

Article

A Wind-Speed-Dependent Discrepancy Between Sentinel-3 Altimeter and ERA5 Reanalysis over the Chinese Nearshore Seas: A 14-Month Buoy-Referenced Assessment

Xiaoyu Tan, Kang Lin, Lieyu Tian *, Yufang Tan, Shidong Wang and Yang Lv

Guangzhou Marine Geological Survey, China Geological Survey, Guangzhou 510075, China; tanxiaoyu@mail.cgs.gov.cn (X.T.)

* Correspondence: tianlieyu@mail.cgs.gov.cn

Abstract

Sentinel-3A and -3B satellite SAR altimeter wind speeds are routinely validated against moored buoys but increasingly benchmarked against ERA5 reanalysis when buoys are unavailable. We assess both reference choices over the Chinese nearshore seas using 14 months of matchups between satellite passes, moored meteorological buoys, and ERA5 wind fields. Against buoys, both altimeters show near-zero mean bias and a roughly flat error level across the wind-speed range. Against ERA5, the discrepancy grows strongly and monotonically with wind speed: the mean satellite-minus-ERA5 bias shifts from approximately -1.5 m/s in light wind to $+1.4$ m/s above Beaufort 6. Sentinel-3A tracks the buoy more closely than Sentinel-3B ($r = 0.71$ vs. 0.58), a gap that persists in the month-to-month RMSE record. Because the altimeter–buoy residual is flat, the wind-speed structure in the altimeter–ERA5 residual can be attributed to ERA5 rather than to the satellite retrieval. A compact quadratic fit to the altimeter–ERA5 residual, inverted to adjust ERA5 wind speed, removes essentially all of this wind-speed-dependent bias (per-bin mean bias reduced to within ± 0.3 m/s), although the remaining scatter is set by representativeness differences that no bias model can remove. These results caution against uncorrected use of ERA5 as a stand-alone reference for altimeter evaluation in light-wind and extreme-wind regimes—over the semi-enclosed Chinese seas studied here, and more generally wherever sparse buoy coverage makes reanalysis the fallback reference for satellite wind validation.

Keywords: Sentinel-3 altimeter; wind speed; ERA5 reanalysis; validation; moored buoy; China Seas; bias correction



Academic Editor: Alan Robins

Received: 26 June 2026

Revised: 18 July 2026

Accepted: 21 July 2026

Published: 31 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

Sea surface wind speed from radar altimeters anchors a large part of operational marine forecasting and marine climate monitoring. Altimeter winds enter scatterometer cross-calibration chains, multi-mission wind climatologies [1,2], and the initialization of wave hindcasts [3,4]. The Sentinel-3 pair (A and B) extends this record within Copernicus; together with Jason-3 and the newer Sentinel-6 mission they define the current nadir-altimeter backbone for ocean wind observation [5,6]. Routine validation of these products therefore has operational consequences: when an altimeter retrieval carries a bias that is not recognized, downstream users accept it as a signal.

The validation itself, however, is reference-dependent. Moored meteorological buoys have long been the de facto standard because their wind measurements are direct, high-

frequency, and largely independent of the altimeter retrieval chain [7,8]. Global buoy–altimeter comparisons have produced the wind-speed calibration corrections used in multi-mission reprocessings. Young et al. [9] consolidated a multi-platform altimeter–radiometer–scatterometer calibration on global buoy networks into a single correction set that has been widely reused, and Takbash et al. [2] extended it to extreme events, arguing that the altimeter wind field is trustworthy once buoy-derived nonlinearity corrections are applied. The more recent reprocessings of Ribal and Young [1,10] use triple collocation against models and scatterometers to cross-validate these corrections and to flag where calibration stability breaks down. For Sentinel-3 specifically, Yang et al. [11] characterized Sentinel-3A’s SRAL globally and against Jason-3, and the follow-up of Yang et al. [7] added Sentinel-3B and reported buoy-referenced wind-speed RMSE in the 1.3–1.7 m/s range, slightly larger than the Jason-3 benchmark; the Chinese HY-2 altimeter series provides independent methodological context [12,13]. This calibration is mature globally, but two features make it insufficient for regional work. Regional buoy networks differ in anemometer height, maintenance, and exposure, so global coefficients do not guarantee regional unbiasedness [14], and the Ku-band response is least stable at exactly the two ends of the wind range: the low-wind limit, where foam cover vanishes and σ_0 saturates, and the high-wind extreme, where the roughness relation flattens [15].

Where buoys are sparse, ERA5 reanalysis wind speed is commonly substituted as a convenient gridded reference. ERA5 assimilates many surface observations and provides temporally continuous, spatially dense wind fields at a 0.25° resolution, but its near-surface winds inherit biases from the boundary-layer parameterization and from the resolution at which synoptic weather systems are represented, and those biases are not uniform across the wind-speed range. Rivas and Stoffelen [16] used ASCAT scatterometer winds to show that ERA5 persistently underestimates ocean wind speed above roughly Beaufort 7, with the deficit growing as wind speed increases; Campos et al. [17] recalibrated ERA5 severe winds against multi-altimeter data over the Atlantic and put the raw underestimate at 8–12% above 18 m/s; and Potisomporn et al. [18] documented the opposite tendency at the light-wind end, an overestimation of low-wind frequency that matters disproportionately for wind-energy siting. Two mechanisms are usually invoked: the IFS boundary-layer scheme smooths the near-surface profile and damps extremes, and the 0.25° grid is too coarse to resolve synoptic structure in semi-enclosed seas [19,20]. For coastal settings in particular, Alkhalidi et al. [21] and Jiang et al. [22] reported wind-speed-dependent ERA5 biases and argued for regional recalibration rather than a uniform offset. These findings converge on a single testable prediction: if the altimeter is nearly unbiased against buoys, then the altimeter-minus-ERA5 residual should retain ERA5’s own wind-speed-dependent bias pattern.

