How Well Are Recent Climate Variability Signals Resolved By Satellite Radiative Flux Estimates?

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1. INTRODUCTION

A definitive aspect of Earth's climate is that although the planet appears to be very close to radiative balance at top-of-atmosphere (TOA), the atmosphere itself and underlying surface are not. Profound exchanges of energy between the atmosphere and oceans, land and cryosphere occur over a range of time and space scales. Determining the character of radiative flux estimates and relating them to variations in other energy fluxes and state variables is key to improving our understanding climate feedback processes; it is also key to improving their representation in predictive models.

Accumulating multi-year data records from broad- and narrow band sensors have given us a short but tantalizing glimpse of variations in radiative fluxes, among these are interannual signals associated with ENSO events, episodic volcanic events (Pinatubo), and perhaps decadal variability. Regarding the latter, analysis of ERBE / ERBS Nonscanner measurements (Wielicki et al., 2002a,b; Chen et al., 2002; also see Wong et al., P6.32 this preprint volume) suggests that TOA fluxes over the 20^o N/S tropical band have changed systematically during the 1990s. Increases in absorbed shortwave radiation of order 3.0 Wm $^{-2}$ countered by increased OLR of approximately 2.0 Wm^{-2} appear to have yielded a net radiation increase to the Earth / Atmosphere system of nearly 1. 0 Wm^{-2} over a period of nearly a decade. These signals are still the subject of some debate (Trenberth, 2002; Wielicki et al., 2002b) and we are struggling to extract them from data sets with noise and artifacts of similar magnitude.

Significant advances continue to be made in constrained modeling of surface radiative fluxes (Stackhouse et al., 2002; Zhang et al., 2004; see also Gupta et al. P6.6 this preprint volume). Comparatively little work as yet has been done to verify climate signals in these data sets. The purpose of this paper is to provide some initial comparisons between two recently updated data sets of reconstructed surface fluxes in terms of their interannual variability over the tropics. Ultimately, the goal is to link these flux variability estimates to the TOA record, to surface turbulent energy fluxes from satellites, and to improve the satellite observational record of climate variability during the satellite era.

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2. RADIATIVE FLUX DATA SETS

Several data sets are key to this study. The ISCCP-FD product (Zhang et al., 2004) is a newly released 18-year record of derived radiative fluxes beginning in July 1983. ISCCP D series cloud retrievals, derived skin temperatures, and operational TOVS temperature and moisture soundings are used to drive the GISS GCM 03 radiative transfer code and produce flux components at TOA, 100, 440, 680 mb and the surface. Total and clear-sky fluxes are available at up to 3h intervals at DX resolution (~ 30 km). In the present study we will use only the TOA and surface fluxes available as monthly means at 2.5^o lat / lon resolution.

In key aspects the GEWEX SRB product is similar to the ISCCP surface fluxes in that it too uses the ISCCP D series clouds as forcing for radiative flux calculations. Retrievals are available on a 1.0^o lat / lon grid at 3h resolution. However, in this 12-year product (July 1983-Oct 1995) the thermodynamic profiles and skin temperatures are taken from the NASA GEOS-1 assimilation data set so clear-sky fluxes can differ significantly from the ISCCP-FD retrievals. SW fluxes are generated using the Pinker/Laszlo shortwave algorithm (Pinker and Laslo, 1992) and LW fluxes are calculated from a modified version of the Fu et al., (1997) code.

In the near future we plan to integrate the CERES (Clouds and the Earth's radiant Energy System) surface fluxes from TRMM, Terra, and Aqua into this comparison.

