Anonymous Referee #1

On the fractional deviation delta_I. This variable occurs through the whole paper, but with different meanings: Of a particular measurement of a dark scene in Figure 1, and thereafter as some (summertime) average in Figure 2, but averaged per SZA bin in Figure 3. Different notations would be helpful.
The fractional deviation delta_I that is used throughout the paper is always from Equation 1. The only difference is how it is averaged.

Then, the definition of Delta_I. It is in relation to a certain 4-term polynomial (is that 3rd order? If not, which polynomial orders?).
I am actually using a 5-degree polynomial (6 term). I have corrected the text and figures. Thanks for catching this.

Is it a constraint that the polynomial becomes zero at SAZ=90? In P5,L11 that is suggested, but is it enforced?
There is no constraint that the polynomial is zero at SZA=90. Added text "*Although the polynomial fit is not constrained to have* I_{obs}*=0 at a solar zenith angle of* 90_o*, it appears so, consistent with this instrument design (Figure 1).* "

I would expect a deviation with respect to the assumed 'truth' (see Figure 1) , so (I_obs - zeta(SZA))/zeta(SZA). I checked my IDL code and the fractional deviation is calculated as (I_obs - zeta(SZA))/zeta(SZA), text and figures have been corrected. Thanks for catching this.

That said, what is the reasoning behind the fractional/relative deviation (as opposed to absolute deviation)? Now measurements near zero reflection are weighted more heavily, and the expression may blow up (especially when having I_obs in the denominator, instead of zeta). We chose this definition because we are ultimately interested in the percentage error in the intensity.

Are low reflectance measurements more important? Note that the curve zeta itself, (P4L12) seems to be fitted by minimizing the absolute deviations (is that the case?) as standard for LS fitting. Yes, the fitted polynomial Figure 1 minimize the absolute deviations.

Further on Figure 1, the cloud (especially of Greenland) seems to have more outliers below than above the polynomial. Why?
The outliers below the polynomial fit (especially over Greenland) are from scenes that have absorbing material (dust, black carbon) in the satellite FOV. Most of the scenes, especially over Antarctica, are free of absorbing material and are at the upper limit of their reflectivity. The ice can get darker but can't get any brighter.

Are the coefficients of the polynomial sensitive to these low outliers? To maintain simplicity we included these outliers in the polynomial fit.

The delta_I is, as said, averaged over summertime. Does that mean that the 14/15 points of NOAA16 in Figure 2 are, on average, zero? The average of all the NOAA-16 scenes will be zero but the annual averages shown in Figure 2 may not exactly be zero.

(NOAA-16 Seems the best choice for reference, but in P4L14 and P4L16, the lifitme is either 2001-2014 or 15 years. Both cannot be true.) Should read 14 year, text corrected.

In Figure 6, the delta_I are averaged for each year, w.r.t. the satellites that were available for each year. That means that with only two satellites active (first year), the points are mirrored around zero. This graph which thus includes these mirroring properties in Figure 6 directly leads to the claim of the uncertainty of 0.35%. But this uncertainty should be different for each year, and years with many satellites should be weighted more than years with two satellites (like 1997) (?) At some point we were doing this. Calculating an uncertainty for each year based on the uncertainty of each individual instrument. In the interest of simplicity, we chose not to present this more complicated approach.

b) On adjusting the intensities. Section 4 starts with the claim that NOAA14 is low biased. How can that be seen in Figure 2? The light orange points do not lie below the NoaA16 points, nor do they lie below the y=0 horizontal line. Can you explain how we should interpret the graph, assuming that the claim is correct?
Oops, My error. I corrected the text

The strategy of inter-calibration works because at any time two or more instruments temporarily overlap (chaining). Is there some weighting of very early instruments in the process involved? Are there weak parts of the chain? Conversely, is the solution around 2007 (halfway NOAA16) better behaved than elsewhere? There is no explicit weighting of earlier instruments in the slope or uncertainty determination. I would speculate that 1997 (at least over Antarctica) is weakest part chain because of grating drive errors.

Is it assumed or actively prescribed that the constant terms c0 are zero? It is assumed that all instruments were perfectly calibrated (no offsets). That might not be true. It does not automatically follow that, in this exercise, prescribing c0=0 would be neces- sary. Of course, it can be tried to allow for non-constant c0 in the inter-calibration. It would probably give better results to allow that freedom (lower residuals) , while necessitating some explaining (...)
Initially, I allowed c0 to vary but was later told by those with intimate knowledge of the SBUV instruments that a non-zero offset not possible with the instruments photomultiplier tubes.

Is it correct that the difference between Figure 4 w.r.t. Figure 2 is the correction of I with the gain factor in Table 1, following with the re-computation of delta_I? Yes
On the remedy of the hysteresis (P9): So the first light observations of Nimbus-7 were removed. But the asociated observations of NOAA16 were not removed, so we do now compare (i.e. in the recomputing process to acquire Figure 4) different summertime averages of delta_I? Is that allowed?
The last two panels of Figure 5 show the solar zenith angle delta_I relationship for NOAA-16 (dark traces). Neither show increasing delta_I with decreasing SZA that Nimbus-7 shows. This is a sign of hysteresis. In fact none of the other instruments show this feature, they are insensitive to SZA.

c) On discussing the events.

The 1992 (P9L17) reduction: is it not visible for Greenland? Why not? (Aerosol transport?) We don't know for sure but yes, probably differences in Sulfate aerosol transport.

In P9L21, reductions are mentioned. When are they correlated (Greenland/Antarctica), and when not? And why?
The darkening events are from regional transport of light-absorbing particles to the FOV of the satellite so we don't expect a coordinated simultaneous response over Greenland and Antarctica

In general, the point you stress here is that the long-term drift is (just) insignificant, but the particular events are well observed by the satellites. That seems OK and well explained. On the other hand, you mention the Polashenski (2015) results to be also 0.05 per decade which is simular (P12L4). If it is insignificant, why mention it? (Can you explain the notation -0.05(0.06) in P11L20 ?)

We mention the Polashenski result because it is an entirely different kind of measurement (in situ). I have added +- before 0.06 to clarify that that it is uncertainty

d) On the graphs. More explaining of the graphs in the caption (in order to have more self-explaining graphs) would be helpful (if that is allowed by the journal).

Technical corrections ———————
P2L9: show |a| negligible long-term trend? Done
P5L19 stokes -> Stokes Done
P8L3: 'they' refers to? Done clarified text
P9L7: So the correction of Deland et al was not so good after all and by discarding these 9 minutes we got rid of all hysteresis by brute force (?) No, that's not really fair to Matt. There are uncertainties associated with Deland's calibration. My changes are within these uncertainties. He is familiar with my results.

