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Assessing the consistency of AVHRR and MODIS L1B reflectance for generating Fundamental Climate Data Records

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[1] Satellite detection of the global climate change signals as small as a few percent per decade in albedo critically depends on consistent and accurately calibrated Level 1B (L1B) data or Fundamental Climate Data Records (FCDRs). Detecting small changes in signal over decades is a major challenge not only to the retrieval of geophysical parameters from satellite observations, but more importantly to the current state-of-the-art calibration, since such small changes can easily be obscured by erroneous variations in the calibration, especially for instruments with no onboard calibration, such as the Advanced Very High Resolution Radiometer (AVHRR). Without dependable FCDRs, its derivative Thematic Climate Data Records (TCDRs) are bound to produce false trends with questionable scientific value. This has been increasingly recognized by more and more remote sensing scientists. In this study we analyzed the consistency of calibrated reflectance from the operational L1B data between AVHRR on NOAA-16 and -17 and between NOAA-16/AVHRR and Aqua/MODIS, based on Simultaneous Nadir Overpass (SNO) observation time series. Analyses suggest that the NOAA-16 and -17/AVHRR operationally calibrated reflectance became consistent two years after the launch of NOAA-17, although they still differ by 9% from the MODIS reflectance for the 0.63 μm band. This study also suggests that the SNO method has reached a high level of relative accuracy (~1.5%) for estimating the consistency for both the 0.63 and 0.84 μm bands between AVHRRs, and a 0.9% relative accuracy between AVHRR and MODIS for the 0.63 μm band. It is believed that the methodology is applicable to all historical AVHRR data for improving the calibration consistency, and work is in progress generating FCDRs from the nearly 30 years of AVHRR data using the SNO and other complimentary methods. A more consistent historical AVHRR L1B data set will be produced for a variety of geophysical products including aerosol, vegetation, cloud, and surface albedo to support global climate change detection studies.

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1. Introduction

[2] Using the nearly 30 years of the Advanced Very High Resolution Radiometer (AVHRR) observations for climate change detection has intrigued numerous remote sensing scientists and led to many studies. Unfortunately, few studies have analyzed the consistency of AVHRR Level 1B (L1B) data which is fundamental for all climate change detection involving multiple satellites, especially given the fact that AVHRR was designed for weather applications, with no requirement for climate quality calibrations. Estimating the consistency of AVHRR solar band measurements from two or more satellites is not a simple task, because AVHRR has no onboard calibration, and the vicarious calibration (or in flight calibration using external targets such as the desert as substitute) using the Libyan Desert relies on assumptions that may not be valid for satellites with different equator crossing times due to such effects as cloud and water vapor variability, and the bi-directional reflectance distribution factor (BRDF) of the calibration sites. The use of the Simultaneous Nadir Overpass method (SNO) in recent years [*Cao et al.*, 2004, 2005] alleviates this problem by evaluating the calibration biases between two satellites at the orbital intersections near nadir within 30 seconds with little ambiguity. However, the intersatellite biases need to be quantified with uncertainties stated. Without knowing the uncertainties, bias estimates may not be reliable.

[3] Calibration consistency between two AVHRRs does not guarantee absolute accuracy. This is because two AVHRRs can agree with each other perfectly and yet both

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could significantly deviate from the true value being measured. Therefore, independent evaluation of the AVHRR calibration has to be performed by comparing with other instruments such as MODIS. Since MODIS has onboard calibration independent of and more accurate than that of AVHRR, the agreement between MODIS and AVHRR is a more rigorous test of the consistency across these two different systems. However, care must be taken to ensure that the effects of Spectral Response Function (SRF) differences are accounted for in the comparisons, since significant differences exist in the SRFs between AVHRR and MODIS. These SRF effects can be evaluated by radiative transfer calculations and hyperspectral observations.

2. Consistency and Accuracy in Satellite Observations

[4] For a satellite radiometer, converting the optoelectric signal of Earth observations in voltage and digital counts to reflectance or radiance relies on a high quality calibration target. For the reflective solar bands, a perfect calibration target would be a solar diffuser with a 100% reflective Lambertian surface that never degrades over the lifetime of the mission. If such a solar diffuser existed, the Earth view measurements could be calibrated against the solar diffuser so that they would be as consistent as the solar diffuser. In reality, perfect solar diffusers do not exist. Instead, they not only degrade over time, but also have BRDF properties that may be difficult to characterize. To solve these problems, several techniques have been used in modern instruments such as the MODIS, including the solar diffuser stability monitor (SDSM), and accurate characterization of the solar diffuser BRDF prelaunch. To get a sense of calibration stability in the context of making consistent Earth view measurements, it is useful to see how the MODIS calibration has performed over the years. Figure 1 shows the normalized instrument response (or inverse of instrument gain) of Aqua/MODIS since launch, based on onboard solar diffuser calibration. The following observations can be made from this figure.

[5] During this 5+ year time period, the min/max range in the normalized response for MODIS band 1 and 2 (at 0.63 μm and 0.84 μm respectively) did not exceed ±3%. The "short term" variability is estimated to be no more than 0.23%, based on the min/max range from 14 samples in the flat portion of the curve between the mid of 2003 and early 2004. The response curve in Figure 1 represents the actual measurement with no modifications other than correcting for the solar diffuser degradation (<1% per year) using the SDSM data [*Xiong et al.*, 2007a]. Therefore, we believe that the MODIS Earth view observations are highly consistent based on the onboard calibration performance, and independent verification through lunar calibration [*Xiong et al.*, 2007b]. However, while consistency provides relative accuracy (relative to the solar diffuser), the absolute accuracy has to be assessed independently. MODIS calibration is traceable to the solar irradiance through the solar diffuser, and its absolute accuracy is required to be within ±2%. Since absolute accuracy is difficult to evaluate, in this study we focus on the consistency between satellite observations, assuming that MODIS is stable and accurate. Unfortunately, absolute accuracy and stability can only be confirmed through more rigorous inter-comparison possibly with future benchmark missions [*Fox et al.*, 2003]. Along the same line, the initial MODIS responsivity decrease and the subsequent increase shown in Figure 1 for these two particular bands need to be further investigated and thoroughly explained. It is true that for the purpose of climate trending, consistency is often more desirable than absolute accuracy, but consistency can be lost when merging multiple data sets if the absolute accuracy is not known.

