The Retrieval of Atmospheric Profiles From Satellite Radiances For NWP Data Assimilation

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Abstract

Atmospheric profiles retrieved from surface based and satellite borne spectrometer radiance measurements contain vertical resolution biases resulting from the limited vertical resolution of the radiance observations. These biases led to vertical resolution aliasing of model background states when these profiles were assimilated into Numerical Weather Prediction (NWP) systems, since the profiles were treated as high vertical resolution radiosonde soundings rather than the low vertical resolution sounding information. In order to achieve a positive impact of the satellite data, NWP centers began to assimilate the radiance observations into the analysis/forecast system rather than the profile retrievals. This change had a consistent positive impact of the satellite data since the assimilation of radiance with its assumed low noise and low vertical resolution characteristics prevented vertical resolution aliasing of the model background fields. For prior generation satellite filter radiometers, this approach was also more efficient than assimilating atmospheric profiles, due to the relatively small number of radiance observations compared to the number of atmospheric profile levels contained in the forecast model. However, the current advanced ultraspectral sounding spectrometers output thousands of spectral channel radiances rather than a couple dozen channels, as was characteristic of prior generation filter radiometers. Thus, the NWP centers are limited to the assimilation of a very small percentage of radiance channel information available. However, profile retrievals utilize almost all the spectral radiance information, which leads to much higher vertical resolution profiles than is achievable from the relatively small subset of the spectral channels used for radiance assimilation. In this paper, a simple method for correcting satellite profile retrievals for vertical resolution dependent biases is formulated. Here the satellite profile retrievals were obtained using the statistical Dual Regression (DR) method used in the University of Wisconsin Community Satellite Processing Package (CSPP) to process Direct Broadcast Aqua AIRS, Metop IASI, and S-NPP CrIS ultraspectal data received at numerous ground stations around the globe. However, the vertical alias correction employed here using the DR retrieval method can be implemented with other retrieval algorithms as well. The utility of the method is demonstrated through several case studies conducted using data collected during two different Suomi-NPP satellite radiance data calibration validation field programs. It is shown that the vertical alias corrected retrievals compare more favorably with radiosonde observations than do the uncorrected profile retrievals, particularly for moisture. It is shown that the alias corrected retrievals enable the diagnoses of pre-convective weather environments better than do either the uncorrected retrievals or the model profiles that were used to achieve the alias-corrected result.

1. Introduction

The Atmospheric Infrared Sounder (AIRS) [Chahine et. al., 2006] on NASA's Aqua satellite was the first US space experiment to demonstrate the ultraspectral sounding technique and capability, while the first operational polar-orbiting satellite implementation, the Infrared Atmospheric Sounding Interferometer (IASI), was initiated on the European Metop-A and Metop-B satellites [Hilton et. al., 2012]. The first NOAA ultraspectral sounder, the Cross-track Infrared Sounder (CrIS), was launched in 2011 on the Suomi-National Polar-orbiting Partnership (SNPP) satellite [Tobin et. al., 2013]. The AIRS, IASI, and CrIS sensors have a spectral resolving power generally greater than 1000, providing the spectral resolution and signal to noise ratio needed to resolve temperature and water vapor profiles with a vertical resolution of 1-2 km, depending on altitude. The CrIS has the distinction of having the lowest noise level of any sounding instrument ever flown. The primary motivation of the ultra-spectral sounding technique was to obtain high vertical resolution atmospheric temperature and moisture profiles needed for improving regional and global scale weather forecasts [Smith, 1991].

The ultra-spectral resolution concept is to measure a large portion of the infrared spectrum of Earth-atmospheric radiance to space in order to obtain a very large number of noise independent spectral channels of atmospheric radiance, each having different altitude sensitivity, for inferring atmospheric profiles of temperature, water vapor, and trace gases. The high spectral resolution and large number of spectral channels both serve to optimize the vertical resolving power of the measurements. Having thousands of measurements, as opposed to tens of measurements, provides an order of magnitude improvement in signal to noise and this enables a much more precise inversion of the integral radiative transfer equation. The result is improved accuracy and higher vertical resolution of retrieved profiles than can be achieved with multi-spectral radiance data. Figure 1 shows the comparison of weighting functions (i.e., vertical resolving power of individual spectral radiances channels) and vertical resolution functions (i.e., the averaging kernals of retrieved temperature profiles) for both low spectral (15 cm^{-1}) and ultra-spectral (0.5 cm^{-1}) resolution radiance observations within the CO_2 band region. As can be seen, although the vertical resolution of individual spectral channels is enhanced by 25%, or less, the vertical sounding resolution is enhanced by a factor of two to three (i.e., 200–300%), as a result of the greatly increased system signal to noise of the ultra-spectral resolution system, assumed to have individual spectral channel noise levels comparable to the 15 cm^{-1} resolution 20 multi-spectral channel system. The sounding accuracy improves as a result of the improvement in vertical sounding resolution as the number of spectral channels increase within the CO_2 and H_2O spectral band regions. In fact, the sounding accuracy tends to improve in proportion to the square root of the number of channels indicating that it is due primarily to the signal to noise advantage of a large number of spectral channels being used for the profile retrieval process. Thus, it is important to utilize as many spectral channels of radiance as possible for the NWP data assimilation process in order to realize the sounding vertical resolution advantage of ultra-spectral resolution radiance measurements. Since the number of retrieval sounding values is much smaller than the number of spectral radiances observed with the ultraspectral sounding instruments, assimilating sounding retrievals, rather than channel radiances, should be the most efficient way to assimilate the information being provided by the satellite sounding instruments.

