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Nadir Correction of AIRS Radiances

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ABSTRACT

A statistical method to correct for the limb effect in off-nadir Atmospheric Infrared Sounder (AIRS) channel radiances is described, using the channel radiance itself and principal components (PCs) of the other channel radiances to account for the multicollinearity. A method of selecting an optimal set of predictors is proposed and demonstrated for one- and two-PC predictors. Validation results with a subset of AIRS channels in the spectral region 649–2664 cm$^{-1}$ show that the mean nadir-corrected brightness temperature (BT) is largely independent of scan angle. More than 66% of the channels have a root-mean-square (rms) bias less than 0.10 K after nadir correction. Limb effect on the standard deviation (SD) of BT is discernible at larger scan angles, mainly for the atmospheric windows and the water vapor channels around 6.7 μm. After nadir correction, nearly all atmospheric window channels unaffected by solar glint and more than 76% of water vapor channels examined have BT SDs brought closer to nadir values. For the window channels affected by solar glint (wavenumber > 2490 cm$^{-1}$), BT SDs at the scan angles with the strongest impact from solar reflection were improved on average by more than 0.6 K after nadir correction.

1. Introduction

The present generation of space-borne hyperspectral infrared sounders such as the Atmospheric Infrared Sounder (AIRS; Gautier et al. 2003), Infrared Atmospheric Sounding Interferometer (IASI; Chalon et al. 2001) and Cross-Track Infrared Scanner (CrIS; Susskind 2006) enable terrestrial radiometric measurements to achieve well beyond what their predecessors such as the High-Resolution Infrared Radiation Sounder (HIRS) can in terms of spectral resolution (Fig. 1). Radiometric measurements of AIRS have been applied to numerical weather prediction (NWP) in Chahine et al. (2006). At the same time, the climatologies of the radiances from these sensors are envisaged to be critical in climate monitoring and benchmarking of climate models (Anderson et al. 2004).

Cross-track scanning sensors such as AIRS detect, for the most part, radiation from off-nadir viewing angles where “limb effect” on observed radiance is significant. The limb effect refers to the change in the intensity of observed radiance at a given frequency due to the optical path of the atmosphere increasing with scan angle. A longer optical path causes the upwelling terrestrial radiation observed in space to be dominated by contributions from higher in the atmosphere. Because of the vertical variation of temperature, the observed equivalent brightness temperature (BT) is different between off-nadir and nadir measurements. If the observed limb brightness temperature is less (more) than the observed brightness temperature at nadir, the limb effect is known as limb cooling (warming).

The severity of the limb effect for off-nadir AIRS radiances can be seen in Fig. 2, which shows the average magnitude of the limb effect for several channels of AIRS over equatorial Indian Ocean and western Pacific Ocean. The difference between the mean brightness temperature at the extreme scan angle and the nadir ranges between 4 and 11 K. For many channels, the standard deviation (SD) of brightness temperature also
deviates increasingly away from the nadir position, but the difference is of a magnitude smaller than the limb effect in the mean brightness temperature (Fig. 2). Correcting the limb warming or cooling will greatly optimize the spatial coverage necessary for building up long-term radiance climatology.

The systematic dependence of the standard deviation of brightness temperature on scan position in Fig. 2 means that, for many channels, the limb effect cannot be simply corrected by adding a function of scan position only to the observed radiance or brightness temperature, because this may only remove the mean off-nadir error. In general, existing nadir-correction methodologies (which recover the nadir radiance from off-nadir radiance by removing the limb effect) usually involve the use of collocated radiance observed by various channels of the sensor as predictors in a linear model to nadir correct the radiance of a target channel. The coefficients of each predictor can be obtained either statistically by calibrating against observed or simulated radiance data or through physical consideration: linear combinations of off-nadir weighting functions of different predictor channels have been used to estimate the weighting function at nadir of the target channel in Advanced Microwave Sounding Unit A (AMSU-A; Goldberg et al. 2001, hereafter G2001).

