Exploring commercial GNSS RO products for Planetary Boundary Layer studies in the Arctic Region

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Abstract.

Commercial Radio Occultation (RO) satellites that track radio signals from the Global Navigation Satellite System (GNSS) are being touted for their observations in polar regions where missions such as COSMIC-2 lack orbital coverage. This study seeks to explore the value of commercial RO satellites, viz. Spire and GeoOptics, for Planetary Boundary Layer (PBL) investigations in the Arctic, a region where favorable lower atmospheric penetration of GNSS RO is vital for representing the persistently shallow PBL. Both Spire and GeoOptics have seemingly improved lower tropospheric penetration capability over the Arctic Ocean compared to other missions such as MetOp, with Spire having nearly one order (two orders) of magnitude greater volume of observations at 500 meters above mean sea level compared to MetOp (GeoOptics). The RO-derived monthly mean Arctic PBLH from GeoOptics is comparable to that retrieved from MetOp as well as the PBLH in the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). The PBLH retrieved from NASA Spire data has relatively less spatial and seasonal variability compared to other datasets. A cut-off altitude threshold of 500 meters for minimum RO penetration height works sufficiently well for representing the Arctic PBLH in all datasets except for NASA Spire dataset which performs better when 300 meters threshold is used. Arctic PBL height (PBLH) representation is not strongly affected by the total number of available observations, the minimum RO penetration altitude, or instrument type, but instead appears sensitive to the choice of processing algorithm used for retrieving bending angle and refractivity profiles. This is the most influential factor which controls the rate of penetration loss in the lower troposphere as well as the PBLH representation.

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Deleted: A seasonal cycle is evident in the RO penetration probability (except for Spire) that is found to be related to the water vapor pressure. For winter months, at the 500m level, which is the standard cut-off threshold used for GNSS RO PBL studies, both products yield a penetration probability of ~80% of total observations over the Arctic Ocean and up to ~100% over the frozen sea ice region. As a result, both products are able to sufficiently represent the shallow Arctic PBLH (less than 300m depth) which is comparable to the PBLH from MERRA-2 reanalysis.
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1 Introduction

The planetary boundary layer (PBL) is a target observable of broad importance to the Earth Science community and the Global Navigation Satellite System (GNSS) Radio Occultation (RO) is a candidate measurable approach for observing the PBL height (PBLH) as recommended by the National Academies of Science Decadal Survey for Earth Science and

Applications from Space report (NASEM 2018, Teixeira et al. 2021). Today, advancing PBL science is inherently reliant on high resolution observations with high frequency sampling that can chiefly be afforded by a single remote sensing instrument/combination of instruments from space. In this regard, GNSS RO comprises a vital measurement technique due to its superior vertical resolution compared to most other space-based instrument technologies allowing penetration up to the lowest 100 meters above the surface. High vertical resolution measurements and deep penetration to the lower atmosphere are deemed vital for polar regions where it is particularly difficult to observe and characterize the persistent surface-based PBL temperature inversion.

1.1 Importance of GNSS RO for Arctic PBL studies: Why commercial data?

The study of the Arctic Ocean PBL can greatly benefit from GNSS RO observations which offer (a) continuous sampling under all weather conditions, (b) the ability to "see" beneath the persistent stratus cloud cover, (c) improved performance over flat surfaces (sea ice, open ocean) compared to sharp varying slopes (land mass), and (d) long-term data record spanning nearly two decades with added coverage from recently launched commercial satellites. Commercial satellites are particular advantageous for high latitude polar studies where there is a notable lapse in coverage following the decommissioning of the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC-1) in 2018. The successor satellite, COSMIC-2, only covers 45°N to 45°S. It is expected that coverage from Spire, GeoOptics, and PlanetiQ satellites can help fill the gaps in the climate data record. First, however, it is necessary to explore the lower atmospheric sounding capability of these commercial missions in comparison to past and current existing operational GNSS RO products in the Arctic. Especially in the Arctic, the refractivity-based method used for determining the PBL height is found to be sensitive to the penetration capability of RO profiles (Ganeshan and Wu 2015). For example, from the analysis of 8 years of COSMIC data it was found that availability of RO profiles over the Arctic Ocean reduced significantly at tangent heights below 1km, which introduces a sensitivity of the retrieved PBL height to the choice of the cut-off altitude used for profile selection. However, it was noted that only the absolute PBLH values were sensitive to the choice of cut-off altitude, whereas the spatial and seasonal variability remain largely unaffected (Ganeshan and Wu 2015). Regardless, it is worthwhile comparing the lower atmospheric penetration capability among various GNSS RO products and exploring factors that can influence this capability, and in turn, influence the Arctic PBLH representation.

