Latitudinally and Seasonally Dependent Zenith-Angle Corrections for Geostationary Satellite IR Brightness Temperatures

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ABSTRACT

The equivalent brightness temperature \( T_b \) recorded by geosynchronous infrared (geo-IR) “window” channel (10.7–11.5 µm) satellite sensors is shown to depend on the zenith angle (local angle from the zenith to the satellite for a pixel’s ground location) in addition to the mix of clouds and surface that would be observed from a direct overhead viewpoint (nadir view). This zenith-angle dependence is characterized, and two corrections are developed from a collection of half-hourly geo-IR pixel data that have been parallax corrected and averaged to a 0.5° latitude/longitude grid for each geosynchronous satellite separately. First, composites of collocated \( T_b \) over tropical regions from the Geostationary Operational Environmental Satellite (GOES)-8/GOES-10 and the Meteosat-5/Meteosat-7 satellite pairs are used to produce robust estimates of isotropic zenith-angle corrections as a function of zenith angle and grid-box-averaged \( T_b \). The corrections range from zero for a zenith angle of \( \pm 26.5° \) to increases of more than 20 K near the limb. Near-limb corrections in clear and very cold thick overcast conditions are smaller but are still positive. This empirical result depends on the surface–tropopause temperature differences, so a second correction was developed. Using collocations from the same two satellite pairs from 60°N to 60°S, differences in uncorrected \( T_b \) divided by differences in the corresponding corrected values were accumulated as a function of latitude and season. The resultant ratios smoothly vary from \( \approx 1 \) in the Tropics to \( \approx 0.5 \) at 60°N and 60°S, with a quicker decrease in the winter hemisphere. In comparison with the uncorrected geo-IR data, there is a 50% reduction in the root-mean-square differences between collocated values from adjacent satellites by applying the latitude/season-adjusted zenith-angle corrections. Histograms of corrected geo-IR \( T_b \) at large zenith angles closely match histograms from collocated near-nadir-view values. Residual difference maps are smooth and indicate intersatellite differences.

1. Introduction

It has been known for decades that IR brightness temperatures \( T_b \), as observed from instrumentation aboard satellites, are colder at locations that are far from the satellite nadir point, a condition coined “limb darkening.” Even though the nadir angle from a geosynchronous satellite is small for such locations, the zenith angle is large, meaning the satellite appears to be low in the sky as viewed from the surface. Limb darkening of IR \( T_b \) presents various problems to forecasters, meteorologists, hydrologists, and climatologists. Operational precipitation estimation techniques such as the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS) autoestimator (Vicente et al. 1996) commonly suffer overestimations of several orders of magnitude when uncorrected limb satellite IR \( T_b \) input data are used, as compared with estimations derived from IR retrieved from near nadir (C. Davenport 1999, personal communication). Rain rates of the autoestimator double for every IR \( T_b \) that is 5 K colder. Another example of the effects of using satellite IR without limb corrections was an \( \approx 40\% \) anomalous increase in Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI; Arkin and Meissner 1987) winter rainfall estimates over South America...
in the early 1990s due to the increased viewing geometry resulting from winter relocation of the GOES-7. For a few years following the failure of GOES-6, GOES-7 was moved from a subsatellite position of 75°W to 112°W for the winter, then back to 75°W for the following Atlantic hurricane season. Obviously the effects of zenith-angle bias in IR \( T_b \) retrieval are substantial to users.

Two mechanisms combine to reduce the observed \( T_b \) for targets with large zenith angles. First, in nonuniform cloudiness, radiation originating from the earth’s surface is more likely to be obstructed by the sides of the clouds toward a satellite at large zenith angles as opposed to a satellite at small zenith angles (Fig. 1, top). We refer to this as a “geometric effect.” The effect on IR transfer through broken clouds has been studied by Liou and Ou (1979), Harshvardhan et al. (1981), Harshvardhan and Weinman (1982), Harshvardhan (1982), and Duvel and Kandel (1984). Raschke et al. (1973) corrected for the anisotropic character of emitted \textit{Nimbus-3} radiation by developing angular dependence models (ADMs) using five cloud scene types. Suttles et al. (1988) developed longwave ADMs dependent on viewing angle, colatitude, scene (four cloud categories), and earth surface type used for inverting broadband radiances into top-of-the atmosphere fluxes. Second, larger zenith angles cause longer optical paths, which decrease the contribution by surface radiation and increase that by attenuation and emission by cloud matter and water vapor (Fig. 1, bottom). We refer to this as a “radiometric effect.” To correct these effects, Wark et al. (1962, 1963), and Abel and Gruber (1979) developed limb-darkening corrections based on regression equations derived from radiative transfer calculations. They used these corrections to adjust nadir-observed radiance to nadir-window radiance from low-orbit polar-orbiting NOAA spacecraft.