The Chinese nearshore seas are a good place to test this prediction, and a place where the answer has practical stakes. The Bohai, Yellow, East China, and northern South China Seas form a chain of semi-enclosed and marginal seas along the Asian continental shelf, where the East Asian monsoon and the coastal geometry together produce wind regimes that change sharply across seasons and over distances of ~100 km: summer-monsoon winds along the coastal corridor rarely exceed 10 m/s, the winter monsoon regularly drives sustained 10–15 m/s winds across the Bohai and Yellow Seas, and tropical cyclones add a non-stationary tail in late summer and autumn [3,4]. Wave- and wind-resource assessments across this region increasingly take altimeter-plus-reanalysis products as input, with ERA5 the de facto reanalysis choice [22–24], yet dedicated validation of ERA5 winds in these nearshore basins remains limited, and validation that separates the altimeter residual from the reanalysis residual is still missing. Adjacent sensors point the same way: the Chinese HY-2B and HY-2C scatterometer validations [25,26] and coastal SAR retrievals with C-band model functions [27,28] both find the low-wind tail and the coastal margin to be the most problematic regimes regardless of the

sensor. Because our question concerns systematic structure in the altimeter–ERA5 residual rather than random-error partitioning, we rely on paired statistics stratified by wind speed and season rather than triple collocation, which by construction is insensitive to systematic bias [29,30].

The present study uses 14 months of Sentinel-3A and -3B altimeter matchups over these seas to place buoy-referenced and ERA5-referenced validation side by side. We ask three questions: whether the Sentinel-3 satellite altimeter wind product carries a wind-speed-dependent error against either reference; whether the two Sentinel-3 satellites behave equivalently or must be treated separately; and whether any residual wind-speed structure in the altimeter–ERA5 discrepancy can be reduced by an empirical correction of ERA5 rather than of the altimeter. The answers determine, concretely, whether ERA5 can stand in for buoys when validating altimeter winds over this region and under what circumstances it should not. This determination carries over to any semi-enclosed or coastal sea where buoys are scarce and ERA5 is the fallback reference.

2. Data and Study Area

2.1. Study Area and Period

The study area covers the Bohai, Yellow, East China, and northern South China Seas (approximately 10°–40° N, 105°–130° E), outlined in Figure 1. The four basins form a connected chain of semi-enclosed and marginal seas along the Asian continental shelf: the Bohai Sea is a shallow, almost land-locked embayment; the Yellow and East China Seas are broad shelf seas bounded by the Chinese mainland to the west and the Korean peninsula and the Ryukyu island arc to the east; and the northern South China Sea opens to the deep basin south of the Taiwan Strait. The domain therefore combines a wide range of coastal geometries and water depths within a single monsoon-driven wind regime, which is what makes it a demanding test bed for a 0.25° reanalysis. The period is January 2023 to February 2024 for the Sentinel-3–ERA5 comparison and August 2023 to February 2024 for the Sentinel-3–buoy comparison, reflecting the availability of the matchup records. The period spans a full seasonal cycle including the summer southwest monsoon, the autumn transition with occasional tropical cyclone activity, and the winter northeast monsoon.

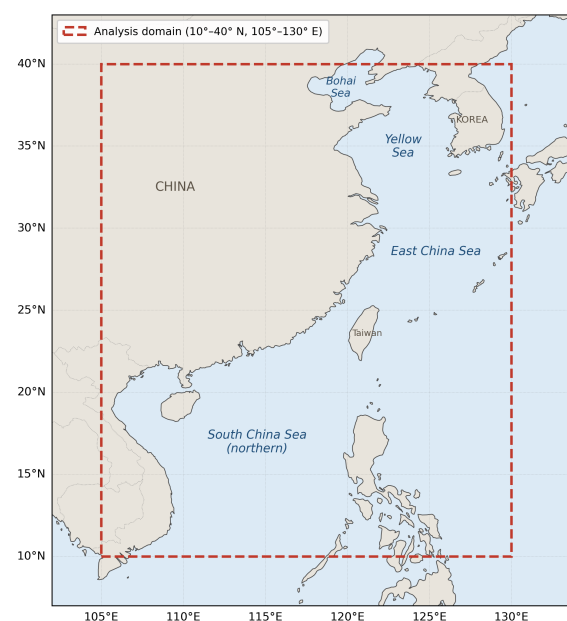


Figure 1. Regional map of the study area. The dashed box outlines the analysis domain (10°–40° N, 105°–130° E), which spans the Bohai, Yellow, East China, and northern South China Seas. Individual buoy mooring positions are omitted because they are operationally restricted (Section 2.3).

2.2. Sentinel-3A and -3B SAR Altimeter

Both Sentinel-3A (launched 2016) and -3B (launched 2018) carry an SRAL dual-frequency radar altimeter operating in the Ku-band as the primary wind-retrieval band. We use Level-2 water products for both satellites, subsetting to the study region. Each satellite pass is treated as one observation event: within each pass we retain per-pass mean wind speed and per-pass statistics (bias, MAD, RMSE) against the collocated reference. Passes flagged for rain contamination, land proximity, or anomalous waveforms are excluded prior to the matchup. The resulting dataset comprises 150 (S3A) and 157 (S3B) passes collocated with the buoy network, and 549 (S3A) and 522 (S3B) passes collocated with ERA5.

