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

Margit Aun[1,2], Kaisa Lakkala[1,3], Ricardo Sanchez[4], Eija Asmi[1,4], Fernando Nollas[4], Outi Meinander[1], Larisa Sogacheva[1], Veerle De Bock[5], Antti Arola[1], Gerrit de Leeuw[1], Veijo Aaltonen[1], David Bolsee[6], Klara Cizkova[7], Alexander Mangold[5], Ladislav Metelka[7], Erko Jakobson[2], Tove Svendby[8], Didier Gillotay[6], and Bert Van Opstal[6]

[1]Finnish Meteorological Institute, Climate Research Programme
[2]University of Tartu, Tartu Observatory, Estonia
[3]Finnish Meteorological Institute, Space and Earth Observation Centre
[4]Servicio Meteorológico Nacional, Argentina
[5]Royal Meteorological Institute of Belgium
[6] Royal Belgian Institute for Space Aeronomy
[7]Czech Hydrometeorological Institute, Solar and Ozone Observatory
[8]Norwegian Institute for Air Research

Correspondence to: Margit Aun (margit.aun@ut.ee)

Abstract. In March 2017, ultraviolet (UV) radiation measurements with a multichannel GUV-2511 radiometer were started in Marambio, Antarctica (64.23° S; 56.62° 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 at the same site with NILU-UV radiometer during 2000–2008 and to data from five stations across Antarctica. Measurements in Marambio showed lower UV radiation levels in 2017/2018 compared to those measured during 2000–2008. Also at several other stations in Antarctica the radiation levels were below average in that period. The maximum UV index (UVI) in Marambio was only 6.2, while, during the time period 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 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.

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1 Introduction

Ultraviolet (UV) radiation is part of the Sun's electromagnetic radiation in the wavelength range from 10 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. The amount of UV 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). Examples of the latter are clouds, ozone and aerosol particles, which all absorb or scatter UV radiation. Any change in these factors will affect UV irradiance. The radiation measured at the surface is also affected by the surface albedo, which determines how much of the radiation is reflected back to the atmosphere (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).

To promote research of stratospheric ozone and UV radiation in Antarctica, a joint 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 the Finnish Meteorological Institute (FMI). UV measurements were carried out from 2000 to 2013 in In Marambio, Ushuaia (54.82° S, 68.32° W) and Belgrano (77.87° S, 34.63° W) (Lakkala et al., 2018). UV radiation data measured in Marambio in the period from 2000–2010 were 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.

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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 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.

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. UV irradiance measurements in Marambio from March 2017 – March 2019 are compared with those from 2000–2008 and to results from other stations measuring UV irradiance in Antarctica from which data are available. Including different measurement sites provides an opportunity to see, whether differences between the latest solar seasons and previous measurements are common for all Antarctica or region-specific, as the factors influencing UV vary widely over the continent.

2 Data and methods

2.1 Measurement sites

Marambio and five more research sites were included for comparison: the Princess Elisabeth Station in Utsteinen, and the stations Troll, Palmer, McMurdo and South Pole. The locations of the stations together with maximum UVI during the season 2017/2018 are shown in Figure 1.

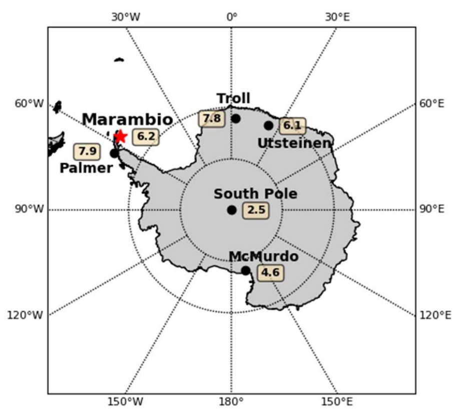

Figure 1: Locations of the stations included in the analysis. The numbers next to the sites show the corresponding maximum UVI measured during the season 2017/2018.

2.1.1 Marambio station

The Marambio station (64.23º S; 56.62º W; 198 m a.s.l.) is located on an island near the eastern part of the Antarctic Peninsula. 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

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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

Since March 2017, GUV-2511 multifilter radiometers, manufactured by Biospherical Instrument Inc., are used to measure UV radiation in Marambio. These instruments measure downwelling irradiance at 305, 313, 320, 340, 380, 555 nm and photosynthetically active radiation (PAR, 400–700 nm). The full width half maximum (FWHM) of the first six channels is 10 nm. For stability, the internal temperature of the instrument is held 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°.
Two GUV instruments are used for the UV measurements in Marambio – while one is measuring in Marambio, the other one is in calibration either in Finland or in the U.S.. The instruments are switched annually in order to transfer the latest calibration to Marambio.

