The extreme Arctic ozone depletion in 2020 as was observed from Svalbard (EXAODEP-2020)

4

Boyan H. Petkov[1,2], Vito Vitale[2], Piero Di Carlo[1,3], Georg H. Hansen[4], Tove M. Svendby[4], Kamil Láska[5], Piotr S. Sobolewski[6], Anna Solomatnikova[7], Kseniya Pavlova[7], Bjørn Johnsen[8], Michał A. Posyniak[6], Josef Elster[9,10], Mauro Mazzola[2], Angelo Lupi[2], Giulio Verazzo[2]

1 Department of Advanced Technologies in Medicine & Dentistry, University G. d'Annunzio, Chieti-Pescara, Italy
2 Institute of Polar Sciences, National Research Council of Italy, Bologna, Italy
3 Center for Advanced Studies and Technology, Chieti, Italy
4 Norwegian Institute for Air Research, Atmosphere and Climate Department, Kjeller, Norway
5 Department of Geography, Faculty of Science, Masaryk University, Brno, Czech Republic
6 Institute of Geophysics Polish Academy of Sciences, Department of Atmospheric Physics, Warsaw, Poland
7 Voeikov Main Geophysical Observatory, Laboratory of Ozone Layer Control, St. Petersburg, Russia
8 Norwegian Radiation and Nuclear Safety Authority, Østerås, Norway
9 Centre for Polar Ecology, Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic
10 Institute of Botany Czech Academy of Sciences, Třeboň, Czech Republic

Corresponding author: Boyan H Petkov, b.petkov@isac.cnr.it
ORCID number: 0000-0002-8328-340X

Keywords: Arctic ozone; extreme ozone depletions; Arctic environment; solar UV irradiance in the Arctic

Update of chapter 8 in SESS report 2018 (UV Ozone)

DOI: https://doi.org/10.5281/zenodo.5751922

1. Introduction

Observations of ozone column density and solar ultraviolet (UV) irradiance (~295 – 400 nm) reaching the ground at Svalbard were presented in the 2018 SESS report (Petkov et al. 2019). Instruments operating at four stations (Table 1) provide data about ozone amount, erythemally weighted UV (UVE) irradiance and intensity of the UV-B (~295 – 315 nm) and UV-A (315 – 400 nm) spectral bands. The devices were compared in the frame of the intercomparison campaign performed in late April 2018 with the aim to unite them in a local network (Petkov et al. 2019).

As was shown in the 2018 SESS report (Petkov et al. 2019), ozone density oscillates during the year, reaching its annual maximum in spring: this is the typical behaviour over the Northern Hemisphere (Brasseur and Solomon 2005). In Antarctica, however, spring is the period when strong stratospheric ozone depletions usually occur (Farman et al. 1985; Solomon et al. 1986, Solomon et al. 2007). This difference is attributed to the polar vortices, which are much less marked in the Arctic. Nevertheless, some unusual ozone reduction events took place in the region around the North Pole during the past three decades. The most pronounced were the ozone depletion episodes observed in 1996, 1997, 2011 and 2020. The magnitude of the 2020 depletion was comparable with the Antarctic ozone hole (Lawrence et al. 2020; Manney et al. 2011 and 2020; Svendby et al. 2021; Weber et al. 2021). It was found that such events are able to impact the ozone column at lower latitudes in both late spring (Petkov et al. 2014 and 2021) and summer (Karpechko et al. 2013), underlining the significance of the polar regions for the environment in the densely populated mid-latitude areas. In this regard, the present chapter update aims to describe the most recent significant ozone reduction registered by the instruments operating in Svalbard.

Table 1: Instruments operating in Svalbard that perform observations of the ozone column and solar UV radiation.

Station (coordinates)	Instruments	Measured parameters	Measurement frequency
Ny-Ålesund (78°56'N, 11°55'E)	Brewer MKIV #050	Ozone column, UVE	~ 20 min
	GUV radiometer	Ozone column, UVE, UV-A, UV-B	1 min
	UV-RAD radiometer	Ozone column, UVE, UV-A, UV-B	5 min
Barentsburg (78°24'N, 14°9'E)	Ozonometer M 124	Ozone column	~ 1 h
Longyearbyen (78°13'N, 15°39'E)	Kipp & Zonen UVS-E-T	UV-E	1 min
Hornsund (77°00'N, 15°33'E)	Kipp & Zonen UVS-AE-T	UV-E	1 min

2. A strong Arctic ozone depletion event occurred in 2020

While satellite-borne instruments can provide a general and large-scale look at the event (see next subsection), the instruments in Svalbard are able to present precisely the development of the event. Moreover, these ground-based measurements allow a quantitative assessment of the effect that ozone variations produce on the solar UV irradiance reaching Earth's surface (discussed in subsection 2.2).

