

Article

Not peer-reviewed version

Long-Term Validation of Aeolus Wind Products in the Brazilian Amazon

[Alexandre Calzavara Yoshida](#)*, [Patricia Cristina Venturini](#), [Fábio Juliano da Silva Lopes](#), [Eduardo Landulfo](#)

Posted Date: 5 June 2024

doi: 10.20944/preprints202406.0278.v1

Keywords: Aeolus satellite; Doppler Wind Lidar; Rayleigh-clear; Mie-cloudy; radiosonde; statistical validation.



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Long-Term Validation of Aeolus Wind Products in the Brazilian Amazon

Alexandre Calzavara Yoshida ^{1,2,*} , Patricia Cristina Venturini ², Fábio Juliano da Silva Lopes ^{1,3}  and Eduardo Landulfo ¹ 

¹ Center for Lasers and Applications (CELAP), Institute of Energy and Nuclear Research (IPEN), São Paulo 05508-000, Brazil;

² Institute of Exact and Natural Sciences of Pontal (ICENP), Federal University of Uberlândia (UFU), Campus Pontal, Ituiutaba 38304-402, Brazil

³ Department of Environmental Sciences, Institute of Environmental, Chemical and Pharmaceutical Sciences (ICAQF), Federal University of São Paulo (UNIFESP), Campus Diadema, São Paulo 09913-030, Brazil

* Correspondence: yoshida@ufu.br

Abstract: The Atmospheric Dynamics Mission ADM-Aeolus was successfully launched in August 2018 by the European Space Agency (ESA). The Aeolus mission carried a single instrument, the first-ever Doppler Wind Lidar (DWL) in space, called Atmospheric LAsER Doppler INstrument (ALADIN). Aeolus circled the Earth in a polar sun-synchronous orbit at about 320 km altitude with a repeat cycle of 7 days, providing vertical profiles of horizontal line-of-sight (HLOS) winds on a global scale. Exceeding scientific expectations, Aeolus, initially designed for a 3-year lifetime, provided global coverage of wind profiles for almost five years. In this long-term validation study, we assessed the accuracy of the Level 2B (L2B) Rayleigh-clear and Mie-cloudy wind products by collecting radiosonde data from three stations in the Brazilian Amazon: Cruzeiro do Sul (7.62° S, 72.67° W), Porto Velho (8.76° S, 63.91° W), and Rio Branco (10.00° S, 67.80° W). Statistical validation was conducted by comparing Aeolus L2B wind products and radiosonde data, launched daily at 12:00 UTC from October 2018 to March 2023. Considering all data collected during the mission period, Pearson's coefficient (R) of 0.73 was observed in Rayleigh-clear and 0.85 in Mie-cloudy, revealing a strong correlation between Aeolus and radiosonde winds. No significant biases were detected, with values of -0.14 m/s for Rayleigh-clear and -0.40 m/s for Mie-cloud, fulfilling the mission requirement of having absolute biases below 0.7 m/s. However, when analyzed annually, in 2022, the bias for Rayleigh-clear was -0.95 m/s, exceeding the mission requirements.

Keywords: Aeolus satellite; Doppler Wind Lidar; Rayleigh-clear; Mie-cloudy; radiosonde; statistical validation

1. Introduction

Numerical weather prediction (NWP) relies on highly complex physical models to describe the dynamics of the atmosphere from an initial state. For the execution of these models and success in terms of forecast quality, a robust computational infrastructure and datasets utilizing the most recent observations of the initial state of the atmosphere are of utmost importance [1]. The increase in global wind profile observations holds significant potential to enhance numerical weather prediction (NWP) [2–6], resulting in more precise forecasts and mitigating the impacts of adverse weather phenomena.

Since 1998, the World Meteorological Organization (WMO) has considered the vertical wind profile measurement on a global scale as a high-priority factor for improving NWP [7]. In 1999, recognizing the inadequacy of the Global Observing System (GOS) in providing satisfactory observations of wind profiles over oceans, regions with sparse populations, and hard-to-reach areas, particularly in the Southern Hemisphere [3,8], the European Space Agency (ESA) approved the Atmospheric Dynamics Mission project. Approximately two decades later, the ADM-Aeolus was launched on August 22, 2018, with an estimated lifetime of three years.

Aeolus, carried on ALADIN, operated in a sun-synchronous orbit at an altitude of 320 km and an inclination of 97 degrees. Traveling at approximately 7.7 km/s, it completed one orbit every 90 minutes, resulting in approximately 16 orbits per day and a global scan every 7 days, totaling 111 orbits. ALADIN, a direct detection doppler wind lidar, operated at an ultraviolet (UV) wavelength of 355 nm at a repetition frequency of 50 Hz, emitting pulses along its line of sight (LOS) at an angle of

35° to the nadir direction [2,9,10]. It provided wind measurements from the ground up to an altitude of 25-30 km and a vertical resolution of 0.25 km to 2 km, delivering molecular (Rayleigh-clear) and particle (Mie-cloudy) wind products. At the end of April 2023, Aeolus initiated the assisted reentry process, and on July 28, 2023, it safely burned up upon reentering the Earth's atmosphere over Antarctica. The Aeolus mission contributed significantly by providing substantial global wind vertical profiles [11–13], filling critical gaps in existing global wind observation systems.

Calibration and validation (Cal/Val) activities for Aeolus Level 2B (L2B) wind products, utilizing airborne, doppler wind lidars, radiosondes, ground-based instruments, and numerical weather prediction (NWP) models, are well-documented in research contributions [14–29].

This paper presents the validation of Aeolus L2B winds using collocated radiosonde data from three stations in the Brazilian Amazon, located at Cruzeiro do Sul (7.62° S, 72.67° W), Porto Velho (8.76° S, 63.91° W) and Rio Branco (10.00° S, 67.80° W). The correlation, biases, and random error observed in the analyses demonstrate that ALADIN doppler wind lidar technology effectively provided global wind measurements.

The text is structured as follows. Section 2 describes the datasets and validation methods used. Section 3 presents the results of the validation process, with an emphasis on correlations, biases, and random errors between the Aeolus and radiosonde datasets. Section 4 the conclusions.

2. Dataset and Methods

This section describes the methodology for comparing the Aeolus products, Rayleigh-clear and Mie-cloudy, with radiosonde wind measurements collected from three stations in the Brazilian Amazon, including the parameters analyzed for statistical validation.

2.1. Aeolus Data

Using a dual-channel optical receiver [9,30], ALADIN measured the wind velocity through molecular and particle (aerosol and cloud) backscatter. The Rayleigh channel received molecular backscatter, employing the double-edge technique [31], utilizing a sequential Fabry–Pérot interferometer. In contrast, the Mie channel focused on particle backscatter, relying on a fringe-imaging technique with Fizeau interferometers [32]. A single measurement, resulting from the accumulation of 20 laser pulses, corresponded to a horizontal resolution of approximately 2.9 km. One Rayleigh wind observation was obtained by averaging up to 30 individual measurements, resulting in a horizontal resolution of 87 km. For the Mie, the horizontal resolution decreased to approximately 10 km after 5 March 2019.

A validity flag defines the quality control (QC) for the Aeolus L2B product. A valid wind measurement has the flag set to 1, while for invalid measurement, it has 0. In this study, only Rayleigh-clear and Mie-cloudy valid winds were considered.

Aeolus baselines wind products used:

- 2B11 (from June 2019 to May 2021);
- 2B12 (from June 2021 to November 2021);
- 2B13 (from December 2021 to March 2022);
- 2B14 (from October 2018 to May 2019, reprocessed data and from April 2022 to August 2022);
- 2B15 (from September 2022 to March 2023).

2.2. Radiosonde Data

Aeolus had, for each station, two overpasses per week, descending and ascending orbit. We focus on descending orbits and radiosondes collected at 12:00 UTC with a maximum 2-hour temporal difference from Aeolus measurements:

- Cruzeiro do Sul on Tuesdays at 10:42 UTC;
- Porto Velho on Saturdays at 10:04 UTC;
- Rio Branco on Sundays at 10:17 UTC.