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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 1st to June 30th, 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 multichannel radiometer, which measures radiation in six channels. There are five channels with centre wavelengths at 305, 312, 320, 340 and 380 nm (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).

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. 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.

The daily doses and maxima have been determined from one-minute averages.

2.2.3 Total column ozone measurements

O_3 data was gathered from multiple sources. For 2017–2019, GUV measurements were used. The calculation of O_3 is based on instrument specific look-up tables and SZA calculations (Bernhard et al., 2005). Daily averages were calculated, using measurements with SZA < 65°, as the calculations show some wavelength dependency at high SZAs . In Marambio, the period during which the SZA goes below that threshold lasts from the middle of September to the middle of March.

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.

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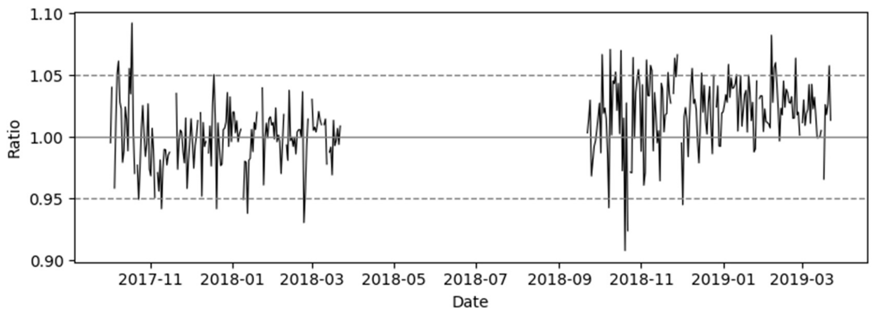

Figure 2: The ratio of GUV and OMI daily column ozone. For GUV daily averages, measurements with SZA below 65 degrees were used.

Satellite data were also used for comparing ozone values from 2017–2019 to the period 2000–2008. For the period 2000–2004, version 8 O_3 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. 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), who found an average difference of 0.6 % (with standard deviation (std) less than 3 %).

2.2.4 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 performed both automatically and manually, the latter by surface meteorological observers (SMO). Cloud observations are part of the manual meteorological observations protocol. In 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. 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

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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), 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).

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). 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. 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.

2.2.5 UV measurements in other Antarctic stations

PE: UV spectral measurements at the PE station are provided by the double 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. 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 %.

UVI 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, manufactured by EKO Instruments (Japan), covering three broadband spectral ranges: 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 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.

Troll: Total ozone and UV data are collected by a NILU-UV instrument (serial number 005), which is calibrated once a month.

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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).

3 Results

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

To describe the radiation levels and compare the past two seasons, daily erythemal doses in Marambio were calculated (Fig. 4). 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 that are not synchronized with the changes in SZA (Fig. 4). In season 2017/2018 erythemal doses were overall considerably lower than in 2018/2019, as clearly demonstrated from the monthly averages of daily doses (Table 1).

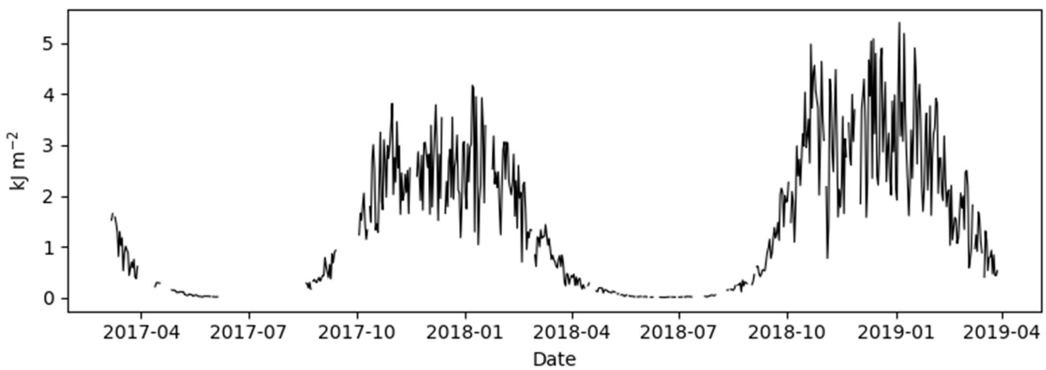

Figure 4: Daily erythemal UV doses in Marambio from March 2017 to March 2019.

