# Impacts of Differing Melt Regimes on Satellite Radar Waveforms and Elevation Retrievals

We would like to thank Anonymous Reviewer 2 for a thoughtful and insightful review of our manuscript and appreciate all the feedback. Below, we have included responses to the points raised.

General Comments:

The introduction of the paper needs to be extended to provide more background, justification, and aim of the study. Explain why these biases are important and what new insights this study will provide to the community.

Thank you for raising this issue. We have reviewed the original manuscript and re-did the introduction and background to include more information on the retracking algorithms investigated, as well as the justification and motivation for this paper (Section 1.2.3 of the Revised Manuscript).

There is no clear justification for why only LeW is used in this study; this should be expanded upon in both the background section and the introduction. Also consider merging the "background" and "introduction" sections to provide a consistent narrative for your study.

Thank you for the suggestions! A more thorough explanation on LeW was added in the introduction section (Section 1.2.3 of the Revised Manuscript). The main reason for choosing LeW is to build upon Nilsson et. al 2015, given that it is fundamentally tied to model-retracker derived elevations. Other auxiliary work has been done with TeS & a Riemann's Sum Integral of the waveform Graphs with these trends are included in a newly created Supplement (Section 2.2 and 2.3 of the Supplement). Given that RSI is correlated with LeW, Nilsson et. al, 2015 found that there was no long-term impact of the backscatter signal on the elevation profile, and there is no noticeable trend in TeS, we felt that it was best to keep to the LeW in the manuscript.

I'm unclear about the main research question? Is the study focused on biases or on the sensitivity of retrackers to surface melt? If it is the latter, this has already been extensively proven in other studies, raising questions about the novelty of this research.

The purpose of this study is to investigate the relationship between Level 1B LeW and elevations derived from the OCOG and ULI retracker, and investigate how these relationships may or may not change depending on what melt regime you are in. We extend the analysis of Nilsson et., al 2015 and investigate this relationship in the dry-snow zone & percolation zone, which to our knowledge, has not been performed. We adjusted the introduction and background to more clearly articulate this (Section 1.2.3 of the revised manuscript)

There is no explanation of how the different geographical areas were chosen; this should be included in the introduction or background of the manuscript.

Thank you for bringing this to our attention. An explanation of study sites was added in Section 2: Methodology. We also included other field sites in the supplement (Section 1.0 of the Supplement). In general, Summit and Raven were chosen to understand LeW responses in different melt regimes, whereas NEEM was used to confirm Nilsson et al. 2015. The auxiliary sites (50km-NEEM and Similar NEEM) described in Section 1 of the supplement are used as controls on NEEM.

The methods section is too vague and lacks detail, even for a short paper. There is no real description of the different steps or the reasons behind them.

The methodology section (Section 2 of the revised manuscript) has been updated significantly to include the workflow used for this paper, along with justifications throughout. We included more information on the clustering and aggregation of data, the curation of data and removal of outliers, and the BEAST algorithm.

The discussion mentions ICESat-2 and laser altimetry data, but it has not been included in the methodology and is presented to the reader in an ad-hoc manner. Add more details about the data and include figures to show the differences, as it seems analyses have been done to obtain these results.

We apologize for the confusion – no analysis has been done regarding ICESat-2, although conversations regarding the platform with the Project's Chief Scientist helped bring awareness to the different capabilities/limitations between that, and CryoSat-2. The wording of that section was revised to not confuse the reader.

The conclusion provides more information about the scope of the study than the introduction. More effort is needed to clearly define the research question and scope of the paper in the introduction to make the research question clear.

We appreciate the input, and the newly updated introduction has been changed to better portray the scope of the study and our main research question (Section 1.2.3). See prior comments on the introduction.

Detailed Comments

L115: Are you applying a mathematical surface to all data within the 125.6 $km^2$ area? Also, I would actually add the dimensions here, such as 10 x 10 km.

We are applying a mathematical surface to the data within the pre-described area, with a circular radius of 20 km. We have corrected the language surrounding this.  Somewhat related, but we changed how we performed our error analysis for the Level 2 elevations; Before – we performed a residual analysis on a LOWESS smoothed function. We simplified it so that the confidence intervals correspond to the predicted elevation values at the absolute study site location based on the 3d mathematical surface.

L133: Why was the "Bayesian Estimator for Abrupt Seasonality and Trend (BEAST) algorithm" used? It's an interesting algorithm, but one can clearly see the impacts in the time series of surface melt, so I'm not sure of the need for it. However, I do think further background needs to be added to better understand the algorithm and its use. Additionally, why is the trend analysis included at all? There are no details explaining its inclusion or necessity.

The BEAST algorithm was used in an exploratory work to identify change detections associated with the Level 1B, LeW, although in this study we use The BEAST algorithm for visualization and noise removal. We added more information about the BEAST algorithm in Section 2.3. The BEAST algorithm, in short, uses Bayesian inference and model averaging to avoid the somewhat arbitrary model-picking process (Zhao et al., 2019), especially considering that the CryoSat-2 Level 1B and Level 2 data have irregularly spaced collections.

L140: I don't really understand this paragraph. I think it needs to be expanded.

The methodology section (Section 2 of the revised manuscript) was updated, along with this small – paragraph, so it provides a better explanation. This paragraph indicates that to properly do a correlation analysis between Level 1B LeW and Level 2 Elevations (given the discrepancies in clustering time), we need to interpolate LeW.

L214: Laser altimetry has not been mentioned before. Is this something that has been investigated in the paper or is it coming from a reference? Is it airborne or space-borne laser altimetry? More details are needed.

We apologize for the confusion; laser altimetry was not investigated in this paper and that statement is referring to a reference. That phrase was reworked to make it less confusing to readers.

L242: The possibility of another melt event can be easily checked using melt data from NSIDC or other sources, so I suggest that this is done or the sentence be removed.

Thank you for noticing this. We removed this sentence in the revised manuscript.

L258: "CryoSAT-2" is misspelled.

Thank you for noticing this mistake. The spelling has been corrected.

L265: From this study, it is clear that the OCOG-retracker should be used as it is closer to the surface and thus less affected by changes in scattering. I think this should be added in the conclusion as a recommendation to use OCOG/Threshold retrackers over model-based retracking algorithms.

That is correct! Conclusions have been altered (Section 5.0 of the Revised Manuscript) to indicate that the OCOG retracker is the preferred retracker within the LRM zone.

References:

Nilsson, J., Vallelonga, P., Simonsen, S. B., Sørensen, L. S., Forsberg, R., Dahl-Jensen, D., Hirabayashi, M., Goto-Azuma, K., Hvidberg, C. S., Kjær, H. A., and Satow, K.: Greenland 2012 melt event effects on CryoSat-2 radar altimetry, Geophys Res Lett, 42, 3919–3926, https://doi.org/10.1002/2015GL063296, 2015.

Zhao, K., Valle, D., Popescu, S., Zhang, X., and Mallick, B.: Hyperspectral remote sensing of plant biochemistry using Bayesian model averaging with variable and band selection, Remote Sens Environ, 132, 102–119, https://doi.org/10.1016/J.RSE.2012.12.026, 2013.

# Impacts of Differing Melt Regimes on Satellite Radar Waveforms and Elevation Retrievals: Supplemental

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## 1.0. Location of Additional Field Sites

We choose Summit Station and Raven to represent locations with differing amounts of surface melt in two melt regimes (Dry Snow and Percolation Zone) (Table 1). The third site, NEEM (Dry Snow Zone), is chosen to compare this study's Level 1B analysis with that of Nilsson et al. (2015). The fourth and fifth sites, 50 km-NEEM and Similar-NEEM, are chosen to be tested to confirm the results of NEEM and to understand the spatial variability of possible melt signature and response in the Level 1B metric time series.

| Site | Coordinates (WGS1984) | Avg. Annual accumulation from 1958 – 2019[a] (mm-w.e) | Avg. Annual Snowmelt from 1958 – 2019[a] (mm-w.e) | Elevation[b] (m) |
|---|---|---|---|---|
| Summit | 72.5833, -38.4500 | 205.50 | 0.52 | 3251 |
| NEEM | 77.4500, -51.0600 | 184.45 | 1.84 | 2481 |
| 50 km-NEEM | 77.2005, -49.3120 | 184.96 | 1.45 | 2581 |
| Similar-NEEM | 77.6000, -40.0000 | 93.08 | 4.10 | 2523 |
| Raven/DYE-1 | 66.4964, -46.2849 | 455.92 | 151.01 | 2200 |

Table 1: Study Sites (Noël et al., 2019[a]; Howat et al., 2015[b])

## 2.0 Waveform Metrics

### 2.1. Leading Edge Width (LeW)

Here, we plot LeW for each site in the paper, as well as our additional sites. Though Summit, Neem, and Raven are all shown in the paper, we reproduce them here for completeness and for comparison with the additional two sites.

