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Assessment of global annual atmospheric energy balance from satellite observations

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[1] Global atmospheric energy balance is one of the fundamental processes for the earth's climate system. This study uses currently available satellite data sets of radiative energy at the top of atmosphere (TOA) and surface as well as latent and sensible heat over the oceans for the year 2000 to assess the global annual energy budget. Over land, surface radiation data are used to constrain assimilated results and to force the radiation, turbulent heat, and heat storage into balance due to a lack of observation-based turbulent heat flux estimates. Global annual means of the TOA net radiation obtained from both satellite direct measurements and calculations are close to zero. The net radiative energy fluxes into the surface and the surface latent heat transported into the atmosphere are about 113 and 86 W/m^2, respectively. The estimated atmospheric and surface heat imbalances are about −8 and 9 W/m^2, respectively, values that are within the uncertainties of surface radiation and sea surface turbulent flux estimates and the likely systematic biases in the analyzed observations. The potential significant additional absorption of solar radiation within the atmosphere suggested by previous studies does not appear to be required to balance the energy budget: the spurious heat imbalances in the current data are much smaller (about half) than those obtained previously and debated about a decade ago. Progress in surface radiation and oceanic turbulent heat flux estimations from satellite measurements has significantly reduced the bias errors in the observed global energy budgets of the climate system.

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1. Introduction

[2] Global atmospheric energy and heat balance is one of the fundamental physical processes of the earth's climate system. Current constructions of the global energy balance are based on the analysis of assimilated data, satellite estimates of global radiant energy and turbulent heat over oceans, and/or the hybrid approach of in-situ and satellite measurements [*Da Silva et al.*, 1994; *Trenberth and Solomon*, 1994; *Rossow and Zhang*, 1995; *Yu et al.*, 1999; *Trenberth and Stepaniak*, 2004; J. Fasullo and K. E. Trenberth, The annual cycle of the energy budget: Meridional structures and poleward transports, submitted to *Journal of Climatology*, 2008, hereinafter referred to as Fasullo and Trenberth, submitted manuscript, 2008; *Zhang et al.*, 2007; and references therein]. With these constructed atmospheric heat fluxes, atmospheric and oceanic poleward heat transports are estimated [e.g., *Zhang and Rossow*, 1997; *Zhang et al.*, 2007; Fasullo and Trenberth, submitted manuscript, 2008]. Model assimilations can also provide global estimates of all major atmospheric energy and heat components. However significant errors associated with these estimates exist and can be as large as about 30 W/m^2 over large (1000 km) scales [*Trenberth and Solomon*, 1994]. Some analysis techniques, especially the method of constraining model analysis results with satellite top-of-atmosphere (TOA) radiation measurements and mass corrections within the assimilation models, are generally critical for reducing the uncertainties in global heat budgets [*Trenberth et al.*, 2002].

[3] Satellite-estimated heat components of the global energy balance are mainly focused on the fluxes of TOA and surface radiative energy and air−sea turbulent heat [e.g., *Wielicki et al.*, 1996; *Zhang and Rossow*, 1997; *Chou et al.*, 1997; *Schulz et al.*, 1997]. Analysis of satellite data indicates that the mean differences among radiative flux data sets may be large enough that direct measurements of annual planetary energy imbalances are still unreliable [*Zhang et al.*, 2007] due to the annual mean TOA biases of about 5 W/m^2 in direct broadband satellite measurements [*Barkstrom et al.*, 1989; *Suttles et al.*, 1992] and of around