P9L17: multiple means 2 in this case. Three instruments: NOAA-9 -11 and -14 had grating drive errors.
P11L15 Figure 8 -> Figure 7. Thank you
P16: Might be an idea to extend the table with lifetime (start-end) per instrument.
P16: c0 is - except for OMPS. Why? P16: consider setting c1 to 1 (without zeros) for nOAA16. Fixed OMPS and NOAA-16 .

Anonymous Referee #2

The figures should be improved significantly by increasing the font size. Font size has been increased

[Abstract, p. 2, lines 12–13] *Three of these darkening events are explained by boreal forest fires using trajectory modeling analysis.* This is true, but this sentence implies that trajectory analysis is a part of this work, which it is not. Suggest removing "using trajectory analysis". Modified abstract, thank you

[Sect. 1, p. 3, lines 5–6] *This paper details the first step: the inter- calibration of radiances from the suite of nadir viewing instruments.* What are the next steps? It would be nice if these were summarized, if even in a single sentence, to provide context. Added text. *"The second step retrieves a Black-sky cloud albedo (BCA) record from the inter-calibrated intensities (Weaver et al. 2020) and compares the BCA with the Shortwave CERES cloud albedo."*

[Sect. 2, p. 4, lines 5–7] *Rather than calibrate these additional instruments with a radiative transfer model using LER, we use an empirical approach to remove the solar zenith angle dependence on intensity.* Although Sect. 3 goes on to explain the empirically based inter-calibration, this statement leaves me wondering why this was chosen over radiative transfer modeling. A simple statement here would establish a context for Sect. 3. I reworked the text. *"At first glance the VLIDORT simulation appears to simulate the observations (red trace Figure 1) and we considered using the* $\boldsymbol{I}$ *to* $\boldsymbol{\theta_o}$ *relationship simulated by VLIDORT as a reference (instead of using NOAA-16). But closer examination shows that the slope of the VLIDORT is shallow compared with the observations. The resulting* $\boldsymbol{\delta I}$ *would still be slightly dependent on* $\boldsymbol{\theta_o}$ *which would complicate the analysis."*

[Sect. 3, p. 5, lines 12–14] *One needs to pay particular attention to make sure the* θ_0 *used is exactly simultaneous with the intensity, since the SBUV instruments have a different* θ_0 *for each wavelength.* A bit more explanation is needed here. These are scanning instruments, and as such wavelengths are not measured simultaneously or at precisely the same solar zenith angle. Is this not reflected in the data product files? Why is particular attention required? I removed the sentence.

[Sect. 3, p. 5, line 19] *...of 663 hPa.* Why was 663 hPa chosen? It is the mean surface pressure for Antarctica

[Sect. 3, p. 6, line 3] *...but the* δI *was still too dependent on* θ_0 *...* What is meant by this? Simply that the slope derived from VLIDORT (as in Figure 1) was too shallow? Yes, I reworked the text, see above.

[Sect. 3, p. 6, lines 5–6] *...Jaross et al (2008). They account for the snow BRDF which* *we omit.* Would you quantify (at least to first order) what impact not accounting for snow BRDF would have on this analysis? Added Paragraph. "*Another, more sophisticated approach to validate sun-normalized radiances over ice sheets is described in Jaross et al. (2008). They account for snow surface BRDF and off-nadir viewing angles. Nadir 330nm reflectances simulated using their snow BRDF model are 1% less than those assuming a Lambertian surface at* $\boldsymbol{\theta_o}$ *=70°; disparities are near zero at* $\boldsymbol{\theta_o}$ *=50°. Our nadir observed* $\boldsymbol{\delta I}$ *was not sensitive to solar azimuth angle over Antarctica.*"

[Sect. 4, p. 6, line 17] . . . *NOAA-14 low biased compared to our reference (Figure 2).* Maybe I am struggling with the color scheme in Figure 2, but NOAA-14 does not appear to be biased low to me. It appears to be positive at least half the time. Am I mis-reading the plot? Oops, My error - corrected the text

[Sect. 4, p. 7, line 2] *After adjustment, the biases are negligible (right panel Figure 3a).* How is "negligible" defined in this context? Yes, the biases have been reduced, but are they now statistically insignificant? I suggest a different word be used or explained more precisely. See below.

Also, this statement seems out of place. It should come *after* the adjustment is described in the following paragraphs. Here, you could lead with a statement about why adjustment is necessary. Yes, good suggestion, Reworked text "*The positive bias for NOAA-17 and 18 is consistent at all* $\boldsymbol{\theta_o}$ *bins and suggests that a simple adjustment of the intensities might reduce these biases.*"

[Sect. 4, p. 7, line 4] *To adjust intensities for a specific instrument a multiplicative factor (*c_1*) is chosen so that* . . . Is the only reason that the additive coefficient, c_0, is not considered because of the PMT zero-offset bias mentioned on p. 5? Is this adequately justified? If so, it would be worth stating here. Initially, my results showed a non zero offset bias. Scientist/Engineers at NASA and SSAI (Science Systems and Applications) have been working for years to improve the calibration of the SBUV radiances to retrieve accurate ozone products; so they are very familiar with the instruments. They told me that radiances from the PMT can't have a non zero offset; rather what I was seeing are non-linearities at low signal levels.

[Sect. 4, p. 8, line 3] . . . *they are not used in the intercalibration, but are used in the later trend analysis.* Are "they" the data affected by the grating drive position errors (presumably corrected for in the trend analysis)? If so, please clarify. And why were they not used (I assume to remove any possibility of contamination)? Please clarify this as well. Yes, the other review picked this up too; text has been clarified. Thank you

[Sect. 4, p. 8, lines 9–10] *It is disconcerting that our correction does not bring them in closer alignment.* If the authors themselves are disconcerted, then I certainly am. Would you please speculate as to why the correction does not improve agreement? What could this mean for the analysis? Perhaps the estimated grating positions are wrong. I don't know what else to do. Further work needs to be done on this disparity.

[Sect. 4, p. 10, lines 2–3] . . . *this merged time series is the geophysical contribution.* It might be more precise to say "this merged time series represents the geophysical contribution". Yes that's better Thank you

[Sect. 5, p. 10, lines 17–18] *For easier comparison we have transcribed the data from their Figure 4 onto our Figure 4c.* It is still a somewhat difficult comparison in Figure 4. It would perhaps be clearer if the merged time series were compared to MODIS in a dedicated plot.

[Sect. 5, p. 11, line 15] . . . *on those dates (Figure 8).* I don't see a Figure 8 in the manuscript. Or is this referring to Damoah et al. (2004)? Should be Figure 7, text has been corrected.

