JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D22101, doi:10.1029/2007JD008435, 2007

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Decadal variations of global energy and ocean heat budget and meridional energy transports inferred from recent global data sets

Yuanchong Zhang,[1] William B. Rossow,[2] Paul Stackhouse Jr.,[3] Anastasia Romanou,[1] and Bruce A. Wielicki[3]

Received 18 January 2007; revised 15 May 2007; accepted 27 June 2007; published 17 November 2007.

[1] We use the most recent global, decades-long data sets, consisting of two satellite-derived top-of-atmosphere (TOA) and surface radiative flux data sets from the International Satellite Cloud Climatology Project Flux product (ISCCP-FD) and the Global Energy and Water Cycle Experiment Surface Radiation Budget project (GEWEX-SRB), three ocean surface turbulent flux data sets from Goddard Satellite-based Surface Turbulent Fluxes (GSSTF), Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite data (HOAPS) and Woods Hole Oceanographic Institution Objectively Analyzed air-sea Fluxes (WHOI) and one ocean heat content (or energy storage rate) data set from Willis et al. to investigate what can be learned about how decadal-scale variations of the global energy budget at TOA are partitioned between the atmosphere and ocean and their mean meridional heat transports. Although the mean differences among the TOA radiative flux data sets are large enough that direct measurements of planetary energy imbalances are still unreliable, comparison of the interannual anomalies of the ocean heat content with the two (satellite-derived) planetary energy imbalances converted to accumulated ocean heat content (or equivalently comparison of the anomalies of ocean heat content converted to ocean heat storage rate with the planetary energy imbalances) show excellent quantitative agreement. These data sets essentially show a heating of the upper ocean since the 1990s but different "trends" at the beginning of this century that need further investigation. The comparison of interannual anomalies of total ocean surface energy fluxes converted to accumulated ocean heat content do not show such good agreement, the former generally indicating a cooling over the past decade. The fact that the anomalies in surface net radiative heating are slightly too large suggests that the latent heat flux anomalies are also too large (causing an overall cooling). The interannual anomalies of the mean meridional heat transport by the atmosphere-ocean system inferred from the two TOA radiative flux data sets all show similar patterns of weakened poleward transport associated with El Niño events. Each event is different in character. The most interesting difference suggested by the latitudinal patterns is that some heat transport anomalies appear in the atmosphere and some in the ocean, but the current quality of the surface turbulent energy flux data sets precludes confirmation. Although not completely successful, we believe that this analysis indicates that these products are somewhat better than might have been expected and that the goal of further work should now be to reduce their uncertainties enough to diagnose the variations of the coupling of the atmosphere and ocean heat exchanges and transports over decadal timescales.

Citation: Zhang, Y., W. B. Rossow, P. Stackhouse Jr., A. Romanou, and B. A. Wielicki (2007), Decadal variations of global energy and ocean heat budget and meridional energy transports inferred from recent global data sets, *J. Geophys. Res.*, *112*, D22101, doi:10.1029/2007JD008435.

1. Introduction

[2] The total energy exchanges within the Earth climate system and their progressive or sometimes abrupt changes are not only fundamental to all climatological studies but also vital to all the living things in the system. The complexity of our atmosphere-ocean-land-cryosphere-biosphere system with all its interactive components and the mixing of natural- and human-caused variations by different forcing agents makes understanding climate

[1]Department of Applied Physics and Applied Mathematics, Columbia University, at NASA Goddard Institute for Space Studies, New York, New York, USA.
[2]Cooperative Remote Sensing Science and Technology Center, City College of New York, New York, New York, USA.
[3]NASA Langley Research Center, Hampton, Virginia, USA.

0148-0227/07/2007JD008435$09.00

change very difficult. Moreover, because of the large thermal inertia of the ocean, ocean heat accumulated over a long time from a small, positive energy imbalance could be a potential "global warming time bomb" if some of this thermal energy from below the thermocline (90% of the ocean water) is released and added to the "realized" global warming of the near-surface environment in other areas and components (including sea surface temperature) of the system in an accelerated or even explosive way [e.g., *Hansen*, 2004; *Hansen et al.*, 2005]. Accurate measurement and prediction of how much heat is stored in the oceans and how it is released to the atmosphere is therefore a crucial task.

[3] Since the advent of satellites, we have for the first time decades-long, global energy flux data sets that can shed new light on the processes controlling ocean-atmosphere energy exchanges and transports. *Wielicki et al.* [2002] recently drew attention to the long-term variations of satellite-measured tropical top-of-atmosphere (TOA) radiative fluxes and *Wong et al.* [2006] compared the anomalies of global TOA net flux with the ocean heat storage rate inferred from ocean observations by *Willis et al.* [2004]. In this study, we use the most recent global data sets (section 2), consisting of two radiative flux data sets, three ocean surface turbulent flux data sets and one ocean heat content (or its equivalent storage rate) data set, to investigate what more can be learned about how the long-term (1–2 decades) variations of the global energy budget at TOA are partitioned between the atmosphere and ocean (sections 3 and 4) and their associated meridional transports (sections 5 and 6). The conclusions are presented in section 7.