3. SURFACE LW VARIABILITY OVER THE TROPICAL OCEANS

Our focus here is principally monthly mean anomalies from annual climatology averaged over the tropical oceans. Regional anomalies of opposing signs typically dominate spatial patterns so the signals evident with this averaging represent integrated effects of variations in the tropical circulation and climate. Figure 1 shows the time series anomalies of upward, downward, and net longwave radiation at the surface ($LW^{\uparrow}$, $LW^{\downarrow}$, and LWnet, respectively) from ISCCP-FD and SRB Rel2. Here we have used the common period 1983-1995 as the climatological base to facilitate comparisons. For the period of overlap the two data sets exhibit substantially different interannual variability. The ISCCP components each have anomaly magnitudes roughly five times as large as the SRB. In addition there is little correlation between the respective components. The $LW^{\uparrow}$ for SRB, by definition, closely follows anomalies of σSST^4 made with Reynolds blended SSTs (Reynolds, 1988). However the corresponding ISCCP $LW^{\uparrow}$ signals are much larger and have a trend consistent with a drop in SST exceeding 1.5K over the period. (Note $-LW^{\downarrow}$ is plotted, so an upward trend corresponds to decreasing SST.) The differences in $LW^{\downarrow}$ for the two data sets are not as pronounced, both showing increases during the 1987/88 El Nino event, but the strong 1992 signals in ISCCP have no counterpart in the SRB fluxes. How do we explain these differences?

In Fig. 2 we plot times series of various SST measurements averaged over the TOGA Atmosphere Ocean (TAO) buoy region along the Equatorial Pacific (8.5°N/S, 135°E to 90°W). We pick this region in order to take advantage of the density of high quality, near-surface bulk SST measurements. Also shown are corresponding Reynolds bulk SSTs, and skin temperature, T_s, retrievals from both AVHRR and the TRMM Microwave Imager (TMI). Clearly the ISCCP T_s retrievals have problems in capturing the interannual signals present in the other data sets and, in fact, contain a spurious downward trend. The trend in ISCCP $LW^{\uparrow}$ or, equivalently, in skin

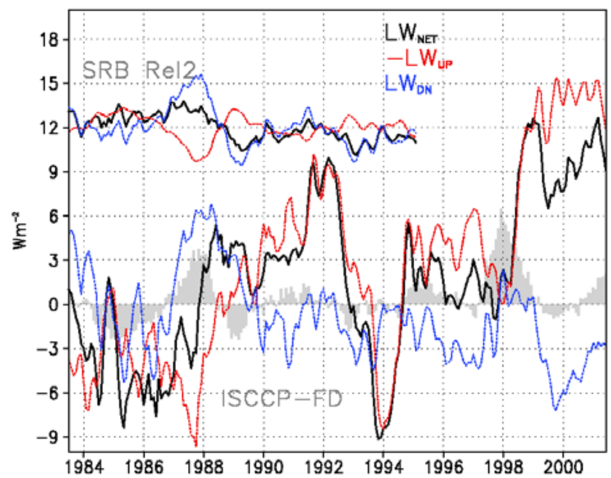

Figure 1. Surface downward longwave ($LW^{\downarrow}$), -upward longwave ($LW^{\uparrow}$), and net longwave (Lwnet) flux anomalies (Wm^{-2}) for ISCCP-FD and SRB Rel2. Anomalies are tropical ocean (30°N/S) monthly mean departures from annual cycle defined by Jul 1983 Oct 1995 period. Note SRB Rel2 fluxes are offset 12 Wm^{-2} for clarity. Also shown are tropical mean Reynolds SST anomalies (K) scaled 10x.

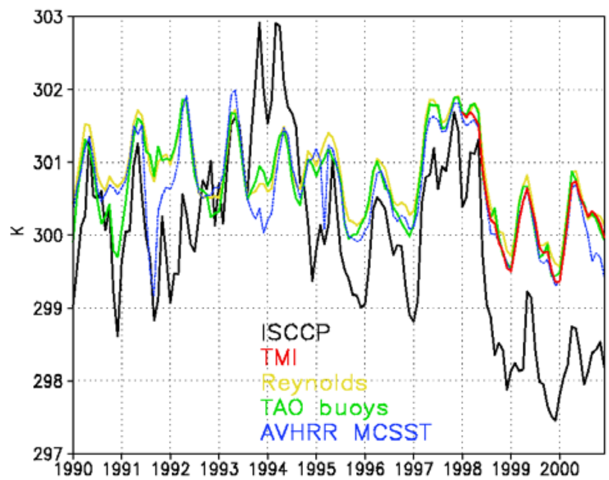

Figure 2. SST time series (K) averaged over the TOGA TAO region from **ISCCP-D retrievals, TRMM Microwave Imager (TMI), Reynolds blended analysis, TAO buoys,** and **AVHRR Multi-Channel Sea-Surface Temperature analysis.**

