AN OVERVIEW OF THE UW HYPERSPECTRAL RETRIEVAL SYSTEM FOR AIRS, IASI AND CrIS

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ABSTRACT

This paper outlines a satellite observation system that supports data-driven applications, such as weather forecasting, environmental management and climate risk assessment. Of specific interest are recent advances in methods that generate a continuum (time-series) of quantitative atmospheric data on both short and long timescales.

SYSTEM OVERVIEW

The University of Wisconsin-Madison (UW) has a history of supporting users across the world with open-source software tools to process satellite data. Rather than being a data warehouse, UW focus on distributing state-of-the art data processing algorithms. This has proven to be highly effective in ensuring data availability even in remote areas; users can receive satellite data via a direct-broadcast antenna and process the raw data into geophysical information in real-time irrespective of their geographic location or quality of Internet access. Efforts at UW started off with support for two instruments, when the International MODIS AIRS Processing Package (IMAPP, http://cimss.ssec.wisc.edu/imapp) was launched in 2000. Today, software tools are distributed for most of the operational instruments on both polar-orbiting and geostationary platforms under the umbrella of the Community Satellite Processing Package (CSPP, cimss.ssec.wisc.edu/cspp). We focus attention here on recent advances made in processing measurements from hyperspectral infrared sounders.

Four hyperspectral infrared sounders are operational in polar orbit. They are the Atmospheric Infrared Sounder (AIRS on Aqua since 2002), the Infrared Atmospheric Sounding Interferometer (IASI on Metop-A since 2006, and Metop-B since 2012) and the Cross-track Infrared Sounder (CrIS on Suomi-NPP since 2011). The high spectral resolution of their measurements ensures sensitivity to changes in the vertical atmospheric state (both thermodynamically and chemically). It is well established that a high spectral resolution in measurements ensures a high vertical resolution in retrieved atmospheric information.

The UW hyperspectral retrieval system has two main algorithm components, namely (1) the retrieval of atmospheric information at instrument resolution, and (2) the assembly of these retrievals in a uniform space-time grid. The first component provides high spatial, high vertical resolution profiles of atmospheric temperature, moisture, trace gases as well as surface and cloud parameters. The second component can take different forms depending on the application, but essentially establishes space-time uniformity among retrievals from different instruments to ensure inter-comparison as well as a continuity (or time-series) of quantitative atmospheric information over short and long timescales.

This modular design allows users to tailor the system to their own needs, whether it is to provide local data in real-time for weather forecasting or to process regional (global) archive data for change detection.

FIRST COMPONENT – RETRIEVE

The retrieval algorithm described here is the dual-regression (DR) method distributed as a stand-alone software package since 2012 under CSPP. It is discussed in detail elsewhere (Smith et al. 2012, Weisz et al. 2013b), but is primarily based on the principles of linear regression. Computationally, it is very fast. Unlike retrieval algorithms that are based on Bayesian optimal estimation, radiative transfer calculations are not performed each time a measurement is inverted. Instead, regression coefficients are applied to the radiances and derived once-off from theoretical simulations of radiance spectra using a large set of all-sky atmospheric conditions. To account for the non-linear relationship between radiances and clouds as well as the associated humidity profiles, coefficients are classified by cloud height. The full set of DR retrieved parameters includes surface (temperature and emissivity) and cloud properties (temperature, emissivity, optical thickness, and height), CO_2 concentration, as well as profiles of temperature, humidity, and ozone. The retrieval of greenhouse gas concentrations (specifically, CO and CH_4) will be added to a future version of the software package.

The DR method provides atmospheric information with a high precision in high latency environments. It is, therefore, ideal for processing hyperspectral measurements in real-time to support operational decision-making. In addition, it is a reliable tool for (re)processing entire archives of global data records for climate-scale analysis. It can be done at a fraction of the resource cost compared to more traditional methods and it is, thus, affordable to keep entire data records up to date with the latest development in this retrieval algorithm. The DR parameters are retrieved simultaneously to preserve geophysical consistency under clear and cloudy conditions at instrument resolution (single field-of-view at ~14 km). Another great advantage is that the DR approach maintains a linear relationship between measured radiances and retrieved geophyisical parameters. This promotes easy interpretation and correlation among retrieval parameters across space-time scales. It is important to note that no cloud-clearing or spatial averaging is performed.