2. Data Sets

[4] The two global radiative flux products are 2 decades long, the International Satellite Cloud Climatology Project Flux product (ISCCP-FD [see *Zhang et al.*, 2004]) and the Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget project (SRB, Rel2.5 and 2.6 for longwave (LW) and shortwave (SW), respectively [see *Stackhouse et al.*, 2001]). Both data sets contain both TOA and surface radiative fluxes that are calculated using (different) radiative transfer models with inputs that describe the properties of clouds from the ISCCP climatology [*Rossow and Schiffer*, 1999] and other (different) data sets describing the properties of the atmosphere and surface, mostly from satellite measurements. These products are global, 3-hourly, covering a 21-year-long period (1984–2004) and reporting upwelling and downwelling broadband LW and SW fluxes. Another global data set contains satellite-measured broadband TOA (SW and LW) fluxes from the Earth Radiation Budget Experiment (ERBE) for the period from April 1985 to January 1989 [*Ramanathan et al.*, 1989] is used for validation of the calculated radiative fluxes [see, e.g., *Zhang et al.*, 2004]. There is also a longer-term TOA flux data set that has been obtained from the Earth Radiation Budget Satellite (ERBS) wide-field-of-view instrument [e.g., *Wielicki et al.*, 2002] but it is not globally complete, covering only ±60° latitude. Since the global data sets suggest that most of the slow changes have occurred at lower latitudes [*Chen et al.*, 2002] and this lower-latitude area covers about 87% of the surface of the Earth, this data set still provides a good check on the other results. Both the calculated products (ISCCP-FD and SRB) have been compared to the tropical changes inferred from the ERBS record in some detail (for FD, see *Zhang et al.* [2004]; for SRB, see *Stackhouse et al.* [2004] and also P. Stackhouse (personal communication, 2007). In particular, the long-term TOA flux anomalies from ISCCP FD and GEWEX SRB agree well quantitatively with ERBS record, which suggests that the larger changes are induced by the cloud cover variations found in the ISCCP data set [*Zhang et al.*, 2004].

[5] Three ocean surface turbulent flux data sets are the Goddard Satellite-based Surface Turbulent Fluxes (GSSTF, version 2), the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite data (HOAPS, version 2) and the Woods Hole Oceanographic Institution Objectively Analyzed air-sea Fluxes (WHOI), covering periods for 1988–2000, 1988–2002, and 1981–2002, respectively. GSSTF is derived from the SSM/I surface winds and air humidity as well as 2-m air and sea surface temperatures (SST) from the National Centers for Environmental Prediction (NCEP) reanalysis [*Chou et al.*, 2004], HOAPS is derived from the Advanced Very High Resolution Radiometer (AVHRR) and SSM/I [*Grassl et al.*, 2000], and WHOI is derived from the Objectively Analyzed air-sea heat Fluxes (OAFlux) Project [*Yu et al.*, 2004] using ship and buoy measurements (this product also includes the ISCCP-FD surface radiative fluxes). This study (for surface fluxes) is based on their common period (1988–2000).

[6] *Willis et al.* [2004] estimated the ocean heat content (OHC) for the upper 750 m of the global ocean directly from in situ temperature profiles and satellite sea surface altimeter data and reported the results on 1° × 1° grid at quarter year intervals with 1-year time resolution (e.g., 1993.00, 1993.25, 1993.50 and 1993.75 OHC represents the accumulated heat over 12 month periods centered at 1 January, April, July and October, respectively) covering the period of 1990 to 2004. Recently, they updated the OHC and extended the period to current (2006) [*Lyman et al.*, 2006]. The corresponding annual mean ocean heat storage rate (OHSR, normalized for the whole area of Earth, also at the nominal quarter-year intervals) is derived from OHC by calculating year-to-year differences of the annual mean heat content, representing the temporal change of net energy for the upper 750 m of the ocean. In this study, we take the OHC at a midpoint of a year (e.g., 1993.50, to represent the yearly value of 1993), and set the reference year = 1993 (= 1993.05, the first year of the time series, see below) unless otherwise indicated. The OHSR is then derived from the difference of the current year and the previous year (e.g., 1995 = 1995.50 OHSR = 1995.50 minus 1994.50 OHC). We use the updated version of the global mean OHC and OHSR directly from Willis et al. However, we only select a period of 1993–2002 for this study because (1) the pre-1993 years are less reliable (J. K. Willis, personal communication, 2006) and (2) an artifact has been found in the data sets beginning from about 2003 (as reflected by *Lyman et al.* [2006]) that leads to some biases that are larger than estimated sampling errors. The artifact has been reported [*Willis et al.*, 2007] and will require substantial work to correct. The global OHC or OHSR data sets are probably not as accurate as previously thought and more thorough