Using retrievals, rather than selected radiance channels as implemented in current NWP assimilation, is important for optimizing information content. Currently, radiance assimilation schemes lose information content by (1) discarding all cloud affected radiances, and (2) employing selected channels from apodized spectra. The first mechanism significantly reduces vertical coverage by eliminating any channels whose weighting functions are sensitive to clouds. Retrievals have an advantage, because the channel weighting functions are much broader than the vertical resolution functions for retrieval (see Figure 1). Also, the Dual Regression retrieval scheme can obtain quality retrievals even in the presence of partial cloudiness [Smith et. al., 2012]. The second mechanism, apodization, especially affects CrIS for which it throws away about 70% of the high spectral resolution information from the key 15 micron CO_2 band (information contained in an isolated feature at an optical path difference of about 0.63 cm, equal to the inverse of the CO_2 line spacing). Apodization itself is mathematically reversible and is not in itself a problem. However, when coupled with channel selection it cannot be reversed and information is loss.

Historically the assimilation of sounding retrievals has proved to be somewhat problematic because the profile retrievals exhibit vertical structure biases toward the a-priori profile (i.e., either the initial guess profile or the mean of the statistics used for regression) due to the low vertical resolution (i.e., "null space") of the radiance observations. This bias was large for retrievals from low spectral resolution filter radiometers (e.g., TOVS) causing vertical resolution aliasing when assimilated into NWP models causing negative impact. Thus, the direct assimilation of the radiances, rather than retrievals, was employed to avoid vertical resolution aliasing and to achieve positive impact. However, for hyperspectral sounding instruments, which contain thousands of spectral channels, radiance assimilation of all the spectral radiances is currently too time consuming for operational use. As a result, only a small subset of spectral channel radiances are assimilated limiting the vertical resolution, which is maximized by utilizing nearly all the spectral channels in the retrieval process. In order to alleviate this problem, a simple and time efficient method for de-aliasing full spectral resolution hyperspectral sounding retrievals is presented here.

2. Removing The Vertical Resolution Alias In Satellite Retrievals

In order to illustrate the sounding retrieval vertical resolution de-aliasing (DA) process, the Dual-Regression (DR) retrieval technique [Smith et al., 2012, Weisz et al., 2013] is used to produce the original retrievals. Because of the limited vertical resolving power of radiance measurements, as illustrated in Figure 1, the vertical structure of the retrieved profile will be aliased towards the mean of the statistical ensemble (or training data set) used to calculate the regression coefficients. By using a dynamic model forecast or analysis, which serves as a better representation of the actual vertical atmospheric structure, this alias can be minimized. For illustration purposes, the NOAA Global Data Assimilation System (GDAS) analysis is used here. However, the forecast (or analysis) from whatever NWP model employed for the actual assimilation process should be used to perform this alias adjustment. As a result, the alias-corrected retrieval will be consistent with the vertical resolution of the model field used in the NWP assimilation process.

