Response to Reviewers

19 September 2018

Manuscript title: Spring and summer time ozone and solar ultraviolet radiation variations over Cape

5 Point, South Africa

Dear Editor,

10 We would like to thank the Reviewers for taking their time to review the manuscript and for providing constructive comments. In the final revised manuscript, we have addressed all of the reviewers' comments. Below we provide a point-by-point response to each of their comments and explain how we revised the manuscript accordingly.

15 **Anonymous Referee #1**

Received and published: 18 July 2018

This manuscript describes ozone and solar UV radiation variations over Cape Point. In this manuscript we can see results for South Africa and the author compares some results with Brazil results.

20 Comparison of TOC and SCO with UV variations shows expectable results. The analysis of the clear sky time series of ozone brings new overview about stratospheric ozone condition on the South hemisphere during the year. My only suggestion is that author should be very careful with definition of clear sky condition because it could strongly affect the results. Next suggestion is that it should be more discussion about results. This manuscript is very descriptive and discussion what phenomena

25 could be responsible for results will improve the paper substantially.

RC1: suggestion is that author should be very careful with definition of clear sky condition because it could strongly affect the results.

Response: We believe that we were sufficiently cautious about our definition of the clear-sky days,

30 and in the revised version of the manuscript we made an effort to state that this is one of the critical

points in the analysis. For that reason, we rephrased parts of Section 2.4.2 on page 6, to draw attention of the reader that: 1) there were no clear-sky observations available for our study site, and 2) hence the need to numerically determine clear-sky days. Our methodology includes three different tests, and we also validated it against measurements for Cape Town, where cloud-cover observations are available.

RC1: Next suggestion is that it should be more discussion about results. This manuscript is very descriptive and discussion what phenomena could be responsible for results will improve the paper substantially.

Response: The full discussion of the phenomena responsible for these results is planned to be presented in a future publication after further research has been carried out. However, in response to the reviewer's comment, the following has been added on page:15, line:14 "In fact, it is well known that Rossby planetary waves are generated due to the development of synoptic disturbances in the troposphere during winter and spring seasons. They propagate vertically through to the stratospheric layers when the zonal winds are westerly (Charney & Drazin, 1961; Leovy, et al., 1985). Moreover, as reported by many authors, gravity and Rossby planetary waves are involved in isentropic transport across the subtropical barrier. Portafaix, et al., 2003 studied the southern subtropical barrier by using MIMOSA model advected PV maps, together with a numerical tool developed by LACy (Reunion University) named DyBaL (Dynamical Barrier Localisation) based on Nakamura formalism (Nakamura, 1996). They showed that the southern subtropical barrier is usually located around 25-30°S, but has an increasing variability during winter and spring. Moreover, using MIMOSA adverted PV fields (Bencherif, et al., 2007; Bencherif, et al., 2003) showed that exchange processes between the stratospheric tropical reservoir and mid-latitudes are episodic and take place through the subtropical barrier due to planetary wave breaking inducing increase or decrease of ozone at tropical and subtropical locations depending on the isentropic levels."

Anonymous Referee #2

Received and published: 30 July 2018

General response: We would like to thank the referee for taking the time to review the manuscript and provide valuable feedback. Clarity and additional information are provided in the responses below.

RC2: Considering the topics of this work, one could separate it in two different parts: The first part includes the climatology of UVB and ozone column at Cape Point, South Africa and the corresponding effect of ozone variations on the surface UVB, while the second part includes the examination of low ozone level cases and their origin at the same station. The used methodology and analysis of the second part is an interesting approach with noteworthy findings. The authors could expand their research on this field and publish a standalone study. In my opinion it does not fit in the first part of the manuscript.

Response: We thank the reviewer for their comment and appreciate their concern that combining the descriptive part of the study together with analyses used in the 'second part' of the study, however, since very few published studies have appeared since the 1990s that describe the climatology of UV-B and ozone in South Africa, we see value in retaining the first part of our paper here to test contextualise the second half.

RC2: My major objections to accept for publishing this manuscript concern its first part. Many related studies have been published, especially during 90's, and the results of this study were quite surprising. This fact makes me very doubtful about the quality and/or the analysis made of the used UVI data.

Response: We have completed the re-calculations, we believe that the results are improved. The differences in findings between this study and those from the 1990's is likely due to the different spectral range of instruments used, temporal resolution and specific location.

RC2: Following, I am quoting some concerns: It is difficult to accept the statement of the authors that there is not aerosol loading at the Cape Point station. Even if the aerosols are not anthropogenic, maritime aerosols affect the site and consequently the UV radiation.

Response: By choosing Cape Point, we assumed that the effect of anthropogenic aerosols on UV radiation was less, say for example in comparison to the City of Cape Town site, but the effect of maritime aerosols is definitely still present. We agree with the referee that in the original version of the paper, we had omitted to be explicit about it, but we made an effort to clearly point this fact in the revised version. For example, in the description of the study area, Section 2.1, page: 3 line: 5, we

added that "…although considered free of air pollution (Slemr, et al., 2008), it may still be affected by maritime aerosols." and later in the same paragraph "… Cape Point offers a setting in which a modification of the UV-B radiation by anthropogenic aerosols can be overlooked." as well as on page: 10, line: 18 "that improvements can be made if the effect of aerosols on UV radiation are considered in future research."

RC2: As the authors report, the instrument detects solar UV radiation in the wavelength range 280-320 nm. The UV index covers the solar wavelength range 280-400 nm. The conversation of MED to UVI is not just a single factor (equation 1 in the manuscript), but it depends also on the solar zenith angle.

Response: We agree with the reviewer and we have made substantial revisions in this regard. We would like to add J-M. Cadet as co-author for the work done based on these revisions. On page: 4, line: 8 the following has been included" To convert from instrument-weighted UV radiation to erythemally-weighted UV radiation, a correction factor was applied as the instrument does not measure the full spectral range of the UV Index (Seckmeyer, et al., 2005; Cadet, et al., 2017)."

Figure 2, Equation 1 and 3, Table 2 and 3, the results and discussion have been updated accordingly in the manuscript.
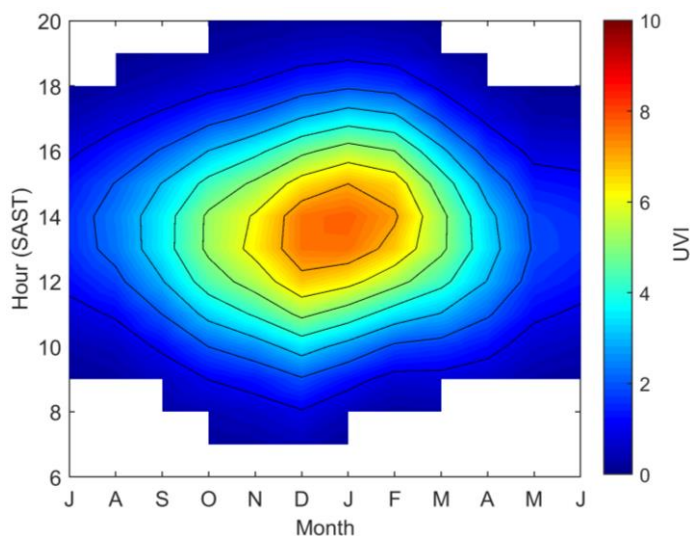
Figure 1: The *UVI* climatology for all sky conditions at Cape Point. The *x*-axis starts with the month of July and ends with June.

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Table 2. The correlation statistics for amount of ozone and *UVI* at Cape Point on clear-sky days (*indicates R^2 values were statistically significant at a 95 % confidence interval).

SZA (°)	TOC: R^2 Expo fit	SCO: R^2 Expo fit	RAF
15	0.25*	0.18*	1.60
20	0.26*	0.23*	0.19
25	0.45*	0.53*	0.26
30	0.28*	0.20*	0.82
35	0.21*	0.11*	0.15
40	0.30*	0.30*	0.42
45	0.26*	0.29*	0.69
Average			**0.59**

5

Table 3. Identified low-ozone events on clear-sky days at Cape Point during spring and summer months and the percentage decrease calculated from the relative climatological monthly mean (* indicates whether the low-ozone event was due to low TOC and/or low SCO values).

Date	TOC (DU)	SCO (DU)	Decrease TOC (%)	Decrease SCO (%)	Increase UVI (%)
30 Jan 2009	253.5*	210.4*	6.1	10.1	30.4
6 Feb 2009	253.9*	222.2*	5.0	4.5	36.2
15 Feb 2009	254.6*	228.3	4.7	1.9	34.2
28 Feb 2011	255.7*	223.2*	4.3	4.1	6.8
16 Jan 2012	268.2	221.9*	0.6	5.1	21.2
8 Feb 2012	257.0*	227.5	3.8	2.2	31.7
13 Nov 2012	256.6*	228.8	13.3	13.3	46.5
14 Nov 2012	261.3*	234.6	11.7	11.1	42.1
6 Sep 2013	265.0*	241.3*	12.7	11.6	22.3
9 Nov 2013	282.3	229.0*	4.6	13.3	21.9
1 Sep 2014	274.7*	223.9*	9.5	18.0	-2.5

2 Sep 2014	258.4*	231.2*	14.9	15.3	-2.3
9 Sep 2014	284.0*	232.3*	6.4	14.9	-5.5
11 Jan 2016	270.6	221.9*	-0.3	5.1	-7.9

RC2: There is no information about the long-term performance of the instrument and the calibration procedures during the study period.