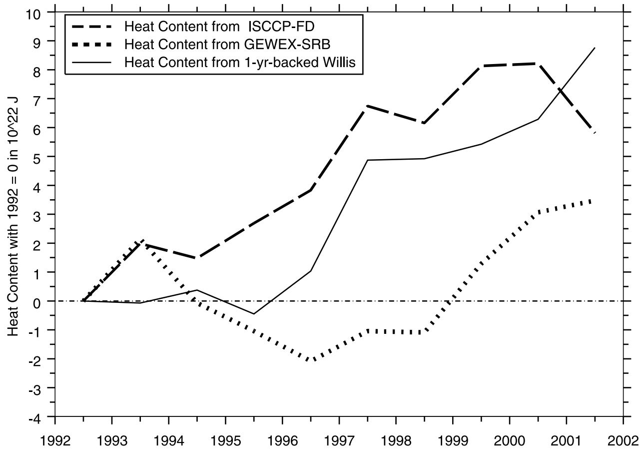

Figure 1. The 12-year (1992–2003) global, annual mean heat content (in 10^{22} J): 1-year-backed Willis et al. (solid, from original 1993–2004) and those converted from original total TOA net radiative flux of ISCCP-FD (dashed) and GEWEX-SRB (dotted).

and systematic instrumental biases corrections are required [*Gouretski and Koltermann*, 2007].

[7] All of the above data sets are mapped to the same 280-km equal-area map and averaged to global (whole Earth or ocean-only as appropriate), annual means (but because the Willis et al. globally mapped data sets are only available for an older version whereas the recently updated version only has global means available at the time of writing, we only directly use their global mean time series).

[8] There are two methods to compare energy fluxes with the results from Willis et al.: directly comparing fluxes with OHSR (in W/m^2, normalized for whole Earth area) or integrating fluxes to heat contents (in Joules) and then comparing with OHC. Both methods are used in this study and, for the latter, we convert our total energy fluxes to heat content after removing the bias from 1993–2002 (or otherwise, see section 3 and Figure 1) and 1993–2000 mean for global TOA and oceanic surface, respectively.

3. Decadal Anomalies of Planetary Energy Imbalance and Ocean Heat Content

[9] Since the external solar forcing of the climate is not constant, varying on diurnal, annual and decadal timescales (at least), and is not geographically uniform, circulations of the ocean-atmosphere system are induced that transport heat to establish local energy balances [e.g., *Goody and Yung*, 1989; *Lorentz*, 1967]. However, other climate forcing factors also change on a variety of timescales, some shorter, some longer than the response time of the ocean-atmosphere system. Hence the TOA total net radiative flux is not zero locally or instantaneously and is probably not precisely zero even in the global, annual mean. This planetary energy imbalance (PEI = TOA total net radiative flux) is the primary forcing that drives climate change as most of the other forcing agents act to alter it. Its longer-term, global determination currently must rely on satellite-observation-based radiative transfer calculations because a globally complete, continuous, long-term (direct-observation-based) radiation budget data set is not available. However, the available satellite radiation budget data sets (NIMBUS-7, ERBE, ScaRab and the Clouds and the Earth's Radiant Energy System (CERES)), some of which provide global coverage for short periods of time, are critical for validating these reconstructions. On the basis of comparisons with ERBE and ERBE-like CERES, the reconstructions of TOA fluxes by the ISCCP-FD and GEWEX-SRB products are estimated to be uncertain by 5–10 W/m^2 for monthly, regional (300 km scale) averages with global mean biases $\approx$2–3 W/m^2 [see *Zhang et al.*, 2004]. This is not yet the required absolute accuracy needed for monitoring PEI, which needs to be determined to <0.5 W/m^2 for global, decadal means. The 21-year average PEI is +2.6 and −2.2 W/m^2 for ISCCP-FD and SRB, respectively. (Note that the ERBE PEI for 1984–1988 is much larger because of some missing SW flux data at low Sun angles [see *Rossow and Zhang*, 1995].)

[10] Even though the absolute accuracy of these data products is not good enough to determine PEI directly, they appear to have enough relative accuracy (precision) to determine decadal variations of PEI. Since the long-term changes in PEI seen in the ISCCP-FD and SRB products appear to be concentrated at lower latitudes, they can be checked against those from the ERBS record [*Wielicki et al.*, 2002]. This comparison shows excellent quantitative agreement (*Zhang et al.* [2004] for FD and P. Stackhouse (personal communication, 2007) for SRB).

