

# The May 2013 SNPP Cal/Val Campaign – Validation of Satellite Soundings

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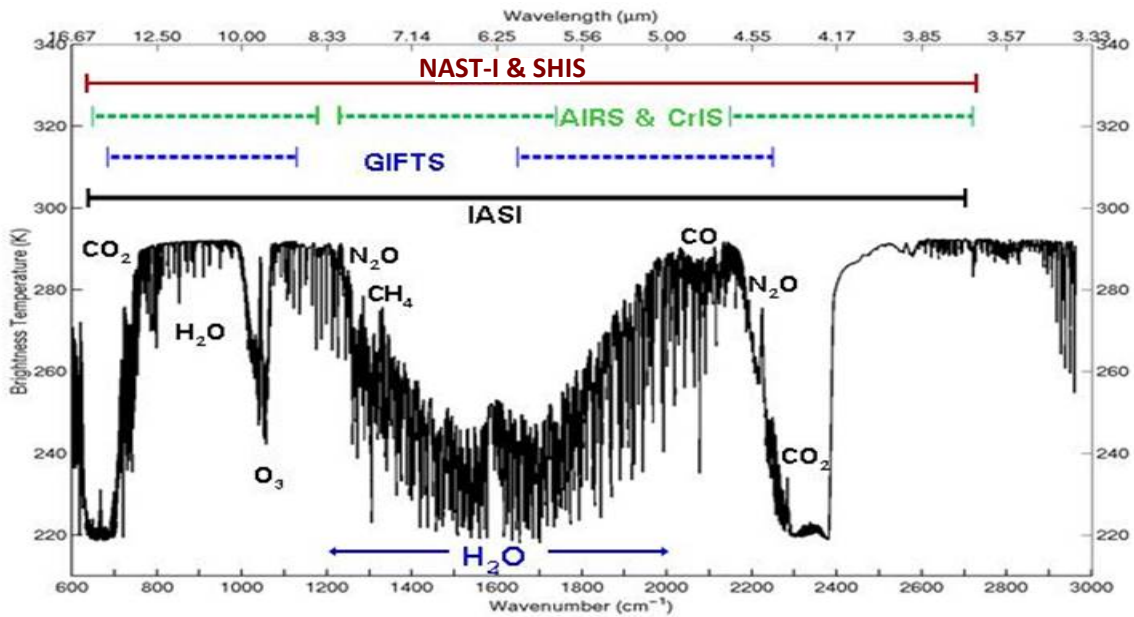
## Abstract

The Suomi-National Polar-orbiting Partnership (SNPP) satellite Calibration/Validation Campaign was held during May 2013. The NASA high altitude (20-km) ER-2 aircraft, which carried the NAST-I and SHIS ultra-spectral interferometer sounders, flew under the Metop-A and -B, Aqua, and SNPP satellites, which carry the IASI, AIRS, and CrIS ultra-spectral sounding instruments, respectively. The purpose of the campaign was to validate both Sensor Data Records (SDRs) and Environmental Data Records (EDRs) derived from the Cross-track Infrared Sounder (CrIS), the Advanced Technology Microwave Sounder (ATMS), and the Visible Infrared Imaging Radiometer Suite (VIIRS). Flights were conducted over clear ocean scenes for SDR validation. For EDR validation, special ground truth radiosonde and surface based upward viewing ultra spectral radiance Planetary Boundary Layer (PBL) sounding observations (i.e., from the AERI and the ASSIST interferometer spectrometers) were obtained at the DOE Southern Great Plains (SGP) ARM CART-site and from a mobile ground site located in Yuma, Arizona. A common physical/statistical sounding retrieval algorithm and statistical database have been applied to the aircraft, ground-based interferometer, and satellite ultra spectral radiance data in order to use the higher spatial resolution aircraft data and higher vertical resolution surface-based interferometer PBL soundings, and radiosonde profiles, to validate the satellite sounding products. Comparisons between the satellite and the surface / airborne ground “truth” measurements are provided. In this paper, special emphasis is given to demonstrate the utility of satellite soundings, and associated atmospheric stability and time tendency observations, made prior to the development of the devastating Moore, OK tornado on May 20, 2013.