[6] In contrast to the MODIS onboard calibration, vicarious calibration typically has much larger short term variability due to atmosphere and surface changes. For example, the Aqua/MODIS five year observations of the Libyan desert site shows that the variability is on the order of 2.3% (1 sigma, or 1 standard deviation), and a 5% change from one observation to the next is not uncommon, due to such factors as cloud and water vapor variability between observations. This is an important justification for future radiometers to have a standard requirement for an onboard solar diffuser, regardless of whether the satellite is in a low Earth orbiting or geostationary orbit. It is possible that the effect of short term variability can be reduced in the long-term time series if the vicarious calibration target is stable for decades (possibly rivals the stability of onboard solar diffuser), but the consistency of the data set in vicarious calibration can easily be broken for many reasons, as demonstrated in this study. Also, larger variability means that it would take longer to detect the small changes in the climate [*Leroy et al.*, 2008]. In the following sections, we will evaluate the consistency between AVHRRs on NOAA-16 and -17, as well as between NOAA-16/AVHRR and Aqua/MODIS using the SNO method.

3. Cross Comparison Between AVHRRS on NOAA-16 and -17

[7] Routine cross comparison between AVHRRs on NOAA-16 and -17 has been performed since 2002 using the SNO method at NOAA/NESDIS. Software has been developed to automatically download the data at the SNOs, from which initially a 101 × 101 nadir window is extracted from the L1B data. A pixel-by-pixel match is performed to remap each pixel from one dataset to another. A regression test is performed by introducing a relative pixel shift between the two images to find the best spatial match to reduce navigation errors. Then a small window (51 × 51 pixels) at nadir is extracted and analyzed. The SNO between these two satellites occur about every 8 days (which is comparable to the MODIS solar band calibration interval of 1–2 weeks), and therefore produces a SNO time series with about 40 SNO data points per year.

[8] Figure 2 shows the SNO time series as a reflectance ratio between AVHRR on NOAA-16 and -17 during a 4.5 year period from mid 2002 to the end of 2006, in which several distinct characteristics in the NOAA/NESDIS AVHRR operational calibration are revealed, and warrants extensive discussion here. First, the calibration biases revealed in this ratio experienced three major time periods. Large discrepancies on the order of 20% are found during some periods, while major improvements are made in later

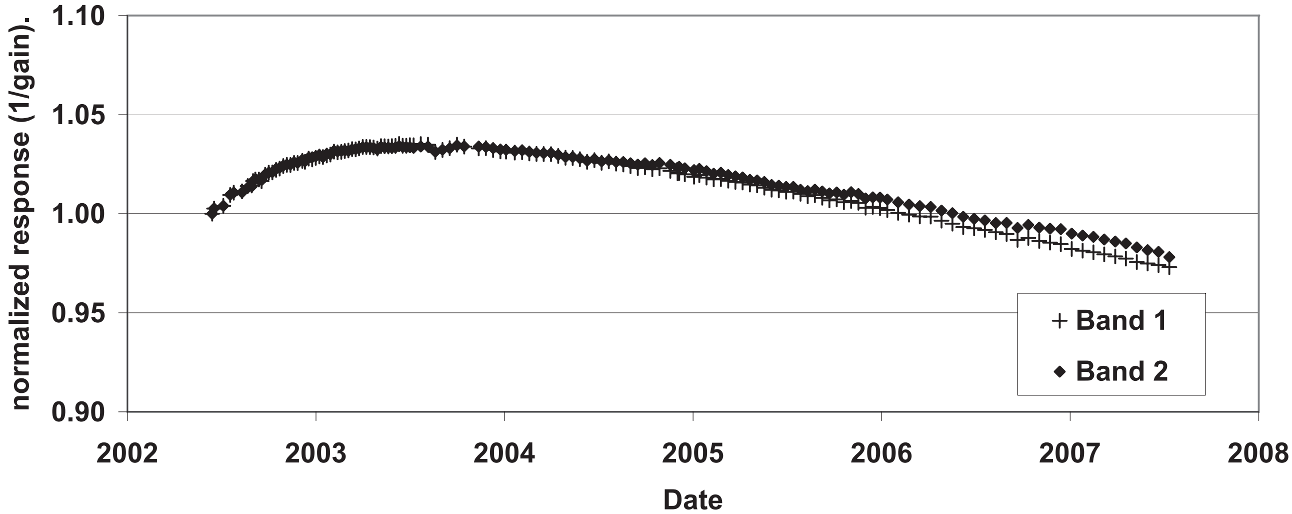

Figure 1. Aqua/MODIS responsivity change since launch (band 1 and 2 only).

years, when both band 1 and band 2 became more consistent between these two satellites.

[9] Second, there are distinct features in each time period. Period 1 started around mid 2002 and lasted for about one year, which corresponds to point A1 to B1 for band 1 and A2 to B2 for band 2. According to our record, neither the NOAA-16 nor NOAA-17/AVHRR was vicariously calibrated during this time period (prelaunch coefficients were used in the L1B data). Therefore the ratio shown in Figure 2 indicates the calibration biases between these two AVHRRs based on prelaunch calibration, which suggests that NOAA-16 Earth view reflectance is higher than that of NOAA-17 by ~5% for band 2, while an opposite bias with the same magnitude existed for band 1. The general upward trend from point A2 to B2 suggests that NOAA-17 band 2 changed about 5% more relative to that for NOAA-16 during the period, while a smaller change occurred for band 1. It is also noted that the variability of the biases in this period is smaller than those for other periods, and the variability is mainly caused by the SNO site variations. Since cloud screening in the polar region is difficult (due to low surface temperature) and has not been applied in this study, the total variability (or uncertainty) of 0.84% (1 sigma) for this period includes the effect of the mixture of cloudy and clear pixels, which therefore is believed to be small. This also suggests that in the later periods, the increased variability may be attributed to uncertainties in deriving the calibration coefficients from the vicarious calibration in the analysis itself, rather than the ability of the SNO method.