[Sect. 6, p. 13, lines 7–9] *These calibrated intensities will be used to derive a UV cloud albedo record over the tropics and midlatitudes since 1980.* Again, how will these be used to derive a UV cloud albedo record? Added addition sentence, see above

Typos:

[Abstract, p. 2, line 9] *While the calibrated intensities show negligible long-term trend over Antarctica, . . .* Add "a" before "negligible". text has been corrected.

[Sect. 1, p. 2, line 19] . . . *deployed a suit of SBUV-2 instruments on board . . .* "suit" should be "suite". text has been corrected.

Inter-Calibration of nine UV sensing instruments over Antarctica and Greenland since 1980

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Abstract

Nadir viewed intensities (radiances) from nine UV sensing satellite instruments are calibrated over the East Antarctic Plateau and Greenland during summer. The calibrated radiances from these UV instruments ultimately will provide a global long-term record of cloud trends and cloud response from ENSO events since 1980. We first remove the strong solar zenith angle dependence from the intensities using an empirical approach rather than a radiative transfer model. Then small multiplicative adjustments are made to these solar zenith angle normalized intensities in order to minimize differences when two or more instruments temporally overlap. While the calibrated intensities show a negligible long-term trend over Antarctica, and a statistically insignificant UV albedo trend of -0.05 % per decade over the interior of Greenland, there are small episodic reductions in intensities which are often seen by multiple instruments. Three of these darkening events are explained by boreal forest. Other events are caused by surface melting or volcanoes. We estimate a 2-sigma uncertainty of 0.35% for the calibrated radiances.

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1. Motivation

In 1980 the Nimbus-7 spacecraft carried the first **S**olar **B**ackscatter in the **UV** (SBUV) instrument into low earth orbit to measure total column ozone. Since then, NOAA has deployed a suite of SBUV-2 instruments on board the NOAA-9, 11, 14, 16, 17, 18 and 19 spacecrafts. Since they were all nadir viewing and thus had limited spatial coverage, NASA also deployed a suite of mapping instruments: Nimbus-7 TOMS (1980), Earth Probe TOMS and the Nadir Mapper (NM) instrument of the Suomi NPP Ozone Mapping Profiler Suite (OMPS, 2012). True to their design, they have provided a long-term

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satellite data record of ozone products; however, they also were intended to measure the earth's reflectivity in the UV at wavelengths insensitive to ozone (331 and 340nm). Aside from a few publications (Herman et al. (2013), Labow et al. (2011) and Weaver et al. (2015)), this data set has not been fully exploited. Our ultimate goal is a long-term record of a UV cloud product that can be directly compared with climate models. This paper details the first step: the inter-calibration of radiances from the suite of nadir viewing instruments. The second step retrieves a Black-sky cloud albedo (BCA) record from the inter-calibrated intensities (Weaver et al. 2020) and compares the BCA with the Shortwave CERES cloud albedo.

2. Previous calibration of UV Satellite records

The backbone of our data record is the suite of eight SBUV instruments starting with the Nimbus-7 in 1980, and ending with NOAA-19 in 2013. Thereafter we use Nadir Mapper (NM) instrument on the Suomi NPP OMPS. Each instrument provides narrowband backscattered intensities near the 340 nm wavelength. We use a radiative transfer model to account for the small differences in each instrument's center wavelength (see Appendix). Regular sun-viewing irradiance measurements (F_{sun}) are made, typically weekly, to provide long-term calibration information. The measured intensities are normalized by F_{sun}, and multiplied by π. Throughout this study **I** refers to the sun normalized intensities.

We start with intensities that have already been calibrated to account for instrument effects such as hysteresis (see Deland et al 2012), and that are reported in the Level-2 datasets for each instrument. The first seven SBUV/2 data sets were previously calibrated by characterizing the instruments over the East Antarctic Plateau ice sheet using **L**ambertian **E**quivalent **R**eflectivity (LER, Huang L.-K. et al. 2003 and Herman et al. 2013). Using a radiative transfer model to calculate LER from the observed intensities removes much of the solar zenith angle ($\boldsymbol{\theta_o}$) dependence, but not all; over the ice sheets LER still decreases with $\boldsymbol{\theta_o}$ especially at high $\boldsymbol{\theta_o}$. While they did an excellent job of characterizing the first seven SBUV/2 instruments, two additional sensors need to be intercalibrated to extend our record forward: the SBUV2 on NOAA-19, and the Suomi NPP OMPS. Rather than calibrate these additional instruments with a radiative transfer model using LER, we use an empirical approach to remove the solar zenith angle dependence on intensity. Using these $\boldsymbol{\theta_o}$-normalized intensities, we inter-calibrate the UV sensors over the East Antarctic Plateau and the Greenland ice sheets.

3. Empirically based inter-calibration

Satellite observed Nadir-viewed intensities over the Antarctic and Greenland ice sheets have an almost linear relationship with solar zenith angle that is easily fitted with a 5-degree polynomial. Figure 1 shows the relationship over both ice sheets for all observations sampled by the SBUV2 on NOAA-16. With a drifting orbit and long lifetime (2001-2014) NOAA-16 sampled a wide range of solar zenith angles so we choose it as our reference instrument. The polynomial fit uses all observations over the instrument's 14 year lifetime and so provides a most probable intensity that the NOAA-16 SBUV2 would observe for a given $\boldsymbol{\theta_o}$. Our calibration approach is to remove the solar zenith angle dependence from the observed intensities ($\mathbf{I_{obs}}$) by using the reference polynomial fits shown in Figure 1. We can test if an observed intensity is high or low compared with the NOAA-16 SBUV2 reference by

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calculating a fractional deviation in terms of intensity ($\boldsymbol{\delta}\mathbf{I}$) from Equation 1. For example, the right panel of Figure 1 shows an anomalously low intensity sampled over a dark scene ($\mathbf{I_{obs}}^{\text{dark scene}}$) observed at a solar zenith angle ($\boldsymbol{\theta}_{\mathbf{o}}^{\text{dark scene}}$) ; it is compared with the intensity that NOAA-16 would likely have observed at that solar zenith angle ($\boldsymbol{\xi}$ ($\boldsymbol{\theta}_{\mathbf{o}}^{\text{dark scene}}$)) . The difference is divided by $\boldsymbol{\xi}$ ($\boldsymbol{\theta}_{\mathbf{o}}^{\text{dark scene}}$) to produce a fractional deviation in intensity $\boldsymbol{\delta}\mathbf{I}$ which is common throughout the manuscript.

$$\delta\mathbf{I} = \frac{\mathbf{I_{obs}} - \xi(\theta_o)}{\xi(\theta_o)} \qquad \text{Equation 1}$$

Each UV instrument has its own unique $\mathbf{I_{obs}}$ to $\boldsymbol{\theta}_{\mathbf{o}}$ relationship mainly because the photomultiplier tube (PMT) for each instrument has a slightly different response function. The underlying scene UV albedo (averaged over an instrument's lifetime) could be slightly different for each instrument, which would also change the $\mathbf{I_{obs}}$ to $\boldsymbol{\theta}_{\mathbf{o}}$ relationship, but we expect the Antarctic plateau albedo to be stable over time. The SBUV PMTs are designed to have a zero-offset bias, i.e. zero current response when there are zero photon counts. Although the polynomial fit is not constrained to have $\mathbf{I_{obs}}$=0 at a solar zenith angle of 90°, it appears so, consistent with this instrument design (Figure 1).

