Answers to Anonymous Referee #2 (RC1)

Referee comment: 1. additional details about the instruments (stability, different spectral/angular sensitivities, QA/QC) and their corresponding datasets (calibration/traceability, corrections, etc.) should be provided. Since different kinds of instruments, furthermore from different stations/institutes (Sect. 3.3) and at different times (Sect. 3.1-3.2) are studied, it is of paramount importance that comparability of the data is ensured. For this purpose, it would be useful that some of the details discussed in manuscript acp-2019-930 by Lakkala et al. (now withdrawn) were included here. Uncertanties for the specific datasets (not only for the general kind of instrument) should be also clearly reported, in order to assess the significance of the observed differences.

Answer: We agree with the comments and the instruments have been more clearly described considering the points of the comment.

Changes in the manuscript:

GUV in Marambio (start l. 146): "The calibration includes two steps: First, a calibration coefficient is calculated for each channel by performing a regression against measurements of the cosine error corrected SUV-100 spectroradiometer. Prior to the regression, the spectra of the SUV-100 are weighted with the spectral response functions of the GUV radiometer. The results are the so-called "response-weighted" irradiances (Seckmeyer et al., 2010) as the spectral response function of the GUV is taken into account. The second step includes the calculation of the UV products. The method is also described in Dahlback (1996) and discussed in detail for the GUV radiometers in Bernhard et al. (2008). A UV product P is calculated using a linear combination of the dark signal corrected signals of the GUV's UV channels V_i:

$$P = \sum_{i=0}^{5} a_i V_i \qquad (4),$$

where the coefficients a_i depend on the calibration factor derived in the first step and the used biological action spectrum, e.g., erythemal response for erythemally weighted irradiances. The coefficients are determined by solving a system of linear equations as described by Bernhard et al. (2008), taking into account the atmospheric conditions at the site (e.g., range of total ozone and surface albedo). The validation of UV products calculated using this method is discussed in Bernhard et al. (2005). The validation results show that the UV index from a GUV instrument can be within 5 % from a well-calibrated spectroradiometer for SZAs smaller than 78°.

The quality control of the measurements in Marambio includes regular cleaning of the diffusor and checking of the levelling. The data is plotted on the web page http://fmiarc.fmi.fi/sub_sites/GUVant/ (last checked Feb 5, 2020), which enables quick quality control by eye. The complete calibration and quality assurance procedure is described in detail in Lakkala et al., 2019. It includes solar comparisons with spectroradiometers at Sodankylä, whose measurement site has similar atmospheric conditions: high SZA, rapidly changing cloud cover, a clean atmosphere and ozone profiles typical for high latitudes. The results show that the differences are within 6 % for comparisons made in 2016—2018 for SZAs lower than 60°. Solar comparisons are also performed at Marambio each time there is a switch of instruments. The first switch was made in Nov 2018, and the difference between the two GUV's was 4-6 %. The difference was due to a drift in the channels of the GUV, which was in regular operation in Marambio. A drift of 2 to 5 % was observed depending on the channel, which is typical for a new instrument. Taking into account the drift of the instrument (5 %) and the uncertainties in the calibration (5 %), the combined uncertainty of the studied GUV measurements was 7 %."

NILU-UV in Marambio, (start l. 176): “The instrument is described in detail in Høiskar et al. (2003), including the method to derive daily doses and UV index which is based on Dahlback (1996). The method is mainly the same as that for retrieving UV products from the GUV radiometers and includes calibration against a reference spectroradiometer. The irradiance scale was traceable to the NIST via the Swedish Testing and Research Institute (SP) (Johnsen et al., 2002). As described in Lakkala et al., 2005, the quality assurance of the NILU-UV measurements included regular lamp measurements and solar comparisons against a regularly calibrated traveling reference radiometer. The measurement capacity of the channels of the NILU-UVs was found to drift during the measurement period, and the data was corrected for this drift using the results of the solar comparisons by transferring the calibration from the traveling reference to the site radiometer. The yearly comparisons between the traveling reference of the network and the SUV-100 spectroradiometer of NSF in Ushuaia showed differences of less than 5 % between the two instruments. Details about the correction are described in Lakkala et al., 2005 and 2018. After the corrections, the combined uncertainty was calculated to be 9.5 % and the expanded uncertainty was 19 % using a coverage factor of 2 for the time period 2000–2008, which is used in this study.”

Brewer in Utsteinen, (start l. 287): “UV spectral measurements at the station are provided by the double-monochromator Brewer spectrophotometer #100 of the Royal Meteorological Institute of Belgium (RMI). Accurate spectral profiles of UV radiation in the 290–325 nm wavelength range are measured. The raw counts are converted to counts per second and corrected for instrument dead time, dark count and temperature. The corrected raw count rates are then divided by the instrument response values. This responsivity is obtained by measuring the response of the Brewer to a source with known radiation (tungsten halogen lamps with a calibration certificate). The spectral erythemal solar UV irradiance, $E_{ery,\lambda}$, (in W m-2 nm-1) is calculated by multiplying Eλ with the appropriate weighting values at each wavelength (CIE action spectrum). UVI values are derived according the method described above. Lamp tests with standard 50 W lamps are performed during calibration campaigns at Uccle (Belgium). Changes in the stability of the instrument between the two calibrations (in 2010 and 2014) remained within 10 %. Note, that the Brewer spectrophotometer is only operated when the station is inhabited (Nov to Feb)”

Noon UVI from Utsteinen, (start l. 300): “The raw data (Volt) are converted into W/m^2 using the factory calibration coefficient and a procedure to consider the deviation of the angular response of the instrument to the ideal cosine response. Calibrated data are converted into UVI. The uncertainty of UVI reaches up to 10 %, due to trends in the calibration and the absence of angular correction.”

NILU-UV in Troll, (start l. 309): “UV products are calculated from measurements of a NILU-UV instrument (serial number 005) with 5 UV channels (302, 312, 320, 340 and 380 nm) and FWHM of about 10 nm. The instrument records data with 1 min time resolution. The relative spectral response function was calculated at the Norwegian Radiation and Nuclear Safety Authority. For absolute calibration, The Sun is used as a light source and irradiance is measured by a reference radiometer at the same time and location as NILU-UV. Once every month, a relative calibration takes place at the station to determine the drift factor and compensate for the degradation of the optical components. (Sztipanov et al., 2020).”

SUV-100 in American stations, (start l. 328): “Version 2 data from the National Oceanic and Atmospheric Administration (NOAA) Antarctic UV Data Repository was used for Palmer, McMurdo and South Pole stations. It is the newest release that has higher accuracy than previous versions and has been corrected for cosine error (Bernhard et al., 2004). UVI values from Database 3 were used. All three stations use the NSF SUV-100 instrument, manufactured by Biospherical Instruments Inc. The uncertainty of biologically relevant UV irradiance is approximately 6 % (Bernhard et al., 2004). The instruments are calibrated periodically using a 200-Watt tungsten-halogen standard lamp, traceable to the NIST.”

References:

Booth, C., Lucas, T., Mestechkina, T., and Tusson, J.: High resolution UV spectral irradiance monitoring program in polar regions - Nearlya decade of data available to polar researchers in ozone and UV-related studies, Antarctic Journal of the United States - Review 1994, 29,20256–259, 1994.

Johnsen, B., Mikkelborg, O., Hannevik, M., Nilsen, L., Saxebøl, G., and Blaasaas, K.: The Norwegian UV-monitoring program Period 1995/96 to 2001, Strålevern Rapport 2002:4, Norwegian Radiation Protection Authority, Østerås, Norway, 2002.

Referee comment: For instance, does any comparison between 2000-2008 and recent datasets make sense with 19% expanded uncertainties?

Answer: Performing UV measurements is not a trivial task as the dynamic range of the irradiance (from short UVB wavelengths to longer UVA wavelengths) is huge. Instruments needs to be adequately characterized (Bernhard and Seckmeyer, 1999) and the measurements need proper quality control procedures (Webb et al. 2003). The NILU-UV time series of Lakkala et al. 2018 has followed state of the art quality assurance procedures for remote multichannel UV radiometer measurements. The uncertainties of the different components of the combined uncertainty are reasonable for UV measurements. The combined uncertainty was 9.5% and the authors think that it is not untypical for UV measurements. The quality assurance of the NILU-UV measurements of Marambio was based on a regularly calibrated traveling reference. The yearly comparisons of this traveling reference and the SUV-100 spectroradiometer of NSF in Ushuaia showed differences of less than 5% (Lakkala et al. 2018).

References:

Bernhard, G. and Seckmeyer, G.: Uncertainty of measurements of spectral solar UV irradiance, J. Geophys. Res., 104, 14 321–14 345, 1999

Webb, A., Gardiner, B., Leszczynski, K., Mohnen, V., Johnston, P.,Harrison, N., and Bigelow, D.: Quality Assurance in Monitoring Solar Ultraviolet Radiation: the State of the Art, Tech. Rep. 146,World Meteorological Organization, Global Atmosphere Watch,2003.

Changes in the manuscript: The following sentence has been added (l. 185): “The yearly comparisons between the traveling reference of the network and the SUV-100 spectroradiometer of NSF in Ushuaia showed differences of less than 5 % between the two instruments.“

Referee comment: Finally, from a more technical point of view, some readers could be interested in knowing how difficult it is to provide reliable measurements and cope with the harsh conditions of the Antarctic continent. For example, is an "inner temperature of 40_C" (l. 153) inside an instrument easy to keep?

Answer: As soon as there is power available, the heating elements are good enough to keep the inner temperature at 40 C. Text has been added about the challenges due to harsh conditions in Antarctica.

Changes in the manuscript: The following sentence has been added to the Introduction (start l. 69): “Due to the harsh meteorological conditions in these polar regions, including very low temperatures and severe snow storms, proper quality assurance procedures are very important (Lakkala et al. 2005). “

And the following to Section 2.1.1. (start l. 134):“ The GUV instrument is also used for UV monitoring at the Antarctic and Arctic sites of the United States National Science Foundation (NSF) UV monitoring network (e.g., Bernhard et al. 2005) and the instrument is robust enough to stand harsh measurement conditions including strong winds, snow, frost formation and rapidly changing or extreme temperatures. As the response of the instrument is sensitive to temperature and humidity, the instrument needs to be adequately sealed and temperature stabilized. The internal temperature of the GUV in Marambio is maintained at 40 °C, which was found enough to keep the instrument clean from frost and snow “

Referee comment: 2. a more refined analysis should be performed on the dataset. This involves: 2a. a better use of the spectral information included in the measurements and of the ancillary data. As far as I understand, every antarctic station includes at least one instrument with narrow-band or even spectral capabilities, with channels centred at wavelengths where the ozone absorption is strong or weak. By analysing separately the different spectral components, the effects of ozone absorption might be disentan- gled from that of other (more spectrally-flat) factors, such as clouds. Indeed, from the abundance of proxies mentioned in Sect. 2.2.4, the reader would expect a more advanced, multivariate analysis including all the data, and a quantification of the relative importance of each factor, which is however missing in the present text. At the moment, only the maximum daily UV index and UV daily doses (which, except for a time integral, convey the same information) are used (they are also derived quantities, not directly measured by the radiometer). Average doses in the UV-A band are reported very quickly in Sect. 3.1 (l. 298-303) without any plot, table or a proper discussion ("other factors also contribute", l. 303). Yet, measurements at this wavelengths could be important to assess the effect of clouds. Without this in-depth analysis, statements such as "in Antarctica the main factor determining the UV levels is total ozone" (l. 384), "lower cloudiness in similar SZAs means more UV radiation reaches the ground" (l. 266-267) or "higher average albedo will lead to higher recorded UV doses" (l. 297) remain unproven and too general, and make the reader wonder what the point of Sect. 3.1 is. The problem here - I guess - is how much each factor contributes, and which factors are the most important based on a convincing analysis. For example, in November and February 2018-2019, cloud cover is higher compared to the same months of the previous season, but UV irradiance is also greater. Intuitively, this is likely due to the ozone increase in 2018-2019, but this is not proven here (a wary reader could suspect that the instrument drifted!). Besides spectral analysis, other methods such as use of RAFs, data splitting between clear and cloudy days, analysis at fixed SZAs (to say nothing of radiative transfer calculations!) could be employed to assess the relative importance of each environmental factor on UV levels.

Answer: The manuscript was supplemented with a longer discussion and analysis of the ozone influence and the part of clouds. The biological effectiveness of UV radiation depends both on the peak values (extreme values for a very short moment can be very dangerous) and on the total daily integral (Lehmann et al., 2019; McKenzie and Lucas, 2018). At high latitudes, due to long days, the daily integral can be important even if the absolute level stays moderate. E.g. for a sunny day with UV index 4 (moderate UV), the daily dose can be higher than for a cloudy day with only few moments with UV index 12 (extreme UV). The authors the choice of studying maximum UV index and daily doses is justifiable from the point of view of the biological effectiveness of UV radiation.

References:

Lehmann, M., Sandmann, H., Pfahlberg, A. B., Uter, W. and Gefeller, O.: Erythemal UV Radiation on Days with Low UV Index Values—an Analysis of Data from the German Solar UV Monitoring Network over a Ten-year Period, Photochemistry and Photobiology, 95(4), 1076–1082, doi:10.1111/php.13092, 2019.

McKenzie, R. L. and Lucas, R. M.: Reassessing Impacts of Extended Daily Exposure to Low Level Solar UV Radiation, Sci Rep, 8(1), 13805–13805, doi:10.1038/s41598-018-32056-3, 2018.

Changes in the manuscript:

In Data and Methods section, (start l. 110): "For describing the effect of O_3 on UV irradiance, the radiation amplification factor (RAF) has been used. RAF is defined as the percentage increase in UV radiation that would result from a 1% decrease in TOC (UNEP, 1998). For small changes, RAF can be calculated as:

$$RAF = -\frac{\Delta E/E}{\Delta TOC/TOC} \qquad (2)$$

where ΔE and ΔTOC are the respective changes of UV irradiance (E) and ozone (TOC). For larger changes, a power law equation should be used as in McKenzie et al (2011):

$$\frac{E^+}{E^-} = (\frac{TOC^-}{TOC^+})^{RAF} \qquad (3)$$

where + shows the case with the higher TOC.

The RAF value depends on multiple factors like SZA, clouds and TOC (Antón et al., 2016). For erythemal irradiance an average value of 1.2 can be used (Antón et al., 2016; McKenzie et al., 2011, Lakkala et al., 2018)"

In result section, (start l. 400): "For describing the effect of O3 on UV irradiance, the RAF with a value of 1.2, has been used. The expected changes in average daily erythemal dose due to a decrease in average TOC between the seasons 2017/2018 and 2018/2019 was calculated for each month from Oct to Feb and compared to the measured changes (Fig. 6). The results were similar when using the power law relationship for calculating RAF (McKenzie et al., 2011) (section 2) for larger changes in O3. In Nov and Feb the increase in monthly average UV from 2017/2018 to 2018/2019 is caused by ozone, but due to higher cloud cover in the second season, the increase is less than calculated solely using RAF. In Oct, more than half of the increase can be explained by the decrease in TOC, the rest is due to the larger cloud cover in 2018/2019 (1.1 oktas), which is the largest difference in monthly averages for those two seasons. In Dec and Jan, less than 1/3 of the increase in average erythemal dose is explained by ozone and the rest of the change is due to other factors. In both months, the average cloud cover is lower in 2018/2019 than in 2017/2018 (0.7 and 0.2 oktas, respectively). In Jan, the average difference in cloud cover is small as is the difference in average TOC (17 DU). However it is important to note the timing when those differences occur. The TOC is lower from Jan 2 to 18, 2019, compared to the same period in 2018. In the first half of January the noon SZA is lower than in the second half. In the second half of Jan 2019, the cloud cover was lower – there are 5 days with daily average cloud cover smaller than 5, at the same time in 2018 there were none. So even though the monthly mean values are similar, there are day-to-day variations and the factors causing higher daily doses in 2019 are different during different days."

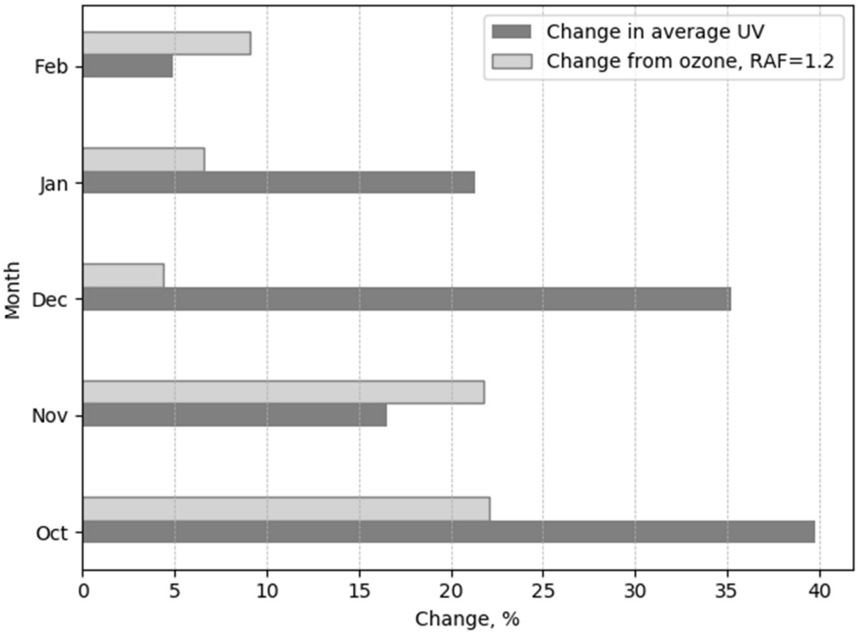

Figure 6: Change in average daily erythemal dose between the seasons 2017/2018 to 2018/2019 for each of the months from Oct to Feb (dark grey) and expected changes due to decrease in average TOC using RAF=1.2 (light grey)."

Referee comment: Finally, I would like to draw attention to the fact that tables (1-2) are not the best way to report information about the effects of the different variables, to understand the correlation with UV levels and to facilitate quantitative interpretation.

Answer: Tables serve as a statistical summary of the monthly values of data. Considering the comments, bold values from table 2 were removed. The analysis has been expanded by describing the effect of O3 on UV irradiance using the radiation amplification factor (RAF).

Changes in the manuscript: Bold values from table 2 were removed. See above for analysis including the RAF.

Referee comment: 2b. improved statistics. The statistics provided in the text are very basic, and they could lead to wrong interpretations. For example, in Fig. 1 the maximum UV index ranges from 2.5 at the South Pole to 7.9 in Palmer. Also, Marambio and Palmer, which are relatively close to each other, show a rather large difference of 1.7. Are these differences a result of "chance" (e.g., short-term effects due to clouds) or are they really representative of different kind of environments? Another example, taken from the abstract (l. 25-26): "The maximum UV index (UVI) in Marambio was only 6.2, while, during the time period 2000-2008, the maximum was 12". Are the authors sure that the maximum yearly/daily UV index is the best indicator to be used in the text? Maxima are suceptible to very specific conditions of clouds, ozone, and period when the instrument is in operation.

Can they use more robust statistics, other than maximum values, or indicators? Could they show some statistical distributions, at least?

Answer: We agree that the maxima UVI is susceptible to very specific conditions. For that reason we are using both, UVI and daily erythemal doses, which show very similar variations. We also supplemented the statistics, so that the variations would be better seen. As for the map, the maximum UVI for the season is just an illustrative fact for the reader. As typically the UV index at northern high latitudes varies between 0 and 6 (at sea level and latitudes above 60 degree) (e.g., Bernard et al. 2019), there is an interest to know the variation range at similar latitudes in the Southern Hemisphere. For this purpose, the maximum UV index was analysed in this study. Also Antarctica is known for low total ozone during spring time stratospheric ozone loss episodes. For a reader familiar with UV indices, it is interesting to know the influence of the possible ozone loss.

Reference: Bernhard G., Fioletov V., Groos J.-U., Ialongo I., Johnsen B., Lakkala K., Manney G., Müller R. Ozone and UV radiation, Bull. Amer. Meteor. Soc., 100 (9), S165-S168, 2019, doi:10.1175/2019BAMSStateoftheClimate.1. [in State of the Climate in 2018]
2019

Changes in the manuscript: The results section was supplemented. Please read the revised manuscript Result section (start l. 334).

Referee comment: Overall, a more quantitative approach should be considered throughout the text. Just quoting the abstract: l. 24, "Measurements in Marambio showed lower UV radiation levels in 2017/2018". Can you quantify the decrease? Can you assess the significance of this difference? L. 20, "the radiation levels were below average": how much below? To help the authors strengthen this part, and to improve readability, I would suggest creating a new section on the analysis "Methods" employed in the study.

Answer: We took a more quantitative approach throughout the manuscript as recommended by the referee. More details were added to the results section, however not in all places, as giving an exact number for each date is not helpful for the reader. Also, descriptions of methods were improved without a separate section.

Changes in the manuscript: Changes were made to “Abstract” (l. 21), “Results” (l. 334) and “Conclusions” (l. 541) sections to make the manuscript more quantitative. Please read the revised manuscript. Methods were improved in Section 2.

Referee comment: 3. State the objectives of the study in the Introduction in a more specific (and less ambitious) way than "discover the temporal variation in UV irradiance levels ... and see the results in spatial context". Indeed, if discovering temporal variations of UV radiations in Marambio is the purpose of the paper, the authors themselves must admit that this was not achieved in the study ("definitive conclusions ... cannot be made based on only two seasons", l. 381-382, this also contradicting what previously stated in the Introduction: "Now, 9 years later, it is possible to search for signals of changes in UV radiation that could reflect the observed changes in the levels of stratospheric ozone"). Also, analysis of the "spatial context" (the second point of the stated purpose of the study) is very poor. Rather, resize the aim stated in the Introduction and split it in more specific, verifiable goals/scientific questions to be answered throughout the text and in the Conclusions.

Answer: The aim of the paper was rephrased to fit the context. Also the results and conclusions sections were rephrased.
Changes in the manuscript: The aim of the paper (start l. 77): “The aim of this paper is to present the results of UV irradiance measurements in Marambio from Mar 2017 to Mar 2019 and to compare them with those from 2000–2008 and also with UV measurements at other Antarctic stations. Including different measurement sites provides an opportunity to investigate, whether differences between the latest solar seasons and previous measurements are common for different Antarctic stations or if they are region-specific, as the factors influencing UV radiation vary widely over the continent”
For other changes, please read the revised manuscript: “Results” (l. 334) and “Conclusions” (l. 541).

Technical corrections

Referee comment: - title, "... in a wider temporal and spatial context": too general, it does not mean anything. Could you rephrase it to be more specific?
Answer: We found that the chosen wording represents the content of the manuscript (that we are not looking just the measurements from 2017-2019 in Marambio, but how these measurements compare to earlier measurements and different locations). However, we decided to shorten the title.
Changes in the manuscript: New title: “Solar UV radiation measurements in Marambio, Antarctica, during years 2017–2019”

Referee comment: l. 20, "radiation": please, be more accurate. Measurements are of "downward globaal irradiance of UV radiation";
Answer: We agree with the comment and made changes to the manuscript
Changes in the manuscript: The 1st sentence of the abstract was changed to (l. 21): “In March 2017, measurements of downward global irradiance of ultraviolet (UV) radiation were started with a multichannel GUV-2511 radiometer in Marambio …”

Referee comment: - l. 34, "10 to 400 nm": did you mean 100 nm? Usually, extreme UV is not considered in the solar spectrum;
Answer: The correct wavelength range is 100 to 400 nm
Changes in the manuscript: l. 36 „..range from 100 to 400 nm“

Referee comment: - l. 35, "absorption in the atmosphere": too vague, can be removed and explained later (l. 38);
Answer: The comment was taken into account and changes were made.
Changes in the manuscript: “due to absorption in the atmosphere” was removed. The sentence was changed to (l. 39): “Examples of the latter are clouds, ozone (O3) and aerosol particles, which can absorb or scatter UV radiation - absorption by O3 is the reason why UV radiation at wavelengths shorter than 280 nm does not reach the ground.”

Referee comment: - l. 36, "geometrical" or "astronomical"?