[11] The determination of the variations of OHC (or its equivalent OHSR), provides an independent check for the energy imbalance of the Earth [see *Wong et al.*, 2006]. From the first law of thermodynamics applied to a portion of the ocean for a designated time interval (a year in the current case), changes in OHC imply a value of OHSR (as an increment of internal energy) and must equal the total heat flux imposed on that portion of the ocean for the same time interval. If we neglect the heat exchanges with the interior of the Earth and continents, work done by the ocean circulation (which is canceled out for global mean OHSR) and the OHSR into the ocean below 750 m (which raises some accuracy questions for using these results to represent the whole ocean), then OHSR is equal to the total ocean surface energy flux (OSEF = sum of net radiative flux minus latent and sensible fluxes into the atmosphere at the surface of the ocean) averaged over the same time interval, but it is not necessarily equal to PEI.

[12] The conventional view is that the time variations of PEI and OHSR generally agree in both phase and magnitude for timescales $\geq$ a year, and therefore they may be directly compared [see, e.g., *Pielke*, 2003]. The primary reason for this view is that, except for the ocean, there is no other component of the climate system that can store the amount of heat equivalent to, say, 1 W/m^2 of global mean net flux sustained for a year ($\approx 1.6*10^{22}$ J) needed to produce a difference between the net TOA and the net surface fluxes large enough to cause a noticeable difference between PEI and OHSR (one of the largest storage terms is increasing water vapor in a warming climate, but observations of annual mean variations (defined by standard deviation) over the passed decades of water vapor abundance of a few percent per decade [e.g., see *Trenberth et al.*, 2005] are equivalent only to about 0.1 W/m^2 based on our

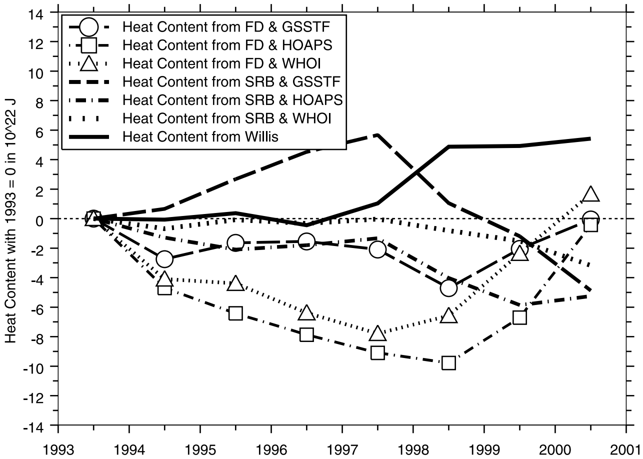

Figure 2. The 8-year (1993–2000) global, annual mean heat content (in 10^{22} J): Willis et al. (solid) and those converted from total oceanic surface energy fluxes: ISCCP-FD combined with GSSTF (dashed with open circles), HOAPS (dash-dotted with open squares) and WHOI (dotted with open triangles), and GEWEX-SRB combined with GSSTF (dashed without marks), HOAPS (dash-dotted without marks) and WHOI (dotted without marks).

calculation for global, annual mean precipitation time series of 1979–2005, averaged from the global data sets from the Global Precipitation Climatological Project (GPCP) [see *Adler et al.*, 2003]). Nevertheless, the relationship between PEI and OHSR is complicated. First, PEI is not a single component at TOA, but consists of three parts: downward and reflected SW and outgoing LW fluxes with very different space-time variations because of the differing effects of clouds, water vapor, temperature and the surface. About 60% of the net SW reaching the ocean surface is converted into water vapor (latent heat flux) and about one third is converted to net surface outgoing LW. Therefore only a few percent of PEI is absorbed by the ocean, mostly the net SW retained by the ocean and gradually mixed to greater depths. All of these considerations mean that the comparison between PEI and OHSR is approximate in both magnitude and timing.

[13] With a reference value of zero at 1993, the 10-year (1993–2002) PEI global mean is -1.2 W/m^2 for both ISCCP-FD and SRB, as compared to +0.86 W/m^2 for OHSR in the upper 750 m of the global ocean (normalized for the whole Earth) from Willis et al. The difference between the PEI values and OHSR is well within the uncertainties for the two kinds of data sets. To reduce effects of systematic errors, we focus on the anomaly time series of OHC, which is the primary result of Willis et al.