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2 W/m^2 in calculated values [*Zhang et al.*, 2004, 2006, 2007]. However, comparison of the interannual anomalies of the ocean heat content with satellite-derived planetary energy variations converted to accumulated ocean heat content (or equivalently comparison of the anomalies of ocean heat storage converted from ocean heat content with the planetary energy imbalances) show excellent quantitative agreement [*Wong et al.*, 2006; *Zhang et al.*, 2007]. Since both anomalies and absolute values of the global energy budget are important for climate studies, quantitative knowledge about the global energy budget from more recent observationally based data sets is needed. An earlier consistency study of blended satellite, in-situ and assimilation data for the global annual mean atmospheric energy budget [*Yu et al.*, 1999] found that the data sets available at that time resulted in a 20 W/m^2 imbalance in the atmospheric heat budget, and that the sign and magnitude of the systematic errors were consistent with the insufficient absorption of solar radiation within atmosphere debated at that time [e.g., *Cess et al.*, 1995]. Although the systematic biases were generally much larger than the TOA radiation uncertainties, these errors might be attributed to large spurious errors in the estimates of sea surface turbulent fluxes and to the combined effects of uncertainties in the radiation and turbulent flux calculations used in the study.

[4] Since there have been significant improvements in both surface radiation and air–sea interaction flux estimates from satellite observations in the last 5–10 years, this paper revisits the consistency issue of the global annual atmospheric energy budget. The overarching goal is to evaluate the magnitude of the systematic biases within current satellite-based data sets and determine if the spurious errors are within the accuracies of current satellite retrievals of radiative and sea surface turbulent fluxes. The data sets are discussed in section 2, and the results are shown in section 3. Major conclusions are summarized in section 4.

2. Data Sets and Analysis Methodology

[5] In this study, satellite observations are employed to estimate TOA radiative fluxes. For surface fluxes, satellite retrievals are used over oceans, and the combined results from satellite estimates of radiant energy and assimilation analyses of surface heat storage and the partition of latent and sensible heat (or the Bowen ratio) are used over land. Three global radiation data sets are used here: data from the Clouds and the Earth's Radiant Energy System (CERES) mission [*Wielicki et al.*, 1996], International Satellite Cloud Climatology Project Flux Data [ISCCP-FD, c.f. *Zhang et al.*, 2004], and Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) data [*Stackhouse et al.*, 2001; *Cox et al.*, 2004]. CERES directly measures TOA outgoing and incoming broadband longwave (LW) and shortwave (SW) radiation for the climate system and calculates the surface radiative fluxes. The CERES data used here are from the Edition 2d product of the CERES Terra surface radiation budget averages (SRBAVG), in which the effect of diurnal cycle has been corrected for the CERES Terra measurements of a sun synchronous orbit. The other two radiation projects (ISCCP and SRB) use different methods to calculate the TOA and surface radiation energy based on ISCCP DX [*Rossow and Schiffer*, 1999] satellite radiances, cloud optical properties (e.g., fraction, optical depth), and surface property retrievals (e.g., surface skin temperature and reflectivity). ISCCP FD uses daily satellite observations of atmospheric temperature and humidity profiles with a boundary layer diurnal cycle while SRB integrates NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System (GEOS) version 4.0.3 [*Bloom et al.*, 2005] 3-hourly surface and 6-hourly upper atmospheric profiles. Both ISCCP and SRB algorithms require Ozone profile information obtained from satellite measurements (e.g., TOMS, TOVS, SMOBA), surface emissivity, and other ancillary data. The ISCCP data used in this study is from the version ISCCP-FD_Ed000. The SW and LW SRB data used are based on release versions 2.8 and 2.5, respectively. All these data have been submitted for the Global Energy and Water Cycle Experiment Radiative Flux Assessment.

[6] The random errors in the TOA monthly mean data at small regional scales (~250 km) associated with these radiation data are reasonably small (~5 W/m^2; see the references listed in the previous paragraph). The global monthly mean random errors are even smaller. The systematic errors in estimating the global annual mean energy budget are about 5 W/m^2 for the direct broadband radiation measurements [*Suttles et al.*, 1992; *Wielicki et al.*, 1996] and around 2 W/m^2 for ISCCP-FD and SRB products [*Zhang et al.*, 2004; *Zhang et al.*, 2007; and also see Figures 1 and 2 later]. At the surface, the instantaneous errors in the radiative fluxes at this scale relative to downwelling surface measurements for the current ISCCP-FD and SRB products are as large as about 30 W/m^2 (Note: SRB differences, especially in the SW, are significantly higher at $1^\circ \times 1^\circ$ degree, 3-hourly resolution due to under-sampling). The regional monthly mean bias errors are significantly smaller, around 10 W/m^2 [*Zhang et al.*, 2004]. Given these uncertainties and noting the levels uncertainties between ISCCP and SRB surface properties [*Zhang et al.*, 2006], we estimate error uncertainties of 10 W/m^2 for net surface radiative fluxes [for additional discussion, c.f. *Koster et al.*, 2006]. The systematic errors for global annual means could be even smaller due to potential cancellations of the bias errors for different climatological regimes.