2.3. Moored Buoys and ERA5

The buoy network consists of moored meteorological buoys operated along the Chinese continental shelf, distributed across the Bohai, Yellow, East China, and northern South China Sea basins that make up the study domain. Anemometers are mounted at 3–5 m above the sea surface and measurements are adjusted to the 10 m neutral-equivalent wind speed using a log-wind profile. The buoys are part of an operational network and their precise coordinates are restricted; individual mooring positions are therefore not disclosed here. ERA5 hourly 10 m wind fields at a 0.25° resolution are bilinearly interpolated to observation locations. For each satellite pass, the per-pass-averaged ERA5 wind speed is computed from the ERA5 grid cells lying within the pass footprint. For buoy matchups, the temporally nearest buoy observation within a 30 min window is paired with the satellite pass.

2.4. Pairwise Matchups

Four datasets form the core of this paper: S3A–buoy, S3B–buoy, S3A–ERA5, S3B–ERA5 (Table 1). The mean satellite-minus-reference bias is derived directly from the per-pass records; aggregate MAD and RMSE are computed as the mean of the per-pass MAD and RMSE, consistent with operational reporting conventions.

Table 1. Aggregate pairwise statistics. Bias is the mean of per-pass satellite-minus-reference. MAD and RMSE are the means of per-pass values. r is the mean per-pass Pearson correlation where available.

Comparison	N	Bias (m/s)	MAD (m/s)	RMSE (m/s)	r
S3A vs. buoy	150	−0.02	1.27	1.60	0.71
S3B vs. buoy	157	−0.04	1.29	1.61	0.58
S3A vs. ERA5	549	+0.03	1.93	2.29	0.44
S3B vs. ERA5	522	+0.11	2.08	2.47	0.45

3. Methodology

3.1. Pairwise Validation Metrics

For each of the four source–reference combinations we compute four standard statistics: the mean bias $\bar{d}$, the median absolute deviation (MAD), the root-mean-square error (RMSE), and the Pearson correlation coefficient r :

$$\bar{d} = \frac{1}{N} \sum_{i=1}^N (x_i - y_i), \quad \text{MAD} = \text{median}_i |x_i - y_i|, \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2}, \quad r = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (y_i - \bar{y})^2}}. \quad (2)$$

Here x_i and y_i are the collocated altimeter and reference (buoy or ERA5) 10 m wind speeds for the i -th matched sample, N is the number of matched samples, and $\bar{x}$ and $\bar{y}$ are the corresponding sample means. The four statistics are evaluated within each satellite pass over its matched samples and then averaged across passes; the correlation r is reported as the mean of the per-pass values. MAD is less sensitive than RMSE to undetected outliers from rain contamination or anomalous waveforms. Per-pass summaries are used rather than a single pooled per-sample matchup because the per-pass statistics are the form that operational altimeter quality-control pipelines actually record.

3.2. Wind-Speed-Stratified Analysis

To resolve wind-speed dependence in the bias, passes are partitioned into five bins based on their per-pass mean reference wind speed: 0–3, 3–6, 6–9, 9–12, and >12 m/s. These boundaries correspond approximately to the Beaufort categories calm-light-breeze, gentle-moderate, fresh-strong, near-gale, and gale-and-above. For each bin we report the number of passes, the mean bias (with standard error), the mean MAD, and the mean RMSE. Bins with fewer than five passes are reported but not interpreted.

Two bin resolutions are used. The five-bin partition above is used for the tabulated statistics. A finer 1 m/s bin resolution is used for Figure 2 to reveal the shape of the bias curve. Bins with fewer than three passes are dropped at this resolution.

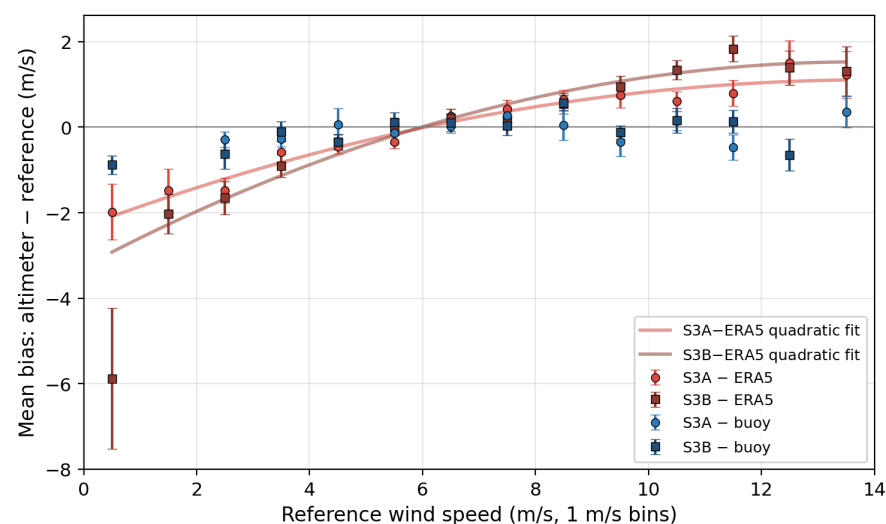


Figure 2. Fine-resolution (1 m/s bin) mean altimeter-minus-reference bias, with standard-error bars. Blue markers are the altimeter–buoy comparisons and red markers the altimeter–ERA5 comparisons; solid lines are the least-squares quadratic fits to the per-pass S3A–ERA5 and S3B–ERA5 residuals (Equation (3)).