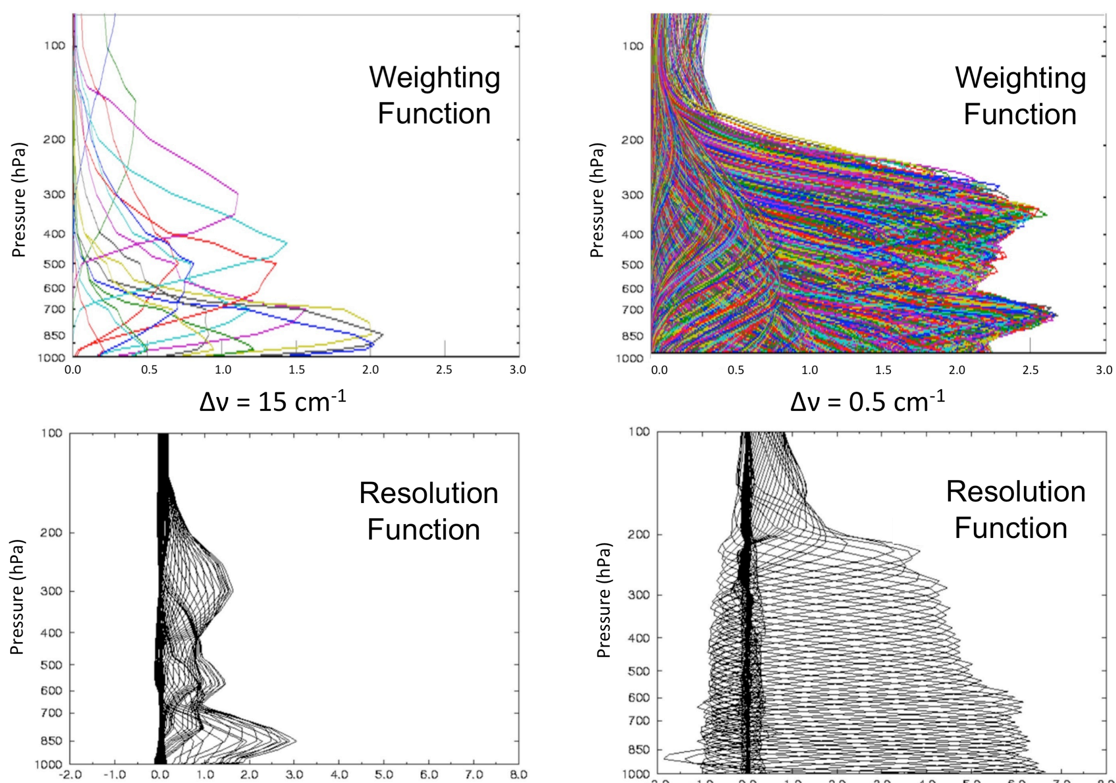

Figure 1. The weighting functions and vertical profile resolution functions (i.e., averaging kernals) for two different instrument spectral resolutions.

The alias adjustment, or de-aliasing (DA), process starts by computing the radiance spectrum from the model profile and producing a sounding retrieval from the calculated radiance spectrum in exactly the same manner (i.e., using the same regression coefficients and the same cloud class for cloudy FOVs) as used with the satellite measured radiance spectrum. A schematic diagram of the de-aliasing procedure is shown in Figure 2.

It is important to mention that the model radiance simulation uses as input surface skin temperature and emissivity conditions, which are consistent with clear-sky radiance observations. For cloudy-sky retrievals the surface air temperature from the model analysis and a unity surface emissivity condition can be used for the clear-sky RTM calculations, as well as the regression coefficients associated with the same cloud class as determined by the original retrieval step. The cloud height class statistics cover cloud fractions ranging between zero (i.e., clear) and unity (i.e., overcast) [Smith, 2012; Weisz, 2013]. The retrieval alias is then computed as the difference between the simulated radiance retrieval and the model profile. Finally, the retrieval vertical alias is removed from the DR retrieved profiles derived from the observed radiance spectrum. Again, the alias is due to the imperfect skill of statistical regression retrieval caused by the relatively low vertical resolution of the radiance-inverted retrieval compared to a model profile.

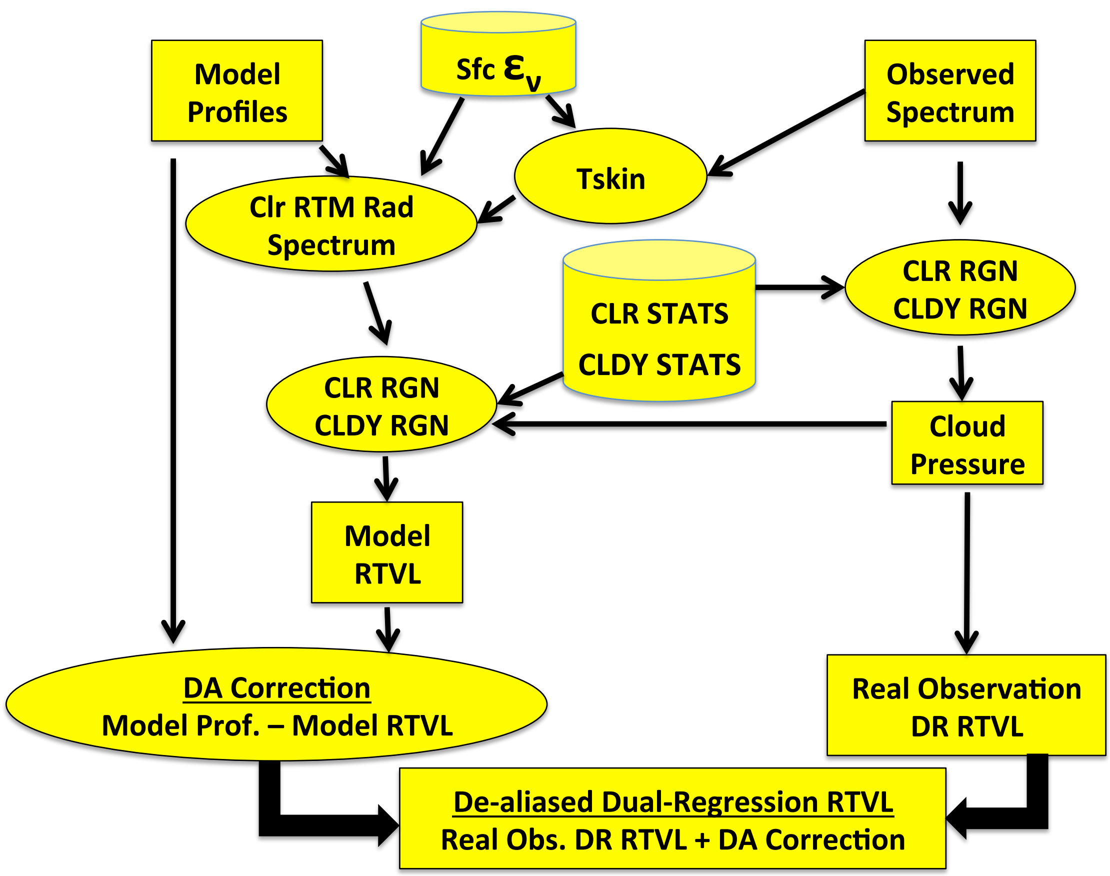

Figure 2. A schematic diagram showing the de-aliasing (DA) process used to determine and eliminate the vertical alias in statistical linear regression retrievals.

