SUPPLEMENTARY MATERIAL

S1. Additional methodological figures (uncorrected LSR' and software framework)

In short, land returns shown in black color below is consistently one order stronger (ranging from 0.00 to 0.05) than ocean returns in subtropical and tropical regions shown in magenta color (always < 0.005). Since sea ice flag is not included in surface flag of L1B Aeolus data, high latitude water cases contain sea ice instances, leading to high OSR values (0.00 – 0.03). As seen, the ocean regions without sea/ice outside high latitudes constitute only a tiny fraction among all observations. As mentioned in the main text, this is plausible from the official Aeolus ground bin detection approach. In most cases, ocean returns do not qualify We discuss the presence of snow in details in the main manuscript. Note that the cases shown below are only illustrative and include not only surface return effects, but also atmospheric effects that are alleviated further.

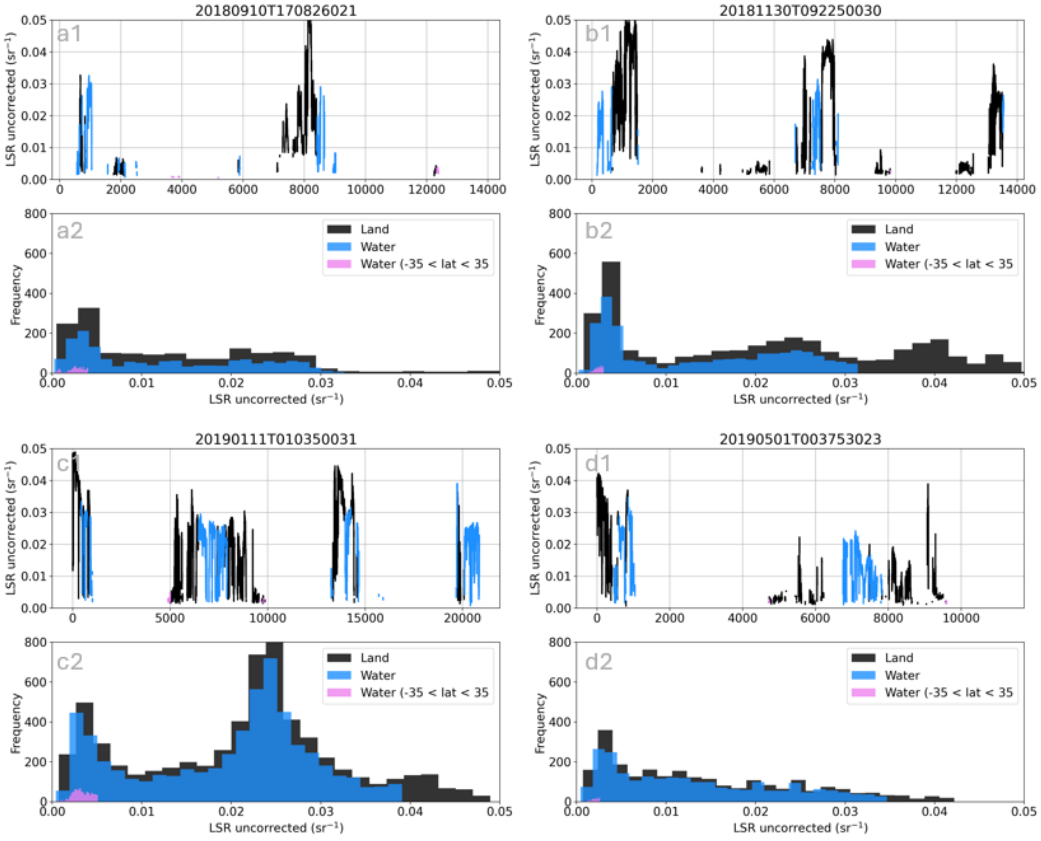

Fig. S.1 Uncorrected LSR (LSR') signal strength plots (panels with marker '1') and histograms (marker '2') shown for the reference orbits we used including: 2018.09.10 (a1, a2), 2018.11.30 (b1, b2), 2019.01.11 (c1, c2) and 2019.05.01 (d1, d2).

