Assessing Hyperspectral Retrieval Algorithms and their Products for Use in Direct Broadcast Applications

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Abstract

Software released under the Community Satellite Processing Package (CSPP) runs stand-alone on direct broadcast (DB) user systems to enhance the latency and reliability of data distribution for real-time applications. Here we are specifically interested in characterizing two hyperspectral retrieval algorithms that are currently available in CSPP, the University of Wisconsin-Madison Dual-Regression (DR) algorithm and the NOAA Unique Combined Atmospheric Processing System (NUCAPS). To address concerns raised by users on how best to use these algorithms to meet specific needs we describe the main differences in algorithm design and discuss the implications of these differences on the retrieval products and their various applications. From the results we report that the two hyperspectral retrieval product suites offer different but complementary skills in DB applications.

1. INTRODUCTION

Hyperspectral infrared sounders, such as AIRS (Atmospheric Infrared Sounder) on EOS-Aqua, IASI (Infrared Atmospheric Sounding Interferometer) on MetOp-A and MetOp-B, and CrIS (Cross-track Infrared Sounder) on Suomi NPP (S-NPP), measure the top-of-atmosphere (TOA) radiance emitted by the Earth system with very high spectral resolution using several thousand channels. The great advantage of high spectral resolution is an increased sensitivity to the vertical structure within the atmospheric column (from surface to TOA). Thus, hyperspectral measurements can be inverted into vertical temperature, moisture and ozone profiles, as well as parameters describing surface and cloud properties.

A single hyperspectral radiance measurement is made up of thousands of spectral values, or channels, and can be computationally expensive to process. For weather forecasting applications that rely on real-time data availability and dissemination it is critical to design retrieval algorithms that can process these large datasets in a timely manner. One retrieval method that has historically been popular in real-time processing environments because of its processing speed is linear regression (e.g., Zhou et al. 2005; Weisz et al. 2007). Linear regression is a statistical method that uses pre-calculated coefficients to invert a radiance measurement into its statistically most probable atmospheric state. The regression coefficients are calculated offline by correlating a diverse set of simulated (or measured) radiances with their coincident atmospheric profiles. For computational efficiency and information preservation, the radiances are often projected into eigenvector space. This allows not only data compression but also noise filtering as only the leading set of eigenvectors is used to represent the radiance measurement. One potential weakness of a straightforward linear retrieval method is that it may not adequately account for the non-linear relationship between the measured radiance and the atmospheric state, in particular that produced by variable cloud height and moisture. Another widely used inversion technique is the optimal estimation method (Rodgers 2000), which incorporates a-priori information as well as radiative transfer and weighting function calculations for every field-of-view (FOV) or field-of-regard (FOR, which consists of an array of FOVs). Whereas optimal estimation retrieval techniques may more adequately account for the non-linearity of the radiance/profile relationship, they can be time-consuming and/or incapable of preserving the high spatial resolution necessary for many real-time applications.

Two hyperspectral retrieval algorithms are currently distributed through the Community Satellite Processing Package (CSPP, http://cimss.ssec.wisc.edu/cspp/): (1) the University of Wisconsin (UW) Dual-Regression (DR) retrieval algorithm, and (2) the NOAA (National Oceanic and Atmospheric Administration) Unique Combined Atmospheric Processing System (NUCAPS). The objective of this paper is to summarize basic differences and highlight the implications these have on the data products and their applications. We do not argue for the superiority of one over the other, but instead discuss product trade-offs due to algorithm design choices. Different algorithms for the same instrument exist because the problem of inverting TOA radiances into atmospheric parameters is at its core ill-posed and under-determined. This means that a unique solution does not exist but instead an estimate is derived based on a set of user requirements. Note that we focus here on the current CSPP distributions of these algorithms and do not comment on their development goals in general. It is important to bear in mind that CSPP aims to reach global direct broadcast users who need locally processed or real-time data products. The algorithms and the main differences are briefly outlined in Section 2. Several case studies representing a variety of weather scenarios are discussed in Section 3 and a summary is given in Section 4.

