

Improved Surface Parameter Retrievals using AIRS/AMSU Data

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ABSTRACT

The AIRS Science Team Version 5.0 retrieval algorithm became operational at the Goddard DAAC in July 2007 generating near real-time products from analysis of AIRS/AMSU sounding data. This algorithm contains many significant theoretical advances over the AIRS Science Team Version 4.0 retrieval algorithm used previously. Two very significant developments of Version 5 are: 1) the development and implementation of an improved Radiative Transfer Algorithm (RTA) which allows for accurate treatment of non-Local Thermodynamic Equilibrium (non-LTE) effects on shortwave sounding channels; and 2) the development of methodology to obtain very accurate case by case product error estimates which are in turn used for quality control. These theoretical improvements taken together enabled a new methodology to be developed which further improves soundings in partially cloudy conditions. In this methodology, longwave CO₂ channel observations in the spectral region 700 cm⁻¹ to 750 cm⁻¹ are used exclusively for cloud clearing purposes, while shortwave CO₂ channels in the spectral region 2195 cm⁻¹ to 2395 cm⁻¹ are used for temperature sounding purposes. This allows for accurate temperature soundings under more difficult cloud conditions. This paper further improves on the methodology used in Version 5 to derive surface skin temperature and surface spectral emissivity from AIRS/AMSU observations. Now, following the approach used to improve tropospheric temperature profiles, surface skin temperature is also derived using only shortwave window channels. This produces improved surface parameters, both day and night, compared to what was obtained in Version 5. These in turn result in improved boundary layer temperatures and retrieved total O₃ burden.

Keywords: High spectral resolution IR sounders, atmospheric sounding, satellite meteorology, new theoretical developments

1. INTRODUCTION

AIRS was launched on EOS Aqua on May 4, 2002, together with AMSU-A and HSB, to form a next generation polar orbiting infrared and microwave atmospheric sounding system.¹ The primary products of AIRS/AMSU-A are twice daily global fields of atmospheric temperature-humidity profiles, ozone profiles, sea/land surface skin temperature, and cloud related parameters including OLR. Also included are the clear column radiances \hat{R}_i used to derive these products, which are representative of the radiances AIRS would have seen if there were no clouds in the field of view. All products also have error estimates. The sounding goals of AIRS are to produce 1 km tropospheric layer mean temperatures with an rms error of 1K, and layer precipitable water with an rms error of 20 percent, in cases with up to 90 percent effective cloud cover. The products are designed for data assimilation purposes so as to improve numerical weather prediction, as well as for the study of climate and meteorological processes. With regard to data assimilation, one can use either the products themselves or the clear column radiances from which the products were derived.

The basic theory used to analyze AIRS/AMSU/HSB data in the presence of clouds, called the at-launch algorithm, and that used in a post-launch algorithm, which differed only in the minor details from the at launch algorithm, has been described previously^{2,3}. The post-launch algorithm, referred to as AIRS Version 4,³ had been used by the Goddard DAAC to analyze and distribute AIRS retrieval products. Susskind⁴ described progress towards the AIRS Version 5 retrieval algorithm. The Version 5 algorithm has since been finished and is now operational at the Goddard DAAC. The Goddard DAAC has reprocessed the entire AIRS/AMSU data set using the improved AIRS Science Team Version 5 retrieval algorithm. The AIRS Version 5 retrieval algorithm has two major improvements compared to Version 4. The first of these improvements results from the incorporation of a new Radiative Transfer Algorithm (RTA), derived by Larrabee Strow and co-workers, that accurately accounts for the effects of Non-Local Thermodynamic Equilibrium (non-LTE) on the radiances in the 4.2 μ m CO₂ band. Non-LTE occurs during the day and, if not properly accounted for, makes radiances in most channels in the 4.2 μ m CO₂ band unusable for retrieval purposes³. Version 5 does not have this limitation. Therefore, following theoretical cloud-clearing principles⁵, Version 5 uses tropospheric sounding 15 μ m

channels only for the purpose of deriving cloud cleared radiances \hat{R}_i and cloud geophysical parameters. The physical retrieval step finds geophysical solutions best matching \hat{R}_i for an ensemble of i channels². In Version 5, most of the 4.2 μm CO_2 channels are used to determine temperature profile, as are 15 μm stratospheric sounding CO_2 channels which are not sensitive to clouds in the field of regard. This combination allows for the ability to produce accurate temperature profiles under more difficult cloud conditions.

The second major improvement in Version 5 is the new methodology to produce accurate case-by-case, level-by-level error estimates of retrieved temperatures at a given pressure level $\delta T(p_i)$, as well as channel by channel clear column radiance error estimates, $\delta \hat{R}_i$. Thresholds of these error estimates are subsequently used for quality control (QC). Susskind⁶ showed that Version 5 produces temperature profiles of comparable accuracy to those of Version 4, but with about twice the percentage of cases deemed acceptable in the middle troposphere, when a standard set of QC thresholds are used. Alternatively, using tighter acceptance thresholds resulted in significantly greater accuracy compared to Version 4 with about a 20% increase in acceptable profiles.

While Version 5 is a significant improvement compared to Version 4, there is still room for improvement. A further improved AIRS Science Team Version 6 algorithm is expected to be completed in late 2008. In this paper, we describe the current status (as of March 2008) of the progress made in the determination of surface skin temperature, surface spectral emissivity, and surface spectral bi-directional reflectance of solar radiation. This results in improvements not only in the retrieved surface parameters, but in other products as well. We refer to the current status system as Version 5⁺.

2. CHANGES IN THE AIRS SCIENCE TEAM RETRIEVAL ALGORITHM

The AIRS Science Team Version 5 retrieval algorithm is basically identical to that described previously²⁻⁴. The key steps of Version 5 are: 1) Start with an initial state consistent with the AIRS/AMSU observed radiance. 2) Derive IR clear column radiances \hat{R}_i^0 valid for the 3x3 AIRS Fields of View (FOVs) within an AMSU-A Field of Regard (FOR) consistent with the observed radiances and the initial state using 58 AIRS cloud clearing channels; 3) Obtain an AIRS regression guess consistent with \hat{R}_i^0 using 1504 AIRS channels; 4) Derive \hat{R}_i^1 consistent with the AIRS radiances making use of the regression guess; 5) Derive all surface and atmospheric parameters using \hat{R}_i^1 for 308 AIRS channels and AMSU radiances; 6) Derive an improved set of clear column radiances \hat{R}_i^2 using the AIRS physically retrieved parameters; 7) Repeat Step 5 using \hat{R}_i^2 to produce the final retrieval state; 8) Derive cloud parameters and OLR consistent with the solution and observed R_i ; 9) Apply initial quality control, which rejects the final solution if the retrieved cloud fraction is greater than 90% or other relatively coarse tests fail. In the event that retrieval is rejected, cloud parameters are determined consistent with the state used for initial cloud clearing, in conjunction with the observed AIRS radiances. Otherwise, cloud parameters are computed using the final retrieval and observed AIRS radiances, and further quality control is applied to individual geophysical parameters.

