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LAND SURFACE TEMPERATURE RETRIEVALS FROM GOES-8 USING EMISSIVITIES RETRIEVED FROM MODIS

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1. INTRODUCTION

NASA and NOAA are combining their efforts to fully utilize current satellite resources to meet the climate research needs of NASA's Earth Science Enterprise and NOAA's operational needs to improve weather forecasting. One area of emphasis is on the evaluation of EOS instruments and algorithms to provide appropriate research data products for NOAA's operational use. A particular EOS instrument that has the ability to provide complementary data products for the NOAA GOES series of satellite instruments is MODIS. The MODIS instruments on NASA's Aqua and Terra satellites have spectral channels in the longwave infrared window region that are similar to those found on the instruments of the GOES satellites with resolutions similar to those planned for the Advanced Baseline Imager of the GOES-R series of satellites. One of the physical parameters produced by the EOS MODIS land surface team that can have a positive impact on the current GOES operationally derived products is surface emissivity.

Knowledge of surface emissivity in the GOES Imager and Sounder infrared channels that receive energy from the earth's surface is necessary for accurate profile retrieval of atmospheric temperature and moisture (Plokhenko and Menzel 2000). Land surface temperature (LST) and total precipitable water (TPW) retrievals are especially sensitive to emissivity assumptions because they rely almost exclusively on these window channel measurements. In order to retrieve these atmospheric and surface geophysical parameters, *a priori* estimates of surface emissivity must be available for forward radiative transfer calculations. Most approaches assume that the surface is a gray-body and use a constant emissivity (spatially and for all channels) in their calculations (Hayden 1988). This approach is based on our lack of understanding of the spatial and spectral variation of surface emissivity for natural surfaces. As part of NASA's EOS activity, the emissivity of the surface in several infrared channels is derived from MODIS data from the Terra and Aqua platforms. These emissivity values have the potential to provide better *a priori* estimates than currently used because they provide spatial and spectral variations not otherwise available. The use of improved estimates of surface emissivity in the GOES retrieval process will have a significant impact on the quality of GOES products used for data assimilation and short-term prediction.

In an attempt to improve the emissivity assumptions used in the GOES Sounder LST retrieval procedure, the incorporation of MODIS high spatial resolution (1 and 5 km) emissivity measurements into the LST procedure is being explored. This paper intercompares the LST retrievals from the GOES-8 Sounder using a constant emissivity assumption with those using MODIS retrieved emissivities. The effects of MODIS emissivities on the LST retrievals are discussed.

2. MODIS EMISSIVITIES AND LST

MODIS land surface temperature products, including emissivity, are produced from two different procedures and are available at different resolutions and projections (Wan 1999). One procedure utilizes a generalized split-window LST algorithm (Wan and Dozier 1996) to produce LST at 1 km resolution. The algorithm utilizes the longwave window channels 31 (10.8–11.3 µm) and 32 (11.8-12.3 µm). The associated emissivities in these channels are also made available. These emissivities are obtained by inferring their values from a classification-based look up table (Snyder et al., 1998) according to pixel land cover types determined from MODIS products of land and snow cover. The inferred emissivities in this spectral region are seen to be fairly constant and near unity (for example channel 32, 0.97-0.99) for all natural land types except rocks and sand (Snyder and Wan, 1998). Emissivities from this method are less certain in semi-arid and arid regions. Emissivities produced by this method are available as a level-2 (L2) 1 km resolution dataset in the

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native swath projection and as higher level datasets. The analysis in this paper uses only the L2 product emissivities from this method.

A second procedure is also employed to retrieve LST as well as emissivities in seven channels. The procedure uses a day/night LST algorithm (Wan and Li, 1997) that uses four channels (29, 31-33) in the 8-13.5 μm spectral range and three channels (20, 22, 23) in the 3.5-4.2 μm spectral range. Measurements are required for both day and night at the same location from the seven channels. The retrieved emissivities are considered more accurate for regions where emissivities vary widely such as arid and semi-arid regions. These data are made available as a level-3 (L3) daily composite product at 5 km resolution in the integerized sinusoidal projection.