## Introduction

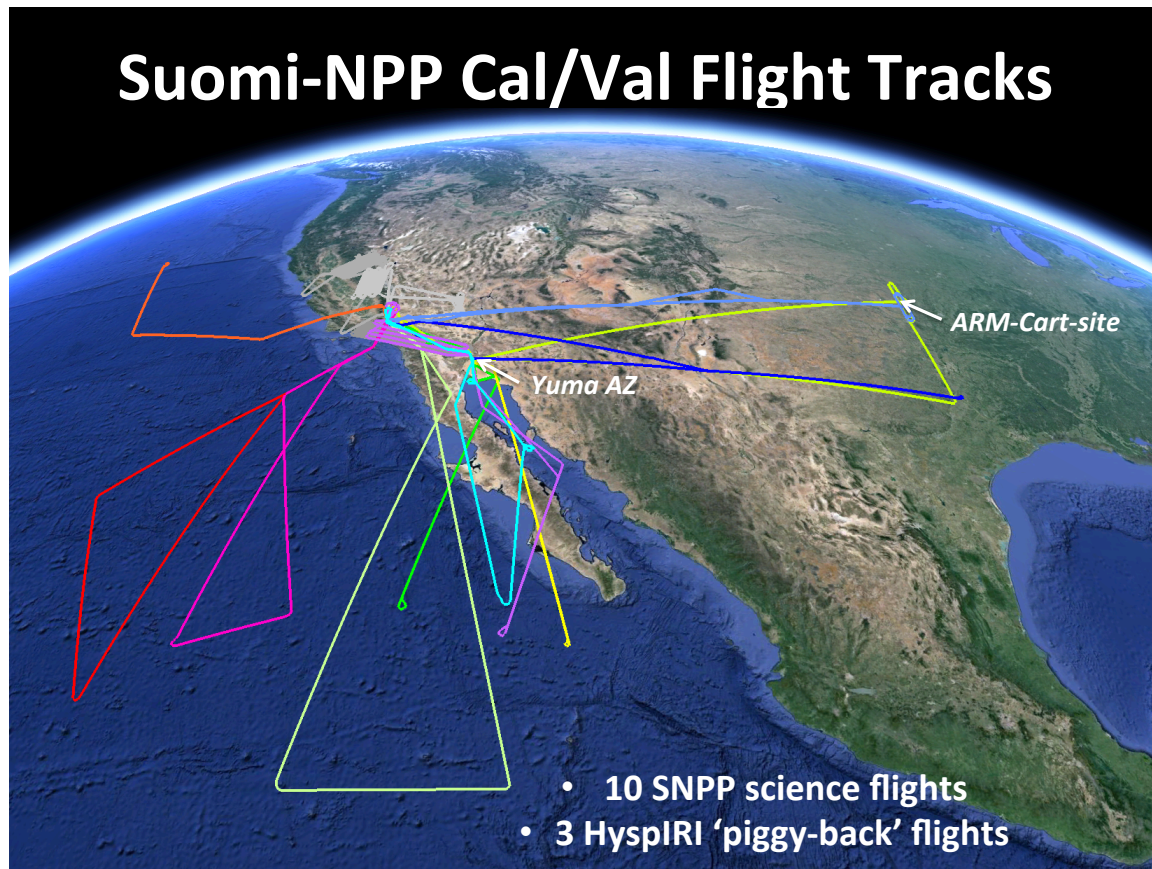
The Suomi National Polar-orbiting Partnership (SNPP) satellite Calibration/Validation Campaign was held during May 2013. The NASA high altitude (20-km) ER-2 aircraft, which carried the NAST-I and SHIS ultra-spectral interferometer sounders, flew under the Metop-A and -B, Aqua, and SNPP satellites, which carry the IASI, AIRS, and CrIS ultra-spectral sounding instruments, respectively. 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 horizontal scanning HIS (S-HIS) and the NPOESS Atmospheric Sounder Testbed-Interferometer, (NAST-I) are

flown on NASA aircraft to demonstrate the value of ultra-spectral resolution data for profiling the atmosphere and for validating the space borne ultra-spectral sounders currently in polar orbit (Taylor et. al., 2008). The Atmospheric Infrared Sounder (AIRS) (Chahine et. al., 2006) on NASA's Aqua satellite was the first US experimental space demonstration of the technique and capability, while the first operational polar orbiting satellite implementation, Infrared Atmospheric Sounding Interferometer (IASI), was initiated on the European MetOp-A and Metop-B satellites (Hilton et. al., 2012). These sensors provided the spectral resolving power from 1000 to 10,000, respectively, 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 first NOAA ultra-spectral 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 CrIS has the distinction of having the lowest noise level of any sounding instrument ever flown. The spectral coverage characteristics of the aircraft and satellite ultra-spectral sounding instruments discussed above are shown in figure 1.



**Figure 1.** The IR spectra used for atmospheric sounding of the atmosphere and the regions used by some of the current ultra-spectral sounders.

Figure 2 (Taylor et. al., 2014) shows the flight tracks of the NASA ER-2 during the SNPP cal/val flight. The flights over the ocean were conducted for CrIS radiance measurement calibration validation. Flight tracks were chosen so as to achieve clear sky conditions over the thermally uniform ocean surface. The results of the CrIS radiance validation during the SNPP Cal/Val campaign are shown by Taylor et. al., (2014) and Larar et. al., (2014). For the CrIS sounder sounding accuracy and utility validation, flights were made over ground truth radiosonde and surface upward looking interferometer validation sites, one established at Yuma AZ and the other being the ARM-CART site at Lamont OK.



**Figure 2.** The NASA ER-2 flight tracks during the SNPP Cal/Val Campaign.

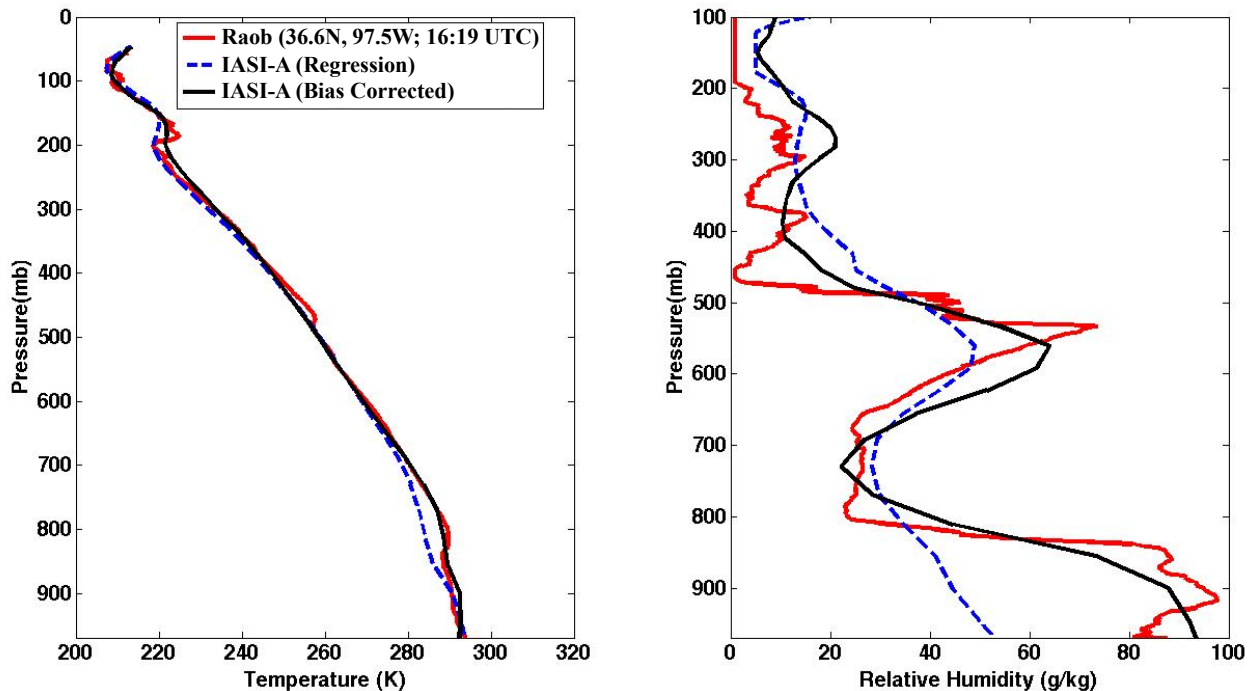
### Validation of Dual Regression Sounding Products

