Interannual Variability of OLR as Observed by AIRS and CERES

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Abstract

The paper examines spatial anomaly time series of Outgoing Longwave Radiation (OLR) and Clear Sky OLR (OLR$_{CLR}$) as determined using observations from CERES Terra and AIRS over the time period September 2002 through June 2011. We find excellent agreement of the two OLR data sets in almost every detail down to the $\pm 1^\circ$ spatial grid point level. The extremely close agreement of OLR anomaly time series derived from observations by two different instruments implies high stability of both sets of results. Anomalies of global mean, and especially tropical mean, OLR are shown to be strongly correlated with an El Niño Index. These correlations explain that the recent global and tropical mean decreases in OLR over the time period studied are primarily the result of a transition from an El Niño condition at the beginning of the data record to La Niña conditions toward the end of the data period. We show that the close correlation of mean OLR anomalies with the El Niño Index can be well accounted for by temporal changes of OLR within two spatial regions, one to the east of, and one to the west of, the NOAA Niño-4 region. Anomalies of OLR in these two spatial regions are both strongly correlated with the El Niño Index as a result of the strong anti-correlation of anomalies of cloud cover and mid-tropospheric water vapor in these two regions with the El Niño Index.

1. Introduction

Outgoing Longwave Radiation (OLR) is a critical component of the Earth’s radiation budget and represents the total radiation going to space emitted by the earth-atmosphere system and integrated over all angles. OLR products have been generated and monitored globally since 1975 based on broad spectral band measurements taken at a given satellite zenith angle by the Earth Radiation Balance (ERB) instrument on the Nimbus-6 and Nimbus-7 satellites [Jacobowitz et al., 1984; Kyle et al., 1993]; the Earth Radiation Budget Experiment (ERBE) instrument on
NOAA-9, NOAA-10, and Earth Radiation Budget Satellite (ERBS) \cite{Barkstrom1989}; the Advanced Very High Resolution Radiometer (AVHRR) instrument on NOAA operational satellites \cite{Gruber1994, references therein}; and most recently by Clouds and Earth’s Radiant Energy System (CERES), which has flown on EOS Terra since 2000 and on EOS Aqua since 2002 \cite{Wielicki1996}. Multiyear OLR data sets have also been generated via radiative transfer calculations, which compute OLR for a given scene using surface, atmospheric, and cloud products for that scene derived from the atmospheric sounders Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) \cite{Susskind1993} and Atmospheric Infrared Sounder (AIRS) \cite{Susskind2011}.

OLR has been widely used as a proxy for tropical convective activity and rainfall, particularly in diagnosing and understanding tropical intraseasonal to interannual variability and monsoons \cite{Kidson2002, Jones2004, Barlow2005, Kiladis2005, HoyosWebster2007, Wong2008, ChiodiHarrison2010, Loeb2012a}. In addition, OLR has been used in studies of earth’s radiation balance \cite{Clement2005, FasulloTrenberth2008} and atmospheric model validation \cite{Allan2003}. More importantly, anomalies and trends of OLR have been used to study climate feedbacks and processes \cite{ChuWang1997, SodenHeld2006, Soden2008, Dessler2008, HuangRamaswamy2009, Chung2010, Dessler2010, Trenberth2010, ZelinkaHartmann2011, Zelinka2012a, Zelinka2012b, VanderHaar2012}. Dessler [2010] has estimated the magnitude of the cloud feedback in response to short-term climate variations by analyzing the top-of-atmosphere radiation budget and surface temperature variations from March 2000 to February 2010, and has found that as the surface warms, cloud changes lead to trapping additional energy, i.e., the longwave cloud feedback is positive. He has
also shown that El Niño/La Niña variability is the primary source of climate variations during this period. Vander Haar et al. [2012] showed that El Niño/La Niña variability also influences global mean total precipitable water, with larger values occurring during El Niño periods. Zelinka and Hartmann [2011] investigated the response of tropical mean cloud parameters to the ENSO cycle and their effect on top of atmosphere radiative fluxes. They found that the tropical mean fractional high cloud cover decreases during El Niño periods, which would tend to raise OLR, while the height of these clouds increases, which would tend to lower OLR. From the radiative perspective, changes in the high cloud fractional cloud cover dominated those of the cloud height, and tropical mean OLR consequently increases during El Niño periods. Zelinka and Hartmann [2011] also validated AIRS water vapor amounts with Microwave Limb Sounder (MLS) measurements for pressures greater than 150 mb. This is significant since we use AIRS-derived 500 mb specific humidity in this study.

This paper has two main objectives. The first objective is to compare anomaly time-series of CERES and AIRS OLR products, generated by the CERES and AIRS Science Teams respectively, over the eight year 10 month overlap period of the two data sets, September 2002 through June 2011. This comparison shows excellent agreement of these anomaly time series down to the 1 x 1° spatial scale. Behavior of OLR over this short time period should not be taken in any way as being indicative of what long term trends might be. The ability to begin to draw potential conclusions as to whether there are long term drifts with regard to the earth’s OLR, beyond the effects of normal interannual variability, would require consistent calibrated global observations for a time period of at least 20 years, if not longer. Nevertheless, a very close agreement of the eight year 10 month OLR anomaly time series derived using two different instruments in two very different manners is an encouraging result. It demonstrates that one can
have confidence in the 1° x 1° OLR anomaly time series as observed by each instrument over the same time period. The second objective of the paper is to explain why recent values of global mean, and especially tropical mean, OLR have been strongly correlated with El Niño/La Niña variability and why both have decreased over the time period under study.

2. AIRS and CERES OLR data sets used

In this paper we use the operational monthly mean OLR and OLR_{CLR} data products produced by the AIRS and CERES Science Teams. We obtained the AIRS OLR products from the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) and the CERES products from the CERES Science Team website.

AIRS was launched on the EOS Aqua satellite in a 1:30 AM/PM local crossing time orbit in May 2002. The operational processing of AIRS data began after AIRS became stable in September 2002. We use the AIRS Version-5 monthly mean Level-3 1° x 1° latitude-longitude grid products which contain separate products generated for each of the 1:30 AM and PM local time orbits. We averaged the AM and PM products together to generate and use a single monthly mean product on the 1° x 1° grid for each month. In addition to AIRS OLR and OLR_{CLR}, we also use the AIRS Level-3 surface skin temperatures, water vapor profiles, and cloud products to demonstrate the behavior of factors contributing significantly to the anomaly time series of OLR. Section 3 provides a discussion of how the AIRS Science Team OLR and OLR_{CLR} products were computed at the GES DISC.

CERES has flown on both EOS Terra, which was launched in December 1999 on a 10:30 AM/PM local crossing time orbit, and on EOS Aqua, the same platform that carries AIRS. The CERES Science Team generates a number of different OLR data sets using CERES observations. The latest versions of the longest record CERES OLR data sets are referred to as
the CERES Energy Balanced And Filled (EBAF) Edition-2.6r data sets, which like AIRS, are Level-3 products presented on a 1° x 1° latitude-longitude grid. The CERES EBAF data set was obtained from http://ceres.larc.nasa.gov/order_data.php. CERES EBAF Edition-2.6r uses the latest calibration improvements with Edition-2 CERES cloud retrievals [Minnis et al., 2008, 2011], angular dependence models [Loeb et al., 2005], and time-space averaging [Doelling et al., 2012]. At the time of this writing, the Level-3 CERES Terra EBAF Edition-2.6r OLR data set extended to June 2011 and the AIRS Level-3 products extended to August 2012. There was no comparable EBAF Edition-2.6 data set available for CERES Aqua. For these reasons, the comparisons shown in this paper use CERES Terra and AIRS OLR products for the overlap time period September 2002 through June 2011.

3. Computation of AIRS OLR as a function of surface and atmospheric conditions

OLR at a given location is affected primarily by the earth’s skin surface temperature, $T_s$; skin surface spectral emissivity, $\varepsilon_s$; atmospheric vertical temperature profile, $T(p)$ and water vapor profile, $q(p)$; as well as the heights, amounts, and spectral emissivities of multiple layers of cloud cover. OLR also depends on the vertical distributions of trace gases such as $O_3(p)$, $CH_4(p)$, $CO_2(p)$, and $CO(p)$. AIRS surface and atmospheric products are derived for each AIRS Field of Regard (FOR), which is comprised of the 3x3 array of AIRS Fields of View (FOVs) lying within a single 45 km Advanced Microwave Sounding Unit (AMSU)-A footprint. OLR can be computed for each FOR, given all the needed geophysical parameters, using an OLR Radiative Transfer Algorithm (RTA). Mehta and Susskind developed such an OLR RTA for use in conjunction with the TOVS retrieved products [Susskind et al., 1997] in order to generate the TOVS Pathfinder Path-A OLR data set [Mehta and Susskind, 1999a, 1999b]. AIRS OLR has
been computed using AIRS/AMSU sounding products in a completely analogous manner, including use of the same Mehta and Susskind OLR RTA [Susskind et al., 2003].