Figure 1 shows the spectral positions of the MODIS longwave channels for which emissivities are retrieved. Also shown are the relative positions of the GOES Imager and Sounder channels. The GOES Sounder channels that could benefit from MODIS channel emissivities are channels 8, 7, and 5. For the GOES Imager, the channel correlation with MODIS is not as good as that of the Sounder. However, the emissivities of channels 31 and 32 of MODIS may provide benefits to the Imager 4 and 5 channels respectively. The analysis in this paper explores the use of the MODIS emissivities for channels 31 and 32 and their application to Sounder channels 8 and 7 respectively.

2.1 MODIS Emissivity

An example of the two different MODIS emissivity products for channels 31 and 32 is seen in Fig. 2. These emissivities are for 8 August 02 and were used in the retrieval analysis that is described in the next section. The top panel shows the L2 emissivities inferred from MODIS land cover and vegetation index information. The bottom panel shows the L3 retrieved emissivities for the same channels. A striking difference is seen in the emissivities associated with the two methods. The inferred emissivities are seen to have very little spatial variability, with the channel 32 emissivities being slightly higher than those for channel 31. The 1-km resolution however does allow for the discernment of urban areas such as Atlanta and Nashville seen most prominently in the channel 31 image. The channel 32 image shows nicely the emissivity differences between the land and the rivers and lakes. Unlike the inferred emissivities, the retrieved emissivities show more variability and are in general lower than the inferred emissivities. However, urban areas and water features such as rivers and lakes are not as evident in the retrieved emissivities partly due to the resolution (5 km) of this product. It has also been observed (not shown) that the retrieved emissivities show a greater seasonal variation than the L2 inferred emissivities. Often seen in the L3 retrieved emissivities are triangular discontinuities similar to the feature seen over Arkansas. This feature appears to be an artifact of the compositing of the swath data into the L3 daily product. Also, differences in the cloud masks between the two emissivity products are frequently observed.

A quantitative comparison between the emissivity products can be made by calculating the area average emissivity and standard deviation of the clear-sky intersection of the emissivity products in Fig. 2. These values are presented in Table 1. The inferred emissivities are seen to have values of near 0.99 with very little difference between the channels. The standard deviation for the inferred emissivities is 0.2% and 0.3% for channels 31 and 32 respectively. The area average of the L3 retrieved emissivities (bottom panel Fig. 2) are 0.928 and 0.916 with standard deviations of 2.9% and 3.4% for channels 31 and 32 respectively. The statistics confirm what is seen in the images concerning absolute values and spatial variability, but other useful information can also be gleaned. The average emissivity difference between channels 31 and 32 for the retrieved L3 product is 0.012 compared to 0.001 for the inferred emissivities. The retrieved emissivities not only show a larger channel difference, but also indicate that the average emissivity for channel 31 is higher than that for channel 32. This is in contrast with the L2 inferred channel emissivities, and is an observation that will be explored in the GOES-8 Sounder retrieval analysis in the section below.

2.2 MODIS LST

The MODIS LST values for 8 August 02 at 1635 UTC from the two retrieval methods discussed above and associated with the above emissivities are shown in the top panel of Fig. 3. The top left panel shows the L2 MODIS LST from the generalized split window algorithm that used the inferred emissivities (Fig. 2 top panels). The top right panel of Fig. 3 shows the L3 LST from the MODIS day/night algorithm that also retrieved the emissivities in Fig. 2 bottom panels. Little difference is seen between the two MODIS LST products except for spatial resolution and cloud coverage. Area average statistics for the LST over the common clear-sky regions of both products (including GOES clear-sky regions shown in Fig. 3 described later) are provided in Table 2. The L3 LST is seen to be warmer than the L2 LST by 0.5 K and has a slightly higher standard deviation. It is interesting to note the close agreement between the two LST products and the apparent disagreement between the associated emissivity products. This may imply that LST, in general, is not very sensitive to the ranges in emissivity