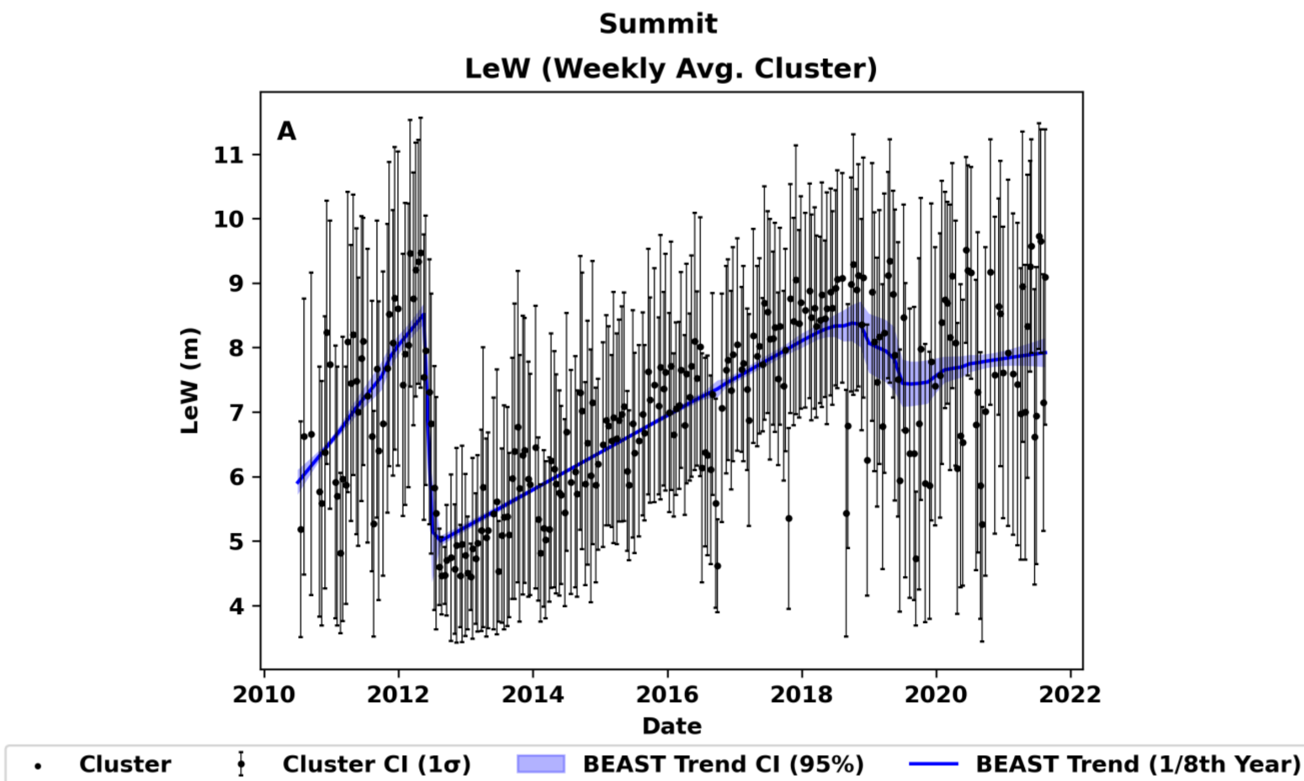


Figure 1A: LeW Trend at Summit Station

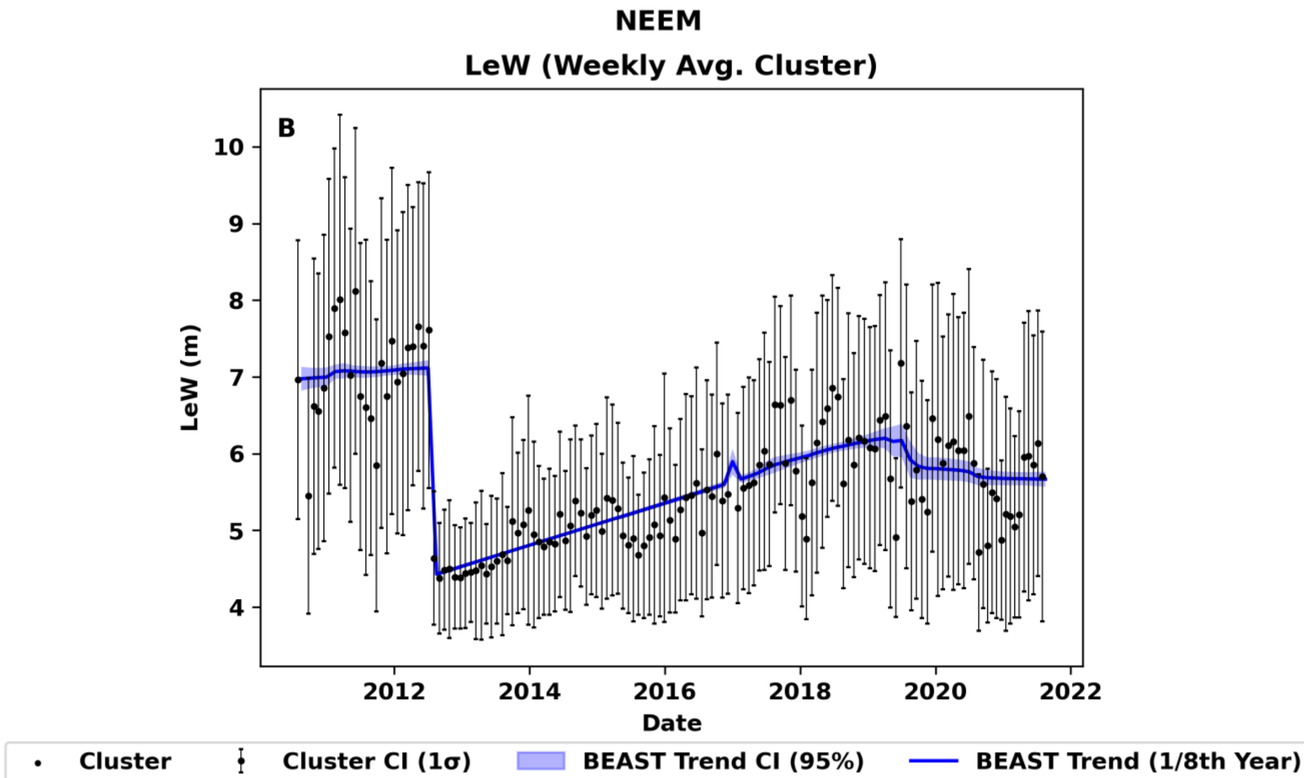


Figure 1B: LeW Trend at NEEM

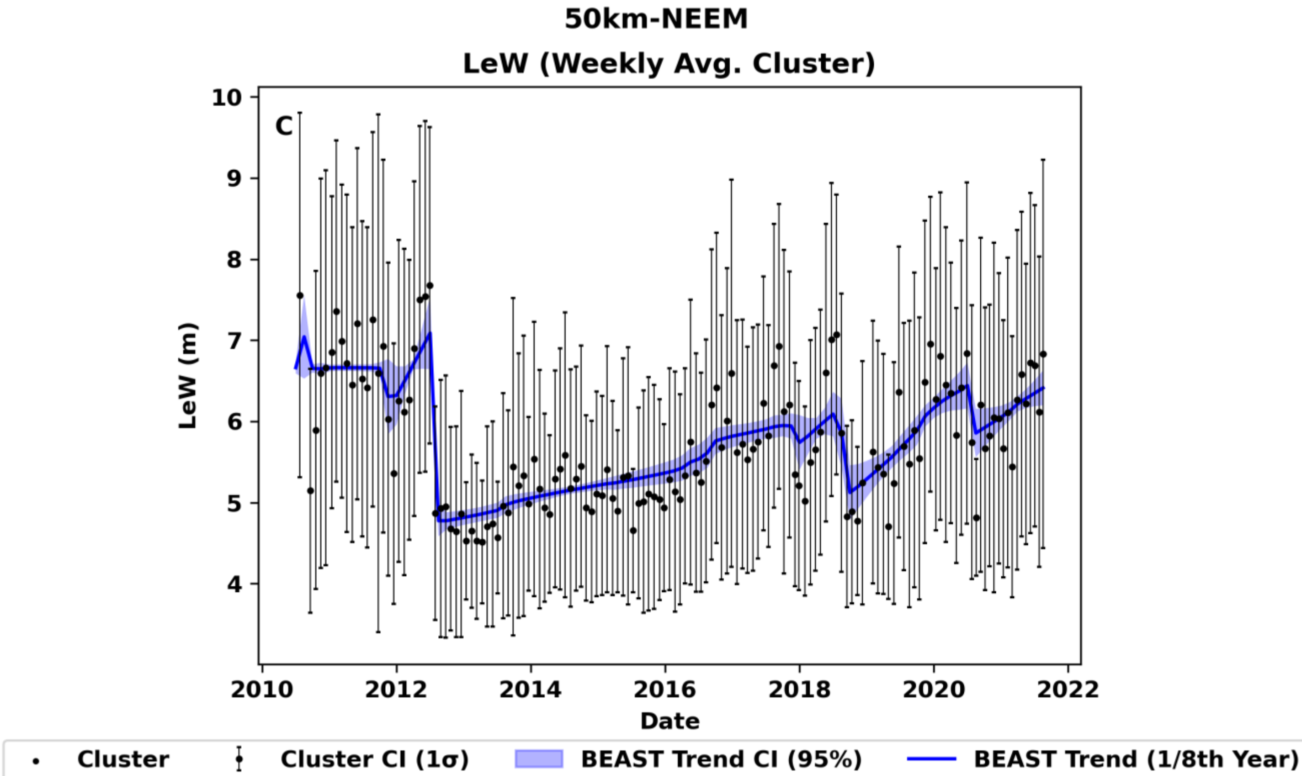


Figure 1C: LeW Trend at 50km-NEEM

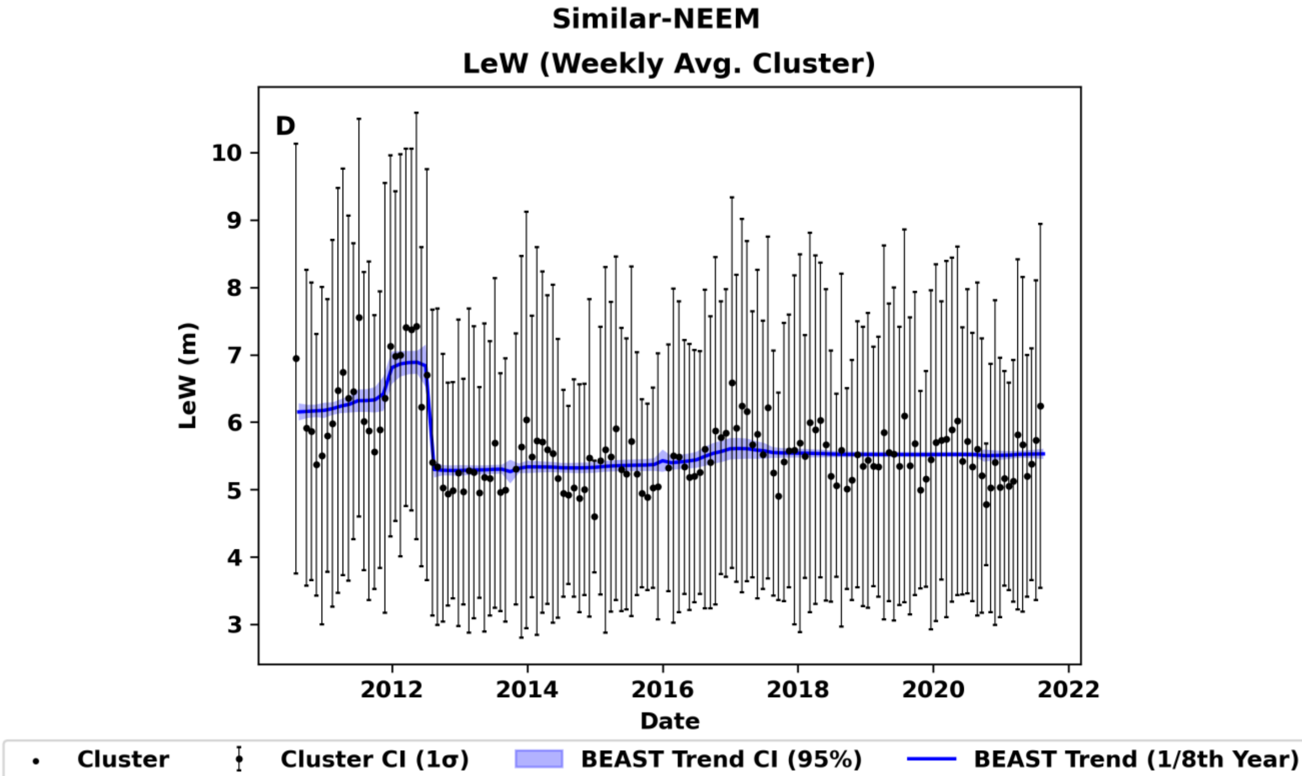


Figure 1D: LeW Trend at Similar-NEEM

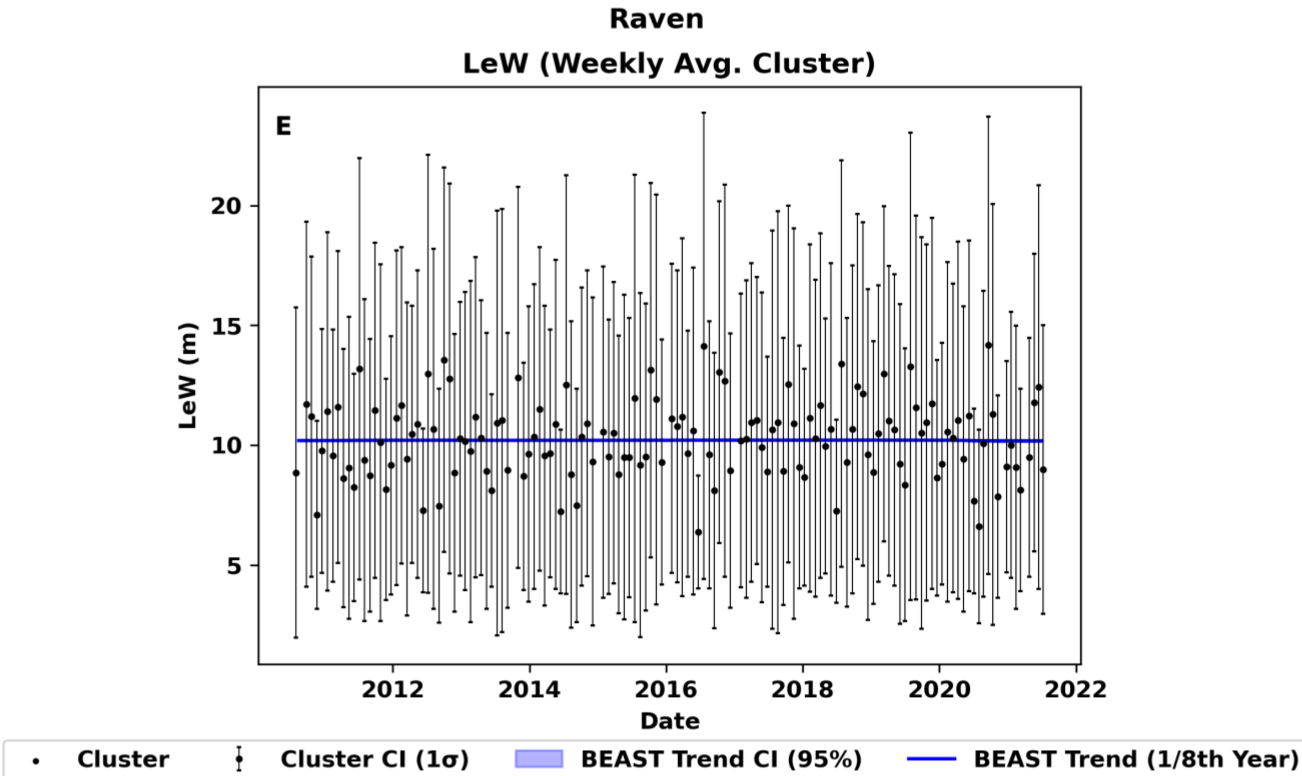


Figure 1E: LeW Trend at Raven

## 2.2 Riemann's Sum Integral (RSI)

Unlike Level 1B data used in this study to calculate and analyse waveform characteristics, SIRAL Level 2 data contain $\sigma^0$ (backscatter coefficient) values derived from each retracking algorithm. $\sigma^0$ is defined as the calibrated backscatter cross section of the pulse return (Dawson and Landy, 2023). $\sigma^0$ values partly depend on waveform amplitudes defined by the retracking algorithms (European Space Agency, 2019). A Riemann Sum Integral (RSI) is calculated for each returning waveform, as the calibration values used to calculate $\sigma^0$ are not known in this study. In this capacity, RSI is equivalent to non-calibrated backscatter.