Although the cloudy FOV NWP Model radiance is simulated as a clear-sky condition (i.e., no cloud parameters are used in the RTM calculation) the retrieval is performed using exactly the same cloud height class radiance PCs and regression coefficients that were used with the cloudy FOV observed radiance spectrum. The use of cloud height class statistics with clear-sky radiances is proper since the cloud height class statistics are valid for instrument FOV cloud fractions ranging between zero (i.e., clear) and unity (i.e., overcast).

Figure 3 shows a comparison between an IASI retrieval and a nearby radiosonde observation for the alias corrected (or de-aliased) and uncorrected (i.e., dual-regression without de-aliasing) retrieval. It can be seen that the regression only retrieval does not capture the finer scale vertical structure shown by the radiosonde, whereas the de-aliased regression retrieval does. The vertical de-aliasing (DA) is most important when fine scale water vapor and temperature vertical structure features exist (e.g., changes of the mid-tropospheric temperature lapse rate and the tropopause structure as shown here).

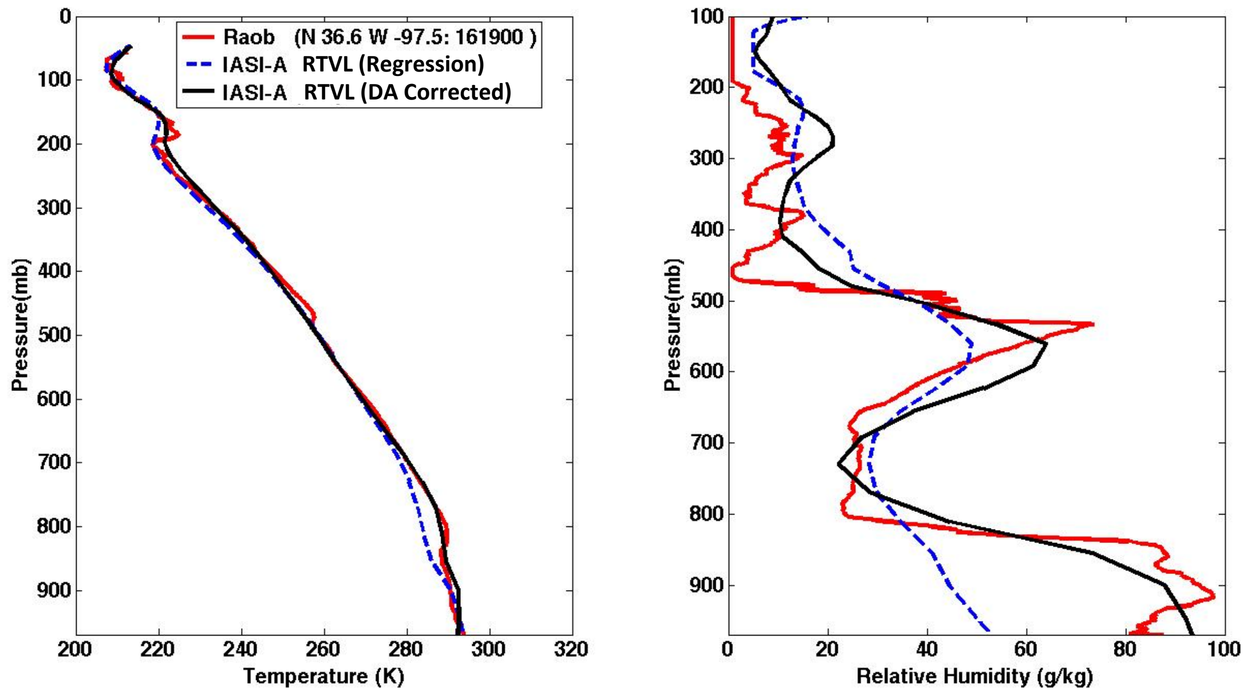

Figure 3. Comparison between an IASI retrieval at 15:56 UTC obtained with the DA corrected and regression without the DA adjustment with a nearby radiosonde observation at the ARM CART-site on May 20, 2013.

Figure 4 shows CrIS retrievals over the Greenland Summit station on March 23, 2015 obtained with the de-aliasing correction (CrIS) and without applying the de-aliasing step (RGN) of the retrieval process. Also shown is the GDAS profile used for the de-aliasing process. As can be seen, the de-aliasing process greatly improves the agreement between the retrieval and the radiosonde observations for this Arctic atmosphere, particularly the strong low-level inversion at the surface and the humidity throughout the troposphere. In this case, the GDAS analysis provides a good representation of the temperature profile leaving little to be improved by the satellite observations. However, the GDAS relative humidity is excessive, as indicated by the radiosonde observations, and the satellite retrievals are in much better agreement with the radiosondes than is the GDAS analysis.