2.1. A general picture of the 2020 Arctic ozone depletion

The appearance of the ozone-reduced areas in the polar regions in spring is considered a result of combined action of dynamical and chemical processes (Brasseur and Solomon 2005; Feng et al. 2021). The polar vortex that forms in early winter and may persist through spring is the main dynamical factor for the ozone depletion episodes in the Antarctic and the Arctic. Isolating huge areas over the poles from the mid-latitude air masses, the vortex contributes to a sharp cooling of the stratosphere. This cooling creates conditions for the formation of the polar stratospheric clouds, which in turn favour heterogeneous reactions leading to the appearance of the active halogen species (chlorine and bromine) that destroy the ozone (Molina and Rowland 1974; Solomon et al. 1986). In Antarctica, the vortex is usually very stable and has given rise to significant ozone depletion almost every year in the past decades. In contrast, the Arctic vortex is frequently disturbed by dynamic processes that make it quite unstable. This impedes the appearance of appreciable stratospheric cooling and, hence, of severe ozone depletion like in the Antarctic. The effects of vortex formation/non-formation are illustrated in figure 1, which presents the potential vorticity (PV) in the Arctic, extracted from the ECMWF database (ECMWF 2021) for three winter–spring months of 2019 and 2020. It is considered that PV is able to

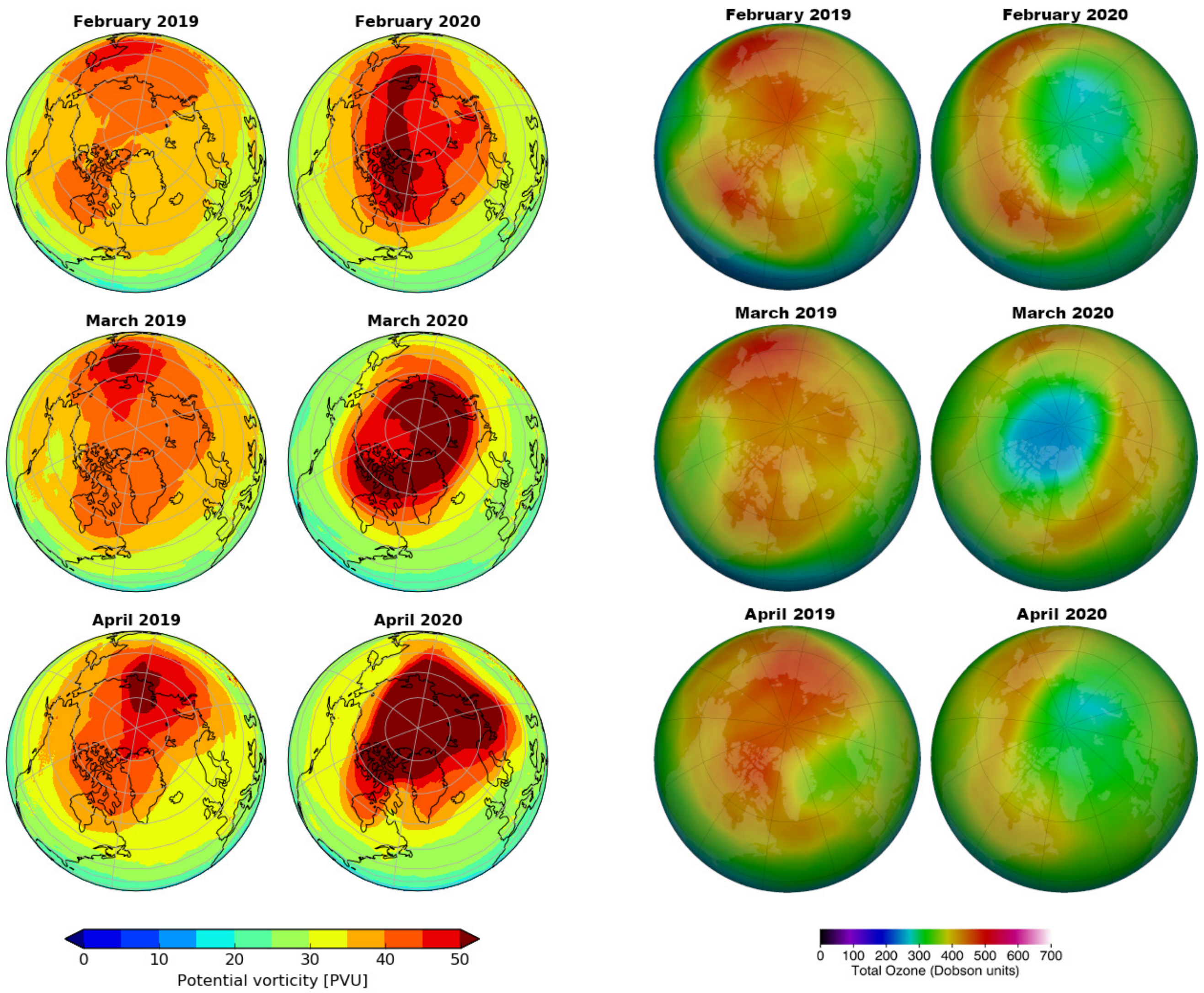

Figure 1: The left two columns represent the monthly mean potential vorticity over the Northern Hemisphere as extracted from ECMWF (2021) database for February-April 2019 and 2020 in the Arctic, while the right two columns give the corresponding ozone amount distributions (NASA 2021).

outline the polar vortex (Hoskins et al. 1985). Actually, figure 1 (left columns) shows the monthly mean PV assuming that such an averaging filters the short-term oscillations and better represents the status of the polar vortex within a month. The two columns on the right side of figure 1 show the distribution of the monthly mean of the ozone column during the corresponding months.