Considering the geolocation differences between Aeolus and radiosonde measurements, the established criterion for horizontal valid distance is a maximum radius of 100 km around the radiosonde station. Table 1 summarizes the mean distance ($\bar{D}$) for each station by year. Throughout the mission's lifetime, slight orbital shifts affected the mean distance from the stations to the Aeolus wind measurements. Notably, in 2022, no data was available from Rio Branco for statistical validation.

Table 1. Overview of the Aeolus mean distance overpasses and available data.

	CRUZEIRO DO SUL		PORTO VELHO		RIO BRANCO	
	N	$\bar{D}$ (km)	N	$\bar{D}$ (km)	N	$\bar{D}$ (km)
2019	550	91.20	3058	54.85	1962	58.20
2020	386	92.81	3101	54.98	2813	56.03
2021	1164	57.65	2046	64.39	1004	64.57
2022	2637	53.50	1469	84.44	11	98.15

Radiosonde data used in this work are available at <http://weather.uwyo.edu/upperair/sounding.html> (last access: 20 April 2023).

2.3. Comparison of Datasets

For comparison, the radiosonde wind (v_{RS}) and direction (φ_{RS}) are projected onto Aeolus horizontal line-of-sight (HLOS). The radiosonde HLOS wind velocity ($v_{RS-HLOS}$) is obtained using:

$$v_{RS-HLOS} = v_{RS} \cos(\varphi_{Aeolus} - \varphi_{RS}), \quad (1)$$

where φ_{Aeolus} is the Aeolus azimuth angle, which depends on geolocation and altitude. Figure 1 present HLOS wind velocity profiles for Aeolus Rayleigh-clear (blue), Aeolus Mie-cloudy (red) and radiosonde HLOS (black), on (a) December 14, 2021, in Cruzeiro do Sul, (b) July 6, 2019, in Porto Velho, and (c) August 25, 2019, in Rio Branco. Across all three locations, the overall agreement between the Aeolus Rayleigh-clear, Mie-cloudy, and radiosonde profiles is notable.

To quantify the comparison's result, the difference between Aeolus HLOS and the corresponding radiosonde HLOS wind is defined as:

$$v_{HLOS-Diff(i)} = v_{Aeolus-HLOS(i)} - v_{RS-HLOS(i)} \quad (2)$$

where $v_{Aeolus-HLOS(i)}$ is Aeolus Rayleigh-clear or Mie-cloudy HLOS wind and ($v_{RS-HLOS}$) is radiosonde HLOS (1).

Figure 2a presents the difference between Aeolus HLOS and radiosonde HLOS ($v_{HLOS-Diff(i)}$) versus Aeolus estimated errors for Rayleigh-clear winds. The difference remains constant until an estimated error of about 8 m/s, after which it gradually begins to increase. Figure 2b shows $v_{HLOS-Diff(i)}$ versus Aeolus estimated errors for Mie-cloudy winds, where it remains constant until an estimated error of about 4 m/s. Following [14], the estimated error threshold was considered 8 m/s for Rayleigh-clear and 4 m/s for Mie-cloudy winds, represented by the red dashed vertical lines.

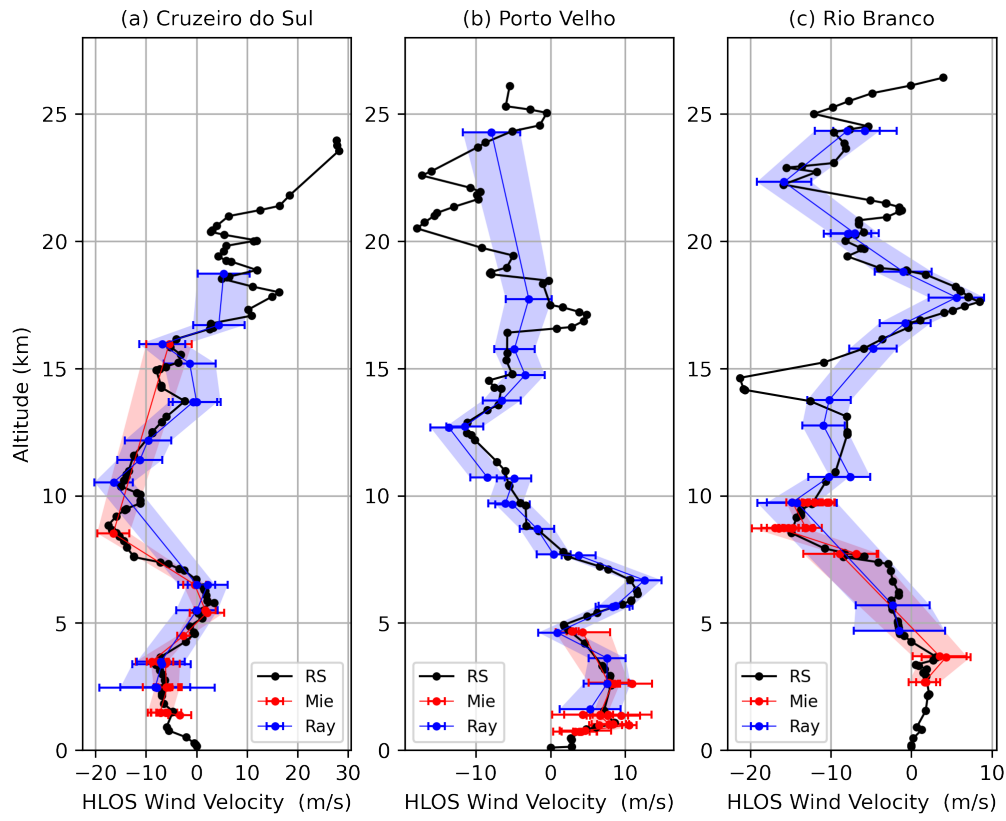


Figure 1. HLOS wind velocity profiles for Aeolus Mie-cloudy (red), Aeolus Rayleigh-clear (blue) and radiosonde (black), on (a) December 14, 2021 in Cruzeiro do Sul, (b) July 06, 2019 in Porto Velho and (c) August 25, 2019 in Rio Branco.

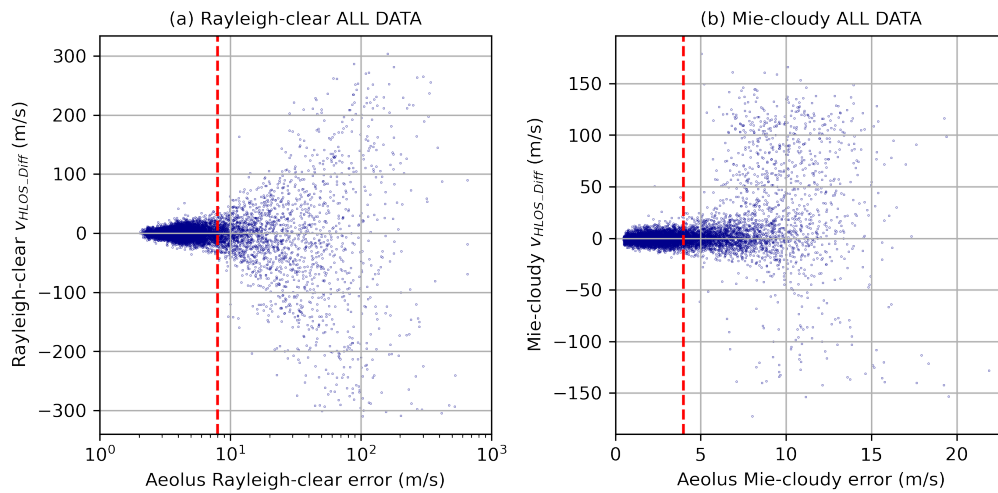


Figure 2. Difference between Aeolus HLOS and corresponding radiosonde HLOS winds versus Aeolus estimated error for (a) Rayleigh-clear and (b) Mie-cloudy products, considering all data. The red dashed vertical lines are the threshold for estimated errors 8 m/s for Rayleigh-clear and 4 m/s for Mie-cloudy.

