

Results from CrIS/ATMS Obtained Using an “AIRS Version-6 Like” Retrieval Algorithm

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ABSTRACT

A main objective of AIRS/AMSU on EOS is to provide accurate sounding products that are used to generate climate data sets. Suomi NPP carries CrIS/ATMS that were designed as follow-ons to AIRS/AMSU. Our objective is to generate a long term climate data set of products derived from CrIS/ATMS to serve as a continuation of the AIRS/AMSU products. We have modified an improved version of the operational AIRS Version-6 retrieval algorithm for use with CrIS/ATMS. CrIS/ATMS products are of very good quality, and are comparable to, and consistent with, those of AIRS.

Keywords: AIRS, CrIS, high spectral resolution IR sounders, retrieval methodology, IR sounding in cloudy conditions, Quality Control.

1. INTRODUCTION

This research is being led by Joel Susskind, both as part of his research as a member of the NPP (NPOESS Preparatory Project) Science Team Sounder Discipline, and also as part of his research as a member of the AIRS (Advanced Infra-Red Sounder) Science Team. The objective of the NPP Science Team Sounder Discipline is to generate Climate Data Records (CDRs) obtained from analysis of CrIS/ATMS (Cross-Track Infra-red Sounder/Advanced Technology Microwave Sounder) data which are consistent with, and can serve as a follow-on to, the CDRs being derived by the AIRS Science Team using AIRS/AMSU (Advanced Microwave Sounding Unit) observations. The Goddard DISC has generated AIRS/AMSU retrieval products, extending from September 2002 through real time, using the AIRS Science Team Version-6 retrieval algorithm. Level-3 gridded monthly mean values of these products, generated using AIRS Version-6, form a state of the art multi-year climate data set, which is expected to continue through 2022 and possibly beyond, as the AIRS instrument is extremely stable. AIRS Version-6 level-3 products include: surface skin temperature T_s and surface spectral emissivity ε_s ; atmospheric total precipitable water W_{TOT} , total column ozone, total column methane, and total column carbon monoxide; profiles of atmospheric temperature $T(p)$, water vapor $q(p)$, ozone $O_3(p)$, methane $CH_4(p)$, and carbon monoxide $CO(p)$; cloud top pressure and effective fractional cloud cover, and Outgoing Longwave Radiation (OLR). The goal of this research is to develop and implement a CrIS/ATMS retrieval system to generate CDRs that are compatible with, and are of comparable quality to, those generated operationally using AIRS/AMSU data. The AIRS Science Team has made considerable improvements in AIRS Science Team retrieval methodology and is working on the development of an improved AIRS Science Team Version-7 retrieval methodology to be used to reprocess all AIRS data in the relatively near future. Research is underway by Dr. Susskind and co-workers at the NASA GSFC (Goddard Space Flight Center) Sounder Research Team (SRT) towards the finalization of the AIRS Version-7 retrieval algorithm, the current version of which is called SRT AIRS Version-6.22. The SRT developed analogous retrieval methodology for analysis of CrIS/ATMS data, called SRT CrIS Version-6.22. Dr. Susskind and co-workers showed AIRS and CrIS results using an earlier SRT Version-6.17 retrieval algorithm at the April 2015 AIRS Science Team Meeting. João Teixeira, the AIRS Science Team Leader, was very impressed by these results and expressed his desire that the AIRS Science Team should develop and use analogous improved retrieval methodologies for the processing of past and future of AIRS data as well as the processing of past and future CrIS/ATMS data for the purpose of generating consistent CDRs.

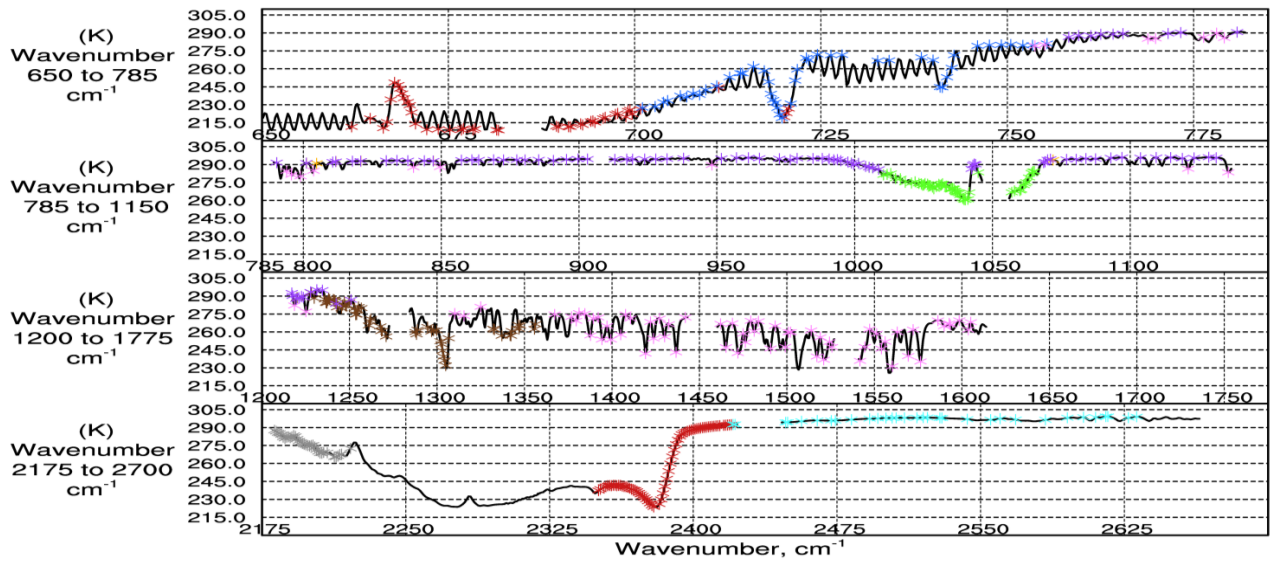
2. AIRS and CrIS

AIRS was launched on Earth Observing System (EOS) Aqua in May 2002, together with AMSU-A and Humidity Sounder Brazil (HSB) (which subsequently failed early in the mission), to form a next generation polar orbiting infrared and microwave atmospheric sounding system¹. AIRS/AMSU had two primary objectives. The first objective was to provide real-time data products available for use by the operational Numerical Weather Prediction Centers in a data assimilation mode to improve the skill of their subsequent forecasts. The second objective was to provide accurate unbiased sounding products with good spatial coverage that are used to generate consistent multi-year climate data sets to study the earth's interannual variability, climate processes, and possibly long-term trends. AIRS is a grating spectrometer with a number of linear arrays of detectors with each detector sensitive to outgoing radiation in a characteristic frequency ν_i , with a roughly Gaussian spectral band pass with half-width $\Delta\nu_i$ (spectral resolution) of roughly $\nu_i/1200$. AIRS contains 2378 spectral channels covering portions of the spectral region 650 cm^{-1} ($15.38\text{ }\mu\text{m}$) through 2665 cm^{-1} ($3.752\text{ }\mu\text{m}$), with corresponding spectral half-widths ranging from approximately 0.5 cm^{-1} to 2.2 cm^{-1} . The spectral sampling interval (except for the existence of a few gaps) is $\nu_i/2400$, giving two AIRS channels per spectral half width. AIRS is accompanied by the temperature sounding 60 GHz microwave instrument AMSU-A. There is a 3x3 array of AIRS footprints within a given AMSU-A footprint, with spatial resolutions of 13 km and 45 km at nadir viewing for AIRS and AMSU respectively. Each AIRS footprint is referred to as a Field of View (FOV), and the AMSU-A footprint is referred to as a Field of Regard (FOR). AIRS retrievals of geophysical parameters are performed on a FOR basis.

