Neural Network Estimation of Atmospheric Thermodynamic State for Weather Forecasting Applications

William J. Blackwell[1], Adam B. Milstein[1], Bradley Zavodsky[2], and Clay B. Blankenship[3]

[1] Lincoln Laboratory, Massachusetts Institute of Technology
244 Wood St., Lexington, MA 02420-9185, U.S.A.
wjb@LL.MIT.EDU
[2] NASA Marshall Space Flight Center/SPoRT, Huntsville, AL, USA
[3] Universities Space Research Association/SPoRT, Huntsville, AL, USA

Abstract. We present recent work using neural network estimation techniques to process satellite observation of the Earth's atmosphere to improve weather forecasting performance. A novel statistical method for the retrieval of atmospheric temperature and moisture (relative humidity) profiles has been developed and evaluated with sounding data from the Atmospheric InfraRed Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU) on the NASA Aqua satellite and the Infrared Atmospheric Sounding Interferometer (IASI) and AMSU on the EUMETAT MetOp-A satellite. The present work focuses on the cloud impact on the AIRS and IASI radiances and explores the use of stochastic cloud clearing mechanisms together with neural network estimation. The algorithm outputs are ingested into a numerical model, and forecast information and decision support tools are then presented to a meteorologist. We discuss the underlying physical problem, the algorithmic framework, and the interaction with forecaster.

Keywords: Neural networks, numerical weather prediction, weather forecasting.

1 Introduction and Overview of the Algorithm Suite

We aim to improve Aqua atmospheric observation capability in the vicinity of severe and extreme weather by incorporating algorithm flexibility to process arbitrary FOV geometries and by fusing data from multiple sensors. The first part of the algorithm development addresses improvements to hyperspectral sounding in the presence of cloud cover, while the second part addresses improvements to characterization of clouds themselves. Currently, cloud-cleared sounding retrievals using the AIRS instrument employ only 1/3 of the instrument's native horizontal resolution, due to the required 3x3 groupings. Hence, measures of atmospheric stability based on AIRS retrievals are precluded from identifying local regions of probable convection smaller

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than the combined ~41 km pixel size at nadir. To overcome this limitation, we are developing a fused AIRS/AMSU/MODIS approach to improve hyperspectral sounding horizontal resolution in the presence of clouds.

The new algorithm suite discussed in this paper comprises a new version of the stochastic cloud clearing/neural network (SCC/NN) retrieval algorithm used as the first guess to the current V6 physical retrieval, adding the flexibility to accommodate smaller configurations of neighboring AIRS spectra as input than the 3x3 AMSU-matched pattern currently used. The algorithm provides enchanced SCC/NN retrievals of temperature and water vapor profiles by fusing the AIRS spectra with collocated MODIS radiances, which have high spatial resolution and can image cloud cover variability, including clear regions, within a single AIRS FOV. This will enable cloud-cleared SCC/NN retrievals of the atmospheric state to be generated at the native AIRS resolution, and with decreased reliance on AMSU for cloud clearing should it become unavailable.

The algorithm suite also provides a cloud vertical distribution product, which will improve Aqua's ability to observe the 3D structure of clouds. Currently Aqua retrievals of cloud properties and their vertical distributions have limitations imposed by the spectral and/or spatial capabilities of the individual instruments used to generate them. MODIS and AIRS cloud retrievals are based on reflective or emissive signatures from cloud tops, while AMSU is sensitive to larger hydrometeors at different altitudes (as our previous precipitation rate retrievals have demonstrated). Other key A-train sensors which directly observe cloud vertical profiles and hydrometeor distribution, such as Cloudsat or CALIOP, are often used to validate other sensors' cloud retrievals, but lack cross-track horizontal coverage. The new fused product will employ a combination of AIRS, MODIS, and AMSU inputs to retrieve cloud vertical profiles. These products are trained with Cloudsat/CALIOP vertical profiles, while retaining the cross-track measurement capability of the Aqua sensors, allowing for global coverage.