RSI at Summit (Figure 2A) is negatively correlated with ULI-retracker derived elevations (TTT, $\alpha$=0.05, r = -0.72, p < 0.0001), and correlated with the OCOG-retracker derived elevations (TTT, $\alpha$=0.05, r = -0.33, p = 0.00058). Similarly, RSI at NEEM (Figure 2B) is negatively correlated with ULI-retracker derived elevations (TTT, $\alpha$=0.05, r = -0.85, p < 0.0001), and correlated with the OCOG-retracker derived elevations (TTT, $\alpha$=0.05, r = -0.40, p = 0.00005). RSI at Raven (Figure 2E) is neither correlated with ULI-retracker derived elevations (TTT, $\alpha$=0.05, r = 0.007289, p = 0.94434) or with the OCOG-retracker derived elevations (TTT, $\alpha$=0.05, r = 0.11896, p = 0.24490).

LeW and RSI are correlated at Summit (TTT, $\alpha$=0.05, r = 0.79, p = <0.00001), NEEM (TTT, $\alpha$=0.05, r = 0.57, p = <0.00001) and Raven (TTT, $\alpha$=0.05, r = 0.60, p = <0.00001). The negative correlations between RSI and ULI-derived Level 2 elevations can be explained by this LeW correlation, which shows that RSI is not calibrated.