AIRS measures Infrared (IR) channel radiances over the interval 650 cm⁻¹ to 2668 cm⁻¹. Most AIRS OLR products shown in this paper were derived using the AIRS Science Team Version-5 retrieval algorithm [Susskind et al., 2011] which generates the values of $T_s$, $\varepsilon$, $T(p)$, $q(p)$, $O_3(p)$, and cloud parameters from which OLR and OLR$_{CLR}$ are computed. The AIRS Version-5 OLR product, referred to as $F$ below, is computed as a sum of fluxes in 14 contiguous spectral bands according to

$$F = \sum_{j=1}^{14} F_j = \sum_{j=1}^{14} \left[ (1 - \alpha \varepsilon_{1j} - \alpha \varepsilon_{zj})F_{j,CLR} + \alpha \varepsilon_{1j} F_{j,CLD1} + \alpha \varepsilon_{zj} F_{j,CLD2} \right]$$

(1)

where $F_{j,CLR}$ is the computed clear sky flux going to space integrated over all angles emanating from spectral band $j$; $F_{j,CLDk}$ is the analogous computed flux emanating from an opaque cloud at cloud top pressure $p_k$; and $\alpha \varepsilon_{kj}$ is the radiatively effective cloud fraction for the cloud at pressure $p_k$, which is given by the product of the geometric fractional cloud cover $\alpha_k$ as seen from above and the emissivity of that cloud in spectral band $j$.

Mehta and Susskind [1999a,1999b] compute $F_{j,CLR}$ according to

$$F_{j,CLR} = \Pi \left[ \varepsilon_j B(\nu_j, T_s) \tau_j(p) + \int_{\ln p_s}^{\ln \bar{p}} B(\nu_j, T(p)) \frac{d\tau_j(p)}{d\ln p} d\ln p \right]$$

(2)

where $B(\nu, T)$ is the Planck Blackbody function evaluated at frequency $\nu$ and temperature $T$, $\nu_j$ is the central frequency of spectral band $j$, $\varepsilon_j$ is the surface emissivity in band $j$, and the term $\tau_j(p)$ represents the effective band averaged atmospheric transmittance in band $j$ from pressure $p$ to the top of the atmosphere $\bar{p}$. Mehta and Susskind parameterize $\tau_j(p)$ as a
function of temperature, moisture, and ozone profile. To first order, the integral in Equation 2 can be approximated by \( B(\nu_j, T(p_j)) \times (1 - \tau_j(p_j)) \) where \( p_j \) is a band effective pressure for which \( \tau_j(p_j) = e^{-\tau}. \) \( F_{j,CLD} \) is computed in an analogous way to \( F_{j,CLR} \), but \( T_s \) is replaced by \( T(p_k) \) and \( p_s \) is replaced by \( p_e \) in Equation 2. According to Equations 1 and 2, everything else being held constant, \( F \) increases with increasing temperature, which increases both the surface and atmospheric contributions in Equation 2. \( F \) also decreases with increasing atmospheric water vapor, which decreases \( \tau_j(p) \), and consequently decreases the band effective pressure \( p_j \) in bands sensitive to water vapor absorption, especially for very moist (tropical) cases. In addition, \( F \) decreases with increasing \( \alpha_e \), especially for high (cold) clouds.

The band transmittance parameterization coefficients used by Mehta and Susskind are computed based on line-by-line calculations [Susskind and Searl, 1978] which used the atmospheric line parameter data base of McClatchey et al. [1972]. The spectral bands used in Equation 1 range from 2 cm\(^{-1}\) through 2750 cm\(^{-1}\). There is no need to make radiometric measurements at all frequencies in order to perform the calculations shown in Equations 1 and 2. The AIRS Version-5 retrieval algorithm determines the surface spectral emissivity \( \varepsilon_v \) as a function of frequency over the AIRS spectral range using AIRS observations. Surface emissivities at frequencies lower than 650 cm\(^{-1}\), which are not observed by AIRS, are set equal to those at 650 cm\(^{-1}\) and are irrelevant with regard to the computation of OLR in any event because the atmosphere is opaque at those frequencies. The AIRS Version-5 retrieval algorithm determines the effective cloud fraction \( \alpha e_{j} \) at 800 cm\(^{-1}\) for each of up to two cloud layers \( k \). The clouds are assumed to be gray, that is, \( \alpha e_{j} \) is assumed to be independent of frequency in the calculation of OLR. This is a valid approximation for opaque clouds but not so for cirrus clouds.
which have a cloud spectral emissivity that depends on the cloud drop size distribution. The results shown later in this paper demonstrate that the gray cloud approximation does not appear to have significant negative consequences with regard to the study of OLR anomaly time-series. No other approximations are made in the calculation of Equation 1.

AIRS $\text{OLR}_{\text{CLR}}$ is also a product computed for each AIRS FOR obtained by setting both $\alpha e_1$ and $\alpha e_2$ equal to zero in Equation 1. Geophysical parameters are determined from AIRS observations under both cloud-free and cloudy conditions, though their quality is poorer under very cloudy conditions, especially at or near the surface. For this reason, the AIRS Version-5 $\text{OLR}_{\text{CLR}}$ product for a given FOR is included in the generation of the Level-3 monthly mean gridded $\text{OLR}_{\text{CLR}}$ product only for those cases in which the AIRS retrieved cloud fraction is less than 90% and which also pass an additional $\text{OLR}_{\text{CLR}}$ quality control procedure which indicates the retrieval is of acceptable accuracy down to the surface [Susskind et al., 2011]. Quality Controlled AIRS Version-5 $\text{OLR}_{\text{CLR}}$ products that are included in the generation of the $\text{OLR}_{\text{CLR}}$ Level-3 product are produced in roughly 75% of the FOR’s observed by AIRS. The OLR product generated for each FOR is always included in the Level-3 OLR product, both because of the need for complete sampling with regard to OLR, and also because computed values of OLR are not affected significantly by surface and atmospheric conditions beneath the cloud in very cloudy cases.

The CERES Science Team uses a different procedure for determining the ensemble of cases to be included in its Level-3 $\text{OLR}_{\text{CLR}}$ product. The gridded CERES $\text{OLR}_{\text{CLR}}$ product is generating by averaging values of CERES OLR only for those CERES footprints determined to be cloud-free by use of coincident Moderate Resolution Imaging Spectroradiometer (MODIS) spectral radiance measurements. The MODIS cloud mask used by the CERES Science Team is
described in Minnis et al. [2011]. As a result of this difference in sampling methodologies, the AIRS monthly mean OLR\textsubscript{CLR} product includes a significantly larger ensemble of cases than that found in the CERES monthly mean OLR\textsubscript{CLR} product. The significant sampling differences between the two ensembles of cases included in each OLR\textsubscript{CLR} data set is most likely the largest factor that would negatively impact the comparison of OLR\textsubscript{CLR} anomaly time series contained in the AIRS and CERES Level-3 data sets.

This paper also shows some results comparing OLR computed using the prototype AIRS Version-6 Science Team retrieval algorithm with the Version-5 OLR product. AIRS Version-6 uses an improved OLR RTA [Iacono et al., 2008] in the computation of OLR. The approach used to compute OLR in Version-6 is very similar to that used in Version-5, with the minor difference that 16 spectral bands are used in the Version-6 OLR RTA as opposed to the 14 bands used in Equation 1. This new OLR RTA also has two very important upgrades compared to Mehta and Susskind [1999a, 1999b]. Most significantly, the new OLR RTA is generated using more up to date line absorption parameters, especially in the very strong water vapor absorption band near 300 cm\textsuperscript{-1}. In addition, the new OLR RTA allows for inclusion of the effects of variations in space and time of CO\textsubscript{2} profiles, as well as those of other minor absorption species such as CO, CH\textsubscript{4}, and N\textsubscript{2}O, in the calculation of OLR, which were not included in the Version-5 OLR RTA. The AIRS Version-6 retrieval algorithm also has other improvements in methodology which lead to improved values of the geophysical parameters themselves [Susskind et al., 2012]. As of the writing of this paper, the AIRS Science Team Version-6 retrieval algorithm has been finalized and will become operational at the Goddard DISC in late 2012. The AIRS Version-6 retrieval algorithm has been tested at the AIRS Science Team Computing
Facility (ASTCF) at JPL for the months of January, April, August, and October for each of 2003, 2007, and 2011. We show some of the OLR related results of these tests later in the paper.

4. Comparison of AIRS and CERES OLR and OLR\textsubscript{CLR} Data Records

Figure 1a shows global mean monthly mean values of AIRS Version-5 OLR and OLR\textsubscript{CLR}, as well as those of CERES Terra EBAF Edition 2.6r OLR and OLR\textsubscript{CLR}, henceforth referred to as CERES OLR and OLR\textsubscript{CLR}, for the overlap period starting September 2002 and extending until June 2011. AIRS OLR and OLR\textsubscript{CLR} products for parts of November 2003 and January 2010 were missing from the daily AIRS data record because the AIRS instrument was turned off on those days, and therefore observations for those days were not included in the generation at the DISC of the monthly mean OLR and OLR\textsubscript{CLR} values for these two months. We used a procedure to generate approximate values of what AIRS monthly mean OLR products for the months November 2003 and January 2010 would have been if the whole month had been observed, and used these approximate values as if they were the observed values in subsequent calculations. These approximated AIRS monthly mean data values were generated on a grid box basis, by setting grid point differences between AIRS and CERES OLR for each of these incomplete months equal to the average value of the corresponding AIRS/CERES differences for the previous month and subsequent month, and adding these differences to the observed CERES monthly mean products for each of the months in question. We used an analogous procedure to synthesize the AIRS OLR\textsubscript{CLR} data records for those two months.

