

Changes in the flow of energy through the Earth's climate system

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Abstract

A review is given of the trends, variability, mean and annual cycle of energy flowing through the climate system, and its storage, release, and transport in the atmosphere, ocean, and land surface as estimated with recent observations, with some new updates using the latest datasets. The current imbalance in radiation at the top-of-atmosphere owing to human-induced increases in greenhouse gases means that the atmosphere, land and ocean are warming up, and ice is melting, leading to a rise in sea level. A discussion is given of our ability to track these changes with current observations and analyses. Current global analyses of the atmosphere and the ocean contain spurious variability on decadal time scales that arises from inadequacies and changes in the observing system. A holistic integrated approach that brings all information to bear can provide constraints on what is happening and where the main weaknesses are in the observing system. Results for ocean heat content are discussed in the light of recent corrections to ocean soundings and new ocean observations, and in the context of the thermosteric contributions to sea level rise.

Zusammenfassung

Diese Studie gibt, basierend auf den neuesten, verfügbaren Beobachtungsdaten, einen Überblick über Trends, Variabilität, Mittelwert und Jahresgang des Energieflusses durch das Klimasystem sowie über seine Speicherung, Freisetzung und seinen Transport in der Atmosphäre, im Ozean und auf Landoberflächen. Das momentane, durch den anthropogenen Treibhausgasanstieg verursachte Strahlungsungleichgewicht bewirkt, dass die Atmosphäre, die Landoberflächen und der Ozean sich erwärmen und das Schmelzen des Eises zu einem Anstieg des Meeresspiegels führt. Unsere augenblickliche Fähigkeit, diese Veränderungen mit Beobachtungen und Analysen zu verfolgen, wird diskutiert. Aktuelle, globale Analysen der Atmosphäre und des Ozeans enthalten teilweise eine unechte Variabilität auf der dekadalen Zeitskala, die von Unzulänglichkeiten und Veränderungen im Beobachtungssystem herrührt. Ein ganzheitlicher, integrierter Ansatz, der alle verfügbaren Informationen berücksichtigt, kann Randbedingungen liefern, die zeigen, wo die Schwächen des Beobachtungssystems liegen. Ergebnisse für den Wärmeinhalt des Ozeans werden im Lichte kürzlich publizierter Korrekturen von früheren Ozeansondierungen und neuer ozeanischer Messungen sowie vor dem Hintergrund des thermosterischen Beitrags zum Anstieg des Meeresspiegels diskutiert.

1 Introduction

Understanding and tracking the changes in the flow of energy through the climate system as the climate changes are important for assessments of what is happening to the climate and what the prospects are in the future. 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. Human activities also contribute directly to local warming through burning of fossil fuels, thereby adding heat, estimated globally to be about one 9,000th (0.01 %) of the normal flow of energy (about 122 PW = Petawatts $\hat{=} 10^{15}$ watts) through the climate system (KARL and TRENBERTH, 2003). Radiative forcing from increased greenhouse gases (IPCC, 2007) is estimated to be about

1.3 % of this amount, and the total net anthropogenic radiative forcing once aerosol cooling is factored in is estimated to be about 0.7 %. The actual imbalance at the top-of-atmosphere (TOA) would increase to about 1.5 % once water vapor and ice-albedo feedbacks are included, but the total is reduced and is estimated to be about 0.5 PW (0.4 %) owing to the other responses of the climate system; by increasing temperatures, outgoing longwave radiation (OLR) is increased as partial compensation. Unfortunately, these values are small enough to yet be directly measured from space, but their consequences can be seen and measured, at least in principle. This article assesses our ability to track such changes.

Therefore in this paper, a review is given of the mean and annual cycle of energy flowing into the climate system and its storage, release, and transport in the atmosphere, ocean, and land surface as estimated with recent observations, with some new updates using the latest datasets. The variability is also considered as a means of assigning sampling error bars and to set the stage for examining the trends. An emphasis is placed on establishing internally consistent quantitative estimates with

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some discussion and assessment of uncertainty. A review is also given of the contributions to sea level rise and the issues that remain in closing the energy budget.

Weather and climate on Earth are determined by the amount and distribution of incoming radiation from the sun (see TRENBERTH and STEPANIAK, 2004). For an equilibrium climate, OLR necessarily balances the incoming absorbed solar radiation (ASR), although there is a complex interaction among the atmosphere, ocean and land domains that couple the two and their balance is only for the annual mean, not individual regions, months or seasons. Incoming radiant energy may be scattered and reflected by clouds and aerosols, or absorbed in the atmosphere. The transmitted radiation is then either absorbed or reflected at the Earth's surface. Radiant solar or shortwave energy is transformed into sensible heat, latent energy (involving different water states), potential energy (involving gravity and height above the surface (or in the oceans, depth below)) and kinetic energy (involving motions) before being emitted back to space as longwave radiant energy. Energy may be stored for some time, transported in various forms, and converted among the different types, giving rise to a rich variety of weather or turbulent phenomena in the atmosphere and ocean. Frictional dissipation generates sensible heat as a part of this process. Moreover, the energy balance can be upset in various ways, changing the climate and associated weather, as discussed in sections 4 and 5.

