Assessment of global annual atmospheric energy balance from satellite observations

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Submitted to Journal of Geophysical Research

January 2008

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Abstract

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 and latent and sensible heat over 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 estimations.

Global annual means of the TOA net radiation obtained from both 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 ~ 9 W/m^2, values that are within the uncertainties of surface radiation and sea surface turbulent flux estimates and 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 at about a decade ago. Progress in surface radiation and oceanic turbulent heat flux estimations from satellite measurements significantly reduces the bias errors in the observed global energy budgets of the climate system.

1. Introduction

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; *Fasullo and Trenberth*, 2007; *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; *Fasullo and Trenberth*, 2007; *Zhang et al.*, 2007]. Model assimilations can also provide global estimates of all atmospheric major energy and heat components. But 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 the 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].

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. 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 in 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 global annual mean atmospheric energy budget [*Yu et al.*, 1999] found that the data sets available at that time resulted in an unbalanced atmospheric heat budget of 20 W/m^2, and 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 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.

Since there are significant improvements in both surface radiation and air-sea interaction flux estimates from satellite observations in last 5-10 years, this paper revisits the consistency issue of global annual atmospheric energy budget. The overarching goal is to evaluate the magnitude of the systematic biases within current satellite-based datasets and determine if the spurious errors are within the accuracies of current satellite retrievals of radiative and sea surface turbulent fluxes. The datasets 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

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 datasets are used here: measurements from the Clouds and the Earth's Radiant Energy System (CERES) mission [*Wielicki et al.*, 1996], the International Satellite Cloud Climatology Project Flux Data [ISCCP-FD, see *Zhang et al.*, 2004], and the Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) data [*Stackhouse et al.*, 2001]. CERES directly measures TOA outgoing and incoming broadband longwave (LW) and shortwave (SW) radiation for the climate system. The other two radiation projects (ISCCP and SRB) calculate the TOA and surface radiation energy based on satellite observations of atmospheric temperature and humidity profiles, cloud optical properties and their spatial distributions, and the surface radiation properties such as skin temperature, emissivity and bidirectional reflection distribution functions. The random errors in the TOA monthly mean data at regional scales (~250 km) associated with these radiation data are reasonably small (~5 W/m^2; see the references listed above). The global monthly mean random errors are even smaller. The systematic errors in estimating the global annual mean energy budget can be as large as about 5 W/m^2 for the direct radiation measurements and within about 2 W/m^2 for ISCC-FD and SRB products. At the surface, the instantaneous errors in the radiative fluxes for the current ISCCP-FD and SRB products are as large as about 30 W/m^2. The regional monthly mean bias errors are significantly smaller, around 10 W/m^2 [*Zhang et al.*, 2004]. The system errors for global annual means could be even smaller due to potential cancellations of the bias errors for different climatological regimes.

The global turbulent heat fluxes from oceans to the atmosphere are based on the version 2 and 3 products of the Goddard Satellite-based Surface Turbulent Fluxes (GSSTF) and Hamburg Ocean Atmosphere Parameters and fluxes from Satellite (HOAPS), respectively, and are estimated from satellite microwave sensors [*Chou et al.*, 1997; *Schulz et al.*, 1997]. The random error for instantaneous flux estimates is approximately 30 W/m^2, and that for monthly regional averages decreases to ~15 W/m^2. The systematic errors are much smaller and within about 7 W/m^2. 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 in the monthly time scale 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 datasets 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 heat constraints for latent and sensible heat fluxes in each regional grid box ($1.25° \times 1°$). Furthermore, the monthly Bowen ratios in each grid box from GLDAS are used to partition the latent and sensible heat fluxes based on the heat 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 scales and essentially eliminate the spurious net flux errors over land.