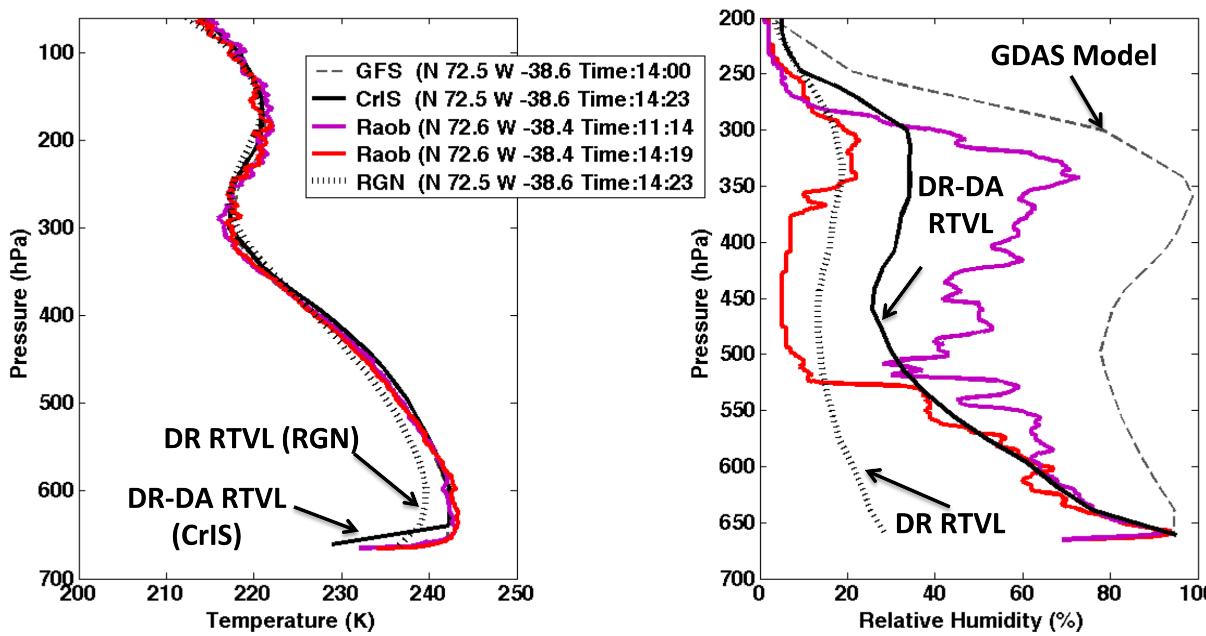

Figure 4. Comparison between a CrIS DR retrieval near the Summit Greenland station obtained with DA adjustment (CrIS) and without the DA adjustment (RGN) with several radiosonde observations at the Summit-site on March 23, 2015.

3. Validation

3.1 Retrieval Radiance Residuals

One way to investigate the impact of the vertical alias adjustment is by computing the radiance residual, which is the difference between the observed radiance spectrum and the spectrum calculated from the retrieved or a model analysis profile. . Small residuals indicate a more accurate representation of the truth by the input profile. Figure 5 shows the standard deviations of the residuals for GDAS, the DR, and DR plus DA for several thousand clear-sky profile retrievals obtained over central North America on 20 May 2013. The vertical alias-corrected retrieval radiance residuals are smaller than both the regression retrieval residuals and the RTM calculated radiance residuals associated with the model profiles used to perform the alias removal. This means that the de-aliased CrIS retrievals are an improvement over the model background field and therefore should have a positive impact on forecast products derived from the assimilation of these profiles. However, there are some spectral regions, particularly the more transparent spectral regions where the alias-corrected residuals are larger than the CrIS instrument noise level. This means that further improvements in retrieval accuracy can be achieved by improving the specification of the surface radiance (i.e., skin temperature and emissivity).

