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Satellite Sounder-Based OLR-, Cloud- and Atmospheric Temperature Climatologies for Climate Analyses

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ABSTRACT

Global energy balance of the Earth-atmosphere system may change due to natural and man-made climate variations. For example, changes in the outgoing longwave radiation (OLR) can be regarded as a crucial indicator of climate variations. Clouds play an important role -still insufficiently assessed- in the global energy balance on all spatial and temporal scales, and satellites provide an ideal platform to measure cloud and large-scale atmospheric variables simultaneously. The TOVS series of satellites were the first to provide this type of information since 1979. OLR [Mehta and Susskind[1]], cloud cover and cloud top pressure [Susskind *et al.*[2]] are among the key climatic parameters computed by the TOVS Pathfinder Path-A algorithm using mainly the retrieved temperature and moisture profiles. AIRS, regarded as the "new and improved TOVS", has a much higher spectral resolution and greater S/N ratio, retrieving climatic parameters with higher accuracy.

First we present encouraging agreements between MODIS and AIRS cloud top pressure (C_{tp}) and 'effective' (A_{eff}, a product of infrared emissivity at 11 μm and physical cloud cover or A_c) cloud fraction seasonal and interannual *variabilities* for selected months. Next we present validation efforts and preliminary trend analyses of TOVS-retrieved C_{tp} and A_{eff}. For example, decadal global trends of the TOVS Path-A and ISCCP-D2 P_c and A_{eff}/A_c values are similar. Furthermore, the TOVS Path-A and ISCCP-AVHRR [available since 1983] cloud fractions correlate even more strongly, including regional trends.

We also present TOVS and AIRS OLR validation effort results and (for the longer-term TOVS Pathfinder Path-A dataset) trend analyses. OLR interannual spatial variabilities from the available state-of-the-art CERES *measurements* and both from the AIRS [Susskind *et al.*[3,4]] and TOVS OLR *computations* are in remarkably good agreement. Global monthly mean CERES and TOVS OLR time series show very good agreement in absolute values also. Finally, we will assess correlations among long-term trends of selected parameters, derived simultaneously from the TOVS Pathfinder Path-A dataset.

Keywords: infrared, remote sensing, satellite sounders, clouds, cloud parameters, outgoing longwave radiation, inter-annual variability, satellite climatic trends

1. INTRODUCTION

It is rather disturbing that close to half a century after the dawn of the satellite era, comprehensive satellite-based atmospheric parameter climatologies are practically nonexistent. Even in recent times satellite data appears to be underused even on shorter timescales. In principle, satellite sounders can provide an ideal platform to retrieve cloud parameters and important atmospheric variables simultaneously and on comparable scales. However, long-term, consistently produced satellite climatologies are still in their infancy due to the plethora of various and variable satellite sensors (and the consequent, often unresolved inter-calibration issues), as well as relatively short-lived missions. To be fair, most Earth-observing satellites were designed to improve (inherently short-term) weather predictions, so using their data to create climatologies is not straightforward. The TOVS satellites were the first to provide comprehensive atmospheric soundings since 1979. For example, the first satellite cloud climatology project (ISCCP) uses TOVS-derived atmospheric temperature profiles to better their product (Zhang *et al.*,[5]). Susskind *et al.*,[2] also have generated cloud fields using TOVS observations. AIRS/AMSU accomplishes the same tasks with a much higher accuracy (Pagano *et al.*,[6]). It is useful for climate change assessments to include the longest possible satellite climatologies, so besides showing preliminary AIRS results, we also focus on the usability of TOVS Path-A-based retrieval results, including (probably) one of the most important parameters of global energy balance namely the OLR. Both AIRS and TOVS Path-A OLR results will be compared to the CERES results [*e. g.,* Wielicki *et al.* [7,8]], flown on the same satellite as AIRS. Global energy balance of the Earth-atmosphere system may change due to natural and man-made climate variations. Changes in the outgoing longwave radiation (OLR), regarded as a crucial indicator of any climate variation, since the planet ultimately has to reach radiative energy balance. In particular, clouds play an important role (still insufficiently assessed) in the global energy balance on all spatial and temporal scales, and satellites provide an ideal platform to measure cloud and large-scale atmospheric variables simultaneously. Of course, proper representation/retrieval of clouds is very important in this context; whatever cloud distribution a retrieval scheme provides, must be consistent with energy balance, *i. e.,* with the observed OLR values. Here we restrict ourselves to the Earth's thermal radiation for now—solar/shortwave energy balance and the retrieval of associated cloud characteristics is an even more difficult issue. We believe part of the discrepancies between AIRS/TOVS and MODIS/ISCCP cloud fields shown in this work, may be related to the "non-energy balance" nature of threshold-based cloud fraction (cloud mask) retrievals by MODIS/ISCCP (*cf.,* King *et al.*[9]; Rossow *et al.* [10]).