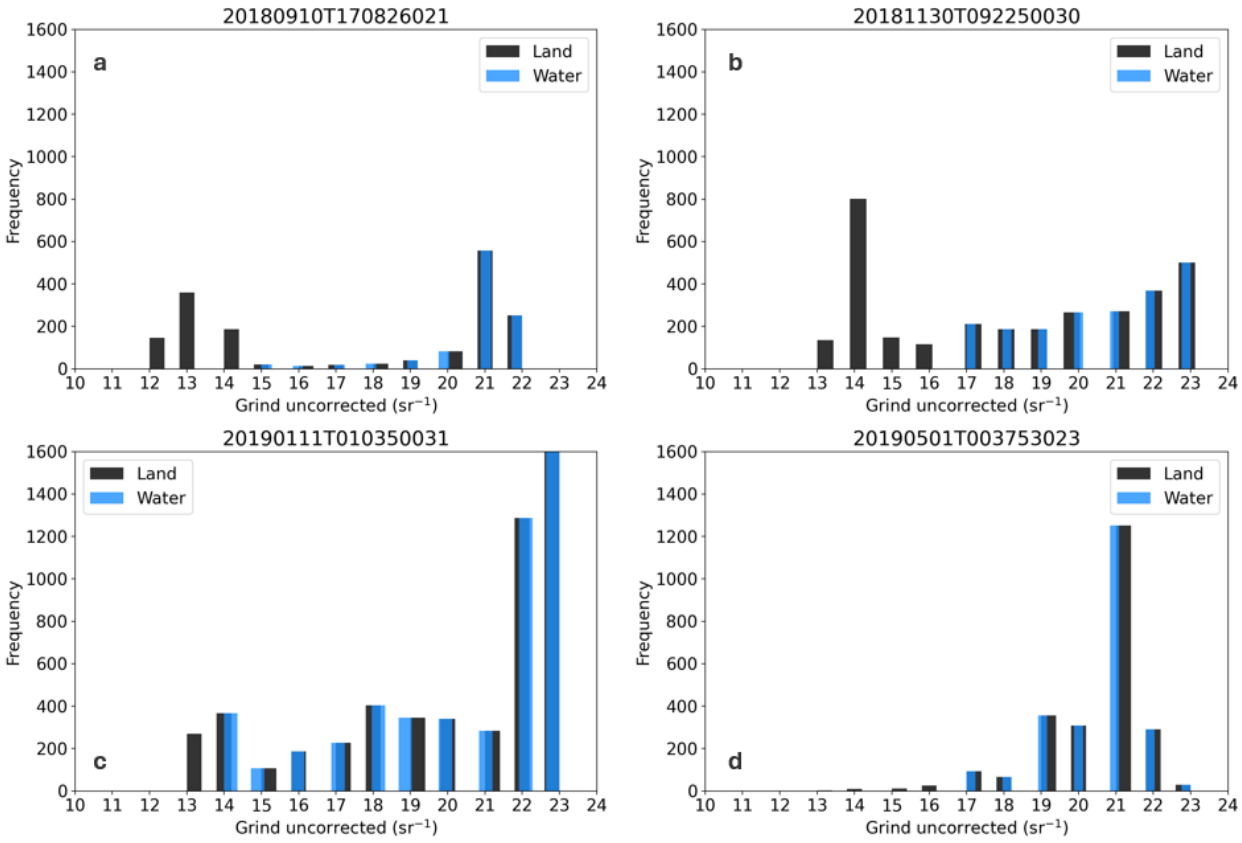

Fig. S.2 The lowest bin in lidar range gate (we count from the top to bottom in vertical dimension here) where ground bin was detected for the reference orbits: 2018.09.10 (a), 2018.11.30 (b), 2019.01.11 (c) and 2019.05.01 (d).

We illustrate below the logic of the LSR software in Fig. S.3. The LSR software consists of two modules including Module 1 that opens the Aeolus input data, allocates all observations with detected surface, quantify LSR for each observation and correct ground signal by applying AOD and RayOD as shown in Eq. 4. Module 2 creates the output data with LSR estimates at the given Aeolus resolution (measurement or observation, depending on the setting) alongside associated uncertainties, auxiliary data might be required for diagnostic purposes (LSR', AOD, RayOD etc), geolocation data and quality flags. The quality flags are used in this paper to produce attenuation-free LSR product. These flags are described in the main manuscript text. Although the original output of Module 2 represents all LSR estimates with detected ground bins at the original Aeolus observation, for the scientific evaluation, in this paper we also used quality-assured LSR product after applying quality flags and gridded LSR product. The LSR gridded product is not the part of the official Aeolus product at the moment. Note that we had previously demonstrated that exactly the very gridded product has good agreement with passive remote sensing, sensitive to land cover change and might be therefore very useful for scientific purposes [Labzovskii et al., 2023]. We emphasize that the software is now being developed and will be available in the prototype version before the official Aeolus Phase-F release.