Poleward of about 75ºS, the surface is primarily covered by oceanic and continental ice sheets. There are few surface latent and sensible heat estimations from both satellites and GLDAS. Our satellite based estimates of global annual energy budget mainly cover the regions north of 75ºS latitude. Because the turbulent fluxes are generally small south of 75ºS, the sensible heat fluxes are assumed to be zero during cold seasons and the precipitation data from the Global Precipitation Climatology Project [GPCP; *Adler et al.*, 2003] are used to fill the turbulent energy gap for these latitudes. 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, due to GPCP underestimates of snowfall and drizzle, the overall errors in the estimates of the turbulent energy in the region may be reduced. 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 that year's satellite products represents the current status of satellite estimations 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.

3. Results

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. The major differences are systematic biases among them, especially between CERES and the other two satellite calculations. As mentioned in the previous section, direct TOA radiation measurements yield a net radiation imbalnce of ~5.5

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, it can be easily removed from interannual variation analysis, resulting in a much smaller (~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, a somewhat larger bias in the SRB fluxes is considered here. Figure 1 shows zonal annual means of TOA (solid curve), surface (dotted curve), and atmosphere (dashed curve) net radiation estimates (note: hereafter all numbers in figures represent global mean values.) 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 that the climate system gains net energy only within ~ $\pm 35^o$ latitudes, and the middle latitudes have the maximum climate heat transports. The variation of zonal surface radiation basically follows the latitudinal pattern of 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 of latitudes. Within the atmosphere, SW absorption is minimal compared to LW emission and the LW radiation cooling into space dominates the atmospheric radiation budget.

The annual zonal means of latent and sensible heat fluxes from the surface to the atmosphere estimated from GSSTF are shown in Figure 2. HOAPS produced results similar to those from GSSTF. Latent heat (solid curve) gradually decreases from more than 100 W/m^2 at low latitudes to nearly zero at poles. A clear relative minimum near the equator is caused by the weak winds of the intertropical convergence zone (ITCZ). Sensible heat fluxes (dashed 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 and 18 W/m^2, respectively. These latent heat fluxes are significantly greater (~ 11 W/m^2) than GPCP measured rainfall latent heat releases (dotted curve). Because there are basically no snowfall and drizzle estimates in the GPCP data set and significant uncertainties in both the rainfall and surface latent heat estimations, the two different estimates in the atmospheric latent heat are reasonably consistent. With full precipitation and surface latent flux retrievals, zonal moisture transports that currently have not been understood could be estimated.

The annual zonal mean distribution of atmospheric total heat fluxes (Figure 3), the combined heating fluxes to the atmosphere from TOA and surface net radiation and surface latent and sensible heat, basically follows the latitudinal pattern of net radiation at TOA and surface except that a minimum exists at equator caused by the low surface turbulent heat fluxes at this region. Combining the strong atmospheric radiative cooling (112 W/m^2) with the slightly weaker turbulent heat flux from 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 in 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 caused 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 (8~9 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 data of satellite, in-situ and assimilation 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 significantly more atmospheric absorption of solar radiation as mentioned by *Yu et al.* [1999] and as debated at about a decade ago.

Global distributions of the oceanic annual mean surface heat budget are shown in Figure 4. Positive values in the figure indicate that oceans gain heat from the atmosphere. Over land and at the annual time scale, 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 to the ocean in these regions is also used for heating the upwelling cold water caused by the 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 those of the Gulf Stream and Kuroshio Current except that the Australian current is much weaker. Oceans generally gain energy from the atmosphere over the annual time scale in tropical regions. Subtropical subsidence areas may have small annual heating budgets due to a combination of climate conditions of dry windy weather (i.e., large latent heat loss) and significant solar radiation. With rapidly decreasing in 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 because of 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 4 clearly shows major features of oceanic dynamics and the dominant mechanism of horizontal heat transports within oceans.

4. Summary

This study uses the measurements taken in the year 2000 from multiple satellites to estimate global annual mean atmospheric heat budget. 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 energy 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 heat budgets are about $-8 \sim 9$ W/m^2. These annual mean global heat imbalances in the atmosphere and at surface are in the same order of magnitude as the uncertainties in the radiation and sea surface turbulent flux estimations and the likely systematic errors in the analyzed data. Although these spurious errors are significant for studies of annual mean global heat budget, they are clearly much smaller (less than half) than those estimated from blended data about decade ago [*Yu et al.*, 1999]. Furthermore, the potentially strong additional absorption of solar radiation within the atmosphere as suggested by *Yu et al.* is not be required in the current analysis of the global energy budget due to much smaller spurious heat imbalances in the data compared to those used by *Yu et al.*. Progress in satellite surface radiation and oceanic turbulent heat flux estimations significantly reduces the bias errors in the observed global energy budgets of the climate system.