The bias and standard deviation (SD) are calculated, for a dataset with a sample of size N , using:

$$bias = \frac{1}{N} \sum_{i=1}^N v_{HLOS-Diff(i)} \quad (3)$$

$$SD = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (v_{HLOS-Diff(i)} - bias)^2} \quad (4)$$

Pearson's correlation coefficient (R) between Aeolus HLOS winds and radiosonde HLOS winds is calculated using:

$$R = \frac{\sum_{i=1}^N (v_{RS-HLOS(i)} - \bar{v}_{RS-HLOS}) (v_{Aeolus-HLOS(i)} - \bar{v}_{Aeolus-HLOS})}{\sqrt{\sum_{i=1}^N (v_{RS-HLOS(i)} - \bar{v}_{RS-HLOS})^2 \sum_{i=1}^N (v_{Aeolus-HLOS(i)} - \bar{v}_{Aeolus-HLOS})^2}} \quad (5)$$

In addition to the bias, SD and Pearson's correlation, the slope and intercept was calculated to evaluate the validation process.

3. Results and Discussion

The initial analysis comprehensively uses all available data from three selected stations in the Brazilian Amazon (Cruzeiro do Sul, Porto Velho, and Rio Branco) from October 2018 to March 2023. By incorporating data from all overpasses, this analysis captures a wide range of wind conditions, providing a robust foundation for assessing the Aeolus' performance and behavior over this period.

Figure 3 shows the time series of systematic errors (monthly bias), considering an all-analyzed period for Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles), including data from all three stations. The time series data is derived from monthly mean values, enhancing statistical robustness by expanding the sample size.

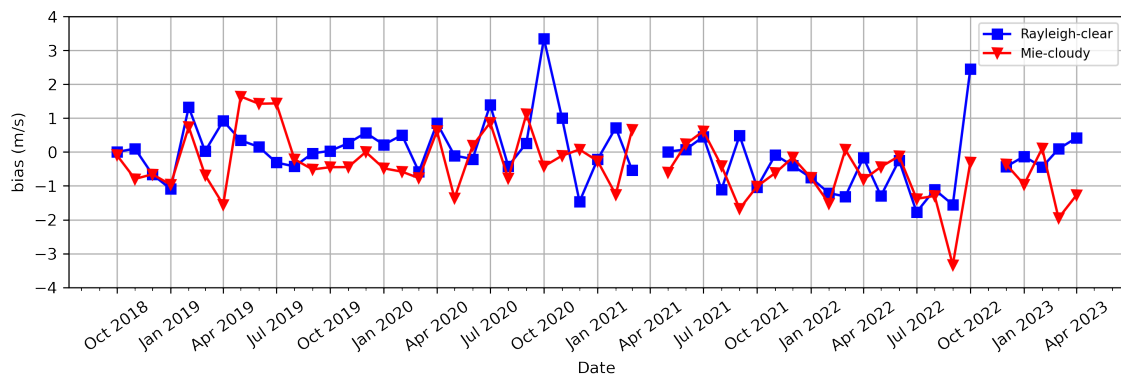


Figure 3. Time series from October 2018 to March 2023 of bias observations in Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles), considering all data.

Figure 4 presents scatter plots of Aeolus HLOS versus radiosonde HLOS winds for (a) Rayleigh-clear and (d) Mie-cloudy winds considering the total data, including all years and all stations. Figure 4b,d show the distribution of $v_{HLOS-Diff(i)}$ for Rayleigh-clear and Mie-cloudy winds, respectively. The analyzed winds, 10837 (6717) for Rayleigh-clear (Mie-cloudy), resulted in a correlation of 0.73 (0.85) and bias -0.17 m/s (-0.40 m/s). These results highlight the presence of strong correlations, particularly notable in the Mie-cloudy observations, along with impressively low bias values.

Figure 5 presents scatter plots of Aeolus HLOS versus radiosonde HLOS winds for (a-d) Rayleigh-clear and (e-f) Mie-cloudy winds, including all stations over the years 2019 to 2023. In 2019, the analysis of 2600 Rayleigh-clear and 1699 Mie-cloudy observations produced a correlation of 0.75 (0.83), bias of 0.06 m/s (-0.28 m/s), and a random error of 6.23 m/s (3.91 m/s). These results indicate a strong correlation, particularly for Mie-cloudy observations, and low bias. In 2020, the analysis of 3058 Rayleigh-clear and 1862 Mie-cloudy observations produced a correlation of 0.71 (0.85), bias of 0.18 m/s (-0.25 m/s), and a random error of 7.41 m/s (4.38 m/s). The strong correlation persists in Mie-cloudy observations, along with the low bias values. For 2021, the analysis of 2202 Rayleigh-clear

and 1116 Mie-cloudy observations yielded a correlation of 0.70 (0.88), bias of -0.22 m/s (-0.41 m/s), and a random error of 8.29 m/s (4.27 m/s). The correlation for Mie-cloudy observations increases, and bias values remaining low. In 2022, the analysis of 2046 Rayleigh-clear and 944 Mie-cloudy observations resulted in a correlation of 0.76 (0.90), bias of -0.95 m/s (-0.70 m/s), and a random error of 7.02 m/s (3.48 m/s). This year shows the highest correlation for Mie-cloudy observations, while the bias is slightly higher and, for Rayleigh-clear, extrapolated the mission requirements. Additionally, the correlations for Rayleigh-clear observations remained relatively stable over the years, ranging from 0.70 to 0.76. This consistency, combined with the high correlations in Mie-cloudy results, indicates robust performance in measuring winds despite varying conditions across different years. Table 2 summarizes the statistical results.