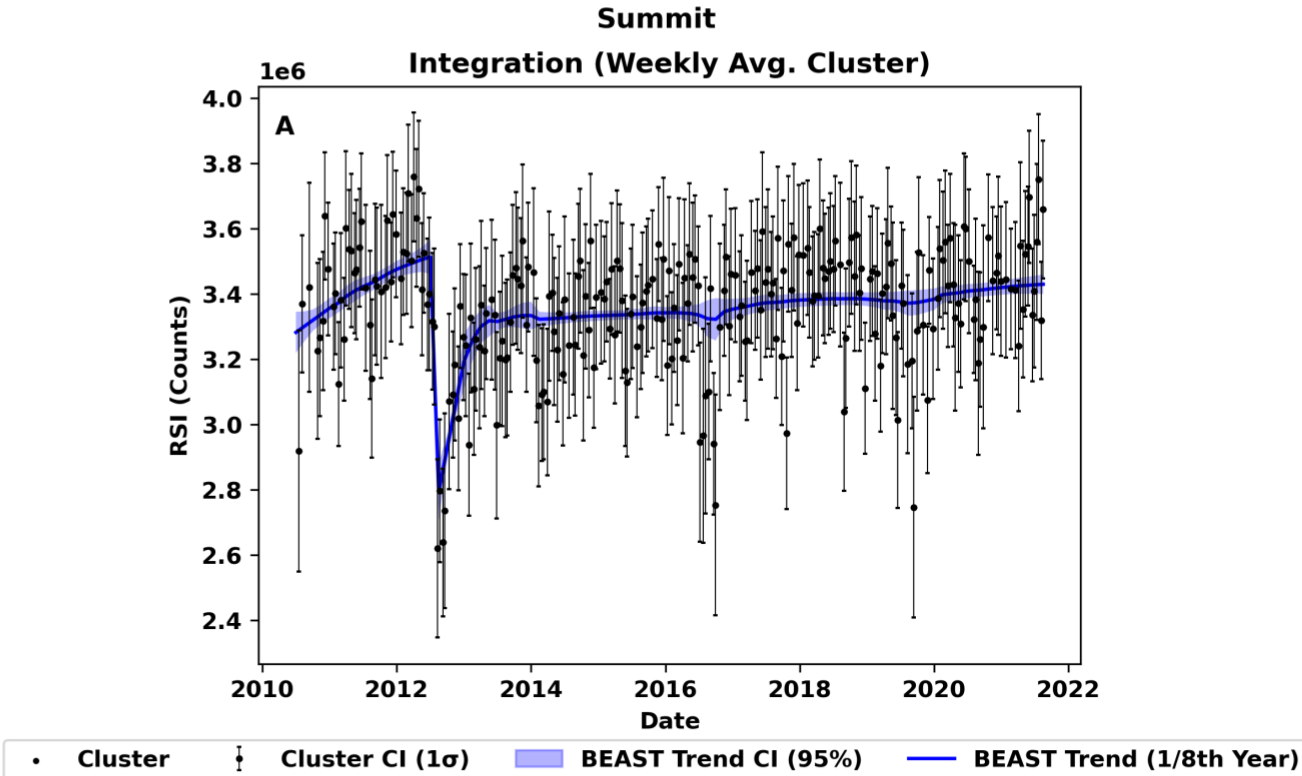


Figure 2A: RSI Trend at Summit Station

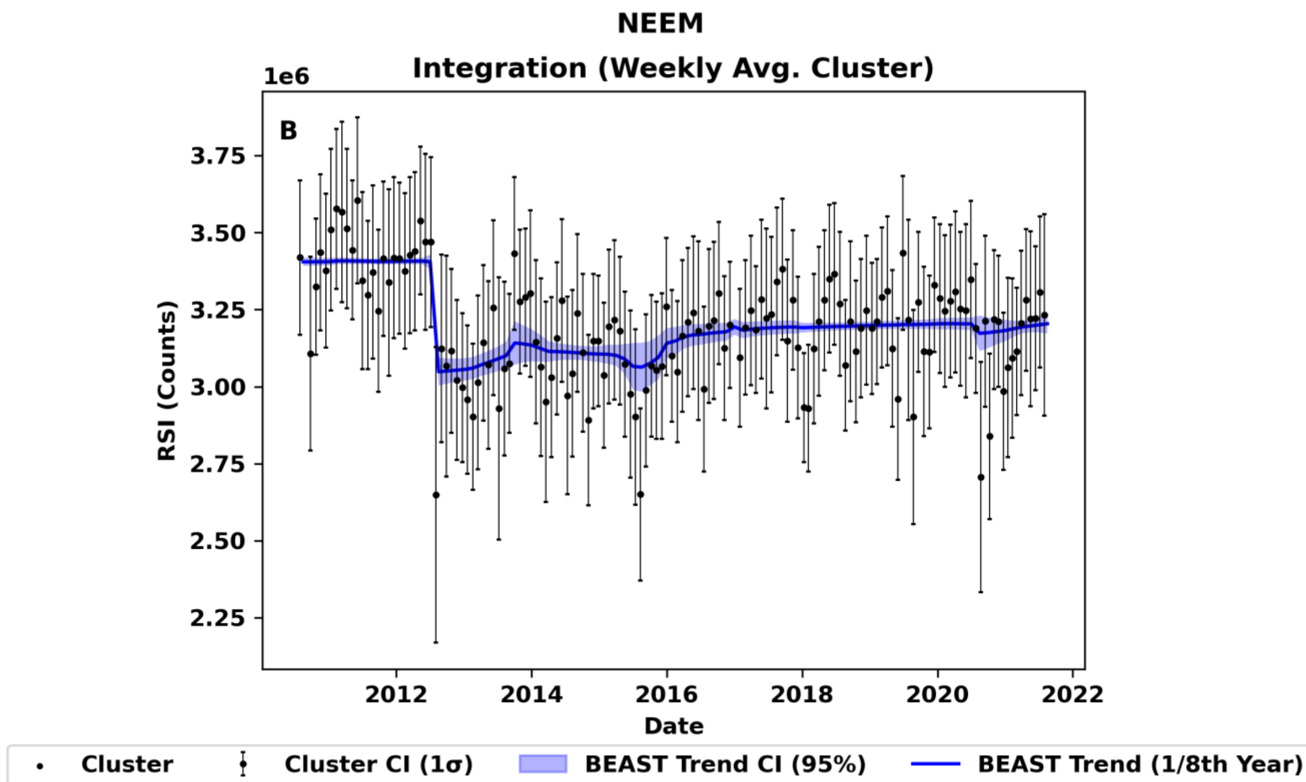


Figure 2B: RSI Trend at NEEM

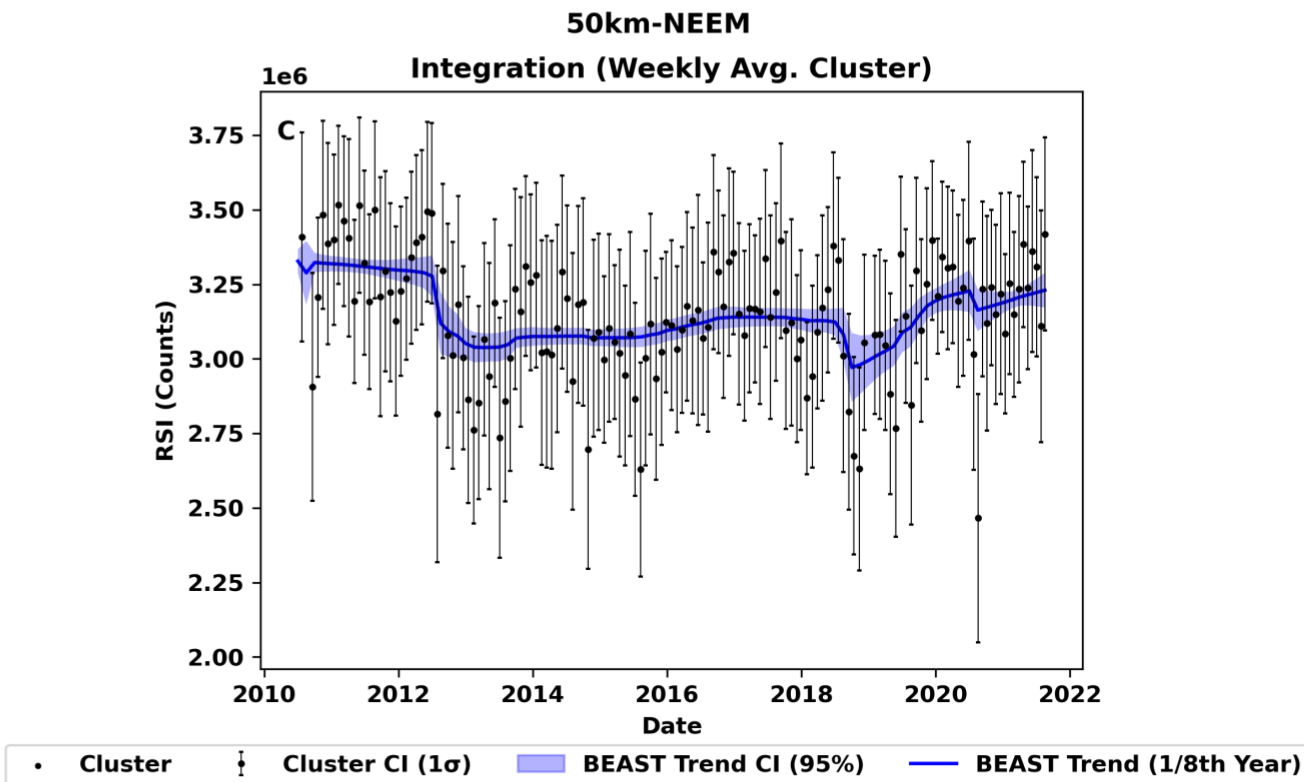


Figure 2C: RSI Trend at 50km-NEEM

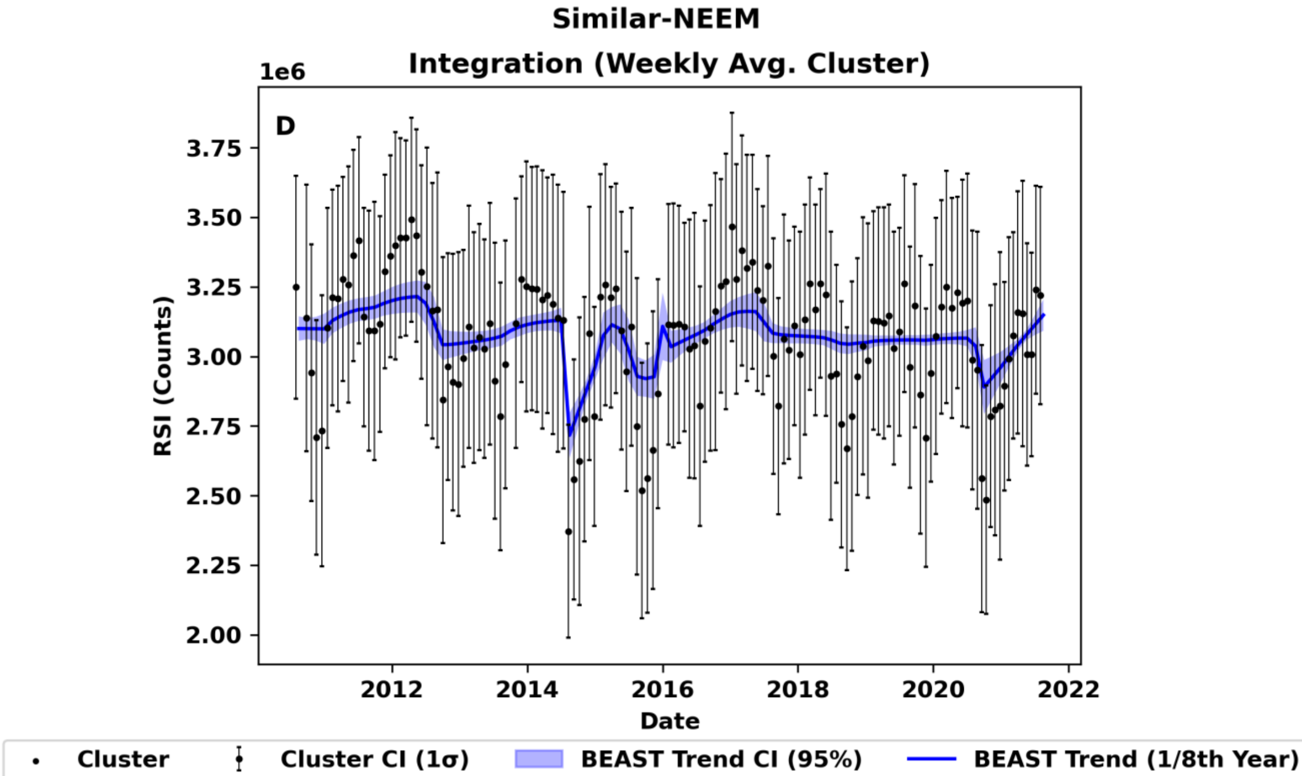


Figure 2D: RSI Trend at Similar-NEEM

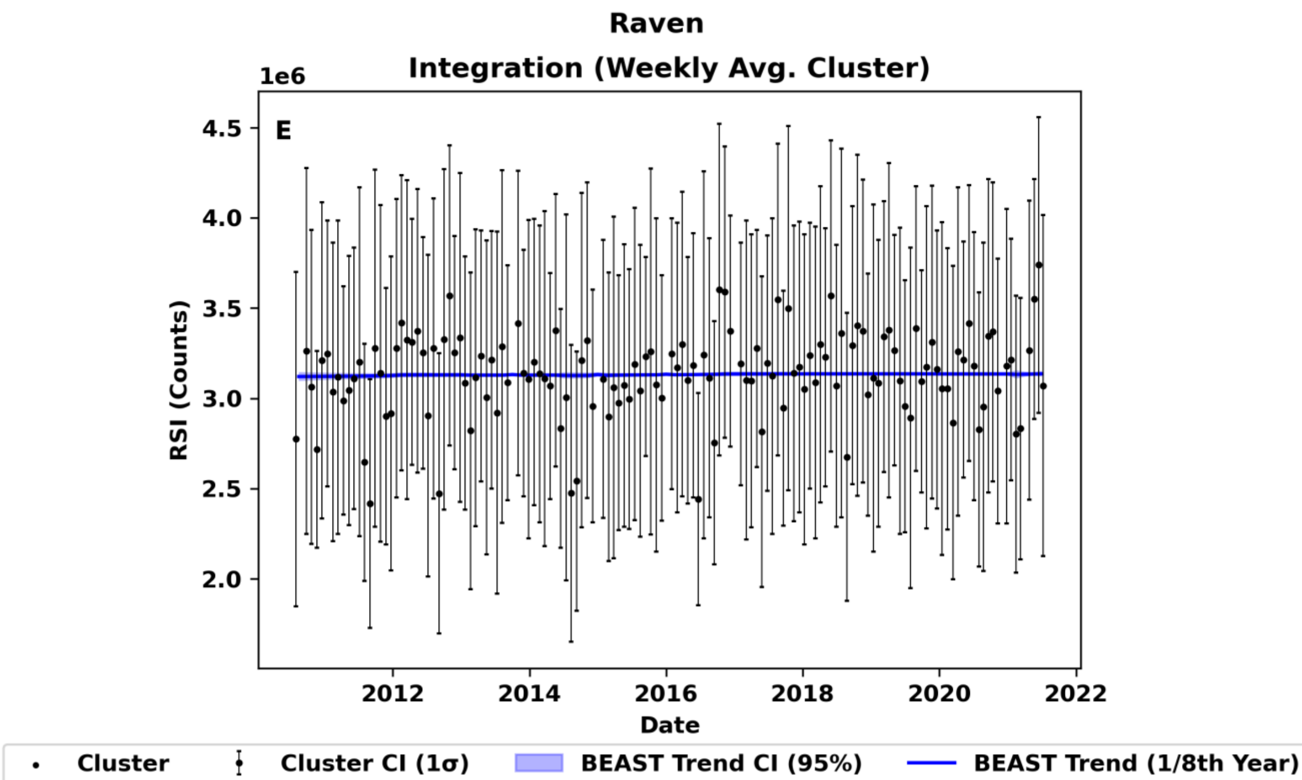


Figure 2E: RSI Trend at Raven

**2.3 Trailing Edge Slope (TeS)**

This study defines the TeS as the slope of best fit line of a least-squares linear regression during sections of maximum power drawdown. To determine what section of the waveform this corresponds to, this study makes use of where the maximum derivative in the latter half of the waveform corresponds to when the waveform tapers back towards baseline noise. The waveform is smoothed using a Savgol Filter (window length: 29, order: 2$^{nd}$) and its derivative is calculated. The TeS is then calculated by applying a best-fit line through the range between the smoothed waveform's peak and the maximum value of the trailing edge smoothed-waveform derivative. We find no relationship between derived elevations and the Trailing Edge Slope, and no noticeable change over the duration of the time series (Figure 3A-E)

