

# Effect of Statistical Bin Resolution on Correlation Strength and Occurrence Maxima in Solar Wind–Ionosphere Coupling Studies

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## Research Article

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# Abstract

Statistical correlation analysis is widely used in space physics to quantify relationships between solar wind parameters and ionospheric responses. However, the choice of bin width in occurrence frequency studies introduces systematic biases that are rarely acknowledged or quantified. Using ion upflow occurrence data from the EISCAT Svalbard Radar (ESR) during the International Polar Year 2007 campaign, we demonstrate that coarse statistical binning systematically inflates Pearson correlation coefficients and suppresses maximum occurrence values across all solar wind and geomagnetic parameters examined. Bin widths were varied systematically across eight parameters, solar wind speed, number density, dynamic pressure, IMF magnitude, dayside coupling function, Sym-H, SML, and SMU, at six resolution levels spanning the range from fine to coarse binning. The Pearson correlation coefficient inflated by between 0.08 and 0.51 across all non-degenerate parameter–flux class combinations when bin width was increased from fine to coarse resolution, with the largest inflation observed for solar wind speed in the high-flux category ( $p$ : 0.35  $\rightarrow$  0.86) and for Sym-H across all flux classes. Bootstrap confidence intervals (CI) demonstrate that the inflated coarse-bin  $p$  values are substantially less reliable than their modest fine-bin counterparts: for example, Vsw low-flux coarse-bin  $p$  = 0.796 has a 95% CI of  $[-0.51, 0.97]$ , whereas fine-bin  $p$  = 0.464 has a CI of  $[0.37, 0.55]$ . Maximum occurrence values were suppressed by up to 81% under coarse binning, with solar wind density in the low-flux category showing the most severe suppression (87.5%  $\rightarrow$  16.5%). Spearman rank correlation is shown to exhibit the same bin-width inflation as Pearson  $p$ , confirming that the artifact is fundamental to the binning process itself and is not resolved by choice of correlation metric. These results demonstrate that reported correlation strengths in solar wind–ionosphere statistical studies are highly sensitive to bin width selection, and urge the community to report results across multiple bin resolutions and to accompany all  $p$  values with bootstrap confidence intervals.

## Plain Language Summary

When scientists study how the solar wind affects Earth's upper atmosphere, they sort measurements into groups called bins and calculate how strongly two quantities correlate. A key but rarely examined choice is how wide to make each bin. This study shows that wider bins systematically exaggerate apparent correlation strength and hide true peak occurrence values. A correlation of 0.35 can appear as 0.86 simply by widening the bins, with no change in the underlying physics. Wider bins also conceal important thresholds: fine-grained analysis reveals that ionospheric ion upflow occurs in nearly every minute under certain solar wind conditions, a finding that wide bins completely obscure. Switching to a different statistical metric does not fix this — the artifact is fundamental to binning itself. We recommend that space physics studies always report results at multiple bin widths and accompany all correlation values with confidence intervals so readers can judge how reliable the numbers are.

## 1. Introduction

Statistical analysis of the relationship between solar wind parameters and ionospheric responses forms a cornerstone of magnetosphere–ionosphere coupling research. Occurrence frequency studies, in which the rate of a given ionospheric phenomenon is computed as a function of upstream solar wind or geomagnetic conditions, have been widely employed to characterise how parameters such as solar wind speed, density, dynamic pressure, interplanetary magnetic field (IMF) magnitude, and geomagnetic indices influence high-latitude ionospheric dynamics (Foster et al., 1998; Ogawa et al., 2009; Skjæveland et al., 2014; Bjoland et al., 2025). A fundamental step in such analyses is the aggregation of individual observations into discrete bins of the independent variable, from which occurrence rates and linear correlation coefficients are computed. The choice of bin width is typically guided by practical considerations such as ensuring sufficient data points per bin or matching the resolution of available instruments, but its influence on the resulting statistical quantities is rarely examined systematically.

The binning of continuous data into discrete intervals is known to affect statistical measures in general. Coarser bins reduce the number of data points in the correlation, averaging over natural variability within each bin and thereby artificially smoothing the occurrence–parameter relationship. This smoothing tends to inflate linear correlation coefficients, a phenomenon related to the ecological fallacy in which group-level statistics misrepresent individual-level relationships (Robinson, 1950). Two mechanisms operate jointly: first, fewer bins reduce the degrees of freedom in the linear fit; second, larger numbers of observations per bin reduces within-bin variance, further smoothing the relationship. Simultaneously, coarse binning suppresses extreme values by averaging high-occurrence bins with neighboring lower-occurrence bins, reducing the apparent maximum occurrence and potentially obscuring physically important thresholds. Despite the well-known theoretical basis for these effects, their practical magnitude in solar wind–ionosphere statistical studies has not been quantified.

Ion upflow, the field-aligned upwelling of ionospheric plasma from the topside ionosphere into the magnetosphere, provides an ideal test case for this investigation. Ion upflows are driven by a combination of Joule heating, ambipolar electric fields, particle precipitation, and lower hybrid frequency waves (Jones et al., 1988; André & Yau, 1997; Yau et al., 2011), and their occurrence has been shown to correlate with solar wind speed, density, dynamic pressure, IMF magnitude and orientation, and geomagnetic activity indices (Foster et al., 1998; Ogawa et al., 2009; Zou et al., 2021). A recent statistical study of this dataset by David et al. (2026) examined ion upflow occurrence using a range of bin widths to ensure statistically robust analysis, motivating the present investigation into how the choice of bin width affects the statistical quantities reported. Several earlier analyses of ion upflow occurrence have been conducted using incoherent scatter radar data spanning periods from hours to a complete solar cycle (Foster et al., 1998; Endo et al., 2000; Buchert et al., 2004; Ogawa et al., 2009; Skjæveland et al., 2014; David et al., 2024, 2025; Bjoland et al., 2025), and the dataset accumulated during the International Polar Year 2007 campaign by the EISCAT Svalbard Radar (ESR) provides more than three hundred thousand field-aligned profiles at solar minimum.

In this study, we use the ESR IPY-2007 ion upflow occurrence dataset to systematically quantify the effect of bin width on two key statistical quantities: the Pearson linear correlation coefficient and the

maximum occurrence percentage. Eight solar wind and geomagnetic parameters are examined across six bin widths spanning from fine to coarse resolution. Bootstrap confidence intervals (CI) are computed for all  $p$  values, and Spearman rank correlation is compared alongside Pearson  $p$  to assess whether choice of metric mitigates the bin-width effect. Ion upflows are classified into low-, medium-, and high-flux categories following David et al. (2018), and the analysis is conducted separately for each flux class.

## 2. Data and Methods

### 2.1 Ion Upflow Dataset

The basis for this study is the 42-m fixed field-aligned dish of the EISCAT Svalbard Radar (ESR; Williams, 1995), operated continuously during the International Polar Year 2007 campaign at solar minimum. The ESR provides electron density, field-aligned ion velocity, ion temperature, and electron temperature at 1-minute temporal resolution across an altitude range of approximately 75–500 km, obtained via the Madrigal database. The IPY 2007 campaign offered near-continuous operation over approximately 300 days, yielding more than 300,000 field-aligned profiles.

Ion upflow events are identified using a field-aligned flux threshold of  $1 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$  (Wahlund & Opgenoorth, 1989; Foster et al., 1998; David et al., 2018), classified into three flux categories: low flux ( $1.0 \times 10^{13} \leq f < 2.5 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$ ), medium flux ( $2.5 \times 10^{13} \leq f < 7.5 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$ ), and high flux ( $f \geq 7.5 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$ ). A total of 82,852, 9,810, and 1,131 low-, medium-, and high-flux events were identified.

### 2.2 Solar Wind and Geomagnetic Data

Solar wind plasma parameters are obtained from OMNIWeb at 1-minute resolution, including solar wind speed ( $v_{sw}$ ), number density ( $n_{sw}$ ), dynamic pressure ( $P_{dyn}$ ), and IMF components. The IMF magnitude  $B_{mag}$  and dayside coupling function  $\Phi_D$  (Milan et al., 2012) are computed as described in David et al. (2026). Geomagnetic activity is characterised using Sym-H and the SuperMAG electrojet indices SML and SMU. A propagation delay of 10 minutes is applied to time-shift solar wind parameters from the magnetosheath to the ionosphere (Ridley et al., 1998; Khan & Cowley, 1999; Milan & Grocott, 2021) and 30 minutes average from L1 Lagrange point to the ionosphere (David et al., 2026).