Answer: The terms from the paper by Kerr (2005) were used

Changes in the manuscript: none

Referee comment: - l. 37, "geophysical" or "atmospheric and geophysical"?

Answer: The terms from the paper by Kerr (2005) were used

Changes in the manuscript: none

Referee comment: - l. 38, "all absorb or scatter": confusing, some of them only absorb or only scatter;

Answer: maybe the word “all” was not the best choice. It was replaced.

Changes in the manuscript: “all” was replaced by “can”: “Examples of the latter are clouds, ozone (O3) and aerosol particles, which can absorb or scatter ….”

Referee comment: - l. 43, "spring" –> "Antarctic spring" (or define months);

Answer: The comment was taken into account and changes were made.

Changes in the manuscript: l. 46**,** “spring” was replace by “Antarctic spring”

Referee comment: - l. 46, "the loss of stratospheric ozone has stopped": unclear, the "ozone hole" still recurs every year;

Answer: It was meant that the decrease of general ozone level from year to year has been stopped, but the annual decrease of ozone during Antarctic spring still exists. The sentences were clarified

Changes in the manuscript: The sentences were rephrased, l. 50: “Although the gradual loss of stratospheric O3 over the years has stopped and the first signs of recovery (such as a statistically significant positive trend in ozone observed over the Antarctic in Sept since 2000) have been noted, the springtime reduction of O3 concentration that leads to the ozone hole still exists over Antarctica (Solomon et al., 2016).”

Referee comment: - l. 46-52: text should be reorganised, since concepts and bibliographic references repeat;

Answer: The paragraph was review and reorganized

Changes in the manuscript: l. 46, **“**In the 1980s, O3 depletion in Antarctica was discovered and this reduction was especially strong during the Antarctic spring (Farman et al., 1985). Since then, successful measures, such as agreed upon in the Montreal Protocol (adopted in 1987), have been taken to protect the ozone layer. Thanks to these efforts, concentrations of O3 depleting substances have declined since the 1990s (WMO, 2018). However, a recent study discovered that the rate of decline of O3 concentration destructive trichlorofluoromethane (CFC-11) has slowed substantially – about 50% since 2012 (Montzka et al., 2018). Although the gradual loss of stratospheric O3 over the years has stopped and the first signs of recovery (such as a statistically significant positive trend in ozone observed over the Antarctic in Sept since 2000) have been noted, the springtime reduction of O3 concentration that leads to the ozone hole still exists over Antarctica (Solomon et al., 2016). According to the latest WMO ozone report (WMO, 2018), there is some indication that the Antarctic ozone hole has diminished in size and depth since the year 2000, but it is affected by meteorological conditions such as temperature and wind, making the natural variability of total ozone column (TOC) large and therefore the detection of recovery difficult. To detect the changes and the expected recovery, continuous measurements of TOC and UV irradiance must be carried out in the region. These measurements also provide the possibility to analyse effects of changes in other climate parameters, such as cloud and aerosol properties and surface albedo, on the UV irradiance near the surface. This is especially important because of the ongoing interaction between climate change and these parameters (IPCC, 2014)."

Referee comment: - Fig. 1: including information about total ozone in the figure would be useful to understand the effects of clouds on max UV indices;
Answer: Adding any more information to figure 1, in our opinion, would make it difficult to read and would not give extra value to the figure.
Changes in the manuscript: none

Referee comment: - Sects. 2.1.1 to 2.1.6: the description of the stations should be homogenised (i.e., the same characteristics for different stations should be mentioned), and it should be limited to the relevant topics for the paper. If, as stated in the Introduction, cloudiness, surface albedo, total ozone and aerosol load are important parameters affecting the UV irradiance, then basic information about these parameters should be provided for each station. Also, is the horizon the same at each site?
Answer: We agree with the comment
Changes in the manuscript: The sections were reorganized and updated. Each station has a separate section (2.1 (Marambio, l. 123), 2.2 (Princess Elisabeth Station in Utsteinen, l. 280), 2.3 (Troll station, l. 304), 2.4 (Palmer, McMurdo and Amundsen-Scott South Pole stations, l. 316)) and information about measurements (previously 2.2.5) was included into each section.

Referee comment: - l. 135: it is not described how the spectrum is derived from single narrow-band measurements. This information is needed before discussing erythemal doses and UV indices;
Answer: A linear combination of channels is used with coefficients for each used channels to derive directly the erythemal dose rates. Full spectrum are not derived. The explanation was added to the text in the section 2.1.1.
Changes in the manuscript: In section 2.1.1, l. 153: "). A UV product P is calculated using a linear combination of the dark signal corrected signals of the GUV's UV channels V_i:

$$P= \sum_{i=0}^{5} a_i V_i \qquad (4),$$

where the coefficients a_i depend on the calibration factor derived in the first step and the used biological action spectrum, e.g., erythemal response for erythemally weighted irradiances. The coefficients are determined by solving a system of linear equations as described by Bernhard et al. (2008), taking into account the atmospheric conditions at the site (e.g., range of total ozone and surface albedo)."

Referee comment: - l. 136: specify here how the "maximum" UV index is defined (i.e., on what average time interval - one-minute averages are mentioned only later, at line 159);
Answer: As said in the submitted manuscript l 135 "From these measurements, using one-minute averages, different products were calculated, including daily erythemal dose and maximum UVI." For that first, 1 minute

average erythemal irradiance and UVI among other products were found and from these 1 minute values daily doses and daily maximum UVI were calculated/found (for GUV and NILU-UV instruments)

Changes in the manuscript: l. 109**,** “For each day, the daily erythemal dose as well as the maximum daily UVI were determined”

Referee comment: - l. 136: summarise how ozone is derived, how perturbation by multiple scattering in clouds and from the surface is overcome/taken into account in the ozone retrieval;

Answer: All conditions have been treated equally. As we have learned, the ozone calculations work better with lower SZA and therefore we have limited the measurements used depending on the SZA – only measurements where SZA was below 65 degrees were used. As of cloud situation, no exceptions have been made. It is said in the manual by Biospherical Instruments Inc. that the ozone calculations from GUV measurements will not work equally well under all conditions, one being the situation with multiple decks of clouds.

Changes in the manuscript: l. 192, “The calculation of TOC is described in Bernhard et al. 2005. It is based on instrument-specific look-up tables and the ratio of irradiances measured at 305 nm and 340 nm. Pre-calculated lookup tables relate TOC to the SZA and the ratio of the irradiances. They are calculated using the radiative transfer model libRadtran (Mayer and Kylling, 2005) in which site-specific conditions (like altitude, albedo, O3 profile etc.) are taken into account. Also, the modelled spectra are weighted with the GUV response functions at 305 and 340 nm.”

Referee comment: - l. 137: provide more information about calculations, and refer to Sect. 2.2.3 (or anticipate the contents of this section here);

Answer: The sections was supplemented according to previous comments

Changes in the manuscript: as described previously

Referee comment: - l. 138, "well-calibrated": provide details about calibration;

Answer: The spectroradiometer is calibrated following the standard calibration procedures as described in detail in Bernhard et al. 2005. The authors think that the details of the spectroradiometer calibration will not give any further information to the reader. The useful information is that the spectroradiometer has to be calibrated following the standard spectroradiometer calibration procedures (Webb et al. 1998), which is the case in Bernhard et al. 2005.

Reference: Webb, A., Gardiner, B., Martin, T., Leszcynski, K., Metzdorf, J.,and Mohnen, V.: Guidelines for Site Quality Control of UV Monitoring, Tech. Rep. 126, World Meteorological Organization, Global Atmosphere Watch, 1998.

Changes in the manuscript: None

Referee comment: - l. 138, "can be within 5%": so, what is the uncertainty for the specific dataset in Marambio? Is it indeed 5%?

Answer: We have improved the description of the uncertainty of the dataset in Marambio.

Changes in the manuscript: : l. 170, “Taking into account the drift of the instrument (5 %) and the uncertainties in the calibration (5 %), the combined uncertainty of the studied GUV measurements was 7 %.”

Referee comment: - Sect. 2.2.2: why was the instrument replaced with a new one?
Answer: The NILU-UV instrument’s channels drifted so much that it was no longer possible to get any reliable measurements (Lakkala et al. 2018). There was no possibility to repair the instrument.
Changes in the manuscript: The following sentence was added to the manuscript, l. 187: „ After 2008 the uncertainty of the measurements increased due to severe drift of the channels, and since 2011 the measurements could no longer be used for research and they were stopped.“

Referee comment: - l. 154: although the instrument is described in detail in another work, it is important to summarise here the main outcomes, since they are useful for the interpretation of the present results
Answer: The authors agree and the text was updated.
Changes in the manuscript: l. 172, “In addition, the Marambio NILU-UV daily dose and maximum UV index time series described in Lakkala et al., 2018 were used. The NILU-UV is a multichannel radiometer, which measures radiation at five UV channels and one PAR channel. The central wavelengths of the UV channels are at 305, 312, 320, 340 and 380 nm and the FWHM for each channel is around 10 nm. The instrument includes a flat Teflon diffuser, interference filters and silicon detectors and the inside temperature of the instrument is maintained at 40 °C. The instrument is described in detail in Høiskar et al. (2003), including the method to derive daily doses and UV index which is based on Dahlback (1996). The method is mainly the same as that for retrieving UV products from the GUV radiometers and includes calibration against a reference spectroradiometer. The irradiance scale was traceable to the NIST via the Swedish Testing and Research Institute (SP) (Johnsen et al., 2002). As described in Lakkala et al., 2005, the quality assurance of the NILU-UV measurements included regular lamp measurements and solar comparisons against a regularly calibrated traveling reference radiometer. The measurement capacity of the channels of the NILU-UVs was found to drift during the measurement period, and the data was corrected for this drift using the results of the solar comparisons by transferring the calibration from the traveling reference to the site radiometer. The yearly comparisons between the traveling reference of the network and the SUV-100 spectroradiometer of NSF in Ushuaia showed differences of less than 5 % between the two instruments. Details about the correction are described in Lakkala et al., 2005 and 2018. After the corrections, the combined uncertainty was calculated to be 9.5 % and the expanded uncertainty was 19 % using a coverage factor of 2 for the time period 2000–2008, which is used in this study. After 2008 the uncertainty of the measurements increased due to severe drift of the channels, and since 2011 the measurements could no longer be used for research and they were stopped.“

Referee comment: - l. 156: similarly to the previous point, it is important to summarise what corrections were applied
Answer: We agree, and the text was updated.
Changes in the manuscript: l. 179, **“**As described in Lakkala et al., 2005, the quality assurance of the NILU-UV measurements included regular lamp measurements and solar comparisons against a regularly calibrated traveling reference radiometer. The measurement capacity of the channels of the NILU-UVs was found to drift during the

measurement period, and the data was corrected for this drift using the results of the solar comparisons by transferring the calibration from the traveling reference to the site radiometer"

Referee comment: - l. 163, "show some wavelength dependency": what does it mean?
Answer: In large SZA-s the total column ozone value depends on the SZA – when SZA changes O_3 changes. As the results of our calculations showed diurnal changes in TOC values, we decided to use SZA region where O_3 values showed no dependency to SZA
Changes in the manuscript: l. 200 "TOC daily averages were calculated from the GUV radiometer measurements, where only observations with SZA < 65° were used as for higher SZA TOC showed a SZA dependency"

Referee comment: - l. 168, "in the Northern Hemisphere": how does that relate to the southern hemisphere?
Answer: There is no reason to assume different instrumental behaviour for Northern and Southern Hemispheres. The reference is brought in to demonstrate the stability and quality of the satellite instrument
Changes in the manuscript: none

Referee comment: - l. 169, "range of 1 +/- 0.05": it is not clear that this is a ratio at this point;
Answer: It is ratio OMI/GUV. The block was clarified.
Changes in the manuscript: Modified sentences, l. 205: "Daily values of the OMI ozone product collocated with the Marambio station (64.125° S, 56.625° W for OMI data) were used and the ratio of daily ozone values OMI/GUV was calculated. In the majority of the days (88 %), the ratio falls in the range of 1 ± 0.05 (Fig. 2)."

Referee comment: Fig. 2: is there are drift of the ratio from 2017-2018 to 2018-2019?
Answer: There is a 2% drift. The average ratio OMI/GUV is 1.00 in 2017/2018 and 1.02 in 2018/2019.
Changes in the manuscript: l. 205, "Daily values of the OMI ozone product collocated with the Marambio station (64.125° S, 56.625° W for OMI data) were used and the ratio of daily ozone values OMI/GUV was calculated. In the majority of the days (88 %), the ratio falls in the range of 1 ± 0.05 (Fig. 2). The median of the ratio OMI/GUV is 1.01 indicating slightly higher values for the OMI data, especially in 2018/2019. There is a small drift between the seasons; the average ratio is 1.00 in 2017/2018 and 1.02 in 2018/2019."

Referee comment: - l. 174: it is not clear from here why this climatology is useful (the reader understands only later in the text that climatological reference values are calculated from these
data);
Answer: As it is said at the beginning of the paragraph period 2000-2008 was used for comparison.
Changes in the manuscript: The sentence was supplemented, l. 216: "Satellite data were also used for comparing TOC values from 2017–2019 to the period 2000–2008 and to explain the changes in erythemal UV doses and maximum UVI values."

Referee comment: - l. 181: does it also apply for Marambio?

Answer: Although in the study conducted by Anton et al. (2010) measurements from Spain are used, we do not see a reason why it should not apply to Marambio.
Changes in the manuscript: None

Referee comment: - Sect. 2.2.4: the proxy data are here discussed without providing an explanation of their use to the reader. This makes reading confusing, please anticipate how the
proxies are employed in the analysis;
Answer: The section (now 2.1.3) was changed
Changes in the manuscript: A short paragraph was added to the beginning of section 2.1.3, l. 224: "For the interpretation of changes in the UV irradiance in Marambio, data for different factors affecting UV radiation and ozone in the atmosphere were collected. This data includes polar vortex information, clouds, aerosols and albedo."

Referee comment: - l. 186, "provide a chemical isolation": unclear;
Answer: The sentence was extended to clarify this.
Changes in the manuscript: Modified sentence, l. 228: "At the same time, the dynamical characteristics of the polar vortex provide a chemical isolation that disables the mixing of mid-latitude air with the polar air and therefore sustain the compounds needed for O3 destruction and formation of ozone hole (Schoeberl and Hartmann, 1991)."

Referee comment: - l. 186-187: rephrase this sentence. Why are you talking about "a" station?
Answer: The sentence was rephrased. Polar vortex data was gathered for each station, but in the end, only information about Marambio station was included to the manuscript.
Changes in the manuscript: "a" was replaced by "Marambio"

Referee comment: - l. 192, "octants": do you mean "oktas"?
Answer: "oktas" is correct
Changes in the manuscript: "octants" was replaced with "oktas"

Referee comment: - l. 199-203: this paragraph can be removed, just cite the reference publication;
Answer: the paragraph demonstrates the value of used cloud data and was left to the manuscript
Changes in the manuscript: none

Referee comment: - Sect. 2.2.5: shouldn't the numbering be 2.3?
Answer: section 2 was restructured
Changes in the manuscript: section 2 was restructured

Referee comment: - Sect. 2.2.5: which of these instruments are actually used in the analysis?
Answer: The entire section 2 was restructured
Changes in the manuscript: Section 2 was restructured for clarity.

Referee comment: - l. 217, "PE": don’t use acronyms that were not introduced before and that are not recurrent;
Answer: As section 2 was restructured, there is no need for using acronyms for stations.
Changes in the manuscript: “PE” is not used

Referee comment: - l. 217, "double Brewer": did you mean "double-monochromator Brewer"?
Answer: It should have been double monochromator
Changes in the manuscript: “double Brewer” was replaced by “double-monochromator Brewer”

Referee comment: - l. 226, "factory calibration": this factor has never been updated?
Answer: The factor was not updated between 2013 and 2018
Changes in the manuscript: None

Referee comment: - l. 226, "a procedure": any bibliographic reference?
Answer: There is no bibliographic reference. The procedure was based on experience gained from the Uccle station. During clear sky days, the angular response was checked and corrected based on a comparison between the pyranometers and a spectrometer having a good angular response for its entrance optics.
Changes in the manuscript: None

Referee comment: - l. 240, "... not synchronized with the changes in SZA": so, what is your explanation? Can you anticipate here an answer?
Answer: This peak is caused by low levels of ozone
Changes in the manuscript: l 337, “The UV irradiances manifest two peaks – one during annual destruction of O3 (the so-called ozone hole) during the local spring (Sept–Nov) and the other one in the summer (Dec–Jan) when noon SZA is the lowest. These periods with high doses were present in both seasons, 2017/2018 and 2018/2019. The largest variations of the UV irradiance occur also during these seasons (spring and early summer).”

Referee comment: - l. 262, "for the months during which the solar irradiance is the highest": why September and March are not included?
Answer: Firstly, in September and March UV irradiance level is much lower as is the absolute variability and secondly, due to high SZA during these months we do not have ozone from GUV for these months (only part of March)
Changes in the manuscript: None

Referee comment: - l. 263, "average cloudiness was lower": can you be more quantitative?
Answer: The text was modified.
Changes in the manuscript: l. 370, “In 2017/2018, cloud cover in Oct, Dec and Jan was higher than in 2018/2019, with the largest difference in Oct (1.1 oktas), while in Nov and Feb the cloud cover was lower by 1 and 0.8 oktas, respectively.”

Referee comment: - Table 2, caption: explain what are the numbers in parentheses; "AOD", include wavelength;
Answer: The numbers in parentheses are standard deviations. AOD is at 550 nm. The caption was supplemented.
Changes in the manuscript: supplemented part of the caption: "…and AOD at 550 nm with std in the parentheses for."

Referee comment: - Table 2, "values that contribute to the higher UV levels in season... are in bold": is there any assessment of the statistical significance of the differences to establish if these values contribute relevantly to higher UV levels? Are differences between seasons greater than their uncertainty?
Answer: No significance study has been conducted; just values that could cause the higher UV levels in season 2018/2019 were highlighted.
Changes in the manuscript: Bold style was removed from Table 2

Referee comment: - l. 276, "the disparity is especially large": can you be more quantitative (e.g., significance)?
Answer: Absolute differences were added.
Changes in the manuscript: Supplemented sentence, l. 397: "…the disparity is especially large in Oct and Nov, 43 and 61 DU respectively (Table 3)."

Referee comment: - l. 295-296, "slightly higher": please, be more quantitative;
Answer: Values were added
Changes in the manuscript: Supplemented part of the sentence, l. 426: "…compared to Feb 2018; the differences are 0.1 and 0.2 respectively."

Referee comment: - l. 301, "was larger": how much?
Answer: 0.12 MJ, however this paragraph was changed.
Changes in the manuscript: l. 437, "Daily doses of UVA (315–400 nm) radiation were also somewhat higher in 2018/2019 than in the previous year, but the difference was not as large as for erythemal radiation. Average daily UVA doses from Oct to Feb in 2017/2018 were 0.78, 1.18, 1.04, 1.04 and 0.91 MJ/m2, in 2018/2019 these numbers were 0.89, 1.04, 1.24, 1.08 and 0.79 MJ/m2 (Lakkala et al., 2019). The different behaviour of erythemal and UVA radiation shows the importance of O3 in causing the significant differences observed between the two seasons for erythemal radiation and UVI, as the UVA is not affected by O3, but mainly by cloud cover and surface albedo"

Referee comment: - l. 306: "there were periods": which ones?
Answer: This is a general introduction and the periods are described later in the paragraph
Changes in the manuscript: l. 453, "In the season 2017/2018 though, there was a long period from spring until the end of the summer (57 days from Oct – Dec), when daily doses were mostly below the long-term daily average. On 16 of these days, the values were even below the long-term minimum. The monthly averages of daily doses in that season were below the long-term values from Oct to Jan (Table 2) with differences from 2.3 % to 25.5 %. The same is true for Sept, but only 13 days of measurements were available for calculating monthly average. In

spring 2018, there was a longer period (Oct 13 – Nov 1), when the daily doses were continuously above the long-term average, and in addition they were above the average for half of the days in Nov and Dec. The monthly average daily erythemal dose in Oct exceeded the long-term average with more than 0.8 kJ/m2. Monthly averaged daily doses were higher than the long-term values also from Dec to Mar. In addition, there were several days in spring 2018 (5 in Oct and 5 in Dec) where the daily doses exceeded the long-term maximum …"

Referee comment: - l. 310 and 315, "On some days" ... "several days": how many? Are the difference significant?
Answer: Exact dates are not always significant as it is just for characterizing the situation. Approximate times for these occurrences can be viewed from Figure 7. However we supplemented the paragraph
Changes in the manuscript: As in previous answer.

Referee comment: - Fig. 7: the white line (climatological average) is not clearly visible;
Answer: Unfortunately adding another colour made figure even less clear, so it was left as it is.
Changes in the manuscript: None

Referee comment: - Fig. 7 and 8: x-axis should report dates (not day of year) for comparability with previous figures and with the dates mentioned in the text;
Answer: x-axis was changed in the figures
Changes in the manuscript: figures were changed.

Referee comment: - l. 338, "The results from the analysis of O3 data are in good correspondence to the recent recorded UV levels": how can the authors state that the correspondence is good?
Answer: It is meant that during low ozone periods UV is high and vice versa as the effect of ozone on UV is well described in literature. The sentence was extended.
Changes in the manuscript: l. 486, "The results from the analysis of TOC data are in good correspondence to the recent recorded UV levels, when considering the negative correlation of these two values."

Referee comment: - l. 344-350: how important are the observed could cover changes on UV irradiances at ground?
Answer: Cloud cover is one of the most important geophysical factor that affect UV radiation and determines the amount of radiation reaching the ground. Heavy clouds can obstruct majority of UV radiation reaching the ground. In certain cases it can also enhance radiation. (Kerr, 2005)
Changes in the manuscript: None

Referee comment: - l. 356, "pattern in" –> "is". However, how can a pattern be seen, from this incomplete dataset?
Answer: The wording was misleading and has been changed.
Changes in the manuscript: Changed paragraph, l. 507: "Higher values in spring 2018 compared to 2017 have been measured at each station, except in Utsteinen from where no measurements are available for spring 2017. For example at South Pole, where recorded UVI are the lowest, the maximum UVI was 1.9 during Oct-Nov in

2017 and 2.9 in 2018. In 2018 the mean UVI for Oct-Nov was also higher (1.5, in 2017 it was 1.0). For Oct and Nov, the mean and maximum values were higher for every station (except for Utsteinen due to lack of measurements). The peaks in spring are mainly caused by low TOC during the ozone hole event. The TOC values were higher for most of the spring in each station (Fig. 10) and there were several days where much larger TOC values were recorded in 2017/2018 compared to 2018/2019, with differences more than 100 DU. Utsteinen and Troll stayed inside the polar vortex until Nov 22 and 21, 2018, respectively, and during some isolated days in the following week. In 2017, these stations were outside the polar vortex by Nov 15 and 13 respectively. The earlier disappearance of the polar vortex in 2017 compared to 2018 was also recorded in Palmer and McMurdo. Palmer was for the first time outside the vortex on Oct 9, 2017, and on Nov 11, 2018, and the corresponding dates for McMurdo were Oct 28, 2017, and Dec 7, 2018."

Referee comment: -l. 358, "the peaks in spring are mainly caused by ozone": have you proven it?
Answer: The conclusion is derived from the analysis of Marambio data, polar vortex data and OMI data.
Changes in the manuscript: None

Referee comment: - Fig. 10: what is the grey line in the first panel? Why are data missing?
Answer: Grey line is noon UVI values, as the other dataset is short for each year. The data gap in figure 10 was caused by a combination of station IT-issues and a late re-installation of the Brewer. In fact, in November 2018 the station operator had to restart and re-configure the whole communication system, including the data server. Therefore, the pyranometer measurements stopped then and could be taken up only later. And the Brewer was only re-installed early December 2018.
Changes in the manuscript: Fig. 10 was renewed

Referee comment: - l. 379, "a number" ... "several": exactly what numbers?
Answer: The exact numbers are provided in section 3.2 and were found irrelevant for conclusions and discussion.
Changes in the manuscript: None

Referee comment: - l. 395, "analyzis" –> "analysis"
Answer: comment taken into account
Changes in the manuscript: "analyzis" was replaced with "analysis"

Answers to Anonymous Referee #1 (RC2)

Referee comment: I believe that the introduction could be enriched, for example the authors could highlight more the need of observations in Antarctica and possibly state some extreme events during the last years that support this need.