2. THE RETRIEVAL ALGORITHMS AND THE DIFFERENCES

2.1 The Dual-Regression retrieval method

The UW Dual-Regression (DR) method (Weisz et al. 2011; Smith et al. 2012; Weisz et al. 2013) is based on linear regression, which makes the method fast and efficient, but it also includes classified statistics and other decision-making steps that account for the non-linearity of atmospheric parameters, in particular the non-linear relationship between measured radiance and clouds. A schematic diagram of the DR retrieval algorithm is shown in Figure 1a. The algorithm provides atmospheric profiles, surface and cloud parameters at a single FOV spatial resolution by using two sets of eigenvector regression coefficients, one set trained on clear-sky atmospheric profile conditions and the other trained on cloud-height-stratified cloudy atmospheric profile conditions. Under clear-sky conditions the clear- and cloudy-trained retrieved temperature profiles will be very close, whereas under cloudy conditions the clear-trained solution will be colder than the cloud-trained solution below the cloud top. The cloud heights are specified as that level where the profiles start to deviate from each other. The profiles are then combined to create the final sounding product.

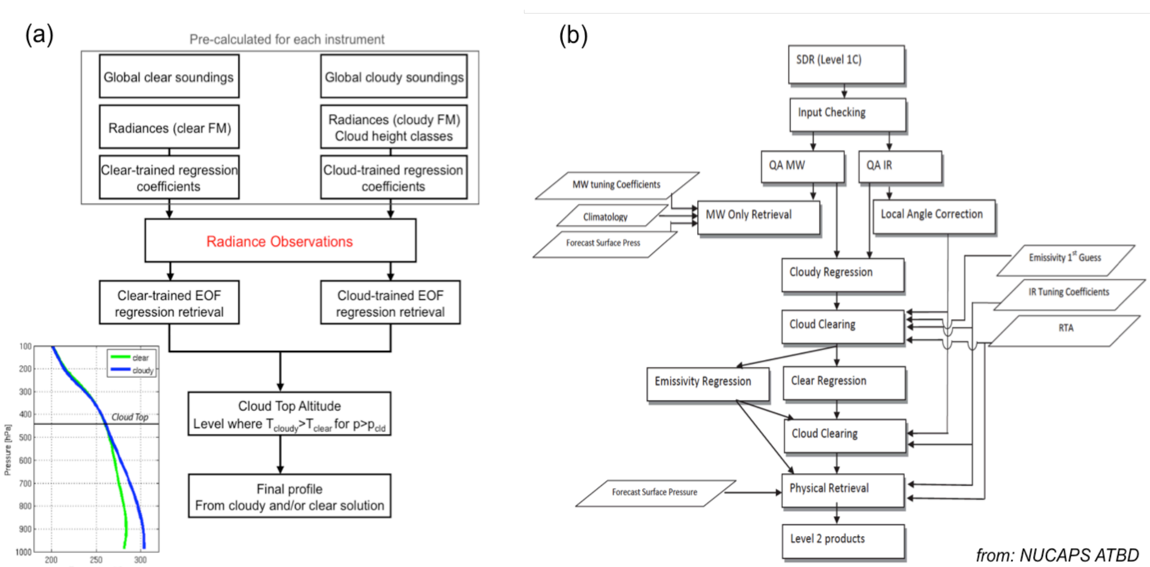

Figure 1. Retrieval algorithm schematic diagram for (a) the Dual-Regression and (b) the NUCAPS retrieval algorithm.

2.2 The NOAA Unique Combined Atmospheric Processing System

The NUCAPS (formerly called the NOAA Unique CrIS/ATMS Processing System) retrieval algorithm (Gambacorta et al. 2012; 2013) comprises multiple steps, which are outlined in the diagram shown in Figure 1b. The retrieval system starts off with an iterative microwave-only retrieval and an eigenvector regression retrieval, which is trained against ECMWF analysis data and CrIS cloudy radiances. Then cloud-clearing is performed, followed by a second regression retrieval, which is now trained on the cloud-cleared radiances. For the regression steps both the CrIS and the ATMS radiances are used. The final step is a physical (or optimal estimation) retrieval, which uses the regression as the first guess, to derive atmospheric profile, cloud and trace gas retrievals. The cloud-cleared radiances as well as the intermediate products (microwave-only retrieval, regression retrieval) are all part of the output product suite.

2.3 The main differences

The main differences between the CSPP hyperspectral retrieval systems, i.e., NUCAPS and UW-DR, are given in Table 1 and can be summarized as follows.