3.3. Monthly and Seasonal Stratification

To track temporal structure, passes are grouped by calendar month. Monthly mean RMSE, MAD, and bias are reported for each of the four source–reference pairs. A coarser three-way partition (summer-monsoon: June–September; transition: October; winter-monsoon: November–February) is used for aggregate summary.

3.4. Empirical ERA5 Correction Model

Given an altimeter–ERA5 bias that varies smoothly with wind speed and an altimeter–buoy bias that is flat, the simplest interpretation is that the wind-speed structure resides in ERA5. Under this interpretation we describe the satellite-minus-ERA5 residual as a low-order polynomial of the reference wind speed w and adopt a quadratic form,

$$\text{bias}_{\text{S3-ERA5}}(w) = a w^2 + b w + c, \quad (3)$$

fitted by ordinary least squares on the per-pass residuals, separately for S3A and S3B. The polynomial order is not assumed: we fit linear, quadratic, and cubic models and select among them with the Akaike and Bayesian information criteria (AIC and BIC), reporting the comparison in Section 4.4. The fitted curve is descriptive; it summarizes the residual in a form that can be applied, in reverse, to adjust ERA5 wind speed: $w_{\text{ERA5}}^{\text{corr}} = w_{\text{ERA5}} + \text{bias}_{\text{S3-ERA5}}(w_{\text{ERA5}})$. We then quantify how much of the systematic, wind-speed-dependent component of the altimeter–ERA5 discrepancy the adjustment removes. This is a sanity check on the interpretation rather than a deployable correction; the latter would require training on an independent subset and validation on held-out passes.

4. Results

4.1. Aggregate Pairwise Statistics

Table 1 summarizes the four pairwise comparisons. Against buoys, both Sentinel-3A and -3B are nearly unbiased in the mean ($|\bar{d}| < 0.04$ m/s) and have MADs around 1.27–1.29 m/s and RMSEs of 1.60–1.61 m/s. Against ERA5, the same altimeters yield MADs of 1.93 (S3A) and 2.08 m/s (S3B) and RMSEs of 2.29 and 2.47 m/s. The change in reference inflates the altimeter RMSE by 43–53% without changing anything about the satellite. The correlation also differs: S3A–buoy $r = 0.71$, compared to S3B–buoy $r = 0.58$; the 0.13 gap in correlation is the largest single difference between the two satellites in the aggregate.

4.2. Wind-Speed-Stratified Bias: Flat Against Buoys, Monotonic Against ERA5

Stratifying by reference wind speed (Table 2) reveals a structural asymmetry that the aggregate statistics conceal. Against the buoy, the altimeter bias hovers within ± 0.34 m/s across the five bins for both satellites; there is no clear wind-speed trend. Against ERA5 the picture is completely different: the altimeter-minus-ERA5 bias swings monotonically from -1.55 m/s (0–3 m/s bin, S3A) to $+1.38$ m/s (12+ m/s, S3A). For S3B the swing is larger still, from -2.31 to $+1.52$ m/s. The two satellites trace nearly the same curve, resolved at 1 m/s in Figure 2.

Table 2. Wind-speed-binned mean bias (m/s) and MAD for the four comparison pairs. Bins defined by the per-pass mean reference wind speed.

Bin (m/s)	S3A vs. Buoy		S3B vs. Buoy		S3A vs. ERA5		S3B vs. ERA5	
	Bias	MAD	Bias	MAD	Bias	MAD	Bias	MAD
0–3	−0.29	1.13	−0.66	1.29	−1.55	2.07	−2.31	2.76
3–6	−0.13	1.37	−0.09	1.27	−0.44	1.87	−0.30	1.94
6–9	+0.12	1.21	+0.22	1.26	+0.43	1.89	+0.29	2.07
9–12	−0.18	1.29	+0.03	1.37	+0.70	1.93	+1.28	2.08
12+	+0.34	1.10	−0.19	1.25	+1.38	2.34	+1.52	2.12

The same wind-speed-dependent pattern dominates the altimeter–ERA5 MAD (Table 2): in the tail bins the mean bias alone is comparable in magnitude to the MAD, whereas the altimeter–buoy MAD in those bins stays at 1.1–1.3 m/s, close to the best the altimeter retrieval can achieve.

4.3. Monthly RMSE Record and Sentinel-3A vs. -3B Consistency

The monthly aggregates (Figure 3) show how stable each pair is over the record. The buoy-referenced RMSE for both satellites stays within a 1.3–1.8 m/s band, with the calmer

late-autumn months (September, November) at the low end. The ERA5-referenced RMSE is 0.5–1.0 m/s higher in nearly every month and shows a larger seasonal swing (1.9–3.1 m/s), with the highest values in the winter and early-spring months—February and March 2023 and again from December 2023 onward—when the winter monsoon and its associated events dominate.