Answer: We agree with the comment and made changes to the introduction

Changes to the manuscript: Change paragraph, l. 46: "In the 1980s, O3 depletion in Antarctica was discovered and this reduction was especially strong during the Antarctic spring (Farman et al., 1985). Since then, successful measures, such as agreed upon in the Montreal Protocol (adopted in 1987), have been taken to protect the ozone layer. Thanks to these efforts, concentrations of O3 depleting substances have declined since the 1990s (WMO, 2018). However, a recent study discovered that the rate of decline of O3 concentration destructive trichlorofluoromethane (CFC-11) has slowed substantially – about 50% since 2012 (Montzka et al., 2018). Although the gradual loss of stratospheric O3 over the years has stopped and the first signs of recovery (such as a statistically significant positive trend in ozone observed over the Antarctic in Sept since 2000) have been noted, the springtime reduction of O3 concentration that leads to the ozone hole still exists over Antarctica (Solomon et al., 2016). According to the latest WMO ozone report (WMO, 2018), there is some indication that the Antarctic ozone hole has diminished in size and depth since the year 2000, but it is affected by meteorological conditions such as temperature and wind, making the natural variability of total ozone column (TOC) large and therefore the detection of recovery difficult. To detect the changes and the expected recovery, continuous measurements of TOC and UV irradiance must be carried out in the region. These measurements also provide the possibility to analyse effects of changes in other climate parameters, such as cloud and aerosol properties and surface albedo, on the UV irradiance near the surface. This is especially important because of the ongoing interaction between climate change and these parameters (IPCC, 2014).”

Referee comment: For the measurement sites it is a bit confusing how the authors introduce the sites. Sometimes they include the instrument information, sometimes not. For some of the stations they give an extended description, for others they don’t mention if any other measurements apart from the UV ones are present. It would be helpful to try be consistent and provide an analytical table with the station information (coordinates, height, type of measurements, instrumentation, duration of measurements etc.)

Answer: We agree with the comment and see the need for changes. We have explained the measurements in Marambio more detailed, as the focus is on analyzing this data.

Changes to the manuscript: The “Data and method” (l. 82) section was restructured and a table (Table 1) with summary information was added. The subsections were reorganized and updated. Each station has a separate section (2.1 (Marambio, l. 123), 2.2 (Princess Elisabeth Station in Utsteinen, l. 280), 2.3 (Troll station, l. 304), 2.4 (Palmer, McMurdo and Amundsen-Scott South Pole stations, l. 316)) and information about measurements (previously 2.2.5) was included into each section.

Referee comment: Line 92: please check this, because the soil doesn’t melt, the snow on top of it does.

Answer: The sentence was modified following your comment

Changes to the manuscript: new sentence, l. 125: **“**During most of the year the soil is frozen and covered with snow.”

Referee comment: For example, the authors often use the references without providing any further explanation especially during the presentation of the data used in this study (e.g. lines 137-138, 154, 156, 162, 206 etc.). The references should work as a guide for the methodology applied in this study or to support findings of this study, or even justify the reason of this research. They shouldn't replace information that is crucial and aims to support the validity of the data presented here.

Answer: L.137-138, 154, 156, 162 and 206 are now explained in more detail. The mentioned references are all presented for an interested reader to find more information about the instruments and methods used. The focus of the current manuscript is on the results of the measurements and going into detailed description in every case would shift the emphasis.

Changes to the manuscript:

l. 143: "The calibration of the instruments is performed using the method presented in Dahlback (1996) and explained in detail in Bernhard et al., (2005). The method includes calibration against a high quality spectroradiometer which, for the GUV radiometers of Marambio, is a SUV-100 spectroradiometer, from the NSF UV monitoring network, whose irradiance scale is traceable to the National Institute of Standards and Technology (NIST) (Booth et al., 1994). The calibration includes two steps: First, a calibration coefficient is calculated for each channel by performing a regression against measurements of the cosine error corrected SUV-100 spectroradiometer. Prior to the regression, the spectra of the SUV-100 are weighted with the spectral response functions of the GUV radiometer. The results are the so-called "response-weighted" irradiances (Seckmeyer et al., 2010) as the spectral response function of the GUV is taken into account. The second step includes the calculation of the UV products. The method is also described in Dahlback (1996) and discussed in detail for the GUV radiometers in Bernhard et al. (2008). A UV product P is calculated using a linear combination of the dark signal corrected signals of the GUV's UV channels V_i:

$$P= \sum_{i=0}^{5} a_i V_i \qquad (4) ,$$

where the coefficients a_i depend on the calibration factor derived in the first step and the used biological action spectrum, e.g., erythemal response for erythemally weighted irradiances. The coefficients are determined by solving a system of linear equations as described by Bernhard et al. (2008), taking into account the atmospheric conditions at the site (e.g., range of total ozone and surface albedo). The validation of UV products calculated using this method is discussed in Bernhard et al. (2005). The validation results show that the UV index from a GUV instrument can be within 5 % from a well-calibrated spectroradiometer for SZAs smaller than 78°."

l. 176: ". The instrument is described in detail in Høiskar et al. (2003), including the method to derive daily doses and UV index which is based on Dahlback (1996). The method is mainly the same as that for retrieving UV products from the GUV radiometers and includes calibration against a reference spectroradiometer"

l. 179: "As described in Lakkala et al., 2005, the quality assurance of the NILU-UV measurements included regular lamp measurements and solar comparisons against a regularly calibrated traveling reference radiometer. The measurement capacity of the channels of the NILU-UVs was found to drift during the measurement period, and the data was corrected for this drift using the results of the solar comparisons by transferring the calibration from the traveling reference to the site radiometer. The yearly comparisons between the traveling reference of the network and the SUV-100 spectroradiometer of NSF in Ushuaia showed differences of less than 5 % between the two instruments. Details about the correction are described in Lakkala et al., 2005 and 2018"

l. 192: “The calculation of TOC is described in Bernhard et al. 2005. It is based on instrument-specific look-up tables and the ratio of irradiances measured at 305 nm and 340 nm. Pre-calculated lookup tables relate TOC to the SZA and the ratio of the irradiances. They are calculated using the radiative transfer model libRadtran (Mayer and Kylling, 2005) in which site-specific conditions (like altitude, albedo, O3 profile etc.) are taken into account. Also, the modelled spectra are weighted with the GUV response functions at 305 and 340 nm. Bernhard et al. 2005 validated the method at several sites, including Antarctic sites, and found that the difference between Total Ozone Spectrometer (TOMS) total ozone and GUV total ozone was within 5 % for SZAs smaller than 75°.”

l. 248: “To describe aerosol characteristics, the Aerosol Optical Depth (AOD) at 550 nm from the Collection 6.1 (Levy et al., 2018) L3 monthly product (MYD08_M3) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Aqua satellite was used. In MYD08_M3, all statistics are sorted into 1°×1° cells on an equal-angle global grid. The Monthly L3 product is computed from the complete set of daily files that span a particular month. Aerosol related parameters in the monthly product required 3 valid Daily (D3) grid cells to populate the monthly aggregate. Aqua is a polar orbiting satellite with an equator-crossing around 13:30 local time. Aqua MODIS has a good performance among all AOD monthly products with small overestimation overall (Sogacheva et al., 2019; Wei et al., 2019).”

Referee comment: The wavelengths that are stated are the nominal ones (lines 132,151). Usually each individual instrument has deviations from the nominal values not only at the wavelength peaks but as well at the spectral responses. Here it is not clear if the datasets were cured for these discrepancies in their spectral and angular characteristics (both the 2 GUVs used and the NILU - this could apply for the rest of the instruments providing the proxy data like the SL501 sensors used for the albedo retrieval).

Answer: GUV and NILU-UV: The spectral response of each channel is taken into account in the calibration process by weighting the reference spectroradiometer spectrum with the spectral response of each GUV/NILU-UV channel. This information has been added to the text.

SL501A radiometers are used for albedo measurements: The radiometers make hemispherical measurements of the incoming irradiance weighted with the action spectrum for UV-induced erythema (McKinlay and Diffey, 1987). One sensor is installed to face upwards to measure downwelling global erythemal UV irradiance including both direct and diffuse components, and the other sensor looks downwards to measure upwelling outgoing hemispherically reflected global diffuse erythemal UV radiation. Albedo is then calculated as the ratio of up-welling to down-welling erythemally weighted UV radiation. As a best practice, sensors with similar spectral and cosine responses are used (more details in Meinander et al., 2008). The Finnish Radiation and Nucleation Safety Authority (STUK) determines the calibration factor for each SL501A sensor, which is used to calibrate the measurement data. The official SL501A trace is to NIST, the National Institute of Standards and Technology (Lakkala et al., 2018). In general, when use is made of albedo measurements by SL501 radiometers with similar spectral responses, errors of less than 1% due to differences in the sensors are expected (WMO, 1996). Accordingly, we have improved description of the SL501 albedo data.

Changes to the manuscript: GUV (Section 2.1.1), added text, l. 143: “The method includes calibration against a high quality spectroradiometer which, for the GUV radiometers of Marambio, is a SUV-100 spectroradiometer, from the NSF UV monitoring network, whose irradiance scale is traceable to the National Institute of Standards and Technology (NIST) (Booth et al., 1994). The calibration includes two steps: First, a calibration coefficient is calculated for each channel by performing a regression against measurements of the cosine error corrected SUV-100 spectroradiometer. Prior to the regression, the spectra of the SUV-100 are weighted with the spectral response functions of the GUV radiometer. The results are the so-called "response-weighted" irradiances (Seckmeyer et al., 2010) as the spectral response function of the GUV is taken into account."

NILU-UV (Section 2.1.1), added text, l. 177: "The method is mainly the same as that for retrieving UV products from the GUV radiometers and includes calibration against a reference spectroradiometer. The irradiance scale was traceable to the NIST via the Swedish Testing and Research Institute (SP) (Johnsen et al., 2002). As described in Lakkala et al., 2005, the quality assurance of the NILU-UV measurements included regular lamp measurements and solar comparisons against a regularly calibrated traveling reference radiometer."

SL501A (Section 2.1.3), modified and added text, l. 256: "The albedo is measured at a fixed height of approximately 2 m from the ground using two broadband SL501A (SolarLight Co.) radiometers. The radiometers make hemispherical measurements of the incoming irradiance weighted with the action spectrum for UV-induced erythema (McKinlay and Diffey, 1987), which also has a contribution from the UVA. One sensor is installed to face upwards to measure downwelling global erythemal UV irradiance including both direct and diffuse components, and the other looks downwards to measure upwelling outgoing hemispherically reflected global diffuse erythemal UV irradiance. The data are recorded in 1-minute intervals. The albedo is then calculated as the ratio of up-welling to down-welling erythemally weighted UV irradiance. The monthly averages of daily noon UV albedo were calculated from these local albedo data. As a best practice, sensors with similar spectral and cosine responses are used (more details in Meinander et al., 2008). The sensors are temperature controlled. In the data file, one column contains the sensor temperature recorded every minute. As SL501A measurements can be temperature affected, temperature records are used for the QA/QC online monitoring of the measurements. The Finnish Radiation and Nucleation Safety Authority (STUK) determines the calibration factor for each SL501 sensor, which is used to calibrate the measurement data. The official SL501A trace is to NIST (Lakkala et al., 2018). Via the primary calibration lamp, the measurements are traceable also to the National Standard Laboratory MIKES, Aalto University (HUT), Finland. The difference in calibration coefficients using NIST and MIKES has been found to be less than 2 %, and in comparison of spectral UV irradiance scales maintained by NIST, PTB (Physikalisch-Technische Bundesanst) and Aalto University, no major differences have been found (Jokela et al., 2000). For these data of calibrated, spectrally characterized and temperature controlled sensors, effects of degradation are not corrected for. Changes in the stability of the sensors between the pre- and post-calibrations remain to be determined. However, it can be noted that any similar temporal degradation of the two SL501A sensors, as measured in percentages, would be compensated when the ratio of the signals is calculated for albedo. Hence, in post-calibrated data, it will be essential to study whether the degradation of one instrument is different from that of the other one. In general, when use is made of albedo measurements by SL501 radiometers with similar spectral responses, errors of less than 1 % due to differences in the sensors are expected (WMO, 1997). As described in Hülsen and Gröbner (2007), the typical total uncertainty for SL501 instruments is 1.7 - 4.3 %."

Referee comment: In line 138 you are stating the general uncertainty provided by Bernhard et al. (2005) but this is not enough to state the uncertainty of your data since you are not using the same serial numbers as in this study. You probably need to use the methodology provided by your references in order to derive the corresponding values for your specific instruments.

Answer: The used calibration method is based on Dahlback (1996) and can be used for multichannel radiometers in general. The characteristics of GUV radiometers having different serial numbers are similar enough, so that the uncertainty provided by Bernhard et al. (2005) can used as estimation for uncertainty of the methodology in general.

Changes to the manuscript: Please read the next answer. The description of the calibration process has been written in more details including appropriate references.

Referee comment: What is the exact calibration process? Do you correct for angular errors? Do you correct for different spectral responses? - Is there any degradation through time between consecutive calibrations? Are you correcting for this and how? - What is the uncertainty of your calibration process and thus the uncertainty of the level 1 data (calibrated irradiances) - What are the overall uncertainty of the derived products? - Do you have any QA/QC flags that indicate possible problems of the data and thus exclude some extremes cases? And one more question would be: how do you homogenize the different datasets used in this study? partially this could be answered by the validity of the calibration process.

Answer: The exact calibration process is described in detail in an ESSD Discussion paper and available from the web: Lakkala et al. 2019 (Lakkala, K., Aun, M., Sanchez, R., Bernhard, G., Asmi, E., Meinander, O., Nollas, F., Hülsen, G., Aaltonen, V., Arola, A., and de Leeuw, G.: New continuous total ozone, UV, VIS and PAR measurements at Marambio 64° S, Antarctica, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2019-227, in review, 2019.). We have added text describing the calibration process in the revised manuscript. We don't correct for the angular error of the final product, but the calibration is done against a cosine characterized SUV spectroradiometer. The spectral response of each channel is taken into account in the calibration process by weighting the SUV spectrum with the spectral response of each GUV channel. A maximum degradation of 5% was measured for the 305 nm channel, and of 2% for the other channels. The changes were considered small enough to accept a stepwise calibration change. Solar comparisons against high quality spectroradiometers have been performed to assess the performance of the instrument, and they are described in Lakkala et al. 2019. This is now explained in the revised manuscript. Considering the calibration uncertainty to be 5% and the maximum drift of the channel between calibration to be 5%, the combined uncertainty is 7%. However, the effect of drift of one single channel to the final product is less, as the final product is a linear combination of several channels.

We do not use QA/QC flags, but we check our data using plots from where problematic data is visible. We use last 5 day plots as our QC tool.

Changes to the manuscript: added text (Section 2.1.1), l. 143: "The calibration of the instruments is performed using the method presented in Dahlback (1996) and explained in detail in Bernhard et al., (2005). The method includes calibration against a high quality spectroradiometer which, for the GUV radiometers of Marambio, is a

SUV-100 spectroradiometer, from the NSF UV monitoring network, whose irradiance scale is traceable to the National Institute of Standards and Technology (NIST) (Booth et al., 1994). The calibration includes two steps: First, a calibration coefficient is calculated for each channel by performing a regression against measurements of the cosine error corrected SUV-100 spectroradiometer. Prior to the regression, the spectra of the SUV-100 are weighted with the spectral response functions of the GUV radiometer. The results are the so-called "response-weighted" irradiances (Seckmeyer et al., 2010) as the spectral response function of the GUV is taken into account."

l. 161: "The quality control of the measurements in Marambio includes regular cleaning of the diffusor and checking of the levelling. The data is plotted on the web page http://fmiarc.fmi.fi/sub_sites/GUVant/ (last checked Feb 5, 2020), which enables quick quality control by eye. The complete calibration and quality assurance procedure is described in detail in Lakkala et al., 2019. It includes solar comparisons with spectroradiometers at Sodankylä, whose measurement site has similar atmospheric conditions: high SZA, rapidly changing cloud cover, a clean atmosphere and ozone profiles typical for high latitudes. The results show that the differences are within 6 % for comparisons made in 2016—2018 for SZAs lower than 60º. Solar comparisons are also performed at Marambio each time there is a switch of instruments. The first switch was made in Nov 2018, and the difference between the two GUV's was 4-6 %. The difference was due to a drift in the channels of the GUV, which was in regular operation in Marambio. A drift of 2 to 5 % was observed depending on the channel, which is typical for a new instrument. Taking into account the drift of the instrument (5 %) and the uncertainties in the calibration (5 %), the combined uncertainty of the studied GUV measurements was 7 %."

Referee comment: Lines 165-170: this statement is not clear since the reader might be confused regarding which dataset you refer to in lines 168-169. Again, the comment in line 167 should follow the results of your analysis as to support them.

Answer: We agree that there might be some confusion and made some changes to the manuscript as follows.

Changes to the manuscript: l. 203: "For comparison, level 3 data with 0.25° resolution from the Ozone Monitoring Instrument (OMI) on board of the Aura satellite (Levelt et al., 2018), received through the NASA Giovanni interface (https://giovanni.gsfc.nasa.gov/giovanni/, last visited 14 Jun 2019), were used. Daily values of the OMI ozone product collocated with the Marambio station (64.125° S, 56.625° W for OMI data) were used and the ratio of daily ozone values OMI/GUV was calculated. In the majority of the days (88 %), the ratio falls in the range of 1 ± 0.05 (Fig. 2). The median of the ratio OMI/GUV is 1.01 indicating slightly higher values for the OMI data, especially in 2018/2019. There is a small drift between the seasons; the average ratio is 1.00 in 2017/2018 and 1.02 in 2018/2019. The OMI ozone product has shown very good stability over time and a low bias between ground-based Dobson-Brewer instruments in the Northern Hemisphere (McPeters et al., 2015). OMI data was used also for other stations included in the study."

Referee comment: For the proxy data, a small reference to the modified potential vorticity could be helpful here. After the proxy data, you also refer to the UV measurements at the remaining stations of the study, but you don't support the datasets with more information on their calibration procedures, uncertainties, and most importantly the procedures that were used to derive the products you are referring to (since this is important to assure the homogeneity of the compared data.

Answer: For potential vorticity, a reference was added: Lait, L. R.: An Alternative Form for Potential Vorticity, J. Atmos. Sci., 51(12), 1754–1759, doi:10.1175/1520-0469(1994)051<1754:AAFFPV>2.0.CO;2, 1994.

Changes to the manuscript: l. 232: "…, the modified potential vorticity, scaled to 475 K, from ERA-Interim data was used (Lait, 1994)."

Referee comment: The results section lacks of comprehensive plots. Please add descriptive y-axis labels (eg Daily UV doses (kJ/m2) instead of KJ/m2, ozone (DU) instead of DU), grid lines would help and titles like the station name would be useful to have. Also, please consider adding appropriate legends (e.g. figure 7 should somehow state that the long term while line comes from the NILU measurements apart from mentioning it in the caption). Add caption for tables and consider plotting the proxy data underneath the UV data to help the reader see the correlation - which is something that you need to elaborate more in the results sections. Likewise, do the same for the spatial analysis (multiple stations).

Answer: Comments about the figures were taken into account. Also, the captions of all tables were checked. The paragraph about ozone effect on measured UV in Marambio was written and a figure added to further elaborate the results section. For other stations no proxy data was added, except O3, to keep the manuscript's focus on Marambio.

Changes to the manuscript: Figures were updated. Please look from the revised manuscript

Referee comment: Why the Palmer, McMurdo and South Pole stations don't have data for the last period seen in this study?

Answer: The data for that season was unavailable during the preparation of the manuscript. However, it has been made available now and it was included into the revised version manuscript

Changes to the manuscript: Figure 10 was updated with season 2018/2019 data for Palmer, McMurdo and South Pole. Section 3.3 was updated.

Section 3.3 was rewritten, l. 501: " As shown in section 3.1, Marambio manifested two very different seasons – in 2017/2018 there was less UV radiation than in 2018/2019 and the daily erythemal doses and UVI were often below long-term averages. Including data from other Antarctic stations gives an opportunity to compare these results and to decide whether the same conclusions can be made in other parts of the continent.

First, the differences between seasons 2017/2018 and 2018/2019 were looked at. This data is available for all the included stations (Figure 10). Higher values in spring 2018 compared to 2017 have been measured at each station, except in Utsteinen from where no measurements are available for spring 2017. For example at South Pole, where recorded UVI are the lowest, the maximum UVI was 1.9 during Oct-Nov in 2017 and 2.9 in 2018. In 2018 the mean UVI for Oct-Nov was also higher (1.5, in 2017 it was 1.0). For Oct and Nov, the mean and maximum values were higher for every station (except for Utsteinen due to lack of measurements). The peaks in spring are mainly caused by low TOC during the ozone hole event. The TOC values were higher for most of the spring in each station (Fig. 10) and there were several days where much larger TOC values were recorded in 2017/2018 compared to 2018/2019, with differences more than 100 DU. Utsteinen and Troll stayed inside the polar vortex until Nov 22 and 21, 2018, respectively, and during some isolated days in the following week. In 2017, these stations were outside the polar vortex by Nov 15 and 13 respectively. The earlier disappearance of the polar vortex in 2017 compared to 2018 was also recorded in Palmer and McMurdo. Palmer was for the first time outside the vortex on Oct 9, 2017, and on Nov 11, 2018, and the corresponding dates for McMurdo were Oct 28, 2017, and Dec 7, 2018.

Compared to long-term variations and averages from the measurements in 2000–2008, irradiances in Marambio in 2017/2018 were below the average value for the end of spring and most of the summer. This kind of comparison was also done using data from the three American stations – Palmer, McMurdo and South Pole. All of these stations had UVI data available for 2000–2008 (Fig. 10). Out of these stations, Palmer is the closest to Marambio - roughly 350 km away and almost at the same latitude. The maximum UVI in Palmer was 7.9 for the 2017/2018 season and 11.6 for the long-term time series. With respect to long-term measurements, season 2017/2018 was similar to the one in Marambio. Also in Palmer longer periods with UVI lower than the average occurred in spring and summer, from Oct to Dec the maximum UVI was smaller than the long term average during 58 days and the largest difference was 3 units (Nov 14, 2017). The longest span of days with maximum UVI below the average was from 5 Nov – 17 Nov, with a mean difference of 1.5 units. Out of the 58 days, the daily maxima were below the historic minimum value during 10 days. This was also the case for McMurdo and South Pole: at both stations, average daily maximum UVI values were measured in 2017/2018 which were below those in the period 2000–2008, especially in Nov and Dec when also the variation between years was the largest. In McMurdo, the longest span of days with below average maximum UVI between Oct and Dec was 27 days (19 Oct – 14 Nov) while in South Pole there were only 7 days in that period when maximum UVI was above the average.

Based on this comparison, it can be concluded that during the season 2017/2018 the long-term average UV irradiance reaching the surface was lower than in the period 2000–2008 across the Antarctic and the results obtained for Marambio were not site specific.”

Answers to Anonymous Referee #3

Referee comment: It was reported a significantly higher UV level during the second season with respect to the first one even in the time when the ozone depletion in Antarctica was finished. Such an occurrence hardly could be explained by ozone column variations only. For instance, the mean January ozone column dropped by about 5.5% from the first to the second season (Table 2) that would cause nearly 7% increase of the mean erythemal dose assuming RAF of about 1.2. However, according to Table 1, the measured increase in the 2018/2019 season was 21% that could be attributed to the predominant role of the other factors discussed in the manuscript. To my opinion even such simple assessments with a short discussion would enhance the weight of obtained results.

Answer: Thank you for the comment, we agree and this sort of analyses has been added.