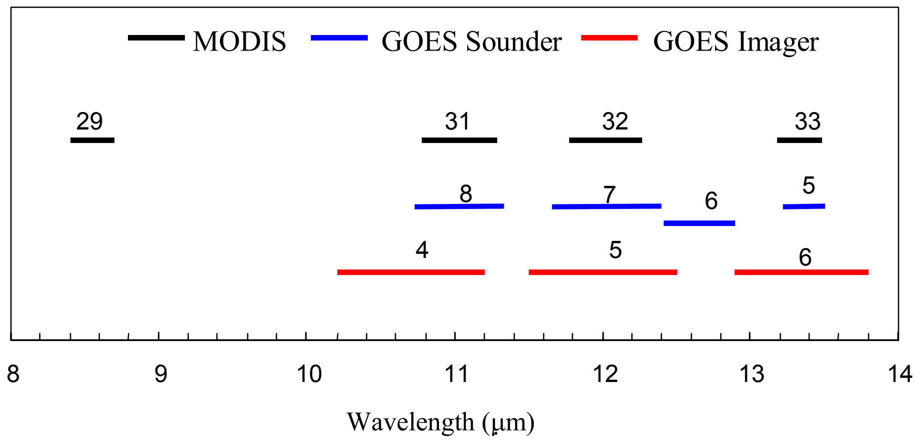

Fig. 1. Relative spectral positions and widths of the longwave MODIS channels for which emissivity is retrieved. Also shown are nearest corresponding channels for GOES Imager and Sounder.

