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Validation of the Aeolus Level-2B wind product over Northern Canada and the Arctic

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Abstract. In August 2018, the European Space Agency launched the Aeolus satellite, whose Atmospheric LAser Doppler INstrument (ALADIN) is the first spaceborne Doppler wind lidar to regularly measure vertical profiles of horizontal line-of-sight (HLOS) winds with global sampling. This mission is intended to assess improvement to numerical weather prediction provided by wind observations in regions poorly constrained by atmospheric mass, such as the tropics, but also, potentially, in polar regions such as the Arctic where direct wind observations are especially sparse. There remain gaps in the evaluation of the Aeolus products over the Arctic region, which is the focus of this contribution. Here, an assessment of the Aeolus Level-2B wind product is carried out from measurement stations in Canada's north, to the pan-Arctic, with Aeolus data being compared to Ka-band radar measurements at Iqaluit, Nunavut; to radiosonde measurements over Northern Canada; to Environment and Climate Change Canada (ECCC)'s short-range forecast; and to the reanalysis product, ERA5, from the European Centre for Medium-Range Weather Forecasts (ECMWF). Periods covered include the early phase during the first laser nominal flight model (FM-A; 2018-09 to 2018-10), the early phase during the second flight laser (FM-B; 2019-08 to 2019-09), and the mid-FM-B periods (2019-12 to 2020-01). The adjusted r-square between Aeolus and other local datasets are around 0.9, except for somewhat lower values in comparison with the ground-based radar, presumably due to limited sampling. This consistency degraded by about 10% for the Rayleigh winds in the summer, presumably due to scattering from the solar background. Over the pan-Arctic, consistency, with correlation greater than 0.8, is found in the Mie channel from the planetary boundary layer to the lower stratosphere (near surface to 16 km a.g.l.) and in the Rayleigh channel from the troposphere to the stratosphere (2 km to 25 km a.g.l.). Zonal and meridional projections of the HLOS winds are separated to account for the systematic changes in HLOS winds arising from sampling wind components from different viewing orientations in the ascending and descending phases. In all cases, Aeolus standard deviations are found to be 20% greater than those from ECCC-B and ERA5. We found that L2B estimated error product for Aeolus is coherent with the differences between Aeolus and the other datasets, and can be used as a guide for expected consistency. Thus, our work confirms the quality of the Aeolus dataset over the Arctic and shows that the new Aeolus L2B wind product provides a valuable addition to current wind products in regions such as the Arctic Ocean region where few direct wind observations have been available to date.

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1 Introduction

A better characterization of the global wind field would advance the initialization of numerical weather prediction (NWP) and thereby improve our knowledge of the characteristics and transport of moisture, energy, and other fields in the global atmosphere (Baker et al.,1995; Graham et al., 2000, Naakka et al., 2019). Altitude resolved wind observations are available from aircraft reports and surfaced-based observations (e.g., radiosondes and wind profilers). However, those are generally scattered and especially rare over large water surfaces like oceans, and the polar regions. Winds derived from passive space-based observations, such as atmospheric motion vectors (AMVs) and spaceborne scatterometer, are retrieved from the movements of clouds and water vapour (Velden et al., 2017; Mizyak et al., 2016) or from scattering from the ocean surface. Satellite-derived AMVs can provide information of winds over multiple tropospheric layers using multispectral water vapor capabilities (Velden et al., 1997; Bormann and Thépaut, 2004; Le Marshall et al., 2008). Overall, AMV products lack precision in terms of altitude assignment and sampling is limited to only a few levels, which limits representation of small-scale vertical structure of the wind profile, for example. Spaceborne scatterometers are limited to ocean near-surface winds and their accuracy is therefore sensitive to surface weather conditions (Chiara et al., 2017; Young et al., 2017). Improving altitude-resolved winds from remote sensing on a global scale requires adoption of active sensors, which have only recently become feasible for deployment from space based platforms (Dabas, 2010).

On 22 August 2018, the European Space Agency (ESA) launched the Aeolus satellite carrying the first spaceborne Doppler wind lidar (DWL) designed to significantly improve altitude-resolved wind observations, from the surface to the stratosphere, on a global scale (Källen, 2018; Reitebuch et al., 2019). The instrument carries an emitting UV laser and two receivers to measure the Doppler shift from backscattering by air molecules (Rayleigh channel) and by aerosols or cloud particles (Mie channel). Aeolus was designed to improve global weather forecasts, with an emphasis on tropical winds, because tropical wind information is required to fully characterize the circulation when balance constraints are weak (Horányi et al., 2015). However, since it is polar orbiting, Aeolus also fills an observation gap in the polar regions, including the Arctic region, which is our focus. It is worthwhile exploring how filling this gap along with other meteorological observations might improve Arctic forecasts (e.g. Yamazaki et al., 2015), and, by extension, prediction outside the Arctic (Naakka et al., 2019; Lawrence et al., 2019), with a potential to influence forecasting and characterization of mid-latitude weather and climate extremes (Walsh et al., 2019; Cohen et al., 2020; Sato et al., 2017). We are thus motivated to invest in understanding the quality of Aeolus data products in the Arctic region, particularly for Canada, given its large territorial extent at high northern latitudes.

The purpose of this paper is to evaluate the quality of Aeolus wind products over Northern Canada and the Arctic in comparison with several available observational products, including the dataset from the Canadian Arctic Weather Science (CAWS) project supersites, that contain a suite of ground based remote sensing and in-situ instruments for enhanced meteorological observations located at Iqaluit, NU (64° N, 69° W) and Whitehorse, YK (61° N, 135° W) (Joe et al., 2020).

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Because of data limitations (see below), only Iqaluit ground-based remote sensing data will be used in this study. As part of the Canadian contribution to the international calibration/validation effort for Aeolus (Martin et al., 2020; Guo et al., 2020; Baars et al., 2020), this project serves to test new technologies and provide cost-effective alternatives to atmospheric monitoring over the northern regions.

In related Arctic-based work, Belova et al. (in review, 2021) have found consistency between Aeolus winds and ground-based radar situated in northern Sweden with insignificant biases and slight increased random errors in the summer. We here expand from this encouraging study by moving from an in-situ focus to specific locations in northern Canada to a pan-Arctic perspective. We evaluate Aeolus wind products co-located with 1) ground-based in-situ, radiosonde and remote sensing observations at the Iqaluit CAWS supersite; 2) radiosonde stations at the Iqaluit and Whitehorse sites and more broadly over Northern Canada; and 3) global data-assimilation based wind products including the short-range forecast from ECCC's operational NWP system (ECCC-B) and the fifth major global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF ERA5). Section 2 provides a description of each of these datasets. Section 3.1 describes the comparison during the early FM-A period (15 September to 16 October 2018) to ground-based measurements in Canada's North, including the Iqaluit supersite and radiosonde stations over the Northern Canada. Section 3.2 describes the broader validation for the regions and periods of analysis over the pan-Arctic (poleward of 70° N) during the early FM-A period, early FM-B period (2 August to 30 September 2019), and mid-FM-B period (1 December to 31 January 2020) for the Aeolus' near real-time (2B02/2B06) and reprocessed (2B10) wind products. A summary and discussion of the results is provided in Sect. 4.

2 Datasets

The near polar-orbiting and sun-synchronous Aeolus satellite measures global atmospheric wind profiles along the DWL's line-of-sight (LOS) from the Earth's surface to the lower stratosphere (Straume et al., 2018). The LOS of Aeolus is perpendicular to its orbital velocity to mitigate contributions from its along-orbit velocity. It points 35° from the nadir to capture a single component of the wind. Its DWL, named Atmospheric LAser Doppler INstrument (ALADIN, Guo et al., 2020), includes two receivers to measure the Doppler shift from the emitting laser along the LOS: a double Fabry-Pérot spectrometer to measure Rayleigh scattering from air molecules and a Fizeau spectrometer to measure Mie scattering from cloud droplets and aerosols. The horizontal line-of-sight (HLOS) wind component can be derived by analyzing the Doppler frequency shift and assuming that the vertical component of winds is negligible. In this section, we will discuss the Aeolus wind product and the other datasets that will be compared with the Aeolus HLOS winds.

2.1 Aeolus L2B HLOS wind product

Aeolus's Level-2B (L2B) products comprise a fully calibrated and processed HLOS wind product, whose wind retrieval method can be found in the Algorithm Theoretical Basis Documents (Rennie et al., 2020a). For both Mie and Rayleigh channels

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each measurement-bin is classified into "cloudy" or "clear" using its optical property information from Level-1B scattering ratio estimates (Rennie et al., 2020a). "Cloudy" classification occurs when the measurement-bins have non-zero particle backscatter, while "clear" classification occurs for predominantly molecular backscatter. Since Mie-cloudy and Rayleigh-clear wind results are considered as superior quality compared to Mie-clear and Rayleigh-cloudy (Martin et al., 2020; Guo et al., 2020; Baars et al., 2020), Mie winds and Rayleigh winds refer exclusively to Mie-cloudy and Rayleigh-clear winds in the rest of this study.

The backscattered signal must be horizontally and vertically averaged to have a sufficient signal-to-noise ratio (SNR) (Drinkwater et al., 2016; Reitebuch et al., 2019; Lux et al., 2020). Stronger signal returns are expected from the Mie scattering than for Rayleigh scattering; therefore, the horizontal resolution is finer for the Mie winds (about 10 km) than for the Rayleigh winds (about 90 km). Similarly, the vertical resolution depends on the signal strength of the measurements. In the PBL (defined here as below 2 km in altitude), the vertical structure allows a finer vertical resolution (500 m). It decreases with altitude to 1 km in the free troposphere (defined here as 2 to 16 km in altitude) and to 2 km in the lower stratosphere (above 16 km in altitude). The Mie channel covers the vertical range up to 16 km in altitude and the Rayleigh channel covers up to 30 km.

Aeolus switched from the first flight laser (FM-A) to the second flight laser (FM-B) due to a decrease in ultraviolet (UV) power output from FM-A at the end of June 2019 (Reitebuch et al., 2019; Lux et al., 2020). Aeolus L2B near real-time baseline products 2B02 and 2B06 are used during early FM-A period (fall 2018) and FM-B period (summer 2019 and winter 2020) respectively. ECMWF has recently published the first reprocessed data (2B10), which covers the period between 24 June and 31 December 2019. The major improvement in this product is a daily updated bias correction accounting for variability of the temperature gradients across the detector telescope's primary mirror M1; additional improvements are mentioned below and in other studies (e.g., Rennie and Isaksen, 2020; Laroche and St. James submitted to QJRMS). A comparison of the statistical results during the overlapping period, summer 2019, between 2B06 and 2B10 will be presented in this study.

The following data selection is carried out in this study:

- L2B product provides a validation flag of 1 (valid) or 0 (invalid) (de Kloe et al., 2016) associated with each range-bin in an observation, and we therefore screen out validation flag value 0 (Baars et al., 2020).
- The quality control recommendation following the Guidance for Aeolus NWP Impact Experiments (Rennie and Isaksen, 2019), including the threshold for L2B estimated observation errors.
- We further reject the outliers by excluding all the data when the difference between the observations and ECCC-B or ERA5 is greater than 30 ms^{-1}. The outliers represent less than 1% of all data; however, the O-B (Observation minus Background) could be as large as 150 ms^{-1}.