**Dual Regression Methodology:** Ultraspectral infrared sounders measure the top-of-atmosphere radiance emitted by the Earth system with very high spectral resolution over a range of several thousand channels. The great advantage of high spectral resolution is an increased sensitivity to the vertical structure within the atmospheric column. The spectrum of relatively low vertical resolution infrared radiances can be deconvoluted (i.e., inverted) to produce vertical profile information about the state of the atmosphere. Retrieval algorithms are designed to maximize the information content, minimize the propagation of noise, and retrieve the most probable atmospheric profile based on the observed radiance spectrum. The Dual-regression (DR) technique (Smith et al., 2012, Weisz et al., 2013) retrieval algorithm, which has its origins with the airborne NAST-I sounding retrieval approach (Zhou et. al, 2003, Smith et. al., 2005), utilizes physically simulated radiance based regression relations to produce atmospheric profiles and surface and cloud parameters at the full resolution of the sounding spectrometer. The DR linear regression ensures the processing speed necessary for real-time applications and includes geophysical classification and threshold tests to account for the non-linear dependence of infrared radiance on moisture and clouds. The DR method utilizes the full information of high-spectral resolution measurements (i.e., all the channels are used). In this application, trace gas profiles are also produced, including ozone, carbon monoxide, methane, and nitrous oxide. The chemistry profile results will be presented elsewhere.

In the Suomi-NPP Calibration and Validation Campaign application discussed here, the Dual Regression statistics are produced using data from the Real-time Air Quality Modeling System (RAQMS), which outputs profiles of temperature, moisture, ozone, carbon monoxide, methane, and nitrous oxide (Pierce, et. al., 2003). A climatology consisting of the entire month of May over the central and western United States (20 – 40N, 95 – 125 W) for the year 2010 was used to generate radiance spectra, using PCRTM (Liu, et. al., 2006) and the regression statistics for each of the satellite and aircraft instruments whose radiances were used in the retrieval process.

A physical radiative transfer based adjustment to the DR retrieval is made on the basis of NOAA’s 13-km resolution Rapid Refresh (RAP) forecast model profile in order to eliminate the statistical bias in the retrieved profile vertical structure to the mean profile of the statistics used to formulate the regression retrieval coefficients. This physical adjustment is produced by computing the radiance spectrum from the forecast profile and producing a sounding retrieval from the calculated radiance spectrum, in exactly the same manner as that used with the real satellite measured radiance spectrum. The difference between the simulated radiance retrieval and the forecast profile is the retrieval bias due to the imperfect skill of the statistical regression relationships. This retrieval bias is removed from the real satellite radiance profile retrieval.

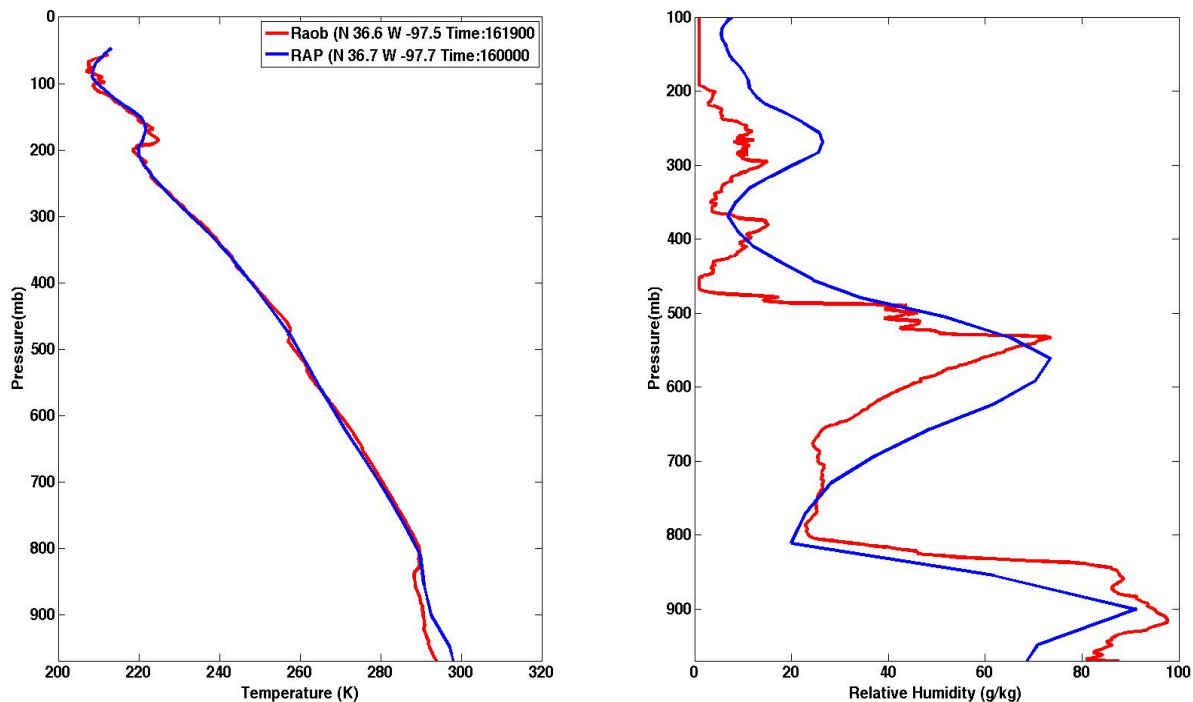
Figure 3 shows a comparison between an IASI retrieval with (i.e., physical statistical) and without (i.e., regression) the retrieval bias removal with a nearby radiosonde observation.