5 **Response**: We acknowledge that the reviewer has made an important comment about the need to express information regarding the calibration of the instruments and the data quality. The following information and additional table have been included in the manuscript regarding the calibration of the Solar Light biometers used at Cape Point on page: 3, line: 16 "Two different instruments were used at Cape Point between 2007 and 2016 (Table 1). The first from January 2007 until March 2016 and the

10 second from April 2016 to December 2016. The SAWS calibrated the instruments at both Solar Light and the Deutscher Wetterdienst (DWD), Lindenberg, Germany. Calibration at Solar Light was according to the "Calibration of the UV radiometer - Procedure and error analysis". At DWD, the instruments were calibrated using the spectrometer SPECTRO 320 D NO 15. During the period of operation for each instrument, the stability was checked by performing inter-comparisons with

15 reference instruments (12010 and 2722) which had been calibrated shortly prior to the inter-comparison.

Table 1: Summary of the instruments and their calibration information

Instrument	Period of Operation	Calibration Information
Instrument 3719	January 2007 – March 2016	Solar Light – June 2006
Instrument 1103	April 2016 – December 2016	Solar Light – June 2006
Inter-comparison Instruments	**Inter-comparison Date**	**Calibration Information**
Instruments 3719 and 12010	October 2012	12010: DWD – August 2012
Instruments 3719 and 2722	January 2014	2722: DWD – July 2013

RC2: Taking into account the longitude of the station, the maximum UVI should be observed around 11h00 UTC and not between 13h00-15h00 UTC. Even the presence of the cloudy days is
5 **not able to shift the time of the maxima observations 2-4 hours in climatology point of view. If there are any special weather phenomena at the station of Cape Point, (i.e. frequency of clear-skies afternoons much higher than clear-skies mornings) the authors should mention it.**

Response: We were further prompted by this referee's comment to look into our tests for determination of clear-sky days and found that Cape Point actually sees more clear-sky afternoons
10 than clear-sky mornings, which could contribute to the shift in the *UVI* maximum. We added this information on page: 8, line: 14 "The maximum *UVI* values are not centred on the local noon, implying that more UV radiation reaches this site in the afternoon. Indeed, as previously mentioned, our clear-sky determination method identified more clear-sky afternoons than clear-sky mornings (Sec. 2.4.2), which under the assumption that cloud cover at Cape Point generally attenuates UV radiation reaching
15 the surface, could explain the observed shift in the *UVI* maximum to about 14h00 SAST." Also, earlier in Section 2.4.2, page: 6, line: 18 "It is interesting to note that at Cape Point, the second test of the clear-sky determination method identified more clear-sky afternoons than clear-sky mornings."

RC2: The results of RAFs at fixed zenith angles convinced me about my previous concerns. I
20 **strongly believe that there are serious mistakes in manipulating the UV data or in the quality of UV data or both. According to my atmospheric physics knowledge, it is impossible the correlation of the RAF at 40 deg to be 0.01 and not significant. I could believe it for SZA higher than 70 deg but not for 40 deg. Even the differences in sun-earth distance could not lead in these results.**

25 **Response:** The reviewer has highlighted an important point and we have taken time to consider this and have re-done the RAF calculations. To clarify the results in Table 3, at SZA 40° the RAF value is 0.42. The following has been included on page: 10, line: 8 "At Cape Point, the RAF value for clear-sky days range between 0.15 and 1.60 with an average RAF value of 0.59. This can be interpreted as for every 1% decrease in TOC, UV-B radiation at the surface will increase by 0.59%. RAF values specific

to ozone and solar UV studies found in the literature range between 0.79 and 1.7 (Massen, 2013). RAF values have been used to describe the effect of other meteorological factors such as clouds and aerosols on surface UV radiation (Serrano, et al., 2008; Massen, 2013). The differences to the RAF values found here and those found in the literature can be attributed to changes in time and location (Massen, 2013). "

RC2: In case I have some satisfactory answers to my concerns, I will be very happy to accept the manuscript for publication.

Response: We made an effort to check our calculations and addressed all the issues raised by the referee. There are a number of instances where we recognised the need to be more specific about our data, as suggested by the reviewer. We hope that the responses given here, and revisions we made to the manuscript will be satisfactory, and that the referee will find the manuscript suitable for publication.

Spring and summer time ozone and solar ultraviolet radiation variations over Cape Point, South Africa

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Abstract. The correlation between solar ultraviolet radiation (UV) and atmospheric ozone is well understood. Decreased stratospheric ozone levels which led to increased solar UV radiation levels at the surface have been recorded. These increased

15   levels of solar UV radiation have potential negative impacts on public health. This study was done to determine whether the break-up of the Antarctic ozone hole has an impact on stratospheric columnar ozone (SCO) and resulting ambient solar UV-B radiation levels at Cape Point, South Africa, over 2007 - 2016. We investigated the correlations between UV Index, calculated from ground-based solar UV-B radiation measurements and satellite-retrieved column ozone data. The strongest anti-correlation on clear-sky days was found at solar zenith angle 25° with exponential fit R^2 values of 0.45 and 0.53 for total ozone

20   column and SCO, respectively. An average radiation amplification factor of 0.59 across all SZAs was calculated for clear-sky days. The MIMIOSA-CHIM model showed that the polar vortex had a limited effect on ozone levels. Tropical air-masses more frequently affect the study site, and this requires further investigation.

Keywords: UV radiation; clear sky; stratospheric ozone

1. Introduction

25   Solar ultraviolet (UV) radiation is a part of the electromagnetic spectrum of energy emitted by the Sun (Diffey, 2002). Solar UV radiation comprises a wavelength band of 100 - 400 nm, however, not all wavelengths reach the Earth. Solar UV radiation is divided into UV-A, UV-B and UV-C bands depending on the wavelength. The UV-C and UV-A bands cover the shortest and longest wavelengths, respectively. The UV-B part of the spectrum spans a wavelength range between 280 - 315 nm (WHO, 2017). The reason behind this sub-division of UV radiation is a large variation in biological effects related to the different

30   wavelengths (Diffey, 2002). Moreover, an interaction of different UV bands with the atmospheric constituents, results in an altered UV radiation reaching the surface: all UV-C and ~90 % of UV-B radiation is absorbed, while the UV-A band is mostly unaffected (WHO, 2017). The amount of solar UV-B radiation at the surface of the Earth is largely impacted by the amount

of atmospheric ozone (Lucas & Ponsonby, 2002), but also several other factors, such as altitude, solar zenith angle (SZA), latitude, and pollution (WHO, 2017). The SZA has a significant impact on the amount of surface solar UV-B radiation (McKenzie, et al., 1996). Under clear-sky conditions and low pollutions levels, atmospheric ozone (of which approximately 90 % is found in the stratosphere) absorbs solar UV-B radiation (Fahey & Hegglin, 2011). A study in the south of Brazil found

5   a strong anti-correlation between ozone and solar UV-B radiation on clear-sky days using fixed SZAs (Guarnieri, et al., 2004).

Anthropogenic and natural factors can cause changes in the amount of atmospheric ozone. Unlike natural ozone variability which is mostly of a seasonal nature and therefore has a reversible character, human activities, such as release of ozone-depleting substances, have led to a long-term ozone decline in a greater part of the atmosphere (Bais, et al., 2015), and, in turn,

10   to higher levels of solar UV-B radiation at the Earth's surface (Fahey & Hegglin, 2011). An outstanding example of ozone depletion is the formation of the Antarctic ozone hole, a phenomenon discovered in the 1980s (Farman, et al., 1985). Each austral spring, a severe ozone depletion occurs under the unique conditions in the Antarctic polar vortex, decreasing total ozone column (TOC) below 220 Dobson Units (DU), a threshold defining the ozone hole.

15   The Antarctic ozone hole has been extensively studied (WMO, 2011). Apart from its direct influence on the ozone amounts in the Southern Hemisphere (Ajtić, et al., 2004; de Laat, et al., 2010) the Antarctic ozone hole affects a wide range of atmospheric phenomena as well as climate of the Southern Hemisphere. For example, ozone depletion over Antarctica has altered atmospheric circulation, temperature and precipitation patterns in the Southern Hemisphere during the austral spring and summer (Brönnimann, et al., 2017; Bandoro, et al., 2014). Another notable consequence of decreased atmospheric ozone is an

20   increase in solar UV radiation at the surface of the Earth, which has been supported by experimental evidence (Herman & McKenzie, 1998). This anti-correlation and association with the Antarctic ozone hole has been confirmed at Lauder, New Zealand (McKenzie, et al., 1999).