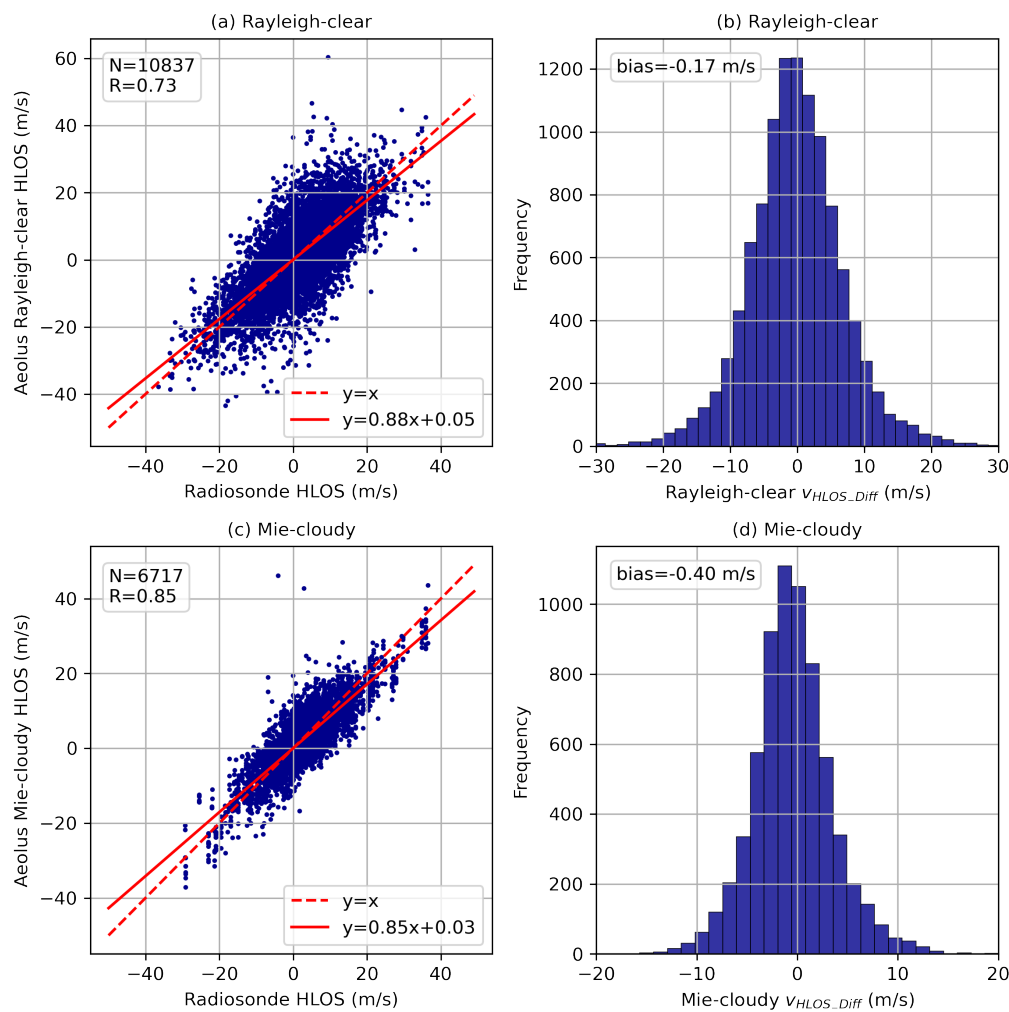


Figure 4. Aeolus HLOS wind versus the radiosonde HLOS wind, for all data, separates in (a) Rayleigh-clear and (c) Mie-cloudy products. The $y = x$ is represented by the red dashed line. The results of fitting the red line, slope and intercept, are in the insets. Frequency distribution of difference between Aeolus HLOS and corresponding radiosonde HLOS winds for all data are separates in (b) Rayleigh-clear and (d) Mie-cloudy products.

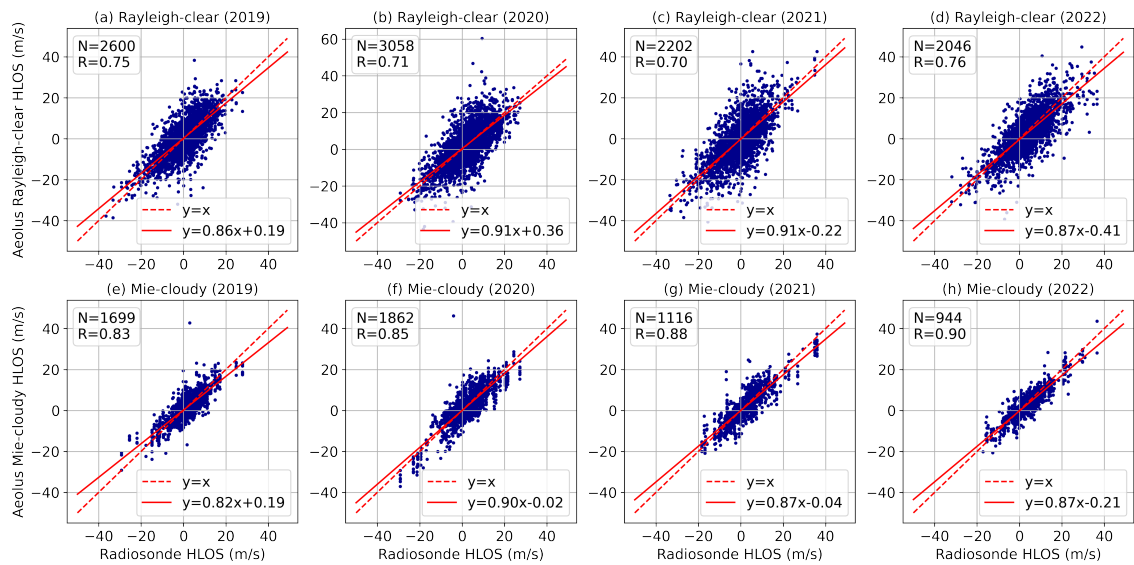


Figure 5. Aeolus HLOS wind versus the radiosonde HLOS wind, for all data over the years 2019, 2020, 2021 and 2022, separates in (a-d) Rayleigh-clear and (e-h) Mie-cloudy products. The $y = x$ is represented by the red dashed line. The results of fitting the red line, slope and intercept, are in the insets.

Table 2. Statistical comparison between Aeolus HLOS winds and radiosonde HLOS winds. Aeolus Rayleigh-clear and Mie-cloudy observations across all stations from 2019 to 2022.

	Rayleigh-clear				Mie-cloudy			
	2019	2020	2021	2022	2019	2020	2021	2022
N	2600	3058	2202	2046	1699	1862	1116	944
R	0.75	0.71	0.70	0.76	0.83	0.85	0.88	0.90
bias (m/s)	0.06	0.18	-0.22	-0.95	-0.28	-0.25	-0.41	-0.70
SD (m/s)	6.23	7.41	8.29	7.02	3.91	4.38	4.27	3.48
Slope	0.86	0.91	0.91	0.87	0.82	0.90	0.87	0.87
Intercept (m/s)	0.19	0.36	-0.22	-0.41	0.19	-0.02	-0.04	-0.21

3.1. Cruzeiro do Sul

Figure 6 shows the time series of systematic errors (monthly bias) at Cruzeiro do Sul from October 2018 to March 2023 for Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles).

Figure 7 presents scatter plots of Aeolus HLOS versus radiosonde HLOS winds at Cruzeiro do Sul for (a-d) Rayleigh-clear and (e-f) Mie-cloudy winds, from 2019 to 2023. In 2019, the analysis of 302 Rayleigh-clear and 165 Mie-cloudy observations produced a correlation of 0.75 (0.82), bias of -0.10 m/s (-0.05 m/s), and a random error of 6.28 m/s (3.21 m/s), indicating a strong correlation and low bias. In 2020, the analysis of 202 Rayleigh-clear and 102 Mie-cloudy observations produced a correlation of 0.75 (0.72), bias of 0.45 m/s (0.93 m/s), and a random error of 6.60 m/s (4.23 m/s). The correlation decreases in Mie-cloudy observations and bias values considerable increase in compared to the previous year, exceeding 0.7 m/s. In 2021, the analysis of 725 Rayleigh-clear and 244 Mie-cloudy observations produced a correlation of 0.67 (0.77), bias of -0.10 m/s (-0.10 m/s), and a random error of 8.47 m/s (4.38 m/s). The first correlation above 0.70 were observed for Rayleigh-clear, in contrast bias values remaining low. In 2022, the analysis of 1384 Rayleigh-clear and 545 Mie-cloudy observations resulted in a correlation of 0.76 (0.90), bias of -1.06 m/s (-0.80 m/s), and a random error of 7.01 m/s

(3.37 m/s). Despite the correlation values being the best compared to previous years, the bias for both products exceeded the threshold of 0.7 m/s. Table 3 summarizes the statistical results.

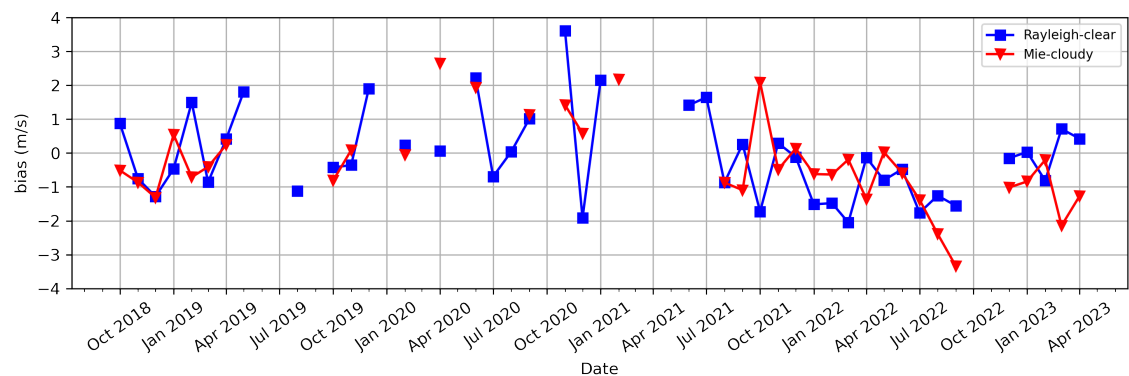


Figure 6. Time series from October 2018 to March 2023 of bias observations in Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles) at Cruzeiro do Sul.