- NUCAPS involves a physical retrieval step (i.e., it requires radiative transfer and weighting function calculations for every FOV or FOR), and is therefore not as fast and computationally efficient as UW-DR. However, NUCAPS can result in more accurate or refined temperature and humidity profiles especially within the planetary boundary layer.
- NUCAPS incorporates microwave data to perform cloud-clearing, and therefore provides sounding information below clouds. This increases the retrieval yield globally under cloudy conditions. The DR method, on the other hand, outputs the vertical atmospheric profiles above optically thick clouds and below thin and broken cloud only (i.e., no sounding information is available below optically thick overcast clouds).
- Dual-Regression provides retrievals for every single FOV (of approx. 14 km at nadir), whereas NUCAPS computes retrieval aggregates for every 3x3 FOV array. NUCAPS sacrifices spatial resolution (which is now approx. 50 km) to provide more soundings below clouds (i.e., the full vertical information content is preserved at the expense of spatial resolution). DR retrieval retains the high spatial resolution information of temperature, water vapor and clouds but sacrifices retrieval yield below clouds.
- Currently CSPP NUCAPS can only be applied to CrIS (and ATMS) measurements. But it is noted that the same retrieval algorithm set-up is currently used to operationally process AIRS/AMSU data, and NUCAPS IASI/AMSU/MHS processing will be installed into CSPP in the near future. CSPP DR can be applied to AIRS, IASI and CrIS radiance data. This multi-sensor capability enables the study of atmospheric dynamics by means of time tendencies derived from the different instruments in consecutive orbits.
- NUCAPS is the NOAA operational algorithm for the JPSS (Joint Polar Satellite System) suite of instruments (being a heritage algorithm of the operational AIRS science team algorithm), whereas DR is an open-source research algorithm, which allows easy access and fast data processing for many applications.

Table 1. Main differences between the two CSPP hyperspectral retrieval algorithms.

Dual-Regression (UW/CIMSS)	NUCAPS (NOAA)
Regression solution	Regression and physical solution
Infrared only	Infrared plus microwave
No retrievals below thick clouds	Retrievals below clouds
Single FOV resolution (~14 km/nadir)	3x3 FOV array (~50 km/nadir)
Multi-instrument (AIRS, IASI, CrIS)	Single IR instrument (CrIS)
Research	Operational

3. CASE STUDIES RESULTS

3.1 Retrieval product comparison

Tropical storm Bill started off the coast of Texas and moved through the United States causing widespread rainfall before it emerged over the Atlantic on 21 June 2015. The remnants still exhibit strong convection as can be seen in the CrIS brightness temperature (BT) and retrieval images shown in Figure 2. Since NUCAPS incorporates cloud-clearing, which in turn uses microwave information, it facilitates higher tropospheric retrieval yields. DR, on the other hand, is capable of providing more details, for instance in cloud altitude, due to its higher spatial resolution. It is noted, white areas in the DR temperature and moisture retrievals refer to regions of opaque clouds, and only qualitatively good NUCAPS retrievals (according to their quality flag) are displayed. NUCAPS cloud top pressures are shown for the first two cloud levels if the cloud fraction exceeds 10%. It should be added that NUCAPS also provides microwave-only cloud pressure and cloud fraction retrievals (not shown here).