We also synthesized some reported monthly mean CERES OLR\textsubscript{CLR} data points for individual 1° x 1° grid boxes because these CERES OLR\textsubscript{CLR} data values appeared to be significant outliers when compared to nearby CERES OLR\textsubscript{CLR} values, as well as with collocated AIRS OLR\textsubscript{CLR} values. For each grid box for each month, we eliminated any reported CERES
OLR\textsubscript{CLR} value that differed by more than 20 W/m\textsuperscript{2} from the corresponding AIRS OLR\textsubscript{CLR} value.

We then spatially interpolated the remaining nearest values of the difference, CERES OLR\textsubscript{CLR} minus AIRS OLR\textsubscript{CLR}, to synthesize approximate values of this difference for the grid boxes that were found to be of questionable accuracy as described above, and then added the appropriate differences to AIRS OLR\textsubscript{CLR} for those grid boxes. Note that only 2.6\% of the CERES OLR\textsubscript{CLR} monthly mean gridded values, which occurred primarily in the vicinity of Antarctica, were synthesized in this manner and used in all subsequent calculations.

We observe a number of features in Figure 1a. The most prominent result is that to first order, the AIRS and CERES OLR and OLR\textsubscript{CLR} data sets appear biased compared to each other.

Figure 1b presents the differences between the AIRS and CERES monthly mean global mean values of OLR and OLR\textsubscript{CLR} shown in Figure 1a. The difference between AIRS Version-5 OLR and CERES OLR shows a small annual cycle superimposed on a nearly constant bias. Part of this annual cycle, with a maximum in June and a minimum in December, may be the result of the large diurnal cycle of OLR over land. The CERES Science Team adjusts for the effects of the diurnal cycle on CERES Terra observations as described in Loeb et al. [2012b, supplementary information]. The AIRS monthly mean OLR product averages daytime and nighttime OLR observations together but does not make any other correction for diurnal cycle. Figure 1b also contains horizontal lines showing the average value of each difference. We show the average value of the difference between AIRS and CERES OLR, computed over the eight year time period September 2002 through August 2010, as a horizontal solid green line, with a value of 8.59 W/m\textsuperscript{2}. We computed this average difference over a full eight year period so as to minimize the effect of the annual cycle on its value.
The differences between AIRS and CERES OLR$_{CLR}$ are similar to, but smaller than, those of OLR, with regard to both their mean value and their seasonal cycle. The mean value of AIRS minus CERES Terra OLR$_{CLR}$, shown as a horizontal solid red line, is 7.96 W/m$^2$. The mean difference between AIRS and CERES OLR$_{CLR}$ values is roughly 0.6 W/m$^2$ less than that of AIRS and CERES OLR. The seasonal cycles of the differences between AIRS and CERES OLR on the one hand, and AIRS and CERES OLR$_{CLR}$ on the other, are displaced in time relative to each other. This displacement might be a result of the significant sampling differences in the cases included in the AIRS and CERES OLR$_{CLR}$ data sets, respectively.

The large biases between the AIRS Version-5 OLR and OLR$_{CLR}$ data records and those of CERES are at first disconcerting but are readily understood. The AIRS OLR product derived using the AIRS Science Team Version-6 retrieval algorithm is expected to have a much smaller bias compared to CERES Terra OLR than does AIRS Version-5 OLR. The substantial, though nearly constant, bias between OLR as computed from AIRS products and observed by CERES is primarily a result of the use of the older set of line by line absorption coefficients in the parameterization of the Version-5 OLR RTA [Mehta and Susskind, 1999a, 1999b], compared to that used in the improved Version-6 OLR RTA [Iacono et al., 2008]. The main difference between the two OLR parameterizations is that the [Iacono et al., 2008] OLR RTA has more absorption in the water vapor rotational band near 300 cm$^{-1}$ than does that of Mehta and Susskind [1999a]. As a result of this, a lower value of OLR will be computed for a given state in Version-6, compared to that computed in Version-5, especially under very moist conditions. Global mean total precipitable water vapor has an annual cycle, with more water vapor in the atmosphere in the northern hemisphere summer, and less in the northern hemisphere winter, as compared to the annual mean [Vonder Haar et al., 2012]. This phenomenon would contribute to the larger (more
positive) differences in the Version-5 OLR monthly mean products from the CERES OLR monthly mean products in the northern hemisphere summer, and smaller (less positive) OLR differences in the northern hemisphere winter, which is consistent with what is shown in Figure 1b.

We indicate monthly mean values of AIRS Version-6 OLR and OLR_{CLR} for the months in which Version-6 was tested at JPL, excluding July 2011 and October 2011, in Figure 1a by blue triangles and blue squares respectively. Figure 1b includes the monthly mean differences between AIRS Version-6 OLR and CERES OLR for these months, shown in green triangles, and the differences between AIRS Version-6 OLR_{CLR} and CERES OLR_{CLR}, shown in red squares. The horizontal dashed green and red lines show the average values of the differences between Version-6 OLR and CERES OLR, and Version-6 OLR_{CLR} and CERES OLR_{CLR}, with mean differences of 3.50 W/m² and 1.02 W/m² respectively. We therefore expect from the results shown in Figure 1b that AIRS Version-6 OLR and OLR_{CLR} time series will be significantly closer to those of CERES Edition 2.6 than the corresponding time series of AIRS Version-5, at least in the mean sense. Most of the remainder of this paper will discuss AIRS Version-5 products, including a comparison of monthly mean anomaly time series of AIRS Version-5 OLR and OLR_{CLR} with those obtained from CERES. Anomaly time-series obtained from two different sets of instruments can agree very well with each other even if the individual data sets are biased against each other, provided the bias for a given month of the year is essentially constant in time.

5. **Comparison of AIRS and CERES Global Mean and Tropical Mean Anomaly Time Series**

We generated AIRS and CERES monthly mean OLR and OLR_{CLR} climatologies on a 1° x 1° spatial resolution for each month of the year by taking the average of the grid box value for that month over an eight-year time period, i.e., the first eight consecutive Januaries, the first
eight consecutive Februaries, etc. The same ensembles of eight Januaries, Februaries, etc., are used in the generation of climatologies for all products shown in this paper. OLR and OLR\textsubscript{CLR} anomalies for a given month in a given year, on a 1 x 1° spatial grid, are defined as the differences between their monthly mean values in that year and their monthly climatologies for that grid box. The area mean anomaly for a given month is defined as the cosine latitude weighted average of the grid box anomalies contained in the area under consideration.

Figure 2a shows the global mean anomaly time series of AIRS Version-5 OLR and CERES OLR for the period September 2002 through June 2011, as well as the difference between the two sets of monthly mean anomalies. Figure 2b shows analogous results for tropical mean OLR anomalies, and Figures 2c and 2d show analogous global mean and tropical mean anomaly time series for the AIRS and CERES OLR\textsubscript{CLR} products. We define the term El Niño Index as the difference of the NOAA monthly mean oceanic Sea Surface Temperature (SST), averaged over the NOAA Niño-4 spatial area 5°N to 5°S latitude and 150°W westward to 160°E longitude, from an eight year NOAA Niño-4 SST monthly mean climatology which we generated based on use of the same eight years that we used in the generation of the OLR climatologies. Figures 2b and 2d include the values of the El Niño Index multiplied by 1.5. All anomaly time-series shown in Figures 2a-2d, as well as anomaly time series shown in subsequent figures, have a linear three point smoother applied to them, in which the “smoothed” value of a data point for a given month is represented as a weighted average of its value and those of the neighboring months using a weight of 0.5 for the actual month and 0.25 for each of the neighboring months.

Tropical mean OLR and OLR\textsubscript{CLR} anomalies both tend to track those of the El Niño Index in phase fairly closely, but the greatest tropical mean OLR anomalies are almost twice as large as
the greatest tropical mean \( \text{OLR}_{\text{CLR}} \) anomalies. Positive values of the El Niño Index (2003, 2005, 2007, early 2010) correspond to El Niño conditions, in which there are positive SST anomalies in the Niño-4 area, and negative values (2008, mid-2010 to June 2011) correspond to La Niña conditions, in which there are negative SST anomalies in the Niño-4 region. Figures 2a and 2c show that an onset of negative global mean anomalies for both OLR and \( \text{OLR}_{\text{CLR}} \) began in late 2007. The negative tropical mean anomalies of both OLR and \( \text{OLR}_{\text{CLR}} \) shown in Figures 2b and 2d are generally considerably larger than the corresponding global mean anomalies, especially after mid-2007. The decreases in global mean OLR and \( \text{OLR}_{\text{CLR}} \) in late 2007 are strongly influenced by the significant reduction in tropical mean OLR and \( \text{OLR}_{\text{CLR}} \) which started a few months earlier. Tropical mean OLR and \( \text{OLR}_{\text{CLR}} \) anomalies became positive starting in late 2009, roughly coincident with the onset of another El Niño event. Very substantial negative global and especially tropical mean OLR anomalies occurred in the period starting mid-2010, when the latest La Niña event began. This relationship between CERES OLR anomalies and El Niño/La Niña activity has been documented in Loeb et al. [2012a, 2012b].

