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A comparison of ISCCP land surface temperature with other satellite and in situ observations

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[1] Land surface skin temperature (LST) estimates from the International Satellite Cloud Climatology Project (ISCCP) are compared with estimates from the satellite instruments AIRS and MODIS, and in situ observations from CEOP. ISCCP has generally slightly warmer nighttime LSTs compared with AIRS and MODIS (global) and CEOP (at specific sites). Differences are smaller than 2K, similar to other reported biases between satellite estimates. Larger differences are found in the day-time LSTs, especially for those regions where large LST values occur. Inspection of the AIRS and ISCCP brightness temperatures at the top of the atmosphere (TOA-BT) reveals that where the LSTs differ so too do the TOA-BT values. Area-averaged day-time TOA-BT values can differ as much as 5K in very dry regions. This could be related to differences in sensor calibration, but also to the large LST gradients at the AIRS mid-day overpass that likely amplify the impact of sensor mismatches. Part of the studied LST differences are also explained by discrepancies in the AIRS and ISCCP characterization of the surface (emissivity) and the atmosphere (water vapor). ISCCP calibration procedures are currently being revised to account better for sensor spectral response differences, and alternative atmospheric and surface data sets are being tested as part of a complete ISCCP reprocessing. This is expected to result in an improved ISCCP LST record.

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1. Introduction

[2] Land surface skin temperature (LST) plays a key role in the interaction between the Earth surface and the atmosphere. The upwelling longwave radiation from the surface directly depends upon the surface skin temperature, and the difference between the skin temperature and the surface air temperature largely controls the energy exchanges at the land-surface boundary [e.g., *Betts*, 2009]. Contrary to the surface air temperature, LST measurements are typically not conducted at weather stations. It can be estimated from observations using an infrared radiometer if the surface emissivity is known, but these measurements are not part of the conventionally observed data. Some data records exist, but mainly from specific measurement campaigns (e.g., the Coordinated Enhanced Observing Period (CEOP) [*Koike*, 2004]).

[3] Under clear sky conditions LST can be globally measured from space by infrared radiometers, with spatial and time resolutions depending on the platform orbit (geostationary or polar) and the sensor design and revisiting time. The longest global data record available is provided by the International Satellite Cloud Climatology Project [*Rossow and Schiffer*, 1999], where polar and geostationary satellite infrared measurements are combined to derive a global LST product starting from 1983. Note that surface temperature retrievals were not a primary goal of the ISCCP analysis. Shortest data records from specific missions also exist. Examples are the LST products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and from the Atmospheric InfraRed Sounder (AIRS), both aboard the EOS-Aqua satellite since 2002.

[4] Satellite LSTs are validated through field campaigns at specific locations [e.g., *Wan*, 2008], or over larger regions and time periods through radiance-based validation studies [e.g., *Tsuang et al.*, 2008]. In most cases the reported LST accuracy at these specific sites is of the order of 1K, in coincidence with the estimated errors from pre-launch studies. Larger differences can be observed at test sites when the inversion algorithm uses the operational auxiliary data (in contrast to the test site data) [e.g., *Coll et al.*, 2011], or when the products from different sensors (using different algorithms and auxiliary data) are compared over large regions and time periods. This is especially true for the day-time comparisons, where the larger heating gradients can result in a viewing geometry dependence for complex terrains [e.g., *Pinheiro et al.*, 2006; *Trigo et al.*, 2008].

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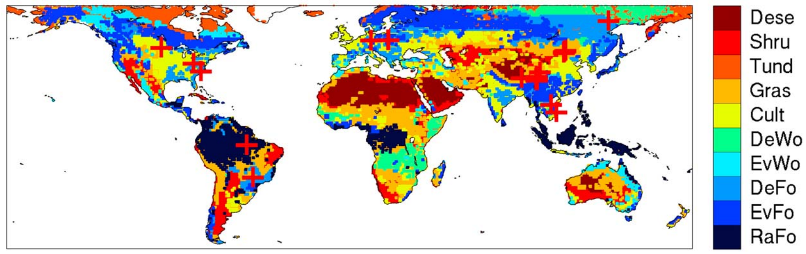

Figure 1. Location of biomes and CEOP stations. The biomes considered are: rain forest (RaFo), evergreen forest (EvFo), deciduous forest (DeFo), evergreen woodlands (EvWo), deciduous woodlands (DeWo), cultivation (Cult), grassland (Gras), tundra (Tund), shrublands (Shru), and deserts (Dese). Red crosses mark the location of the stations included in the analysis.