We also show estimates of Intensity calculated by the radiative transfer model VLIDORT (**V**ector **LI**nearized **D**iscrete **O**rdinate **R**adiative **T**ransfer package, Spurr, 2006). Here we assume Lambertian surface albedo of .95, and Rayleigh atmosphere with surface pressure of 663 hPa. The number of half-space quadrature streams is 40; the number of Stokes vector parameters is 3. At first glance the

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VLIDORT simulation appears to simulate the observations (red trace Figure 1) and we considered using the **I** to $\boldsymbol{\theta}_o$ relationship simulated by VLIDORT as a reference (instead of using NOAA-16). But closer examination shows that the slope of the VLIDORT is shallow compared with the observations. The resulting $\boldsymbol{\delta}$**I** would still be slightly dependent on $\boldsymbol{\theta}_o$ which would complicate the analysis.

Another, more sophisticated approach to validate sun-normalized radiances over ice sheets is described in Jaross et al (2008). They account for snow surface BRDF and off-nadir viewing angles. Nadir 330nm reflectances simulated using their snow BRDF model are 1% less than those assuming a Lambertian surface at $\boldsymbol{\theta}_o$ =70°; disparities are near zero at $\boldsymbol{\theta}_o$ =50°. Our nadir observed $\boldsymbol{\delta}$**I** is not sensitive to solar azimuth angle over Antarctica.

The suite of SBUV/2 instruments provides nadir observations with a 170x170km **F**ield **O**f **V**iew (FOV). But the OMPS Mapper instrument has a smaller nominal 50x50km FOV, except at the two most nadir viewing positions. Here the FOV widths are 20 and 30 km (Seftor el al 2017). For consistency, we only used the Mapper viewing positions that were within a nadir-centered hypothetical 170x170km SBUV FOV and aggregated their intensities (area weighted) prior to calculating $\boldsymbol{\delta}$**I**. For each instrument we calculate the summertime annual mean and plot the timeseries for both ice sheets (Figure 2).

4. Adjusting the intensities

The pre-calibrated intensities SBUV2 instruments on board NOAA-17, -18 and -19 appear to be high biased compared to our reference (Figure 2). As described below, a cost-optimization approach is used to adjust the intensities and reduce these disparities. Figure 2 only shows the summertime average $\boldsymbol{\delta}$**I**, but when calibrating instruments, it is instructive to examine the $\boldsymbol{\delta}$**I** dependence on $\boldsymbol{\theta}_o$ for individual

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years. The left panel of Figure 3a shows this for 2006 when the reference and three other instruments were operational. The positive bias for NOAA-17 and 18 is consistent at all $\boldsymbol{\theta_o}$ bins and suggests that a simple adjustment of the intensities might reduce these biases. All instruments show a similar skewed $\boldsymbol{\delta}\mathbf{I}$ distribution, at each $\boldsymbol{\theta_o}$ bin, toward low values of $\boldsymbol{\delta}\mathbf{I}$.

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To adjust intensities for a specific instrument a multiplicative factor (c_1) is chosen so that the adjusted intensities are a linear function of the original intensities: $\mathbf{I}_{\mathbf{adj}} = c_1 * \mathbf{I}_{\mathbf{original}} + c_0$. Adjusting the multiplicative factor (c_1) changes the gain, (intensity per observed photon counts) of the instrument. To inter-calibrate all instruments with respect to NOAA-16 we use a minimum-cost optimization algorithm to solve for a set of c_1 values that minimizes $\boldsymbol{\delta}\mathbf{I}$ disparities between temporally overlapping instruments. The c_1 for each instrument, except the reference, is allowed to vary; Table 1 shows the gain changes made to each instrument. Note that c_1 does not depend on time, so the interannual variability of a specific SBUV instrument remains intact after the calibration.

Only the highest quality observations are used for the inter-calibration. Observations are limited to $\boldsymbol{\theta_o}$ less than 75^o because at higher $\boldsymbol{\theta_o}$ ozone absorption and straylight effects become significant and contaminate results. Furthermore, SBUV observations that have a grating drive error and observations that are likely impacted by PMT hysteresis are not used to intercalibrate.

The grating drive selects the wavelength of a SBUV measurement. Sometimes, but not too often, the grating drive selects the wrong value and the intensities are measured at a wavelength different than the

SBUV instrument's nominal wavelength. Inclusion of observations with uncorrected grating errors will confuse our results, since our analysis assumes that intensities to derive $\delta \mathbf{I}$ are all at the same wavelength. Fortunately, the grating drive position is archived so we can apply a correction (see Appendix); however, the observations with uncorrected grating errors are not used in the intercalibration, but are used in the later trend analysis. Figure 4 shows the summertime average empirically adjusted $\delta \mathbf{I}$ over both ice sheets after applying the gain changes in Table 1. Solid circles exclude observations with grating drive errors and open circles include corrected observations. There is clearly tighter match between overlapping instruments compared with Figure 2. But there still are disparities between overlapping instruments between 1997 and 1999 when multiple instruments suffer from grating errors. It is disconcerting that our correction does not bring them in closer alignment.

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Both Nimbus-7 and to a lesser extent NOAA-9, suffered from PMT hysteresis. These earlier PMTs were not able to quickly respond to the 4 orders of magnitude signal changes that occur when the satellite first comes out of darkness on each orbit and the instrument sees its first light. For Nimbus-7 hysteresis errors are between 4 and 9% at first light over Antarctica and lessen as the PMT adjusts to the bright scenes over the ice sheet. By the time the Nimbus-7 reaches Greenland the PMT is equilibrated and there is no hysteresis error. (Maximum hysteresis errors of NOAA-9 are 2%.). The intensity observations for these early instruments have been corrected for hysteresis (Deland et al., 2001). Still, we initially were unable to match Nimbus-7 with the other instruments; there was good agreement over Antarctica but over Greenland Nimbus-7 was about 1% higher than the others (Figure 2).