temperature, is puzzling since ISCCP inter-calibration of the AVHRR 11 micron channel data used for these retrievals de-trends each sensor record and references it to that of AVHRR on NOAA9. Interannual variability should be permitted by this procedure, but not trends across the entire record (Brest et al., 1997). The problem we believe is with the use of operational TOVS moisture soundings to correct for water vapor absorption / emission effects in the 11 micron data. A comparison (not shown) of precipitable water time series over the tropical oceans from TOVS and from the more accurate Special Sensor Microwave Imager, SSM/I, (Wentz 1997) shows that the TOVS interannual variability is much larger and that it also decreases in time. There is a particularly large decrease in TOVS precipitable water accompanying the start of the Advanced TOVS sensor on NOAA15 after May 1998. Because of these problems with the water vapor retrievals compared to microwave estimates, the water vapor attenuation correction performed in the ISCCP processing induces spurious temporal variability in SST retrievals and, hence, $LW^{\uparrow}$.

Understanding the disagreement between SRB and ISCCP-FD $LW^{\downarrow}$ is somewhat more involved. The questionable accuracy of TOVS water vapor suggested that we begin by examining the clear-sky flux, $LWCS^{\downarrow}$. We first made a simple calculation to see if we could reconstruct the tropical mean signals using only precipitable water and temperature information. Figure 3 shows a calculation using the Dilley and O'Brien (1998) statistical algorithm driven by ISCCP D2 TOVS precipitable water and 740 hPa temperature. The latter quantity correlates closely with Reynolds SST and with MSU2 mean lower tropospheric temperatures. We added 14K to the 740 hPa temperature values to make their climatological magnitude roughly equal to the near-surface temperature although this does not affect the anomaly magnitudes[1]. The interannual variability of this signal is remarkably close to that of the ISCCP-FD data and shows that we can understand the FD variations in terms of the precipitable water and bulk lower tropospheric temperature. We then performed an alternate calculation using NCAR/NCEP Reanalysis 2m temperatures and precipitable water from the Wentz (1997) Version 5 derived

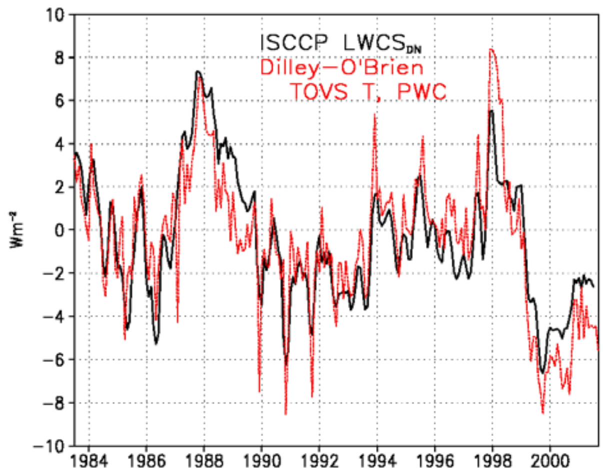

Figure 3. $LWCS^{\downarrow}$ anomalies (Wm^{-2}) for ISCCP-FD and Dilley-O'Brien statistical calculation using TOVS precipitable water and lower tropospheric temperature.