1.2 A background of GNSS RO neutral atmosphere technique

In the GNSS RO technique, the neutral atmosphere is considered as the atmospheric path consisting of the troposphere and stratosphere (up to 60km) which is refractive and electrically neutral, unlike the ionosphere. The neutral atmosphere has both dry and wet components that contribute to the refraction, with the wet component becoming more important closer to the surface. Not all RO profiles reach the surface, and in fact, there can be an exponential drop in the fraction of available RO observations (penetration probability) as we go towards the surface (Ganeshan and Wu 2015) which is primarily due to decrease in the signal-to-noise ratio (SNR) caused by atmospheric defocusing effects (Wu et al. 2022). However, factors

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such as instrument design, neutral atmosphere excess phase computation method, and choice of bending angle processing algorithm can also affect the penetration probability profile for a given atmospheric path.

A thorough understanding of factors affecting RO penetration is desirable to help minimize sampling bias as well as to ensure data continuity and consistency in climate records. However, this is difficult to achieve, given the existence of vast number of GNSS RO missions and different versions of products from a single mission that are periodically reprocessed to remain up-to-date with advances in software and processing algorithms. This study aims to provide a comparison of the penetration capability of new commercial GNSS RO data products against other existing products in the Arctic as the first step towards establishing a climate ready, long-term continuous dataset that can be used for Arctic PBL investigations. For the purpose of removing ambiguity resulting from software updates and to ensure consistency, only those RO products that have been re-processed with the same software version are compared against Spire and GeoOptics.

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2 Datasets and Methodology

2.1 GNSS RO

2.1.1. Commercial datasets

The goal of this study is to explore the value of commercial GNSS RO products for PBL studies in the Arctic Ocean (north of 60°N excluding land areas) by comparing with other GNSS RO mission products such as COSMIC and the Meteorological Operational satellite programme (MetOp). The commercial GNSS RO data evaluated in this study are purchased by NASA through the Commercial SmallSat Data Acquisition (CSDA) program. In addition, this study also compares freely available commercial data purchased for near-real time operations by NOAA, for available brief periods of overlap with the NASA purchased commercial data.

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NASA Spire data are available from Nov 2019 through Jan 2022, and NASA GeoOptics data are available from Jan 2020 to Apr 2021. Spire data are provided at a similar vertical grid and resolution as other GNSS RO missions (such as COSMIC, COSMIC-2, MetOp) where the lowest level of valid observations differs from profile to profile because the penetration depth achieved by each radio occultation is unique, depending primarily on the signal-to-noise ratio (SNR) profile. GeoOptics data, on the other hand, are provided on a uniform 100m vertical spacing grid, along with a quality flag that is used to determine the lowest penetration level. GeoOptics uses phase matching methodology in RO processing, a wave optics technique designed to extract the full information from the received wave field. The quality flag is applied in two ways: (i) blanket criteria that checks the range of the amplitude of computed phase match integral and cumulative number of phase jumps within the upper neutral atmosphere (between 8 to 40 km), cutting off the profile at lower levels if the above checks are failed, and (ii) individual criteria that flags each level as “good” or “bad” based on the presence or absence of sharp features (moisture and temperature gradients) that can cause significant deviation of the bending angle relative to a smoothed background bending angle profile. In this study, only profiles satisfying the blanket criteria are considered as the focus is on the lower troposphere (surface to 5km), and moreover, each of these profiles are evaluated individually to determine the minimum penetration depth ascertained by the lowest above-surface level with a "good" quality flag. If a "sharp" PBL inversion layer with poor QC flag exists above the minimum penetration depth, this is not disregarded.

The NOAA Spire and GeoOptics data purchased for near-real time operations are downloaded from the University Corporation for Atmospheric Research (UCAR; http://www.cosmic.ucar.edu/) website. In the case of GeoOptics, the overlap between NOAA and NASA data is during the month of April 2021, and for Spire, the months of October 2021 and February 2024 are chosen to compare overlapping data. All references to "Spire" and "GeoOptics" in this paper imply NASA purchased commercial RO data unless explicitly specified to be NOAA purchased datasets.

2.1.2. Other datasets

A major focus of this study will be comparisons between three contemporaneous datasets, viz. NASA Spire, NASA GeoOptics, and the re-processed EUMETSAT MetOp data from Radio Occultation Meteorology Satellite Applications Facility (ROM SAF). In addition, COSMIC and COSMIC-2 data from University Corporation for Atmospheric Research (UCAR) will also be used to compare RO penetration statistics. Two versions of reprocessed COSMIC data (COSMIC 2013 and COSMIC 2021) are obtained for the period ranging from 2007 to 2013 and from 2007 to 2017, respectively. COSMIC data ceased to be produced at the time of launch of commercial satellites thereby limiting their use for comparative analysis. For this study, they serve as a climatological record of RO penetration statistics over the Arctic Ocean against which characteristics of newer datasets can be compared.

