



A multi-instrument framework for boundary layer wind and turbulence profiling

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Abstract. Characterizing how the planetary boundary layer varies in space and time requires reliable, continuous wind and turbulence profiles from the surface into the lower troposphere. No single instrument spans this height range. Although combining complementary instruments is well-established practice, there is still no widely adopted, transparent method for turning these measurements into analysis-ready profile products. We present WINDPROF, an open-source framework that combines measurements from scanning and profiling Doppler lidars, radar wind profilers, tower-mounted sonic anemometers, and surface meteorological stations. It produces 10-minute profiles of wind speed, direction, vertical velocity, turbulence intensity, turbulence kinetic energy, and velocity-component standard deviations on a standardized vertical grid. The framework applies instrument-specific quality control and retrieves winds using velocity-azimuth display fitting. Turbulence statistics are estimated using Reynolds decomposition, with lidar beam-geometry biases corrected in the mean wind speed used to calculate turbulence intensity. Profiles are then merged using a height-dependent hierarchical strategy. We demonstrate the framework using 19 months of observations from four coastal sites during the Third Wind Forecast Improvement Project (WFIP3). Comparisons between co-located lidars, pooled within each site, yielded wind speed root-mean-square errors of 0.36–0.78 m s⁻¹, while merged data availability below 200 m above ground level ranged from 84 % to 98 %. During coastal fog, median data availability at 100–300 m was 39.3 % at a site relying exclusively on optical instruments, compared with 94.5 % at a radar-equipped site, demonstrating the value of complementary measurement technologies. Comparison with an independently developed Bayesian optimal-estimation retrieval at Nantucket showed close agreement (mean difference = +0.160 m



s^{-1} , root-mean-square error = 0.851 m s^{-1} , $r = 0.990$). Differences were larger near low-level jet maxima and during periods of rapid wind change, consistent with the methods' different averaging times.

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1 Introduction

The planetary boundary layer is the atmosphere's interface with the surface, through which momentum, heat, moisture, and trace constituents are exchanged with the free troposphere. Its vertical structure is a primary control on weather forecasting (Fernández-González et al., 2017; Olson et al., 2019; Pentikäinen et al., 2023; Shaw et al., 2019; Wilczak et al., 2019) and air quality (Su et al., 2018). Over coastal and marine regions, the planetary boundary layer differs substantially from its continental counterpart. Wind structure and variability are governed by interactions between air-sea temperature contrasts, spatially heterogeneous surface roughness, and mesoscale phenomena including low-level jets (LLJs), sea-breeze circulations, and internal boundary layers forming at the land-sea interface (Garratt, 1990; Krishnamurthy et al., 2023; Shaw et al., 2022; Sullivan et al., 2020). Resolving these processes and evaluating the parameterizations that represent them in numerical models requires vertically resolved observations of wind and turbulence that extend from near the surface through the depth of the boundary layer and into the lower free troposphere.

No single remote sensing or in situ instrument is capable of providing such observations in isolation. Doppler lidars retrieve winds and turbulence via velocity-azimuth display (VAD) or Doppler beam swinging (DBS) techniques (Browning and Wexler, 1968; Newsom and Krishnamurthy, 2022) and perform well throughout the aerosol-laden lower boundary layer, but their signal degrades in precipitation and fog and cannot penetrate optically thick clouds (Päschke et al., 2015; Mariani et al., 2020; Hogan et al., 2009). Radar wind profilers rely on Bragg scattering from refractive-index inhomogeneities (Tatarskii, 1961) and therefore operate reliably during precipitation and at greater altitudes but suffer from a near-surface blind zone, coarser vertical resolution, and occasional contamination from migrating biota and sea clutter (Wilczak et al., 1995). Sonic anemometers provide direct, high-frequency measurements of the three-dimensional wind vector suitable for state variable and



eddy-covariance turbulence analysis (Kaimal and Finnigan, 1994), yet they sample only at the fixed heights of the supporting tower infrastructure. Because these measurement principles complement one another, the instruments have long been deployed together in boundary-layer field campaigns (Poulos et al., 2002; Barthelmie et al., 2014; Lundquist et al., 2017; Fernando et al., 2019), and several studies have demonstrated that multi-instrument synthesis can yield a more complete representation of boundary layer structure than any platform alone (Adler et al., 2019).

Reproducible, openly documented methods for integrating wind and turbulence observations from a variety of in situ and remote sensing instruments into analysis-ready products nonetheless remain scarce. Contributing instruments differ in temporal sampling, coordinate convention, height reference, and quality control philosophy. Sampling geometry differs too, with lidars and radars averaging over volumes that grow with range while anemometers measure at a point. Recent similar efforts (Dias Neto et al., 2023) have demonstrated the value of transparent, well-documented integration procedures for cloud radar and lidar synthesis, but comparable open frameworks for boundary layer wind and turbulence profiling remain scarce. Integrated wind and turbulence products are therefore often campaign-specific, difficult to reproduce, and hard to compare across studies. The framework presented here is a response to those limitations.

The Third Wind Forecast Improvement Project (WFIP3), sponsored by the U.S. Department of Energy (DOE) and the National Oceanic and Atmospheric Administration (NOAA), provides both the observational dataset and the scientific motivation for the present work (Adler et al., 2026; Bodini et al., 2026b, a; Kirincich et al., 2023, 2026; Krishnamurthy et al., 2025). Between February 2024 and September 2025, WFIP3 deployed scanning and profiling Doppler lidars, radar wind profilers, sonic anemometers, and surface meteorological suites at four of the WFIP3 coastal sites across the northern Mid-Atlantic Bight. The deployment spans a range of instrument combinations and coastal exposures, which is what makes it a useful test of the framework.

In this paper we present and evaluate WINDPROF, a standardized framework for producing integrated 10-minute profiles of horizontal wind speed, wind direction, vertical velocity, and turbulence measurements (turbulence intensity (TI), turbulence kinetic energy (TKE), and velocity-component standard deviations) from the full WFIP3 instrument suite. This framework follows manufacturer and operator recommendations for instrument-specific quality control. It retrieves horizontal winds using least-squares VAD fitting (Banakh and Smalikho, 2013; Browning and Wexler, 1968; Waldteufel and Corbin, 1979; Krishnamurthy et al., 2013) and calculates turbulence statistics using established Reynolds-decomposition practices (Kaimal and Finnigan, 1994; Stull, 1988). For turbulence intensity, it uses a hybrid estimate of mean wind speed that corrects biases caused by lidar beam geometry (Rosenbusch et al., 2021). Measurements from multiple instrument types are then combined hierarchically depending on height. Uncertainty is propagated from the VAD fit residuals and assessed empirically against inter-instrument spread. The methodology is designed to be portable to other multi-instrument campaigns, the derived data products are archived with digital object identifiers (DOIs), and the processing code is publicly available.

We pursue three scientific objectives. First, we quantify the consistency of co-located lidar and radar retrievals using sonic anemometers as a near-surface wind-direction reference and identify the conditions under which that agreement degrades. Second, we examine how measurement performance degrades during marine fog and assess the extent to which complementary measurement technologies preserve data availability under optically challenging conditions. Third, we compare the hierarchical



retrieval against an independent Bayesian optimal-estimation framework (WINDoe; Gebauer and Bell, 2024) applied to the same underlying observations at the Nantucket site to establish where the two methodologies diverge and how sensitive the retrieved profiles are to that choice of method.

This paper is organized as follows. Section 2 describes the WFIP3 coastal observation sites and their instrumentation. Section 3 details the processing methodology, including the VAD retrieval, turbulence estimation, quality control, merging strategy, and uncertainty quantification. Sections 4–6 evaluate the resulting profiles through inter-instrument comparisons, a coastal fog case study, and a comparison against the WINDoe optimal-estimation retrieval. Section 7 summarizes the conclusions and provides usage recommendations.

2 Observational sites and instrumentation

Observations were collected at four coastal sites distributed across the northern Mid-Atlantic Bight, the coastal ocean region extending from Cape Cod, Massachusetts, to New York. The four sites were Nantucket (NANT) Island's wastewater treatment facility, the Highlands Center at Cape Cod (CACO) in Massachusetts, the Block Island (BLOC) airport, and a coastal site in Rhode Island (RHOD) (Fig. 1). These span a range of coastal exposures, from the more exposed locations at Block Island and Nantucket to the more sheltered ones at Cape Cod and Rhode Island. Each site was instrumented with a combination of remote sensing and in situ systems selected to resolve vertical wind and turbulence structure from the surface through the lower troposphere, with specific configurations reflecting available tower infrastructure and campaign priorities (Table 1).

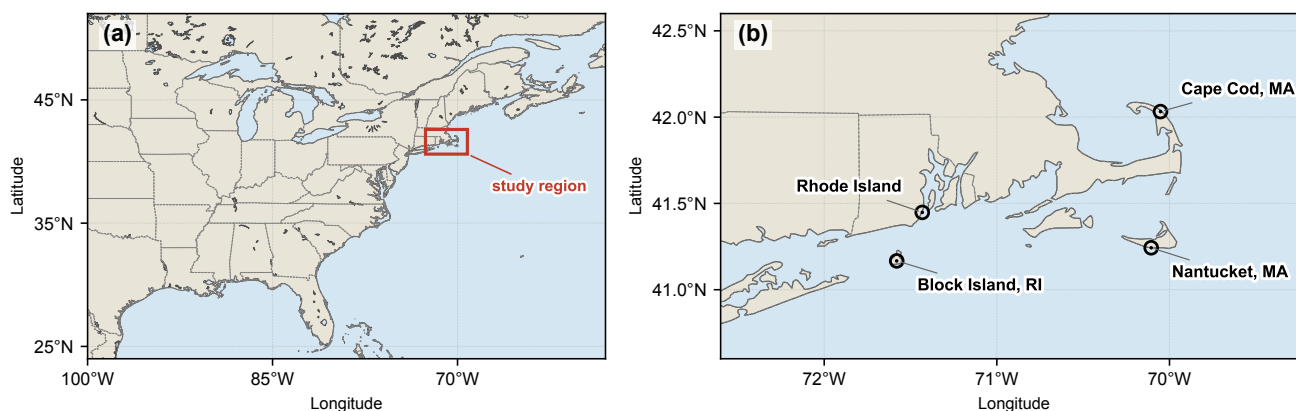


Figure 1. (a) Regional context, with the red box marking the study region. (b) Locations of the four WFIP3 coastal observation sites used in this study: Nantucket (NANT), Cape Cod (CACO), Block Island (BLOC), and Rhode Island (RHOD). Sites sample a range of coastal exposures across the northern Mid-Atlantic Bight. Land areas are shaded tan; ocean and coastal waters are shaded blue.



Table 1. WFIP3 coastal site characteristics and instrument configurations. Instrument identifiers (z01, z02, z03) correspond to DOE Wind Data Hub datastream naming conventions. Site location represents the spatial mean of instrument positions; site elevation is the mean of instrument elevations above sea level (ASL).

Site	Location	Coverage Period	Scanning Lidar	Profiling Lidar	Radar	Anemometer	Surface Met
Nantucket, MA	41.243°N, 70.104°W 4 m ASL	Feb 1, 2024 – Sep 9, 2025	Halo XR+ (z01), XR (z02)	WindCube V2.1 (z03)	915 MHz	METEK uSonic-3 Class A (z02)	Full ^a
Block Island, RI	41.167°N, 71.580°W 35 m ASL	Feb 1, 2024 – Sep 8, 2025	Halo XR (z01)	WindCube V1 (z03)	915 MHz	R.M. Young propeller-vane ^b (z01)	Full ^a
Cape Cod, MA	42.032°N, 70.052°W 47 m ASL	Feb 1, 2024 – Sep 6, 2025	Halo XR+ (z02)	WindCube V2 (z01)	- ^c	Gill R3-50 (z01, z02)	Full ^a
Rhode Island	41.448°N, 71.432°W 3 m ASL	Feb 7, 2024 – Sep 4, 2025	Halo Galion (z01)	ZephIR- 300 (z03)	Excluded ^c	Gill R3-50 (z01)	Partial (no precip)

In situ datastreams: nant.met.z02.a0 (sonic); caco.sonic.z01.c1, caco.sonic.z02.c1, rhod.sonic.z01.c1 (EddyPro);

bloc.met.z01.c1, nant.met.z05.c1 (surface meteorology); caco.met.z01.00, rhod.met.z01.a0 (surface meteorology).

^a “Full” surface met includes measurements of pressure, air temperature, relative humidity, and precipitation.

^b Block Island has no sonic anemometer; near-surface wind at 10 m above ground level is measured by an R.M. Young propeller-vane forming part of the NOAA Physical Sciences Laboratory (PSL) surface meteorological suite. It provides wind speed and direction but no turbulence quantities.

^c Rhode Island radar data were excluded from the current release due to ongoing instrument validation; the Cape Cod radar wind profiler ceased operating in January 2025 and could not be repaired, and its record was not incorporated (Sect. 2.1).

100 2.1 Remote sensing instrumentation

Scanning Doppler lidars were deployed at all four sites to obtain vertical profiles of horizontal wind speed through VAD retrievals and to estimate turbulence from scan-to-scan variability (Pearson et al., 2009). All lidars operated in the 1.5–1.6 μm wavelength range. The Halo XR and XR+ units and the ZephIR-300 operate at 1.565 μm , and the Halo Galion and the WindCube profilers operate at 1.543 μm . Scanning lidar retrievals below 100 m above ground level (AGL) are excluded from the product; on the 60° cone that layer comprises the lowest range gates, adjacent to the instruments’ minimum range, and the profiling lidars, which point near vertically, cover it instead. Scan configurations varied with deployment. BLOC z01, RHOD z01, NANT z02, and CACO z02 performed standard six-beam VAD scans at 60° elevation, with cycle times of ~25 s (BLOC z01, RHOD z01), ~28 s (NANT z02), and ~30 s (CACO z02). Instrument failures elsewhere in the campaign led to the NANT z02 unit being moved off the Nantucket site, and NANT z01, which had run a different scan pattern until 26 June 2024, was switched to the standard boundary layer profiling mode of six-beam VAD scans. NANT z01 therefore operated in two distinct configurations over the deployment. Through late June 2024 it alternated near-horizontal azimuthal sector sweeps (86–164° at ~0.5° elevation, for horizontal wind mapping) with periodic elevation sweeps for vertical profiling, the full sequence repeating



roughly every 5 minutes; usable VAD retrievals were sparse during this period. From 26 June 2024 onward it operated a six-beam VAD at 60° elevation (~28 s cycle) interleaved with periodic vertical stares, consistent with the other sites.

115 Profiling Doppler lidars provided vertical wind profiles at fixed height gates using DBS (Robey and Lundquist, 2022) or continuous-wave configurations (Smith et al., 2006). Four models were deployed across the campaign: Leosphere WindCube V2.1 at Nantucket, WindCube V1 at Block Island, WindCube V2 at Cape Cod, and ZephIR-300 at Rhode Island. The WindCube V1 (Block Island) uses a four-beam DBS scan; the V2.1 and V2 use a five-beam DBS scan (four oblique plus one vertical); the ZephIR-300 is a continuous-wave system that scans a 360° cone with its beam inclined 30° from the vertical.
 120 Maximum profiling heights ranged from 200 to 300 m under favorable aerosol conditions, with 10-minute averaging periods standard across instruments.

The instruments differ substantially in the volume of air each measurement samples, which should be considered when comparing turbulence quantities across platforms. The pulsed WindCube systems have a fixed range-gate probe length (approximately 20 m for the V1 and V2), whereas the continuous-wave ZephIR has a probe length that grows with the square of
 125 height, from 0.07 m at 10 m to 30 m at 200 m (Knoop et al., 2021). For an inclined beam, vertical spacing equals the spacing along the beam multiplied by the sine of its elevation angle. Table 2 lists the scanning lidars' range-gate spacing and minimum and maximum ranges along the beam. These distances are converted to true heights by projecting vertically during the VAD processing described in Sect. 3. At the scanning lidars' 60° elevation, $\sin 60^\circ = 0.866$, so a 30 m spacing along the beam corresponds to about 26 m vertically. The profiling lidars report heights that are already vertical, so their tabulated values need no
 130 conversion. Spacing is also not the same as the volume each measurement averages over. The scanning Halo lidars average over a conical volume that widens with range, whereas the tower-mounted sonic anemometers are effectively point measurements. The mismatch is most pronounced when point-scale sonic turbulence is compared against volume-averaged lidar turbulence.