[14] Figure 1 essentially shows an increase of the OHC of the upper ocean from all three data sets over the past decade (OHC is from the ISCCP FD and GEWEX SRB TOA fluxes) but with different ‘‘trends’’ at the beginning of the 21st century; if this agreement implies reliable accuracy for the longer PEI data sets, then ocean heating has been underway for at least the past 2 decades. In Figure 1, OHC from Willis et al. is backward shifted by one year (1993.50 to 1992.50, etc.), and, accordingly, OHC (converted from PEI as described in section 2) from ISCCP-FD and SRB are for their original periods, 1992–2001, so the reference year is now set to 1992 (all OHC = 0; midpoint is used for a yearly value in all the plots in this paper). The correlation with the Willis et al. record is 0.84 for ISCCP-FD and 0.52 for SRB and the mean (rms) differences are +1.4 (1.7) and -2.7 (2.7) $\times 10^{22}$ J for ISCCP-FD and SRB, respectively (if no lag is assumed the correlations become -0.46 and -0.23). Note that in Figure 1, the large drop of ISCCP-FD beginning in 2001 may be partly an artifact because the surface LW fluxes are significantly altered by a change of the operational analysis procedure for the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) temperature and humidity profiles used in ISCCP-FD analysis [*Zhang et al.*, 2006]. We obtain similar results for OHSR: the correlation coefficients are 0.42 and 0.43, and the mean (rms) differences are +2.5 (1.4) and 1.0 (1.1) W/m^2 for ISCCP-FD and SRB, respectively (if no lag is assumed the correlations become -0.46 and -0.23). A similar good correspondence was found by *Wong et al.* [2006] between the PEI from the ERBS (not globally complete) and CERES and OHSR records from *Willis et al.* [2004].

4. Decadal Anomalies of Surface Energy Imbalance and Ocean Heat Content

[15] With the two surface net radiative flux data sets (ISCCP-FD and SRB) and three turbulent heat flux data sets (GSSTF, HOAPS and WHOI), we can construct six total ocean surface energy flux (OSEF) data sets. As explained in section 2, OSEF can be accumulated to OHC that can then be compared with the Willis et al. OHC record. Figure 2 shows the annual mean OHC anomalies for the six OSEF-derived and Willis et al. for the period of 1993–2000 (referenced to 1993 = 0). All six curves have a common trend for 1991–1993 (not shown) that is probably related to the radiative effects of stratospheric aerosol from the Mt. Pinatubo eruption. The surface flux products (with one exception) show a cooling over this time period: since the net surface radiation shows a heating (which may be slightly too large [cf. *Zhang et al.*, 2004]), this result suggests that the latent heat fluxes are too large. Overall the uncertainties in OSEF are still too large (e.g., from *Bentamy et al.* [2003], the latent heat flux may be summarized as having an uncertainty >25 W/m^2; the sensible heat flux usually has at least 50% uncertainty, that is, about 5 W/m^2; the surface total net radiative flux may have about 10–15 W/m^2 uncertainty [*Zhang et al.*, 2004]. Therefore the total uncertainty for OSEF may be $\geq$20–30 W/m^2 in our conservative estimates.) to justify a more detailed analysis. The average bias (rms difference) between all six OSEF series and the OHC is -4.3 (3.8) $\times 10^{22}$ J (these differences are equivalent to net flux biases of a few W/m^2 globally accumulated over a year).

5. Mean Meridional Energy Transports

[16] From the TOA zonal mean total net radiative flux, we can infer the mean meridional energy transport of the ocean-atmosphere system required for balancing local energy loss or gain using the Surface and Planetary Energy Balance (SPEB) method referred to by *Zhang and Rossow*

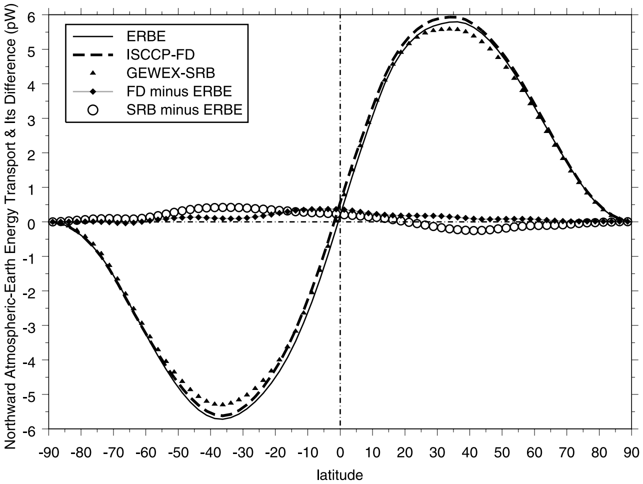

Figure 3. Northward meridional energy transport (in Peta Watts) of the atmospheric-Earth system from 16-month-based 85048901 annual mean total TOA net radiative flux (i.e., averaged from 4-year-mean 4 seasonal months) for ERBE (solid), ISCCP-FD (dashed) and GEWEX-SRB (dotted), and the differences of FD (solid diamonds) and SRB (open circles) with respect to ERBE.