Our analysis investigated the anti-correlation between the content of ozone in the atmosphere and solar UV-B radiation over

25   the Western Cape Province, South Africa. The objectives in our study were: 1) to determine the climatology of solar UV-B radiation and the climatology of TOC and stratospheric column ozone (SCO) for Cape Point, South Africa; 2) to determine clear-sky days for Cape Point and use them to analyse the anti-correlation between solar UV-B radiation and TOC, on one hand, and solar UV-B radiation and SCO, on the other hand; 3) to identify low TOC and SCO events at Cape Point during spring and summer months; 4) to use a transport model to determine the origin of ozone-poor air observed during low-ozone

30   events; and 5) to explore whether the Antarctic ozone hole influenced the identified low-ozone events at Cape Point. To the best of our knowledge these objectives, in a South African context, and in relation to increased solar UV-B radiation over South Africa directly related to the Antarctic ozone depletion, have not been studied before.

2. Data and methods

2.1 UV data

The study site was Cape Point (34.35 °S, 18.50 °E, 230 m a.s.l.) a weather station in the Western Cape, South Africa (Fig. 1). The station is one of the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) baseline monitoring sites (GAW, 2015). It is located around 60 km south of Cape Town and although considered free of air pollution (Slemr, et al., 2008), it may still be affected by maritime aerosols. Since aerosols can have a pronounced effect on the amount of UV radiation reaching the surface (Bais, et al., 2015), our choice of Cape Point offers a setting in which a modification of the UV-B radiation by anthropogenic aerosols can be overlooked.
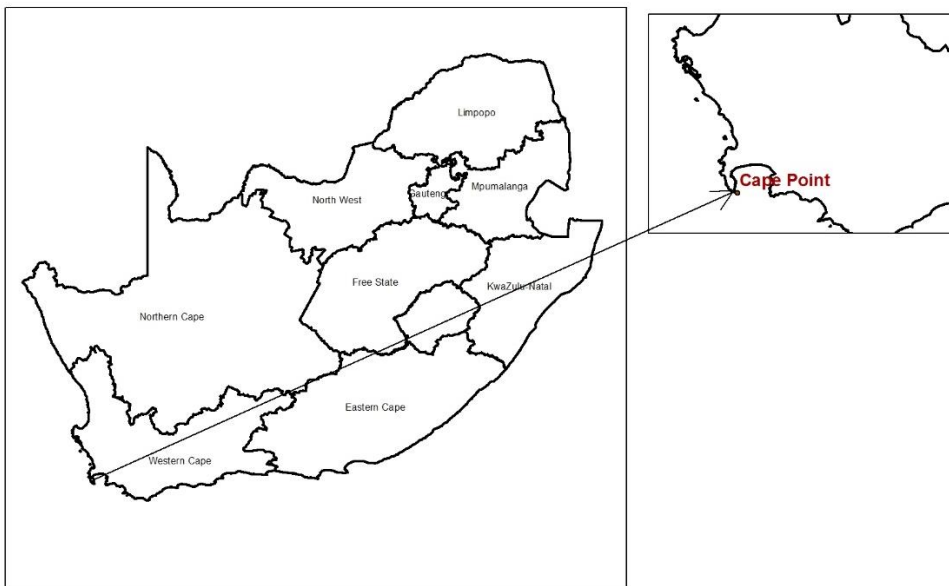
Figure 2: The map of South Africa and the location of the SAWS Cape Point Weather station in the Western Cape (L. Thobela, SAWS 2018).

Hourly solar UV-B radiation data were obtained from the South Africa Weather Service (SAWS) for Cape Point station for the period 2007 - 2016. The solar UV-B radiation measurements were made with the Solar Light Model Biometer 501 Radiometer. The biometer measures solar UV radiation with a wavelength of 280 - 320 nm. The measured solar UV radiation is proportional to the analogue voltage output from the biometer with a controlled internal temperature (Solarlight, 2014). Two different instruments were used at Cape Point between 2007 and 2016 (Table 1). The first from January 2007 until March 2016 and the second from April 2016 to December 2016. The SAWS calibrated the instruments at both Solar Light and the Deutscher Wetterdienst (DWD), Lindenberg, Germany. Calibration at Solar Light was according to the "Calibration of the UV radiometer - Procedure and error analysis". At DWD, the instruments were calibrated using the spectrometer SPECTRO 320 D NO 15.

11

During the period of operation for each instrument, the stability was checked by performing inter-comparisons with reference instruments (12010 and 2722) which had been calibrated shortly prior to the inter-comparison.

Table 2: Summary of the instruments and their calibration information

Instrument	Period of Operation	Calibration Information
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Inter-comparison Instruments	**Inter-comparison Date**	**Calibration Information**
Instruments 3719 and 12010	October 2012	12010: DWD – August 2012
Instruments 3719 and 2722	January 2014	2722: DWD – July 2013
Instruments 1103 and 12010	November 2016	12010: Solar Light – June 2015

5 Measurements are given in Minimal Erythemal Dose (MED) units where 1 MED is defined by SAWS as 210 Jm^{-2} and any incorrect or missing values were indicated in the dataset. During October 2016, the measured MED values exceeded the expected values and were corrected with a correction factor as recommend by the SAWS. Despite periods of missing data during the study years, there were 3 129 days of useable solar UV-B data for Cape Point. To convert from instrument-weighted UV radiation to erythemally-weighted UV radiation, a correction factor was applied as the instrument does not measure the

10 full spectral range of the UV Index (Seckmeyer, et al., 2005; Cadet, et al., 2017). Solar UV-B radiation values in MED were converted to UV Index (*UVI*) using:

$$UVI = MED[h^{-1}]\frac{210[J \cdot m^{-2}] \times 40[m^2 \cdot W^{-1}]}{3600[s]} \tag{1}$$

where UVI is the UV Index value and MED is the hourly Minimal Erythemal Dose units.

15 **2.2 Column ozone data**

TOC and SCO data were obtained for 2007 – 2016 (inclusive) for the grid area which was bound by the following coordinates - West: 16.5 °E, South: 36.35 °S, East: 20.6 °E, North: 31.98 °S. This grid area limited the TOC and SCO data to the area directly above Cape Point. The daily TOC data were measured with the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite. OMI has a spatial resolution of 0.25° which results in a ground resolution at nadir with a range of 13 km x 24 km to

20 13 km x 48 km (Levelt, et al., 2006).

The daily SCO data were measured with the Microwave Limb Sounder (MLS) instrument on NASA's Aura satellite. The MLS ozone data consisted of ozone profiles at 55 pressure levels and SCO values up to the thermal tropopause. The thermal tropopause is determined by the temperature data taken by the MLS instrument. The ozone profiles were used between 261 - 0.02 hPa (Livesey, et al., 2017). The daily SCO values were extracted from the MLS data files.

2.3 Transport model

The Mesoscale Isentropic Transport Model of Stratospheric Ozone by Advection and Chemistry (Modèle Isentropique du transport Méso-échelle de l'ozone stratosphérique par advection avec CHIMIE or MIMOSA-CHIM) was used to identify the source of ozone-poor air above Cape Point. MIMOSA-CHIM results from the off-line coupling of the MIMOSA dynamical model (Hauchecorne, et al., 2002) from the Reactive Processes Ruling the Ozone Budget in the Stratosphere (REPROBUS) chemistry model (Lefèvre, et al., 1994). The ability of MIMOSA-CHIM to simulate and analyze the transport of stratospheric air-masses has been highlighted in several previous studies over the polar regions (Kuttippurath, et al., 2013; Kuttippurath, et al., 2015; Tripathi, et al., 2007; Semane, et al., 2006; Marchand, et al., 2003). The dynamical component of the model is forced by meteorological data such as wind, temperature, and pressure fields from the European Centre for Medium-Range Weather Forecasts (EMCWF) daily analyses. The dynamical component of potential vorticity (PV) was used to trace the origin of ozone-poor air-masses. PV can be used as a quasi-passive tracer when diabatic and frictional terms are small. Therefore, over short periods of time, PV is conserved on isentropic surfaces following the motion (Holton & Hakim, 2013). A spatial area from 10 °N to 90 °S was used for the model with a 1° x 1° resolution. The model has stratospheric isentropic levels ranging from 350 - 950 K. The MIMOSA-CHIM model created an output file for every 6 hours and simulations were initialised to run for approximately 14 days prior to each low-ozone event to account for the model spin-up period. The PV maps were analysed at isentropic levels that correspond to 18 km, 20 km and 24 km above ground level, thus covering the lower part of the ozone layer (Sivakumar & Ogunniyi, 2017).

2.4 Method

2.4.1 Climatologies

The hourly average for each day in a specific month across the 10-year period was used to determine the solar UV radiation climatology at Cape Point. All days were used to determine the climatology, regardless of cloud conditions. The TOC and SCO climatologies were calculated using monthly averages. The climatologies and patterns analysed used all available days with data.

2.4.2 Determination of clear-sky days

Clouds are an important factor that attenuate or enhance the solar UV-B radiation at the Earth's surface (Bais, et al., 2015). Thus, determining cloud-free days is a step towards removing a contribution of all factors except amount of atmospheric ozone.

As shown by (McKenzie, et al., 1991) stronger correlation between ozone and solar UV-B radiation may be obtained if the days with clouds are removed.