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During the early FM-A period, a global constant bias offset of -1.35 ms^{-1} was added to the Mie winds to bring them into better agreement with the ECMWF model (Rennie and Isaksen, 2019). The Aeolus observation heights were also systematically increased by 250 m due to a known calibration issue (Rennie and Isaksen, 2019). The biases of FM-B HLOS arising mainly from the telescope primary mirror M1 temperature gradients (Rennie and Isaksen, 2020) should be corrected as much as possible before any use for validation against other wind measurements or data assimilation. Fortunately, these biases vary mostly with the orbital node and latitude and partly with longitude and height, facilitating such bias correction. ECCC has developed a bias correction scheme similar to the ECMWF as described in Rennie and Isaksen (2020); see Laroche and St. James (submitted to QJRMS). It is a dynamic bias correction based on the mean observation minus ECCC-B background (O-B) from the previous 7 days as a function of orbit phase and latitude. It is applied for both Rayleigh and Mie HLOS winds. For the Rayleigh HLOS winds, the correction is also a function of longitude, binned in 10 degrees latitude by 36 degrees longitude sectors.

To project the wind vector in a given dataset into the Aeolus HLOS, we use

$$v_{HLOS} = -u \sin\varphi - v \cos\varphi, \quad (1)$$

where v_{HLOS} is the HLOS wind component, u is the zonal wind component, v is the meridional wind component, and φ is the azimuth of the LOS. This equation is used for all the datasets described below to obtain the HLOS winds. Conversely, we can also project the HLOS wind vector into the west-east and north-south directions (Wright et al., in review, 2021) for some analysis (Sect. 3.2), using

$$v_{HLOS,u} = -v_{HLOS} \cdot \sin(\varphi), \quad (2)$$

$$v_{HLOS,v} = -v_{HLOS} \cdot \cos(\varphi). \quad (3)$$

To repeat, these quantities do not represent zonal and meridional components of the total wind field, but the zonal and meridional projection of the vector component of the wind along the HLOS of Aeolus.

2.2 ECCC-B: Short-range forecast (background) from ECCC

The background from ECCC, termed “ECCC-B”, is the 9-h short-range forecast used in the operational four-dimensional ensemble-variational (4D-EnVar) data assimilation scheme (Buehner et al., 2015). The forecast model is the operational Global Environmental Multiscale (GEM) (McTaggart-Cowan et al., 2019) with 15 km horizontal grid spacing and 84 vertical levels. There are over 13 million observations assimilated daily during the periods examined in this study, which include data from infrared (56.1% of all observations assimilated) and microwave (27.7%) satellite sounders and imagers, aircraft (9.6%), atmospheric motion vectors (2.3%), radiosondes (2.1%), scatterometers (1.0%), near-surface observations (0.7%), satellite-based radio occultation (0.4%). ECCC-B is then linearly interpolated to Aeolus measurement locations and times.

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2.3 Reanalysis ERA5

The ERA5 hourly data on 37 pressure levels from the ECMWF has been considered in validating the Aeolus measurements. This dataset is based on a four-dimensional variational (4DVar) data assimilation using Cycle 41r2 of the IFS which was introduced operationally in 2016. It provides hourly estimates of atmospheric, land, and oceanic climate variables, available from 1950 to present. Data is gridded in a regular latitude-longitude grid of 0.25 degrees. A further discussion of the ERA5 configuration can be found in Hersbach et al. (2018 and 2020).

2.4 Ground-based measurements at Iqaluit, Whitehorse, and other radiosonde stations

The CAWS project, led by ECCC, aims to characterize and improve scientific understanding of Arctic weather, climate, and cryospheric systems through enhanced meteorological observation capacity (Joe et al., 2020; Mariani et al., 2018). It also seeks to improve weather forecasts in the Canadian Arctic, test new technologies, and calibrate and validate space-based observations. ECCC's Iqaluit and Whitehorse sites (Fig. 1), so-called "supersites", were identified as "hot spots" for both extreme weather and transportation infrastructure that merited additional instrumentation. They provide researchers and forecasters with real-time weather observations which can be used in evaluating NWP models. Connected to ECCC's observational science mission, locating these weather stations at high latitudes also tests the ability of the coordinated instrument suites to operate in extreme cold conditions.

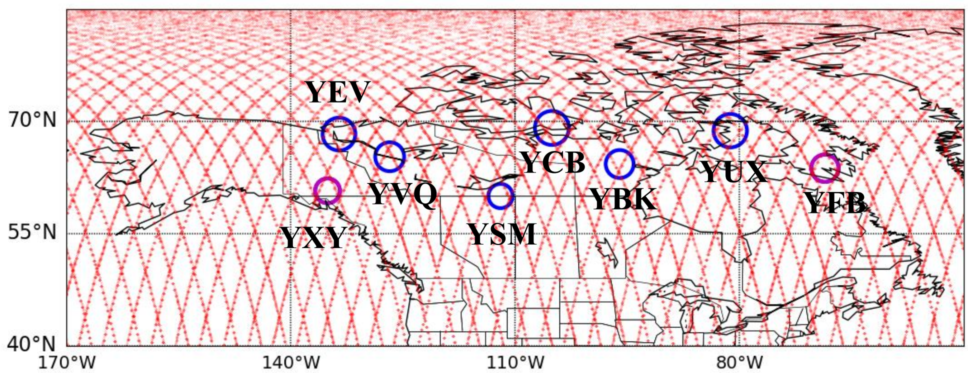

Figure 1. Aeolus's overpasses centred over northern Canada (red dots) during the first week of August 2019. The magenta 90-km radius circles centred on Iqaluit (YFB) and Whitehorse (YXY) within which coincident Aeolus overpasses were compared with other datasets (some circles appear differently sized because of map-projection distortion). The blue circles indicate the locations of other radiosonde stations over the Canadian Arctic: Inuvik (YEV), Fort Smith (YSM), Hall Beach (YUX), Cambridge Bay (YCB), Norman Wells Ua (YVQ), and Baker Lake (YBK).

The Iqaluit site is situated in a valley to the north-east overlooking Frobisher Bay in the vicinity of 300 m hills. There are three instruments at Iqaluit site that provide wind profiles measurements: the radiosonde, Ka-band radar, and Doppler lidar. Vaisala RS92 radiosondes (Mariani et al., 2018) were launched twice daily at 00 and 12 Coordinated Universal Time (UTC). They measure vector wind profiles with a vertical resolution of roughly 15 m (depending on ascent speed) up to about 30 km above ground level. The ECCC Whitehorse site, situated in a valley between two mountains, also has the radiosondes that operate similarly to the ones at the Iqaluit.

The dual-polarization cloud Doppler Ka-band radar at Iqaluit measures the LOS wind speed, fog backscatter, and depolarization ratio every 15 minutes. The radar measures the LOS wind with 14 m resolution and the LOS range goes from 5 to 30 km, depending on hydrometeor concentration. The horizontal winds are derived using a high angle plan position indicator (PPI) 75 degrees scan using the VAD (Velocity-Azimuth-Display) algorithm (Lhermitte and Atlas, 1962; Wang et al., 2010). In other words, it is scanning with a fixed elevation angle (φ) while azimuth angle (θ) is varied and known. The radial velocity is given by

$$v_r = u \sin\theta\, cos\varphi + v \cos\theta \cos\varphi + w \sin\varphi, \quad (4)$$

where w is the vertical wind component. By fitting the data and assuming uniform winds at each range, these three unknown parameters can be derived at each vertical level.

Lastly, the Doppler lidar measures the LOS component of wind and, similar to the radar, can retrieve horizontal winds via the VAD method. However, it is used only for visual comparison in this study (in the example profiles of Fig. 2) because it has very few coincident measurements with Aeolus due to its small vertical range, about 3 km a.g.l. or the cloud base height. Nevertheless, the Doppler lidar wind-profile observations were found to have measurements consistent with radiosondes (Mariani et al., 2020), which should be borne in mind when considering our validation of Aeolus against radiosondes.

Other than the ECCC supersites, we also validate the Aeolus wind product to the radiosonde measurements over the Canadian Arctic at ground stations in Inuvik, Fort Smith, Hall Beach, Cambridge Bay, Norman Wells Ua, and Baker Lake (Fig. 1). They operate similarly to the radiosondes at the supersites and measure vector wind profiles. Some of the stations launch the radiosondes four times a day at 00, 06, 12, and 18 UTC. However, this does not affect the temporal criteria (see Sect. 2.5).

2.5 Coincidence criteria

For the ground-based validation, the criterion for coincidence of Aeolus overpasses is that the distance from the sites to the measurements is no more than 90 km (horizontal resolution of Aeolus Rayleigh winds). The Aeolus measurements are compared to the in-situ measurements that are available in the nearest time. Thus, the temporal criterion is different for different

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instruments. The radiosondes are launched at 00 and 12 UTC. Fortunately, the Aeolus overpasses North America around these times and overpasses Asia around 06 and 18 UTC. Therefore, although the radiosondes have poor temporal resolution, the nearest measured profile to the Aeolus measurements is within one to two hours. However, the radiosonde measurements are sometimes missing when the weather condition does not permit launching the sonde (e.g., high surface winds). The Ka-band radar at Iqaluit scans every 15 minutes. By taking the closest time, the temporal criterion for the radar is 7.5 minutes. We then compare these in-situ measurements to the bias-corrected and quality-controlled Aeolus measurements using the three processes of data selection as described above.