The current Version 5⁺ retrieval system is essentially identical to that of Version 5, except for details in the physical retrieval step 5 (and 7). The physical retrieval process is comprised of a number of sequential steps listed below, each using \hat{R}_i for its own sets of channels. Geophysical parameters solved for in a given step are generally held fixed when solving for different sets of geophysical parameters in subsequent steps. In Version 5, the sequential steps are: 1) Solve for surface parameters; 2) Solve for atmospheric temperature profile $T(p)$; 3) Solve for atmospheric moisture profile $q(p)$; 4) Solve for ozone profile $\text{O}_3(p)$; and 5) subsequently solve for $\text{CO}(p)$ and $\text{CH}_4(p)$. Version 5⁺ adds a new step to solve for longwave surface spectral emissivity performed between step 3) and step 4).

2.1 Version 5⁺ changes in the surface parameter retrieval step

Two types of changes have been made to the surface parameter retrieval step: 1) Changes to the form of the perturbation equations used to update the surface spectral emissivity ϵ_v and surface spectral bi-directional reflectance ρ_v and 2)

changes in the channel set and emissivity and reflectivity functions being perturbed. In addition, there is a modification made to the initial guess ρ_v^0 .

2.1.1 Changes in the form of the emissivity and reflectivity perturbation equations

A product of the AIRS regression step is the initial IR surface spectral emissivity state ϵ_v^0 . An initial surface bi-directional reflectance state ρ_v^0 is generated indirectly from ϵ_v^0 according to the assumption of a Lambertian surface:

$$\rho_v^0 = \frac{1 - \epsilon_v^0}{\pi} \quad 1)$$

In Version 5, the physical surface spectral emissivity and spectral bi-directional reflectance products were determined, using ϵ_v^0 and ρ_v^0 as a first guess, according to

$$\epsilon_v = \epsilon_v^0 + \sum_i A_i F_i(v) \quad 2a)$$

and

$$\rho_v = \rho_v^0 + \sum_i B_i G_i(v) \quad 2b)$$

where $F_i(v)$ and $G_i(v)$ are pre-assigned spectral trapezoidal perturbation functions and A_i and B_i are unknown coefficients solved for in the surface parameter retrieval step. One problem with use of Equation 2 in Version 5 is that occasionally, unphysical values of $\epsilon_v > 1$ or $\rho_v < 0$ would occur.

This perturbation methodology has been improved in Version 5⁺, in which we write

$$(1 - \epsilon_v) = (1 - \epsilon_v^0) [1 + \sum_i A_i F_i(v)] \quad 3a)$$

and

$$\rho_v = (\rho_v^0) [1 + \sum_i B_i G_i(v)] \quad 3b)$$

There has also been a modification made to the initial guess ρ_v^0 to be used in Equation 3b. Equation 1) does not provide an accurate initial guess for ρ_v^0 for two reasons. The first is that the surface is usually not Lambertian. The second, and potentially more significant limitation in the use of Equation 1), is that ρ_v is used in a term in the radiative transfer equation which multiplies the incoming solar radiation striking the earth's surface H_v . In general H_v will be attenuated by clouds partially obscuring the atmospheric path from the sun to the earth's surface being observed with cloud fraction α_{sun} . These clouds should not be confused with clouds partially obscuring the path from the surface to the satellite, whose effects are accounted for when generating \hat{R}_i . This unknown attenuation would result in an effective value of ρ_v which is the true value multiplied by $(1 - \alpha_{\text{sun}})$.

Computed brightness temperatures in shortwave window channels during the day are very sensitive to ρ_v , with sensitivity increasing with frequency. An otherwise reasonable initial guess can produce values of $\hat{\Theta}_i - \Theta_i^0$, where $\hat{\Theta}_i$ is the clear column brightness temperature and Θ_i^0 is the brightness temperature computed from the guess state, that differ from each other by 10K or more when compared at 2448 cm^{-1} and 2646 cm^{-1} . In Version 5⁺, we set

$$\rho_v^0 = d \left(\frac{1 - \epsilon_v^0}{\pi} \right) \quad 4)$$

where d is determined such that $(\hat{\Theta}_{2646} - \Theta_{2646}^0) = (\hat{\Theta}_{2448} - \Theta_{2448}^0)$ when Θ_i^0 uses ρ_v^0 given by Equation 4. This constant is frequency independent.

The form of Equation 3a resulted from the realization that the signal in ϵ_v is the amount it differs from a blackbody surface, with $\epsilon_v = 1$. There are two practical benefits in the form of Equation 3. The first is that ϵ_v is always ≤ 1 and ρ_v is ≥ 0 as long as both hold for the first guess and each A_i and B_i is ≥ -1 . Occasionally, the physical retrieval step now results in values of A_i or $B_i < -1$, in which case, they are set to -0.99. The second benefit of equation 3 is that for surfaces expected to have spectral emissivities close to 1.0, such as ocean and ice, the retrieved spectral emissivities will always remain close to 1.0. This stabilizes the solution.

2.1.2 Changes in the channels and functions used to determine T_s , ϵ_v , and ρ_v

In Version 5, T_s , ϵ_v , and ρ_v were all solved for in a single retrieval step. 15 longwave window channels between 758 cm^{-1} and 1228 cm^{-1} , and 10 shortwave window channels between 2456 cm^{-1} and 2658 cm^{-1} were used simultaneously to determine T_s along with two coefficients A_1 and A_2 of longwave spectral perturbation functions $F_1(v)$, one coefficient A_3 of a shortwave spectral perturbation function, and one coefficient B_1 of the spectral bi-directional reflectance perturbation function G_1 .

The methodology used in Version 5⁺ represents a significant change in the philosophy in the determination of surface skin temperature T_s . Rather than use both longwave window channels (in which observations are not affected by reflected solar radiation) and shortwave window channels (which can be affected significantly by reflected solar radiation) to determine T_s , we now use only 57 shortwave window channels between 2396 cm^{-1} and 2660 cm^{-1} to determine T_s , simultaneously with coefficients of 2 shortwave spectral emissivity perturbation functions, A_{1s} and A_{2s} , and 2 values of spectral bi-directional functions B_1 and B_2 .