The atmosphere does not have much capability to store heat. The heat capacity of the global atmosphere corresponds to that of only a 3.5 m layer of the ocean (see TRENBERTH and STEPANIAK, 2004). However, the depth of ocean actively involved in climate is much greater than that. The specific heat of dry land 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 (e.g., as the depth for most of the variations over annual time scales). Accordingly, land plays a much smaller role than the ocean in the storage of heat and in providing a memory for the climate system. Major 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. Hence, ice sheets and glaciers do not play a strong role in global mean heat capacity except on greater than century time scales, while sea ice is important where it forms. Unlike land, however, ice caps and ice sheets melt, altering sea level albeit fairly slowly.

The oceans cover about 71 % of the Earth's surface and contain 97 % of the Earth's water. Through their fluid motions, their high heat capacity, and their ecosystems, the oceans play a central role in shaping the Earth's climate and its variability. The seasonal variations in heating penetrate into the ocean through a combination of radiation, convective overturning (in which

cooled surface waters sink while warmer more buoyant waters below rise) and mechanical stirring by winds. These processes mix heat through the mixed layer. Accordingly, it is vital to monitor and understand changes in the oceans and their effects on weather and climate.

The first part of this paper is mostly a summary and extension of work mainly documented in three recent articles. FASULLO and TRENBERTH (2008a) provide an assessment of the global energy budgets at TOA and the surface, for the global atmosphere, and ocean and land domains based on a synthesis of satellite retrievals, reanalysis fields, a land surface simulation, and ocean temperature estimates. The TOA budget is constrained to match estimates of the global imbalance during recent periods of satellite coverage associated with changes in atmospheric composition and climate. FASULLO and TRENBERTH (2008b) go on to evaluate the meridional structure and transports of energy in the atmosphere, ocean and land for the mean and annual cycle zonal averages over the ocean, land and global domains. TRENBERTH and FASULLO (2008) delve into the ocean heat budget in considerable detail and provide a comprehensive assessment of uncertainty. Section 5 surveys results from many other recent studies with a focus on sea level changes. Changes in sea level, perhaps more than any other variable, are a measure of warming. As heat penetrates, the ocean expands and sea level rises. Further, some heat goes into melting of glaciers, land ice and ice sheets, adding mass to the oceans and again increasing sea level. Hence a review is given of issues and understanding of this aspect of the energy storage changes. Moreover, changes in sea level have major impacts on coastal regions and storm surges, and thus are important for society.

2 Methods and datasets

At the TOA, adjusted radiances from Earth Radiation Budget Experiment (ERBE) and Clouds and the Earth's Radiant Energy System (CERES) are used. In the atmosphere, reanalyses from the National Centers for Environmental Prediction/NCAR reanalysis (NRA) (KALNAY et al., 1996) and the second generation European Centre for Medium Range Weather Forecasts (ECMWF) Reanalysis (ERA-40) (UPPALA et al., 2005) and recent Japanese Reanalysis (JRA) (ONOGI et al., 2007) are used as they contain the most comprehensive estimates of global atmospheric temperature and moisture fields. Vertically-integrated quantities for energy components, the transports, and divergences have been computed and archived. Details are given by FASULLO and TRENBERTH (2008a, b).

The net upward surface flux (F_S) over ocean is derived as the residual of TOA and atmospheric energy budgets, and is compared with direct calculations of ocean heat content (O_E) and its tendency ($\delta O_E/\delta t$) from several ocean temperature datasets. The ocean datasets used include the World Ocean Atlas 2005

(WOA; LOCARNINI et al., 2006), the ocean analysis of the Japanese Meteorological Agency Version 6.2 (JMA; ISHII et al., 2006), and the Global Ocean Data Assimilation System (GODAS; BEHRINGER, 2006), along with some consideration of the ECCO (Estimating the Circulation and Climate of the Ocean) analyses (STAMMER et al., 2004) from Global Ocean Data Assimilation Experiment (GODAE) <http://www.ecco-group.org/las/servlets/dataset?catitem=532> (WUNSCH et al., 2007) and from Germany (GECCO) (KÖHL and STAMMER, 2008).