The difference between the PV patterns in 2019 and 2020 is obvious. While the PV contours outline a large area with rather high PV values for each of the months in 2020, no similar picture can be identified in 2019. As mentioned, this is due to the frequent perturbations of the Arctic vortex; the monthly mean PV in 2019 depicts a quite weak vortex. It should be noted that the development of the 2019 vortex represents typical Arctic behaviour, whereas in 2020 the vortex was exceptionally strong (and long-lasting). Figure 1 demonstrates also the response of the ozone column to the vortex features. In 2019 the ozone content was close to the normal values whereas in 2020, areas characterised by significantly reduced total ozone can be recognised in each of the monthly patterns. Svalbard was inside or in the periphery of these areas, and the next subsection presents a picture of the ozone depletion using results from the instruments operating in Svalbard.

2.2. The development of the 2020 ozone depletion over Svalbard and its consequences

The behaviour of the ozone column over Svalbard in the spring of 2020 is presented in figure 2. All the instruments registered a deep minimum that lasted about a month, from late March to late April. This minimum was found to be nearly 150 DU below the climatological value; this represents an almost 40% decrease. At the same time, this minimum is about 70 DU lower than the 2.5-percentile of the climatological mean value. In the second half of April, the ozone column sharply returned to average values with episodical drops under the 2.5-percentile level.

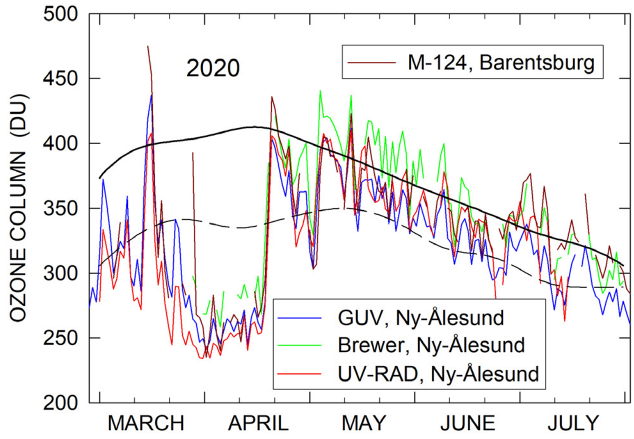

Figure 2: Time patterns of the daily ozone column, observed over Svalbard by the instruments located in Ny-Ålesund and Barentsburg during the first half of 2020. The solid black curve shows the mean annual ozone course during the period and the dashed curve represents the 2.5-percentile. Both parameters were estimated from historical measurements performed at Ny-Ålesund during the past 20 years (Petkov et al. 2019; Svendby et al. 2021).