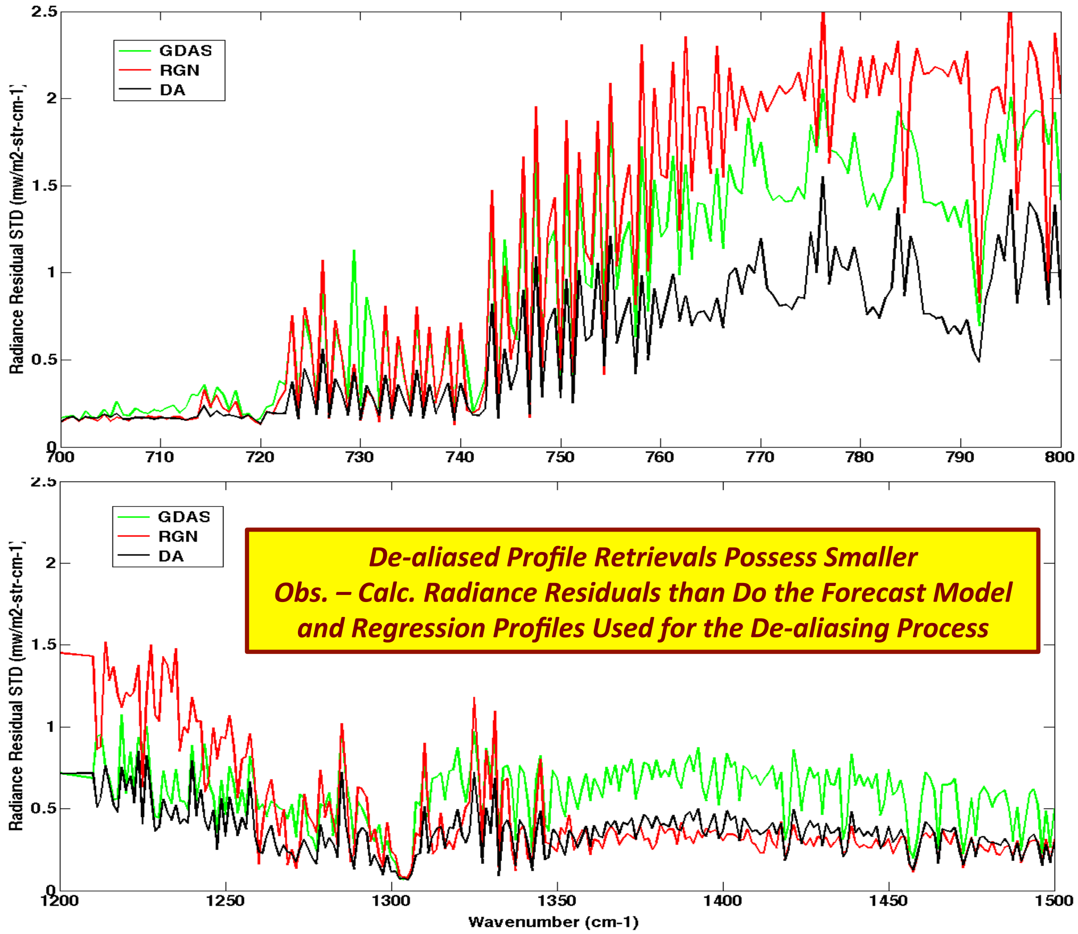

Figure 5. Standard deviations of the clear sky brightness temperature residuals for GDAS (green), dual-regression (red) and dual-regression plus de-aliasing (black) for the 710-760 cm^{-1} spectral range (top) and the 1200-1500 cm^{-1} spectral range (bottom) obtained over central North America on 20 May 2013.

3.2 Dropsonde Validation

Numerous simultaneous and geographically coincident S-HIS (Scanning High-resolution Interferometer Sounder) and AVAPS (Airborne Vertical Atmospheric Profiling System) dropsonde measurements were collected during the NASA Hurricane and Severe Storm Sentinel (HS3) mission during the Atlantic hurricane seasons of 2012 through 2014. S-HIS has a unapodized spectral resolution of 0.5 cm^{-1} with a spectral coverage from 580 – 3000 cm^{-1} and was flown onboard the unmanned Global Hawk aircraft at 20 km altitude during the HS3 missions.

The mean and the standard deviations of the differences between GDAS and AVAPS, and S-HIS and AVAPS for all the data obtained during the 2014 HS3 experiment are shown in Figure 6. The top panel is for all comparisons whereas the bottom panel is for cases where the GDAS-AVAPS differences exceed 1.5 times the standard deviation of their differences for all profiles (as shown in the top panel). When all the cases are considered, the difference between the absolute and relative accuracy of the S-HIS and GDAS profiles is small, with both sounding errors being less than 1 K, which is only slightly larger than the accuracy of the AVAPS assumed to be the “truth”. However, when the sample is restricted to those profile comparisons where there is a significant error in the GDAS soundings, the S-HIS accuracy is far superior to the accuracy of the GDAS, with the mean and standard deviation of the errors being only slightly larger than it is for entire sample of profiles. This result illustrates indicates the fact that the error in the alias-corrected retrievals is relatively independent of the error in the model forecast analysis profile used for the de-aliasing process. The small negative bias in the temperature retrievals might be due to a forward model radiance bias error, which was not corrected for the HS3 S-HIS retrievals.