The difference between AIRS and CERES tropical mean OLR anomaly time series, shown in green in Figure 2b, is generally in phase with the El Niño Index, with a temporal correlation of 0.52. This is a result of fact that both positive and negative tropical mean AIRS OLR anomalies are slightly larger in magnitude than those of CERES. An analogous result is found with regard to the difference between AIRS and CERES global mean OLR, which has a temporal correlation of 0.51 with the El Niño Index.

5.1 Average Rates of Change and El Niño Correlations of Anomaly Time Series

We define the Average Rate of Change (ARC) of an anomaly time series as the slope of the linear least squares fit of the anomaly time series. We use the term Average Rate of Change
to describe the slope of an anomaly time series rather than the term trend, which is generally used to characterize long-term multi-decadal data sets rather than the eight year 10 month period studied in this paper. Figure 2b shows that the El Niño Index is highly non-linear over this time period, with fluctuating values that are primarily positive at the start of the time period and substantially negative at the end of the time period. The ARC of the El Niño Index, computed over the time period September 2002 through June 2011, is -0.123 ± 0.046 K/yr. The uncertainties shown here and subsequently represent twice the standard error, σ, of the regression slope of the linear least squares fit [Draper and Smith, 1981]. The precise value of the ARC of the El Niño Index, which depends on the beginning and end of the time period used in the calculation, is less important than its sign, which shows that the Niño-4 region has cooled on the average over the time period under study.

Spatial distributions of ARCs of OLR and other geophysical parameters, shown later in the paper, are very coherent and are particularly informative with regard to the understanding of why global mean and tropical mean OLR decreased over the period September 2002 through June 2011. In this context, it is also very informative to examine the spatial distribution of temporal correlations of 1° x 1° grid point anomaly time series with that of the El Niño Index. We define these temporal correlations of anomaly time series around the earth with the single anomaly time series of $T_s$ averaged over the NOAA Niño-4 region as El Niño Correlations (ENCs). ENCs are indicative of the agreement in both the phase and magnitude between the time series of grid point anomalies and the El Niño Index. Unlike ARCs, ENCs should not depend significantly on the precise beginning and end of the time series used to compute them if these correlations hold up over long time periods. In those spatial areas in which the ARCs of OLR are strongly influenced by El Niño/La Niña activity, there should be a very close agreement between
the spatial patterns of ARCs of OLR with those of the ENCs of OLR, and these patterns will be of opposite sign as a result of the negative ARC of the El Niño Index.

Table 1a shows global mean and tropical mean values of the ARCs of AIRS OLR and CERES Terra OLR anomalies over the time period September 2002 through June 2011, the standard deviations between the two sets of global mean and tropical mean anomaly time series, and the temporal correlations between each global mean and each tropical mean anomaly time series. All statistics use values of the three point smoothed anomaly time series shown in Figure 2. The agreement of the ARCs of both global mean and tropical mean anomaly time series found in the AIRS and CERES OLR records is on the order of ±0.03 W/m²/yr, which is within the uncertainty of the respective sets of ARCs. The temporal correlations of the AIRS and CERES OLR anomaly time series with each other are 0.955 and 0.991 for global mean OLR and tropical mean OLR respectively. Both AIRS and CERES OLR anomaly time series show that global mean OLR has decreased on the average on the order of 0.075 W/m²/yr over the time period September 2002 through June 2011, and that tropical mean OLR has decreased at a rate of roughly -0.168 W/m²/yr from the beginning of the time period to the end. Demonstration of the ability to obtain close agreement between global and tropical mean ARCs of AIRS and CERES OLR anomaly time series, obtained in very different manners, is more significant than the values of the ARCs themselves, which are influenced by the actual time period used in the AIRS/CERES OLR data record comparison.

Table 1b shows analogous statistics comparing AIRS and CERES OLR_{CLR} anomaly time series. The correlations between the AIRS and CERES OLR_{CLR} anomaly time series are still high, but somewhat reduced from those of the OLR anomaly time series. In addition, the standard deviations of the OLR_{CLR} anomaly differences are also somewhat larger than those of
OLR, and the global and tropical mean ARCs of OLR$_\text{CLR}$ found in both data sets, while still negative, do not agree as closely as those of OLR. Nevertheless, the agreement obtained between anomaly time series of AIRS and CERES OLR$_\text{CLR}$ is better than might be expected given the significant sampling differences between the cases included in each monthly mean OLR$_\text{CLR}$ data set.

Table 1c shows temporal correlations between global mean and tropical mean anomaly time series of OLR and OLR$_\text{CLR}$ as well as the correlations of the anomaly time series with the El Niño Index (ENCs). We show correlations using AIRS time series above the diagonal in bold and those using CERES time series beneath the diagonal. As shown in Table 1c, the temporal correlation between the CERES global and tropical mean OLR anomaly time series is 0.646, and the corresponding correlation for the AIRS anomaly time series is 0.705. This confirms that tropical anomalies provide a significant contribution to the global OLR anomaly time series found in both data sets. The CERES and AIRS tropical mean OLR anomaly time series also correlate very highly with the El Niño Index, with correlations greater than 0.8. CERES and AIRS tropical mean OLR$_\text{CLR}$ anomaly time series also have high correlations with the El Niño Index, though somewhat smaller than those of the corresponding OLR data sets. Both sets of global OLR and OLR$_\text{CLR}$ anomaly time series also show moderate correlations, on the order of 0.55, with the El Niño Index. These correlations of global and tropical anomaly time series with the El Niño Index further imply that the recent short term decreases in global and tropical OLR over the time period September 2002 through June 2011, as observed by both AIRS and CERES, are strongly influenced by changes from El Niño conditions at the beginning of the time series to La Niña conditions at the end. The comparisons shown in the remainder of this paper deal only with AIRS and CERES OLR anomaly time series.
5.2 The Spatial Distribution of ARCs and ENCs of OLR

This section compares the spatial distribution of ARCs of AIRS and CERES OLR with each other on a 1° latitude by 1° longitude basis, as well as the spatial distribution of the correlations of each anomaly time series with the El Niño Index (ENCs). These comparisons not only show excellent agreement of ARCs and ENCs of AIRS OLR products with those of CERES on a small spatial scale, but also depict the spatial regions that have been contributing significantly to the short term decreases in global mean and tropical mean values of OLR over the period under study.

All values for a given grid point shown in subsequent spatial plots such as Figures 3a-3d, have a three point smoother applied to them in the latitude domain, as well as in the longitude domain. These figures all contain boxes surrounding three areas. A box, shown in gray, surrounds the NOAA Niño-4 region, 5°N to 5°S and 150°W westward to 160°E. A second box, shown in black, lies to the west of the Niño-4 region and encompasses the area between 20°N and 20°S from 90°E eastward to 135°E. Much has been written about the meteorology of this region, which includes the Maritime Continent and the Western Pacific Warm Pool, as well as Darwin Australia, particularly with regard to its response to El Niño/La Niña activity. In particular, the Southern Oscillation Index (SOI), which represents the monthly mean value of Tahiti sea level pressure minus that of Darwin, is well known to be strongly anti-correlated with SST anomalies in the region of El Niño activity, and the two phenomena are often linked together with the single acronym El Niño/Southern Oscillation (ENSO). We will refer to the area encompassed by this box as the Warm Pool Maritime Continent (WPMC region). A third box, also shown in black, covers portions of the eastern tropical Pacific Ocean, northern South America, and the equatorial Atlantic Ocean and is the composite of three adjacent rectangles:
5°N to 20°S, 140°W to 95°W; 8°N to 20°S, 95°W to 70°W; and 8°N to 8°S, 70°W to 10°E. We will refer to the area encompassed by these three contiguous rectangles as the Equatorial Eastern Pacific and Atlantic (EEPA) region. Less attention has been paid to the meteorology of this region and its response to El Niño, especially the Atlantic Ocean portion of the EEPA region.

The global spatial distributions of OLR ARCs over the time period September 2002 through June 2011 are shown in Figures 3a and 3b for AIRS and CERES, respectively. As discussed previously, more significant than the precise values of the ARCs shown in Figure 3 is the very coherent spatial structure of the ARCs of OLR. Figures 3a and 3b demonstrate two very important points. The first is the virtually indistinguishable spatial distributions of the ARCs of AIRS OLR and of CERES OLR. Figure 3c shows their difference, with a spatial correlation of 0.99 between the ARCs of the two OLR data sets, and a standard deviation of 0.11 W/m²/yr. The global mean AIRS OLR ARC for this period is 0.035 W/m²/yr lower (more negative) than that of CERES. This small difference in OLR ARCs is not uniform, but occurs primarily near 30°S latitude, especially over Eastern Australia in which the large negative ARCs of OLR are greater in AIRS than in CERES. The same negative difference in OLR ARCs is also observed in another region near 30°S, extending from 120°W eastward to about 50°W, in which both AIRS and CERES OLR ARCs are positive.