### 2.3 Binning Methodology and Statistical Measures

For each parameter, the occurrence frequency of ion upflow is computed as:

$$occ = (No\ of\ events / No\ of\ observation) \times 100\%$$

with  $1\sigma$  binomial uncertainty  $\sigma = 100\% \times \sqrt{[p(1-p)/No\ of\ observation]}$ . The Pearson linear correlation coefficient  $p$  and Spearman rank correlation  $p_s$  are computed over a restricted fit range for each parameter, defined consistently across all bin widths tested. Bin widths yielding fewer than 5 data points in the fit range are treated as degenerate and excluded from headline statistics, as such cases produce correlation coefficients that reflect the mathematical constraint of fitting a line through too few

points rather than any physical relationship. The fine bin widths correspond to those applied in the highest-resolution analysis of this dataset (David et al., 2026), while the coarse bin widths represent those recommended for statistically robust reporting. Table 1 lists all bin widths tested. Bootstrap 95% confidence intervals for  $\rho$  are computed using 1000 resamples of the fit-range data points.

Eight parameters are examined:  $v_{sw}$ ,  $n_{sw}$ ,  $P_{dyn}$ ,  $B_{mag}$ ,  $\Phi_D$ ,  $Sym - H$ ,  $SML$ , and  $SMU$ . For each parameter, the bin width is varied systematically across six levels from fine to coarse resolution.

Table 1  
Summary of parameters examined, bin widths (bw) tested, fit ranges, and x-axis clipping. † Sym-H bw = 20 yields only 3 fit bins and is excluded from headline statistics.

| Parameter          | Symbol   | Unit               | Bin Widths Tested     | Fit Range | x Clip     |
|--------------------|----------|--------------------|-----------------------|-----------|------------|
| Solar wind speed   | vsw      | km s <sup>-1</sup> | 1, 5, 10, 25, 50, 100 | 300–700   | None       |
| Solar wind density | nsw      | cm <sup>-3</sup>   | 0.1, 0.5, 1, 2, 5, 10 | 0–50      | None       |
| IMF magnitude      | Bmag     | nT                 | 0.1, 0.5, 1, 2, 5     | 0–15      | None       |
| Dynamic pressure   | Pdyn     | nPa                | 0.1, 0.5, 1, 2, 5     | 0–7       | 0–16 nPa   |
| Coupling function  | $\Phi_D$ | kV                 | 1, 5, 10, 20, 30      | 0–100     | None       |
| Sym-H              | Sym-H    | nT                 | 0.1, 1, 5, 10, 20†    | –40 to 0  | None       |
| Lower electrojet   | SML      | nT                 | 1, 10, 50, 100, 200   | –900 to 0 | –1250 to 0 |
| Upper electrojet   | SMU      | nT                 | 1, 10, 25, 50, 100    | 0–350     | 0–750      |

### 3. Results

Results are organised into two subsections. Section 3.1 presents the effect of bin width on  $\rho$  (Pearson and Spearman) for all eight parameters, including bootstrap confidence intervals. Section 3.2 presents the effect on maximum occurrence percentage. Table 2 summarises Pearson  $\rho$  with bootstrap CIs at fine and coarse bin widths. Table 3 summarises maximum occurrence values. Table 4 provides the Spearman comparison. Figures 1 and 2 show the full  $\rho$  dependence on bin width across all tested resolutions. Figures 3 and 4 show the maximum occurrence trends. Figures 5, 6, and 7 provide side-by-side comparisons of selected parameters at fine versus coarse bin widths.

### 3.1 Effect of Bin Width on Pearson Correlation Coefficient

Figure 1 shows the Pearson  $\rho$  as a function of bin width for all eight parameters and three flux classes. Across nearly all parameters and flux classes,  $\rho$  increases monotonically as bin width increases, driven jointly by the reduction in the number of fit-range data points and by the increase in observations per bin which reduces within-bin variance. Two mechanisms therefore reinforce each other: fewer data points in the correlation increases leverage for any individual point, while higher N per bin produces smoother,

less scattered occurrence estimates. This is related to but not identical to the ecological fallacy (Robinson, 1950); it also reflects standard error scaling in which larger samples per group produce more precise group means. Figure 2 summarises the  $\Delta\rho = \rho(\text{coarse}) - \rho(\text{fine})$  values across all parameters.

Bootstrap confidence intervals (Table 2) reveal a critical asymmetry: fine-bin  $\rho$  values, despite appearing modest, are statistically well-determined because they are based on 300–800 fit-range data points. Coarse-bin  $\rho$  values, despite appearing impressively high, often have extremely wide confidence intervals because they are based on only 4–10 bins. For example, Vsw low-flux fine-bin  $\rho = 0.464$  has 95% CI [0.37, 0.55], whereas the coarse-bin  $\rho = 0.796$  has CI [– 0.51, 0.97], statistically indistinguishable from zero. SMU medium-flux coarse-bin  $\rho = 0.332$  has CI [– 0.47, 0.98], spanning the full range from moderate anticorrelation to near-perfect correlation. The inflation of  $\rho$  by coarse binning therefore not only misrepresents the strength of the relationship but also yields less reliable estimates than the fine-bin analysis it appears to improve upon.

For solar wind speed (vsw),  $\rho$  in the low-flux category increases from 0.464 at fine bin width (1 km s<sup>–1</sup>) to 0.796 at coarse bin width (50 km s<sup>–1</sup>), an inflation of  $\delta\rho = +0.332$ . The inflation is more severe in the medium-flux category ( $\rho$ : 0.609 → 0.935) and most pronounced in the high-flux category ( $\rho$ : 0.350 → 0.862,  $\delta\rho = +0.512$ ). A side-by-side panel comparison is shown in Fig. 5.

For solar wind number density (nsw), the low-flux  $\rho$  rises from 0.484 to 0.972 ( $\delta\rho = +0.488$ ). The high-flux category is notable in showing only minimal inflation ( $\rho$ : 0.715 → 0.718,  $\delta\rho = +0.003$ ), suggesting the high-flux upflow–density relationship is genuinely linear at all resolutions. The side-by-side comparison is shown in Fig. 6.

For IMF magnitude, inflation is strong: low-flux 0.913 → 0.994 (+ 0.081), medium-flux 0.711 → 0.930 (+ 0.219), high-flux 0.550 → 0.742 (+ 0.192). For dynamic pressure, high-flux  $\rho$  rises from 0.642 to 0.977 (+ 0.335), substantially driven by binning. For the coupling function, inflation is more moderate (high-flux: 0.825 → 0.924, + 0.099), reflecting that the coupling function relationship is already strong at fine resolution.

For Sym-H, the coarse bin width of 10 nT yields only 4 fit bins (fewer than the 5-bin minimum), flagged as degenerate in Fig. 1 and excluded from headline statistics. At bw = 5 nT (9 fit bins),  $\rho$  reaches – 0.882 for low flux, already strongly inflated from the fine-bin value of – 0.616. For SML, low-flux  $\rho$  rises from – 0.605 to – 0.979 at coarse bins.

The SuperMAG upper auroral electrojet index SMU presents the most notable exception. Medium-flux  $\rho$  remains low and non-monotonic at all bin widths (fine: 0.232, coarse: 0.332), and the coarse-bin 95% CI [– 0.47, 0.98] is so wide as to be meaningless. This behaviour reflects a genuine absence of a strong linear relationship at any resolution. The side-by-side comparison for SMU is shown in Fig. 7.

## 3.2 Effect of Bin Width on Maximum Occurrence Percentage

Figure 3 shows the maximum occurrence percentage as a function of bin width for all parameters and flux classes. For most parameters, maximum occurrence decreases as bin width increases, as high-occurrence fine bins are averaged with lower-occurrence neighboring bins. Figure 4 provides a direct comparison of fine-bin versus coarse-bin maximum occurrence values for each parameter. The most severe suppression is observed for solar wind number density in the low-flux category: maximum occurrence falls from 87.5% at fine bin width to 16.5% at coarse bin width (81% suppression). The fine-resolution data reveal that when solar wind density is in the range 30–50 cm<sup>-3</sup>, ion upflow occurs in nearly nine out of ten minutes, a threshold behaviour entirely concealed by coarse binning.