[10] Period 2 started near mid 2003 and lasted about a year, which corresponds to point C to D for band 2 and B1 to E for band 1. A distinct feature of this period is the large jump for band 2 in the reflectance ratio from 1.076 to 1.183 (~10%) from point B2 to C. Our record shows that this large jump is caused by the operational implementation of the vicarious calibration for AVHRR on NOAA-16 around mid 2003, when a ~11% change was made to the opera-

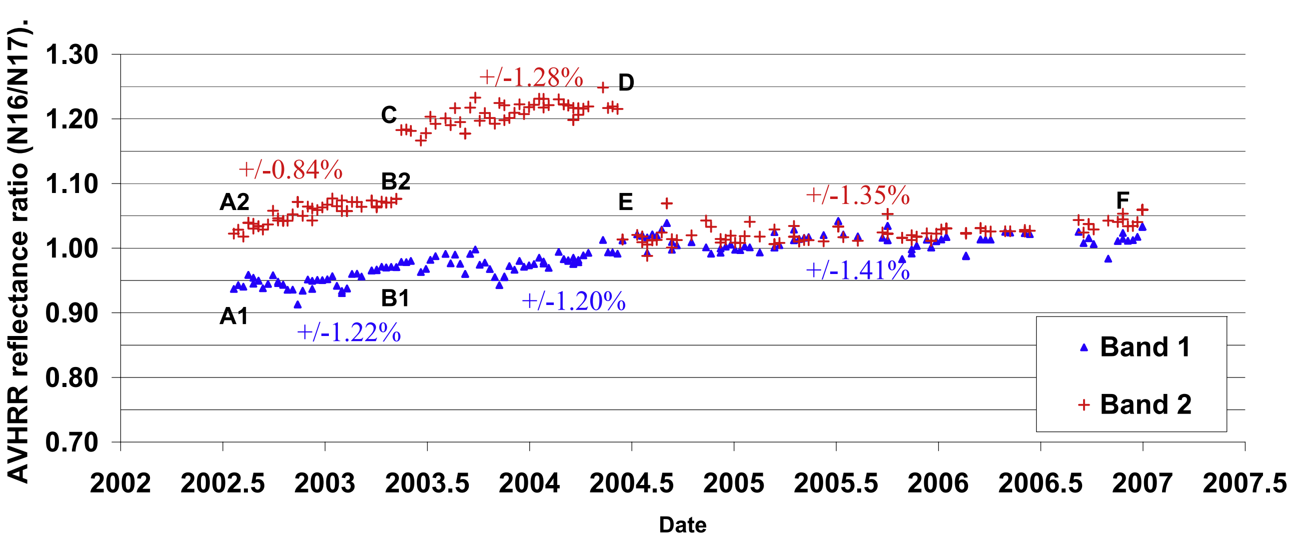

Figure 2. SNO Time Series between AVHRR on NOAA-16 and -17 (value% represents 1 sigma uncertainty, or the residual after a linear fit, for the period indicated).

tional calibration slope for band 2 (NOAA-17 was not vicariously calibrated until mid 2004). Assuming that the NOAA-16/AVHRR operational calibration was stable during the period, the upward trend from point C to D represents the degradation of NOAA-17/AVHRR band 2 which is on the order of 5% per year. For band 1 during the same time period, much smaller changes are observed (about 2% for band 1 from point B1 to E), suggesting that the prelaunch and postlaunch calibration for NOAA-16 agreed relatively well, and no significant degradation is observed for this band.

[11] Period 3 (from point E to F in Figure 2) started around mid 2004 till 2007, which is represented by a fairly consistent reflectance ratio near 1.0 for both band 1 and 2, suggesting that the NOAA-16 and -17/AVHRR calibration agrees well for both bands, although a residual bias still exists, since most of the data points are not centered around the ratio of 1.0, and a slight upward trend in the bias or calibration drift is also observed. Since NOAA-16 equator crossing time has changed during the period of study, further investigation is needed to see whether this slight upward trend is related to the BRDF effect of the Libyan Desert target. Nevertheless, Figure 2 provides strong evidence that once both NOAA-16 and -17/AVHRR are calibrated operationally using the Libyan Desert Target, their calibration becomes more consistent. Without operational calibration, both large biases and drifts over time have caused problems in the L1B data, as demonstrated in the time periods before mid 2004. For period 3, the residual bias (above the perfect agreement ratio of 1.0) of 1.38% and 2.63% for band 1 and 2 respectively is relatively small compared to the expected relatively accuracy of vicarious calibration. More importantly, the variations in the residual bias (1.43% for band 1 and 1.61% for band 2, 1 sigma) are very small, which suggests that both the bias estimates and the SNO method itself are highly accurate.

[12] It should be noted that the discrepancies depicted in Figure 2 apply to all L1B data for NOAA-16 and -17/AVHRR for the periods indicated, not just the SNO subset. This is because the calibration coefficients (the root cause for the discrepancies) for the solar bands of AVHRR are constants that remain the same regardless of where and when the observations are made, before they are updated manually once a month. Therefore, we believe that the standard operational L1B data set is not suited for long-term time series studies because of the inconsistency in the calibration. In fact, using the L1B reflectance data for long-term study for this time period will have two possible consequences: either the time series (such as aerosol, NDVI, Albedo, or other geophysical products) show large jumps that match the three time periods depicted in Figure 2, or the retrieval is insensitive to such large reflectance variations. In both cases, the scientific value of such long-term studies may become highly questionable.

4. Cross Comparison Between AVHRR and MODIS

[13] Although the AVHRR calibrations agree relatively well between NOAA-16 and -17 satellites in recent years, this relative agreement provides little information about their absolute accuracy. In prelaunch, the AVHRR was calibrated using NIST traceable Integrating Spheres, which provides the SI (abbreviated from the French *Le Système International d'unités, or* International System of Units) traceability. However, once the instrument is launched, this traceability is lost because the AVHRR has no onboard calibration and the instrument response changes over time. Ideally this on-orbit traceability problem will be solved when SI traceable standards in orbit (the so-called benchmark mission measurements) are used for cross calibration. However, since such standards are not yet available in-orbit, cross comparison/calibration with instruments that have onboard calibration (such as MODIS) is an alternative. In this study we use the SNO method to analyze the calibration biases between AVHRR and MODIS. A 3.5 year SNO time series is developed to examine the variations and consistency between the AVHRR and MODIS observations at the SNOs. Since MODIS has onboard calibration, in this study we use Aqua/MODIS calibration as a quasi-standard in evaluating the calibration bias and consistency of the AVHRR.

[14] Aqua has an altitude of 705 km while NOAA-16 is more than 100 km higher. As a result of this altitude difference, they observe the same place at the same time every 2-3 days in the polar regions at ~±80 latitude [*Cao et al.*, 2004]. Our objective is to quantify the relative calibration biases for the two reflective solar bands between AVHRR and MODIS at 0.63 μm and 0.84 μm. The 1.61 μm band of AVHRR is not used in this study because it is not always available, due to channel switching. Table 1 shows the major parameters of concern in this study for AVHRR and MODIS.

[15] Based on solar diffuser and lunar trending, studies have shown that the MODIS calibration is very stable [*Xiong et al.*, 2007] and the absolute calibration accuracy is probably within 2%. This is in contrast to AVHRR where the operational calibration has depended mainly on vicarious calibration using the Libyan Desert. The estimated AVHRR calibration accuracy is on the order of ±5% (for a nominal desert reflectance of ~38%, or ± 5% of 38 = ±1.9%). However, as it is suggested in this study, larger differences between MODIS and AVHRR have been found.