The most important scientific point of Figures 3a and 3b is that while the global mean and tropical mean ARCs of OLR are negative, there is considerable spatially coherent longitudinal structure of the ARCs of OLR at a given latitude, with differing signs and amplitudes. This structure is largest in the tropics, but is found at other latitudes as well. Figure 3 shows that positive OLR ARCs as large as 4.2 W/m²/yr exist in the vicinity of the equatorial dateline, including and surrounding the Niño-4 region. These are more than compensated for, in
the tropical mean sense, by negative OLR ARCs at other longitudes, as large as $3.2 \text{ W/m}^2/\text{yr}$ near the equator over Indonesia, in the vicinity of 120°E longitude, which lies within the WPMC region. Indeed, ARCs of OLR within the entire WPMC region are very negative over the period September 2002 through June 2011. ARC’s of OLR within the spatially larger EEPA region are also negative over this time period though less so than over the WPMC region. As demonstrated in Figure 3, the ARC of OLR over Darwin, contained within the WPMC region, is opposite in sign to that of Tahiti, near 18°S and 150°W. As stated previously, tropical OLR in a given region will decrease with increasing convective activity, which leads to both increases in mid-tropospheric water vapor as well as more high clouds. Increasing convective activity in a given region is also associated with decreases in sea level pressure in that region. The reverse phenomena will occur in the case of increasing subsidence in a given region.

There are many possible factors contributing to the patterns of spatial distribution of the relatively small differences of AIRS OLR ARCs and CERES OLR ARCs shown in Figure 3c. Our analysis of the twelve months in which Version-6 OLR products were generated indicates that the agreement of spatial patterns of AIRS Version-6 OLR ARCs with those of CERES will be even better than what was obtained using Version-5. We approximated what the difference would be of Version-5 OLR ARCs from those obtained using Version-6, on a grid point basis, by taking the slope of the linear least squares fit of Version-5 OLR minus Version-6 OLR, as a function of time, for each of the 12 months in which Version-6 products were generated. Spatial patterns of these approximated differences in OLR ARCs are shown in Figure 3d. There is a remarkable similarity in the spatial patterns of OLR ARC differences shown in Figures 3c and 3d. This indicates that the differences between Version-6 OLR ARCs and those of CERES will be even smaller than those found with regard to Version-5 OLR, because a large part of the grid
point differences between AIRS and CERES OLR ARCs will be accounted for using ARCs of AIRS Version-6 OLR.

Figures 4a-4c are analogous to Figures 3a-3c but show patterns of ENCs of AIRS and CERES OLR and their difference. ENCs represent correlations and are therefore unitless, with values ranging from -1.0 to 1.0. The color scales of Figures 4a, 4b, and 4c are reversed from those of Figures 3a, 3b, and 3c because regions of positive (negative) ARCs generally correspond to regions of negative (positive) ENCs. As found with regard to ARCs of OLR, there is again considerable spatial structure, and excellent agreement, in the ENCs of AIRS and CERES OLR, with a global spatial correlation of 0.97. This agreement shows that not only are the slopes of high spatial resolution anomaly time series of AIRS and CERES OLR in close agreement with each other, but implies that the anomaly time series themselves are also in close agreement.

The spatial structure of ENCs of OLR closely follows that of the OLR ARCs but with opposite sign (that is, contains similar colors), especially in the tropics. For example, the area of large positive ARCs of OLR including and surrounding the NOAA Niño-4 region, shown in green and red in Figures 3a and 3b, has OLR anomalies which are strongly anti-correlated with the El Niño Index, and are also shown in green and red in Figures 4a and 4b. This demonstrates that periods of positive SST anomalies in the Niño-4 region correspond to negative OLR anomalies in the Niño-4 region and surrounding areas. The reverse situation is found within the WPMC and EEPA regions, which contain blue and yellow colors in both Figures 3a and 3b as well as in 4a and 4b, indicative of substantial negative OLR ARCs and substantial positive OLR ENCs in these regions. This anti-correlation of the spatial distributions of ARCs and ENCs of tropical OLR between September 2002 and June 2011 indicates that the tropical ARCs of OLR
shown in Figure 3 are very strongly influenced by time periods containing significant El Niño/La Niña activity.

The inverse relationship between spatial patterns of ARCs and ENCs holds in some extra-tropical areas as well. Globally, the spatial distribution of ARCs and ENCs of OLR have correlations with each other of -0.78 and -0.79 for AIRS and CERES, respectively. It is interesting to note that differences between ARCs of AIRS and CERES OLR (Fig. 3c) are also anti-correlated with (that is, have similar colors to) the differences in their ENCs (Fig. 4c), which shows that AIRS tropical OLR anomaly correlations with El Niño activity are slightly higher than CERES OLR anomaly correlations, thus resulting in slightly more negative tropical mean ARCs of AIRS OLR compared to CERES, as shown in Table 1a.

Figures 4a and 4b are very similar in appearance to Figure 3 of Davies and Molloy [2012], which shows the spatial distribution of the temporal correlation of cloud top height anomalies H’ derived from Multiangle Imaging Spectro-Radiometer (MISR) with the SOI over the period 2000 through 2010. Davies and Molloy have red colors showing negative correlations of cloud height anomalies H’ with the SOI. The agreement of colors in Figures 4a with those of Davies and Molloy [2012] is expected because OLR decreases with increasing H’ on the one hand, and the SOI is out of phase with the El Niño Index on the other.

The spatial correlations of the anomaly time series of AIRS OLR with those of CERES OLR for each 1° by 1° grid point are shown in Figure 4d. The global mean AIRS/CERES OLR anomaly time series correlation, on a 1° x 1° spatial scale, is 0.93, with the largest differences occurring in the mid-latitudes and over convective areas in South America and Africa. This shows that as with their ARCs and ENCs, AIRS and CERES OLR anomaly time series on a 1° x 1° spatial scale also agree closely with each other.
Table 1a shows that both AIRS and CERES OLR anomaly time series confirm that global mean and especially tropical mean OLR decreased over the time period under study. As depicted in Figure 3, the largest OLR ARCs occur in the tropics within the WPMC region and near the dateline surrounding the Niño-4 region. OLR ARCs in these areas are roughly equal to each other and of opposite sign. The effects of the large positive and negative tropical OLR ARCs near the dateline and over the WPMC region tend to cancel in the zonal mean sense. The first 3 lines of Table 2 show values of ARCs and ENCs of OLR averaged over different spatial regions related to the WPMC region, as determined using each of the AIRS and CERES OLR data sets. The first line of Table 2 shows statistics related to ARCs and ENCs of OLR computed only within the WPMC region. AIRS and CERES both show very large negative ARCs and very high positive ENCs of OLR within this region. The second and third lines of Table 2 show values of global and tropical mean ARCs and ENCs of OLR computed only over areas outside of the WPMC regions. The tropical mean OLR ARC over the period September 2002 through June 2011, computed as previously, but after replacing OLR ARCs in the WPMC region by zeroes, is 0.004 ± 0.054 W/m²/yr for AIRS and 0.034 ± 0.053 W/m²/yr for CERES. Both of these values are essentially zero, given their uncertainties. In addition, ENC’s of tropical mean OLR outside of the WPMC region are both very low. Likewise, the global mean AIRS OLR ARC, computed after excluding ARCs within the WPMC region, is -0.030 ± 0.028 W/m²/yr, and is 0.005 ± 0.027 W/m²/yr for CERES, again both essentially zero. This indicates that both OLR data sets show that a substantial part of the recent negative global mean and tropical mean OLR ARCs results from the contribution of OLR anomalies contained within the WPMC region to the overall statistics. These statistics can give rise to the misleading conclusion that the response of OLR
within the WPMC region to El Niño activity is the sole cause of the fact that tropical and global mean OLR anomalies are strongly correlated with El Niño/La Niña. This is not the case.

Figure 3 shows that OLR ARCs are negative over the EEPA region as well. While ARCs of OLR over the EEPA region are not as negative as those over the WPMC region, the spatial extent of the EEPA region is considerably larger than that of the WPMC region. The last three lines of Table 2 show statistics for OLR anomalies computed both within and outside of the EEPA region analogous to those shown for the WPMC region. Exclusion of OLR within the EEPA region from the calculations of otherwise global and tropical mean ARCs likewise accounts for most of the negative ARCs of global and tropical mean OLR found during the period under study. The fact that OLR has been decreasing over the study period, and that OLR anomalies are strongly correlated with the El Niño Index over this period, is not the result of OLR changes within either the WPMC region or the EEPA region. Rather, it is the result of the fact that there are two such regions in the tropics, one to the east and one to the west of the Niño-4 region, in which OLR anomalies are each out of phase with, and individually compensate for, those in the Niño-4 region.

5.3. Longitudinal Distribution of Equatorial Anomaly Time Series: Hovmöller Diagrams

Figures 3 and 4 show that the tropics contain large spatially coherent areas with alternating values of positive and negative ARCs and ENCs of OLR over the time period under study. Figures 5a and 5b present Hovmöller diagrams showing time series of monthly mean AIRS and CERES OLR anomalies (vertical scale), integrated over the latitude range 5°N through 5°S, in each 1° longitude bin (horizontal scale) for the time period September 2002 through June 2011. These Hovmöller diagrams demonstrate the origin of the ARCs and ENCs of near equatorial OLR shown in Figures 3 and 4. The difference between the AIRS OLR Hovmöller
diagram and the CERES OLR Hovmöller diagram is shown in Figure 5c. Figures 5a and 5b, and all subsequent Hovmöller diagrams, have a small amount of smoothing applied to them. A five point (five month) linear smoothing was applied in the vertical and a 15 point (15 degree) linear smoothing was applied in the horizontal to minimize the effects of small discontinuities between adjacent rectangular grid points on the figures. Most of the Hovmöller domain 5°N to 5°S is ocean. There are three relatively small land areas near the equator: South America, Africa, and Indonesia. These land areas each lie between the three sets of thin black vertical lines shown in Figure 5. The longitudinal extent of the Niño-4 region is also indicated in Figure 5 by two vertical gray lines.