Nadir corrections have mostly been reported for sensors with lower spectral resolution, such as the Television and Infrared Observation Satellite-N (TIROS-N) Operational Vertical Sounder (e.g., Koehler 1989) and AMSU-A (e.g., Goldberg and Fleming 1995; G2001). There are comparatively fewer reports addressing hyperspectral sounders such as AIRS, for which it is difficult to directly use infrared channel radiances as predictors in a statistical model because of the multiple collinearity between the channel radiances (Fig. 3). Fortunately, such a concern can be addressed using the principal component (PC) scores (PCS) of AIRS channel radiances as predictors. PC predictors were used within the AIRS science team algorithm (Chahine et al. 2001; Goldberg et al. 2003) for local limb correction of AIRS radiances between neighboring fields of view (FOVs) as part of a cloud-clearing algorithm and for generating the AIRS first-guess atmospheric soundings (Chahine et al. 2001).

In an independent study, Goldberg (2009) used PC predictors for nadir correction of AIRS channel radiance. In his method, the nadir-corrected radiances are reconstructed from 200 nadir-corrected PC scores of AIRS channel radiance. Nadir correction of each PC score involves a linear model similar to that for direct nadir correction of channel radiance for AMSU-A (G2001), but it uses the target PC score itself and six other PC scores of the largest variance as predictors. In the author’s work, a different approach to nadir correction was carried out: AIRS channel radiances were directly adjusted and not reconstructed; the set of predictors for the nadir-corrected radiance is a “hybrid” union of the unadjusted radiance of the target channel itself and one or two PC scores, where the PC scores are computed from the group of unadjusted channel radiances less the target channel. The purpose of this paper is to develop a regression model with PC predictors to...
nadir correct AIRS radiances, specifically addressing the problems of channel profusion and multicollinearity for nadir correction in hyperspectral sensing. This model is purely statistical with no physical consideration included when determining the model parameters. Because the variability of the observed radiance across the AIRS channels can be different by an order of magnitude (Fig. 4), PCs with the largest eigenvalues will be dominated by those channels with large variance; however, whether these PCs will make the best set of predictors for nadir correcting for any given channel is uncertain. This question is addressed in this paper through a method that selects the optimal predictors for a nadir-correcting model with a predefined number of PC predictors. A one-PC-predictor model and a restricted two-PC-predictor model are calibrated, and their skill is validated and discussed.

The remainder of the discussion is structured as follows: the method of nadir correcting AIRS channel radiances is described in section 2; the data for this work is described in section 3; the details of the model calibration are elaborated in section 4; the results of validation tests and discussion are in section 5; and the conclusions are found in section 6.

2. Methodology

a. Background

The model developed in this paper was motivated by the empirical model in G2001 for the nadir correction of AMSU-A brightness temperature through the direct use of neighboring microwave channels. In G2001, the nadir-corrected BT $y_{ij}$ for AMSU-A channel $i$ at scan angle $j$ is modeled as a linear combination of BT at the same scan angle taken from $M$ number of AMSU-A channels, $x_{ij} = (x_{1j}, x_{2j}, \ldots, x_{Mj})$, the choice of which may depend on the target channel $i$. Thus,

$$y_{ij} = x_{ij}^T b_{ij},$$

where $b_{ij} = (b_{ij}^1, b_{ij}^2, \ldots, b_{ij}^M)$ is a column vector of coefficients to be determined and the superscript $T$ denotes the matrix transpose operation. G2001 estimated $b_{ij}$ by a constrained least squares regression of BT observations $y_{ij}$ against $x_{ij}$, where $()'$ denotes averaging in a latitudinal band $l$ over sufficiently long time; $y_{ij}'$ is approximated as $x_{ij}'$, the average observed BT $x_{ij}$ in the target channel $i$ at the scan angle $J$ corresponding to nadir. The implicit assumption is that $b_{ij}$ is independent of space and time. From G2001,

$$b_{ij} = (X_{ij} X_{ij}^T)^{-1} (X_{ij} y_{ij} + \lambda u),$$

where $X_{ij}$ is an $M \times L$ matrix comprising column vectors $\{x_{ij}'/l = 1, 2, \ldots, L\}$; $y_{ij} = (y_{ij}^1, y_{ij}^2, \ldots, y_{ij}^l)$ is a column vector; $u$ is an column vector of $M$ unit elements; and $\lambda$ is the Lagrangian multiplier,

$$\lambda = \frac{1 - u^T (X_{ij} X_{ij}^T)^{-1} (X_{ij} y_{ij})}{u^T (X_{ij} X_{ij}^T)^{-1} u}.$$
For most of channels of AMSU-A, G2001 found that only the BT of the target channel and its two neighboring channels are sufficient to specify $x_i$ in Eq. (1): that is, $x_i = (x_{i-1}, x_{i}, x_{i+1})$.

b. Model development

Because the G2001 method demonstrated excellent skill in nadir correcting BT of AMSU-A, a model to nadir correct AIRS radiance was developed from that of G2001 as follows.