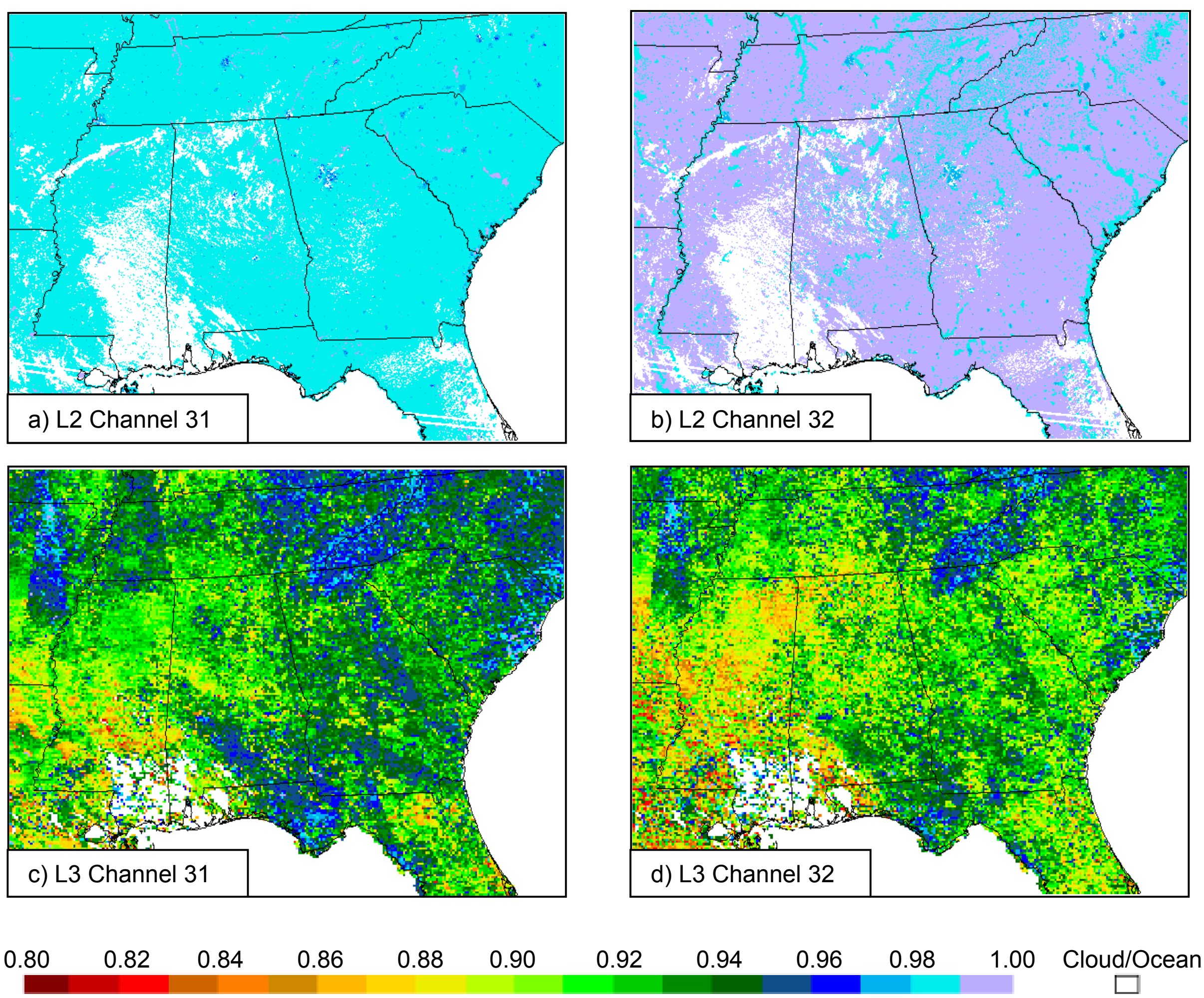

Fig. 2. MODIS channel 31 and 32 inferred emissivities (level 2 data) used in MODIS split window algorithm that are determined according to land cover type (top panel a & b), and MODIS retrieved emissivities (level 3 data) from the day/night algorithm (bottom panel c & d).

depicted in Fig. 2 and Table 1. To test this implication and to determine whether MODIS derived emissivities can add significant additional information in the retrieval of LST using GOES instruments, an analysis was performed incorporating MODIS emissivities in a GOES-8 Sounder LST retrieval process. The results of this analysis are presented next.

3. GOES-8 SOUNDER LST RETRIEVALS

GOES-8 Sounder LST retrievals were performed for four cases, each having a different emissivity assumption. Case 1 used the MODIS L2 inferred emissivities, case 2 used the MODIS L3 retrieved emissivities, case 3 used a spatially constant emissivity of 0.98 in each channel, and case 4 used a spatially constant emissivity with values having similar spectral characteristics as the MODIS retrieved L3 emissivities. The LST algorithm used for the retrievals is a physical split window technique that uses the longwave window channels of the GOES Imager or Sounder (Jedlovec 1987; Suggs et al. 1998). The technique is an approach based on a perturbation formulation of the radiative transfer equation similar to that described by Hayden et al. (1996). The technique requires first-guess profiles of temperature and moisture from which transmittance is calculated. The first-guess profiles are provided by model forecasts, and the model surface air temperature is used for the first-guess LST. The algorithm requires an emissivity input; for the GOES longwave channels, a value of 0.98 is usually applied. For all the retrieval cases, Sounder retrievals are made at single pixel resolution over the southeast U. S. region at 1545 and 1645 UTC, which bounds the 1635 UTC MODIS LST retrievals discussed above. A first-guess field is provided by PSU/NCAR MM5 model forecasts from the 0000 UTC cycle, which are generated on an operational basis at the Global Hydrology and Climate Center. A GOES Sounder derived cloud mask was also applied in the retrieval process. In regions where no MODIS emissivity is available, no retrievals were performed.