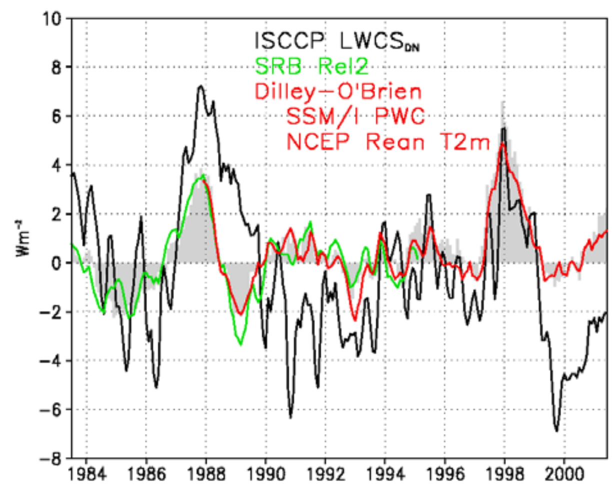

Figure 4. $LWCS^{\downarrow}$ anomalies (Wm^{-2}) for ISCCP-FD, SRB Rel2 and Dilley-O'Brien statistical calculation using Wentz precipitable water and NCEP reanalysis 2m temperature. Anomalies are with respect to period Jan 1988-Oct 1995. Also shown are tropical mean Reynolds SST anomalies (K) scaled 10x.

from Special Sensor Microwave Imager (SSM/I) retrievals. This calculation, along with the SRB and original FD $LWCS^{\downarrow}$ is shown in Fig 4. Anomalies are calculated relative to the common 1988/95 base period for the SSM/I and SRB Rel2 for comparison. This revised estimate of variability in downward clear sky longwave irradiance agrees well with the SRB Rel2 retrieval during the period of overlap. The

[1] *We initially used the ISCCP D2 near-surface temperature but found that this quantity exhibits interannual variations anti-correlated to those of ISCCP T_s and also unlike either the TOVS 740 hPa temperature or Reynolds SST. We suspect that this retrieved quantity, although perhaps reliable in a climatological sense, lacks a realistic interannual behavior because it is derived in conjunction with T_s.*

anomalously low LWCS$^{\downarrow}$ during 1990-1993 and after 1998 in the ISCCP-FD is consistent with the spurious dryness in the TOVS precipitable water at these times. The closer phasing and anti-correlation of the new calculation with SST anomalies is consistent with a robust water vapor feedback signal in the tropical oceanic planetary boundary layer.

Because the ISCCP FD retrievals include a cloud forcing calculation we could add this to our revised LWCS$^{\downarrow}$ estimate and recover a total sky estimate $LW_{rev}^{\downarrow}$. However, cloud forcing depends strongly on water vapor below cloud base so the ISCCP-FD contains at least some error due to uncertainties in TOVS water vapor. Comparison of the ISCCP-FD and SRB Rel2 cloud forcing anomaly time series in Fig. 5 shows significant differences. The elevated ISCCP-FD cloud forcing in 1991/2 exceeds that of SRB Rel2 by ~ 2.0 Wm^{-2} and largely offsets LWCS$^{\downarrow}$ during that period (Fig. 4). We have attempted a revised LWCF$^{\downarrow}$ based broadly on the methodology the methodology of Gupta et al., (1992) using Wentz (1997) precipitable water and cloud bases for low, middle and high clouds arbitrarily specified to reside at 925, 700 and 500 mb, respectively. Cloud base temperatures were taken as the NCEP reanalysis values at those levels and cloud fractions for low, middle, and high clouds from ISCCP are used. Despite its ad hoc nature this revised calculation, also shown in Fig. 5, yields an interannual trend which is consistent with the SRB Rel2 estimate. Averaged over the tropics, signals from ENSO events are indistinguishable from background noise and the most prominent signal is the long-term downward trend in cloud forcing. This behavior contrasts with the LWCS$^{\downarrow}$ signal which is dominated by the water vapor changes associated with ENSO SST anomalies and exhibits little systematic long term trend.