[16] Observations from these AVHRR and MODIS corresponding solar bands are highly correlated, though not identical, despite the wider bandwith for AVHRR than that for MODIS. In the polar regions where the SNOs occur, the surface is largely covered by snow and ice, and their relatively flat spectral reflectance, as well as the dry atmosphere reduce the effect of spectral differences between AVHRR and MODIS bands in the comparison. This is especially true in the Antarctic, which is considered an ideal calibration site on the Earth [*Masonis and Warren*, 2001; *Jaross and Warner*, 2008]. In particular, it is also noted that at 0.63 μm, the spectral differences between MODIS and AVHRR bands should have negligible effect in the comparisons in the polar regions. Therefore, it is believed that the inter-comparisons of MODIS and AVHRR solar bands at the SNOs should reveal the relative calibration biases with very small uncertainties.

[17] In a previous paper, a prototypical study using Terra/MODIS to calibrate NOAA-16/AVHRR using collocated/coincidental observations was presented for two sample 1 km AVHRR datasets [*Heidinger et al.*, 2002] to demon-

Table 1. In-Band Solar Spectral Irradiance (Esun) for AVHRR and MODIS (Unit: W/m^2-μm)

Band	Wavelength	NOAA-16/AVHRR[a] (Inband/Bandwidth)	Aqua/MODIS[b]	Esun ratio (AVHRR/MODIS)
1	0.63 μm	133.2/0.081 = 1644.4	1602.0	1.0265
2	0.84 μm	243.1/0.235 = 1034.5	990.3	1.0446

[a]Values extracted from the NOAA KLM user's guide, Appendix D.
[b]Values provided by the MODIS Characterization Support Team (MCST) which are calculated based on *Thuillier et al.* [1998] (0.4–0.8 μm), and *Neckel and Labs* [1984] (0.8–1.1 μm).

strate the usefulness of this method. The goal was to explore the utility of using MODIS to calibrate the new dual-gain reflectance channels of the AVHRR. In that study, the MODIS calibrated reflectance was regressed against the digital count from AVHRR at the SNO on a pixel-by-pixel basis, which produced calibration coefficients for AVHRR using MODIS observations. These coefficients were then compared with the AVHRR prelaunch values.

[18] Since the SNO method was first presented at the SPIE conference in 2002 [*Cao and Heidinger*, 2002], it has generated much interest in the science community. A collaborative study between the MODIS characterization support team (MCST) and NOAA scientists led to an extended study of intercalibration between MODIS and AVHRR since 2002. In early 2003, several 1 km LAC (Local Area Coverage) acquisitions were made at the NOAA-16 and Terra/MODIS SNO for the inter-calibration studies. However, it was found that scheduling such events was problematic, since there may often be schedule conflicts with other higher priority tasks. As a result, it was decided to use the GAC (Global Area Coverage) data because of their availability. GAC data is sampled every three LAC scan-lines along track and averaged every 4 pixels cross-track, thus introducing more uncertainties in the analysis. Nevertheless, AVHRR GAC data have been used consistently since 2003 to study the intersatellite biases between NOAA-16/AVHRR and Aqua/MODIS.

[19] The details of the SNO method have been described elsewhere [*Cao and Heidinger* 2002; *Heidinger et al.*, 2002; *Cao et al.*, 2004, 2005]. In essence the MODIS pixels are remapped to AVHRR GAC pixels at the simultaneous nadir overpasses (within 30 seconds), which occur about every 2–3 days between NOAA-16/AVHRR and Aqua/MODIS in the ±70 to ±80 deg latitude. Since the GAC data is nominally 3 km × 5 km resolution while the MODIS data is at 1 km resolution, there are subtle differences in how the match is handled by different analyses, such as averaging vs. sampling the MODIS pixels to match the GAC pixels. However, as it is discussed later, we found that using slightly different details in the analysis did not affect the conclusions of this study.

[20] Uncertainties can be further reduced through redundant analysis of the same SNO time series by independent groups, using different software implementations of the same general SNO methodology with differences in the implementation details. The Aqua/MODIS and NOAA-16/AVHRR data at the SNOs were independently analyzed both by the MCST and NOAA scientists. The MCST started the analysis since 2003, while NOAA scientists performed similar analysis independently in 2005 and 2006. Each implemented their own software, and applied it to essentially the same data sets, except that the MCST team at the time used fewer SNO cases and restricted the data to the Arctic only. The NOAA analysis on the other hand included more SNO cases, with both Arctic and Antarctic data at nearly all solar zenith angles.

[21] The MCST was most interested in using AVHRR as a transfer radiometer to check the calibration consistency between Aqua/MODIS and Terra/MODIS at the SNOs [*Wu et al.*, 2007]. As a result, the relative difference between

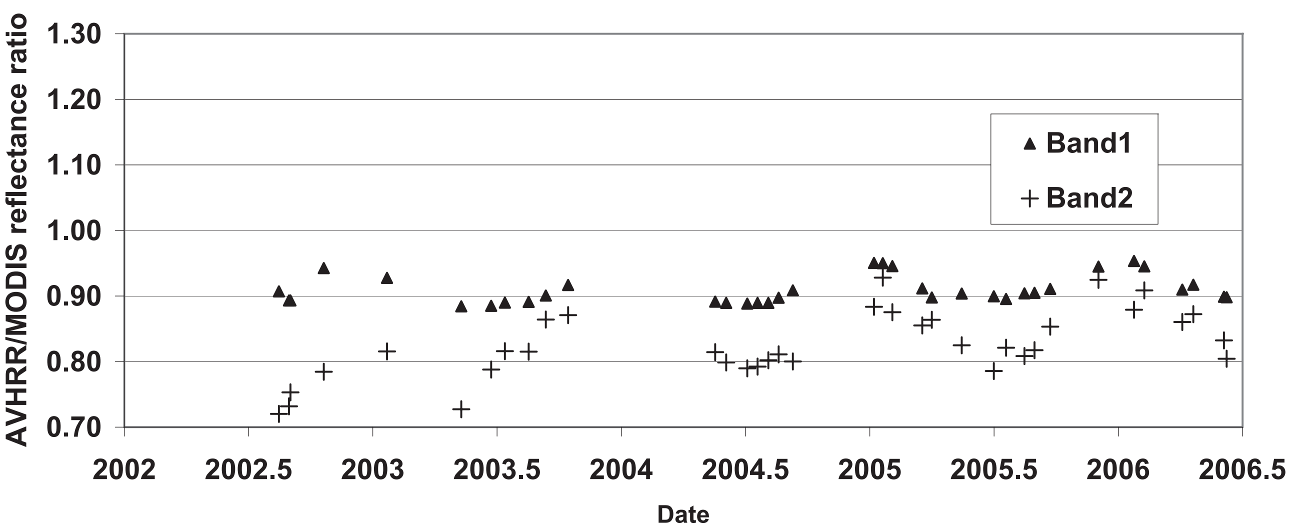

Figure 3. SNO Time Series of the NOAA-16/AVHRR and Aqua/MODIS reflectance ratio (SNO sample subset analyzed by the MCST).