[7] Inter-comparisons of the annual mean net radiation estimates among the SRB, CERES and ISCCP for the year 2000 are shown in Figure 1. The SRB and CERES estimates are $1^\circ \times 1^\circ$ gridded means, while $2.5^\circ \times 2.5^\circ$ grid boxes are used by ISCCP. In order to compare with ISCCP data, the original $1^\circ \times 1^\circ$ SRB values are interpolated to $2.5^\circ \times 2.5^\circ$ grid boxes. It can be seen that, for the TOA case, the differences among SRB, CERES and ISCCP are small but still significant (e.g., -2.5 W/m^2). The root mean square (rms) differences, mainly caused by random errors within and among different data sets, can be as large as around 10 W/m^2. For the surface radiation, both bias and rms differences are significantly larger and reach ~ -7 and 17 W/m^2, respectively. These difference values, especially the bias differences, are clearly consistent with the uncertainty estimates reported in the literature and discussed in the previous paragraph.

[8] The global turbulent heat fluxes from oceans to the atmosphere used in this study are based on the version 2 products of the Goddard Satellite-based Surface Turbulent

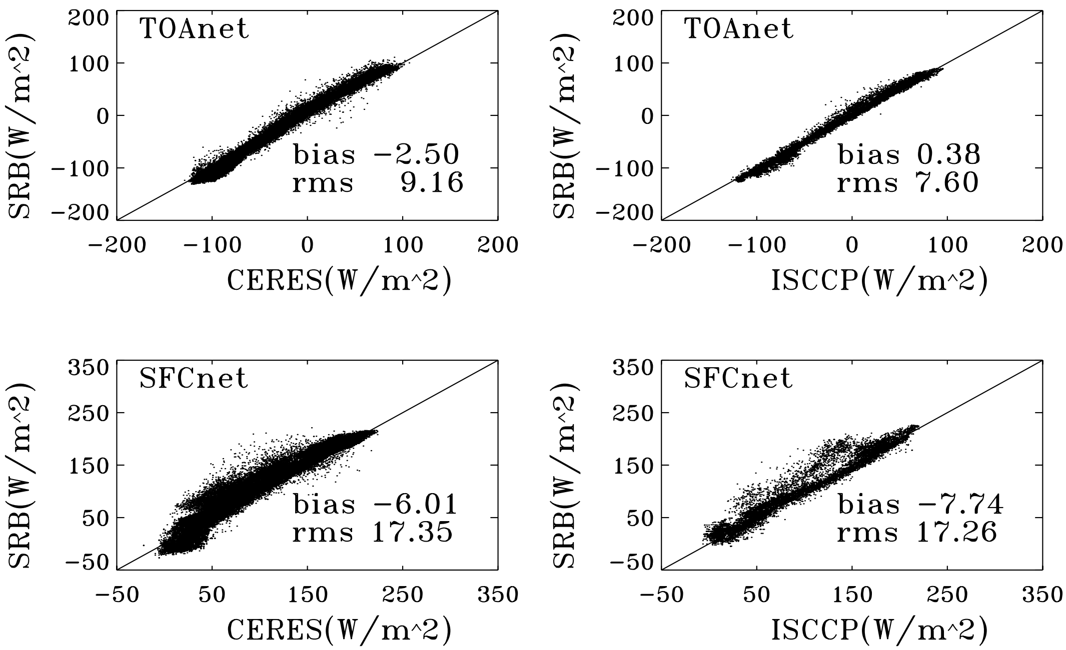

Figure 1. Comparisons of the annual mean radiative fluxes of 1° × 1° gridded box data between SRB and CERES (left panels) and of 2.5° × 2.5° gridded box estimates between SRB and ISCCP (right panels) for TOA (upper panels) and surface (lower panels) for the year 2000. The values listed in each panel are the bias (*y* axis values−*x* axis values) and RMS errors.