3 Results

3.1 Validation against ground-based measurements in the Canadian Arctic

We evaluated the vertical HLOS wind profile observations from coincident Aeolus overpasses for Iqaluit and Whitehorse against ground-based measurements, ECCC-B, and reanalysis. Our evaluation was limited to the early FM-A phase of Aeolus because the Ka-band radar at Iqaluit has been turned off for repairs since 1 August 2019. Figure 2 shows examples of wind

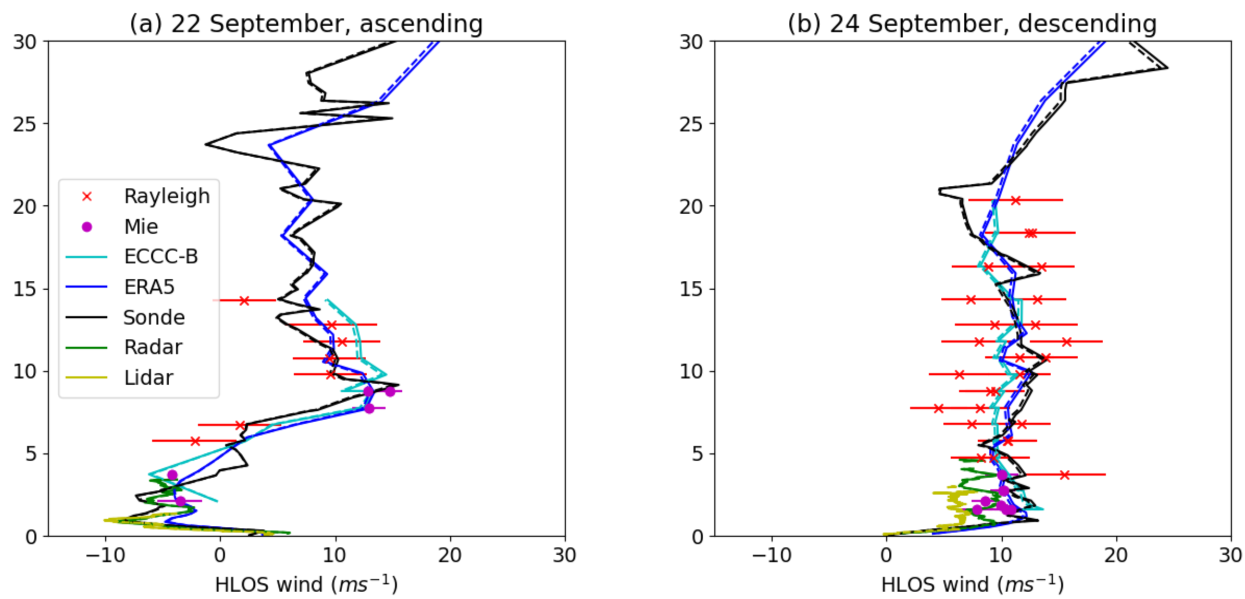

Figure 2. HLOS wind profile observations from 1) coincident Aeolus overpasses (Rayleigh and Mie winds, along with L2B estimated error, i.e. wind error quantifier for each observation, 2) ECCC-B, i.e. the short-range forecast (background) from the ECCC numerical weather prediction model, 3) ERA5, and 4) ground-based remote sensing observations (radiosonde, Ka-band radar, and lidar measurements), on (a) September 22nd and (b) September 24th, 2018. Also shown are zonal component of the HLOS winds (dashed line). The HLOS winds are plotted so that their zonal component is positive eastward.

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profile measurements on (a) 22 September when Aeolus was in its ascending orbit and (b) 24 September 2018 when Aeolus was in its descending orbit, at the Iqaluit site. The HLOS wind profile is shown, along with profiles of the zonal projection of the HLOS component (dashed curves), $v_{HLOS,u}$ from equation (2), for ERA5, radiosonde, Ka-band radar, and lidar. When the measured HLOS winds are positive westward, i.e., when Aeolus is in its ascending orbits, we plot the profile of negative HLOS winds to ease the interpretation. The Ka-band radar's vertical range extends to less than 5 km in both profiles, around where there are Mie wind measurements from Aeolus, because its vertical range depends on hydrometeor concentration; the lidar's vertical range only extends to around 2 to 3 km. Due to the limited region of comparison, the agreement between Aeolus and radar is less good as we will discuss later, and we will not consider the lidar measurements in this study.

It can be seen that Aeolus consistently captures some of the basic structure of the wind profiles compared to in-situ measurements, ERA5 reanalysis, and ECCC-B. Because the structure of the solid lines is very similar to the dashed lines, it is evident that Aeolus is providing predominantly zonal wind information even at high latitudes (63° N) where the LOS has a greater meridional component than at low latitudes. On 22 September, Aeolus detects an easterly wind feature in the lower atmosphere and accurately picks up the change of sign around 5 km altitude. On 24 September, Aeolus measures westerly winds in reasonable overall agreement with the other data.

Figures 3 and 4 show scatter plots between the different datasets and frequency distributions in percentage around Iqaluit (black) and Whitehorse (blue) sites. Figure 3 compares Aeolus-Rayleigh-Clear against the other products and Fig. 4 compares Aeolus-Mie-Cloudy against the other products. Aeolus provides more Rayleigh measurements than Mie winds during fall 2018, because the Rayleigh channel measures winds under clear-sky conditions and has greater vertical extent, while the Mie channel measures winds under cloudy or high-aerosol conditions.

To measure consistency of vertical profiles, we calculate the adjusted r-squared statistic, r^2_{adj}, using

$$r^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}, \quad (5)$$

$$r^2_{adj} = 1 - \frac{(1-r^2)(N-1)}{N-p-1}, \quad (6)$$

where y_i is the Aeolus measurements (or other dataset shown on the y-axis), $\hat{y}_i$ is the estimated HLOS wind using linear regression, $\bar{y}$ is the mean of y, N is the total number of measurements, and p is the number of profiles. The r^2_{adj} are shown in each panel legend in brackets. The adjustment avoids overestimating the raw correlation from the scatterplots by accounting for within-profile agreement.

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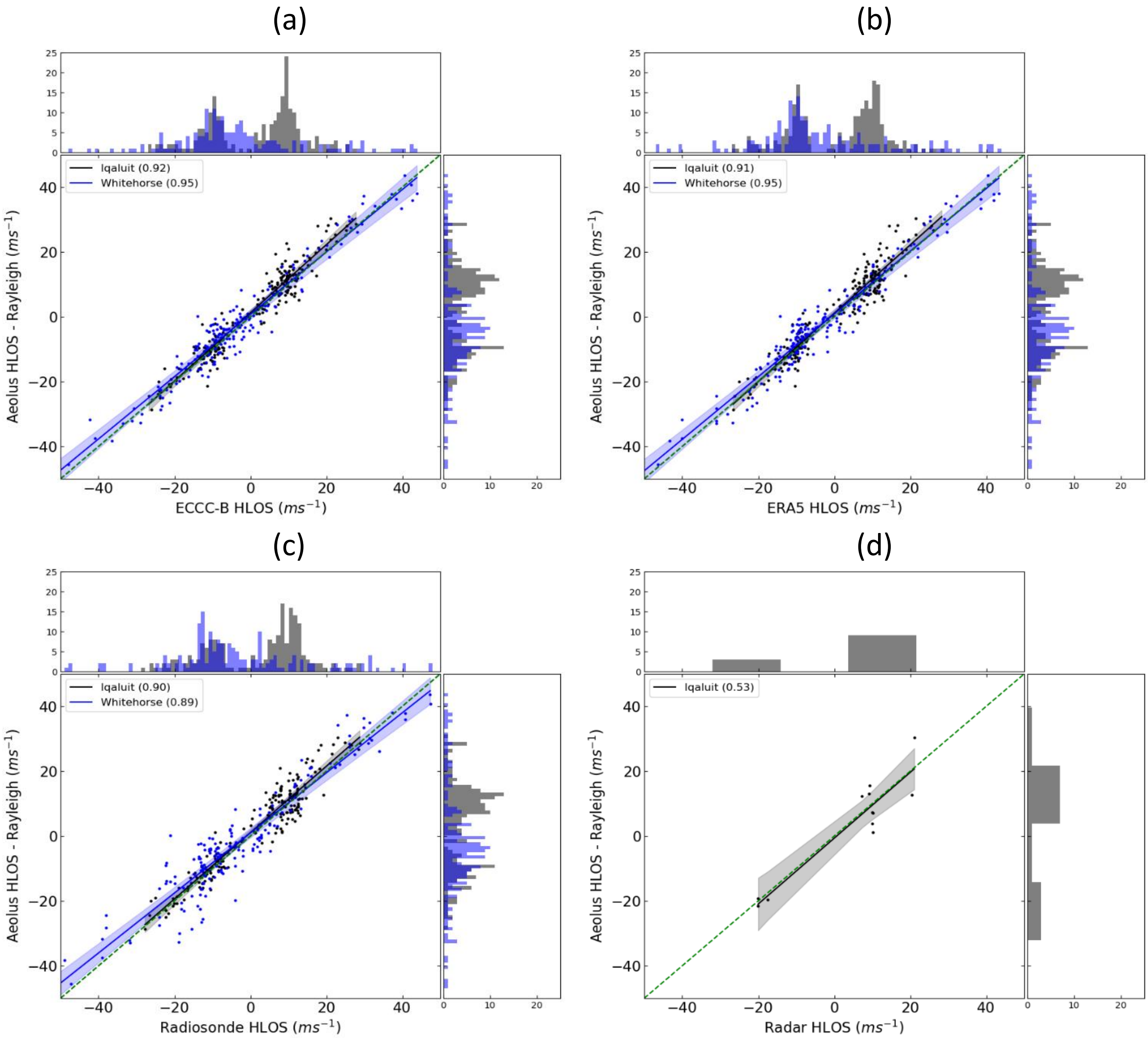

Figure 3. Scatter plots between Aeolus Rayleigh winds and (a) background, (b) ERA5, (c) radiosondes, and (d) Ka-band Radar and frequency distributions in percentage around Iqaluit and Whitehorse supersites during the early FM-A period. The numbers in brackets are the adjusted r-square between datasets whose degrees of freedom are the number of profiles during the period of analysis.

Overall, the datasets show strong consistency. ECCC-B and ERA5 are highly mutually consistent (Figure S1a; with adjusted r-squared greater than 0.97) and therefore show similar consistency with Aeolus (Fig. 3a-b and 4a-b). The ECCC-B has correlation of 0.92 and 0.95 with Aeolus Rayleigh winds and 0.87 and 0.98 with Aeolus Mie winds at Iqaluit and Whitehorse sites respectively. The ERA5 shows somewhat slightly lower correlation: 0.91 and 0.95 with Rayleigh winds and

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0.81 and 0.99 with Mie winds. This difference might be attributed to enhanced resolution and sampling in ECCC-B compared to ERA5: ECCC-B features fine horizontal resolution (15 km grid) and vertical resolution (84 vertical levels) and a relatively short (15-minute) time step.