The isolated fine-bin maximum in the SMU high-flux category (3.6% at SMU = 606.5 nT) is based on a single observation bin containing only 1 upflow event in 15 total minutes (95% CI on 6.7% occurrence: [0.2%, 31.9%]). Coarse binning aggregates this bin with neighboring bins to produce a more stable estimate of 6.7% that is paradoxically higher than the fine-bin maximum. This confirms that the fine-bin maximum for SMU high-flux is upward-biased by very low counts and should not be interpreted as a physical threshold.

For solar wind speed, low-flux maximum occurrence falls from 50.0% to 21.1% (58% suppression). For SML, 100.0% at fine bins falls to 40.4% at coarse bins (60% suppression), the fine-resolution finding that low-flux upflow occurs in every minute when SML exceeds approximately 800 nT is a physically meaningful saturation threshold concealed by coarse binning. Table 3 summarises all maximum occurrence values.

Table 2

Pearson  $\rho$  at fine and coarse bin widths (bw) with bootstrap 95% confidence intervals in brackets. † Sym-H coarse bw = 10 has only 4 fit bins (degenerate); shown for completeness but excluded from headline statistics.

| Parameter | Fine bw | Coarse bw | $\rho$ Low (fine)        | $\rho$ Low (coarse)       | $\rho$ Med (fine)        | $\rho$ Med (coarse)       | $\rho$ High (fine)       | $\rho$ High (coarse)      |
|-----------|---------|-----------|--------------------------|---------------------------|--------------------------|---------------------------|--------------------------|---------------------------|
| Vsw       | 1       | 50        | 0.464<br>[0.37, 0.55]    | 0.796 [-0.51, 0.97]       | 0.609<br>[0.55, 0.66]    | 0.935<br>[0.88, 1.00]     | 0.350<br>[0.30, 0.46]    | 0.862<br>[0.72, 0.98]     |
| nsw       | 0.1     | 5         | 0.484<br>[0.42, 0.54]    | 0.972<br>[0.93, 1.00]     | 0.582<br>[0.52, 0.65]    | 0.889<br>[0.81, 0.96]     | 0.715<br>[0.63, 0.82]    | 0.718<br>[0.62, 0.96]     |
| Bmag      | 0.1     | 2         | 0.913<br>[0.88, 0.94]    | 0.994<br>[0.99, 1.00]     | 0.711<br>[0.63, 0.78]    | 0.930<br>[0.87, 0.99]     | 0.550<br>[0.47, 0.64]    | 0.742<br>[0.67, 0.99]     |
| Pdyn      | 0.1     | 1         | 0.869<br>[0.80, 0.93]    | 0.967<br>[0.89, 1.00]     | 0.721<br>[0.58, 0.83]    | 0.919<br>[0.65, 1.00]     | 0.642<br>[0.51, 0.76]    | 0.978<br>[0.96, 1.00]     |
| Coupling  | 1       | 10        | 0.805<br>[0.75, 0.86]    | 0.961<br>[0.91, 1.00]     | 0.770<br>[0.72, 0.85]    | 0.958<br>[0.94, 0.99]     | 0.825<br>[0.78, 0.89]    | 0.924<br>[0.89, 0.99]     |
| Sym-H     | 0.1     | 10†       | -0.616<br>[-0.81, -0.41] | -0.987<br>[-1.00, -0.98]† | -0.700<br>[-0.84, -0.57] | -0.968<br>[-1.00, -0.94]† | -0.602<br>[-0.79, -0.38] | -0.964<br>[-1.00, -0.88]† |
| SML       | 1       | 100       | -0.605<br>[-0.64, -0.57] | -0.979<br>[-1.00, -0.96]  | -0.527<br>[-0.61, -0.48] | -0.868<br>[-1.00, -0.83]  | -0.543<br>[-0.70, -0.49] | -0.735<br>[-0.98, -0.67]  |
| SMU       | 1       | 50        | 0.578<br>[0.49, 0.66]    | 0.809<br>[0.15, 1.00]     | 0.232<br>[0.15, 0.32]    | 0.332<br>[-0.47, 0.98]    | 0.558<br>[0.47, 0.69]    | 0.920<br>[0.76, 1.00]     |

Table 3

Maximum occurrence percentage at fine and coarse bin widths, with percentage change ( $\Delta\%$ ). Negative = suppression; positive = increase (SMU high-flux anomaly, see Section 3.2).

| Parameter | Low fine% | Low coarse% | Low $\Delta\%$ | Med fine% | Med coarse% | Med $\Delta\%$ | High fine% | High coarse% | High $\Delta\%$ |
|-----------|-----------|-------------|----------------|-----------|-------------|----------------|------------|--------------|-----------------|
| Vsw       | 50.0      | 21.1        | -58            | 20.0      | 9.7         | -52            | 1.6        | 1.3          | -19             |
| nsw       | 87.5      | 16.5        | -81            | 35.6      | 22.7        | -36            | 9.1        | 8.9          | -2              |
| Bmag      | 40.3      | 21.6        | -46            | 31.0      | 7.1         | -77            | 2.2        | 0.6          | -73             |
| Pdyn      | 52.3      | 17.8        | -66            | 15.9      | 8.7         | -45            | 0.9        | 0.8          | -11             |
| Coupling  | 83.3      | 69.2        | -17            | 42.9      | 16.5        | -62            | 12.5       | 7.5          | -40             |
| Sym-H     | 37.5      | 11.9        | -68            | 25.0      | 5.1         | -80            | 1.6        | 1.6          | 0               |
| SML       | 100.0     | 40.4        | -60            | 44.4      | 23.8        | -46            | 50.0       | 28.6         | -43             |
| SMU       | 100.0     | 25.6        | -74            | 33.3      | 16.7        | -50            | 3.6        | 6.7          | + 86            |

### 3.3 Spearman Rank Correlation Comparison

Table 4 compares Pearson  $\rho$  and Spearman rank correlation  $\rho_s$  at fine and coarse bin widths for selected parameters. Spearman  $\rho_s$  exhibits the same monotonic inflation with bin width as Pearson  $\rho$  across all parameters examined. In some cases the inflation is even more pronounced: for solar wind density in the low-flux category, Spearman  $\rho_s$  increases from 0.473 to 0.988 ( $\delta\rho_s = +0.515$ ) compared to Pearson  $\delta\rho = +0.488$ . For Sym-H and SML, Spearman  $\rho_s$  reaches -1.000 at coarse bins in all flux classes, indicating perfect monotonic anticorrelation in as few as 4–5 bins, a result that is mathematically trivial rather than scientifically meaningful. These results confirm that the bin-width inflation artifact is a fundamental property of the binning process itself and is not resolved by the choice of correlation metric.

Table 4

Pearson  $\rho$  and Spearman  $\rho_s$  at fine and coarse bin widths for selected parameters and flux classes. Both metrics inflate with increasing bin width. † = coarse bin flagged as degenerate (< 5 fit bins).

| Parameter | Flux   | Fine Pearson $\rho$ | Fine Spearman $\rho_s$ | Coarse Pearson $\rho$ | Coarse Spearman $\rho_s$ |
|-----------|--------|---------------------|------------------------|-----------------------|--------------------------|
| Vsw       | Low    | 0.464               | 0.460                  | 0.796                 | 0.619                    |
| Vsw       | Medium | 0.609               | 0.626                  | 0.935                 | 0.976                    |
| Vsw       | High   | 0.350               | 0.437                  | 0.862                 | 0.881                    |
| nsw       | Low    | 0.484               | 0.473                  | 0.972                 | 0.988                    |
| nsw       | Medium | 0.582               | 0.606                  | 0.889                 | 0.952                    |
| nsw       | High   | 0.715               | 0.656                  | 0.718                 | 0.952                    |
| Bmag      | Low    | 0.913               | 0.932                  | 0.994                 | 1.000                    |
| Sym-H     | Low    | -0.616              | -0.655                 | -0.987†               | -1.000†                  |
| SML       | Low    | -0.605              | -0.682                 | -0.979                | -1.000                   |
| SMU       | Medium | 0.232               | 0.236                  | 0.332                 | 0.500                    |

## 4. Discussion

The results provide the first systematic quantification of bin-width effects on correlation coefficients and maximum occurrence values in solar wind–ionosphere statistical studies. Two principal findings emerge: (1) coarse binning inflates  $\rho$  by 0.003 to 0.512 across the parameter–flux class combinations examined; and (2) coarse binning suppresses maximum occurrence values by 17–81% for most parameters. A third finding, which strengthens rather than undermines the main argument, is that the inflated coarse-bin  $\rho$  values are statistically less reliable than the modest fine-bin values, as evidenced by their much wider bootstrap confidence intervals.