Radar wind profilers at Nantucket and Block Island extended coverage through the depth of the boundary layer and into the lower free troposphere. The 915 MHz profilers used three-beam configurations (one vertical, two oblique at 66.4° elevation)
 135 with consensus averaging to retrieve horizontal and vertical winds (Carter et al., 1995; Ecklund et al., 1988). Each profile is a 29-minute consensus average emitted at a ~15-minute cadence, so successive profiles overlap by ~14 minutes and are not statistically independent. Vertical range-gate spacing was 58 m in low mode and 97 m in high mode. Prior to consensus averaging, the profiler data undergo quality control for ground clutter (Jordan et al., 1997), radio frequency interference, intermittent hard targets (Bianco et al., 2013), and second-trip echoes; the consensus winds ingested here are therefore already
 140 screened at the source, and the criteria described in Sect. 3 are applied on top of that processing. At Nantucket, a beam steering relay malfunction limited the profiler to vertical beam operation only from 10 May 00:00 UTC to 16 May 16:00 UTC, 2025; radar data over that window were excluded from merged products. Rhode Island radar data were excluded from the current release due to ongoing instrument validation. The Cape Cod radar wind profiler stopped operating in January 2025 and could not be repaired. Its January 2024 to January 2025 record is not included in this release but will be evaluated for a future release.
 145 Table 2 summarizes the technical specifications of all remote sensing instruments.

The ingested data levels differ by instrument class: standardized files (a0) for the scanning lidars (radial velocities) and the Nantucket sonic anemometer, raw vendor profiles (00) for the profiling lidars and radar wind profilers, EddyPro-derived



10-minute statistics (c1) for the Cape Cod and Rhode Island sonic stations, and reformatted NOAA surface meteorology (c1) at Nantucket and Block Island; full datastream identifiers and DOIs are listed in the code and data availability section.

Table 2. Technical specifications of remote sensing instruments deployed during WFIP3. Scanning lidars performed VAD or sector scans; profiling lidars used DBS or continuous wave configurations. The sample interval analyzed is the cadence of the records ingested for each instrument, which differs by instrument; all are aggregated to 10-minute averages for analysis.

Instrument	Type	Achieved Top ^a median (p90)	Range Gate	Min Range	Max Range (nominal)	Sample Interval Analyzed ^b
Halo XR (BLOC z01) ^c	Scanning	0.8 (2.4) km	30 m	75 m along-beam	6 km	26 s
Halo XR+ (NANT z01) ^d	Scanning	1.1 (3.7) km	30 m	75 m along-beam	12 km	28 s
Halo XR (NANT z02)	Scanning	0.8 (2.5) km	30 m	75 m along-beam	6.2 km	28 s
Halo Galion (RHOD z01)	Scanning	1.0 (2.4) km	30 m	75 m along-beam	6 km	25 s
Halo XR+ (CACO z02) ^e	Scanning	1.3 (3.9) km	30 m	75 m along-beam	12 km	30 s
WindCube V1 (BLOC z03)	Profiling	220 m	20 m	40 m AGL	200 m	2 min
WindCube V2.1 (NANT z03)	Profiling	190 m	20 m	40 m AGL	300 m	3.9 s
WindCube V2 (CACO z01)	Profiling	280 m	20 m	40 m AGL	200 m	10 min
ZephIR-300 (RHOD z03)	Profiling	280 m	0.07–30 m ^f	10 m AGL	300 m	1 s
NOAA PSL 915 MHz	Radar	1.7 (4.6) km (NANT),	58 m (low),	121 m AGL	6.1 km	15 min
		1.9 (5.0) km (BLOC)	97 m (high)			

^a Achieved profile top varies with aerosol load and cloud. The radar maximum range is the high-mode ceiling; the low mode reaches 2.9 km and the two combine into a single profile. For the profiling lidars the entry is the topmost configured gate, which is fixed. The radar's first gate is also nominal; the lowest gate that typically returns a valid wind is 190 m at Nantucket and 130 m at Block Island.

^b Native cadences differ: BLOC z03 outputs 2 min averaged profiles; NANT z03 a 5-beam DBS cycle every 3.9 s; RHOD z03 a 360° conical scan sampled at 50 Hz, output at 1 s; the radars emit a 29 min consensus every ~15 min, so successive profiles overlap by ~14 min and are not statistically independent.

^c System #216. 60 m range gates to 12 km until 14 February 2024, 30 m to 6 km thereafter; tabulated values are the latter configuration.

^d System #184. Azimuthal sector sweeps at ~0.5° elevation (86–164°) alternating with elevation sweeps, ~5-min cycle, until 26 June 2024, then a 6-position VAD at 60° tabulated cadence is the VAD mode.

^e AllSky variant; beam azimuth corrected to true north during processing.

^f Continuous-wave lidar; probe length grows with the square of height, 0.07 m at 10 m to 30 m at 200 m (Knoop et al., 2021).

150 2.2 In situ instrumentation

Sonic anemometers deployed on tower infrastructure measured three-dimensional wind components at 10–20 Hz, providing direct turbulence measurements near the surface (Bonin et al., 2016): at 5 m at Nantucket, 4 m at Rhode Island, and 4 and 10 m at Cape Cod (z01 and z02). Block Island has no sonic anemometer. Its winds at 10 m are measured by a propeller-vane anemometer which provides wind speed and direction but no turbulence statistics. Additional surface sensors recorded



155 atmospheric pressure, temperature, and relative humidity at intervals of 10 minutes or less. Sensors at Nantucket, Block Island,
and Cape Cod also recorded precipitation accumulation at these intervals.

3 Data processing methodology

3.1 Processing overview

Transforming heterogeneous wind measurements from multiple instrument types into standardized 10-minute profiles requires
160 reconciling different data structures, temporal sampling strategies, and quality control conventions. The processing framework
applied here proceeds through five stages: instrument-specific data ingestion and quality control; wind vector retrieval using
VAD methods; turbulence parameter calculation; hierarchical profile merging; and uncertainty quantification (Fig. 2).

All measurements were assigned to non-overlapping 10-minute output windows, each labeled by the start of its window
(e.g., the HH:00 average spans HH:00:00–HH:09:59 UTC), accommodating a range of native temporal resolutions spanning
165 high-frequency sonic anemometer data (10–20 Hz), scanning lidar scan cycles (~ 25 – 30 s for standard VAD scans, up to
 ~ 5 minutes for the NANT z01 dual-mode sector scan), profiling lidar output intervals ranging from ~ 1 s to 10 minutes,
and radar 29-minute consensus averages emitted at ~ 15 -minute cadence (Table 2). Each 10-minute window uses the radar
consensus record whose averaging period overlaps it most. Ties are resolved by choosing the record whose midpoint is closest
to the window midpoint. Adjacent windows therefore often share a record, and the radar data retain their 29-minute averaging
170 period. Bringing the instruments onto a common time grid required different aggregation methods while preserving available
turbulence information, as in previous multi-instrument campaigns (Dias Neto et al., 2023).

Wind and turbulence profiles were interpolated to a standardized grid of height above ground level with hybrid spacing:
dedicated levels at 4, 5, and 10 m matching the measured heights of the tower-mounted sonic anemometers, then 20 m intervals
to 100 m AGL and 30 m intervals above, extending in each interval to the highest level reached by any contributing instrument.
175 Single-height instruments occupy their exact measurement height as isolated points, with no interpolation to adjacent levels,
so no sonic anemometer is displaced across the strongly sheared surface layer. Heights reported by each instrument are already
referenced to the instrument (i.e., AGL); the terrain elevation for each instrument was obtained from the U.S. Geological Survey
National Map Elevation Point Query Service using deployment coordinates and is stored as a separate variable, so height above
sea level can be recovered as the sum of the AGL height and this ground elevation.

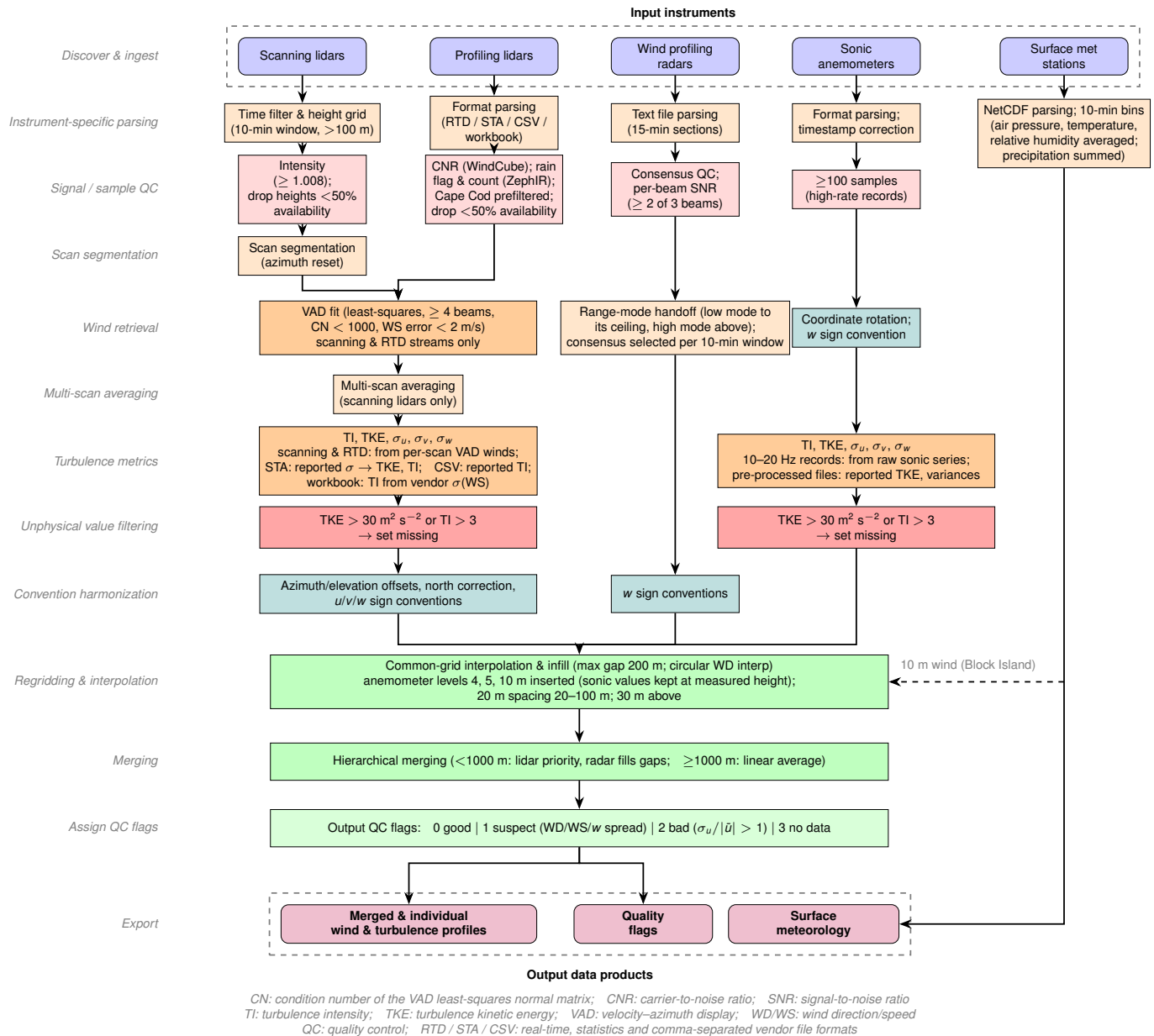


Figure 2. Multi-instrument processing workflow for integrating scanning lidars, profiling lidar, wind profiling radar, sonic anemometers and surface meteorological stations into merged 10-minute wind and turbulence profiles, quality flags, and surface meteorology. Color coding groups stages by processing category: blue, input instruments; red, quality control; orange, wind retrieval and turbulence derivation; teal, convention harmonization; green, regridding and hierarchical merging; purple, output products.



180 3.2 Coordinate system transformations

Each instrument reports its observations in a different coordinate convention, and these must be reconciled before integration. Scanning and profiling lidars measure radial velocities in beam coordinates, from which wind components must be extracted. Sonic anemometers measure in an instrument-fixed frame requiring rotation to a standard meteorological reference. Vertical velocity sign conventions were verified against concurrent precipitation observations, confirming that downward motion
 185 ($w < 0$) corresponded to rainfall events as expected. All wind measurements were then transformed to a common true-north meteorological convention (u = eastward, v = northward, w = upward positive) through site- and instrument-specific azimuth corrections. Most instruments were physically aligned to true north during deployment, requiring corrections of less than 2° , while instruments with non-north mounting orientations required larger adjustments (e.g., -80.8° for NANT z01, and a 180° term at three scanning lidars). Corrections applied are included in the processing code configuration, which keeps the correc-
 190 tion traceable. Beyond these geometric alignment corrections, a residual systematic offset of -16.34° was identified at the NANT z01 scanning lidar and applied empirically. It was determined as the campaign-mean circular bias of z01 wind direction relative to the co-located profiling lidar (z03), independently corroborated against the radar wind profiler; applying it removes the bias and reduces the z01–z03 directional root-mean-square error (RMSE) substantially. Its magnitude is comparable to the local magnetic declination ($\sim 14^\circ$ W), but because the instrument heading methodology should already reference true north,
 195 an instrument-configuration bias is the more likely source. The internal compass headings reported in the instrument files are not used in this processing; wind directions are corrected only with the fixed, externally determined azimuth offsets recorded in the processing configuration, ensuring full traceability.

3.3 Wind profile retrieval

Wind profiles from scanning instruments were retrieved using the VAD method (Banakh and Smalikho, 2013; Browning and
 200 Wexler, 1968; Waldteufel and Corbin, 1979; Newsom and Krishnamurthy, 2022). For conical scans at fixed elevation angle θ , the radial velocity V_r at azimuth α relates to wind components as:

$$V_r(\alpha) = u \cdot \sin(\alpha + \Delta\alpha) \cdot \cos(\theta + \Delta\theta) + v \cdot \cos(\alpha + \Delta\alpha) \cdot \cos(\theta + \Delta\theta) + w \cdot \sin(\theta + \Delta\theta) \quad (1)$$

where u , v , w are the eastward, northward, and vertical wind components (m s^{-1}), respectively, $\Delta\alpha$ is the lidar azimuth offset and $\Delta\theta$ is the lidar elevation offset. This relationship assumes horizontal homogeneity of the wind field over the scan volume
 205 and steady flow during the scan duration.

Between 3 and 24 complete scans were obtained per 10-minute period depending on instrument scan cycle duration (~ 25 –
 30 s for standard VAD scans, longer for the NANT z01 dual-mode sector scan), with each scan providing radial velocity measurements at each height gate. Wind components were retrieved by forming the normal equations of the overdetermined system (N equations, 3 unknowns) and solving them by pseudo-inverse. The system is solved once per 10-minute window and
 210 height gate, over the valid azimuth positions of every scan in that window together, so N is the pooled beam count across those scans; per-scan retrievals are computed separately and feed only the turbulence metrics of Sect. 3.4. Profiling lidars used four-



or five-beam DBS or continuous-wave configurations. Of these, only the Nantucket profiling lidar delivers raw radial velocities to the pipeline, and its winds are retrieved through the same VAD module as the scanning lidars; the Block Island, Cape Cod, and Rhode Island profiling lidars supply vendor-processed wind statistics (and, where available, within-window variances) that are ingested directly at their fixed height gates. Raw radial velocities are archived for the Cape Cod profiling lidar at ~ 1.4 Hz and could support component-resolved turbulence at that site in future work. VAD-derived uncertainties therefore exist only for the scanning lidars and the Nantucket profiling lidar.

For the scanning lidars, the retrieval uses only beams within 2° of the nominal 60° elevation. For the Nantucket profiling lidar, the retrieval uses the four inclined beams at their fixed 62° elevation and excludes the vertical beam. Vertical stares and low-elevation sector sweeps interleaved with some VAD cycles are excluded from both the fit and the beam count, as their geometry does not constrain the horizontal wind solution.