The AIRS/AMSU (flying on the EOS-AQUA satellite) sounding retrieval methodology allows for the retrieval of key atmospheric/surface parameters under partially cloudy conditions (Susskind *et al.*[3,4]). In addition, cloud and OLR parameters are also derived from the AIRS/AMSU observations. The following bullets highlight an overview of the AIRS/AMSU retrieval methodology in more detail:

•Physically-based system;
•Independent of GCM except for surface pressure;
•Uses cloud cleared radiances to produce solution;
•Basic steps:
1) Microwave product parameters – solution agrees with AMSU-A radiances;
2) Initial cloud clearing using microwave product;
3) AIRS regression guess parameters based on cloud cleared radiances;
4) Update cloud clearing using AIRS regression guess parameters;
5) Sequentially determine surface parameters, temperature, moisture, ozone, CO, and CH_4 profiles;

•Apply quality control:
a) Select retrieved state - coupled AIRS/AMSU or AMSU only retrieval parameters;
b) Determine cloud parameters consistent with retrieved state and observed radiances. One set per Field-of-View of effective cloud fraction (A_{eff}) for up to two cloud layers, as well as cloud top pressure (C_{tp}) for up to two cloud layers;
c) Compute OLR and clear-sky OLR from all parameters via radiative transfer.

The question arises whether observed variabilities/trends in the *longest-running satellite climatologies* could be useful for a *direct, observational detection* of ongoing climate change. In other words, are there any satellite climatologies "mature" enough for climatic *trend* assessments?

Here we present initial results that imply that the *TOVS Path-A* dataset may be a good candidate and the AIRS retrievals could extend this type of satellite soundings-based datasets well into the future. How do we substantiate this claim? We use cross-validations, *e. g.,* OLR with CERES, clouds with ISCCP. It should be an *essential prerequisite* for any dataset to accurately depict *interannual variability* in order to be considered a candidate for *trend assessments*. Even for rather short-term satellite datasets, cross-validation of mutually consistent depictions of interannual variability can be accomplished. The *longest* validated satellite dataset(s) could then be used for trend assessment(s).

The TOVS Path-A dataset is probably the longest, consistently produced satellite dataset. The following bullets highlight an overview of the TOVS Path-A retrieval methodology:

• Physically based system, although it also uses a general circulation model for initialization. Note that this type of model use is not needed for the AIRS algorithm;

• Uses cloud cleared radiances to produce solutions for atmospheric temperature and humidity profiles;
• Determines cloud parameters *consistent* with the retrieved state and the observed radiances;
• Computes (All-Sky) OLR and clear-sky OLR from all parameters via radiative transfer.

Like the AIRS cloud retrieval scheme, the TOVS algorithm also retrieves C_{tp} and A_{eff}. Note that the TOVS Path-A cloud and OLR datasets used here are time-of-day [to 7:30 am] corrected. On the other hand, the preliminary results regarding other long-term TOVS Path-A dataset parameters are not yet corrected. Like the AIRS algorithm, the TOVS Path-A cloud clearing is essentially an "energy-balance" approach, *i. e.,* the ["observed" – "computed"] radiance errors are minimized with the retrieved/inferred cloud distribution. However, only a single cloud *layer* is allowed to form in a TOVS footprint, whilst the AIRS algorithm allows for up to 2 layers.

2. RESULTS

a) AIRS-MODIS cloud parameter retrieval intercomparisons:

The MODIS cloud data were obtained from the GSFC DAAC [***http://daac.gsfc.nasa.gov/data/dataset/MODIS-Aqua/02_Atmosphere/01_Level_2/03_Cloud_Prod/***]. We have shown earlier (Molnar and Susskind[11]) that there were significant differences between AIRS and MODIS cloud retrievals. However, when we created *differences* of monthly mean retrieval results to assess applicability of these cloud retrievals for climate variability studies, we see more reassuring results:

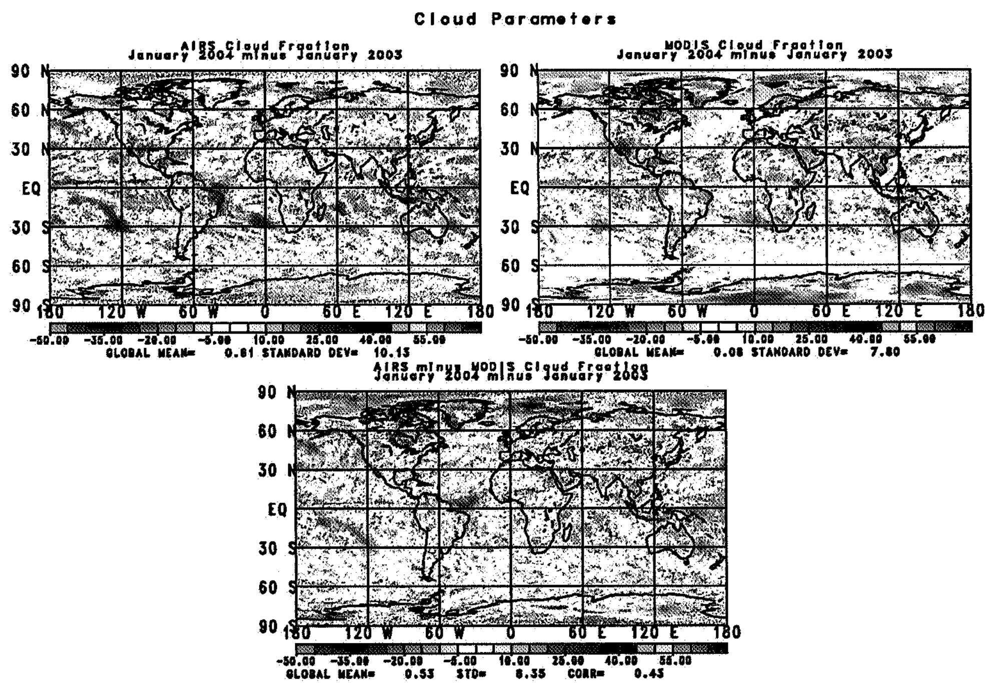

Figure 1

Fig. 1 shows AIRS-MODIS January 2003 and January 2004 cloud field difference intercomparisons in "combined" (both A_{eff} and C_{tp} are depicted concurrently) plots, *i. e.,* the inter-annual variabilities as seen by each instrument, as well as the differences between the two retrieval results. Note that in the left 4 panels of Fig. 2 clouds are shown for 7 bins in terms of cloud top pressure (bin borders are shown above the color bars), and within each bin darker color shades indicate increasing cloud fractions in 5 bins of 20% cloud fraction range in each.

Note the general correspondence of the *inter-annual variability* patterns [*despite* that the AIRS mean cloud fraction is ~43% *vs.* ~67% of MODIS, whilst the AIRS mean cloud top pressure is ~520 mb *vs.* ~670 mb of MODIS], meaning that climatic trend-recognition could be close to identical for both retrieval schemes. This is further reinforced by the similar depiction of the much larger intra-seasonal differences, illustrated in Fig. 2, showing August 2004 *vs.* January 2004 clouds fields and their differences. Again, despite significant biases the intra-seasonal *differences* are quite close.

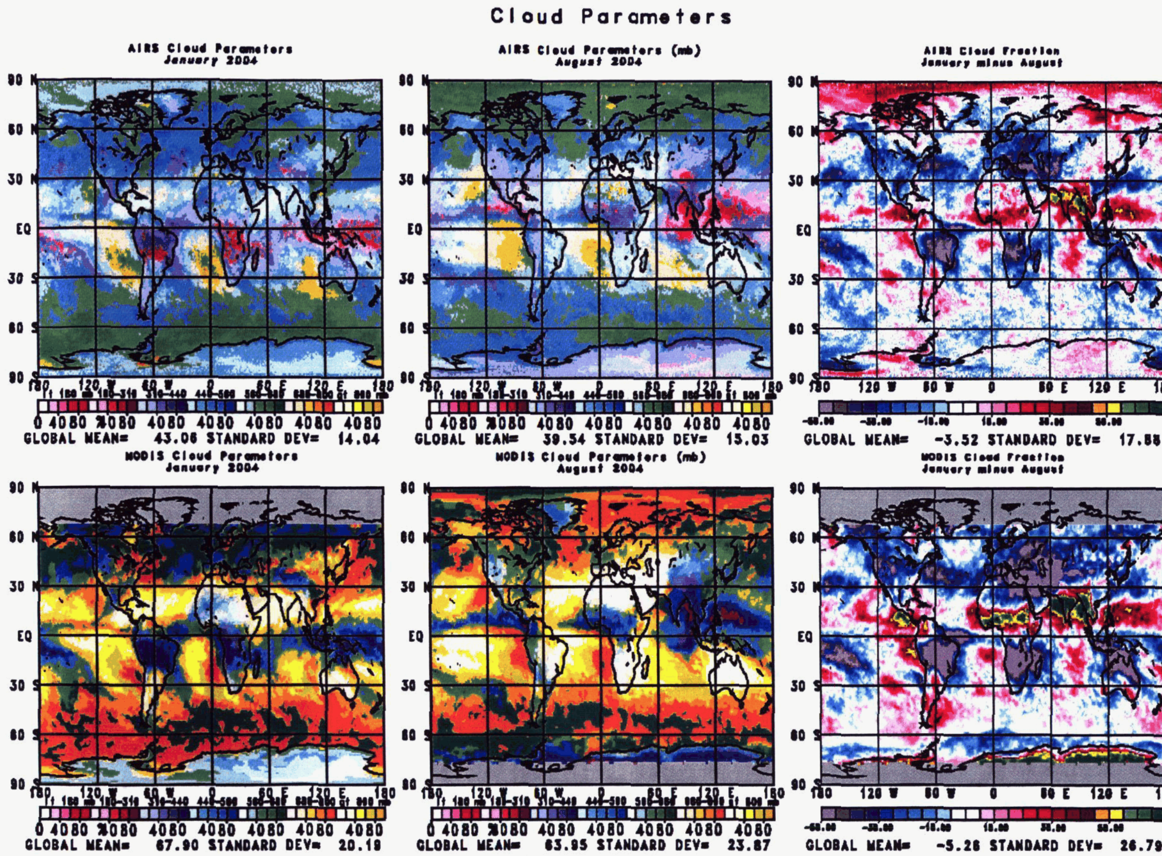

Figure 2

Not surprisingly, the AIRS/MODIS A_{eff} correlations are significantly better when looking at the much larger January *vs.* August 2004 "seasonal" differences (~0.84) *vs.* the ~0.62 exhibited by the inter-annual correlations.