Two complementary mechanisms drive  $\rho$  inflation simultaneously. First, coarser binning reduces the number of data points in the correlation, increasing the sensitivity of  $\rho$  to individual points (ecological fallacy; Robinson, 1950). Second, larger  $N$  per bin reduces within-bin variance, producing smoother and more linearly-behaving occurrence estimates. Both effects reinforce each other: a 50-fold increase in bin width (e.g., Vsw from 1 to 50 km s<sup>-1</sup>) simultaneously reduces the number of fit-range data points from approximately 400 to 8 and increases mean  $N$  per bin by a factor of approximately 44. The implication is that  $\rho$  values reported in binned solar wind–ionosphere studies should be understood as upper bounds on the true correlation strength, with the width of the bootstrap confidence interval providing an essential measure of reliability that the point estimate alone does not convey.

The suppression of maximum occurrence values deserves particular attention for space weather applications. The finding that low-flux upflow occurs in every minute when SML exceeds approximately

800 nT, visible only at fine bin widths, represents a practically useful threshold for predictive modelling. Coarse binning dilutes this threshold to a approximately 40% maximum occurrence that conveys no sense of saturation. Similarly, the near-saturation of low-flux upflow at solar wind densities of 30–50  $\text{cm}^{-3}$  is physically meaningful but invisible at 5  $\text{cm}^{-3}$  bin widths.

The SMU anomaly, where medium-flux  $\rho$  remains consistently low and non-monotonic at all bin widths, confirms that the eastward auroral electrojet lacks a strong linear coupling to ion upflow at any statistical resolution. This contrasts with SML (westward electrojet), which shows strong and systematically inflating correlations. The physical interpretation (Joule heating and particle precipitation driven by the westward rather than eastward electrojet) is therefore reinforced rather than complicated by the bin-width analysis.

The demonstration that Spearman  $\rho_s$  inflates with bin width at least as much as Pearson  $\rho$  is an important negative result. It shows that the community cannot escape the bin-width artifact by switching correlation metrics. The appropriate response is to report results across multiple bin widths and to accompany  $\rho$  values with bootstrap confidence intervals, which provide the reader with the information needed to assess both the magnitude and the reliability of reported correlations.

## 5. Conclusions

We have presented the first systematic quantification of the effect of statistical bin width on Pearson correlation coefficients, Spearman rank correlations, bootstrap confidence intervals, and maximum occurrence percentages in solar wind–ionosphere occurrence frequency studies. The principal conclusions are:

Coarse binning systematically inflates  $\rho$ . Across 23 out of 24 non-degenerate parameter–flux class combinations,  $\rho$  increases monotonically with bin width, driven by two reinforcing mechanisms: fewer fit-range data points and higher  $N$  per bin. Inflation ranges from  $\delta \rho = +0.003$  (nsw, high flux) to  $+0.512$  (vsw, high flux).

Inflated coarse-bin  $\rho$  values are statistically unreliable. Bootstrap confidence intervals demonstrate that coarse-bin  $\rho$  values based on 4–10 bins are often statistically indistinguishable from zero, while the corresponding fine-bin values have narrow, well-determined CIs. Fine-bin  $\rho$  is both more honest and more reliable.

Coarse binning suppresses maximum occurrence values by 17–81%, concealing physically important saturation thresholds. The finding that low-flux upflow occurs in 100% of minutes when SML exceeds approximately 800 nT is visible only at fine bin widths.

Spearman rank correlation exhibits the same bin-width inflation as Pearson  $\rho$ . The artifact is fundamental to the binning process itself, not to the choice of correlation metric.

Degenerate cases (fewer than 5 fit bins) must be excluded from headline statistics. At very coarse bin widths, apparent correlations of  $\rho = -1.000$  can arise purely from the mathematical constraint of fitting a line through 3–4 points.

Practical recommendations: (a) Report  $\rho$  and maximum occurrence across multiple bin widths; (b) accompany all  $\rho$  values with bootstrap 95% confidence intervals; (c) apply a minimum fit-bin threshold (we recommend  $\geq 5$ ); (d) use fine bin widths when identifying physical thresholds in maximum occurrence.

## Declarations

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### Data Availability

EISCAT data: <https://www.eiscat.se/> (Madrigal database).

OMNIWeb: <https://omniweb.gsfc.nasa.gov/>

SuperMAG: <https://supermag.jhuapl.edu/>.

**Competing interests:** The authors declare no competing interests.

## References

1. André, M., & Yau, A. (1997). Theories and observations of ion energization and outflow in the high latitude magnetosphere. *Space Science Reviews*, 80(1), 27–48. [https://doi.org/10.1007/978-94-009-0045-5\\_2](https://doi.org/10.1007/978-94-009-0045-5_2)
2. Bjoland, L. M., Ogawa, Y., & Haaland, S. (2025). Characteristics of the ambipolar electric field during ion upflow events. *Earth Planets and Space*, 77(1), 78. <https://doi.org/10.1186/s40623-025-02217-6>
3. Buchert, S. C., Ogawa, Y., Fujii, R., & Van Eyken, A. P. (2004). Observations of diverging field-aligned ion flow with the ESR. *Annales Geophysicae*, 22(3), 889–899. <https://doi.org/10.5194/angeo-22-889-2004>
4. David, T. W., Wright, D. M., Milan, S. E., Cowley, S. W. H., Davies, J. A., & McCrea, I. (2018). A study of observations of ionospheric upwelling made by the EISCAT Svalbard Radar during the International

- Polar Year Campaign of 2007. *Journal of Geophysical Research Space Physics*, 123(3), 2192–2203. <https://doi.org/10.1002/2017ja024802>
5. David, T. W., Michael, C. M., Wright, D., Talabi, A. T., & Ajetunmobi, A. E. (2024). Ionospheric upwelling and the level of associated noise at solar minimum. *Annales Geophysicae*, 42(2), 349–354. <https://doi.org/10.5194/angeo-42-349-2024>
  6. David, T. W., Michael, C. M., Wright, D. M., Talabi, A. T., Ajetunmobi, A. E., Awoyinka, T. D., & Kareem, S. O. (2025). Case studies of drivers of ionospheric upwellings. *Indian Journal of Physics*, 99(10), 3977–3987. <https://doi.org/10.1007/s12648-025-03582-4>
  7. David, T. W., Michael, C. M., Adetunji, E. O., Wright, D. M., Talabi, A. T., & Ajetunmobi, A. E. (2026). Statistical analysis of ion upflow occurrence in relation to the upstream solar wind plasma parameters and terrestrial magnetic activity during the IPY-ESR 2007 observations. *Advances in Space Research*, 77(9), 9617–9632. <https://doi.org/10.1016/j.asr.2026.03.020>
  8. Endo, M., Fujii, R., Ogawa, Y., Buchert, S. C., Nozawa, S., Watanabe, S., & Yoshida, N. (2000). Ion upflow and downflow at the topside ionosphere observed by the EISCAT VHF radar. *Annales Geophysicae*, 18(2), 170–181. <https://doi.org/10.1007/s00585-000-0170-3>
  9. Foster, C., Lester, M., & Davies, J. A. (1998). A statistical study of diurnal, seasonal and solar cycle variations of F-region and topside auroral upflows observed by EISCAT between 1984 and 1996. *Annales Geophysicae*, 16(10), 1144–1158. <https://doi.org/10.1007/s00585-998-1144-0>
  10. Jones, G. O. L., Williams, P. J. S., Winsor, K. J., Lockwood, M., & Suvanto, K. (1988). Large plasma velocities along the magnetic field line in the auroral zone. *Nature*, 336(6196), 231–232. <https://doi.org/10.1038/336231a0>
  11. Khan, H., & Cowley, S. W. H. (1999). Observations of the response time of high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data. *Annales Geophysicae*, 17(10), 1306–1335. <https://doi.org/10.1007/s00585-999-1306-8>
  12. Milan, S. E., Gosling, J. S., & Hubert, B. (2012a). Relationship between interplanetary parameters and the magnetopause reconnection rate quantified from observations of the expanding polar cap. *Journal of Geophysical Research Atmospheres*, 117(A3). <https://doi.org/10.1029/2011ja017082>
  13. Milan, S. E., & Grocott, A. (2021). High latitude ionospheric convection. *Geophysical Monograph*, 21–47. <https://doi.org/10.1002/9781119815617.ch2>
  14. Ogawa, Y., Buchert, S. C., Fujii, R., Nozawa, S., & Van Eyken, A. P. (2009). Characteristics of ion upflow and downflow observed with the European Incoherent Scatter Svalbard radar. *Journal of Geophysical Research Atmospheres*, 114(A5). <https://doi.org/10.1029/2008ja013817>
  15. Ridley, A. J., Lu, G., Clauer, C. R., & Papitashvili, V. O. (1998). A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique. *Journal of Geophysical Research Atmospheres*, 103(A3), 4023–4039. <https://doi.org/10.1029/97ja03328>
  16. Robinson, W. S. (1950). Ecological correlations and the behavior of individuals. *American Sociological Review*, 15(3), 351–357. <https://doi.org/10.2307/2087176>