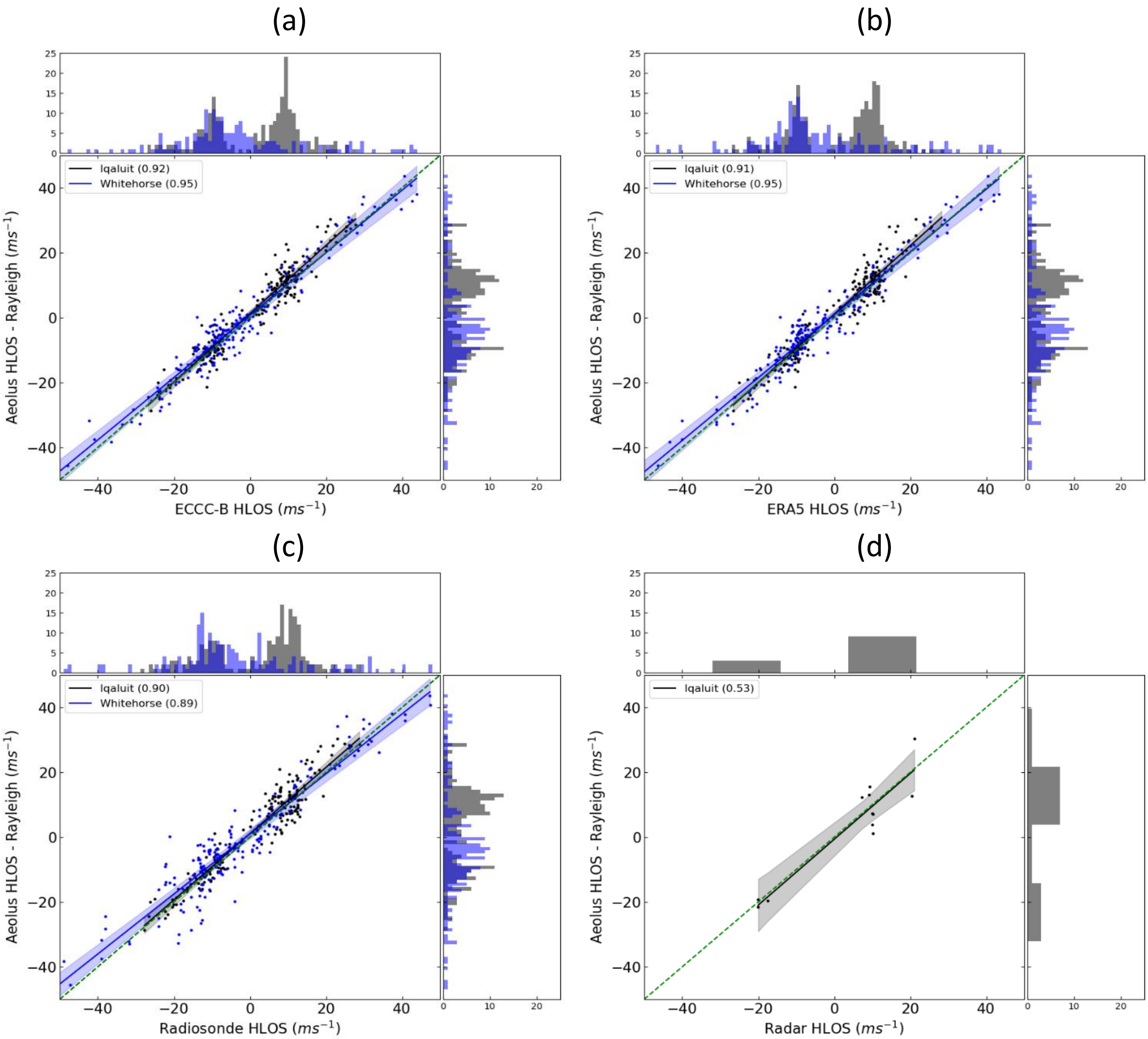

Figure 4. Similar to Figure 3, but scatter plots between Aeolus Mie winds and other datasets.

Along with the consistency between ECCC-B and ERA5, these two datasets are also consistent with the radiosonde data (Fig. S1), which is expected, because radiosonde measurements are used in the operational ECCC and ECMWF data

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assimilation systems. All adjusted r-squared values in this comparison are above 0.95 for both sites. On the other hand, the adjusted r-squared between Aeolus winds and Ka-band radar at Iqaluit are only 0.53 for Rayleigh winds and 0.66 for Mie winds. As mentioned earlier, this might reflect a sampling bias because the vertical range of the instrument is relatively limited due to the atmospheric composition and there are therefore relatively few points to sample. In addition, at larger ranges, the radar measures winds further from the radar and so the radar's measurement covers a larger volume. The validity of the assumption of uniform winds for the VAD calculation to be correct becomes less accurate as the range increases. However, we are comparing the VAD wind profile to a large distance along the track (87 km for Rayleigh winds and 12 km for the FM-B Mie winds with around 15 m of laser footprint near the ground) as well, so this might not be the main cause. Another possible issue could be the topography. The lower altitudes where we have radar (and lidar) observations are heavily influenced by local topography that can cause increased variability in the wind field. Therefore, the worse agreement with the 87 km averaged wind observations from Aeolus might arise from the fact that Aeolus "averaged out" or filtered out the wind variability due to the topography over this large 15 × 87000 m region for the Rayleigh winds. This demonstrates an important challenge when comparing two spatial averaged measurements that are not exactly collocated. Generally, the sampling for these measurements from radar is highly limited, which tends to reduce the agreement compared to the other datasets; nevertheless, the radar continues to provide a valuable independent measure of the winds.

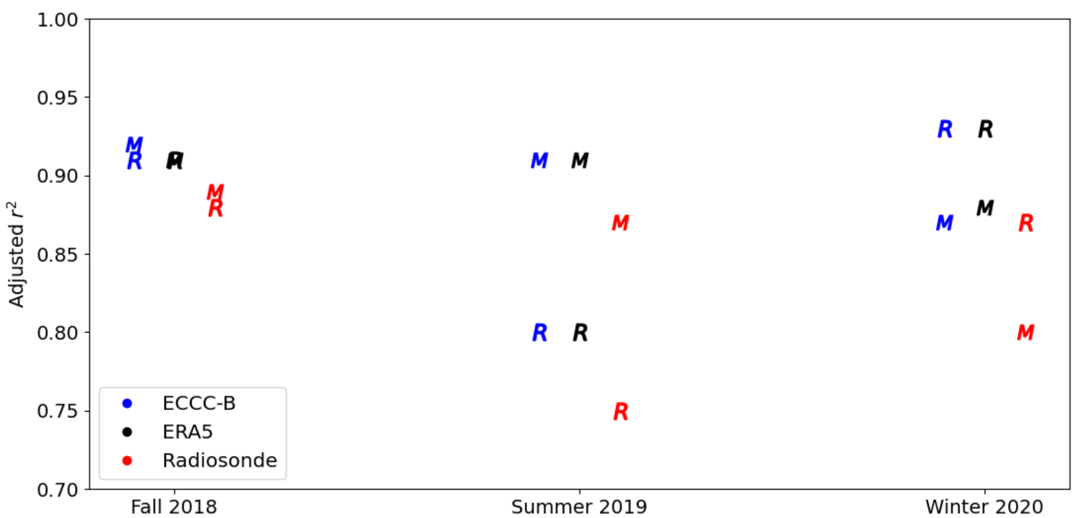

Figure 5. Adjusted r-squared of vertical HLOS wind profiles from coincident Aeolus (Rayleigh, R, and Mie, M) overpasses near radiosonde stations over the Canadian Arctic (shown in Figure 1) and ECCC-B, ERA5, and radiosonde measurements during fall 2018 (early FM-A), summer 2019 (early FM-B), and winter 2020 (mid-FM-B).

We broaden the region of analysis to the Canadian Arctic by incorporating all available Canadian Arctic radiosonde stations that provide wind profile observations. Figure 5 shows a comparison of adjusted r-squared between 2B02/2B06 Aeolus

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and ECCC-B, ERA5, and radiosonde measurements coincident with the radiosonde stations shown in Fig. 1, during early FM-A, early FM-B, and mid-FM-B periods. Aeolus wind profiles are less consistent (dropped by around 5%) with radiosonde measurements than with ECCC-B and ERA5 for both Rayleigh and Mie channels during all three periods of analysis. This might have been anticipated given that radiosonde sampling is more localized and thus more susceptible to discrepancies arising from lack of coincidence, compared to Aeolus and the analyses, which feature sampling over a larger spatial region.

A systematic difference between the three measurement periods is apparent. Rayleigh winds could be very sensitive to the solar background noise that contaminates the weak Rayleigh backscatter signal under clear sky condition. Random errors caused by the solar background radiation (SBR) were anticipated. Aeolus points towards the sun-synchronous night-side of its orbit to minimize the impact of SBR on the wind observations (Kanitz et al., 2019; Zhang et al., 2020). However, the impact is greater than expected, especially during summertime over the Arctic where the Rayleigh random errors can be as high as 8 ms^{-1} (Zhang et al., 2019; Krisch et al., 2020, Reitebuch et al., 2020). As a result, as will also be shown below, the consistency of Aeolus Rayleigh winds with other datasets markedly worsens during summer.

3.2 Pan-Arctic validation against background and reanalysis products

We now broaden our analysis even further to evaluate Aeolus wind measurements over the whole Arctic, including over the Arctic Ocean, where wind observations are particularly sparse. We evaluate the HLOS winds in relation to the ECCC-B and ERA5 products poleward of 70° N. Note that we exclude the measurements over a region that partially covers Greenland, North Atlantic Ocean, and Iceland (50° W to 5° E and 52.5° N to 80° N) in September 2019 because Aeolus had a different range bin setting over this area for AVARTAR-I campaign purposes (Fehr et al., 2020). The time-series of the estimated errors from 2B06 (solid line) and 2B10 (dashed line) datasets and the root-mean-square difference (RMSD) between the Aeolus Rayleigh winds and ECCC-B data are shown in Fig. 6. The estimated errors and RMSD over the excluded region (blue) have a sudden jump on September 9th while the rest of the Arctic (black) shows a consistent decrease in estimated errors and RMSD. The reprocessed data has improved estimated errors and RMSD; however, the jump is still visible. During this period, the satellite was measuring at a finer vertical resolution to compare with research-flight measurements. Thus, the derived winds were averaging over fewer measurements. The Rayleigh winds are particularly noisy due to the loss in optical signal on the atmospheric and internal path (Reitebuch et al., 2020), which emphasizes the seasonal variation of the solar background noise during boreal summer and perhaps also reflects the attempt to measure finer vertical scales. Thus, as a trade-off of having high vertical resolution, the Aeolus estimated errors are larger for this specific range bin setting. For the consistency of the data quality, we thus exclude the measurements for this period and region from subsequent analysis.

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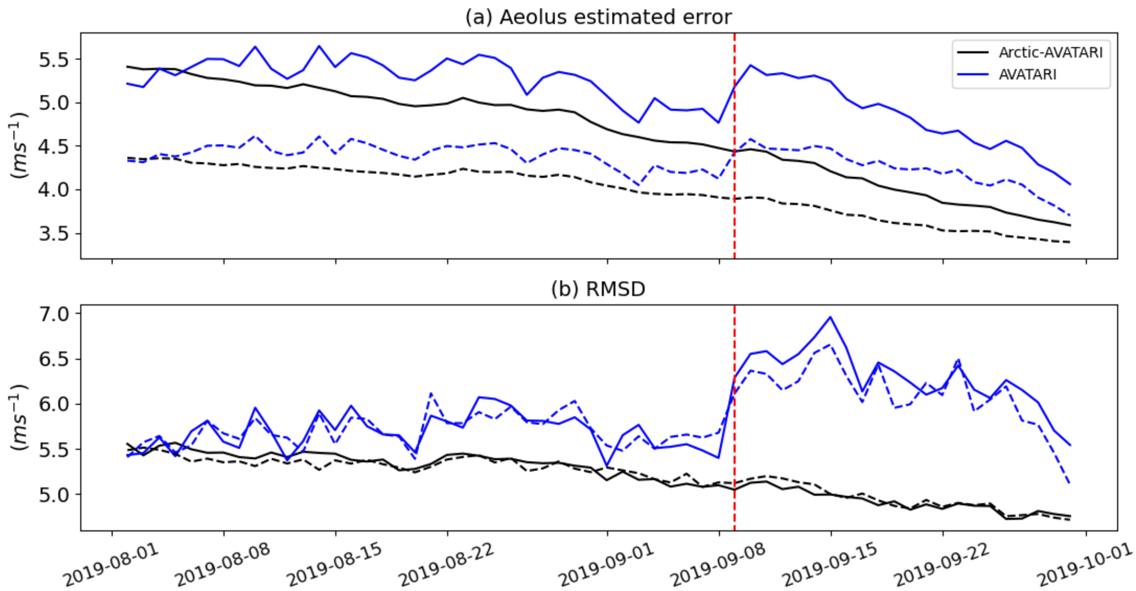

Figure 6. Time-series of (a) Aeolus L2B estimated error and (b) RMSD between the ECCC-B and Aeolus 2B06 (solid) and 2B10 (dashed) data from 2 August to 30 September 2019. The data is averaged over the region with different range bin setting for the AVATAR-I campaign (blue) and over the rest of the Arctic (black).