A key feature of the algorithm suite is the improvement of severe weather forecasting through 1) assimilation of the retrieved profiles into numerical weather prediction (NWP) models and 2) direct evaluation of the retrieved profiles by forecasters to determine the vertical structure of the lower atmosphere for situational awareness. Retrievals from AIRS have been successfully assimilated to improve extreme weather forecasts in short-term, regional numerical weather prediction models and have been used to help determine atmospheric instability for convection through analysis of temperature lapse rates and moisture. Current state-of-the-art, however, has been limited to clear areas on the periphery of the severe weather. The new algorithm suite will provide useful retrievals in cloudy areas to provide further forecast improvement.

2 Background

Hyperspectral infrared sounders such as AIRS and CrIS add critical information for severe weather forecasting by filling in some of the temporal and spatial voids in the radiosonde network. The Aqua satellite fills the temporal void in the radiosonde network over North America by placing the satellite in an orbit with a local afternoon Equatorial crossing time of 1:30 P.M. (Parkinson 2003). The CrIS sensor on the Suomi-NPP satellite is on a similar orbit with overpass times that are 1—3 hours after Aqua. This time is ideal for capturing the environment for nearly all weakly-forced convection and in cases where daytime heating might enhance the strength of any initiated convection. From a spatial standpoint, AIRS and CrIS soundings are provided in a swath that is approximately 1500 km in width with a horizontal spatial resolution of approximately 50-km at nadir. Retrievals from these hyperspectral sounders can be made over land and water regardless of geopolitical borders, which allows for forecasters to obtain valuable information in regions where traditional radiosonde data are not available.

AIRS retrieved temperature and moisture profiles can positively impact severe weather forecasting in several important ways. For example, Zavodsky et al. (2012) demonstrated how the assimilation of AIRS profiles resulted in a better short-term NWP forecast of a tornado outbreak along the Gulf Coast of the United States. In this work, the main impact of the profiles on the NWP model occurred in clear air over the Gulf of Mexico by improving the model's characterization of instability being advected into an approaching shortwave disturbance. Blankenship et al. (2013) showed that AIRS profiles have some positive impact on the characterization of atmospheric river features, which are narrow bands of low-level precipitation that impact the West Coast of the United States and can lead to flash flooding and landslides. In this work, though, the impact of assimilating the AIRS profiles has been limited due to the feature of interest (the atmospheric river) being characterized by thick cloud cover resulting in fewer AIRS profiles available for assimilation. In this particular case, improved retrieval yield and quality in cloudy regions would result in larger impact from the AIRS observations and better NWP forecasts.

From a situational awareness perspective, soundings have been used to help determine atmospheric instability for convection through analysis of temperature lapse rates and moisture (e.g. Iwasaki et al. 2010). Another application is to investigate mid-latitude and tropical cyclones that are transitioning to extratropical. A recent study by Wu (2012) investigated the impact of AIRS moisture retrievals on the near-storm environment for Superstorm Sandy. Both of these studies, however, focused on clear areas around the storm edge. With improved soundings closer to the storms themselves, it is possible for much greater forecast improvement.