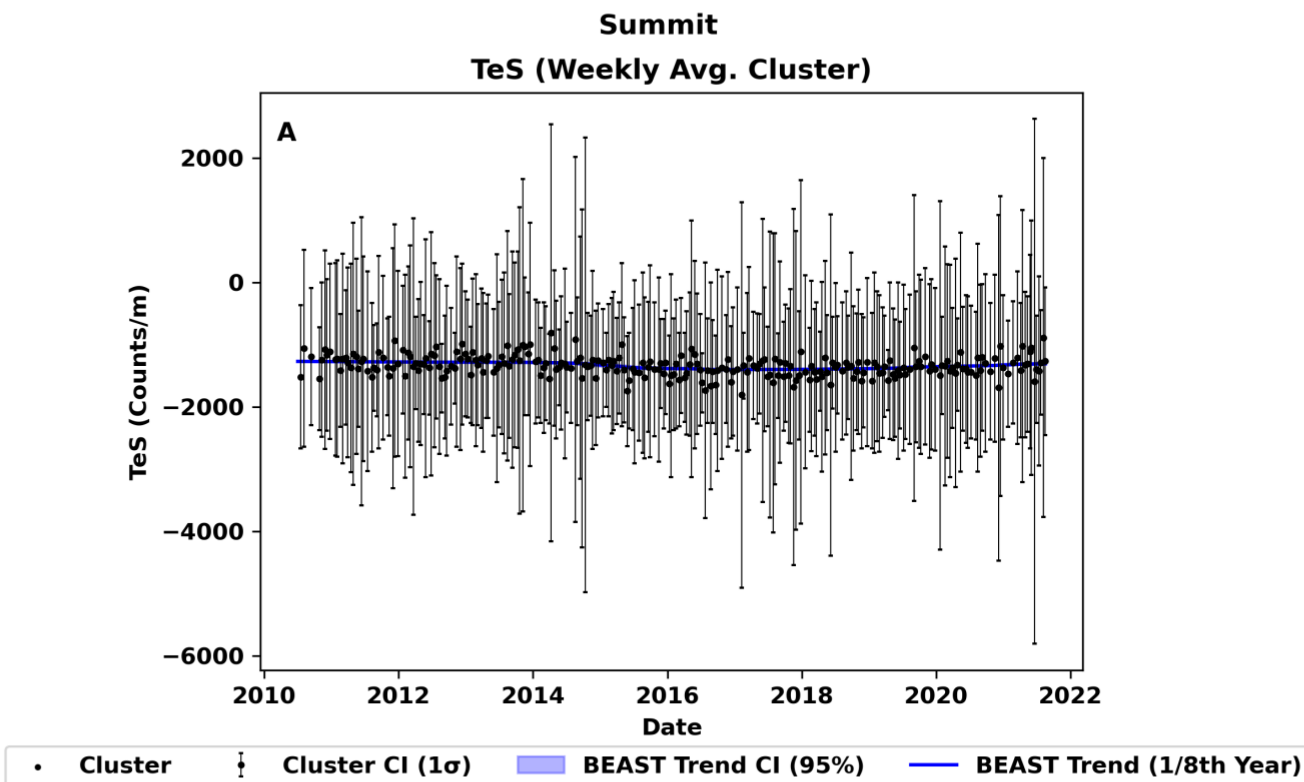


Figure 3A: TeS Trend at Summit Station

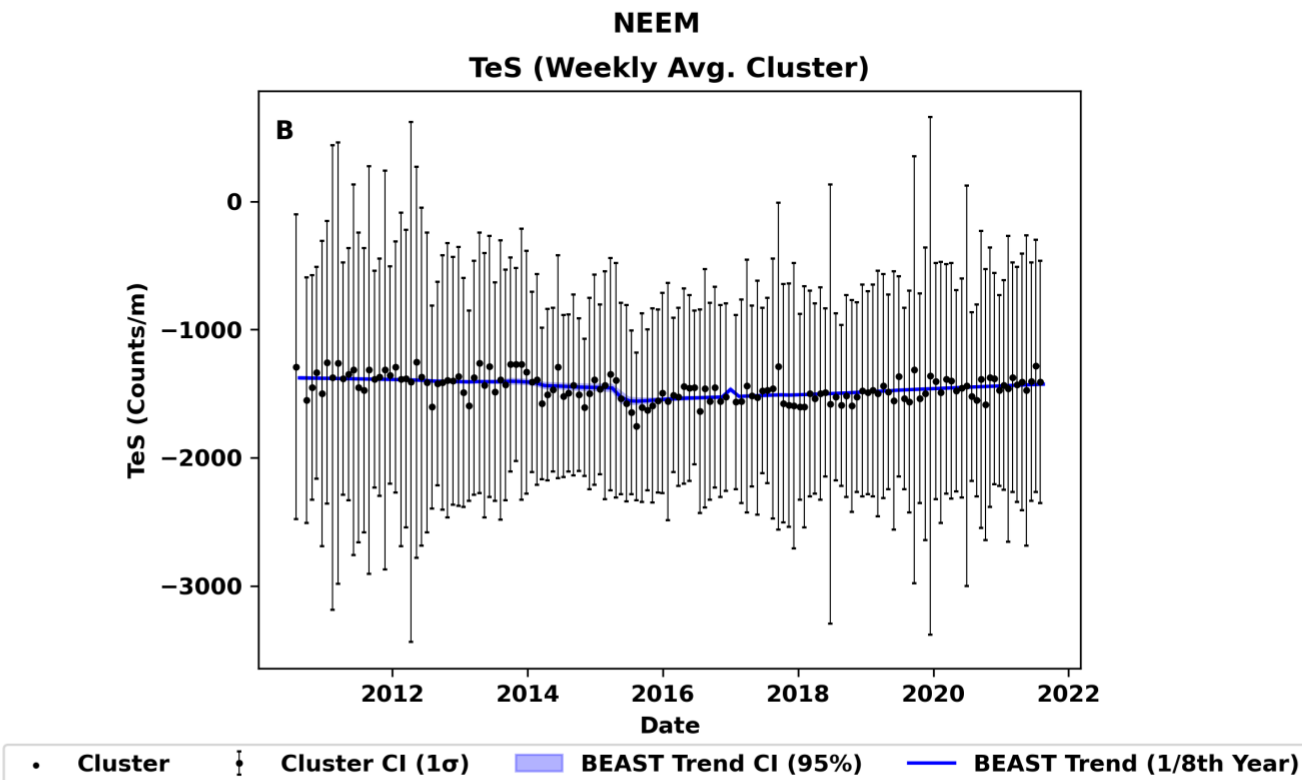


Figure 3B: TeS Trend at NEEM

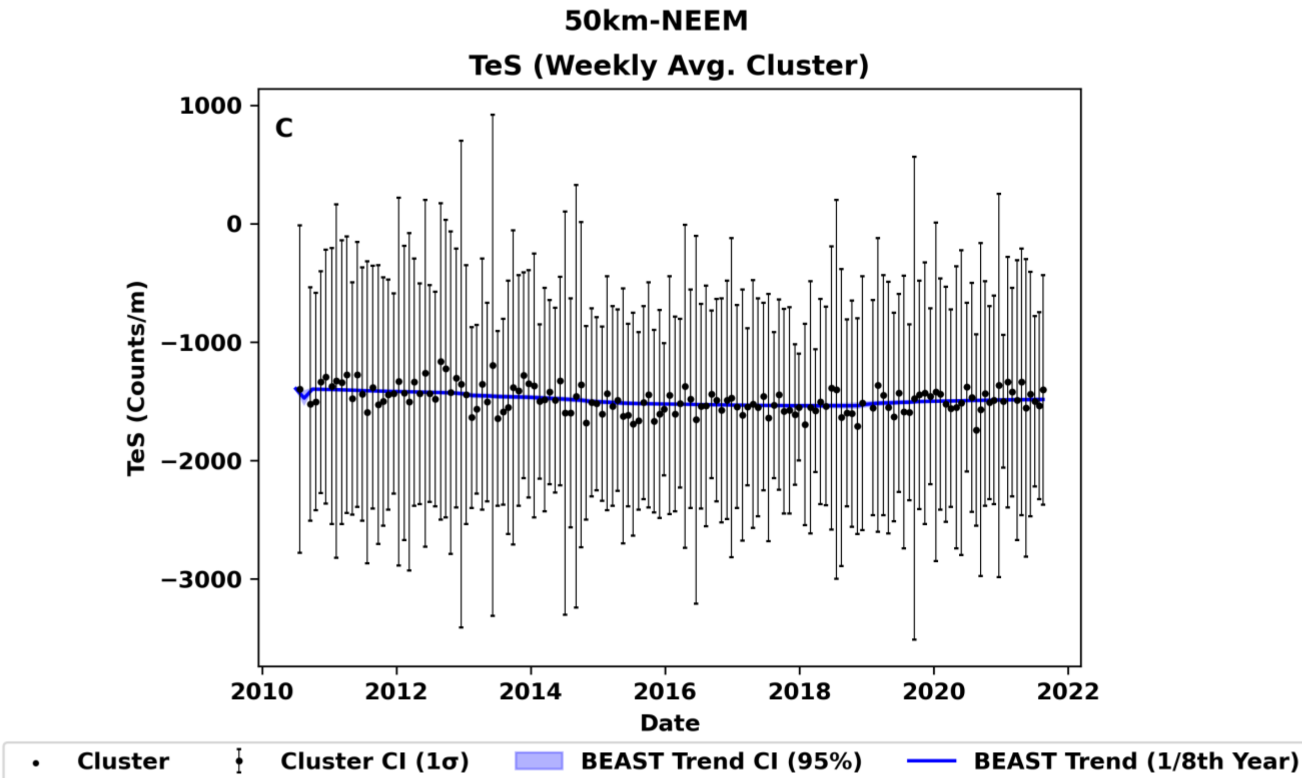


Figure 3C: TeS Trend at 50km-NEEM

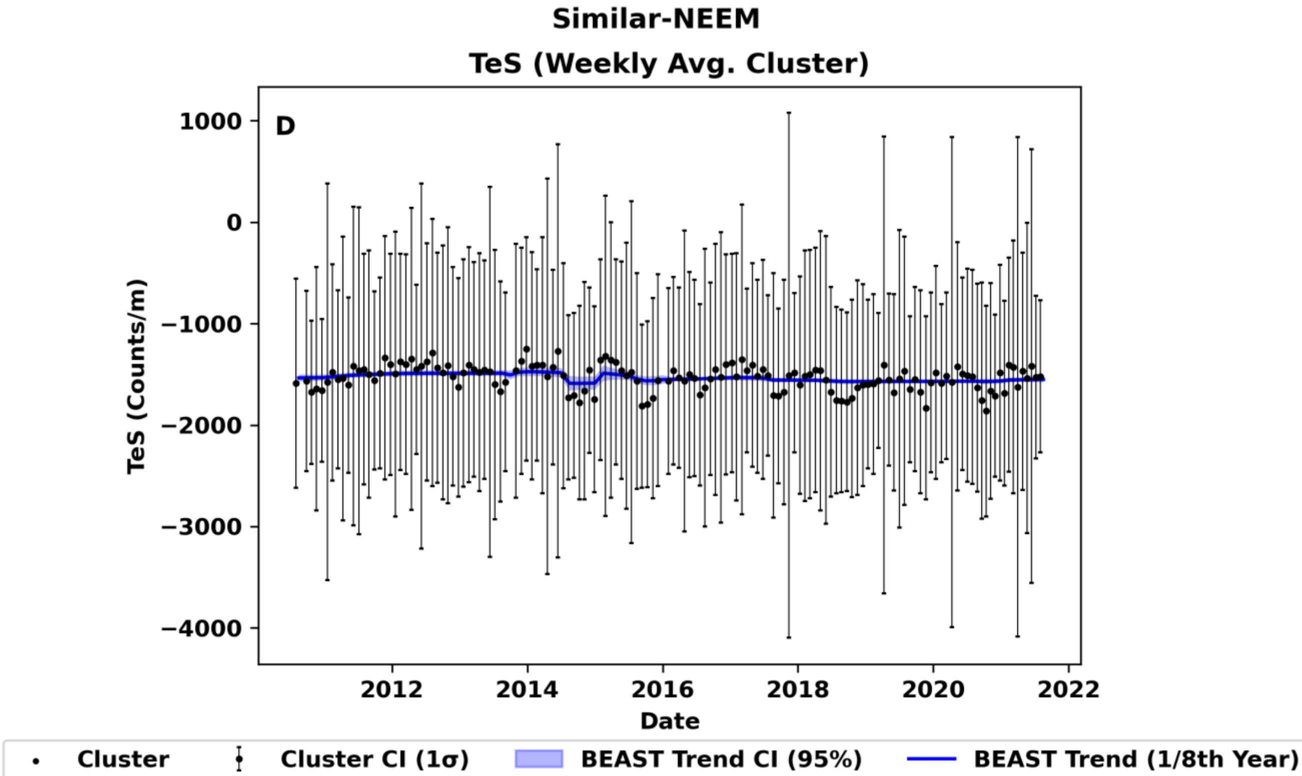


Figure 3D: TeS Trend at Similar-NEEM

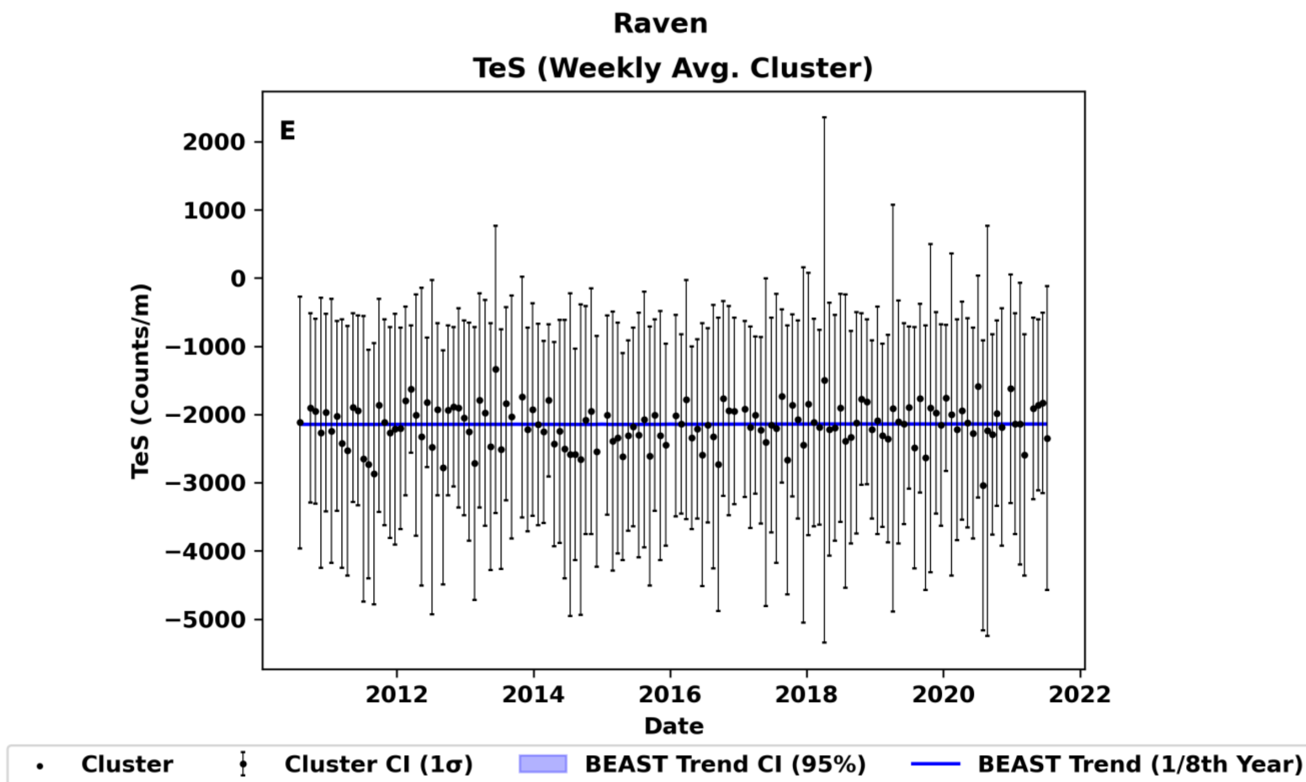


Figure 3E: TeS Trend at Raven

**3.0 Elevation Plots**

Here, we plot LeW with Level 2 ULI and OCOG Elevations for each site in the paper, as well as our additional sites. Though Summit, Neem, and Raven are all shown in the paper, we reproduce them here for completeness and for comparison with the additional two sites.