By expanding the region of analysis, we obtain a larger sample, which allows us to look at the separate ascending and descending orbit phases, frequency distributions in different layers in the atmosphere, correlations along the Aeolus track in different atmospheric layers, and the geographic variation of correlations between vertical HLOS profiles. We define four atmospheric layers: the planetary boundary layer (PBL, in the vertical range up to 2km), the free troposphere (2-8 km), the upper troposphere/lower stratosphere (UTLS, 8-16 km), and the stratosphere (altitudes greater than 16 km). Rayleigh winds are more frequently sampled in the UTLS and the stratosphere since often cloud layers are too optically thick for the laser to penetrate (an example distribution for winter 2020 over the Arctic is shown in Fig. 7a). The Mie channel measures winds under cloudy or polluted condition and thus has more measurements in the PBL than in the stratosphere (e.g., Fig. 7c). Furthermore, some components of the ascending and descending measurements cancel in the average owing to the angle of the LOS. Therefore, to avoid this artefact, we also compare the projected HLOS wind vector into its zonal (positive to the east) and meridional (positive to the north) components as shown in Fig. 7e and g for Aeolus and ECCC-B HLOS winds. By doing this decomposition, the distributions for ascending and descending measurements are more aligned (Fig. 7f) and we notice that the HLOS winds can also provide some information about the vertical variation of the HLOS winds that are projected onto the zonal direction (Fig. 7e and g). The distributions are positively skewed because the winds are mainly westerly over the Arctic in the winter.

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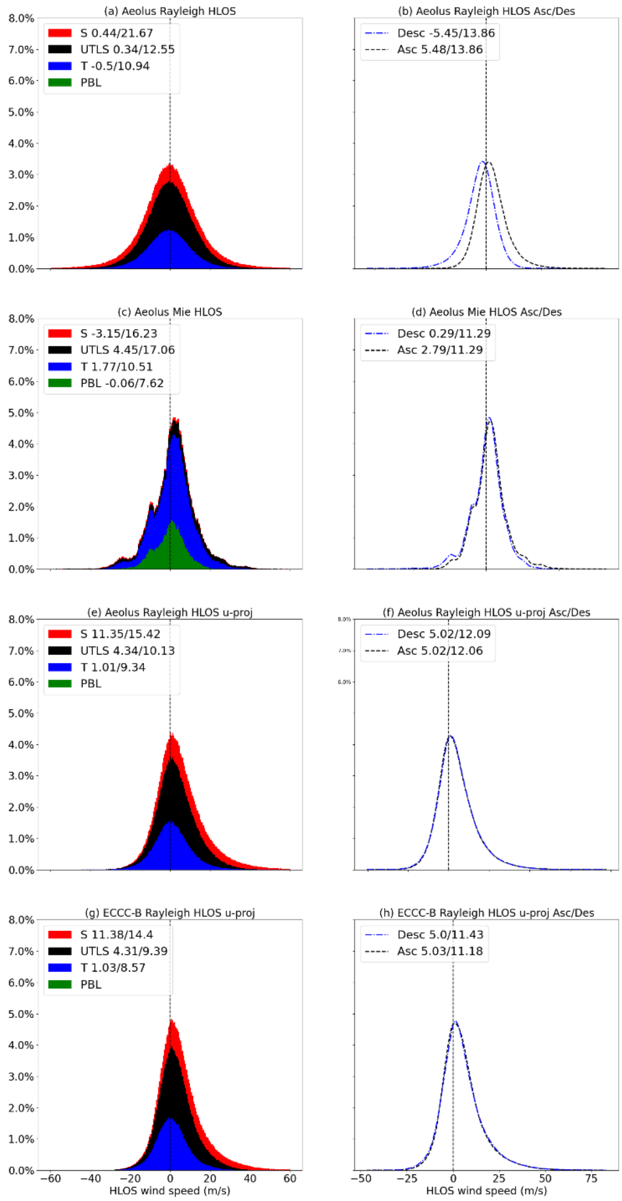

Figure 7. Aeolus Rayleigh ((a) and (b)) and Mie ((c) and (d)) HLOS measurement frequency distributions (%) during winter 2020 over the Arctic (>70N). The HLOS winds are projected onto the east-west directions ((e) to (h)) from Aeolus measurements and ECCC-B HLOS
350 winds. The panels on the right show the distribution of ascending and descending measurements separately. The means and standard deviations of distributions in each level are listed in the figure legends.

We compare the distributions of Aeolus, ECCC-B, and ERA5 winds during fall 2018, summer 2019, and winter 2020 over the Arctic, as summarized in Fig. 8, which shows the distributions of the HLOS winds, its zonal and meridional

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projections, and the zonal and meridional winds from the reanalysis. Since ECCC-B and ERA5 are mutually consistent, only the results from ECCC-B are displayed here. The standard deviations are indicated with horizontal bars. The measurements are decomposed into Rayleigh (blue) and Mie winds (black). They are further decomposed into ascending (indicated with upright triangles) and descending (inverted triangles) measurements. The last two columns in each panel represent the total zonal and meridional winds from ERA5. Both the observations and the model derived winds agree that aggregated HLOS winds have larger standard deviations than their zonal and meridional projected components. The large range on the HLOS distribution plots is controlled to an important extent by the systematic variation of the measurement angle: partially opposing HLOS winds can arise during ascending and descending orbits. Therefore, the means of all measurements (dots: including ascending and descending measurements) are generally somewhere between the means of ascending and descending measurements.

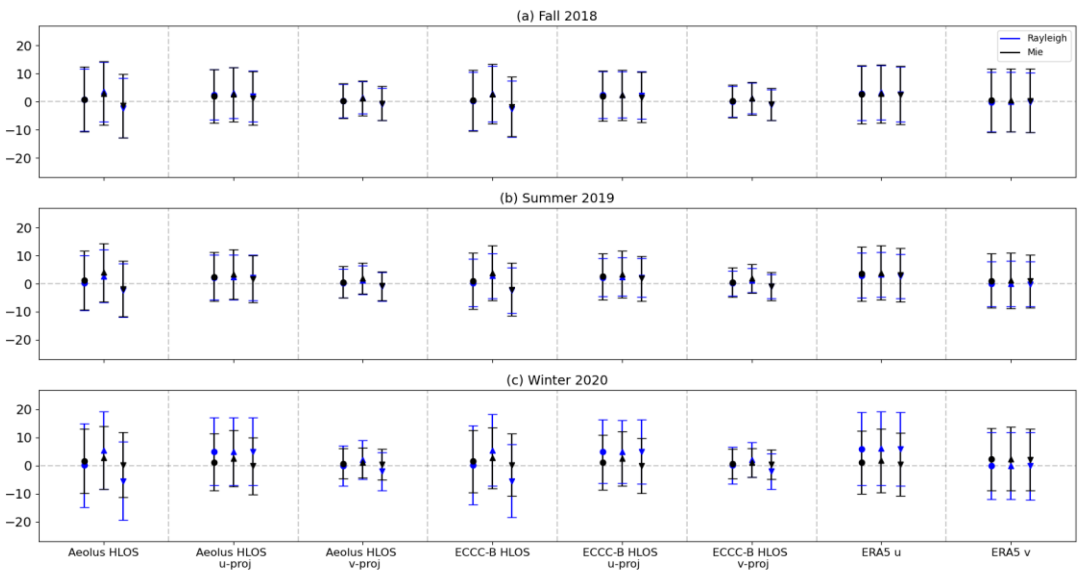

Figure 8. Means and standard deviations of Aeolus Rayleigh (blue) and Mie (black) HLOS winds, zonal and meridional components of Aeolus and ECCC-B HLOS winds, and zonal and meridional winds from the reanalysis ERA5, over the Arctic, during (a) boreal fall 2018, (b) summer 2019, and (c) winter 2020 (c). The dots represent Aeolus measurements in the atmosphere which can be decomposed into ascending (upright triangles) and descending (inverted triangles) measurements.

The averaged zonal and meridional winds from ERA5 at observation locations during ascending, descending, and both, are more aligned as expected. The standard deviations of the distributions of the zonal component of HLOS winds (columns 2 and 5) are similar to the ones from total zonal winds from ERA5 (column 7); however, the standard deviations of the meridional component of HLOS winds (columns 3 and 6) are about 50% smaller than the standard deviations of total meridional winds (column 8). For example, in winter 2020, the standard deviations of Aeolus Rayleigh and ERA5 HLOS v-

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projected winds are only 7.15 ms^{-1} and 6.64 ms^{-1}, but the standard deviation of the ERA5 meridional winds is as large as 11.95 ms^{-1}. Aeolus as designed provides mostly zonal information even over the Arctic.