Fluxes (GSSTF), and are estimated from satellite microwave sensors [*Chou et al.*, 1997]. The random error for instantaneous turbulent flux estimates is approximately 30 W/m^2, mostly determined by the error (~29.0 W/m^2) in latent heat fluxes. The random latent heat error for monthly regional averages decreases to ~15 W/m^2, while that in sensible heat estimates is around 4 W/m^2. The instantaneous flux errors were estimated from the direct comparison of satellite turbulent heat fluxes with in-situ ship observations, and the errors for monthly regional means were calculated from the differences between satellite estimates and the Comprehensive Ocean-Atmosphere Data Set (COADS) [*Chou et al.*, 1997]. There are various sources causing the errors in the satellite estimated turbulent fluxes: from the bulk formulas in describing air−sea interactions to the input variables estimated from satellites for turbulent flux estimations. Even model assimilated sea surface air temperatures, which currently cannot be retrieved from satellite measurements, would introduce some uncertainties in sensible heat estimates. Among these error sources, the errors in input variables estimated by satellites such as surface air humidity, wind speed and sea surface skin temperature generally have the biggest effects on the estimation of turbulent fluxes. More detailed discussions on the validation and error analysis of satellite turbulent flux estimates can be found in previous studies [cf. *Chou et al.*, 1995, 1997; *Liu*, 1988; *Schulz et al.*, 1997; and references therein]. The systematic errors of the satellite turbulent flux estimates are generally much smaller than their random errors, but still significant (~7 W/m^2 with about 6 and 1 W/m^2 for latent and sensible heat fluxes, respectively; [*Chou et al.*, 1997]) for annual atmospheric energy balances.

[9] Since there are no global land surface turbulent flux observations, the latent and sensible heat fluxes are calculated from a combination of the results from the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004] and the SRB radiation data. Because the temperature of regional land surfaces may vary from one month to another, there are small heat storage changes at the monthly timescale for a particular region. At the global annual mean scale, the land heat storage change [*Huang*, 2006] is much smaller than the systematic errors in the current data sets and the potential satellite-observed climate system energy imbalance. Our analysis confirms that the GLDAS yields negligible changes in the global annual mean heat storage. Also, the regional horizontal heat transport within land surfaces is much smaller than the storage change and can be ignored. Thus, this study uses surface SRB radiation and regional monthly heat storage from GLDAS as constraints for the latent and sensible heat fluxes in each regional grid box (1.25° × 1°). Furthermore, the monthly Bowen ratios in each grid box from GLDAS are used to partition the latent and sensible heat fluxes based on the constraints of SRB radiation and GLDAS storage fluxes. In this way, we have forced the land surface energy budget into balance at the global annual mean scale and essentially eliminated spurious net flux errors over land. This process could add additional uncertainty to the overall result due to the assumption that radiation data provide a correct measure for land surface energy balance, but that is the best that can be done with currently available measurements.

[10] Poleward of about 75°S, the surface is primarily covered by oceanic and continental ice sheets. There are few surface latent and sensible heat estimates from either satellites or GLDAS. Our satellite based estimates of global annual energy budget mainly cover the regions north of 75°S latitude. Because the turbulent fluxes are generally small south of 75°S, the sensible heat fluxes are assumed to

