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Towards Aiding Aviation Safety: Detection of Cold Air Aloft Using COSMIC RO and AIRS Hyperspectral IR Sounder

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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. Meteorologists of the National Weather Service (NWS) Center Weather Service Unit (CWSU) in Anchorage, Alaska (AK) are responsible to assist in providing weather information to air traffic controllers who overlook a region containing Alaska and parts of the Arctic Ocean to the North. While forecast models are used as prediction tools for such 'cold air events', the forecasts are not always accurate or timely enough. Additionally, real time observations available to forecasters are limited to the sparse radiosonde network and isolated aircraft reports. Figure (Fig) 1 illustrates the sparse, geographical coverage of the NWS radiosonde sites. Thus, a desire and need for 3-D real-time observations has been made known by forecasters. With such observations, forecasters could better issue pilot advisories that alert when fuel temperatures need to be monitored or when flight paths need to be diverted around cold air masses. 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.

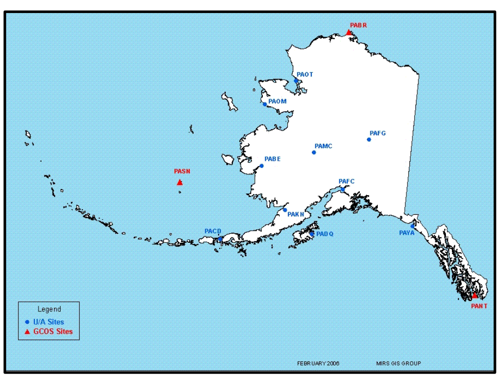

Figure 1. Locations of National Weather Service radiosonde stations, obtained from http://www.ua.nws.noaa.gov/nws_upper.htm.

Collaboration on this cold air aloft issue is currently ongoing between the AK NWS office 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 temperatures fields from real-time hyperspectral infrared (IR) sounder retrievals (Stevens et al., 2015; Smith et al., 2015; Weisz et al., 2015). In this paper the potential to use radio occultation (RO) data to supplement and add information to the IR sounder and radiosonde data is investigated. It provides insight on how RO and hyperspectral IR sounder retrievals could be used together in real-time applications to make use of the direct broadcast capability on Suomi-NPP and JPSS and the product applications available through the Community Satellite Processing Package (CSPP) project.

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). Measurements are located pseudo-randomly in time and space. Additionally, the dry temperature product neglects the presence of water vapor, but has high accuracy in the upper-troposphere and lower-stratosphere (UTLS) around typical flight altitudes. These qualities of RO data prompt the following questions which are addressed in this paper:

1] Can RO's higher vertical resolution assist in assignment of the vertical extent of cold air?

2] What is the frequency of the RO profile occurrence?

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, cosmic2013, and metopa2011 datasets. Global Forecast System (GFS) temperature data collocated to the RO profile locations is also used from cosmic2013. COSMIC is a U.S./Taiwanese mission of 6 satellite receivers, though only 2 are currently in operation. The EUMETSAT METOP series of polar orbiting satellites each house a single RO receiver, a Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS)—here only GRAS data from METOP-A is used. 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.sci.gsfc.nasa.gov/AIRS/data-holdings/by-data-product/data_products.shtml). The product used is Level 2 version 6 AIRX2SUP. Quality control consists of using the flag PBest by excluding profile levels with pressures greater than PBest.

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. METHODOLOGY

Comparisons of AIRS IR sounder and COSMIC RO temperatures are performed to highlight each of the instrumentations strengths in this application. To facilitate the comparison, a profile-to-profile RO and hyperspectral IR sounder matchup methodology is applied. This technique minimizes spatiotemporal mismatch error by use of a one hour time criterion and by accounting for the RO's unique profile geometry and horizontal resolution. Details of the method can be found in Feltz et al. (2014a, 2014b).