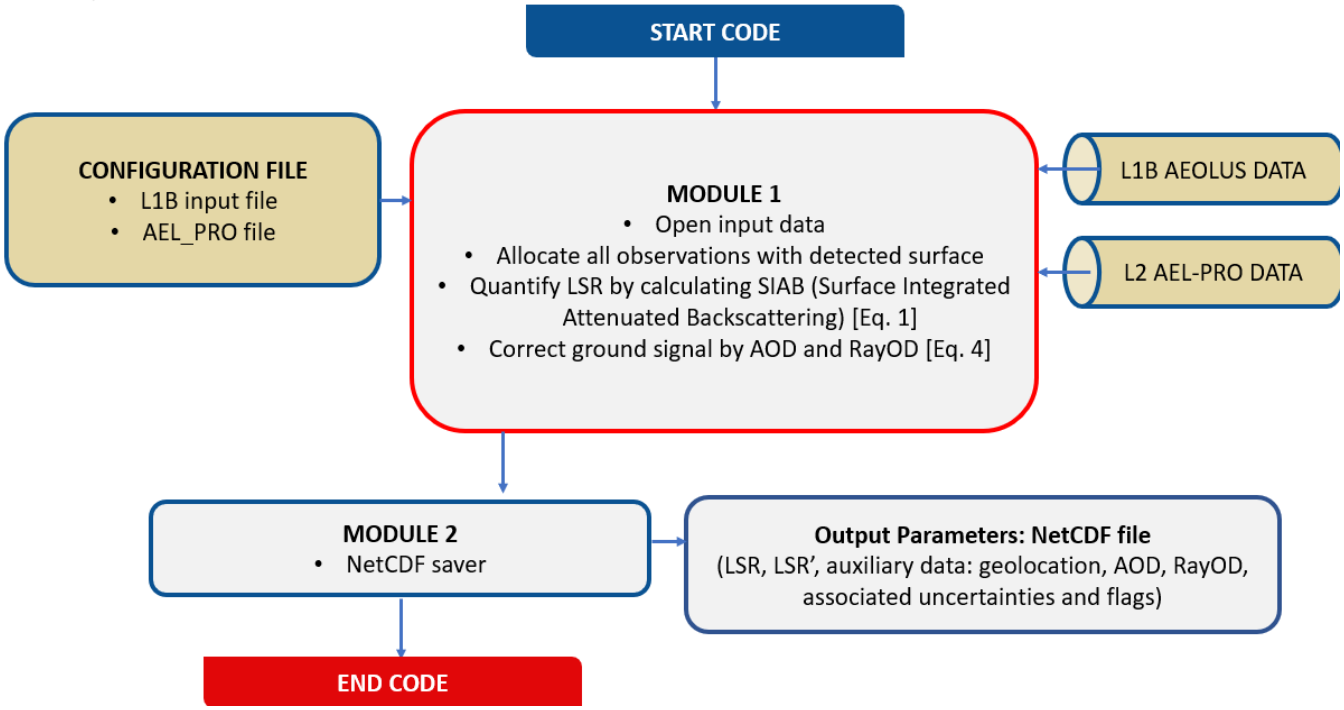

Fig. S3. Schematic representation of the LSR algorithm as to be implemented within the L2A Aeolus product

S2. Filtering out attenuated LSR observations

In this section, we illustrate some examples of LSR observations cleaned and not cleaned by applying 'qflag' or Aeolus quality flag described in the main manuscript. Fig. S4 below shows Aeolus LSR observations from September 2018 with all unfiltered observations (violet), only observations where ground bin was located by the official algorithm (red), observations with qflag = 0 (yellow) and observations with qflag = 0, AOD < 1.0. We call these observations "clear" in the main manuscript. As seen, the number of clear observations can dramatically differ depending on the strategy. The observations shown in violet are not useful because they do not contain any ground detection signal according to the official surface detection algorithm. They only illustrate the total number of available orbits with observations, not of which can be applied for the LSR retrieval. There is no visible difference between red-colored observations, which contain ground detection signal and those observations we marked as attenuation free by yellow color. In other words, the official ground detection algorithm works approximately nearly as effective as the qflag-based filtering of attenuative features introduced in our previous work [Labzovskii et al. 2023] about Aeolus LSR. Green-colored observations in Figure S1 represent clear, final LSR estimates that are used in the final analysis for September 2018. For other months, we use the same procedure to produce clearest LSR observations.