Three criteria were applied to assess the reliability of each VAD retrieval. First, a minimum of four valid azimuth positions was required. Although three positions are formally sufficient to solve for the three wind components, an exactly determined three-beam fit passes through all three points with zero residual, leaving no residual degrees of freedom in that scan's contribution to the fit; four positions provide the redundancy needed to estimate the fit uncertainty and apply the error-based rejection criterion. Relaxing this minimum to three would add 0.01 % of retrieved time-height points at Nantucket, Block Island, and Rhode Island, and 2.1 % at Cape Cod, the latter concentrated above 1 km. Second, the condition number of the normal matrix $X^T X$ (which measures how strongly the azimuthal sampling geometry amplifies radial-velocity noise into the retrieved components) was required to remain below 1000, ensuring both numerical stability and adequate azimuthal sampling diversity. Third, wind speed uncertainty derived from chi-square error propagation of VAD fit residuals, estimated using Newsom and Krishnamurthy (2022), was required to satisfy $\sigma_{WS} < 2.0 \text{ m s}^{-1}$. Retrievals exceeding this uncertainty threshold were excluded from merged profiles. Data availability per height level was recorded as the fraction of beams passing signal quality thresholds. Height levels whose availability fell below 50 % within a window were discarded before merging.

Wind speed and direction were subsequently calculated as $WS = \sqrt{u^2 + v^2}$ and $WD = \text{atan2}(-u, -v) \times (180/\pi)$, adjusted to meteorological convention (0° = north, clockwise positive).

3.4 Turbulence parameter estimation

Turbulence metrics were derived using different methodologies depending on the data source and native temporal resolution. Every instrument requires temporal averaging to separate the mean flow from its fluctuations, but they differ in what that averaging represents. Sonic anemometers sample at a point at 10–20 Hz, whereas the remote sensors average over a measurement volume and at a far coarser cadence. The instrument types also resolve different portions of the turbulence spectrum. Sonic anemometers resolve the inertial subrange and provide turbulence measurements in the conventional sense. The lidar-derived quantities are instead formed from scan-to-scan variability sampled at the instrument scan cadence (~ 25 – 30 s) over the 10-minute window, and therefore characterize larger-scale wind variability, spanning the meso- γ range, rather than inertial-subrange turbulence (Sathe and Mann, 2012). Lidar TKE and turbulence intensity (TI) should accordingly be interpreted as measures of resolved-scale wind variability, and are not directly comparable to the small-scale turbulence resolved by the sonic



anemometers. Turbulence intensity in particular is computed by different definitions across instruments. Where individual retrievals are available within the 10-minute window (the scanning lidars, the Nantucket profiling lidar, and the Nantucket sonic anemometer), turbulence intensity uses the hybrid wind speed denominator described below. For instruments that provide only pre-averaged 10-minute statistics, the turbulence intensity calculation depends on the instrument. The Cape Cod and Rhode
 250 Island profiling lidars use vendor-reported turbulence intensity. For the Block Island profiling lidar, turbulence intensity is the square root of turbulence kinetic energy (TKE) divided by mean wind speed, with TKE calculated from the vendor-reported component standard deviations. The Cape Cod and Rhode Island sonic anemometers use the along-wind standard deviation divided by mean wind speed. The specific method used for each instrument is recorded in the per-variable metadata of the output files. Because these definitions are not strictly commensurate, the merged turbulence intensity should be interpreted
 255 with reference to the contributing instruments at each height.

For scanning and profiling lidars providing raw radial velocities, turbulence statistics were calculated from time series of individual scan retrievals within each 10-minute window. At least three complete scan retrievals were required before velocity variances were computed. Each VAD fit additionally required a minimum number of valid azimuth positions (Sect. 3.3). VAD fitting was applied to each scan independently, producing time series of (u, v, w) components at $\sim 25\text{--}30$ s resolution
 260 for standard VAD scans (coarser for the NANT z01 dual-mode sector scan) depending on instrument scan configuration. Reynolds decomposition separated the 10-minute temporal mean flow $(\bar{u}, \bar{v}, \bar{w})$ from fluctuating components (u', v', w') , from which velocity standard deviations $(\sigma_u, \sigma_v, \sigma_w)$ were calculated following standard atmospheric turbulence practice (Kaimal and Finnigan, 1994; Stull, 1988). The same 10-minute Reynolds decomposition window was applied across all instruments, including the sonic anemometers (whose high-frequency records likewise require temporal averaging to separate mean and
 265 fluctuating components). We note that a longer averaging period (traditionally 30 minutes for flux and turbulence estimation) is often preferred, and that a 10-minute window may underestimate the lower-frequency contributions to turbulence (Agarwal and Lundquist, 2026); the shorter window was adopted here to keep turbulence consistent with the other 10-minute meteorological quantities in the product. We also acknowledge that applying direct Reynolds decomposition to lidar-derived velocity components can bias the estimated turbulence statistics due to cross-contamination (Sathe et al., 2015).

270 Turbulence kinetic energy was computed as:

$$\text{TKE} = \frac{1}{2} (\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \quad (2)$$

Turbulence intensity was computed using a hybrid wind speed formulation developed to minimize biases specific to lidar beam geometry (Rosenbusch et al., 2021). Scalar averaging of lidar-reconstructed wind speeds overestimates the cup-equivalent wind speed under strong turbulence, because decorrelated vertical wind speed fluctuations enter each instantaneous reconstruction through the inclined beam geometry. Similarly, vector averaging underestimates the cup-equivalent wind speed because
 275 fluctuations perpendicular to the mean flow (i.e., wind direction fluctuations) vanish from the time-averaged components. A linear combination of the two averages cancels these opposing biases to first order (Rosenbusch et al., 2021):



$$WS_{\text{hybrid}} = \alpha WS_{\text{scalar}} + (1 - \alpha) WS_{\text{vector}} \quad (3)$$

where WS_{scalar} is the 10-minute mean of instantaneous horizontal wind speed magnitudes and $WS_{\text{vector}} = \sqrt{\bar{u}^2 + \bar{v}^2}$ is the
 280 vector-averaged wind speed. The theoretically optimal scalar weight under turbulence assumptions consistent with International Electrotechnical Commission (IEC) design standards is $\alpha = 2/3$. Empirical analysis across 38 lidar-to-cup verification campaigns provided in Rosenbusch et al. (2021) yielded an ensemble mean of $\alpha \approx 0.55$, within the cross-site variability of the theoretical value. We adopt $\alpha = 0.55$, noting that values within $\alpha \in [0.55, 2/3]$ cannot be statistically distinguished from one another given currently available verification data (Rosenbusch et al., 2021). The hybrid formulation was verified through
 285 comparisons between profiling lidars and cup anemometers. Because the biases it corrects also arise in other inclined-beam wind retrievals, we extend its use to the scanning lidars' VAD retrievals, applying the same coefficient.

Turbulence intensity was calculated as:

$$TI = \frac{\sigma_{ws}}{WS_{\text{hybrid}}} \quad (4)$$

when $WS_{\text{hybrid}} \geq 0.1 \text{ m s}^{-1}$. Here, σ_{ws} is the standard deviation of the instantaneous scalar wind speed retrievals within
 290 each 10-minute window.

Rosenbusch et al. (2021) developed the hybrid formulation for mean wind speed only. Using it as the turbulence intensity denominator is a further extension made here. This follows the cup-anemometer convention of dividing the standard deviation of horizontal wind speed by its mean (International Electrotechnical Commission, 2019), rather than defining turbulence intensity from component variances or TKE. This correction applies to the mean only. The individual scan speeds used to calculate
 295 σ_{ws} still include the projected vertical-velocity contribution described above, which biases lidar turbulence intensity upward relative to a point measurement. This contributes to the cross-contamination noted above.

Because turbulence intensity normalizes the velocity variability by the mean wind speed, lower daytime wind speeds can raise TI even when the underlying variance is unchanged. Daily and seasonal TI patterns therefore partly reflect changes in mean wind speed. Turbulence kinetic energy, which carries no wind speed normalization, therefore provides a complementary,
 300 denominator-free measure of the variance; where the diurnal cycles of TI and TKE diverge, the TI signal is driven by the wind speed denominator and not by a change in mixing intensity.

Sonic anemometers deployed at fixed heights provided high-frequency (10–20 Hz) three-dimensional wind measurements, yielding $\mathcal{O}(10^4)$ samples per 10-minute period. For instruments with hourly file structures, raw time series were extracted for each 10-minute interval; a minimum of 100 valid samples was required. Reynolds decomposition and velocity variance
 305 calculations followed the same formulas as the lidar scan-based methods, with the substantially higher sampling rate enabling resolution of smaller-scale turbulence. Because sonic anemometers provide point-like measurements and are not subject to the inter-beam spatial separation inherent to mono-static lidar, no hybrid averaging correction was applied to sonic-derived wind speeds. The raw Nantucket sonic-anemometer data pass through the same turbulence routine as the lidar retrievals, including



the hybrid denominator, so they share the same TI definition. The Cape Cod and Rhode Island sonic anemometers instead
 310 provide pre-averaged statistics and use the along-wind standard deviation divided by mean wind speed.

Turbulence measurements are checked against physical criteria before merging. The exception is the Rhode Island profil-
 ing lidar, whose vendor-reported TI receives no additional screening. Profiles are rejected if TKE exceeds $30 \text{ m}^2 \text{ s}^{-2}$, above
 the maximum observed in well-mixed convective boundary layers (Kaimal and Finnigan, 1994; Lenschow et al., 1980; Stull,
 1988), or if TI exceeds 3.0, which is inconsistent with IEC design envelopes and reported atmospheric conditions (International
 315 Electrotechnical Commission, 2019; Türk and Emeis, 2010). A third criterion rejected profiles where TKE exceeded $15 \text{ m}^2 \text{ s}^{-2}$
 simultaneously with any velocity-component standard deviation exceeding 10 m s^{-1} , a combination the first criterion already
 excludes and which is retained as an explicit guard. Together these pre-merge criteria withheld a small fraction of calculated
 turbulence profiles across all sites, with the highest rejection rates occurring during precipitation events and instrument mal-
 function periods. Rejected profiles are withheld rather than flagged, so a screened cell is indistinguishable in the delivered files
 320 from one where no measurement was made. No equivalent absolute bound is applied to horizontal wind speed, since plausible
 values span the full range from calm to jet-stream conditions across the profile's vertical extent. Wind speeds exceeding 60 m
 s^{-1} do survive quality control, at a rate of order $10^{-3} \%$ of good-quality retrievals and predominantly at heights above 4 km
 where returns are sparse. Users requiring strict physical bounds should screen on the accompanying wind speed uncertainty
 field or impose application-specific limits or quality flags (Sect. 3.6).

325 3.5 Hierarchical profile merging

The merging stage combines the individual instrument retrievals into best-estimate wind and turbulence profiles, with a height-
 dependent strategy that favors the lidars where they report, because they (1) resolve the profile more finely in height than the
 radar, and (2) represent each 10-minute window with retrievals made within it, where the radar contributes a single consensus
 profile averaged over 29 minutes. Below 1000 m AGL , radar data are excluded at any height level where lidar data are available;
 330 the radar contributes only where no lidar measurement exists. At and above 1000 m , all available instruments contribute equally.
 At near-surface heights ($4\text{--}10 \text{ m AGL}$), the in situ sensors are generally the sole data source, though the continuous-wave
 profiling lidar at Rhode Island also samples from 10 m .

Where multiple instruments contribute valid data at the same height, each variable is averaged separately. Wind direction
 uses circular vector averaging to handle the $0^\circ/360^\circ$ boundary correctly (Berens, 2009). Merged wind speed is the average
 335 of the reported speeds, not the speed calculated from an averaged wind vector. Similarly, merged TKE is the average of the
 instruments' TKE estimates, not a value recalculated from the merged component standard deviations.

For each 10-minute interval, each instrument's profile was interpolated onto the standardized height grid using linear interpo-
 lation within its measured height range; no extrapolation beyond an instrument's uppermost valid measurement was performed.
 Single-height instruments such as sonic anemometers were assigned to the grid level at their measurement height (Sect. 3.1),
 340 with no interpolation to adjacent levels. To preserve profile integrity, no interpolation was performed across gaps exceeding
 200 m between consecutive valid measurement heights within a single instrument's profile. The merged value was stored for



each grid point and time step, alongside the contributing instruments' own uncertainty fields and a per-time-step record of which instruments contributed.

Figure 3 illustrates the merging rules for one 10-minute interval. Each instrument contributes up to its highest valid measurement: the propeller-vane anemometer at 10 m, the profiling lidar from 40 to 220 m, and the scanning lidar up to 2050 m. Above 2050 m, only the radar contributes. Although three instruments report data between 130 and 220 m, the merged values there use only the two lidars. Below 1000 m, radar data are excluded wherever lidar data are available. The merged profile is continuous across the plotted height range. At every shared height in panel (b), the radar and scanning lidar differ by less than two standard deviations of the scanning lidar's scan-to-scan wind speed.

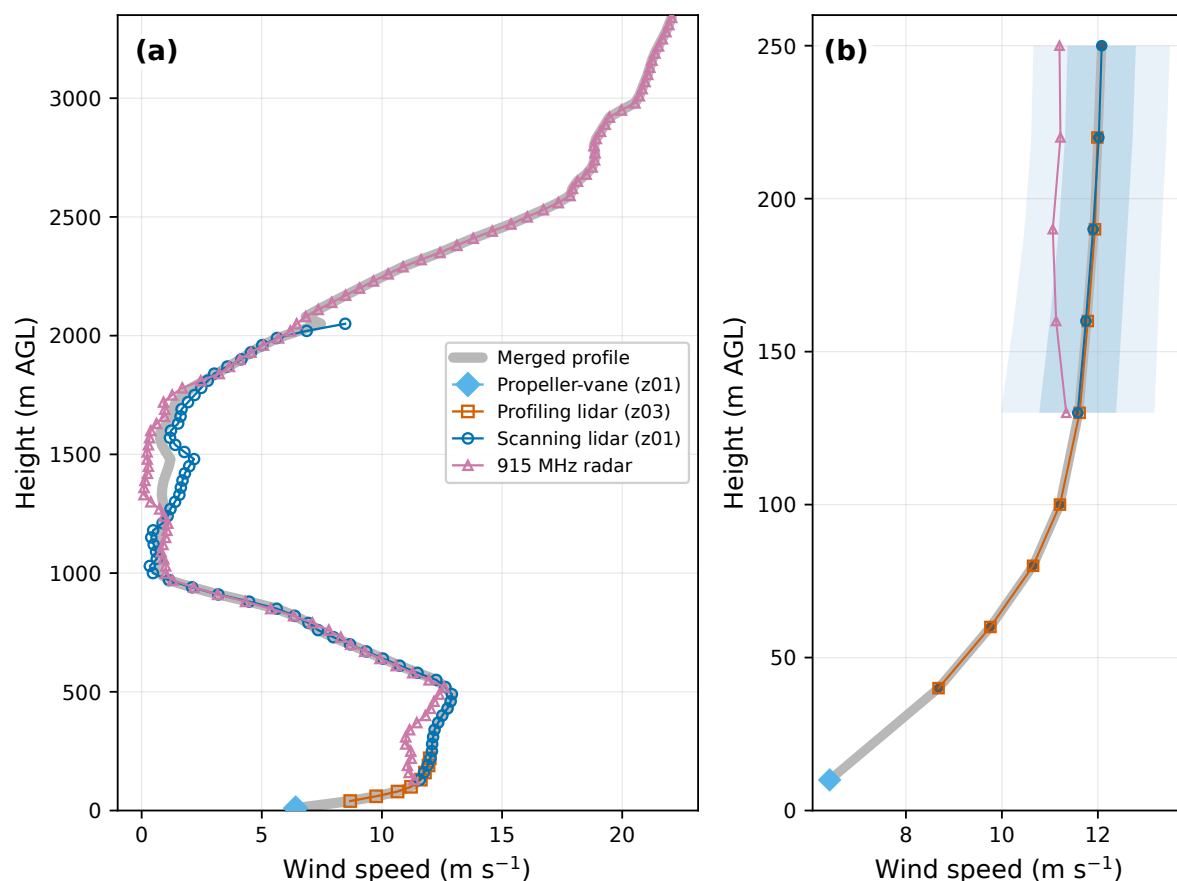


Figure 3. Example merged wind profile during a low-level jet at Block Island on 13 February 2024 at 08:10 UTC. (a) Full profile. (b) Lowest 250 m. Individual instrument measurements and the merged profile are shown at the corresponding grid heights. Below 1000 m, radar measurements are shown for comparison but do not contribute to the merged profile where lidar data are available. Shading in (b) shows ± 1 and ± 2 standard deviations of the scanning lidar's scan-to-scan wind speed within the 10-minute window (Sect. 3.4); it is variability of the wind, not measurement uncertainty, and no other instrument reports an equivalent. The scanning-lidar event log flags this interval as an LLJ with its nose at 490 m; wind speed increases again above 1030 m.