Such a profound ozone column decrease was expected to cause a considerable increase in the solar UV-B irradiance reaching the ground, as UV-B penetrance is quite sensitive to ozone changes. This is confirmed by the upper panel of figure 3, where the daily integrated values (daily doses) of radiation in the UV-B range are presented for 2018 – 2020. It is seen that the annual course of UV-B doses is quite similar for the years 2018 and 2019, which were characterised by normal ozone amounts, while the development seen in 2020 shows a doubling of the values in March – April, when the ozone column reached the extreme minimum shown in figure 1. At the same time, the evolution of UV-A irradiance (lower panel of Fig. 3), which only weakly depends on the ozone column, shows almost the same behaviour in 2020 as in the previous two years. These findings confirm the strong relationship between the ozone column and surface UV-B irradiance.

Figure 4 exhibits the daily doses of the erythemal UV irradiance (UVE) calculated through the weighting of the solar radiation by the erythemal action spectrum (Mckinlay and Diffey 1987). It shows that UVE irradiance was also subject to significant enhancement, similarly to the UV-B band. These results are consistent with those obtained by Bernhard et al. (2020), who observed a 75% increase in ultraviolet index in Canada in March 2020.

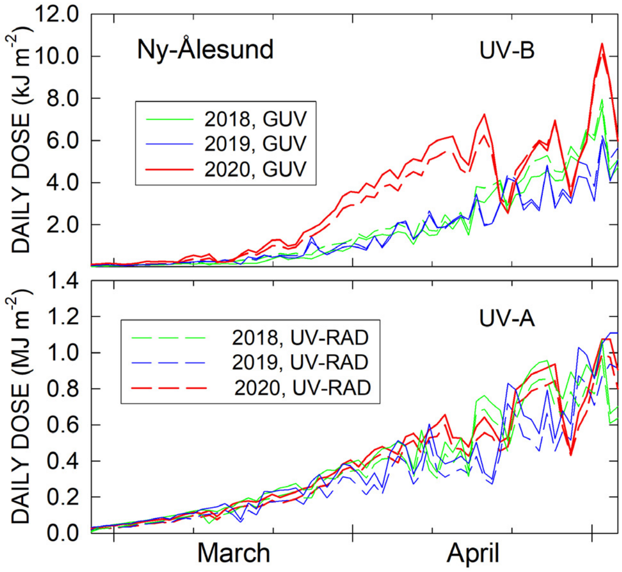

Figure 3: Daily UV-B and UV-A doses registered by GUV (solid curves) and UV-RAD (dashed curves) at Ny-Ålesund during the early spring periods of 2018 – 2020. The discrepancy between GUV and UV-RAD data that is particularly marked in the period of the ozone reduction, can be attributed to the different approaches applied to extract the doses from the output voltages of both instruments, which approaches depend on the ozone behaviour and other geometrical factors (see WMO (2010) and Petkov et al. (2006) for GUV and UV-RAD, respectively).