2.1.3. Deriving PBLH from GNSS RO

The PBLH is derived from the GNSS RO refractivity profile using the bottom-up search approach described in Ganeshan and Wu (2015), identifying the first minima of the refractivity gradient to exceed -40 N-unit km^{-1} and assigning the corresponding altitude as the PBLH. This approach is specifically useful for deriving the height of the PBL inversion over the Arctic during winter months. A cut-off altitude threshold, set to 500m, is applied to only include RO profiles that reach this altitude or lower. This is the typical cut-off altitude used for GNSS RO based PBL studies (Ao et al. 2012, Guo et al. 2011) that has also proven useful for Arctic PBLH retrieval (Ganeshan and Wu 2015). Ganeshan and Wu (2015) showed that even though the magnitude of the retrieved PBLH is sensitive to the cut-off altitude, its spatiotemporal variability remained unaffected by the choice of this threshold.

2.2 Reanalysis data

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Deleted: In addition to NOAA commercial data, we also use COSMIC data and MetOp data from UCAR for comparisons with NASA purchased Spire and GeoOptics products. Two versions of reprocessed COSMIC data (COSMIC 2013 and COSMIC 2021) are obtained for the period ranging from 2007 to 2013 and from 2007 to 2017, respectively. Similarly, the post-processed MetOp data (metopa, metopb, and metopc) are also obtained from the UCAR website from Oct 2019 to Dec 2020. The MetOp data are available contemporaneously as the NASA commercial RO data, however, COSMIC data ceased to be produced at the time of launch of commercial satellites thereby limiting their use for comparative analysis.

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Recently, year-long radiosonde launches were performed over the frozen Arctic Ocean as part of the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition that involved taking measurements from a transpolar drifting ice-breaker, R/V Polarstern, from Oct 2019 to Sep 2020. During MOSAiC, radiosondes were launched at least every 6 hours for the duration of the expedition (Männel et al. 2021). Using the temperature in the radiosonde dataset (Maturilli et al., 2021) and applying the World Meteorological Organization (Jarraud 2008) equation (eq. 1), one can estimate the saturation vapor pressure at each level. In the following equation, e_w is the saturation vapor pressure in hPa, and t is the temperature in K.

$e_w = 6.112\, e^{(17.62\, t/(243.12 + t))}$……………………………………………..(eq. 1)

After deriving e_w, it is possible to infer the water vapor pressure (wvp) using the percentage relative humidity from radiosonde (RH) and applying eq. 2:

wvp = e_w*RH*0.01……………………………………………….....(eq. 2)

The average daily wvp and wvp gradients are calculated at different levels (500, 600, and 700m) in order to test the robustness of the relationship between moisture and RO penetration probability at various altitudes. The wvp gradient at a given altitude is simply the rate of change of wvp within a 100m layer at that altitude.

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The MERRA-2 reanalysis product (Gelaro et al. 2017) is used to obtain the monthly mean PBL height and the monthly mean sea ice fraction over the Arctic Ocean. In MERRA-2, the PBL depth is defined as the model level where the eddy heat diffusivity coefficient (K_H) value falls below 2 m^2 s^{-1} threshold (McGrath-Spangler et al., 2015). The GEOS atmospheric model used in MERRA-2 includes separate parameterizations for stable and unstable PBLs. The non-local Lock et al. (2000) scheme is used to parameterize turbulence in unstable boundary layers, whereas, the model employs a first-order local turbulence closure scheme, Louis et al. (1982), for stable boundary layers. The Louis scheme is expected to be more active in regions such as the Arctic Ocean which are typically characterized by stable conditions. The scheme estimates heat and momentum diffusivity coefficients based on the turbulent length scale and bulk Richardson number at each time step wherein the former is determined by the PBL depth from the previous time step (Ganeshan and Yang 2019). In case of persistent stable conditions, such as over the frozen Arctic Ocean, the turbulent length scales are expectedly small, implying that the model diffusivity coefficients are largely based on the bulk Richardson number. Thus, MERRA-2 PBLH over Arctic is thus inherently sensitive to wind and temperature gradients (used for computing the bulk Richardson number), making it comparable to the PBL temperature inversion which is detected by GNSS RO.

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The horizontal resolution of MERRA-2 products are approximately ~0.5 degree, and the GNSS RO derived monthly mean penetration probability and monthly PBL height characteristics are interpolated on the MERRA-2 grid for ease of comparison. The vertical grid of MERRA-2 is based on terrain-following sigma coordinate. In general, the first model level over the Arctic Ocean is around 50 meters above surface and the spacing is approximately 100 meters within the lowest five model levels.

