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Visualizing Cold Air Aloft with Radio Occultation and Hyperspectral Infrared Sounders: Investigating Aviation Safety Purposes

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1. INTRODUCTION

Cold air temperatures located at jet cruising altitudes are an aviation safety concern, as jet fuel can gelify when exposed to such cold temperatures for extended periods of time. Recently, meteorologists at National Weather Service (NWS) offices have made known the need for 3-D real-time observations for use in forecasting these cold air aloft occurrences. Currently, the only real-time observations NWS forecasters have access to are from the sparse radiosonde network and isolated aircraft reports. Additionally, while numerical forecast models are available as well, their output is not always accurate or timely enough. With real-time 3-D observations, forecasters could better issue pilot advisories that alert when jet fuel temperatures need to be monitored or when flight paths need to be diverted around cold air masses.

Collaboration on this cold air aloft issue is currently ongoing between the NWS Center Weather Service Unit (CWSU) in Anchorage, Alaska and researchers from GINA, SPoRT, CIRA, and CIMSS under a newly funded proposal that is part of the JPSS proving ground and risk reduction (PGRR) activities. This initiative aims to develop visualization tools of 3-D temperature fields using real-time hyperspectral infrared (IR) sounder data (Stevens et al., 2015; Smith et al., 2015; Weisz et al., 2015). This real-time aspect is enabled by the capabilities of direct broadcast of the Suomi-NPP/JPSS satellites to the University of Alaska Fairbanks (UAF) Geographic Information Network of Alaska (GINA). The hyperspectral sounder data is then processed using the Community Satellite Processing Package (CSPP) in real-time and visualized in the AWIPS system. Work has also been done to visualize cold air temperatures overlaid with flight levels that bound the vertical distribution of the cold air using the Microwave Integrated Retrieval System (MIRS) (Dostalek et al., 2016). These images are being hosted by the Regional and Mesoscale Meteorology Branch website (http://rammb.cira.colostate.edu/ramsdis/online/cold_air_aloft.asp).

Previous work has also been done to investigate the utility of radio occultation (RO) data in supplementing the existing radiosonde network and hyperspectral IR and microwave (MW) sounder data in visualizing cold air aloft (Feltz et al. 2016). RO temperature profiles, being derived from phase delays of GPS signals occulted by the earth's atmosphere, have a high vertical resolution of ~0.1-1 km and a horizontal resolution of ~200 km along the raypath (Kursinski et al., 1997). Additionally, RO dry temperature products, which neglect the presence of water vapor, have a high accuracy in the upper-troposphere and lower-stratosphere (UTLS) around typical flight altitudes (Feltz et al. 2014; e.g. Das and Pan, 2014). As previous conclusions show, these attributes make RO data a good candidate for identifying more exactly the highest and lowest altitudes which bound the cold air mass. Additionally, though RO measurements are pseudo-random profiles in time and space and don't offer as many samples as IR/MW sounders, RO data was found to help fill in the temporal gaps of the radiosondes network. Table 1 shows a subjective evaluation of the IR sounder, RO, and radiosonde measurement systems contributions in detecting and characterizing cold air aloft (Feltz et al. 2016). It demonstrates that using a combination of measurement systems, which each have different strengths, provides the most ideal coverage for visualizing cold air aloft. Recommendations for paths forward from this previous work are as follows: 1) some form of real-time RO data is made available for NWS forecasters to use in the cold air aloft forecasting routines, or 2) RO data is used to provide an 'uncertainty estimate cushion' on the IR sounder temperature profiles in the form of error bars, so that warnings or advisories could be put out when a higher threshold of temperature is reported by the IR sounder product. This paper makes demonstrations of these two recommendations.

Table 1. Subjective evaluation of various measurement systems contributions to cold air aloft over the Alaska region.