Bias and RMS statistics of differences, as well as mean temperatures, are computed for various time and latitude zones. Statistics are computed for all matchup profiles, the 25% coldest profiles, and the 5% coldest profiles, as defined by the coldest temperature in the 90 – 400 hPa layer. While temperature differences would normally be smoothed with an averaging kernel in the assessment of an IR sounder product using a higher vertical resolution measurement, it is desired here to see how advantageous it could be to use the higher vertical resolution RO product.

Time series of differences are first resampled to a frequency of 24 times per day and then filtered with boxcar smoothers to obtain daily and approximately monthly averaged time series.

4. RESULTS

An example matchup case between COSMIC, AIRS, and an ARM and NWS radiosonde over the Barrow, AK ARM site is shown in Fig 2. The NUCAPS, COSMIC, and NWS sonde measurements were obtained within ~1 hour's time of each other, while the ARM sonde recorded temperatures ~6 hours later. Overlaid temperatures illustrate how COSMIC is able to capture quite well the coldest sub -65°C temperatures seen by the sondes at the tropopause level. While NUCAPS is able to capture the general structure of the temperature profile throughout the altitudes shown, it is not able to resolve the coldest tropopause point.

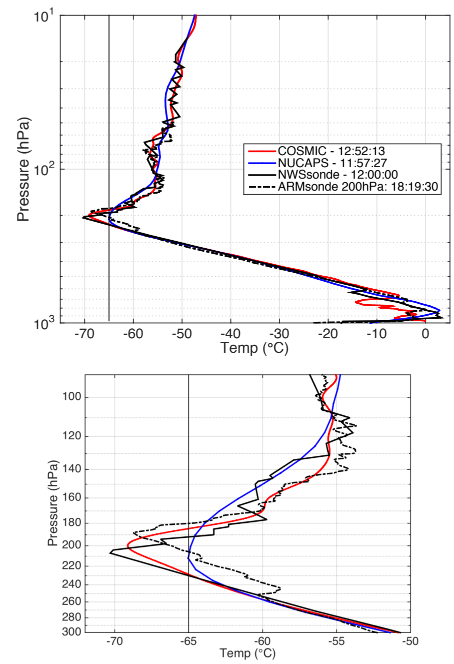

Figure 2. Overlaid temperature profiles from an example COSMIC, AIRS, NWS sonde, and ARM sonde matchup over the Barrow, AK ARM site on 24 Feb 2014 (top) with a zoomed view of the tropopause (bottom). UTC times are noted in the legend.

COSMIC and AIRS comparisons for the Arctic, 60°N to 90°N, winter months (DJF) over 7 years from 2007-2013 are shown in Fig 3. A focus is set on the 500-70 hPa vertical range, with typical flight levels bounded by black lines. Water vapor contamination of the RO dry temperature product should be negligible at these altitudes in the dry polar winter atmosphere. The top panel shows mean temperatures of all Arctic winter profiles and of the 25% and 5% coldest profiles, showing that on average cold, -65°C air is located above ~250 hPa. The bias and RMS statistics reveal that the COSMIC and AIRS profiles recording the coldest temperature profiles exhibit a slightly larger bias than the warmer profiles. Biases are quite small, being under 0.5 K within the 500 to 100 hPa layer, while the RMS is between 1.0 -1.5 K.