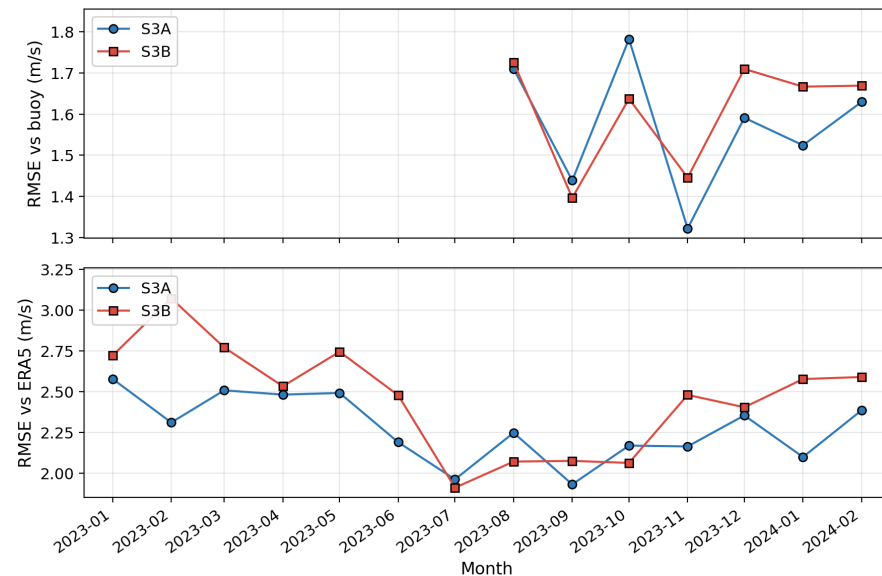


Figure 3. Monthly mean RMSE for Sentinel-3A (blue circles) and -3B (red squares) against the buoy (**top**) and against ERA5 (**bottom**). Months are ordered chronologically; the ERA5 record spans January 2023–February 2024, whereas the buoy record begins in August 2023.

Across months, Sentinel-3A and -3B are close to one another in buoy-referenced RMSE (typical month-to-month difference < 0.15 m/s) but diverge more in ERA5-referenced RMSE, where S3B is typically 0.1–0.4 m/s worse than S3A. This is consistent with the aggregate correlation gap ($r = 0.71$ vs. 0.58) and suggests that the two satellites should not be treated as interchangeable without recalibration when merged into a combined multi-mission product.

4.4. Empirical ERA5 Correction Results

Before fixing the functional form, we compared linear, quadratic, and cubic fits of the per-pass altimeter–ERA5 residual against reference wind speed (Table 3). For S3A the quadratic is preferred by both AIC and BIC, and adding a cubic term brings no improvement (R^2 unchanged at 0.18, cubic coefficient ≈ 0 , and both criteria worsen). For S3B the cubic exhibits a marginal gain (R^2 from 0.24 to 0.25; $\Delta\text{BIC} \approx 1.6$), driven mainly by the sparse lowest-wind bin. We therefore keep the quadratic as the common, parsimonious form for both satellites: it captures the rise-then-saturate shape visible in Figure 2 while avoiding an extra parameter that the data do not consistently support.

The fitted quadratics are

$$\begin{aligned}\text{bias}_{\text{S3A-ERA5}}(w) &= -0.018w^2 + 0.491w - 2.328 \quad (R^2 = 0.18), \\ \text{bias}_{\text{S3B-ERA5}}(w) &= -0.025w^2 + 0.698w - 3.264 \quad (R^2 = 0.24),\end{aligned}$$

with w and the bias in m/s. The negative quadratic term encodes the flattening of the residual at high wind speed (Figure 2). The low R^2 is expected and informative: only about a fifth of the pass-to-pass scatter in the residual is explained by wind speed, so the correction targets the *systematic*, wind-speed-dependent part of the discrepancy, not its random part.

Table 3. Model selection for the altimeter–ERA5 residual as a function of reference wind speed. R^2 , AIC, and BIC for ordinary-least-squares polynomial fits on the per-pass residuals. Lower AIC/BIC is better; the preferred order per satellite is in bold.

Pair	Model	R^2	AIC	BIC
S3A–ERA5	Linear	0.161	513.6	522.2
	Quadratic	0.177	505.4	518.3
	Cubic	0.177	507.4	524.6
S3B–ERA5	Linear	0.221	560.0	568.6
	Quadratic	0.242	547.9	560.7
	Cubic	0.253	542.0	559.1

That systematic part is what the adjustment removes. Applying the fits in reverse to ERA5 wind speed collapses the wind-speed-binned mean bias from a -1.55 to $+1.38$ m/s swing (S3A) and a -2.31 to $+1.52$ m/s swing (S3B) down to within ± 0.30 m/s in every bin. The root-mean-square of the per-pass mean bias (the systematic component the fit can act on) falls from 1.74 to 1.58 m/s for S3A and from 1.93 to 1.68 m/s for S3B. The full per-pass RMSE (2.29 and 2.47 m/s) is little changed, because it is dominated by within-pass and representativeness scatter: the buoy is a point measurement collocated with a pass average, whereas ERA5 is a gridded 0.25° field averaged to the same along-track scale, and this mismatch is irreducible by any bias model. In short, the wind-speed-dependent structure that separates ERA5-referenced from buoy-referenced validation is almost entirely removable, but the residual scatter that remains after removing it is not. We stress that these fits are descriptive statistics evaluated on the same data; a deployable correction would require training and validation on independent subsets.