The studies cited for both of these effects were carried out for low-orbit satellites, but geostationary satellites suffer the same effects as well. This is demonstrated in Fig. 2 (top), which depicts a merger of window-channel IR from Meteosat-7 (0° subsatellite longitude) and Meteosat-5 (63°E). The data seam was placed at 70°E to contrast high-zenith-angle Meteosat-7 with near-nadir Meteosat-5. The limb \( T_b \) of the Meteosat-7 (just west of 70°E) are colder than those of Meteosat-5 for all conditions, clear to cloudy, at all latitudes, providing a noticeable demarcation at the seam.

The goals of this work are twofold. First, by eliminating systematic bias in satellite IR ranging from warm surface to cold cloud-top retrievals, associated error can be eliminated or reduced in IR-derived products and assessments made from IR. We show results of models that we developed that reduce the IR limb-darkening bias that is produced by the combination of the radiometric and geometric effects. The contributions of each of these effects are evaluated separately in section 6. Scientists need IR \( T_b \) retrieved from all satellite geometries to look, as closely as possible, as if the retrievals were performed from nadir geometry, enabling the creation of fields of IR, whether for one satellite domain or globally, to be as homogenous as possible. Second, investigation and quantification of total limb error as well as determination of the error contribution due to 1) originally retrieved \( T_b \), 2) zenith angle, 3) latitude, and 4) season can assist those who wish to conduct studies into the physical retrieval of parameters influencing limb darkening. Note at this point that this work is by no means an attempt to obtain physical information about clouds, cloud amount, water vapor, or surface temperature from satellite retrievals. However, there is a strong need to remove the effects of these factors on satellite IR retrievals.

In this paper, we describe the development of a method to adjust IR \( T_b \) for individual pixels. We show that the magnitude of the correction depends not only on zenith angle, but on the retrieved \( T_b \) of the pixel, season, and latitude as well. This work was made possible by a new, near-global (60°N–60°S) full-resolution “window-channel” infrared dataset for all available geostationary satellites (described in section 2) along with newly developed tools to manipulate these data that were developed recently at the Climate Prediction Center (CPC; Janowiak et al. 2001). An empirical model simulating the basic zenith-angle dependence is constructed using tropical IR data in section 3. Latitudinal and seasonal parameters are used to fit the empirical model to observational IR data in section 4. In section

![Fig. 1. (top) Illustration of two-dimensional optically thick cumulus clouds and surface radiation as observed from a nadir satellite (dashed) and the geometric effect as observed from a limb satellite (solid). (bottom) Illustration of horizontally homogeneous optically thin cloud and surface radiation as observed from a nadir satellite (dashed) and the increased optical path through cloud matter and water vapor from the radiometric effect as observed from a limb satellite (solid).](image-url)
Fig. 2. Meteosat-7 (subsatellite long 0°) channel-5 IR west of 70°E, Meteosat-5 (subsatellite long 63°E) east of 70°E 1800 UTC 5 Aug 1999 with (top) no corrections and (bottom) corrections for zenith-angle effects.
5, we present applications of this research and discuss the effectiveness of the corrections. In section 6, the relative contributions of geometric versus radiometric effects are evaluated. A summary and vision of future directions in this research appear in section 7.

2. Data

Full-resolution IR data [nominally 4 km for GOES and 5 km for Geostationary Meteorological Satellite (GMS) and Meteosat] have been archived at CPC from all available geostationary satellites since October 1998. These satellites include the GMS-5 (140°E subsatellite longitude position), Meteosat-7 (0°), and both GOES (75° and 135°W). The data are obtained from the Man–Computer Interactive Data Access System provided by NESDIS. Beginning in February 1999, IR data from the Meteosat-5 satellite (repositioned to 63°E) also became available. Full-disc IR images are available every 0.5 h from the Meteosat satellites, every 1 h from GMS, and every 3 h from GOES. Hemispheric and regional subsets of full-disc scans are available from the GOES satellites every 0.5 h, and these subsets are assembled to construct as near a full-disc image as possible. The IR obtained from the various satellites peak at slightly different frequencies (10.7, 11.0, and 11.5 μm for GOES, GMS, and Meteosat, respectively), so some systematic differences exist. No absolute intercalibration has been performed.