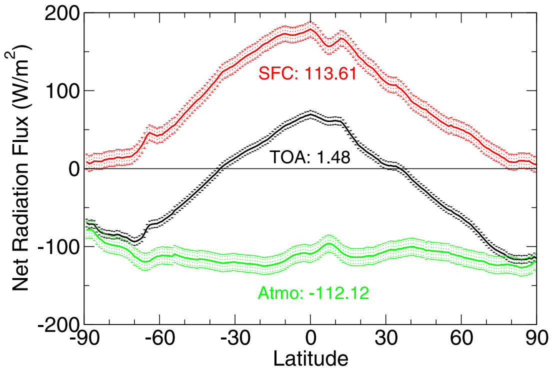

Figure 2. Annual zonal mean net radiation at TOA (black), over surface (sfc; red) and within the atmosphere (green). Hereafter, the numbers for individual curves shown in the figure are their corresponding global annual means. The shaded areas represent error bars. For polar regions, the errors are plotted the same as other places. Due to limited observational data for flux validation, the actual errors in the regions could be bigger.

be zero during cold seasons, and the precipitation data from the One-Degree Daily Global Precipitation Climatology Project [1DD GPCP; *Huffman et al.*, 2001; *Adler et al.*, 2003] are used to fill the turbulent energy gap for these latitudes. These 1DD GPCP data are designed to add up to the monthly GPCP products, so the quality of these data is essentially the same as the Version-2 GPCP monthly precipitation analysis [*Adler et al.*, 2003], except for the shorter temporal record (G. Huffman, personal communications, 2008). For monthly regional means, the errors range from 10% to 30% with an overall average around 16% [*Adler et al.*, 2003]. Since the surfaces are very cold and there is only a small amount of moisture transported into the high latitudes, the latent heat estimated from precipitation and the assumed zero sensible heat fluxes from surface to atmosphere could overestimate the turbulent fluxes. On the other hand, since GPCP underestimates snowfall and drizzle, the overall errors in the estimates of the turbulent energy in the region may be reduced.

[11] Finally, all analyzed data are collected for the year 2000. There were no special climate events, such as significant El Nino, La Nina, or volcanic activities during this year. An analysis of this year's satellite products represents the current status of satellite estimates of the global energy budget under normal climate conditions. Also, 2000 is the only year that satellite sea surface turbulent flux data from the GSSTF overlap with CERES radiation measurements (10-months).

3. Results

[12] Comparisons of the CERES, SRB and ISCCP TOA radiative fluxes reveal that the basic global patterns of annual mean TOA SW and LW fluxes, especially those for zonal averages, from all three data sets are very similar (also c.f., Figure 1 and its related discussion). The major differences are systematic biases among them, especially between CERES and the other two satellite calculations. As mentioned in the previous section, the direct broadband TOA radiation measurements yield a net radiation imbalance of $\sim$5.0 W/m^2 for the global annual mean, while SRB data result in a systematic imbalance of about 1.5 W/m^2. Because this 5 W/m^2 imbalance has existed in the direct TOA radiation measurements for about 2 decades [*Barkstrom et al.*, 1989], it can be easily removed from interannual variation analysis, resulting in a much smaller ($\sim$0.5 W/m^2) residual systematic imbalance. In order to obtain a conservative annual energy budget and more realistic current satellite-based energy imbalance estimate, the SRB fluxes with a somewhat larger bias are used in the following annual energy budget analysis.