Our remedy was to first calibrate the SBUV instruments *only* over Greenland where Nimbus-7 is free of hysteresis error. As expected, all temporally overlapping instruments agreed over Greenland, but over Antarctica Nimbus-7 was low by about 1% compared with NOAA-9 and NOAA-11. Then we started removing Nimbus-7 observations; first those within 1 minute of first light, then 2 minutes. With every minute of observations removed, the disparity over Antarctica lessened. We achieved the good agreement seen in Figure 4 by removing 9 minutes of Nimbus-7 observations after first light.

Figure 5 shows the $\boldsymbol{\theta_o}$ dependence on the empirically adjusted $\boldsymbol{\delta}$**I** for selected years. All the SBUVs, except for Nimbus-7 and NOAA-9, have an almost flat (<0.005) $\boldsymbol{\delta}$**I** dependence with $\boldsymbol{\theta_o}$. A flat $\boldsymbol{\theta_o}$ dependence indicates that the PMT response is similar to the NOAA-16. Over Greenland $\boldsymbol{\delta}$**I** dependence with $\boldsymbol{\theta_o}$ is not quite as flat (Figure 3b). The suppression of $\boldsymbol{\delta}$**I** at $\boldsymbol{\theta_o} > 57^o$ and time after first light < 9 minutes is seen for all years of Nimbus-7. Even though these suppressed observations ($\boldsymbol{\theta_o}$ > 57^o) were previously corrected for hysteresis, artifacts remain and they are not used in any analysis.

Multiple instruments show coincident reduction of **δI** over Antarctica in January 1992 (Figure 4) most likely from aerosols transported to the Antarctic after the eruption of Mt Pinatubo 6 months earlier in 1991 (left panel Figure 3c). The April 1982 eruption of El Chichon likely contributed to the coincident reduction in 1983; other anomalies occur in 2001, 2010 and 2013. Likewise, there are coincident reductions in **δI** over Greenland.

To estimate the uncertainty in the SBUV intensity from instrument calibration alone we first average the **δI** over the coincident satellites for each year; this merged time series represents the geophysical contribution. Absolute departures from this merged time series (Figure 6) are attributed to instrument calibration uncertainty. Two times the standard deviation of the fractional departures of all the SBUVs and OMPS (using both ice caps) is about 0.0035. We conclude that annual averages of **I** have a 2-sigma uncertainty of 0.35%.

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5. Greenland Ice Sheet

The albedo of the Greenland Ice Sheet is of interest because it contributes to changes in the surface energy balance and surface melting. The variability of our UV **δI** record is consistent with the MODIS albedo data set. A recent study presents time series of the surface reflectance over the Greenland Ice Sheet from the Collection 5 (C5) and C6 MODIS data sets (Casey et al. 2017). While the older C5 set shows strong darkening of the ice sheet since 2000 (not shown), C6 has negligible trends that are not statistically significant. They report surface reflectance for the channel closest to our UV channel (MODIS Band 3, 459nm) for dry snow conditions (locations with ice surface elevations > 2000 m) and for wet snow conditions (elevations < 2000 m). For easier comparison we have transcribed the data from their Figure 4 onto our Figure 4c. Many of the same episodic events in the MODIS C6 record that limit measurements to wet snow conditions (solid blue trace Figure 4c) are also seen by the UV instruments (Figure 4b and c): darkening in the NH summer of 2003, 2010 and 2012. The 2012 darkening was likely driven by anomalous surface melting over Greenland. Satellite estimates of meltday area from microwave brightness temperatures (Nghiem et al., 2012) and mass loss from the NASA GRACE instrument both suggest strong surface melting in 2012.

Surface or airborne light-absorbing aerosols that originate from boreal forest fires can explain some of the other reductions of UV **δI** over Greenland. The 1995 darkening episode is likely caused by forest fires in Canada. Using a trajectory model, Wotawa and Trainer (2000) estimate that CO emitted from the large fires in western Canada reach Greenland on 1 July (their figure 2). Using a similar technique, Stohl et al 2006 estimate that CO from Alaskan and Canadian fires in 2004 reached Summit Greenland on about 16 July. Their figure 11 shows elevated levels of observed and trajectory-modeled CO from 16 July to 2 August. Finally, the global travels of smoke from the 2003 fires in South eastern Russia are documented by Damoah et al. (2004) using a trajectory model and MODIS satellite images. They estimate a 24 May arrival time over Greenland (their Figure 2). A time-series of daily values of UV **δI** over Greenland show abrupt reductions by the SBUV instruments operating on those dates (Figure 7). There are other dramatic darkening events, likely caused by either forest fire smoke or surface melting (e.g. 2006 and 2008), that we could not find in the literature.

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While the shorter C6 record shows no apparent trend, our UV record shows a weak, though statistically insignificant reduction in UV **δI** over Greenland: -0.05 (+-0.06) decade^{-1} at locations with elevations > 2000 meters (Figure 4b). Impurities in the snow as detected by insitu analysis are consistent with our observed trend. Polashenski (et al 2015) measured the concentrations of light absorbing impurities (LAI) in 67 snow pits across North West Greenland ice sheet in 2013 and 2014 and compared them

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with studies that analyzed snow from the past 6 decades. Increases in black carbon or dust concentrations relative to recent decades were small and corresponded to snow albedo reductions of at most 0.31, or ~0.05 per decade which is similar to our UV satellite estimate. The snow studies also record episodic events that darken the snow 1-2%, similar to the 1995, 2003 and 2004 darkening we see in the SBUV satellite record.

6. Discussion / Summary

The East Antarctic Plateau is the preferred ice sheet for performing radiance calibration. Its very low temperatures and clear pristine conditions, except for the occasional volcanic eruption, all maintain a stable surface albedo with time. In contrast, the interior Greenland ice sheet is darkened every few years by air-borne particles from Boreal wild fires or from albedo changes caused by widespread surface melting. Since we are not doing an absolute calibration, but a relative calibration (using NOAA-16 as a reference instrument), Greenland's albedo variations (~2%) test how well the SBUV instruments respond to changes in the albedo. Moreover, including it in our calibration analysis enables a characterization of instrument hysteresis errors mainly with Nimbus-7 over Antarctica. Once removed, it matters little whether both ice sheets or only Antarctica are used to determine the multiplicative gain coefficients (c_1), the UV **δI** trends over both ice sheets are almost the same.