The pixels are remapped from the native satellite projection to an equal-angle latitude/longitude grid of approximately 4 km at the equator. Locations of pixel \( t_b \) less than 260 K and zenith angles greater than 35° are corrected for geometric parallax effects by determining the height of the cloud top using the retrieved pixel \( t_b \) indexed to standard-atmosphere height and then geometrically computing the location of the pixel in earth coordinates (latitude/longitude). Results of both parallax navigation and zenith-angle correction of IR \( t_b \) will be shown in section 5. The uncorrected \( t_b \), (i.e., no zenith-angle correction adjustment) is used for pixel relocations due to parallax. This notion is counterintuitive, because it would seem that a “zenith-angle-corrected” \( t_b \) should be used, given that the height of the pixel determines the earth location to which it is assigned. For very cold, opaque scenes it does not matter much which \( t_b \) is used, because the zenith-angle \( t_b \) correction (section 3) is small for very cold scenes. For pixels with relatively cold, optically thin cloud, however, the difference can be substantial, because the retrieved \( t_b \) has contributions from both the cold cloud and from warmer features below the cloud because of the transparent nature of the cloud. Original locations from which pixels are moved (and not replaced by other relocated pixels) are set to missing values, because information at these locations has been blocked by the clouds along the viewing path to the satellite. Missing IR pixel regions exist on the side of the cloud opposite the satellite nadir position in parallax-corrected IR images.

Because the size of the field of view in the native satellite projection increases with increasing zenith angle, the remapping to a fixed (smaller) grid may result in repeating values. For example, the 4-km IR field of view near GOES nadir increases to nearly 12 km at high zenith angles. Therefore, for this example, three successive pixels would have the same IR \( t_b \) in the remapped data at the edges of the GOES disk. Because IR from neighboring satellites are merged by taking the pixel with the smaller zenith angle, “pixel stretching” in the globally merged IR field occurs only when a neighboring satellite image is missing.

The primary dataset in this study is a spatially aggregated (0.5° × 0.5° latitude/longitude) half-hourly version of the remapped data described above for the domain 60°N–60°S and the period of February 1999 to the present. It contains statistics of IR \( t_b \) for each grid-box, as follows:

1) fraction of pixels less than 235 K (GPI estimates of precipitation),
2) mean IR \( t_b \),
3) spatial standard deviation of the pixel IR \( t_b \),
4) the warmest and coldest IR \( t_b \) pixel in the grid box, and
5) an indicator of the geostationary satellite from which these data were retrieved.

These data are stored both as merged satellite global maps and individual satellite maps. The latter form preserves the data in overlap regions, that is, regions scanned by two satellites. These overlap data enabled the comparison of instantaneous mean \( t_b \) for a given 0.5° × 0.5° lat/long box from two different satellites at widely ranging viewing angles. In this paper, these instantaneous 0.5° × 0.5° lat/long box averages will be referred to as IR \( t_b \); an individual IR pixel observation will be referred as an IR pixel.

3. Determining zenith-angle effects in the Tropics

An example of differences in uncorrected IR \( t_b \) between adjacent pairs of operational geostationary satellites in the five overlap regions (Fig. 3, top), clearly shows the zenith-angle effect. We adopt the convention of referring to the “limb” satellite as that for which zenith angles increase when moving toward the sub-satellite position of a “nadir” satellite. Furthermore, differences between the limb and nadir satellites are computed by subtracting the eastern satellite value from the western satellite value. Zenith angles are generally greater than 65° for the limb satellite and less than 25° for the nadir satellite at the edges of these overlap areas in the Tropics. The exception to this result is that, for the GMS-5 and GOES-10 pair, the limb satellite has larger zenith angles at the other satellite’s nadir region, because their subsatellite positions are relatively far
Fig. 3. (top) IR difference (K), western satellite minus eastern satellite for satellite pair overlap regions, 23 Aug 1999. (bottom) IR (K) derived from satellite with largest zenith angle within satellite pair overlap region (i.e., GOES-8 = 145°–105°W long, GOES-10 = 105°–65°W long), 23 Aug 1999.

Apart (85° of longitude). Differences at the middle of the overlap region should average to zero, because the geometry is the same for both satellites. However, at the edges of these overlap areas $T_b$ differences relative to the nadir satellite often exceed 10 K. The larger differences are located where the averaged $T_b$ of the limb satellite are cold (Fig. 3, bottom), indicating clouds. Limb differences are generally smaller for cloudless conditions (~10°S and 145°–140°W). For both cloudy and cloudless conditions, the limb cooling effect increases with zenith angle. The differences are generally symmetrical about the midpoint of the satellite overlap coverage. Asymmetries indicate instrument calibration differences. In recent intersatellite studies, we have determined that IR $T_b$ derived from Meteosat-5 (11.5 μm) are colder than those of GMS-5 (11.0 μm) for coincident observations with the same satellite geometry, and the enhanced limb effects of Meteosat-5 against nadir GMS-5 (~110°–133°E, Fig. 3, bottom) agree with this result.