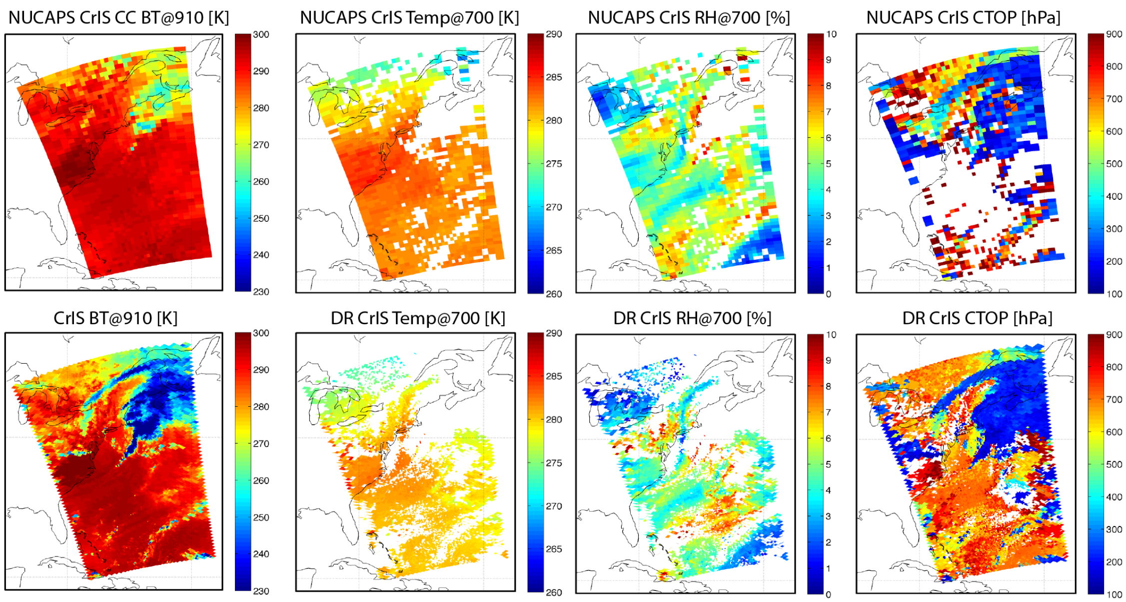

Figure 2. Top row: NUCAPS cloud-cleared BT at 910 cm^{-1}, NUCAPS retrievals of temperature at 700 hPa, relative humidity at 700 hPa and cloud top pressures. Bottom row: CrIS BT at 910 cm^{-1}, UW-DR retrievals of temperature at 700 hPa, relative humidity at 700 hPa and cloud top pressures. On 21 June 2015.

The second event, where two strong cyclones (typhoons Chan-hom and Nangka) are captured in one S-NPP overpass on 8 July 2015, is illustrated in Figure 3. NUCAPS, UW-DR, and NCEP/GDAS (National Centers for Environmental/Prediction Global Data Assimilation System) temperature and relative humidity cross-sections are shown along a line, which passes through typhoon Nangka. As mentioned above, individual NUCAPS retrievals, which do not pass the quality control, as well as DR retrievals under opaque clouds, are not displayed. However, DR retrievals are always available from TOA down to the cloud top; therefore the height and the extent of the cloud cover are clearly noticeable from these plots. Although the vertical structure of temperature and relative humidity is similar among the different retrieval algorithms and the model analysis, some differences (e.g., in upper tropospheric humidity) are prominent.

Ongoing work includes the in-depth investigation of the causes (e.g., degradation of spatial resolution, shortcomings in algorithm design) of these product differences as well as the characterization of product attributes such as uncertainty. To accomplish that, more inter-comparisons with independent sources (e.g., radiosonde observations, model analysis and forecast, aircraft, ground-based and satellite data) for a variety of atmospheric conditions will be conducted. The results will strengthen not only algorithm development, as needed to achieve

CSPP user requirements, but also the optimal and increased utility of hyperspectral satellite data in meteorological and environmental real-time applications.