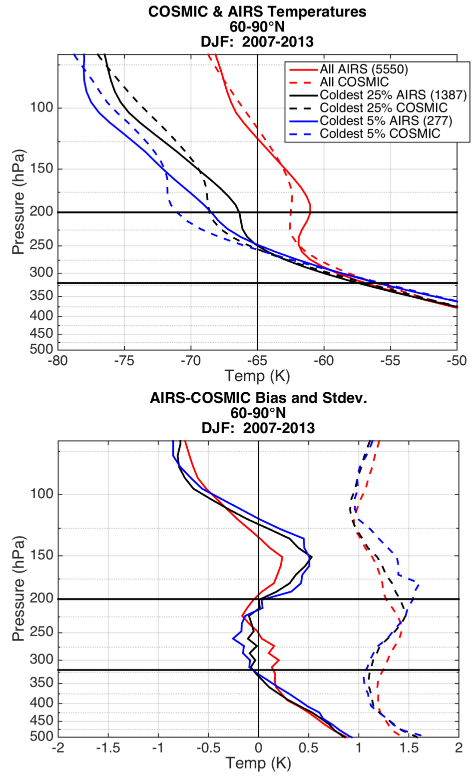

Figure 3. COSMIC and AIRS mean temperatures (top) and AIRS minus COSMIC bias (soild) and standard deviation (dashed) (bottom) for 60°N to 90°N, 2007-2013 winter months (DJF) for all the profiles (red) and the coldest 25% (black) and 5% (blue) profiles. Typical flight levels bounded by horizontal black lines.

Figure 4 illustrates the same type of analysis for COSMIC and NUCAPS with the addition of collocated GFS temperatures over the single winter season of 2013 - 2014. Mean temperatures are again located in the top panel and show a similarity between COSMIC and GFS which is partially artificial due to the assimilation of RO data into the forecast model. Biases for profiles with colder temperatures are again larger than for warmer profiles, reaching over 1.75 K for NUCAPS minus GFS and 2.25 K for NUCAPS minus COSMIC. The RMS is seen to be over 1.5 K for all sets of profile differences shown. While these results should be carefully considered, it is noted that the numbers of samples for these comparisons are small, so the coldest 5% profile statistics may not prove to be the most robust. The performance of the NUCAPS temperature retrievals in the altitude range of interest will be evaluated using more cold air cases in the future.

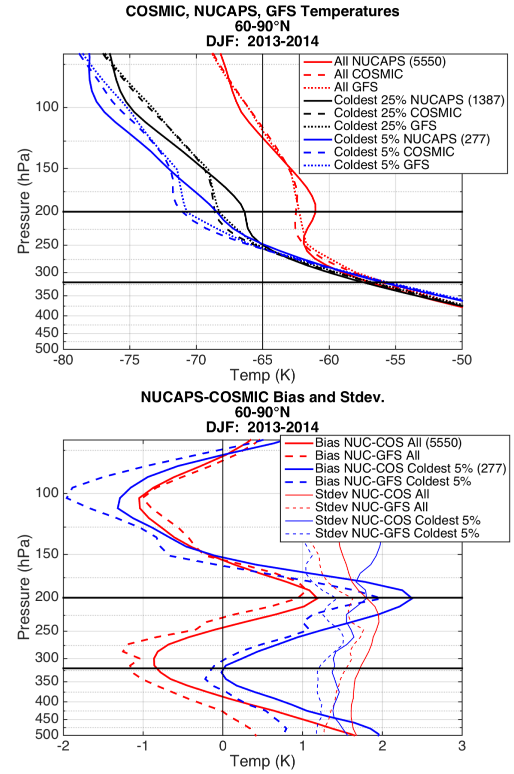

Figure 4. COSMIC, NUCAPS, and GFS mean temperatures (top) and NUCAPS-COSMIC & NUCAPS-GFS bias and standard deviation (bottom) for 60°N to 90°N over the winter season (DJF) from 2013-2014 for all the profiles (red) and the coldest 25% (black) and 5% (blue) profiles. Typical flight levels bounded by horizontal black lines.

Time series of GFS minus COSMIC and GFS minus NUCAPS differences are shown in Fig 5 for three pressure levels located around typical flight altitudes with daily and monthly filtered results overlaid. The daily filtered results highlight seemingly chaotic daily variations but still reveal the longer temporal, seasonal trends highlighted by the monthly filtered results. The GFS minus COSMIC monthly bias is within 0.2 K, 0.4 K, and 0.75 K at the ~150 hPa, 200 hPa, and 247 hPa levels. Again, the assimilation of RO data into the GFS model partially explains this similarity. The larger bias at 247 hPa during summer months is posited to be due to the RO dry temperature cold bias caused by water vapor contamination. The GFS minus NUCAPS bias is larger, staying within 2 K at all levels and exhibits longer periodic structures through the seasons.