Combining these revised estimates of LWCS$^{\downarrow}$ and LWCF yields a revised LW$^{\downarrow}$ at the surface, $LW_{rev}^{\downarrow}$ (Fig 6). Here we have also estimated $LW_{rev}^{\uparrow}$ from σT_s^4 using Reynolds SSTs assuming a surface emissivity of 1.0. The revised net LW at the surface, LW_{rev}, and the individual components contrast strongly with the original ISCCP-FD flux components depicted in Fig. 1. In agreement with the SRB, the revised calculations show a much more muted response to SST changes; they are also of comparable

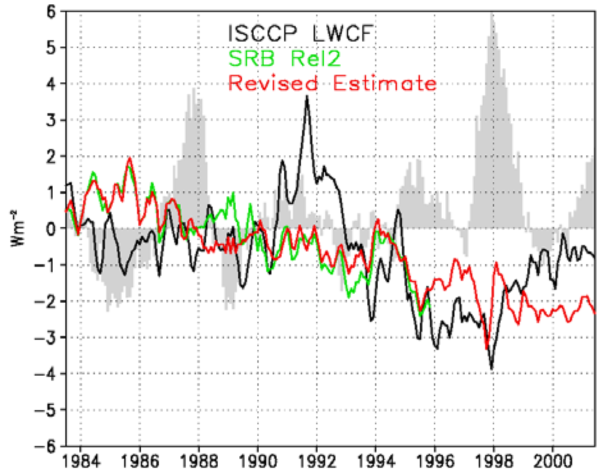

Figure 5. Surface longwave cloud forcing anomalies (Wm^{-2}) for ISCCP-FD, SRB Rel2, and revised estimate (see text for details of calculation). SST anomalies scaled 10x.

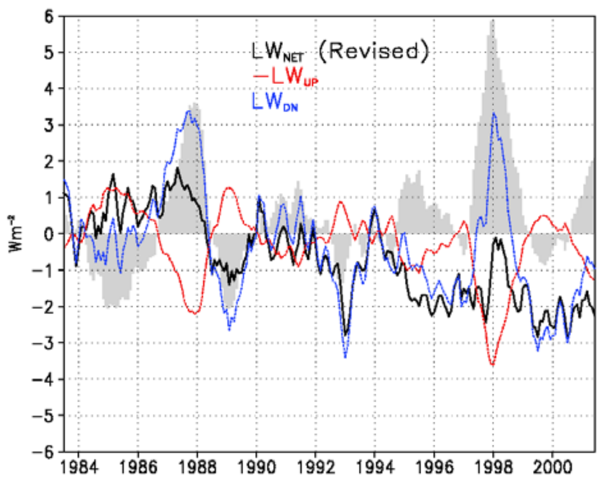

Figure 6. Anomalies of revised surface longwave flux (Wm^{-2}). LW$^{\uparrow}$ is σSST^4 with Reynolds values. LW$^{\downarrow}$ is sum of LWCS$^{\downarrow}$ is from Fig. 4 and revised surface cloud forcing from Fig. 5. SST anomalies scaled 10x.

scale to variations seen in the ERBS Nonscanner time series. The strong anti-correlation between $LW_{rev}^{\downarrow}$ and $LW_{rev}^{\uparrow}$ supports the inference of a strong water vapor feedback at the surface in conjunction with ENSO events.

4. ISCCP CLOUD VARIATIONS

Because of high water vapor content in the atmospheric boundary layer over the tropical oceans surface LWCF is typically almost an order of magnitude smaller than LWCS$^{\downarrow}$. Thus, it seems surprising that the trend of surface LWCF for each of the three estimates in Fig. 5 is of the same order of magnitude as LWCS$^{\downarrow}$ variations and that LWCF also determines the downward trend in surface net LW. A partial explanation for this is that the strong clear-sky greenhouse effect and water vapor feedback insure that *net* LWCS is typically only a factor of 2 or 3 larger than LWCF. Clearly the decreasing ISCCP cloud fractional cover with time is a driving factor. To investigate the cloud behavior more closely we plot monthly anomalies of zonally averaged mean cloud fraction (%) around the globe as a function of time (Fig. 7).