Most of these ocean datasets are based on conventional ocean observations, such as expendable bathy thermographs (XBTs), which have recently been shown to contain previously undetected errors in the assumed drop rate (GOURETSKI and KOLTERMANN, 2007), and these are discussed in section 5. After 1992, observations from spaced-based altimeters have become available to provide global sea level measurements. Beginning about 2002, a revolution in ocean observations occurred with the deployment of the profiling ARGO floats globally, to provide measurements of the upper 2000 m of the ocean of temperature and salinity. Section 5 discusses the impacts of these new observations.

Over land F_S from a stand-alone simulation of the Community Land Model forced by observed fields is used. Comprehensive depiction of the energy budget during the ERBE (February 1985 to April 1989) and CERES (Mar. 2000 to May 2004) periods were constructed that match estimates of the global, global-ocean, and global-land imbalances (FASULLO and TRENBERTH, 2008a,b). LIN et al. (2008) discuss the difficulties in assessing global atmospheric energy balance from satellite observations. In addition, the annual cycle of the energy budget during both periods has been examined and compared with $\delta O_E/\delta t$.

3 Global mean and annual cycle

A summary of the overall energy balance for the global atmosphere, ocean and land domains for the recent CERES period (about 2000 to 2004) is given in Fig. 1 (from FASULLO and TRENBERTH, 2008a). $\nabla \cdot \mathbf{F}_A$ is the divergence of the atmospheric energy transport and in Fig. 1 is given for the net transport of energy from ocean to land on an annual mean basis. The standard deviation of the interannual variability has been estimated and is given by σ_I , with plus or minus $2\sigma_I$ given in the figure. As described by FASULLO and TRENBERTH (2008a) the net imbalance in the TOA radiation is assigned to be 0.5 ± 0.3 PW (0.9 W m^{-2}) based on model results and ocean heat content changes, out of a net flow through the climate system of about 122 PW of energy (as given by the ASR and OLR). Hence the imbalance is about 0.4 %. Most of this goes into the oceans, and about 0.01 PW goes into land and melting of ice. However, there is an annual mean transport of energy by the atmosphere from ocean to land regions of 2.2 ± 0.1 PW primarily in the northern winter when the transport exceeds 5 PW.

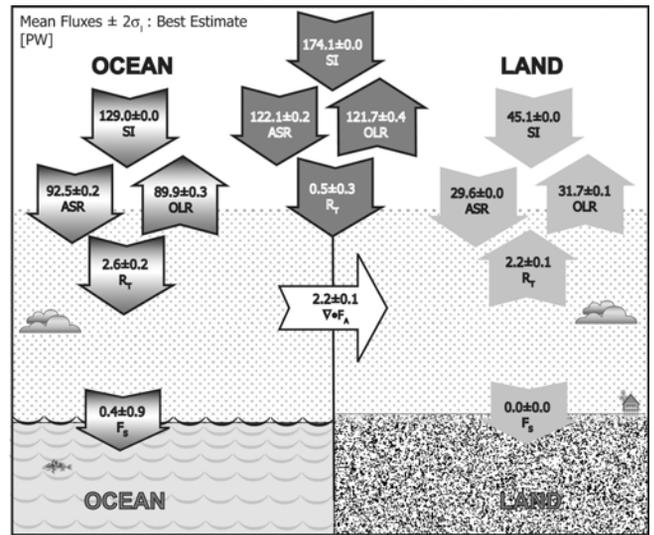


Figure 1: CERES-period March 2000 to May 2004 mean best-estimate TOA fluxes [PW] globally (center grey) and for global-land (right, light grey) and global-ocean (left) regions. SI is the solar irradiance and the net downward radiation $R_T = ASR - OLR$. The arrows show the direction of the flow. The net surface flux is also given along with the energy flow from ocean to land. Adapted from FASULLO and TRENBERTH (2008a).

The annual cycle in TOA radiation is perhaps surprisingly large: it is mostly caused by changes in distance of the Earth from the sun. However, the maximum does not coincide with 3 January, which is when perihelion occurs, because the global albedo decreases from January into February. Hence the peak ASR and net radiation occur in February, with the net radiation 4.3 PW higher than the annual mean. Moreover the annual cycle of net radiation is larger than the ASR because OLR is dominated by land regions and is out-of-phase in its annual cycle. The ocean values tend to follow the ocean-dominated southern hemisphere, while the land values follow the northern hemisphere. Over ocean, the albedo undergoes a semiannual cycle associated with monsoons and cloud changes. Over land, albedo is highest in northern winter in association with snow cover variations and the changing irradiance over Antarctica.

Atmospheric energy storage variations with the annual cycle are small but not negligible. These are well established by the atmospheric observations. The surface energy balance is computed as a residual from the TOA and atmospheric values. The annual cycle (Fig. 2) shows a small surface flux of order 1 PW into and out of the land domain associated with changing land moisture and snow and ice cover, with maximum land heating in May and cooling in November. The inferred ocean surface flux is therefore larger than the global mean surface flux, and closely follows the TOA radiation, with a maximum energy out of the oceans in June, when radiation is lowest in the southern hemisphere.