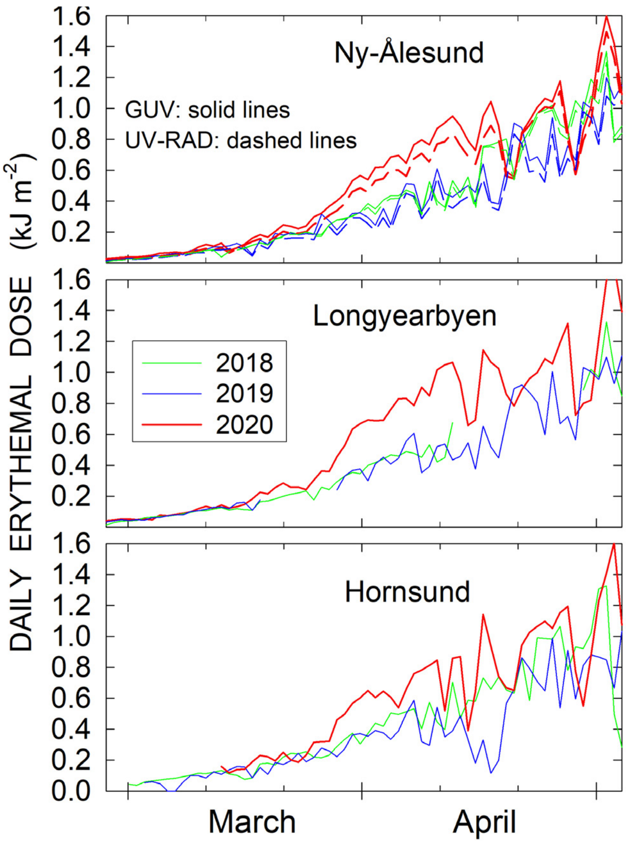

Figure 4: Evolution of the daily UVE doses observed at three of the Svalbard stations in March – April of 2018, 2019 and 2020. As in the case of the patterns in figure 3, the discrepancy between GUV and UV-RAD is attributed to the different techniques applied to extract the erythemal irradiance from the corresponding output voltages.

Studies performed to analyse the dependence of UV radiation on the ozone column led to the introduction of the so-called radiation amplification factor (RAF, Madronich et al. 1998) determined by the equation:

$$\frac{I}{I_0} = \left(\frac{Q}{Q_0}\right)^{-\mathrm{RAF}}, \qquad (1)$$

where UV irradiances I and I_0 correspond to the ozone columns Q and Q_0, respectively. The RAF is usually determined empirically under cloud-free sky and at a certain solar elevation, to underline the effect of the ozone on UV radiation and reduce the impact of clouds and aerosols. However, we could formally assess RAF through Eq. (1) by taking into account the daily mean ozone column given in figure 2 and daily UV-B and UVE irradiance doses presented in figures 3 and 4, respectively. In this case the effect of clouds, aerosols and solar elevation turns out to be smoothed but it persists in the RAF assessments. The estimate shows that the RAF varied between 2 and 3 for UV-B and from 1.1 to 1.4 for UVE doses. These values are consistent with assessments reported in other studies (Antón et al. 2011; Bais and Zerefos 1993; Blumthaler et al. 1995; Lakkala et al. 2018; Petkov et al. 2012; Seckmeyer et al. 2005). Hence, the 2020 ozone depletion in the Arctic led to an increase in the UV-B and UVE irradiance levels. This increase in both UV-B and UVE agrees with the established relationship between ozone and UV radiation. The consistency between the RAFs calculated here using data obtained under a range of conditions involving factors that impact UV-B and UVE (e.g., clouds, aerosols, low solar elevation), and RAFs calculated conventionally (i.e. using data obtained in the absence of such factors) suggests that the effect of ozone depletion was dominant in spring 2020. In other words, even though cloud cover can significantly reduce the UV radiation reaching the ground during the day, the depleted ozone column over Svalbard turned out to be a decisive factor for the UV-B irradiance level over relatively long periods.

The appreciable increase in the short-wave part of the solar UV irradiance observed in Svalbard in the period of the strong ozone reduction was an unusual deviation from the common spring environmental conditions in the Arctic. Such an occurrence can be assumed to be able to cause stress on the plants and animals (e.g. Kvíderová et al. 2019) living in Svalbard. The expected effects of UV radiation on the polar ecosystems will be a subject of future studies.

3. Unanswered questions

The recurrence of the atypically strong winter polar vortices in the Arctic can be considered a consequence of the effects of climate change on Arctic stratosphere dynamics. These occurrences caused at least three appreciable ozone depletion episodes in the past 30 years that led to corresponding increase in solar UV irradiance on the ground. Such an increase is likely to impact the Svalbard ecosystems on both short and long time scales, but these effects have not been studied yet. Another important issue that needs to be addressed concerns the interconnection between climate change and ozone evolution in both Arctic and densely populated mid-latitude areas.