CrIS/ATMS was launched on Suomi-NPP in October 2011 as part of a sequence of Low Earth Orbiting satellite missions under the Joint Polar Satellite System (JPSS). The future JPSS missions, J1 and J2, are currently scheduled for launches in the second quarter of 2017 and the fourth quarter of 2021 respectively. The J1 mission will be very similar to NPP, using the same spacecraft and instrument complement. CrIS² and ATMS are advanced infra-red and microwave atmospheric sounders that were designed as follow-ons to the AIRS and AMSU instruments flying on EOS Aqua. CrIS is an interferometer with similar spectral coverage and noise characteristics to those of AIRS. CrIS contains three spectral bands: band 1 covering 650 cm^{-1} to 1095 cm^{-1} ; band 2 covering 1210 cm^{-1} to 1750 cm^{-1} ; and band 3 covering 2155 cm^{-1} to 2550 cm^{-1} . Unlike a grating instrument which is characterized by a roughly constant resolving power, the “spectral resolution” of an interferometer is constant within a band, and it depends on the maximum Optical Path Displacement L of that band. As currently configured, $L = 0.8\text{ cm}$, 0.4 cm , and 0.2 cm for CrIS bands 1, 2, and 3 respectively. The spectral sampling interval of an interferometer is given by $1/2L$, corresponding to 0.625 cm^{-1} in band 1, 1.25 cm^{-1} in band 2, and 2.5 cm^{-1} in band 3. The intrinsic “spectral resolution” of an interferometer is not well defined because channel spectral response functions of an interferometer depend on the type of apodization used to transform the interferogram into the radiance domain, and unlike those of AIRS, the spectral response functions have side lobes which are apodization dependent. Barnett et al.³ show that use of a Hamming apodization function provides an optimum balance between minimizing the width of the central lobe of the spectral response function (which is a measure of spectral resolution) on the one hand, and the size of the spectral side lobes on the other. Using Hamming apodization, the full width at half maximum of the central lobe, which can be thought of as the spectral resolution in a band, is given by $0.9/L$, which corresponds to 1.112 cm^{-1} , 2.25 cm^{-1} , and 4.5 cm^{-1} for bands 1-3 respectively. Both the spectral sampling and “spectral resolution” of CrIS channels are roughly twice as coarse as those of corresponding AIRS channels.

Even though the hardware of AIRS and CrIS are quite different from each other, the intrinsic sounding capabilities of the two instruments are quite similar to each other. Figure 1a shows an example of a cloud free AIRS brightness temperature spectrum computed for a tropical scene. The AIRS spectrum indicates the locations of channels used in different steps in SRT Version-6.22. AIRS channels are used somewhat differently in SRT Version-6.22 than in AIRS Version-6, the largest difference being that in SRT Version-6.22, some tropospheric sounding channels in the $15\text{ }\mu\text{m}$ CO_2 band are now used both in the $T(p)$ retrieval step as well as in the generation of cloud clearing coefficients. In Version-6, they were used only in the generation of cloud clearing coefficients. Different sets of channels, shown in different colors, are used for different purposes as discussed later. Figure 1b shows the Hamming Apodized CrIS spectrum computed for

Sample AIRS Cloud Free Brightness Temperature Spectrum Version-6.22 Channels



Sample CrIS Cloud Free Brightness Temperature Spectrum Version-6.22 Channels

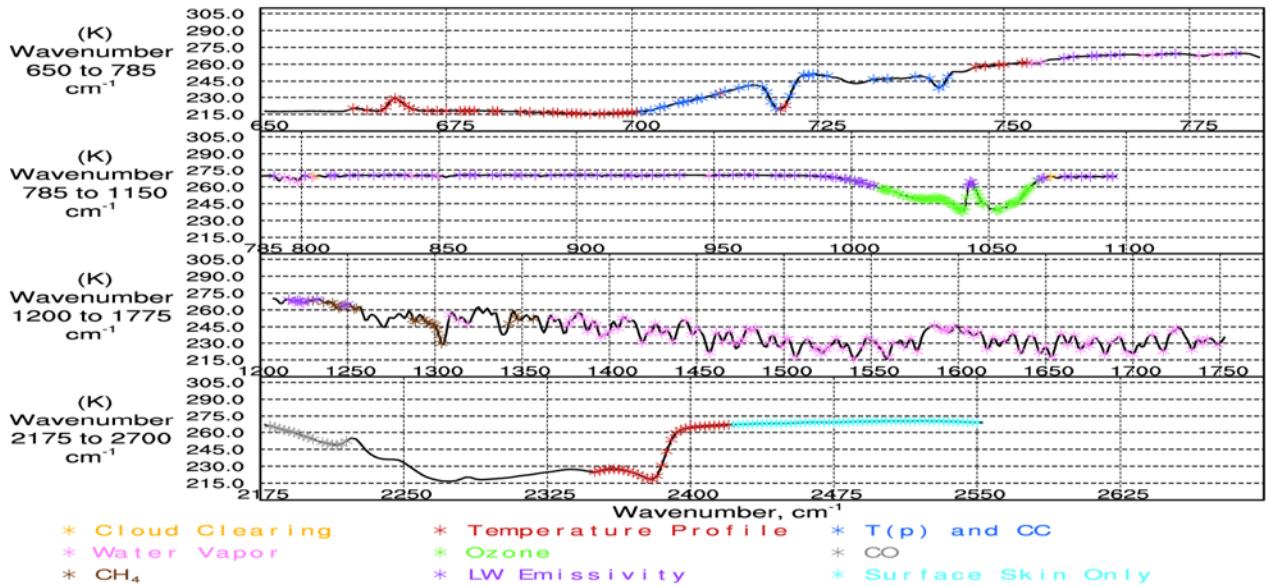


Figure 1. Sample AIRS and CrIS brightness temperature computed for a cloud free scene. The AIRS and CrIS channels we use in different steps in the retrieval process are indicated in the figure by different colored stars.

the same scene and shows analogous sets of channels which we use to analyze CrIS/ATMS data in the SRT Version-6.22 CrIS/ATMS retrieval algorithm. AIRS spectra have some gaps within a spectral region, while CrIS spectra are contiguous within a band. Figure 1 shows that the spectral coverages of AIRS and CrIS are similar to each other. AIRS extends further than CrIS in the longwave window region, with additional channels covering 1095 cm^{-1} to 1137 cm^{-1} ; CrIS extends further than AIRS in the water vapor band from 1614 cm^{-1} to 1750 cm^{-1} ; and AIRS extends further in the shortwave window region from 2550 cm^{-1} to 2667 cm^{-1} .

3. THE SRT VERSION 6.22 RETRIEVAL ALGORITHM

The SRT Version-6.22 AIRS retrieval algorithm contains relatively minor, but significant, improvements in retrieval methodology compared to the operational AIRS Version-6 retrieval algorithm. All versions of the AIRS Science Team retrieval algorithm are physically based and determine a set of geophysical parameters, X_j , such that radiances computed from the state X_j best match clear column radiances \hat{R}_i , where \hat{R}_i is a derived parameter representing the radiance channel i would have seen if the AMSU FOR, on which the AIRS retrieval is generated, were completely clear. Susskind et al.⁴ described the AIRS Science Team Version-4 retrieval algorithm which introduced a Quality Control (QC) concept that generated different QC flags for a given profile as a function of height, and also had separate QC flags related to surface skin temperature. The AIRS Science Team Version-5 retrieval algorithm⁵ contained many significant further improvements in retrieval methodology, the most important of which was the set of channels used to retrieve the atmospheric temperature profile $T(p)$. The AIRS Version-6 retrieval algorithm⁶ contained many further improvement in retrieval methodology and is currently being used operationally to generate AIRS level-3 CDRs. Both Version-5 and Version-6 follow cloud clearing theory^{7,8}, which states that 15 μm (660 cm^{-1}) CO_2 tropospheric sounding channels should not be used to retrieve $T(p)$ in a FOR, but rather should be used only to generate coefficients which provide \hat{R}_i for all channels in that FOR, because errors in cloud clearing coefficients result in larger errors in clear column brightness temperature, $\hat{\theta}_i$, for channels in the 15 μm CO_2 band than for channels in the 4.2 μm CO_2 band. The SRT Version-6.22 AIRS retrieval algorithm relaxes this rigid approach and uses many 15 μm tropospheric sounding CO_2 channels for both cloud clearing and temperature sounding purposes. We now determine $T(p)$ using not only \hat{R}_i in 15 μm stratospheric sounding CO_2 channels and in 4.2 μm (2370 cm^{-1}) tropospheric sounding CO_2 channels, both shown in red in Figure 1, but also in some tropospheric sounding 15 μm CO_2 channels that are also used to determine cloud clearing coefficients, shown in blue. Additional longwave channels, shown in orange, are used for cloud clearing purposes only. A total of 62 channels are used for cloud clearing purposes between 701 cm^{-1} and 1228 cm^{-1} . In Version-6.22, individual channels are excluded from use in either the $T(p)$ or $q(p)$ retrieval steps for a given case if $\hat{\theta}_i$, the clear column brightness temperature for channel i , differs by more than 5K from $\bar{\theta}_i$, where $\bar{\theta}_i$ is the mean channel i brightness temperature averaged over the FOR. This test was not part of Version-6 which used radiances for all temperature sounding channels in the temperature profile retrieval step for each case. In the AIRS Version-6.22 surface skin temperature retrieval step, we simultaneously determine T_s , $\varepsilon_{sw}(v)$, and $\rho_{sw}(v)$ using only the shortwave window channels between 2420 cm^{-1} and 2664 cm^{-1} , which are shown in light blue in Figure 1, along with the 24 highest frequency (red) AIRS $T(p)$ channels, which we also use in the $T(p)$ retrieval step. Surface longwave spectral emissivity $\varepsilon_{lw}(v)$ is determined in a subsequent step in Version-6 and Version-6.22 using window channels between 758 cm^{-1} and 1251 cm^{-1} , shown in purple in Figure 1. In Version-6.22, the water vapor profile $q(p)$ retrieval step uses \hat{R}_i in channels (pink stars) in the spectral ranges 758 cm^{-1} to 1605 cm^{-1} ; the $O_3(p)$ retrieval uses \hat{R}_i in channels (green stars) between 997 cm^{-1} and 1069 cm^{-1} ; the $CO(p)$ retrieval uses \hat{R}_i in channels (gray stars) between 2181 cm^{-1} and 2221 cm^{-1} ; and the $CH_4(p)$ retrieval uses \hat{R}_i in channels (brown stars) between 1220 cm^{-1} and 1356 cm^{-1} . Version-6.22 uses many more channels in both the $q(p)$ and $O_3(p)$ retrieval steps than was used in Version-6. This increase in the channels used in each retrieval step, as well as other modifications to the $q(p)$ and $O_3(p)$ retrieval algorithms, resulted in significantly improved $q(p)$ and $O_3(p)$ products in Version-6.22 as compared to Version-6. Indeed, it is primarily because of the significant improvement in Version-6.22 water vapor and ozone products compared to Version-6 that the AIRS Science Team plans to reprocess all AIRS data in the relatively near future.