Changes in the manuscript: In Data and Methods section, l. 110: "For describing the effect of O_3 on UV irradiance, the radiation amplification factor (RAF) has been used. RAF is defined as the percentage increase in UV radiation that would result from a 1% decrease in TOC (UNEP, 1998). For small changes, RAF can be calculated as:

$$RAF = -\frac{\Delta E/E}{\Delta TOC/TOC} \qquad (2)$$

where ΔE and ΔTOC are the respective changes of UV irradiance (E) and ozone (TOC). For larger changes, a power law equation should be used as in McKenzie et al (2011):

$$\frac{E^{+}}{E^{-}} = (\frac{TOC^{-}}{TOC^{+}})^{RAF} \qquad (3)$$

where + shows the case with the higher TOC.

The RAF value depends on multiple factors like SZA, clouds and TOC (Antón et al., 2016). For erythemal irradiance an average value of 1.2 can be used (Antón et al., 2016; McKenzie et al., 2011, Lakkala et al., 2018)." In the "Results" section, l. 400: "For describing the effect of O3 on UV irradiance, the RAF with a value of 1.2, has been used. The expected changes in average daily erythemal dose due to a decrease in average TOC between the seasons 2017/2018 and 2018/2019 was calculated for each month from Oct to Feb and compared to the measured changes (Fig. 6). The results were similar when using the power law relationship for calculating RAF (McKenzie et al., 2011) (section 2) for larger changes in O3. In Nov and Feb the increase in monthly average UV from 2017/2018 to 2018/2019 is caused by ozone, but due to higher cloud cover in the second season, the increase is less than calculated solely using RAF. In Oct, more than half of the increase can be explained by the decrease in TOC, the rest is due to the larger cloud cover in 2018/2019 (1.1 oktas), which is the largest difference in monthly averages for those two seasons. In Dec and Jan, less than 1/3 of the increase in average erythemal dose is explained by ozone and the rest of the change is due to other factors. In both months, the average cloud cover is lower in 2018/2019 than in 2017/2018 (0.7 and 0.2 oktas, respectively). In Jan, the average difference in cloud cover is small as is the difference in average TOC (17 DU). However it is important to note the timing when those differences occur. The TOC is lower from Jan 2 to 18, 2019, compared to the same period in 2018. In the first half of January the noon SZA is lower than in the second half. In the second half of Jan 2019, the cloud cover was lower – there are 5 days with daily average cloud cover smaller than 5, at the same time in 2018 there were none. So even though the monthly mean values are similar, there are day-to-day variations and the factors causing higher daily doses in 2019 are different during different days."

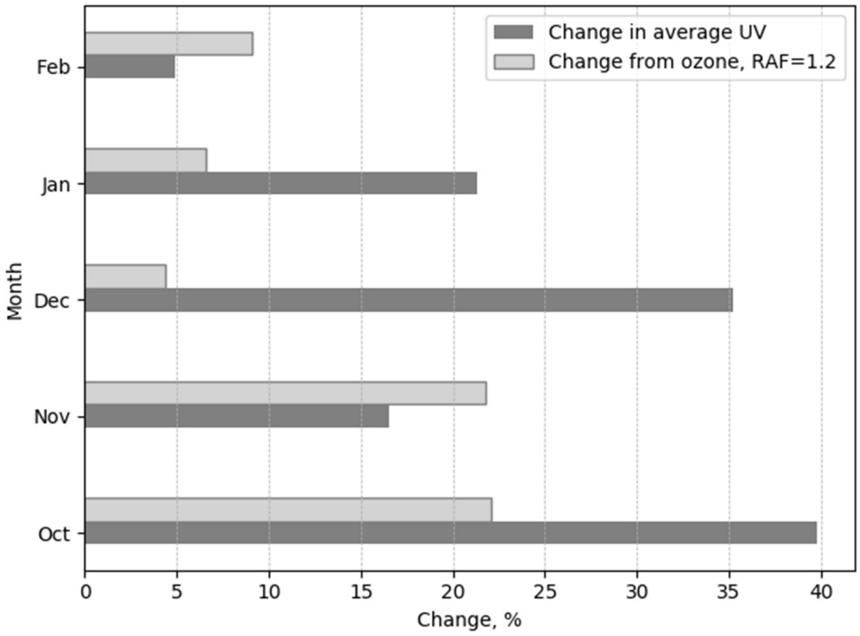

Figure 6: Change in average daily erythemal dose between the seasons 2017/2018 to 2018/2019 for each of the months from Oct to Feb (dark grey) and expected changes due to decrease in average TOC using RAF=1.2 (light grey).”

Referee comment: At the beginning of the introduction, the authors claim that “UV radiation at wavelengths smaller than 280 nm does not reach the surface of the Earth”. To my knowledge the short wavelength border of the solar irradiance at the ground is no less than 295 nm, so I would ask the authors to provide references confirming their statement.

Answer: It is generally said, that UV radiation below 280 nm (UV-C, 100 – 280 nm) does not reach the ground**.** The exact smallest wavelength measured at a ground station is dependent on the geographical location, time of the year/day, atmospheric conditions and also on instrument sensitivity. Therefore, we would like to keep it general here.

Changes in the manuscript: added reference (UNEP, 1998)

Referee comment: In addition, in the line 62 it is said that “The data from 2000–2008 serve as a reference for times when there were not yet signs of ozone recovery”, while above, in the line 45 it is mentioned that “Thanks to these efforts, concentrations of ozone depleting substances have declined since the 1990s (WMO, 2018), the loss of stratospheric ozone has stopped and the first signs of recovery have been noted (Solomon et al., 2016)”. In the cited article of Solomon, 2000 is considered as year, where fingerprints of healing could be recognized. Hence, I suggest a reformulation of the motives leading to choose 2000-2008 as a reference period.

Answer: We agree with the comment and changed the sentence

Changes in the manuscript: The rewritten sentence, l. 64: “… data from 2000–2008 serve as a reference for times when the recovery of the ozone layer was at its beginning.”

Referee comment: For instance, the paragraph between lines 165 and 170 shortly introduces the OMI dataset and immediately after it is said that the data were taken for a certain geographical point and majority of the points in Fig. 2 are in a certain range and are characterised by a certain median. It is not explained that the geographical point was chosen to be maximally close to Marambio station, that the points in the figure represent the ratio between GUV and OMI instruments and that namely the distribution of this ratio has a median of 1.01. It is true that a part of this information can be found in the figure but I think that the meaning of the used parameters should be explained in the text. Moreover, it is not indicated if the ratio is GUV/OMI or OMI/GUV, which gives an idea about over- or underestimation of one device with respect to the other.

Answer: We agree with the comment, that the paragraph and figure has been changed. The used ratio is OMI/GUV

Changes in the manuscript: Changes, l. 205: "Daily values of the OMI ozone product collocated with the Marambio station (64.125° S, 56.625° W for OMI data) were used and the ratio of daily ozone values OMI/GUV was calculated. In the majority of the days (88 %), the ratio falls in the range of 1 ± 0.05 (Fig. 2). The median of the ratio OMI/GUV is 1.01 indicating slightly higher values for the OMI data, especially in 2018/2019. There is a small drift between the seasons; the average ratio is 1.00 in 2017/2018 and 1.02 in 2018/2019."

Figure 2 was modified.

Referee comment: The numeration of the figures jumps from 2 to 4 and the same is in the text, figuure 3 is missing.

Answer: Thank you for pointing it out.

Changes in the manuscript: Figure numbers were fixed.

Referee comment: In addition, on the y-axis of the most of the figures only the measurement units are given without the corresponding parameters.

Answer: We agree, the parameters have been added

Changes in the manuscript: y-axis titles for figures were changed.

Referee comment: I suggest to include "Solar" at the beginning of the title.

Answer: We agree

Changes in the manuscript: the title was changed to: "Solar UV radiation measurements in Marambio, Antarctica, during years 2017–2019"

Referee comment: l. 159. "The daily doses and UVI maxima: : :".

Answer: the comment was taken into account

Changes in the manuscript: "UVI" was added

Referee comment: In the legend of Table 1, the standard deviation is indicated by both "std" and "St. Dev."

Answer: we have checked the manuscript on consistent use of notation.

Changes in the manuscript: "St. Dev." was changed to "std"

Referee comment: l. 356. "..similar pattern is also present in Troll:: : :".

Answer: mistake was noticed. The entire section has been rewritten.

Changes in the manuscript: Please read the revised manuscript, l. 501, section 3.3.

Referee comment: Legend of Fig. 10. What is the meaning of the gray and black curves in the upper panel, which of them is maximum or noon UVIs?

Answer: Noon UVI values were with grey line. This figure has been updated.

Changes in the manuscript: New Figure 10:

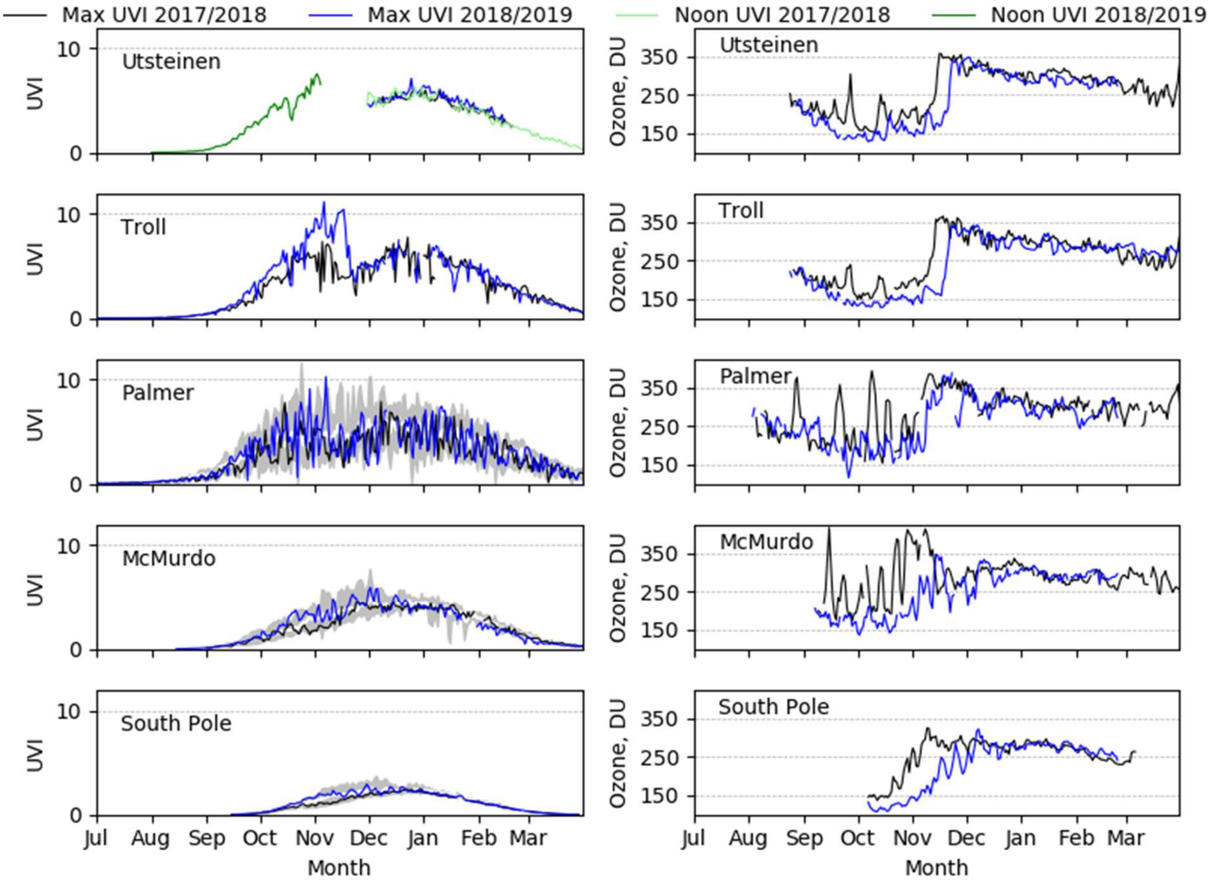

Figure 10: Maximum daily UVI (left) and daily TOC (right) for different Antarctic stations for 2017/2018 (black line) and 2018/2019 (blue line). In the Utsteinen UVI plot, noon UVI values (2017/2018 - light green, 2018/2019 dark green) have been added to get longer time-series. In the plots of UVI in Palmer, McMurdo and South Pole the long-term (2000–2008) averages (white line) and variations (grey area) have been added.

Referee comment: l. 382. Repetition of "also".

Answer: Comment taken into account

Changes in the manuscript: Please check the previous answer.

Solar UV radiation measurements in Marambio, Antarctica~~,~~ during years 2017–2019 ~~in a wider temporal and spatial context~~

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Abstract. In March 2017, measurements of downward global irradiance of ultraviolet (UV) radiation ~~measurements~~were started with a multichannel GUV-2511 radiometer~~ were started~~ in Marambio, Antarctica (64.23º S; 56.62º W), by the Finnish Meteorological Institute (FMI) in collaboration with the Argentinian National Meteorological Service (SMN). These measurements were analysed and the results were compared to previous measurements performed at the same site with ~~NILU-UV~~the radiometer of the Antarctic NILU-UV network during 2000–2008 and to data from five stations across Antarctica. ~~Measurements in Marambio showed~~ In 2017/2018 the monthly average erythemal daily doses from Oct to Jan were lower ~~UV radiation levels in 2017/2018 compared to~~ than those ~~measured during~~ averaged over 2000~~–~~-2008~~.~~ with differences from 2.3 % to 25.5 %. In 2017/2018 the average daily erythemal dose from Sept to Mar was 1.88 kJ/m^2, while in 2018/2019 it was 23 % larger (2.37 kJ/m^2). Also at several other stations in Antarctica the UV radiation levels in 2017/2018 were below average~~ in that period.~~. The maximum UV ~~index~~indices (UVI) in Marambio ~~was only~~were 6.2~~, while,~~ and 9.5 in 2017/2018 and 2018/2019, respectively, whereas during ~~the time period~~years 2000–2008, the maximum was 12. ~~In 2018/2019, the radiation levels were higher than in the previous year and the maximum UVI recorded in Marambio was 9.5. In Marambio, the largest variation of the UV radiation are during the spring and early summer when the stratospheric ozone concentration is at a minimum (the so-called ozone hole). Beside cloud~~Cloud cover, the strength of the polar vortex and the stratospheric ozone depletion are the primary factors that influence the surface UV radiation levels in ~~Antarctica. As the recovery of the ozone layer is slow, the continuation of the measurements is crucial in order to be able to detect long-term changes in UV levels in Antarctica~~Marambio. The largest variations of UV irradiance occur during spring and early summer when noon SZA is low and the stratospheric ozone concentration is at a minimum (the so-called ozone hole). In 2017/2018, coincident low total ozone column and low cloudiness near solar noon did not occur, and no extreme UV indices were measured.

1 Introduction

Ultraviolet (UV) radiation is part of the Sun's electromagnetic radiation in the wavelength range from ~~10~~100 to 400 nm; UV radiation at wavelengths smaller than 280 nm does not reach the surface of the Earth ~~due to absorption in the atmosphere.~~(UNEP, 1998). The amount of UV radiation reaching the ground depends on various factors that can be divided into geometrical (including the distance between the Sun and the Earth and the solar zenith angle (SZA) at a given location) and geophysical factors ~~(Kerr, 2005).~~(Kerr, 2005). Examples of the latter are clouds, ozone (O_3) and aerosol particles, which ~~all~~can absorb or scatter UV radiation~~.~~ - absorption by O_3 is the reason why UV radiation at wavelengths shorter than 280 nm does not reach the ground. Any change in these factors will affect UV irradiance. The ~~radiation~~UV irradiance measured at the surface is also affected by the surface albedo, which determines how much of the UV radiation is reflected back to the atmosphere ~~(Kerr, 2005).~~(Kerr, 2005). This effect is most important when the surface is covered with snow, because snow has a high albedo and therefore reflects more radiation, which in turn can be scattered back to the surface.

~~In the 1980s, ozone depletion in Antarctica was discovered and this reduction was especially strong during spring (Farman et al., 1985). Since then, successful measures, such as agreed in the Montreal Protocol (adopted in 1987), have been taken to protect the ozone layer. Thanks to these efforts, concentrations of ozone depleting substances have declined since the 1990s (WMO, 2018), the loss of stratospheric ozone has stopped and the first signs of recovery have been noted (Solomon et al., 2016). However, a recent study discovered, that the rate of decline in ozone destructive trichlorofluoromethane (CFC-11) has slowed substantially – about 50% since year 2012 (Montzka et al., 2018). The ozone hole still exists over Antarctica. According to the latest WMO ozone report (WMO, 2018) there is some indication that the Antarctic ozone hole has diminished in size and depth since the year 2000, but it is affected by meteorological conditions such as temperature and wind, making the natural variability of ozone large and therefore the detection of recovery difficult. However, statistically significant positive trends in ozone have been observed in the Antarctic in September since 2000 (Solomon et al., 2016).~~

In the 1980s, O_3 depletion in Antarctica was discovered and this reduction was especially strong during the Antarctic spring (Farman et al., 1985). Since then, successful measures, such as agreed upon in the Montreal Protocol (adopted in 1987), have been taken to protect the ozone layer. Thanks to these efforts, concentrations of O_3 depleting substances have declined since the 1990s (WMO, 2018). However, a recent study discovered that the rate of decline of O_3 concentration destructive trichlorofluoromethane (CFC-11) has slowed substantially – about 50% since 2012 (Montzka et al., 2018). Although the gradual loss of stratospheric O_3 over the years has stopped and the first signs of recovery (such as a statistically significant positive trend in ozone observed over the Antarctic in Sept since 2000) have been noted, the springtime reduction of O_3 concentration that leads to the ozone hole still exists over Antarctica (Solomon et al., 2016). According to the latest WMO ozone report (WMO, 2018), there is some indication that the Antarctic ozone hole has diminished in size and depth since the year 2000, but it is affected by meteorological conditions such as temperature and wind, making the natural variability of total ozone column (TOC) large and therefore the detection of recovery difficult. To detect the changes and the expected recovery, continuous measurements of TOC and UV irradiance must be carried out in the region. These measurements also provide the possibility to analyse effects of changes in other climate parameters, such as cloud and aerosol properties and surface albedo, on the UV irradiance near the surface. This is especially important because of the ongoing interaction between climate change and these parameters (IPCC, 2014).

To promote the research of stratospheric ~~ozone~~O_3 and UV radiation in Antarctica, ~~a joint~~the Finnish Meteorological Institute (FMI) started UV irradiance measurements in Marambio (64.23º S; 56.62º W) in collaboration with Argentina's National Meteorological Service (SMN) in Mar 2017. These measurements are used to assess the current situation and they can be compared to earlier measurements from the NILU-UV Antarctic network (Lakkala et al. 2018) whose data from 2000–2008 serve as a reference for times when the recovery of the ozone layer was at its beginning. The Antarctic NILU-UV radiometer network was established as a collaboration between the Spanish State Meteorological Agency (AEMET), Argentina's National Directorate of the Antarctic - Argentinian Antarctic Institute (DNA-IAA) and FMI in 1999/2000. Within the ~~Finnish Meteorological Institute (FMI).~~network, UV irradiance measurements were carried out from 2000 to 2013 in ~~In~~ Marambio, Ushuaia ~~(~~Global Atmospheric Watch (GAW) station in southern Argentina (54.82° S, 68.32° W) and Belgrano, Antarctica (77.87° S, 34.63° W) ~~(Lakkala et al., 2018). UV radiation data measured in~~(Lakkala et al., 2018). Due to the harsh meteorological conditions in these polar regions, including very low temperatures and severe snow storms, proper quality assurance procedures are very important (Lakkala et al. 2005). For Marambio~~ in~~, UV irradiance measured during the period ~~from~~ 2000–2010 ~~were~~was found reliable and was analysed and compared to UV data measured simultaneously at ~~the~~ Ushuaia ~~Global Atmospheric Watch (GAW) station~~ in ~~southern Argentina (~~Lakkala et al. 2018~~).~~

~~In March 2017, FMI restarted the UV measurements in Marambio in collaboration with Argentina's National Meteorological Service (SMN). The results of these measurements allow for the assessment of the current situation and compare it to the earlier results. The data from 2000–2008 serve as a reference for times when there were not yet signs of ozone recovery. Now, 9 years later, it is possible to search for signals of changes in UV radiation that could reflect the observed changes in the levels of the stratospheric ozone.~~. At both stations, daily

~~In this work, two different UV products derived from the measurements are used. The first parameter is the~~ erythemal ~~daily dose, which is calculated from erythemal irradiance. It is defined as the effective irradiance obtained by integrating the spectral irradiance weighted by the CIE reference action spectrum for~~ UV~~-induced erythema on the human skin up to 400 nm and normalized to 1.0 below 298 nm (McKinlay and Diffey, 1987). The second parameter is the~~ doses during spring O_3 loss episodes could even exceed doses in the summer when they naturally are supposed to be higher due to lower noon SZA. The highest daily maximum UV index (UVI~~), which is calculated by multiplying the effective erythemal irradiance (in W/m^2) by 40 m^2/W and has no units)~~ measured in Marambio was 12, in Nov 2007; in Ushuaia the highest daily maximum UVI was 13, which was measured in Nov of the years 2003 and 2009.

The aim of this paper is to ~~discover the temporal variation in UV irradiance levels at the Antarctic Peninsula station Marambio and see the results in spatial context.~~present the results of UV irradiance measurements in Marambio from ~~March~~Mar 2017 ~~– March~~to Mar 2019 ~~are compared~~and to compare them with those from 2000–2008 and ~~to results from~~also with UV measurements at other ~~stations measuring UV irradiance in Antarctica from which data are available.~~Antarctic stations. Including different measurement sites provides an opportunity to ~~see~~investigate, whether differences between the latest solar seasons and previous measurements are common for ~~all Antarctica~~different Antarctic stations or if they are region-specific, as the factors influencing UV radiation vary widely over the continent.

2 Data and methods

~~2.1 Measurement sites~~

~~Marambio and~~In addition to Marambio’s measurements, data from five more research sites ~~were included for comparison~~are used in the analysis: the Princess Elisabeth Station ~~in~~at Utsteinen, and the stations Troll, Palmer, McMurdo and South Pole. The locations of the stations together with the maximum UVI during the season 2017/2018 are shown in Figure 1~~.~~ and the summary information about the location, instruments and used data periods are presented in Table 1.

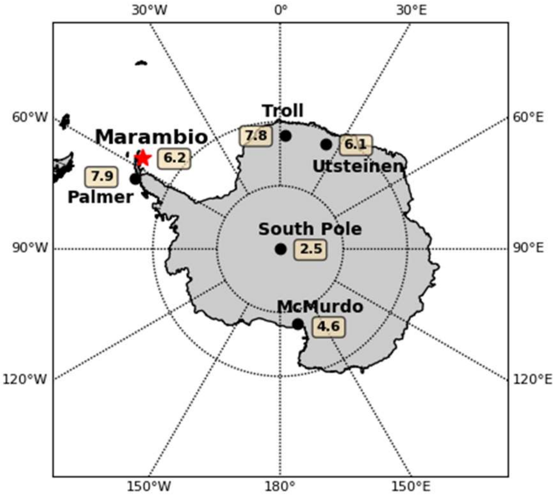


Figure 1: Locations of the stations included in the analysis. The numbers next to the sites show the corresponding maximum UVI measured during the season 2017/2018.

Table 1. Measurement stations with their locations, altitudes, used UV instrument and daily product types (erythemal dose (D_{ery}), UVA dose (D_{UVA})) and period of data used in the analysis.