	Hyperspectral IR Sounders	Radio Occultation	Radiosondes
Vertical Resolution	Fair	Good	Good
Horizontal Coverage	Good	Poor	Poor
Time Frequency	Fair	Fair	Poor

While in this paper cold temperatures are defined as temperatures below -65°C, fuel temperatures on jets are monitored below much warmer temperatures due to the highly variant freezing properties of the fuel mixtures.

2. DATA

Radio occultation data was obtained from UCAR's COSMIC Data Analysis and Archival Center (CDAAC) (http://cdaac-www.cosmic.ucar.edu/ - cdaac/products.html). The dry temperature products were used from the cosmic version 2010.2640 and cosmic2013. COSMIC is a U.S./Taiwanese mission of 6 satellite receivers, though only 2 are currently in operation. The Quality control is applied by excluding profiles marked 'bad' by the flag included in the CDAAC files.

AIRS data was obtained from the Goddard Earth Sciences Data and Information Services Center (http://disc.gsfc.nasa.gov/AIRS/data-holdings/by-data-product/data_products.shtml).

NOAA NUCAPS Environmental Data Record (EDR) temperature retrievals derived from the CrIS/ATMS sounding suite were obtained from the NOAA Comprehensive Large Array - Data Stewardship System (CLASS) website at http://www.class.ncdc.noaa.gov/saa/products/welcome. Quality control consists of using only accepted retrievals as indicated by the 'Quality Flag' variable.

Atmospheric Radiation Measurement (ARM) data was retrieved through the DOE ARM data archive (http://www.archive.arm.gov/armlogin/login.jsp). Vaisala-processed profiling data from balloon-borne sounding systems was used from the Northern Slope of Alaska site.

3. RADIOSONDE, HYPERSPECTRAL IR SOUNDER, AND RO COMPARISONS

This section details results from comparisons of radiosonde, COSMIC RO, and NUCAPS hyperspectral IR sounder matchup temperatures over the Arctic region. In all comparisons, NUCAPS "raypath-averaged" profiles are used to mimic the horizontal resolution and unique geometry of each RO profile (Feltz et al. 2014).

Figure 1 illustrates a matchup case over the Barrow, AK ARM site. While the radiosonde measured the 100mb pressure level ~2 hrs after the COSMIC and NUCAPS profiles, the COSMIC and NUCAPS measurements were taken over the ARM site within 5 minutes of each other. Figure 1a shows overlaid temperature profiles, and Figure 1b shows a map of profile locations. This case exemplifies how the IR sounder, while able to capture the general profile structure, is not able to capture the coldest tropopause layer as do the radiosonde and RO profile. The IR sounder's measurement technique inherently smooths over the fine atmospheric layers, and typically displaces the height of minimum temperatures.

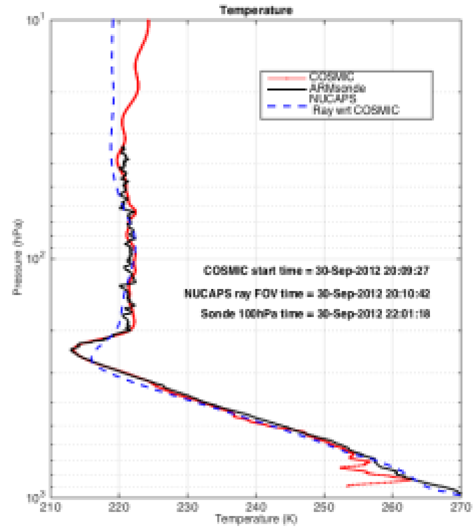

Figure 1a. 30 September 2012 ~20 UTC overlaid COSMIC (red), NSA radiosonde (black), and NUCAPS raypath (blue) temperatures for a matchup case over Barrow, AK.