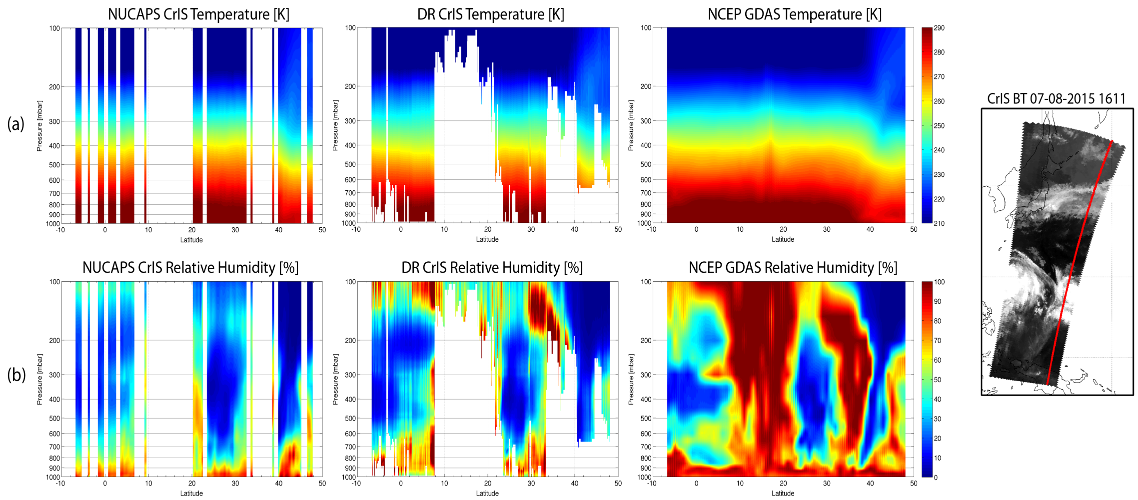

Figure 3. (a) Temperature cross-section along the red line shown in the BT image on the far right for NUCAPS (left), DR (middle) and NCEP GDAS (right). (b) Relative humidity cross-section along the red line shown in the BT image on the far right for NUCAPS (left), DR (middle) and NCEP GDAS (right). On 8 July 2015.

3.2 A time-series of atmospheric parameters

Since retrievals can now be derived from four hyperspectral satellite sounders, a new source of information is available for real-time applications. For example, a time sequence of hyperspectral retrievals provides new and valuable information on the dynamics of a storm's pre-convective environment (Weisz et al. 2015). Currently four operational sounders onboard polar-orbiting satellites provide at least eight overpasses above the same location on the globe every day. Being able to process data from multiple instruments in consecutive orbits with the same algorithm is a beneficial feature of the DR retrieval software, advantageous for many applications. Figure 4 shows the IASI-A, IASI-B, AIRS and CrIS cloud top pressures (for clouds above 450 hPa), retrieved by the DR algorithm, for a large mesoscale convective system (MCS), which developed over South Dakota and moved eastwards on 27 August 2015.

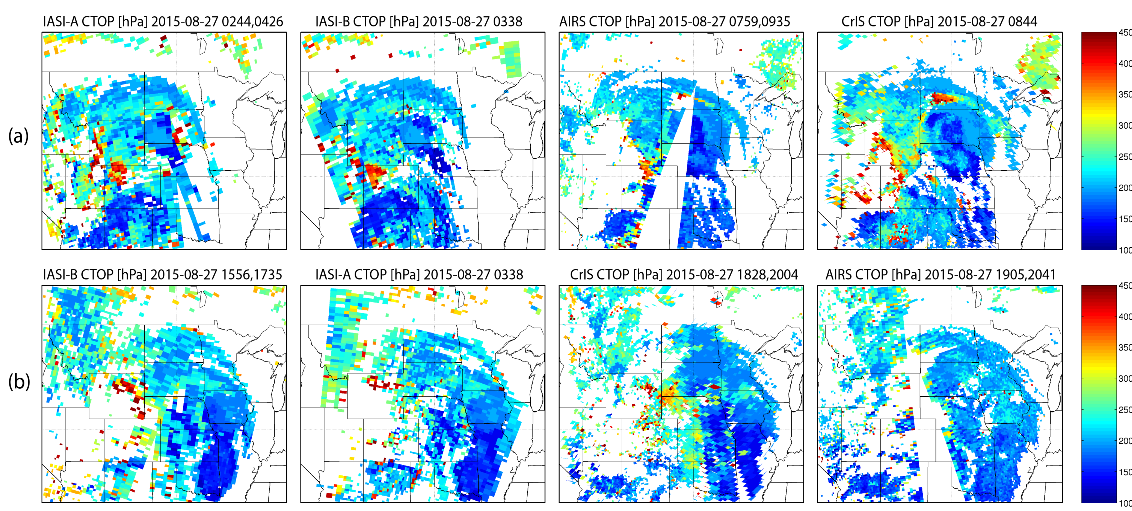

Figure 4. Cloud top pressures (shown are high clouds only) retrieved from Metop-A IASI, Metop-B IASI, AIRS and CrIS measurements using the UW-DR algorithm. The measurements start time of each overpass is stated in the title of each subpanel. (a) first and (b) second overpass on 27 Aug 2015.