The SAWS Cape Point site has no cloud cover data available. For that reason, we used a clear-sky determination method by Bodeker and McKenzie (1996) to find cloudy days and consequently, remove them from our further analysis. Prior to that, we tested our clear-sky methodology against measurements from the Cape Town weather station where cloud cover is available.

First, days with solar UV-B measurements, TOC and SCO data were divided into seasons: summer – December, January, February (DJF), autumn – March, April, May (MAM), winter – June, July, August (JJA) and spring – September, October, November (SON). Then, Clear-sky days were determined using three different tests.

The first test only considered the daily linear correlation between the UVI values measured before solar noon and the values after solar noon. Solar noon was determined as the hour interval with the lowest SZA value. Days with a linear correlation below 0.8 in the DJF, MAM and SON seasons were removed and were considered to be cloudy days. The first test was not performed on the winter season, when the UVI values were low, as well as the correlation values.

The second test looked for a monotonic increase before solar noon and a monotonic decrease after solar noon for each day. On clear-sky days, UVI values before and after solar noon should monotonically increase and decrease, respectively. If monotonicity did not hold for the UVI values on a specific day, it was assumed that there was some cloud present on that day. The monotonicity test was performed for all seasons. It is interesting to note that at Cape Point, the second test of the clear-sky determination method identified more clear-sky afternoons than clear-sky mornings.

The third test removed days when the UVI values did not reach a threshold maximum value. This test was applied to all seasons. The threshold was determined as a value of 1.5 standard deviations (1.5 STD) below the UVI monthly average. The monthly average and standard deviations were determined from the solar UV-B radiation climatology for Cape Point.

We tested the validity of the clear-sky days' determination using the solar UV-B radiation dataset and cloud cover data from the Cape Town weather station. In the test, we used the daily 06h00 UTC and 12h00 UTC cloud cover observations, and randomly selected two years for the validation. The results showed that when the observations indicated more than 4/8ths of cloud present, our methodology also identified these days as cloudy. Furthermore, we examined the diurnal radiometric curves from another year and found that the determined clear-sky days' radiometric curves closely followed the expected diurnal radiometric curve. This validation implied that the clear-sky tests removed approximately 87 % of cloudy days. Overall, approximately 500 days were determined to be clear-sky days that had UV-B, TOC and SCO data and they were used in our further analyses. For the DJF, MAM, JJA and SON seasons there was 150, 104, 137 and 102 clear-sky days respectively.

2.4.3 Correlations

In addition to removing anthropogenic aerosols by choosing an air pollution free site and alleviating cloud effects by looking only at the clear-sky days, the correlation between solar UV-B radiation and ozone can be better observed when controlling SZA (Booth & Madronich, 1994). To calculate ten-minute SZAs for Cape Point, we applied an online tool, Measurement and Instrument Data Centre, Solar Position Calculator (MIDC SPA)(https://midcdmz.nrel.gov/solpos/spa.html accessed February 2017), which uses the date, time and location of the site of interest and has an accuracy of +/-0.0003° (Reda & Andreas, 2008).

The strength of the correlation between the amount of ozone (TOC and SCO data) and solar UV-B radiation was determined using the first order exponential fit (Guarnieri, et al., 2004):

$$y = ae^{bx} \tag{2}$$

Where; $y = UVI$ and x = ozone values (TOC or SCO).

The significance of the goodness of fit was determined for a 95 % confidence interval. The log UVI (y-axis) values were taken to test whether the goodness of fit R^2 values of the exponential fits were statistically significant (Hazarika, 2013).

2.4.4 Radiation Amplification Factor

The Radiation Amplification Factor (RAF) describes a relationship between ozone values and solar UV-B radiation (Booth & Madronich, 1994). The RAF was introduced as a quantification of the effect that decreased ozone concentrations have on solar UV-B radiation levels. The RAF is a unitless coefficient of sensitivity and here we used its definition given by Booth & Madronich (1994) in Equation 3. The RAF value at fixed SZAs was calculated using a specific clear-sky day compared to another random clear-sky day from a different year (Booth & Madronich, 1994).

$$RAF = \ln\left(\frac{O3}{O3'}\right) / \ln\left(\frac{UVI'}{UVI}\right) \tag{3}$$

where O3 and O3' are the first and second ozone values and UVI and UVI' are the first and second UV measurements, respectively.

2.4.5 Low-ozone days

Days of low TOC and SCO values were determined from the set of clear-sky days, but only during spring and summer seasons, when solar UV radiation levels are highest. Days of low TOC values might not have had low SCO values and vice versa. Low TOC and SCO days were determined as days when the respective values were below 1.5 STD from the mean as determined in the climatology analyses (Schuch, et al., 2015).

We then used the MIMOSA-CHIM model to identify whether the origin of ozone-poor air-masses was from the polar region. In other words, on low-ozone days we looked into the maps of advected PV from MIMOSA-CHIM to identify the source of ozone-poor air parcels over the study area.

5 **3. Results and discussion**

3.1 Climatologies and trends

3.1.1 *UVI* climatology

The monthly means of *UVI* for Cape Point during 2007–2016 were calculated as a function of time of the day and month of the year (Fig. 2). This climatology provides a reliable baseline against which observations can be compared and reveals the

10 general patterns of the *UVI* signal recorded at the surface over the investigated 10-year period.
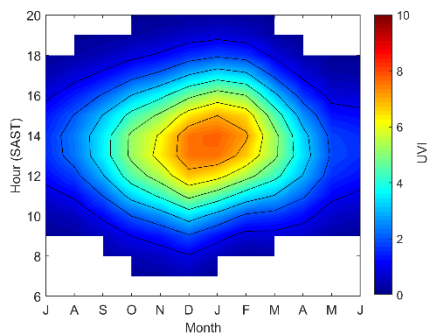
Figure 3: The *UVI* climatology for all sky conditions at Cape Point. The *x*-axis starts with the month of July and ends with June.

At Cape Point, the *UVI* maximum value of approximately 8 UVI occurs between 13h00 and 15h00 South African Standard

15 time (SAST) time, which corresponds to between 11h00 and 13h00 UTC, (Fig. 2). The maximum *UVI* values are not centred on the local noon, implying that more UV radiation reaches this site in the afternoon. Indeed, as previously mentioned, our clear-sky determination method identified more clear-sky afternoons than clear-sky mornings (Sec. 2.4.2), which under the assumption that cloud cover at Cape Point generally attenuates UV radiation reaching the surface, could explain the observed shift in the *UVI* maximum to about 14h00 SAST.

20

The seasons of maximum (DJF) and minimum (JJA) solar UV-B radiation at Cape Point are as expected for a site in the Southern Hemisphere and are similar to those found in studies at other South African sites, namely Pretoria, Durban, De Aar, and Port Elisabeth and Cape Town (Wright, et al., 2011; Cadet, et al., 2017). The maximum *UVI* values found in this study occur at similar times to Cadet, et al., 2017; Wright, et al., 2011.

16

3.1.2 Ozone climatologies

At Cape Point, TOC (with the maximum of 303.4 DU) and SCO (with the maximum of 273.1 DU) values peaked during September and decreased to a minimum in February for SCO (232.65 DU) and April for TOC (254.49 DU) (Fig. 3). The variations in TOC and SCO are largest at the maximum values and smallest at the minimum values. Over Irene in Pretoria the greatest variation in SCO was seen during spring (Paul, et al., 1998), which is in agreement with our results. It is suggested that this variability in TOC is due to the movement of midlatitude weather systems which move further north during the Southern Hemisphere winter (Diab, et al., 1992). The climatology of TOC over South Africa is mainly affected by atmospheric dynamics rather than by the effects of atmospheric chemistry (Bodeker & Scourfield, 1998).
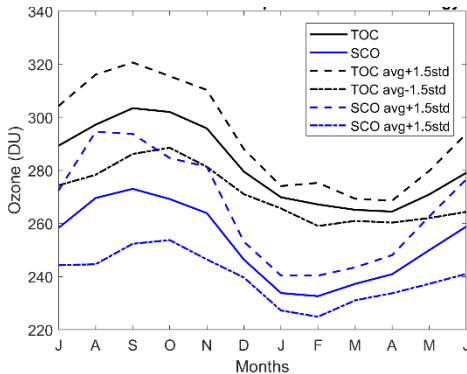
Figure 4: Monthly means and +/- 1.5 STD for total ozone column and stratospheric column ozone starting in July and ending in June.

The increase in TOC values during the winter months and the maximum during spring months are due to an ozone-rich midlatitude ridge that forms on the equator-side of the polar vortex. The ridge is a result of a distorted meridional flow caused by the Antarctic polar vortex that forms in late autumn. The vortex prevents poleward transport of the air, and thus allows for a build-up of ozone-rich air in midlatitudes. The lower TOC values over summer could be due to the dilution effect of ozone-poor air from the Antarctic ozone hole. The dilution effect occurs when the vortex breaks-up (Bodeker & Scourfield, 1998; Ajtić, et al., 2004).