[5] Characterizing the origin of these differences is of importance. On the one hand, they can signal potential difficulties in the LST inversions (e.g., cloud contamination, emissivity mismatches, heating effects due to different observation and illumination angles). On the other hand, they can provide a better idea of uncertainty more applicable to typical data users (e.g., users evaluating global models with the satellite LST estimates [e.g., *Bodas-Salcedo et al.*, 2008], assimilating the estimates [e.g., *Bosilovich et al.*, 2007], or using the estimates as an input to parameterize other surface variables [e.g., *Jiménez et al.*, 2009]). With these objectives in mind, we present here a comparison of the ISCCP LSTs with the estimates from AIRS, MODIS, and some in situ observations from CEOP, followed by a more detailed analysis of the differences between ISCCP and AIRS. The LST estimates are described in section 2, the analysis of the LST differences is presented in section 3, and the discussion and conclusions are given in section 4.

2. Data

[6] The products compared are the January and July 2003 and 2004 clear sky estimates from ISCCP (DX product, with a resolution of ~30 km and 3 hours [*Rossow and Schiffer*, 1999]), the L3 product from MODIS/AQUA (collection 4, MYD11B1 product, with a resolution of ~5 km and 2 daily overpasses at ~1.30 am (night) and ~1.30 pm (day) local time [*Wan et al.*, 2002]), the L2 product from AIRS (version 5, AIRI2CCF/AIRX2RET products, with a resolution of ~45 km and same daily overpasses as MODIS [*Aumann et al.*, 2003]), and in situ measurements from CEOP (point measurements, with a measurement interval of 1/2 hour [*Koike*, 2004]).

[7] The algorithms used to derive the satellite products are of similar nature (based on radiative transfer calculations), but they differ in the source of ancillary and spectral information. ISCCP uses a single-channel algorithm (the ~11 μm channel from the available geostationary and NOAA-AVHRR polar sensors), with the onboard target channel calibration followed by a sensor inter-calibration to produce an homogeneous multisensor radiance data set [*Brest et al.*, 1997]. Both types of observations are archived, but a hierarchy of satellites is used in the gridded ISCCP products (geostationary data are preferred over polar orbiter data equatorward of 55°, and preference is given to the lower observing angles). The original ISCCP retrieval treats all surfaces as black bodies with unit emissivity. However, in this study the LSTs are corrected by a very simple scheme based on land cover type emissivities [*Zhang et al.*, 2004], here adapted to the biome classification from [*Matthews*, 1983] that will be used in the analysis of the LST differences (the unit emissivity value is reduced by ~0.02 for some of the biomes). The atmospheric contribution uses temperature and water vapor profiles from the TIROS Operational Vertical Sounder (TOVS) data set. MODIS uses an algorithm to retrieve simultaneously day and night LST and emissivity from 7 infrared bands, assuming a constant emissivity between day and night overpasses [*Wan and Li*, 1997]. A priori information about the atmospheric water vapor and temperature profiles is updated during the retrieval by using the other MODIS sounding channels. AIRS independently retrieves day and night LST and emissivities from a number of high spectral resolution infrared channels and 6 microwave channels (AMSU-A accompanying instrument) [*Susskind et al.*, 2003]. Temperature and water vapor profiles come at first from the microwave retrieval, with the water vapor profiles updated during the surface retrieval.

[8] For the AIRS-MODIS-ISCCP comparison (section 3.1), the global products are homogenized by first interpolating ISCCP values in time to the common AIRS and MODIS local time overpass, followed by interpolating the AIRS and MODIS values in space to the ISCCP equal area grid (~1/4° × 1/4° at the equator). Only clear-sky estimates, using the cloud flag from the product with the finest spatial resolution (MODIS), have been compared. For the comparison with the CEOP in-situ data, matches with the global products were identified based on a 1/2 hour time window and a ~25 × 25 km^2 box around the station location. The location of the stations considered is plotted in Figure 1, together with the biome classification used in the analysis of the LST differences. The AIRS-ISCCP comparison (sections 3.2 and 3.3) is carried out over two specific regions (Africa and America) by using the archived Meteosat-7, GOES-10 (Western sector), and GOES-8 (Jan-2003) and GOES-12 (Jul-2003 and 2004) (Eastern Sector), no interpolations are done, and only clear-sky pixels from AIRS and ISCCP with pixel centers within 10 km and time acquisitions within 15 min are compared. To compare the AIRS-ISCCP TOA-BTs, we reduce the AIRS high resolution spectra to match the Meteosat and GOES spectral