MODIS and AVHRR is not as important to them as the differences between the two MODIS instruments revealed by AVHRR. Therefore, although it was found that the two MODIS agree within 2% using AVHRR as a transfer radiometer with the SNO calibration, little was discussed about the differences between AVHRR and MODIS. Figure 3 shows the SNO time series from mid 2002 to mid 2006 between AVHRR and MODIS for the 0.63 μm and 0.84 μm bands. There are several important findings from this figure.

[22] First, the reflectance ratio for the AVHRR/MODIS 0.63 μm band has a mean value around 0.917, which suggests that AVHRR reflectance at the SNO is about 9% lower than the simultaneous observations made by MODIS. Second, there is an oscillation in the reflectance ratio which increases in the winter and decreases in the summer. However, the radiance ratio (calculated separately for MODIS and AVHRR) did not show such a pattern. Third, for the 0.84 μm band, there is a large spread in the ratio between AVHRR and MODIS, especially before 2004. Understanding these features requires detailed analysis of the AVHRR calibration.

[23] The AVHRR reflective solar band calibration is fundamentally different from that of MODIS (the latter relies on an onboard solar diffuser). Since the AVHRR calibration relies on the long-term observations of the Libyan Desert, the nominal ±5% uncertainty is primarily caused by the uncertainties in the desert observations related to a number of factors. In addition to the overall uncertainty, there are also inconsistencies due to latency issues of vicarious calibration, for example, as discussed previously, NOAA-16/AVHRR was not calibrated until two years after launch, and as a result, the coefficients in the L1B data were presumably using prelaunch values before 2003. However, recently it was also found that the prelaunch values in the L1B could be inconsistent due to data processing errors. On the other hand, it has been shown that the MODIS calibration is consistent based on both solar diffuser and lunar trending. Independent analysis of this same SNO time series by NOAA scientists produced a very similar mean reflectance ratio of 0.91, and confirmed the seasonal oscillation of this reflectance ratio. A detailed comparison between AVHRR and MODIS on the calibration procedure suggests that the oscillation is caused by the fact that the AVHRR definition of nominal albedo does not include the correction for Sun-Earth distance, which has an effect of a maximum 6% oscillation with season (or ± 3% around the mean). To clarify the AVHRR calibration procedure, here we revisit the general formula for the solar reflected band calibration using Earth targets.

[24] For a stable Earth target used for vicarious calibration, such as the Libyan Desert, both the surface and top of atmosphere reflectance are assumed to be stable for decades. The difference between the surface vs. top of atmosphere reflectance is due to the atmospheric effects, and for the purpose of calibration, here we are only interested in the top of the atmosphere (TOA) reflectance (ρ). We further assume that the TOA reflectance is Lambertian. Note that under the above assumptions, ρ is an inherent property of the surface and the atmosphere, not of the solar illumination. Therefore, it is neither a function of Sun-Earth distance nor a function of the solar zenith angle.

[25] For a Lambertian target with 100% reflectance, the reflected solar radiance at the top of the atmosphere can be computed as:

$$R_{100} = (E_{SUN}/D_{SE})\cos(\theta)/\pi \tag{1}$$

Where R_{100} = reflected solar radiance at the top of the atmosphere for a 100% reflective Lambertian target at a given location and time, E_{SUN} = in-band extraterrestrial solar irradiance for a given band, D_{SE} = normalized Sun-Earth distance at the time of observation, θ = solar zenith angle, π = projected solid angle for a hemisphere, used to convert from irradiance to radiance for a Lambertian surface.

[26] The TOA reflectance of an actual target is the ratio between the satellite observed radiance (R_{OBS}), which is converted from the observed delta count from the instrument, and R_{100}:

$$\rho = R_{OBS}/R_{100} = R_{OBS}/[(E_{SUN}/D_{SE})\cos(\theta)/\pi] \tag{2}$$

Since θ varies for each pixel, it was decided by both the AVHRR and MODIS community that cos(θ) should not be applied in the L1B data, but rather should be handled by the users. In effect, the retrieved quantify from MODIS L1B is:

$$\begin{aligned}\rho\cos(\theta) &= R_{OBS}/[(E_{SUN}/D_{SE})/\pi] \\ &= \text{offset} + \text{scalefactor} \times \text{digital number}\end{aligned} \tag{3}$$

For AVHRR a similar definition is used except that the term D_{SE} is not applied to the L1B data either. As a result, the retrieved quantity from AVHRR L1B is:

$$\rho\cos(\theta)/D_{SE} = R_{OBS}/[(E_{SUN})/\pi] = \text{intercept} + \text{slope} \times \text{count} \tag{4}$$

[27] Therefore, although both AVHRR and MODIS retrieved L1B values are called "nominal albedo" or "reflectance factor", their actual quantity is different by D_{SE}, which varies with season by ±3 % with a mean value of 1.0. According to equation (4), AVHRR data users should multiply this D_{SE} factor for all the data from L1B (ρ cos(θ)), in addition to dividing by the cos(θ) for each pixel, in order to retrieve the TOA reflectance (ρ). It is true that the effect of D_{SE} (±3%) is probably small compared to other uncertainties in product retrieval algorithms, but it is significant for climate studies. The NOAA KLM user's guide does indicate that the retrieved quantity from L1B is the TOA reflectance when the Sun is at "normal incidence" (or directly overhead), and at a "mean Sun-Earth distance", but does not explain what a user must do to retrieve the correct TOA reflectance.