The main motivation for this modified approach is the same as that for using only shortwave CO_2 absorption channels in the determination of tropospheric temperature profile. Cloud clearing errors will now result in smaller errors of T_s . This enables accurate determination of T_s under a wider range of more difficult cloud conditions, in an analogous manner to what was found when only shortwave CO_2 absorption channels were used to determine tropospheric $T(p)$ (Version 5) compared to the simultaneous use of longwave and shortwave CO_2 channels to determine $T(p)$ (Version 4).⁶ Coefficients of 3 longwave spectral perturbation functions are now solved for, using 70 window channels between 756 cm^{-1} and 1234 cm^{-1} , in a new separate step performed subsequent to the steps retrieving T_s , $T(p)$, and $q(p)$. Values of T_s , $T(p)$, and $q(p)$ are assumed known and held fixed in the determination of longwave spectral emissivity. This makes the longwave spectral emissivity retrieval step extremely stable. We expect to be able to accurately determine coefficients of more than 3 longwave emissivity functions in the future, but we have not attempted to do this yet.

This approach to use only shortwave window channel observations to determine T_s has never been tried previously, or at least successfully utilized previously, because of concerns (or problems) in accounting for effects of reflected solar radiation during the day on the shortwave window channels. As will be shown later, results of this new approach are actually better during the day than at night.

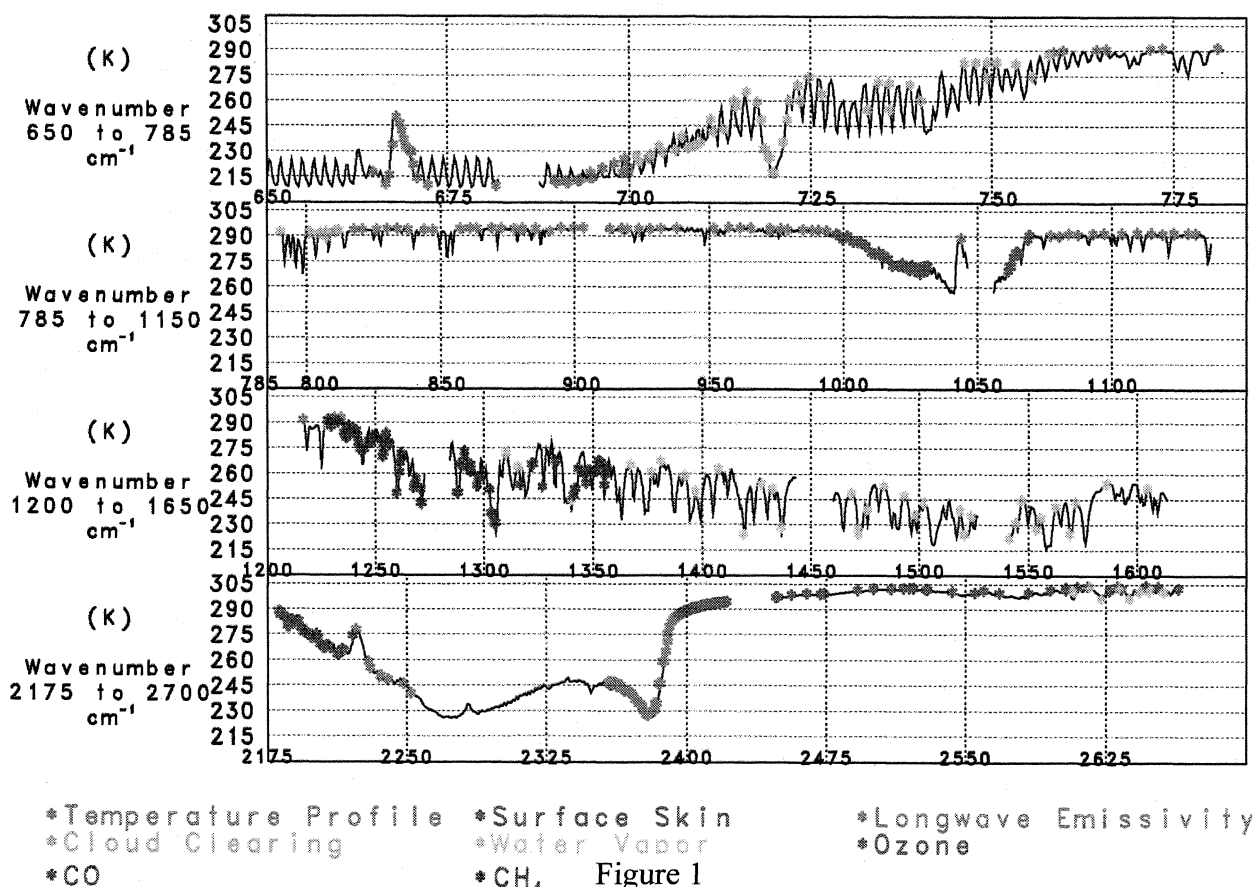
2.2 Changes in the temperature profile retrieval step

The temperature profile retrieval step in Version 5⁺ not only solves for $T(p)$ as before, but also simultaneously updates T_s , A_{1s} , A_{2s} , B_1 , and B_2 . The temperature profile retrieval step now includes the 57 shortwave window channels used in the surface parameter retrieval step along with the same temperature profile retrieval channels used in Version 5.0. The temperature profile retrieval step is otherwise unchanged.

Figure 1 shows a typical AIRS cloud free brightness temperature spectrum. Channels used for different purposes are indicated in the figure. The 70 channels used to determine the coefficients of the 3 longwave emissivity perturbation functions are shown in purple. These include a channel in the center of the O_3 absorption band (channels used to determine O_3 profile are shown in green) which helps in the determination of the spectral emissivity in the O_3 absorption region. The 57 channels used to determine surface skin temperature and shortwave values of ϵ_v and ρ_v are shown in blue. These are also used in conjunction with the red temperature sounding channels, most of which are in the spectral interval 2358 cm^{-1} – 2395 cm^{-1} . Stratospheric sounding 15 μm CO_2 absorption channels between 660 cm^{-1} and 700 cm^{-1}

are also included in the temperature profile retrieval step, along with some N₂O absorption channels in the vicinity of 2200 cm⁻¹. Determination of \bar{R}_i is performed using the yellow cloud clearing channels, found mostly in the 15 μ m CO₂ absorption region with $\nu_i > 700$ cm⁻¹. Also included are some longwave window channels.

Sample AIRS Cloud Free Brightness Temperature



3. Improved results using Version 5⁺

Most of the changes made for Version 5⁺ were in the retrieval of the surface parameters T_s and ϵ_i . These have led to improved products over land and ocean.