Intensities at the 340 nm wavelength channel observed by eight nadir-viewing SBUV satellite instruments and the OMPS scanning instrument are intercalibrated over the Antarctic and Greenland ice sheets. The approach is to compare observed intensities that have been normalized by solar zenith angle. After the inter-calibration, we estimate a 2-sigma uncertainty of 0.35% based on temporally overlapping sensors. Multiple instruments respond in unison to known darkening events that sometimes can be explained by volcanic aerosols, soot from boreal forest fires, or surface meltwater. These calibrated intensities will be used to derive a UV cloud albedo record over the tropics and midlatitudes since 1980.

Appendix - Accounting for small wavelength differences

Each instrument provides narrowband backscattered intensities close to but not exactly at 340 nm wavelength. For example, the Nimbus-7, NOAA-9 and NOAA-14 have nominal center wavelengths of 339.90, 339.75, 340.05 nm and Full Width Half Maximum (FWHM) of 1.0, 1.132 and 1.132nm, respectively. These seemingly small wavelength differences will change observed intensities by several tenths of a percent at high solar zenith angles. Using the VLIDORT Radiative Transfer Model we create a 2-dimensional table of intensities at 0.1 nm wavelength resolution and at 10º SZA resolution. A Lambertian surface of 0.95 albedo is assumed. For each instrument we determine a simulated intensity $\mathbf{I_{sim}}$ by convolving the instrument's FWHM across the center wavelength of the instrument. To account for the wavelength and FWHM difference between a non-reference instrument (e.g. Nimbus-7) and our reference instrument NOAA-16 we multiply the observed intensities from Nimbus-7 by $\mathbf{I\ (\theta_o)_{sim}^{NOAA\text{-}16}\ /\ I\ (\theta_o)_{sim}^{Nimbus\text{-}7}}$. Note that the wavelength correction is dependent on solar zenith angle.

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Linear equation for empirical δI Adjustment

$$I_{adj} = c_1 * I_{original} + c_0$$

	c_0	c_1
Nimbus-7 SBUV	-	0.9913
NOAA-9 SBUV/2	-	1.0013
NOAA-11 SBUV/2	-	1.0002
NOAA-14 SBUV/2	-	1.0011
NOAA-16 SBUV/2	-	1
NOAA-17 SBUV/2	-	0.9962
NOAA-18 SBUV/2	-	0.9936
NOAA-19 SBUV/2	-	0.9976
OMPS-Mapper	-	0.9972

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Table 1. Gain c_1 and offset c_0 values used to make adjustments to observed intensities for UV sensing instruments.

Figure 1

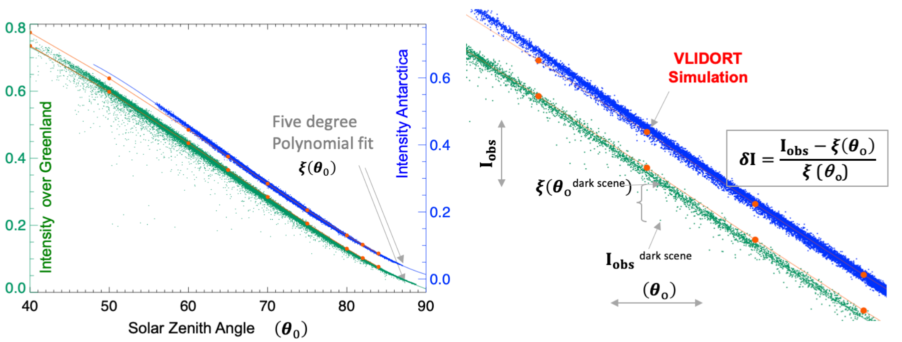

Figure 1. Measured Intensity at 340 nm from the NOAA-16 SBUV versus Solar Zenith Angle over the Antarctic Plateau (blue) and Greenland (green). Each point is a nadir-viewed observation at the native Field of View (170 km by 170 km) during the summer (fifteen days on either side of solstice). Also shown is a polynomial fit and a radiative transfer simulation (red) assuming a Lambertian surface albedo of .95, a Rayleigh atmosphere with surface pressure of 663 hPa. Note that the Greenland intensities are offset from the Antarctic ones. The right panel shows a zoomed in view (see text for details).

Figure 1

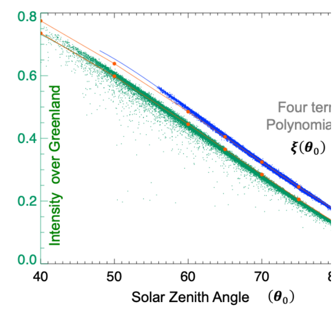

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Figure 2

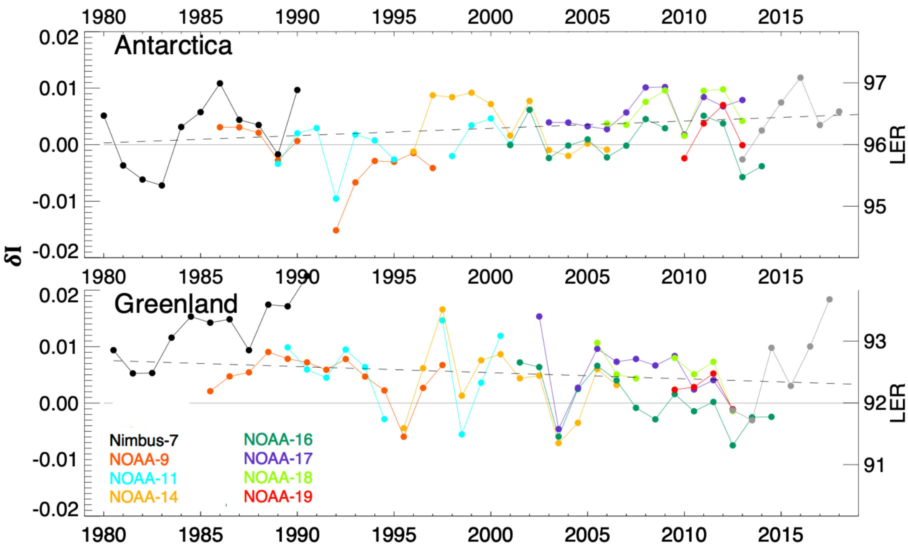
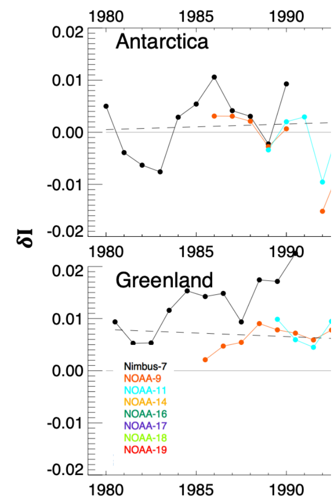


Figure 2. Inter-annual variability of previously calibrated **δI** for the SBUV instruments (colored) and OMPS mapper (grey) over Antarctica and Greenland. The right-hand axis shows the corresponding change in LER.