[28] After correcting the Sun-Earth distance factor, the seasonal oscillation in the bias between AVHRR and MODIS has largely disappeared and the mean bias becomes more consistent for this SNO time series. It is noted that the fact that the SNO time series can detect the ±3% Sun-Earth distance effect suggests that the SNO method itself has an accuracy significantly better than ±3%. In addition, we eliminated the SNO cases where the solar zenith angle is greater than 80 degrees because at such large solar zenith

Table 2. NOAA-16/AVHRR to Aqua/MODIS Reflectance Ratio From the SNO Time Series

	MCST		NOAA (Entire Period)		NOAA (Period 2 Only)	
	Band 1	Band 2	Band 1	Band 2	Band 1	Band 2
Time period	08/15/02–09/19/06	08/15/02 – 09/19/06	07/06/02 – 12/26/05	07/06/02 – 12/26/05	11/20/03–12/26/05	11/20/03–12/26/05
Mean ratio	0.917	0.832	0.913	0.826	0.912	0.847
St. dev.	0.0087	0.0398	0.0092	0.0420	0.0072	0.0285
N Cases	37	37	105	105	65	65

angles, the AVHRR instrument itself is vulnerable to solar intrusion in the fore optics [*Cao et al.*, 2001]. In the final analysis, Table 2 shows that the bias between AVHRR and MODIS for band 1 is ~9.1% with an uncertainty of ± 0.9% (1 sigma). This result is highly significant for both understanding the uncertainty of the SNO method, and evaluating the consistency between MODIS and AVHRR data. For the SNO method, this means that independent analysis by different groups produced the same result. The uncertainty of ±0.9% (1 sigma) is better than most methods used for vicariously calibrating the solar bands at 0.63 μm between MODIS and AVHRR.

[29] Figure 4 shows that there is no significant trend observed for band 1 in the AVHRR/MODIS ratio during this 3.5 year period, indicating that either the degradation has been accounted for in the operational calibration, or there is no significant degradation for this NOAA-16/AVHRR band. This also suggests that the vicarious calibration provided a relatively stable calibration for AVHRR, despite the large difference from the MODIS calibration.

[30] For the 0.84 μm band, Figure 4 shows that the SNO time series can be divided into two distinct time periods. Period one started mid 2002 and ended around mid 2003, which is the period with no vicarious calibration for NOAA-16/AVHRR. Period two covers mid 2003 to 2006, when the AVHRR was calibrated vicariously. While period 1 suggests that there is a 20–30 % difference between AVHRR and MODIS, period 2 suggests that the vicarious calibration narrowed this gap down to 10–20%. We found that the switch from period 1 to 2 is caused by a large one-time adjustment of the operational calibration coefficients for this band when the operational calibration for NOAA-16/AVHRR started. In fact, if the statistics are computed for period 2, its seasonal variation for period 2 is reduced to ±2.9% around the mean reflectance ratio of 0.85, or a difference of ~15% according to this time series. Although this variation is not large given the uncertainties of vicarious calibration, it is more than three times of that for band 1, and it is caused by a combination of SRF difference, and water vapor and surface spectral reflectance variability at the SNO sites.

[31] Given the fact that AVHRR and MODIS do not have the same SRF for either band, the reflectance ratios deviating from 1.0 are not unexpected. Intuitively, this ratio should be around 1.0 for the 0.63 μm band and less than 1.0 for the 0.84 μm band (due to water vapor absorption effect for AVHRR). The question now is given the SRF differences, what the actual reflectance ratios should be for these two bands. To answer this question, both model calculations and hyperspectral observations are analyzed and results are presented in the next section.

5. Using Hyperion SNO Data to Estimate the Reflectance Ratio Between AVHRR and MODIS

[32] Analyses in the previous sections show that using the SNO method, very accurate inter-calibration has been achieved for bands with similar spectral response functions (such as the 0.63 μm band between AVHRR and MODIS). However, for bands with very different spectral response functions and affected by water vapor, larger uncertainties exist in the analysis because of the variability in the results.

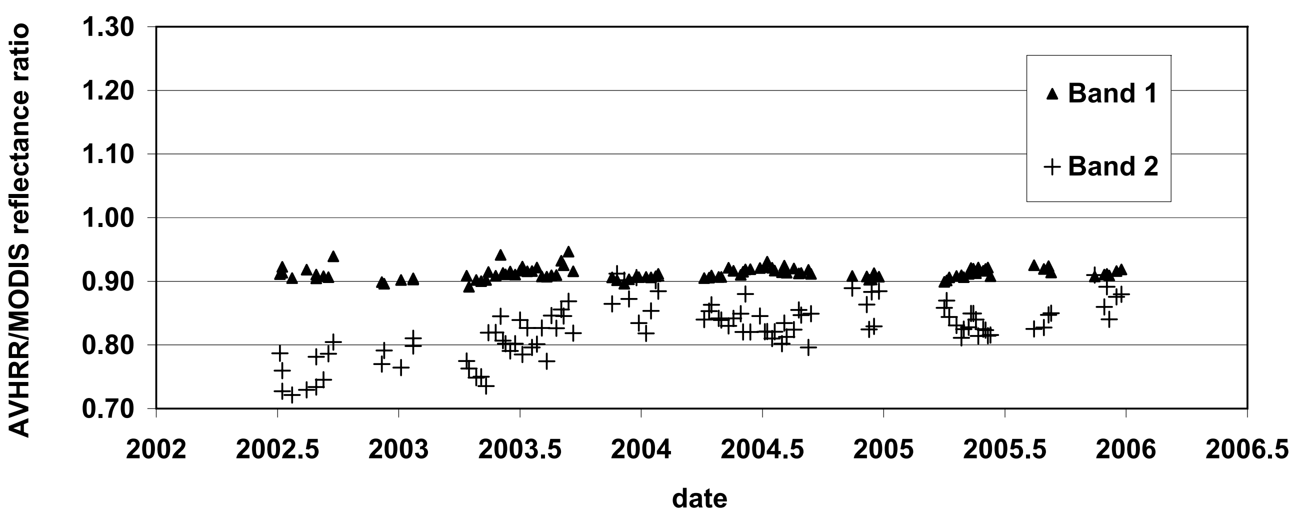

Figure 4. NOAA-16/AVHRR to Aqua/MODIS reflectance ratio SNO time series after Sun-Earth distance correction (excluding data with SZA > 80 deg).

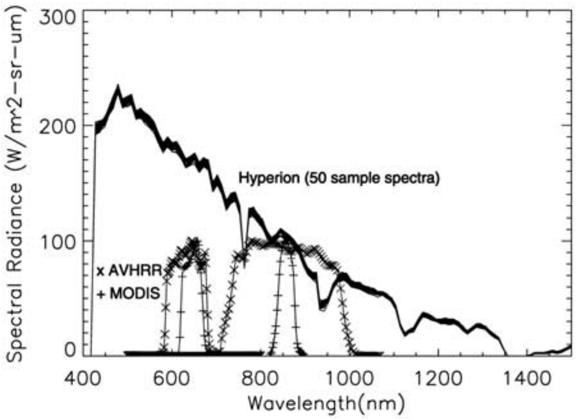

Figure 5. Example Hyperion Spectra at the SNO region (overlaid with AVHRR and MODIS band 1 & 2 spectral response functions).