In late 2012 a multi-instrument capability was added to support all operational polar-orbiting sounders, namely AIRS, IASI, CrIS. For the first time, users could obtain a regular and consistent time-series of daily atmospheric soundings across the globe. With four sounders in orbit, this means at least eight measurements per day. This has proven a vital addition. Since then we have worked with forecasters across the world to demonstrate the value of this added capability in real-time systems (Smith N. et al. 2013c,d, Smith W.L.Sr. et al. 2013, Weisz et al. 2014a). We have also demonstrated how severe weather prediction benefits from a high frequency of atmospheric soundings (Weisz et al. 2014b,c). In high latitude regions, like Alaska, as many as 20 swaths of soundings are available when all operational sounders are utilized. This has opened the door wide open to quantitative real-time observation and time-series analysis of weather systems.

In Figure 1 we demonstrate the quality of some of the DR retrieval products in the Alaskan region. In addition to visible satellite imagery, users now have fast access to quantitative information about the 3-D environment. In this figure CrIS retrieval products of relative humidity, cloud height and cloud optical thickness are compared to an 11.45 μm VIIRS image. Three individual profile retrievals from this region were selected and plotted in Figure 2. Here, DR retrievals of atmospheric temperature and dewpoint temperature are plotted on a skew-t plot (black lines) and compared to space-time coincident NCEP/GDAS (Global Data Assimilation System) reanalysis profiles of the same parameters (magenta lines). These are from a low-, mid- and high-cloud regions, respectively. DR retrievals are generated from the surface (or cloud top height) to top of atmosphere. As seen, the hyperspectral infrared sounder retrievals provide independent, quantitative data that compliment traditional data sources used in forecasting, such as satellite imagery.
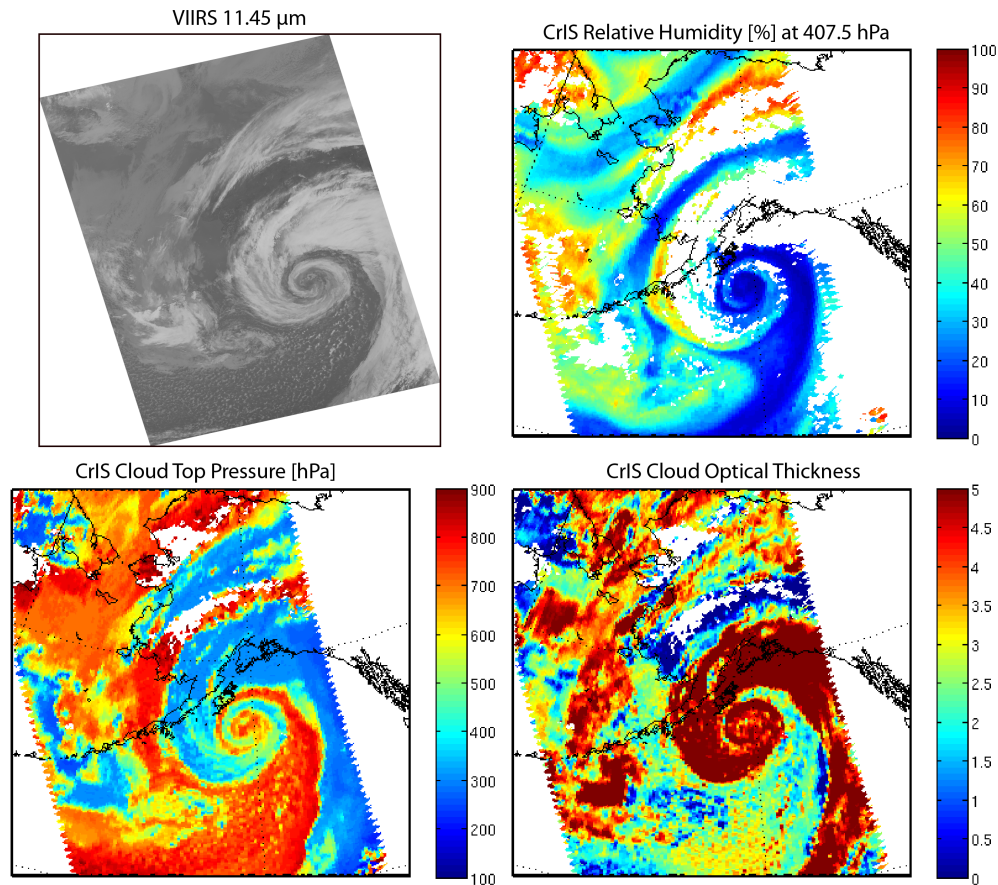
Figure 1: Low pressure system over the gulf of Alaska on 2012-09-26. Top left: VIIRS window channel (at 11.45 µm) image. Top right: CrIS DR retrieval of relative humidity at 407.5 hPa. Bottom left: CrIS DR retrieval of cloud top pressure. Bottom right: CrIS DR retrieval of cloud optical thickness.
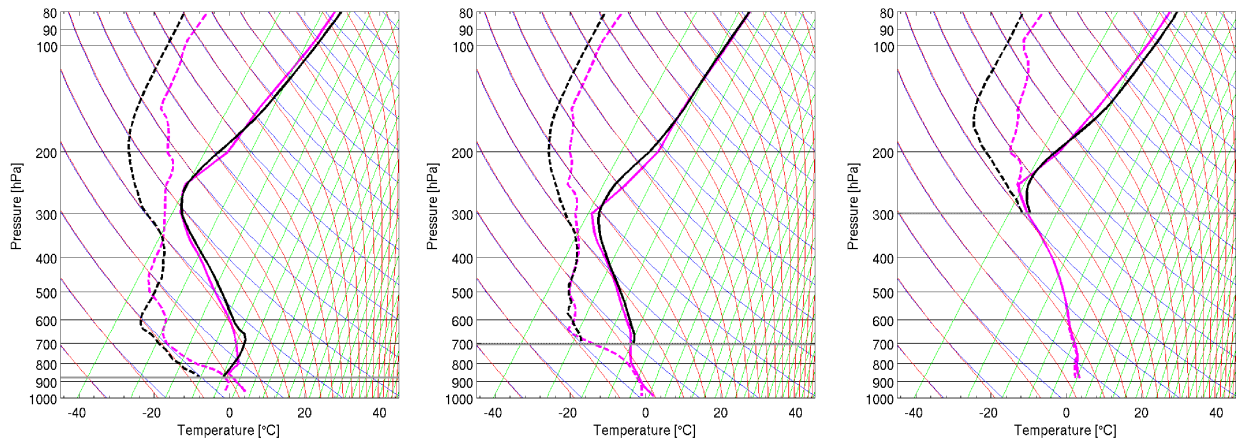