b) TOVS Path-A and ISCCP D2 and "ISCCP-AVHRR" cloud parameter retrieval intercomparisons:

Unless mentioned otherwise, we use the official monthly mean gridded [on a 2.5° grid] ISCCP cloud products [referred to as ISCCP D2, and available trough the ISCCP WEB-site at ***http://isccp.giss.nasa.gov/products/browsed2.html***] for comparisons with the corresponding TOVS gridded [on a 1.0° grid] products. Keep in mind that since there were no available ISCCP A_{eff} products, the ISCCP A_c values were *expected* to be consistently larger than the A_{eff} of TOVS. This is immediately obvious by looking at the actual global monthly mean time series plots of A_c/A_{eff} as well C_{tp}. Figs. 3 [global means] and 4 ['tropical' means, meaning +/-30°] exhibit considerable annual/semiannual variabilities but weak temporal correlations [except in the tropical A_c/A_{eff} till 1998] and trends. The actual global mean trends for the 16 yr [1985-2000] long 'higher quality' subset of these datasets are: a 1% decrease in the TOVS Path-A A_{eff} *vs.* a 2.5% decrease in the ISCCP A_c and a 4.1 hPa decrease in the TOVS C_{tp} *vs.* a 12 hPa decrease in the ISCCP C_{tp}.

The trends are almost the same for the respective *anomalies*, which were obtained by subtracting the *mean annual cycles* of the respective parameters from the respective time series. These mean annual cycles are shown on Fig. 5. Interestingly, the mean annual ISCCP D2 A_c and TOVS Path-A A_{eff} values anticorrelate very strongly all over the year [Corr. Coeff. = -0.915], whilst the corresponding C_{tp} values correlate for the first 5 months of the year and anticorrelate for the rest of the months, except September [overall Corr. Coeff. = 0.721].