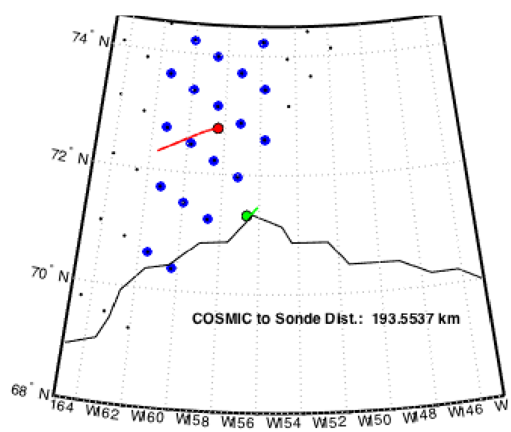

Figure 1b. Map of Fig 1a matchup case showing COSMIC profile (red line), ARM sonde profile (green line), and NUCAPS FOVs used in raypath average profile (blue dots).

Figure 2 shows statistics from an aggregation of matchups that occurred over the NSA Barrow ARM site over a 3-year time period (all seasons included). Matchup criteria were a 3 hour coincident measurement period and a 300 km cutoff for the distance between profile locations. Statistics show the NUCAPS minus ARM radiosonde and NUCAPS minus RO results having a systematic ~350-100 hPa vertical oscillation in the bias and the RMS error. This is a characteristic result seen when the IR sounder smooths over the cold temperature layer that the RO/sonde detects. The bias between the RO and radiosonde is seen to mainly be under 0.25 K.

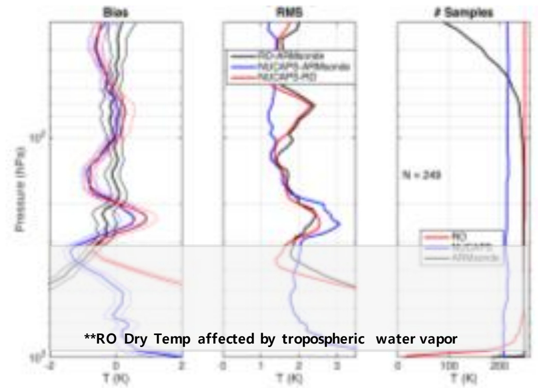

Figure 2. Bias (solid) with bias uncertainty (dotted) (left panel), RMS (middle panel), and number of samples statistics for ARMsonde, NUCAPS, and COSMIC RO matchups for 3 years over Barrow, AK. Note RO dry temperature product is affected by atmospheric water vapor below ~200mb.

Figure 3 quantifies the effect of the different vertical resolutions of the COSMIC RO and NOAA Cross Track Infrared Sounder (CrIS) NUCAPS hyperspectral IR sounder temperature products. In other words, it illustrates what the RO is able to resolve in the vertical that the IR sounder is not due to their inherent measurement techniques. To quantify this effect, January 2014 Arctic zone (60-90N) NUCAPS and COSMIC matchup cases having a 1 hr time criterion were found, and their differences taken. Next, CrIS averaging kernels (AKs) for each matchup NUCAPS temperature profile were computed. Finally, the following double differences were taken, with AK* denoting the AK application: AK*(IR-RO) – (IR-RO). Averaging kernel matrices replicate the smoothing that a retrieval from infrared radiances induces. Averaging kernels, defined by the rows of the AK matrix, thus ideally represent the measurements' sensitivities to temperature at various heights of the atmosphere.

Bias and standard deviations for the above described collection of differences are overlaid with the differences themselves in Figure 3. On average (see Figure 3's thick solid black line), the RO is able to resolve just over 1 K larger magnitudes of temperatures than the CrIS sounder. As shown by the dashed standard deviation lines, 32% of the time the RO is able to resolve magnitudes over 2 K larger than the IR, and for some extreme profiles the RO resolves over 6 K magnitude larger temperature features.

These comparisons quantify the potential of RO to be used for assessing the vertical extent of the elevated cold pool and for providing uncertainties on the IR sounder products. Similar results can be expected in comparison with microwave sounding.