Joyce and Arkin (1997) developed an empirical method to reduce pentad and monthly GPI (Arkin and Meisner 1987) as a function of zenith angle. By comparing collocated GPI derived from geostationary satellite limb views (zenith angles 22°–59°) with GPI derived from geostationary satellite nadir views (zenith angles < 22°), they determined a GPI correction that decreased the precipitation estimates at a linear rate of 9% per 10° of zenith angle for zenith angles larger than 26°. In this study, we adopt the method in Joyce and Arkin (1997)
of comparing all possible pairs of GPI estimates in the GOES-7/Meteosat-3 overlap region. We apply it to mean IR $T_b$ (instead of GPI) and at a higher temporal and spatial resolution (half-hourly, 0.5° × 0.5° latitude/longitude instead of pentad, 2.5° × 2.5° latitude/longitude). In addition, the comparisons are conducted over two overlap regions: GOES-8/GOES-10 and Meteosat-5/Meteosat-7. The subsatellite positions and overlap coverage areas of operational geostationary satellites that were in orbit for the data record used in this study are listed in Table 1.

The overlap regions of GOES-8/GOES-10 and Meteosat-5/Meteosat-7 were chosen primarily for the relative proximity of their subsatellite positions, which enables a study of a large range of zenith angles, and secondarily because calibrations for the satellites in each pair compare closely with each other. For both of these geostationary satellite pairs, datasets were assembled that contain the coincident retrieved IR $T_b$ difference and the limb satellite zenith angle to the target for all earth locations that can be viewed by both satellites for each 0.5 h during the period of 24 May–15 June 1999. Comparisons were considered only for those cases in which the zenith angle of the nadir satellite to the target was less than 26.5°, which resulted in corresponding “limb satellite” zenith angles between 42° and 80°, depending on the amount of overlap between the satellite pairs. This exercise was performed twice for each satellite pair, first with the satellite to the west as the limb satellite, and then the satellite to the east. The comparisons were then binned at 2° limb-satellite zenith-angle increments and 5-K coldest-satellite $T_b$ increments, and the mean of the differences within each bin was computed. The vast majority of coldest-satellite $T_b$ came from the limb satellite, but in rare cases the nadir satellite retrieval was colder. We speculate that this occurs because of small differences in the time of observation between the satellite pairs or navigational disparities between the two satellites, both of which can result in mismatches of small features.

Plots of the limb-nadir-satellite IR $T_b$ differences for the two satellite pairs (Figs. 4a,h,d,e) show increasing differences with increasing zenith angle, in agreement with Joyce and Arkin (1997) results, but also depend strongly on limb $T_b$. These differences maximize to over 15 K for large zenith angles and $T_b$ near 235 K and decrease rapidly for colder $T_b$, even at large zenith angles. The biases decrease as limb satellite $T_b$ moves from ~235 to 290 K (typical of cloudless tropical conditions) for all zenith angles and satellite combinations. This result suggests that cloud interaction has a larger effect than water vapor absorption on decreasing limb IR $T_b$. The biases increase again for the Meteosat cases (Figs. 4d,e) for limb $T_b$ greater than 290 K. The observations that contribute to the increased bias in this part of the profile have been isolated to satellite collocations occurring over land during local afternoon. In a limb-nadir-satellite $T_b$ difference profile (not shown) developed from all satellite collocations occurring over land and during local afternoon, differences decrease smoothly from 235 to 315 K. The patterns of IR $T_b$ differences among the two overlap regions described above are very similar, although the magnitudes of the differences are different, possibly due to different cloud types indigenous to each satellite nadir region, different surface type (land, sea), and thus variable contribution of surface radiation for each satellite nadir region, or small calibration differences existing among the instruments aboard the various spacecraft.

Because the pattern of the differences is very similar between the two satellite pairs, we averaged the IR $T_b$ differences for the two satellite pairs (Figs. 4c,e) and used those averages to develop a universal zenith-angle correction model (Fig. 5, left). This model is incomplete because the range of limb-satellite zenith angles is limited by the combination of the fixed locations of the satellites and the geometry restriction of the nadir satellite and because of the relatively few observations of extreme IR $T_b$ (<200 K and >310 K). Therefore, the corrections depicted in Fig. 5 (left) were extrapolated to fill out the table (Fig. 5, right). The corrections were linearly extrapolated to 160 K on the cold end. Extrapolation to 330 K on the warm end was more tenuous, because such $T_b$ are only observed by satellites with near-nadir observations of desert surfaces, so the extrapolations were based on Meteosat comparisons alone. Extrapolations were also performed for all zenith angles between 26° and 46° and greater than 80°. No limb corrections are applied to observations with satellite zenith angles less than 26°, because the corrections become very small close to the nadir point (Joyce and Arkin 1997). Last, the resulting “filled-out” correction table (Fig. 5, right) was bilinearly interpolated from the original 5-K, 2° bins to 1-K, 1° bins.