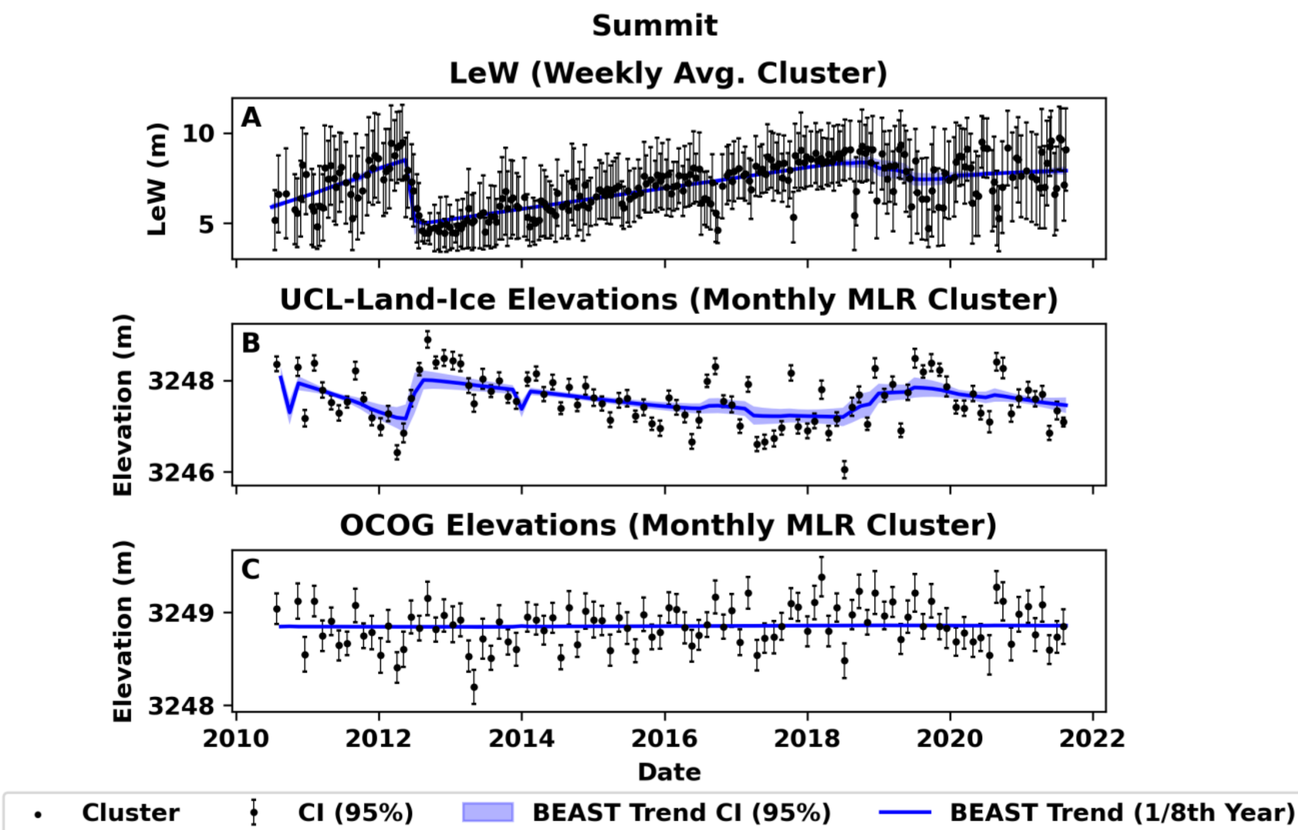


Figure 4: LeW and Level 2 ULI and OCOG Elevation Trends at Summit Station

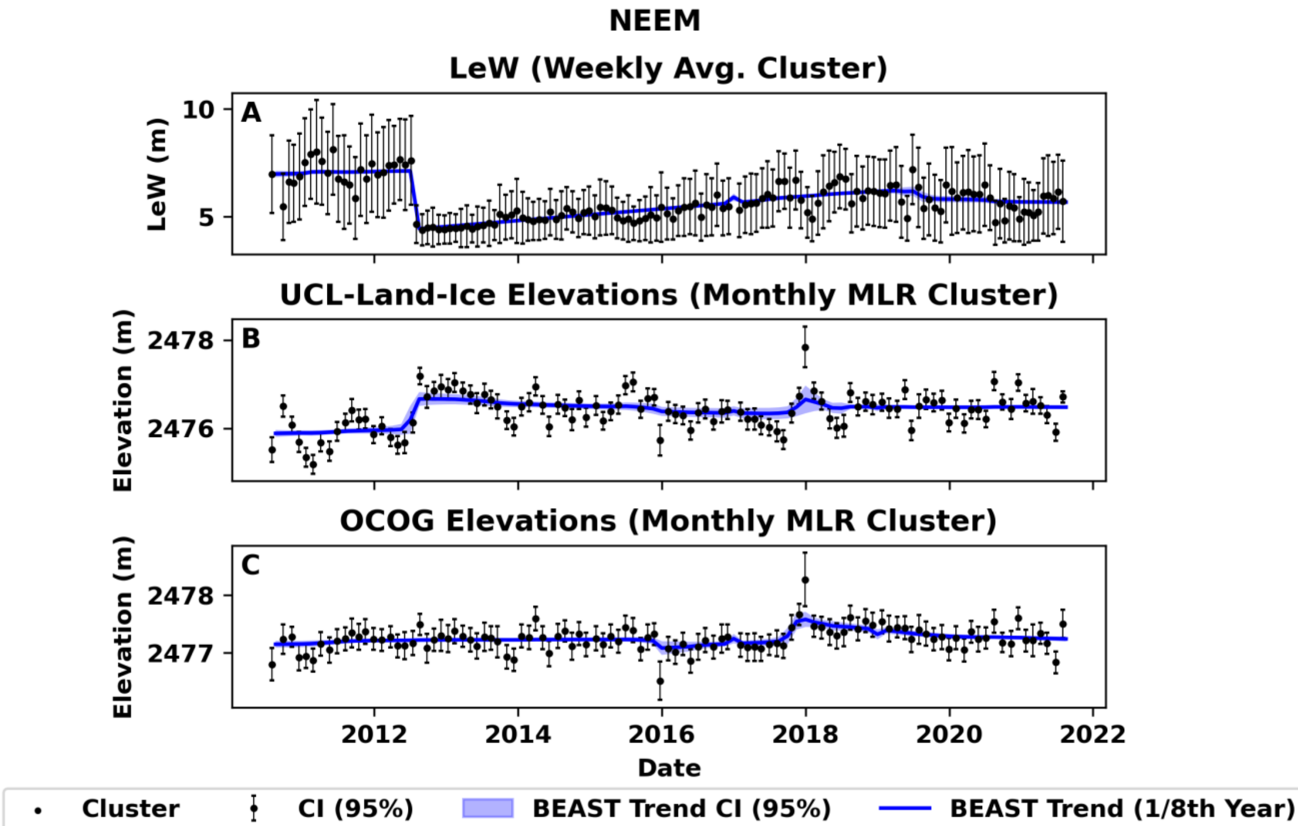


Figure 5: LeW and Level 2 ULI and OCOG Elevation Trends at NEEM

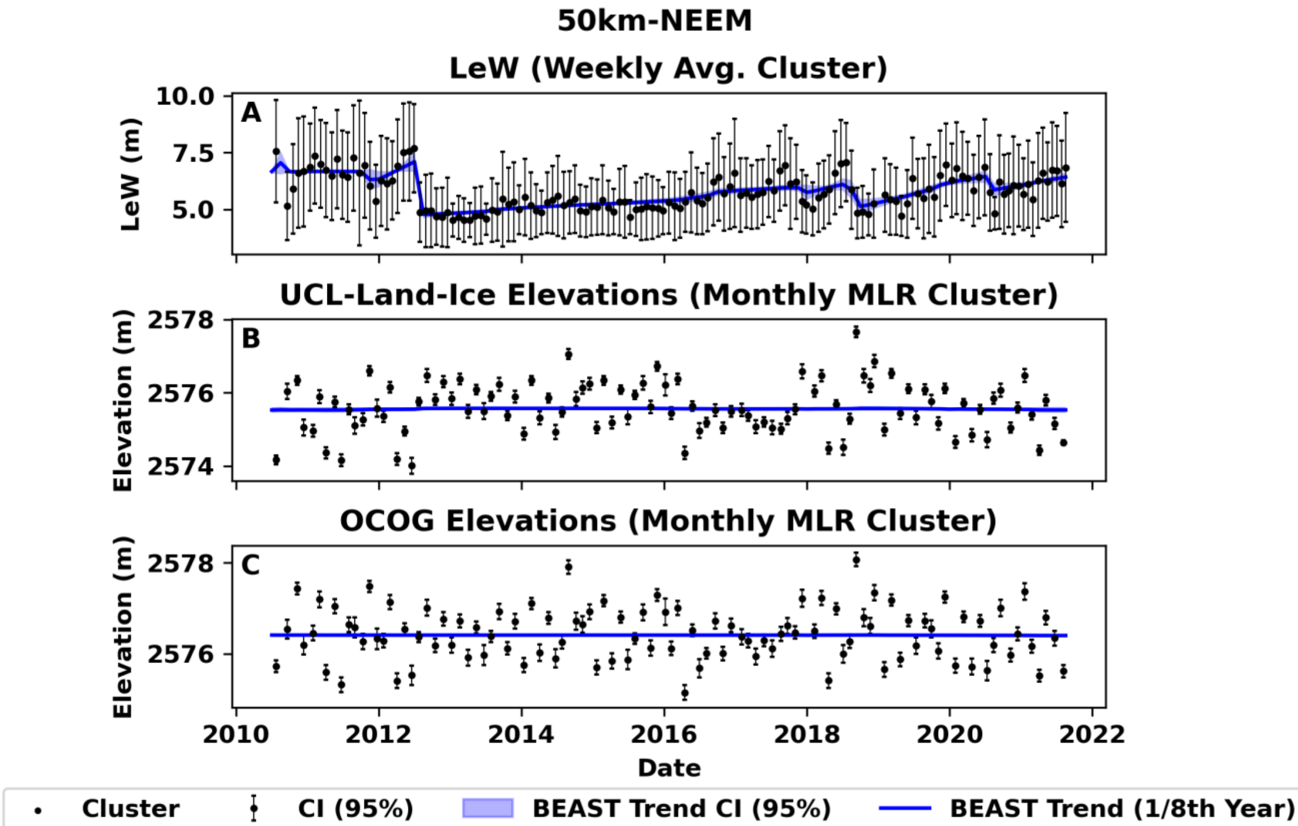


Figure 6: LeW and Level 2 ULI and OCOG Elevation Trends at 50km-NEEM

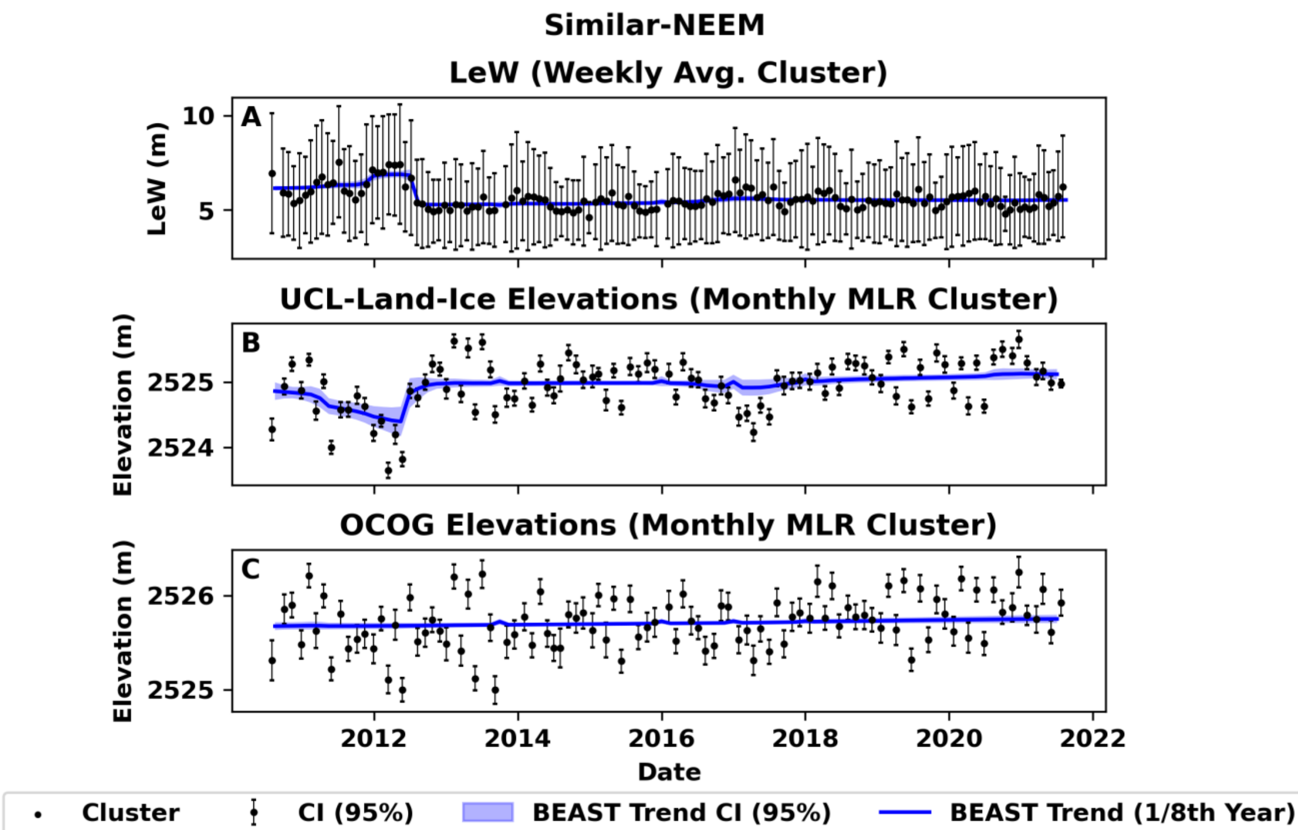


Figure 7: LeW and Level 2 ULI and OCOG Elevation Trends at Similar-NEEM

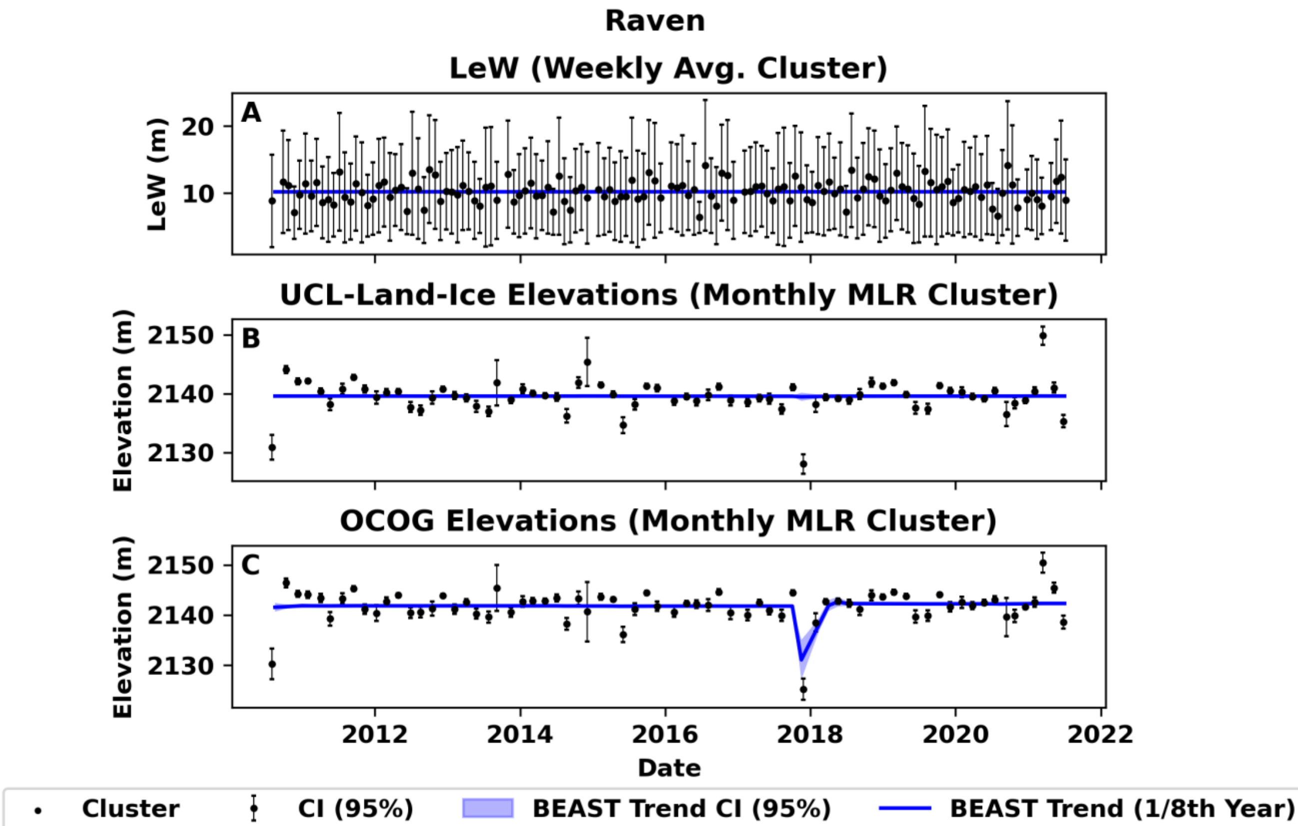


Figure 8: LeW and Level 2 ULI and OCOG Elevation Trends at Raven

**4.0 Outliers**

Level 1b waveforms that deviated from ideal were removed before the clustering and aggregation steps. Outliers were removed if the waveform array was incorrectly clipped and contained a second LeS after the TeS of the beginning, if they contained any Level 0, 1B, or Leap Error Flags, or contained irregularities that caused scripting error (Ronan et al., 2024). In addition, if the following conditions are met, a waveform is deemed as an outlier:

1. $LE \geq 64\ (Range\ Bins)$
    a. Explanation: When the leading-edge width of the clipped Level 1B waveform is greater than or equal to 64 range bins, corresponding to half the range bins of an un-clipped waveform.
    b. Purpose: Removes waveforms with abnormally large Les (Figure 9)

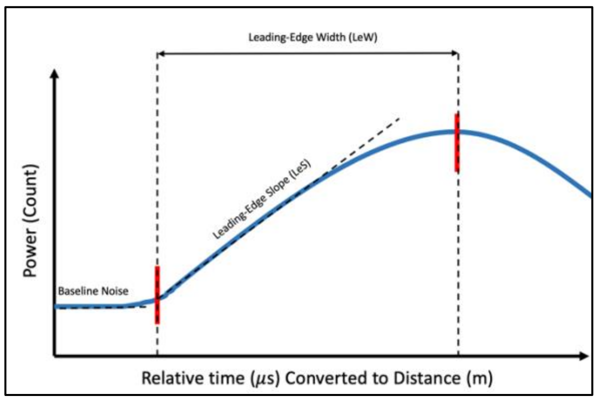


Figure 9: Illustration of Waveform with an abnormally large LE.