We use analogous sets of channels in our analysis of CrIS/ATMS data. AIRS resolves CO_2 absorption lines in the 15 μm band, and the locations of the AIRS channels we use for determining $T(p)$ and for cloud clearing lie primarily between the CO_2 lines. CrIS does not resolve these lines as well, but the CrIS 15 μm channels we use for these purposes are located at roughly the same frequencies as those we use for AIRS. A potentially significant limitation of CrIS is that the shortwave band extends to only 2550 cm^{-1} , and this could potentially degrade the surface parameter retrieval somewhat compared to AIRS.

2.1 Steps in the SRT Version 6.22 retrieval algorithm used for both AIRS and CrIS

AIRS retrievals of all geophysical parameters are physically based and represent states $X_{j,c}$ derived for case c that best match a set of clear column radiances $\hat{R}_{i,c}$ for the subset of AIRS channels i used in that step in the retrieval process. \hat{R}_i for any channel is given by a channel independent linear combination of the observations in that channel in each of the nine AIRS FOV's within the FOR on which the solution is being obtained. Retrievals of geophysical parameters are performed sequentially, that is, only a subset of the geophysical parameters within the state X_j are modified in a given step. The steps in the AIRS Version-6.22 physical retrieval process are identical to those of AIRS Version-6 and are as follows: A Neural-Net start-up procedure is used to generate the initial state X^o . Initial clear column radiances \hat{R}_i^o in a FOR are generated for all channels i using the initial state X^o and cloud-clearing coefficients for that FOR which are generated using observed radiances in the cloud clearing channels in each of the nine FOV's in the FOR⁶. The state X^o is also used as the initial guess to the physical retrieval process in which AIRS/AMSU observations are used to retrieve sequentially: a) T_s, ε_{sw} , and ρ_{sw} ; b) $T(p)$; c) atmospheric moisture profile, $q(p)$; d) $\varepsilon_{lw}(v)$; e) atmospheric ozone profile, $O_3(p)$; f) atmospheric CO profile, $CO(p)$; and g) atmospheric CH₄ profile, $CH_4(p)$. In Version-6.22, the spectral emissivity in the vicinity of the O_3 band is also updated, along with the ozone profile, in the $O_3(p)$ retrieval step. Cloud properties and OLR are then computed after the retrieval is completed so as to be consistent with observed radiances R_i and those computed from the final retrieved state X . These steps are done sequentially, solving only for the variables to be determined in each retrieval step while using previously determined variables as fixed. The objective in each step (a-g) is to find solutions which best match \hat{R}_i for the subset of channels selected for use in that step, bearing in mind the channel noise covariance matrix. Steps a-g are ordered so as to allow for selection of channels in each step which are primarily sensitive to variables to be determined in that step or determined in a previous step, and are relatively insensitive to other parameters. Separation of the problem in this manner allows for the retrieval in each step to be made as linear as possible. The steps used in CrIS Version-6.22 are identical to those of AIRS Version-6.22.

As in AIRS Version-6⁶, Neural-Net methodology is used to generate the first guess for $T^o(p)$, $q^o(p)$, and T^o_{surf} for each CrIS/ATMS FOR. The CrIS/ATMS Neural-Net coefficients were trained by Bill Blackwell and co-workers at Lincoln Labs using data on select time periods^{9,10}. These coefficients are then used on all time periods. The CrIS Neural-Net coefficients were trained using CrIS/ATMS observations early in the mission. CrIS and ATMS calibration procedures were modified in November 2013. The quality of CrIS/ATMS retrievals improved after this change, even though the Neural-Net coefficients began to produce a biased first guess. CrIS Neural-Net coefficients will need retraining once CrIS/ATMS calibration procedures are finalized. Level-1 calibration procedures for both ATMS and CrIS are still being evaluated and upgraded. We will eventually reprocess all CrIS/ATMS with the finalized level 1-b products. Nevertheless, we plan to process, analyze, and compare results of many months of monthly mean products of AIRS Version-6.22 and CrIS Version-6.22 products in the near future to assess compatibility between the two sets of level-3 CDRs. Bill Blackwell has indicated that he will generate new CrIS/ATMS Neural-Net coefficients trained on CrIS/ATMS radiances using the new calibration procedures when the data is available. In the meantime, we are using and evaluating results using his old CrIS/ATMS Neural-Net coefficients. We have selected December 4, 2013 for our first set of experiments. This day was selected because EOS and NPP orbits align reasonably well on this day and it occurs after the CrIS/ATMS calibration procedures were both improved.

4. COMPARISON OF RESULTS OBTAINED USING AIRS VERSION-6, SRT AIRS VERSION 6.22, AND SRT CrIS VERSION 6.22

This section compares QC'd AIRS results we derived using the AIRS Version-6 retrieval algorithm, QC'd AIRS results using the Version-6.22 retrieval algorithm, and QC'd CrIS results we derived using CrIS Version-6.22. Figure 2 shows $T(p)$ statistics of the differences of QC'd Version-6 AIRS, Version-6.22 AIRS, and Version-6.22 CrIS retrievals from a collocated ECMWF 3 hour forecast, which we take as "truth", for a global ensemble of cases on December 4, 2013. Panel (a) shows the percentage of QC'd cases accepted as a function of height; panel (b) shows RMS differences of QC'd 1 km layer mean temperatures from the collocated ECMWF 3-hour forecast considered as "truth"; and panel (c) shows biases of QC'd 1 km layer mean differences from ECMWF. We refer to differences from ECMWF as "errors". Version-6 and Version-6.22 QC methodology is based on the use of thresholds of error estimates for a given state⁶. AIRS and CrIS retrievals all designate two characteristic