**Figure 3.** Comparison between an IASI retrieval at 15:56 UTC obtained with (i.e., Bias Corrected) and without (i.e., regression) the retrieval bias adjustment with a nearby radiosonde observation at the ARM CART-site at 16:19 UTC.

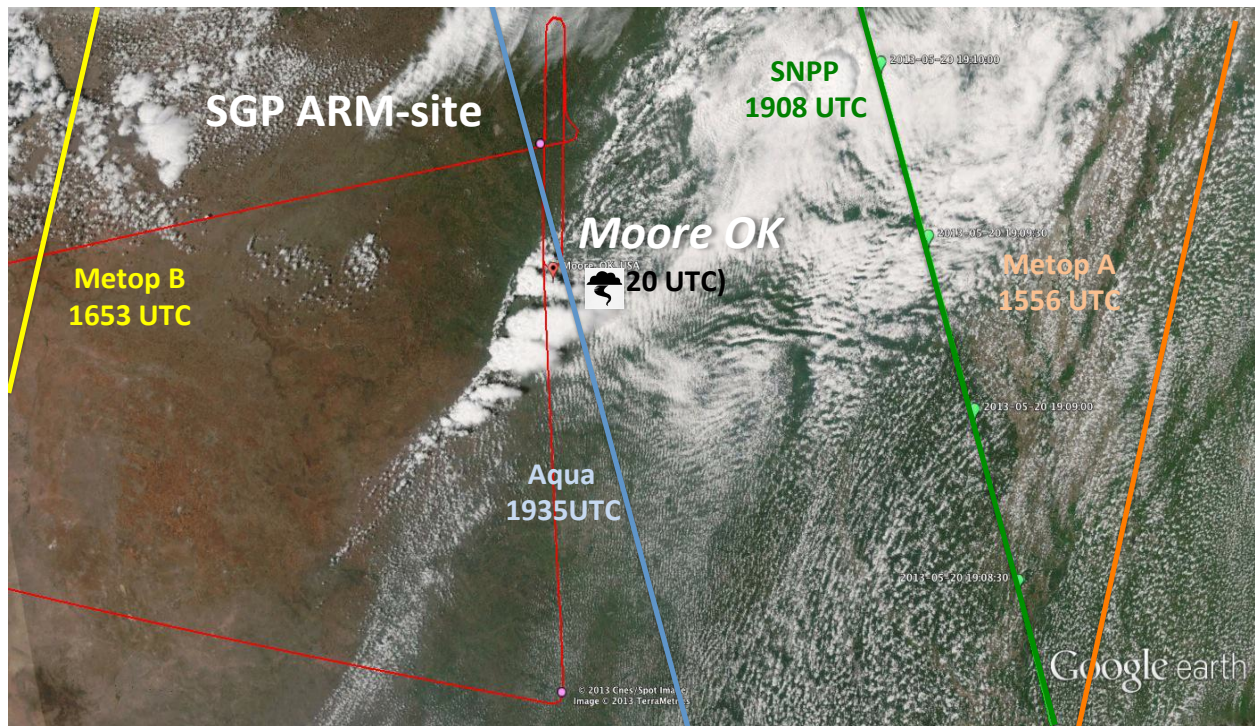
As can be seen the finer scale vertical structure shown by the radiosonde that is not captured in the regression retrieval is captured in the bias corrected retrieval. One might think that the bias correction forces the retrieval to agree with the forecast profile used for determining the bias

correction. Figure 4, which shows a comparison between the forecast profile used for the bias correction with the radiosonde, clearly illustrates that this is not the case. The bias corrected IASI retrieval shown in figure 3 compares much better with the radiosonde observation than does the RAP forecast profile used for determining the correction, particularly for relative humidity and for the temperature profile in the lower troposphere. Thus, the bias corrected retrieval combines the sounding information contained in the radiance spectrum with the forecast vertical structure information not resolved by the radiance spectrum in order to produce the most probable atmospheric profile associated with the radiance observations.



**Figure 4.** Comparison between the RAP 1600 UTC forecast profile used for the bias adjustment and the radiosonde observation at the ARM CART-site at 16:19 UTC.