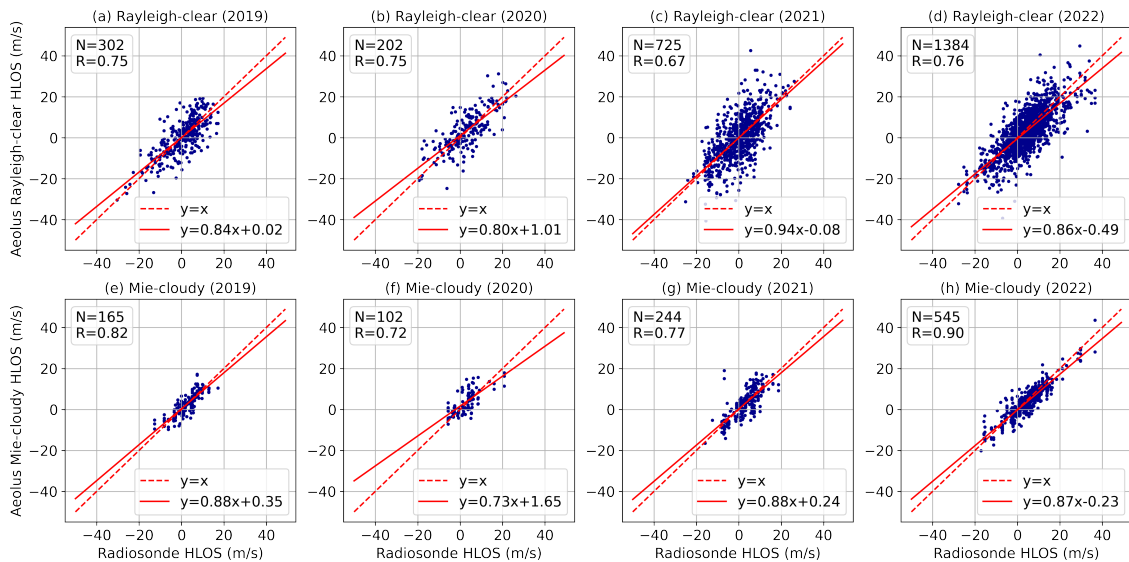


Figure 7. Aeolus HLOS wind versus the radiosonde HLOS wind, for Cruzeiro do Sul over the years 2019, 2020, 2021 and 2022, separates in (a-d) Rayleigh-clear and (e-h) Mie-cloudy products. The $y = x$ is represented by the red dashed line. The results of fitting the red line, slope and intercept, are in the insets.

Table 3. Statistical comparison between Aeolus HLOS winds and radiosonde HLOS winds. Aeolus Rayleigh-clear and Mie-cloudy observations from 2019 to 2022 at Cruzeiro do Sul.

	Rayleigh-clear				Mie-cloudy			
	2019	2020	2021	2022	2019	2020	2021	2022
N	302	202	725	1384	165	102	244	545
R	0.75	0.75	0.67	0.76	0.82	0.72	0.77	0.90
bias (m/s)	-0.10	0.45	-0.10	-1.06	0.05	0.93	-0.10	-0.80
SD (m/s)	6.28	6.60	8.47	7.01	3.21	4.23	4.38	3.37
Slope	0.84	0.80	0.94	0.86	0.88	0.73	0.88	0.87
Intercept (m/s)	0.02	1.01	-0.08	-0.49	0.35	1.65	0.24	-0.23

3.2. Porto Velho

Figure 8 shows the time series of systematic errors (monthly bias) at Porto Velho from October 2018 to March 2023 for Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles).

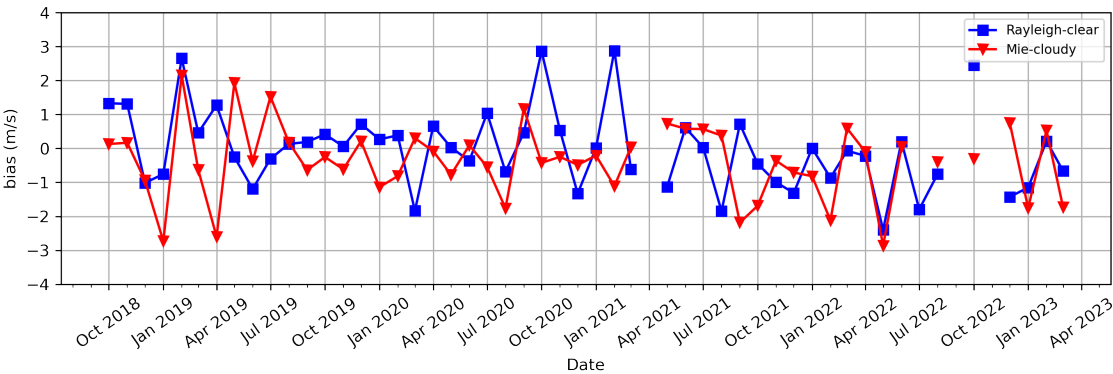


Figure 8. Time series from October 2018 to March 2023 of bias observations in Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles) at Porto Velho.

Figure 9 presents Scatter plots of Aeolus HLOS wind versus radiosonde HLOS wind for Porto Velho from 2019 to 2022, Rayleigh-clear (a-d) and Mie-cloudy (e-h) products. In 2019, the analysis of 1333 Rayleigh-clear and 959 Mie-cloudy observations yielded a correlation of 0.74 (0.84), with a bias of 0.28 m/s (-0.20 m/s), and a random error of 6.35 m/s (4.08 m/s), indicating a reasonably strong correlation and low bias. In 2020, the analysis of 1432 Rayleigh-clear and 956 Mie-cloudy observations resulted in a correlation of 0.70 (0.79), accompanied by a bias of 0.12 m/s (-0.35 m/s), and a random error of 7.50 m/s (4.31 m/s), suggesting a moderate correlation and slightly higher bias compared to the previous year. In 2021, the analysis of 984 Rayleigh-clear and 587 Mie-cloudy observations resulted a correlation of 0.70 (0.90), alongside a bias of -0.23 m/s (-0.30 m/s), and a random error of 8.40 m/s (4.08 m/s), indicating a maintained correlation level with slight fluctuations in bias. In 2022, the analysis of 659 Rayleigh-clear and 398 Mie-cloudy observations yielded a correlation of 0.76 (0.90), coupled with a bias of -0.74 m/s (-0.57 m/s), and a random error of 7.03 m/s (3.64 m/s), suggesting an improved correlation and a slightly decreased bias compared to the previous year. Table 4 summarizes the statistical results.

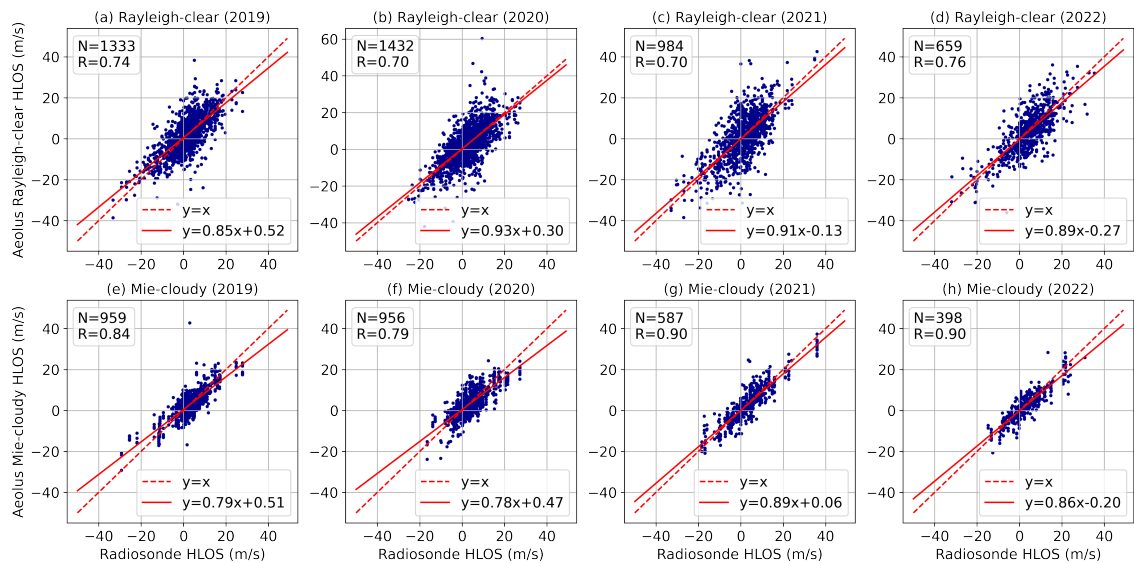


Figure 9. Aeolus HLOS wind versus the radiosonde HLOS wind, for PORTO VELHO over the years 2019, 2020, 2021 and 2022, separates in (a-d) Rayleigh-clear and (e-h) Mie-cloudy products. The $y = x$ is represented by the red dashed line. The results of fitting the red line, slope and intercept, are in the insets.