Table 1: Monthly averages of daily erythemal doses (kJ/m²) 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 averages with St. Dev for 2000–2008 are also included, and discussed in section 3.2.

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	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 of the daily maximum UVI closely follow those of the daily erythemal doses in both seasons (Fig. 5). 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). In the second season, the maximum UVI was much higher, 9.5 (Nov 6, 2018), and there were 59 days when UVI exceeded 6. Out of those, 10 days had very high values (UVI 8–10, WHO, 2002).

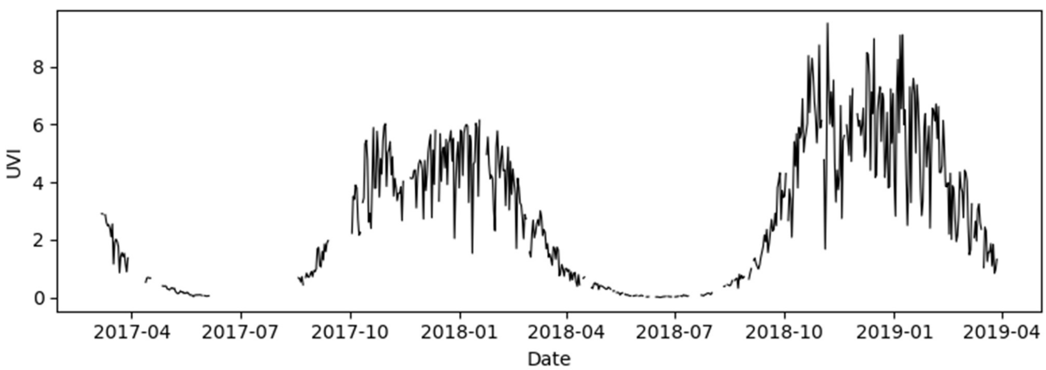

Figure 5: Daily maximum UV indexes in Marambio from March 2017 – March 2019.

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

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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.

Table 2: Monthly average total cloudiness (octas), total column ozone (DU) and AOD with std 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 COVER, OCTAS		OZONE, 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 value of O_3 in 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 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 value in Antarctica is influenced by the polar vortex. For estimating whether Marambio station was inside or outside the polar vortex, potential vorticity analysis was carried out (see section 2.2.4). Potential vorticity was lower than the chosen limit of -36 on 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 2017/2018 and 2018/2019 season respectively. The first day since September 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 and October), on which the Marambio station was outside the polar vortex and more ozone was present in the atmospheric column above.

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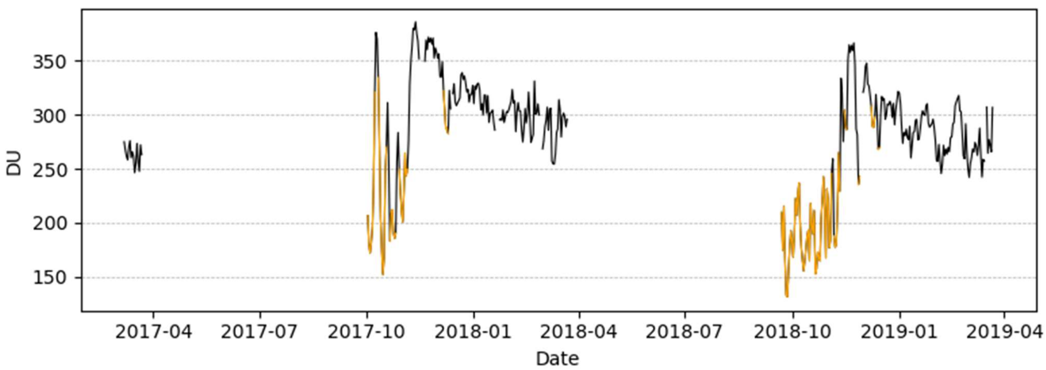

Figure 6: Daily average ozone column at Marambio calculated from GUV measurements with SZA > 65 degrees (2017–2019). Days during which the station was inside polar vortex (vorticity < -36) are in orange.

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.