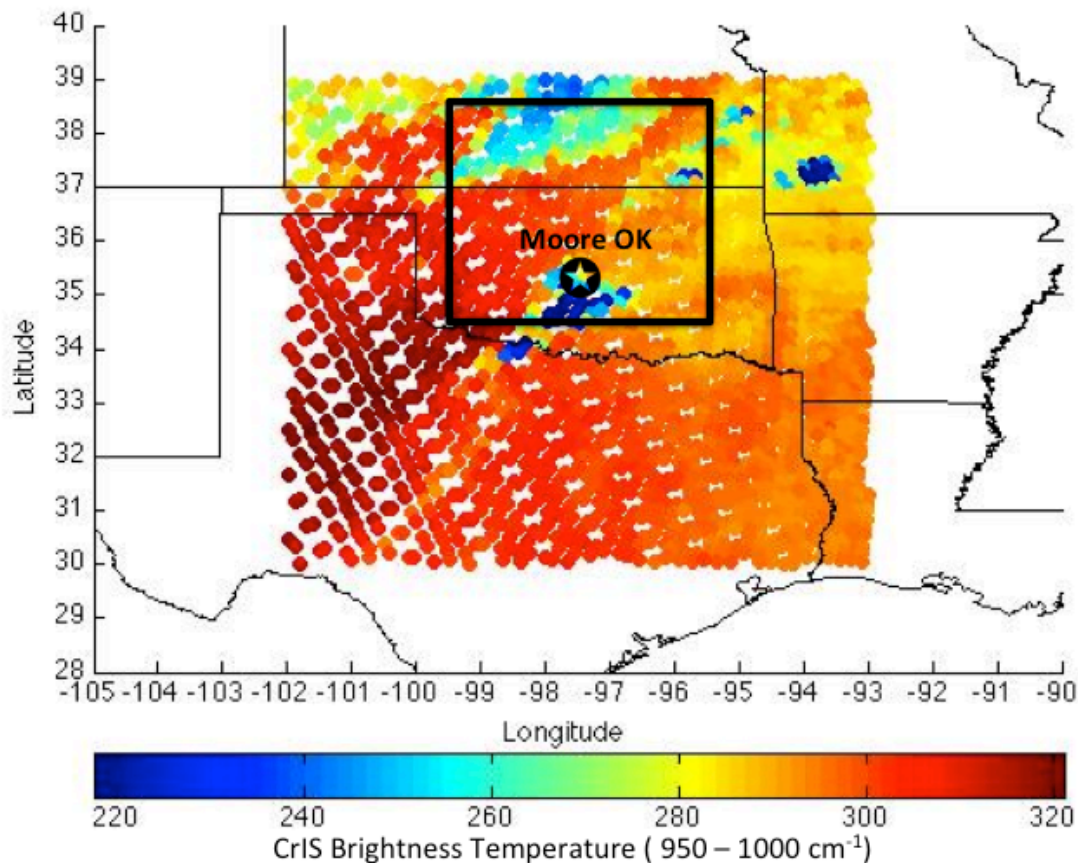
**May 20 Oklahoma Severe Weather Validation Flight:** On May 20, an ER-2 validation flight was flown from Palmdale California to Oklahoma in order to validate CrIS soundings associated with a forecasted severe weather outbreak. The flight track is shown in yellow on figure 2. A special radiosonde observation at the DOE ARM-site in Lamont, Oklahoma was scheduled for the time of the SNPP overpass time. During the flight mission a deadly EF-5 tornado developed one hour after the SNPP satellite overpass near Moore Oklahoma to the south of the ARM-site. Figure 5 shows the ground tracks of the Metop-A, Metop-B, SNPP, an Aqua satellite overpasses, which occurred before and during the initiation of the severe weather outbreak. Metop-A, Metop-B, and SNPP observed the atmospheric conditions about four, three, and one hour before the severe weather occurrence, while Aqua observed the atmospheric conditions at the time of the severe weather outbreak. The Moore, OK tornado, which occurred about 20 UTC killed 24 people and destroyed approximately 2300 houses.



**Figure 5.** Satellite orbits and ER-2 flight tracks over the Oklahoma region, which experienced severe weather on 20 May 2013.

Figure 6 shows the SNPP CrIS “window” channel ( $950 - 1000 \text{ cm}^{-1}$ ) brightness temperature observed for the Oklahoma / Texas region. The rectangular outline around Moore, OK illustrates the mesoscale region for which the soundings derived from the satellite and aircraft data are shown in subsequent figures. The starred circle denotes the location of Moore, OK. It can be seen from the brightness temperature values that the convection associated with the Moore Tornado had already been initiated south of Moore at the time of the SNPP overpass.