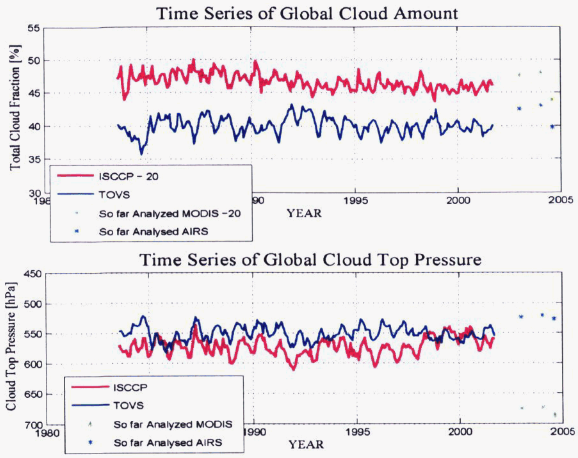

Figure 3

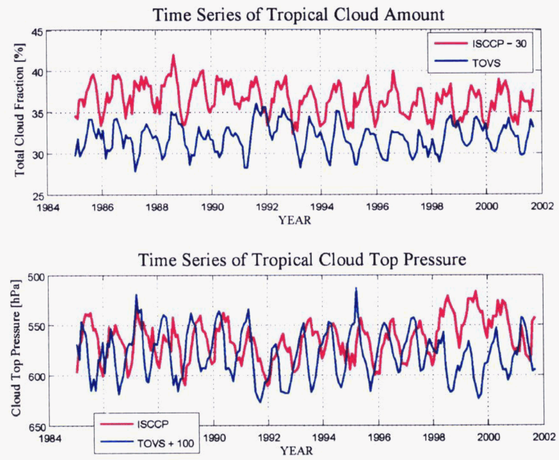

Figure 4

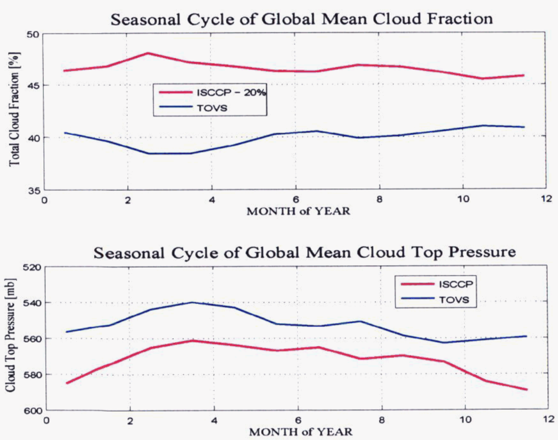

Figure 5

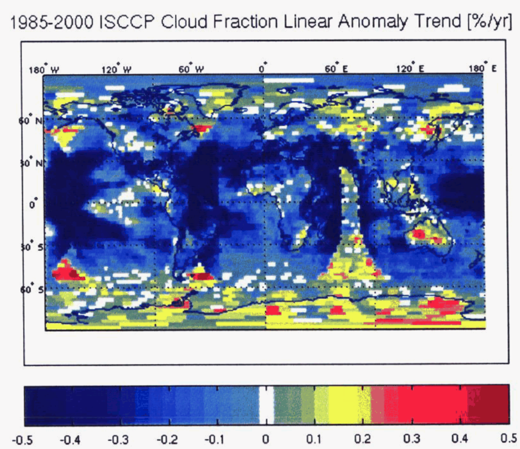

Figure 6

Correlations of TOVS Path-A *vs.* ISCCP D2 intra-seasonal and interannual cloud parameter variabilities were tested to be at least as good or better than for the AIRS *vs.* MODIS ones described in the previous section, so we proceeded to the next step by creating *trend maps* for the above-mentioned 16-yr period. Fig. 6 shows the ISCCP D2 A_c linear anomaly trend on a 2.5° grid, whilst Fig. 7 is the same for TOVS Path-A A_{eff}. Little correspondence is obvious, and the apparent geostationary satellite footprints on the ISCCP D2 trend map are quite disturbing. The same can be concluded from Figs. 8 and 9 depicting the corresponding C_{tp} trend maps.

Of course, the trends exhibited by a 16-yr long dataset may be skewed by internal variability with comparable periods, like the El Niño. For example, by extending the TOVS Aeff time period limits to 1980 through 2004 we can see a very different trend map [Fig. 10]. However, a number of regional trends (*e. g.,* North America, most of China and the Atlantic Basin, around Antarctica) still persist indicating ‘fingerprints’ of long-term climate change related effects.

All in all, the trend maps of TOVS Path-A *vs.* ISCCP D2 do not seem to match, so we have addressed what

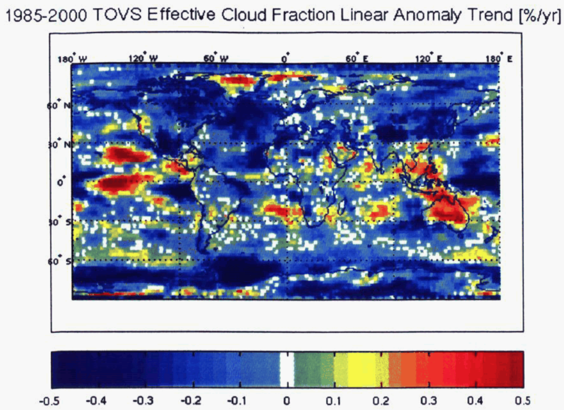

Figure 7

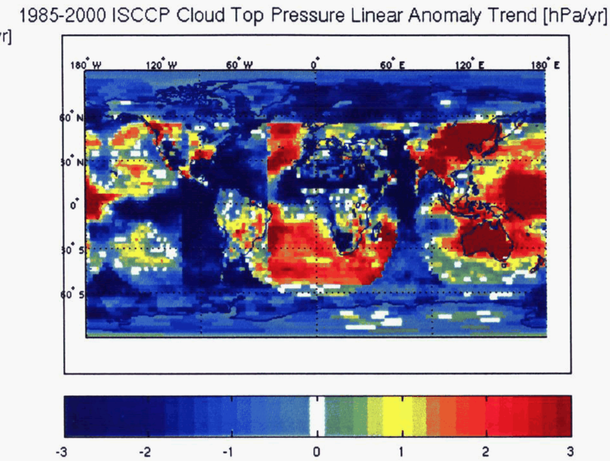

Figure 8

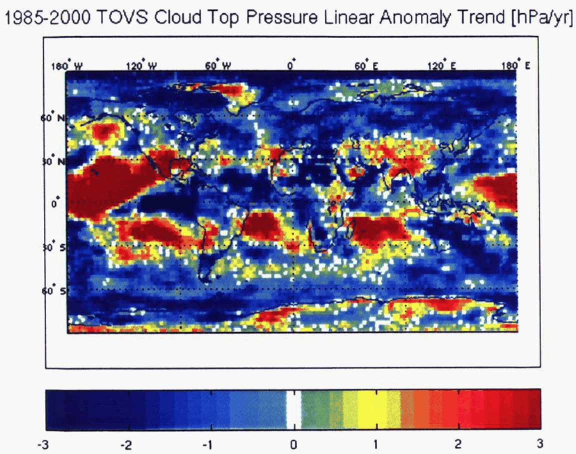

Figure 9

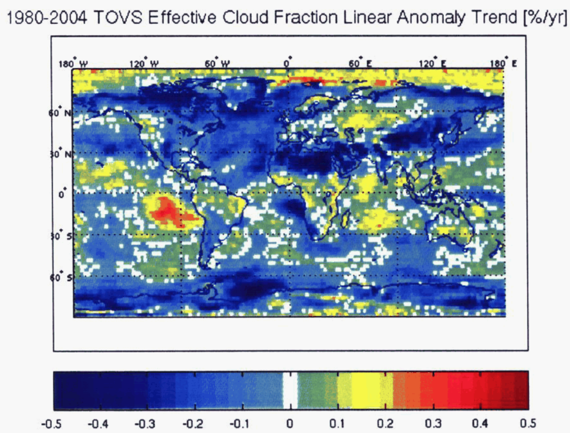

Figure 10

happens when we average the trends longitudinally, *i. e.,* what do the zonal mean trends tell us?