Station	**Location**	**Height (a.s.l.)**	**UV instrument type**	**Product**	**Period included**
Marambio	64.23º S; 56.62º W	198 m	NILU-UV GUV	Max. UVI, D_{ery} Max. UVI, D_{ery}, D_{UVA}	2000–2008 2017–2019
Utsteinen	71.95° S; 23.35° E	1390 m	Brewer UVB pyranometer MS212W	Max. UVI Noon UVI	2017–2019 2017–2018
Troll	72.00° S; 2.53° E	1553 m	NILU-UV	Max. UVI	2017–2019
Palmer	64.77° S; 64.05° W	21 m	SUV-100	Max. UVI	2000–2008 2017–2019
McMurdo	77.83° S; 166.67° E	183 m	SUV-100	Max. UVI	2000–2008 2017–2019

South Pole	90.0° S; 0.0° E	2835 m	SUV-100	Max. UVI	2000–2008 2017–2019

In this work, mainly two different UV products derived from the measurements are used. The first parameter is the erythemal daily dose (H) (in J/m^2), which is calculated from the dose rate of erythemal irradiance (D) (in W/m^2) from the beginning of the day (T1) to the end (T2).

$$H = \int_{T1}^{T2} D(T)dT \qquad (1)$$

D is defined as the effective irradiance obtained by integrating the spectral irradiance weighted by the CIE reference action spectrum for UV-induced erythema on the human skin up to 400 nm and normalized to 1.0 below 298 nm (McKinlay and Diffey, 1987).

The second parameter is UVI, which is calculated by multiplying the effective erythemal irradiance (in W/m^2) by 40 m^2/W and has no units (Fioletov et al., 2010). As typically the UVI at northern high latitudes varies between 0 and 6 (at sea level and latitudes above 60 degree) (e.g., Bernard et al. 2019), there is an interest to know the variation range at similar latitudes in the Southern Hemisphere. For this purpose, the maximum daily UVI was analysed in this study.

In the current study, the data were divided into two periods – 2017/2018 and 2018/2019. To take the local annual solar cycle into account, solar seasons were used instead of calendar years. In case of no polar night, a solar season is defined as the period lasting from Jul 1st to Jun 30th, the next year. For most of the stations in Antarctica, the measurement period is much shorter, e.g. at South Pole the solar season lasts only from Sept to Mar. A full day was defined using the UTC time both for the UV and proxy data. For each day, the daily erythemal dose as well as the maximum daily UVI were determined.

For describing the effect of O_3 on UV irradiance, the radiation amplification factor (RAF) has been used. RAF is defined as the percentage increase in UV radiation that would result from a 1% decrease in TOC (UNEP, 1998). For small changes, RAF can be calculated as:

$$RAF = -\frac{\Delta E/E}{\Delta TOC/TOC} \qquad (2)$$

where ΔE and ΔTOC are the respective changes of UV irradiance (E) and ozone (TOC). For larger changes, a power law equation should be used as in McKenzie et al (2011):

$$\frac{E^{+}}{E^{-}} = (\frac{TOC^{-}}{TOC^{+}})^{RAF} \qquad (3)$$

where + shows the case with the higher TOC.

The RAF value depends on multiple factors like SZA, clouds and TOC (Antón et al., 2016). For erythemal irradiance an average value of 1.2 can be used (Antón et al., 2016; McKenzie et al., 2011, Lakkala et al., 2018).

2.1~~2.1.1 Marambio station~~

Marambio station

The Marambio station ~~(64.23º S; 56.62º W; 198 m a.s.l.) is~~ is located on an island ~~near the eastern part~~east of the Antarctic Peninsula (see Fig. 1). The monthly mean temperatures in Marambio vary between −30 and +10 °C. ~~.~~During most of the year, the soil is frozen and covered with snow. The prevailing wind directions are from the southwest and the northwest and the wind speed can reach values close to 100 km/h.

The station~~ was founded in 1969 and~~ is part of the World Meteorological Organization (WMO) Regional station network and data is regularly reported to the World Ozone and UV Data Centre (WOUDC).

~~Currently, the station serves as the main logistic hub for the Argentinian Antarctic operations and it has several well-established atmospheric science projects. These include, for example, ozone, UV and greenhouse gas measurements, meteorological observations and aerosol studies performed year-round. Ozonesondes are launched mainly during the ozone hole season. Also, a variety of geological, biological and glaciological studies are carried out mainly by the Antarctic National Direction.~~

~~The monthly mean temperatures in Marambio vary between −30 and +10 °C. The uppermost layer of the soil can partly melt during the summer, but during most of the year the soil is covered with snow. Winds are predominant from the southwest and the northwest and can reach speeds close to 100 km/h.~~

~~The station is operational all year-round and the number of people varies between a minimum of around 50 in the winter to a maximum of about 150 in the summer.~~

~~2.1.2 Princess Elisabeth Station in Utsteinen~~

~~The Belgian Antarctic Princess Elisabeth (PE) station (71.95° S; 23.35° E; 1390 m a.s.l.) is located on the granite ridge of the Utsteinen Nunatak in Dronning Maud Land, East Antarctica (Herenz et al., 2019; Pattyn et al., 2010). It is located about 200 km inland from the Antarctic coast and lies north of the Sør Rondane mountain range, which has peaks up to 3300 m a.s.l. The station lies in the escarpment zone between the Antarctic inland plateau and the coast where it experiences the influence of both synoptic weather systems and katabatic winds (Gorodetskaya et al., 2013). It has been designed as a zero emission station that is inhabited from November until the end of February.~~

~~2.1.3 Troll station~~

~~The Norwegian Institute for Air Research (NILU) monitoring activity at the Troll station was established in 2007, initially near the main Troll station, in late January 2014 it was moved to the mountain Trollhaugen (70.00° S; 2.53° E). The Trollhaugen observatory is approximately 1 km east of the Troll research station in the Jutulsessen nunatak area, Queen Maud Land, about 235 km from the coast and 1553 m a.s.l. The station is unperturbed by local activity.~~

~~Troll/Trollhaugen is one of the few observatories that has continuous year-round monitoring in Antarctica. NILU is in charge of the scientific activities, while technical personnel from the Norwegian Polar Institute are responsible for daily maintenance.~~

~~2.1.4 Palmer station~~

~~Palmer station is the closest to Marambio out of all the selected stations. It is situated on Ansver Island (64.77° S; 64.05° W; 21 m a.s.l) just outside the Antarctic Circle. It is one of the United States Antarctic UV Network stations, established in 1965 and is one of the stations in Antarctica that is opened all year. (Information from https://esrl.noaa.gov/gmd/grad/antuv/Palmer.jsp, last visited 13 June 2019).~~

~~2.1.5 McMurdo station~~

~~McMurdo station is also a part of the United States Antarctic UV Network and is located on the Southern tip of Ross Island (77.83° S; 166.67° E; 183 m a.s.l.). UV measurements started in 1988. The Solar season lasts from August to April, but the station is opened all year round. (Information from https://esrl.noaa.gov/gmd/grad/antuv/McMurdo.jsp, last visited 13 June 2019).~~

~~2.1.6 Amundsen-Scott South Pole station~~

~~This is the 3rd station in the United States Antarctic UV Network, where UV instruments were installed in 1988. It is located at the geographic South Pole (90.0° S; 0.0° E; 2835 m a.s.l). The Solar season lasts there from September to March. The annual average temperature at the pole is -49 °C. The conditions are quite different from all the other stations as there is almost no diurnal change in SZA. The meteorological conditions at the station are stable. There is also low cloudiness, constant snow and very low air pollutant levels. (Information from https://esrl.noaa.gov/gmd/grad/antuv/SouthPole.jsp, last visited 13 June 2019).~~

~~2.2 Marambio data~~

~~2.2.1 GUV filter radiometer~~

2.1.1 UV measurements

Since ~~March~~Mar 2017, GUV-2511 multifilter radiometers, manufactured by Biospherical Instrument Inc., are used to measure UV ~~radiation~~irradiance in Marambio. These instruments measure the downwelling irradiance at wavelengths of 305, 313, 320, 340, 380, 555 nm and photosynthetically active radiation (PAR, 400–700 nm~~).~~), which are provided as one-minute averages. The full width half maximum (FWHM) of the first six channels is 10 nm. ~~For stability, the~~ The angular response of the instrument determined by the manufacturer is 0-5 % from 0^o to 70^o and ±10% from 71^o to 85^o. The GUV instrument is also used for UV monitoring at the Antarctic and Arctic sites of the United States National Science Foundation (NSF) UV monitoring network (e.g., Bernhard et al. 2005) and the instrument is robust enough to stand harsh measurement conditions including strong winds, snow, frost formation and rapidly changing or extreme temperatures. As the response of the instrument is sensitive to temperature and humidity, the instrument needs to be adequately sealed and temperature stabilized. The internal temperature of the ~~instrument~~GUV in Marambio is ~~held~~maintained at 40 °C~~.~~

~~From these measurements, using one-minute averages, different products were calculated, including daily erythemal dose and maximum UVI. Also, total column ozone (O_3) is calculated as a major factor influencing the amount of UV radiation reaching the ground. The characteristics and calculation of these data products are explained in detail in Bernhard et al. (2005). Following Bernhard et al. (2005) the UV index from a GUV instrument can be within 5 % from well-calibrated spectroradiometer for~~

~~SZAs smaller than 78°. The difference between Total Ozone Spectrometer (TOMS) total ozone and GUV total ozone was within 5 % for SZAs smaller than 75°.~~, which was found enough to keep the instrument clean from frost and snow.

Two GUV instruments are used for the UV measurements in Marambio – while one of them is measuring in Marambio, the other one is in calibration either in Finland or in the ~~U.S..~~United States (Lakkala et al. 2019). The instruments are switched annually in order to transfer the latest calibration to Marambio and thus maintain the homogeneity of the measurement time series.

~~In the current study, the data were divided into two periods – 2017/2018 and 2018/2019. To take the local annual sun cycle into account, Solar seasons were used instead of calendar years. In case of no polar night, a season is defined as a period lasting from July 1^{st} to June 30^{th}, the next year. In most of the stations in Antarctica, the measurement period is much shorter, e.g. in South Pole the season lasts only from September to March. A full day was defined using the UTC time both for the UV and proxy data.~~

~~2.2.2 NILU-UV radiometer~~

~~During 2000–2013, UV measurements in Marambio were conducted with a NILU-UV~~ The calibration of the instruments is performed using the method presented in Dahlback (1996) and explained in detail in Bernhard et al., (2005). The method includes calibration against a high quality spectroradiometer which, for the GUV radiometers of Marambio, is a SUV-100 spectroradiometer, from the NSF UV monitoring network, whose irradiance scale is traceable to the National Institute of Standards and Technology (NIST) (Booth et al., 1994). The calibration includes two steps: First, a calibration coefficient is calculated for each channel by performing a regression against measurements of the cosine error corrected SUV-100 spectroradiometer. Prior to the regression, the spectra of the SUV-100 are weighted with the spectral response functions of the GUV radiometer. The results are the so-called “response-weighted” irradiances (Seckmeyer et al., 2010) as the spectral response function of the GUV is taken into account. The second step includes the calculation of the UV products. The method is also described in Dahlback (1996) and discussed in detail for the GUV radiometers in Bernhard et al. (2008). A UV product P is calculated using a linear combination of the dark signal corrected signals of the GUV’s UV channels V_i:

$$P= \sum_{i=0}^{5} a_i V_i \qquad (4)$$

where the coefficients a_i depend on the calibration factor derived in the first step and the used biological action spectrum, e.g., erythemal response for erythemally weighted irradiances. The coefficients are determined by solving a system of linear equations as described by Bernhard et al. (2008), taking into account the atmospheric conditions at the site (e.g., range of total ozone and surface albedo). The validation of UV products calculated using this method is discussed in Bernhard et al. (2005). The validation results show that the UV index from a GUV instrument can be within 5 % from a well-calibrated spectroradiometer for SZAs smaller than 78°.

The quality control of the measurements in Marambio includes regular cleaning of the diffusor and checking of the levelling. The data is plotted on the web page http://fmiarc.fmi.fi/sub_sites/GUVant/ (last checked Feb 5, 2020), which enables quick quality control by eye. The complete calibration and quality assurance procedure is described in detail in Lakkala et al., 2019. It includes solar comparisons with spectroradiometers at Sodankylä, whose measurement site has similar atmospheric conditions: high SZA, rapidly changing cloud cover, a clean atmosphere and ozone profiles typical for high latitudes. The results show that the differences are within 6 % for comparisons made in 2016—2018 for SZAs lower than 60°. Solar comparisons are also performed at Marambio each time there is a switch of instruments. The first switch was made in Nov 2018, and the difference between the two GUV's was 4-6 %. The difference was due to a drift in the channels of the GUV, which was in regular operation in Marambio. A drift of 2 to 5 % was observed depending on the channel, which is typical for a new instrument. Taking into account the drift of the instrument (5 %) and the uncertainties in the calibration (5 %), the combined uncertainty of the studied GUV measurements was 7 %.

In addition, the Marambio NILU-UV daily dose and maximum UV index time series described in Lakkala et al., 2018 were used. The NILU-UV is a multichannel radiometer, which measures radiation ~~in six channels. There are ~~at five UV channels ~~with centre~~and one PAR channel. The central wavelengths of the UV channels are at 305, 312, 320, 340 and 380 nm ~~(~~and the FWHM for each channel is around 10 nm~~), and one channel measuring PAR~~. The instrument includes a flat Teflon diffuser, interference filters and silicon detectors and the ~~instrument is kept with an inner temperature of 40 °C. The instrument is described in detail in Høiskar et al. (2003).~~

inside temperature of the instrument is maintained at 40 °C. The instrument is described in detail in Høiskar et al. (2003), including the method to derive daily doses and UV index which is based on Dahlback (1996). The method is mainly the same as that for retrieving UV products from the GUV radiometers and includes calibration against a reference spectroradiometer. The irradiance scale was traceable to the NIST via the Swedish Testing and Research Institute (SP) (Johnsen et al., 2002). As described in Lakkala et al., 2005, the quality assurance of the NILU-UV measurements included regular lamp measurements and solar comparisons against a regularly calibrated traveling reference radiometer. The measurement capacity of the channels of the NILU-UVs was found to drift during the measurement period~~ (Lakkala et al., 2005), and the data was corrected for this drift in Lakkala et al. 2018.~~, and the data was corrected for this drift using the results of the solar comparisons by transferring the calibration from the traveling reference to the site radiometer. The yearly comparisons between the traveling reference of the network and the SUV-100 spectroradiometer of NSF in Ushuaia showed differences of less than 5 % between the two instruments. Details about the correction are described in Lakkala et al., 2005 and 2018. After the corrections, the combined uncertainty was calculated to be 9.5 % and the expanded uncertainty was 19 % using a coverage factor of 2 for the time period 2000–2008, which is used in this study. After 2008 the uncertainty of the measurements increased due to severe drift of the channels, and since 2011 the measurements could no longer be used for research and they were stopped.

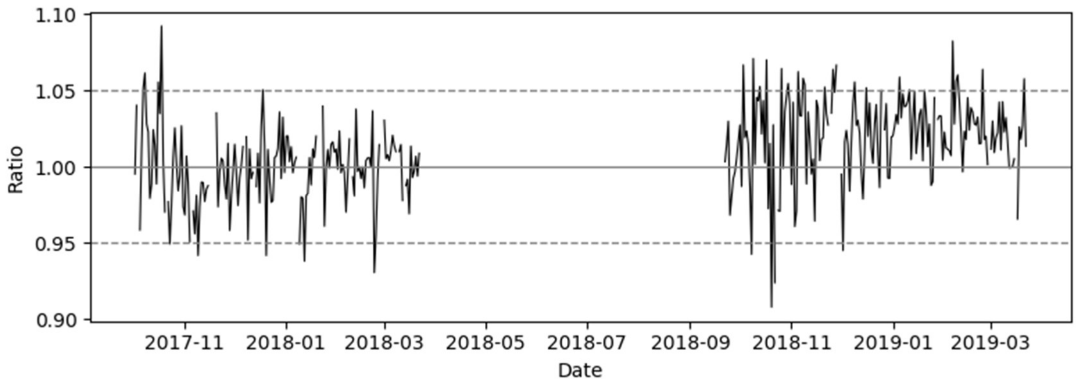
~~The~~From the NILU-UV measurements, the average, minimum and maximum erythemal daily doses and ~~maxima have been ~~the maximum daily UV indices were determined for each day from one-minute averages.

2.1.2~~.3~~ Total column ozone measurements

~~O_3~~TOC data was gathered from multiple sources. For 2017–2019, measurements from the GUV ~~measurements~~radiometers were used. The calculation of ~~O_3~~TOC is described in Bernhard et al. 2005. It is based on instrument~~-~~-specific look-up tables and the ratio of irradiances measured at 305 nm and 340 nm. Pre-calculated lookup tables relate TOC to the SZA ~~calculations (Bernhard et al., 2005). Daily~~ and the ratio of the irradiances. They are calculated using the radiative transfer model libRadtran (Mayer and Kylling, 2005) in which site-specific conditions (like altitude, albedo, O_3 profile etc.) are taken into account. Also, the modelled spectra are weighted with the GUV response functions at 305 and 340 nm. Bernhard et al. 2005 validated the method at several sites, including Antarctic sites, and found that the difference between Total Ozone Spectrometer (TOMS) total ozone and GUV total ozone was within 5 % for SZAs smaller than 75°.

TOC daily averages were calculated~~, using~~ from the GUV radiometer measurements, where only observations with SZA < 65~~°,~~° were used as ~~the calculations show some wavelength~~for higher SZA TOC showed a SZA dependency~~ at high SZAs .~~. In Marambio, the period during which the SZA goes below that threshold lasts from the middle of ~~September~~Sept to the middle of ~~March~~Mar.

~~For comparison, level 3 data with 0.25° resolution from the Ozone Monitoring Instrument (OMI) on board of the Aura satellite (Levelt et al., 2018), received through NASA Giovanni interface (https://giovanni.gsfc.nasa.gov/giovanni/, last visited 14 June 2019), were used. The OMI ozone product has shown very good stability over time and a low bias between ground-based Dobson-Brewer instruments in the Northern Hemisphere (McPeters et al., 2015). The dataset includes daily values for the site 64.125° S and 56.625° W. The majority of data points (88 %) fall in the range of 1 ± 0.05 (Fig. 2). The median of the ratio is 1.01.~~



For comparison, level 3 data with 0.25° resolution from the Ozone Monitoring Instrument (OMI) on board of the Aura satellite (Levelt et al., 2018), received through the NASA Giovanni interface (https://giovanni.gsfc.nasa.gov/giovanni/, last visited 14 Jun 2019), were used. Daily values of the OMI ozone product collocated with the Marambio station (64.125° S, 56.625° W for OMI data) were used and the ratio of daily ozone values OMI/GUV was calculated. In the majority of the days (88 %), the ratio falls in the range of 1 ± 0.05 (Fig. 2). The median of the ratio OMI/GUV is 1.01 indicating slightly higher values for the OMI data, especially in 2018/2019. There is a small drift between the seasons; the average ratio is 1.00 in 2017/2018 and 1.02 in 2018/2019. The OMI ozone product has shown very good stability over time and a low bias between ground-based Dobson-Brewer instruments in the Northern Hemisphere (McPeters et al., 2015). OMI data was used also for other stations included in the study.

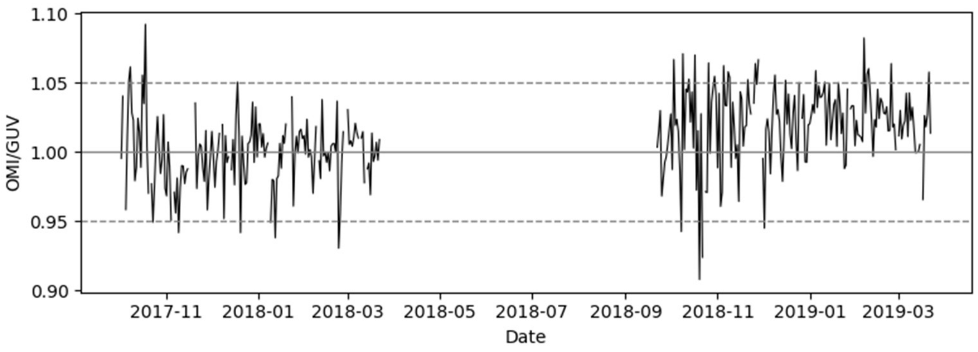


Figure 2: The ratio of OMI/GUV ~~and OMI~~ daily ~~column ozone~~TOC from 2017–2019. For GUV daily averages, measurements with SZA below 65 degrees were used.

Satellite data were also used for comparing ~~ozone~~TOC values from 2017–2019 to the period 2000–2008~~.~~ and to explain the changes in erythemal UV doses and maximum UVI values. For the period 2000–2004, version 8 ~~O_3~~TOC data from Earth Probe (EP) TOMS were used. This dataset is available on a 1° x 1.25° grid and was taken for coordinates 64.5° S and 56.875° W~~.~~, which represent the Marambio station. For 2005–2008, OMI data were used, as described in the previous paragraph. The difference of the location between TOMS and OMI ~~comes from the disagreement in resolution, as user input for both resources was the same. The good agreement between the two instruments has been presented by Anton et al. (2010),~~is due to the different resolution. The good agreement between the two instruments has been presented by Anton et al. (2010), who found an average difference of 0.6 % (with standard deviation (std) less than 3 %).

2.~~2.4~~1.3 Proxy data

~~*Polar vortex:* In Antarctica, the ozone level is strongly affected by the presence of the polar vortex. It establishes conditions with extremely low temperature and the formation of polar stratospheric clouds (PSCs), which are essential for chemical processes to activate compounds capable to destruct ozone. At the same time, the dynamical characteristics of the polar vortex provide a chemical isolation (Schoeberl and Hartmann, 1991). It was assessed whether a station was inside or outside of the polar vortex to describe the local conditions and compare seasons 2017/2018 and 2018/2019. For that, the modified potential vorticity, scaled to 475 K, from ERA-Interim data was used. Similar to Lakkala et al. (2018) – when the value was smaller than –36, the station was inside the polar vortex.~~

~~*Clouds:* Meteorological observations in Marambio are~~ For the interpretation of changes in the UV irradiance in Marambio, data for different factors affecting UV radiation and ozone in the atmosphere were collected. This data includes polar vortex information, clouds, aerosols and albedo.

Polar vortex: In Antarctica, TOC is strongly affected by the presence of the polar vortex. It establishes conditions with extremely low temperatures and the formation of polar stratospheric clouds (PSCs), which are essential for chemical processes to activate compounds capable to destruct O_3. At the same time, the dynamical characteristics of the polar vortex provide a chemical isolation that disables the mixing of mid-latitude air with the polar air and therefore sustain the compounds needed for O_3 destruction and formation of ozone hole (Schoeberl and Hartmann, 1991). To investigate the influence of the polar vortex on our observations, the location of the Marambio station with reference to the polar vortex was determined for the seasons 2017/2018 and 2018/2019. For this, the modified potential vorticity, scaled to 475 K, from ERA-Interim data was used (Lait, 1994). Similar to Lakkala et al. (2018) – when the value was smaller than –36, the station was considered to be inside the polar vortex. The same method was used for gathering the information about polar vortex for the other stations.

Clouds: Cloud data used in this study are from observations performed ~~both automatically and manually, the latter~~ by surface meteorological observers (SMO~~).~~) in Marambio. Cloud observations are part of the manual meteorological observations protocol. ~~In~~During hourly observations, the SMO performs a visual inspection of the sky defining the cloud type and the ~~cloudiness in octants, thus determining the~~ cloud cover in oktas. The cloud type is further connected with the cloud altitude, which is divided into low, medium and high level clouds. The total amount of clouds in these three levels is also visually estimated according to a standardized protocol. In Marambio, because of the location and the lack of obstacles, it is possible to view the entire sky. This allows the SMO to detect different type of clouds at different heights if the low cloud cover allows it. However, occasionally, the arrival of fog, a heavy snowstorm or ~~of~~ another exceptional high concentration event may prevent the observation of the sky above the surface.

The cloud meteorological observations in Marambio follow the protocols recommended by the World Meteorological Organization (WMO) based on the cloud atlas ~~(WMO, 2017),~~(WMO, 2017), which was developed and is governed by the international community. Therefore, it constitutes the frame of reference for all visual cloud meteorological observations by surface meteorological observers and is an official meteorological observation method.

From the cloud observations dataset, daily ~~averages~~ and ~~then~~ monthly averages were calculated for total and low cloud cover.