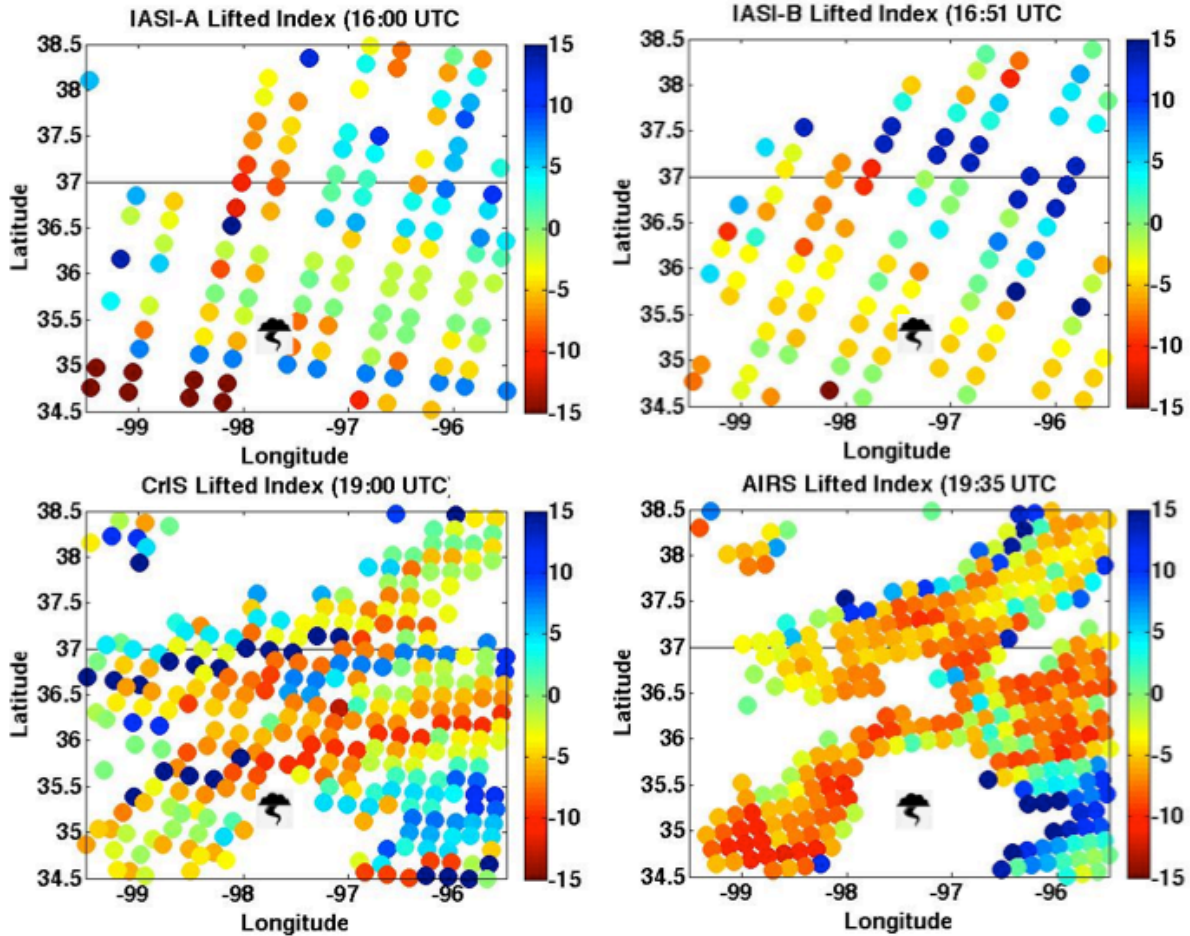
For a tornado to develop low-level moisture, atmospheric instability resulting from warm moist air lying beneath cold dry air aloft, and a lifting mechanism must exist. The thermodynamics and dynamics act together with warm moist air within the boundary layer converging into an area where there is the advection of cold dry air aloft, as associated with a cold front or a dry line. Such dry lines are common in the central plains region of the United States where dry air from the North or West meets warm moist air moving northward from the Gulf of Mexico. Typically, the convection is initially suppressed by a temperature inversion produced by nocturnal cooling and associated subsidence. Once the nocturnal “moisture capping” inversion erodes due to daytime surface heating, the warm air rises rapidly as an updraft and produces the thunderstorm. Some of the most violent tornadoes develop from super cell thunderstorms, which are characterized by persistent rotating updrafts of air. The jet stream adds yet more energy to this development. On May 20<sup>th</sup> the weather conditions of warm moist air convergence under cold dry air along a frontal boundary combined over central Oklahoma with strong wind shear due to the presence of a jet stream to produce a violent tornado outbreak.



**Figure 6.** SNPP CrIS observed brightness temperature for the spectral region  $950 - 1000 \text{ cm}^{-1}$ . The rectangular outline illustrates the geographical area for which subsequent figures are shown.

The main variable presented here was the Lifted Index (LI) stability parameter, which is derived from the retrieved temperature and moisture soundings. The lifted index is a measure of the buoyancy of the atmosphere. Decreasing values of LI indicate destabilizing conditions and an increasing probability of convective storm development. Negative values of LI indicate unstable atmospheric conditions with LI values below -5 indicative of a high probability for strong thunderstorm development.

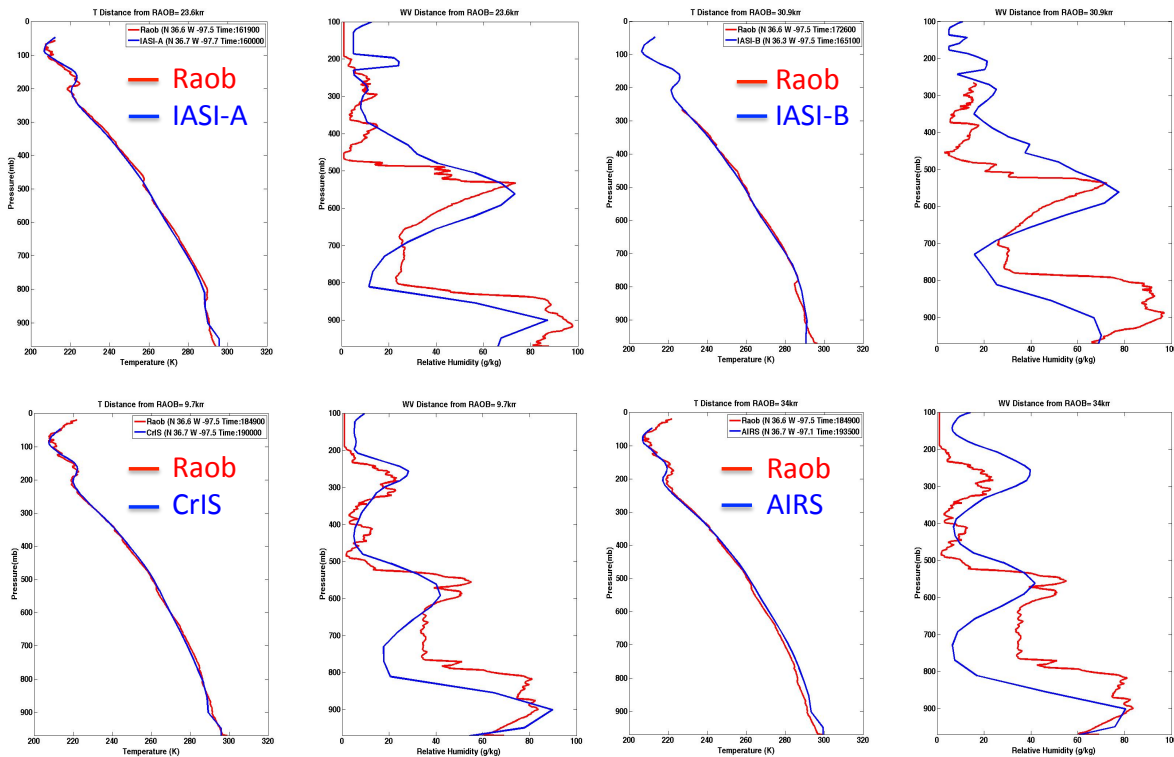
Figure 7 shows the LI values obtained from the DR retrievals from IASI-A (upper left panel), IASI-B (upper right panel), CrIS (lower left panel), and AIRS (lower right panel), which clearly show how the stability of the atmosphere decreased dramatically over Oklahoma during the morning and early afternoon hours of 20 May 2013. The tornado symbol on each panel denotes the location of Moore, OK. These CrIS and AIRS observations, which were obtained one hour and one-half hour before the Moore Tornado show extreme negative LI values in the vicinity of Moore, OK. The white areas of these images show that soundings could not be obtained down to the surface directly over Moore because of the heavy cloud cover generated by the convection initiated just prior to the SNPP overpass.