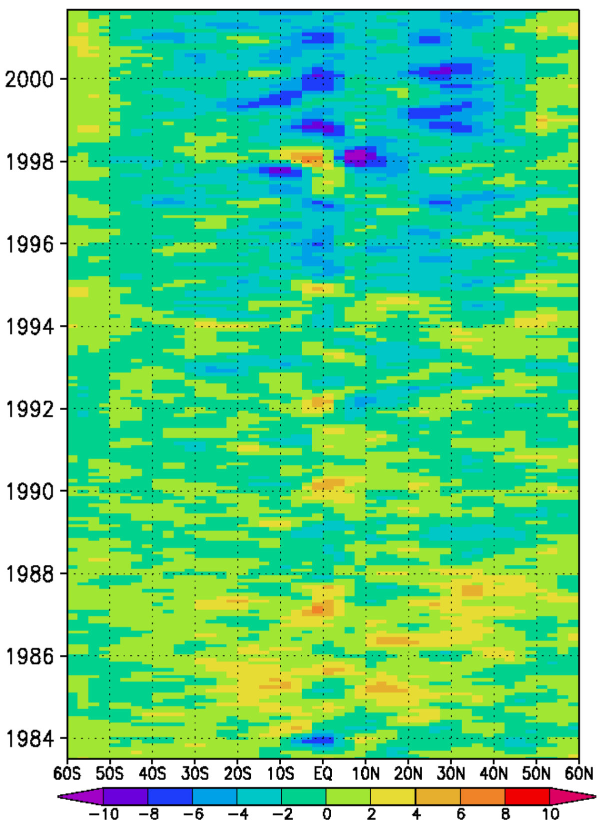

Figure 7. Monthly anomalies of zonally averaged ISCCP-D2 mean cloud fraction (%) around the globe as a function of time.

We see a general trend of decreasing cloudiness that is present at all latitudes equatorward of about 45^{o}. Cloudiness decreases after 1994 appear to be centered near the equator and in the N. hemisphere subtropics. In the equatorial regions ENSO warm events (1987, 1992, 1995, 1997/8) and cold events (1983/4, 1988/9, 1996/7, 1998-2001) appear as cloudiness maxima (minima) straddling the equator and having some suggestion of dipole like structure (1984, 1998). The cloudiness decreases are driven largely by changes in low and high cloud amounts focused in the central Pacific ocean (not shown). It is difficult to see any obvious breaks associated with satellite changes although there is a hint that after early 1998 the detection of the annual cycle may have changed.

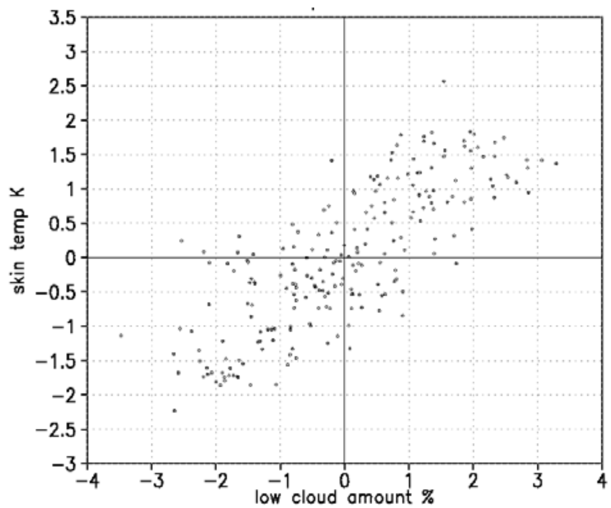

Figure 8. Scatter plot of monthly ISCCP D2 tropical ocean skin temperature anomalies against monthly low cloud amount anomalies.

Because the effect of low clouds on downward longwave irradiance, though weak compared to water vapor in the tropics, is expected to be larger than the effect of higher clouds we have examined their variability. Figure 8 shows a scatter plot of anomalies in ISCCP low cloud fraction against the retrieved T_s. Each point represents a monthly-mean, area averaged anomaly. Given that we know from earlier discussion that the trend and most interannual variability in the retrieved T_s is non-physical, the relatively close correlation between T_s and low cloud variations is somewhat disturbing. Cloud identification in ISCCP is done using temporal and spatial variability detection and should be largely independent of sensor calibration. We are trying to understand the source of this cloud amount-skin temperature relationship.