3.1 Improvements over ocean

Figure 2a shows the Version 5⁺ quality controlled surface skin temperature for ascending (daytime) orbits for January 25, 2003. Grey indicates missing data resulting from orbit gaps or areas that were too cloudy to perform a quality controlled successful retrieval. Figure 2c shows the difference in surface skin temperature between Version 5⁺ and Version 5 (red means Version 5⁺ is warmer). The largest differences occur over land, where we do not have a good measure of the true values of T_s . Significant differences also occur over ocean, where we use the ECMWF SST analysis as a measure of truth. Maximum sun-glint over ocean occurs slightly left of center of the ascending orbits. Figure 2c shows Version 5⁺ tends to be warmer than Version 5 to the left of the scan, and cooler to the right. Figure 2d shows that T_s determined using Version 5 over ocean tends to be too cold (blue) compared to ECMWF at the left of the scan, and too warm (red) at the right of the scan. Figure 2b shows much better agreement with ECMWF of T_s determined over ocean using Version 5⁺.

Surface Skin Temperature (K) January 25, 2003

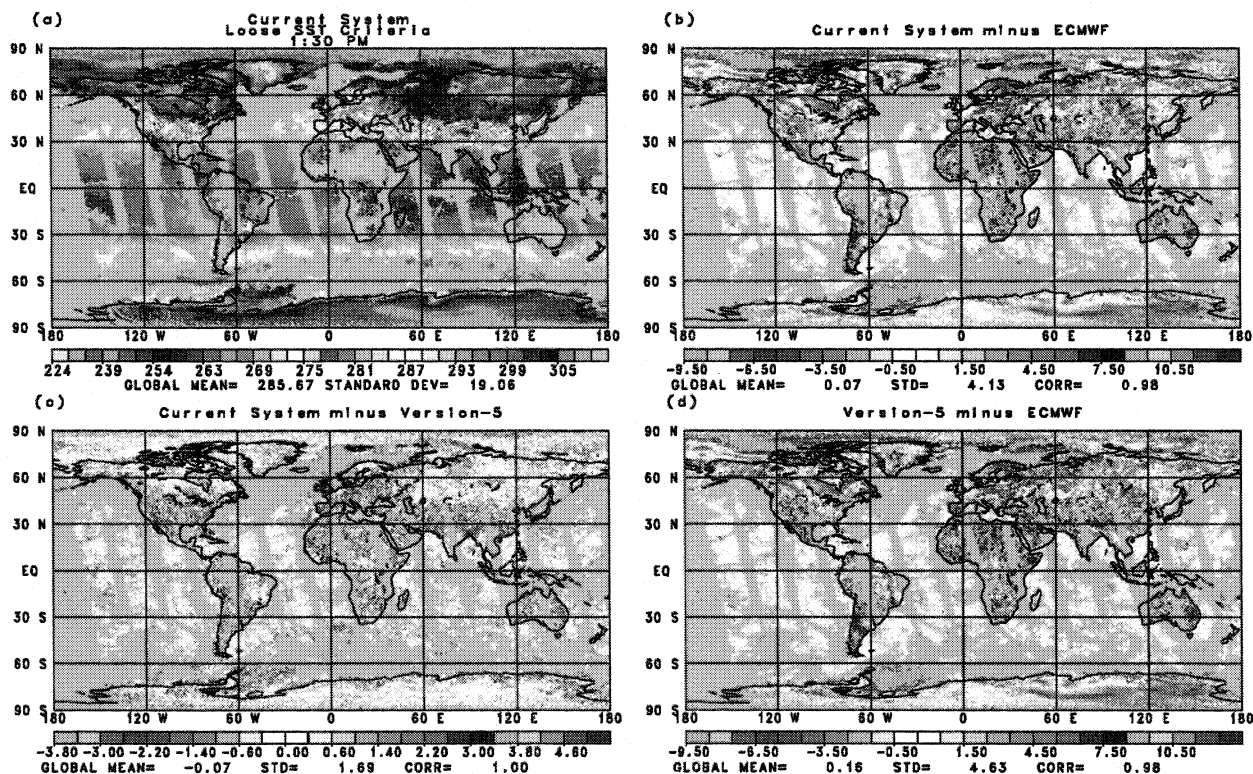


Figure 2

Surface Skin Temperature Difference from ECMWF September 6, 2002, January 25, 2003, September 29, 2004 50 N to 50 S Non-Frozen Ocean Daytime and Nighttime combined

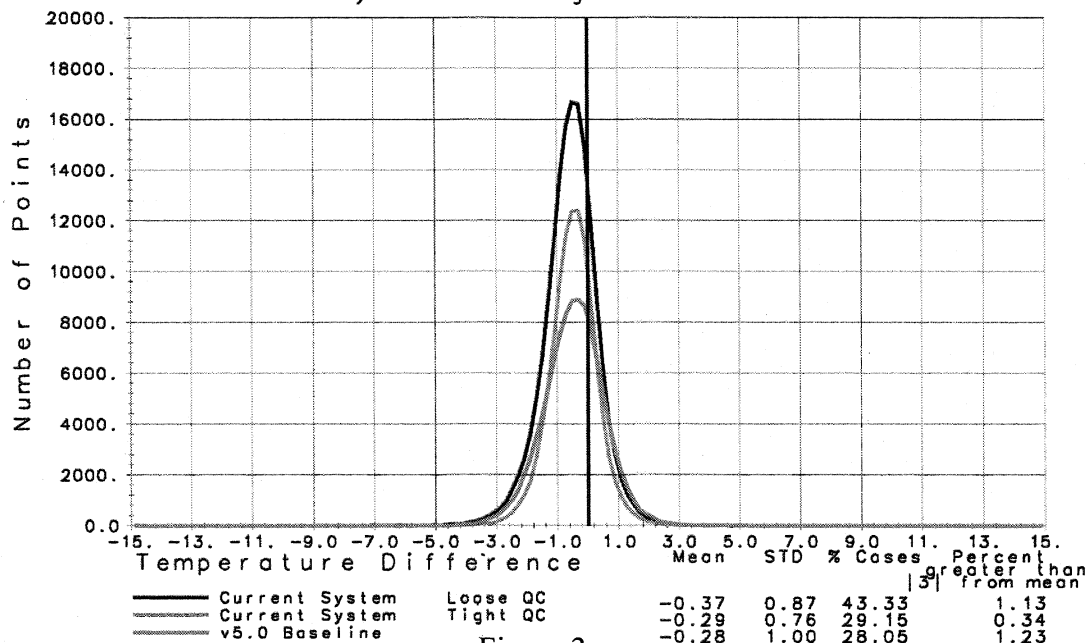


Figure 3

Figure 3 shows the number of quality controlled values of T_s versus their difference from ECMWF “truth” for all accepted daytime and nighttime retrievals over ocean, 50°N-50°S, for a composite of 3 days in which Version 5⁺ was tested. Also shown in the mean difference from ECMWF, the standard deviation of ($T_s - \text{ECMWF}$), the percent of the retrievals passing QC, and the percent of the accepted retrievals classified as outliers, i.e., $|T_s - \text{ECMWF}| > 3K$ from the mean difference. Version 5 results are shown in red. Version 5⁺ results are shown with two different QC δT_s thresholds. The tight threshold (grey) results in similar percentage yield compared to Version 5, but gives SST’s with a significantly lower standard deviation from ECMWF, as well as a lesser percent of outliers. The loose QC threshold (black) provides results with a substantial increase in accepted retrievals compared to Version 5, but still with a lower standard deviation of errors and percent outliers. This considerable improvement in retrieved SST is a direct result of using shortwave channels to determine T_s , and longwave channels for cloud clearing, so as to be able to determine accurate values of T_s under more difficult cloud conditions. Figure 2a showed the spatial coverage and accuracy of Version 5⁺ T_s using the Loose QC threshold.