1) As in G2001, the nadir-corrected radiance for a target AIRS channel $i$ at a given scan position $j$ is a linear combination of the unadjusted radiance at the target channel $i$ at several other AIRS channels at the same scan position. Unlike G2001, to overcome the issues of channel profusion and multiple collinearity between channel radiances, Eq. (1) was modified for AIRS by employing $z_{ij} = (z_{ij1}, z_{ij2}, \ldots, z_{ijN})$ of the set of unadjusted channel radiances less the target channel $i$ at scan position $j$. Thus,

$$y_{ij} - \langle y_{ij} \rangle = b_{ij}^0(x_{ij} - \langle x_{ij} \rangle) + \sum_{k=1}^{N} b_{ij}^k z_{ij}^k,$$ (4)

where $y_{ij}$ and $x_{ij}$ are the nadir-corrected and unadjusted radiances, respectively, in target channel $i$ at scan position $j$ and the angle brackets denote the average over all radiances measurements. By definition,

$$z_{ij}^k = (x_{ij} - \langle x_{ij} \rangle)^T p_{ij}^k,$$ (5)

where $x_{ij} = (x_{ij1}, x_{ij2}, \ldots, x_{iM})$ excludes the target radiance $x_{ij}$ (i.e., taking $i > M$ without loss of generality) and $p_{ij}^k$ is an $M$-dimensional eigenvector of the covariance matrix of $x_{ij} - \langle x_{ij} \rangle$. In principle, for a given target channel $i$, the set of principal components $\{p_{ij}^k | k = 1, \ldots, M\}$ could be different for different scan position $j$.

2) As in G2001, the sum of the model coefficients in Eq. (4) was constrained to be unity:

$$\sum_{k=0}^{N} b_{ij}^k = 1.$$ (6)

This constraint on the regression is reasonable: in the limit as scan position $j$ approaches nadir $J$, the nadir-corrected radiance $y_{ij}$ in the target channel should approach its unadjusted value $x_{ij}$. Equation (6) ensures that this does occur as the contributions from the other channels diminish to zero: that is, $b_{ij}^0 \rightarrow 1$ as $b_{ij}^k \rightarrow 0$ for $k = 1, 2, \ldots, N$.

3) As in G2001, the coefficients $b_{ij}^k$ were determined by constrained least squares regression of average radiances in latitudinal bands to filter off the variability in the observed radiances unrelated to scan position. Thus, Eqs. (2) and (3) could still be used by suitably redefining $y_{ij} = (y_{ij1}, y_{ij2}, \ldots, y_{ijL}) - \langle y_{ij} \rangle u$ and redefining $X_{ij}$ as an $(N + 1) \times L$ matrix comprising column vectors $\{z_{ij}^l: l = 1, 2, \ldots, L\}$, where $z_{ij}^l = (z_{ij1}^l, z_{ij2}^l, \ldots, z_{ijN}^l)$.

c. Selection of PCs

In this work, only one set of PCs for each given target channel was computed regardless of scan position by using the combined covariance matrix over all scan positions. This had the advantage of reducing the number of PCs to be stored during computation. The linear span of each set of PCs (and hence the dimension $M$ of the corresponding vector space) was maximized to include all channels except the target channel, thus avoiding arbitrariness in deciding the choice of channel subsets.

The use of PCS as predictors in Eq. (4) has two main advantages: 1) they are mutually uncorrelated, thus providing the greatest modeling capacity for a small number of predictors, and 2) the fractional contribution of the PCs to the total variance of AIRS radiances (less the target channel radiance) provides a natural selection criterion for the most suitable predictors. Of all $M$ PCs, there are only $M'$ that possess large variance and have a correlation $\rho$ with the target channel radiance of less than $\rho_c$ (some chosen cutoff value). These $M'$ PCs were first selected as candidate PC predictors. The correlation $\rho$ must not be large; otherwise, the modeling capacity of the predictors is reduced. An optimal subset of $N$ PC predictors was determined from all possible $M'C_N$ combinations among these $M'$ candidates, where $N$ was kept reasonably small to avoid overcalibration.