AIRS and CERES Hovmöller diagrams of tropical OLR anomalies are essentially identical, with a correlation coefficient of 0.995 between them. Some of the largest differences between the AIRS and CERES tropical anomaly time series occur in November 2003 and January 2010, the two months for which AIRS data was synthesized. The differences between AIRS and CERES in these two months would have been much larger if the AIRS “monthly mean” OLR products stored at the GES DISC were used in the calculations, as was done originally. In both cases, the AIRS “monthly mean” products of the DISC represented averages over less than a month time period, while the CERES data represented observations taken over the entire month. The fact that the remainder of the OLR anomaly differences shown in Figure 5c were so small alerted us to check, and correct for, the cause of the problem found in the data obtained from the GES DISC for these two months.

The anomaly time series shown in Figure 5 depict the phase relationship of OLR anomalies at different longitudes in the vicinity of the equator as a function of time. Such figures provide insight into the spatial distribution of tropical ARCs and ENCs of OLR in the vicinity of
the equator shown in Figures 3 and 4. In the Niño-4 region, equatorial OLR anomalies were very negative in late 2002/early 2003, which corresponds to an El Niño period. Very positive OLR anomalies in the Niño-4 region occur from mid-2007 through early 2009 and mid-2010 through June 2011, both during La Niña periods. These features give rise to the substantial positive OLR ARC shown in Figures 3a and 3b over the Niño-4 region. Figure 3 shows very negative values of OLR ARCs near the equator between 90°E and 135°E longitudes, within the WPMC region.

Figure 5 shows that equatorial OLR anomalies between 90°E and 135°E are out of phase with those in the Niño-4 region and are of comparable magnitude. Figure 5 also shows that equatorial OLR anomalies from 140°W eastward to 10°E, within the longitudinal domain of the EEPA region, tend to be smaller than, and out of phase with, those in the Niño-4 region, especially during La Niña periods. This phenomenon gives rise to the negative equatorial OLR ARCs shown in Figure 3 contained within the EEPA region. The phase relationships discussed above are also reflected in the ENCs of equatorial OLR shown in Figure 4.

Figures 3 to 5 show that the spatial patterns of both the Average Rates of Change and El Niño Correlations of OLR over the time period September 2002 through June 2011, as observed by AIRS and CERES, are in excellent agreement with each other, as are their equatorial anomaly time series in the vicinity of the equator. Both CERES and AIRS OLR products show that the period September 2002 through June 2011 is marked by a substantial decrease in global mean OLR, on the order of −0.075 W/m²/yr, and a larger decrease in tropical mean OLR on the order of −0.165 W/m²/yr. This agreement of Average Rates of Change of OLR anomaly time series, derived from observations by two different instruments, in totally independent and different manners, implies that both sets of OLR products must be stable over the eight year 10 month period in which they were compared. There should be little question that there actually was a
significant decrease of global mean OLR over the time period September 2002 through June 2011, and that the majority of the decrease occurred in the tropics.

These results, found by both CERES and AIRS, should not be taken as indicative of what will happen in the future. It mainly shows that OLR anomalies and their Average Rates of Change can be determined very accurately by two totally independent instrumental and theoretical approaches. The agreement of anomaly time series of OLR as determined using CERES and AIRS observations also indirectly validates the anomaly time series of the AIRS derived products used in the computation of AIRS OLR, at least for the time period September 2002 through June 2011. The next section uses anomaly time series of AIRS derived products to explain the factors contributing to the anomaly time series of OLR over the period under study and why OLR anomalies are strongly correlated with the El Niño Index.

6. The Effect of Phases of El Niño/La Niña on Tropical Water Vapor, Cloud Cover, and OLR Anomaly Time Series

As discussed previously, OLR increases with both increasing skin temperatures $T_s$ as well as with increasing temperature profile $T(p)$, and in general, everything else being equal, decreases with increasing radiatively effective cloud fraction $\alpha\varepsilon$ and with increasing water vapor $q(p)$. It is impractical to show results relating to anomaly time series of all the important geophysical parameters affecting those of OLR. In this paper, for demonstrative purposes, we concentrate on $T_s$, 500 mb specific humidity which we refer to as $q_{500}$, and $\alpha\varepsilon$. The OLR calculations of course take into account the detailed changes in the entire water vapor profile and the heights and amounts of clouds, as well as those of the temperature and ozone profiles on which OLR also depends. To first order, OLR responds linearly to changes in $T$ ($\Delta T$) and $\alpha\varepsilon$.
(Δαε), and in the case of water vapor q, OLR responds linearly to changes in \( \ln(q) \) (Δln(q)), which corresponds to percent change in \( q \) (Δq/q).

Figures 6a and 6b show the spatial distribution of the ARCs and ENCs of AIRS Version-5 \( T_s \) over the period September 2002 through June 2011. As with OLR, the monthly mean anomaly used in the computation of ARCs and ENCs of \( T_s \) is given by the difference of the monthly mean value of \( T_s \) for a given year from its climatological value. The color code used in Figure 6a, showing ARCs of \( T_s \), is analogous to that used in Figure 3, showing ARCs of OLR, with positive values depicted in reds and greens, and negative values depicted in blues and yellows. In addition, as with Figures 4a and 4b, red and green colors in Figure 6b indicate negative ENCs, and blue, yellow, and orange colors indicate positive ENCs.

A number of important features are found in Figure 6a. While the global mean ARC of \( T_s \) is essentially zero over this time period, there are areas in which significant positive and negative \( T_s \) ARCs exist. There has been considerable warming near the North Pole over this time period, as well as considerable warming and cooling in different areas over Northern Hemisphere extra-tropical land. In addition, there has been substantial cooling over much of Africa, especially south of 15°S, as well as over much of Australia. All of these areas in which extra-tropical land has either warmed or cooled considerably over the time period under study are also characterized by increases or decreases in OLR as shown in Figure 3. This is consistent with the fact that everything else being equal, increases (decreases) in \( T_s \) result in increases (decreases) in OLR.

Another prominent feature shown in Figure 6a is that the tropics are marked by substantial oceanic surface temperature cooling within and immediately surrounding the Niño-4 region encompassed by the gray rectangle. This area of oceanic cooling over the last nine years is surrounded to the south, west, and north by areas in which oceanic warming has occurred
during this period, though to a lesser extent. Figure 3 shows that OLR changes in these oceanic areas are considerable, and unlike over extra-tropical land, are of opposite sign to those of the changes in $T_s$. This indicates that the changes in tropical oceanic OLR in these regions are driven primarily by changes in water vapor profile and cloud cover rather than by changes in $T_s$.

Figure 6b shows that, as is the case with regard to OLR, ENCs of $T_s$ are generally of opposite sign (similar color) to their ARCs. The global mean spatial correlation of ARCs and ENCs of $T_s$ with each other is -0.56, which is still appreciable but smaller than that for OLR. It is apparent from Figures 6a and 6b that the considerable cooling of $T_s$ that took place over South Africa and Australia is related to a strong in phase relationship of $T_s$ with El Niño/La Niña activity in these areas. On the other hand, the significant changes in $T_s$ that occurred over Northern Hemisphere extra-tropical land, such as the warming that occurred near the North Pole, are not closely related to El Niño activity, at least in an unlagged sense, because ENCs of $T_s$ in these areas are not appreciable. It is also interesting to note that in some equatorial oceanic areas, such as in the vicinities of 90°W and 60°E, $T_s$ anomalies had moderate positive correlations with the El Niño Index but $T_s$ in those areas had very small Average Rates of Change. In addition, while ARCs and ENCs of OLR within the WPMC region and the EEPA region were all large and of the same sign, this is not the case with regard to $T_s$ in these regions.

Figures 6c and 6d show ENCs of $q_{500}$ and $\alpha e$ respectively. With regard to $q_{500}$, the monthly mean anomalies used in the generation of ARCs and ENCs are in units of % change and are given by $[(q_{500} - q_{500}^{\text{clim}})/q_{500}^{\text{clim}}]$ where $q_{500}^{\text{clim}}$ is the monthly climatological value of $q_{500}$ for that grid box. This is the appropriate value to use because, as stated previously, changes in OLR are linear to first order with changes in $\ln(q)$. Anomalies of $\alpha e$ are treated analogously to those
of OLR and $T_s$. In the tropics, ARCs of $q_{500}$ and $\alpha\varepsilon$ (not shown) are out of phase with ENCs of these parameters, as was the case with ARCs and ENCs of OLR. ENCs of $q_{500}$ and $\alpha\varepsilon$ are each very positive in the Niño-4 region, as are ENCs of $T_s$. These high positive correlations with the El Niño Index indicate that a significant overall mid-tropospheric drying and a corresponding overall decrease in cloud cover occurred in the Niño-4 region over the period under study. An analogous situation occurred in the areas of warming surface skin temperature surrounding the Niño-4 region, in which ENCs of $q_{500}$ and $\alpha\varepsilon$ are very negative, indicative of considerable mid-tropospheric moistening as well as increasing cloud cover in these surrounding regions during the period under study. Unlike $T_s$, however, there are also large negative ENCs of $q_{500}$ and $\alpha\varepsilon$ contained within most of the WPMC and the EEPA regions over this time period, indicative of both considerable mid-tropospheric moistening and increasing cloud cover over these two regions. Of particular significance are the large negative ENCs of cloud fraction, and even more so, of 500 mb specific humidity, contained within the EEPA region off the West Coast of South America, indicative of both moistening and increased cloudiness in this area over the time period under study. This phenomenon is what gave rise to the large positive ENCs and large negative ARCs of OLR off the west coast of South America, as shown in Figures 4 and 3 respectively.