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 1 − 3) 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 estimations 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.

Acknowledgement. The authors would like to express their appreciation to M. Rodell, G. Gibson, C.A. Schlosser, P. Houser, D. Young, and T. Wong for their valuable comments. This research was supported by the NASA Energy and Water cycle Studies (NEWS) program and CERES mission. SRB products and sea surface data were obtained from the NASA Langley Atmospheric Sciences Data Center in Hampton, Virginia and Goddard Distributed Active Archive Center in Greenbelt, Maryland, respectively.

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Figure captions

Fig. 1. Annual zonal mean net radiation at TOA (solid), over surface (sfc; dotted) and within the atmosphere (dashed). Hereafter, the numbers for individual curves shown in the figure are their corresponding global annual means.

Fig. 2. Annual zonal means of surface latent (solid) and sensible (dashed) heat fluxes. Also plotted is the latent heat (dotted) estimated from precipitation measurements.

Fig. 3. Annual zonal means of atmospheric (solid) and surface (dashed) heat budgets.

Fig. 4. Annual mean sea surface heat budget in W/m^2. Positive values indicate that oceans gain heat from the atmosphere.

Figures

Fig. 1 Annual zonal mean net radiation at TOA (solid), over surface (sfc; dotted) and within the atmosphere (dashed). Hereafter, the numbers for individual curves shown in the figure are their corresponding global annual means.

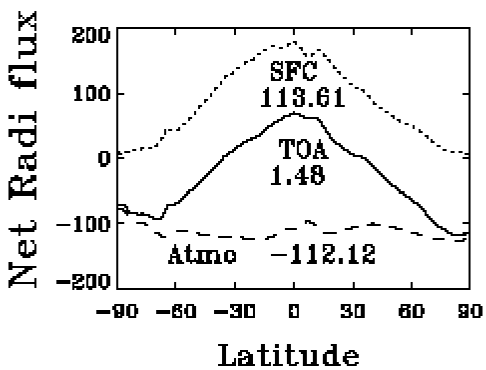

Fig. 2 Annual zonal means of surface latent (solid) and sensible (dashed) heat fluxes. Also plotted is the latent heat (dotted) estimated from precipitation measurements.

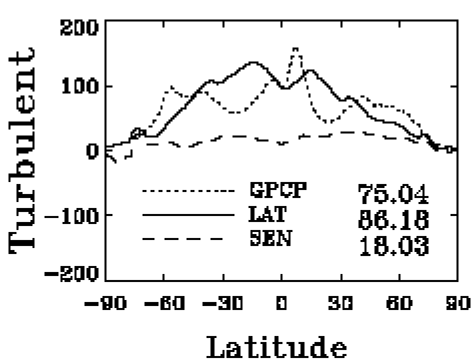

Fig. 3 Annual zonal means of atmospheric (solid) and surface (dashed) heat budgets.

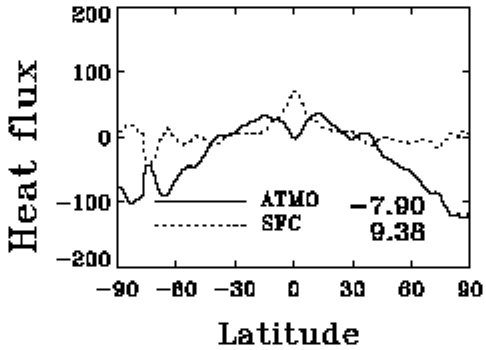

Fig. 4 Annual mean sea surface heat budget in W/m^2. Positive values indicate that oceans gain heat from the atmosphere.