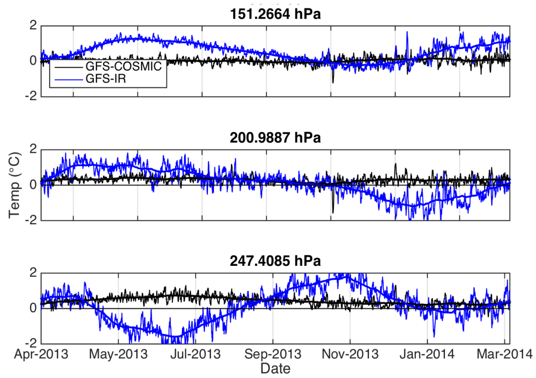

Figure 5. Overlaid GFS-COSMIC and GFS-NUCAPS monthly and daily averaged temperature biases for 60°N-90°N at 3 different pressure levels.

The next series of figures addresses the second question prompted in the introduction and aims to shed light on RO measurement distributions through space and time, specifically in the Arctic region over Alaska. Two different missions of RO receivers were selected to investigate this topic—the COSMIC network and a single GRAS instrument from the METOP series; however, multiple other RO missions offer measurements. It is noted that the satellite orbit geometry of the satellites housing the RO receivers has an effect on the RO measurement distribution. This is demonstrated by the planned future COSMIC-2 Tropics mission which is planned to be launched in late September and will provide RO measurements within the tropical region. Likewise, a COSMIC-2 Polar mission is planned to provide increased coverage over the poles; however, the mission planning is not as advanced and the launch date is as far off as late 2018.

Figure 6 depicts average monthly distributions of RO profile locations for a 2°x2° degree grid. For both COSMIC and GRAS the number of samples has maxima in the mid-latitude regions and decreases from there towards the poles. COSMIC measured ~1900 profiles per day globally over the years 2007-2014, though the number has been decreasing with time as some of the network's receivers have been lost. The single METOP-A GRAS receiver measures about ~590 profiles per day globally.

Figure 7 is a map of the COSMIC and GRAS profile locations for a single day in winter time and illustrates the pseudo-random locations of the RO measurements. Time series of daily profile numbers for a defined region over AK (highlighted by red boxes in Fig 7) are shown in Fig 8. COSMIC offered about 40 profiles/day and GRAS offered about 15/day over the time periods shown. Large variation in the number of samples per day is seen.

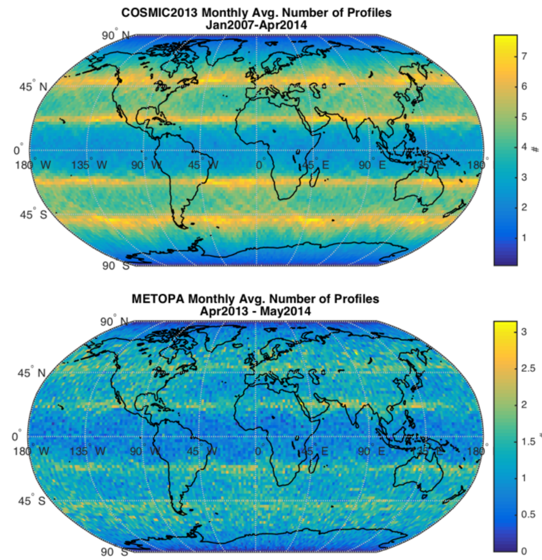

Figure 6. COSMIC (top) and METOP-A GRAS (bottom) monthly average number of profiles on a 2°x2° degree grid over the time periods noted in the title.

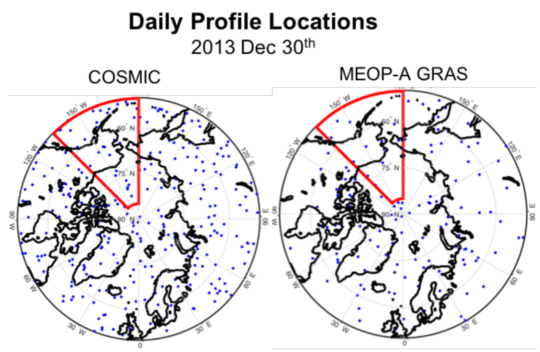

Figure 7. COSMIC (left) and METOP-A GRAS (right) 30 December 2013 profile locations.