3.2 Correlation between the amount of ozone and *UVI*

The first order exponential goodness of fit R^2 values at fixed SZAs (Table 2) describe the anti-correlation between the amount of ozone in the atmosphere and *UVI*. The strongest anti-correlation was found at a fixed SZA 25° for both TOC and SCO. In this study the first order exponential fit was used to describe the anti-correlation between ozone and solar UV radiation as in some instance this is best described with a non-linear fit (Guarnieri, et al., 2004). A study on the anti-correlation between solar UV-B irradiance and TOC in southern Brazil found that the percentage of the R^2 values for exponential fits (66.0 -85.0%)

17

explained the variations in solar UV-B irradiance due to TOC variations on clear-sky days at the same fixed SZA categories used in our study (Guarnieri, et al., 2004).

Table 2. The correlation statistics for amount of ozone and *UVI* at Cape Point on clear-sky days (*indicates R^2 values were statistically significant at a 95 % confidence interval**).**

SZA (°)	TOC: R^2 Expo fit	SCO: R^2 Expo fit	RAF
15	0.25*	0.18*	1.60
20	0.26*	0.23*	0.19
25	0.45*	0.53*	0.26
30	0.28*	0.20*	0.82
35	0.21*	0.11*	0.15
40	0.30*	0.30*	0.42
45	0.26*	0.29*	0.69
Average			**0.59**

The exponential R^2 values of TOC found at Cape Point at a fixed SZAs were much lower than those southern Brazil. In this study and in other studies the R^2 value is smaller sat the largest SZAs (Guarnieri, et al., 2004; Wolfram, et al., 2012).

At Cape Point, the RAF value for clear-sky days range between 0.15 and 1.60 with an average RAF value of 0.59. This can be interpreted as for every 1% decrease in TOC, UV-B radiation at the surface will increase by 0.59%. RAF values specific to ozone and solar UV studies found in the literature range between 0.79 and 1.7 (Massen, 2013). RAF values have been used to describe the effect of other meteorological factors such as clouds and aerosols on surface UV radiation (Serrano, et al., 2008; Massen, 2013). The differences to the RAF values found here and those found in the literature can be attributed to changes in time and location (Massen, 2013).

Salt build-up on the biometer at Cape Point may also have contributed to the accuracy of measurements taken by the biometer. Solar UV-B radiation data with a higher temporal resolution (e.g. 10 minutes) may have provided more data points for the analysis at fixed SZAs. Higher temporal resolution solar UV-B radiation data would have improved the determination of clear-sky days. An improvement on the correlation and RAF values could be made by investigating the aerosol concentrations over the station.

3.3 Low-ozone events

Low-ozone events which occurred during the SON and DJF months were identified from the time series of TOC and SCO data on clear-sky days (Fig. 4). The highest frequency of low TOC and low SCO events occurred during January months and January and December months, respectively.
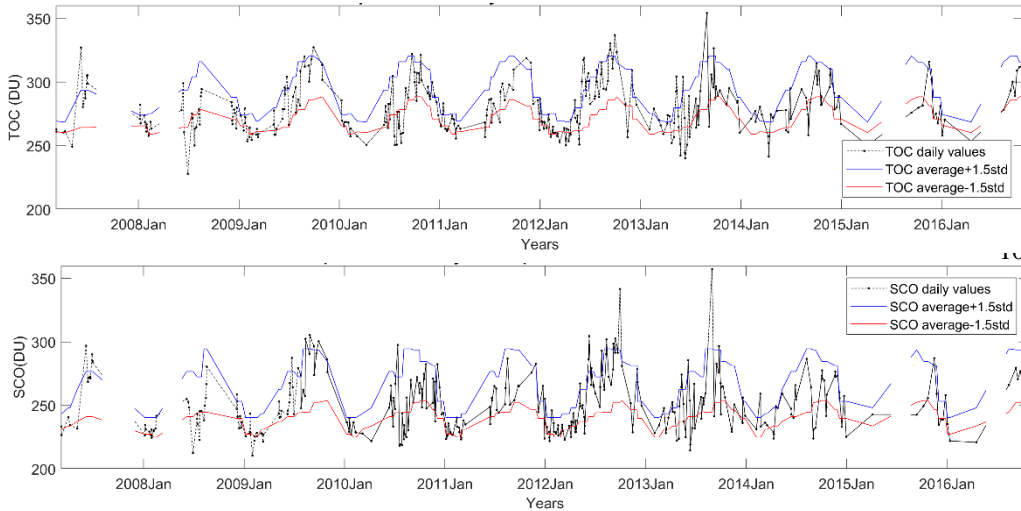

Figure 4*: **TOC (top) and SCO (bottom) values on clear-sky days over Cape Point and an indication of the average ±1.5 STD limits. Each dot corresponds to a TOC and SCO measurement on a clear-sky day from 2007-2016. Interrupted lines indicate missing data.**

20   The low TOC and low SCO events along with the respective percentage decrease in TOC and SCO (Table 3) represent some of the largest decreases that occurred in DJF and SON seasons between 2007 and 2016 on clear-sky days. The DJF seasons of 2009/2010 and 2015/2016 are classified as El Niño years (Climate Prediction Center Internet Team, 2015). During these seasons higher TOC levels are expected over the midlatitude regions (Kalicharran, et al., 1993). From the identified low TOC events at Cape Point, none occurred during El Niño years.

25

This analysis aimed to discuss effects of stratospheric ozone and tropospheric ozone on surface UV-B radiation variations. When TOC and SCO reductions are similar, the effect of stratospheric ozone decrease is dominant. Conversely, when the reduction of TOC is high, and the reduction of SCO is low, the effect of tropospheric ozone is dominant.

30

Table 3. Identified low-ozone events on clear-sky days at Cape Point during spring and summer months and the percentage decrease calculated from the relative climatological monthly mean (* indicates whether the low-ozone event was due to low TOC and/or low SCO values)**.**

Date	TOC (DU)	SCO (DU)	Decrease TOC (%)	Decrease SCO (%)	Increase *UVI* (%)
30 Jan 2009	253.5*	210.4*	6.1	10.1	30.4
6 Feb 2009	253.9*	222.2*	5.0	4.5	36.2
15 Feb 2009	254.6*	228.3	4.7	1.9	34.2
28 Feb 2011	255.7*	223.2*	4.3	4.1	6.8
16 Jan 2012	268.2	221.9*	0.6	5.1	21.2
8 Feb 2012	257.0*	227.5	3.8	2.2	31.7
13 Nov 2012	256.6*	228.8	13.3	13.3	46.5
14 Nov 2012	261.3*	234.6	11.7	11.1	42.1
6 Sep 2013	265.0*	241.3*	12.7	11.6	22.3
9 Nov 2013	282.3	229.0*	4.6	13.3	21.9
1 Sep 2014	274.7*	223.9*	9.5	18.0	-2.5
2 Sep 2014	258.4*	231.2*	14.9	15.3	-2.3
9 Sep 2014	284.0*	232.3*	6.4	14.9	-5.5
11 Jan 2016	270.6	221.9*	-0.3	5.1	-7.9

5   All of the low-ozone events which occurred during January were due to decreased SCO. A decrease of 10.1% in SCO was recorded on 30 January 2009 with a TOC decrease of 6.1%. During February months we obtained the weakest reductions in TOC and SCO. Low-ozone events that occurred during September were mainly due to stratospheric ozone decreases, with the largest ozone reduction recorded on 1 September 2014 (18 % in SCO reduction) (Table 3).

10   We compared the *UVI* levels recorded during low-ozone events within the SON and DJF seasons to the *UVI* climatology to determine if the ozone reductions reflected on the *UVI* levels during low-ozone events. At Cape Point, the largest increases in the *UVI* levels were recorded for low-ozone events during November. The largest increase (46.5 %) in *UVI* occurred on 13 November 2012.

15   In the Southern Hemisphere, during the spring season (SON) low-ozone events are predominately due to the distortion and filamentation of the Antarctic ozone hole and to the dilution of the associated polar vortex. The dilution effect occurs later in the early summer season, when ozone-poor air masses from the polar region mix with air masses from the midlatitudes and result in decreased ozone concentrations (Ajtić, et al., 2004). There are no studies that refer to low-ozone events at Cape Point.

In South Africa, a decrease in TOC was observed over Irene (25.9°S, 28.2°E) during May 2002 when TOC levels were 8 – 12 % below normal and at a minimum of 219.0 DU (Semane, et al., 2006). The relative position of the surface high- or low-pressure can result in increases or decreases in TOC. The effect on TOC by weather systems is seasonal dependent (Barsby & Diab, 1995).

5

The increased levels of solar UV-B radiation found in this study due to low SCO events are similar to those found at other Southern Hemisphere sites (Gies, et al., 2013; McKenzie, et al., 1999; Abarca, et al., 2002). It is possible that low-ozone events that occurred over Cape Point during 2007-2016 have not been included. These events might have fallen outside the methods used in this study or were not considered due to the availability of solar UV-B radiation, TOC or SCO data. Moreover, it

10 should be noted that the Cape Point site being located at 34° South, at the southern limit of the tropical stratospheric reservoir. Cape Point can be affected by dynamical and transport processes, and therefore air masses of different latitude origins can pass over it. Indeed, over our study period from September to February, the obtained low ozone event could be of polar origin, i.e., in relation with the extension and distortion of the polar vortex, or of tropical origin, i.e., in relation with isentropic air-masses transport across the subtropical barrier, as reported by (Semane, et al., 2006; Bencherif, et al., 2011; Bencherif, et al., 2007).