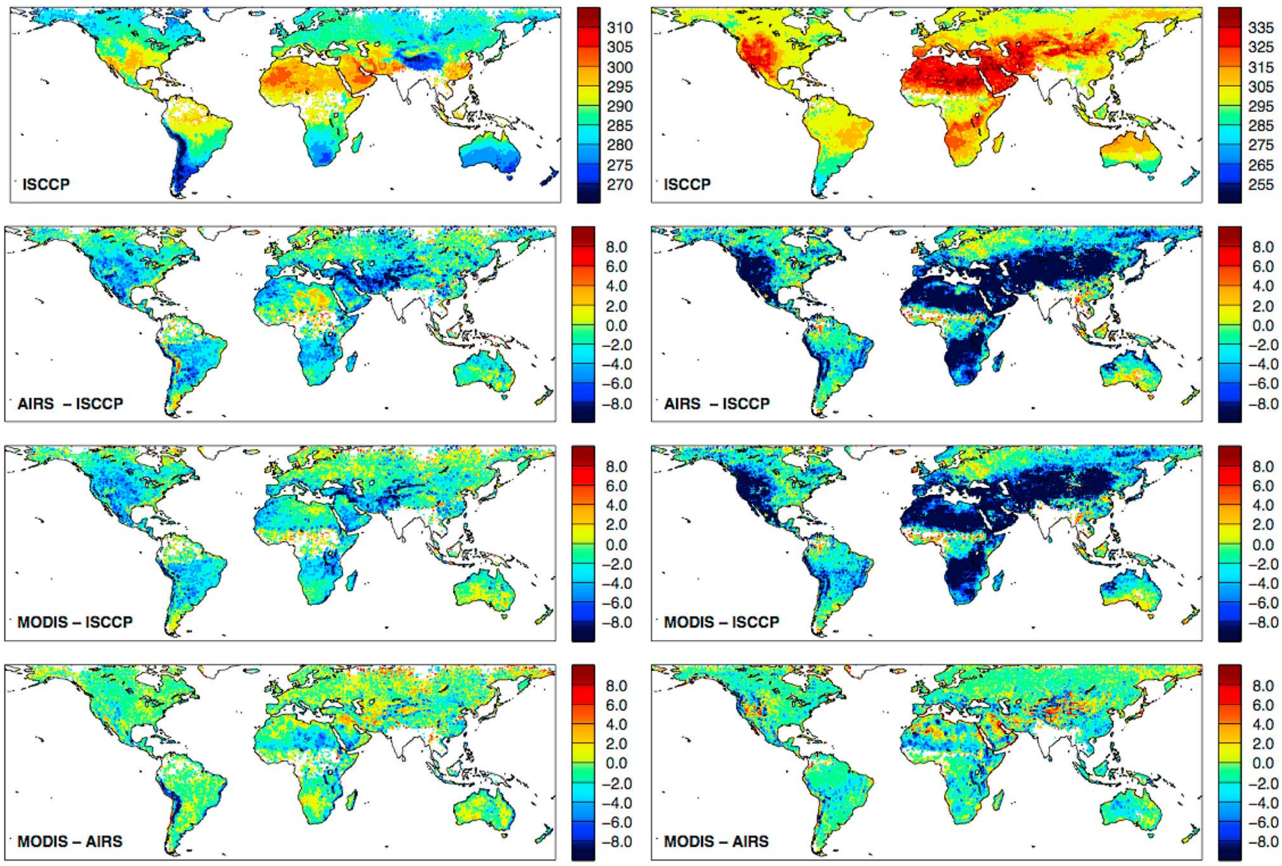

Figure 2. Example of July 2003 (left) nighttime and (right) day-time LSTs. From top to bottom: LST from ISCCP, LST differences between AIRS and ISCCP, MODIS and ISCCP, and MODIS and AIRS. The temperatures are given in K, note that the nighttime and day-time temperature scales are different.

responses by convolving the AIRS spectra with the Meteosat and GOES spectral response functions.

3. Analysis

3.1. Land Surface Temperatures

[9] An example of AIRS, ISCPP, and MODIS monthly LSTs and their differences is given in Figure 2 for July 2003. AIRS and MODIS LSTs are closer to each other than they are to ISCCP LSTs. Some relatively large differences between AIRS and MODIS can be seen in particular regions (e.g., over North Africa), but the differences are in general smaller than the differences of either of these two products to ISCPP. For most regions ISCCP has larger LSTs, especially at day-time for regions with large LSTs, although colder ISCCP LSTs can also be observed in some particular regions (e.g., parts of Central Africa and Southern Australia at day-time).

[10] Figure 3 (left) quantifies the 2003 LST differences for different biomes. AIRS and MODIS LSTs are relatively close, compared to ISCCP. The largest AIRS and MODIS difference is found for the regions classified as shrublands (∼1.5 K). The day-time differences between ISCCP and AIRS/MODIS can be much larger for some biomes (e.g., for the decidous woodlands, where the day-time LSTs differences are close to 10 K). In comparison, the nighttime differences are much smaller for those biomes with large day-time differences (e.g., ∼2 K for the deciduous woodlands). The global nighttime and day-time differences between ISCCP and AIRS/MODIS are of the order of 2 K and 4 K, respectively, with ISCCP biome-averaged LSTs always warmer than AIRS/MODIS. These differences agree well with the figures reported by *Moncet et al.* [2011] for an ISCCP and MODIS comparison.