350 3.6 Quality flagging and traceability

Each merged wind variable carries a per-parameter quality control (QC) flag with four levels: 0 = good, 1 = suspect, 2 = bad, 3 = no value present, i.e., either no measurement was made or the value was rejected by quality control. Flag 1 is assigned when inter-instrument disagreement exceeds parameter-specific thresholds: wind speed spread greater than $\max(1.5, 0.5 \times \text{median WS}) \text{ m s}^{-1}$, wind direction circular spread exceeding 30° , or vertical velocity spread exceeding 2.0 m s^{-1} ; or when
 355 extreme vertical velocities ($|w| > 7.0 \text{ m s}^{-1}$) are observed. Flag 2 is reserved for turbulence levels inconsistent with a meaningful mean flow estimate, $\sigma_u/|\bar{u}| > 1.0$, where σ_u is the turbulence standard deviation of Sect. 3.4 rather than the fit uncertainty of Sect. 3.8. Users requiring research-grade data should filter to QC = 0; QC = 1 data are retained for applications where inter-instrument spread can be tolerated or investigated. The strength of the QC = 0 designation varies with instrument coverage. Where two or more instruments contribute to a height, it indicates both that the value passed instrument-level quality control
 360 and that contributing instruments agreed; where a single instrument covers a height, as is common above the lidar ceiling, it indicates only the former. The `instrument_availability` bitmask in each file identifies the instruments contributing at each time step. It is not resolved by height, so it distinguishes time periods with multi-instrument corroboration from single-source periods rather than identifying which instruments contributed at a given level.

To support traceability, individual instrument retrievals are stored alongside merged profiles, allowing users to assess source-
 365 level data quality and conduct instrument-specific validation independently of the merged product.

3.7 Empirical threshold determination and anomaly detection

Vertical velocity retrievals were flagged as suspect when $|w| > 7 \text{ m s}^{-1}$, a threshold consistent with the upper bound of observed convective boundary layer updrafts (Kaimal and Finnigan, 1994; Stull, 1988). Convective downdrafts, outflows, and gravity waves can briefly exceed this threshold. The flag therefore identifies retrievals for review rather than marking a strict physical
 370 limit. Of the 16.7 million instrument-level retrievals in the delivered product, 0.156 % exceeded the threshold. Radar retrievals at Block Island and Nantucket accounted for 96 % of these cases. Exceedances affected 0.379 % and 0.342 % of the two radars' retrievals, respectively. Nearly all indicated downward motion: 100 % at Block Island and 99 % at Nantucket. This pattern is consistent with hydrometeor fall speeds during heavy precipitation rather than instrument artifacts. The Cape Cod z02 lidar contributes most of the remainder (0.036 % of its retrievals, of mixed sign, with occasional magnitudes up to $\pm 45 \text{ m s}^{-1}$); no
 375 other lidar or sonic anemometer exceeded the threshold in more than a handful of retrievals. The flag is carried by the merged product, and instrument-level vertical velocity fields are not flagged by this criterion.

Vertical velocity carries an interpretive caveat that applies to all remote sensors in the suite. Both radar and lidar measure the reflectivity- or backscatter-weighted motion of scatterers instead of air motion alone, so during precipitation and fog the retrieved w includes hydrometeor fall speeds. Campaign-mean w is consequently most negative for the radars, which continue
 380 to profile where the lidars lose signal and which remain sensitive to hydrometeor fall speeds throughout the profile. The lidars additionally carry constant per-instrument offsets in campaign-mean w , spanning -0.29 to $+0.13 \text{ m s}^{-1}$ across the scanning lidars and invariant with height, time of day, and season; height-matched differences between co-located instruments are con-



stant across the profile, and one instrument is offset positive, identifying these as line-of-sight biases, not scatterer motion. Pairwise vertical velocity correlations between instruments are positive at every site, confirming consistent sign conventions; a constant offset does not affect correlation. These offsets are documented rather than corrected. Because they are constant, differences and contrasts between conditions measured by the same instrument at the same height are unaffected, but absolute campaign-mean w is biased at the per-instrument level. All scanning lidar w values in the product derive from the VAD inversion; vertical stare data are excluded from the retrieval entirely (Sect. 3.3). Users interpreting w as air motion should screen for precipitation, or restrict analysis to the sonic anemometers, which measure air motion directly.

Wind direction uncertainties from VAD fitting exhibited singular behavior at low wind speeds due to mathematical dependence on WS^{-2} in the error propagation formula. Analysis of 9.1 million data points across 1,973 instrument files identified $WS = 2.0 \text{ m s}^{-1}$ as the threshold below which direction uncertainty estimates become unreliable. Applying this threshold reduced the fraction of files containing unphysical direction errors ($> 180^\circ$) from 17.3% to 1.8% while retaining 96.7% of the data; remaining values are capped at 180° , so no direction uncertainty in the delivered product exceeds that bound.

Two periods of anomalous radar behavior were identified during post-campaign analysis. The Rhode Island radar showed systematic directional anomalies from February 2025 onward and was excluded from the data product pending validation by the instrument team, and the Nantucket radar suffered a beam steering malfunction between 10 and 16 May 2025 (Sect. 2.1). Data from both periods were removed before merging, so they do not appear in the merged product and are not represented in its agreement flags.

3.8 Uncertainty quantification

Wind component uncertainties were estimated from VAD least-squares fit residuals using chi-square error propagation. The variance scaling factor $s^2 = \chi^2/\text{dof}$ (where χ^2 is the sum of squared residuals and $\text{dof} = N_{\text{beams}} - 3$) was combined with the diagonal elements of the covariance matrix $(X^T X)^{-1}$ to produce component uncertainties $\sigma_u, \sigma_v, \sigma_w$; these are fit uncertainties and are distinct from the turbulence standard deviations written with the same symbols in Sect. 3.4.

Derived parameter uncertainties were calculated as per Newsom et al. (2017):

$$\sigma_{WS} = \sqrt{(u \cdot \sigma_u)^2 + (v \cdot \sigma_v)^2} / WS \quad (5)$$

and

$$\sigma_{WD} = (180/\pi) \times \sqrt{(u \cdot \sigma_v)^2 + (v \cdot \sigma_u)^2} / WS^2 \quad (6)$$

for $WS \geq 2.0 \text{ m s}^{-1}$, yielding instrument-dependent σ_{WS} values, typically below 0.5 m s^{-1} for good signal conditions. Wind direction uncertainty was capped at 180° and set to NaN (Not a Number) for $WS < 2.0 \text{ m s}^{-1}$, where the WS^{-2} dependence produces singular behavior. Retrievals with $\sigma_{WS} > 2.0 \text{ m s}^{-1}$ were rejected.

These VAD-derived uncertainties are carried through the merging pipeline per contributing instrument; no additional uncertainty inflation is applied during height interpolation or vertical gap filling. They are delivered per contributing instrument such that the merged product carries no single merged uncertainty variable, so users requiring an uncertainty on a merged value



415 should take it from the error field of the instrument contributing at that height. Comparison with observed inter-instrument spread suggests these formal uncertainties underestimate true representativeness uncertainty (Sect. 4.2).

4 Validation and data quality assessment

We assess the merged product in three ways: agreement among co-located instruments, vertical and temporal availability of the merged data, and effectiveness of the quality control scheme. Together, they indicate how much confidence users can place
420 in the profiles, and where that confidence degrades.

4.1 Inter-instrument comparison

Inter-instrument agreement was assessed by comparing co-located measurements at identical time-height points where multiple instruments provided valid retrievals. Comparisons were restricted to good-quality data and required wind speeds exceeding 2 m s^{-1} for wind direction analysis; the wind direction agreement flag was not applied, so the direction statistics retain
425 the disagreement they measure. Flag 1 identifies disagreement between instruments. The wind speed statistics below therefore describe agreement among retrievals that have already passed this check. The flag rates reported later show how often retrievals failed the check.



Table 3. Agreement between co-located instruments at matching times and heights, after the screening described in the text. Mean difference is A minus B; RMSE is the root-mean-square error. The correlation coefficient r is Pearson’s correlation for wind speed and circular correlation for wind direction. Scanning–profiling lidar comparisons cover their overlapping heights: 100–280 m above ground level for wind speed and 100–200 m AGL for wind direction. Lidar–radar comparisons include all overlapping heights. The Nantucket z01/z02 pair has no overlapping retrievals (Sect. 2.1).

Site	Pair (A/B)	Wind speed (m s ^{−1})				Wind direction (°)			
		<i>N</i>	Mean diff.	RMSE	<i>r</i>	<i>N</i>	Mean diff.	RMSE	<i>r</i>
<i>Scanning lidar (A) vs profiling lidar (B)</i>									
Nantucket	z01/z03	96,668	−0.11	0.22	0.9994	94,628	+0.05	1.4	0.9997
Nantucket	z02/z03	29,729	−0.14	0.93	0.9872	29,530	+2.42	13.9	0.9767
Block Island	z01/z03	146,095	−0.20	0.36	0.9982	115,573	+6.76	7.1	0.9990
Cape Cod	z02/z01	246,812	−0.35	0.78	0.9895	129,816	+0.02	7.9	0.9928
Rhode Island	z01/z03	205,529	−0.03	0.59	0.9874	106,531	+2.55	19.5	0.9693
<i>Lidar (A) vs radar wind profiler (B)</i>									
Nantucket	z01/radar	836,670	+0.30	1.44 ^a	0.9749	804,391	+1.21	6.9	0.9919
Nantucket	z02/radar	219,184	+0.62	1.95 ^a	0.9622	210,736	+6.45	19.3	0.9378
Nantucket	z03/radar	38,290	+0.90	1.44 ^b	0.9831	37,327	+2.12	7.6	0.9931
Block Island	z01/radar	941,249	+0.17	0.78 ^a	0.9916	911,237	+4.54	8.0	0.9905
Block Island	z03/radar	160,291	+0.24	0.68	0.9914	156,123	−2.20	5.5	0.9943

^a Above 500 m AGL, wind speed RMSE is 1.39 m s^{-1} for Nantucket z01, 1.98 m s^{-1} for Nantucket z02, and 0.87 m s^{-1} for Block Island z01.

^b The Nantucket profiling lidar overlaps only the radar’s lowest valid range gate, limiting this comparison to 190 m AGL.

Wind speed statistics for the lidar pairs were computed over the 100–280 m AGL layer where scanning and profiling lidars overlap (Table 3). The Nantucket z01/z02 pair yielded no overlapping retrievals and does not contribute, because z01 ran a sector scan during the early deployment before transitioning to a standard VAD (Sect. 2.1). Lidar-lidar RMSE is $\sim 0.6 \text{ m s}^{-1}$ pooled over the five pairs and, pooled by site, ranges from 0.36 m s^{-1} at Block Island to 0.78 m s^{-1} at Cape Cod, with correlation exceeding $r = 0.96$ and systematic differences of at most 0.35 m s^{-1} for every pair. The scanning lidars share a common scan configuration, so this range reflects the instruments paired at each site and the conditions there rather than differences in scan geometry.

Wind direction intercomparison employed circular statistics (Berens, 2009), computed across 100–200 m AGL (the height range over which scanning and profiling lidars overlap at all four sites) for the same scanning–profiling pairs (Table 3). Circular correlation coefficients exceed $r = 0.96$ for all pairs, and circular RMSE ranges from 1.4° at Nantucket to 19.5° at Rhode Island. At Rhode Island, most wind direction differences are small: 92 % fall within 5° , and the main cluster has an RMSE of 3.5° . About 1 % differ by nearly 180° , raising the overall RMSE. These large differences occur mainly at low wind speeds, consistent with the directional ambiguity of continuous-wave profiling, and none occur above 10 m s^{-1} . The Nantucket and Cape Cod mean differences are the offsets remaining after empirical azimuth corrections. The Block Island value has not



been corrected. Because those two corrections were fitted over the full campaign against these same co-located instruments, their near-zero residuals are expected by construction and are not evidence of independent agreement. The sonic anemometers are referenced to true north in the delivered product, following correction of a documented upstream azimuth offset at the Nantucket 5 m sonic, but that does not make any single instrument an absolute reference, as each carries its own mounting alignment uncertainty. Where three instruments overlap, however, a persistent disagreement can be attributed to one of them, since when two agree and the third does not, the third is the likely outlier. On that basis an empirical azimuth correction was applied at Nantucket, where the scanning lidar departed from both the co-located profiling lidar and the radar wind profiler by an amount too large to attribute to mounting tolerance (Sect. 3.2). Smaller residual offsets are documented rather than corrected: at Block Island the scanning lidar sits $+4.5^\circ$ from the radar and $+6.8^\circ$ from the profiling lidar, within the range plausibly explained by alignment and scan geometry. At Cape Cod the co-located sonic anemometers resolve a difference that the two lidars alone could not. With the measured veer between the sonic and lidar heights removed, the profiling lidar sits within 2° of the sonic reference while the scanning lidar sits near $+16^\circ$. That offset is constant across wind speed bins and direction sectors and varies by less than 0.2° across the full 130–250 m overlap. A flow-dependent difference would not behave this way, and the magnitude matches the local magnetic declination. A -14.5° correction was therefore applied to the Cape Cod scanning lidar. Height-dependence of RMSE is weak at Nantucket and Block Island ($< 0.3^\circ$ variation across the 130–190 m grid levels) and modest at Cape Cod (0.5°), while at Rhode Island RMSE grows monotonically from 17.8° at 130 m to 21.3° at 190 m.

Scanning lidar and radar wind profiler directions agree closely at the two radar-equipped sites, except for the short Nantucket z02 record (Table 3). Wind speed agreement between the two instrument types is 0.87 m s^{-1} (Block Island) and 1.39 m s^{-1} (Nantucket) above 500 m AGL, degrading below 200 m where the comparison relies on the radar’s lowest range gates immediately above its blind zone.

4.2 Data availability and measurement uncertainty

Merged wind speed availability below 200 m AGL ranged from 84 % at Rhode Island to 98 % at Block Island, exceeding 90 % at the other three sites, and decreased with height as environmental signal loss and quality control screening removed returns (Fig. 4). At every site the merged profile carried a quality-controlled wind at some height in more than 99.9 % of 10-minute windows, so these differences describe where in the column returns were available, not whether the site was delivering a profile at all. Nantucket and Block Island, whose 915 MHz radar wind profilers are included in this release, never dropped below 10 % availability across the 6 km analysis domain, whereas Cape Cod and Rhode Island fell below that level within the lowest 2.5 km; this is the practical gain from combining instrument types, and this redundancy is the point of the merge. When the Nantucket scanning lidar fell to a small fraction of its normal VAD retrieval volume from 20 July 2025 onward, all 6,727 10-minute profiles present in the Nantucket record over the remaining 50 days still carried a merged wind, sustained by the co-located radar wind profiler and profiling lidar. Gaps in the merged product are overwhelmingly partial rather than total: windows carrying no quality-controlled wind at any height account for 0.022 % of the record, so a missing value is almost always a height-dependent loss within a column that is otherwise reporting.



VAD wind speed uncertainty is instrument-dependent rather than uniform across sites (Fig. 5). Below 2 km the uncertainty curves of all instruments overlap across both wind regimes. Aloft, under strong winds, they separate into two groups that do not overlap at all, the Block Island and Nantucket z01 scanning lidars reporting markedly smaller uncertainty than the Nantucket z02, Cape Cod, and Rhode Island scanning lidars, mainly because aerosol loading, and with it the number of valid returns, falls off with height. Because a single wind vector is fitted to every beam of the 10-minute window, this uncertainty measures departures from wind uniformity over that window and across the scan cone, which is roughly 1.2 km wide at 1 km height for the 60° geometry used here. It rises with the within-window standard deviation of all three wind components alike (Spearman rank correlations of 0.72–0.97, and 0.78–0.98 with turbulence kinetic energy), and horizontal variability supplies roughly 70 % of it. Its dependence on mean wind speed is weak (0.18–0.26), because the explicit wind speed normalization in the error propagation cancels algebraically, leaving only the speed dependence the fit residual itself carries. These errors, propagated from the VAD least-squares fit covariance matrix, reflect internal scan consistency rather than absolute retrieval accuracy: over the 100–200 m layer, where co-located instruments allow the comparison, the mean VAD uncertainty of 0.112 m s^{-1} underestimates the observed inter-instrument spread, the sample standard deviation of the co-located instruments' wind speeds at each time-height point with at least two contributors, of 0.324 m s^{-1} by a factor of ~ 2.9 (2.1 among the lidars alone, the only instruments contributing VAD uncertainties), reflecting the representativeness uncertainty that formal fit errors do not capture. Users requiring rigorous uncertainty quantification should use inter-instrument spread as the more conservative estimate. The vendor-processed profiling lidars (Block Island z03, Cape Cod z01, Rhode Island z03) do not pass through the VAD retrieval and so carry no VAD uncertainty; among the profiling units, only the Nantucket z03 contributes.