The annual cycle of TOA radiation can be compared with the rates of change in ocean heat content stor-

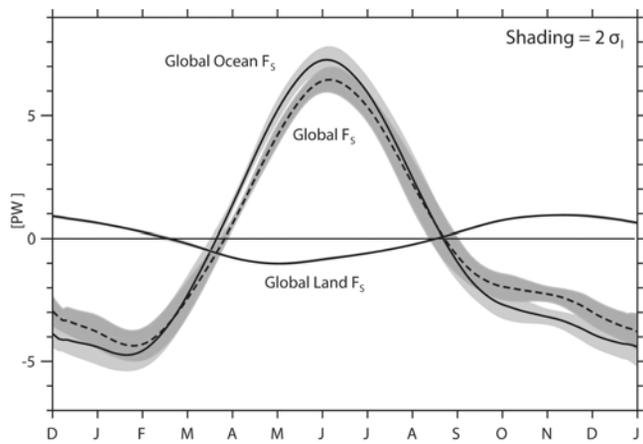


Figure 2: Global, global-ocean, and global-land estimates of net upwards surface flux (F_S) are shown in PW where shading represents $\pm 2\sigma_I$ of monthly means. Adapted from FASULLO and TRENBERTH (2008a).

age (grey curves) from 4 different products (Fig. 3). In TRENBERTH and FASULLO (2008 a, b) comparisons are also made with F_S for the global ocean and locally. When the changes in ocean heat content are combined with the radiation and changes in land and atmospheric storage, the residual should be zero (black curves in Fig. 3). The residuals have a prominent semi-annual cycle and are largest for the WOA and JMA products, somewhat improved for GODAS, and best for ECCO. Residuals of order 1 PW are not unexpected owing to lack of consideration of sea-ice changes and use of somewhat different periods of the data. However, in situ estimates of the annual variation of O_E are unrealistically large (FASULLO and TRENBERTH, 2008 a, b). Largest differences occur among products over the southern oceans south of 40°S . This is not surprising in the pre-ARGO era, as observations were lacking or non-existent in this region, especially in winter (see discussion in WUNSCH et al., 2007 and LYMAN and JOHNSON, 2008).

In the ocean, F_S in the tropics is balanced principally by the transport of ocean energy (mainly heat) (F_O) and its divergence ($\nabla \bullet F_O$) while in mid-latitudes it is largely balanced locally by changes in ocean heat storage. The annual and zonal mean meridional energy transport by the atmosphere and ocean, and their sum (Fig. 4) (FASULLO and TRENBERTH, 2008b; TRENBERTH and FASULLO, 2008) show that the atmospheric transports dominate except in the tropics. There is a pronounced annual cycle of poleward ocean heat transport into the winter hemisphere exceeding 4 PW in the tropics but the annual mean value across the equator is near zero. For the annual mean the poleward transport by the ocean peaks at 11°S at 1.2 PW and 15°N at 1.7 PW.

4 Variability and trends

The transport of energy from ocean to land (or vice versa) can be computed directly from the atmospheric

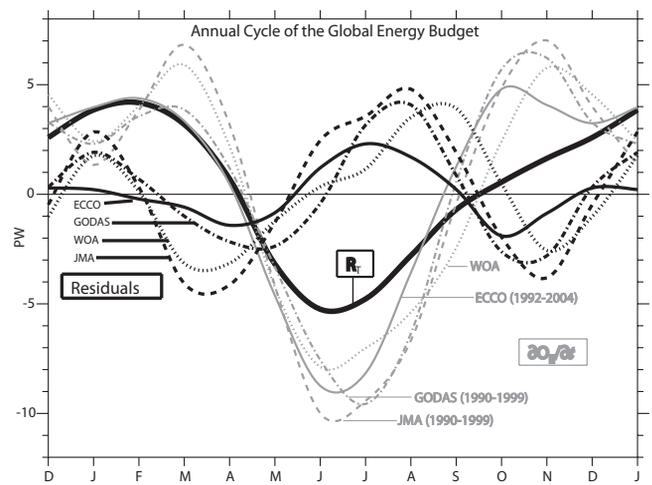


Figure 3: The annual cycle of TOA radiation (heavy black) can be compared with the rates of change in ocean heat content storage (grey curves) from 4 different products as labeled. When combined with the radiation and change in land and atmospheric storage, the residual should be zero (black curves).