[11] Figure 3 (right) shows the differences of AIRS/MODIS/ISCCP LSTs with the in situ 2003 CEOP measurements. The stations are grouped by biome type. Note the very small number of observations (compared with the number of matches for the global statistics), and the difficulties of comparing a point measurement with the much larger satellite footprint. In general terms, the in situ comparison agrees with the main findings of the previous global comparison: ISCCP LSTs are warmer than AIRS/MODIS, AIRS and MODIS LSTs are closer (compared with ISCCP) for most biomes, and nighttime LSTs differences are smaller than during the day. The largest differences with CEOP occur for the grassland stations, which also exhibit a large difference between the day-time ISCCP LST and AIRS/MODIS. Averaged over all stations, the nighttime LST differences between AIRS, MODIS and ISCCP are smaller than the individual differences of each satellite product with CEOP (of the order of 1 K, with the satellites LSTs being colder). The satellite day-time differences with CEOP are larger and of opposite sign, with the ISCCP and CEOP

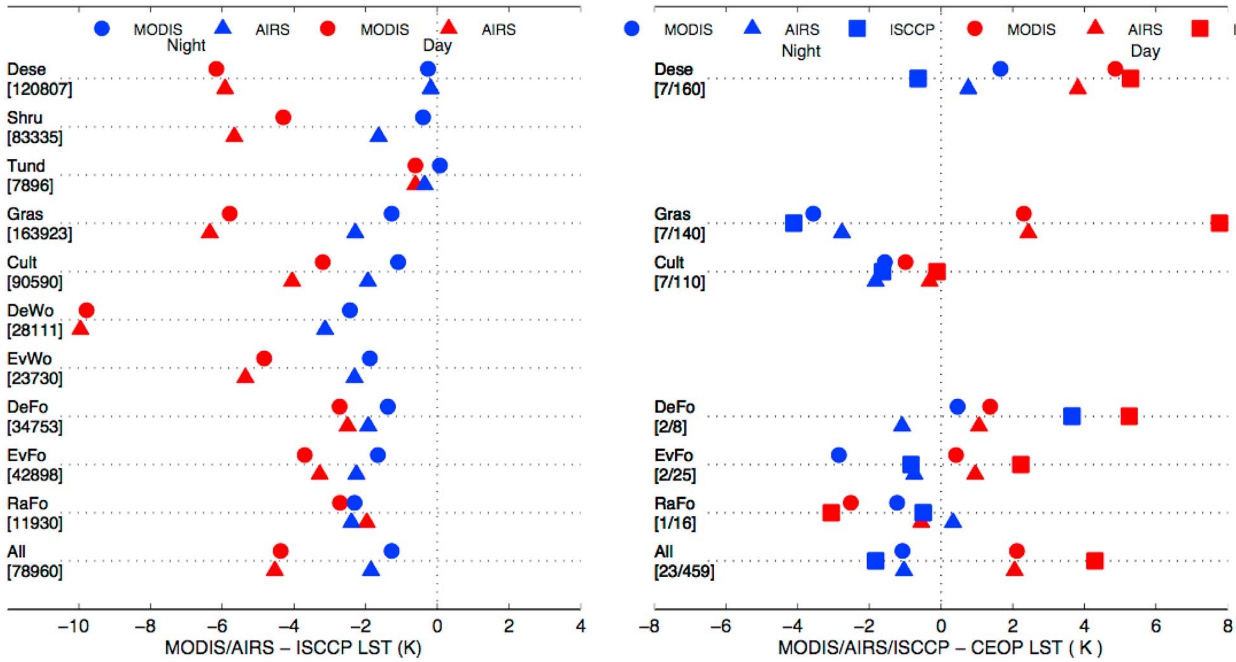

Figure 3. 2003 biome-averaged nighttime (blue) and day-time (red) LST differences between MODIS (circles), AIRS (triangles), and ISCCP (squares). (left) MODIS and AIRS LST differences with ISCCP. (right) MODIS, AIRS and ISCCP LST differences with CEOP (stations classified by biome). The numbers give the number of pixels (left) and stations/pixels (right) included in each biome average.

differences larger (∼4 K), compared with AIRS/MODIS and CEOP differences (∼2 K). The positive (day) and negative (night) satellite and CEOP differences suggest a smaller amplitude of the in situ LST diurnal cycle, but the small number of coincidences precludes any further analysis.