The skill of a PC-predictor set over a given set of scan positions $S$ may be measured by the root-mean-square (rms) differences defined as

$$s_m = \sqrt{\frac{1}{K} \sum_{j \in S} (m_j - m)^2},$$

$$s_\sigma = \sqrt{\frac{1}{K} \sum_{j \in S} (\sigma_j - \sigma)^2},$$ (7)

where $m_j$ and $\sigma_j$ are the mean and SD of nadir-corrected BT of $y_{ij}$ at scan position $j$ over all space and time, while $m$ and $\sigma$ are the corresponding statistics for the BT of $y_{ij}$ at nadir position $J$. Here, $K$ is the number of scan angles in the set $S$. If the nadir-correction model is perfect, $s_m = s_\sigma = 0$. The skill score $s_m$ is the rms bias and is expected to be small because of the unbiased nature of the constrained least squares estimation of the model.
coefficients in Eq. (2). However, the skill score $s_p$ may not necessarily be small. Therefore, the set of $N$ PCs that had the smallest $s_p$ over all scan angles (i.e., $S = \{jj = 1, \ldots, 30\}$) was chosen as the optimal PC-predictor set.

3. Data description

Daily level-2 cloud-cleared AIRS radiances for August 2007 for the region 15°S–20°N, 60°E–180° from the Goddard Earth Sciences (GES) Data and Information Services Center (DISC; available online at http://disc.gsfc.nasa.gov/AIRS/data_products.shtml) were used to calibrate and validate the nadir-correction method described in section 2. The region was selected because 1) it has large oceanic coverage; 2) its climatological sea surface temperature is relatively homogeneous, thereby reducing the effect of spatial variation in surface temperature on the observed radiance; and 3) we are particularly interested in the application of AIRS observations to the Indo-Pacific warm pool as part of our initiative toward enhancing regional observation capability in which satellite remote sensing plays a vital role (Koh and Teo 2009).

Removal of the impact of clouds on the AIRS radiance measurements had been achieved using colocated microwave measurements by the accompanying AMSU-A sensor on board the Aqua satellite, which is less affected by nonprecipitating clouds than AIRS measurements. Details of the cloud removal methodology can be found in Chahine et al. (2001) and Susskind et al. (2003). The cloud removal algorithm reduces the spatial resolution of AIRS to that of AMSU-A (i.e., 30 cross-track scan positions). Although cloud clearing inevitably introduces more uncertainty into the radiances, it is necessary, because the tropics are cloud covered most of the time. This study used 318 out of the 324 channel radiances disseminated to major NWP centers (Goldberg et al. 2003) after leaving out channels that were not working for the test period. This set of 318 channel radiance data is referred to as the “test channels.” The test channels were indexed such that wavenumber increases monotonically (cf. Fig. 1) and included the 4.2- and 15-µm CO$_2$ bands, the 6.7-µm water vapor band, the O$_3$ bands around 9.6 µm, and several atmospheric windows in the infrared region. Only radiances from oceanic FOVs whose cloud clearances were flagged as the highest quality were selected. The selected data were partitioned so that the radiances from the first 15 days of the month were used for calibrating the nadir-correction model [i.e., finding $b_{ij}$ in Eq. (4)] and the remaining data were used to verify the calibration.

4. Calibration

The model was calibrated separately for radiances observed during daytime (from local sunrise to sunset) and during nighttime (from local sunset to sunrise). The reason for having different calibrations for day and night is because there are diurnal differences in the limb effect for several window channels at the higher infrared frequencies. For a given channel $i$, the asymmetry $A_i$ of the limb effect about the nadir may be defined as the root-mean-square difference between the mean channel BT of the 318 AIRS channels [cf. Eq. (8)]. Channels indexed 295 and beyond (to the right of the dotted vertical line) have significant solar glint contamination in their daytime radiance.

\[
A_i = \sqrt{\frac{1}{J} \sum_{j=1}^{J} (x_{ij} - \langle x_{ij} \rangle)^2},
\]

where $J = 15$ and the total number of scan positions is 30 in this work. Figure 5 shows that the asymmetry $A_i$ is noticeably larger during daytime than nighttime for channel indexes 295 and beyond (wavenumber $> 2420$ cm$^{-1}$). The observed asymmetry for these channels is due to solar reflection at the sea surface contributing to the observed radiances and hence altering the limb effect.