2.1 Technical Approach and Methodology

Present approaches for hyperspectral sounding using the AIRS and AMSU instruments use 3x3 "golf ball" groupings of AIRS spectra coinciding with AMSU measurement positions to obtain a cloud-cleared radiance spectrum. In the currently operational Version 6 Aqua AIRS Level 2 retrievals, both the statistical first guess (developed by MIT-LL under our previous Science of Terra and Aqua program) and the physical retrieval algorithm employ such groupings for their different, respective cloud-clearing approaches. The SCC/NN algorithm used as the statistical first guess is shown in Fig. 1, in which the Stochastic Cloud Clearing (SCC) algorithm computes a cloud-cleared radiance spectrum, and each cloud-cleared spectrum is subsequently transformed using projected principal components. Neural networks then operate on the cloud-cleared radiances to compute soundings of temperature and water vapor. SCC, shown in Fig. 2, derives an empirical relationship between cloud-free and cloudy radiances through the use of a global training set derived from European Center for Medium-range Weather Forecasting (ECMWF) fields together with the AIRS Stand-Alone Radiative Transfer Algorithm (SARTA). From the 3x3 AIRS fields of view, SCC computes an effective average from the warmest spectra: the clearest FOV for channels having weighting functions that peak below 5 km, an average of the four clearest FOVs for weighting functions peaking between 5 and 10 km, and an average of all nine FOVs for higher altitudes. It also determines the difference between this average and the coldest spectrum. SCC then estimates a single cloud-cleared spectrum by performing a series of simple linear and nonlinear operations on noise-adjusted principal components of the IR inputs, along with 5 AMSU channels, and other inputs (forecast surface pressure, and secant of scan angle). The combination of the SCC algorithm and neural network retrievals of temperature and water vapor (henceforth “SNN-fixed” for fixed 3x3 fields of regard) has proven resilient to even heavy cloud cover. Recent work has focused on retrieval error Jacobians (Blackwell 2012) and error analysis and characterization for improved quality control

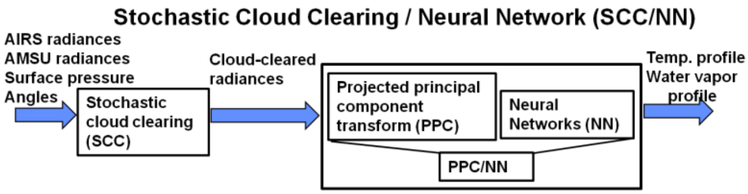

Fig. 1. Stochastic Cloud-Clearing/Neural Network (SNN-fixed) algorithm overview

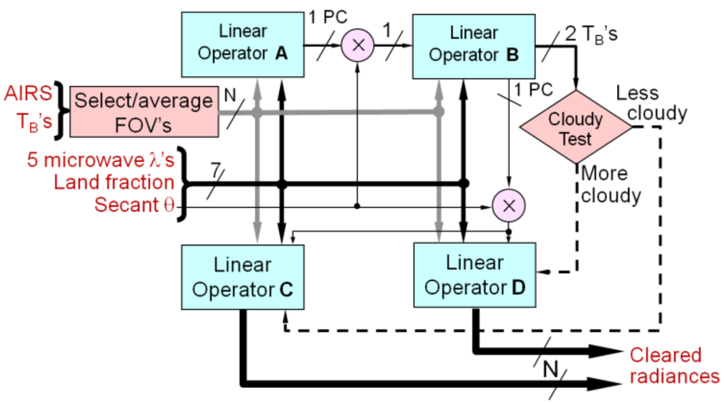

Fig. 2. Stochastic Cloud-Clearing algorithm

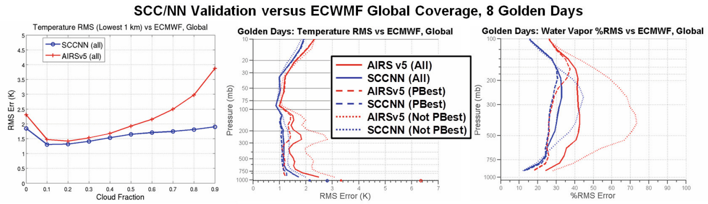

Fig. 3. SNN-fixed validation result, with global coverage over 8 "golden" days: Temperature results versus cloud fraction, temperature RMS, and water vapor mixing ratio %RMS

(Tao 2013). Fig. 3 shows SNN-fixed validation performance versus ECMWF, including temperature RMS error versus cloud fraction for the lowest 1 km layer, temperature profile RMS error, and water vapor % RMS error, illustrating significant improvement over the AIRS version 5 retrievals under cloudy conditions (including profiles not designated "PBest").

The use of nine AIRS FOVs in each golf ball offers many opportunities per sounding to avoid or minimize clouds. However, all nine FOVs are not likely needed for cloud-clearing in the majority of cases. In addition, there is no reason in principle why all neighboring AIRS FOVs used to cloud-clear an AIRS spectrum must originate from the same AMSU-centered "golf ball".