17. Skjæveland, Å., Moen, J., & Carlson, H. C. (2014). Which cusp upflow events can possibly turn into outflows? *Journal of Geophysical Research Space Physics*, 119(8), 6876–6890.  
<https://doi.org/10.1002/2013ja019495>
18. Wahlund, J., & Opgenoorth, H. J. (1989). EISCAT observations of strong ion outflows from the F-region ionosphere during auroral activity: Preliminary results. *Geophysical Research Letters*, 16(7), 727–730. <https://doi.org/10.1029/gl016i007p00727>
19. Williams, P. J. S. (1995). A Multi-Antenna capability for the EISCAT Svalbard radar. *Journal of Geomagnetism and Geoelectricity*, 47(8), 685–698. <https://doi.org/10.5636/jgg.47.685>
20. Yau, A. W., Peterson, W., & Abe, T. (2011b). Influences of the Ionosphere, Thermosphere and Magnetosphere on Ion Outflows. In *The Dynamic Magnetosphere*, (pp. 283–314).  
[https://doi.org/10.1007/978-94-007-0501-2\\_16](https://doi.org/10.1007/978-94-007-0501-2_16)
21. Zou, S., Ren, J., Wang, Z., Sun, H., & Chen, Y. (2021). Impact of Storm-Enhanced density (SED) on ion upflow fluxes during geomagnetic storm. *Frontiers in Astronomy and Space Sciences*, 8.  
<https://doi.org/10.3389/fspas.2021.746429>

## Figures

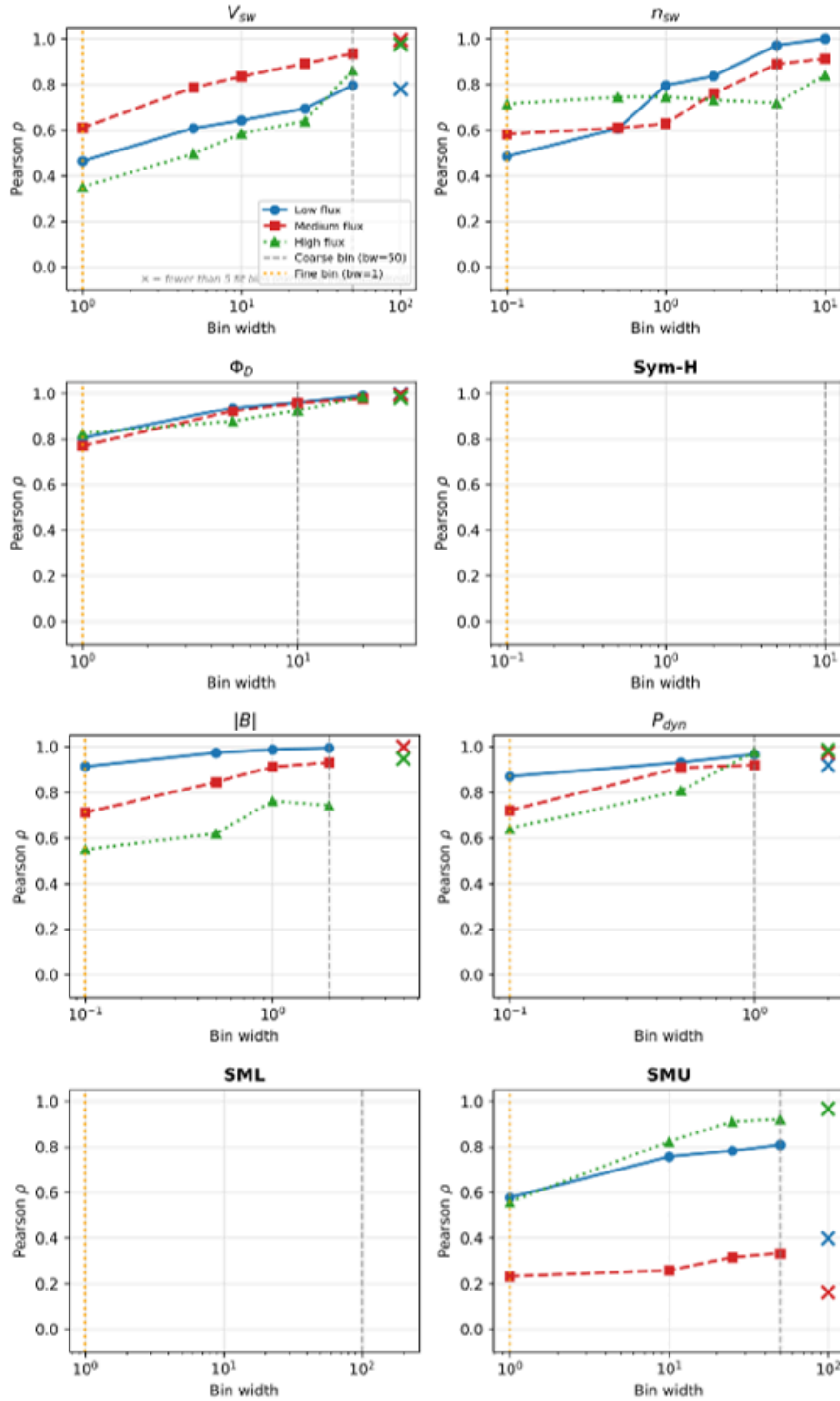


Figure 1

Pearson correlation coefficient ( $\rho$ ) as a function of bin width for all eight solar wind and geomagnetic parameters. Low flux (blue circles), medium flux (red squares), high flux (green triangles). Orange dotted line = fine bin width; grey dashed line = coarse bin width.  $\times$  marks denote degenerate cases with fewer than 5 fit bins, which are excluded from headline statistics. Note the monotonic increase of  $\rho$  with bin width for most parameters, and the anomalous  $SMU$  medium-flux panel (lower right).