The day or night radiances from the calibration data set were grouped in a latitudinal band of size 0.5°. The band-averaged radiance $x_{ij}$ at latitude $l$ was used for PC analysis. Out of the set of 317 PCs for each test channel during day or night, a Bartlett test (Jackson 1991) on the associated eigenvalues suggested that the PCs with the two smallest eigenvalues were equal at 5% significance level and so the corresponding PCS were rejected. Although, in principle, the $M'$ candidate PCs depend on the choice of correlation cutoff $\rho_c$, it was found that, for all test channels, only about two PCs have correlation

![Fig. 5. Asymmetry $A_i$ (in K) of the mean day (thick line) and night (thin line) BT of the 318 AIRS channels [cf. Eq. (8)]. Channels indexed 295 and beyond (to the right of the dotted vertical line) have significant solar glint contamination in their daytime radiance.](Image)
higher than 0.1 with the target channel radiance. This means that \( \rho_c \) could be any number larger than 0.1, and almost the same set of \( M' \) candidate PCs would result, which implies that in practice, our final results are robust to the choice of \( \rho_c \). In the results presented, \( \rho_c \) was set to 0.7 for all channels to eliminate only those PCs with the highest correlation with the target channel that could severely reduce the modeling capacity of Eq. (4).

In this work, the one-PC-predictor model (i.e., \( N = 1 \)) represented by Eq. (4) was first calibrated. This model was selected for investigation because it is the simplest nontrivial form of Eq. (4) that utilizes information from the channels other than the target channel for nadir correction. Nadir radiance was approximated as the channels other than the target channel for nadir correction. Nadir radiance was approximated as the

\[ \mathbf{\Sigma}_{ij} \approx \frac{1}{2}(x_{15} + x_{16}) \]

The \( M' \) possible choices (where \( 313 \leq M' \leq 315 \)) of the single PC predictor \( \mathbf{\tau}_{ij}^d \) and the target channel radiance \( y_i' \) were regressed with the nadir radiances to obtain day or night model coefficients \( b_{ij} \). The model coefficients were finally used to nadir correct for each radiance measurement \( x_{ij} \) to \( y_{ij}' \), as in Eq. (4). The single PC predictor that yields the smallest skill score \( s_\sigma \) in Eq. (5) was identified as the optimal choice for validation.

5. Validation results and discussion

The calibrated one-PC-predictor nadir-correction model was validated using the validation data described in section 3. Because limb effect increases with increasing scan angle, it is important to assess the performance of the nadir-correction model at the larger scan angles. To this end, the improvement to the BT mean and SD in each test channel was analyzed separately for two sets of scan angles: \( S_1 \), which contains the 14 larger scan angles (scan positions 1–7 and 24–30), and \( S_2 \), which contains the other smaller scan angles (scan positions 8–14 and 17–23). Scan positions 15 and 16 were used to estimate nadir observations, so they were not analyzed. The same statistics to those in Eq. (7) were computed for the two sets, and they are denoted by \( s_{m1} \) and \( s_{m2} \) for nadir-corrected BT in the set \( S_i \).

As expected from the least squares regression methodology, the limb effect as well as the solar glint effect in the mean BT was greatly reduced for all scan positions away from nadir in all channels (Fig. 6 and Table 1). The rms bias for all channels after nadir correction (ANC) is less than 0.36 K, with more than 66% and more than 50% of the channels having rms biases less than 0.10 and 0.05 K, respectively.

Figure 7 shows the rms difference in BT SD as a function of channel indexes. For most of the CO\(_2\) channels (indexes 1–125 and around 255–280) and the O\(_3\) channels (indexes around 145–160), the limb effect in BT SD is small even at large scan angles; about 71% of these channels have \( s_{\sigma,1} \) less than 0.05 K before adjustment. For these channels, nadir correction has little impact on BT SD, apart from several channels around 4.2 \( \mu \)m (indexes 255–264 and 274–280) showing small deterioration in nighttime BT SD (Fig. 7c).