5. Discussion

5.1. The Buoy–ERA5 Asymmetry

The central empirical result is that the Sentinel-3 altimeter–buoy residual is flat in wind speed while the altimeter–ERA5 residual is monotonically wind-speed-dependent. Because both references are being measured by the same altimeter at the same time, the difference cannot be attributed to the satellite. The natural reading is that ERA5 wind speed in this region has a wind-speed-dependent bias itself—overestimating light winds, underestimating strong winds—and that the altimeter–ERA5 residual reveals this through a swap of the reference. This reading matches the global ASCAT–ERA5 pattern reported by Rivas and Stoffelen [16] and the Atlantic altimeter–ERA5 severe-wind recalibration of Campos et al. [17], and it is consistent with the low-wind overprediction bias in the UK coastal setting noted by Potisomporn et al. [18]. The Chinese nearshore seas thus appear not to be exceptional: the same ERA5 curvature that global studies have found also applies here, and at a magnitude strong enough to dominate satellite-validation conclusions if ERA5 is used without correction.

5.2. Physical Origin of the ERA5 Wind-Speed Bias

The two mechanisms most commonly invoked—boundary-layer parameterization and resolution—both plausibly operate here. ERA5 uses a prognostic boundary-layer scheme that ties near-surface wind to a surface-roughness-dependent log profile; at low wind speeds the surface-layer similarity relations tend to over-diagnose the 10 m wind when true near-surface stratification is stable, and at high wind speeds the parameterized momentum flux is capped by a saturation drag coefficient that underestimates open-ocean momentum exchange [19,21]. Both effects drive the observed curvature in the same direction. The 0.25° grid resolution is also too coarse to resolve the land–sea contrasts in the Bohai and Yellow

Seas, where a single ERA5 cell can straddle coastline or port structures and the grid-cell mean wind cannot match a local buoy footprint. Consistent with this, Jiang et al. [22] found that a higher-resolution land-assimilation system outperformed ERA5 over the Hainan coastal strip—an adjacent and relevantly similar regional setting.

5.3. Sentinel-3A vs. -3B

The persistent 0.13 gap in buoy-referenced correlation between S3A and S3B, together with the larger monthly RMSE of S3B against ERA5, is a cleaner separation between the two satellites than the aggregate MAD suggests. This result is consistent with the global cross-calibration findings of Yang et al. [7], who reported that S3B wind retrievals carry slightly larger residual errors than S3A even after Jason-3 cross-calibration. From an operational perspective, the implication is that Sentinel-3A and -3B wind-speed products should not be combined at the track level without applying per-satellite recalibration; if they are merged blindly, the A–B inconsistency leaks into the combined product as additional random error.

5.4. A Practical Recommendation for Regional Validation

The findings of this study lead to a simple operational guideline. For altimeter validation in the Chinese nearshore seas, ERA5 is acceptable as a backup reference only after the altimeter–ERA5 residual has been corrected for wind-speed dependence, and only if the user is interested in mid-range winds (approximately 4–10 m/s) where the ERA5 bias is small. For extreme-wind or low-wind regimes, ERA5-based validation without correction over-reads the altimeter error by a factor that can approach two, as Table 2 shows.

5.5. Transferability to Other Water Bodies

The results above are specific to the Chinese nearshore seas, but the mechanism behind them is not, and it is worth being explicit about how far they should be expected to carry. The wind-speed-dependent discrepancy we isolate does not originate in the satellite: it originates in the reanalysis, in two features of ERA5 that are global rather than regional. The IFS boundary-layer scheme that damps the near-surface wind extremes is the same everywhere, and the 0.25° grid is equally unable to resolve land–sea contrasts in any basin whose coastal structure is finer than a grid cell. The published record is consistent with this reading: the same sign and shape of ERA5 error have been reported against ASCAT globally [16], against altimeters in the Atlantic [17], and at the light-wind end around the UK [18], with coastal studies elsewhere reaching the same conclusion that a regional recalibration is needed rather than a global offset [21,22]. Our contribution is not to discover the pattern but to show, with the altimeter held fixed against two references at once, that the pattern belongs to ERA5.

What transfers, then, is the diagnosis and the procedure, not the numbers. We would expect a similar wind-speed-dependent altimeter–ERA5 discrepancy in any semi-enclosed or marginal sea with comparable characteristics: a coastline and bathymetry structured on scales below the reanalysis grid, a strong seasonal forcing that populates both the light-wind and the strong-wind tails, and a sparse buoy network that tempts users to adopt ERA5 as the default reference. The Mediterranean, Black, Baltic, Adriatic, and Japan/East Seas, the Persian Gulf, and the coastal margins of the North Sea all satisfy these conditions, and the Sentinel-3 pair samples them on the same repeat cycle. The coefficients in Section 4.4, by contrast, should not be reused. They absorb the local wind climatology and the local coastal geometry, and refitting them requires exactly what we had here: an independent in situ reference over a full seasonal cycle. The practical recommendation for a new basin is therefore the workflow rather than the equation—establish the altimeter–buoy residual first, confirm that it is flat, and only then read the altimeter–ERA5 residual

as a statement about the reanalysis and fit the correction locally. By the same logic the finding is not specific to Sentinel-3: because the wind-speed structure resides in ERA5, any nadir altimeter benchmarked against ERA5 over these seas—Jason-3, Sentinel-6, or the HY-2 series—should inherit the same apparent error, and the same correction strategy should apply.

5.6. Limitations

This study covers a single regional domain and a 14-month record. These 14 months span a complete seasonal cycle (summer monsoon, autumn transition with tropical-cyclone activity, and winter monsoon), so the wind-speed-dependent pattern reported here is sampled across the full range of regional wind regimes. A longer, multi-year record would nonetheless tighten the extreme-wind estimates, where passes are sparsest, and reveal any interannual drift; extending the series is the most valuable next step. The quadratic correction is fit and evaluated on the same data rather than cross-validated. ERA5 wind speed is treated as a single product without distinguishing between interpolation effects and native reanalysis error. And the satellite-pass-level statistics, rather than sample-level matchups, constrain how far the results can be pushed on within-pass variability.