Hovmöller diagrams provide a good depiction of the interrelationship of equatorial anomalies of different geophysical parameters as a function of time and longitude, as discussed above. The Hovmöller diagram of monthly mean AIRS $T_s$ anomalies (K) for the period September 2002 through June 2011 is shown in Figure 7a, and those of $q_{500}(\%)$ and $\alpha\varepsilon(\%)$ are shown in Figures 7b and 7c. As in Figure 5, the vertical gray lines in Figure 7 delineate the longitudinal band containing the Niño-4 region, 150°W longitude westward to 160°E. Figure 7a clearly demonstrates that the large negative $T_s$ ARC in the Niño-4 region, shown in Figure 6a, is
the result of the transition from an El Niño condition (locally positive $T_s$ anomaly) at the end of 2002 to La Niña conditions (locally negative $T_s$ anomalies) over the time periods late 2007 through 2008, and especially late 2010 through mid-2011. Equatorial $T_s$ anomalies between 100°E and 140°E, within the WPMC region, tend to be smaller than, and of opposite sign to, those in the vicinity of the dateline. This gives rise to the band of weaker positive $T_s$ ARCs near the equator from 100°E to 140°E shown in Figure 6a. $T_s$ anomalies in the equatorial Atlantic Ocean are also to some extent out of phase with those in the Niño-4 region, resulting in the small positive ARCs, and moderately negative ENCs, of $T_s$ in the equatorial Atlantic Ocean as shown in Figures 6a and 6b.

Anomalies of $q_{500}$ and $\alpha_e$ within the Niño-4 region generally follow those of $T_s$ very closely, both in magnitude and in phase. This indicates, not surprisingly, that positive SST anomalies in the Niño-4 region correspond to periods of increased convection in that area, leading to enhancement of moisture in the mid-troposphere as well as increases in cloud cover. Conversely, negative SST anomalies in the Niño-4 area correspond to periods of decreased convection (increased subsidence) leading to periods of a drier mid-troposphere and decreases in cloud cover. Water vapor and cloud cover anomalies in the WPMC region, from roughly 90°E to 135°E, are out of phase with those near the dateline, as was found for $T_s$. Unlike $T_s$ anomalies in the WPMC region, which were smaller than those near the dateline, $q_{500}$ and $\alpha_e$ anomalies in the WPMC region are closer in magnitude to those near the dateline. This is the result of the westward shift of the area of maximum convection during La Niña periods from the dateline to the WPMC region. This out-of-phase relationship gives rise to the very substantial negative ENCs of $q_{500}$ and $\alpha_e$ over Indonesia during this time period, as depicted in Figures 6c and 6d.
Figures 6c and 6d contain substantial negative ENCs of $q_{500}$ and $\alpha\varepsilon$ in some tropical locations in which no significant changes in $T_s$ exist. The most notable of these is off the west coast of South America, in the vicinity of 5°N to 20°S from 120°W eastward to 80°W, which is a part of the EEPA region. There is also another region of positive $q_{500}$ ENCs near the equator going across South America and extending eastward along the Atlantic Ocean to about 10°E longitude, which is also contained within the EEPA region. Figures 7b and 7c show that equatorial water vapor and cloud cover anomalies off the west coast of South America are often out of phase with those at the dateline, especially during the large La Niña events in 2007-2008 and 2010-2011. This demonstrates that La Niña periods of decreased convection near the dateline also correspond to periods of increased convection eastward of 120°E, as a result of the eastward shift of the convective branch of the Walker circulation during La Niña periods [Power and Smith, 2007; Zhou et al., 2011]. The same relationship is found to a lesser extent over the Atlantic Ocean extending to 10°E longitude at the eastern end of the EEPA region.

The Hovmöller diagrams of $q_{500}$ and $\alpha\varepsilon$, shown in Figures 7b and 7c, are both strongly anti-correlated with that of OLR, shown in Figure 5. The Hovmöller diagrams of $q_{500}$ and $\alpha\varepsilon$ have correlations with those of AIRS OLR of -0.79 and -0.93 respectively, and have correlations of -0.79 and -0.92 with those of CERES OLR. This further demonstrates that anomalies in tropical mid-tropospheric water vapor, and especially in cloud cover, are the driving forces behind changes in tropical OLR.

The previous discussion was related primarily to the tropics. Figures 6a and 6b also show that spatial patterns of ENCs of $q_{500}$ and $\alpha\varepsilon$ over the entire latitude range 60°N to 60°S are in general similar to each other. Note, for example, that the large negative ENCs of $q_{500}$ and $\alpha\varepsilon$ found over the WPMC region each extend southeastward toward and beyond the southern tip of
South America. In addition, the large positive ENCs of $q_{500}$ and $\alpha e$ found over the Niño-4 region continue toward and across southern South America in the area that lies immediately to the north of that described above. Similar features appear in the spatial distributions of the ARCs of $q_{500}$ and $\alpha e$, which are not shown in this paper. In addition, these same features are found, with reversed colors, in the ARCs of AIRS and CERES OLR shown in Figures 3a and 3b because increases in $q_{500}$ and $\alpha e$ tend to result in decreases in OLR.

An examination of the small differences between the ARCs of AIRS and CERES OLR shown in Figure 3c, which we will refer to as $\Delta$OLR ARC, also shows similar patterns to those found in the ENCs (as well as in the ARCs) of $\alpha e$. Figure 8 depicts the relationship between $\Delta$OLR ARC and $\alpha e$ ARC in terms of a scatter diagram relating values of these two quantities for all grid points 60°N to 60°S. It is apparent from Figure 8 that there is a tendency for grid points with positive ARCs of $\alpha e$ to be more associated with those having negative values of $\Delta$OLR ARC, with the reverse being true for grid points with negative ARCs of $\alpha e$. The blue line shows the linear least squares fit through the points shown in the figure, which has a slope of $-0.0743 \pm 0.0028$ (W/m²/yr)/(%/yr).

At least part of this correlation between ARCs of cloud cover and the difference between ARCs of AIRS and ARCs of CERES OLR is a result of the fact that the Version-5 AIRS OLR RTA does not account for enough absorption in the water vapor rotational band. This is the main reason that computed AIRS Version-5 OLR values are biased high compared to CERES OLR. For a given scene, the error in the computation of AIRS Version-5 OLR will tend to decrease with increasing cloud cover, especially for high clouds, because clouds obscure a substantial portion of the water vapor in the scene. Consequently, for more cloudy cases, AIRS computed Version-5 OLR is closer to the value observed by CERES than for less cloudy cases. Increasing
cloud fraction over time for a given grid box therefore results in decreasing the (positive) computed differences of AIRS OLR relative to the CERES OLR, while simultaneously producing a negative contribution to AIRS OLR anomalies which are computed relative to the more positive AIRS climatology. Our preliminary estimate of how Version-6 OLR ARCs will differ from those of Version-5, shown in Figure 3d, indicates that spatial differences between the ARCs of AIRS Version-6 OLR and those of CERES OLR should indeed be even smaller than those between Version-5 OLR and CERES OLR.

7. Summary

The first part of this paper compared September 2002 through June 2011 anomaly time series of OLR and OLR_{CLR} data records, determined from CERES observations as generated by the CERES Science Team, and from AIRS observations as generated by the AIRS Science Team. Excellent agreement was found between the CERES and AIRS OLR anomaly time series down to the 1° latitude by 1° longitude spatial scale. CERES and AIRS data records both show that global mean and tropical mean OLR have decreased over the time period under study, and more significantly, that both global and tropical mean OLR anomaly time series are strongly correlated with El Niño/La Niña variability as expressed by the El Niño Index as defined in this paper. This high correlation, as well as the decrease in global and tropical mean OLR over the time period under study, was shown to result primarily from changes in mid-tropospheric water vapor and cloud cover in two equatorial regions, one to the east of, and one to the west of, the Niño-4 region, both in response to El Niño/La Niña activity.

The AIRS results shown in this paper were based on products derived using the AIRS Science Team Version-5 retrieval algorithm. The AIRS Version-6 retrieval algorithm is expected to become operational in late 2012, and will be used to analyze all future AIRS observations as
well as to reanalyze all previous AIRS observations. AIRS Version-6 OLR and OLR_{CLR} data
records should be much closer in the mean to those of CERES, and in addition, it is expected that
AIRS Version-6 OLR ARCs will show even better agreement with CERES OLR ARCs than that
found in AIRS Version-5. AIRS Version-6 data records will also include monthly mean values
of the spectral components of OLR averaged over each of the 16 contiguous spectral bands used
in the computation of OLR in Version-6. Anomaly time series of OLR computed only over each
of these spectral intervals, and the spatial distribution of their Average Rates of Change and El
Niño Correlations, will provide important additional information to help understand the effect of
El Niño/La Niña oscillations on OLR. We plan to conduct further studies comparing AIRS
Version-6 OLR with CERES OLR products as well as evaluating ARCs and ENCs of the
spectral components of AIRS OLR.