Figures 4 and 5 give an indication of the improvement in retrieved values of ϵ_v over ocean as determined by Version 5⁺ compared to Version 5. Ocean spectral emissivity is reasonably well described by the Masuda model⁷. At a given frequency, it is a small function of wind speed and a larger function of satellite zenith angle. Up to changes in wind speed, the surface emissivity over ocean should be relatively close to that predicted by the Masuda model, and not change appreciably at a given zenith angle, nor change appreciably from day to night. Figures 4a and 4b show the angular dependence of the 3 day mean of the difference of retrieved values of ϵ_v from the Masuda model for 950 cm^{-1} and 2400 cm^{-1} respectively. Version 5⁺ values are in black for AM cases and grey for PM cases, while Version 5 values

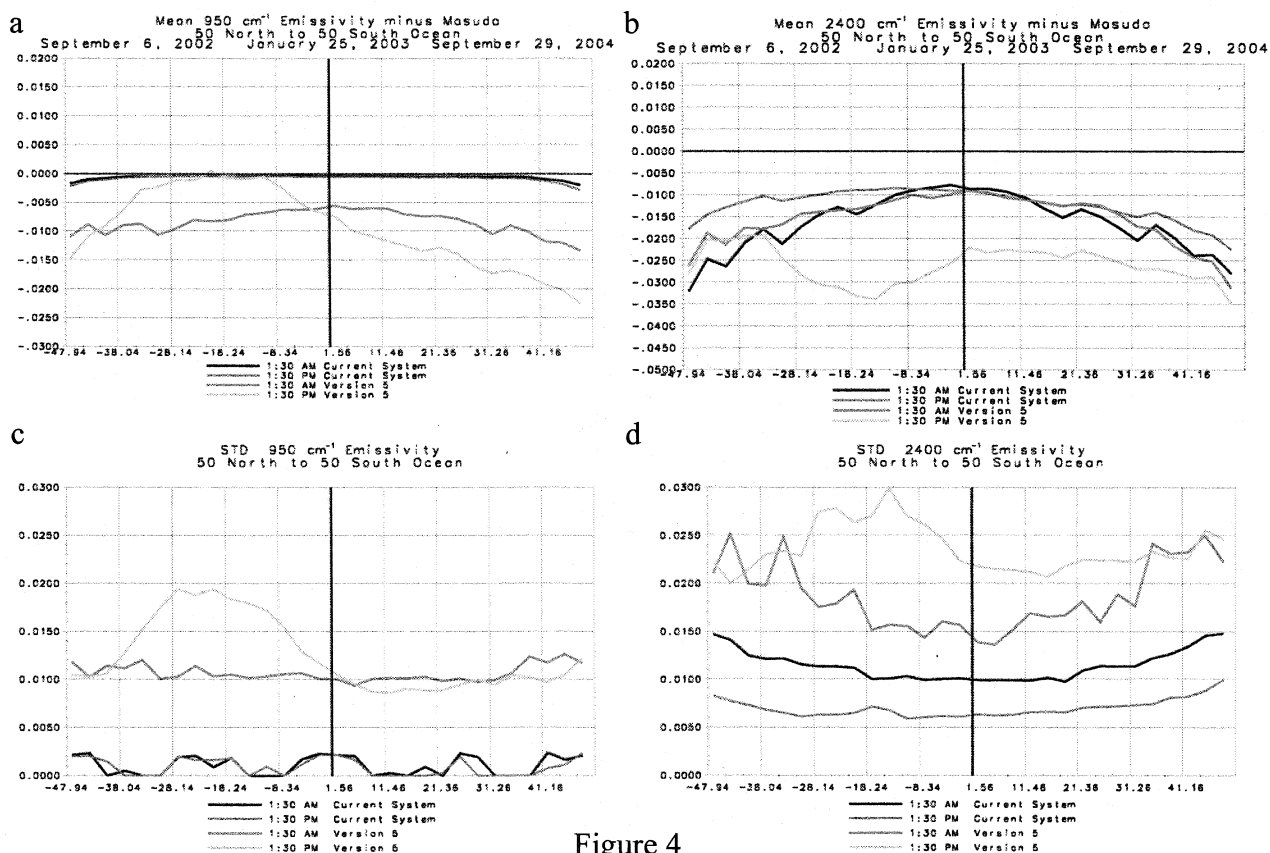


Figure 4

are in dark blue and light blue for AM and PM cases respectively. Maximum sun-glint occurs in the vicinity of -20° satellite zenith angle. Figures 4c and 4d show analogous results for the standard deviation of retrieved values of ϵ_v at a given satellite zenith angle. It is apparent that the mean retrieved values of ϵ over ocean at 950 cm^{-1} and 2400 cm^{-1} are considerably closer to the Masuda model, both day and night, using Version 5⁺ compared to Version 5. In addition they are also much more stable, having a considerably lower standard deviation day and night. It is informative to see that Version 5 standard deviations of ϵ_v are larger during the day than at night, especially in the sun-glint area ($\approx -20^\circ$). In Version 5⁺, the standard deviations are very small day and night at 950 cm^{-1} and are actually lower during the day than at night at 2400 cm^{-1} , with no indication of instabilities as a result of sun-glint.

Figure 5 shows the mean difference of AM and PM retrieved surface emissivities for four frequencies. These AM/PM differences are considerably smaller in Version 5⁺ than in Version 5.