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3 Results and Discussions

3.1 Sensitivity of RO penetration loss to bending angle retrieval method

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GNSS RO profiles of bending angle and refractivity observations are characterized by a loss of signal (decrease in SNR) as we approach the surface due to atmospheric defocusing effects (Wu et al. 2022). However, the rate of penetration loss is expectedly different for various RO missions due to diversity in the design of GNSS receivers and SNR capabilities, but it can also be different for measurements from the same instrument due to inherent disparity in excess phase computations and bending angle retrieval algorithms. For example, older versions of the same product, such as COSMIC 2013, can differ significantly from newer reprocessed versions (COSMIC 2021) due to advances in excess phase computations, retrieval software, GNSS orbits, clock, and earth orientation products (UCAR Data Release, 2022).

Figure 1 compares the rate of RO penetration loss over the Arctic Ocean for different GNSS RO missions (COSMIC, MetOp, Spire, GeoOptics) as well as for different products from the same mission (COSMIC 2013 vs. COSMIC 2021; Spire NASA vs. Spire NOAA; GeoOptics NASA vs. GeoOptics NOAA). Clearly, the penetration loss is less significant for the newer version of COSMIC data (COSMIC 2021) compared to the older version (COSMIC 2013) due to the aforementioned major advances in computations and retrieval software. For contemporaneously processed commercial

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data products, viz. Spire NASA vs Spire NOAA and/or GeoOptics NASA vs. GeoOptics NOAA, the differences in penetration probability are generally confined to the lowest 1 km. These differences are solely due to the choice of processing algorithm used for retrieving the bending angle and refractivity profiles. Figure 2 (a) shows the penetration loss for a common subset of NASA purchased and NOAA purchased Spire profiles. The former is processed by the vendor while the latter is processed by UCAR from L1b purchased data. Even though the same physical radio occultations are compared, the two products have clearly distinctive penetration patterns within the lowest 500 meters. On the contrary, when comparing NOAA Spire profiles with COSMIC-2 profiles over the tropics, both processed by UCAR, there is little to no difference in the penetration probabilities (Fig. 2(b)). Thus, processing software appears to have a greater bearing on RO penetration loss compared to instrument hardware.

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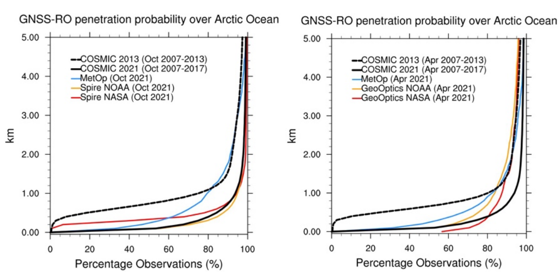

Fig. 1 RO penetration loss with altitude over the Arctic Ocean (north of 60°N) from different products comparing **(left)** COSMIC, MetOp, Spire for the month of October and **(right)** COSMIC, MetOp, GeoOptics for the month of April.

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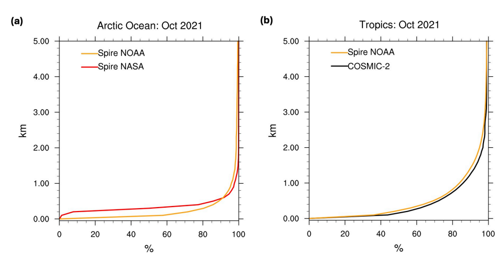

Fig. 2 RO penetration loss with altitude for October 2021 showing **(a)** differences in penetration probabilities for a common subset of monthly radio occultations over the Arctic Ocean obtained from a single mission/instrument (Spire) processed by different centers and **(b)** similarities in penetration probabilities for different sources of monthly radio occultations over the Tropics (30°S to 30°N) obtained from two separate missions but processed by the same center (UCAR).

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3.2 RO penetration over the Arctic Ocean

The top panel of Figure 3 compares the minimum altitude of RO penetration over the Arctic Ocean for NASA Spire, NASA GeoOptics and MetOp data. Spire has deeper penetration throughout the Arctic Ocean compared to MetOp which is expected due to the less pronounced rate of loss of penetration below 3km (as seen in Fig. 1). GeoOptics has the lowest and highest values of minimum RO penetration altitude compared to the other two datasets, with the lows occurring over the frozen ocean in the Beaufort Sea region and to the north of Greenland, and the highs occurring over the Atlantic storm track region. A similar pattern of enhanced RO penetration loss in the storm track region was also observed in COSMIC data (Ganeshan and Wu 2015).