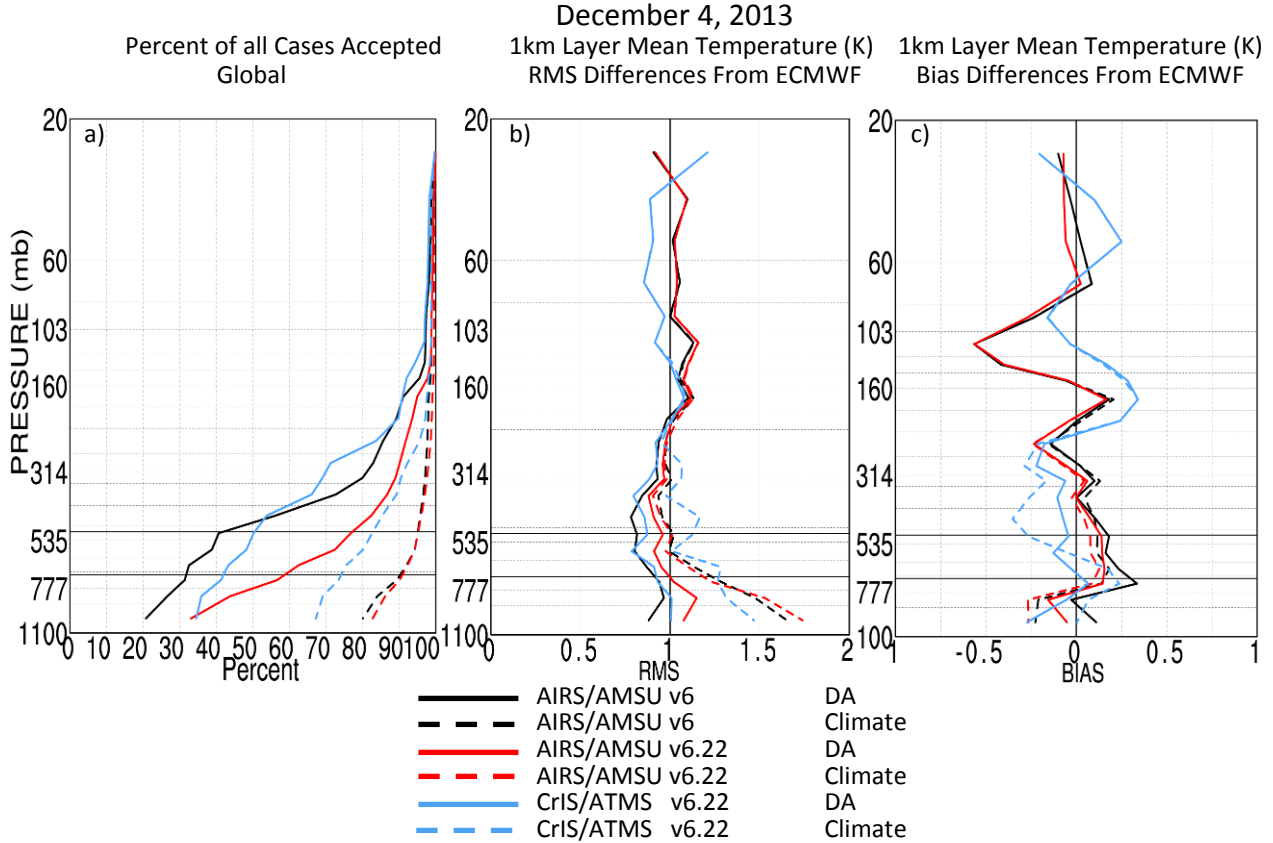


Figure 2. Global QC'd 1 km layer mean temperature profile statistics for December 4, 2013 for different retrievals and different QC thresholds. a) Percent of all cases accepted; b) 1 km layer mean RMS differences from collocated ECMWF 3-hour forecast; c) 1 km layer mean bias from ECMWF.

pressures for each temperature profile, p_{best} and p_{good} , to be used for Data Assimilation (DA) purposes and for the generation of level-3 products used for climate studies respectively. DA statistics include all cases down to p_{best} and climate statistics include all cases down to p_{good} , which must be greater than or equal to p_{best} . $T(p)$ and $q(p)$ products for a given case are flagged at QC=0 down to p_{best} , QC=1 between p_{best} and p_{good} , and QC=2 beneath p_{good} .

The solid red and solid blue lines in Figure 2 show statistics for Version-6.22 AIRS and CrIS results using their appropriate DA QC thresholds, and the dashed red and blue lines show results using their Climate QC thresholds. Analogous Version-6 results are shown in the solid and dashed black lines. The yields of AIRS Version-6 and Version-6.22 retrievals with Climate QC are extremely high throughout the atmosphere, with values greater of 95% at 500 mb and roughly 80% at the surface. Products passing Climate QC (QC=0,1) are the ones used to generate the level-3 products which form the CDRs. Global mean RMS errors of both AIRS Version-6 and AIRS Version-6.22 retrieved 1 km layer mean temperatures using Climate QC are essentially 1K down to 500 mb, and grow to about 1.7K

near 1000 mb. The differences between AIRS Version-6 and Version-6.22 $T(p)$ retrieval methodology are relatively small, as is the accuracy of the $T(p)$ results. Achievement of this very high yield and high accuracy is extremely valuable in the generation of highly representative level-3 CDRs. RMS errors of AIRS Version-6 retrievals with DA Quality Control are less than 1K throughout the troposphere, which is a requirement from the perspective of assimilation of QC'd values of $T(p)$ to improve forecast skill¹¹. The global yields of tropospheric Version-6 AIRS retrievals using DA QC are considerably lower than those using Climate QC, but this is less important from the DA perspective than the high accuracy of the ensemble of accepted retrievals. Nevertheless, we have conducted data assimilation experiments using AIRS Version-6 retrieved products and have found that even though the retrievals passing DA QC thresholds were very accurate, the spatial coverage was inadequate,

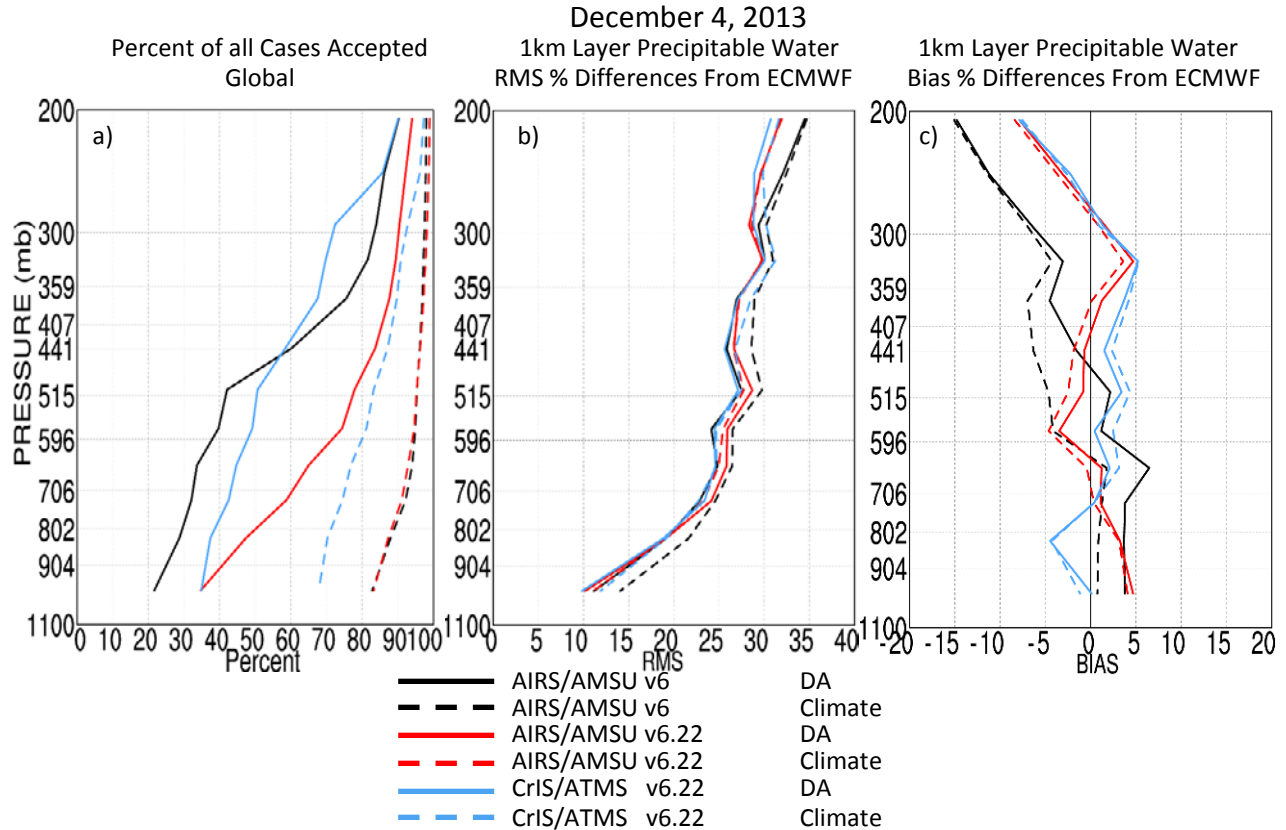


Figure 3. Global QC'd 1 km layer precipitable water profile statistics for December 4, 2013 for different retrievals and different QC thresholds. a) Percent of all cases accepted; b) 1 km layer precipitable water RMS % differences from collocated ECMWF 3-hour forecast; c) 1 km layer precipitable water bias % differences from ECMWF.