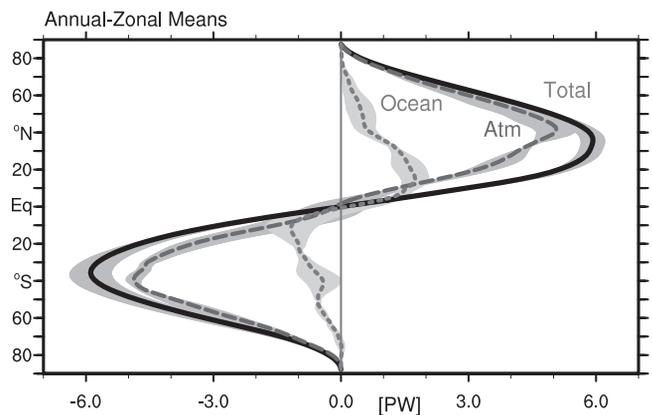


Figure 4: ERBE-period zonal mean meridional energy transport by total (solid) as inferred from ERBE R_T , the atmosphere (dashed) based on NRA, and by the ocean (dotted) as implied ERBE+NRA F_S and GODAS $\delta O_E/\delta t$ accompanied with the associated $\pm 2\sigma$ range (shaded). Adapted from FASULLO and TRENBERTH (2008b).

reanalyses and also inferred from the observations from space of radiation over land, by accounting for the small changes in land and atmospheric storage (Fig. 5). By using a 12-month running mean in Fig. 5 the annual cycle is removed but an instantaneous change is smeared over a 12 month period. After 1990 the estimates are within about 1 PW and some interannual variability (such as the peak in 1996) is reproduced.

Within the atmosphere the NRA reanalyses depict a mean ocean to land transport of about 2 PW during the ERBE period, consistent with inferences from TOA fluxes. However, during the CERES period, the computed NRA land-ocean transport is 2.7 ± 0.2 PW and is inconsistent with satellite estimates. The ERA-40 estimates are less consistent over time than for NRA and the inconsistencies are associated, in part, with estab-

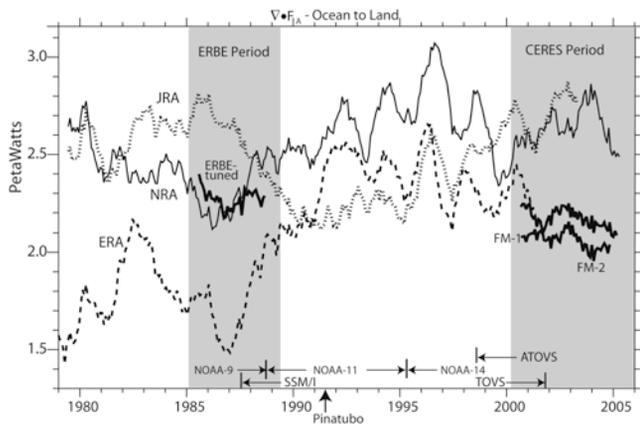


Figure 5: Ocean to land energy transport in PW as 12-month running means inferred from ERBE and CERES R_T over land and NRA $\delta A_E/\delta t$ fields (see text, dark black). Transports from NRA (thin solid), ERA-40 (dashed) and JRA (dotted) fields are also shown. Major observing system changes that affected the time series are given in lower part of the figure. Both ERA-40 and JRA experience major drifts with introduction of SSM/I observations in July 1987 and transitions of NOAA-9 to NOAA 11 in 1988 and NOAA-11 to NOAA-14 in 1995. ERA-40 values jump after Pinatubo erupted in 1991. The TOVS to ATOVS transition affected NRA and JRA in particular.

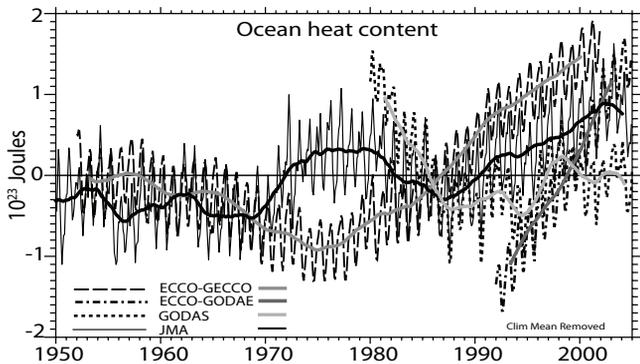


Figure 6: Comparison of the ocean heat content analyses from JMA (solid), GODAS (dotted) and ECCO (GODAE) (dot-dashed) and GECCO from 1950 to 2006. Values are considered more reliable after 1992 when altimetry estimates were available of sea level. The long-term mean is removed. Three year running means are used to remove the annual cycle and provide some smoothing (solid grey curves).