Having presented in the preceding text the necessary background on zenith-angle IR bias and our methodology to correct it, and to illustrate further the concepts discussed, we present the following four scenarios to help to synthesize the information presented so far.

**Scenario I.** Consider a $T_b$ averaged over a 0.5° lat/
Fig. 4. Difference between 0.5° × 0.5° lat/long average IR (K) as a function of limb angle (x axis) and limb \( T_b \) (y axis) for 24 May–15 Jun 1999 for (a) GOES-10 (limb) and GOES-8 (nadir, zenith angle < 26.5°), (b) GOES-8 (limb) and GOES-10 (nadir), (c) GOES-8 and GOES-10 limb differences combined, (d) Meteosat-7 (limb) and Meteosat-5 (nadir), (e) Meteosat-5 (limb) and Meteosat-7 (nadir), and (f) Meteosat-5 and Meteosat-7 limb differences combined.

Fig. 5. (left) Averaged error profiles from the GOES-8 + -10 and Meteosat-5 + -7 are averaged together for 24 May–15 Jun 1999. (right) The resulting error table is extrapolated to nadir and extreme zenith angles and maximum and minimum limb \( T_b \), both as a function of limb angle (x axis) and limb \( T_b \) (y axis).
long region that represents an optically thick but partly cloudy scene. The emitted radiation originating from the earth’s surface and lower atmosphere on the vector toward the limb satellite is geometrically blocked by the cloud closer to the satellite (i.e., geometric effect) and appears as “cloud shadows.” Because these pixels are set to missing through a parallax correction, the retrieved integrated limb \( T_b \) does not include information from these warmer regions and thus is erroneously cold in comparison with the direct overhead satellite case. The geometric effect on integrated \( T_b \) is similar (not shown) in non-parallax-corrected data, because cold clouds scanned on a limb are elongated as opposed to cloud shadows (missing values) from parallax-corrected data.

**Scenario II.** Consider a grid box that is covered by optically thin cloud. This will be the case whether the satellite has an overhead view or a highly inclined (large zenith angle) view. In this case the radiometric effect (Fig. 1, bottom) dominates, that is, the radiant energy along the vector from the earth to the satellite has to traverse a longer path through the atmosphere for a satellite with a large zenith angle as compared with a near-nadir satellite. Because of this fact, more of the energy emitted from the earth’s surface and lower atmosphere is absorbed by both cloud and water vapor, and thus the scene appears to be colder for the satellite with a limb view.

**Scenario III.** Consider a pixel that is entirely covered with very cold cloud. Because the scene is totally cloudy, there is minimal geometric effect. A very cold cloud (\(<200 \text{ K}\)) is most likely optically thick with very little contribution from the surface and atmosphere below the cloud top. Thus, the retrieved integrated \( T_b \) for this scene should be nearly the same for high- and low-zenith-angle views. This result is borne out by Fig. 4.

**Scenario IV.** Consider a pixel that is very warm (\(>290 \text{ K}\)), likely representing emittance from the earth’s surface and lower atmosphere with little or no cloud attenuation. The only attenuation here is likely to be from water vapor, and it is relatively small, \(~6 \text{ K}\) at a satellite zenith angle of 70° and limb \( T_b \) of 290 K (Fig. 4). As noted earlier, this error increases as limb \( T_b \) increases beyond 290 K, because the difference between the hot surface temperature and temperature of the atmosphere (from which water vapor absorption occurs) is increased.

4. Latitudinal and seasonal dependence on midlatitude zenith-angle corrections

When \( T_b \)-dependent zenith-angle corrections are applied to the pixel-resolution IR data for each satellite and then the data are merged to form a single global map, the \( T_b \) discontinuities that appear at the boundaries of neighboring satellites (Fig. 2, top) are essentially removed in the Tropics, but poleward of about 25° the corrections may be too large (not shown). This overcorrection is due to smaller temperature contrast between cloud tops and the earth’s surface in the midlatitudes than in the Tropics (particularly during the winter). The correction table developed in section 3 is derived from data in the Tropics, so additional corrections are needed for midlatitudes.