6. Conclusions

Over 14 months of Sentinel-3A and -3B matchups across the Chinese nearshore seas, the altimeter–buoy residual is approximately flat in wind speed while the altimeter–ERA5 residual swings from about -1.5 m/s in low wind to about $+1.4$ m/s in high wind. Because the altimeter is the common factor, the curvature resides in ERA5 rather than the satellite. A compact quadratic correction applied to ERA5 removes essentially all of this wind-speed-dependent structure, collapsing the per-bin mean bias to within ± 0.3 m/s and reducing the systematic bias RMS from 1.74 to 1.58 m/s for Sentinel-3A, while the irreducible representativeness scatter is left unchanged. Sentinel-3A outperforms 3B in buoy-referenced correlation ($r = 0.71$ vs. 0.58) and in month-to-month consistency against ERA5, a gap large enough that the two satellites should not be merged at the track level without per-satellite recalibration. For regional altimeter validation, ERA5 remains a useful reference only after wind-speed-dependent correction; used raw, it distorts error attribution most heavily in the low-wind and extreme-wind regimes that matter most for operational marine forecasting. Although demonstrated here for the Chinese nearshore seas and the Sentinel-3 pair, the approach of checking a reanalysis reference against buoys before adopting it, and correcting the wind-speed-dependent part of the discrepancy, applies to any semi-enclosed or coastal sea where direct observations are sparse and reanalysis is used as the fallback benchmark for satellite wind validation. Because the wind-speed structure resides in ERA5 rather than in the retrieval, the same apparent error should be expected wherever a coastline and bathymetry finer than the 0.25° grid meet a strong seasonal wind forcing—the Mediterranean, Black, Baltic, and Japan/East Seas and the Persian Gulf are natural candidates—and for any nadir altimeter benchmarked against ERA5 there, including Jason-3, Sentinel-6, and the HY-2 series. What transfers is the diagnosis and the workflow, not the fitted coefficients: the latter absorb the local wind climatology and coastal geometry and must be re-estimated against a local in situ reference (Section 5.5).

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

Funding: This work was supported in part by the Director’s Research Fund of Guangzhou Marine Geological Survey under Grant 2023GMGSJZJJ00027 and in part by the Key-Area Research and Development Program of Guangdong Province under Grant 2020B1111020002.

Data Availability Statement: Sentinel-3 Level-2 products are available from the Copernicus Open Access Hub. ERA5 data are available from the Copernicus Climate Data Store. Buoy observations are available from the corresponding author on reasonable request.