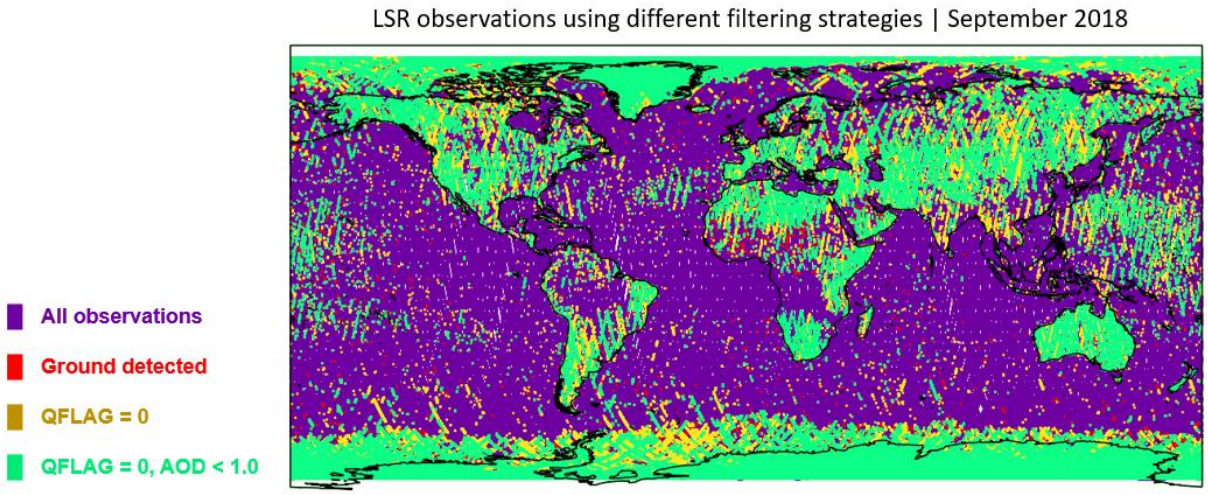

Fig. S.4 Aeolus LSR observations from September 2018 with all unfiltered observations (violet), only observations where ground bin was located by the official algorithm (red), observations with qflag = 0 (yellow) and observations with qflag = 0, AOD < 1.0.

For clarity, we quantified the number clear (e.g. green-colored) observations used in the final analysis in Table S2 below. As expected, for all months, only some fraction of Aeolus LSR observations contain ground signal (see column 'Ground Detected' in Table S2 below. In percentage, the number of observations containing ground ranges from 8% (September 2018) to 22% (January 2019) during FM-A period from the total number of observations. As seen, in absolute terms, these numbers correspond to the range of 465,044 – 1,132,018 ground-containing observations per months. Among these observations with ground signal within, the majority of observations passed the aforementioned criteria to be considered clear. The number of clear observations per month range from 366,529 (September 2018) to 1,026,869 (March 2019) during FM-A period.

Table S.2 Statistics on the LSR data abundance for FM-A period.

date	All	Ground Detected (GD)	GD & qflag = 0	GD & qflag = 0 & AOD < 1
2018/09	5,480,310	465,044	393,218	366,529
2018/10	6,398,400	645,696	520,056	482,108
2018/11	5,937,690	1,115,751	874,464	808,765
2018/12	6,213,600	1,255,028	972,504	898,912
2019/01	2,760,390	605,257	470,673	436,531
2019/02	2,659,800	520,681	359,191	330,899
2019/03	6,512,100	1,324,018	1,128,701	1,026,869
2019/04	6,263,430	1,168,668	949,454	859,650
2019/05	6,507,330	959,369	728,891	660,989