[1997]. Figure 3 shows the 1985–1988 mean transports for ISCCP-FD, SRB and ERBE: also shown are the differences between the former two and ERBE. In general, the three transports have excellent agreement within about 0.4 peta-Watts (pW). Compared with ERBE, SRB has smaller northward transports of up to 0.4 pW over the southern tropical and extratropical zones as well as at 25–50°N but larger transports over the northern equatorial zones, whereas ISCCP-FD has smaller transports of up to 0.3 pW over the southern tropical zones but larger transports of up to 0.3 pW over 0–35°N. The comparison reinforces the conclusion of

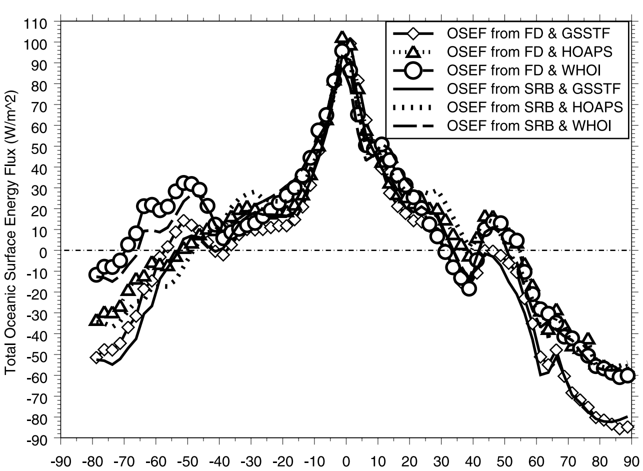

Figure 4. Zonal mean total oceanic surface energy flux (in W/m^2) from 1988–2000 annual mean for ISCCP-FD combined with GSSTF (solid with open diamonds), HOAPS (dotted with open triangles) and WHOI (dashed with open circles), and GEWEX-SRB combined with GSSTF (solid without marks), HOAPS (dotted without marks) and WHOI (dashed without marks).

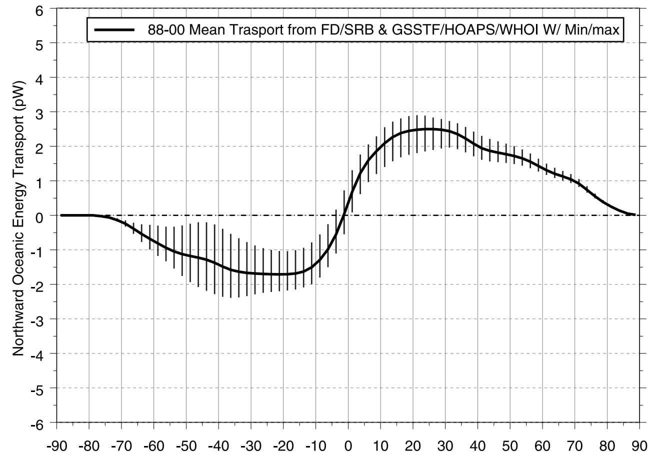

Figure 5. Mean northward oceanic meridional energy transport (in Peta Watts), averaged from the six transports calculated from the six 1988–2000 zonal, annual mean total oceanic surface energy flux as shown in Figure 4. The vertical bars indicate their individual ranges from their mean.

Zhang and Rossow [1997] that the TOA net flux estimate is not the largest source of uncertainty in estimating mean meridional energy transports.

[17] Figure 4 shows the mean zonal average OSEF for 1988–2000 (common period) for the six combinations of data. They exhibit good agreement, within about 10 W/m^2 or so, over the tropical-subtropical zone but begin to deviate in middle latitudes toward the poles, where the differences are up to about 40 W/m^2. (latitudes poleward of ~75° may be ignored where turbulent fluxes are either extrapolated or unreliable). The differences are especially large near Antarctica. From the grouping of the six combinations, it is clear that the larger differences at higher latitudes are caused by disagreements among the surface turbulent flux data sets, not the surface radiative flux data sets. In the north polar region, the GSSTF data set is the outlier, whereas in the south polar region, there is no agreement among the three turbulent flux data sets. In absolute terms, the average of the global mean OSEF is +21 W m^{-2}, suggesting that these data sets still have significant biases. If we remove the global mean bias from the zonal mean OSEF values, we can calculate six mean meridional energy transports for the ocean (and the corresponding atmospheric transports by differencing the TOA and ocean transports). Figure 5 shows the average ocean heat transport with the error bars indicating the range of values. The discrepancy among the six transports is large, up to 2 pW at around 30–50°S, which cannot be ascribed to random error alone.