In cases 1 and 2, MODIS pixel resolution emissivities at the GOES Sounder retrieval location were averaged so as to be consistent with the Sounder pixel size (~10 km). In this manner the spatial variability of the MODIS emissivities was taken into account in the GOES retrieval process. GOES Sounder 1645 UTC LST retrievals for cases 1 and 2 are shown in the middle panel of Fig. 3. Significant differences are seen between the two cases. GOES LST values using the L2 MODIS emissivities (left) are seen to be generally cooler than case 2 LST values that used MODIS L3 retrieved emissivities. Case 2 LST values are also seen to have more variation and a considerable number of failed retrievals. A failed retrieval implies a quality check failure due to conditions such as LST values out of bounds, LST not converging, first guess and observed brightness temperature difference threshold failure, and matrix condition flags. Area averaged statistics for cases 1 and 2 are given in Table 3 for common clear-sky regions (including MODIS LST clear-sky regions shown in Fig. 3 top panel). The Case 1 LST average is approximately 2.5 degrees cooler than that of case 2, with a standard deviation difference of approximately a factor of 2.0 and 2.5 for 1645 and 1545 UTC respectively. These values are in contrast with the LST difference seen between the MODIS L2 and L3 products. The GOES retrievals appear to be much more sensitive to the emissivity differences seen between the MODIS L2 inferred and L3 retrieved emissivities.

For case 3, GOES retrievals used an emissivity assumption of 0.98, which is commonly used when *a priori* information is not available. In this case the emissivity is held constant spatially and the same for each channel. LST values for this case are shown in the bottom left panel of Fig. 3. The area average statistics are also given in Table 3. The average LST and standard deviation for this case are almost identical to the case 1 values, as might be expected. The fine scale features in the MODIS L2 emissivity (case 1) essentially have no impact on the standard deviation as compared to the case 3 standard deviation. This is most likely due to the 10 km resolution of the Sounder retrievals.

Case 4 GOES retrievals used emissivities of 0.980 and 0.968 for GOES-8 Sounder channels 8 and 7 respectively. These values were obtained by assuming a magnitude for the channel 8 emissivity near that of the MODIS L2 channel 31 emissivity and applying a channel difference consistent with the mean MODIS L3 emissivity. Thus, the mean MODIS L3 emissivity

Table 1. Area averaged mean MODIS emissivities and standard deviation (SD) for the regions in Fig. 2.

Channel	Level 2		Level 3	
	Mean	SD	Mean	SD
31	0.986	0.002	0.928	0.027
32	0.987	0.003	0.916	0.031

Table 2. Area averaged mean MODIS LST and standard deviation (SD) for the regions in Fig. 3 (top panel).