especially at high latitudes. We therefore loosened the DA QC thresholds in AIRS Version-6.22. Percent yields of AIRS Version-6.22 retrievals passing DA QC are now significantly higher than those of Version-6. RMS errors are somewhat poorer than in Version 6, but are still on the order of 1K. In the results shown in this paper, we used the same DA and QC thresholds for Version-6.22 CrIS/ATMS retrievals as we used for Version-6.22 AIRS/AMSU. Version-6 CrIS yields at 500 mb and 1000 mb with Climate QC are lower than those of AIRS, but are still very high with values of 83% and 70% at 500 mb and the surface respectively. CrIS $T(p)$ errors with Climate QC are somewhat larger than those of AIRS, but are still very good. Version-6.22 CrIS/ATMS errors with DA QC are somewhat smaller than those of AIRS but with a reduction in yield. The biases of all sets of $T(p)$ retrievals are relatively small, but are larger for AIRS than for CrIS near 100 mb.

Figure 3 shows analogous statistics to those in Figure 2, but for percentage errors of 1 km layer precipitable water vapor from the surface to 200 mb. Version-6.22 AIRS and CrIS results are of comparable accuracy to each other and both are improved considerably compared to AIRS Version-6, especially with Climate QC. The $q(p)$ bias structures of both Version-6.22 AIRS and Version-6.22 CrIS are much better than that of AIRS Version-6, in which retrievals are biased very dry in the mid-upper troposphere.

Figure 4 shows counts of Quality Controlled Ocean Surface Skin Temperatures (SST's) over the latitude range 50°N to 50°S as a function of the difference between T_s and ECMWF "truth" for the same day. The counts of accepted AIRS Version-6.22 retrievals are shown in red and pink using Climate T_s QC thresholds and DA T_s QC thresholds respectively. Analogous statistics for CrIS Version-6.22 retrievals are shown in dark blue and light blue; and AIRS Version-6 in black and gray. The AIRS and CrIS level-3 ocean surface skin temperature products we generate include all cases passing Climate QC. We use a different approach in Version-6 and Version-6.22 to

Surface Skin Temperature Difference December 4, 2013 Daytime and Nighttime combined 50 N to 50 S Non-Frozen Ocean

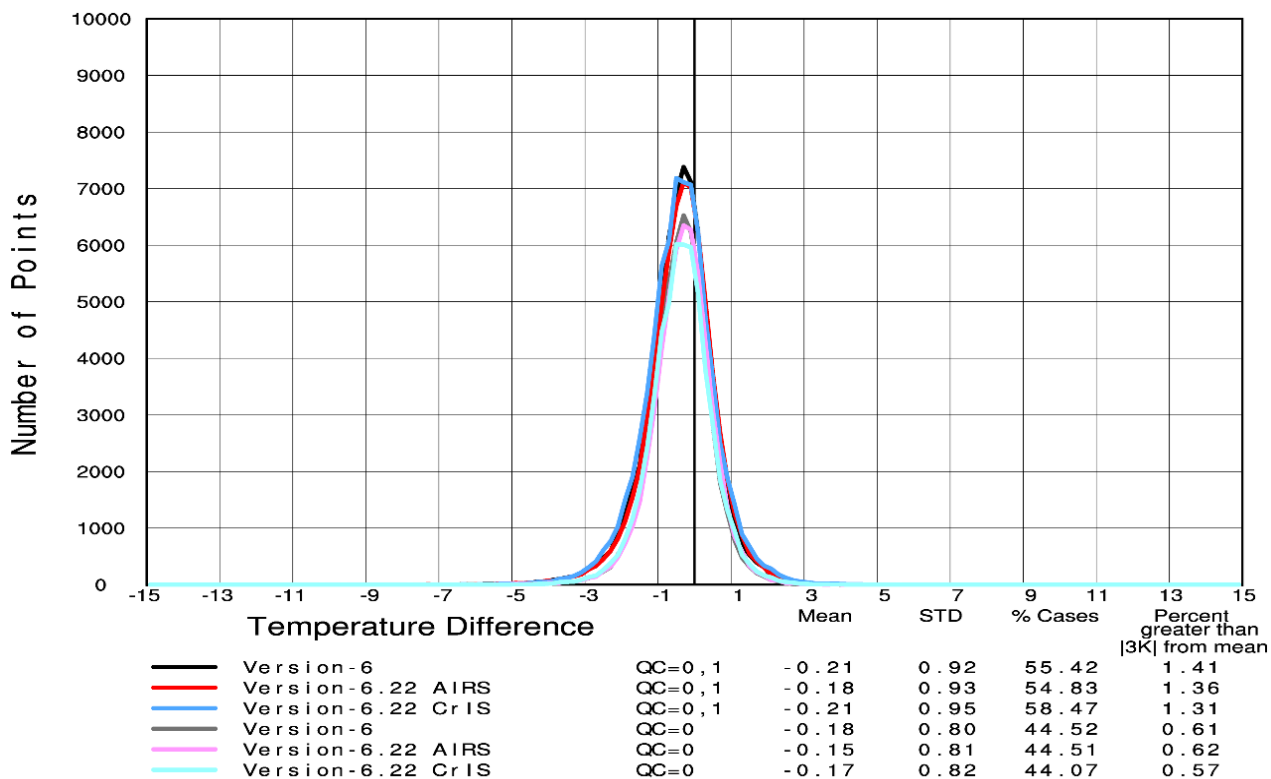


Figure 4. Counts of QC'd values as a function of errors of AIRS Version-6, AIRS Version-6.22 and CrIS Version-6.22 sea surface temperatures using each DA (QC=0) and Climate (QC=0,1) QC thresholds.

generate level-3 T_s products over land and ice, in which T_s for a given case is included as long as p_{good} is at most 1.5 km above the surface.

Figure 4 contains statistics for each set of QC'd retrievals showing the mean difference from ECMWF, the standard deviation (STD) of the ensemble differences, the percentage of all possible cases included in the QC'd ensemble, and the percentage of all accepted cases with absolute differences from ECMWF of more than 3K from the mean difference, which we refer to as outliers. There was essentially no change in the surface skin temperature retrieval step in Version-6.22 as compared to Version-6. AIRS Version-6 T_s with Climate QC accepts 55.42% of all cases over oceans, with a mean difference from ECMWF of -0.21K and a STD of 0.92K, and contains 1.41% outliers. With tighter DA T_s QC thresholds, the AIRS Version-6 yield drops to 44.52%, and the bias and STD drop to -0.18K and 0.80K respectively, with a remarkably low outlier value of 0.61%. AIRS and CrIS Version-6.22 T_s statistics are both comparable to what is obtained from AIRS Version-6. This shows that the fact that the CrIS spectral range at the high frequency end of the spectrum is shorter than that of AIRS does not significantly degrade ocean surface skin temperature performance.

Figures 2-4 show global mean statistics comparing the accuracy of the different data sets. The next set of figures compare the spatial distributions of Version-6.22 AIRS/AMSU and Version-6.22 CrIS/ATMS retrievals of different geophysical parameters passing Climate QC with each other for December 4, 2013. The major improvements in Version-6.22 as compared to Version-6 are with respect to the retrievals of ozone and water vapor. Figures 5a-c show fields of AIRS Version-6, AIRS Version-6.22, and CrIS Version-6.22 total ozone for the 1:30 PM ascending orbits of EOS Aqua and NPP, and compares them to total O_3 obtained from the UV instrument OMI on EOS Aura. The interorbit gaps of CrIS are smaller than those of AIRS because CrIS flies on NPP, which has a higher orbit than EOS Aqua, on which AIRS flies. OMI is considered the Gold Standard with