~~*Aerosols*: To describe the aerosol characteristics, level 3 monthly means of the aerosol optical depth (AOD) at 550 nm from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Aqua satellite were used. Detailed description and quality provided by Levy et al. (2018).~~

Aerosols: To describe aerosol characteristics, the Aerosol Optical Depth (AOD) at 550 nm from the Collection 6.1 (Levy et al., 2018) L3 monthly product (MYD08_M3) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Aqua satellite was used. In MYD08_M3, all statistics are sorted into 1°×1° cells on an equal-angle global grid. The Monthly L3 product is computed from the complete set of daily files that span a particular month. Aerosol related parameters in the monthly product required 3 valid Daily (D3) grid cells to populate the monthly aggregate. Aqua is a polar orbiting satellite with an equator-crossing around 13:30 local time. Aqua MODIS has a good performance among all AOD monthly products with small overestimation overall (Sogacheva et al., 2019; Wei et al., 2019).

Albedo: The continuous surface UV albedo measurements started in Marambio in 2013, as an Argentinian-Finnish scientific co-operation. The albedo is measured at a fixed height of approximately 2 m from the ground using two broadband ~~SL501 (SolarLight Co.) radiometers. One sensor is installed to face upwards, and the other downwards. As a best practice, sensors with similar spectral and cosine responses are used (more details in Meinander et al., 2008).~~SL501A (SolarLight Co.) radiometers. The radiometers make hemispherical measurements of the incoming irradiance weighted with the action spectrum for UV-induced erythema ~~(McKinlay and Diffey, 1987), which also has a contribution from the UVA. The data are recorded in 1-minute intervals.~~(McKinlay and Diffey, 1987), which also has a contribution from the UVA. One sensor is installed to face upwards to measure downwelling global erythemal UV irradiance including both direct and diffuse components, and the other one looks downwards to measure upwelling outgoing hemispherically reflected global diffuse erythemal UV irradiance. The data are recorded in 1-minute intervals. The albedo is then calculated as the ratio of up-welling to down-welling erythemally weighted UV irradiance. The monthly averages of daily noon UV albedo were calculated from these local albedo data. As a best practice, sensors with similar spectral and cosine responses are used (more details in Meinander et al., 2008). The sensors are temperature controlled. In the data file, one column contains the sensor temperature recorded every minute. As SL501A measurements can be temperature affected, temperature records are used for the QA/QC online monitoring of the measurements. The Finnish Radiation and Nucleation Safety Authority (STUK) determines the calibration factor for each SL501 sensor, which is used to calibrate the measurement data. ~~The albedo is then calculated as the ratio of up-welling to down-welling erythemally weighted UV radiation. The monthly averages of daily noon UV albedo were calculated from this data.~~ The official SL501A trace is to NIST (Lakkala et al., 2018). Via the primary calibration lamp, the measurements are traceable also to the National Standard Laboratory MIKES, Aalto University (HUT), Finland. The difference in calibration coefficients using NIST and MIKES has been found to be less than 2 %, and a comparison of spectral UV irradiance scales maintained by NIST, PTB (Physikalisch-Technische Bundesanst) and Aalto University shows that there are no major differences (Jokela et al., 2000). For these data of calibrated, spectrally characterized and temperature controlled sensors, effects of degradation are not corrected for. Changes in the stability of the sensors between the pre- and post-calibrations remain to be determined. However, it can be noted that any similar temporal degradation of the two SL501A sensors, as measured in percentages, would be compensated when the ratio of the signals is calculated for albedo. Hence, in post-calibrated data, it will be essential to study whether the degradation of one instrument is different from that of the other one. In general, when use is made of albedo measurements by SL501 radiometers with similar spectral responses, errors due to differences in the sensors are expected to be less than 1 %, (WMO, 1997). As described in Hülsen and Gröbner (2007), the typical total uncertainty for SL501 instruments is 1.7 - 4.3 %.

2.2~~.5 UV measurements~~ Princess Elisabeth Station in ~~other~~Utsteinen

The Belgian Antarctic ~~stations~~Princess Elisabeth station is located on the granite ridge of the Utsteinen Nunatak in Dronning Maud Land, East Antarctica (Herenz et al., 2019; Pattyn et al., 2010), see Figure 1. It is located about 200 km inland from the Antarctic coast and lies north of the Sør Rondane mountain range. The station lies in the escarpment zone between the Antarctic inland plateau and the coast where it experiences the influence of both synoptic weather systems and katabatic winds (Gorodetskaya et al., 2013). It has been designed as a zero emission station that is inhabited from Nov until the end of Feb, with remote access to instruments during winter.

~~*PE:*~~ UV spectral measurements at the ~~PE~~ station are provided by the double-monochromator Brewer spectrophotometer #100 of the Royal Meteorological Institute of Belgium (RMI). Accurate spectral profiles of UV radiation in the 290–325 nm wavelength range are measured. The raw counts are converted to counts per second and corrected for instrument dead time, dark count and temperature. The corrected raw count rates are then divided by the instrument response values. This responsivity is obtained by measuring the response of the Brewer to a source with known radiation (tungsten halogen lamps with a calibration certificate). The spectral erythemal solar UV irradiance, $E_{ery,\lambda}$, (in W m^{-2} nm^{-1}) is calculated by multiplying E_λ with the appropriate weighting values at each wavelength (CIE action spectrum). UVI values are derived according the method described above. Lamp tests with standard 50 W lamps are performed during calibration campaigns at Uccle (Belgium). Changes in the stability of the instrument between the two calibrations (in 2010 and 2014) remained within 10 %. Note, that the Brewer spectrophotometer is only operated when the station is inhabited (Nov to Feb).

Noon UVI values used in this study are from measurements~~,~~ conducted by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB~~), started in 2012. A weatherproof container was installed to perform continuous measurements of the solar global irradiance. Three pyranometers,~~) using a pyranometer, manufactured by EKO Instruments (Japan), ~~covering three broadband spectral ranges:~~for UVB (model MS212W, 280–315 nm~~), UVA (model MS212A, 315–400 nm) and Total (model MS402F, 285–3000 nm), are used.~~). The UVB pyranometer, equipped with a quartz dome and stabilized temperature, provides global irradiance measurements that are averaged every minute. The raw data (Volt) are converted into W/m² using ~~a~~the factory calibration coefficient and a procedure to consider the deviation of the angular response of the instrument to the ideal cosine response. Calibrated data are converted into UVI. The uncertainty of UVI reaches up to 10 %, due to trends in the calibration and the absence of angular correction.

2.3 Troll~~: Total ozone~~ station

The Troll station is operated by the Norwegian Institute for Air Research (NILU) at Trollhaugen. The observatory is located at approximately 1 km east of the Troll research station in the Jutulsessen nunatak area, Queen Maud Land, about 235 km from the coast and 1553 m a.s.l. (Fig. 1). The station is unperturbed by local activity and has continuous year-round monitoring in Antarctica.

UV ~~data~~products are ~~collected by~~ calculated from measurements of a NILU-UV instrument (serial number 005~~), which is calibrated once a~~) with 5 UV channels (302, 312, 320, 340 and 380 nm) and FWHM of about 10 nm. The instrument records data with 1 min time resolution. The relative spectral response function was calculated at the Norwegian Radiation and Nuclear Safety Authority. For absolute calibration, The Sun is used as a light source and irradiance is measured by a reference radiometer at the same time and location as NILU-UV. Once every month~~.~~, a relative calibration takes place at the station to determine the drift factor and compensate for the degradation of the optical components. (Sztipanov et al., 2020).

2.4 Palmer, McMurdo and Amundsen-Scott South Pole stations

Palmer, McMurdo and Amundsen-Scott South Pole stations (see Fig. 1 for locations) are all part of the United States Antarctic UV Network and the data an information about the sites were received through the network website (https://esrl.noaa.gov/gmd/grad/antuv/, last visited Jan 16, 2020).

Out of all the selected stations, Palmer is the closest to Marambio. It is situated on Ansver Island just outside the Antarctic Circle. (Information from https://esrl.noaa.gov/gmd/grad/antuv/Palmer.jsp, last visited Jun 13, 2019).

McMurdo station is located on the Southern tip of Ross Island. The Solar season lasts from Aug to Apr, but the station is opened all year round. (Information from https://esrl.noaa.gov/gmd/grad/antuv/McMurdo.jsp, last visited Jun 13, 2019).

South Pole station is located at the geographic South Pole. The Solar season lasts there from Sept to Mar. The annual average temperature at the pole is -49 °C. The conditions are quite different from all the other stations as there is almost no diurnal change in SZA. The meteorological conditions at the station are stable. ~~For *Palmer*, *McMurdo* and *South Pole*, the data were received through the NOAA Antarctic UV Monitoring Network website (https://esrl.noaa.gov/gmd/grad/antuv/, last visited 12. June, 2019). The version 2 dataset was used, the newest release that has higher accuracy than previous versions and has been corrected for cosine error (Bernhard et al., 2004). UVI values from Database 3 were used. All three stations use the United States National Science Foundation (NSF) UV Spectroradiometer system (SUV-100), manufactured by Biospherical Instruments Inc. The uncertainty of biologically relevant UV irradiance is approximately 6 % (Bernhard et al., 2004).~~

There is also low cloud cover, constant snow and very low air pollutant levels. (Information from https://esrl.noaa.gov/gmd/grad/antuv/SouthPole.jsp, last visited Jun 13, 2019).

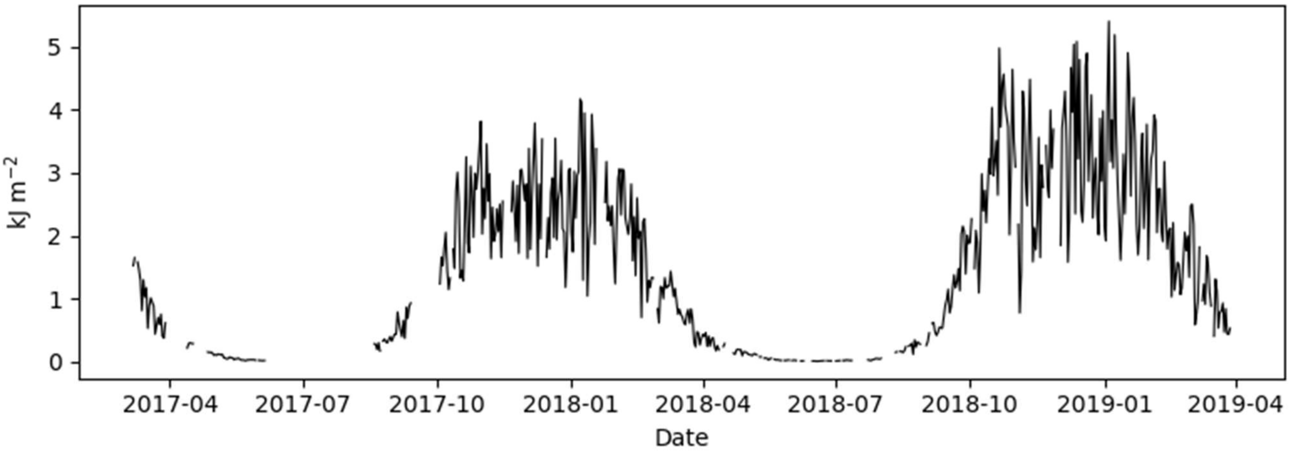
Version 2 data from the National Oceanic and Atmospheric Administration (NOAA) Antarctic UV Data Repository was used for Palmer, McMurdo and South Pole stations. It is the newest release that has higher accuracy than previous versions and has been corrected for cosine error (Bernhard et al., 2004). UVI values from Database 3 were used. All three stations use the NSF SUV-100 instrument, manufactured by Biospherical Instruments Inc. The uncertainty of biologically relevant UV irradiance is approximately 6 % (Bernhard et al., 2004). The instruments are calibrated periodically using a 200-Watt tungsten-halogen standard lamp, traceable to the NIST.

3 Results

3.1 Characteristics of UV ~~and Ozone~~radiation in Marambio, 2017–2019

To describe the UV radiation levels and compare the past two seasons, daily erythemal UV doses in Marambio were calculated (Fig. ~~4~~3). The UV irradiances manifest two peaks – one during annual destruction of O_3 (the so-called ozone hole) during the local spring (Sept–Nov) and the other one in the summer (Dec–Jan) when noon SZA is the lowest. These periods with high doses were present in both seasons, 2017/2018 and 2018/2019. The largest variations of the UV irradiance occur also during these seasons (spring and early summer). The standard deviation of the erythemal daily dose in Oct 2017 and 2018 was 0.99 kJ/m^2 and in Jan 2018 and 2019 1.02 kJ/m^2, in Sept and Mar it is around 0.5 kJ/m^2. There is a visible difference between the measured UV irradiances in 2017/2018 and 2018/2019 (Fig. 3). In 2017/2018 the average daily erythemal dose from Sept – Mar was 1.88 kJ/m^2, while in the next season it was 23 % larger (2.37 kJ/m^2) and the monthly average of daily doses was lower in each month during 2017/2018 compared to the corresponding month in 2018/2019 (Table 2).

The maximum daily erythemal doses measured in ~~the~~ seasons 2017/2018 and 2018/2019 were 4.17 kJ/m² (on Jan 7, 2018) and 5.40 kJ/m² (on Jan 4, 2019~~)~~), respectively~~. Although both maxima were measured during the local summer, there are also apparent peaks in daily doses in spring~~, i.e. a difference of more than 25%. The maximum daily dose of 2017/2018 was exceeded on 20 days (during the months of Oct 2018 to Jan 2019) in 2018/2019, which shows that ~~are not synchronized with the changes in SZA (Fig. 4). In season 2017/2018 erythemal doses~~ daily doses were ~~overall considerably lower than in 2018/2019, as clearly demonstrated from the monthly averages of daily doses (Table 1).~~systematically larger in that period than in the year before.



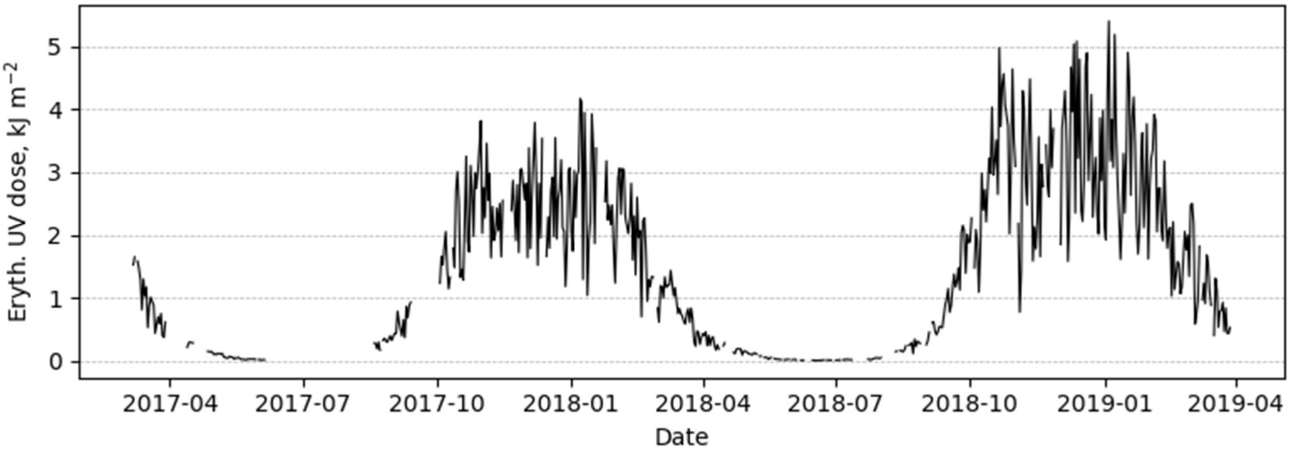


Figure ~~4~~3: Daily erythemal UV doses in Marambio from ~~March~~Mar 2017 to ~~March~~Mar 2019.

Table ~~1~~2: Monthly averages of daily erythemal doses (kJ/m^2) from Sept to Mar with std (in brackets) for the seasons 2017/2018 and 2018/2019. Higher values in each month are in bold. ~~Monthly~~For Sept 2017, 13 days were available, for the rest of the months at least 25 days were included. For comparison, monthly averages with ~~St. Dev~~std for the years 2000–2008 are ~~also~~ included in the third column, and discussed in section 3.2.

	2017/2018	**2018/2019**	**2000-2008**
SEPT	0.61 (0.21)	**1.02** (0.58)	1.05 (0.65)
OCT	2.16 (0.78)	**3.02** (1.00)	2.21 (0.97)
NOV	2.43 (0.48)	**2.83** (0.96)	2.91 (1.15)
DEC	2.50 (0.70)	**3.38** (1.05)	3.23 (1.00)
JAN	2.58 (0.89)	**3.13** (1.06)	2.93 (0.97)
FEB	2.04 (0.67)	**2.14** (0.81)	1.87 (0.70)
MAR	0.82 (0.33)	**1.08** (0.61)	0.82 (0.35)

The ~~variations~~variation of the daily maximum UVI closely ~~follow those~~follows that of the daily erythemal doses in both seasons (Fig. ~~5~~4). In season 2017/2018, the daily maximum UVI values were overall lower than 6, with high values (UVI 6–7, according to the WHO categorization, ~~WHO, 2002), on only 3 days. The maximum value was 6.2 (measured on Jan 18, 2018).~~WHO, 2002), on only 3 days. The maximum value was 6.2 (measured on Jan 18, 2018). In the second season, the maximum UVI was much higher, 9.5 (Nov 6, 2018), and there were 59 days ~~when~~on which the UVI exceeded 6. Out of those, 10 days had very high values (UVI 8–10, WHO, 2002).

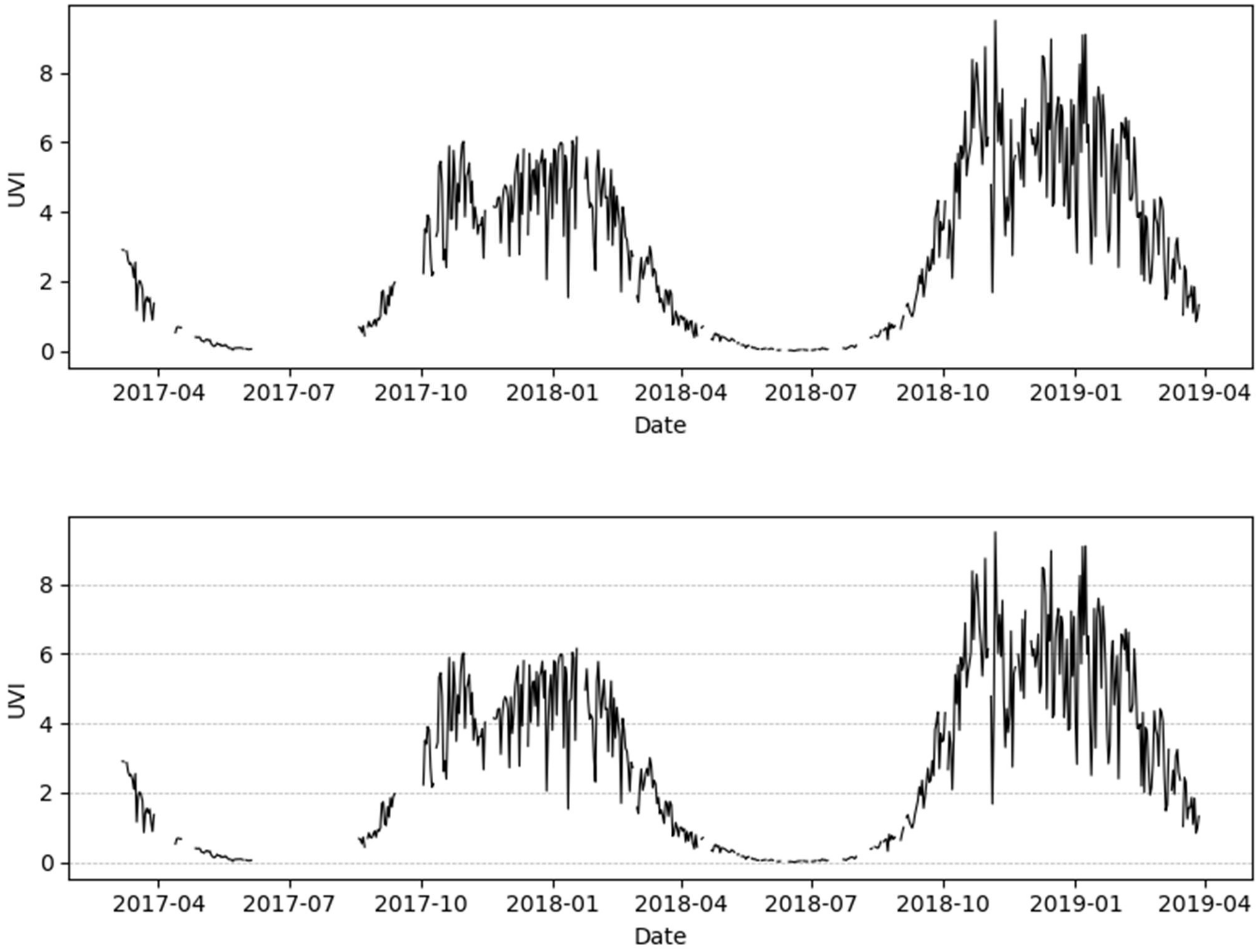


Figure ~~5~~4: Daily maximum UV ~~indexes~~indices in Marambio from ~~March~~Mar 2017 – ~~March~~Mar 2019.

~~Variations in factors affecting UV irradiance on the ground level must be the reason for the considerable differences between the two seasons. The most important of these factors are cloudiness and ozone (Kerr, 2005; Seckmeyer et al., 1996). The influence of AOD and albedo will also be investigated.~~

~~The monthly averaged cloud cover for the months during which the solar irradiance is the highest in Marambio (Oct–Feb), is presented in Table 2. In October, December and January average cloudiness was lower in season 2018/2019, with the largest difference of 1.1 octas in October. As the effect of clouds on UV depends on the cloud types (Lopez et al., 2009), the same calculations of monthly averages and comparison between months were done for low clouds, but the results were very similar in terms of differences between the seasons. As clouds mainly attenuate radiation, lower cloudiness in similar SZAs means more UV radiation reaches the ground.~~

Variations in factors affecting UV irradiance at ground level must be the reason for the considerable differences between the two seasons. The most important factors influencing UV are cloud cover and O_3 (Kerr, 2005; Seckmeyer et al., 1996). Also, albedo and aerosol can cause the variations in erythemal UV.

The monthly averaged cloud cover for the months during which the solar irradiance is the highest in Marambio (Oct–Feb), is presented in Table 3. In 2017/2018, cloud cover in Oct, Dec and Jan was higher than in 2018/2019, with the largest difference in Oct (1.1 oktas), while in Nov and Feb the cloud cover was lower by 1 and 0.8 oktas, respectively. As the effect of clouds on UV irradiance depends on the types of cloud (Lopez et al., 2009), the same calculations of monthly averages and comparison between months were done for low clouds, but the results were very similar with respect to differences between the seasons. As clouds mainly attenuate radiation, smaller cloud cover but similar SZA, results in more UV radiation reaching the ground. This means that, for our dataset, cloud cover can qualitatively explain part of the lower UV values observed in Oct, Dec. and Jan in 2017/2018 compared to the 2018/2019. In Nov and Feb the average cloud cover is lower in 2017/2018 compared to 2018/2019, meaning there are other factors causing the lower UV doses in 2017/2018 during those months in comparison to 2018/2019.