Albedo, which also affects the UV irradiation measured in Marambio, is mainly dependent on the snow cover. Unfortunately, albedo measurements are not available at Marambio for all months in 2018/2019. The data that is available shows slightly higher monthly average for the daily noon albedo in Nov 2018, compared to Nov 2017 and in Feb 2019 compared to Feb 2018. Higher average albedo will lead to higher recorded UV doses.

Daily doses of UVA (315–400 nm) radiation were also somewhat higher in 2018/2019, but the difference was not as large as for erythemal radiation. Average daily UVA doses from October to January in 2017/2018 were 0.78, 1.18, 1.04 and 1.04 MJ/m^2, in 2018/2019 the numbers were 0.89, 1.04, 1.24 and 1.08 MJ/m^2 respectively. In February the average of daily UVA doses was larger in 2017/2018 than the year after. The different behaviour of erythemal and UVA radiation shows the importance of ozone in causing the significant differences between the two seasons for erythemal radiation and UVI. At the same time, the slightly larger daily doses show that other factors also contribute to the higher amount of radiation in 2018/2019.

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

The past two UV seasons in Marambio have not been extraordinary, although there were periods when the erythemal daily doses and maximum UVI was noticeably different from the averages in the period 2000–2008. In general, daily erythemal

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doses measured during 2017–2019 fall in the range of long-term fluctuation of daily doses measured between 2000–2008 (Fig. 7). In the season 2017/2018 though, there was a long period from the middle of spring until the end of summer, when daily doses were mostly below the long-term daily average. On some days, the values even were below the long-term minimum. The monthly averages of daily doses in that season were below the long-term values from September to January (Table 1). In 2018/2019, daily doses were much larger. In spring, there was a longer period where doses were continuously above the long-term average. The monthly average daily erythemal dose in October exceeded the long-term one with more than 0.8 kJ/m^2. Monthly averaged daily doses were higher than the long-term values also from December to March. In addition, there were several days where the daily doses exceeded the long-term maximum, although the highest erythemal daily dose recorded with NILU-UV was over 6.9 kJ/m^2 (Nov 19, 2007) and none of the daily doses reached that high in recent seasons.

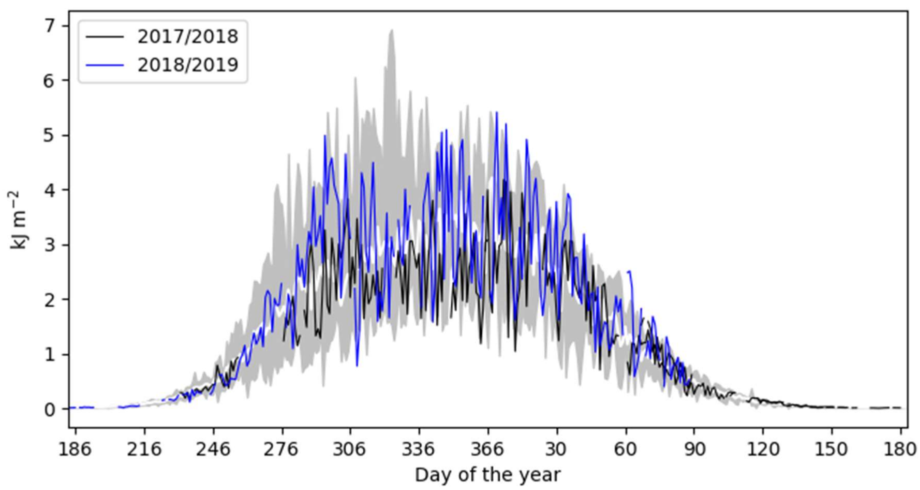

Figure 7: Comparison of daily doses from GUV measurements in Marambio in season 2017/2018 (black line) and 2018/2019 (blue line) with long-term measurements (2000–2008). The white line is the long-term (2000–2008) mean and the grey area is set between long-term maxima and minima for each day.

For the daily maximum UVI, the situation was similar to that of daily erythemal doses (Fig. 8). The maximum value recorded in 2000–2008 was 12 and no measurement from 2017–2019 reached that high. Long-term daily maximum values were exceeded in 19 cases during 2017/2018. The majority of these days were in April 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 of days was 110 and 26 respectively.