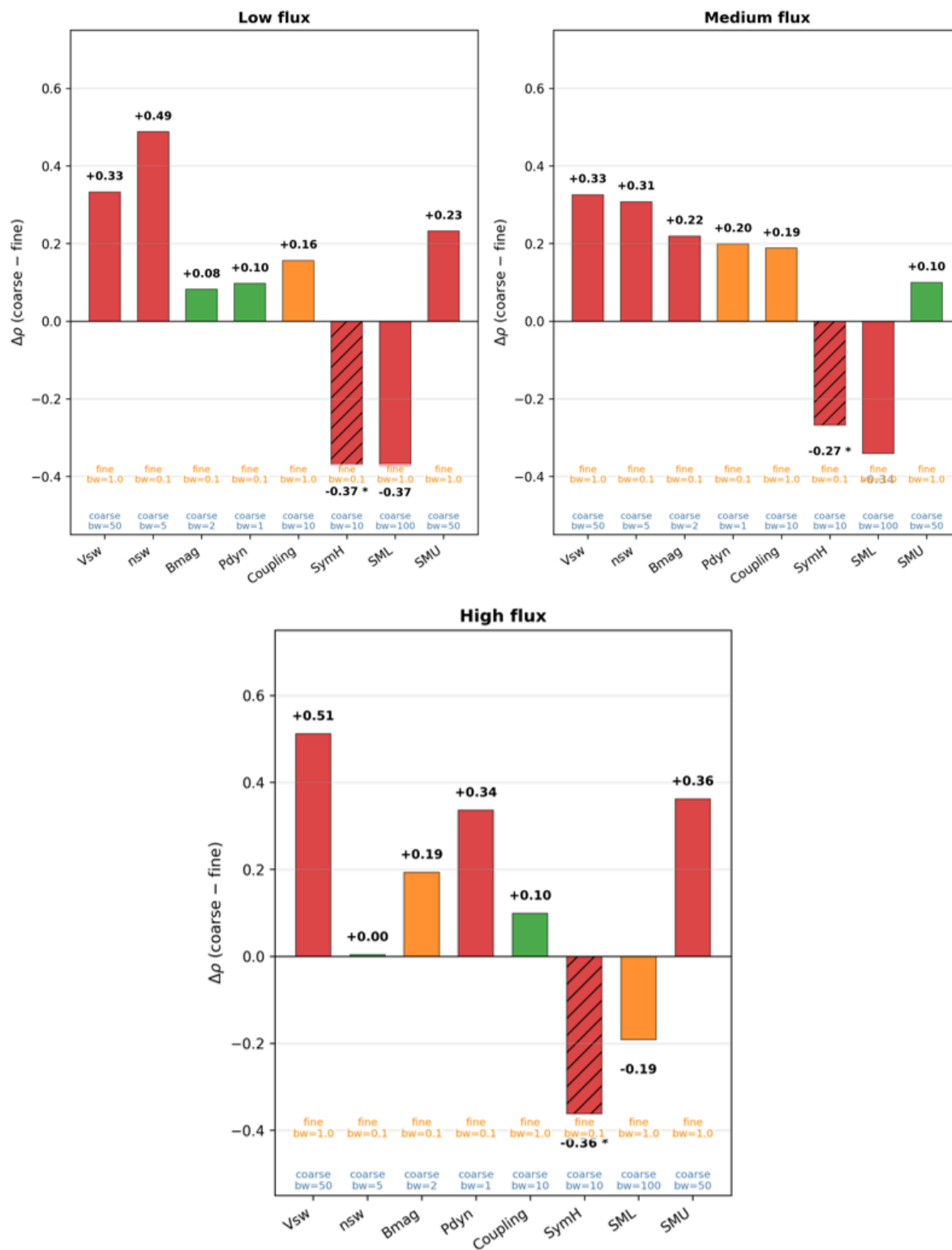


**Figure 2**

Correlation inflation  $\Delta\rho = \rho(\text{coarse}) - \rho(\text{fine})$  for each parameter and flux class. Red = large ( $|\Delta\rho| > 0.2$ ); orange = moderate ( $0.1 - 0.2$ ); green = small ( $< 0.1$ ). Hatching (//) indicates cases where the coarse bin width yields fewer than 5 fit bins, noted but not used as headline results. Fine and coarse bin widths for each parameter are indicated below each bar.

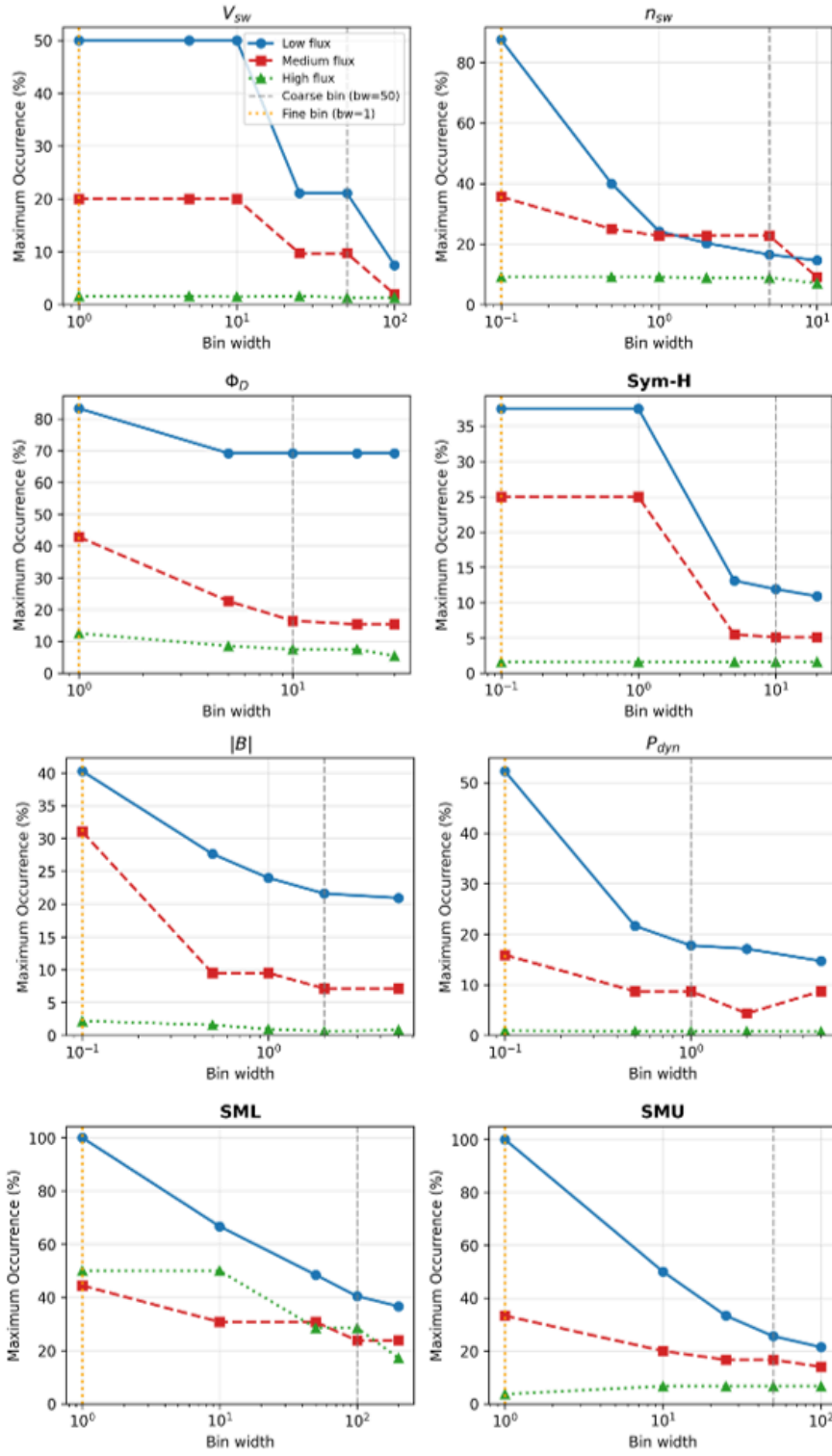


**Figure 3**

Maximum occurrence percentage as a function of bin width for all eight parameters. Conventions as Figure 1. The general downward trend for most parameters reflects suppression of peak occurrence values by coarse binning. Note the SMU high-flux anomaly (green triangles, lower right panel) where coarse binning produces a paradoxically higher maximum due to fine-bin count sparsity.