3.2. Top-of-Atmosphere Brightness Temperatures

[12] The ISCCP and AIRS/MODIS differences are too large to be explained only by space and time coincidence issues. To further characterize the differences the ISCCP and AIRS top-of-atmosphere brightness temperatures (TOA-BTs) are discussed here. Figure 4 (left) shows biome-averaged AIRS and ISCCP TOA-BTs for 2003 and 2004. For the individual biomes, nighttime AIRS and ISCCP TOA-BTs are in general closer than during the day. During the day-time, the TOA-BTs are in most cases closer over the GOES region than over the Meteosat region. For most biomes both products show larger day-time TOA-BTs in 2003 than in 2004, with larger year to year differences for the Meteosat region, and for the ISCCP temperatures. Figure 4 (right) shows that, in general, similar patterns to the TOA-BTs can be seen for the LSTs. The day-time 2003 to 2004 LSTs differences are larger for the Meteosat region and the ISCCP, specially for the drier biomes that are associated to larger temperatures. For instance, there is a ∼10 K 2003 to 2004 LST difference over grasslands for ISCCP at the Meteosat region, compared with ∼5 K for AIRS. These differences are approximately double of the respective ISCCP and AIRS 2003 to 2004 TOA-BT differences for the same biome and region.

[13] The mean temperatures reported in Figures 3 and 4 suggest a scaling of the TOA-BTs and LSTs differences with the absolute value of the temperatures. This is explored further in Figure 5, where the temperature differences over the Meteosat region are plotted separately for 2003 and 2004. For both years, there is an increase of the TOA-BT differences when the TOA-BTs start to be larger than ∼290 K. Warmer temperatures can be observed again for 2003, as seen in Figure 3. The differences with the ISCCP TOA-BTs with the sensor inter-calibration removed are also plotted. The agreement with the AIRS TOA-BTs seems closer now, but the short period analyzed cannot be used to draw any conclusions about the ISCCP sensor inter-calibration. For the LSTs a similar behavior can be observed: larger LST differences for the largest temperature, but this time with larger slopes than for the TOA-BTs. The discontinuity in the individual LST differences observed at the end of the temperature range is related to the coding of the ISCCP temperature values, where LSTs > 345 K are stored at a fixed value of 345 K. The larger variability (larger standard deviations for each temperature bin) observed in the LST differences, compared with the TOA-BT, likely reflects differences in the characterizations of the atmosphere and the surface. A similar analysis for the GOES region (figure not displayed) shows similar difference patterns, but restricted to the smaller temperature range associated to the biome types existing in this region.

3.3. Atmospheric/Surface Characterization

[14] Figure 6 (top) shows the difference (calculated over both years) between AIRS and ISCCP nighttime LSTs as a function of the difference of the AIRS and ISCCP emissivities, the water vapor column, and the surface air temperature. Different viewing and illumination angles can also be responsible for the observed LST differences, but a clear relationship (not plotted) is not apparent here. The clearest