5. SUMMARY

We have compared two recent versions of satellite-based retrievals of radiative fluxes-- the GISS ISCCP-FD and the GEWEX SRB Rel2. Our initial work here has centered on the surface fluxes in tropical ocean regions and included as yet only the longwave components. Our findings suggest that signals of interannual variability and trends present in the ISCCP-FD have been compromised by uncertainties in the water vapor soundings in the TOVS operational products used to derive ISCCP skin temperature and calculate surface longwave fluxes:

(i) ISCCP ocean skin temperature, though perfectly acceptable in a climatological sense and in spatial structure, does not agree with any currently accepted measures of SST variability, thus, compromising $LW^{\uparrow}$.

(ii) $LWCS^{\downarrow}$ fluxes suffer too from the lack of fidelity of water vapor variations in TOVS operational data.

(iii) Using statistical algorithms for surface longwave fluxes, more accurate precipitable water from microwave sensors, and reasonably accurate SSTs, LWCS fluxes and variability over ocean areas are recovered that agree well with current SRB Rel 2 fluxes.

(iv) Trends in cloud forcing over the tropical oceans appear larger that one would expect and produce a trend of decreasing LWnet to the ocean surface in both the ISCCP-FD and SRB Rel2 data sets. The veracity of this forcing and the associated trend in low cloudiness needs much more attention.

We have considered here only the surface longwave fluxes. Given the problems with T_s and the ISCCP water vapor, how do we know that variations in the TOA LW fluxes and, in general the shortwave fluxes are not compromised? Zhang et al., (2004) have shown that the decadal trends in TOA LW, SW and net radiation are in reasonable agreement between ISCCP-FD and ERBE / ERBS Nonscanner data sets[2]. It is well known that in tropical regions TOA and surface longwave fluxes are poorly correlated by virtue of strong water vapor greenhouse effect. TOA longwave fluxes are more sensitive to upper-tropospheric moisture so surface temperature changes in very moist regions are never a factor. However this does not explain changes in dry regions such as the subtropics. We suspect that a fortuitous error cancellation may be relevant for the clear sky longwave fluxes. Since ISCCP T_s has absorbed the inconsistency of “corrections” to the 11 micron channel for water vapor and temperature, errors such as the precipitous drop in TOVS water vapor in 1998 have been built into T_s. For example, with a “drier” atmosphere after May 1998 provided by the TOVS soundings, retrieved ISCCP T_s values become artificially lowered, compensating an increase in longwave emission that would result from a spuriously dry atmosphere. These effects may compensate to a significant degree in the calculation of TOA LWCS fluxes. However, the trend in TOA LW fluxes is more controlled by cloudiness changes which as noted above deserve closer scrutiny. SW fluxes, on the other hand are much better correlated between the surface and TOA. We are beginning to look at these quantities and the effect of water vapor and cloudiness changes and will provide some assessment at the meeting.

One should keep in mind that the signals we have discussed are very small (several Wm^{-2}) in comparison to instantaneous or even climatological mean fluxes. For seasonal and climatological spatial flux values the ISCCP-FD retrievals constitute a valuable resource. A further point to note is that the SRB Rel2 clear-sky fluxes by construction represent the GEOS 1 assimilated product. In the tropics these quantities are subject to the physics uncertainties of a first generation reanalysis system. Despite the fact that our recalculated longwave fluxes agree with their variability they cannot be regarded as definitive.

With respect to the overall question posed in this paper of how well climate variability signals are resolved in terms of radiative fluxes, there is encouragement that clear-sky variations can be (or with reprocessing of data sets, will be) reliably detected over ocean. Land issues here have not been assessed and obviously are a more challenging issue. Variations in cloud amount and radiative properties are still of great uncertainty. Considerable advances in cloud processes understanding are being made, but

[2] The relationship for LW (SW) changes is improved (only slightly degraded) after orbital decay corrections to the ERBE data are made.

this knowledge has yet to clear up uncertainties in historical satellite records.

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