15 The following sub-section discusses low ozone events with regard to the dynamical situations and origins of air-masses above the study site.

3.4 Origin of ozone-poor air

In this section the model results from MIMOSA-CHIM are shown for a selection on low-ozone events. The latitude origin of air masses was classified according to the colour scale on the PV maps. Blue colours indicate air-masses with relatively high

20 PV values, implying their polar origins, while red colours indicate relatively low PV values of tropical origin.

The origin of the air-masses for low-ozone events in January (Table 3) and February (Table 4) shows a consistent pattern: in the lower parts of the stratosphere, at 425 K, the air was of tropical origin; higher up, at 475 K, of midlatitude origin; and at 600 K, air masses from the polar region were above Cape Point. This pattern in illustrated in the PV maps from MIMOSA-

25 CHIM of the low-ozone event on 16 January 2012 (Fig. 5), which best demonstrates all January events. During this event, we identified low SCO (Table 2). Similarly, the PV maps from MIMOSA-CHIM for the low-ozone event on 6 February 2009 (Fig. 6) best demonstrate the situation for February months.

Our results imply that the low-ozone events during the months of January and February were not directly influenced by the

30 Antarctic ozone hole as by that time, the polar vortex is already broken up. However, it is possible that these events are a consequence of the ensuing mixing of the polar ozone-poor air that reduces the midlatitudes ozone concentrations (Ajtić et al. 2004).

Table 3. Origin of ozone-poor air at isentropic levels for low ozone events in January.

Date	Origin at 425 K	Origin at 475 K	Origin at 600 K
30 Jan 2009	Tropical	Midlatitude	Polar
16 Jan 2012	Tropical	Midlatitude	Polar
11 Jan 2016	Tropical	Midlatitude	Polar

Table 4. Origin of ozone-poor air at isentropic levels for low ozone events in February.

5

| Date	Origin at 425 K	Origin at 475 K	Origin at 600 K
6 Feb 2009	Tropical	Midlatitude	Polar
15 Feb 2009	Tropical	Midlatitude	Polar
28 Feb 2011	Tropical	Midlatitude	Polar
8 Feb 2012	Tropical	Midlatitude	Polar

(a)   (b)   (c)
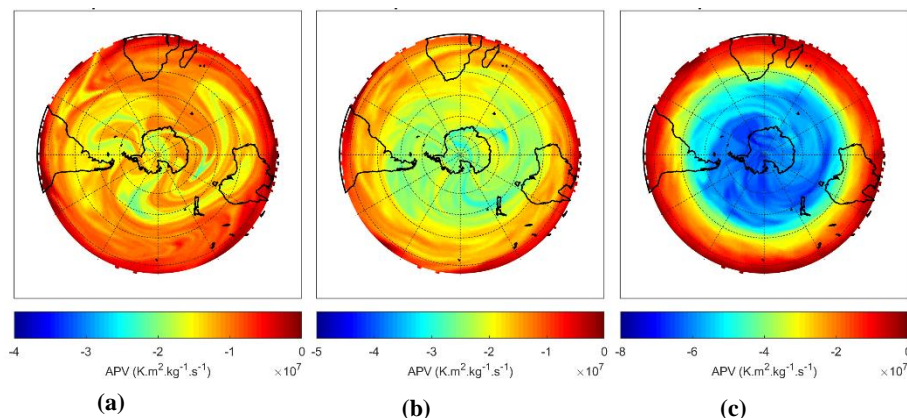
Figure 5: PV maps from MIMOSA-CHIM at 425 K (a), 475 K (b) and 600 K (c) on 16 January 2012.

The origin of air-masses for low-ozone events during September (Table 5) and the PV maps from MIMOSA-CHIM for the
10 low-ozone event on 2 September 2014 (Fig. 7) shows the transport of tropical air-masses southward over the study site. During
September months there was less mixing of air-masses across latitudinal boundaries.
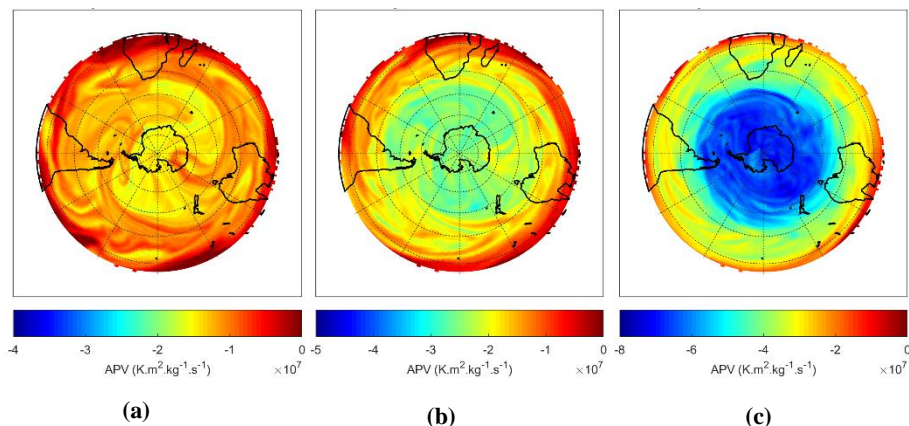
Figure 6: PV maps from MIMOSA-CHIM at 425 K (a), 475 K (b) and 600 K (c) on 6 February 2009.

Table 5. Origin of ozone-poor air at isentropic levels for low ozone events in September.

Date	Origin at 435 K	Origin at 485 K	Origin at 600 K
6 Sep 2013	Tropical	Midlatitude	Midlatitude - Polar
1 Sep 2014	Tropical	Tropical	Midlatitude - Polar
2 Sep 2014	Tropical	Tropical	Midlatitude - Polar
9 Sep 2014	Tropical	Tropical	Midlatitude - Polar
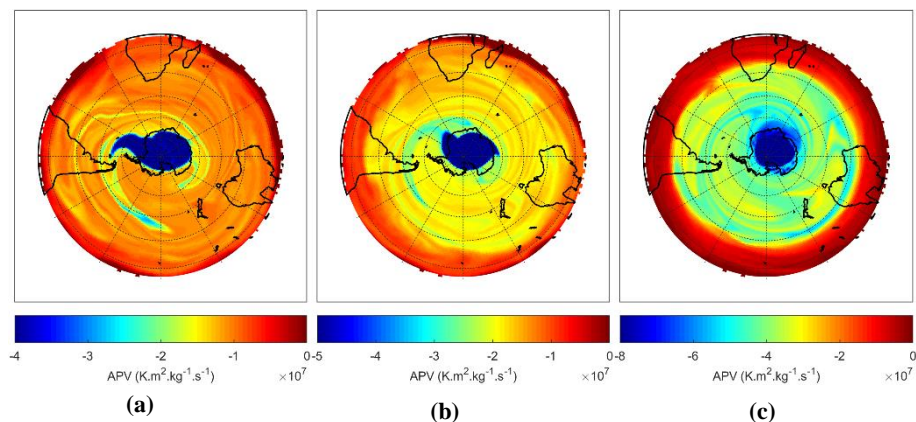
Figure 7: PV maps from MIMOSA-CHIM at 435 K (a), 485 K (b) and 600 K (c) on 2 September 2014.

The origin of air-masses for low-ozone events in November (Table 6) shows that at 600 K polar air-masses do affect the study site but ozone hole is no longer present over Antarctica. The PV maps from MIMOSA-CHIM for the low-ozone event on 14 November 2012 (Fig. 8) best demonstrate the situation for November months.

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Table 6. Origin of ozone-poor air at isentropic levels for low ozone events in November.

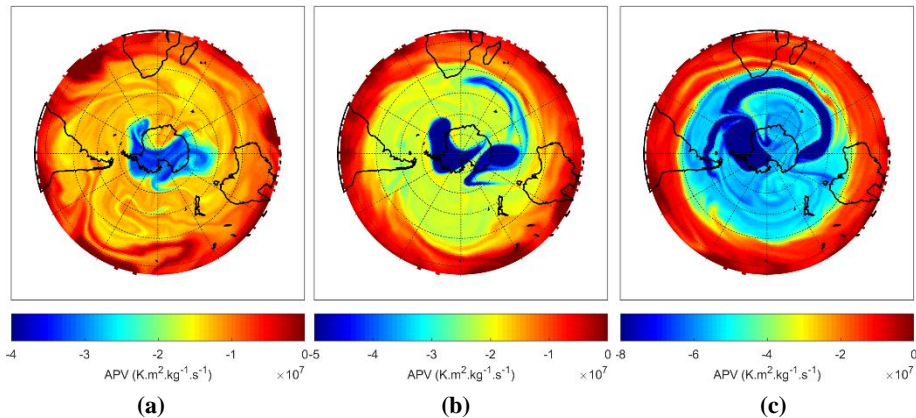| Date	Origin at 435 K	Origin at 480 K	Origin at 600 K
13 Nov 2012	Tropical	Midlatitude	Polar
14 Nov 2012	Tropical	Midlatitude	Polar
09 Nov 2013	Tropical	Midlatitude	Polar

(a) (b) (c)

Figure 8: PV maps from MIMOSA-CHIM at 435 K (a), 485 K (b) and 600 K (c) on 14 November 2012.