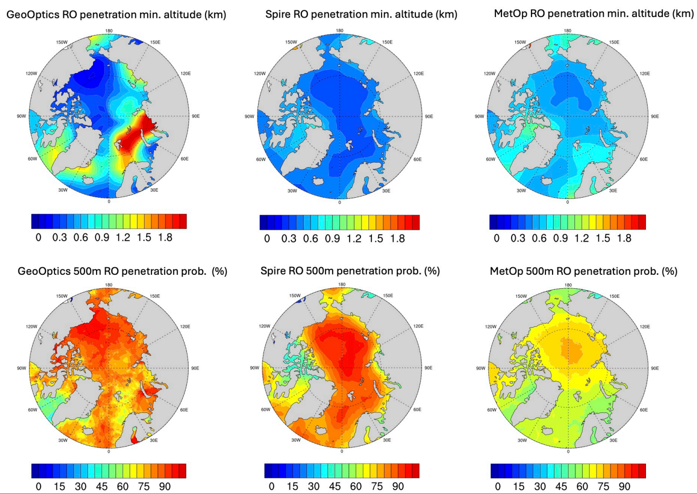

Fig. 3 RO penetration statistics over the Arctic Ocean for December 2020 comparing NASA spire, NOAA Spire and MetOp datasets showing **(top)** the minimum altitude of RO penetration and (b) the RO penetration probability at 500m altitude.

Based on previous studies involving RO-derived PBLH (Ao et al. 2012; Ganeshan and Wu 2015), a 500m cut-off altitude is chosen to select profiles used for retrieving the PBLH. Figure 3 (bottom panel) compares the RO penetration probability at 500m altitude between the three datasets. In general, both commercial products have a high fraction of RO observations (~80%) reaching 500 meters altitude compared to MetOp (~65%). The penetration capability of MetOp is higher over the frozen Arctic Ocean compared to the open ice-free ocean, a pattern that was similarly observed for COSMIC data (Ganeshan and Wu 2015). It has been previously speculated (Ao et al. 2012, Ganeshan and Wu 2015, Chang et al. 2022) that there is a negative relationship between water vapor amount and RO penetration depth, with increased lower atmospheric penetration typically observed in regions away from the tropics, specifically over the dry north pole. Figure 4 compares the time-series

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of total number of available RO observations at 500m altitude over the Arctic Ocean. Spire has the maximum number of daily observations, nearly an order (two orders) of magnitude greater than MetOp (GeoOptics).

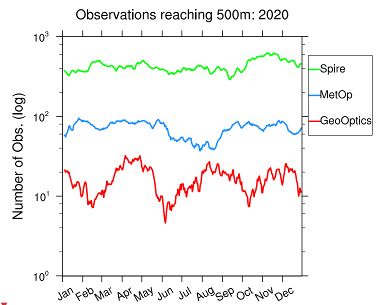

Fig. 4 Annual time-series of number of RO observations reaching 500m altitude or lower over the Arctic Ocean for the year 2020. The daily observations are smoothed using a 5-day running average filter.

3.3 Performance of commercial GNSS RO datasets for refractivity-based PBLH over Arctic

This section will focus on exploring the potential for using commercial RO data for Arctic winter PBL studies using the cut-off altitude threshold of 500m to select RO profiles, as described previously (section 2.1.3 and section 3.1). Ganeshan and Wu (2015) showed that the minimum refractivity gradient method works well to detect PBL temperature inversions over the Arctic Ocean during winter months (November – April). Due to the lack of moisture in the atmosphere, the refractivity gradient minima is found to be sensitive to the positive temperature gradient maxima (i.e. temperature inversions).

Figures 5-7 compare the monthly RO-derived PBLH characteristics for each product during the cold season months of the year 2020 (January – April, and November – December). The adopted methodology (Ganeshan and Wu 2015) described in section 2.1.3, appears to work well for GeoOptics and MetOp, which clearly show the expected distribution of shallow PBLH over sea ice versus deeper PBLH over the Atlantic sector (compare to Figure 8), with GeoOptics showing a stronger constrast between the two regions. The extreme high values of GeoOptics based PBLH in the Atlantic Sector seems to be related to the high minimum penetration altitude in this region (seen in top panel of Fig. 3). A seasonal evolution in the retrieved PBLH is evident in both GeoOptics and MetOp datasets with the lowest values generally observed during January, February and March, and highest values in November, which is in good agreement with MERRA-2 derived PBLH (Figure 9). On the other hand, Spire derived mean PBLH appears to have lesser spatial and seasonal variation compared to the other two datasets and compared to MERRA-2, which could be because of the increased vertical smoothing applied to their bending angle product (Bowler 2020) that may limit the effective vertical resolution of refractivity and the range of refractivity-derived PBLH values.