4.3 Seasonal and diurnal structure

Seasonal mean diurnal wind speed and turbulence intensity profiles reveal systematic cross-site differences in boundary layer structure over the 19-month campaign (Figs. 6 and 7). Wind speeds are slowest in summer at all sites, as expected from seasonal synoptic forcing over the northeast U.S. shelf and consistent with previous observations in this region (Bodini et al., 2019). Above 500 m winter is the fastest season at every site, while below 500 m spring exceeds winter by $0.3\text{--}0.5 \text{ m s}^{-1}$ at all four sites. The diurnal cycle in turbulence intensity is strongest at Block Island. A daytime convective peak is present at all four sites between 14 and 20 UTC during summer and autumn, consistent with daytime boundary layer mixing. At all four sites the profiling lidars extend the turbulence record below 100 m; no scanning lidar contributes a turbulence intensity below that height at any site. Turbulence intensity in that layer is markedly higher than aloft, with a campaign median of 0.13 against 0.05 above 100 m and an interquartile range of 0.09–0.19; site medians span 0.12 at Nantucket to 0.16 at Rhode Island. The afternoon enhancement differs in amplitude between sites. At Cape Cod, TI in the 40–120 m layer rises from 0.09 at night to 0.16 between 14 and 20 UTC in summer (a factor of 1.8), against 0.10 to 0.15 in autumn (1.5). Large values of surface TI at Rhode Island reflect frequent low wind speeds at that site (28.9 % of observations below 2 m s^{-1}), which inflate TI as the denominator approaches zero. Across the full campaign, TI ranged from 0.01 to 0.22 (5th–95th percentile; median 0.05) and TKE from 0.02 to $2.05 \text{ m}^2 \text{ s}^{-2}$ (median $0.21 \text{ m}^2 \text{ s}^{-2}$), overlapping the $0.1\text{--}3.0 \text{ m}^2 \text{ s}^{-2}$ range reported for open-ocean and coastal environments (Türk and Emeis, 2010) and seen previously in this region (Bodini et al., 2019).

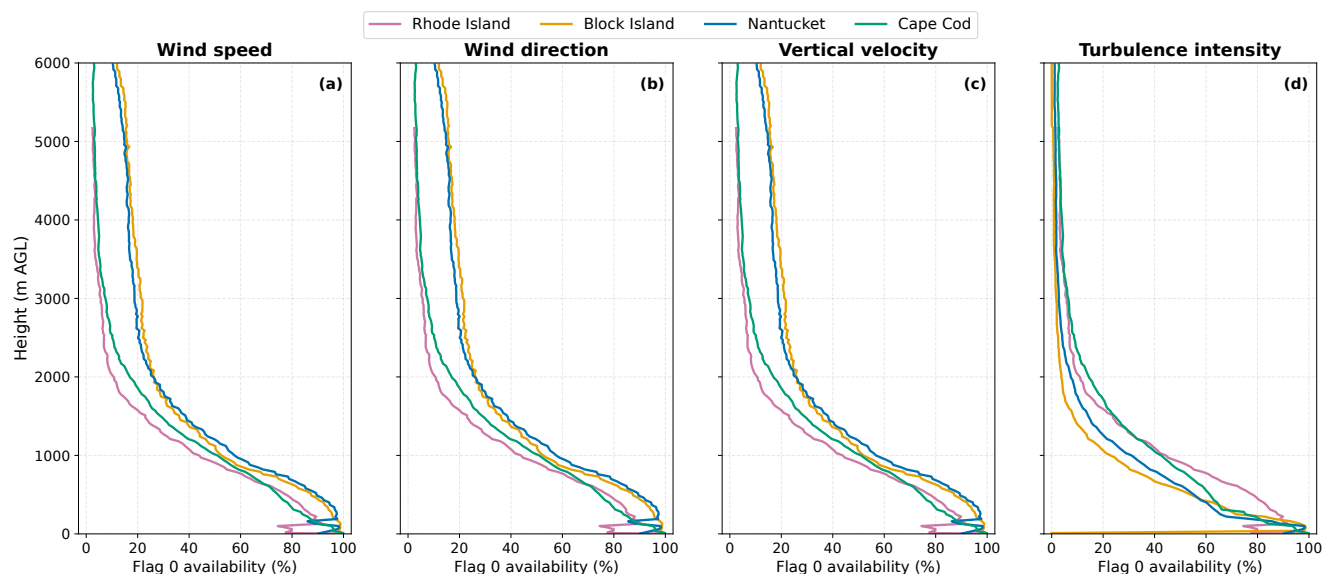


Figure 4. Data availability as a function of height for wind speed, wind direction, vertical velocity, and turbulence intensity at all four sites (February 2024–September 2025). Availability below 200 m AGL ranges from 84 % (Rhode Island) to 98 % (Block Island) and decreases with height. Block Island and Nantucket retain higher availability of wind speed, direction and vertical velocity above 1000 m owing to their 915 MHz radar wind profilers. Turbulence intensity availability is more restricted than the mean wind parameters at Nantucket, Block Island, and Cape Cod; at the two radar sites this is because variance estimates require lidar or sonic anemometer retrievals, which do not extend as far aloft as the radar.

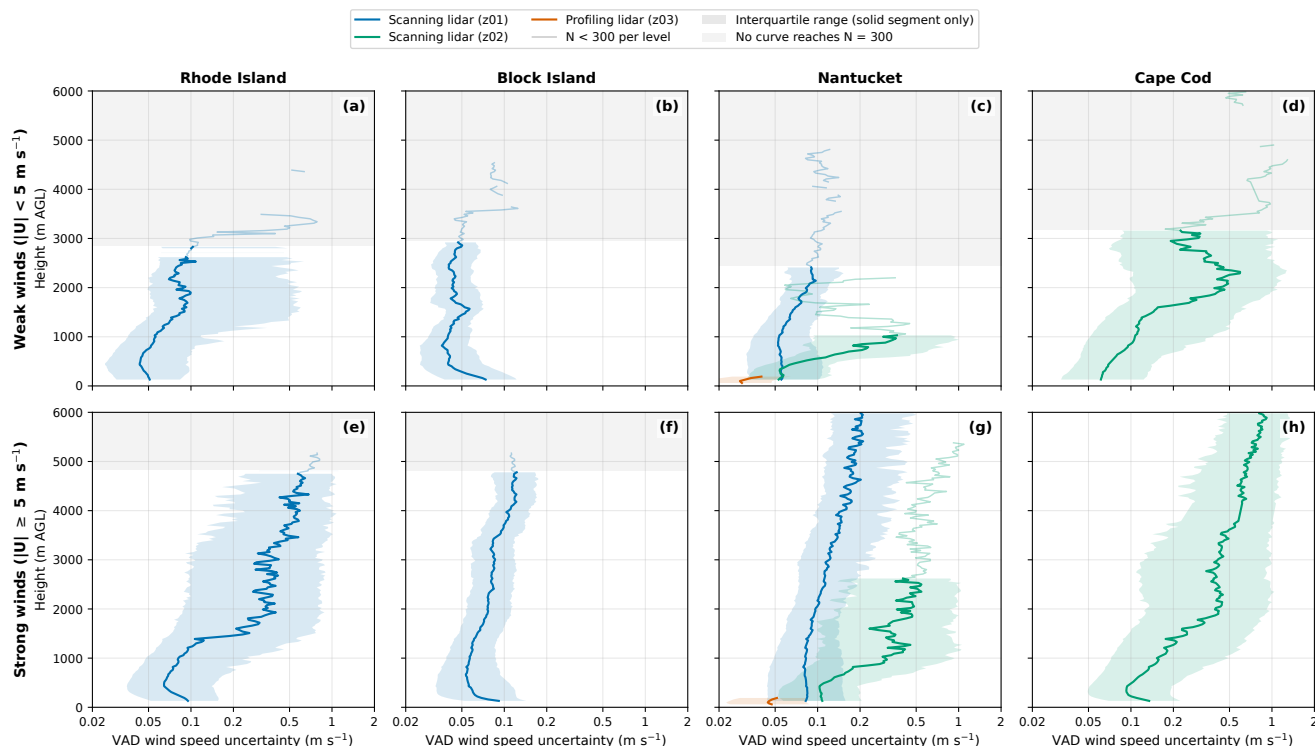


Figure 5. Median VAD wind speed uncertainty as a function of height for each lidar passing through the VAD retrieval, namely, the scanning lidars at all four sites and the Nantucket z03 profiling lidar, stratified by weak winds ($|U| < 5 \text{ m s}^{-1}$, top row) and strong winds ($|U| \geq 5 \text{ m s}^{-1}$, bottom row), for all four sites. Shading in both rows shows the 25th–75th percentile range. Uncertainty is instrument-dependent and the dependence grows with height: below 2 km all curves overlap (medians $0.03\text{--}0.47 \text{ m s}^{-1}$), while under strong winds the instruments separate into two groups. The Block Island and Nantucket z01 scanning lidars span $0.08\text{--}0.12 \text{ m s}^{-1}$ over 2–3 km and $0.08\text{--}0.21 \text{ m s}^{-1}$ above 3 km, against $0.28\text{--}0.55$ and $0.30\text{--}0.92 \text{ m s}^{-1}$ for the Nantucket z02, Cape Cod and Rhode Island scanning lidars; the Nantucket z03 profiling lidar belongs to the first group but reports only to 190 m. Curves fade where that instrument’s own sample count falls below 300 profiles; the shaded span marks heights where no instrument reaches 300. A faded curve beside a solid one indicates that one instrument is well sampled at that height while another is not. The horizontal axis is logarithmic because the separation between instruments is multiplicative, so equal ratios occupy equal horizontal distance.

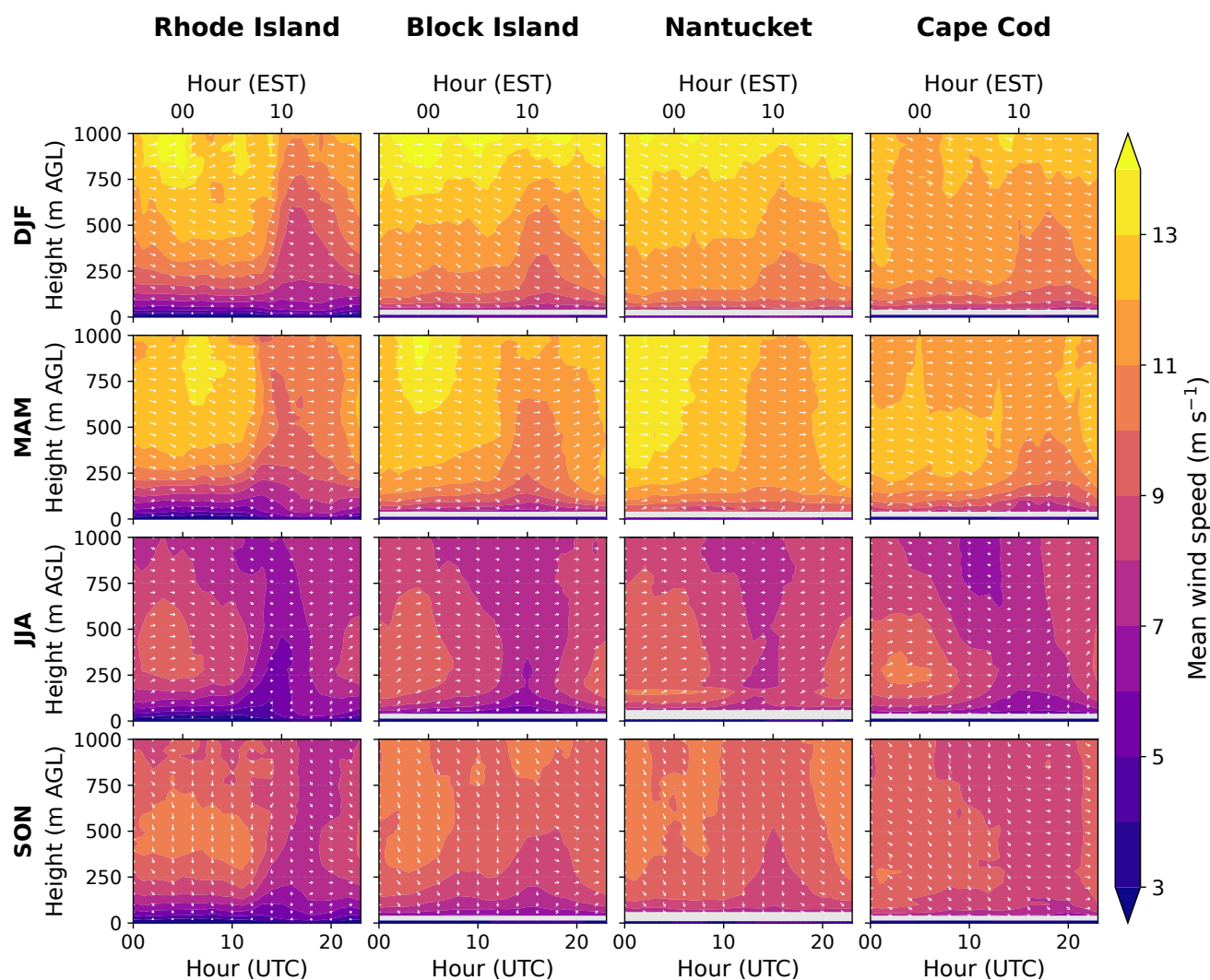


Figure 6. Seasonal mean diurnal wind speed (color fill, m s^{-1}) and direction (white arrows) as a function of height AGL and hour of day (UTC, with local Eastern Standard Time on the upper axis) for all four WFIP3 sites and seasons (December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); September, October, November (SON)), composited over February 2024–September 2025. Color fill shows profiling instruments from their lowest range gate. Near-surface in situ levels (sonic anemometers; the 10 m propeller-vane at Block Island) are drawn as a continuous band at the base of each panel, extended to the ground for legibility; each measurement level lies at its true height. The layer between the topmost in situ level and the first range gate is unobserved at Cape Cod, Nantucket, and Block Island.

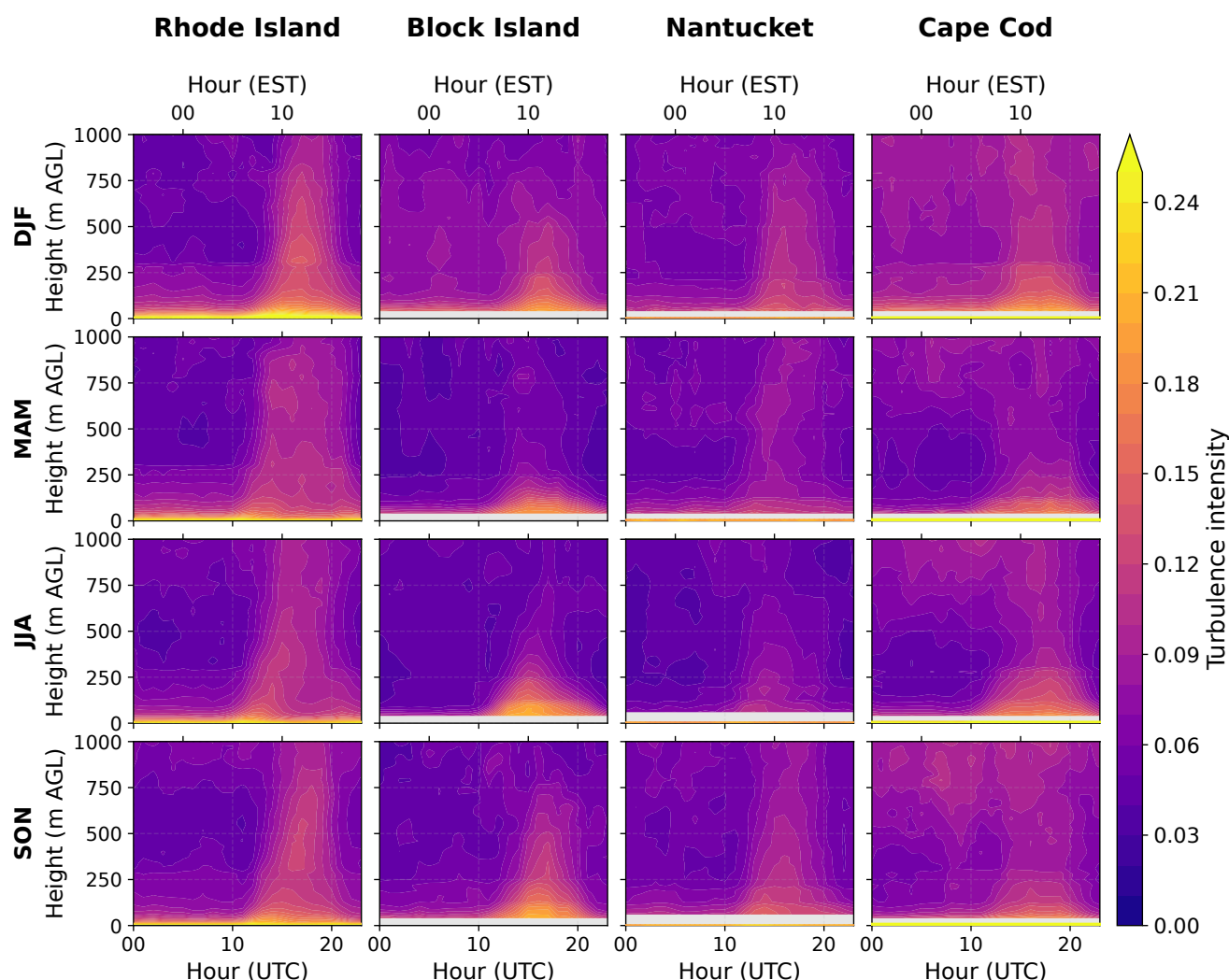


Figure 7. Seasonal mean diurnal turbulence intensity as a function of height AGL and hour of day (UTC, with local Eastern Standard Time on the upper axis) for all four WFIP3 sites and seasons, composited over February 2024–September 2025. Color fill shows profiling instruments from their lowest range gate. Sonic anemometer levels are drawn as a continuous band at the base of each panel, extended to the ground for legibility; each measurement level lies at its true height. Block Island has no in situ turbulence measurement and therefore no surface band. The layer between the topmost sonic anemometer and the first range gate is unobserved at Cape Cod and Nantucket, and the whole layer below the first range gate is unobserved at Block Island.