Figure 2: Skew-T plots of temperature (solid line) and dewpoint temperature (dash line) from (left to right) clear-sky, low-cloud and high-cloud scenes, respectively, in the low-pressure system depicted in Figure 1. The black lines denote DR retrievals and the magenta lines NCEP/GDAS reanalysis profiles.

Current work is underway to refine the DR trace gas retrieval capability. Intermediate products will be validated with measurements from the FRAPPÉ (Front Range Air Pollution and Photochemistry Experiment) field campaign in July 2014. Moreover, we are working at diversifying the range of available uncertainty metrics so that users may incorporate these products more readily into their existing information systems. With a growing availability of satellite data from multiple instruments and retrieval algorithms, future work will include a full inter-comparison and correlation analysis among different data products to promote the optimization of user applications.

SECOND COMPONENT – ASSEMBLE

The second component of the UW hyperspectral retrieval system concerns the projection of satellite data from their instrument-specific domain to a uniform space-time domain. The development of methods to assemble data in a robust, transparent, flexible and scalable manner is a key component in supporting data-intensive fields of research and application. For example, severe weather forecasting, disaster management and climate risk assessment all require sophisticated and reliable information about environmental variability at a range of space-time scales. We provide here a broad summary of recent efforts.

Data assembly and aggregation varies greatly in strategy and scope depending on the target application. The key elements (decision steps) that make up a robust instrument-independent space-time gridding (STG) method are described in Smith N. et al. (2013a). In Figure 3 below shows a time series of hyperspectral sounder measurements and DR retrievals are depicted over the gulf of Alaska. In the top panel the measured brightness temperature (BT) from a window channel (910 cm^{-1}) is displayed for IASI (at 21:29 UTC), CrIS (at 23:19 UTC) and AIRS (at 23:47 UTC) in consecutive overpasses. In the bottom panel the relative humidity differences between these instruments demonstrate how changes over time can be quantified.
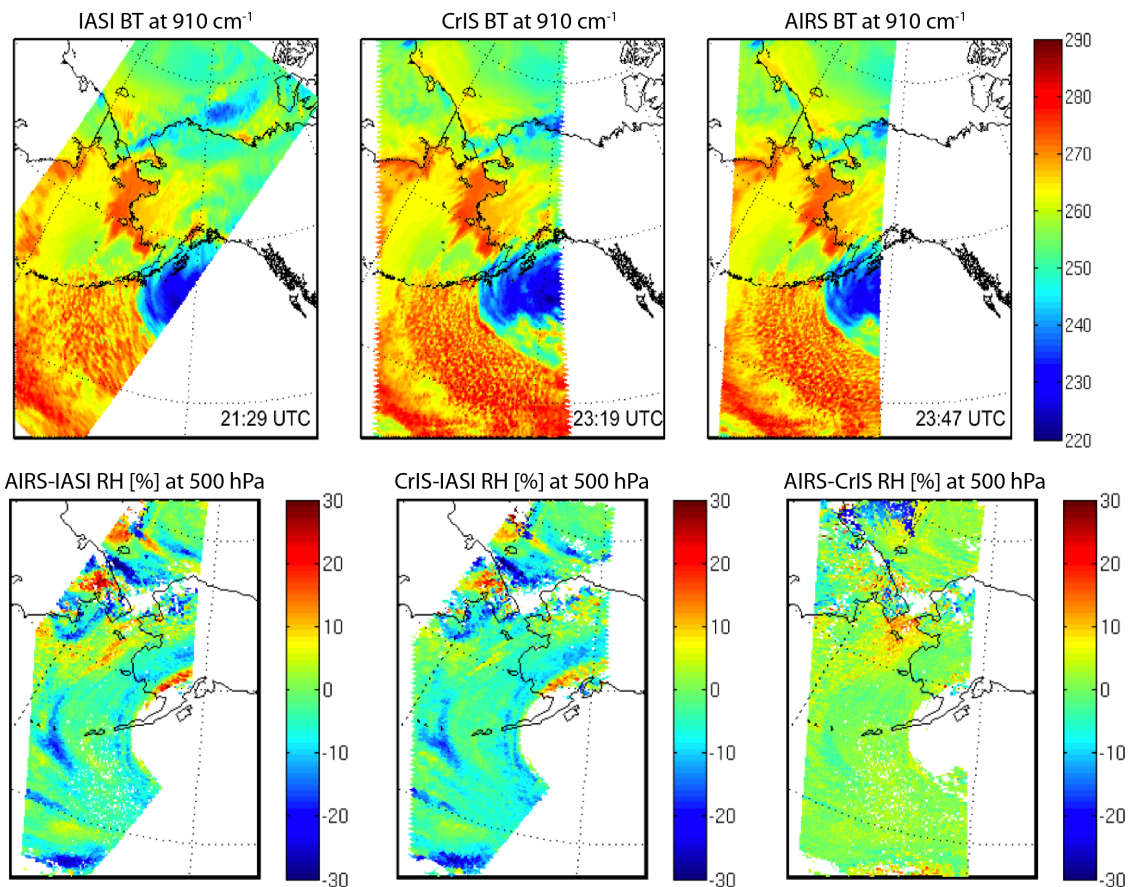

Figure 3: The benefits of multi-instrument analysis on a uniform grid. Top panel: Time series of brightness temperature (BT) from consecutive overpasses of IASI, CrIS and AIRS over the gulf of Alaska. Bottom panel: Time tendencies, or absolute differences between two instruments, of DR retrieved relative humidity (RH).