Time	Level 2		Level 3	
	Mean (K)	SD (K)	Mean (K)	SD (K)
1635	304.4	2.8	304.9	3.1

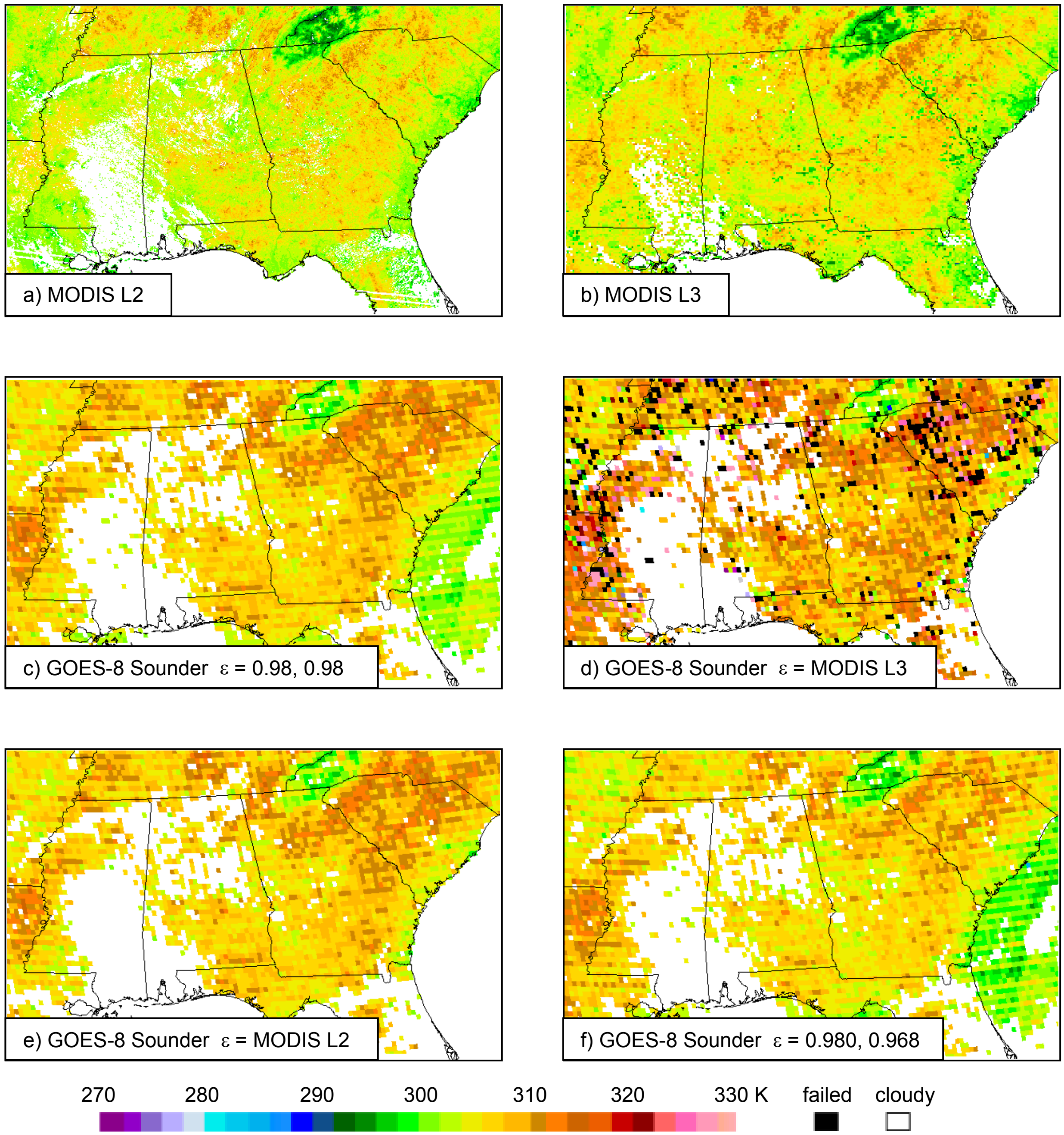

Fig. 3. MODIS LST (a) level 2 data from the split window algorithm, and (b) level 3 data from the day/night algorithm. GOES Sounder LST using (c) MODIS level 2 inferred emissivities and (d) using MODIS level 3 retrieved emissivities. GOES Sounder LST (e) using a spatially and spectrally constant emissivity of 0.98, and (f) using spatially constant emissivities of 0.980 and 0.968 for channels 8 and 7 respectively.

Table 3. GOES-8 Sounder area averaged mean LST and standard deviation (SD) for four different emissivity assumptions.

Time	ε = MODIS L2		ε = MODIS L3		ε = 0.98		ε = 0.980 0.968	
	Mean (K)	SD (K)	Mean (K)	SD (K)	Mean (K)	SD (K)	Mean (K)	SD (K)
1545	305.1	2.5	307.5	6.2	305.2	2.5	304.5	2.7
1645	307.1	2.9	309.9	5.9	307.3	2.9	306.3	3.0

difference of 0.012 (Table 1) was applied, making the GOES Sounder channel 7 value equal to 0.968. Case 4 retrievals are shown in Fig. 3 bottom right panel and the area average statistics are given in Table 3. Overall, the mean LST for this case is seen to be cooler than the other three cases. The spatial variability, as seen in Fig. 3, is seen to agree with cases 1 and 3, and the LST for this case compares more favorably with the MODIS L3 LST (top right) than the other cases. This case illustrates the sensitivity of the LST retrieval to changes in spectral differences in emissivity. It is interesting that when both Sounder channel emissivities are lowered, as in case 2 with respect to case 3, the retrieved LST increases. However, when only one channel emissivity is lowered (case 4) the average LST is decreased with respect to case 3.