To ensure a stability of LSR retrieval to attenuative feature filtering strategies, we illustrate Fig S3 below. It shows the difference between original strategy of AOD-based filtering of LSR. To remind, Fig. 2 in the main text shows a procedure of filtering out attenuated LSRs. The step 2 on Fig. 2 includes the point of filtering out aerosol-attenuated cases of LSR detection at the threshold of AOD = 1.0. In other words, for gridding, all the LSR values corresponding to AOD > 1.0 values are filtered out from the analysis. Since this choice is rather arbitrary and comes from the experience of our previous study [Labzovskii et al., 2023], here we tested the sensitivity of LSR to this AOD threshold. Ideally, LSR should not be very sensitive to minor changes in AOD thresholding. The reasons are: (1) we should have enough clear observations per each grid cell to calculate LSR means and (2) most attenuated signals are filtered out at the quality flag checking stage. Thus, AOD filtering ensures that we not include some possibly wrong retrieval values and we do not bias our results towards weaker LSR in the regions, where AOD might be high (in this case, LSR is being attenuated not due to the surface reflectivity effects, but due to atmospheric effects). Due to this, we quickly tested the difference in LSR data abundance depending on the flexible AOD threshold for the Aeolus FM-A period (see Fig-s S4 and S5 below). We calculated averaged LSR estimates at 2.5 x 2.5o resolution with different thresholds. We found only a minor difference in LSR estimates between various AOD thresholds (0.50, 0.75, 1.00, 1.25, 1.50). Interestingly, despite the large difference between highest (1.50) and the lowest threshold (0.50), the data availability hardly varies mostly over water where signal is weak. For instance, in 2018/09 our selected threshold of AOD of 1.00 results in 5 221 grid cells. At the same time, lowering the threshold only slightly affects LSR grid estimate abundance by lowering the amount of cells down to 5 121 at 0.75 and to 4 806 at 0.50 threshold. Meanwhile, raising a threshold up to 1.25 and 1.50 values yields just slightly higher number of grid cells, as said above, most found above water with 5 272 cells at 1.25 and 5 300 cells for 1.50. The differences between LSR estimates at different AOD thresholds are relatively consistent for other months as well, so we did not provide more detailed statistics here. Overall, with the OFC strategy of surface detection, AOD = 1.0 seems like a reasonable choice since most attenuated cases are already filtered out at the quality flag application stage.

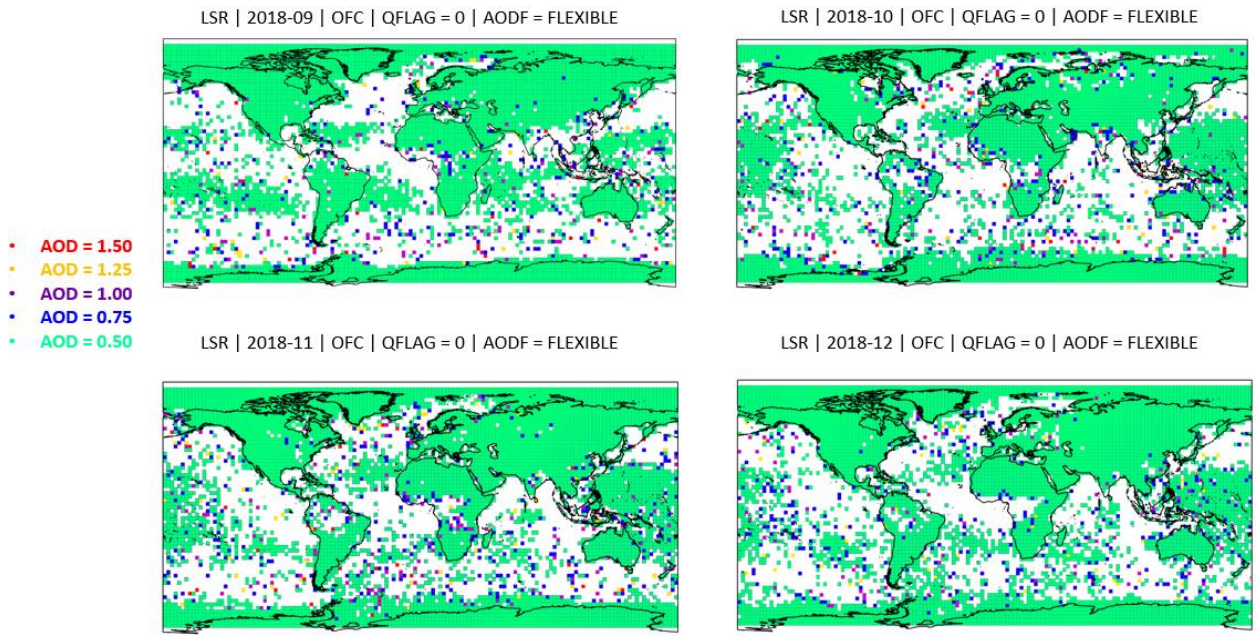

Fig S4 Sensitivity experiment using different AOD filtering strategies for September 2018, October 2018, November 2018 and December 2018. Color denotes the maximum AOD value below which LSR was considered completely attenuated.