Figure 2



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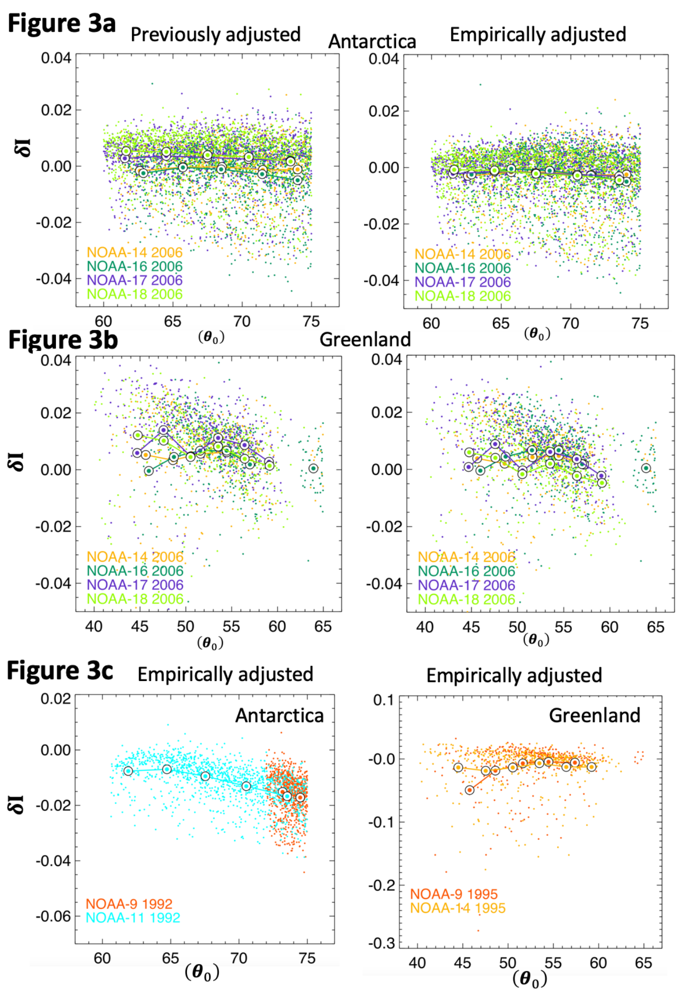

Figure 3. **δI** for all FOVs observed over the ice sheets plotted against solar zenith angle ($\boldsymbol{\theta_o}$) for specific years. The large circles are averages of **δI** binned by solar zenith angle. Figure 3a shows the previously

calibrated **δI** on the left and our empirically calibrated **δI** over Antarctica on the right for 2006. Figure 3b is same but over Greenland for 2006. Figure 3c shows our empirically calibrated values over Antarctica in 1992 and Greenland in 1995.

Figure 4

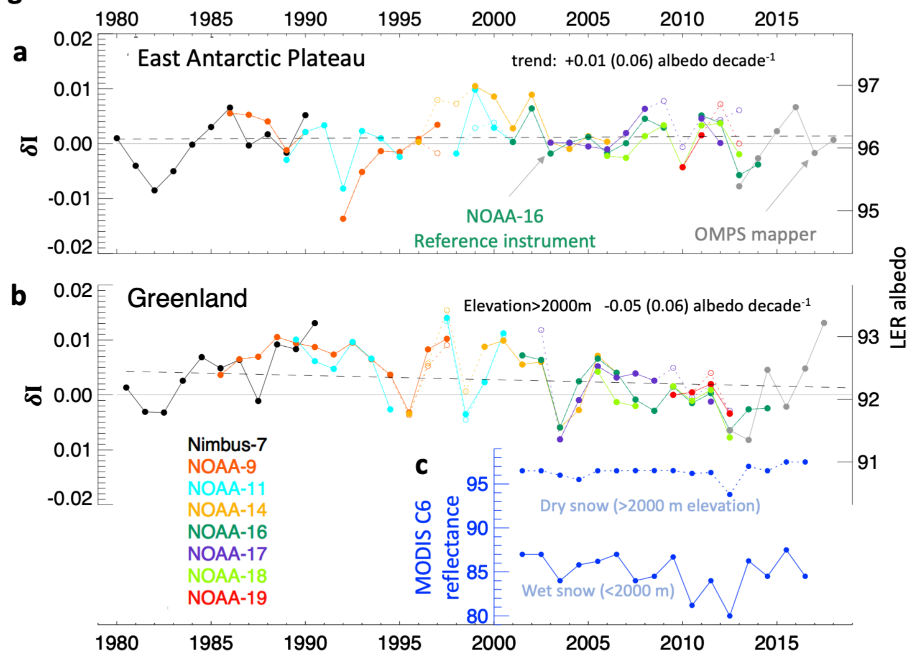

Figure 4. Inter-annual variability of our **δI** for the SBUV instruments (colored) and the OMPS Mapper (grey) over Antarctica (a) and interior locations over Greenland with ice surface elevations above 2000 meters (b). The right-hand axis shows the corresponding change in LER. Annual means plotted with solid circles only include observations with correct grating drive positions; open circles also include those with grating drive errors that have been corrected (see text). The lowest panel (Figure 4c) shows MODIS Collection 6 reflectance for Band 3 (459nm) at elevations above 2000 meters (dry snow conditions dashed trace) and below 2000 meters (wet snow conditions solid trace).