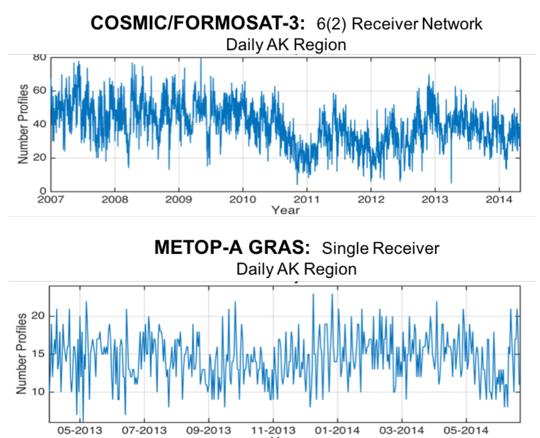

Figure 8. COSMIC (top) and METOP-A GRAS (bottom) daily number of samples within the defined AK region highlighted in Fig 7 by red boxes.

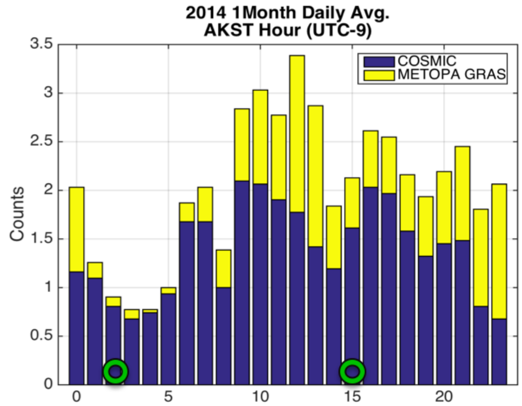

Figure 9. A bar graph of the daily average number of profiles from COSMIC and METOP-A GRAS for each AK Standard Time hour over the month of January 2014 for the AK region defined by red boxes in Fig 7. NWS 00Z and 12Z radiosonde launch times are marked by green circles.

The AK region distribution of the RO number of profiles over AK Standard Time local hour for an example month is shown in Fig 9. The distribution changes through time, with the RO missions providing more or less measurements for each hour of the day. The 00Z and 12Z NWS sonde launch times are marked by green circles and help show how the RO measurements help to fill in the temporal gaps between the radiosondes. On average, COSMIC and METOP-A GRAS offer about 2 samples/hr or 48 samples/day over the AK region. While RO provides this advantage, it is noted that the polar orbiting satellites housing the hyperspectral IR sounders make numerous passes over the polar regions per day, and thus with their wide horizontal swath coverage offer far more profile observations.

5. CONCLUSIONS

The aviation safety hazard of cold air aloft has prompted weather forecasters to make the need of 3-D real-time observations known. Currently, hyperspectral IR sounder data is planned to be integrated into the AWIPS system under a recently funded PGRR proposal. Here, the utility of RO as a means to supplement the IR sounder data was investigated. This investigation revealed that the higher vertical resolution of RO and its high accuracy in the UTLS compliments IR sounders by providing more information on the actual temperature and vertical location of the cold air masses. Additionally, RO helps fill in the temporal gaps of the radiosondes, though it doesn't offer as many samples as IR sounders. Table 1 shows a subjective evaluation of the IR sounder, RO, and radiosonde measurement systems contributions in detecting and characterizing cold air aloft. It demonstrates that the key is to use a combination of the different strengths of each measurement system.

Table 10. 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

From these conclusions recommendations for paths forward are as follows: it is recommended that either 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.

Future work will focus on combining the NUCAPS operational IR soundings available from ATMS/CrIS sensors on the NOAA J1 satellite with RO soundings from the operational GRAS GNSS receiver on the EUMETSAT METOP platforms. This work is expected to provide timely three dimensional characterization of cold air aloft over the Alaska NWS flight region.

Acknowledgments

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