**Figure 7.** LI values obtained from IASI-A (upper left panel), IASI-B (upper right panel), CrIS (lower left panel), and AIRS (lower right panel).

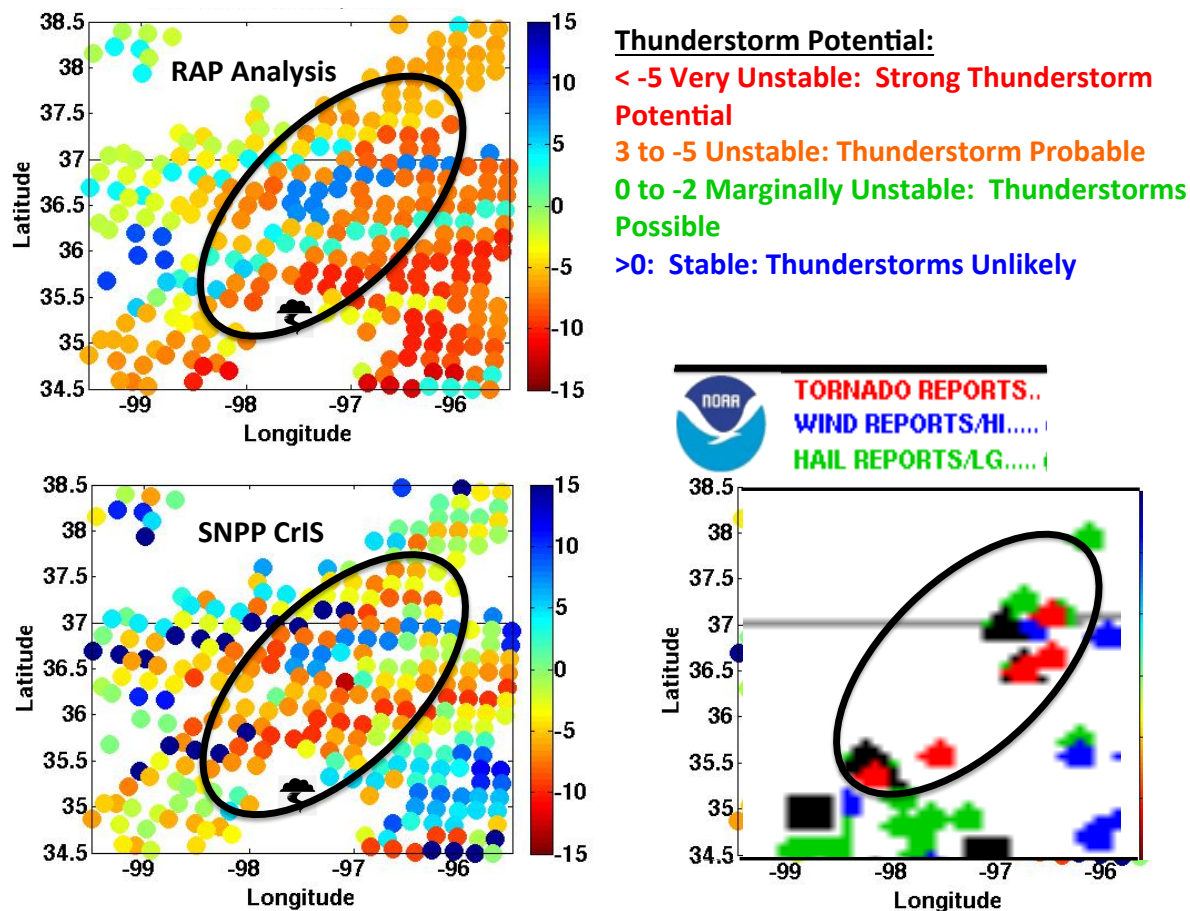
Figure 8 shows Comparison between the retrievals closest in space and time to the ARM-site radiosonde observations. The radiosonde observation times shown in the four panels are 1619 UTC for the IASI-A, 1726 for the IASI-B, and 1849 for the CrIS and AIRS comparisons. One can see that the agreement between the satellite retrievals with the radiosonde observations is similar for the four instruments although IASI-B has the poorest agreement with the lower tropospheric water vapor and AIRS has the poorest agreement with lower tropospheric temperature. The retrievals from all four instruments show the large-scale vertical humidity structure shown by the radiosonde, with particularly close agreement for the IASI-A and CrIS retrievals.