6. Anomalies of Meridional Ocean-Atmospheric Energy Transports

[18] We have produced all of the meridional energy transports for the ocean-atmosphere system and for the ocean and atmosphere, separately, from all the annual mean total energy data sets (two for PEI at TOA and six for OSEF). Then we determined the transport anomalies (relative to 1993–1997 mean because there was no strong

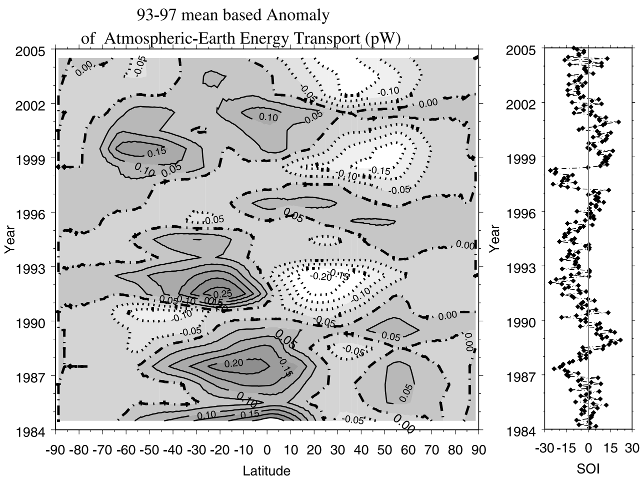

Figure 6. (left) Latitude-year contour anomaly map of the northward meridional energy transport (in Peta Watts) for the atmospheric-Earth system derived from annual mean ISCCP-FD total TOA radiative flux (anomaly is based on 1993–1997 mean). Solid (dotted) is for Positive (negative) values with thick dash-dotted for zero line. (right) Southern Oscillation Index (SOI) that is selected from SOI time series of January 1876 to April 2007 with1887–1989 base period (see text).

El Niño event during that period) for all the available years. Because the OSEF uncertainties are large (section 4), there is little common pattern to the separate atmosphere and ocean heat transport anomalies. The much better agreement of PEI does show some common patterns in the ocean-atmosphere heat transport anomalies: we show the latitude-year anomaly contour map from ISCCP-FD in Figure 6 (left). The most striking features are dipoles closely associated in time with the three major El Niño events in 1986/1987, 1991/1992 and 1997/1998. All dipoles show a weakening of poleward energy transports for both hemispheres (since positive transport means northward transport, decreased poleward transport is a negative anomaly in the northern hemisphere and a positive anomaly in the southern hemisphere) by up to 0.2 pW. For the 1986/1987 and 1991/1992 events, the dipoles appear nearly centered in time on the event, but for the 1997/1998 event the dipole lags the event by almost 1 year. Also notable are the differing latitudinal positions and magnitudes (and anomaly areas) of the dipoles: the dipoles are much closer to the equator in the 1991/1992 event than during the 1997/1998 event, which may be a consequence of the radiative effects of the Mt. Pinatubo aerosol, but the 1986/1987 also has low-latitude dipoles with a much stronger anomaly in the southern than northern hemisphere. There is no obvious dipole for 2002/2003 El Niño perhaps because the current ISCCP-FD data record ends in December 2004 and an anomaly in LW fluxes is introduced in 2001 when the TOVS analysis changed as explained in section 3. The SRB anomalies (not shown) have similar features to those in Figure 6. For a comparison, also shown in Figure 6 (right) is the Southern Oscillation Index (SOI), selected from SOI time series of January 1876 to April 2007 with 1887–1989 base period, where SOI is defined by Troup's calculation method [*Troup*, 1965] (which uses monthly mean surface pressure anomaly, defined by difference between Tahiti and Darwin, minus its 1887–1989 mean, then divided by its 1887–1989 standard deviation and multiplied by a factor of 10. The data sets are available at http://www.longpaddock.qld.gov.au/SeasonalClimateOutlook/SouthernOscillationIndex/SOIDataFiles/index.html). From SOI series, the accurate timing and patterns may probably not be the nature of El Niño events as SOI really does not have accurately defined timing and patterns (or how we can define El Niño in some more accurate way?). The whole story is certainly far from clear and it should be investigated but the flux data sets have to be improved first. We have also examined the corresponding ocean and atmosphere transport anomalies separately but they do not suggest conclusively whether the transport anomalies occur primarily in the ocean or atmosphere because of the large uncertainties. Nevertheless the lower-latitude features in Figure 6 might be predominantly ocean transport anomalies whereas the midlatitude features might be predominantly atmosphere transport anomalies.

7. Conclusions

[19] The first purpose of this study was to evaluate the state of the art regarding the capability of available data products for determining the decadal variation of the energy imbalance of the Earth based on two kinds of the recent global data sets, namely, planetary energy imbalance (PEI) and the total oceanic surface energy flux (OSEF), by comparing them with an independent data set of oceanic heat content (OHC, after conversion to fluxes) or ocean heat storage rate (OHSR). The independent estimates of the planetary energy imbalance over the past 2 decades appear consistent with variations of the upper ocean heat content even though both kinds of data sets have their own accuracy limitations and there is still some ambiguity in the relationship between them (see below). Further improvements of these several data products (PEI and OHC/OHSR) may in the near future lead to closure of the energy imbalance of the Earth. On the other hand, however, although recent radiative flux data sets appear to have narrowed the uncertainties somewhat, the surface turbulent fluxes still disagree on average by 20–30 W m^{-2}, especially at higher latitudes. As a result, OSEF has not yet reached the stage where it can independently verify the ocean heat storage rate (since OSEF = OHSR). Improving the accuracy of these fluxes is a critical goal for advancing understanding of the longer-term variations of the global ocean-atmosphere coupling. We believe that the results suggest that with more effort to reduce further the uncertainties of the surface turbulent fluxes such an analysis will provide useful and accurate picture of the interaction between ocean and atmosphere in addition to verifying the energy imbalance of the earth. Achieving this goal is also a crucial part of completing the quantitative description of the global energy and water cycle with sufficient resolution to allow for diagnosis of the causes of its variations over timescales of 1–10 years or more.