Because geostationary satellites are at the equator, it is not possible to perform the previous geostationary-satellite limb-nadir comparisons at midlatitudes. Rather, a second-order correction for midlatitude locations was determined by comparing the ratio of the summed observed IR \( T_b \) differences with the summed difference in their \( T_b \) corrections [Eq. (1)] for the GOES and Meteosat satellite pairs in their geostationary satellite overlap regions:

\[
R(l, t) = \frac{\sum_{i=1}^{N} |\text{LMBIR}_{li} - \text{NADIR}_{li}|}{\sum_{i=1}^{N} |\text{CLMBIR}_{li} - \text{CNADIR}_{li}|}
\]

where \( i \) is the \( T_b \) observation in a 0.5° latitude bin \( l; t \) is season; LMBIR and NADIR represent \( T_b \) for collocated targets for the satellite with the larger and smaller satellite zenith angle, respectively; and CLMBIR and CNADIR represent the equatorial-zenith-angle-corrected \( T_b \) that is appropriate for the zenith angle and \( T_b \) for the satellite with the larger and smaller zenith angle, respectively. The broad longitudinal averages should cause the correction to average out of the numerator and denominator if the surface–tropopause temperature difference is close to that of the Tropics. However, if that difference is smaller, the average satellite \( T_b \) difference in the numerator will be smaller than that in the denominator. The seasonal and latitudinal cycle in zenith angle dependency is resolved by binning \( R(l, t) \) ratios for every 0.5° of latitude from 60°N to 60°S over eight periods during 1999–2000. The transition from Northern Hemisphere winter to summer is shown by ratios for 26–27 February, 11–18 April, 24 May–21 June, and 21–30 July (Fig. 6). These ratios (Fig. 6) are far from unity outside of the Tropics (\(~0.5–0.8\)), especially in the winter hemisphere. Note that the ratios increase from February to July in the Northern Hemisphere as the oceans, land, and lower atmosphere warm up and are closer to the tropical surface temperatures than they are during the cool season. The reverse is true in the Southern Hemisphere, because the February-to-July period is a transition from the warm to the cool season. This observation demonstrates the need to incorporate a seasonal dependence in the midlatitude corrections. Based on these results, the full \( T_b \) correction is the product of the original correction as developed in the Tropics and the ratio [Eq. (1), Fig. 6] appropriate for the latitude and the time of year.
5. Evaluation of parallax and zenith-angle corrections

The equatorial-zenith-angle correction model was applied to parallax-corrected data for the month of August 1999 using seasonal and latitudinal parameters fit to 21–30 July data. Mean differences for 23 August 1999 in the $T_b$ of satellite pairs in the overlap regions (Fig. 7) are substantially smaller than in the uncorrected data (Fig. 3, top). In addition, the pattern of the differences does not exhibit the zonal orientation seen in the uncorrected data (attributable to the limb effects), but rather the differences are isotropic, which suggests residual differences in instrument calibration. The Meteosat-5 satellite still has regions of colder $T_b$ than the GMS-5 satellite in their overlap region, confirming recent calibration disparities noted by the authors.

The parallax correction (section 2) that occurs before the zenith-angle correction is a re-navigation of IR pixels based on zenith angle and original pixel $T_b$. Parallax corrections alone increase correlation between collocated limb and nadir GOES satellite IR $T_b$ retrievals by 0.03 to 0.06 (Fig. 8, dashed and dotted lines) for limb zenith angles greater than 60° and cloudy observations defined here by nadir satellite IR $T_b$ colder than 270 K, during 18–24 July 2000. By then applying the zenith-angle correction to the parallax-navigated IR, the correlation increase nearly doubles (Fig. 8, solid lines). If the warm observations are included, the correlation (not shown) patterns are similar, however the increase in correlation from parallax-only correcting is less than half of the correlation improvement when using the total correction. This difference is because the zenith-angle correction is much less for warmer retrievals (Fig. 5) and there is no parallax correction for IR pixel retrievals warmer than 265 K.

The effectiveness of the total zenith-angle correction is clearly demonstrated by the substantial decrease in the cold limb $T_b$ bias in the three satellite overlap regions of GOES-10/GOES-8, Meteosat-7/Meteosat-5, and GOES-8/Meteosat-7 during 22–29 August 1999 (Fig. 9). In all cases, the differences show little dependence on zenith angle. The largest differences occur in the GOES-8/Meteosat-7 comparison (Figs. 9e,f); however, those differences mostly offset each other and appear as possible calibration differences. The rms error in the
Fig. 8. (left) Correlation of 0.5° lat/long cloudy IR (nadir satellite < 270 K) from GOES-10 limb satellite and GOES-8 nadir, 18–24 Jul 2000: no corrections = dotted, parallax corrected = dashed, parallax and limb corrected = solid; (right) same, but for GOES-8 limb satellite, and GOES-10 nadir satellite.