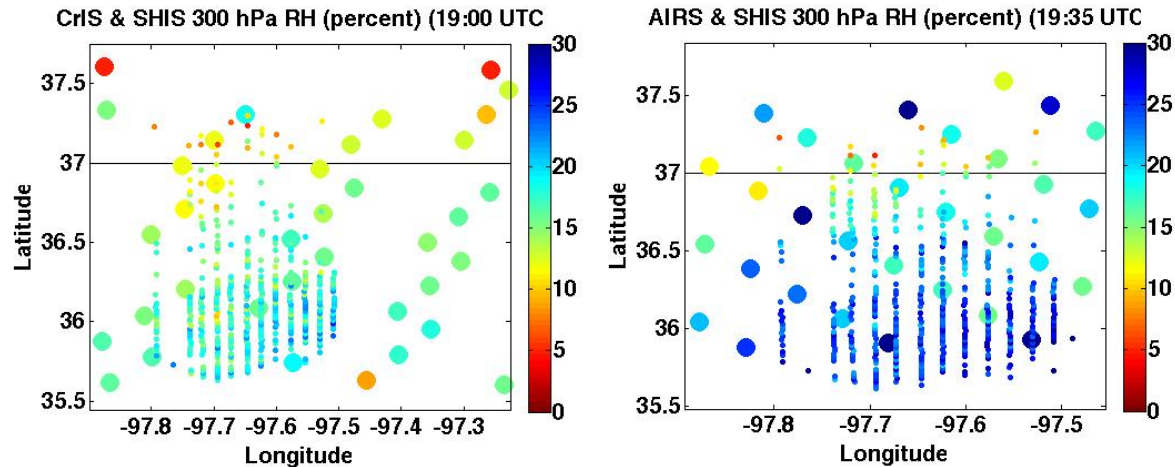
**Figure 8.** Comparison between the retrievals closest in space and time to an ARM-site radiosonde observation.

Figure 9 shows the comparison of CrIS sounding estimates of LI compared to those computed from the RAP temperature and moisture analysis profiles closest to the CrIS sounding locations. Also shown is a plot of the reports of severe weather that occurred on May 20, 2013. The major differences between the CrIS and the RAP analysis values are within the Southwest and Southeast portions of the area shown. The tornado occurrences, shown within the oval outline, occurred within a region of extreme instabilities values indicated by both the CrIS and the RAP. However, the RAP also had extreme instability values in regions of apparent thunderstorm activity lacked the intensity needed to produce Tornadoes. The CrIS data show much less instability for these regions and therefore seem to better differentiate between the regions where tornadoes were produced from those regions void of a tornado occurrence. Of course the most useful result for forecasting the precise locations and onset times of these tornadoes (e.g., the Moore, OK tornado) would be gained by incorporating the satellite sounding data into the RAP analysis/forecast operation.



**Figure 9.** Comparison of CrIS sounding estimates of LI (lower left panel) compared to those computed from the RAP temperature and moisture analysis profiles closest to the CrIS sounding locations (upper left hand panel). Also shown is a plot of the reports of severe weather that occurred on May 20, 2013 (lower right panel).

Finally, figure 10 shows how aircraft interferometer sounding measurements can be used to validate satellite products. The large circles indicate the 13-km ground resolution SNPP and Aqua satellite sounding measurements whereas the small circles indicate the 2-km ground resolution SHIS aircraft soundings. In this case, the significant 35 minute change of 300-hPa relative humidity between 1900 UTC and 19:35 UTC, shown by the CrIS and AIRS soundings at these times, is validated using the SHIS soundings obtained at both of these overpass times. As can be seen the upper level humidity increased significantly (i.e., 15% or more) between the times of the SNPP and Aqua satellite overpasses of Oklahoma (i.e. south of 37 N), apparently due to the rapid increase in convection during this time period. One might question whether this change was real or simply due to the difference in sounding instruments (i.e., AIRS vs. CrIS) for the two sounding times. However, having profile measurements from the same airborne sounding instrument (i.e., SHIS) at both of these two satellite overpass times, enables this satellite observed atmospheric dynamics to be verified.



**Figure 10.** CrIS, AIRS, and SHIS 300-hPa relative humidity measurements shown at two different times (i.e., 19:00 UTC and 19:35 UTC) on May 20, 2013. The large circles denote the 13-km foot ground resolution satellite measurements whereas the small circles denote the 2-km ground resolution SHIS aircraft observations.

### Summary and Conclusions

During the NOAA/NASA May 2013 Suomi NPP Calibration Validation Campaign, sounding retrieval results for the Metop-A and -B IASI, Aqua AIRS, and SNPP CrIS have been produced for the Oklahoma region for a severe storm day, May 20, 2013. It is shown through comparisons with the ARM-site radiosonde observations that the accuracy of the retrievals from all four instruments is comparable. In particular it is shown that the retrievals obtained at four different local times provided by the four instruments provide useful information on the atmospheric stability changes associated with the onset of severe weather. It is also shown that significant time changes in atmospheric humidity retrieved from radiance observations from multiple satellites in different orbits can be validated using retrievals obtained from radiance spectra observed with a single aircraft interferometer, which observes the area of interest at the times of the different satellite overpasses. Finally, it appears from comparisons with the profiles provided by RAP model analyses that the satellite soundings provide additional information to that contained in mesoscale model analyses that do not benefit from the use of the satellite data. An important step toward achieving the full severe weather forecasting potential of full resolution satellite ultraspectral radiance derived soundings is their assimilation into the operational mesoscale analysis/forecast system.

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