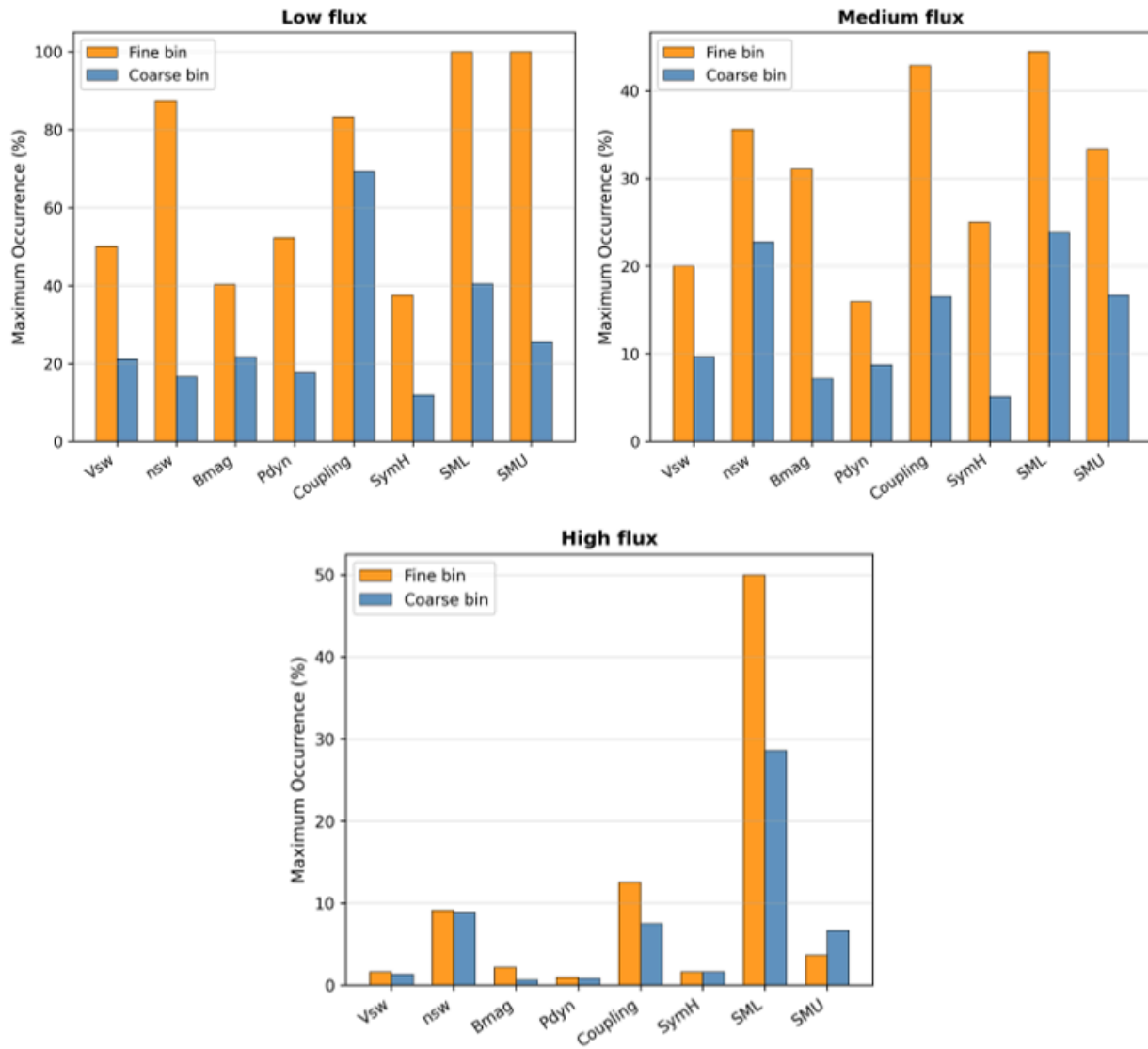


**Figure 4**

Maximum occurrence percentage at the fine bin width (orange) versus the coarse bin width (blue) for each parameter and flux class. Height differences between paired bars quantify the suppression attributable to coarse binning. The SMU high-flux case (rightmost bar pair, right panel) shows coarse bin taller than fine, due to the low-count artifact discussed in Section 3.2.

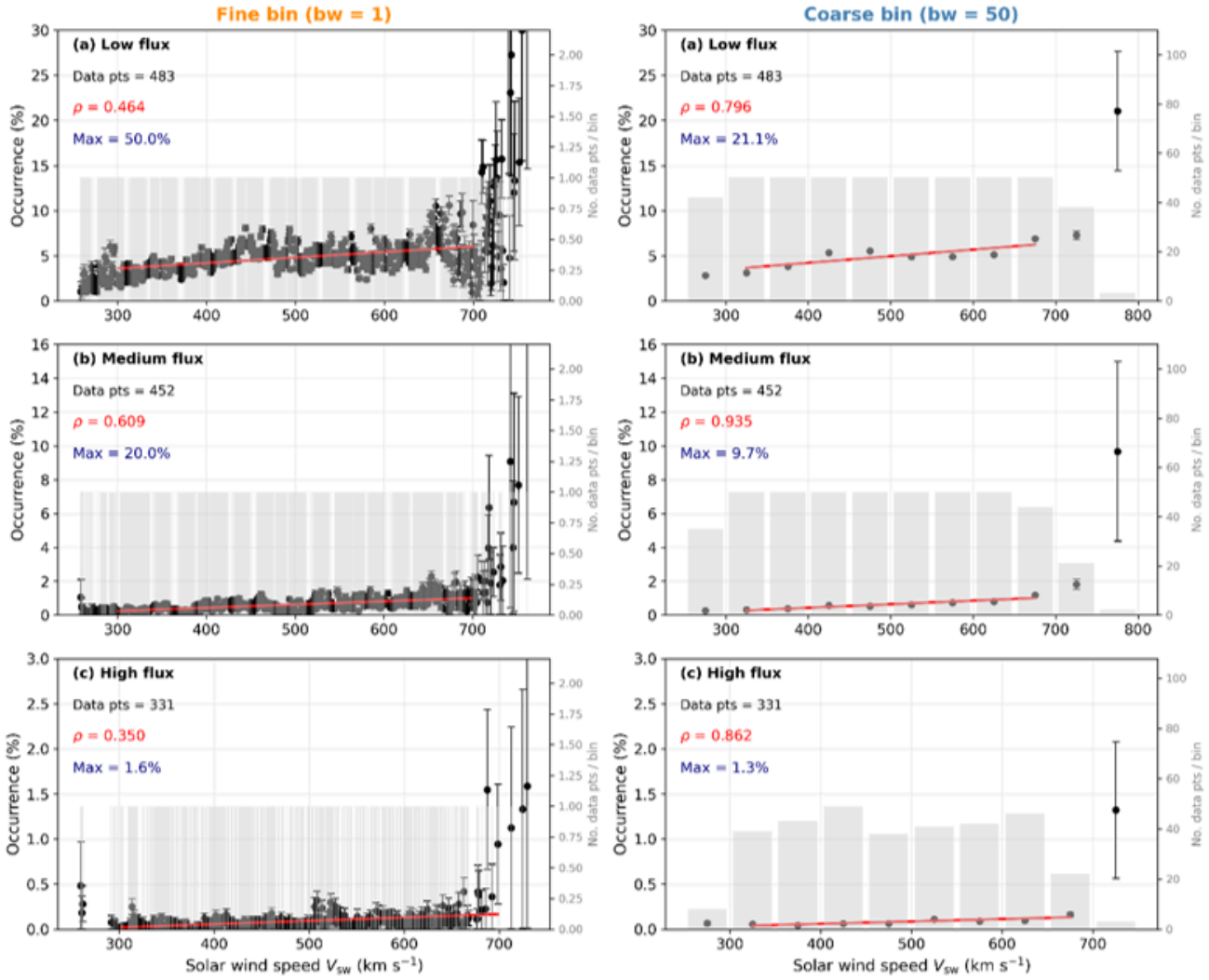


**Figure 5**

Occurrence of ion upflow as a function of solar wind speed  $V_{sw}$  for (a) low, (b) medium, and (c) high flux classes. Left: fine bin ( $bw = 1 \text{ km s}^{-1}$ ). Right: coarse bin ( $bw = 50 \text{ km s}^{-1}$ ). Black circles with  $1\sigma$  binomial error bars show occurrence; grey shaded bars show the number of data points per bin; red line shows the least-squares linear fit. Pearson  $\rho$  (red) and maximum occurrence (blue) are annotated in each panel.