Table ~~2~~3: Monthly average total ~~cloudiness (octas), total column ozone~~cloud cover (oktas), TOC (DU~~)~~), AOD at 550 nm and ~~AOD~~albedo with std in the parentheses for five months in the seasons 2017/2018 and 2018/2019. ~~Values that contribute to the higher UV levels in season 2018/2019 are in bold.~~

	~~CLOUD~~cloud cover, ~~OCTAS~~oktas		**~~OZONE~~TOC, DU**		**AOD**		**albedo**	
	2017/2018	2018/2019	2017/2018	2018/2019	2017/2018	2018/2019	2017/2018	2018/2019
Oct	5.9 (2.1)	4.8 (1.9)	234 (61)	191 (26)	NA	0.155	0.3 (0.1)	NA
Nov	5.1 (2.1)	6.1 (1.7)	336 (54)	275 (65)	0.097	0.112	0.1 (0.1)	0.2 (0.2)
Dec	6.6 (1.2)	5.9 (1.8)	321 (18)	309 (18)	0.072	0.089	0.2 (0.1)	0.2 (0.2)
Jan	6.9 (1.5)	6.7 (1.5)	307 (12)	290 (13)	0.076	0.089	0.2 (0.1)	NA
Feb	6.2 (1.2)	7.0 (1.5)	301 (15)	278 (21)	0.136	0.096	0.2 (0.2)	0.4 (0.1)

~~Another important factor influencing the UV radiation reaching the ground is O$_3$, especially in Antarctica, where the ozone hole appears annually.~~ The daily ~~averages of O$_3$ are shown in Figure 6. The~~ average TOC values are plotted in Fig. 5. The TOC value ~~of O$_3$ in~~averaged over the season 2017/2018 was 297 DU (std 49 DU) with a minimum of 152 DU and a maximum of 386 DU ~~(for the period where the maximum SZA is below 65°).~~. In ~~the~~ 2018/2019 ~~period~~, the average was 12 % smaller, 263 DU (std 53 DU) with a minimum of 131 DU and a maximum of 367 DU. ~~The averages are also lower for each month in 2018/2019 and the disparity is especially large in October and November (Table 2). These are the months, during which the ozone hole occurs and the thickness of the ozone layer is most variable.~~

~~The total column ozone~~The TOC value in Antarctica is influenced by the location of the polar vortex~~.~~: inside the polar vortex, TOC values are generally lower. For estimating whether the Marambio station was inside or outside the polar vortex, potential vorticity analysis was carried out (see section 2.2.4). ~~Potential~~The potential vorticity was lower than the chosen limit of -36 ~~on~~during a total of 130 days in the season 2017/2018 and 134 days in 2018/2019. In spring ~~(Sept–Dec),~~, when the ozone hole is present, Marambio was inside the polar vortex for 68 ~~and 83~~ days ~~for the~~during 2017/2018 and 83 days during 2018/2019 ~~season respectively.~~. The first day since ~~September~~Sept 2018, when the potential vorticity was not lower than -36, was Nov 5. In 2017, the situation was much less stable with several days (both in ~~September~~Sept and ~~October~~Oct), on which the Marambio station was outside the polar vortex and more ozone was present in the atmospheric column above.

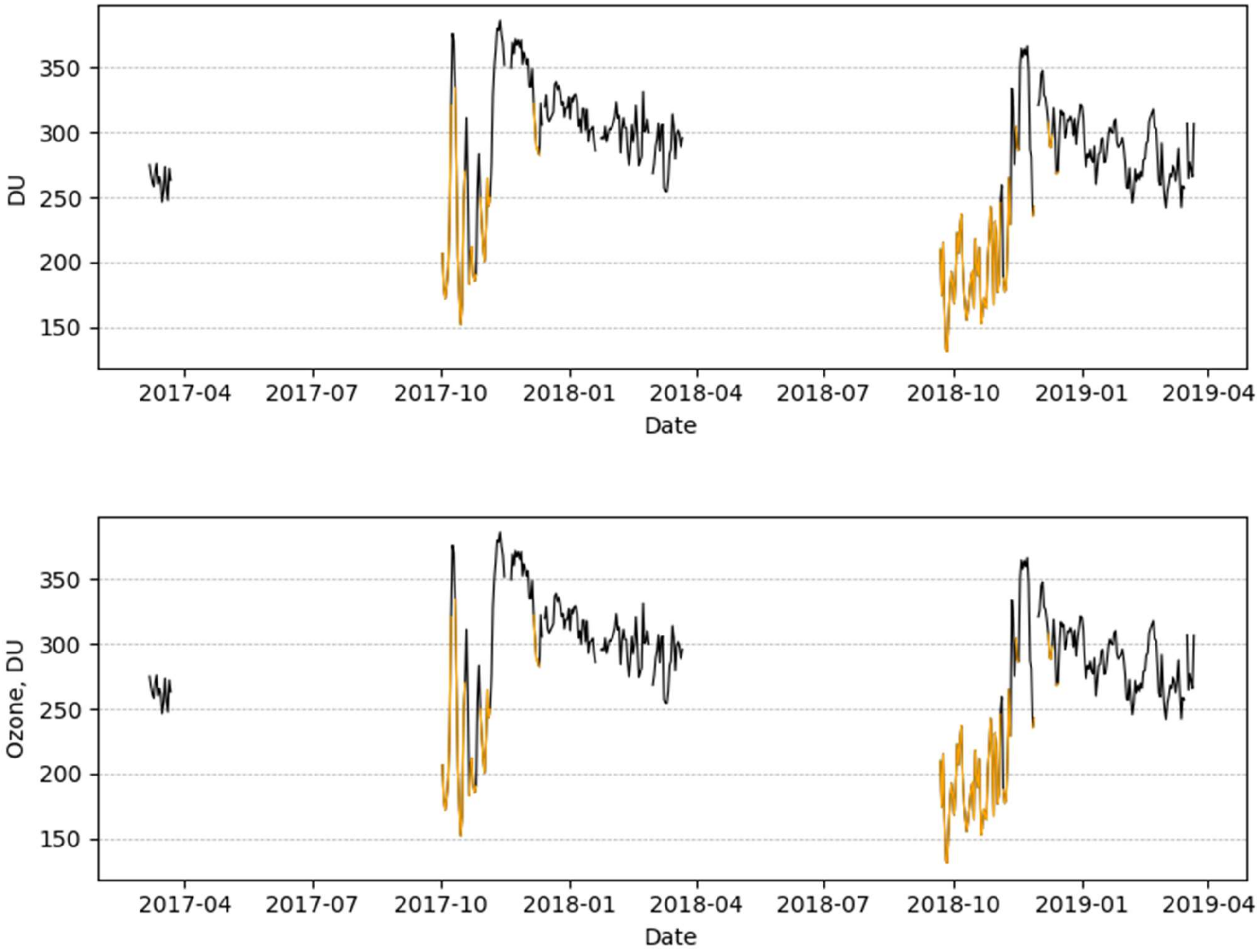


Figure ~~6~~5: Daily average ~~ozone column~~TOC at Marambio calculated from GUV measurements with SZA ~~>~~≤ 65 degrees (2017–2019). Days during which the station was inside the polar vortex (vorticity < -36) are in orange.

~~Aerosol concentrations in Marambio are low and the aerosol mixture consists mainly of sulphate, sea salt and crustal mineral components (Asmi et al., 2018). The AOD monthly averages are lower than 0.2 in both years (Table 2). The differences between months of 2017/2018 and 2018/2019 are within the known uncertainty (around 0.05 + 20 % over land and 0.03 + 15 % over ocean, Levy et al., 2013). This means that regarding AOD, no significant difference was found between the two time periods.~~

The monthly averages are lower for each month in 2018/2019 and the disparity is especially large in Oct and Nov, 43 and 61 DU respectively (Table 3). These are the months, during which the ozone hole occurs and the thickness of the ozone layer is most variable.

For describing the effect of O_3 on UV irradiance, the RAF with a value of 1.2, has been used. The expected changes in average daily erythemal dose due to a decrease in average TOC between the seasons 2017/2018 and 2018/2019 was calculated for each month from Oct to Feb and compared to the measured changes (Fig. 6). The results were similar when using the power law relationship for calculating RAF (McKenzie et al., 2011) (section 2) for larger changes in O_3. In Nov and Feb the increase in monthly average UV from 2017/2018 to 2018/2019 is caused by ozone, but due to higher cloud cover in the second season, the increase is less than calculated solely using RAF. In Oct, more than half of the increase can be explained by the decrease in TOC, the rest is due to the larger cloud cover in 2018/2019 (1.1 oktas), which is the largest difference in monthly averages for those two seasons. In Dec and Jan, less than 1/3 of the increase in average erythemal dose is explained by ozone and the rest of the change is due to other factors. In both months, the average cloud cover is lower in 2018/2019 than in 2017/2018 (0.7 and 0.2 oktas, respectively). In Jan, the average difference in cloud cover is small as is the difference in average TOC (17 DU). However it is important to note the timing when those differences occur. The TOC is lower from Jan 2 to 18, 2019, compared to the same period in 2018. In the first half of January the noon SZA is lower than in the second half. In the second half of Jan 2019, the cloud cover was lower – there are 5 days with daily average cloud cover smaller than 5, at the same time in 2018 there were none. So even though the monthly mean values are similar, there are day-to-day variations and the factors causing higher daily doses in 2019 are different during different days.

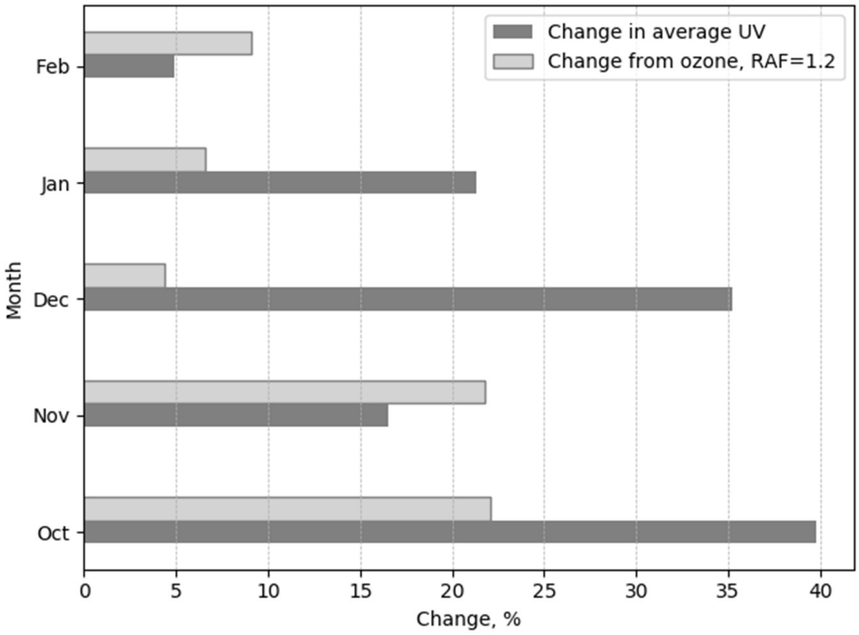


Figure 6: Change in average daily erythemal dose between the seasons 2017/2018 to 2018/2019 for each of the months from Oct to Feb (dark grey) and expected changes due to decrease in average TOC using RAF=1.2 (light grey).

Aerosol concentrations in Marambio are low and the aerosol mixture consists mainly of sulphate, sea salt and crustal mineral components (Asmi et al., 2018). The AOD monthly averages are lower than 0.2 in both years (Table 3). The differences between the different months in 2017/2018 and 2018/2019 are within the known uncertainty (around 0.05 + 20 % over land and 0.03 + 15 % over ocean, Levy et al., 2013). This means that regarding AOD, no significant difference was found between the two time periods.

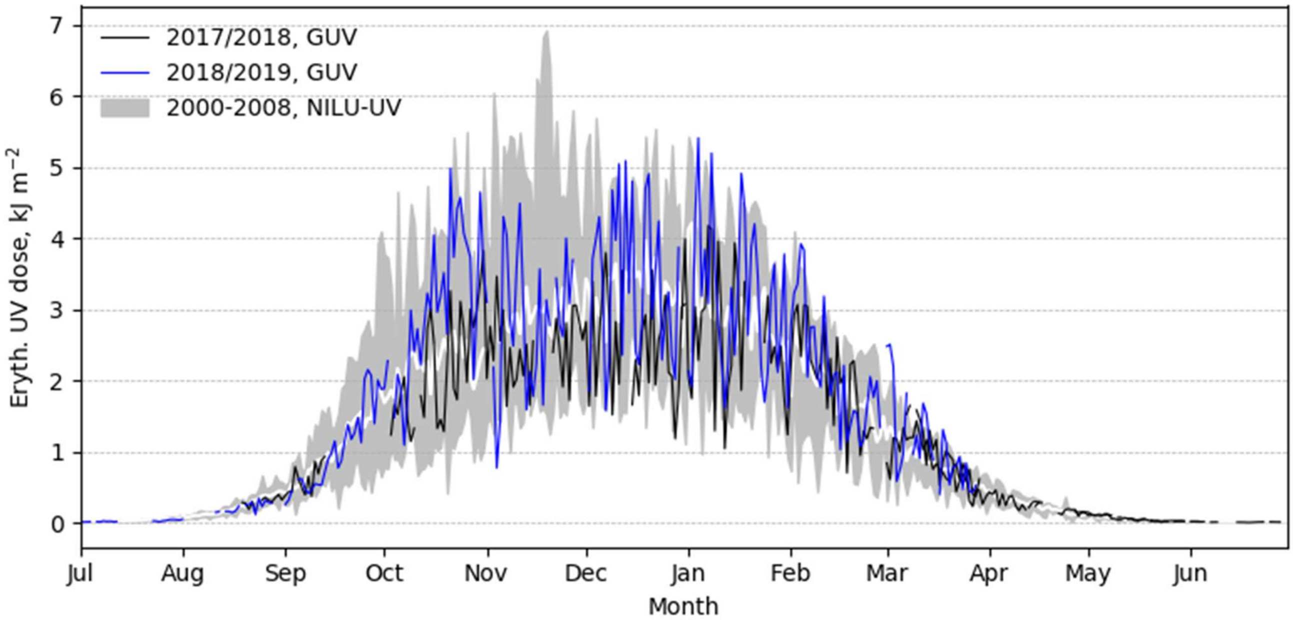
Albedo, which also affects the UV ~~irradiation~~irradiance measured in Marambio, ~~is~~ mainly ~~dependent~~depends on ~~the~~ snow cover. Unfortunately, albedo measurements are not available at Marambio for all months in 2018/2019. The data that is available shows a slightly higher monthly average for the daily noon albedo in Nov 2018, compared to Nov 2017 and in Feb 2019 compared to Feb 2018~~.~~; the differences are 0.1 and 0.2 respectively. Higher average albedo will lead to higher recorded UV doses, which supports our finding of higher UV levels in 2018/2019 compared to 2017/2018. Snow on the surface has been shown to increase the monthly erythemal doses by more than 20% (Kylling et al., 2000). These authors report that clouds reduce the monthly erythemal doses by 20–40%. The averages in the presented data were calculated from 21 - 30 daily noon albedo values per month except for Oct 2017, when only 8 values were available). Hence, it can be concluded that these data showed a slight year-to-year differences in surface UV albedo for Nov and Feb, and no difference for Dec. Oct and Jan could not be compared due to missing data. Albedo changes are likely connected with changes in surface conditions (snow, no snow, or impurities on snow). Our albedo data demonstrate the need for continuous measurements of albedo and UV doses to detect seasonal and year-to-year variability, and long-term changes and trends. They also indicate a further need to study the reasons behind the observed albedo changes from one season to another.

Daily doses of UVA (315–400 nm) radiation were also somewhat higher in 2018/2019 than in the previous year, but the difference was not as large as for erythemal radiation. Average daily UVA doses from ~~October~~Oct to ~~January~~Feb in 2017/2018 were 0.78, 1.18, 1.04~~ and~~, 1.04 and 0.91 MJ/m^2, in 2018/2019 ~~the~~these numbers were 0.89, 1.04, 1.24~~ and~~, 1.08 and 0.79 MJ/m^2 ~~respectively. In February the average of daily UVA doses was larger in 2017/2018 than the year after.~~(Lakkala et al., 2019). The different behaviour of erythemal and UVA radiation shows the importance of ~~ozone~~O$_3$ in causing the significant differences observed between the two seasons for erythemal radiation and UVI~~. At~~, as the ~~same time, the slightly larger daily doses show~~UVA is not affected by O$_3$, but mainly by cloud cover and surface albedo.

Proxy data together with UVA data shows that the cause behind low erythemal irradiance in Marambio is mainly from a combination of the influences of O$_3$ and clouds, as no conclusions can be drawn from the albedo data. In Oct over half of the difference in UV can be explained by O$_3$ while the other ~~factors also contribute to~~half is explained by the higher ~~amount of radiation in~~ cloud cover in 2017. In Nov and Feb the lower cloud cover in 2017/2018~~/2019~~ reduced the effect of O$_3$ and in Jan and Dec most of the difference is caused by differences in cloud cover.

3.2 Comparison with previous (2000–2008) measurements in Marambio

The past two UV seasons in Marambio have not been ~~extraordinary~~extreme, although there were periods when the erythemal daily doses and maximum UVI ~~was~~were noticeably different from the averages in the period 2000–2008. In general, daily erythemal doses measured during 2017–2019 fall in the range of the long-term ~~fluctuation~~fluctuations of daily doses measured between 2000~~–~~ and 2008 (Fig. 7). In the season 2017/2018 though, there was a long period from ~~the middle of~~ spring until the end of the summer~~,~~ (57 days from Oct – Dec), when daily doses were mostly below the long-term daily average. On ~~some~~16 of these days, the values were even~~ were~~ below the long-term minimum. The monthly averages of daily doses in that season were below the long-term values from ~~September~~Oct to ~~January~~Jan (Table ~~1). In 2018/2019, daily doses were much larger.~~ 2) with differences from 2.3 % to 25.5 %. The same is true for Sept, but only 13 days of measurements were available for calculating monthly average. In spring 2018, there was a longer period ~~where~~(Oct 13 – Nov 1), when the daily doses were continuously above the long-term average~~.~~, and in addition they were above the average for half of the days in Nov and Dec. The monthly average daily erythemal dose in ~~October~~Oct exceeded the long-term ~~one~~average with more than 0.8 kJ/m^2. Monthly averaged daily doses were higher than the long-term values also from ~~December~~Dec to ~~March~~Mar. In addition, there were several days in spring 2018 (5 in Oct and 5 in Dec) where the daily doses exceeded the long-term maximum, although the highest erythemal daily dose recorded ~~with NILU-UV~~during 2000–2008 was over 6.9 kJ/m^2 (Nov 19, 2007) and none of the daily doses reached that high in recent seasons.



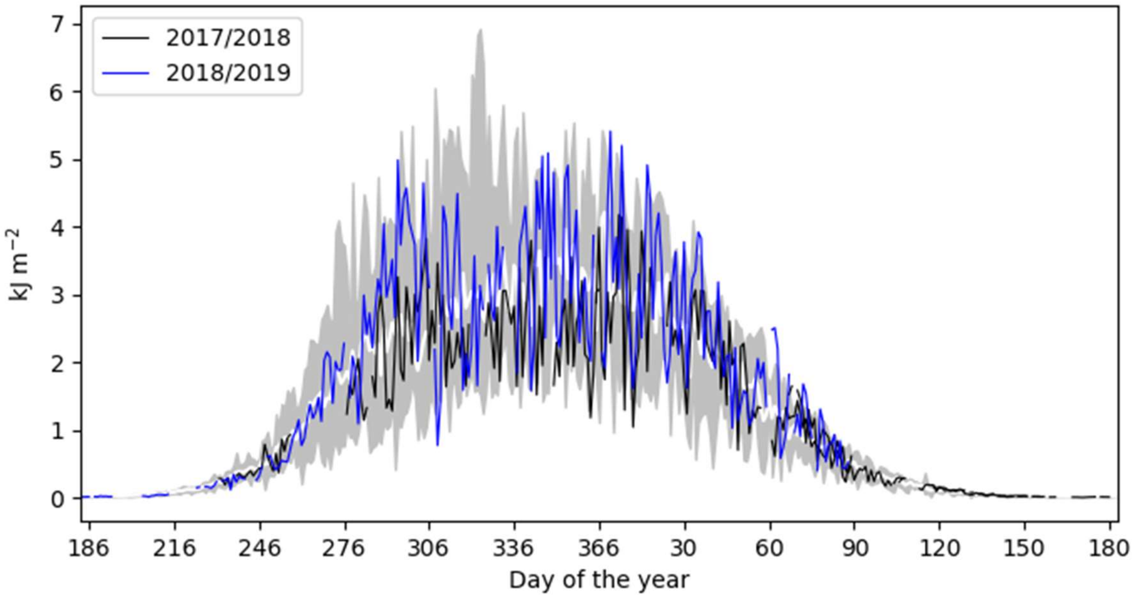
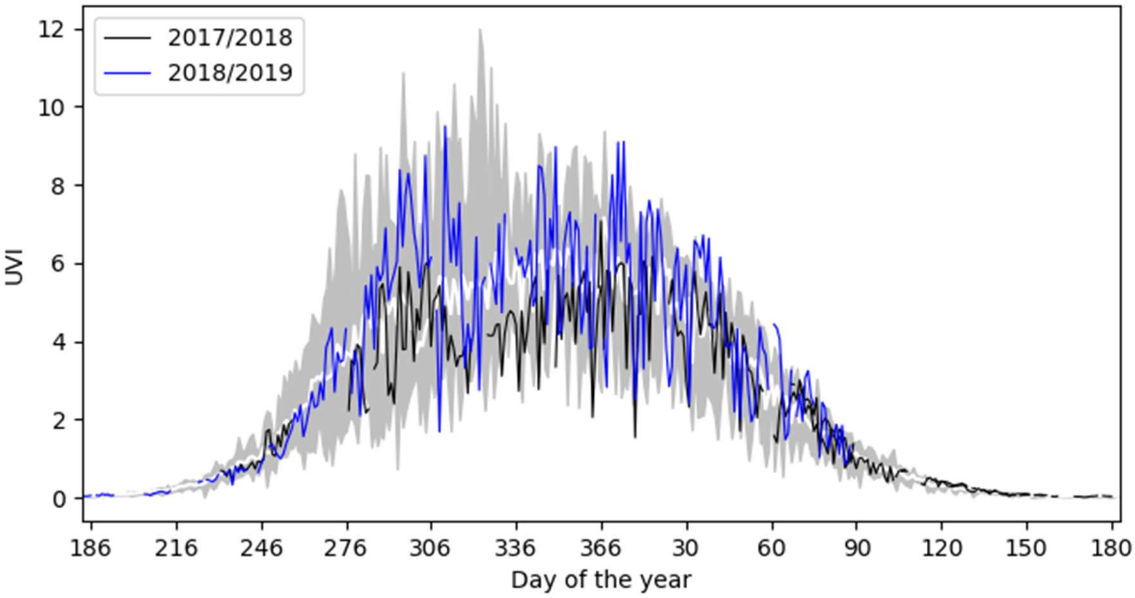


Figure 7: Comparison of daily erythemal UV doses from GUV measurements in Marambio in ~~season~~seasons 2017/2018 (black line) and 2018/2019 (blue line) with long-term measurements (2000–2008). The white line is the long-term (2000–2008) mean and the grey area is set between long-term maxima and minima for each day.

For the daily maximum UVI, the situation was similar to that of the daily erythemal doses (Fig. 8). The maximum value recorded in 2000–2008 was 12 and no measurement from 2017–2019 reached that high~~.~~ as no such low TOC together with low cloud cover occurred for 2017-2019. Long-term daily maximum values were exceeded ~~in~~on 19 ~~cases~~days during 2017/2018. The majority of these days were in ~~April~~Apr and May and none in the spring. In 2018/2019, there were 30 such days - 6 in spring, including the day with the record of 9.5. During a large part of 2017/2018, UVI was below the long-term daily maximum mean (127 days). On 43 days UVI values even went below the long-term minimum. In 2018/2019, the ~~amount~~number of days during which the UVI was below the long-term daily maximum mean and below the long-term minimum was 110 and 26 respectively.