We apply the SCC technique over smaller FOV groupings than the current 3x3 (henceforth "SNN-flex" for flexible fields of regard), potentially allowing for nearly native horizontal resolution near atmospheric features of interest, while maintaining or improving resilience to cloud cover. Fig. 4 shows two examples of such groupings. The first illustrated approach shows 2x2 groupings of AIRS FOVs, superimposed over the nearest respective AMSU measurement positions, with adjacent groupings overlapping to allow closer spacing of neighboring soundings. To demonstrate the possible impact of using this approach, we computed a preliminary example retrieval product by adapting the inputs to the existing SNN-fixed code. (We note that this is preliminary due to the use of the existing SNN-fixed training statistics, which are optimized for 3x3 golf balls.)

Even with the resolution and information improvements potentially available with choice of smaller, overlapping "golf ball" groupings of FOVs for cloud-clearing, variations in cloud cover and number of cloud formations suggest that use of the same number and configuration of FOV groupings are not required for every sounding. In Fig. 4, the second depicted cloud-clearing approach shows more sophisticated FOV groupings, which will allow for even further improvements in sounding resolution. In this approach, FOV groupings of more arbitrary size and position are dynamically and automatically selected to optimize rejection of the local cloud cover. We will develop the SCC-flex cloud-clearing approach and validate it via comparisons with reference datasets such as ECMWF reanalysis fields, GPS radio occultation, and radiosondes. A detailed study of the expected tradeoffs between the number of local FOVs used for cloud-clearing versus cloud depth and number of cloud formations is now a work in progress.

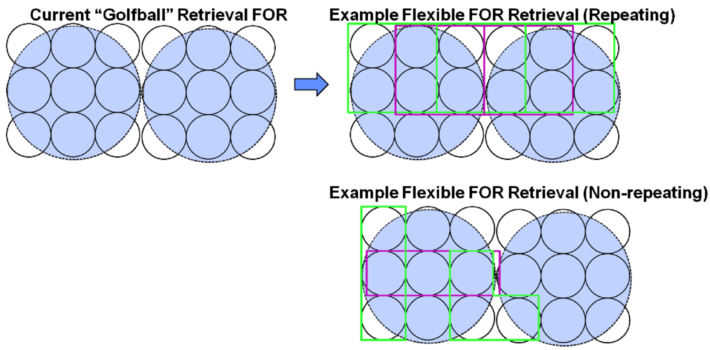

Fig. 4. Current 3x3 AMSU-centered AIRS retrieval locations, and examples of proposed more flexible alternatives, including overlapping, repeating 2x2 groupings of AIRS FOVs, and more arbitrary, dynamically chosen optimal groupings

2.2 Use of Retrieved Profiles in Situational Awareness

Severe Weather Outbreaks

Operational forecasters have used AIRS profiles directly for situational awareness. SPoRT has created an interactive website[1] that allows operational forecasters to compare profiles from AIRS, the Infrared Atmospheric Soundering Interferometer (IASI), and Cross-track Infrared Sounder (CrIS) to radiosonde observations and operational regional forecast systems. Initial feedback from forecasters from the Huntsville, AL, Raleigh, NC, and Charleston, WV National Weather Service (NWS) Weather Forecast Offices (WFOs) indicated that the hyperspectral profiles are most useful in providing guidance regarding the quality of the operational regional NWP models used for situational awareness. Because the models themselves offer relatively coarse vertical resolution soundings, a comparison of model soundings to independent observations from hyperspectral sounders can lead to greater confidence in a model forecast. Forecasters have found that mid-level water vapor and temperature profile lapse rates—two ingredients necessary for convection—are specific areas where retrieved profiles from hyperspectral sounders could be best used. Figure 5 is an example of how the page is used. A forecaster pulls up a hyperspectral sounding (from AIRS, IASI, or CrIS) and then pulls up a comparison sounding from either a radiosonde or regional model (either the North American Mesoscale (NAM) or Rapid Refresh (RAP)). In this example, the AIRS sounding provides the forecaster with confidence that the moist near-surface and mid-level drying exhibited by the RAP model are likely realistic depictions of the atmospheric state. In the figure, the thin line in the AIRS profile represents data that did not pass quality control due to clouds. With better yields from the new SNN-flex AIRS/AMSU/MODIS retrieval in cloudy conditions, forecasters will have a larger amount of data to use.