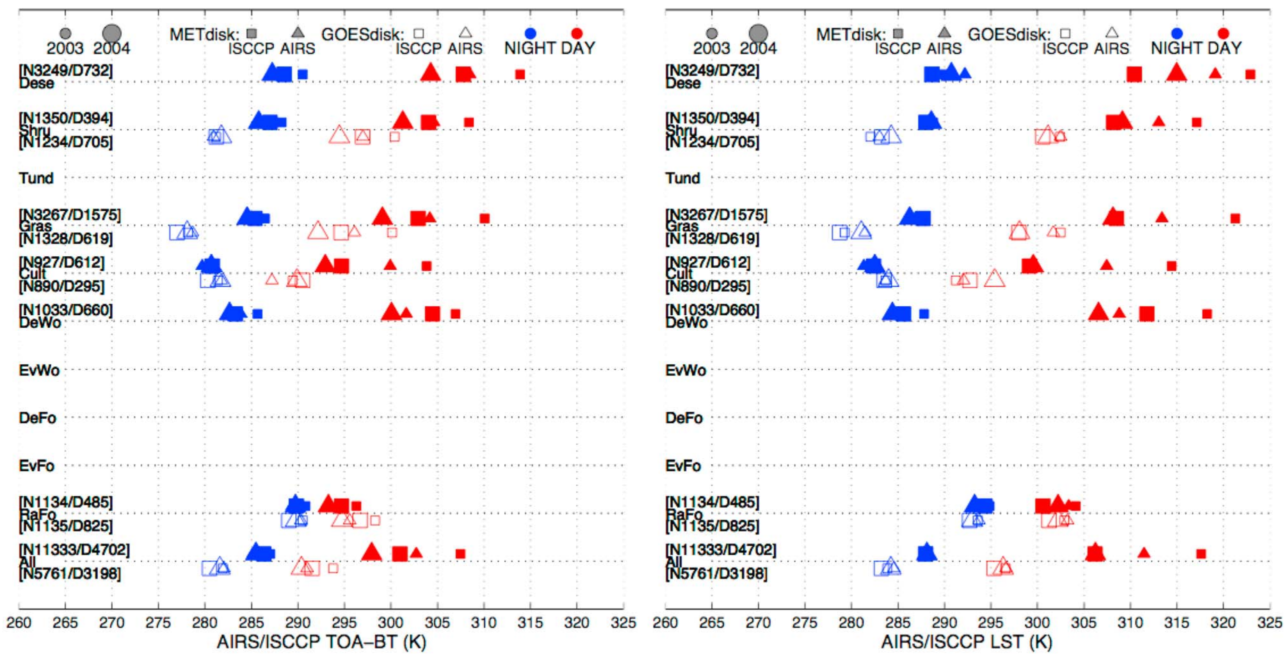

Figure 4. Biome-averaged nighttime (blue) and day-time (red) temperatures for AIRS (triangles) and ISCCP (squares). (left) TOA-BTs for 2003 (small symbols) and 2004 (large), with the AIRS and ISCCP averages presented separately for the Meteosat disk (closed symbols) and GOES (open symbols). (right) Similar but for LSTs. The numbers give the number of biome pixels averaged for nighttime (N) and day-time (D).

dependence is observed for emissivities: because the emissivity differences are so small, the LST differences are approximately proportional to the emissivity differences. The water vapor dependence shows the expected relationship (i.e., a more humid atmosphere will transmit less and should result in a larger retrieved LST for a same observed radiance), with a more defined relationship for the Meteosat region (compared with the GOES region). The dependence with the surface air temperature is less clear, with different behavior for the Meteosat and GOES regions. *Vogel et al.* [2011] analyzed radiative transfer simulations for the SEVIRI 12 um channel, where random perturbations of 2K (air temperature), 10% (water vapor), and 0.02 (emissivity) resulted in root mean square errors of approximately 0.7, 04, and 0.3 K in the TOA-BTs, respectively. Figure 6 shows larger sensitivities of the retrieved LSTs to the same parameters. This is expected as the retrieved LST is not only affected by uncertainty in the inputs to the radiative transfer calculations, but also by other inversion errors that can potentially amplify the sensitivity of the retrieved LST to these parameters.

[15] A summary plot showing the correlation of the ISCCP and AIRS LST differences with the other related differences is given in Figure 6 (bottom). The highest correlation happens for the TOA-BT differences (~0.5 (0.7) for the Meteosat (GOES) region). Smaller correlations are found for the emissivity and the water vapor, and even smaller for the air temperature at the surface and the viewing angle. In general the correlations are different for the nighttime and day-time, and for the Meteosat and GOES regions, which may reflect specific particularities of the periods/regions analyzed. For instance, the correlation with the emissivities is higher for the Meteosat region, which may be related to the more variable emissivities and largest LSTs over the deserts (a fixed emissivity is assumed in the ISCCP corrected LST over the deserts).

4. Discussion and Conclusions

[16] The ISCCP nighttime land surface temperature (LST) shows reasonable agreement with the other products. ISCCP has generally slightly warmer nighttime LSTs compared with AIRS and MODIS (global) and CEOP (at specific sites). The global differences are <2 K, comparable to other reported biases between sensors (e.g., MODIS and SEVIRI biases from *Trigo et al.* [2008]), although lager differences can be observed for specific regions (e.g., in Figure 2 for North Eastern Africa and high latitudes). ISCCP and AIRS discrepancies in the characterization of surface emissivities and the atmospheric temperature and humidity resulted in the expected LST differences, suggesting that part of the LST differences can be attributed to these sources. Larger differences were found in the day-time LSTs, especially for those biomes where large LST values occur. There the biome-averaged day-time difference can be larger than 5K. Subsequent investigation revealed a subtle error in the ISCCP retrieval code when calculating the temperature dependence of the water vapor infrared absorption/emission in the lowest atmospheric layer that acts to increase the retrieved LST slightly as a function of the difference between near-surface air and skin temperature; the increase is larger at larger temperatures. This error can account for some part of the generally warmer bias of ISCCP LST values, for the fact that this warm bias is smaller at night,