There are two approaches to further investigate this problem. One is to perform model calculations, the other is to use hyperspectral data to study this effect. In a previous study, we performed extensive forward calculations using MODTRAN4 with the spectral response functions of Aqua/MODIS and NOAA16/AVHRR. Three types of atmosphere were used, including mid-latitude summer, subarctic summer, and subarctic winter, to see the variation of the AVHRR/MODIS ratio in a variety of atmospheric conditions. For each atmosphere, both dry and normal water vapor profiles were used. Also, forward calculations included four types of surfaces representing the polar land cover, including snow, sea ice, and tundra, with desert for reference. The results have been presented in a previous paper [*Cao et al.*, 2007] and here we only provide a brief summary. In short, for band 1, the theoretically calculated AVHRR/MODIS reflectance ratio has little variation with different atmosphere and water vapor amount. The only significant variation is among the different surface types, which varies from 1.0 for sea ice to 0.96 for desert. For band 2 at 0.84 μm, water vapor can cause this ratio to vary by as much as 30%. The difference among surface types is also large (>15%). As a result, the uncertainty in evaluating the bias between the AVHRR and MODIS bands based on model calculations is too large (compared to the 2.9% uncertainty already achieved from the SNO time series) to make definitive conclusions for this band.

[33] To solve this problem, in this study we took an alternative approach by using the Hyperion hyperspectral observations at the SNO sites. By convolving the spectral response of each instrument with the hyperspectral observations, the in-band spectral radiance for each band and instrument can be calculated (Figure 5). Since this is based on instrument observations at the actual SNO site, the band radiance or reflectance ratio therefore is more realistic than those derived from the model calculations. Note that in this approach, the absolute radiometric calibration of the hyperspectral instrument is not as critical as in direct comparisons of radiances, since the broad band radiance is derived from the same spectral radiance of hyperspectral measurements. It is noted that this reflectance ratio method works particularly well for signals with a large dynamic range, such as the reflected sunlight. Based on discussion with the EO-1/Hyperion scientists, the absolute radiometric calibration of Hyperion should not affect the results of this analysis in the band radiance or reflectance ratio [Ong and Ungar, personal communications, 2007].

[34] Hyperion is a hyperspectral instrument on NASA's EO-1 satellite that covers the 0.4 to 2.5 μm spectral region with 242 bands with a 30 meter ground sample distance (GSD). Hyperion data has been made available since EO-1 launch on Nov. 21, 2000 (by scheduled requests only). The potential use of Hyperion data for calibrating AVHRR and MODIS has been explored in a previous study where the technical issues including spectral and spatial characteristics have been discussed [*Cao et al.*, 2006]. Working with USGS and NASA, we have acquired three special Hyperion data sets, two at the SNO in the Arctic region, and one at the Gobi desert to support the current study. Table 3 lists the date and location of these acquisitions.

[35] In this study, data from only one nadir detector (detector #127) is used to avoid spectral artifacts of Hyperion, which is a pushbroom system with 256 cross-track detectors, and each has its own unique spectral characteristics. First, the nadir spectral radiance is extracted and scaled to the correct unit. Then the spectra are convolved with the spectral response functions of NOAA-16/AVHRR and Aqua/MODIS. The following formula is used for the convolution:

$$R = \frac{\int_{\lambda 1}^{\lambda 2} r(\lambda) SRF(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} SRF(\lambda) d\lambda} \quad (5)$$

Where R= the spectral radiance for the broad band instrument with a given spectral response function (SRF), such as AVHRR and MODIS. SRF(λ) = spectral response function of the broad band instrument of interest, such as AVHRR and MODIS. r(λ) = spectral radiance from Hyperion nadir pixels. λ1, and λ2 = lower and upper wavelength limits for the band.

[36] The same Hyperion nadir pixel spectra are convolved with AVHRR and MODIS spectral response functions (Figure 5), which produces the theoretical radiances for these instruments with a 30 meter resolution. The radiance ratio between AVHRR and MODIS is computed for all the

Table 3. Hyperion SNO Data Acquisitions

	1st Hyperion SNO	2nd Hyperion SNO	Hyperion Gobi Desert site
Date	April 22, 2007	May 19, 2007	Oct. 12, 2006
Latitude/Longitude	80.96/44.15	80.71/−146.75	40.96/94.48
range	79.94/34.90	80.24/−150.71	39.14/94.03
Scanlines	6977	3401	6964

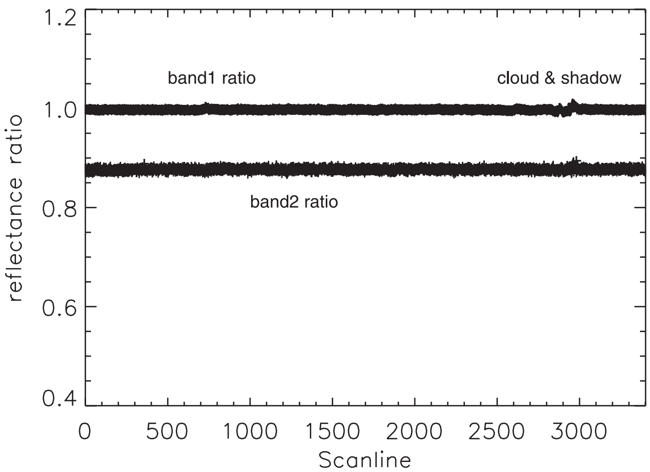

Figure 6. NOAA-16/AVHRR to Aqua/MODIS reflectance ratio computed from the 2nd Hyperion SNO data set.

nadir pixels along-track, and the reflectance ratio is derived by dividing the Esun ratio presented in Table 1, according to equation (2). Note that the Esun ratio is sensitive to the solar spectrum used, the accuracy of the spectral response functions, and the precision of the numbers in the calculations, which represent another source of uncertainty in the comparisons. To address this issue, we performed independent calculations of the inband solar spectral irradiance in Table 1 based on both the Nickel&Labs (from the 6S radiative transfer model, version 2, July 1997), and the *Thuillier et al.* [2003] solar spectrum, and found that while the values in Table 1 are not exactly repeatable due to the reasons mentioned above, the Esun ratios are consistent to better than 0.2% for band 1 and 0.36% for band 2, as long as the solar spectrum are used consistently in computing the Esun values for both AVHRR and MODIS.