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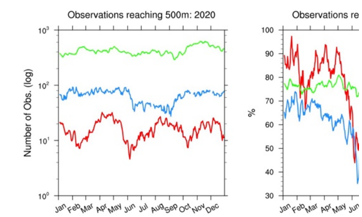

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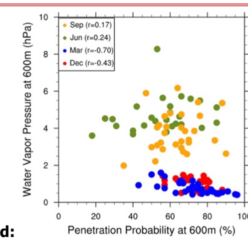

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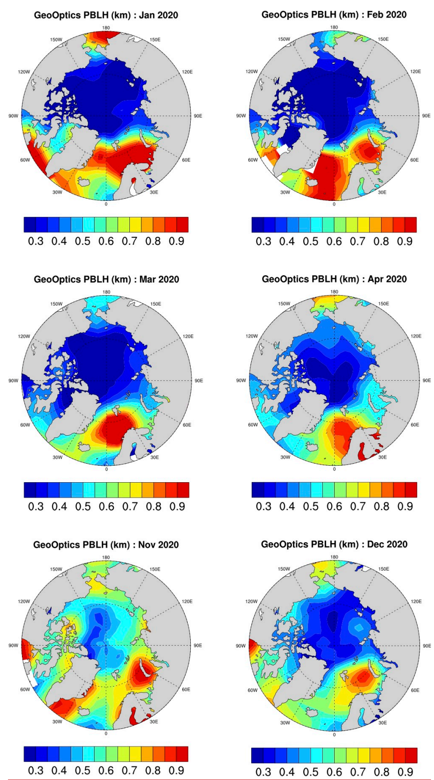

Fig. 5 NASA GeoOptics derived monthly Arctic PBLH for cold season months of the year 2020.

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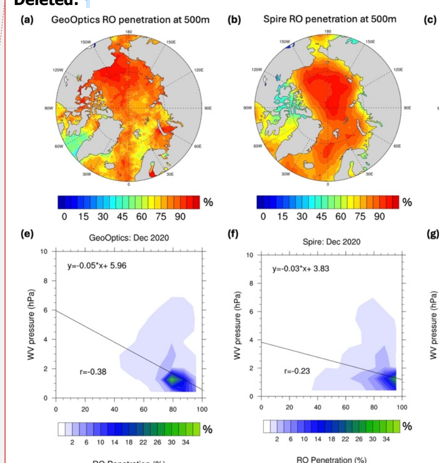

Fig. 5 (top) Arctic maps showing the monthly mean penetration probability of GNSS RO measurements reaching 500m altitude from **(a)** GeoOptics, **(b)** Spire, and **(c)** MetOp, and **(d)** the monthly mean water vapor pressure from MERRA-2 at approximately 500m altitude for Dec 2020, and **(bottom)** bivariate probability density functions of MERRA-2 water vapor at approximately 500m altitude and the 500m RO penetration probability for Dec 2020 from **(e)** GeoOptics, **(f)** Spire, and **(g)** MetOp data.¶ ... [7]

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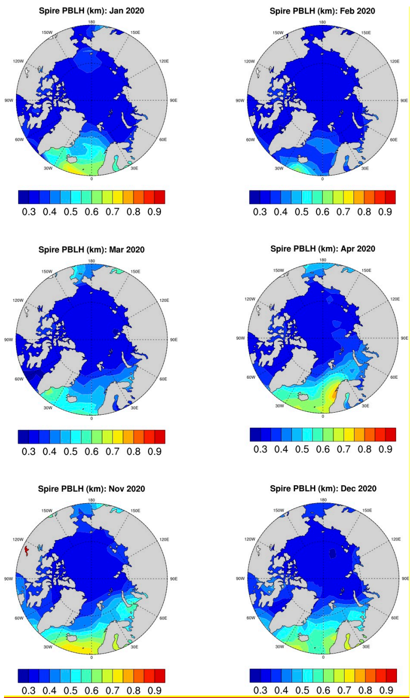

Fig. 6 NASA Spire derived monthly Arctic PBLH for cold season months of the year 2020.

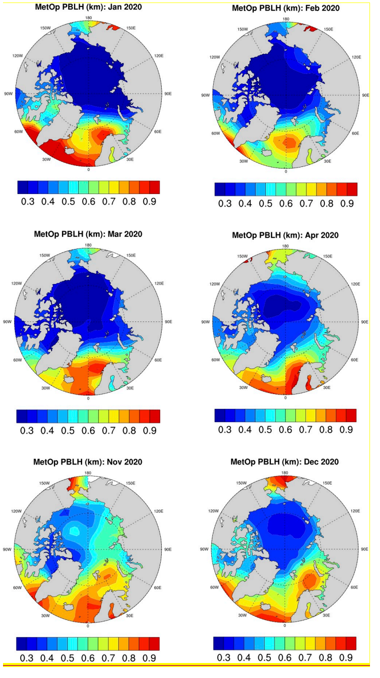

Fig. 7 MetOP derived monthly Arctic PBLH for cold season months of the year 2020.