The PV maps from MIMOSA-CHIM suggest that the Antarctic polar vortex air-masses with low-ozone levels have a limited effect on the ozone levels over Cape Point, South Africa. Instead, the study site is largely influenced by ozone-poor air-masses from sub-tropical regions. The effect of these sub-tropical air-masses on ozone concentrations is dependent on isentropic level and time of year. In fact, it is well known that Rossby planetary waves are generated due to the development of synoptic disturbances in the troposphere during winter and spring seasons. They propagate vertically through to the stratospheric layers when the zonal winds are westerly (Charney & Drazin, 1961; Leovy, et al., 1985). Moreover, as reported by many authors, gravity and Rossby planetary waves are involved in isentropic transport across the subtropical barrier. Portafaix, et al., 2003 studied the southern subtropical barrier by using MIMOSA model advected PV maps, together with a numerical tool developed by LACy (Reunion University) named DyBaL (Dynamical Barrier Localisation) based on Nakamura formalism (Nakamura, 1996). They showed that the southern subtropical barrier is usually located around 25-30°S but has an increasing variability during winter and spring. Moreover, using MIMOSA adverted PV fields (Bencherif, et al., 2007; Bencherif, et al., 2003) showed that exchange processes between the stratospheric tropical reservoir and mid-latitudes are episodic and take place through the subtropical barrier due to planetary wave breaking inducing increase or decrease of ozone at tropical and subtropical locations depending on the isentropic levels. It is known that atmospheric ozone over South Africa is mainly impacted by dynamical factors (Bodeker, et al., 2002). Another dynamical factor that influences ozone over the study area is stratospheric-tropospheric exchanges which mostly influence SCO levels. One or a combination of these dynamical factors likely result in low-ozone levels over Cape Point.

24

4. Conclusion

This study evaluated the anti-correlation between ground-based solar UV-B radiation and satellite ozone observations based on clear-sky days at Cape Point, South Africa. The study further investigated whether the break-up of the Antarctic ozone hole during spring/summer has an impact on the ozone concentrations over the study area and, as a result, affects solar UV-B radiation levels.

The solar UV-B climatology for Cape Point as well as the climatologies of TOC and SCO followed the expected annual cycle for the Southern Hemisphere. The determination of clear-sky days proved to be reliable in identifying cloudy days. The clear-sky tests removed approximately 87 % of days that were affected by cloud cover. At Cape Point, at SZA 25°, an exponential goodness of fit R^2 value of 0.45 and 0.53 for TOC and SCO, respectively, was found. An average RAF value of 0.59 was found across all SZAs.

Our results imply that the break-up of the Antarctic polar vortex has a limited influence on the SCO concentrations over Cape Point. The study site was affected to some extent by Antarctic polar air-masses during November months predominately at 600 K. During September low-ozone events, there was less exchange of air-masses between latitudes compared to other months and the study site was mostly under the influence of midlatitude air-masses. The study site seems to be more frequently affected by air-masses from the tropical regions, especially in the lower stratosphere. Further, the influence of tropical air-masses on the study site is larger during January and February months. During low SCO events in September and November, the recorded *UVI* levels were ~20 % above the climatological monthly mean.

The relationship between atmospheric ozone and solar UV-B radiation is well understood around the world. The impact of the Antarctic ozone hole on atmospheric ozone concentrations over South Africa is less well understood. Our study showed instances when the Antarctic ozone hole seems to have a limited effect on ozone concentrations over Cape Point but also showed the effect of tropical air-masses on ozone levels at Cape Point.

Data availability

The solar UV-B radiation data are available from the South African Weather Service on request. The total ozone column and stratospheric column ozone data are available on-line from the sources as stated in the manuscript.

Author contribution

J.D.P. and C.Y.W. conceived and designed the experiments; J.D.P. performed the experiments; J.D.P. and C.Y.W. analysed the data; J.M.C assisted with data conversion. J.V.A., H.B. and N.B. contributed to data analysis and interpretation. J.D.P and C.Y.W. wrote the paper. All authors contributed towards the preparation of the paper.

Competing interests

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References

Abarca, J. F., Casiccia, C. C. & Zamorano, F. D., 2002. Increase in sunburns and photosensitivity disorders at the edge of the Antarctic ozone hole, Southern Chile, 1986-2000. *J. Am. Acad. Dermatol.,* 46(2), pp. 193-199. doi:10.1067/mjd.2002.118556.

Ajtić, J. et al., 2004. Dilution of the Antarctic ozone hole into the southern midlatitudes. *J. Geophys. Res.,* 109(D17107), pp. 1-9. doi:10.1029/2003JD004500.

Bais, A. F. et al., 2015. Ozone depletion and climate change: Impacts on UV radiation. *Photochem. Photobiol. Sci.,* Volume 14, pp. 19-52. doi:10.1039/c4pp90032d.

Bandoro, J. et al., 2014. Influences of the Antarctic Ozone Hole on Southern Hemispheric Summer Climate Change. *J. Clim.,* Volume 27, pp. 6245-6264. DOI: 10.1175/JCLI-D-13-00698.1.

Barsby, J. & Diab, R. D., 1995. Total ozone and synoptic weather relationships over southern Africa and surrounding oceans. *J. Geophys. Res.,* 100(D2), pp. 3023-3032. doi:10.1029/94JD01987.

Bencherif, H. et al., 2007. Examination of the 2002 major warming in the southen hemisphere using ground-based and Odin/SMR assimilated data: Stratospheric ozone distributions and tropic/mid-latitude exchange. *Can. J. Phys.,* 85(11), pp. 1287-1300.doi: 10.1139/P07-143.

Bencherif, H. et al., 2011. Analysis of a rapid increase of stratospheric ozone during late austral summer 2008 over Kerguelen (49.4° S, 70.3° E). *Atmospheric Chem.and Phys.,* Volume 11, pp. 363-373.

Bencherif, H. et al., 2003. LIDAR observations of lower stratospheric aerosols over South Africa linked to large scale transport across the southern subtropical barrier. *J. Atm. and Solar-Terrestrial Phy.,* Volume 65, pp. 707-715.

Bodeker, G. E. & Scourfield, M. W., 1998. Estimated past and future variability in UV radiation in South Africa based on trends in total ozone. *S. Afr. J. Sci.,* 94(1).

5   Bodeker, G. E., Struthers, H. & Connor, B. J., 2002. Dynamical containment of Antarctic ozone depletion. *Geophys. Res. Lett.,* 29(7), p. 1098. doi:10.1029/2001GL014206.

Booth, C. R. & Madronich, S., 1994. Radiation Amplification Factors: Improved formulation accounts for large increases in ultraviolet radiation associated with Antarctic ozone depletion. In: *Ultraviolet Radiation in Antarctica: Measurements and Biological Effects.* Washington, D. C: American Geophysical Union, pp. 39-42. doi:10.1029/AR062p0039.

10 Brönnimann, S. et al., 2017. Tropical circulation and precipitation response to ozone depletion and recovery. *Environ. Res. Lett.,* Volume 12, https://doi.org/10.1088/1748-9326/aa7416.

Cadet, J.-M.et al., 2017. Comparison of Ground-Based and Satellite-Derived Solar UV Index Levels at Six South African Sites. *International Journal of Environmental Reseach and Public Health,* Volume 14,.doi:10.3390/ijerph14111384.

Charney, J. G. & Drazin, P. G., 1961. Propagation of planetary-scale distrubances from the lower into the upper atmosphere.

15 *L. Geophys Res.,* Volume 66, pp. 83-109.

Climate Prediction Center Internet Team, 2015. *Cold and warm episodes by season.* [Online] Available at:

http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml[Accessed 30 August 2017].

de Laat, A. et al., 2010. Extreme sunbathing: Three weeks of small total O3 columns and high UV radiation over the southern tip of South America during the 2009 Antartci O3 hole season. *Geophys. Res. Lett.,* 37(L14805),. doi:10.1029/2010GL043699.

20 Diab, R. et al., 1992. Satellite observations of total ozone above South Africa. *S. Afr. Geogr. J.,* Volume 74, pp. 13-18.

Diffey, B. L., 2002. Sources and measurement of ultraviolet radiation. *Methods,* Volume 28, pp. 4-13.

Fahey, D. W. & Hegglin, M. L., 2011. Twenty Questions and Answers About the Ozone Layer: 2010 Update. In: *Scientific Assesment of Ozone depletion: 2010.* Geneva: World Meteorological Organisation, p. 72.