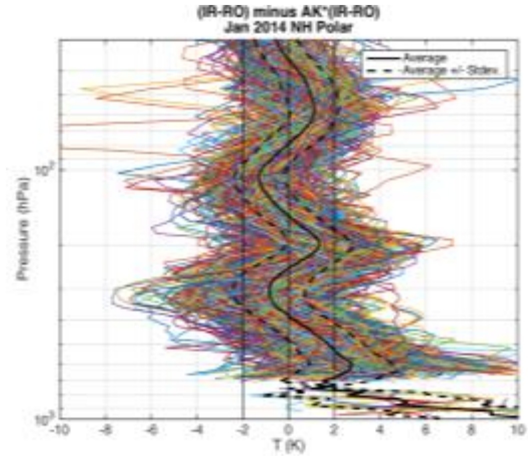

Figure 3. January 2014 NH 90N-60N AK*(NUCAPS-COSMIC) – (NUCAPS-COSMIC) matchup differences (multi-colored overlaid) with their average (thick solid black), and average +/- standard deviation (thick dashed black).

3. EXAMPLE VISUALIZATIONS FOR OPERATIONAL USE

The figures contained in this section illustrate the potential of RO data to be visualized in a 3D environment in tandem with hyperspectral IR/MW sounder data. A specific 'cold air aloft event' that took place over Barrow, AK on 24 Feb 2014 is used. An AIRS Dual Regression (DR) granule product measured over the region at ~12:35UTC is used with the COSMIC RO profiles that were closest in time and space. Land height of the figures is from the geopotential heights of the GFS model. See Weisz et al. (2015) for DR details.

Figure 4 visualizes the AIRS DR granule, highlighting the location and height of lowest level -37ºC temperatures. The spatial area of heights at this temperature value is highlighted in the middle and bottom panels. Figure 5 shows the AIRS DR ~12:35 UTC granule and a COSMIC profile measured a few minutes later at ~12:38 UTC. AIRS temperatures from -65ºC to -63ºC are shown by an isosurface and help pull out the vertical location and horizontal extent of the coldest air within the granule. The coincident COSMIC profile's location is overlaid and is colored by temperature.

Finally, Figure 6 visualizes the AIRS granule and COSMIC profile in the form of volume renderings of <-60ºC temperatures. The vertical extent, as well as location, of the COSMIC profile that reports temperatures less than -60 ºC is shown by the yellow line, while the location of the AIRS less than -60 ºC temperatures is shown as multicolored pixels. This figures illustrates a convenient method of demarcating vertical extent of cold air seen by both the RO and IR sounder profiles.