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

References

- Ribal, A.; Young, I.R. 33 years of globally calibrated wave height and wind speed data based on altimeter observations. *Sci. Data* **2019**, *6*, 77. [[CrossRef](#)] [[PubMed](#)]
- Takbash, A.; Young, I.R.; Breivik, Ø. Global Wind Speed and Wave Height Extremes Derived from Long-Duration Satellite Records. *J. Clim.* **2019**, *32*, 109–126. [[CrossRef](#)]
- Wu, W.; Li, P.; Zhai, F.; Gu, Y.; Liu, Z. Evaluation of different wind resources in simulating wave height for the Bohai, Yellow, and East China Seas during winter monsoons. *Cont. Shelf Res.* **2020**, *207*, 104217. [[CrossRef](#)]
- Shao, Z.; Liang, B.; Li, H.; Wu, G.; Wu, Z. Blended wind fields for wave modeling of tropical cyclones in the South China Sea and East China Sea. *Appl. Ocean. Res.* **2018**, *71*, 20–33. [[CrossRef](#)]
- Scharroo, R.; Bonekamp, H.; Ponsard, C.; Parisot, F.; von Engeln, A.; Tahtadjev, M.; de Vriendt, K.; Montagner, F. Jason continuity of services: Continuing the Jason altimeter data records as Copernicus Sentinel-6. *Ocean. Sci.* **2016**, *12*, 471–479. [[CrossRef](#)]
- Abdalla, S.; Kolahchi, A.A.; Ablain, M.; Adusumilli, S.; Bhowmick, S.A.; Alou-Font, E.; Amarouche, L.; Andersen, O.B.; Antich, H.; Aouf, L.; et al. Altimetry for the future: Building on 25 years of progress. *Adv. Space Res.* **2021**, *68*, 319–363. [[CrossRef](#)]
- Yang, J.; Zhang, J.; Jia, Y.; Lin, C.; Zhang, L. Validation of Sentinel-3A/3B and Jason-3 Altimeter Wind Speeds and Significant Wave Heights Using Buoy and ASCAT Data. *Remote Sens.* **2020**, *12*, 2079. [[CrossRef](#)]
- Yang, J.; Zhang, J. Validation of Sentinel-3A/3B Satellite Altimetry Wave Heights with Buoy and Jason-3 Data. *Sensors* **2019**, *19*, 2914. [[CrossRef](#)] [[PubMed](#)]
- Young, I.R.; Sanina, E.; Babanin, A.V. Calibration and Cross Validation of a Global Wind and Wave Database of Altimeter, Radiometer, and Scatterometer Measurements. *J. Atmos. Ocean. Technol.* **2017**, *34*, 1285–1306. [[CrossRef](#)]
- Ribal, A.; Young, I.R. Global Calibration and Error Estimation of Altimeter, Scatterometer, and Radiometer Wind Speed Using Triple Collocation. *Remote Sens.* **2020**, *12*, 1997. [[CrossRef](#)]
- Yang, J.; Zhang, J.; Wang, C. Sentinel-3A SRAL Global Statistical Assessment and Cross-Calibration with Jason-3. *Remote Sens.* **2019**, *11*, 1573. [[CrossRef](#)]
- Liu, Q.; Babanin, A.V.; Guan, C.; Zieger, S.; Sun, J.; Jia, Y. Calibration and Validation of HY-2 Altimeter Wave Height. *J. Atmos. Ocean. Technol.* **2016**, *33*, 919–936. [[CrossRef](#)]
- Wang, J.; Aouf, L.; Jia, Y.; Zhang, Y. Validation and Calibration of Significant Wave Height and Wind Speed Retrievals from HY2B Altimeter Based on Deep Learning. *Remote Sens.* **2020**, *12*, 2858. [[CrossRef](#)]
- Ribal, A.; Young, I.R. Calibration and Cross Validation of Global Ocean Wind Speed Based on Scatterometer Observations. *J. Atmos. Ocean. Technol.* **2020**, *37*, 279–297. [[CrossRef](#)]
- Hersbach, H.; Stoffelen, A.; de Haan, S. An improved C-band scatterometer ocean geophysical model function: CMOD5. *J. Geophys. Res. Ocean.* **2007**, *112*, C03006. [[CrossRef](#)]
- Rivas, M.B.; Stoffelen, A. Characterizing ERA-Interim and ERA5 surface wind biases using ASCAT. *Ocean. Sci.* **2019**, *15*, 831–852. [[CrossRef](#)]
- Campos, R.M.; Gramscianinov, C.B.; de Camargo, R.; da Silva Dias, P.L. Assessment and Calibration of ERA5 Severe Winds in the Atlantic Ocean Using Satellite Data. *Remote Sens.* **2022**, *14*, 4918. [[CrossRef](#)]
- Potisomporn, P.; Adcock, T.A.A.; Vogel, C. Evaluating ERA5 reanalysis predictions of low wind speed events around the UK. *Energy Rep.* **2023**, *10*, 4781–4790. [[CrossRef](#)]
- Gualtieri, G. Reliability of ERA5 Reanalysis Data for Wind Resource Assessment: A Comparison against Tall Towers. *Energies* **2021**, *14*, 4169. [[CrossRef](#)]
- Çalışır, E.; Soran, M.B.; Akpınar, A. Quality of the ERA5 and CFSR winds and their contribution to wave modelling performance in a semi-closed sea. *J. Oper. Oceanogr.* **2023**, *16*, 106–130. [[CrossRef](#)]
- Alkhalidi, M.; Al-Dabbous, A.N.; Al-Dabbous, S.K. Evaluating the Accuracy of the ERA5 Model in Predicting Wind Speeds Across Coastal and Offshore Regions. *J. Mar. Sci. Eng.* **2025**, *13*, 149. [[CrossRef](#)]
- Jiang, Y.; Han, S.; Shi, C.; Gao, T.; Zhen, H.; Liu, X. Evaluation of HRCLDAS and ERA5 Datasets for Near-Surface Wind over Hainan Island and South China Sea. *Atmosphere* **2021**, *12*, 766. [[CrossRef](#)]

23. Chang, R.; Zhu, R.; Badger, M.; Hasager, C.B.; Xing, X.; Jiang, Y. Offshore Wind Resources Assessment from Multiple Satellite Data and WRF Modeling over South China Sea. *Remote Sens.* **2015**, *7*, 467–487. [[CrossRef](#)]
24. Yaakob, O.; Hashim, F.E.; Omar, K.M.; Din, A.H.M.; Koh, K.K. Satellite-based wave data and wave energy resource assessment for South China Sea. *Renew. Energy* **2016**, *88*, 359–371. [[CrossRef](#)]
25. Wang, Z.; Stoffelen, A.; Zou, J.; Lin, W.; Portabella, M.; Zhang, Y. Validation of New Sea Surface Wind Products From Scatterometers Onboard the HY-2B and MetOp-C Satellites. *IEEE Trans. Geosci. Remote Sens.* **2020**, *58*, 4387–4394. [[CrossRef](#)]
26. Wang, Z.; Zou, J.; Stoffelen, A.; Zhang, Y.; Lang, S.; Xu, X. Scatterometer Sea Surface Wind Product Validation for HY-2C. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2021**, *14*, 6156–6164. [[CrossRef](#)]
27. Lu, Y.; Zhang, B.; Perrie, W.; Li, X.; Wang, H. A C-Band Geophysical Model Function for Determining Coastal Wind Speed Using Synthetic Aperture Radar. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2018**, *11*, 2417–2428. [[CrossRef](#)]
28. Hasager, C.B.; Hahmann, A.N.; Ahsbahs, T.; Karagali, I.; Göçmen, T.; Floors, R.; Clausen, N.E.; Badger, M.; Peña, A. Europe's offshore winds assessed with synthetic aperture radar, ASCAT and WRF. *Wind. Energy Sci.* **2020**, *5*, 375–390. [[CrossRef](#)]
29. Abdalla, S.; Chiara, G.D. Estimating Random Errors of Scatterometer, Altimeter, and Model Wind Speed Data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2017**, *10*, 2406–2414. [[CrossRef](#)]
30. Tsamalis, C. Clarifications on the equations and the sample number in triple collocation analysis. *Remote Sens. Environ.* **2022**, *272*, 112936. [[CrossRef](#)]

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