2. $\frac{dy}{dx}(LE) \leq 500\ (\frac{Counts}{m})$
    a. Explanation: When any of the derivative values of the LE is below 500 Counts/m
    b. Purpose: Ensures only waveforms with straight LE (and waveform's with abnormally low LeS, Figure 9) are included, and those with a plateau (Figure 10) along the LE are not included.

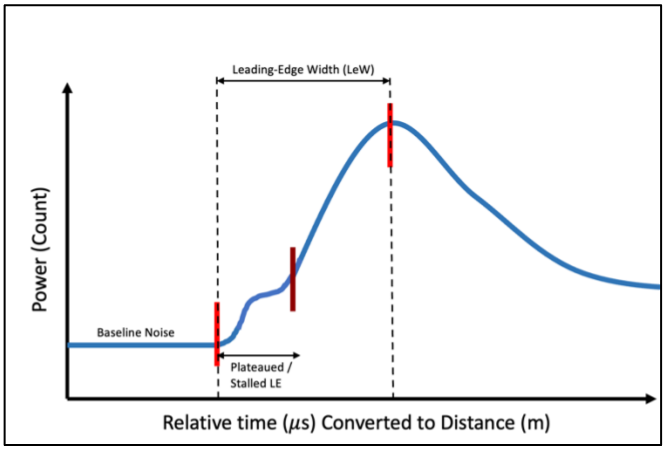


Figure 10: Illustration of Waveform with a plateaued LE

3. $\bar{X}_{S:Pre-LE} \geq \bar{X}_{R:Pre-LE} + 2\sigma_{\bar{X}_{R:Pre-LE}}$ , where $\bar{X}_{S:Pre-LE}$ is the mean power of the selected waveform between eight and two positions before the beginning of the LE and $\bar{X}_{R:Pre-LE}$ is the mean power of the ideal waveform between eight and two positions before the beginning of the LE. $\bar{X}_{R:Pre-LE}$ is equivalent to [0, 137.8, 137.6, 363.8, 359.2, 1194]. This array was determined by empirically examining different "ideal" waveforms.
   c. Explanation: When the selected waveform's baseline noise floor is above two standard deviations of an "ideal" waveforms.
   d. Purpose: Ensures only waveforms with properly clipped LEs and baseline noise floors are included.

### 5.0. Climatology -LeW Plots

Plotting monthly averages of LeW yields no noticeable trend. These results are expected, given that we argue the LeW time series is not significantly altered by season, and is a function of a changing shallow subsurface.