In order to evaluate the SNN-flex AIRS/AMSU/MODIS soundings for their value added to convection situational awareness, these soundings will be incorporated as an

[1] `http://weather.msfc.nasa.gov/sport/hyperspectral_comparisons/`

additional entry in the SPoRT Hyperspectral Comparison page for evaluation by both research staff and operational forecasters. As convective events occur around the Continental United States, the soundings in cloudy regions will be compared to the retrievals in non-cloudy regions to determine value-added to the forecast process. Feedback will be provided to the product development team to guide further improvements to the product for these types of cases.

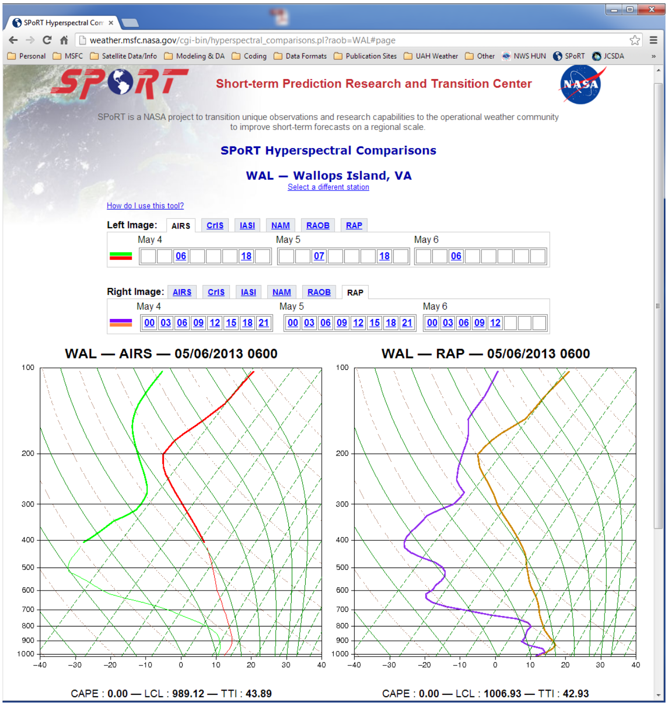

Fig. 5. Sample sounding comparison between an AIRS sounding and the Rapid Refresh (RAP), the short-term, high-resolution model used operationally by the National Weather Service taken from the SPoRT Hyperspectral Comparison Website

Mid-Latitude Cyclones and Transitioning Extratropical Lows

Mid-latitude cyclones can be responsible for any number of significant weather events including severe thunderstorms and flooding. The vertical distribution of temperature and moisture in and around these storms influences how a storm system will intensify. In particular, intensification of mid-latitude cyclones is defined by increases in potential vorticity, which are associated with intrusion of stratospheric air (Zavodsky et al. 2013). Additionally, these stratospheric air intrusions have been linked to non-convective wind events that can cause significant damage to life and property (Knox et al. 2011, Ashley and Black 2008). Many times, these stratospheric air events occur close to the center of a mid-latitude storm, where clouds are prevalent, so additional information on upper level temperature and moisture in cloudy regions will yield improved storm analysis. Ongoing work at SPoRT has examined mid-latitude cyclone development for a number of cases, including an early February 2013 blizzard that impacted the Northeast. Here, CrIS soundings have been used to find areas of stratospheric air intrusion by identifying soundings that exhibit a similar characteristic dryness as the stratospheric air above the tropopause. Figure 6 shows one such CrIS sounding in which the height of the tropopause has been identified as 400 hPa along with nearly constant dew points from the tropopause down to the lower troposphere.