[13] Figure 2 shows zonal annual means of TOA (black curve), surface (red curve), and atmosphere (green curve) net radiation estimates (note: all numbers in this and later figures represent global mean values). The shaded areas around each curve in this and the next two figures indicate the uncertainties (or error bars) of their corresponding flux estimates. These error bars are calculated based on the global error analyses as discussed in the previous section. For individual zonal bands, accurate estimates of the error bars are not available at present due to insufficient validation data. Thus, the actual errors, especially those for high latitudes, may not be the same as the values plotted in the figures. At high latitudes, there are limited or even no in situ measurements for the validation of satellite estimates due to the harsh climate conditions. Thus, the errors in satellite estimates at these latitudes could be significantly higher. For middle latitudes and the tropics, actual errors should be close to what is estimated in the figures due to more agreeable measurement environments and large amounts of validation data. Integration of the TOA radiative fluxes from the poles to the equator represents the net meridional heat transports of the general circulation of the climate system. It can be seen from the TOA radiation plot (black curve in Figure 2) that the climate system gains net energy only within $\sim\pm35°$ latitudes, and the middle latitudes have the maximum climatological heat transports. The variation of zonal surface radiation basically follows the latitudinal pattern of the TOA radiation except that the surface radiation is about 110 W/m^2 higher due to small differences in surface upwelling and downwelling LW radiation and to the dominant influence of solar radiation. The atmospheric net radiation, i.e., the difference between TOA and surface radiative fluxes is rather uniform, around -110 W/m^2 for most latitudes. Within the atmosphere, SW absorption ($\sim$67 W/m^2) is minimal compared to LW emission ($\sim$324 W/m^2 back to surface), and LW radiative cooling into space ($\sim$235 W/m^2) dominates the atmospheric radiation budget.

[14] The annual zonal means of latent and sensible heat fluxes from the surface to the atmosphere estimated from GSSTF and SRB modified GLDAS (c.f. previous discussions) are shown in Figure 3. The latent heat flux (red curve) gradually decreases from more than 100 W/m^2 at low latitudes to nearly zero at the poles. A clear relative minimum near the equator is caused by the weak winds of the intertropical convergence zone (ITCZ). Sensible heat fluxes (green curve) are generally small compared to latent heat fluxes and range from about 0 to 25 W/m^2. The global annual averaged latent heat and sensible heat fluxes are 86

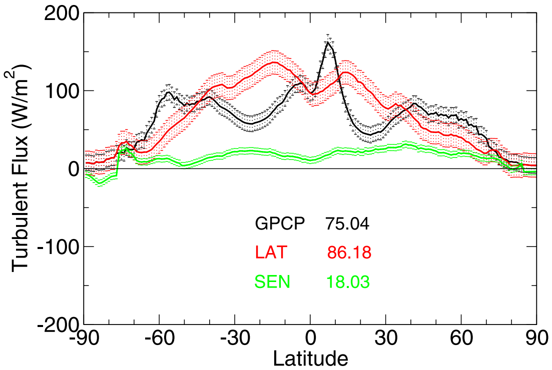

Figure 3. Same as Figure 2 except for the annual zonal means of surface latent (red) and sensible (green) heat fluxes. Also plotted is the latent heat (black) estimated from precipitation measurements.

and 18 W/m^2, respectively. These latent heat fluxes are significantly greater (~11 W/m^2) than GPCP measured rainfall latent heat releases (black curve). The 11 W/m^2 latent heat difference is almost 13% of the total, which could be larger than the systematic error of the sea surface latent heat estimates.

[15] GPCP cannot retrieve snowfall amounts during middle latitude winter time and in the polar regions. Also, the light rain from shallow (or warm) convection, such as drizzle, is generally missed by current GPCP satellite algorithms due to its weak scattering of microwave radiation and low-contrast warm cloud tops for infrared measurements. Furthermore, there are significant uncertainties in both the rainfall and surface latent heat estimates, as discussed in the previous section. Thus, the two different estimates of the global annual atmospheric latent heat flux are reasonably consistent. With full precipitation and surface latent flux retrievals, zonal moisture transports that currently have not been understood could be estimated.