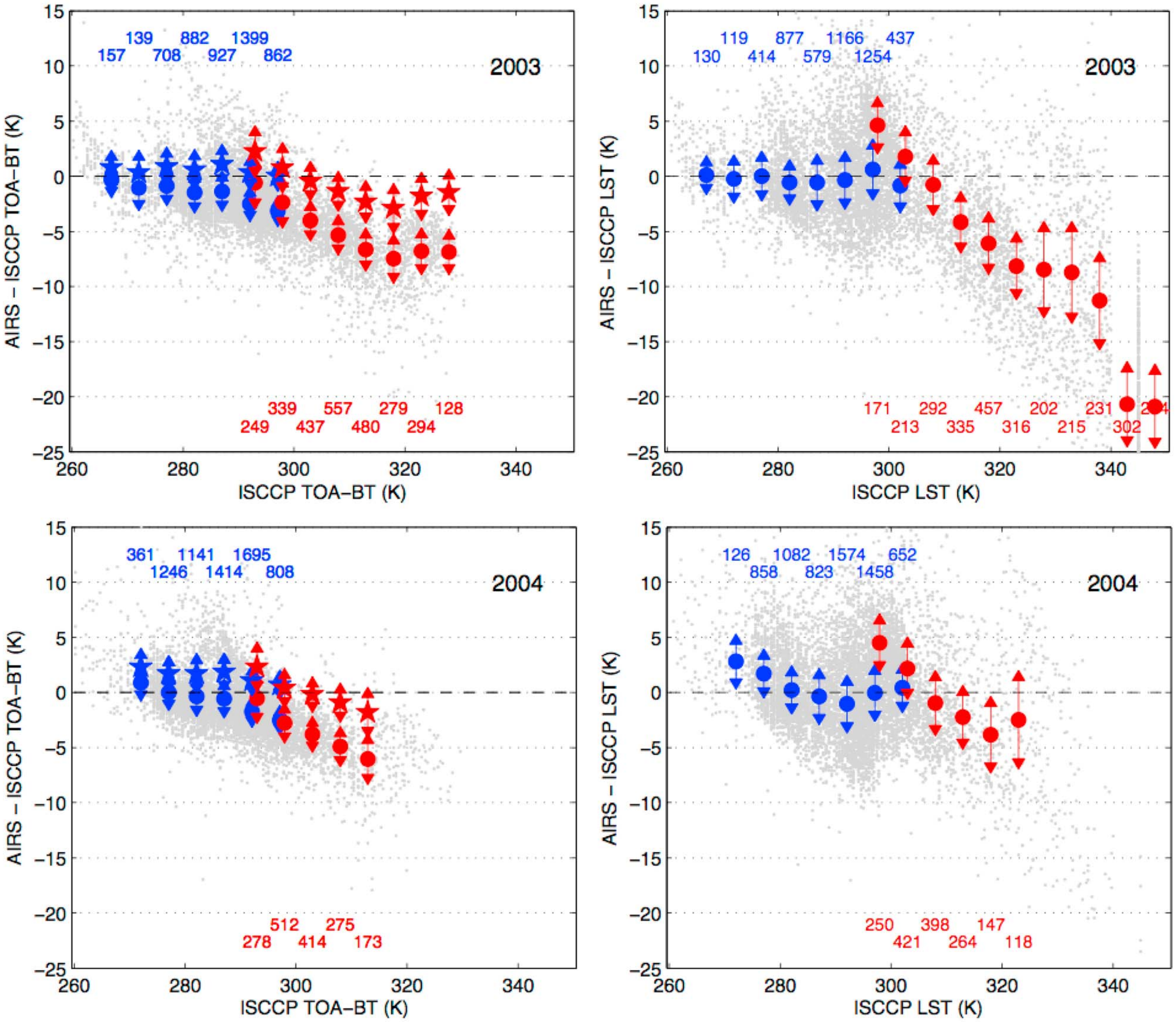

Figure 5. The 2003 and 2004 nighttime (blue) and day-time (red) differences between AIRS and ISCCP over the Meteosat region. (left) TOA-BTs, circles for the differences with the ISCCP inter-calibrated radiances used to derive the LSTs, stars for the differences with the ISCCP inter-calibration removed. (right) LSTs. The symbols give the mean value for a given LST bin; the arrow one standard deviation centered around the mean; the grey dots the individual pixel differences. The numbers give the number of pixels averaged per temperature bin (only bins with more than 100 pixels are displayed).

when the skin-air temperature difference is small, than during the day, when the skin-air temperature difference is much larger, and for the fact that the warm bias generally increases with larger LST. Further global analyses have shown that the magnitude of this effect is mainly notable for LST larger than 320 K, and that this problem can explain much of the extreme differences found over the desert regions.