Similarly, tropical cyclones (warm-core) transitioning to extratropical (cold-core) could benefit from knowledge of upper level temperature and moisture due to the complex nature of the mechanisms that result in this transition. Superstorm Sandy is a good example of a storm that underwent such a transition in the hours before landfall, where use of soundings from hyperspectral sounders could aid in situational awareness of this transitioning. In addition, the storm was extremely large in size with cloud cover stretching from Florida through the Canadian Maritimes up to two days prior to landfall. With these extremely cloudy conditions, very few observations from the Version 5 AIRS sounding algorithm were of high enough quality for forecaster use. Work has been performed in coordination with operational forecasters to evaluate AIRS retrievals ability to detect these features for transitioning tropical cyclones (e.g. Folmer et al. 2012).

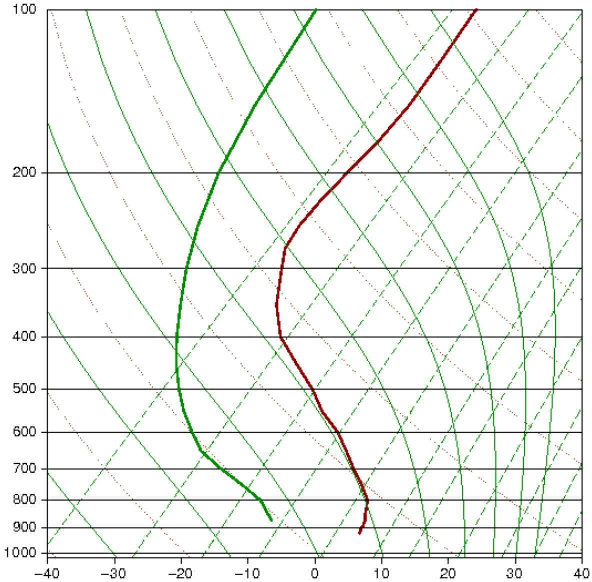

Fig. 6. CrIS temperature (red) and dew point (green) sounding from near Washington, D.C. on 9 February 2013 at 0700 UTC depicting stratospheric air signature to be evaluated for cloudy soundings

Evaluation of the SNN-flex AIRS/AMSU/MODIS soundings for mid-latitude cyclone events is being performed similarly to the convective events. For storms over the Continental U.S., the hyperspectral sounder website will be used to examine the new soundings in and around cloud features to determine the value added in cloudy regions. For transitioning extratropical storms, soundings from granules of the SNN-flex AIRS/AMSU/MODIS data will be generated in the most important regions of storm development to determine the impact of the new soundings.

3 Summary and Conclusions

The focus of the proposed work is the use of advanced signal and image processing techniques developed in cooperation with the AIRS Science Team during the last several years to improve the manner in which high-resolution (spectral, spatial, temporal, and radiometric) data are processed and combined in the retrieval of geophysical products. The specific enhancements discussed in this proposal are intended to substantially improve the performance of the AIRS Level 2 algorithm in heavily clouded regions. The SNN-flex enhancements discussed in this proposal are directly based on methods that have been extensively validated with excellent performance demonstrated in the targeted regions. Combination of the AIRS/AMSU SNN-flex enhancements with the addition of MODIS data would result in fundamental performance improvements across the entire algorithm (yield, profile accuracy, and cloud clearing accuracy). These improvements would further potentially improve the data assimilation impact of AIRS data, and the assessment of these forecast improvements as part of this proposal will guide the direction of this work. The enhancements described in this proposal can be implemented as part of an AIRS-only retrieval, meaning that improvements discussed above can be realized even if AMSU should continue to degrade or fail completely. This work is expected to build on the research in atmospheric profile estimation performed using data from AIRS/AMSU/HSB, TRMM, AMSR-E. It is also expected to contribute to atmospheric profile estimation algorithms for ATMS/CrIS/VIIRS on SNPP/JPSS. Work proposed herein would be particularly relevant to the design and implementation of future microwave geostationary sensors and their potential synergistic use with other infrared sensors.

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