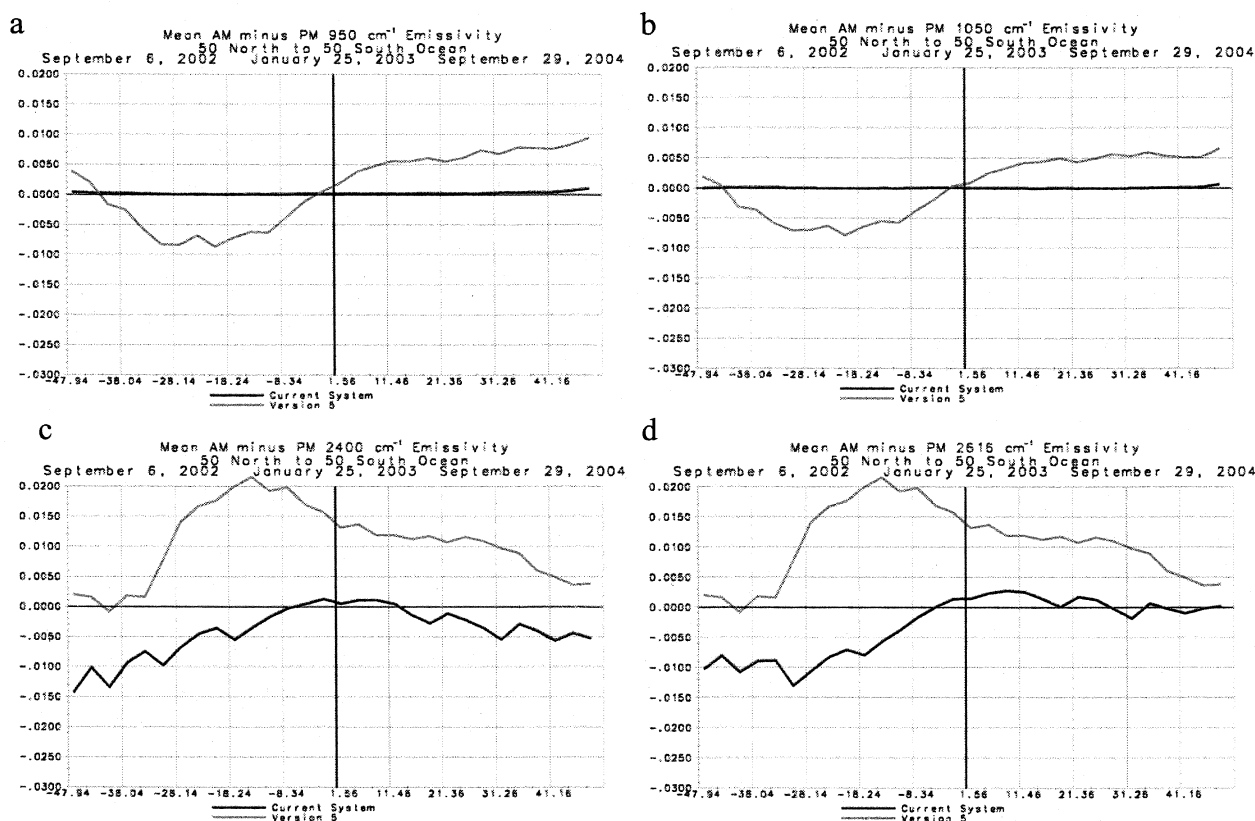


Figure 5

3.2 Improvements over land

Unlike ocean where both surface skin temperature and surface spectral emissivity are reasonably well known, there is no good measure of truth over land for either quantity. Therefore, we use indirect means to evaluate any improvements in retrieved surface parameters. While we do not have a good measure of surface spectral emissivity at a given location, we know it should not change appreciably from day to night. Figure 6 shows mean differences of retrieved surface emissivity as a function of zenith angle over land. Day/night differences of retrieved emissivity using Version 5⁺ over land are considerably lower than they were using Version 5. This result is analogous to what was found over ocean (see Figure 5).