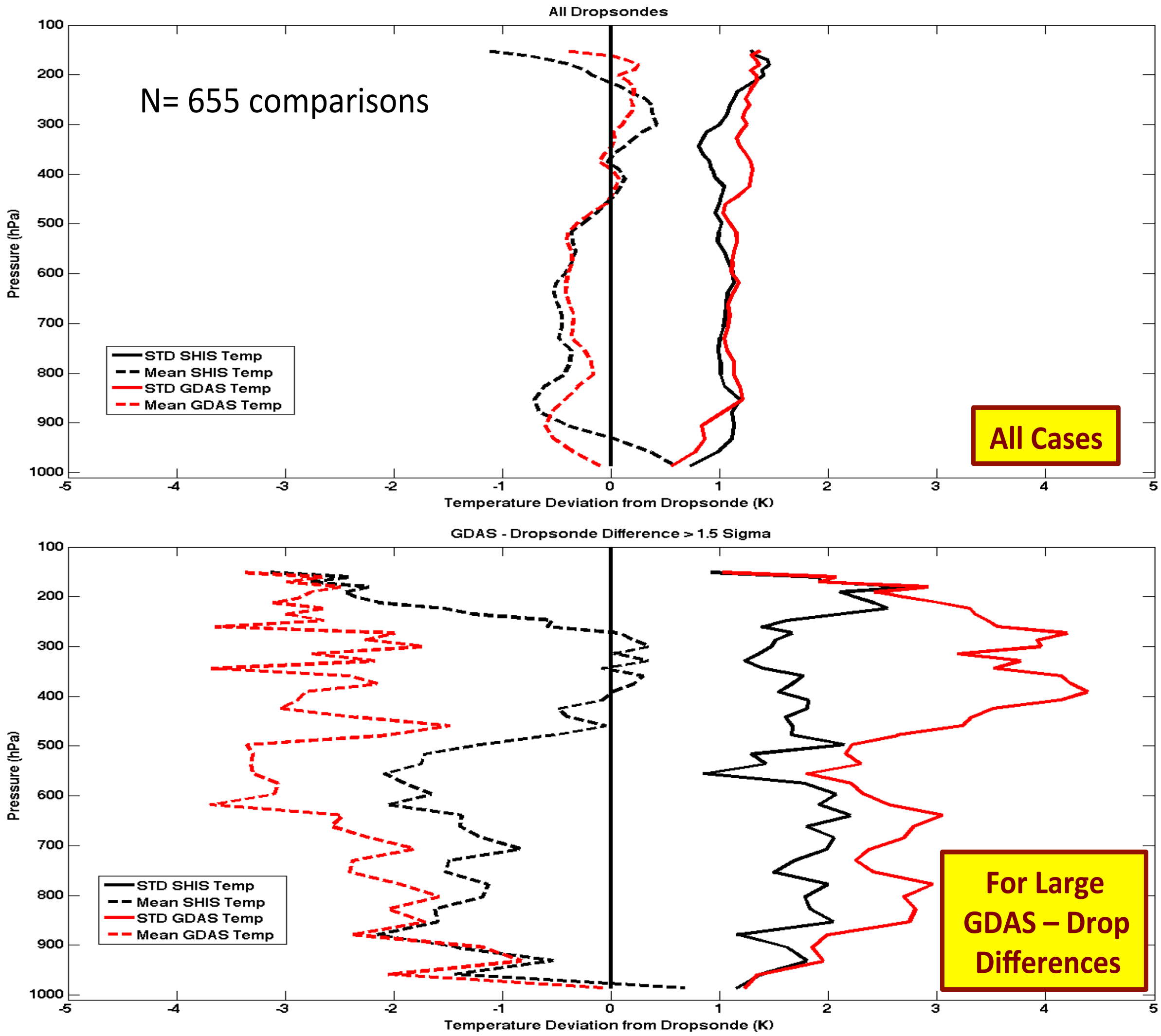

Figure 6. Bias (dashed) and standard deviation (solid) of S-HIS minus AVAPS dropsonde (black) and GDAS minus AVAPS dropsonde (red) profile differences. Left panel show results using all cases, and right panel shows only those cases where the GDAS-AVAPS difference exceeds 1.5 times the original GDAS standard deviation.

4. Observations Associated With Pre-Tornado Outbreak Atmospheric Conditions

As part of the May 2013 SNPP calibration/validation campaign, the NASA ER-2 was flown from Palmdale, California to Oklahoma to validate CrIS soundings associated with a forecasted severe weather outbreak. A special radiosonde observation at the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program site in Lamont, Oklahoma (OK) was scheduled for the time of the SNPP overpass time. During the flight mission a devastating EF-5 tornado touched down near Moore, Oklahoma on 20 May 2013 shortly after 20 UTC. The Metop-A, Metop-B, S-NPP and Aqua overpasses occurred approx. 4 hours, 3 hours, 1 hour, and 30 minutes, respectively, before the tornado touch-down (Weisz et. al., 2015)

Figure 7 shows a comparison between CrIS retrievals of the lifted index (LI) parameter obtained using the original regression (RGN CrIS) method (upper left panel) and with the de-aliasing (DA CrIS) adjustment (upper right panel) Vs. the GDAS LI analysis (center left panel) and Storm Prediction Center (SPC, www.spc.noaa.gov) severe weather reports (center right panel). The location of the Moore Oklahoma is shown by the tornado symbol. Negative LI values indicate unstable atmospheric conditions, and therefore increased probability of severe storm development. Although, the pure regression retrievals generally agrees with GDAS analysis in showing the same region of atmospheric instability (i.e., in the southeast portion of the region), the DA adjusted CrIS retrievals display much more intense instability for the regions where the Moore tornado and subsequent severe weather developed as shown in the SPC reports.

The bottom panels of figure 7 also display the two-hour change in atmospheric stability (i.e., the LI parameter), obtained by comparing CrIS LI values with Metop-B IASI LI values observed two-hours prior to the SNPP overpass. The DR retrievals (bottom left) show the same spatial information as the CrIS-only retrievals (center left); however, the LI tendencies derived from the de-aliased CrIS and IASI retrievals (bottom right) show more isolated pockets of rapidly decreasing stability in locations where the most intense severe weather occurred, which is confirmed by NOAA's SPC reports. The white areas in the LI panels refer to cloudy regions where the LI index could not be retrieved. It is seen that severe weather indices (and their time changes) obtained from ultraspectral can be very beneficial for severe storm monitoring and forecasting.