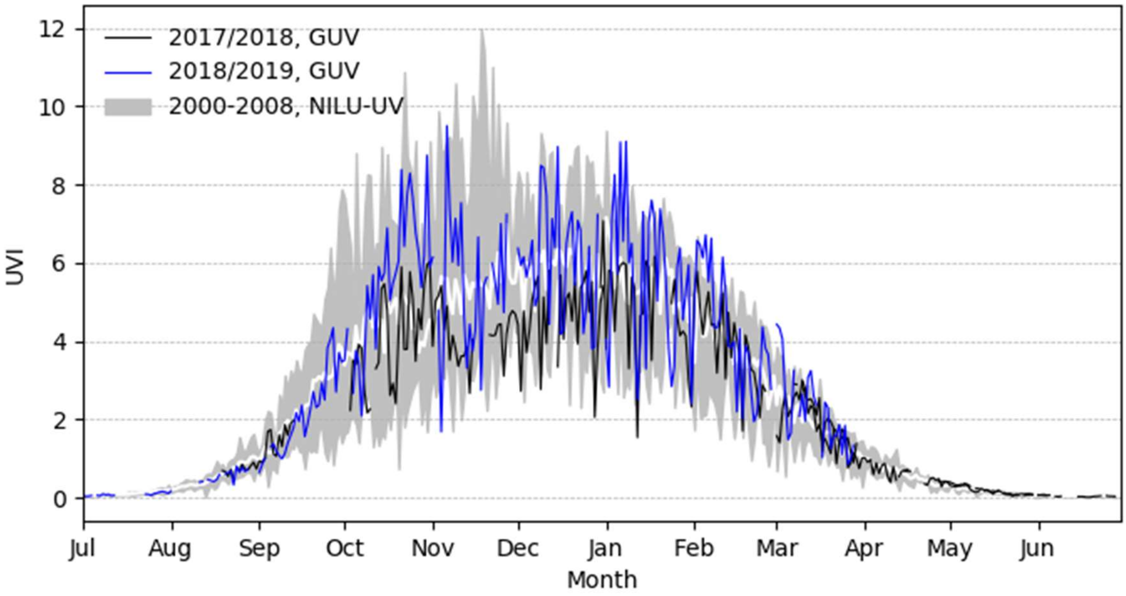
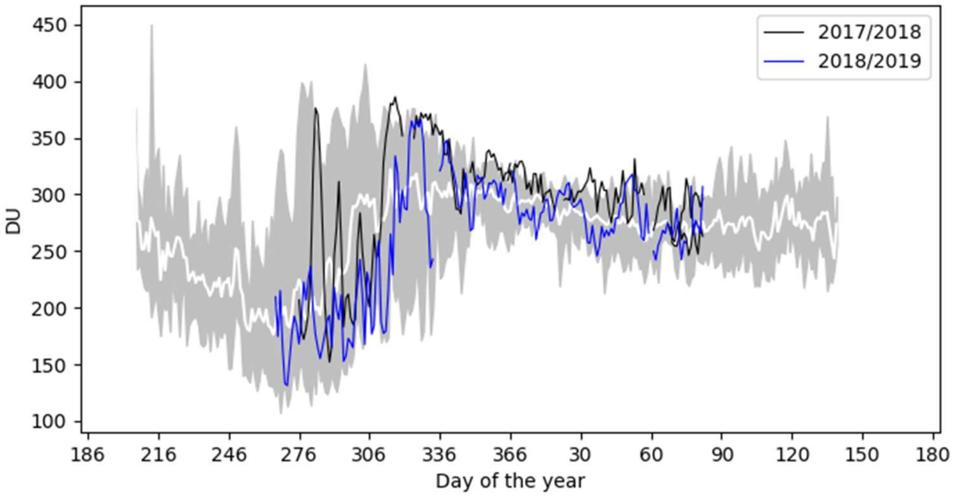


Figure 8: Comparison of daily maximum UVI from GUV measurements in Marambio in ~~season~~the seasons 2017/2018 (black line) and 2018/2019 (blue line) with long-term measurements (2000–2008). The white line is the historical mean (2000-2008) and the grey area is set between historic maxima and minima of maximum UVI for each day.

The sharp drop in maximum UVI values (from 5.4 to 2.6 in ~~November~~10 days) in Nov 2017 is coincident with the abrupt rise in ~~O_3~~TOC (from 243 to 368 DU for the same period) that at its peak exceeds even the long-term variation limits. The general ~~ozone~~TOC level stayed high until the end of summer in ~~March~~Mar 2018 compared to the measurements from 2000–2008 (Fig. 9). Daily ~~O_3~~TOC was higher than the long-term maximum on 54 ~~days~~ out of 162 days in the season 2017/2018 and there is only 1 day (Oct 31, 2017) ~~where~~when the ~~ozone~~TOC value was lower than the long-term minimum. In the next season, there were only 14 days when the maximum values were exceeded and 9 when new daily minima were set. The results from the analysis of ~~O_3~~TOC data are in good correspondence to the recent recorded UV levels, when considering the negative correlation of these two values.



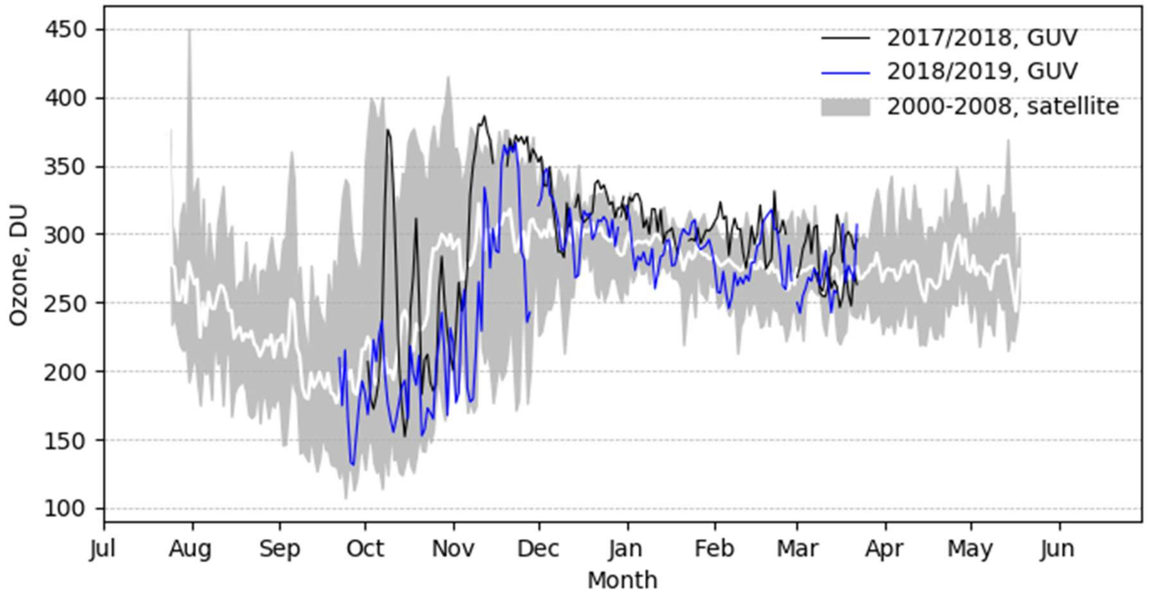


Figure 9: Comparison of ~~ozone~~TOC calculated from GUV in Marambio in ~~season~~seasons 2017/2018 (black line) and 2018/2019 (blue line) with long-term measurements (2000–2008) from satellites. The white line is the long-term daily average (2000-2008) and the grey area is the region between the period’s daily maxima and minima.

Long-term averages ~~in~~of cloud cover in Marambio show an annual cycle for both total and low cloud cover. The total cloud cover is lowest during ~~the winter (July–~~Jul and Aug~~), where~~, when averages are ~~below~~smaller than 4.5 ~~octas~~oktas, and highest during summer~~ (~~, in Dec~~–~~ and Jan~~),~~, where they are ~~over~~more than 6.1 ~~octas~~oktas. This pattern is also present in the seasons of 2017/2018 and 2018/2019 (Table ~~2~~3). Compared to the 2000–2008 averages, in ~~the~~ 2017/2018 ~~all months between October and~~

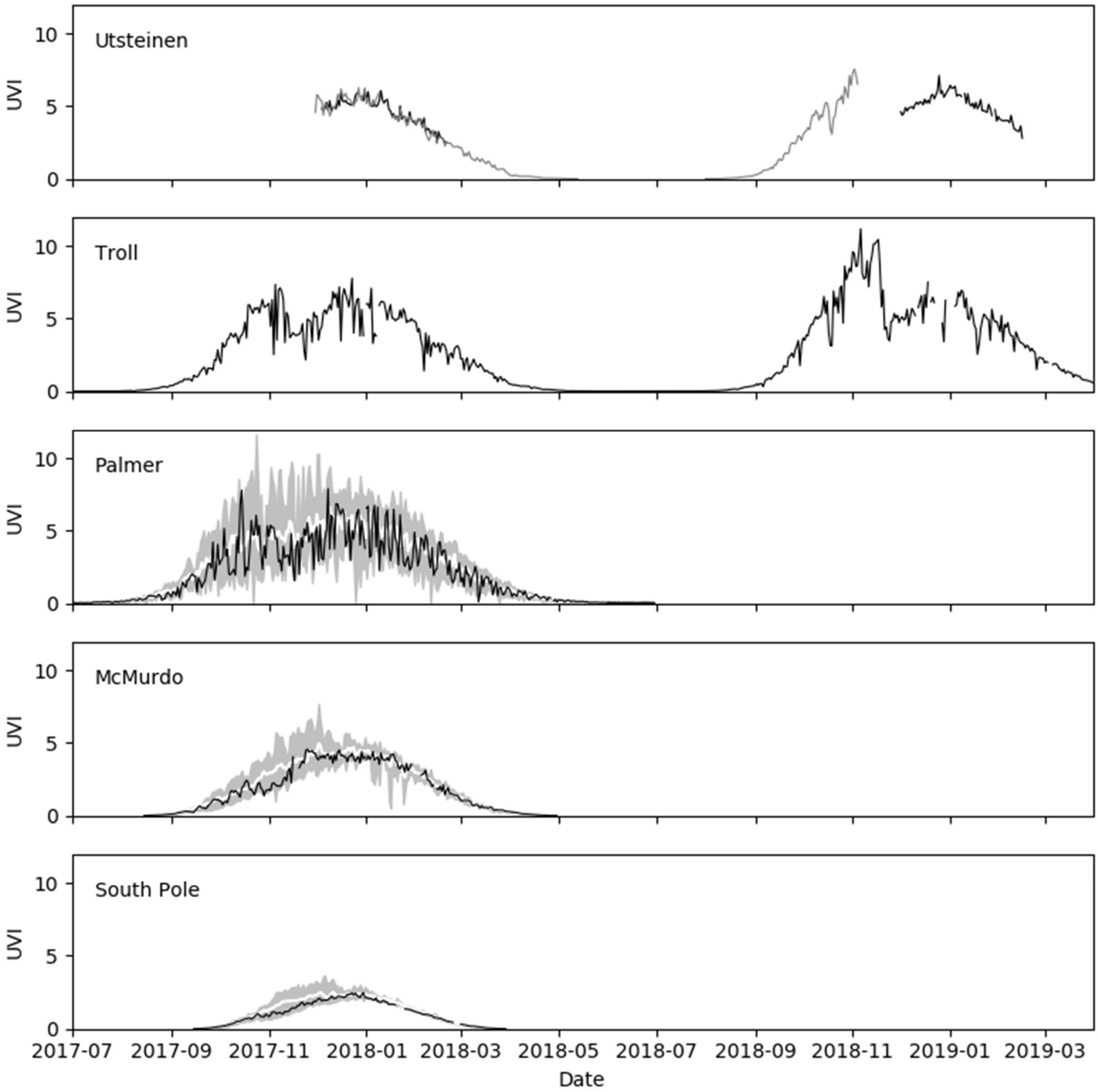
~~February were~~ the cloud cover was slightly ~~cloudier~~higher than the average for all months between Oct and Feb, with the exception of ~~November, which~~Nov, when cloud cover was about 1 ~~octant less cloudy.~~okta smaller. Higher than average cloud cover contributes to the lower than average daily erythemal doses. In ~~the~~ 2018/2019, the average cloud cover in Nov and Dec was similar to the long-term average~~ in November and December~~, whereas ~~October~~in Oct the cloud cover was ~~less cloudy~~smaller and ~~January~~during Jan and ~~February were more cloudy~~Feb the cloud cover was larger than the average.

3.3 Comparison of Marambio measurements to other stations

As shown in section 3.1, Marambio manifested two very different seasons – in 2017/2018 there was less UV radiation than in 2018/2019~~. Data for both of those two periods are also available for Utsteinen and Troll. Both of these research sites are far from Marambio and further south. In Utsteinen, daily maximum UVI values were only slightly higher in 2018/2019 than in 2017/2018. However, the analysis of noon UVI values showed clearly higher values in spring 2018 than in 2017 (Fig. 10). A similar pattern in also present in Troll: in spring 2018 the maximum UVI values were much higher than in 2017, but in December 2018 and January 2019 the values were similar or even lower than in previous seasons (Fig. 10). The peaks in spring are mainly caused by ozone, as in Marambio. Utsteinen and Troll stayed inside the polar vortex until 22nd and 21st Nov 2018 respectively, and during some isolated days in the following week.~~ and the daily erythemal doses and UVI were often below long-term averages. Including data from other Antarctic stations gives an opportunity to compare these results and to decide whether the same conclusions can be made in other parts of the continent.

First, the differences between seasons 2017/2018 and 2018/2019 were looked at. This data is available for all the included stations (Figure 10). Higher values in spring 2018 compared to 2017 have been measured at each station, except in Utsteinen from where no measurements are available for spring 2017. For example at South Pole, where recorded UVI are the lowest, the maximum UVI was 1.9 during Oct-Nov in 2017 and 2.9 in 2018. In 2018 the mean UVI for Oct-Nov was also higher (1.5, in 2017 it was 1.0). For Oct and Nov, the mean and maximum values were higher for every station (except for Utsteinen due to lack of measurements). The peaks in spring are mainly caused by low TOC during the ozone hole event. The TOC values were higher for most of the spring in each station (Fig. 10) and there were several days where much larger TOC values were recorded in 2017/2018 compared to 2018/2019, with differences more than 100 DU. Utsteinen and Troll stayed inside the polar vortex until Nov 22 and 21, 2018, respectively, and during some isolated days in the following week. In 2017, these stations were outside the polar vortex by Nov 15 and 13 respectively. The earlier disappearance of the polar vortex in 2017 compared to 2018 was also recorded in Palmer and McMurdo. Palmer was for the first time outside the vortex on Oct 9, 2017, and on Nov 11, 2018, and the corresponding dates for McMurdo were Oct 28, 2017, and Dec 7, 2018.

Compared to long-term variations and averages from the measurements in 2000–2008, ~~recorded radiation levels~~irradiances in Marambio in 2017/2018 were below the average value for the end of spring and most of the summer. This kind of comparison was also done using data from the three American stations – Palmer, McMurdo and South Pole. All of these stations had UVI data available for ~~2017/2018 and for~~ 2000–2008 (Fig. 10). Out of these stations, Palmer is the closest to Marambio - roughly 350 km away and almost ~~on~~at the same latitude. The maximum UVI in Palmer was 7.9 for the 2017/2018 season and 11.6 for the long-term time series. With respect to long-term measurements, season 2017/2018 was similar to the one in Marambio. Also in Palmer longer periods with UVI lower than the average occurred in spring and summer~~.~~, from Oct to Dec the maximum UVI was smaller than the long term average during 58 days and the largest difference was 3 units (Nov 14, 2017). The longest span of days with maximum UVI below the average was from 5 Nov – 17 Nov, with a mean difference of 1.5 units. Out of the 58 days, the daily maxima were below the historic minimum value during 10 days. This was also the case for McMurdo and South Pole: ~~in~~at both stations, ~~below 2000–2008~~ average daily maximum UVI values were measured in 2017/2018 which were below those in the period 2000–2008, especially in ~~November~~Nov and ~~December~~Dec when also the variation between years was the largest. In McMurdo, the longest span of days with below average maximum UVI between Oct and Dec was 27 days (19 Oct – 14 Nov) while in South Pole there were only 7 days in that period when maximum UVI was above the average.



Based on this comparison, it can be concluded that during the season 2017/2018 the long-term average UV irradiance reaching the surface was lower than in the period 2000–2008 across the Antarctic and the results obtained for Marambio were not site specific.

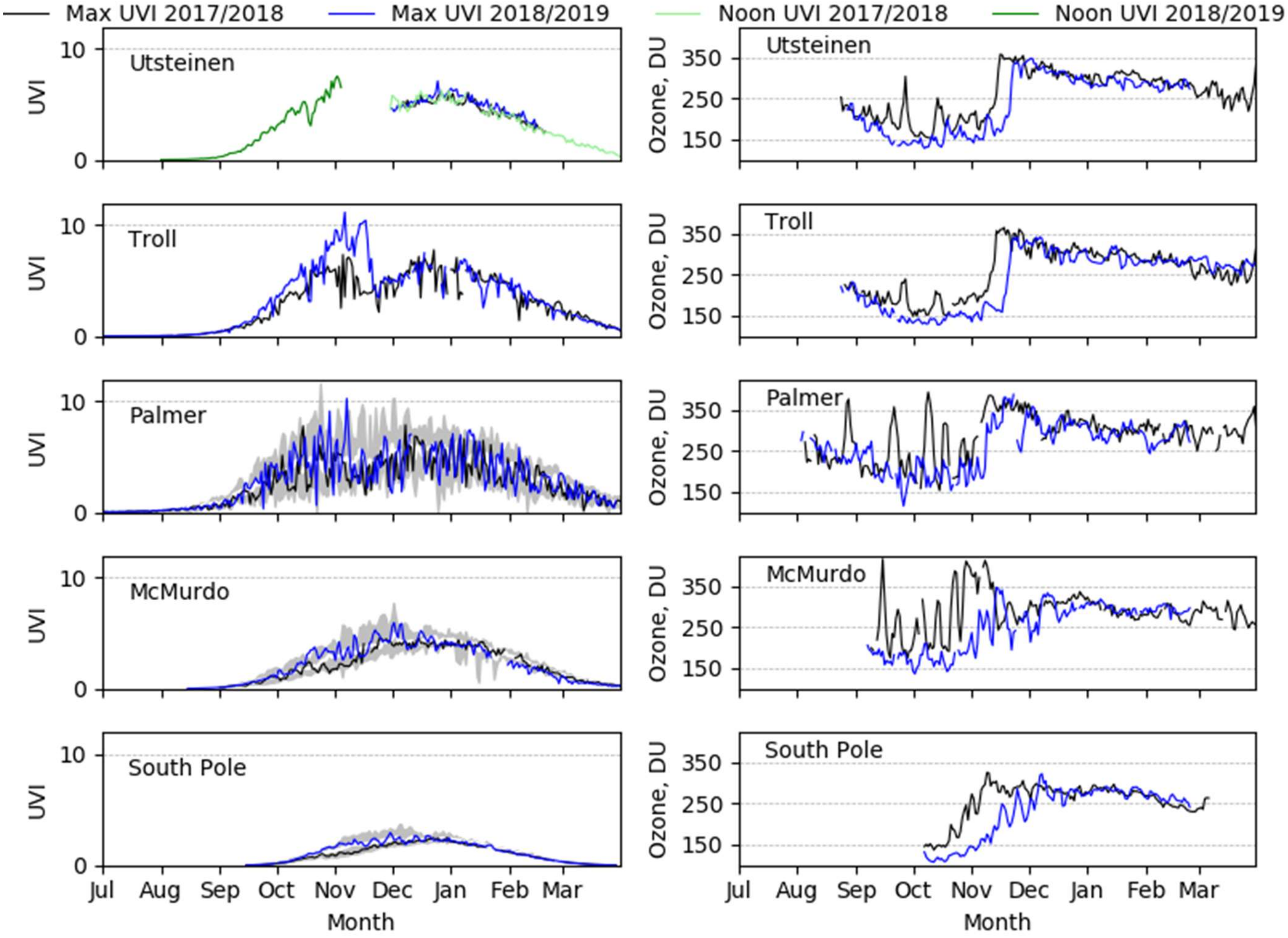


Figure 10: Maximum daily UVI (left) and daily TOC (right) for different Antarctic stations~~.~~ for 2017/2018 (black line) and 2018/2019 (blue line). In the ~~Utsteien~~ Utsteinen UVI plot, noon UVI values (2017/2018 - light green, 2018/2019 dark green) have been added to get longer time-series. In the plots of ~~the~~UVI in Palmer, McMurdo and South Pole the long-term (2000–2008) averages (white line) and variations (grey area) have been added.

4 Conclusions

In 2017, ~~the FMI in cooperation with the SMN started~~ UV measurements with a GUV-2511 multichannel radiometer were started in Marambio, Antarctica, by FMI in cooperation with the SMN, started. These measurements were analysed and compared to measurements from 2000–2008 performed with a NILU-UV radiometer at the same station and with data from five other research stations in Antarctica.

Recent measurements show that in 2017/2018 the ~~general UV levels~~ average daily erythemal dose from Sept – Mar was 23 % lower than the year after and the monthly average daily doses were lower ~~than~~for each month with values varying between 4.8% (Feb) and 50.3% (Sept, where less data was available for 2017). The difference between the two subsequent seasons is also visible from the maximum UVI data – in 2017/2018 there were 3 days with maximum UVI above 6 units, compared to 59 days in 2018/2019. ~~UV levels~~The daily doses in 2017/2018 were also lower than the long-term average ~~in~~of 2000–2008 (for 57 days from Oct to Dec) and a number (16) of new daily minimum values were recorded. In 2018/2019, several new daily maximum values were recorded and the daily doses fluctuated around the long-term average. ~~This means that definitive conclusions about the recent changes in UV~~ The lower UV radiation levels in ~~Antarctica compared to those in the period 2000-2008 cannot be made based on only two seasons.~~2017/2018 were not specific for Marambio. Lower than long-term average maximum UVI values were also measured ~~also~~ at other stations~~ across Antarctica~~, such as Palmer, McMurdo and South Pole, during the solar season 2017/2018. ~~—~~Also, the average maximum UVI was lower in 2017/2018 compared to 2018/2019 for each station included in the dataset.

~~This~~As changes in surface UV irradiance depend mainly on changes in TOC, cloud cover, aerosols and ground albedo, those UV affecting factors were analysed in this study ~~shows that, in Antarctica, the main factor determining the~~ for Marambio. The computed changes in UV ~~levels is total~~ irradiance due to ozone~~,~~ using RAF value of 1.2, explain the observed changes for Nov, Feb and during a large part of Oct. The role of cloud cover was clearly seen in Dec, and to a lesser degree in Oct and Nov, when cloud cover qualitatively explains changes which ~~has large variations from year to~~ could not be ascribed to changes in TOC. In this study, the roles of aerosols and albedo are of minor influence because the variation of these factors in Marambio was small from one year~~. When a station is inside~~ to the other.

The impact of the polar vortex~~, ozone levels are much lower than outside and therefore much more UV radiation reaches the ground. In~~ was analysed: in spring 2017, higher than usual ~~total column ozone~~TOC was measured during several days resulting in less UV radiation reaching the ground. During that period, the ~~influence~~position of the polar vortex over Marambio alternated frequently. That resulted in ~~higher than usual ozone column concentrations~~less favourable atmospheric conditions for deep O_3 depletion during several days allowing less transmission of UV radiation in the atmospheric column.

Due to the large fluctuation in ~~ozone~~TOC and the effect of other factors like clouds, ~~aerosols and albedo,~~ the natural variability of UV irradiance is large from year to year~~ is large~~. Therefore, it is important to continue the measurements in Antarctica to be able to ~~see~~monitor long-term changes and to determine whether the long awaited recovery of the ozone layer is taking place ~~(WMO, 2018).~~(WMO, 2018).

Author's contributions. MA programmed Marambio's GUV data processing, analysed the data and led the manuscript; KL participated in data ~~analyzis~~analysis and contributed to the writing of the manuscript; RS, EA, FN, OM, LS and EJ collected and contributed proxy data for the Marambio station and contributed to the writing of the manuscript. VA collected and contributed proxy data; AA and GdL consulted on research and contributed to the writing of the manuscript; VdB, AM, DB, TS, LM, KC collected and contributed data for other stations and contributed to the writing of the manuscript; DG and BVO collected and contributed data for other stations.

Data availability. Data is available upon request from the authors. Data from OMI and TOMS are publicly available through https://giovanni.gsfc.nasa.gov/giovanni/.

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