lished shortcomings of ERA-40 fields during the 1990s. In particular, major changes in the observing system occurred with the introduction of SSM/I (Special Sensor Microwave Imager) data in 1987 (that were not used in NRA) and problems occurred following the Mount Pinatubo eruption in 1991 whose aerosol contaminated the radiances that were assimilated in ERA-40 (whereas NRA used retrievals) (UPPALA et al., 2005). The JRA reanalyses similarly suffer from major discontinuities associated with the introduction of SSM/I

data in 1987, the satellite transitions from NOAA-9 to NOAA-11 in late 1988 and NOAA-11 to NOAA-14 in 1995, and the switch from TOVS (TIROS-N (Television and Infrared Observation Satellite) operational vertical sounder) to the Advanced TOVS (ATOVS) from 1998 to 2001 (when both instruments were flying on different satellites) that was implemented abruptly in JRA in November 1998. The latter changes also affected the NRA analyses. Accordingly, the decadal variability in Fig. 5 is largely spurious and is not reproducible. The estimates from the satellite products are more realistic but changes from the ERBE to CERES periods may not be real. As shown here, the decadal variability is poorly replicated, and this has been confirmed in further analysis (TRENBERTH and SMITH, 2008).

We have also examined the time series of ocean heat content from several of the ocean analyses (Fig. 6). For the ocean multivariate analyses, these are considered much more reliable after the introduction of satellite altimetry in 1992 (LYMAN and JOHNSON, 2008). Two estimates of heat content integrated from the surface down to 700 m are provided for the earlier years from the GECCO (KÖHL and STAMMER, 2008) and from the JMA ocean data alone, while the GODAS product (down to 800 m) begins in 1980. From 1992 to 2006 the ECCO-GODAE estimate (down to 800 m) (WUNSCH et al., 2007) is also included. The long-term mean is removed from each and the depth of integration used was a compromise between including greater depths versus noise. In general, the recent trends (after 1988) for ocean heat content integrated down to 700 m depth are 122 ± 10 % of those down to 400 m depth. The 0.4 PW of the estimated current imbalance at TOA which goes into the ocean implies a change of 1.26×10^{23} J/decade, similar to the GECCO changes after 1985. Again, the decadal variability is poorly replicated. However, none of these studies used the corrections to XBT data and are mostly pre-ARGO (see section 5). CARTON and SANTORELLI (2008) present recent results through 2002 from several other ocean data assimilations and, since they all have similar procedures and data-streams, the results are close to the JMA results in Fig. 6. GILLE (2008) provides evidence that warming of the southern oceans is real in spite of the data shortcomings. WUNSCH et al. (2007) provide a very good discussion of error sources.

Hence decadal and longer term variability in both atmosphere and ocean for the energy quantities is not well replicated and mostly demonstrably wrong. Some shorter-term variability associated with El Niño events is reproduced. This highlights the challenges for future reanalyses to diminish the effects of the changing observing system on the results.

5 Sea level rise

As noted above, there is a current radiative imbalance at the top-of-the-atmosphere of about 0.9 W m^{-2} owing to increases of greenhouse gases, notably carbon dioxide,

in the atmosphere (FASULLO and TRENBERTH, 2008a). This 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. Where is this heat going? Some heat melts glaciers and ice, contributing mass to the ocean and thus eustatic sea level rise (LEVITUS et al., 2001). Some heat enters the ocean and increases temperatures and ocean heat content (section 4; Fig 6), leading to expansion of the ocean and thus thermosteric sea level rise. Only very small amounts of heat enter the ice-free land surface, as noted above. LEVITUS et al. (2000) estimated that the heat content of the oceans increased on average by about 0.3 W m^{-2} over the past several decades, but in a somewhat irregular fashion. Larger rates in recent decades are discussed below. Hence the main candidate for a heat sink is the oceans, and sea level rise synthesizes both expansion and added mass from melting of ice elements. Accordingly it is an excellent indicator of warming. Nevertheless, there are complications in the interpretation, as noted below.

To be more concrete, a 1 mm rise in sea level requires melting of 360 Gt of ice (e.g., WOUTERS et al., 2008) which takes 1.2×10^{20} 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 saline ocean does not have a maximum in density at 4°C as fresh water does). The amount of warming required to produce 1 mm sea level rise if the heat is deposited in the top 700 m of the ocean can take from 50 to 75×10^{20} J, or $\sim 110 \times 10^{20}$ J if deposited below 700 m depth (these values are deduced from information given by KÖHL and STAMMER, 2008, and elsewhere). Hence melting ice is a factor of about 40 to 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. For comparison, 0.9 W m^{-2} integrated globally is equivalent to about 1.4×10^{22} J/yr, which is a sea level equivalent of ~ 107 mm from ice melt or 1.3 to 2.7 mm from thermosteric ocean expansion. Accordingly, for sea level rise to be useful for energy budgets it is essential to know the eustatic and thermosteric components. Controversy remains about longer-term sea level rise (MUNK, 2003; CABANES et al., 2001; MILLER and DOUGLAS, 2004); WHITE et al. (2005) note how sea level from coastal stations differs from global values for limited periods of time. Nevertheless, sea level was estimated to have risen throughout the 20th century by 1.5 ± 0.5 mm/yr (IPCC, 2001) although this estimate has been increased to 1.8 ± 0.5 mm/yr (CHURCH et al., 2004; WHITE et al., 2005), and about 0.3 mm/yr is from isostatic rebound.