[17] Inspection of the AIRS and ISCCP brightness temperatures at the top of the atmosphere (TOA-BT) revealed that where the LSTs differ so too do the TOA-BT values. LST and TOA-BT differences correlated well, more for GOES than Meteosat. The nighttime TOA-BT differences are higher than the reported values between AIRS and MODIS of *Tobin et al.* [2006] (global mean differences for the MODIS window channels within 0.1 K), but it should be noted that AIRS and MODIS were mounted on the same platform and measuring at the same view angles, assuring nearly perfect collocations, which is not the case for the AIRS and ISCCP comparison here. The TOA-BT differences were notably larger for the biomes with the larger LSTs differences, where averaged TOA-BT values for temperature bins above 320 K differ by as much as 5K. This suggests possible discrepancies in the sensor calibrations for this very large temperatures, where the observed brightness temperatures are outside the range defined by the onboard calibration targets for most radiometers. TOA-BT discrepancies can also be related to the ISCCP sensor inter-calibration procedure. ISCCP attempts to normalize all radiometers to the same standard by comparing coincident

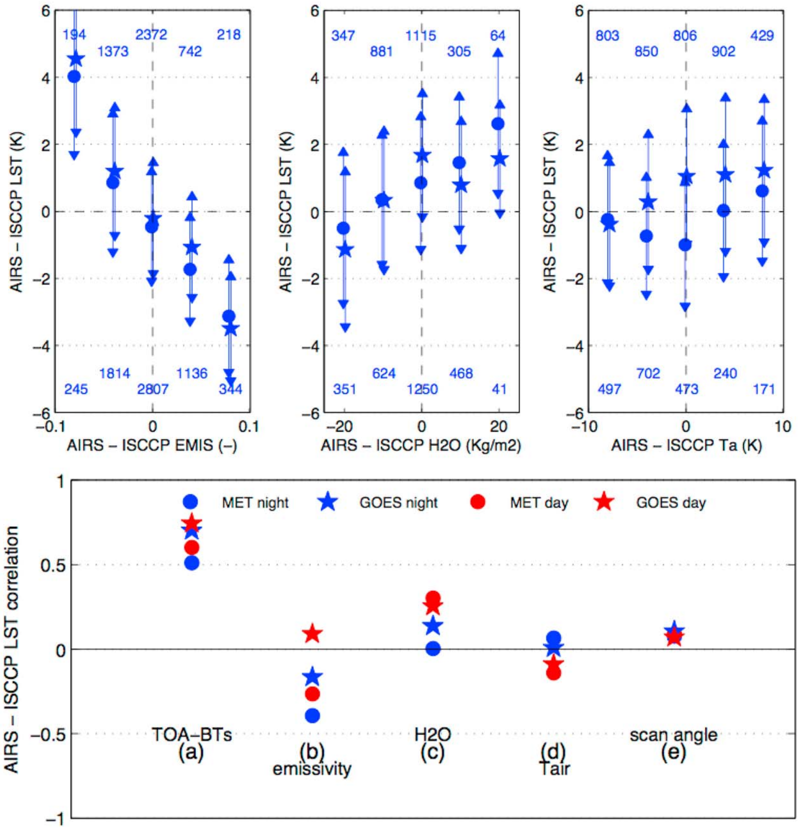

Figure 6. Characterization of the AIRS and ISCCP nighttime (blue) and day-time (red) LST differences over the Meteosat (circles) and GOES (stars) disks. (top) AIRS and ISCCP nighttime LST differences as a function of the difference of the AIRS and ISCCP emissivities (left), water vapor column (middle), and the surface air temperature (right). Numbers, circles, and arrows as in Figure 5, with top numbers for Meteosat, bottom numbers for GOES. (bottom) Correlation between AIRS and ISCCP LST differenceand the differences in the AIRS and ISCCP TOA-BTs (correlation a), emissivities (correlation b), water vapor columns (correlation c), surface air temperatures (correlation d), and the AIRS scan angle (correlation e).

and simultaneous measurements from the geostationary satellites to the concurrent "afternoon" polar orbiter. Because of differences in the radiometer spectral responses, this can introduce small residual differences between the inter-calibrated brightness temperature measurements. As water vapor abundance tends to be correlated with LST, the residual effects of spectral response differences would increase for larger TOA-BT and LST. We have found that the largest spectral response difference happens to be between GOES radiometers and the first generation Meteosat radiometers, but under the most extreme conditions, they do not seem to result in LST differences larger than 1K. In general, care has to be taken in drawing conclusions, especially for the regions with large LSTs, as the day-time AIRS overpass near the LST peak time and the large LST gradients at that time of the day can clearly amplify the impact of the time and spatial mismatches.

[18] Although specific for the three LST products compared, this study illustrates the general importance of intersensor evaluations to complement the description of product uncertainty provided by the pre-launch site-specific ground validations. The results suggest that, to achieve the desired accuracy of LSTs of 1–2 K, this requires a better understanding of the differences already found in the TOA-BT, and an improved characterization of the atmosphere and surface properties that affect the retrieval of LST. ISCCP is currently undergoing a complete re-processing, where calibration procedures are being revised to account better for spectral response difference and alternative data sets to characterize the atmosphere and surface are being tested. This will allow for improved understanding of the discrepancies with other products and should result in an improved ISCCP LST record.

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