Figure 8 shows an overall agreement between Aeolus, ECCC-B, and ERA5, and more analysis is required to bring out the differences between the datasets. One way to do so is to separately investigate the consistency between Aeolus and ECCC-B or ERA5 HLOS winds in the PBL, troposphere, UTLS, and stratosphere. Figure 9 shows normalized Taylor diagrams

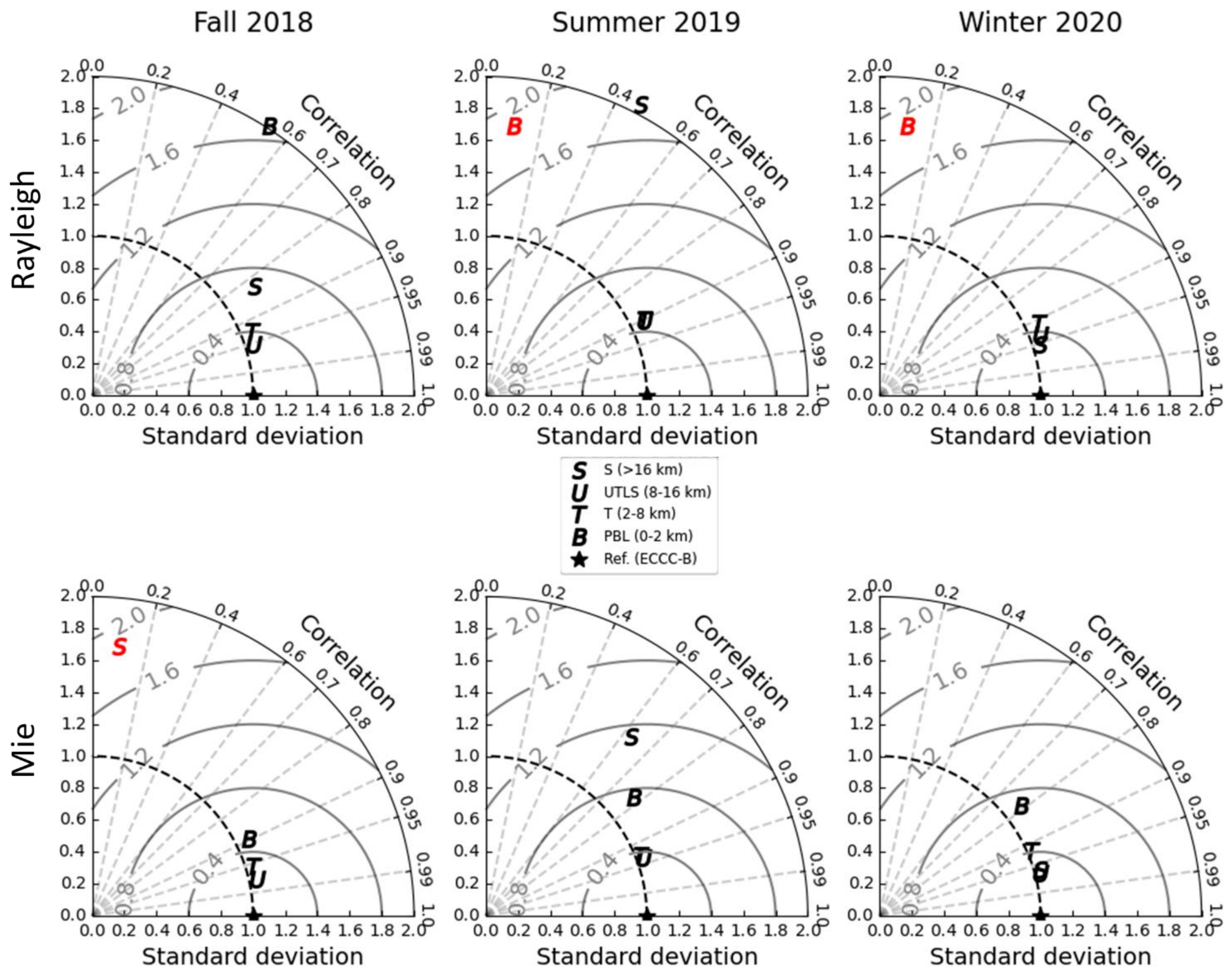

Figure 9. Normalized Taylor diagrams with ECCC-B as references for Aeolus measurements over the Arctic. The correlation coefficients and standard deviations are calculated for each layer. The angle indicates the correlation between Aeolus measurements and the reference. The distance to the origin represents the normalized standard deviation and to the star (reference) represents the normalized root-mean square error. Rows are distinguished by channels; columns are distinguished by seasons. The red markers on top left of panels represent layers with normalized standard deviations that are outside the range shown (> 2.2).

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(Taylor, 2001), with ECCC-B as reference, for Aeolus Rayleigh and Mie measurements over the Arctic during the three seasons of analysis. The Taylor diagrams with ERA5 as reference (not shown here) have nearly overlapping results because ERA5 and ECCC-B are mutually consistent. The angle indicates the correlation between Aeolus measurements and ECCC-B. The distance to the origin represents the standard deviation and to the star (reference point (1,0)) represents the RMSD; both statistics are normalized by the standard deviation of reference data. The 1.0 normalized standard deviation is highlighted; data that falls outside the dashed quarter circle is noisier than the reference data. Figure 9 shows that Aeolus data consistently has more structure than ECCC-B during all three periods and for both Rayleigh and Mie winds. Its standard deviations are greater than those from ECCC-B by a factor of 1.05 to 1.40. This might imply that Aeolus provides noisier data, that the ECCC-B is missing some extreme values in its wind-component distribution, or both. However, the RMSD are generally within one normalized standard deviation and correlations are normally greater than 0.8. During the boreal summer period, the data in the stratosphere seem to agree less with the ECCC-B data, reflecting reduced sampling, solar background noise that is most effective during summer as mentioned earlier, and other possible errors (Reitebuch et al., 2020).

Generally, the Rayleigh-clear channel provides consistent data with the ECCC-B through the troposphere (T in Fig. 9), the UTLS (U) and the stratosphere (S), while the Mie-cloudy channel provides consistency from the PBL (B) to the lower stratosphere. This reflects the vertical sampling and instrument characteristics and reveals effective complementarity of the instrument and retrieval design. For this reason, in the next paragraph, where we investigate the spatial distribution of the consistency in the lower and upper atmospheric regions, we exclude the Rayleigh winds in the PBL and the Mie winds in the stratosphere.

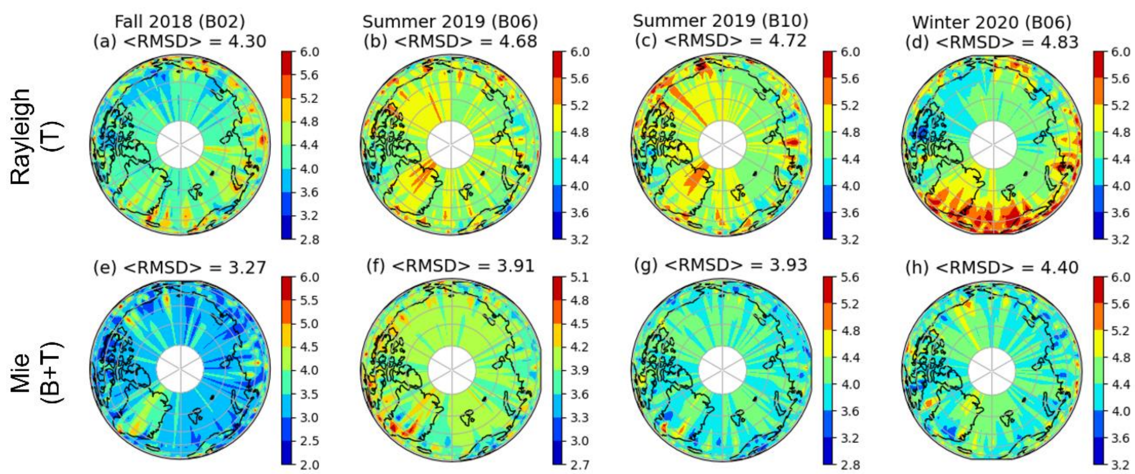

Figure 10. RMSD of Aeolus and ECCC-B vertical HLOS wind profiles for selected lower-atmospheric regions (Rayleigh T and Mie B+T) during fall 2018, summer 2019, and winter 2020.

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Figure 10 shows the RMSD between Aeolus and ECCC-B for Rayleigh tropospheric (T) and Mie PBL + tropospheric (B+T) profiles, and Fig. 11 shows the same but for Rayleigh UTLS + stratosphere (U+S) and Mie UTLS (U) measurements. Since the estimated errors and RMSD were consistently decreasing in September 2019 over the Arctic except for the region with different range bin setting (Fig. 6), to avoid misinterpretation of the results on the maps, we exclude the data during this period over the entire Arctic. The maps are plotted using nearly equal surface area, similar to the Lambert grid, with longitude grid of 3 degrees and latitude grid of inverse cosine of latitude degrees. For instance, a grid point at 60° N is 3° × 2° and a grid at 80° N is 3° × 5.7°. The averaged RMSD shown in angle brackets are simply the mean of the RMSD from all the grid cells. The first two and the last columns represent the distributions using the near real-time 2B06 dataset; the third column shows the distributions using the reprocessed 2B10 data during the early FM-B period.

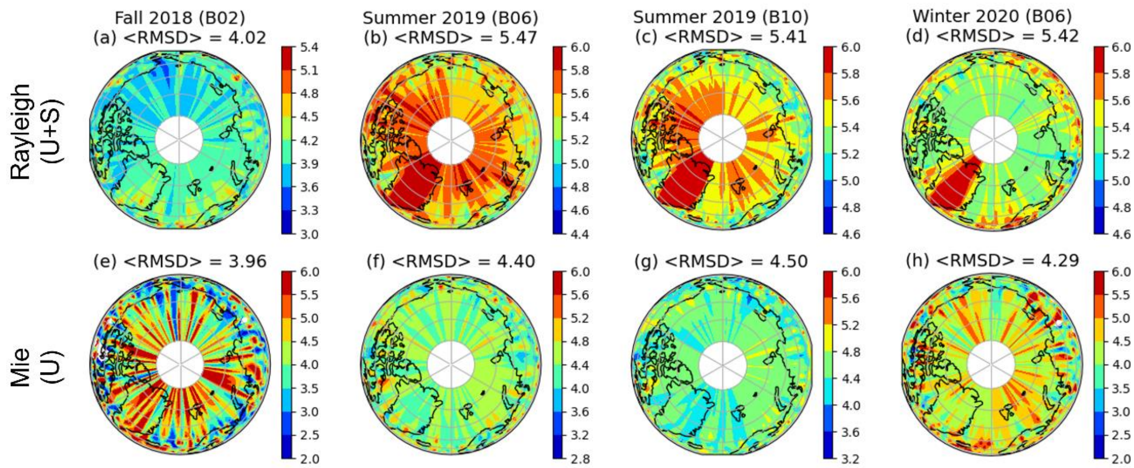

Figure 11. Similar to Figure 9, but for selected upper-atmospheric regions (Rayleigh U+S and Mie U).

The distributions of the RMSD are relatively homogeneous across oceanic, ice-covered, and continental regions. This suggests that the overall good agreement seen for the in-situ Iqaluit and Whitehorse data as well as the Northern Canadian region in the radiosonde network extends from land to the ocean regions without obvious systematic differences in consistency. The agreement between Aeolus and ECCC-B for the Mie winds is greater than for the Rayleigh winds for all three periods of analysis. The RMSD for the Mie winds lie between 3.2 ms^{-1} and 4.4 ms^{-1} in the lower atmosphere and between 3.9 ms^{-1} and 4.5 ms^{-1} in the upper atmosphere, and for Rayleigh winds, between 4.3 ms^{-1} and 4.9 ms^{-1} in the lower atmosphere and between 4.0 ms^{-1} and 5.5 ms^{-1} aloft. This was anticipated because the Rayleigh winds are noisier for reasons alluded to above. The RMSD does not vary systematically between the lower-atmosphere and the upper-atmosphere comparisons in Fig. 10 and 11, but the differences could be anticipated from the estimated error product (as shown in Fig. S2 and S3). For example, estimated errors were comparable in the upper and lower atmosphere layers for the Fall 2018 data, were greater for both layers for

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Summer 2019, and were greater in the upper atmosphere than in the lower atmosphere for Summer 2019. These same characteristics generally apply to the RMSD statistics.