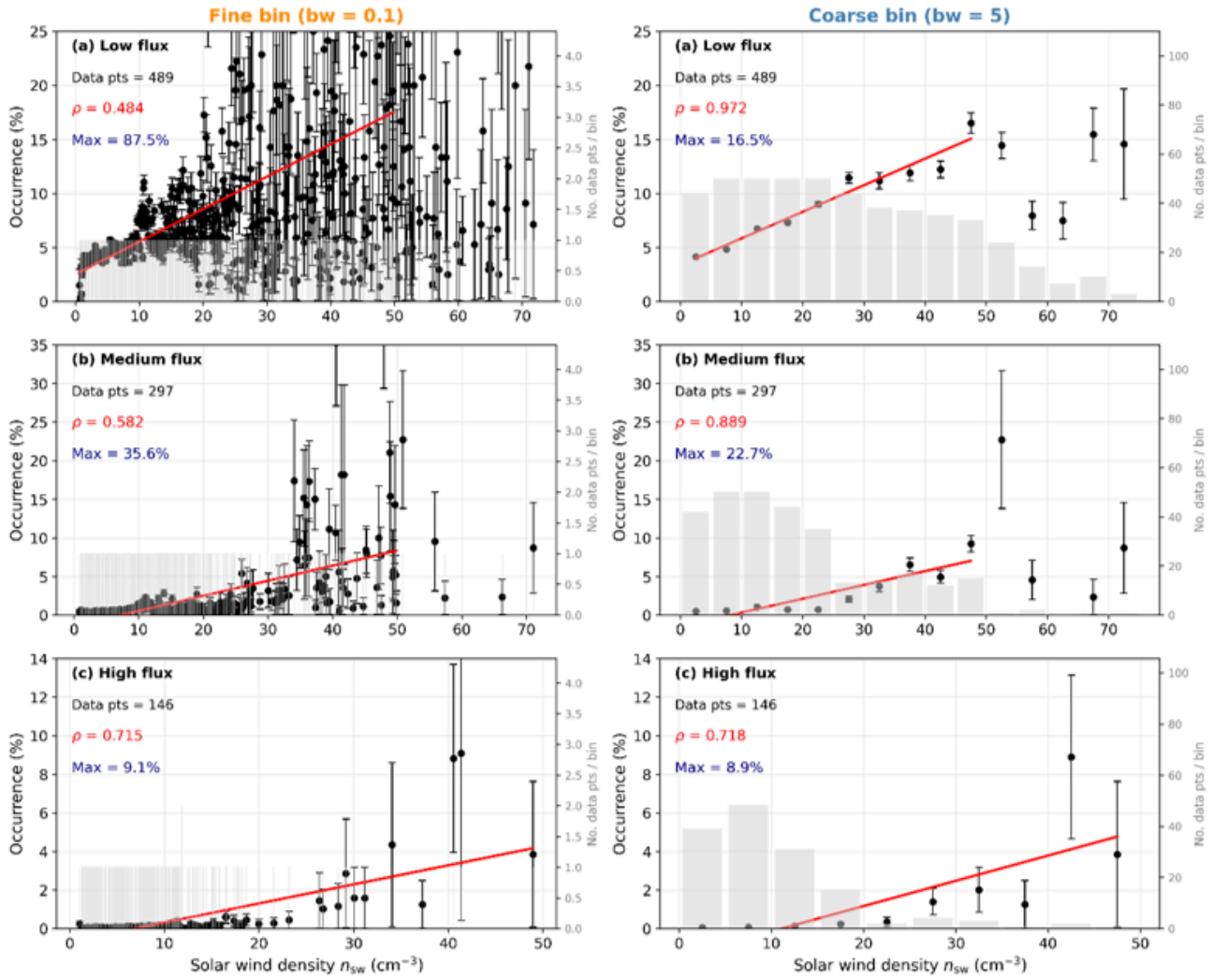


**Figure 6**

Same as Figure 5 for solar wind number density  $n_{sw}$ . Fine bin ( $bw = 0.1 \text{ cm}^{-3}$ , left); coarse bin ( $bw = 5 \text{ cm}^{-3}$ , right). Note the severe suppression of maximum occurrence from 87.5% to 16.5% in the low-flux category, and the negligible change in  $\rho$  for the high-flux category ( $0.715 \rightarrow 0.718$ ), the only case where the relationship is robust to bin width.

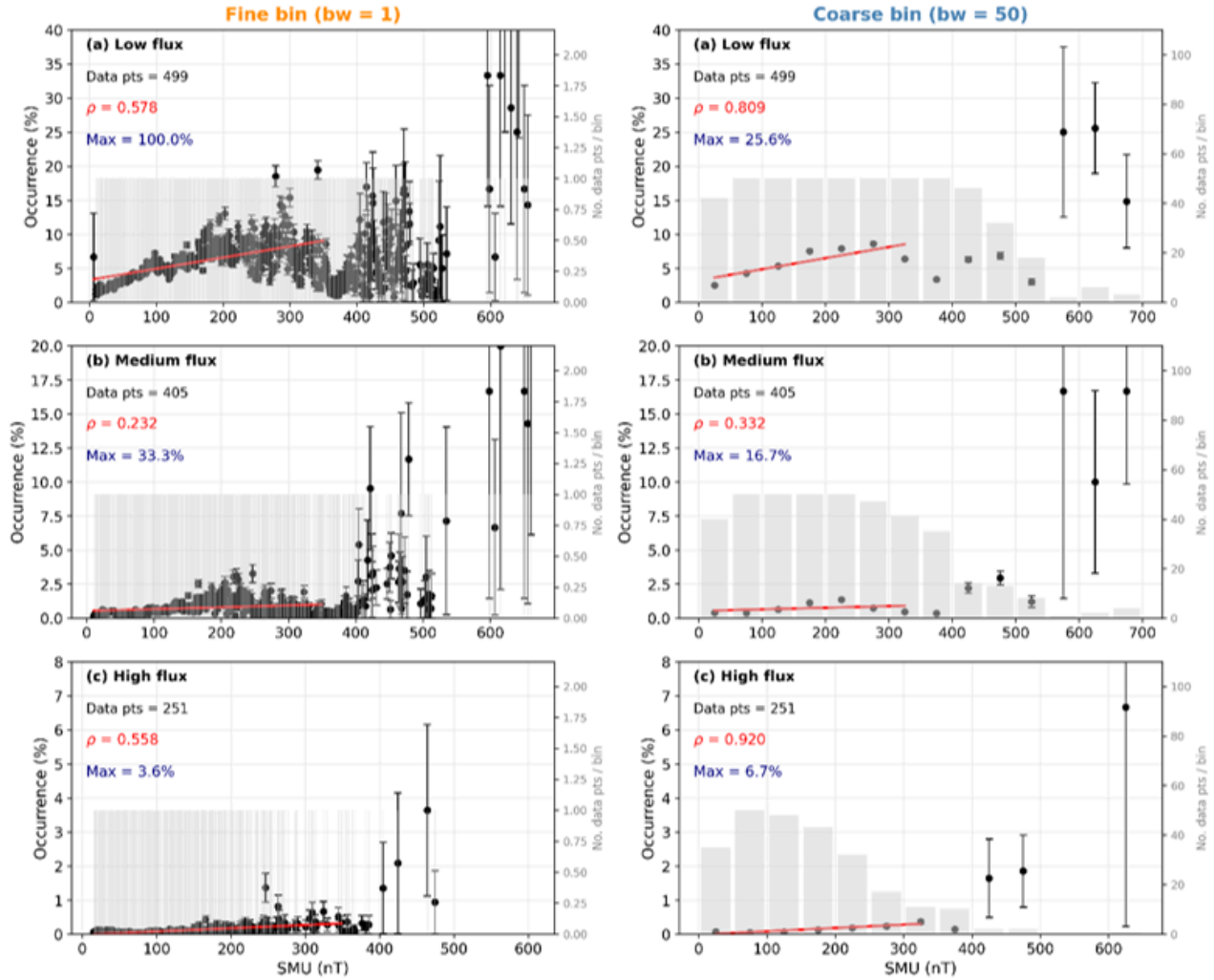


**Figure 7**

Same as Figure 5 for the SuperMAG upper auroral electrojet index SMU. Fine bin (bw = 1 nT, left); coarse bin (bw = 50 nT, right). This parameter shows anomalous bin-width behaviour: medium-flux  $\rho$  remains low and non-monotonic at all resolutions, and the high-flux maximum occurrence increases under coarse binning due to fine-bin count sparsity (Section 3.2).