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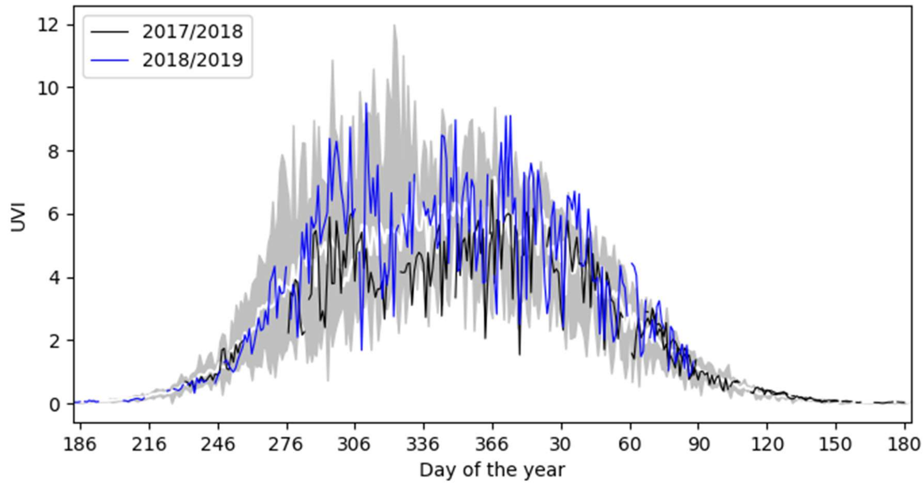

Figure 8: Comparison of daily maximum UVI from GUV measurements in Marambio in season 2017/2018 (black line) and 2018/2019 (blue line) with long-term measurements (2000–2008). The white line is the historical mean and the grey area is set between historic maxima and minima for each day.

The sharp drop in UVI values in November 2017 is coincident with the abrupt rise in O_3 that at its peak exceeds even the long-term variation limits. The general ozone level stayed high until the end of summer in March 2018 compared to the measurements from 2000–2008 (Fig. 9). Daily O_3 was higher than the long-term maximum on 54 days out of 162 in season 2017/2018 and there is only 1 day (Oct 31, 2017) where the ozone 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 data are in good correspondence to the recent recorded UV levels.

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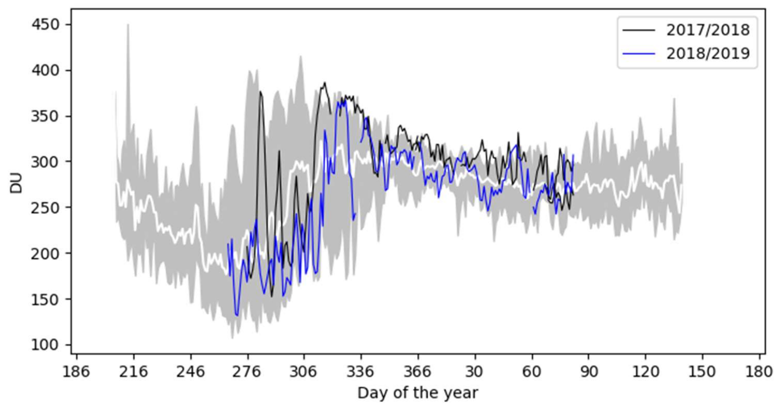

Figure 9: Comparison of ozone calculated from GUV in Marambio in season 2017/2018 (black line) and 2018/2019 (blue line) with long-term measurements (2000–2008) from satellites. The white line is the long-term daily average and the grey area is the region between the period's daily maxima and minima.

Long-term averages in 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–Aug), where averages are below 4.5 octas, and highest during summer (Dec–Jan), where they are over 6.1 octas. This pattern is also present in seasons 2017/2018 and 2018/2019 (Table 2). Compared to 2000–2008 averages, in the 2017/2018 all months between October and February were slightly cloudier than the average, with the exception of November, which was about 1 octant less cloudy. In the 2018/2019, the average cloud cover was similar to the long-term average in November and December, whereas October was less cloudy and January and February were more cloudy 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.

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Compared to long-term variations and averages from the measurements in 2000–2008, recorded radiation levels 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 three American stations – Palmer, McMurdo and South Pole. All of these stations had 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 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. This was also the case for McMurdo and South Pole: in both stations, below 2000–2008 average daily maximum UVI values were measured, especially in November and December when also the variation between years was the largest.