The following discussion focuses on the evidence for the post-1992 period where the eustatic contribution seems to have been increasing over time yet sea level rise continues at about the same rate. Earlier studies sug-

gested that most of the sea level rise from 1992 to 2000 of 3 mm/year was thermosteric (CABANES et al., 2001; CAZENAVE and NEREM, 2004) but strong observational evidence for a significant eustatic contribution of order 1.2 mm/yr during this period suggested instead that about 60 % of the increase was thermosteric (LOMBARD et al., 2005). The rate of sea level rise from 1993 to 2007, when accurate satellite-based global measurements of sea level from TOPEX/Poseidon and Jason altimetry are available (Church et al., 2004), average about 3.1 mm/year (e.g., WILLIS et al., 2008; DOMINGUES et al., 2008). Whether the recent acceleration is representative and will be sustained or merely reflects low values near the start of the global record from Mount Pinatubo cooling after 1991 is not yet clear. Accordingly IPCC in the Fourth Assessment Report (AR4) (IPCC, 2007) did not consider that a statement about possible acceleration of sea level rise was possible.

The energy that goes into melting land ice is manifested in the ocean through changes in salinity. DICKSON et al. (2002) and CURRY et al. (2003) find a freshening in the North Atlantic and also south of 25°S over the past four decades, while salinity has increased in the tropics and subtropics, especially in the upper 500 m. The implication is for substantial increases in moisture transport by the atmosphere from the subtropics to higher latitudes, perhaps in association with changes in atmospheric circulation, such as the North Atlantic Oscillation (NAO). If this is the main process of importance then it has small effects on global mean sea level as fresh water is redistributed. However, ANTONOV et al. (2002) suggest that there is a secular decrease in overall ocean salinity, raising questions about the role of melting glaciers in sea level rise. WADHAMS and MUNK (2004) suggested that the 20th century eustatic rise was 0.6 mm/yr. Updated estimates of contributions from glaciers and small ice caps (e.g., MEIER et al., 2007) and from the ice sheets of Antarctica and Greenland (e.g., KRABILL et al., 2004) are summarized by IPCC (2007) who conclude that added mass to the oceans provides recent eustatic rise of about 1.2 mm/yr (also RIGNOT et al., 2008; DOMINGUES et al., 2008). WOUTERS et al. (2008) provide recent evidence that ice melt in Greenland has accelerated from 2003 to January 2008.

Estimates of contributions from changes in storage of water on land in reservoirs and dams are that they may account for -0.55 mm/yr sea level equivalent (CHAO et al., 2008), or perhaps as much as -1 ± 0.2 mm/yr with irrigation accounting for another -0.56 ± 0.06 mm/yr (CAZENAVE et al., 2000), but these are compensated for by ground water mining, urbanization, and deforestation effects. This obviously depends on the time frame, and other small contributions also exist. The net sum of land effects is now thought to be small although decadal variations may be negatively correlated with thermosteric sea level change (NGO-DUC et al., 2005; DOMINGUES et al., 2008).

The steric contribution from thermal expansion is based mostly on the analysis of the historical record

(e.g., LEVITUS et al., 2000, 2001; and section 4). Yet that record is based on sub-surface ocean measurements which are inadequate in many areas; for instance little or no sampling over many parts of the southern oceans (WUNSCH et al., 2007; FASULLO and TRENBERTH, 2008b; GILLE, 2008; LYMAN and JOHNSON, 2008). Moreover considerable uncertainty was revealed in the record from XBTs (GOURETSKI and KOLTERMANN, 2007) and how they match up with soundings from ARGO floats, indicating that revisions in drop rates for XBTs were warranted.