Table 4. Statistical comparison between Aeolus HLOS winds and radiosonde HLOS winds. Aeolus Rayleigh-clear and Mie-cloudy observations from 2019 to 2022 at Porto Velho.

	Rayleigh-clear				Mie-cloudy			
	2019	2020	2021	2022	2019	2020	2021	2022
N	1333	1432	984	659	959	956	587	398
R	0.74	0.70	0.70	0.76	0.84	0.79	0.90	0.90
bias (m/s)	0.28	0.12	-0.23	-0.74	-0.20	-0.35	-0.30	-0.57
SD (m/s)	6.35	7.50	8.40	7.03	4.08	4.31	4.08	3.64
Slope	0.85	0.93	0.91	0.89	0.79	0.78	0.89	0.86
Intercept (m/s)	0.52	0.30	-0.13	-0.27	0.51	0.47	0.06	-0.20

3.3. Rio Branco

Figure 10 shows the time series of systematic errors (monthly bias) at Rio Branco from October 2018 to December 2021 for Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles). The time series data, both aggregated and per station, reveal numerous instances where the Rayleigh-clear and Mie-cloudy biases closely coincide despite minor inconsistencies. This alignment strongly indicates consistent performance across both channels during these periods.

Figure 11 presents Scatter plots of Aeolus HLOS wind versus radiosonde HLOS wind for Rio Branco from 2019 to 2022, Rayleigh-clear (a-d) and Mie-cloudy (e-h) products. In 2019, the analysis of 965 Rayleigh-clear and 575 Mie-cloudy observations produced the following results: correlation 0.74 (0.80), bias -0.19 m/s (-0.50 m/s), and random error 6.05 m/s (3.81 m/s), suggesting a reasonably strong correlation despite variations in bias. In 2020, the examination of 1424 Rayleigh-clear and 804 Mie-cloudy observations produced the following findings: correlation 0.71 (0.89), accompanied by a bias of 0.20 m/s (-0.29 m/s), and random error 7.42 m/s (4.46 m/s), indicating a persistent strong correlation for Mie-cloudy product. In 2021, the analysis of 493 Rayleigh-clear and 285 Mie-cloudy observations unveiled a correlation of 0.74 (0.88), bias of -0.36 m/s (-0.90 m/s), and random error

7.79 m/s (4.54 m/s), suggesting a consistent correlation with significant variations in bias. Table 5 summarizes these statistical results.

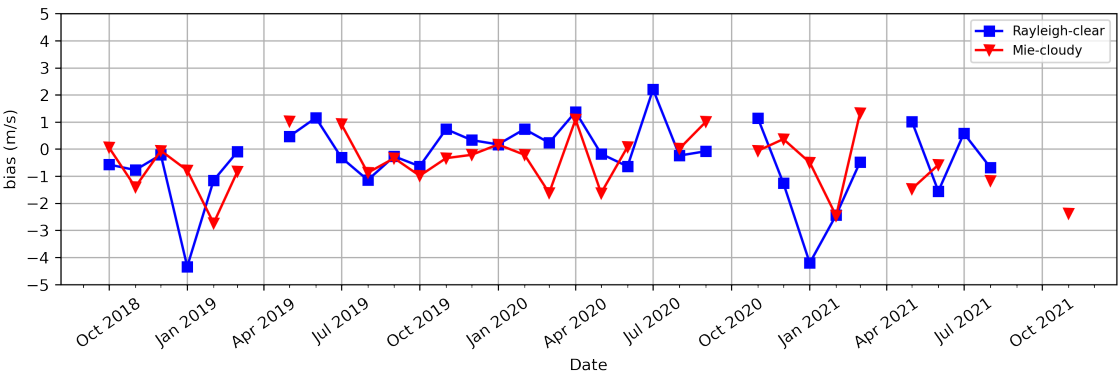


Figure 10. Time series from October 2018 to December 2021 of bias observations in Aeolus Rayleigh-clear (blue squares) and Mie-cloudy (red triangles) at Rio Branco.

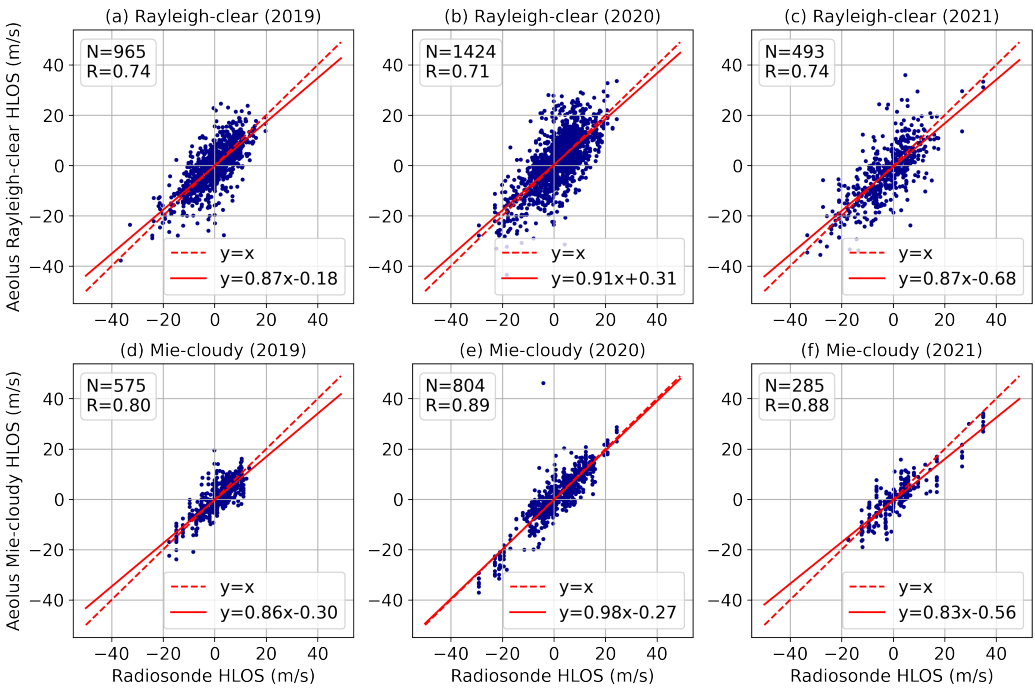


Figure 11. Aeolus HLOS wind versus the radiosonde HLOS wind, for Rio Branco over the years 2019, 2020 and 2021, separates in (a-c) Rayleigh-clear and (d-f) Mie-cloudy products. The $y = x$ is represented by the red dashed line. The results of fitting the red line, slope and intercept, are in the insets.

Table 5. Statistical comparison between Aeolus HLOS winds and radiosonde HLOS winds. Aeolus Rayleigh-clear and Mie-cloudy observations from 2019 to 2021 at Rio Branco.