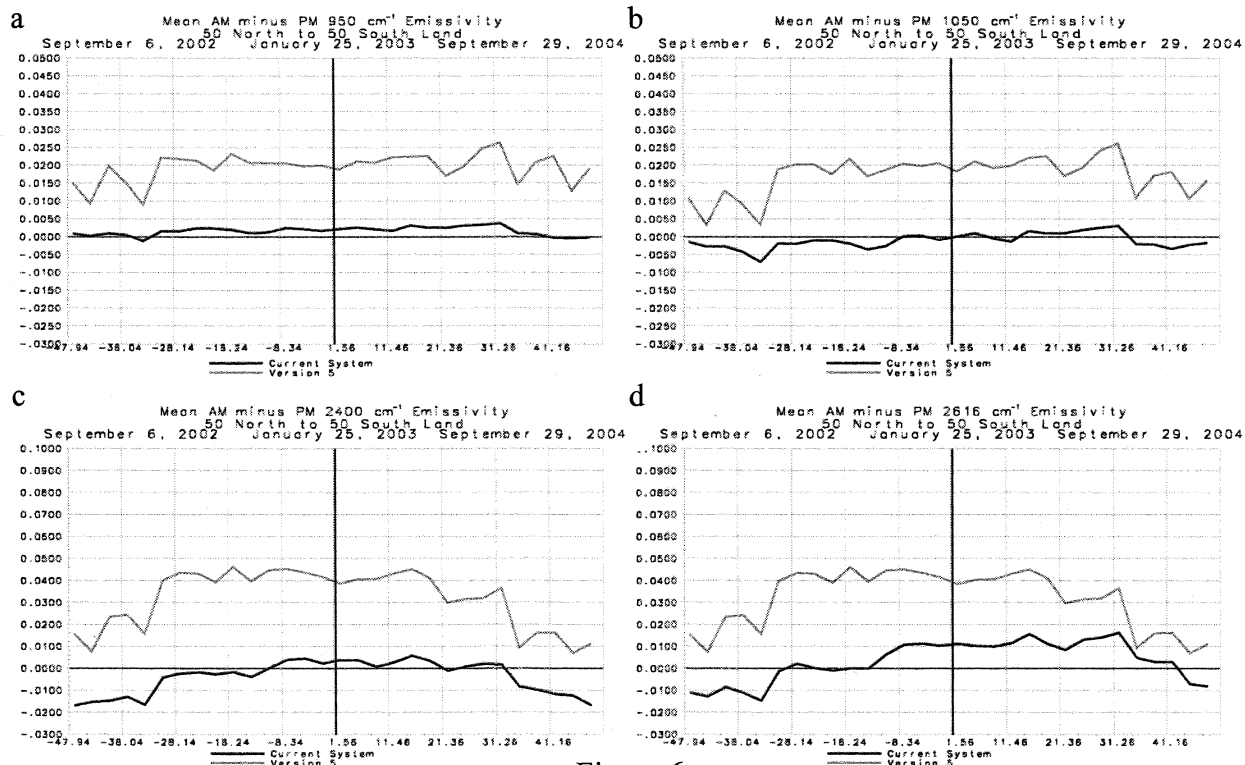


Figure 6

September 6, 2002, January 25, 2003, and September 29, 2004
AIRS IR Emissivity

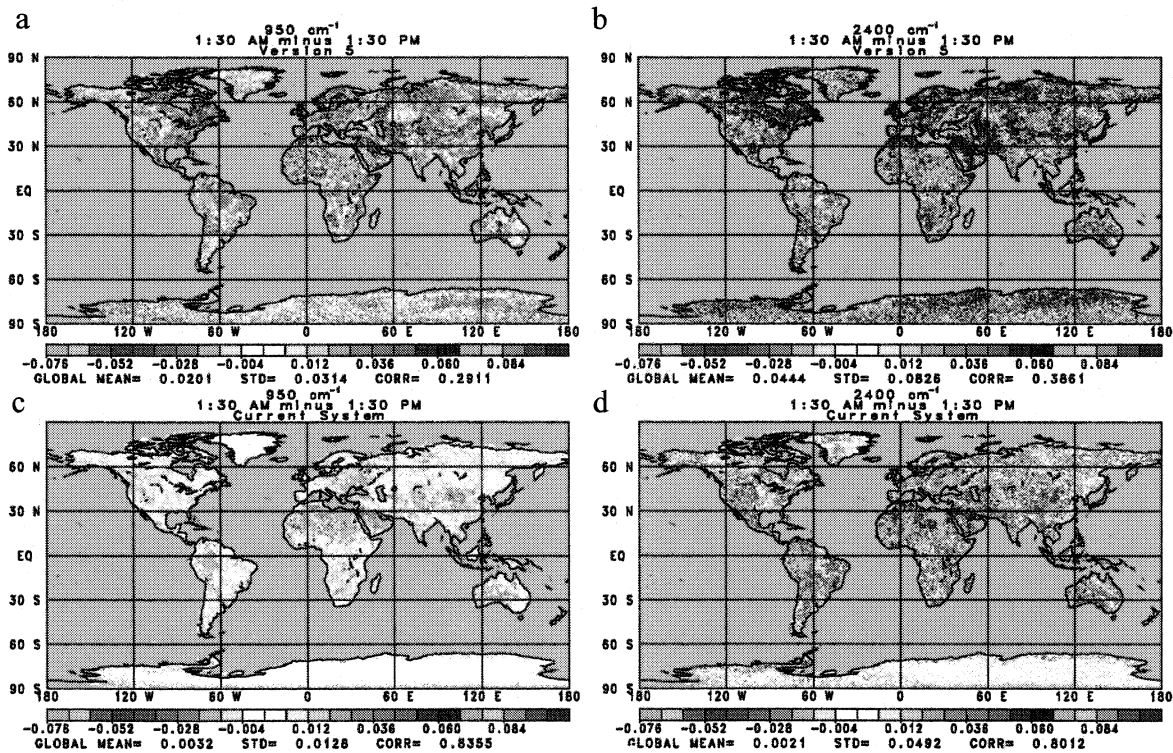


Figure 7

Figure 7 shows the spatial distribution of the AM/PM differences of retrieved emissivity over land at 950 cm^{-1} and 2400 cm^{-1} . These differences are much smaller in Version 5⁺ (Figure 7c and 7d) than in Version 5 (Figures 7a and 7b), especially over ice. The spatial correlation of the day and night emissivity maps are given in the figure, and are much higher at both frequencies in Version 5⁺ (≈ 0.8) than in Version 5 (≈ 0.3).

Figure 8a and 8b shows RMS 1 km layer mean differences of quality controlled day and night oceanic and land temperature profile retrievals from a colocated ECMWF analysis determined using Version 5 (red) and Version 5⁺ (grey). It is apparent that the improvement in retrieved surface parameters has also improved the accuracy of the quality controlled temperature profile by about 0.1K in the lowest 2 km of the atmosphere over ocean, and by 0.2K over land.