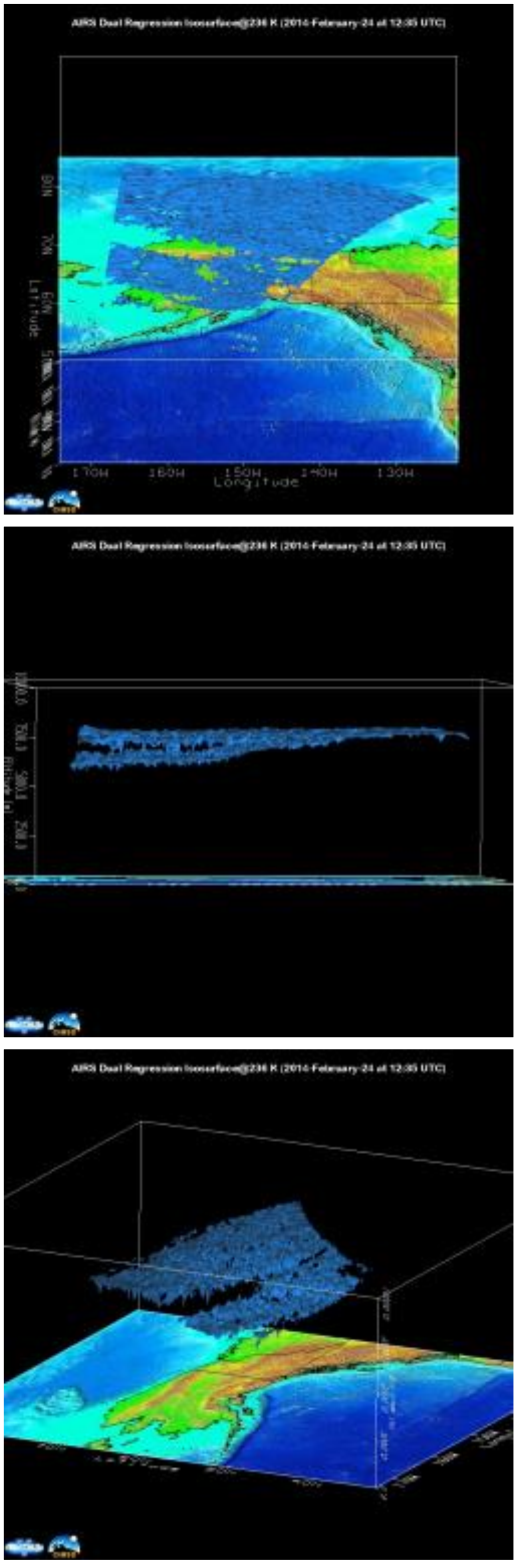

Figure 4. 24 Feb 2014 ~23:35 UTC AIRS Dual DR -37ºC isosurface. (Only AIRS pressure levels from the surface to ~130mb are shown, so only lower height of isosurface is shown.)

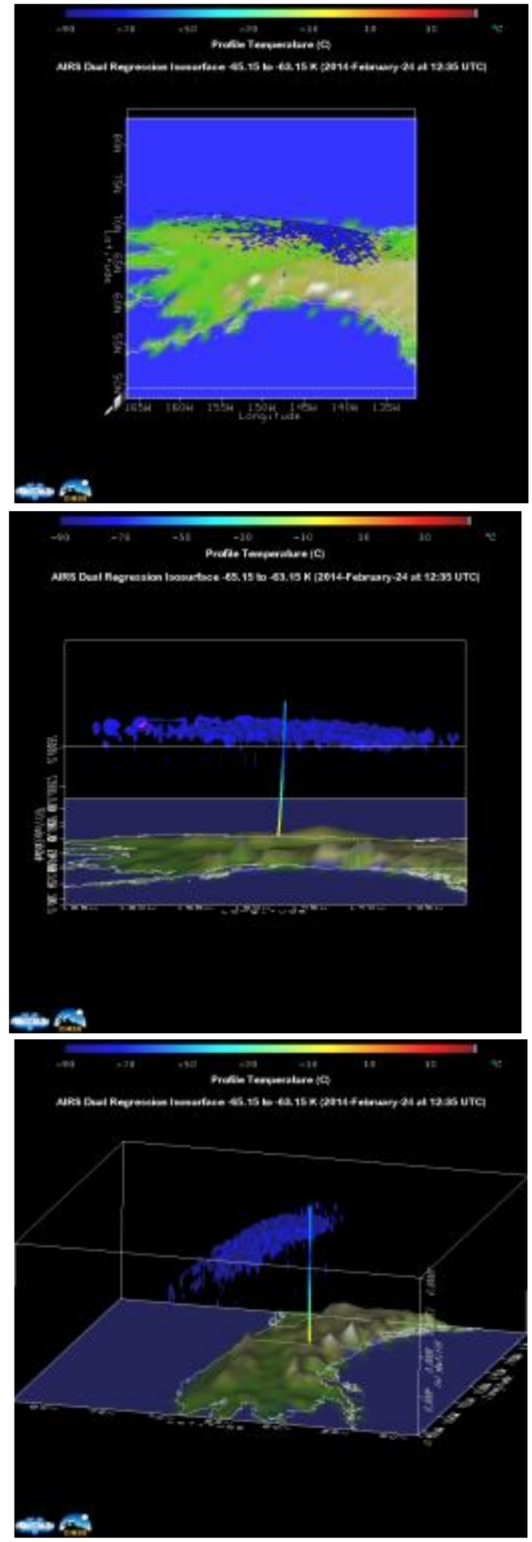

Figure 5. 24 Feb 2014 ~12:35 UTC AIRS DR granule isosurface for temperatures from -65 to -63ºC (blue). A coincident (~12:38 UTC) COSMIC RO profile is shown with temperature as indicated by the colorbar.