In summary:

A) The ISCCP D2 A_c trends are negative at all latitudes;

B) The TOVS Path-A A_{eff} trends are slightly positive in the Tropics;

C) The ISCCP D2 A_c and the TOVS Path-A A_{eff} trends correlate strongly in the Tropics;

D) The C_{tp} trends anticorrelate in Southern Hemispheric Tropics and in the 40°N-70°N, as well as the 60°S-80°S latitude zones.

So, nothing much is noteworthy except C), but now comes the surprise:

In addition to the "official" ISCCP D2 climatologies,

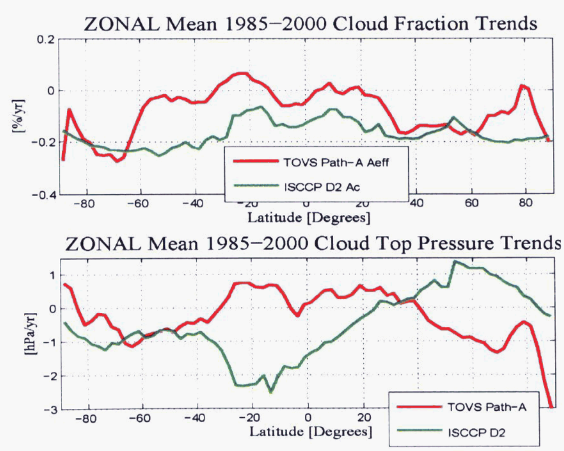

Figure 11

Garrett Campbell [2005-personal communication] also computed cloud fraction anomaly trends using only the polar orbiter based ISCCP data, referred to as the "ISCCP-AVHRR" dataset. That means that the geostationary satellite analysis "footprints" are expected to disappear from the trend maps.

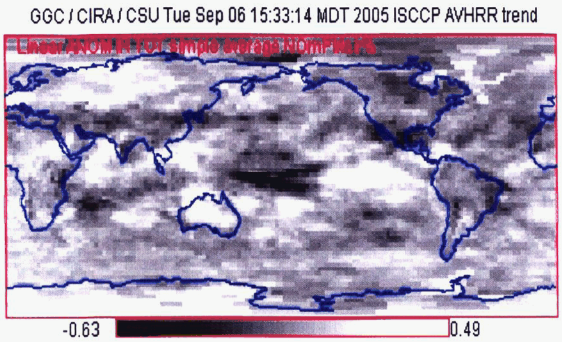

Figure 12

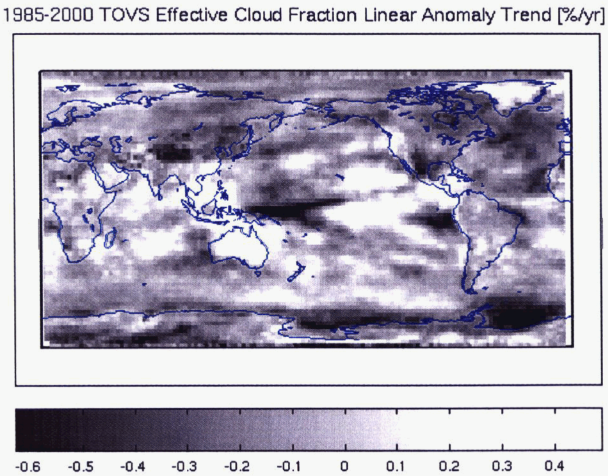

Figure 13

Figs 12 and 13 now show, on the same map-projection and the same gray-scale, the ISCCP-AVHRR and TOVS Path-A cloud fraction trends, respectively. Actually, Fig. 13 is the same as Fig. 7, but matching the plotting characteristics of Campbell's original figure [we got the figure only, not the original data, so we adjusted our plotting routine to depict the TOVS Path-A data the same way]. Now the improvement over the Fig. 6 *vs*. Fig. 7 inter-comparison is striking. The regional patterns are now very similar for most areas, so for long-term climate analyses the ISCCP geostationary data do not help at all, at least as currently processed/calibrated.

All in all: 1) Significant spatial pattern characterizes the trends, despite the global or Tropical *average* trends being small;

2) There appears to be an apparent ENSO (El Niño-Southern Oscillation)-like signal in the trends of the Tropics;

3) TOVS Path-A and ISCCP-AVHRR Trend patterns are quite close. In fact, the good correspondence between the *grid-scale spatial trends* of cloud cover of ISCCP-AVHRR and TOVS Path-A indicates that these climatologies [*derived in completely differing manner*] may already be mature enough even for trend assessments.