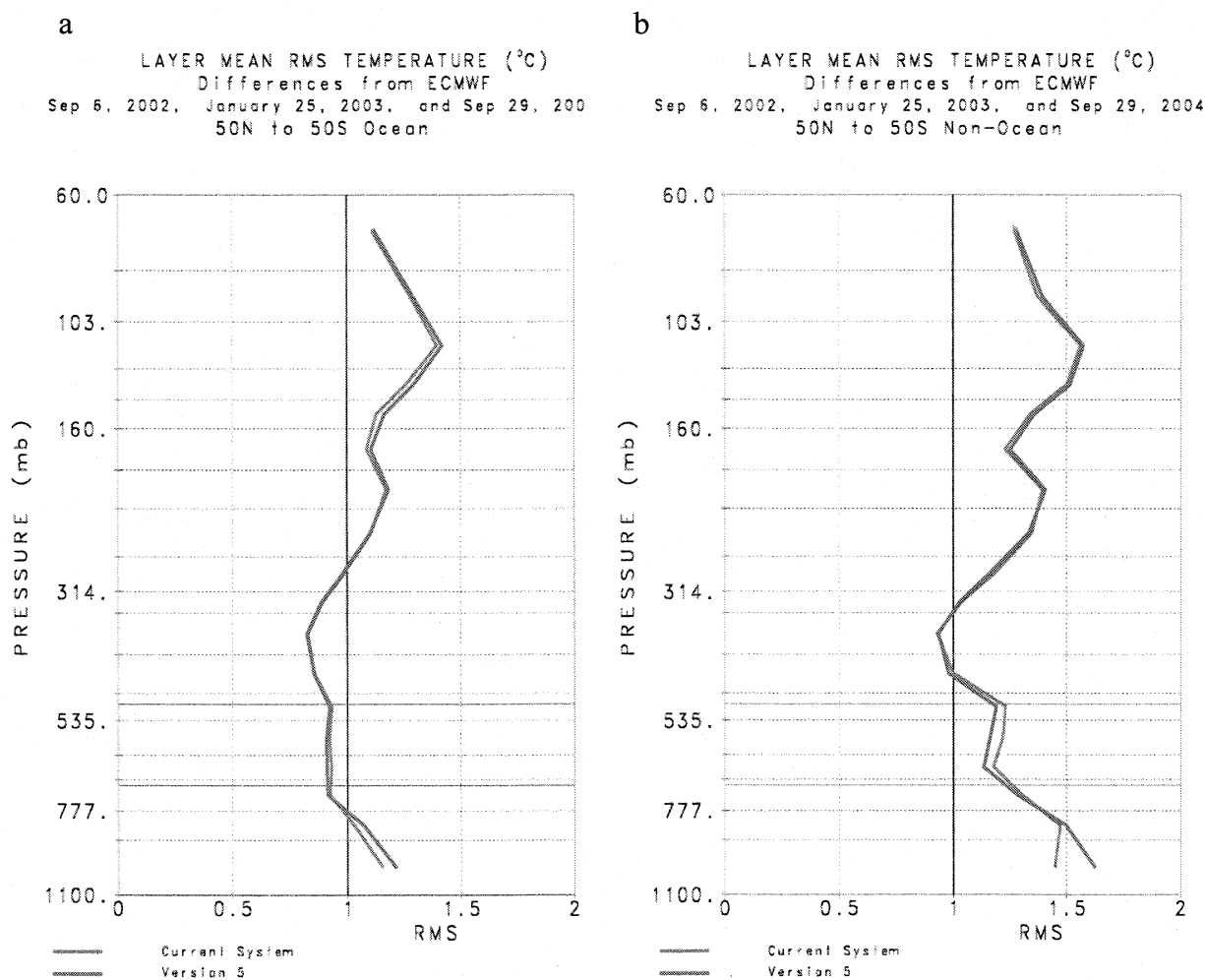


Figure 8

OZONE (DU)
January 25, 2003

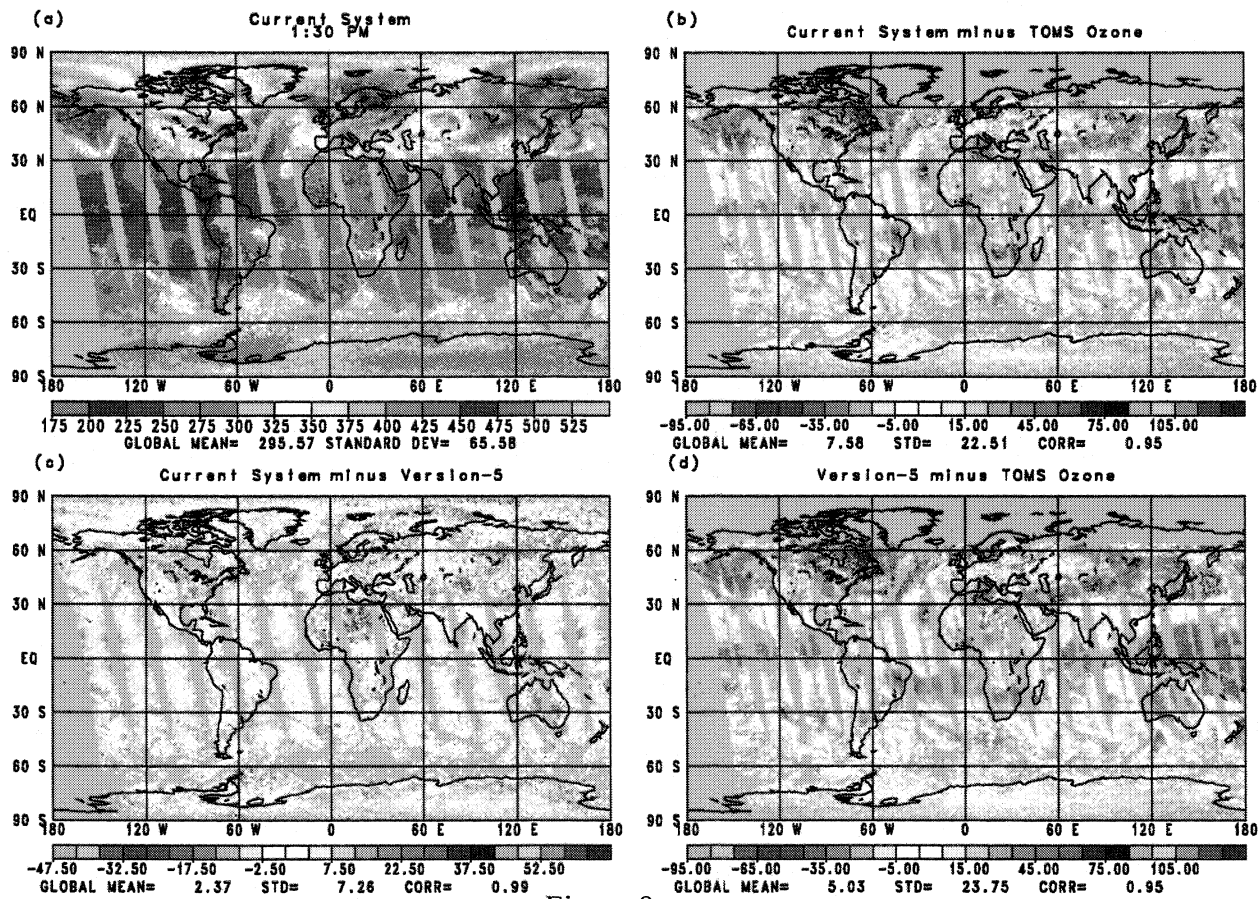


Figure 9

Figure 9 gives an indication of the improvement in total ozone, as compared to colocated TOMS total ozone, resulting from the changes made in Version 5⁺. Figure 9a shows the quality controlled AIRS Version 5⁺ total O₃ field derived for daytime orbits on January 25, 2003. Figure 9c shows Version 5⁺ total ozone minus Version 5 total O₃ (red means Version 5⁺ is higher). Total O₃ retrieved over ocean has increased compared to Version 5, especially at the end of the scan. Figure 9d shows that Version 5 total O₃ tended to be low compared to TOMS over ocean. Figure 9b shows agreement of total O₃ with TOMS is now improved over ocean.

Over Northern Hemisphere extra-tropical land, total O₃ retrieved using Version 5⁺ is generally lower than that retrieved using Version 5. In the central Sahara desert, total O₃ is now significantly higher than it was in Version 5. All of these changes are in the correct direction so as to decrease differences from TOMS of Version 5⁺ total O₃ over land compared to Version 5 total O₃. Note that no changes have been made to the O₃ profile retrieval step, so the improvements are an indirect result of improvements in skin temperature and surface emissivity near 1050 cm⁻¹.

4. Summary

Improved methodology has been developed to determine surface skin temperature T_s and surface spectral emissivity ϵ_v from AIRS/AMSU observations under partial cloud cover. In this methodology, only shortwave window channels are used to simultaneously determine T_s and shortwave values of ϵ_v , along with shortwave values of effective surface bi-directional reflectance of solar radiation ρ_v . Longwave values of ϵ_v are determined in a subsequent step using only longwave window channels, consistent with the previously derived value of T_s . This results in considerable improvement in retrieved surface parameters compared to what was obtained using Version 5, both day and night. It also allows for very accurate soundings of SST under more difficult cloud conditions compared to the methodology used in Version 5. The improvement in retrieved surface parameters also resulted in improved values of quality controlled boundary layer temperatures as well as of total O_3 . This research is being conducted as part of the development of the new AIRS Science Team Version 6 retrieval algorithm which is expected to be completed in late 2008 and used by the Goddard DAAC starting in 2009.

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