	Rayleigh-clear			Mie-cloudy		
	2019	2020	2021	2019	2020	2021
N	965	1424	493	575	804	285
R	0.74	0.71	0.74	0.80	0.89	0.88
bias (m/s)	-0.19	0.20	-0.36	-0.50	-0.29	-0.90
SD (m/s)	6.05	7.42	7.79	3.81	4.46	4.54
Slope	0.87	0.91	0.87	0.86	0.98	0.83
Intercept (m/s)	-0.18	0.31	-0.68	-0.30	-0.27	-0.56

4. Conclusions

This study validated the Aeolus Level 2B (L2B) Rayleigh-clear and Mie-cloudy wind products using radiosonde data from three stations in the Brazilian Amazon. High correlation coefficients of 0.73 for Rayleigh-clear and 0.85 for Mie-cloudy, between Aeolus and radiosonde measurements, suggest that Aeolus wind products are reliable for capturing wind profiles in the studied region, which can improve numerical weather prediction (NWP) models.

Observed biases for all data were -0.14 m/s for Rayleigh-clear and -0.40 m/s for Mie-cloudy, within mission requirements. Although the overall biases met these requirements, certain stations and years showed biases exceeding them for Rayleigh-clear or Mie-cloudy products, in line with results obtained in previous Aeolus validation [16,17,19,24]. It is important to note that validation studies rely on data availability and local conditions. The strong agreement among data sets from three different validation stations enhances the consistency of the results.

In conclusion, the Aeolus wind products demonstrated solid performance in the validation conducted in the Brazilian Amazon. These results highlight the importance of the Aeolus mission for improving weather forecasts and understanding wind profiles in critical regions.

Author Contributions: Conceptualization, A.C.Y., P.C.V. and F.J.S.L.; methodology, A.C.Y. and P.C.V.; software, A.C.Y. and P.C.V.; validation, A.C.Y., P.C.V. and F.J.S.L.; formal analysis, A.C.Y. and E.L.; investigation, A.C.Y. and P.C.V.; resources, E.L.; data curation, A.C.Y. and P.C.V.; writing—original draft preparation, A.C.Y. and P.C.V.; writing—review and editing, A.C.Y., P.C.V., F.J.S.L. and E.L.; visualization, A.C.Y., P.C.V., F.J.S.L. and E.L.; supervision, E.L.; project administration, E.L.; funding acquisition, E.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Council for Scientific and Technological Development (CNPq) projects 432515/2018-6 and 406775/2023-0.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Aeolus data: <https://aeolus.services/> Radiosonde data :<http://weather.uwyo.edu/upperair/sounding.html>

Acknowledgments: The authors thank the ViREs for Aeolus.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Baker, W.E.; Atlas, R.; Cardinali, C.; Clement, A.; Emmitt, G.D.; Gentry, B.M.; Hardesty, R.M.; Källén, E.; Kavaya, M.J.; Langland, R.; Ma, Z.; Masutani, M.; McCarty, W.; Pierce, R.B.; Pu, Z.; Riishojgaard, L.P.; Ryan, J.; Tucker, S.; Weissmann, M.; Yoe, J.G. Lidar-Measured Wind Profiles: The Missing Link in the Global Observing System. *Bulletin of the American Meteorological Society* **2014**, *95*, 543–564. doi:10.1175/BAMS-D-12-00164.1.

2. Stoffelen, A.; Marseille, G.J.; Bouttier, F.; Vasiljevic, D.; De Haan, S.; Cardinali, C. ADM-Aeolus Doppler wind lidar Observing System Simulation Experiment. *Quarterly Journal of the Royal Meteorological Society* **2006**, *132*, 1927–1947. doi:10.1256/qj.05.83.

3. Haan, S.d.; Stoffelen, A. Assimilation of High-Resolution Mode-S Wind and Temperature Observations in a Regional NWP Model for Nowcasting Applications. *Weather and Forecasting* **2012**, *27*, 918–937. Publisher: American Meteorological Society Section: Weather and Forecasting, doi:10.1175/WAF-D-11-00088.1.
4. Bauer, P.; Thorpe, A.; Brunet, G. The quiet revolution of numerical weather prediction. *Nature* **2015**, *525*, 47–55. doi:10.1038/nature14956.
5. Horányi, A.; Cardinali, C.; Rennie, M.; Isaksen, L. The assimilation of horizontal line-of-sight wind information into the ECMWF data assimilation and forecasting system. Part I: The assessment of wind impact. *Quarterly Journal of the Royal Meteorological Society* **2015**, *141*, 1223–1232. doi:10.1002/qj.2430.
6. Illingworth, A.J.; Battaglia, A.; Bradford, J.; Forsythe, M.; Joe, P.; Kollias, P.; Lean, K.; Lori, M.; Mahfouf, J.F.; Melo, S.; Midthassel, R.; Munro, Y.; Nicol, J.; Potthast, R.; Rennie, M.; Stein, T.H.M.; Tanelli, S.; Tridon, F.; Walden, C.J.; Wolde, M. WIVERN: A New Satellite Concept to Provide Global In-Cloud Winds, Precipitation, and Cloud Properties. *Bulletin of the American Meteorological Society* **2018**, *99*, 1669–1687. doi:10.1175/BAMS-D-16-0047.1.
7. WMO. Preliminary statement of guidance regarding how well satellite capabilities meet WMO user requirements in several application areas. Technical Report WMO/TD-No.913, World Meteorological Organization, Geneva, 1998.
8. Weissmann, M.; Cardinali, C. Impact of airborne Doppler lidar observations on ECMWF forecasts. *Quarterly Journal of the Royal Meteorological Society*, *133*, 107–116. doi:10.1002/qj.16.
9. Reitebuch, O.; Lemmerz, C.; Nagel, E.; Paffrath, U.; Durand, Y.; Endemann, M.; Fabre, F.; Chaloupy, M. The Airborne Demonstrator for the Direct-Detection Doppler Wind Lidar ALADIN on ADM-Aeolus. Part I: Instrument Design and Comparison to Satellite Instrument. *Journal of Atmospheric and Oceanic Technology* **2009**, *26*, 2501–2515. doi:10.1175/2009JTECHA1309.1.
10. Straume, A.G.; Rennie, M.; Isaksen, L.; Kloe, J.d.; Marseille, G.J.; Stoffelen, A.; Flament, T.; Stieglitz, H.; Dabas, A.; Huber, D.; Reitebuch, O.; Lemmerz, C.; Lux, O.; Marksteiner, U.; Weiler, F.; Witschas, B.; Meringer, M.; Schmidt, K.; Nikolaus, I.; Geiss, A.; Flamant, P.; Kanitz, T.; Wernham, D.; Bismarck, J.v.; Bley, S.; Fehr, T.; Floberghagen, R.; Parinello, T. ESA's Space-Based Doppler Wind Lidar Mission Aeolus – First Wind and Aerosol Product Assessment Results. *EPJ Web of Conferences* **2020**, *237*, 01007. Publisher: EDP Sciences, doi:10.1051/epjconf/202023701007.
11. Rennie, M.P.; Isaksen, L.; Weiler, F.; de Kloe, J.; Kanitz, T.; Reitebuch, O. The impact of Aeolus wind retrievals on ECMWF global weather forecasts. *Quarterly Journal of the Royal Meteorological Society* **2021**, *147*, 3555–3586. doi:10.1002/qj.4142.
12. Garrett, K.; Liu, H.; Ide, K.; Hoffman, R.N.; Lukens, K.E. Optimization and impact assessment of Aeolus HLOS wind assimilation in NOAA's global forecast system. *Quarterly Journal of the Royal Meteorological Society* **2022**, *148*. doi:10.1002/qj.4331.
13. Borne, M.; Knippertz, P.; Weissmann, M.; Martin, A.; Rennie, M.; Cress, A. Impact of Aeolus wind lidar observations on the representation of the West African monsoon circulation in the ECMWF and DWD forecasting systems. *Quarterly Journal of the Royal Meteorological Society* **2023**, *149*, 933–958. doi:10.1002/qj.4442.
14. Witschas, B.; Lemmerz, C.; Geiß, A.; Lux, O.; Marksteiner, U.; Rahm, S.; Reitebuch, O.; Weiler, F. First validation of Aeolus wind observations by airborne Doppler wind lidar measurements. *Atmospheric Measurement Techniques* **2020**, *13*, 2381–2396. Publisher: Copernicus GmbH, doi:10.5194/amt-13-2381-2020.
15. Lux, O.; Lemmerz, C.; Weiler, F.; Marksteiner, U.; Witschas, B.; Rahm, S.; Geiß, A.; Reitebuch, O. Intercomparison of wind observations from the European Space Agency's Aeolus satellite mission and the ALADIN Airborne Demonstrator. *Atmospheric Measurement Techniques* **2020**, *13*, 2075–2097. Publisher: Copernicus GmbH, doi:10.5194/amt-13-2075-2020.
16. Baars, H.; Herzog, A.; Heese, B.; Ohneiser, K.; Hanbuch, K.; Hofer, J.; Yin, Z.; Engelmann, R.; Wandinger, U. Validation of Aeolus wind products above the Atlantic Ocean. *Atmospheric Measurement Techniques* **2020**, *13*, 6007–6024. Publisher: Copernicus GmbH, doi:10.5194/amt-13-6007-2020.
17. Martin, A.; Weissmann, M.; Reitebuch, O.; Rennie, M.; Geiß, A.; Cress, A. Validation of Aeolus winds using radiosonde observations and numerical weather prediction model equivalents. *Atmospheric Measurement Techniques* **2021**, *14*, 2167–2183. Publisher: Copernicus GmbH, doi:10.5194/amt-14-2167-2021.
18. Belova, E.; Kirkwood, S.; Voelger, P.; Chatterjee, S.; Satheesan, K.; Hagelin, S.; Lindskog, M.; Körnich, H. Validation of Aeolus winds using ground-based radars in Antarctica and in northern Sweden. *Atmospheric Measurement Techniques* **2021**, *14*, 5415–5428. Publisher: Copernicus GmbH, doi:10.5194/amt-14-5415-2021.