510 4.4 Quality control effectiveness

Suspect data flagging rates were uniformly low. Between 100 and 200 m they ran 0.005–0.19 % for wind speed and 0.05–1.36 % for wind direction. Physics-based screening acts earlier, before merging, and withholds a value rather than flagging it, so those rejections appear as absent data rather than in these rates. Across 14.1 million assessed wind speed cells, inter-instrument



agreement filtering flagged 0.058 % as suspect (QC flag = 1), with the corresponding wind direction rate 0.138 %; both indicate
 515 that the contributing instruments rarely disagreed by more than the configured thresholds. Wind direction is flagged more often
 because the two thresholds differ in stringency. The direction test trips on a circular spread exceeding 30°, whereas the wind
 speed criterion, an absolute spread greater than $\max(1.5, 0.5 \times \text{median WS}) \text{ m s}^{-1}$, is seldom met. Windows in which the
 merged product carried no quality-controlled wind at any height occurred in 75 of 333,631 site-windows (0.022 %; the 10-
 minute windows present in the delivered files, summed over the four sites), 74 of them at Nantucket, so every site delivered
 520 a usable profile in more than 99.9 % of 10-minute windows. This measures completeness of the merged product rather than
 instrument uptime: an instrument that is offline or whose every retrieval fails quality control registers here only when no other
 instrument at the site fills the column.

5 Case study: coastal fog events

Marine fog is a recurrent feature of the northeast U.S. shelf, driven primarily by warm, moist air advecting over the cold shelf
 525 waters of the Mid-Atlantic Bight during spring and summer (Tardif and Rasmussen, 2007; Fernando et al., 2021; Kirincich
 et al., 2023; Bodini et al., 2026b). Here we use the WINDPROF product to study the behavior of the wind profiles during fog
 events. Beyond its well-documented impacts on aviation and marine navigation, fog presents a specific challenge for boundary
 layer remote sensing. The optical attenuation that reduces visibility also degrades lidar signal quality, potentially compromising
 retrieved wind profiles throughout the lower boundary layer.

530 Fog events at Cape Cod were identified from the extinction coefficient profile delivered by the co-located ceilometer
 (`caco.ceil.z01.c0`) at its lowest range gate (10 m; single gate, no vertical averaging), converted to an equivalent hori-
 zontal visibility using the Koschmieder equation (Koschmieder, 1925; Middleton, 1957):

$$V = \frac{-\ln \varepsilon}{\sigma_{\text{ext}}} \approx \frac{3.91}{\sigma_{\text{ext}}} \quad (7)$$

where V is horizontal visibility, σ_{ext} the ceilometer-derived extinction coefficient, and $\varepsilon = 0.02$ the threshold contrast, the
 535 minimum luminance contrast at which a distant object remains distinguishable from its background, conventionally taken
 as 0.02 in the Koschmieder relation. Selecting periods where visibility remained below 1000 m for at least 60 consecutive
 minutes yielded 37 events. Events on the same day separated by less than two hours were merged into single episodes since
 brief clearings within a fog episode do not constitute independent occurrences, which gave 25 Cape Cod episodes for analysis
 against 37 matched clear-sky periods. The Cape Cod ceilometer record begins in late February 2025 and is sparse through
 540 March, so fog detection at that site effectively spans April–August 2025; all detected events fall in April–July, consistent with
 the advection-fog season over the shelf.

At Block Island, fog events were identified from Automated Surface Observing System (ASOS) horizontal visibility obser-
 vations using the same 1000 m (~ 0.621 statute miles) threshold, yielding 122 events over the full campaign period (94 episodes
 after the same merging). Reported ASOS visibility is quantized in statute miles, so the effective Block Island threshold is 805
 545 m (0.5 statute miles), while the Cape Cod threshold expressed as a 5 % contrast meteorological optical range corresponds to



approximately 767 m; the two are closely comparable in practice and both are stricter than the nominal value. Every detected Block Island event coincided with at least one ASOS fog weather code report. This agreement is expected by construction, since ASOS assigns fog codes from the same visibility measurement that defines our threshold, and it should not be read as independent validation. In the reverse direction, 18.9 % of fog-coded observations fall outside detected events; all are below-threshold periods shorter than the 60-minute duration criterion and are excluded by design. No equivalent crosscheck is available at Cape Cod. The two methods also differ in sensing geometry. The Cape Cod extinction is sampled at 10 m in a vertically pointing column and converted to an equivalent horizontal visibility, whereas ASOS measures horizontal visibility directly, so the two thresholds are not directly interchangeable. Non-fog baseline periods at Block Island ($n = 108$) were matched by month and time of day from days with visibility exceeding 7 statute miles. Individual contrasts draw on subsets of this baseline, since not every metric is defined at every height on every period. Availability statistics retain exact-zero values in both fog and clear conditions, so that intervals of complete signal loss contribute to the medians instead of being discarded.

5.1 Wind profile signatures

Fog-associated changes in boundary layer structure were more modest and less consistent than the availability impacts. At Cape Cod, neither surface turbulence kinetic energy nor surface wind speed differed significantly between fog and clear episodes. Of the fourteen contrasts tested (Welch's t -test), two fell below $p = 0.05$: vertical velocity at 40 m, which averaged 0.18 m s^{-1} more positive during fog than in clear conditions ($p = 0.005$; Cohen's $d = 0.90$, the difference in means expressed in pooled standard deviations), and wind shear across the surface-to-40-m layer, which was weaker during fog ($p = 0.047$, $d = -0.55$). These comparisons use 23 fog episodes and 31 clear periods, rather than the full samples of 25 and 37. Two April 2025 episodes lack profiling-lidar returns below 100 m, leaving the quantities being compared undefined at heights of 40 m and above. Given the sample size and the number of comparisons tested, we report both results without further interpretation. Seasonally, fog activity peaked in July (22 of 37 detected events), consistent with Cape Cod's advection fog climatology (Tardif and Rasmussen, 2007).

At Block Island, fog episodes showed significantly more negative vertical velocity at 40–80 m (-0.10 to -0.19 m s^{-1} , versus -0.03 to $+0.01 \text{ m s}^{-1}$ in clear conditions; $p \leq 2 \times 10^{-4}$, Cohen's d up to -1.0) and reduced surface wind speeds (2.8 versus 3.8 m s^{-1} , $p < 10^{-4}$, $d = -0.64$), while turbulence intensity differences were not significant at any level; the only other contrast below $p = 0.05$ was wind shear across 60–100 m ($p = 0.046$, $d = +0.34$), consistent with chance given the number of contrasts tested. The downward vertical-velocity shift must be read alongside the measurement caveat of Sect. 3.7. Lidar vertical velocities are backscatter-weighted and include hydrometeor fall speeds, and fog droplets are present in exactly these conditions. These observations do not separate droplet fall speed from air motion, so the downward shift is not attributed here to subsidence. The kinematic signals therefore differ between the two sites. The clearest and most transferable fog response in this dataset is that of the observing system itself.

One signature is consistent across both sites (Fig. 8). Fog episodes occurred under southerly flow with a mean wind direction at 100 m of 200° at Cape Cod and 185° at Block Island, contrasted with westerly to northwesterly flow during the matched clear periods (255° and 282° respectively), with modestly lower wind speeds in fog (7.2 versus 8.7 m s^{-1} at Cape Cod, 7.4



580 versus 8.0 m s^{-1} at Block Island; wind speed is not shown in the figure). This corresponds to the flow regime associated with advection fog over the northeast shelf, in which warm, moist air is carried over cold shelf water (Tardif and Rasmussen, 2007).

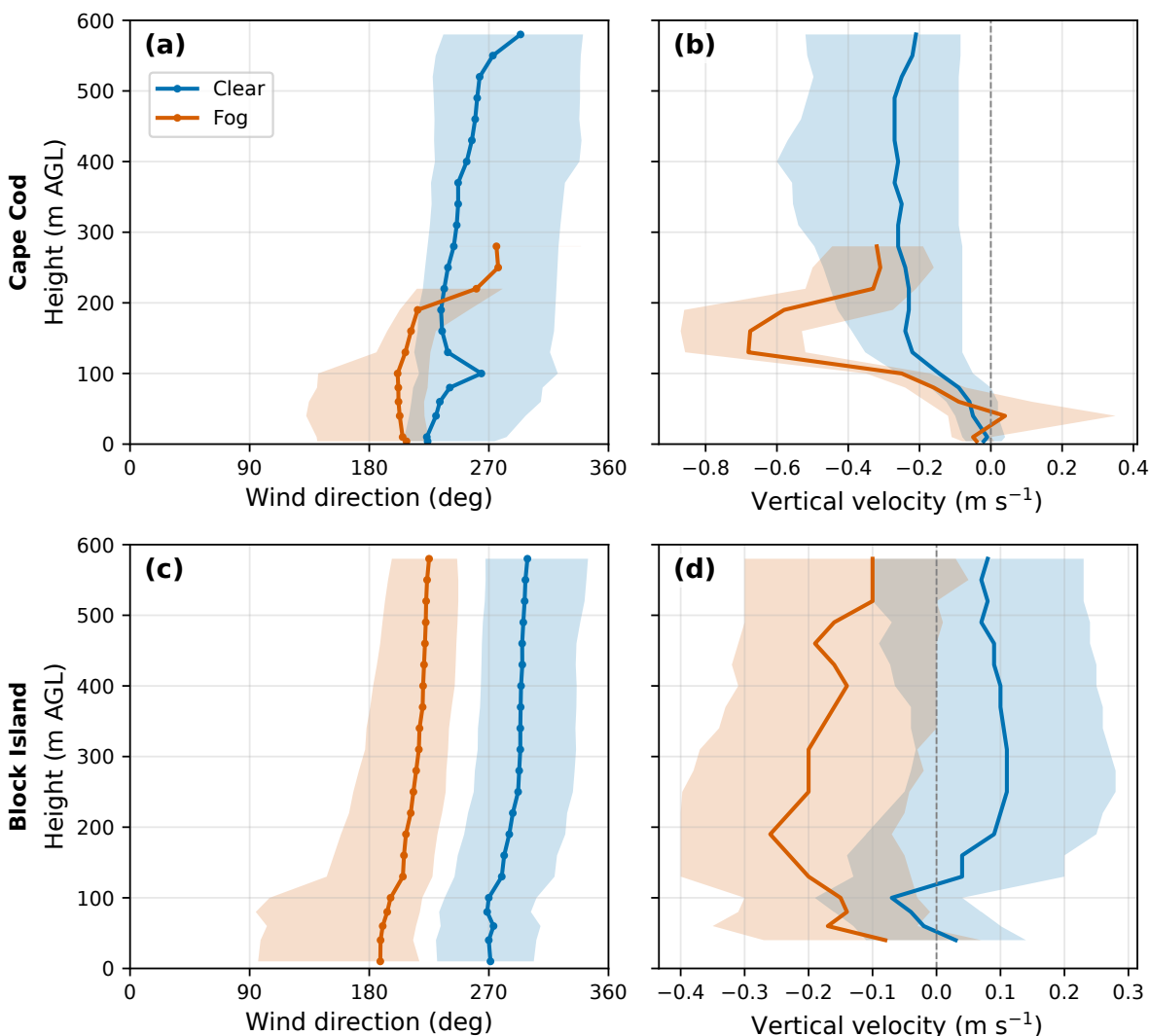


Figure 8. Median vertical profiles of wind direction and vertical velocity during fog episodes (orange) and matched clear periods (blue) at Cape Cod (a, b) and Block Island (c, d), with interquartile shading. Wind direction separates at both sites, with fog occurring under southerly flow. At Cape Cod the fog profiles terminate near 280 m and, above roughly 100 m, derive from the minority of fog intervals in which the lidars retained signal (Fig. 9). Above approximately 130 m the merged fog profile at Block Island is radar-dominated (92.5 % of valid cells are radar-only, versus 31.3 % under clear conditions), so the fog and clear curves there draw on different instrument populations; the vertical velocity values quoted in the text are from 40–80 m, where the profiling lidar is the sole contributor at that site. Radar and lidar vertical velocities are reflectivity- or backscatter-weighted and include hydrometeor fall speeds (Sect. 3.7). Profiles use quality-controlled retrievals from the merged product below 600 m.

5.2 Measurement performance

The impact of fog on data availability differed markedly between sites, determined primarily by whether the instrument suite included sensors operating on non-optical measurement principles (Fig. 9). Fog increased scanning lidar measurement uncertainty at both sites: wind speed error rises by 406 % at Cape Cod (0.068 to 0.343 m s⁻¹, rank-biserial $r = -0.95$, the effect size accompanying the Mann-Whitney test) and by 63 % at Block Island (0.047 to 0.077 m s⁻¹, $r = -0.48$), computed over retrievals passing quality control. The two sites differ in scanning lidar model, in scan cycle time, in the instrument used for fog detection, and in the period sampled, so the difference in magnitude between them is not attributed here to a single cause.