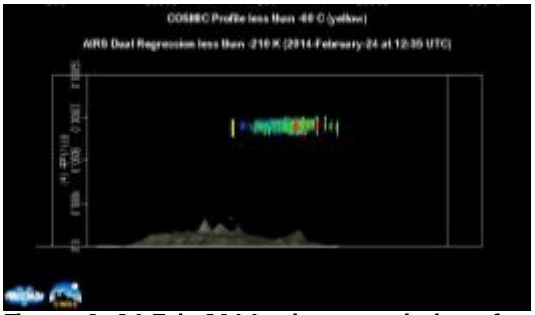

Figure 6. 24 Feb 2014 volume rendering of <-60ºC temps for COSMIC (yellow line) and AIRS DR (blue to red pixels). The vertical extent of the cold air aloft is clearly apparent.

5. PRELIMINARY CONCLUSIONS

This paper illustrated the potential of radio occultation to be employed in real-time 3D observation visualizations of cold air aloft for aviation safety purposes.

First, comparisons between COSMIC RO, NUCAPS IR sounder, and radiosondes quantified typical errors between product temperature profiles. Quantitative statistics were computed to characterize the uncertainty estimates of the IR sounder retrievals. It could be valuable to know the extent to which potential warm biases are present in MW/IR sounder products around flight levels.

Second, example 3D visualizations of hyperspectral IR sounder and RO data were provided. These figures illustrate the value of leveraging the high accuracy and vertical resolution RO temperature profiles in marking the vertical bounds of the cold air masses. If forecasters can know the vertical extent of the cold temperatures, then pilots could be advised where they could safely fly beneath the cold air mass.

6. PATHS FORWARD

Here, we outline the next steps that could be taken in getting RO data available in routine operational real-time visualizations for cold air aloft forecasting purposes.

While this paper utilized the UCAR COSMIC network as the RO data source, currently no data from this network is real-time in an operational sense. A “real-time” product is available from the CDAAC, but this has a latency of up to a few hours and is not guaranteed within this time frame. This network, which is at the end of its lifetime and has been slowly degrading in the number of samples that it supplies, will soon be supplemented with the launch of the COSMIC-2 mission. However, the first half of COSMIC-2 mission that is planned to be launched by the end of 2016 will only provide measurements over tropical latitudes. The second half planned to cover the polar zones is not expected to be launched until 2018 or 2019.

However, RO data is also available from the EUMETSAT METOP series of polar orbiting satellites. Each METOP satellite houses a single RO receiver, a Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS). Currently, as quoted from private communication with John Paquette from NOAA, “NOAA/NESDIS and EUMETSAT are collaborating on an enterprise network to transmit large volumes of satellite data between the two agencies. … Testing is going well, and the goal is to get a component of this network operational in early 2017.” In the interim, a real-time product from the GRAS instruments is available from the EUMETSAT Radio Occultation Meteorology Satellite Applications Facility (ROM SAF): http://www.romsaf.org.

Acknowledgments

Many thanks to co-author Joleen Feltz for creating the McIDAS-V visualizations. Acknowledgement is given to the U.S. Department of Energy as part of the Atmospheric Radiation Measurement (ARM) Climate Research Facility for the NSA site radiosonde data that were used as well as the NPSO (Taiwan’s National Space Organization) and UCAR (University Corporation for Atmospheric Research) for access to the COSMIC data. NOAA NUCAPS data was obtained from the CLASS system. AIRS Level 2 Temperature data was obtained through the NASA’s GESDISC at http://disc.sci.gsfc.nasa.gov. This work was funded by grant number: NA15NES4320001.

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