Another way to illustrate parameters indispensible to reliable and accurate forecasts like atmospheric motion, pre-convective instability changes, and moisture transport, is the use of temporal differences (or time tendencies). This is shown for relative humidity at the 300-hPa pressure level in Figure 5 for the same MCS event. Absolute time differences and the change per hour for three combinations of instrument pairs are displayed. Consequently, hyperspectral observations from different instruments in consecutive orbits provide high-time frequency information, and can therefore be used to prepare for future hyperspectral sounder instruments in geostationary orbit.

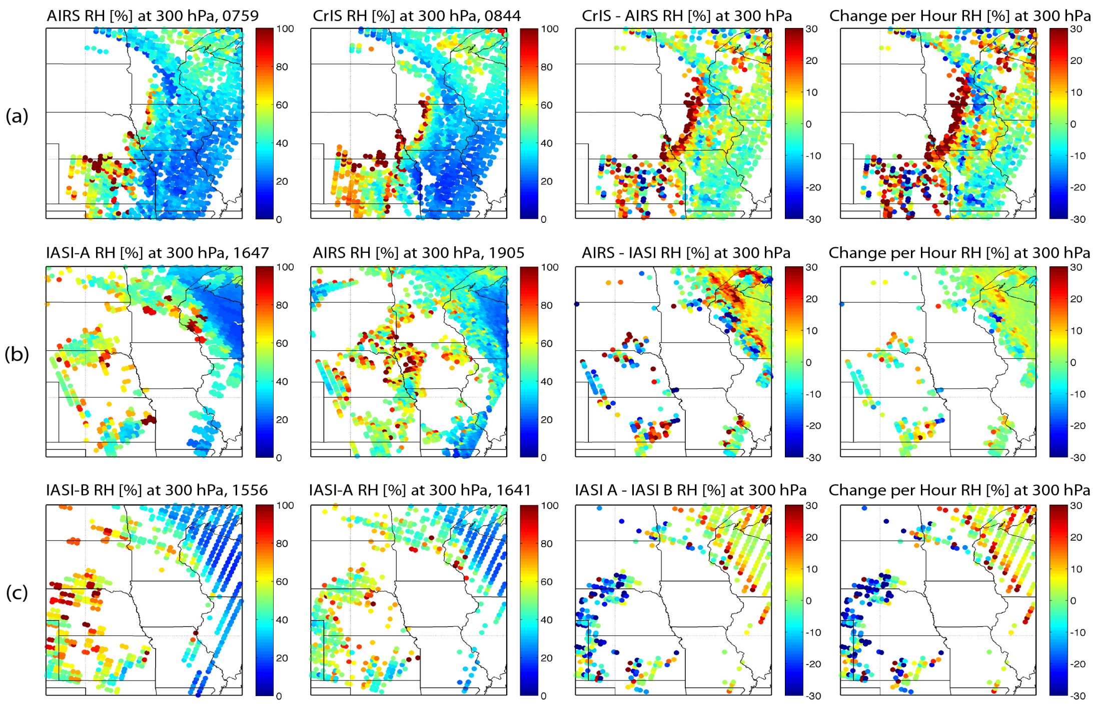

Figure 5. Relative Humidity at 300 hPa, absolute difference and the change per hour between the instruments of a pair for (a) AIRS and CrIS, (b) Metop-A IASI and AIRS, and (c) Metop-B IASI and Metop-A IASI. The measurement start time of each overpass is stated in the title of each subpanel. On 27 Aug 2015.

3.3 From user inspired research to operations

Collaboration and continued communication with the user community is a critical part of CSPP. This section describes how close user collaboration helped to identify the need of a new product and to prioritize its investigation. It also serves as an example of research potentially becoming operational. Early 2014 Alaskan region researchers and forecasters posed the question if hyperspectral sounders can be used to detect very cold air layers over the Arctic. Extremely low air temperature (less than -60 degrees Celsius) in the upper troposphere may cause the fuel of commercial airlines on transpolar flights to jellify. Since only a few in-situ measurements are currently available monitoring and forecasting capabilities would strongly benefit from additional information such as retrievals from hyperspectral satellite sounders. A number of cold air aloft (CAA) events, which usually last a few days and occur during the winter months, have been investigated and the feasibility of using hyperspectral temperature retrievals in cold air detection could be confirmed by our results (e.g., Weisz et al. 2014; Stevens et al. 2015). Since then a NOAA JPSS funded project has been established. The main goal of the CAA working group is to make this new product operationally available by preparing the display of the direct broadcast CSPP NUCAPS temperature retrievals in AWIPS (Advanced Weather Interactive Processing System). Figure 6 shows NUCAPS and DR CrIS temperature retrievals at the 200-hPa pressure level for all available S-NPP overpasses on 2 March 2015. The cold air blob readily visible over Alaska and northwestern Canada was part of a four-day CAA event, which was the first of two events occurring in March 2015.