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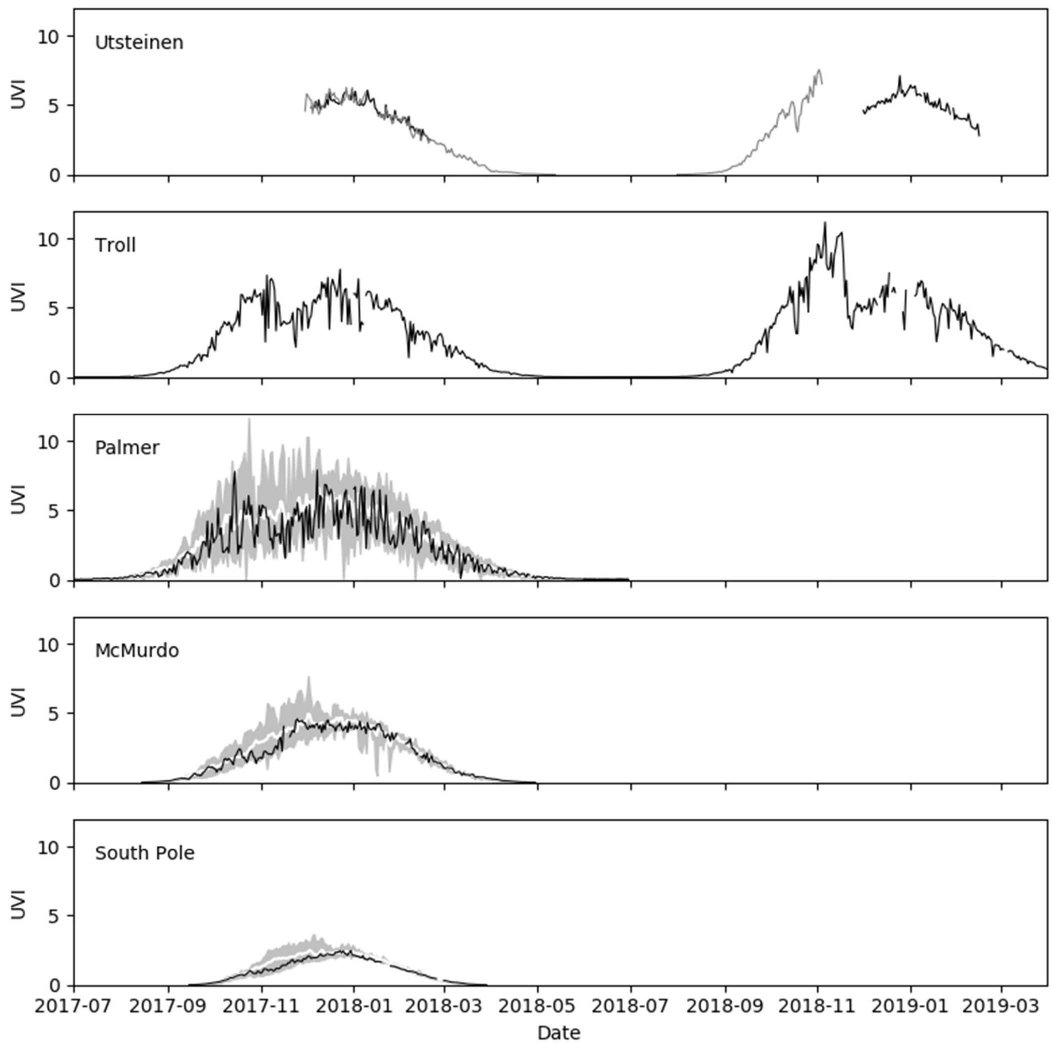

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Figure 10: Maximum daily UVI for different Antarctic stations. In the Utsteien plot, noon UVI values have been added to get longer time-series. In the plots of the Palmer, McMurdo and South Pole the long-term (2000–2008) averages (white line) and variations (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 in Marambio, Antarctica. 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 were lower than in 2018/2019. UV levels 2017/2018 were also lower than the average in 2000–2008 and a number 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 levels in Antarctica compared to those in the period 2000-2008 cannot be made based on only two seasons. Lower than average values were also measured also at other stations across Antarctica during the solar season 2017/2018.

This study shows that, in Antarctica, the main factor determining the UV levels is total ozone, which has large variations from year to year. When a station is inside the polar vortex, ozone levels are much lower than outside and therefore much more UV radiation reaches the ground. In spring 2017, higher than usual total column ozone was measured during several days resulting in less UV radiation reaching the ground. During that period, the influence of the polar vortex over Marambio alternated frequently. That resulted in higher than usual ozone column concentrations during several days allowing less transmission of UV radiation in the atmospheric column.

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

Author's contributions. MA programmed Marambio's GUV data processing, analysed the data and led the manuscript; KL participated in data analyzis 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.

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