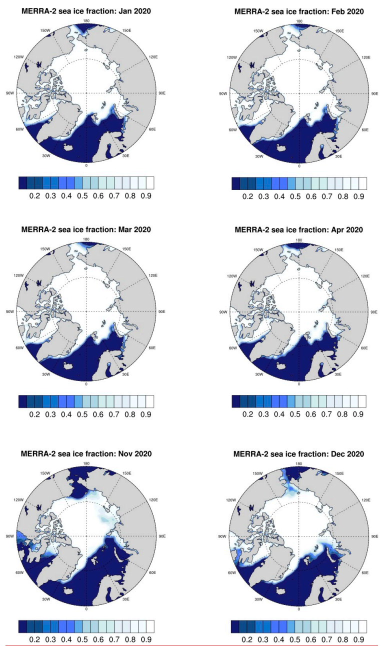

Fig. 8 MERRA-2 monthly Arctic sea-ice fraction for cold season months of the year 2020.

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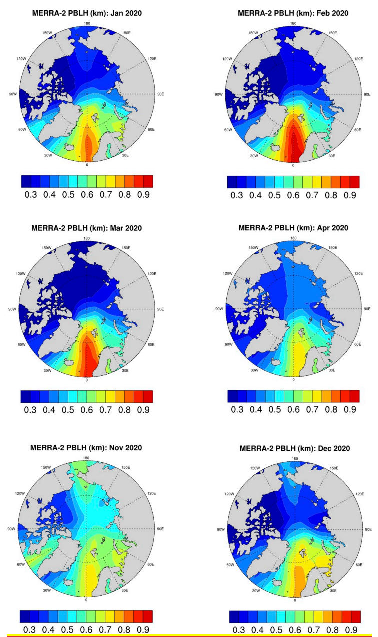

Fig. 9 MERRA-2 monthly PBLH showing the seasonal evolution and spatial variability of Arctic PBLH for cold season months of the year 2020.

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3.4 Sensitivity to cut-off altitude

As explained in section 1.2, a sampling bias may occur in the retrieved PBLH due to any sharp drop in available RO profiles, thereby necessitating the selection of an optimal cut-off altitude threshold for minimum RO penetration height. The cut-off altitude, in some sense, is a first guess estimate of the expected typical height of the PBL. Although the standard cut-off altitude of 500m has been regarded as sufficient for deriving refractivity-based PBLH from COSMIC RO observations in the Arctic, it has been noted to be less than ideal for inferring PBL depth in the case of shallow PBLs (Ao et al. 2012) and may even contribute to a positive bias in regions such as the central Arctic Ocean (Ganeshan and Wu 2015). It appears, however, that the 500m cut-off altitude when applied to NASA GeoOptics and MetOp is sufficient for obtaining a realistic representation of the shallow Arctic PBLH. However, in the case of NASA Spire data, the derived PBLH values are slightly higher compared to the other two RO datasets and MERRA-2 reanalyses (Fig. 6). It is worth investigating whether the standard 500m cut-off altitude is suboptimal for NASA Spire data.

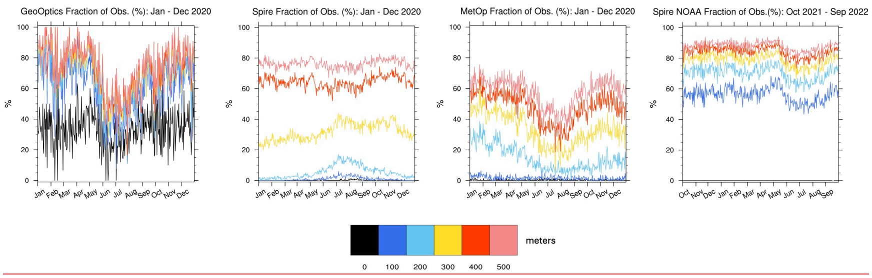

Fig. 10 Annual time-series of penetration probability in the lowest 500 meters for (a) NASA GeoOptics, (b) NASA Spire, (c) MetOp, and (d) NOAA Spire data.

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Figure 10 shows the annual time-series of the fraction of available RO observations in the lowest 500m. The percentage of available NASA Spire RO profiles has two significant drops going from 400 to 300m and then from 300 to 200m which could potentially lead to a positive bias in the retrieved PBLH values when the standard cut-off altitude of 500m is chosen. No such sharp drop is seen for GeoOptics and MetOp datasets. Moreover, a similar comparison with the Spire NOAA product shows that this sharp rate of decline only exists in the NASA Spire data.