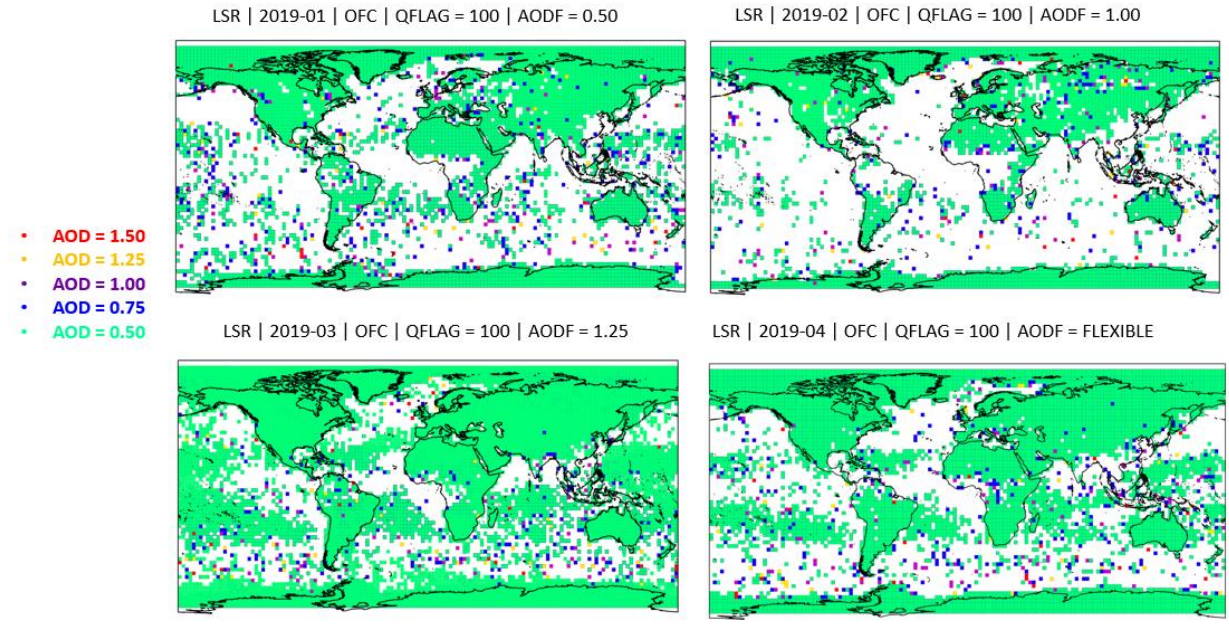

Fig S5 Sensitivity experiment using different AOD filtering strategies for January 2019, February 2019, March 2019 and April 2019. Color denotes the maximum AOD value below which LSR was considered completely attenuated.

Table S.3 below is shown to familiarize a reader with a complete list of codes, denoting atmosphere features in AEL_FM algorithm, incorporated in the latest AEL_PRO version.

Table S.3 List of atmospheric features according to AEL_FM classification incorporated into AEL_PRO dataset used for filtering out attenuated LSR cases for the final analysis

0	Clear sky tropospheric
100	Clear sky and used in Pass1 (tropospheric)
200	Clear sky and used in Pass1 (stratospheric)
1	Water cloud
101	Water cloud and used in Pass1 (tropospheric)
201	Water cloud and used in Pass1 (stratospheric)
2	Ice cloud tropospheric
102	Ice cloud tropospheric and used in Pass 1
3	Tropospheric aerosol
103	Tropospheric aerosol and used in Pass 1
13	Stratospheric Aerosol
213	Stratospheric Aerosol and used in Pass1
11	PSC-Type 1
211	PSC-Type 1 and used in Pass1
12	PSC-Type 2
212	PSC-Type 2 and used in Pass 1
1000 >= Index <2000	Attenuated and is tropospheric
2000 >= Index <10000	Attenuated and is stratospheric
Index > 10000	Surface

Below, we illustrate several additional regional figures, illustrating the regional analysis we described in section 3.3 To be specific, Fig. S7 shows Antarctica and Central Greenland (snow-covered regions).

