component. The steric contributions range from −0.5 ± 0.5 mm/yr for mid-2003–mid-2007 [40] to 0.4 ± 0.1 mm/yr [11] to 0.8 ± 0.8 mm/yr [41] for 2004–mid-2008 (with 95% confidence limits).

The sum: The components accounted for are listed approximately in Table 1, where the Leuliette and Miller [41] values (±1 standard deviation) and corresponding ocean heat content are used for the ocean because they are closest to bridging the gap. Linear trends over such short periods add uncertainties of about ± 0.5 mm/yr (±1 standard deviation). Data for 2008 are not yet complete. Sea level rise is roughly accounted for within 15% uncertainties, although large discrepancies exist among the components. However, satisfying the SLR constraint by shifting the balance from thermosteric to eustatic components does not satisfy the energy constraint. Accounting for the known contributions to energy uptake still leaves a likely residual of $30–100 \times 10^{20}$ J/yr, although total error bars overlap. Possibly this heat is being sequestered in the deep ocean below the 900 m depth used for the ARGO analyses where it would contribute about 0.4–0.5 mm/yr sea level rise, and then the land ice melt estimate would have to go down. Or the warming is not really present? In this case, the blame would point to the atmosphere and cloud changes, and it should be confirmed by CERES and MODIS measurements. However, preliminary estimates for 2006 through 2008 suggest that net radiation heating increased, which if true exacerbates the imbalance identified here.

Concluding remarks

In this paper we have assembled the available information on the global energy balance for recent years. Many components of the Earth system play some role, and their monitoring is improving but falls short of what is required. Although one climate requirement is for absolute accuracy whereby observations are linked to benchmark measurements, as is extensively discussed in a workshop report [46,47], a more achievable goal is to have continuity and overlapping measurements that are stable in time, thereby allowing changes to be tracked. Hence observations need to be taken in ways that satisfy the Global Climate Observing System climate monitoring principles and ensure long-term continuity and that have the ability to discern small but persistent signals [48].

Although the sea level budget is reasonably closed for the post-2003 period, the global energy budget is not closed. Increasing land ice melt at expense of ocean expansion to account for sea level rise has consequences for the energy budget. Accordingly another much needed component is the TOA radiation, but CERES [49] data exist only through 2005 and are not yet long or reliable enough to bring to bear on this question. This highlights the need to bring the CERES TOA radiation up to date along with reprocessed cloud data while ensuring that changes in the ocean, sea ice and sea level are maintained with adequate quality control and sampling to provide estimates reliable enough to address the questions posed in the introduction.

To better understand and predict regional climate change, it is vital to be able to distinguish between short-lived climate anomalies, such as caused by El Niño or La Niña events, and those that are intrinsically part of climate change, whether a slow adjustment or trend, such as the warming of land surface temperatures relative to the ocean and changes in precipitation characteristics. Regional climate change also depends greatly on patterns or modes of variability being sustained and thus relies on inertia in the climate system that resides mostly in the oceans and ice components of the climate system. A climate information system that firstly determines what is taking place and then establishes why is better able to provide a sound basis for predictions and which can answer important questions such as 'Has global warming really slowed or not?' Decisions are being made that depend on improved information about how and why our climate system is varying and changing, and the implications.

Acknowledgements

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- •• of outstanding interest

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