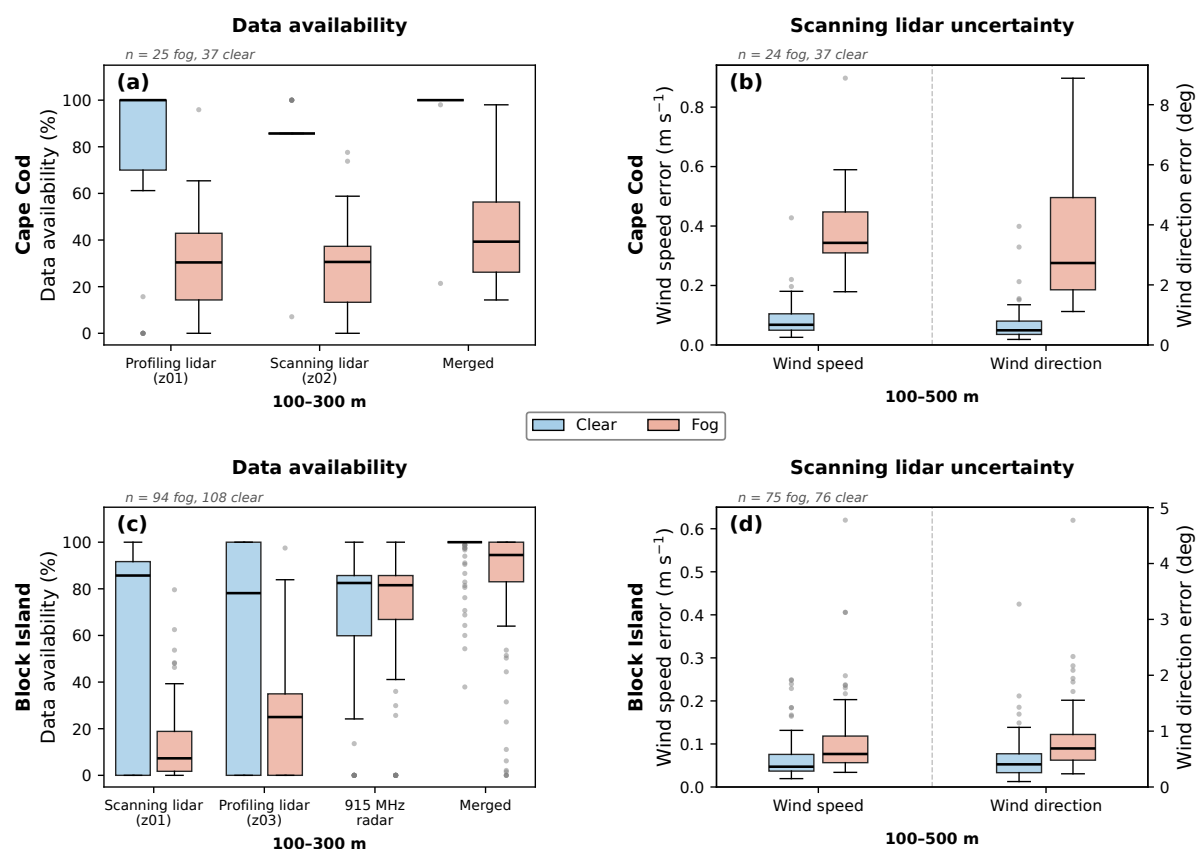


Figure 9. Fog impact on wind profile data availability and measurement uncertainty at Cape Cod and Block Island. (a, c) Median data availability at 100–300 m by instrument during fog and clear conditions, where each episode contributes one value. At Cape Cod (a, b), every instrument reaching this layer is optical and fog degradation is shared across the suite, leaving the merged product with no non-optical source (median availability 39.3 % during fog). At Block Island (c, d), the 915 MHz radar is essentially unaffected by fog (rank-biserial $r = 0.00$, against $r = 0.46$ and 0.50 for the two co-located lidars), enabling the merged product to retain 94.5 % coverage. (b, d) Scanning lidar wind speed error (left axis) and wind direction error (right axis) at 100–500 m. Box plots show median, interquartile range (IQR), and $1.5 \times \text{IQR}$ whiskers.



At Cape Cod, fog reduced scanning lidar availability at 100–300 m from a median of 85.7 % to 30.6 % (rank-biserial $r = 0.95$), and profiling lidar availability from 100 % to 30.4 % ($r = 0.63$), as expected when fog attenuates the optical signal. Because both instruments rely on aerosol backscatter, they fail together. The merged product retains 39.3 % availability during fog ($p < 10^{-11}$), modestly more than either lidar alone. The merge recovers intervals in which one instrument holds signal while the other does not, but with no non-optical source available to compensate for their shared failure mode.

At Block Island, lidar-based instruments showed comparable degradation: scanning lidar availability dropped from 85.7 % to 7.3 % ($p < 10^{-7}$), and profiling lidar from 78.2 % to 25.0 % ($p < 10^{-9}$). The 915 MHz wind profiling radar, however, was essentially unaffected: median availability differed by less than one percentage point between fog and clear conditions (82.5 % to 81.6 %), a difference indistinguishable from zero (rank-biserial $r = 0.00$) in a sample that resolved the far larger changes in the co-located lidars ($r = 0.46$ and 0.50). This resilience follows from its reliance on Bragg scattering from refractive-index inhomogeneities rather than aerosol backscatter (Tatarskii, 1961), and it carries the merged product: availability during fog remains at 94.5 % ($p < 10^{-10}$ for the 5.5 percentage-point decline), roughly 2.4 times the 39.3 % retained at Cape Cod, where the radar is excluded from this release. Between 100 and 500 m, where the radar and both lidars overlap, the RMSE of radar–lidar wind speed differences is $0.59\text{--}0.70\text{ m s}^{-1}$ in clear conditions and $0.71\text{--}1.07\text{ m s}^{-1}$ during fog. Lower wind speeds during fog do not explain this increase. In comparisons with the scanning lidar, the increase occurs mainly at wind speeds of 10 m s^{-1} or higher. Wind direction uncertainty at the Block Island scanning lidar rose by 70 % (0.406° to 0.690° , $r = -0.50$), a degradation as modest, relative to Cape Cod, as that in wind speed.

Multi-instrument merging therefore provides fog resilience only when the instrument suite includes sensors with different measurement physics. Where all instruments rely on optical backscatter, as at Cape Cod, the merged product inherits their shared vulnerability to fog attenuation. For observing-system design, a radar-lidar pairing of the kind deployed at Block Island buys little in clear conditions but carries the record through fog, precipitation, and other low-visibility periods.

6 Comparison with an optimal estimation retrieval

Hierarchical merging is one of several strategies available for combining heterogeneous boundary layer observations into unified profile products. A fundamentally different approach is Bayesian optimal estimation, in which observations are combined with prior constraints from climatology or a numerical weather prediction forecast through a formal statistical inversion (Rodgers, 2000). To assess the extent to which choice of integration framework affects the resulting wind profiles, we compared 17 months of collocated retrievals at Nantucket (February 2024–June 2025) against the WINDoe optimal estimation algorithm (Adler, 2026; Adler et al., 2026; Gebauer and Bell, 2024). Both retrievals draw on the same scanning and profiling Doppler lidar, sonic anemometer, and profiling radar observations.

The two approaches differ in several methodological respects beyond their mathematical framework. The hierarchical merging presented here operates at 10-minute resolution and retains instrument-level measurements without imposing vertical smoothness, whereas WINDoe produces retrievals every 15 minutes, each a 30-minute average centered on its time stamp, with a vertical covariance structure embedded in its Bayesian prior. Each merged-product window was therefore paired with



the WINDoe retrieval whose averaging window is nearest in time so that every 10-minute window lies wholly within the 30-minute retrieval window it is compared against (median offset between window centers is 2.5 minutes). The comparison consequently retains a difference in temporal support, a 10-minute average against a 30-minute one. This difference in temporal
 625 sampling contributes to the scatter reported below and is largest when winds are most variable. The two products also differ in which instruments contribute below 1000 m. The hierarchical merging uses the radar only where no lidar measurement is available (Sect. 3.5), whereas WINDoe assimilates lidar and radar observations together, weighted by their signal-to-noise ratio. Agreement below 1000 m therefore reflects a difference in merging philosophy as well as in retrieval method.

Comparisons were further restricted to data flagged as good quality in the merged product ($QC = 0$) and to WINDoe retrievals
 630 with component uncertainties $\sigma_u, \sigma_v \leq 2.5 \text{ m s}^{-1}$, the empirically determined screening threshold of Adler et al. (2026). The optimal-estimation retrieval provides a value at every height and time, even when observations are missing. A large σ indicates either conflicting observations or strong influence from the prior. The prior consists of the monthly climatological mean wind profile and its covariance (Adler et al., 2026). The retrieval relies more heavily on this information where observations are missing or provide little constraint. This screen retains 84–95 % of WINDoe retrievals per month (median 93 %). The vertical
 635 analysis range spans 40–1000 m AGL, with the lower bound set as the lowest level where overlapping data are available. Few matched pairs are available below 60 m. Their number rises sharply between 60 and 70 m, then more gradually at greater heights. Coverage below 60 m is also limited in time: nearly all pairs come from February to early April 2024, with none in summer or autumn. Values at 40 and 50 m are interpolated rather than directly measured. The upper limit reflects the wind profiling radar’s effective measurement ceiling (94 % temporal availability). Scanning lidar retrievals are excluded below 100
 640 m AGL in the merged product and therefore do not contribute to the lowest portion of the comparison range. This procedure yielded 74,163 matched 10-minute windows. Because each window contributes a matched pair at most heights across the 40–1000 m comparison range, the pointwise sample entering the height-resolved statistics is substantially larger than the number of windows. For each time window, we linearly interpolate the merged product from its native height grid onto the WINDoe retrieval levels. Comparisons and the sample counts in Table 4 therefore use this finer grid. Figure 10 shows the per-height
 645 statistics, and the table reports the pooled, seasonal, and steadiness-stratified statistics with the number of valid pairs in each.

Intercomparison of an optimal-estimation retrieval against a higher-resolution product normally requires accounting for the retrieval’s averaging kernels, since prior-imposed smoothing broadens sharp features, and a pointwise comparison charges that smoothing to the retrieval (Rodgers and Connor, 2003). That concern is small in this case. WINDoe reports an effective vertical resolution of approximately 12 m throughout 60–1000 m, comparable to or finer than the 30 m spacing of the merged
 650 product’s grid over most of that range, and its cumulative degrees of freedom for signal reach ~ 79 by 1000 m across roughly 100 retrieval levels. This adjustment accounts for the difference in vertical resolution. The prior still constrains the retrieval where observations provide little information, but observations dominate over the height range compared here. The reported differences therefore reflect differences between the retrieval methods, rather than unequal vertical smoothing.

Overall agreement between the two retrievals is strong, with a mean difference of $+0.160 \text{ m s}^{-1}$ (merged product higher),
 655 an RMSE of 0.851 m s^{-1} , and a correlation coefficient of 0.990 (Table 4). We describe signed offsets between the two products as differences rather than biases throughout: neither retrieval constitutes a reference truth, so the sign indicates which method



reports faster winds, not which is correct. Because the two methods ingest largely the same observations, a high correlation is partly guaranteed by construction, and we therefore focus below on where the two disagree. The difference profile is near zero from 40 to 170 m (within $\pm 0.09 \text{ m s}^{-1}$), steps up at 180 m, and reaches a maximum of $+0.25 \text{ m s}^{-1}$ at 200 m before declining to $+0.067 \text{ m s}^{-1}$ at 990 m. RMSE grows from 0.44 m s^{-1} near 90 m to a broad maximum between 250 and 600 m ($0.90\text{--}0.95 \text{ m s}^{-1}$, peaking at 0.95 m s^{-1} near 580 m) before decreasing to 0.58 m s^{-1} at 990 m. The step at 180 m (Fig. 10b) lies close to the profiling lidar’s 190 m ceiling, above which only the scanning lidar contributes.

Table 4. Wind speed comparison statistics between the integrated profile product and the WINDoe optimal estimation retrieval, for the full dataset, by season, and by wind steadiness. Statistics were computed from 17 months of collocated observations (February 2024–June 2025) at heights from 40 to 1000 m AGL. N indicates the number of valid pointwise wind speed comparisons contributing to each statistic, and MAE is the mean absolute error. The lower block stratifies into terciles the pairs for which the 10-minute wind speed change $|\Delta U|$ at fixed height is defined (tercile boundaries 0.163 and 0.470 m s^{-1} per 10 minutes).

Condition	N	Mean diff. (m s^{-1})	RMSE (m s^{-1})	MAE (m s^{-1})	r
All Data	5,695,881	+0.160	0.851	0.446	0.990
Winter (DJF)	1,331,832	+0.081	0.603	0.422	0.996
Spring (MAM)	2,012,037	+0.288	1.254	0.606	0.982
Summer (JJA)	1,250,405	+0.088	0.436	0.310	0.996
Fall (SON)	1,101,607	+0.104	0.466	0.336	0.996
Steadiest tercile	1,844,792	+0.120	0.625	0.351	0.995
Middle tercile	1,846,335	+0.155	0.708	0.375	0.993
Most variable tercile	1,836,837	+0.214	1.135	0.612	0.985

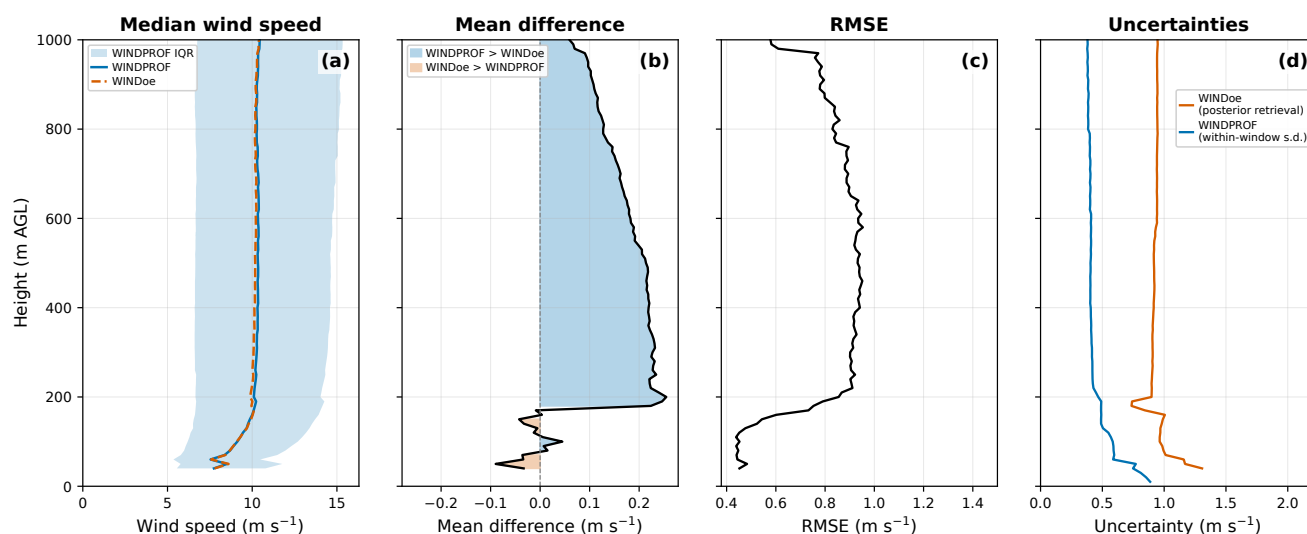


Figure 10. Vertical profile comparison between the integrated profile product and WINDoe wind speed retrievals (40–1000 m AGL, except the merged product’s standard deviation in panel (d), which extends to 10 m): (a) median wind speed profiles of both products, with interquartile range shading for the merged product, (b) mean difference profile, (c) RMSE profile, and (d) median uncertainty profiles: WINDoe’s posterior retrieval uncertainty and the merged product’s within-window standard deviation, which measure different quantities and are not directly comparable. The step in mean difference near 180 m lies close to the profiling lidar’s 190 m ceiling, above which only the scanning lidar contributes.

Seasonal agreement varies by a factor of approximately three, with closest agreement in summer and fall ($\text{RMSE} = 0.436$ and 0.466 m s^{-1}), intermediate agreement in winter (0.603 m s^{-1}), and weakest agreement in spring (1.254 m s^{-1}). The seasonal contrast is variance-dominated: the squared mean difference accounts for at most 5.3 % of RMSE^2 in any season (range 1.8–5.3 %), so the seasonal variation in agreement arises from how the two methods process transient atmospheric variability rather than from the mean difference, which is positive in every season. Spring over the northeast U.S. shelf is characterized by strong synoptic variability and frequent coastal frontal passages (Kirincich et al., 2026; Lombardo and Colle, 2012, 2013; Sorooshian et al., 2020), conditions under which the two methods’ different treatments of vertical smoothness and temporal averaging would be expected to diverge most. That spring stands apart is not an artifact of the comparison protocol: matching each merged-product window to the retrieval window containing it (Sect. 6) reduced summer and fall RMSE by roughly half relative to a looser overlap-based pairing, while spring RMSE was essentially unchanged; the springtime divergence therefore survives when time stamp mismatch is reduced, though the difference in averaging period remains.