During winter 2020, the observation errors were greater (around 3.6 ms^{-1}) from the Southern Greenland to North-western Russia in the lower atmosphere, which corresponds to the region with RMSD around 6.0 ms^{-1} between Aeolus Rayleigh winds and ECCC-B. By the same token, the estimated errors were greater during the summer 2019 over the Greenland and oceanic region (around 6.9 ms^{-1}), and during the winter 2020 over the Greenland (around 3.9 ms^{-1}) in the upper atmosphere. Whatever the source of these changes (e.g., summertime solar background noise amplification or calibration errors coinciding with the start of laser-B stream), it is noteworthy that the estimated error product contains potentially useful information for validation purposes. Because such information is useful for error characterization in NWP, as we will discuss below, a more detailed investigation into the estimated error product, including its seasonal, geographic, and flow dependence, is warranted.

Note that the first reprocessed data, 2B10, only overlaps with one of the three periods of study: August to September 2019. The estimated observational errors have decreased compared to the 2B06 data since the bias due to the M1 mirror temperature dependent has been corrected and the dark current signals have been removed using a better quality control. The third columns in Fig. 10 to 11 show the RMSD between the Aeolus reprocessed data and the ECCC-B vertical HLOS wind profiles and during the summer 2019. No significant improvement is seen here because we have implemented a weekly updated dynamic bias correction to the near real time data. Nevertheless, the reprocessed data will help inter-comparison within weather centers for their NWP experiments since it does not need further bias correction on the L2B products.

4 Summary and conclusion

In August 2018, ESA successfully launched the first spaceborne DWL Aeolus to measure global wind profile measurements along its LOS, using the instrument's Rayleigh and Mie channel receivers. Only Rayleigh-clear winds and Mie-cloudy winds are considered in the validation. In this work, the Aeolus data product are bias corrected and quality controlled using the quality flag from the L2B product, estimated error screening following ECMWF's guidance, and the screening when O-B is greater than 30 ms^{-1} to remove any additional outliers. Our results show consistent Aeolus data products around the sites with the 9-h short-range forecast from ECCC ("background", ECCC-B), reanalysis ERA5 from ECMWF, and in-situ measurements using radiosondes and Ka-band radar, for the period September 15th to October 16th, 2018. For example, the adjusted r-squared between Aeolus Rayleigh winds and ECCC-B is 0.92, and 0.91 between Aeolus and ERA5 at the Iqaluit site. For the Aeolus Mie winds, the statistical results are 0.87 with ECCC-B and 0.81 with ERA5. The comparison with the Ka-band radar at Iqaluit has been limited to the early phase of Aeolus lifetime due to some technical issues from the ground-based radar. The agreement between Aeolus wind product and the Ka-band radar is systematically worse than with the forecasts and reanalysis products. Possible issues include: the radar provides more localized measurements than Aeolus, the radar's sampling is very limited, and

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the winds at lower altitudes, where the radar samples winds, are greatly influenced by the topography. As a result, the adjusted r-squared between Aeolus winds and the Ka-band radar are 0.53 for the Rayleigh winds and 0.66 for the Mie winds. Nevertheless, we were able to validate Aeolus wind products with ECCC-B, ERA5, and radiosonde measurements around other radiosonde sites for the periods September 15th to October 16th, 2018, August 2nd to September 30th, 2019, and December 1st to January 31st, 2020. This comparison raises the issue of solar background noise at high latitudes during summertime, which degrades the adjusted r-squared of the Rayleigh winds by about 10% during the early FM-B period (Fig. 5). This issue extends to the analysis of the pan-Arctic, where the effect of solar background radiation is even larger over polar regions where there are 24 hours periods of sunlight in summer (Fig. 11b-c).

In our analysis of the pan-Arctic region, Taylor diagrams reveal that the standard deviations of Aeolus winds are 5 to 40% greater than ECCC-B in every layer. Future work could investigate whether this discrepancy arises because Aeolus provides noisier measurements due to limitations of the processed observations or because Aeolus is measuring structural detail not captured in the forecast and reanalysis. Yet, they show consistent HLOS winds with correlations higher than 0.8 except during summer in the stratosphere and normalized standard errors within one standard deviation of ECCC-B. Finally, the spatial correlations of Aeolus and ECCC-B vertical wind profiles confirm their mutual consistency. We have found some initial evidence that the estimated error product is also a good predictor of RMSD between Aeolus and the reanalysis, which could be useful for constraining future forecasts.

In conclusion, the mutual consistency between Aeolus and the short-range forecast and reanalysis over the Arctic suggests that Aeolus provides reliable wind measurements that can further advance our knowledge on circulation and further improve current NWP models, and also suggests that the ERA5 reanalysis and ECCC-B provide good estimates of the circulation over the Arctic, reflecting the volume of satellite data assimilated daily (over 1 million observations, mainly radiances) and mass balance constraints that hold at high latitudes. It remains open, however, how the consistency between Aeolus and available analyzed data depends on horizontal and vertical scale. It is reassuring that this consistency is seen in a vertical range extending from the planetary boundary layer in the Mie channel in all three observation periods to the stratosphere in the Rayleigh channel (in the non-summer periods). The promise of added value to forecasts from Aeolus winds is already being borne out at several centers that have assimilated Aeolus data into their operational NWP model and are seeing positive impact (e.g., Rennie and Isaksen, 2020). A focus on predictability of weather systems in the Arctic, and on predictability from wind information centred in the Arctic, is the subject of current work.

Data availability

The Ka-band radar at Iqaluit and ECCC-B data used in this paper can be provided by the corresponding author (gina.chou@mail.utoronto.ca) upon request. The ERA5 data can be downloaded from the Copernicus Climate Change Service (C3S) Climate Date Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview).

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The radiosondes data can be downloaded from http://weather.uwyo.edu/upperair/sounding.html. Aeolus L2B data can be obtained from the VirES visualization tool (https://aeolus.services/).

Author contribution

Chih Chun Chou prepared the main part of the paper and performed the statistical analyses of Aeolus data, in-situ measurements, ECCC-B, and ERA5 data. Paul Kushner and Stéphane Laroche guided Chih Chun Chou for the analyses and the written part. Stéphane Laroche provided the ECCC-B data and Zen Mariani provided the in-situ measurements at Iqaluit and Whitehorse supersites. Zen Mariani, Peter Rodriguez, and Stella Melo provided guidance in reading and retrieving the radar data. All co-authors helped review the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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References

Baars, H., Herzog, A., Heese, B., Ohneiser, K., Hanbuch, K., Hofer, J., Yin, Z., Engelmann, R., and Wandinger, U.: Validation of Aeolus wind products above the Atlantic Ocean, Atmos. Meas. Tech., 13, 6007–6024, https://doi.org/10.5194/amt-13-6007-2020, 2020.

Baker, W. E. et al.: Lidar measured winds from space: A key component for weather and climate. – Bull. Amer. Meteor. Soc. 76, 869–888, 1995.

Bormann N, Thépaut J-N: Impact of MODIS polar winds in ECMWF's 4D-VAR data assimilation system. Mon. Weather Rev. 132: 929–940, 2004.

Belova, E., Kirkwood, S., Voelger, P., Chatterjee, S., Satheesan, K., Hagelin, S., Lindskog, M., and Körnich, H.: Validation of Aeolus winds using ground-based radars in Antarctica and in northern Sweden, Atmos. Meas. Tech. Discuss. [preprint], https://doi.org/10.5194/amt-2021-54, in review, 2021.

Buehner, M. et al.: Implementation of Deterministic Weather Forecasting Systems Based on Ensemble–Variational Data Assimilation at Environment Canada. Part I: The Global System. Mon. Wea. Rev., 143, 2532–2559, https://doi.org/10.1175/MWR-D-14-00354.1, 2015.

Chiara, G. D., M. Bonavita and S. J. English: Improving the Assimilation of Scatterometer Wind Observations in Global NWP, in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 10, no. 5, pp. 2415-2423, doi: 10.1109/JSTARS.2017.2691011, 2017.

Cohen, J., Zhang, X., Francis, J. et al.: Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. Nat. Clim. Chang. 10, 20–29, https://doi.org/10.1038/s41558-019-0662-y, 2020.

Dabas, A: Observing the atmospheric wind from space. CR Geosci., 342, 370–379, 2010.

de Kloe, J., Stoffelen, A., Tan, D., Andersson, E., Rennie, M., Dabas, A., Poli, P., and Huber, D.: ADM-Aeolus Level-2B/2C Processor Input/Output Data Definitions Interface Control Document, https://earth.esa.int/pi/esa?type=file&table=aotarget&cmd=image&alias=ADM_Aeolus_L2B_Input_Output_DD_ICD, last access: 3 November 2020, 2016.

Drinkwater, M., M. Borgeaud, A. Elfving, P. Goudy, W. Lengert: ADM-Aeolus Mission Requirements Document. Mission Science Division, AE-RP-ESA-SY-001 EOP-SM/2047, 2016.

Fehr, T., Amiridis, V., Bley, S., Cocquerez, P., Lemmerz, C., Močnik, G., Skofronick-Jackson, G., and Straume, A. G.: Aeolus Calibration, Validation and Science Campaigns , EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-19778, https://doi.org/10.5194/egusphere-egu2020-19778, 2020.

Graham, R. J., Anderson, S. R., & Bader, M. J.: The relative utility of current observation systems to global-scale NWP forecasts. Quarterly Journal of the Royal Meteorological Society, 126(568), 2435–2460. https://doi.org/10.1002/qj.49712656805, 2020.

Guo, J., Liu, B., Gong, W., Shi, L., Zhang, Y., Ma, Y., Zhang, J., Chen, T., Bai, K., Stoffelen, A., de Leeuw, G., and Xu, X.: Technical Note: First comparison of wind observations from ESA's satellite mission Aeolus and ground-based Radar wind profiler network of China, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2020-869, in review, 2020.

Horányi, A., C. Cardinali, M. Rennie, and L. Isaksen: The assimilation of horizontal line-of-sight wind information into the ECMWF data assimilation and forecasting system. Part I: The assessment of wind impact. Quart. J. Roy. Meteor. Soc., 141, 1223–1232, https://doi.org/10.1002/qj.2430, 2015.

Hersbach, H., Bell, B., Berrisford, P., et al.: The ERA5 global reanalysis. Q J R Meteorol Soc. 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803, 2020.