The results shown in this paper should not be taken as to be indicative of how OLR will
change in the future, especially with regard to possible increases or decreases in global mean
OLR. The EOS satellites carrying AIRS and CERES are expected to last about 20 years. A 20
year time series of overlapping AIRS and CERES OLR data records would be a very useful first
step towards monitoring and understanding long term variability and possibly drifts of OLR.

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Global and tropical mean statistical comparisons of AIRS and CERES OLR anomaly time series for the period September 2002 through June 2011. Shown are the Average Rates of Change, the standard deviations between the anomaly time series, and the temporal correlations of the anomaly time series.

Table 1a. OLR Anomaly Time Series Comparison
September 2002 through June 2011

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Global</th>
<th>Tropical</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS ARC (W/m²/yr)</td>
<td>$-0.094 \pm 0.026$</td>
<td>$-0.183 \pm 0.070$</td>
</tr>
<tr>
<td>CERES Terra ARC (W/m²/yr)</td>
<td>$-0.059 \pm 0.022$</td>
<td>$-0.154 \pm 0.066$</td>
</tr>
<tr>
<td>AIRS Minus CERES STD (W/m²)</td>
<td>0.136</td>
<td>0.155</td>
</tr>
<tr>
<td>AIRS/CERES Correlation</td>
<td>0.955</td>
<td>0.991</td>
</tr>
</tbody>
</table>

Table 1b. OLR CLR Anomaly Time Series Comparison
September 2002 through June 2011

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Global</th>
<th>Tropical</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS ARC (W/m²/yr)</td>
<td>$-0.021 \pm 0.020$</td>
<td>$-0.072 \pm 0.042$</td>
</tr>
<tr>
<td>CERES Terra ARC (W/m²/yr)</td>
<td>$-0.089 \pm 0.020$</td>
<td>$-0.144 \pm 0.044$</td>
</tr>
<tr>
<td>AIRS Minus CERES STD (W/m²)</td>
<td>0.222</td>
<td>0.247</td>
</tr>
<tr>
<td>AIRS/CERES Correlation</td>
<td>0.772</td>
<td>0.936</td>
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</tbody>
</table>

Global and tropical mean statistical comparisons of AIRS and CERES OLR CLR anomaly time series for the period September 2002 through June 2011. Shown are the Average Rates of Change, the standard deviations between the anomaly time series, and the temporal correlations of the anomaly time series.
<table>
<thead>
<tr>
<th>Spatial Area</th>
<th>OLR ARC (W/m²/yr)</th>
<th>OLR ENC</th>
<th>OLR ARC (W/m²/yr)</th>
<th>OLR ENC</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPMC Region</td>
<td>-1.502 ± 0.525</td>
<td>0.871</td>
<td>-1.496 ± 0.529</td>
<td>0.870</td>
</tr>
<tr>
<td>Tropical outside WPMC Region</td>
<td>0.004 ± 0.054</td>
<td>0.050</td>
<td>0.034 ± 0.053</td>
<td>0.101</td>
</tr>
<tr>
<td>Global outside WPMC Region</td>
<td>-0.030 ± 0.028</td>
<td>-0.129</td>
<td>0.005 ± 0.027</td>
<td>-0.372</td>
</tr>
<tr>
<td>EEPA Region</td>
<td>-0.631 ± 0.158</td>
<td>0.767</td>
<td>-0.611 ± 0.154</td>
<td>0.761</td>
</tr>
<tr>
<td>Tropical outside EEPA Region</td>
<td>-0.037 ± 0.048</td>
<td>0.599</td>
<td>-0.011 ± 0.047</td>
<td>0.511</td>
</tr>
<tr>
<td>Global outside EEPA Region</td>
<td>-0.044 ± 0.020</td>
<td>0.256</td>
<td>-0.011 ± 0.019</td>
<td>0.039</td>
</tr>
</tbody>
</table>
Figure 1

a) Monthly mean global mean time series values of AIRS Version-5 and CERES Terra Edition-2.6 OLR and OLR\textsubscript{CLR} for the period September 2002 through June 2011. Monthly mean values of AIRS Version-6 OLR and OLR\textsubscript{CLR} products are also shown for ten months for which they have been calculated. b) Global monthly mean differences of values shown for Figure 1a. The green and red horizontal lines show the average values of the differences between AIRS and CERES OLR and AIRS and CERES OLR\textsubscript{CLR}, respectively.

Figure 2

Monthly mean global mean AIRS and CERES OLR anomaly time series, and their differences for the period September 2002 through June 2011. a) Global mean OLR anomalies, b) Tropical mean (20°N to 20°S) anomalies, as well as the El Niño Index multiplied by 1.5, c) As in a) but for OLR\textsubscript{CLR}, d) As in b) but for OLR\textsubscript{CLR}.

Figure 3

Spatial 1° latitude by 1° longitude distribution of OLR ARCs over the time period September 2002 through June 2011. The NOAA Niño-4 region is outlined in gray and the WPMC and EEPA regions are outlined in black in this and most subsequent figures showing spatial distributions of ARCs of different parameters. a) AIRS OLR ARCs, b) CERES OLR ARCs, c) AIRS OLR ARCs minus CERES OLR ARCs, d) AIRS Version-5 OLR ARCs minus AIRS Version-6 OLR ARCs.
Figure 4
Spatial 1° latitude by 1° longitude distribution of OLR correlations over the time period September 2002 through June 2011: a) AIRS OLR ENCs, b) CERES OLR ENCs, c) AIRS OLR ENCs minus CERES OLR ENCs, d) AIRS and CERES OLR temporal anomaly correlations.

Figure 5
Hovmöller diagram for time series of monthly mean anomalies (vertical scale) integrated over the latitude range 5°N through 5°S in each 1° longitude bin (horizontal scale) for the period September 2002 through June 2011. a) AIRS OLR, b) CERES OLR, c) the difference between AIRS OLR and CERES OLR anomalies.

Figure 6
Spatial distribution of ARCs and ENCs of AIRS retrieved geophysical parameters for the period September 2002 through June 2011. a) ARCs of Surface Skin Temperature (K/yr), b) ENCs of Surface Skin Temperature, c) ENCs of q_{500}, d) ENCs of αe.

Figure 7
Hovmöller diagrams of anomalies of AIRS retrieved products. The longitudinal domain of the NOAA Niño-4 region is encompassed by the gray vertical lines. a) T_{skin}(K), b) q_{500}(%), c) αe(%).

Figure 8
A scatter plot comparing AIRS values of OLR ARC minus CERES OLR ARC (ΔOLR ARC) with those of cloud fraction ARC for all grid points 60°N to 60°S.
Table 1a
Global and tropical mean statistical comparisons of AIRS and CERES OLR anomaly time series for the period September 2002 through June 2011. Shown are the Average Rates of Change, the standard deviations between the anomaly time series, and the temporal correlations of the anomaly time series.

Table 1b
Global and tropical mean statistical comparisons of AIRS and CERES OLR$^\text{CLR}$ anomaly time series for the period September 2002 through June 2011. Shown are the Average Rates of Change, the standard deviations between the anomaly time series, and the temporal correlations of the anomaly time series.

Table 1c
Temporal correlations of AIRS and CERES OLR and OLR$^\text{CLR}$ global and tropical mean anomaly time series. Correlations using AIRS data records are shown above the diagonal in bold and those using CERES data are shown beneath the diagonal.

Table 2
Area mean Average Rates of Change of AIRS and CERES OLR anomaly time series, and the correlation between the OLR anomaly time series and the El Niño Index, computed over different spatial domains for the period September 2002 through June 2011.
Global OLR and Clear Sky OLR
September 2002 through June 2011

OLR Time Series

OLR Differences

Figure 1
Figure 2

OLR Anomaly Time Series
September 2002 through June 2011

Figure 2
Average Rates of Change (W/m²/yr)
September 2002 through June 2011

Figure 3
OLR Anomaly Correlations
September 2002 through June 2011

a) AIRS ENCs

Global Mean=0.03       STD=0.36

b) CERES ENCs

Global Mean=0.04       STD=0.33

c) AIRS ENCs minus CERES ENCs

Global Mean=0.01   STD=0.06   Corr=0.97

d) AIRS/CERES Temporal Anomaly Correlations

Global Mean=0.93       STD=0.04

Figure 4
Figure 5

OLR Anomalies (W/m²)  Tropics 5°N to 5°S
Monthlies, September 2002 through June 2011

a) AIRS  b) CERES  c) AIRS minus CERES

Correlation=0.995
AIRS Products September 2002 through June 2011

a) $T_s$ ARCs (K/yr)

b) $T_s$ ENCs

c) 500 mb Specific Humidity ENCs

d) Effective Cloud Fraction ENCs

Figure 6
AIRS Anomalies    Tropics 5°N to 5°S
Monthlies, September 2002 through June 2011

a) Skin Temperature (K)   b) 500 mb Specific Humidity (%)  c) Cloud Fraction (%)

Figure 7
60°N to 60°S Grid Point Scatter Diagram
ΔOLR ARC vs. Cloud Fraction ARC

Slope = \(-0.0743\, (W/m^2/yr)/(\%/yr)\)

Figure 8