A comprehensive synthesis of the (uncorrected) ocean observations in a model framework by the GECCO consortium (KÖHL and STAMMER, 2008) for 1952 to 2001 finds the increase in thermosteric sea level rise on average about double that of LEVITUS et al. (2000). It amounts to 1.2 mm yr^{-1} over the top 750 m and 1.8 mm yr^{-1} over the total water column from 1992 to 2001, which corresponds to a heat flux into the ocean of 1.5 W m^{-2} . In contrast, for 1993 to 2004 WUNSCH et al. (2007) find 1.1 mm/yr from freshwater mass input to the ocean but only 0.5 mm/yr from thermosteric effects. JEVREJEVA et al. (2008) reexamine sea level rise from island and coastal tide gauge stations and ocean heat content but used uncorrected values of the latter, and their results highlight the spurious nature of the variability in ocean heat content prior to recent corrections. However, the global freshwater flux and salinity are not well constrained by observations, and model results depend on the deep ocean temperature trends that are also poorly constrained by observations. The 1.5 W m^{-2} gains in ocean heat from KÖHL and STAMMER (2008) correspond to a global value of 1.05 W m^{-2} which is slightly high compared with the FASULLO and TRENBERTH (2008a) estimate for 2001–04 of 0.9 W m^{-2} , but is probably too high for the 1990s.

Direct estimates of increases in ocean heat content have undergone vacillations and major revisions in recent years. Estimates for the decade up to 2003 placed $1.6 \pm 0.3 \text{ mm/yr}$ of the total sea level rise as being the thermosteric contribution for the upper 750 m, corresponding in terms of energy to $0.86 \pm 0.12 \text{ W m}^{-2}$ into the ocean (WILLIS et al., 2004), or about 0.6 W m^{-2} globally. Note that because of the heat content change at deeper layers, this is almost half of the KÖHL and STAMMER (2008) value. But between 2003 and 2005, early estimates of ocean heat content suggested a downturn (LYMAN et al., 2006), while sea level continued to rise at similar rates, so that the in situ record was incompatible with satellite altimetry (LOMBARD et al., 2006). This was subsequently found to arise partly from ARGO float data problems that have now supposedly been corrected or omitted (WILLIS et al., 2007). Several new re-analyses 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 sea level of $1.6 \pm 0.2 \text{ mm/yr}$ from 1961 to 2003 (DOMINGUES et al., 2008; WIJFFELS et al., 2008; ISHII and KIMOTO,

accepted; LEVITUS et al., 2009).

For the 4 year (mid-2003 to mid-2007) 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 (WILLIS et al., 2008) but substantial discrepancies in trends exist of order 2 mm/yr . Part of this discrepancy can be accounted for by improved land-sea masks and better resolution in the GRACE measurements (Sean SWENSON, 2008; pers. communication), which increase the linear trend in ocean mass sea level equivalent from 0.9 to 1.4 mm/yr over this period. CAZENAVE et al. (2008) claim to have resolved the discrepancies as they find increased contributions from melting land ice of 2 mm/yr for 2003 to 2008 based on an alternative GRACE data analysis that includes a substantial Glacial Isostatic Adjustment. WOUTERS et al. (2008) isolate the Greenland contribution to sea level rise from 2003 to January 2008 and show an increasing rate over time that is largest in 2007.

In summary, while sea level rise is a good indicator of the heating of the planet the interpretation is not straightforward. The roughly comparable eustatic and thermosteric contributions to sea level rise for 1992 to 2003 occurs because the much more efficient use of heat to melt land ice is offset by the very small areas where vulnerable land ice occurs, and the energy balance is consistent with TOA observations and model results. Whether or not the sea level budget is closed for the post 2003 period, however, it is not clear that the global energy budget is closed, because sea level rise is much greater for land ice melt versus ocean expansion for a given amount of heat.

It is possible for radiative forcing from increasing greenhouse gases to be offset entirely for a year or two by order up to a 1 % increase in cloud, and fluctuations of this duration and magnitude occur in the corrected High Resolution Infrared Radiometer Sounder (HIRS) cloud observations from 1979 through 2001 (WYLIE et al. 2005). Accordingly another much needed component is the TOA radiation, but CERES data exist only through 2005 and are not yet long enough to bring to bear on this question. This highlights the need to bring the CERES TOA radiation up to date and to reprocess the International Satellite Cloud Climatology Project (ISCCP) cloud record to better constrain cloud changes since 2004.

The ARGO floats plus fixed moored arrays (such as the TAO/TRITON array in the tropical Pacific) are a boon to addressing the ocean spatial sampling problem that is prevalent prior to about 2002, and also address the much needed measurements of salinity, so that the expectation is for enormous positive impact on understanding changes in heat content and sea level in the ocean that are vital parts of the global energy budget. Nonetheless, processing of ARGO data indicates that it is not without problems associated with different cali-

bration and manufacturers of the instruments; a problem common for atmospheric measurements. Indeed, it is surprising that since 2003, just when a new ARGO observing system has come into being, that there has been no apparent increase in ocean heat content even as sea level rise has continued, and further exploration of this aspect is called for as well.

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