We also performed TOVS Path-A trend analyses for several key levels of atmospheric temperature and moisture profiles. A more detailed analysis is under progress regarding their values and interrelations. Here we mention results, which may have implications whether the "Lindzen-effect" (Lindzen[12]) could be operating on the global scale. According to Lindzen, increased convection, expected due to greenhouse warming, may lead to decreasing upper tropospheric humidity [UTH], which in turn increases OLR in the subsidence regions, thus cooling the Earth. According to Fig. 14 this is not the case; instead of a negative correlation between UTH and OLR anomalies, we find a rather high [0.60] positive correlation for the 25-yr long period 1980 through 2004. The other anomaly time

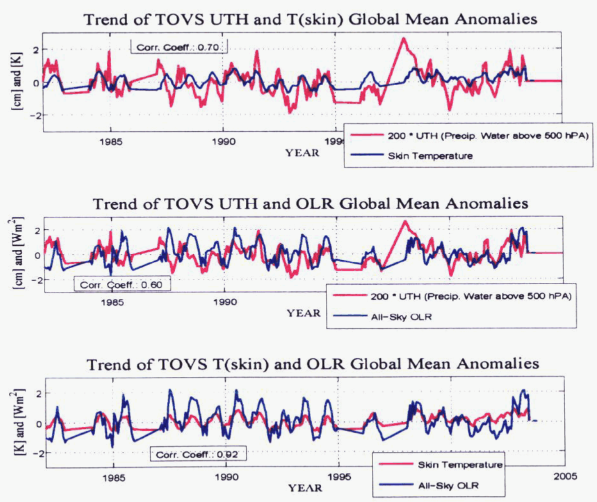

Figure 14

series correlations are also consistent with the scientific consensus: surface skin temperature and UTH correlate strongly and positively, and an even stronger positive correlation is observed between the OLR and surface skin temperature.

c) OLR Inter-comparisons:

Both the CERES and the AIRS instruments are on the same satellite [Aqua]. The "result" of this is clearly illustrated [Fig. 15] by the excellent correspondence between AIRS and CERES monthly mean OLR interannual variabilities. The CERES data were obtained through the Langley CERES data product center [***http://eosweb.larc.nasa.gov/project/ceres/table_ceres.php***].