[20] We have pointed out that the relationship to be expected between variations in the planetary energy imbalance and the variations of the upper ocean heat storage rate is actually quite complex, involving a lot of internal energy

exchanges and feedback loops in addition to both horizontal and vertical transports over a range of timescales. Moreover, although we may know the state of the (upper-only) ocean and its temporal differentials (e.g., OHSR as used in this paper), we are here faced with a fundamental problem: we do not know the initial tendencies of the heat content of the deeper parts of the ocean; that is, we may never know the initial conditions completely. As a result, we cannot be sure what to expect in such a short time record. Despite the uncertainties of the flux data sets, we obtain some good correlations of the time series of OHC and PEI with the most accurate in situ and satellite-derived OHC (or OHSR) from Willis et al., which also has its own problems, mainly instrument bias correction and under sampling as recently reported. The results are not yet good enough to detect the small energy storage in the form of increasing water vapor abundance in a warming climate. The difficulties with the net LW fluxes and the turbulent fluxes need to reduced.

[21] In considering the total energy transports that can be inferred from the boundary fluxes, we reinforce the conclusion of *Zhang and Rossow* [1997] that the total ocean-atmosphere transport is constrained by the top-of-atmosphere radiation to within about 0.2 pW. Consequently, the anomalies in the total transport over the 2-decade record that we have described appear to be reliable, showing interesting ENSO-related variations [cf. *Trenberth and Stepaniak*, 2001]. The basic pattern is a weakening of the poleward energy transport near the time of the El Niño event. However, the three events we can examine differ in detail: the strong 1997/1998 event appears to lead the transport anomaly by about one year, whereas the preceding and weaker events appear to coincide with the transport anomaly. The strong event also exhibits transport anomalies at higher latitudes than for the other events: given the relative roles of the oceanic and atmospheric transports at different latitudes, this might suggest that the middle latitude atmospheric transports were more perturbed than the oceanic transports during the 1997/1998 El Niño, but that it is the low-latitude oceanic transports that are more perturbed in the other two El Niños. We have also found that the transport anomalies in each hemisphere are approximately equal but not during the 1986/1987 event, which appears perturbed mostly in the southern hemisphere. Since the transport anomaly we calculated here is only that "required" by the TOA radiation imbalance and is not necessarily the actual ones because of uncertainties in the data and the varying time delay of the realization of the required transport, the possible cause-effect relationship between the transport and El Niño is not clear yet but is key to understanding the effects on the global climate. Another motivation for improving the quality of these fluxes is the desire to separate these energy transport anomalies into their oceanic and atmospheric components, as well as separating dry energy and water transports. With the current products, there did not seem to be a coherent pattern to the partitioning of the ENSO anomalies shown in Figure 6.

[22] Lest we end on a negative note, we should emphasize that we have picked the hardest problem to apply these data to: the interannual variations of the global energy budget and the transports. Despite the somewhat large systematic variations, variations on synoptic to seasonal cycles are more reproducible among the products, so that their availability makes possible a number of diagnostic studies of the ocean-atmosphere coupling.

[23] **Acknowledgments.** We first thank Josh Willis, John Lyman and Greg Johnson for supplying us with the revised and extended oceanic content data set as well as the critical comments on our first draft. We would like to dedicate this paper to the memory of Sue-Hsien Chou, who had produced one of the ocean surface turbulent flux data sets (GSSTF) we used in this analysis. Working at NASA Goddard Space Flight Center, she was part of a group, led by Robert Adler, that began thinking early on about satellite remote sensing analyses of the water exchanges over the ocean as part of the Global Precipitation Climatology Project and the Tropical Rainfall Measurement Mission. We also acknowledge support for this work from NASA programs managed by Donald Anderson and Jared Entin. Finally, we thank two anonymous reviewers for their constructive suggestions and comments.

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A. Romanou and Y. Zhang, Department of Applied Physics and Applied Mathematics, Columbia University, at NASA Goddard Institute for Space Studies, New York, NY 10025, USA. (yzhang@giss.nasa.gov)

W. B. Rossow, Cooperative Remote Sensing Science and Technology Center, City College of New York, New York, NY 10031, USA.

P. Stackhouse Jr. and B. A. Wielicki, NASA Langley Research Center, Hampton, VA 23680, USA.