Consequently, the PBLH retrievals from NASA Spire are recomputed using a lower cut-off altitude threshold of 300m, and the resulting PBLH values are found to be significantly lower. Despite an improvement in the PBLH magnitude, the poor granularity in its spatial features and the lack of seasonal variability (as seen in Fig. 6) continue to persist. Figure 11 shows the Arctic PBLH for February 2020 comparing two sets of retrievals from NASA Spire data using both cut-off altitude thresholds (i.e. 500m and 300m). Even though the 300m cut-off altitude better captures the shallow PBLs, it does not improve the qualitative representation of the Arctic PBLH. On the other hand, comparisons of RO-derived PBLH with NOAA Spire data showed better agreement with other products (now shown). In summary, an optimal cut-off altitude threshold for NASA Spire data appears to be 300m, however, the representation of spatiotemporal variability in the derived PBLH remains unsatisfactory. It appears that while RO penetration capability can affect the choice of cut-off altitude and derived PBLH values, the qualitative differences in Arctic PBLH representation are mostly due to different processing softwares.

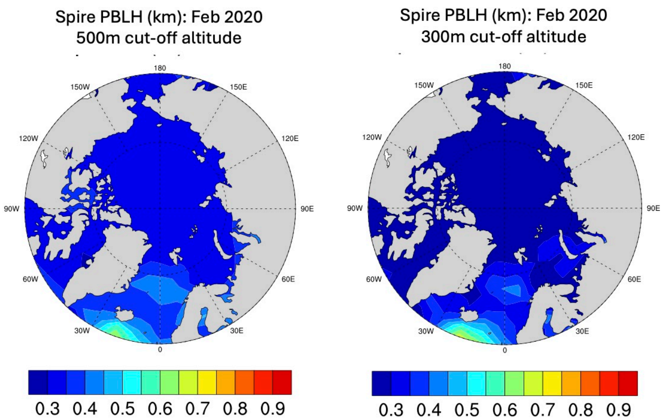

Fig. 11 PBLH retrieved from NASA Spire data using (a) 500m and (b) 300m cut-off altitude threshold for minimum RO penetration depth.

4 Summary and Conclusions

This study explores the use of commercial GNSS RO neutral atmosphere products from Spire and Geoptics to advance Arctic PBL studies. The launch of commercial GNSS RO CubeSat receivers such as Spire and GeoOptics presents an unparalleled opportunity for high-latitude PBL studies which are presently impacted by the loss of COSMIC-1 and the lacking coverage by its successor COSMIC-2. In order to continue to support PBL studies in polar regions, the new GNSS RO products must have sufficient lower atmospheric penetration capability, and the ability to sample shallow PBL temperature inversions that often persist in polar regions. This study attempts to provide a comparison of the penetration capability of the new commercial and other existing GNSS RO data products in the Arctic as the first step towards establishing a climate ready, long-term continuous dataset that can be used for Arctic PBL investigations.

Both commercial products, purchased by NASA, are found to have an improved lower atmospheric penetration capability over the Arctic Ocean compared to contemporaneous MetOp observations from EUMETSAT as evidenced by lower minimum penetration depths achieved over the frozen Arctic Ocean and higher penetration probability at the standard cut-of altitude of 500m. The resulting PBLH derived from the commercial RO products, however, seems relatively independent of this advancement. Overall, the monthly mean PBLH pattern and seasonal evolution over the Arctic Ocean are best represented by NASA GeoOptics and MetOp data, in agreement with MERRA-2. On the other hand, PBLH retrieved from NASA Spire data, despite having improved lower tropospheric penetration, has insufficient spatial granularity and seasonality which is better represented in other datasets.

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In fact, the rate of decline of RO penetration within the PBL appears to be an influential factor affecting the choice of cut-off altitude threshold for PBLH retrieval. For products in which the rate of decline is smooth, the standard cut-off altitude for RO penetration depth (i.e. 500m) works well, however, for products such as NASA Spire, where the rate of decline is drastic within the lowest 500 meters, the PBLH representation is improved when a lower cut-off altitude (i.e. 300m) is used. Regardless, the spatiotemporal variability and qualitative representation of the Arctic PBLH appears to be independent of the choice of cut-off altitude threshold. A preliminary comparison with NOAA Spire data suggests that the refractivity-based PBLH is more sensitive to the choice of processing software used for retrieving bending angle profiles. The methodology used to obtain neutral atmosphere products from excess phase data is thus crucial for both lower tropospheric penetration probability and for Arctic PBLH representation.

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