[37] Nevertheless, it is arguable that since the spatial resolution is significantly different between Hyperion and the broad band instruments here, the resolution differences may introduce uncertainties. However, this issue is resolved if the radiance or reflectance ratio is stable for the acquired dataset which covers hundreds of kilometers. Since the Hyperion spectra were convolved with MODIS and AVHRR spectral response at the nadir pixel on a scan-line by scan-line basis, any spatial variation would have appeared in Figure 6 as well as the scan-line statistics (note the small variation for band 1 in Fgure 6 due to cloud and shadow is near the noise level). Table 4 shows that the variation across scan-lines for this data set is not significant because the standard deviation in the reflectance ratio is on the order of 0.2% for band 1 and 0.3–1.6% for band 2 for the two Hyperion SNO data sets.

[38] For the 0.63 μm band (band 1), it was found that the AVHRR/MODIS reflectance ratio is between 0.99 to 1.0 from the two Hyperion SNO data sets (Table 4). For comparison, this ratio over the Gobi desert is 0.99 (with a larger standard deviation). These values are comparable to those from the model calculations. Note that the Hyperion spectral resolution is on the order of 10 nm, and the spectral sampling interval of the spectral response functions of AVHRR and MODIS are on the order of 2–3 nm. In the spectral convolution, the Hyperion spectra should first be resampled at a finer resolution to match the spectral interval of the spectral response functions. Otherwise, a large error in the convolution will be introduced. However, despite the good agreement between model calculation and Hyperion observations, the uncertainty in both approaches is difficult to estimate until more analyses with additional Hyperion data sets are performed. The Hyperion calibration accuracy also needs to be better quantified, especially since the degradation rate is not the same for different bands which may introduce spectral dependent biases, and in the operations at USGS no correction or adjustment is made to account for the Hyperion instrument degradation. Nevertheless, the current estimate for the theoretical reflectance ratio between AVHRR and MODIS for the 0.63 μm band is 1.0, compared to the actual value of 0.91 from the AVHRR and MODIS SNO data discussed in previous sections. As a result, it is concluded that the actual bias between AVHRR and MODIS for this band is 9%.

[39] For the 0.84 μm band (band 2), the AVHRR/MODIS reflectance ratio derived from Hyperion is ~0.88 and consistent. This ratio is slightly higher than that for the desert region, which can be explained by a drier atmosphere and different surface spectral reflectance at the SNO sites. Combining the theoretical ratio of 0.88 with the actual SNO observations (estimated to be 0.85), we conclude that the bias between AVHRR and MODIS for this band is only ~3%.

[40] Our result can be compared indirectly with previous studies. For example, in *Rao et al.* [2003], it was found that ATSR and MODIS had excellent agreement in the Libyan Desert observations, although the result disagrees with that of AVHRR by more than ten percent. For the 0.63 μm band, both MODIS and ATSR produced a reflectance of ~42% for the 0.66 μm band, in contrast to the 37.8% of AVHRR as a standard established in the scientific literature. This discrepancy is also observed by other scientists in independent studies [Heidinger, personal communications, 2006]. However, for the 0.84 μm band, most previous studies are inconclusive because of the large uncertainties in comparing this band.

[41] Finding the root cause of the bias between AVHRR and MODIS is beyond the scope of this paper. Briefly, MODIS has onboard calibration and is believed to be more accurate than that of AVHRR, which relies on vicarious calibration using the Libyan Desert, for which the spectral reflectance has not been characterized. In fact, the so-called AVHRR calibration traceability and standard is based on a

Table 4. Reflectance Ratio Between AVHRR and MODIS Computed From Hyperion Observations

		1st Hyperion SNO		2nd Hyperion SNO		Hyperion Gobi Desert	
	Band	Refl. Ratio	St. dev.	Refl. Ratio	St. dev.	Refl. Ratio	St. dev.
AVHRR/MODIS	b1	0.99	0.001753	1.00	0.001602	0.99	0.007018
AVHRR/MODIS	b2	0.88	0.015666	0.88	0.002925	0.87	0.018703

study in the 1980s, when an airborne radiometer measured the White Sand desert site at an AVHRR overpass and the calibration was then transferred to the Libyan Desert with AVHRR [*Smith et al.*, 1988]. However, whether this is the cause of the bias between MODIS and AVHRR requires further investigation. Further comparison in the future involving ATSR would provide another independent evaluation of the AVHRR calibration bias.

6. Conclusions

[42] While the 4.5 year SNO time series between NOAA-16 and -17/AVHRR revealed several inconsistencies in the operational calibration, major improvements are found since mid 2004, when the AVHRR calibrations and observations were made consistent between these two satellites. It was also found that the uncertainty in making this estimate using the SNO time series is ~1.5% (1 sigma) for both the 0.63 and 0.84 μm bands. This result is especially impressive for the 0.84 μm band, for which the calibration uncertainties are typically large due to the effect of water vapor. This also demonstrates that the SNO method works well as long as the spectral response functions of the two instruments in the comparison are the same or very similar.

[43] Although the AVHRRs on NOAA-16 and -17 agree well, they disagree with MODIS measurements at the SNOs based on a 3.5 year SNO time series between Aqua/MODIS and NOAA-16/AVHRR. The 0.63 μm band of AVHRR was found to be 9% lower than that of the corresponding MODIS band, with small uncertainties in the estimate. For the 0.84 μm band, the bias is 15% where a 12% is expected based on Hyperion observations, but with a larger uncertainty due to the large differences in the spectral response functions between AVHRR and MODIS. It is recommended that L1B data users should assess the consistency of the data before constructing long-term time series for climate studies for the results to be credible. It is noted that consistency is not the same as absolute accuracy, which is more difficult to assess. However, establishing consistency is an important step for improved long-term time series studies.

[44] It is believed that the method used in this study is applicable to all historical AVHRR data for improving the calibration consistency, and work is in progress generating FCDRs from the nearly 30 years of AVHRR data using the SNO and other complimentary methods. Future studies involving other similar instruments will also further improve the accuracy of AVHRR calibration. We plan to perform more comparisons internationally through the Committee on Earth Observation Satellites/Working Group on Cal/Val (CEOS/WGCV) and the World Meteorological Organization/Global Space-based Inter-calibration System (WMO/GSICS) programs. By contributing to the generation of more consistent FCDRs, these efforts will provide strong support to global climate change detection studies.

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