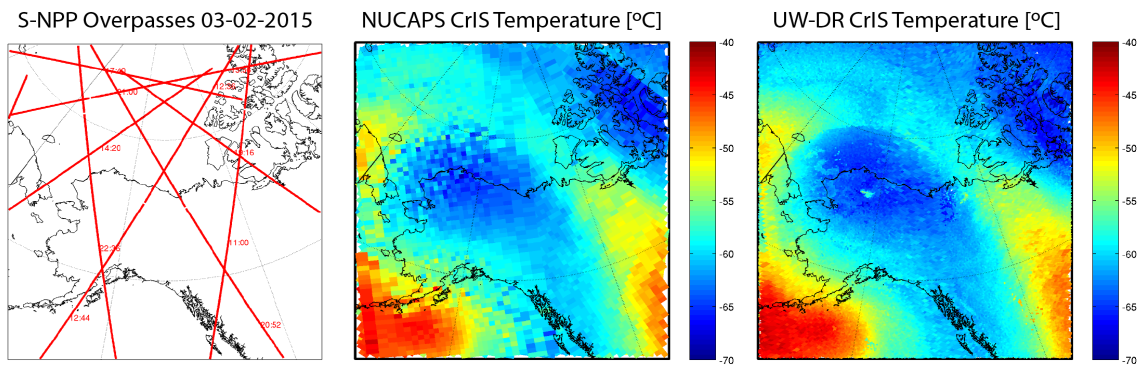

Figure 6. Suomi-NPP orbital nadir tracks for 2 March 2015 (left); NUCAPS CrIS temperature at 200 hPa (middle), and UW-DR CrIS temperature at 200 hPa (right).

4. SUMMARY

The Community Satellite Processing Package (CSPP) makes two hyperspectral retrieval algorithms, the UW/CIMSS Dual-Regression (DR) and the NOAA Unique Combined Atmospheric Processing System (NUCAPS), available to the meteorological, environmental and scientific satellite community. Brief algorithm descriptions, their main differences and their implications on products and real-time applications are given here. This represents a first step towards providing the direct broadcast (DB) user community with clear guidance on which algorithm to use in certain applications.

Dual-Regression is based on linear regression (i.e., it is optimized for speed), whereas NUCAPS incorporates optimal estimation (i.e., it is optimized for accuracy). DR provides the retrieval products for every single field-of-view (FOV) and NUCAPS for every 3x3 FOV array. Results from applying both algorithms to the same weather events indicate that differences in algorithm design and methodology produce differences in the retrieved parameters. For example, while NUCAPS provides a higher global yield in retrievals due to the incorporation of microwave data, the DR retrieval technique allows for more details in the products (such as cloud height) due its higher spatial resolution. We have also shown that, despite the differences, together a complementary and more comprehensive view of real atmospheric conditions can be provided. Another difference is that currently CSPP NUCAPS provides CrIS retrievals only, whereas DR is capable of processing AIRS, IASI and CrIS measurements, which allows the study of atmospheric parameters in a time-series. In general, the results of this study confirm that hyperspectral retrieval products have the potential to improve weather monitoring and forecasting capabilities by providing independent and detailed information about atmospheric vertical structure, clouds and the surface to complement traditional data sources.

Providing relevant information on algorithms and products together with close user collaboration is essential to supporting research and operational applications. These factors can also help identify new real-time applications, as illustrated with the detection of cold air layers over the Arctic, which is important to ensure aviation safety. Furthermore, this work will help to improve the DR and NUCAPS retrieval algorithms in order to optimize application dependent spatial and vertical information from the hyperspectral sounders (for example by expanding current uncertainty and quality measures). Overall, this will contribute to our continued efforts to enhance the use of hyperspectral retrieval products in real-time applications, and to serve DB users by making the best possible data products available.

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