The larger limb effect on BT SD is in the water vapor and window channels. Figure 8 shows representative examples of BT SD as a function of scan angle before nadir correction (BNC) and after nadir correction for water vapor channels and window channels unaffected and affected by solar glint. The rms differences of BT SD from nadir values for selected water vapor and window channels are summarized in Table 2. Except for window channels affected by solar glint during daytime, significant limb effect on BT SD is mainly confined to the larger scan angles. For the window channels affected by solar glint during daytime, the largest deviation of BT SD from the nadir value occurs over the smaller scan angles where the solar reflection has the strongest impact (cf. Fig. 8, bottom left, and channel indexes 300 and beyond in Fig. 7b).

With the exception of the window channels affected by solar glint during daytime, BT SD at larger scan angles for water vapor and atmospheric window channels are much closer to nadir values after nadir correction (cf. Table 2). In fact, more than 76% of the water vapor channels and nearly 100% of the atmospheric window channels unaffected by solar glint in Table 2 have the rms difference of BT SD from nadir value reduced regardless of daytime or nighttime. In fact, all window channels in Table 2 have their BT SD improved by more than 0.1 K during nighttime. For the channels affected by solar glint during daytime, the nadir-corrected BT SD improved the most at scan angles affected by solar reflection (cf. Fig. 8, bottom left), resulting in an average improvement of more than 0.6 K for \( s_{\sigma,2} \) for the channel indexes 300 and beyond (cf. Table 2).

Although no explicit parameters were included to account for solar glint effects in channels 295 and beyond, the nadir-correction model is able to effectively remove the average BT bias (Fig. 6) and to much reduce the difference between the SD of BT and the corresponding nadir SD value (Figs. 7, 8 and Table 2). The reason is that the \( \text{Aqua} \) satellite is on a sun-synchronous orbit, and hence the solar position relative to the satellite within a fixed narrow latitude range does not change much between the calibration and validation datasets. However, because the radiances from scan positions 15 and 16 used to estimate nadir radiance were contaminated by solar glint for these channels, the nadir-corrected radiances would still include a solar glint bias.
One appealing feature of the one-PC-predictor model over multiple-PC-predictor models is the feasibility of searching through the entire set of candidate PCs (numbering between 313 and 315 for all channels) for the optimal predictor using only a computer workstation. At present, identifying the optimal set of predictors for a multiple-PC-predictor model by searching through all possible predictor combinations would be computationally too prohibitive: a two-PC-predictor model would require a search through 49 455 combinations for each and every channel, assuming 315 candidate predictors per channel.

The question of what number of predictors to use in Eq. (4) is an important one in principle. Thus, to partly address this question without incurring too much computational cost, a two-PC-predictor model was further investigated whereby the predictor set was restricted among the 30 PCs that together explain more than 99% of the total variance and with correlation less than 0.7 with the target channel radiance. Thus, only 435 predictor

![Figure 6](image)

**FIG. 6.** (a) Unadjusted and nadir-corrected BT bias from nadir values for several off-nadir scan angles as a function of the channel indexes for both daytime and nighttime for the one-PC-predictor model. The selected scan angles are eight of the larger scan angles, with four from either side of the nadir (scan angle indexes 1, 3, 5, 7, 24, 26, 28, and 30). Note that the vertical scale for the nadir-corrected BT bias is 5 times magnified compared to that for the unadjusted BT bias. (b) As in (a), but for eight of the smaller scan angles, four of which from either side of the nadir (scan angle indexes 9, 11, 13, 15, 17, 19, 21, and 23).

| TABLE 1. Summary of rms BT bias at larger scan angles ($s_{m,1}$) and smaller scan angles ($s_{m,2}$) ANC for both daytime and nighttime [cf. Eq. (7) with $K = 14$ and $S = S_1$ or $S_2$]: the maximum value among all test channels and the percentage of test channels with values less than 0.1 and 0.05 K are shown. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $s_{m,1}$                       | Max (K) | 0.1 (K) | 0.05 (K)      | Max (K) | 0.1 (K) | 0.05 (K)      |
| Day                             | 0.36    | 85.2   | 54.7           | 0.32    | 82.4   | 67.0           |
| Night                           | 0.32    | 66.4   | 50.6           | 0.21    | 87.7   | 65.4           |
sets were considered for each test channel. The model was calibrated and validated using the same dataset as for the one-PC-predictor model.