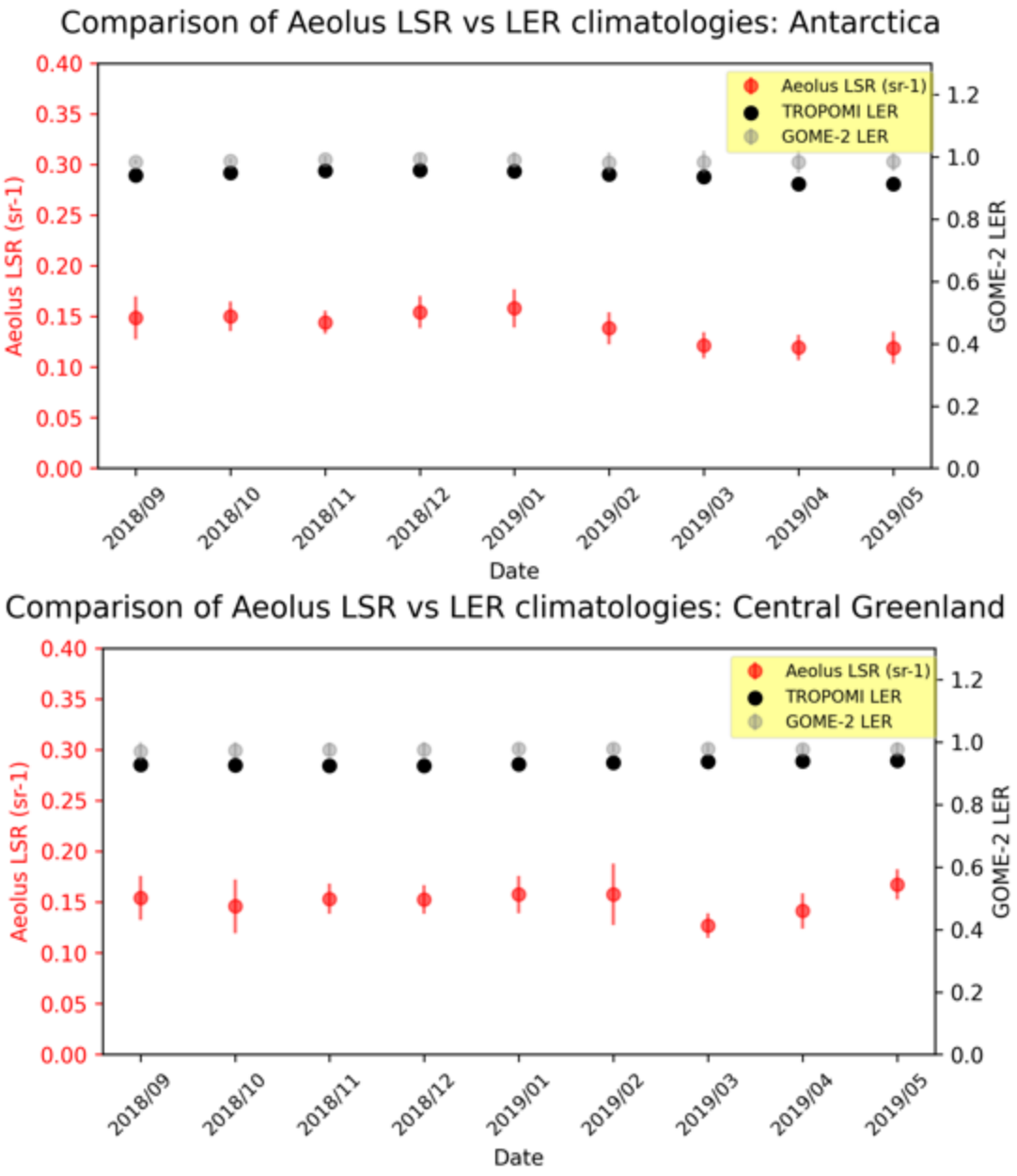

Fig. S7 LSR (red) comparison with LERT (black) and LERG (grey) for: a – Antarctica, b – Central Greenland. Error bars are taken from one-sigma monthly deviations of average LSR.