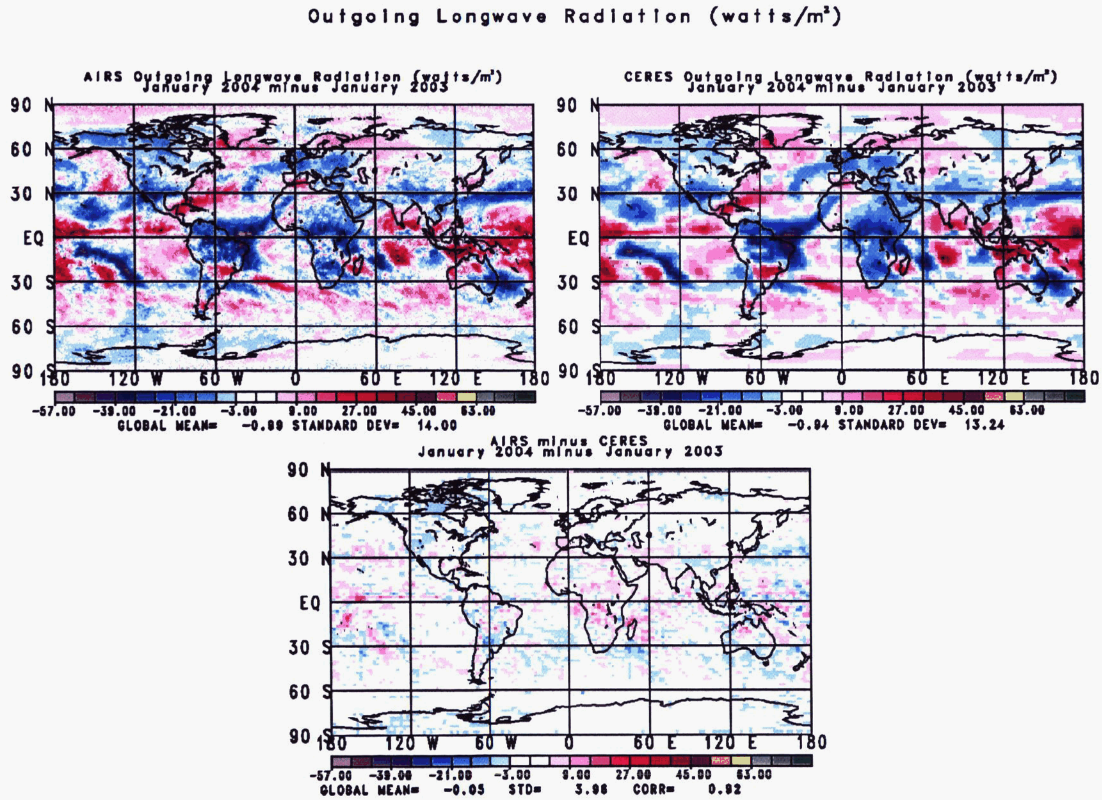

Figure 15

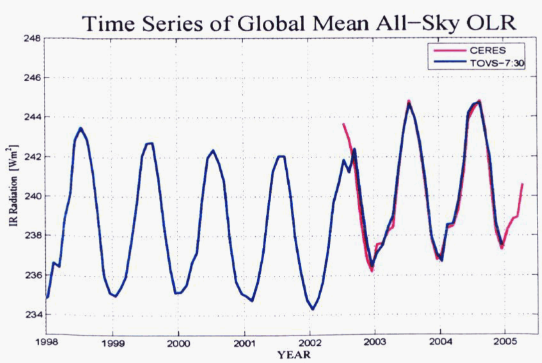

Figure 16

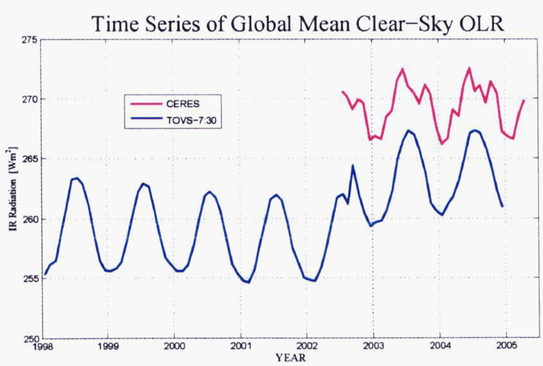

Figure 17

We also performed TOVS Path-A trend analyses for OLR and Clear-sky OLR. The excellent correspondence (even in terms of absolute values) of the global mean TOVS and CERES OLR time series is especially striking [Fig. 16]. The global mean TOVS clear-sky OLR time series [Fig. 17] is also highly correlated with that of CERES. Of course, long-term regional trend maps could only be obtained from the TOVS dataset. Fig. 18 illustrates the 1985-2000 OLR trends, exhibiting an ENSO-like pattern, which is similar to the corresponding TOVS A_{eff} anomaly trend map. However, on the global average, the TOVS C_{tp} anomalies correlate better with the OLR anomalies.

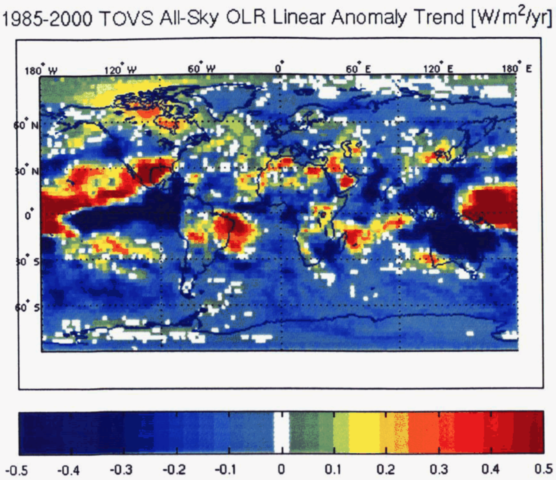

Figure 18

3. SUMMARY

- OLR interannual spatial variabilities from the available state-of-the-art CERES *measurements* and both from the AIRS and TOVS OLR *computations* are in remarkably good agreement, a very reassuring result regarding the overall quality of the AIRS and TOVS Path-A retrieval schemes.

- Global mean TOVS OLR variability even in absolute terms is extremely close to that of the 'state-of-the-art' CERES values.

- AIRS and MODIS effective cloud fraction and cloud top pressure intra-seasonal and interannual *anomalies* correlate well enough to *allow both datasets to be used for climate change assessments*. This happens despite cloud top pressures of the AIRS (and of the ISCCP) clouds are consistently greater than that of MODIS.

- Likewise, ISCCP [in particular ISCCP-AVHRR] and TOVS Path-A effective cloud fraction and cloud top pressure interannual *anomalies* correlate well enough *to allow these datasets to be considered for climate change studies*, despite much larger cloud fractions for the ISCCP retrievals in general. Cloud top pressures were quite close for both datasets both spatially and (especially) temporally.

- We believe that studies like this could provide an impetus for a more 'enthusiastic' use of the existing satellite datasets for long-term climate analyses in general. We strongly encourage the use of the TOVS Path-A dataset due to its unprecedented internal consistency (as well as due to the validation efforts described here). We hope that the AIRS-based dataset will complement/continue these satellite-sounder-based climatologies well into the future.

- These considerations are still preliminary, so we plan to extend the scope of these initial intercomparisons, including comparative assessments using other atmospheric parameters.

Future Work:
The trends of rather short time series of climatic parameters can be significantly distorted by relatively short-period natural variability cycles [*e. g.,* ENSO]. We plan to explore to find ways to minimize their effects on trends. For example, known, ENSO-affected areas/months may be simply omitted from the trend-analysis

database (based on PCA, for example). We plan to explore this path to make the 16 and 25-year TOVS (or the planned *combined* TOVS/AIRS 25+ years) trends more consistent with each other.

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