The rms difference of nadir-corrected BT bias (not shown) and standard deviation of the “restricted” two-PC-predictor model were similar to those of the one-PC-predictor model, with the exception of greater improvement in the daytime BT SD at the larger scan angles for the solar glint channels after nadir correction for the two-PC-predictor model (Fig. 9a). Between these two models, the one-PC-predictor model is arguably more satisfactory for its simplicity and for the global optimality of its predictor. Moreover, less information needs to be retained during the practical implementation of the algorithm. However, the complete answer to the question whether a multiple-PC-predictor model would be superior to the one-PC-predictor model awaits the incorporation of more effective optimization strategies if PCs of smaller variance were to be included.

The presented nadir-correction model inherently assumes that the nadir radiance could be obtained by a linear combination of off-nadir radiances and the model parameters can be determined through linear regression. For most channels in AMSU-A, such a linear model is theoretically sound because of the near-linear dependence of radiance on atmospheric temperature within the microwave frequencies and the relative insensitivity of AMSU-A channel weighting functions to atmospheric conditions, as shown by Goldberg and Fleming (1995) and G2001. On the other hand, the Planck function in the infrared has a stronger nonlinearity in temperature, and the transmittance in this region of the electromagnetic spectrum is more sensitive to fluctuations of water vapor. This means that, in principle, the model parameters may not be completely stationary between the calibration and validation datasets for infrared soundings.

Despite the last apparent drawback, the presented nadir-correction model for AIRS performs just as well as the fully statistical model of G2001 for AMSU-A in improving $s_r$. Our validation of the G2001 fully statistical model for oceanic cloud-free FOVs over the same geographical region as earlier showed that the average fractional reduction of $s_r$ is about 61% for AMSU-A channels showing improvement in $s_r$ after the nadir correction. This value is near the average fractional reduction of nighttime $s_r$ (55%) for the AIRS channels used in Table 2.
6. Conclusions

A method to correct the limb effect of observed AIRS radiances at scan positions away from nadir was reported. This method uses an empirical linear model in which the target channel radiance and principal component scores of the other channel radiances are predictors for the nadir-corrected radiance. The selection criterion for the optimal principal component predictor uses a skill score computed from the standard deviation rather than the mean of brightness temperature at each scan position. A one-PC-predictor model was calibrated and validated.

TABLE 2. The rms difference in BT SD $s_{ij}$ for the set $S_i$ of scan angles [cf. Eq. (7) with $K = 14$], averaged over selected water vapor channels and window channels unaffected (window I) and affected (window II) by solar glint. The values BNC and ANC are listed. $L$ is the number of channels for each channel type, $Q_i$ is the percentage of the $L$ channels for which BT SD decreased ANC, and $R_i$ is the percentage for which this decrease is greater than 0.1 K. The channel indexes $i$ (and the corresponding wavenumbers in brackets) are $i = 186–232$ (1308–1605 cm$^{-1}$) for water vapor channels; $i = 129–139, 163, 165–170, 172, 175, 176$ (804–979 and 1072–1230 cm$^{-1}$) for window I; and $i = 300–318$ (2492–2664 cm$^{-1}$) for window II.
over the Indo-Pacific warm pool (15°S–20°N, 60°E–180°)
for the subset of 318 AIRS channels useful to numerical
weather prediction.

The biases in the average BT resulting from limb ef-
fect were reduced significantly for all scan positions
away from nadir. The water vapor and window channels
unaffected by solar glint show improvement in their BT
SD for the larger scan angles by more than 55% where
limb effect is most prominent. For the CO$_2$ and O$_3$
channels where the difference in BT SD from nadir
values is small in the first place, there is little or no
improvement. The nadir-correction method reduces the
impact of solar glint on the affected window channel BT
in both the mean and SD, although channels beyond
2420 cm$^{-1}$ may be still affected by residual solar glint
bias.

Two issues that may constrain the performance of the
model were discussed. First, global optimality of the
PC-predictor set was only confirmed for the one-PC-
predictor model with the available computer resource.
For larger number of PC-predictor sets, if the explained
variance was not to be used as a criterion for restricting
the number of candidate PCs, better optimization pro-
cedures have to be sought for the computation to be
practical. Second, the model relies on the linear com-
bination of channel radiances to correct for the limb
effect of a target channel. Thus, its performance may be
limited by the nonlinearity of the Planck function with
temperature in infrared frequencies and the sensitivity
of many infrared channels to water vapor concentra-
tion. Despite these uncertainties, the one-PC-predictor
model performed as well as the G2001 statistical nadir-
correction model for microwave radiances where the
same uncertainties are less severe.

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