Below, we demonstrate another version of Fig. 17 illustrating scatterplots between LSR and NDVI, but with snow cover values of > 0.05 being filtered out. In other words, this is a figure, illustrating pure LSR – NDVI comparison.

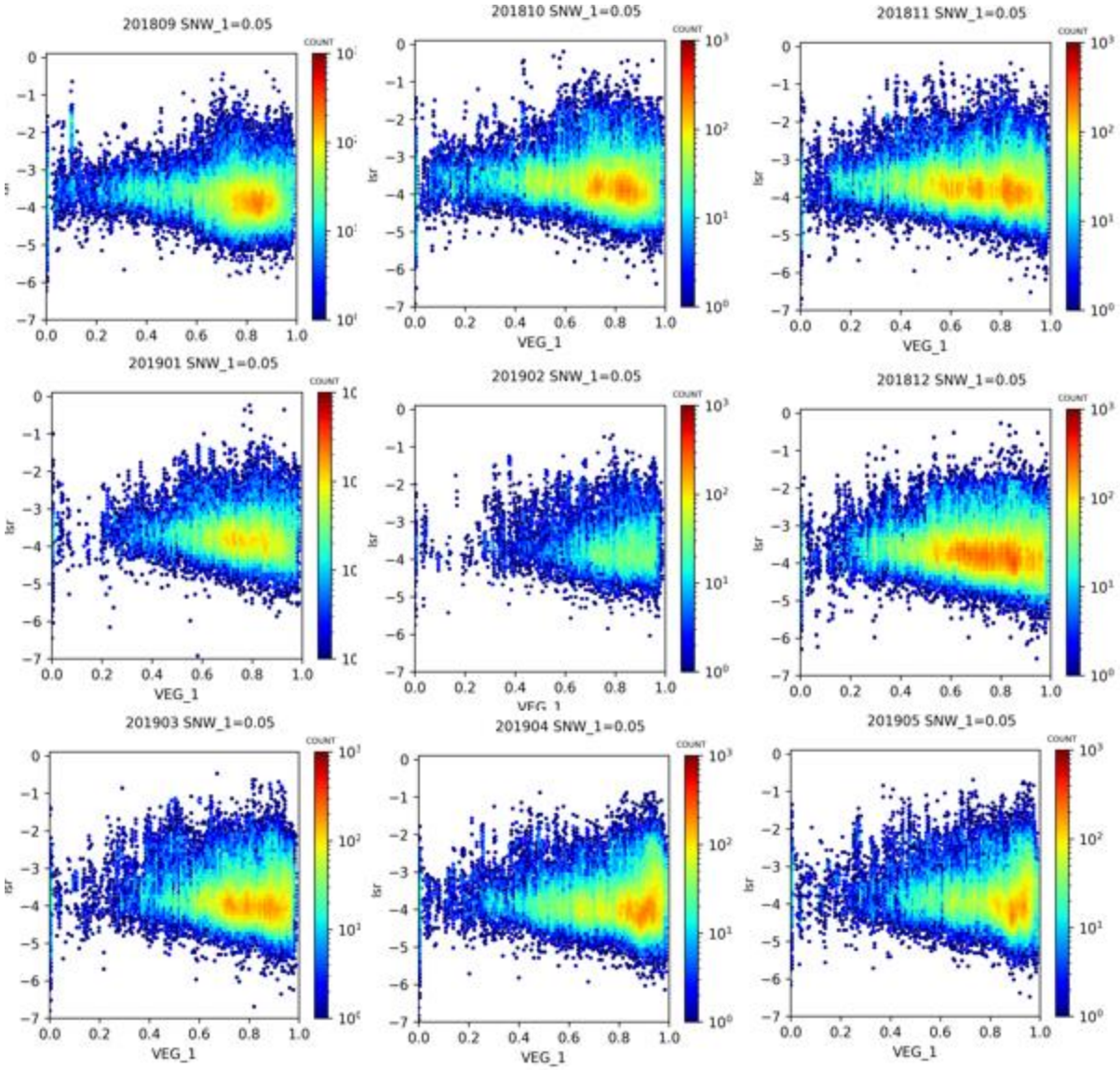

Fig. S8 Monthly scatterplots comparing LSR (sr-1) and NDVI (VEG_1) for the entire FM-A period. Y-axis and colorbar are both shown in logarithmic scales. Snow cover mask applied, whereas all observations corresponding to snow cover > 0.05 are filtered out from the analysis.