5. Summary

A method is developed to minimize errors in the DR retrieved profile vertical structure resulting from the limited vertical resolution of the radiance observations. Vertical resolution dependent errors can cause a vertical aliasing of the vertical structure contained in forecast model background fields, thereby limiting the positive influence of the satellite sounding data on the analysis/forecast accuracy. Applying de-aliasing corrections to the DR retrievals produces temperature and water vapor profiles that possess a vertical resolution that is similar to that of the NWP model fields. Furthermore, the accuracy of the corrected profiles is generally superior to that of the model profiles used for the de-aliasing process. Therefore the de-aliased DR satellite retrievals can be used in the same way as conventional observations (e.g., radiosondes) for the diagnosis and forecasting of significant weather events. Ongoing and near-future work includes the assimilation of the vertical resolution de-aliased profiles obtained from the Aqua, Metop, and SNPP satellite measurements to improve global and regional numerical weather predictions.

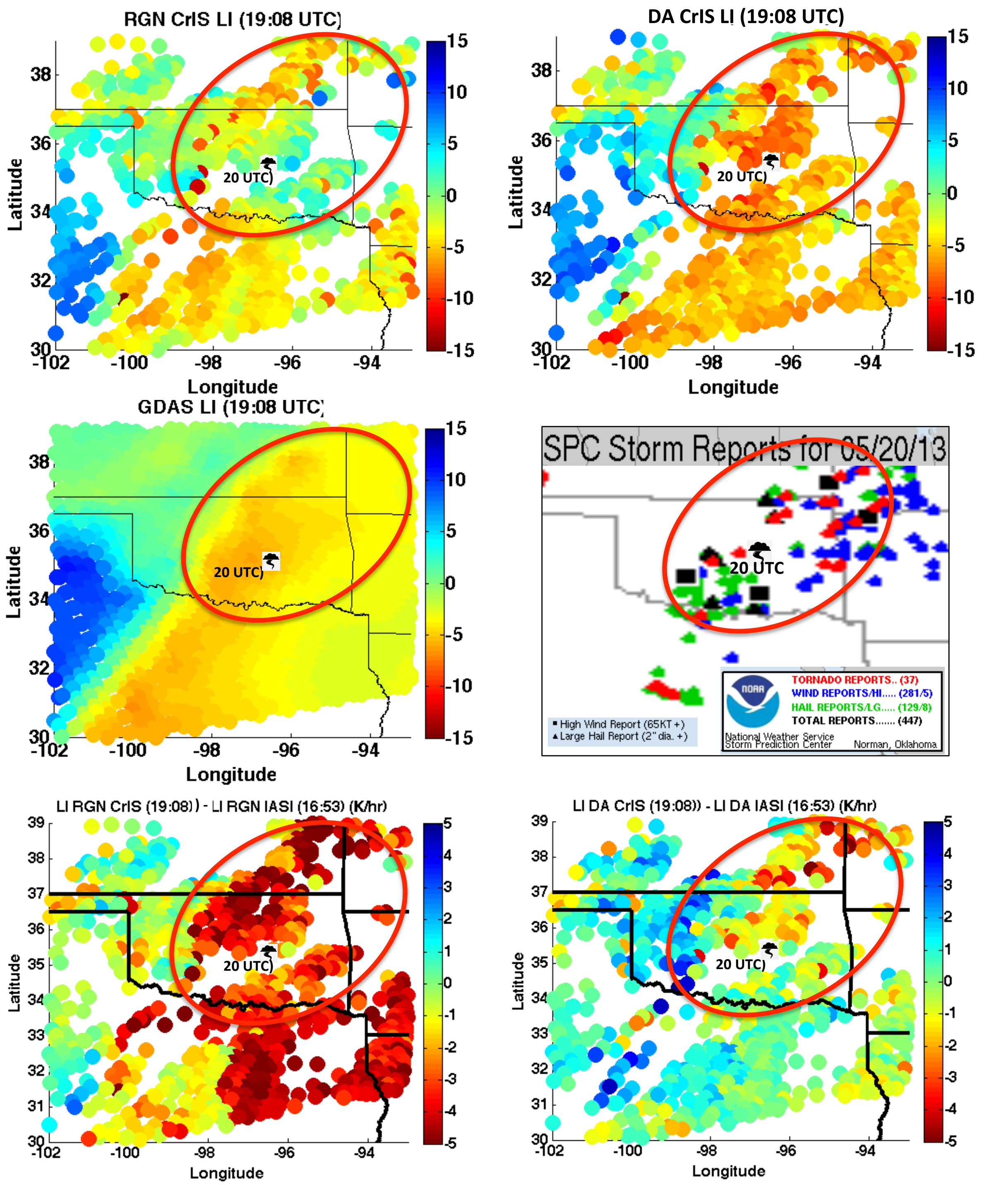

Figure 7. Comparison between CrIS LI stability parameter retrievals obtained using the original regression (RGN CrIS) method (upper left panel) and with the De-Aliasing (DA CrIS) adjustment (upper right panel). Also shown are the GDAS LI analysis (center left panel), Storm Prediction Center (SPC) severe weather reports (center right panel), and the tendency of LI obtained from the difference between CrIS LI values and the geographically closest IASI LI values observed 2-hours earlier (lower left and lower right panels). The location of the Moore Oklahoma is shown by the tornado symbol.

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