LLJs are a recurrent feature of the northeast shelf boundary layer (Aird et al., 2022; Bodini et al., 2026a; Quint et al., 2025), and their organized, strongly sheared structure makes them a useful test case for evaluating inter-method consistency under well-defined atmospheric conditions. LLJ events at Nantucket were taken from the scanning-lidar event-log product (`nant.lidar.eventlog.z01.c2`; Krishnamurthy 2025b), generated from the 10-minute wind statistics of the NANT z01 scanning lidar (`nant.lidar.10min.z01.c1`; Krishnamurthy 2025c, described in Bodini et al. 2026b). The event log



flags an LLJ using the classification of Bonner (1968), a distinct wind speed maximum below 700 m whose speed falls off by a
 680 threshold amount at some height above the nose, on a four-rung ladder of nose speed and fall-off (10/5, 12/6, 16/8 and 20/10 m
 s^{-1}). The weakest rung extends below Bonner’s original three criteria and accounts for 38.9 % of the occurrences reported here.
 Because the event log is derived from the scanning lidar, its LLJ population is bounded by that instrument’s vertical reach. A
 jet whose fall-off lies above the lidar’s ceiling is not flagged, so the reported nose-height distribution is weighted toward lower
 jets. The event log reports nose height, nose wind speed, and shear above and below the nose at 10-minute cadence, with
 685 Reynolds-stress estimates following Sathe et al. (2015) and signal-quality filtering following Beck and Kühn (2017).

Over February 2024–September 2025 the event log identifies 3,841 LLJ occurrences at Nantucket, with a median nose height
 of ~ 280 m AGL (10th–90th percentile: 170–530 m). The profiling lidar alone reports a valid wind at the jet nose height in
 only 7.6 % of these events, owing to its ~ 200 m ceiling, whereas the scanning lidar does so in 98.1 % and the merged product
 in 99.6 %; these are coverage fractions of nose levels identified by the event log rather than detection skill. The merge thus
 690 preserves the scanning lidar’s LLJ observability and slightly extends it, recovering jet noses at times when the scanning lidar
 alone did not report. For the comparison analysis, we use the 3,753 LLJ profiles falling within the July 2024–June 2025 subset
 where continuous event logs and WINDoe retrievals are both available (7.2 % of the 52,419 profiles compared in that period).

Scatter between the two methods is comparable during LLJ events and under non-LLJ conditions (RMSE 0.535 versus
 0.512 m s^{-1} ; correlation 0.9967 versus 0.9963; Table 5). What differs under jet conditions is a systematic offset rather than the
 695 scatter. The merged product exceeds WINDoe by $+0.167 \text{ m s}^{-1}$ during LLJ events, compared with $+0.092 \text{ m s}^{-1}$ otherwise.
 A small systematic offset does persist during LLJ events, and compositing the difference profiles in nose-relative coordinates
 confirms that it is concentrated at the jet core: across the subset of events matched to a comparison window (median nose
 height 280 m AGL; 10th–90th percentile 170–520 m, against 170–530 m for the full event log), the merged product exceeds
 WINDoe by $+0.39 \text{ m s}^{-1}$ within 100 m of the nose, compared with $+0.10 \text{ m s}^{-1}$ more than 150 m away from it, a factor of 3.8.
 700 This localization is consistent with the difference in temporal support between the two products: a jet whose nose height and
 speed evolve within half an hour is smoothed in WINDoe’s 30-minute average, reducing the retrieved maximum, whereas the
 merged product’s 10-minute windows preserve more of the peak. The effect is largest precisely where the profile’s curvature is
 greatest and diminishes away from the nose (Fig. 11). The jet nose is identified from the scanning lidar’s 10-minute maximum.
 Since this lidar also supplies most of the data in the merged product at jet-nose heights, selecting its maximum may therefore
 705 contribute to the offset at the nose, alongside differences in temporal averaging.

Table 5. Wind speed comparison statistics during LLJ events and under non-LLJ conditions. LLJ events identified from the Nantucket
 scanning-lidar event log `nant.lidar.eventlog.z01.c2` (Krishnamurthy, 2025b) (July 2024–June 2025 only). Of 52,419 profiles in
 the restricted period, 49,637 matched an event-log record within the 6-minute pairing tolerance and are classified below; unmatched profiles
 are excluded.

Condition	N (profiles)	Mean diff. (m s^{-1})	RMSE (m s^{-1})	r
Non-LLJ	45,884	0.092	0.512	0.9963
LLJ Events	3,753	0.167	0.535	0.9967

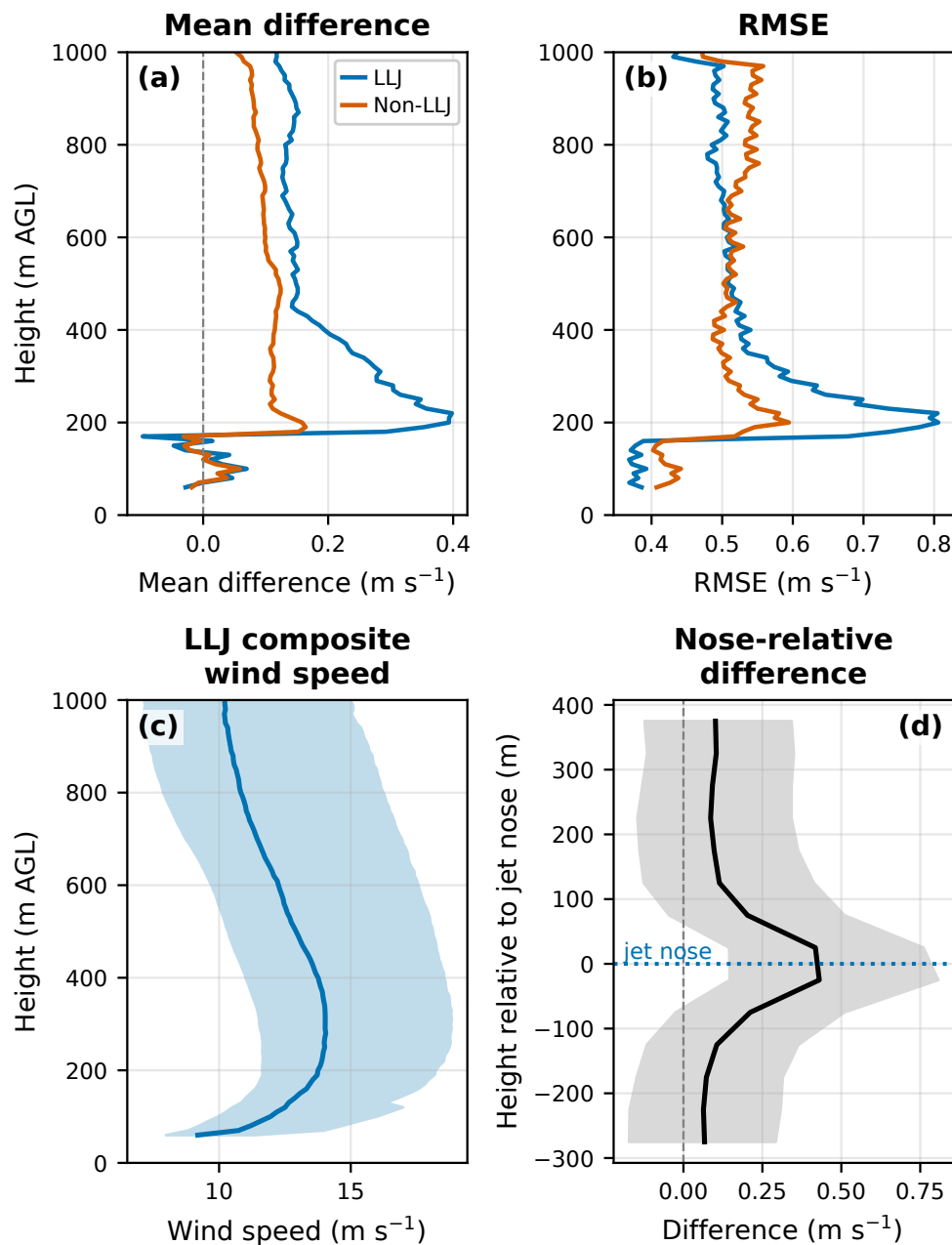


Figure 11. Comparison between the integrated profile product and WINDoe during LLJ events versus non-LLJ conditions (Nantucket, July 2024–June 2025; $N_{\text{LLJ}} = 3,753$). (a) Mean difference profiles for LLJ and non-LLJ conditions, which differ most between 170 and 220 m. (b) RMSE profiles: scatter is comparable in both regimes (0.535 m s^{-1} during LLJ events versus 0.512 m s^{-1} otherwise). Both panels show a feature between 170 and 220 m. (c) Median composite wind speed profile of the merged product during LLJ events, with interquartile range shading. (d) Difference profiles composited in nose-relative coordinates, in which the offset concentrates at the jet core.



We also stratified the same comparison by how rapidly the wind is changing. Splitting the pointwise comparisons into terciles of the 10-minute wind speed change $|\Delta U|$ yields RMSE rising from 0.625 m s^{-1} in the steadiest tercile to 1.135 m s^{-1} in the most rapidly changing, with the mean difference rising in step ($+0.120$ to $+0.214 \text{ m s}^{-1}$; Table 4). The ordering is monotonic within every combination of wind speed and turbulence intensity examined, so it is not an artifact of either covariate. The LLJ core offset, the spring RMSE maximum, and this ramp sensitivity are all consistent with sensitivity to temporal averaging, although differences in source weighting and vertical smoothing may also contribute. The two methods differ most where the wind evolves fastest relative to their temporal supports, a 10-minute average against a 30-minute one, and not in any particular meteorological regime.

Hierarchical merging and optimal estimation thus converge on nearly identical profiles under well-structured conditions, and differ mainly in transitional regimes, where the wind evolves within the averaging window of either method and the climatological prior gives WINDoe no information about that evolution. Because both retrievals are publicly archived, users can select or combine methods according to the needs of specific applications; the comparison presented here is intended to characterize their methodological differences rather than to identify a preferred approach.

7 Conclusions

This paper has presented WINDPROF, an open framework for integrating heterogeneous boundary layer wind and turbulence observations into unified profile products, applied here to the 19-month WFIP3 campaign across four coastal sites in the northern Mid-Atlantic Bight. The resulting 10-minute merged profiles of wind speed, direction, vertical velocity, and turbulence measurements span February 2024 through September 2025 and form a standardized, traceable basis for studies of marine boundary layer structure and for numerical model evaluation over the region.

We report three main findings. First, integrated multi-instrument retrievals over the northeast U.S. shelf are highly consistent with one another, with lidar-lidar wind speed RMSE of $0.36\text{--}0.78 \text{ m s}^{-1}$ across sites and systematic differences of at most 0.35 m s^{-1} . Data availability below 200 m AGL ranged from 84 % to 98 %, exceeding 90 % at three of the four sites, and the merged product delivered a quality-controlled wind at some height in more than 99.9 % of 10-minute windows throughout the campaign. Fewer than 0.1 % of merged wind speed values were flagged as suspect by inter-instrument agreement tests, indicating that the contributing retrievals were largely consistent where they overlapped. Formal VAD retrieval uncertainties nonetheless underestimate the observed inter-instrument spread, as fit-based errors do not capture representativeness uncertainty. Users requiring rigorous uncertainty quantification should adopt inter-instrument spread as a more conservative estimate.

Second, the coastal fog events show where multi-instrument merging helps under optically degraded conditions and where it does not. At Cape Cod, where the profiling instruments rely on optical backscatter, fog reduced merged product availability at 100–300 m from 100 % to 39.3 %. At Block Island, the 915 MHz radar wind profiler was essentially unaffected by fog (82.5 % to 81.6 %; rank-biserial $r = 0.00$, against $r = 0.46$ and 0.50 for the co-located lidars), enabling the merged product to retain 94.5 % coverage. Merging alone cannot compensate for a failure mode that every instrument shares, so resilience to fog and similar obstructions has to come from including a sensor that relies on different measurement physics.



Third, comparison against an independently developed Bayesian optimal estimation retrieval (WINDoe) applied to the same
 740 underlying observations reveals strong overall agreement (mean difference = $+0.160 \text{ m s}^{-1}$, RMSE = 0.851 m s^{-1} , $r = 0.990$)
 but small systematic differences that are diagnostically informative. Seasonal RMSE differences are variance-dominated, with
 the squared mean difference accounting for at most 5.3 % of RMSE² in any season, so the seasonal variation in agreement
 lies in how each handles transient atmospheric variability rather than in the mean difference, which is positive in every season.
 Agreement is close in both jet and non-jet conditions (RMSE 0.535 versus 0.512 m s^{-1}), but LLJs carry a systematic offset
 745 that nose-relative compositing localizes to the jet core ($+0.39 \text{ m s}^{-1}$ within 100 m of the nose, against $+0.10 \text{ m s}^{-1}$ well
 away from it). This is what would be expected if the longer-averaged retrieval smears a jet maximum that evolves within its
 averaging window.

One caveat applies to the turbulence quantities throughout. Only the sonic anemometers resolve inertial-subrange turbulence
 in the conventional sense; the lidar-derived variances characterize larger-scale (meso- γ) wind variability sampled at the scan
 750 cadence, not the small-scale cascade. Users comparing turbulence across the merged product, or interpreting its diurnal and
 seasonal structure, should account for both this scale disparity and the wind speed normalization in turbulence intensity, which
 imprints the diurnal wind speed cycle onto TI independently of changes in mixing.

The framework detailed here is generalizable to other multi-instrument campaigns, and has already been applied at three
 sites in the American WAKE ExperiMeNt (AWAKEN) (Moriarty et al., 2024; Bodini, 2026a, b, c). Its processing pipeline
 755 requires only instrument-specific readers, quality control thresholds, and coordinate system definitions; the merging, quality
 flagging, and uncertainty propagation operate independently of specific instrument types. All WFIP3 datasets are archived
 on the DOE Wind Data Hub with site-specific DOIs, and the processing code is publicly available, so other campaigns can
 reproduce the products presented here or reuse the framework instead of rebuilding an equivalent one. The data files follow the
 Climate and Forecast (CF-1.10) and Attribute Convention for Data Discovery (ACDD-1.3) metadata conventions. Each quality
 760 flag is linked to the variable it describes, and the license is provided in machine-readable form. These features follow Wind
 Data Hub recommendations for AI-ready data (Wind Data Hub, 2026).

Code and data availability. The WINDPROF merged best-estimate wind profile datasets from the WFIP3 campaign are publicly available
 through the Wind Data Hub maintained by the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation. Data for
 each of the four sites can be accessed at <https://wdh.energy.gov/ds/wfip3/> with the following DOIs: Nantucket ([https://doi.org/10.21947/](https://doi.org/10.21947/3014081)
 765 [3014081](https://doi.org/10.21947/3014081)), Block Island (<https://doi.org/10.21947/3014087>), Cape Cod (<https://doi.org/10.21947/3014349>), and Rhode Island (<https://doi.org/10.21947/3014814>) (Lipari, 2026a, b, c, d). The WFIP3 input datastreams from which these products were derived are separately archived
 on the Wind Data Hub: scanning Doppler lidars (Bodini, 2023, 2025; Jackson, 2025; Modjeski et al., 2024; Newsom, 2024), profiling
 Doppler lidars (Cinquino, 2025; Lundquist and Zalkind, 2023; Wharton, 2024a, b), 915 MHz radar wind profilers (Krishnamurthy, 2025a, d),
 sonic anemometer and surface meteorology datastreams (Argonne National Laboratory, 2024; Bianco et al., 2025a, b; Pal, 2025; Pekour,
 770 2025a, b, c, d), and the Cape Cod ceilometer used for fog detection in Sect. 5 (Bodini and Scholbrock, 2025). The Block Island fog events
 in Sect. 5 were identified from Automated Surface Observing System visibility at Block Island State Airport (station BID), obtained from
 the Iowa Environmental Mesonet archive (Iowa Environmental Mesonet, 2026). The WINDoe optimal-estimation wind retrievals used for



the comparison in Sect. 6 are separately archived on the Wind Data Hub for the Nantucket site (<https://doi.org/10.21947/2997968>) (Adler, 2026). The WINDPROF processing code is publicly available at <https://github.com/5erena/WINDPROF>.

775 *Author contributions.* SL and RK designed the merging framework. SL wrote the processing software, performed the analysis, and prepared the manuscript. RK, AK, and DDT led the WFIP3 field campaign and its observational design (Kirincich et al., 2023). BA and DDT applied the WINDoe optimal-estimation retrieval (Gebauer and Bell, 2024) and contributed the comparison framework. LB provided the NOAA profiler quality control procedures. NB, SLe, JKL, RKN, SW, RJ and HJSF deployed and provided Doppler lidar datasets. LB, MP, and JO provided the surface meteorological datasets, and SP and MP provided the sonic anemometer datasets. PM operated the Rhode Island
780 and Cape Cod radar wind profilers, advised on the treatment of their consensus products, and led the performance investigation on which the Rhode Island exclusion rests. MK supported the data-system configuration and verified that the delivered product metadata met archive standards. All authors reviewed and edited the manuscript. Authors after RK are listed alphabetically.

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