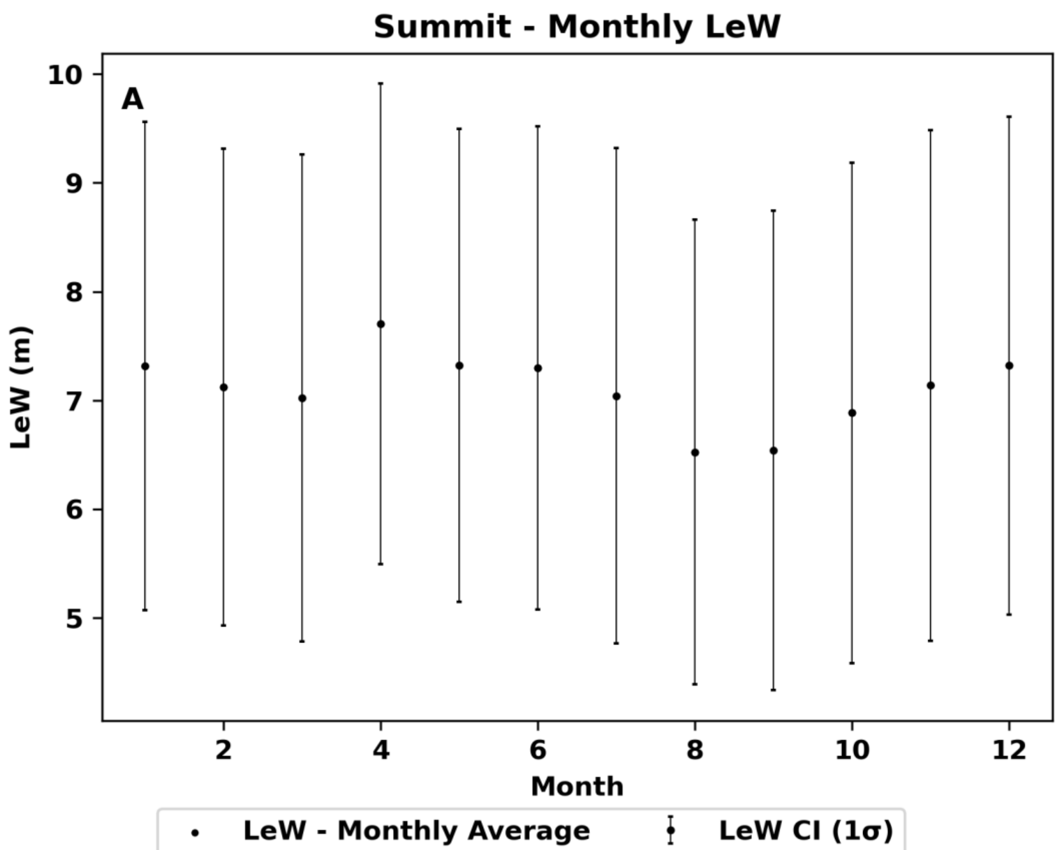


Figure 11A: Average LeW per month in the 2010-2021 time series at Summit Station

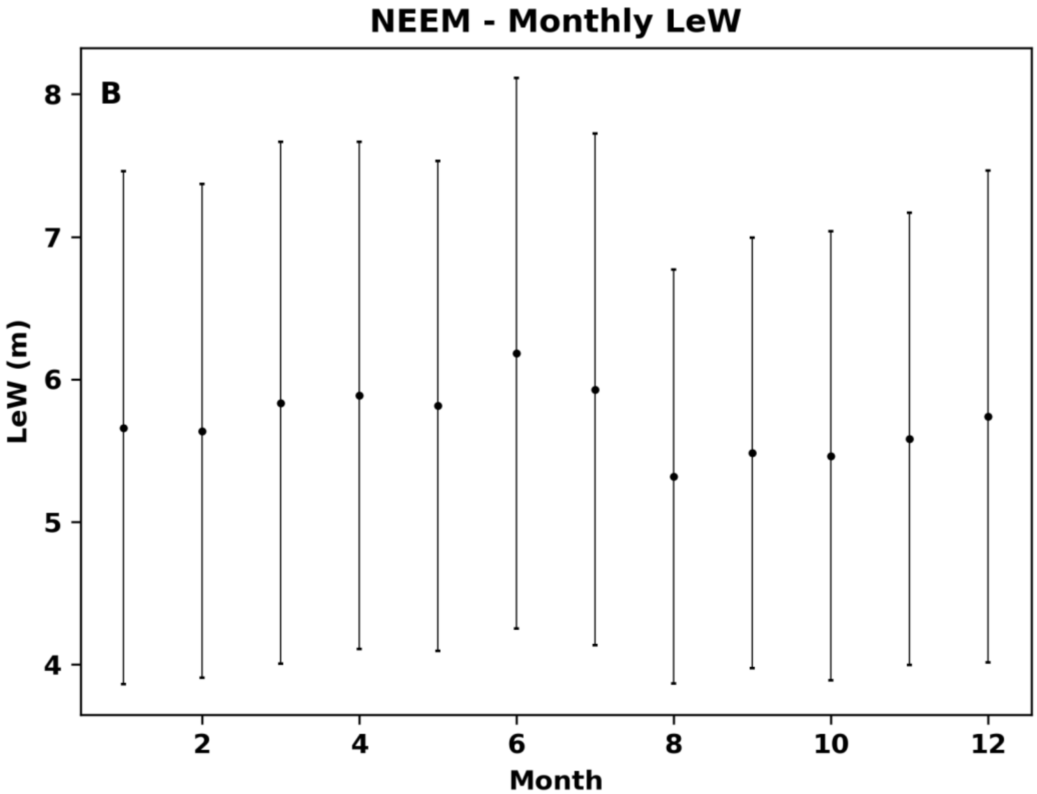

Figure 11B: Average LeW per month in the 2010-2021 time series at NEEM

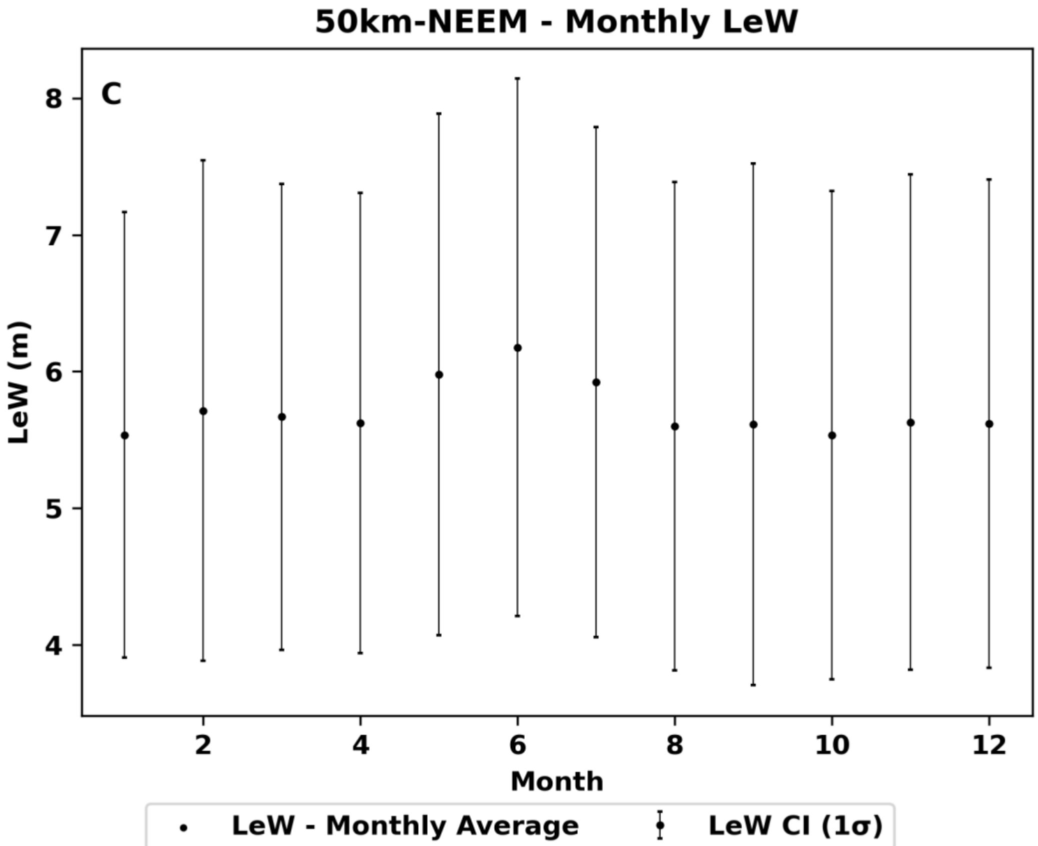


Figure 11C: Average LeW per month in the 2010-2021 time series at 50km-NEEM

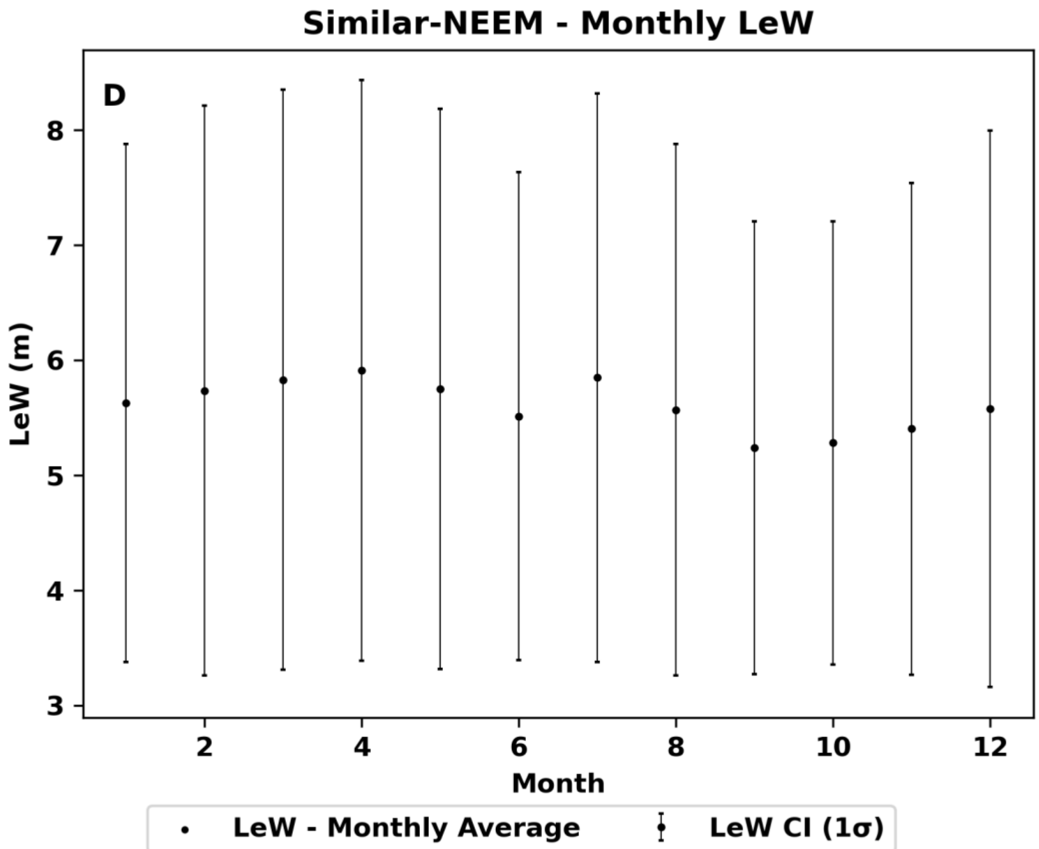


Figure 11D: Average LeW per month in the 2010-2021 time series at Similar-NEEM

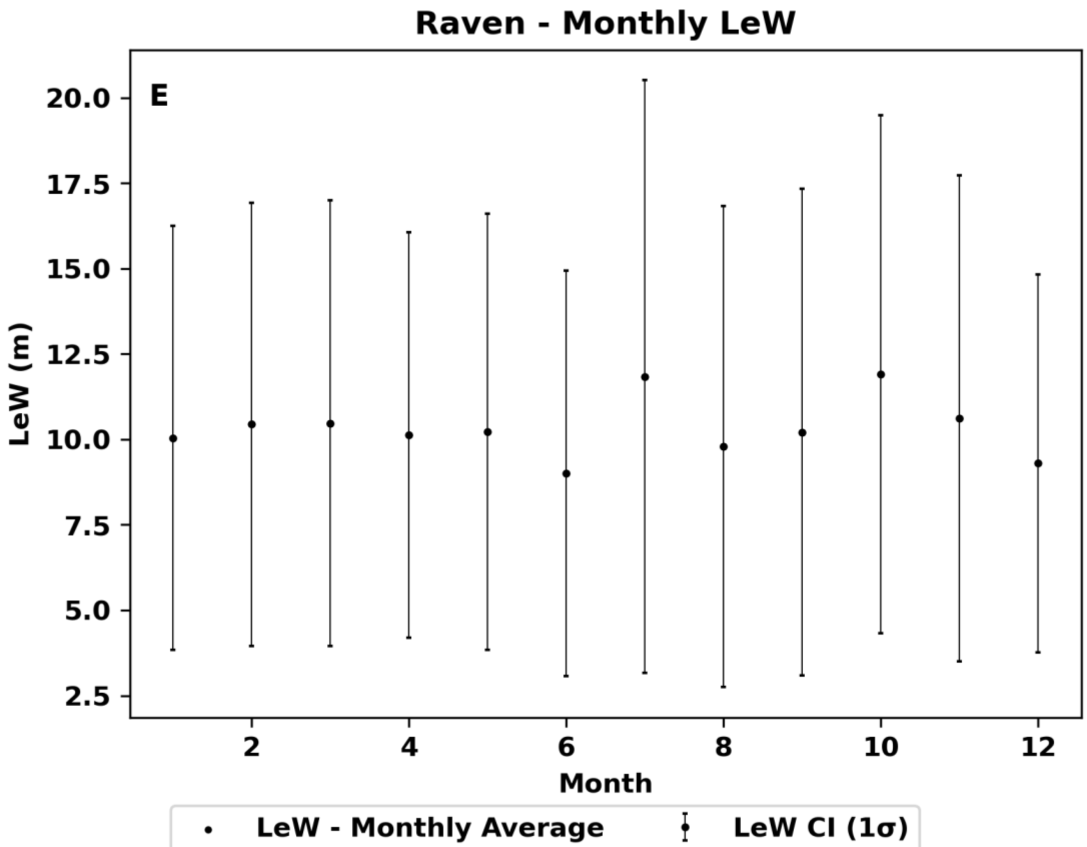


Figure 11E: Average LeW per month in the 2010-2021 time series at Raven

**6.0 References**


Dawson, G. J. and Landy, J. C.: Comparing elevation and backscatter retrievals from CryoSat-2 and ICESat-2 over Arctic summer sea ice, Cryosphere, 17, 4165–4178, https://doi.org/10.5194/TC-17-4165-2023, 2023.

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Noël, B., van de Berg, W. J., Lhermitte, S., and van den Broeke, M. R.: Rapid ablation zone expansion amplifies north Greenland mass loss, Sci Adv, 5, https://doi.org/10.1126/SCIADV.AAW0123/SUPPL_FILE/AAW0123_SM.PDF, 2019.