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Figure 5

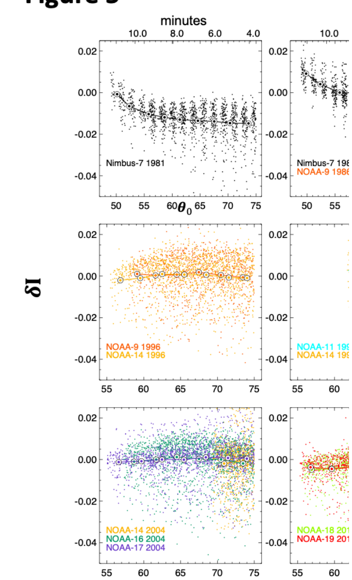

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Figure 5

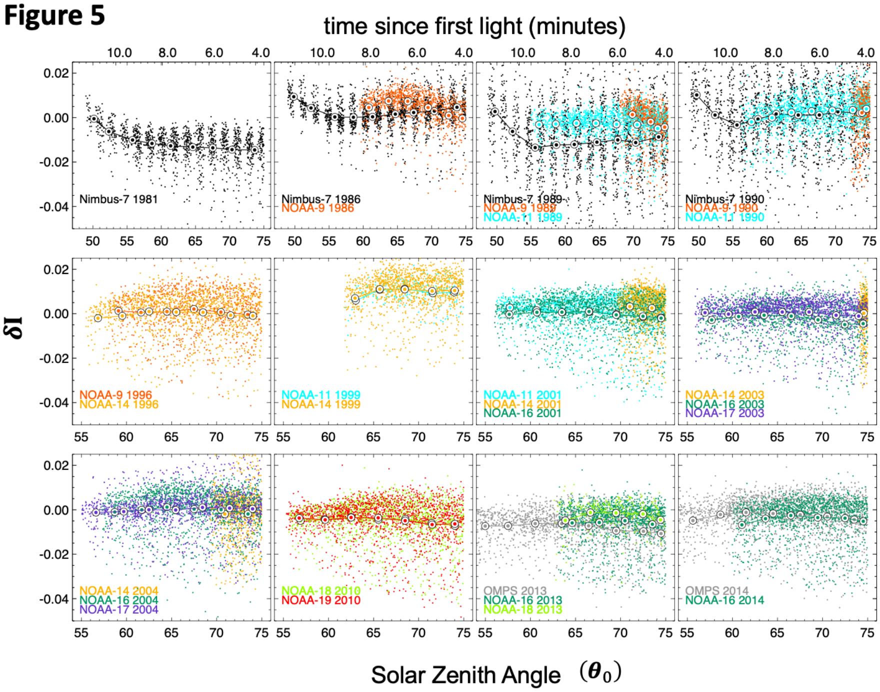


Figure 5. Empirically calibrated for all FOVs observed over Antarctica plotted against solar zenith angle ($\boldsymbol{\theta_o}$) for selected years. The top four panels show the suppression of **δI** during the first 7-10 minutes after Nimbus-7 sees its first light at the start of a new orbit. At first light, time=0 and $\boldsymbol{\theta_o}$ =90°. The time after first light (minutes) is shown at top of first four panels.

Figure 6

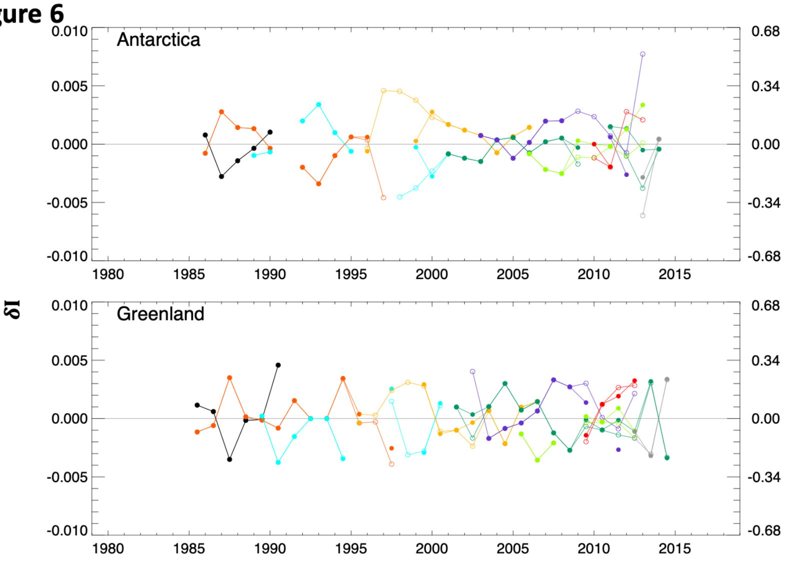


Figure 6. same as Figure 4 except that merged-satellite average is removed.

Figure 7

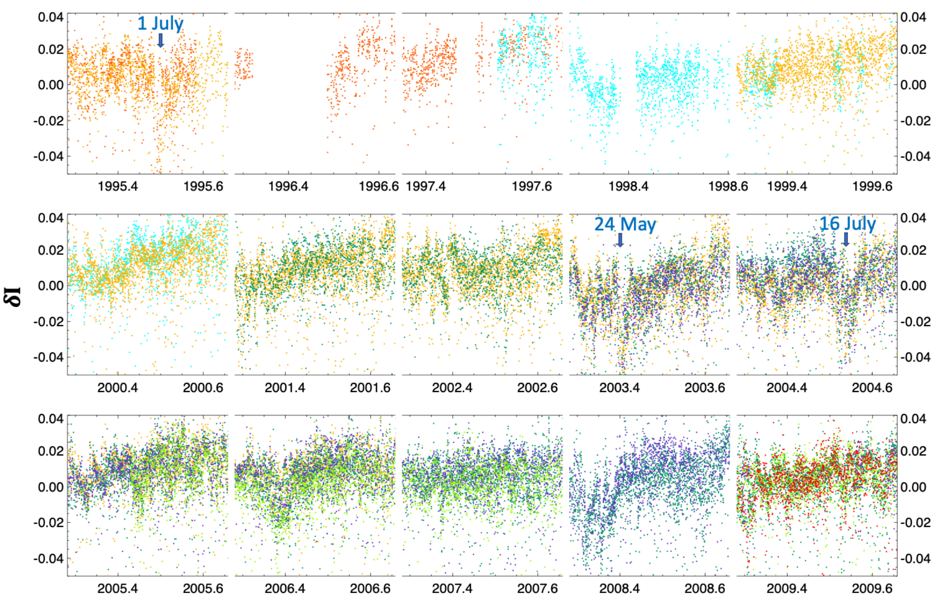
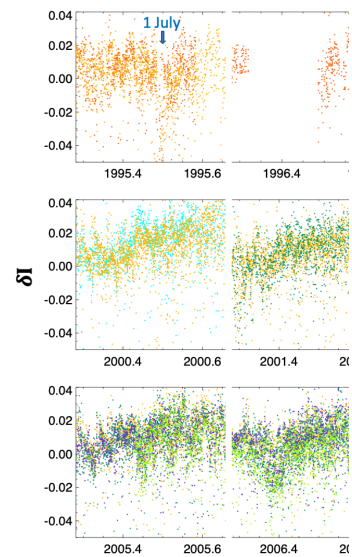


Figure 7. Time series of empirically calibrated **δI** for all FOVs observed over Greenland for selected years. Blue arrows indicate estimated dates when CO from boreal forest fires reach Greenland (see text). Color scheme is same as other figures.

Figure 7



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