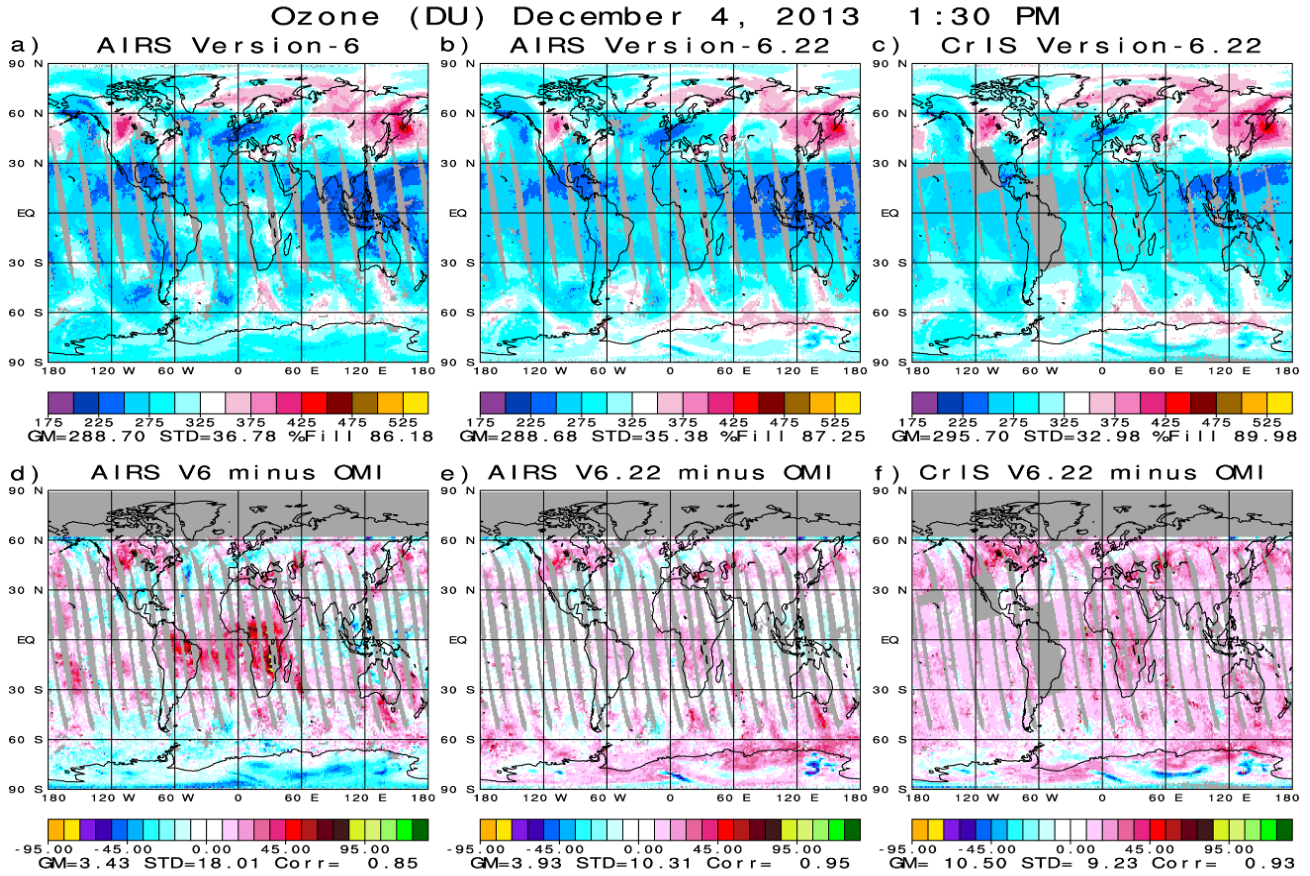
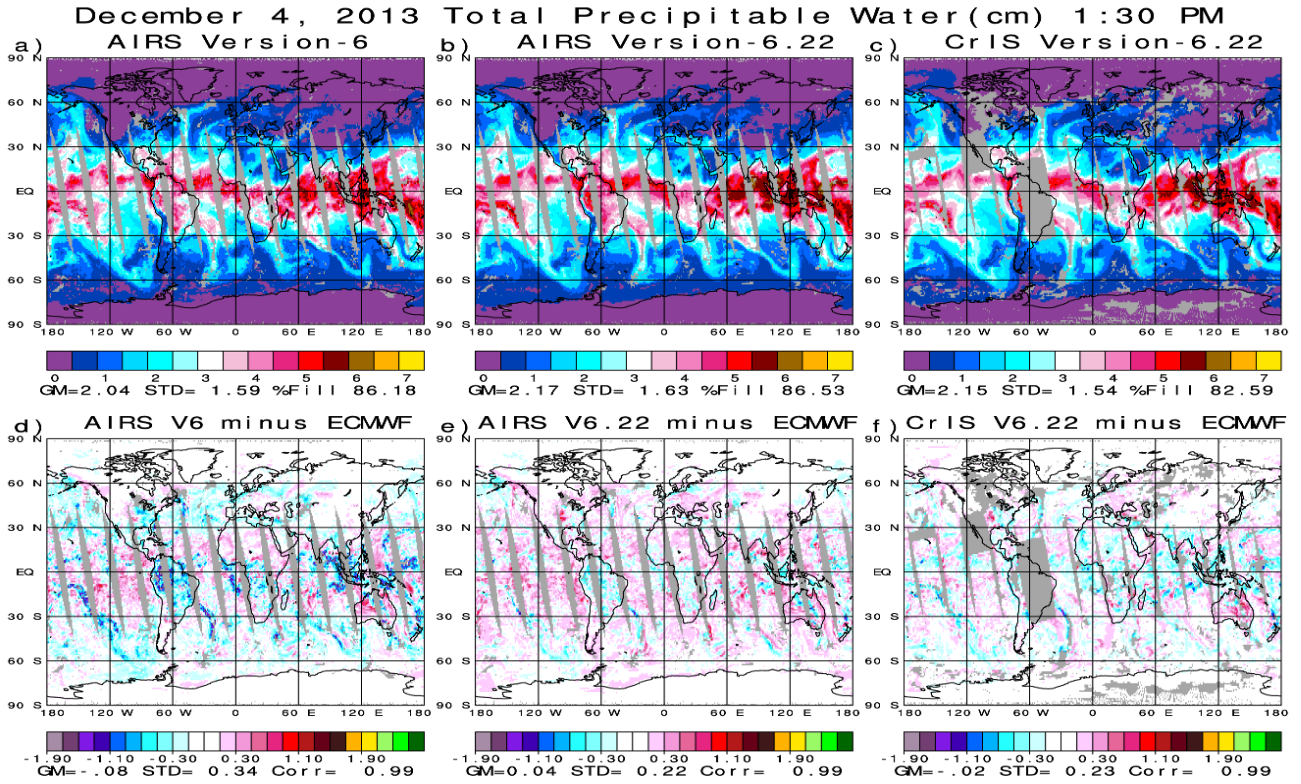


Figure 5. AIRS Version-6, AIRS Version-6.22, and CrIS Version-6.22 QC'd fields of total O_3 for ascending orbits on December 4, 2013, and their differences from OMI.

regard to the measurement of total O_3 . A limitation of OMI, however, is that as a UV instrument, O_3 cannot be determined from OMI at night or during polar winter. The differences of each total O_3 field from those of OMI are shown in Figures 5d-f. OMI has no values of total O_3 in polar winter so the difference fields contain no data north of 60°N latitude. AIRS Version-6.22 total ozone agrees much better with OMI than does AIRS Version-6, as shown in Figures 5d and 5f. Though the agreement of AIRS Version-6.22 total O_3 with that of OMI is not perfect, the spatial standard deviation of the difference between AIRS and OMI total O_3 has been reduced from 18.01 DU in AIRS Version-6 to 10.31 DU in AIRS Version-6.22. The spatial correlation with OMI of the two fields has also increased from 0.85 to 0.95, which is a significant improvement. The comparable statistics relating Version-6.22 CrIS total O_3 to that of OMI are similar to those of Version-6.22. AIRS Version-6.22 CrIS total O_3 is biased high compared to AIRS by about 7 DU. The ultimate objective of this research is to generate long term

CDRs of different geophysical parameters, derived from different instruments, and perform research using their monthly mean $1^\circ \times 1^\circ$ anomaly time series. The anomaly for a given field for a given month obtained from analysis of a given instrument is defined as its difference from the monthly mean climatology for that month for that instrument. From this perspective, a bias between two data sets is not a significant problem if it is constant in time. Nevertheless, we will be doing further research to try to understand the reason for, and possibly reduce, this bias between values of AIRS and CrIS total O_3 .