19. Iwai, H.; Aoki, M.; Oshiro, M.; Ishii, S. Validation of Aeolus Level 2B wind products using wind profilers, ground-based Doppler wind lidars, and radiosondes in Japan. *Atmospheric Measurement Techniques* **2021**, *14*, 7255–7275. Publisher: Copernicus GmbH, doi:10.5194/amt-14-7255-2021.
20. Wu, S.; Sun, K.; Dai, G.; Wang, X.; Liu, X.; Liu, B.; Song, X.; Reitebuch, O.; Li, R.; Yin, J.; Wang, X. Inter-comparison of wind measurements in the atmospheric boundary layer and the lower troposphere with Aeolus and a ground-based coherent Doppler lidar network over China. *Atmospheric Measurement Techniques* **2022**, *15*, 131–148. Publisher: Copernicus GmbH, doi:10.5194/amt-15-131-2022.
21. Bley, S.; Rennie, M.; Žagar, N.; Pinol Sole, M.; Straume, A.G.; Antifaev, J.; Candido, S.; Carver, R.; Fehr, T.; von Bismarck, J.; Hünnerbein, A.; Deneke, H. Validation of the Aeolus L2B Rayleigh winds and ECMWF short-range forecasts in the upper troposphere and lower stratosphere using Loon super pressure balloon observations. *Quarterly Journal of the Royal Meteorological Society* **2022**, *148*, 3852–3868. _eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4391>, doi:10.1002/qj.4391.
22. Chou, C.C.; Kushner, P.J.; Laroche, S.; Mariani, Z.; Rodriguez, P.; Melo, S.; Fletcher, C.G. Validation of the Aeolus Level-2B wind product over Northern Canada and the Arctic. *Atmospheric Measurement Techniques* **2022**, *15*, 4443–4461. Publisher: Copernicus GmbH, doi:10.5194/amt-15-4443-2022.
23. Witschas, B.; Lemmerz, C.; Geiß, A.; Lux, O.; Marksteiner, U.; Rahm, S.; Reitebuch, O.; Schäfler, A.; Weiler, F. Validation of the Aeolus L2B wind product with airborne wind lidar measurements in the polar North Atlantic region and in the tropics. *Atmospheric Measurement Techniques* **2022**, *15*, 7049–7070. Publisher: Copernicus GmbH, doi:10.5194/amt-15-7049-2022.
24. Abril-Gago, J.; Ortiz-Amezcu, P.; Bermejo-Pantaleón, D.; Andújar-Maqueda, J.; Bravo-Aranda, J.A.; Granados-Muñoz, M.J.; Navas-Guzmán, F.; Alados-Arboledas, L.; Foyo-Moreno, I.; Guerrero-Rascado, J.L. Validation activities of Aeolus wind products on the southeastern Iberian Peninsula. *Atmospheric Chemistry and Physics* **2023**, *23*, 8453–8471. Publisher: Copernicus GmbH, doi:10.5194/acp-23-8453-2023.
25. Baars, H.; Walchester, J.; Basharova, E.; Gebauer, H.; Radenz, M.; Bühl, J.; Barja, B.; Wandinger, U.; Seifert, P. Long-term validation of Aeolus L2B wind products at Punta Arenas, Chile, and Leipzig, Germany. *Atmospheric Measurement Techniques* **2023**, *16*, 3809–3834. Publisher: Copernicus GmbH, doi:10.5194/amt-16-3809-2023.
26. Kirkwood, S.; Belova, E.; Voelger, P.; Chatterjee, S.; Satheesan, K. Extended validation of Aeolus winds with wind-profiling radars in Antarctica and Arctic Sweden. *Atmospheric Measurement Techniques* **2023**, *16*, 4215–4227. Publisher: Copernicus GmbH, doi:10.5194/amt-16-4215-2023.
27. Ratynski, M.; Khaykin, S.; Hauchecorne, A.; Wing, R.; Cammas, J.P.; Hello, Y.; Keckhut, P. Validation of Aeolus wind profiles using ground-based lidar and radiosonde observations at Réunion island and the Observatoire de Haute-Provence. *Atmospheric Measurement Techniques* **2023**, *16*, 997–1016. Publisher: Copernicus GmbH, doi:10.5194/amt-16-997-2023.
28. Borne, M.; Knippertz, P.; Weissmann, M.; Witschas, B.; Flamant, C.; Rios-Berrios, R.; Veals, P. Validation of Aeolus L2B products over the tropical Atlantic using radiosondes. *Atmospheric Measurement Techniques* **2024**, *17*, 561–581. Publisher: Copernicus GmbH, doi:10.5194/amt-17-561-2024.
29. Yoshida, A.C.; da Silva Lopes, F.J.; Venturini, P.C.; Cacheffo, A.; Guerrero-Rascado, J.L.; Landulfo, E. Validation of Aeolus Wind Product at Cruzeiro do Sul-Brazil. *Space-based Lidar Remote Sensing Techniques and Emerging Technologies*; Singh, U.N.; Tzeremes, G.; Refaat, T.F.; Ribes Pleguezuelo, P., Eds.; Springer Nature Switzerland: Cham, 2024; pp. 319–328. doi:10.1007/978-3-031-53618-2_28.
30. Witschas, B.; Lemmerz, C.; Lux, O.; Marksteiner, U.; Reitebuch, O.; Weiler, F.; Fabre, F.; Dabas, A.; Flament, T.; Huber, D.; Vaughan, M. Spectral performance analysis of the Aeolus Fabry–Pérot and Fizeau interferometers during the first years of operation. *Atmospheric Measurement Techniques* **2022**, *15*, 1465–1489. doi:10.5194/amt-15-1465-2022.

31. Flesia, C.; Korb, C.L. Theory of the double-edge molecular technique for Doppler lidar wind measurement. *Applied Optics* **1999**, *38*, 432–440. doi:10.1364/AO.38.000432.
32. McKay, J.A. Assessment of a multibeam Fizeau wedge interferometer for Doppler wind lidar. *Applied Optics* **2002**, *41*, 1760–1767. doi:10.1364/AO.41.001760.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.