Hersbach, H., P. de Rosnay, B. Bell, D. Schepers, A. Simmons, C. Soci, S. Abdalla, M. Alonso Balmaseda, G. Balsamo, P. Bechtold, P. Berrisford, J. Bidlot, E. de Boisséson, M. Bonavita, P. Browne, R. Buizza, P. Dahlgren, D. Dee, R. Dragani, M. Diamantakis, J. Flemming, R. Forbes, A. Geer, T. Haiden, E. Hólm, L. Haimberger, R. Hogan, A. Horányi, M. Janisková, P. Laloyaux, P. Lopez, J. Muñoz-Sabater, C. Peubey, R. Radu, D. Richardson, J.-N. Thépaut, F. Vitart, X. Yang, E. Zsótér & H. Zuo: Operational global reanalysis: progress, future directions and synergies with NWP, ECMWF ERA Report Series 27, 2018.

https://doi.org/10.5194/amt-2021-247
Preprint. Discussion started: 19 August 2021

Joe, P., Melon, S., Burrows, W., Casati, B., Crawford, R.W., Deghan, A., Gascon, G., Mariani, Z., Milbrandt, J., Strawbridge, K.: The Canadian Arctic Weather Science Project: Introduction to the Iqaluit Site. Bull. Am. Met. Soc., 101, E109-E128, https://doi.org/10.1175/BAMS-D-18-0291.1, 2020.

Källen, E.: Scientific motivation for ADM-Aeolus mission, EPJ Web of Conferences, 176, 02 008, https://doi.org/10.1051/epjconf/201817602008, 2018.

Kanitz, T., Lochard, J., Marshall, J., McGoldrick, P., Lecrenier, O., Bravetti, P., Reitebuch, O., Rennie, M., Wernham, D., and Elfving, A.: Aeolus first light: first glimpse, in: International Conference on Space Optics – ICSO 2018, 9– 12 October 2018, Chania, Greece, vol. 11180, 659–664, https://doi.org/10.1117/12.2535982, 2019.

Krisch, I., C. Lemmerz, O. Lux, U. Marksteiner, O. Reitebuch, F. Weiler, B. Witschas, F. Bracci, M. Meringer, K. Schmidt, D. Huber, I. Nikolaus, M. Vaughan, A. Dabas, T. Flament, D. Trapon, S. Abdalla, L. Isaksen, M. Rennie, D. Donovan, J. de Kloe, G.-J. Marseille, A. Stoffelen, T. Kanitz, A.-G. Straume, D. Wernham, J. von Bismarck, S. Bley, P. Fischer, T. Parinello: Data quality of Aeolus wind measurements. In: Geophysical Research Abstracts. EGU General Assembly 2020, 04.-08. Mai 2020, Wien, Österreich. DOI: 10.5194/egusphere-egu2020-9471, 2020.

Lawrence, H., N. Bormann, I. Sandu, J. Day, J. Farnan, P. Bauer: Use and impact of Arctic observations in the ECMWF Numerical Weather Prediction system. Q J R Meteorol Soc.; 145: 3432– 3454. https://doi.org/10.1002/qj.3628, 2019.

Le Marshall, J., J. Jung, T. Zapotocny, C. Redder, M. Dunn, J. Daniels, and L. P. Riishojgaard: Impact of MODIS atmospheric motion vectors on a global NWP system. Aust. Meteor. Mag., 57, 45–51, 2008.

Lhermitte, R. M., and D. Atlas: Precipitation motion by pulse Doppler radar. Proc. Ninth Weather Radar Conf., Kansas City, MO, Amer. Meteor. Soc., 218–223, 1962.

Lux, O., D. Wernham, P. Bravetti, P. McGoldrick, O. Lecrenier, W. Riede, A. D'Ottavi, V.D. Sanctis, M. Schillinger, J. Lochard, J. Marshall, C. Lemmerz, F. Weiler, L. Mondin, A. Ciapponi, T. Kanitz, A. Elfving, T. Parrinello, and O. Reitebuch: High-power and frequency-stable ultraviolet laser performance in space for the wind lidar on Aeolus, Opt. Lett. 45, 1443-1446, 2020.

Mariani, Z., Crawford, R., Casati, B., Lemay, F.: A Multi-Year Evaluation of Doppler Lidar Wind-Profile Observations in the Arctic. *Remote Sens. 12*, 323. https://doi.org/10.3390/rs12020323, 2020.

Mariani, Z., Dehghan, A., Gascon, G., Joe, P., Hudak, D., Strawbridge, K., & Corriveau, J.: Multi-instrument observations of prolonged stratified wind layers at Iqaluit, Nunavut. Geophysical Research Letters, 45, 1654–1660. https://doi.org/10.1002/2017GL076907, 2018.

Martin, A., Weissmann, M., Reitebuch, O., Rennie, M., Geiß, A., and Cress, A.: Validation of Aeolus winds using radiosonde observations and NWP model equivalents, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2020-404, in review, 2020.

McTaggart-Cowan, R., Vaillancourt, P. A., Zadra, A., Chamberland, S., Charron, M., Corvec, S., et al.: Modernization of atmospheric physics parameterization in Canadian NWP. Journal of Advances in Modeling Earth Systems, 11, https://doi.org/10.1029/2019MS001781, 2019.

Mizyak, V.G., Shlyaeva, A.V., and Tolstykh, M.A.: Using satellite-derived Atmospheric Motion Vector (AMV) observations in the ensemble data assimilation system. Russ. Meteorol. Hydrol. 41, 439-446, https://doi.org/10.3103/S1068373916060091, 2016.

Naakka, T., T. Nygård, M. Tjernström, T. Vihma, R. Pirazzini, and I. M. Brooks: The impact of radiosounding observations on numerical weather prediction analyses in the arctic, Geophys. Res. Lett., vol. 46, no. 14, p. 46, 2019.

Reitebuch, O., I, Krisch, C. Lemmerz, O. Lux, U. Marksteiner, N. Masoumzadeh, F. Weiler, B. Witschas, F. Bracci, M. Meringer, K. Schmidt, D. Huber, I. Nikolaus, F. Fabre, M. Vaughan, K. Reissig, A. Dabas, T. Flament, A. Lacour, T. Parrinello: Assessment of the Aeolus performance and bias correction - results from the Aeolus DISC, Online, Aeolus Cal/Val and Science Workshop, http://elib.dlr.de/138648/, 2020.

Reitebuch, O., Lemmerz, C., Lux, O., Marksteiner, U., Rahm, S., Weiler, F., Witschas, B., Meringer, M., Schmidt, K., Huber, D., Nikolaus, I., Geiss, A., Vaughan, M., Dabas, A., Flament, T., Stieglitz, H., Isaksen, L., Rennie, M., de Kloe, J., Marseille, G.- J., Stoffelen, A., Wernham, D., Kanitz, T., Straume, A.-G., Fehr, T., von Bismark, J., Floberghagen, R., and Parrinello, T.: Initial assessment of the performance of the first Wind Lidar in space on Aeolus, in: International Laser Radar Conference, Hefei, China, 24–28 June 2019.

Rennie, M. and Isaksen, L.: Guidance for Aeolus NWP Impact Experiments during the period September 2018 to November 2019. Updated information to Aeolus CAL/VAL PIs performing NWP Impact Assessment Experiments, 2019.

Rennie, M. and Isaksen, L.: The NWP Impact of Aeolus Level-2B Winds at ECMWF, https://www.ecmwf.int/sites/default/files/elibrary/2020/19538-nwp-impact-aeolus-level-2b-winds-ecmwf.pdf, last access: 5 November 2020, 2020.

Rennie, M., Tan, D., Andersson, E., Poli, P., Dabas, A., De Kloe, J., Marseille, G.-J., and Stoffelen, A.: Aeolus Level-2B Algorithm Theoretical Basis Document (Mathematical Description of the Aeolus L2B Processor), https://earth.esa.int/pi/esa?type=file&table=aotarget& cmd=image&alias=Aeolus_L2B_Algorithm_TBD, last access: 3 November 2020, 2020a.

Sato, K., J. Inoue, A. Yamazaki, J.-H. Kim, M. Maturilli, K. Dethloff, S. R. Hudson, and M. A. Granskog: Improved forecasts of winter weather extremes over midlatitudes with extra Arctic observations, J. Geophys. Res. Oceans, 122, 775–787, doi:10.1002/ 2016JC012197, 2017.

Straume, A. G., and Coauthors: Aeolus Sensor, Data Processing and Product Description. Aeolus CAL/VAL community, 28 October 2018, 2018.

Taylor, K. E.: Summarizing multiple aspects of model performance in a single diagram, J. Geophys. Res., 106(D7), 7183– 7192, doi:10.1029/2000JD900719, 2001.

Velden, C. S., C. M. Hayden, S. J. Nieman, W. P. Menzel, S.Wanzong, and J. S. Goerss: Upper-tropospheric winds derived from geostationary satellite water vapor observations. Bull. Amer. Meteor. Soc., 78, 173–195, doi:10.1175/ 1520-0477(1997)078,0173:UTWDFG.2.0.CO;2, 1997.

Velden, C., W. E. Lewis, W. Bresky, D. Stettner, J. Daniels, and S. Wanzong: Assimilation of High-Resolution Satellite-Derived Atmospheric Motion Vectors: Impact on HWRF Forecasts of Tropical Cyclone Track and Intensity. Mon. Wea. Rev., 145, 1107–1125, https://doi.org/10.1175/MWR-D-16-0229.1, 2017.

Walsh, J.E., T.J. Ballinger, E. S. Euskirchen, E. Hanna, J. Mård, J.E. Overland, H. Tangen, T. Vihma: Extreme weather and climate events in northern areas: A review, Earth-Science Reviews, Volume 209, 103324, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2020.103324, 2020.

Wang, Z., Z. Liu, L. Liu, S. Wu, B. Liu, Z. Li, and X. Chu: Iodine-filter-based mobile Doppler lidar to make continuous and full-azimuth-scanned wind measurements: data acquisition and analysis system, data retrieval methods, and error analysis, Appl. Opt. 49, 6960-6978, 2010.

Wright, C. J., Hall, R. J., Banyard, T. P., Hindley, N. P., Mitchell, D. M., and Seviour, W. J. M.: Dynamical and Surface Impacts of the January 2021 Sudden Stratospheric Warming in Novel Aeolus Wind Observations, MLS and ERA5, Weather Clim. Dynam. Discuss. [preprint], https://doi.org/10.5194/wcd-2021-16, in review, 2021.

Young, I. R., Sanina, E., and Babanin, A. V.: Calibration and Cross Validation of a Global Wind and Wave Database of Altimeter, Radiometer, and Scatterometer Measurements. Journal of Atmospheric and Oceanic Technology 34, 1285–1306, 2017.

Yamazaki, A, Inoue, J, Dethloff, K, Maturilli, M, and König-Langlo, G: Impact of radiosonde observations on forecasting summertime Arctic cyclone formation. J. Geophys. Res. Atmos., 120, 3249– 3273. doi: 10.1002/2014JD022925, 2015.

Zhang, C., X. Sun, R. Zhang, S. Zhao, W. Lu, Y. Liu, and Z. Fan: Impact of solar background radiation on the accuracy of wind observations of spaceborne Doppler wind lidars based on their orbits and optical parameters, Opt. Express 27, A936-A952, 2019.

Zhang, C., X. Sun, W. Lu, Y. Shi, N. Dou, and S. Li.: On the relationship between wind observation accuracy and the ascending node of sun-synchronous orbit for the Aeolus-type spaceborne Doppler wind lidar, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2020-202, 2020.