Fig. 9. Bias between 0.5° x 0.5° lat/long mean IR from limb and nadir satellites, 22–29 Aug 1999. No limb corrections to limb IR = dots, parallax and limb corrected = solid, dashed = no parallax corrections but limb corrected (model also without parallax): (a) GOES-10 limb, GOES-8 nadir; (b) GOES-8 limb, GOES-10 nadir; (c) Meteosat-7 limb, Meteosat-5 nadir; (d) Meteosat-5 limb, Meteosat-7 nadir; (e) GOES-8 limb, Meteosat-7 nadir; and (f) Meteosat-7, limb, GOES-8 nadir.
limb-satellite zenith-angle-corrected data relative to nadir-satellite retrievals is reduced by about 50% in comparison with uncorrected data (Fig. 10) for the GOES, Meteosat, and GOES-8/Meteosat-7 satellite pairs for 22–29 August 1999. The corrections extend the range of limb-satellite zenith angles 10°–20° farther for the same amount of accuracy when compared with uncorrected IR retrievals.

Further evidence of the efficacy of this correction strategy is provided by comparing the frequency distribution of nadir satellite-observed IR $T_b$ with that from the non-limb-corrected and limb-corrected extreme limb-view IR $T_b$ retrievals. To make these comparisons, histograms of $T_b$ were constructed over 5-K intervals for $T_b$ in the three satellite overlap regions defined earlier. Histograms were computed for near-nadir satellite views (zenith angles < 26°) and for limb satellite views (zenith angles between 74° and 76°) over the period of 22–29 August 1999. The counts for each of the studies vary because of differences in the number of full-disk images from each satellite as well as the variation in overlap domain for each study area. A comparison of these histograms (Fig. 11) shows a decisive improvement in the corrected limb data as compared with the uncorrected data, particularly for the GOES-10/8 comparisons and Meteosat-7/5 comparisons, because the sensors in each pair are closely calibrated. The GOES-8/Meteosat-7 comparisons indicate substantial improvement; however, the complementary warm displacement of the limb-corrected GOES-8 to nadir Meteosat-7 histograms and the cold displacement of the limb-corrected Meteosat-7 to the nadir GOES-8 histograms indicate possible calibration differences between the IR sensors aboard these spacecraft.

An empirically derived correction scheme such as the one described in this paper cannot properly correct the IR $T_b$ in all situations. The correction scheme works best in the Tropics where most of the nadir satellite data reside that were available to develop the model and works poorest at high latitudes, because nadir view is not possible from geostationary orbit. The majority of the correction problems in the Tropics will occur at large zenith angles for instances where cloud conditions substantially vary from the latitudinal average or large de-
viations occur in the average lower-atmosphere water vapor content for the warmer IR $T_b$. Overcorrection should occur for clouds that are both opaque and horizontally homogenous. These clouds attenuate most surface emission (for all viewing geometries) and have little geometric effect. There is also a substantial diurnal cycle (not shown) in the zenith-angle effect in the Tropics over land but not ocean. The zenith-angle effect over land is larger than the current tropical model (all observations) during the afternoon, when the land–cloud temperature contrast is the greatest, and is weaker during the night. In a similar manner, midlatitude corrections are subject to land surface temperature deviations from mean climate in addition to the variable effects of different cloud properties already discussed. Presently, over- (under-) correction would occur during a midlatitude cold (warm) event and during night (day) when the land–cloud temperature contrast is weaker (stronger) than average climate values.

To summarize, a significant improvement is possible using the scheme, even with the deviations from average conditions that are known to occur. A virtually seamless map of zenith-angle-corrected, globally merged (60°N–60°S) IR $T_b$ is shown in Fig. 12. By removing systematic zenith angle effects in geostationary satellite IR retrievals, systematically dependent precipitation overestimation using IR imagery is also removed. Previously, precipitation estimation methods such as the GPI overestimated rainfall at geographic locations farthest away from a geostationary subsatellite position (Joyce and Arkin 1997), because the viewing geometry for a geostationary satellite remains the same for a given earth location. In the next section, we discuss the relative importance of the geometric and radiometric cloud effects.

6. Discussion of the geometric and radiometric effects

As outlined in the introduction, the limb effects are due primarily to a geometric effect and a radiometric
effect. Respectively, these denote viewing cloud sides as well as tops and viewing along longer optical paths. Both effects make the scene appear colder than at nadir. Data on each effect were accumulated by separating limb-satellite overcast cases (i.e., complete cloud cover over an entire $0.5^\circ \times 0.5^\circ$ grid box) from partly cloudy cases in the satellite overlap regions. To do this, the spatial standard deviation (denoted hereinafter as SSD) of IR pixels within each collocated near-nadir satellite grid box was used to isolate cases of overcast and partly cloudy conditions similar to the method used by Coakley and Bretherton (1982). Statistics were gathered at limb-satellite IR $T_b$ bins of 5 K and 2° zenith-angle bins. Based on preliminary work, at cold gridbox $T_b$ (cloud), small ($\leq 2$ K) SSDs imply complete homogenous cloud cover over the grid box, and boxes with higher spatial variability ($>10$ K) suggest a mixture of cloud and clear areas or a mixture of high and low cloud. Cases were accumulated for bins in which the nadir-view SSDs are less than 2, 2.0–5.0, 5.0–10.0, and greater than 10 K (Fig. 13). For cold gridbox $T_b$ ($<255$ K), we argue that it is justified to consider all but the highest SSD class ($>10$ K) to represent primarily horizontally homogeneous clouds. Bias corrections of 10, 20, or even 25 K are unlikely to be dominated by geometric effects if collocated nadir-satellite SSD is less than 10 K. Essentially, the small SSD in vertical extent noted above makes it unlikely that low (warm) pixels geometrically blocked by higher cloud at high zenith angles are so warm that cloud geometry is the major contributor to these large correction biases.