Figures 6a-c shows derived QC'd fields of Total Precipitable Water (W_{TOT}) for the ascending (1:30 PM) orbits of AIRS and CrIS, and Figures 6d-f show their differences from the ECMWF 3 hour forecast for this time period, which we take as truth. As with regard to total O_3 burden, water vapor profile is the other geophysical parameter in which AIRS Version-6.22 retrieval methodology is significantly improved compared to that of AIRS



Figures 6. Derived QC'd fields of Total Precipitable Water (W_{TOT}) for the ascending (1:30 PM) orbits of AIRS and CrIS, and their differences from the ECMWF 3-hour forecast for this time period, which we take as truth.

Version-6. Figure 6d shows that global mean values of AIRS Version-6 W_{TOT} are biased negative compared to ECMWF by -0.08 cm, which is 3.5% lower than the global mean value of W_{TOT} . This negative global mean bias compared to truth arises primarily in spatial areas containing large amounts of high cloud cover, which are also marked by locally large amounts of W_{TOT} .

Figures 6d and 6e show that AIRS Version-6.22 W_{TOT} agrees much better with ECMWF than does AIRS Version-6 W_{TOT} , both with regard to global mean and spatial standard deviation. Values of W_{TOT} in areas of extensive high cloud cover are still somewhat low compared to ECMWF, but the errors in W_{TOT} as compared to ECMWF are reduced

considerably in Version-6.22. Figure 6f shows that Version-6.22 CrIS W_{TOT} also agrees with ECMWF much better than does AIRS Version-6, and is almost as accurate as that of AIRS Version-6.22. Figures 5 and 6 compare the accuracy of Version-6.22 AIRS and CrIS values of total O_3 and W_{TOT} to that of AIRS Version-6, and demonstrate how both AIRS and CrIS results are now much improved compared to those of AIRS Version-6. Figures 7-9 deal with products in which little change has been made to retrieval methodology in Version-6.22. These results compare only AIRS Version-6.22 products on a single day with those of CrIS Version-6.22 to demonstrate the compatibility of the two data sets on a daily basis. Some differences are observed between the single day fields, mostly between the retrieved cloud products as well as the derived values of OLR. Part of these differences may be an artifact resulting from the different characteristics of the AIRS and CrIS instruments. In addition, AIRS and CrIS are on different orbits in different altitudes and AIRS and CrIS do not see exactly the same scenes, nor do they see them at the same time or at the satellite zenith angle. Even the same clouds can appear different at different zenith angles because the instruments see the sides of the clouds. Much more important will be compatibility of monthly mean values of these data sets and their interannual differences. Figures 7 a-c show AIRS Version-6.22 QC'd values of surface skin temperature T_s , using climate QC, and their difference, for the ascending orbit on December 4, 2013. Figures 7 d-f show analogous results for 700 mb

December 4, 2013 1:30 PM

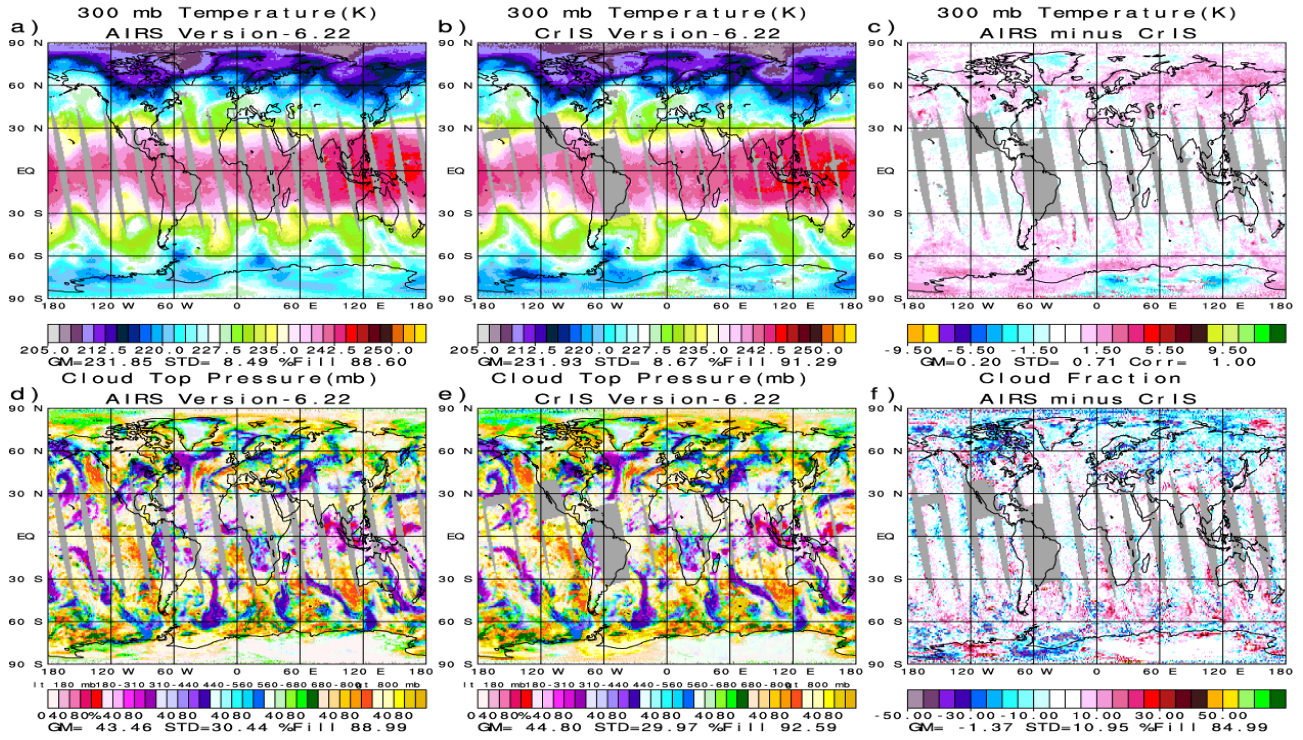


Figure 7. AIRS and CrIS retrieved values of surface skin temperature and 700 mb temperature for ascending orbits on December 4, 2013.

December 4, 2013 1:30 PM

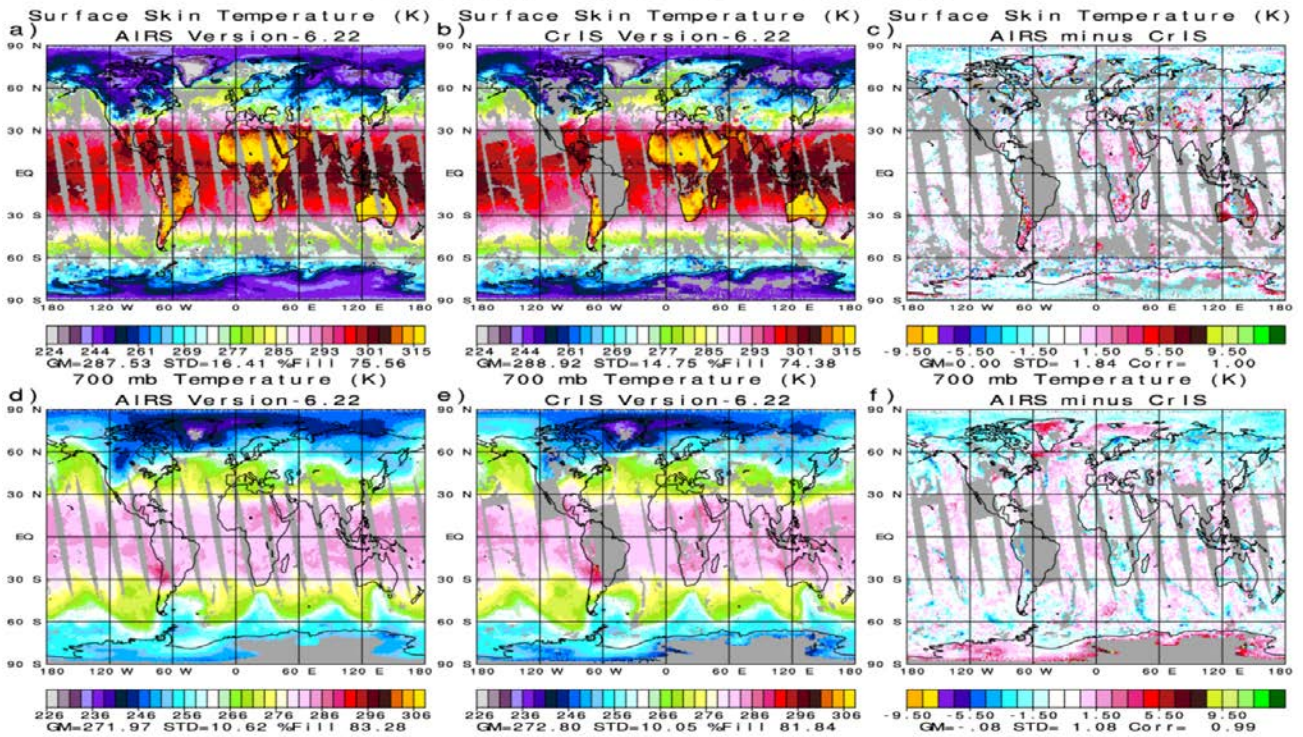


Figure 8. AIRS and CrIS retrieved values of 300 mb temperatures and cloud parameters from December 4, 2013.