Farman, J. C., Gardinier, B. G. & Shanklin, J. D., 1985. Large losses of total ozone in Antarctica reveal seasonal CIO/NO

25 interaction. *Nature,* Volume 315, p. 207.

GAW, 2015. *GAWSIS Station information system.* [Online] Available at:

https://gawsis.meteoswiss.ch/GAWSIS//index.html#/search/station/stationReportDetails/465[Accessed 12 June 2017].

Gies, P. et al., 2013. Low ozone over southern Australia in August 2011 and its imapct on solar ultraviolet radiation levels. *J. Photochem. Photobiol.,* Volume 89, pp. 984-994. doi:10.1111/php.12076.

30 Guarnieri, R. A. et al., 2004. A study of the anticorrelations between ozone and UV-B radiation using linear and exponential fits in southern Brazil. *Advances in Space Research,* Volume 34, pp. 764-768.

Hauchecorne, A. et al., 2002. Quantification of the transport of chemical constituents from the polar vortex to midlatitudes in the lower stratosphere using the high-resolution advection model MIMOSA and effective diffusivity. *J. Geophys. Res.,* 107(D20),. 8289. doi:10.1029/2001JD000491.

27

Hazarika, N., 2013. *Correlation and Data Transformations.* [Online] Available at: https://blog.majestic.com/case-studies/correlation-data-transformations/[Accessed 11 August 2017].

Herman, J. R. & McKenzie, R. L., 1998. Ultraviolet radiation at the Earth's surface. In: *Scientific Assesment of ozone depletion: 1998.* s.l.:World Meteorological Organisation.

Holton, J. R. & Hakim, G. J., 2013. Circulation, Vorticity and potential vorticity. In: *An Introduction to dynamic meteorology.* Fifth ed. Oxford: Academic Press, p. 121.

Kalicharran, S., Diab, R. D. & Sokolic, F., 1993. Trends in total ozone over southern African stations between 1979 and 1991. *Geophys. Res. Lett.,* 20(24), pp. 2877-2880. doi:10.1029/93GL03427.

Kuttippurath, J. et al., 2015. Variability in Antarctic ozone loss in the last decade (2004-2013):high resolution simulation compared to Aura MLS observations. *Atmos. Chem. Phys.,* Volume 15, pp. 10385-10397 doi: 10.5194/acp-15-10385-2015.

Kuttippurath, J. et al., 2013. Antarctic ozone loss in 1979-2010: first sign of ozone recovery. *Atmos. Chem. Phys.,* Volume 13, pp. 1625-1635 doi: 10.5194/acp-13-1625-2013.

Lefèvre, F. et al., 1994. Chemistry of the 199-1992 stratospheric winter: three-dimensional model simulations. *J. Geophys. Res.,* Volume 99, pp. 8183-8195.

Leovy, C. B. et al., 1985. Transport of ozone in the middle stratosphere: evidence for planetary wave breaking. *J. Atmospheric Sci.,* Volume 42, pp. 230-244.

Levelt, P. F. et al., 2006. Science Objectives of the ozone monitoring instrument. *IEEE transcations on Geoscience and Remote Sensing*, may,. 1199-1208.DOI:10.1109/TGRS.2006.872336.

Livesey, N. J. et al., 2017. *The earth observing system (EOS) Aura microwave limb sounder (MLS) Version 4.2xlevel 2 data quality and description document..* [Online] Available at: https://mls.jpl.nasa.gov/data/v4-2_data_quality_document.pdf [Accessed 25 April 2017].

Lucas, R. M. & Ponsonby, A.-L., 2002. Ultraviolet radiation and health: friend and foe. *Med. J. Aust.,* 11(177), pp. 594-598.

Madronich, S., Mckenzie, R. L., Björn, L. O. & Caldwell, M. M., 1998. Changes in biologically active ultraviolet radiation reaching the Earth's surface. *J. Photochem. Photobiol.,* Volume 46, pp. 5-19.

Marchand, M. S. et al., 2003. Influence of polar ozone loss on northern midlatitude regions estimated by a high-resolution chemistry transport model during winter 1999/2000. *J. Geophys. Res.,* 108(D5),. 8326. doi:10.1029/2001JD000906.

Massen, F., 2013. *Computing the Radiation Amplification Factor RAF using a sudden dip in Total Ozone Column measured at Diekirch, Luxembourg.* [Online] Available at: http://meteo.lcd.lu/papers/MASSEN/RAF_from_sudden_TOC_dip.pdf [Accessed 22 August 2017].

McKenzie, R., Connor, B. & Bodeker, G., 1999. Increased summertime UV radiation in New Zealand in response to ozone loss. *Science,* Volume 285, pp. 1709-1711.

McKenzie, R. L., Bodeker, G. E., Keep, D. J. & Kotkamp, M., 1996. UV Radiation in New Zealand:North-to-South differences between two sites, and relationship to other latitudes. *Weather and climate,* 16(1), pp. 17-26.

McKenzie, R. L., Matthews, W. A. & Johnston, P. V., 1991. The relationship between Erythemal UV and ozone derived from spectral irradiance measurements. *Geophys. Res. Lett.,* 18(12), pp. 2269-2272. doi: 10.1029/91GL02786.

Paul, J., Fortuin, F. & Kelder, H., 1998. An ozone climatology based on ozonesonde and satellite measurements. *J. Geophys. Res.,* 103(D24), pp. 31/709-734. doi:10.1029/1998JD200008.

Portafaix, t., Morel, B., Bencherif, H. & Baldy, S., 2003. Fine-scale study of a thick stratospheric ozone lamina at the edge of the southern subtropical barrier. *J.Geophys. Res.,* Volume 108,. doi:10.1029/2002JD002741.

Prause, A. R. & Scourfield, M. W., 2002. Surface erythemal irradiance and total column ozone above Durban, South Africa, for period 1996-1998. *S. Afr. J. Sci.,* Volume 98, pp. 186-188.

Reda, I. & Andreas, A., 2008. *NREL's Solar Position Algorithm (SPA).* [Online] Available at:

https://www.nrel.gov/midc/spa/[Accessed 26 April 2017].

Schuch, A. P. et al., 2015. Identification o finfluential eventsconcerning theAntarctic ozone hole over southern Brazil and the biological effects induced by UVB and UVA radiation in an endemic treefrog species. *Ecotoxicology and Environmental Safety,* Volume 118, pp. 190-198.http://dx.doi.org/10.1016/j.ecoenv.2015.04.029.

Seckmeyer, G. et al., 2005. *A. Instruments to MeasureSolar Ultraviolet Radiation. Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance,* Geneva, Switzerland: World Meteorological Organization (WMO).

Semane, N. et al., 2006. An unusual stratospheric ozone decrease in the southern hemisphere subtropics linked to isentropic air-mass transport as observed over Irene(25.5°S, 28.1°E) in mid-May 2002. *Atmos. Chem. Phys.,* Volume 6, pp. 1927-1936.

Serrano, A., Anton, M., Cancillo, M. L. & Garcia, J. A., 2008. Proposal of a new erythemal UV radiation amplification factor. *Atm. Chem. Phys.,* Volume 8, pp. 1089-1111.

Sivakumar, V. & Ogunniyi, J., 2017. Ozone climatology and variablity over Irene, South Africa detrermined by ground based and satellite observations. Part 1: Vertical variations in the troposphere and stratopshere. *Atmosfera,* 30(4), pp. 337-353.

Slemr, F., Brunke, E. G., Labuschagne, C. & Ebinghaus, R., 2008. Total gaseous mercury concentrations at the Cape Point GAW station and their seasonality. *Geophys. Res. Lett.,* 35(L11807),. doi:10.1029/2008GL033741.

Solarlight, 2014. *Solar Light.* [Online] Available at: http://solarlight.com/wp-content/uploads/2015/01/Meters_Model-501-.pdf[Accessed 23 January 2017].

Tripathi, O. P. et al., 2007. Comparison of polar ozone loss rates simulated by one-dimensional and three-dimensional models with match observations in recent Antarctic and Arctic winters. *J. Geophys. Res.,* 112(D12307), doi: 10.1029/2006JD008370.

University of Reunion, 2016. *The Uses of Digtal.* [Online] Available at: http://numerique.univ-reunion.fr/ressources/centre-de-calcul/simulations/ [Accessed 30 August 2017].

WHO, 2017. *Ultraviolet radiation and the INTERSUN Programme.* [Online] Available at:

http://www.who.int/uv/uv_and_health/en/[Accessed January 25 2017].

WMO, 2011. *Scientific Asessment of Ozone Depletion:2010, Global Ozone Research and Monitoring Project- Report No52,* Geneva, Switzerland: s.n.

Wolfram, E. A. et al., 2012. The unusual persistence of an ozone hole over a southern mid-latitude station during the Antarctic spring 2009: a multi-instrument study. *Ann. Geophys.,* Volume 30, pp. 1435-1449. doi:10.5194/angeo-30-1435-2012.

Wright, C. Y., Coetzee, G. & Ncongwane, K., 2011. Ambient solar UV radiation and seasonal trends in potential sunburn risk among schoolchilren in South Africa. *S. Afr. J. Child Health,* 5(2), pp. 33-38.