[16] The annual mean zonal distribution of atmospheric total heat fluxes (Figure 4), i.e., the combined heating fluxes to the atmosphere from TOA and surface radiation and surface latent and sensible heat, basically follows the latitudinal pattern of net radiation at the TOA and surface except that a minimum exists at the equator caused by the low surface turbulent heat fluxes in this region. Combining the strong atmospheric radiative cooling (112 W/m^2) with the slightly weaker turbulent heat flux from the surface to the atmosphere (104 W/m^2), this analysis results in an estimated annual mean global atmospheric heat imbalance of about −8 W/m^2. Since the averaged atmospheric heat storage change at annual and global scales is negligible (considerably smaller than 1 W/m^2), this global atmospheric heat imbalance is clearly a spurious error of the atmospheric heat budget. Similar to this atmospheric heat imbalance, the estimated global annual mean surface total heat imbalance is about 9.4 W/m^2. Although there has been some slight heating of the oceans and the earth's climate system in recent years [*Wong et al.*, 2006], the relatively high value of 9.4 W/m^2 in surface heating is largely the result of the various errors in the input data that cause a complementary bias in the atmospheric heat budget. When the systematic errors in turbulent (~7 W/m^2) and radiative (~10 W/m^2) heat fluxes are considered, the systematic error (−8 to 9 W/m^2) in global total energy budget is not a surprise. Actually, this systematic error is less than half of what was estimated from the blended satellite, in-situ, and assimilation data in *Yu et al.* [1999]. Also, this spurious error is within the current understanding of the uncertainties in global radiation and turbulent flux estimates. Thus, there is no need to invoke the need for excess atmospheric absorption of solar radiation as mentioned by *Yu et al.* [1999] and as debated about a decade ago.

[17] Global distributions of the oceanic annual mean surface heat budget are shown in Figure 5. Positive values in the figure indicate that oceans gain heat from the atmosphere. Over land and at the annual timescale, there is almost no net heating due to the negligible heat storage and the forced balance among the radiative and latent and sensible heat fluxes, and the heat storage in this study, as mentioned before. Over oceans, regional net heating from the atmosphere is mostly used for horizontal heat transports with a relatively small part for vertical heat mixing. Since a portion of our estimates of the regional annual surface heat budgets, especially of those with small absolute numbers, is from bias errors in the regional estimations of radiative and turbulent heat fluxes, the estimated annual budgets with an absolute value exceeding ~10 W/m^2 could be significant for this analysis. For areas such as the ITCZ and those having strong ocean currents, heat horizontal transports dominate the estimated budgets. The equatorial area, particularly in the eastern parts of the ocean basins, is the major heat source of the oceans. It has a large net radiant energy gain, loses a comparatively small amount of turbulent heat, and has a surface heat budget as large as about 100 W/m^2. The heat in the eastern ocean basins is generally moved to western basins by easterlies, then transported to higher latitudes. Some of the surface heat taken up by the ocean in these regions is also used for heating the upwelling cold water caused by Ekman pumping. Both the Gulf Stream and Kuroshio Current play critical roles in latitudinal heat transports. They bring warm water from low latitudes to middle and high latitudes and release considerable latent heat into atmosphere. Combining turbulent cooling with radiative heating, we still find heat losses of more than 60 W/m^2 in these oceanic current regions. Large areas of the West Australia Current have cooling features similar to

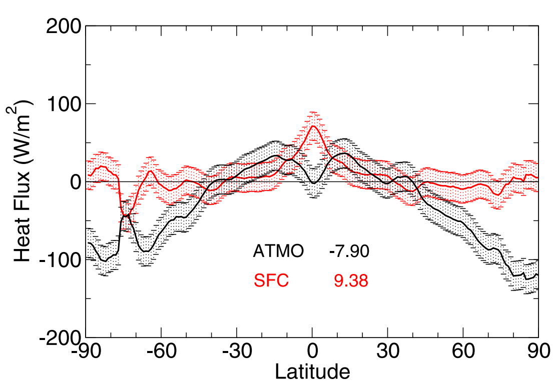

Figure 4. Same as Figure 2 except for the annual zonal means of atmospheric (black) and surface (red) heat budgets.