A comparison plot of the area averaged LST for the four cases together with the MODIS LST is given in Fig. 4. It is seen that by interpolating between the 1545 and 1645 UTC GOES LST, a comparison can be made with the MODIS LST values. It should be noted that the GOES values were plotted using the start time of the GOES soundings for CONUS. The actual time corresponding to the southeast soundings is on the order of 10 minutes later. In Fig. 4 the GOES LST retrievals show a significant sensitivity to emissivity changes consistent with the difference between the MODIS L2 and L3 emissivities (an approximate 5% emissivity variation). This is in contrast with the MODIS L2 and L3 LST difference. Also seen is that the GOES retrievals using the MODIS L3 retrieved emissivities produce LST values that depart the most from the MODIS LST. However, by using the MODIS L3 emissivity channel difference information along with the L2 absolute values (ε = 0.98, 0.968), a closer agreement with MODIS LST is obtained. It is possible that the resulting differences seen between the GOES and MODIS LST, which range between approximately 1–4.5 K depending on the emissivity assumption used in the GOES retrieval, may be attributed to resolution differences and biases in the GOES retrieval algorithm. It is apparent however that surface emissivity is an important parameter in the LST retrieval process, and an improved knowledge of its magnitude and spectral and spatial variation is needed.

4. SUMMARY

Knowledge of the surface emissivity in the past has relied mostly upon inferences from laboratory measurements coupled with observed land and vegetation characterizations of the surface. This type of emissivity information is provided in the MODIS L2 product. However, retrieved emissivities such as provided by the MODIS L3 product have the potential of providing additional information regarding seasonal and spatial variability and the spectral variation between sensor channels. The analysis above demonstrates the sensitivity of the GOES Sounder LST retrieval to the surface emissivity. The sensitivity is significant (1–4.5 K) for emissivity differences seen between the MODIS products. Although the magnitude of the MODIS L3 emissivity product is of concern and will need to be studied further, the spectral variation of the emissivity characterized by this product, which is in contrast with the MODIS L2 product, may in itself be useful information that may improve LST retrievals from the GOES Sounder.

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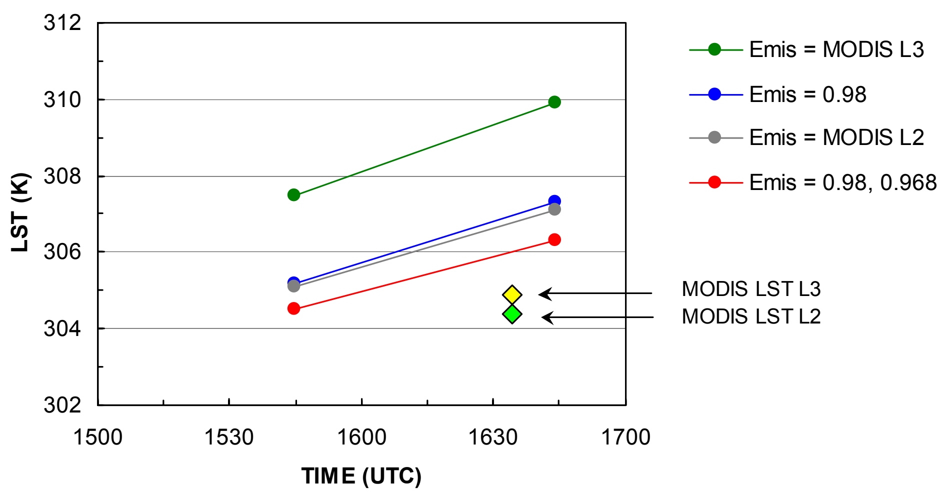

Fig. 4. Comparison of area averaged GOES-8 Sounder mean LST retrieved using different surface emissivity assumptions. Also shown are the area averaged MODIS level 2 and level 3 LST values.