temperature $T(700)$. Agreement in the tropics is extremely good for both fields. Global mean values of CrIS Version-6.22 $T(700)$ are colder than those of AIRS by 0.08K. Version-6.22 CrIS values of both T_s and $T(700)$ are somewhat lower than those of Version-6.22 AIRS at high latitudes for reasons we do not understand as of yet. In addition, CrIS values of $T(700)$ are lower than those of AIRS in some extra-tropical areas containing large amounts of high cloud cover over ocean. This might imply that our Version-6 CrIS/ATMS retrievals perform more poorly than those of Version-6 AIRS/AMSU in regions containing large amounts of high clouds, and that we are under-correcting cloud effects on CrIS radiances in the generation of values of $\hat{\theta}_i$ in these cases. These oceanic areas tend to show up as gaps in Figure 7c, because SST QC procedures tend to reject the cloudiest cases even with Climate QC.

Figures 8a-c compare AIRS and CrIS retrieved values of 300 mb temperature $T(300)$. Results again show excellent agreement, especially in the tropics. Values of CrIS $T(300)$ tend to be higher than those of AIRS over high latitude land regions. The spatial structure of the differences between AIRS and CrIS values of $T(700)$ and $T(300)$ are to some extent correlated with each other. The global mean value of AIRS $T(300)$ is 0.08K lower than that of CrIS. Figure 2c indicates that at 300 mb, AIRS has a spurious negative bias at 300 mb while CrIS does not.

Figures 8d-f compare cloud parameters derived from AIRS and on CrIS on December 4, 2013. Figures 8d and 8e show both the cloud top pressure and total cloud fraction as seen from above. Results are shown in seven different color scales indicative of ranges of retrieved cloud top pressure, as shown in the caption beneath each figure. Shades of reds and purples indicate differing amounts of high clouds, blues and greens indicate mid-level clouds, and oranges and yellows indicate low clouds. Lighter colors indicate lower cloud fractions, and more intense colors indicate larger cloud fractions. The agreement between the retrieved cloud parameters is excellent. Some differences occur at high latitudes and we will try to identify and possibly correct the sources of these differences, which may be a consequence of the differences in retrieved values of T_s and $T(p)$.

Figures 9a-c compare values of AIRS and CrIS values of OLR, each computed using their retrieved products,

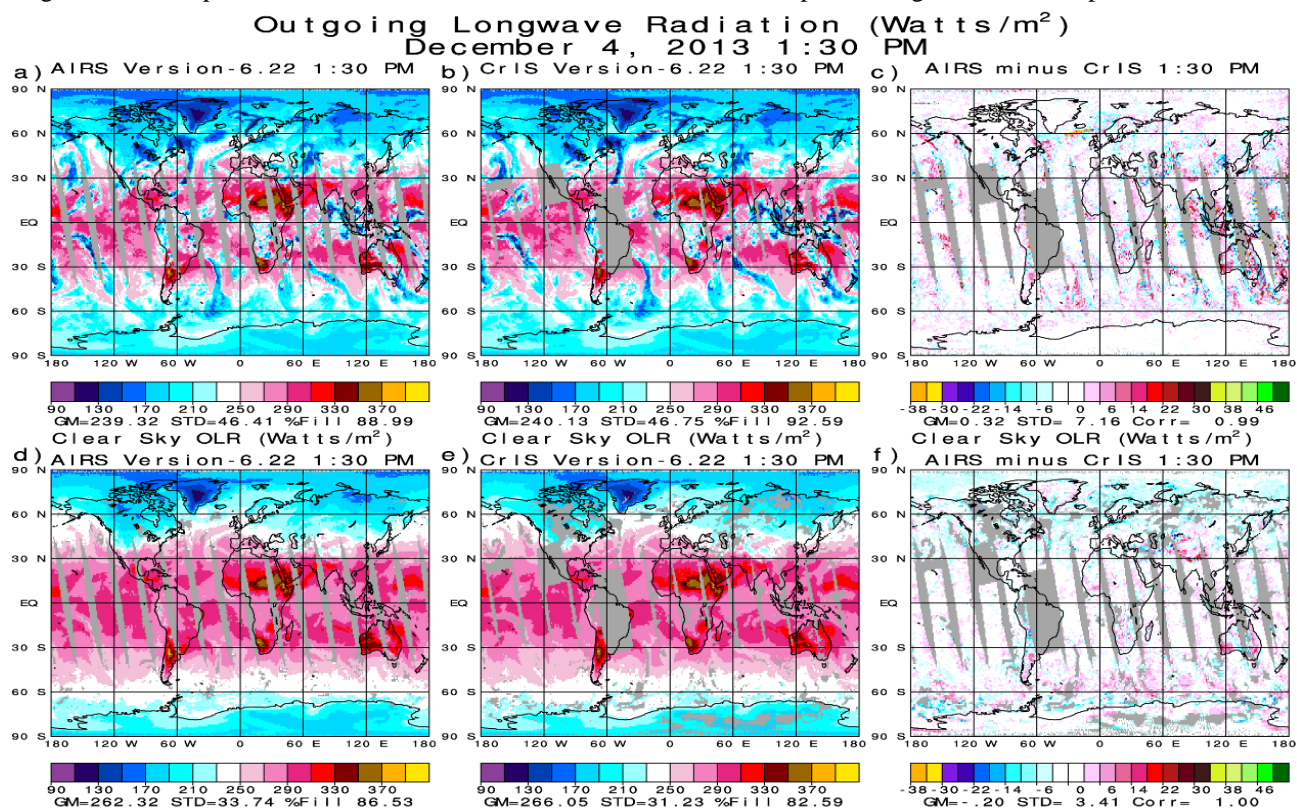


Figure 9. AIRS and CrIS values for computed OLR and clear sky OLR for ascending orbits on December 4, 2013.

and Figures 9d-f compare values of clear sky OLR computed from AIRS and CrIS. The agreement between the two data sets with regard to both OLR and clear sky OLR on a daily basis is excellent, given the small sampling differences as discussed previously. AIRS and CrIS global mean values of OLR and clear sky OLR both agree with each other to within $\pm 0.3 \text{ W/m}^2$. Susskind et al^{12,13} show that monthly mean values of AIRS Version-6 OLR and clear sky OLR match those over the time period September 2002-January 2014 of CERES extremely well both in terms of their absolute values and anomaly time series. It is encouraging that we should be able to get the same excellent comparison between CrIS and CERES OLR and clear sky OLR time series as we get with AIRS and CERES.

5. SUMMARY

The AIRS Science Team has made considerable improvements to the AIRS Version-6 retrieval algorithm and plans to reprocess all old AIRS data and process future AIRS data using an improved, but not yet finalized AIRS Version-7 retrieval algorithm, the current version of which is called AIRS Version-6.22. We have developed analogous retrieval methodology, called CrIS Version-6.22, for use in the processing of all CrIS data. AIRS and CrIS Version-6.22 results, as studied on a single day, are very similar to each other and both significantly better than those of AIRS Version-6. The AIRS Science Team is preparing to process many months in common of AIRS and CrIS data using Version-6.22, or further improved retrieval methodology, to test the inter-compatibility of many AIRS and CrIS level-3 retrieval products in a monthly mean sense, and will also compare the interannual differences of these geophysical parameters. Improvements are still being made with regard to the calibration methodologies used for both CrIS and ATMS. All CrIS/ATMS will be reprocessed using the finalized AIRS Version-7 retrieval algorithm when it is ready and also using the recalibrated CrIS and ATMS observations when they are ready. Many years of AIRS and CrIS Version-7 level-3 products will be generated. Monthly mean fields and their inter-annual differences will be compared to assess the compatibility of AIRS and CrIS CDRs.

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