A month of CrIS cloud top pressure analysis is presented in Figure 4. The frequency of high clouds (< 440 hPa) in the top panel characterizes its global distribution. A comparison is made with high clouds retrieved from CALIOP lidar, which is in a similar orbit as CrIS. The difference in monthly averages of high cloud top pressure between CrIS and CALIOP (bottom panel) illustrates the zonal nature of high cloud DR retrieval accuracy from CrIS radiances.

CrIS High Clouds Frequency (May 2012)

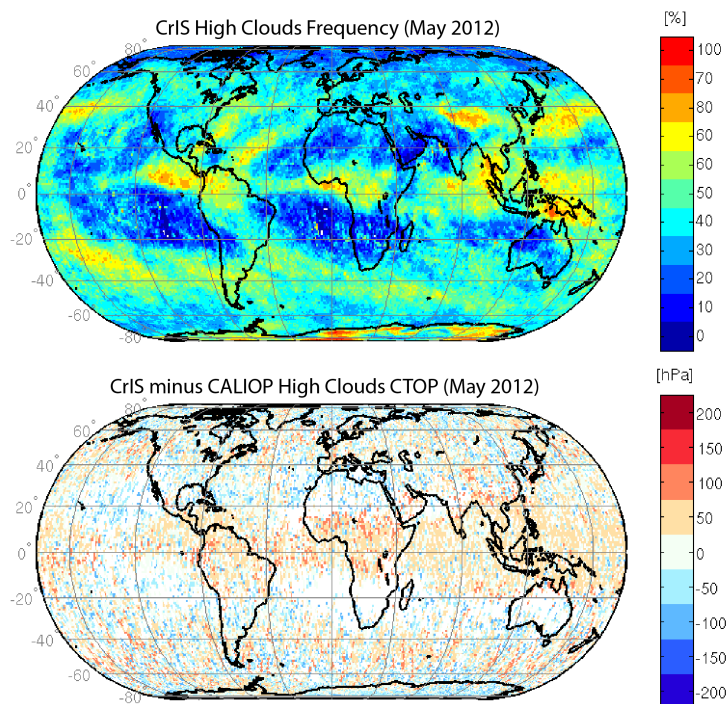CrIS minus CALIOP High Clouds CTOP (May 2012)

Figure 4: A month (May 2012) of DR cloud top pressure retrievals of high clouds (< 440 hPa) on 1-degree global grid. Top panel: CrIS high cloud frequency. Bottom panel: Monthly average of differences between CrIS and CALIOP high cloud retrievals.

Apart from these examples, the STG method has been applied to a number of studies analyzing a suite of parameters across different scales (e.g., Smith N. et al. 2013b, Weisz et al. 2013a). In collaboration with the UW CLARREO Science Definition Team (SDT), the DR and STG algorithms were applied to the entire records of AIRS (2002–), IASI (2007–), and CrIS (2012–) radiance measurements to promote comparisons of climate trend retrievals among different sources to determine potential limitations and the suitability of DR for diagnosing climate change signals in geophysical parameters (Smith W.L.Sr. et al. 2014).

A key concern in data assembly and aggregation across space-time scales is the propagation of uncertainty from radiance measurements and retrieval data products to statistical aggregates across large scales. The term "uncertainty" is an expression of doubt regarding the correctness of the result and can result from both systematic and random effects. Current efforts focus on analyzing different sources of uncertainty and their propagation through space and time (e.g. Smith N. et al. 2014, Smith W.L. et al. 2014).

Other tools developed at UW that processes the multi-instrument DR retrievals for real-time decision-making is polar2grid (http://www.ssec.wisc.edu/software/polar2grid/) and IDEA-I (Infusing satellite Data into Environmental Applications – International, http://idea-i.ssec.wisc.edu/). The former converts DR retrieval products into AWIPS format and its beta-version is currently being tested by Alaskan forecasters. The latter uses DR retrievals of ozone in air quality forecasting (more details given by Cintineo et al. 2014).

SUMMARY

The UW hyperspectral retrieval system is a multi-sensor, multi-tier system with proven accuracy and precision. It is designed to be flexible, resource efficient and robust enough to support data-intensive Earth system science and applications from small- to large-scale.

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