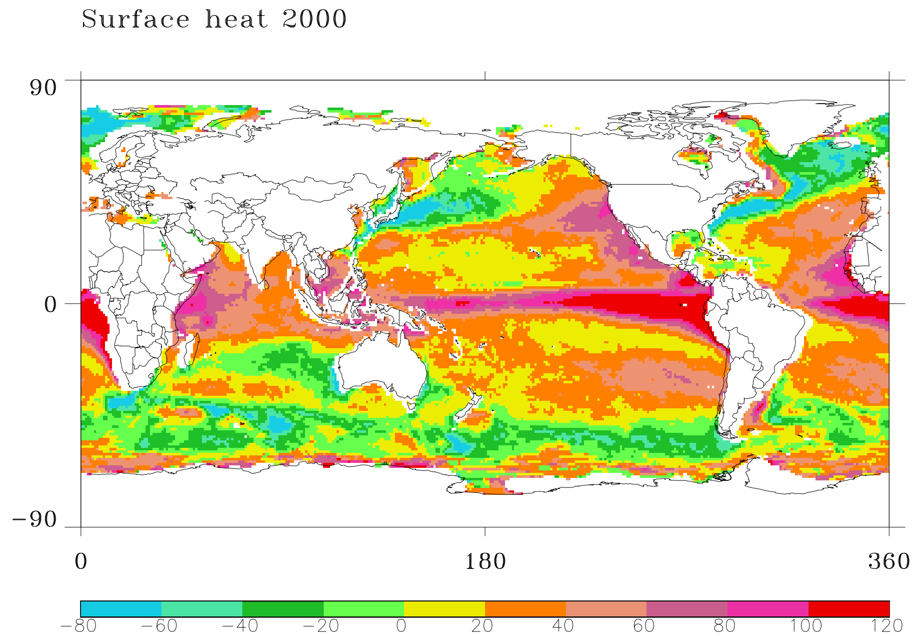

Figure 5. Annual mean sea surface heat budget in W/m^2. Positive values indicate that oceans gain heat from the atmosphere.

those of the Gulf Stream and Kuroshio Current except that the Australian current is much weaker.

[18] Oceans generally gain energy from the atmosphere over the annual timescale in tropical regions. Subtropical subsidence areas may have small annual heating budgets due to offsetting climate conditions of dry windy weather (i.e., large latent heat loss) and significant solar irradiation. With rapidly decreasing solar radiation with increasing latitude accompanied by smaller reductions in turbulent fluxes, the sea surface at higher latitudes releases heat into the atmosphere. It is due to the oceanic horizontal heat transport along with some vertical heat mixing that the basic heat balance over sea surfaces is reached. The heat budget distribution in Figure 5 clearly shows major features of oceanic dynamics and the dominant mechanism of horizontal heat transports within oceans.

4. Summary

[19] This study uses measurements taken in the year 2000 from multiple satellites to estimate the global annual mean atmospheric and surface energy budgets. At the top-of-atmosphere, net radiative fluxes into the atmosphere obtained from both direct radiant energy measurements and radiation calculations using satellite-observed atmospheric profiles are close to zero. The global means of net radiative flux into the surface and surface latent heat flux into the atmosphere are about 113 and 86 W/m^2, respectively. The atmospheric and surface net energy budgets are about -8 and 9 W/m^2, respectively. These annual mean global heat imbalances in the atmosphere and at the surface are of the same order of magnitude as the uncertainties in the radiation and sea surface turbulent flux estimates and the likely systematic errors in the analyzed data. Although these spurious errors are significant for studies of the annual mean global heat budget, they are clearly much smaller (less than half) than those estimated from blended data about a decade ago [*Yu et al.*, 1999]. For this reason, the potentially strong additional absorption of solar radiation within the atmosphere as suggested by *Yu et al.* is not required in the current analysis of the global energy budget. Progress in satellite surface radiation and oceanic turbulent heat flux estimations has significantly reduced the bias errors in the observed global energy budgets of the climate system.

[20] Future work will be targeted on shrinking systematic errors in satellite estimates of surface radiative and turbulent heat fluxes. Removal of systematic heat budget errors would provide a great opportunity to use zonal annual means (such as those plotted in Figures 2–4) to estimate meridional heat transports of the earth's climate system and separate the heat transports into atmospheric and oceanic components. Combining advanced precipitation measurements with surface latent heat estimates would also enable the estimation of atmospheric meridional moisture transports at an accuracy beyond that can be determined from the current, very limited measurements and observationally based knowledge.

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