The highest percentage of cold limb-satellite $0.5^\circ \times 0.5^\circ$ gridbox $T_b$ possessing characteristics of broken or horizontally irregular cloudiness (nadir SSDs $>10$ K) falls in the range of $\sim 210–255$ K (Fig. 13i), composing approximately $\frac{1}{3}$ to $\frac{1}{2}$ of all cases. Note that, for the $T_b$ range of $\sim 210–255$ K, the error pattern for the broken cloudiness case (Fig. 13j) is very close to the error pattern for the more horizontally homogeneous cloud (Figs. 13a,d,g, that is, SSD of pixels $<10$ K). This result suggests that the radiometric effect on limb cooling produces biases similar to the geometric effect at these $T_b$. This is not trivial, because the percentage of the categories for which the radiative effect should dominate makes up $\frac{1}{3}$ to $\frac{2}{3}$ of the total cold cloud cases (Figs. 13c,f,i).

One noticeable difference is for limb $T_b$ colder than 210 K and in the range 255–290 K, where errors for cases of smaller IR-pixel SSDs (Figs. 13a,d), are generally less than for the cases of higher spatial variability (Figs. 13g,j). As limb $T_b$ drops below 210 K, the frequencies increase in smaller pixel SSD categories (Figs. 13c,f), which indicates more situations of homogenous cold, opaque, cloud shields. Similar results were obtained by repeating Fig. 13 using the standard deviation of the pixels as determined from the limb satellite, however, it is not shown because of the intention to demonstrate these statistics without any possible degradation of cloud properties. The current model does not stratify by pixel SSD, and these findings indicate that it would only improve results for the limited cases of limb $T_b$ of 255–290 K and colder than 210 K.
Fig. 13. Difference between non-limb-corrected 0.5° × 0.5° lat/long IR (K) derived from limb and nadir satellites as a function of limb angle, 19–23 Jul 1999, x axis = limb angle, y axis = limb $T_b$: (a) nadir satellite SSD (K) < 2, (b) 2 < SSD < 5, (c) 5 < SSD < 10, and (d) SSD > 10; counts of limb satellite $T_b$ for (e) nadir satellite SSD < 2, (f) 2 < SSD < 5, (g) 5 < SSD < 10, and (h) SSD > 10; frequency of limb satellite $T_b$ for (i) nadir satellite SSD < 2, (j) 2 < SSD < 5, (k) 5 < SSD < 10, and (l) SSD > 10.
7. Conclusions and future work

Zenith-angle dependence in geostationary satellite 0.5° × 0.5° lat/long “window” IR has been determined by collocating pairs of IR T_b for which the zenith angles of one satellite are restricted to less than 26.5° and the zenith angles of the other satellite range over 44°±80°. The resulting IR limb error profiles from these satellite pairs are similar in pattern and magnitude, with errors greater than 20 K for limb T_b near 235 K. There is a seasonal and latitudinal dependency in satellite T_b zenith-angle effects that diminishes the corrections by about 50% of the tropical values for midlatitude winter-season areas. The IR corrections generally remove zenith-angle dependency bias, reduce rms by ~50%, and remove seams where extreme limb IR data are merged with nadir IR data. The remaining averaged differences of corrected IR between satellites in their overlap regions are not systematic in viewing geometry. This result gives confidence not only to use a larger portion of a geostationary satellite IR image for uses such as estimating precipitation, but also that estimates will not possess a predisposed geographic bias based on proximity to subsatellite position. The zenith-angle correction will be implemented in the GPCP 1° lat/long IR histograms in the near future. Those who wish to use IR limb correction models may contact either of the first two authors. The provided correction subroutine needs IR T_b observation, zenith angle, yearday, and latitude of observation as input; corrected IR T_b is the output.

Future work will focus on evaluating the diurnal cycle in the zenith-angle effects over land. The possible utility of including cloud properties also will be researched, particularly for limb T_b colder than 210 K and in the 255–290 K range.

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