4. Recommendations for the future

- In view of the unanswered questions, studies on the surface UV irradiance increase should be performed jointly with experts on experimental physiology and polar ecosystems.
- All instruments operating at Svalbard should be coordinated in a regional network to ensure reliable and coherent data over a large area of Svalbard in a long-term perspective.
- In particular, the coverage of UV spectral observations should be improved.
- The solar UV observation network should be extended across the Fram Strait to Eastern Greenland.
- The effects of climate change on the frequency of profound ozone reductions in the Arctic need to be taken into account in future studies.

5. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider[1]
Ozone_ EXAODEP-2020	Ozone column (DU)	March – July, 2020	Svalbard (Ny-Ålesund, Barentsburg)	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/77556de7-c3ec-48f7-883e-6d9e6ad3c03c	Tove M. Svendby (NILU), Boyan H. Petkov (ISP-CNR), Anna Solomatnikova (GGO)
UV_ EXAODEP-2020	Daily erythemal, UV-B and UV-A irradiance doses (W m-2)	March – July, 2020	Svalbard (Ny-Ålesund, Longyearbyen, Hornsund)		Bjørn Johnsen (NILU), Boyan H. Petkov (ISP-CNR), Kamil Láska (MU), Piotr S. Sobolewski (PAS)

1 Abbreviations can be found in the list of institutions in the beginning of the report

6. Acknowledgements

This work was supported by the Research Council of Norway, project number 291644, Svalbard Integrated Arctic Earth Observing System – Knowledge Centre, operational phase. The authors gratefully acknowledge the USA National Aeronautics and Space Administration (NASA) for providing the maps of the ozone column distributions and the European Centre for Medium-Range Weather Forecasts (ECMWF) for furnishing the data about potential vorticity. This research was developed as a part of the RiS 3305 Project 'Ultraviolet Irradiance Variability in the Arctic'.

7. References

Antón M, Serrano A, Cancillo ML, García JA, Madronich S (2011) Empirical evaluation of a simple analytical formula for the Ultraviolet Index. Photochem. Photobiol. 87, 478–482. https://doi.org/10.1111/j.1751-1097.2010.00860.x

Bais AF, Zerefos CS (1993) Effect of changes in ozone on solar UV-B radiation at Reykjavik, Proc. SPIE 2049, Atmospheric Radiation, https://doi.org/10.1117/12.163519

Bernhard GH, Fioletov VE, Grooß J-U, Ialongo I, Johnsen B, Lakkala K, Manney GL, Müller R, Svendby T (2020) Record-breaking increases in Arctic solar ultraviolet radiation caused by exceptionally large ozone depletion in 2020. Geophys Res Lett, 47: e2020GL090844, https://doi.org/10.1029/2020GL090844

Blumthaler M, Salzgeber M, Ambach W (1995) Ozone and ultraviolet – B irradiances: experimental determination of the radiation amplification factor. Photochemistry and Photobiology, 61, 159-162. https://doi.org/10.1111/j.1751-1097.1995.tb03954.x

Brasseur GP, Solomon S (2005) Aeronomy of the Middle Atmosphere. Springer Verlag

ECMWF (European Centre for Medium-Range Weather Forecasts), ERA-5 reanalyses (https://cds.climate.copernicus.eu/#!/home), last accessed in August 2021

Farman JC, Gardiner BG, Shanklin JD (1985) Large losses of total ozone in Antarctica reveal seasonal C1Ox/NOx interaction. Nature 315: 207-210. https://doi.org/10.1038/315207a0

Feng W, Dhomse SS, Arosio C, Weber M, Burrows JP, Santee ML, Chipperfield MP (2021) Arctic ozone depletion in 2019/20: Roles of chemistry, dynamics and the Montreal Protocol. Geophysical Research Letters, 48, e2020GL091911, https://doi.org/10.1029/2020GL091911

Hoskins BJ, McIntyre ME, Robertson AW (1985) On the use and significance of isentropic potential-vorticity maps. Q J R Meteorol Soc 111: 877–946. https://doi.org/10.1002/qj.49711147002

Karpechko AY, Backman L, Thölix L, Ialongo I, Andersson M, Fioletov V, Heikkilä A, Johnsen B, Koskela T, Kyrölä E, Lakkala K, Myhre CL, Rex M, Sofieva VF, Tamminen J, Wohltmann I (2013) The link between springtime total ozone and summer UV radiation in Northern Hemisphere extratropics, J. Geophys. Res. Atmos., 118, 8649–8661, https://doi.org/10.1002/jgrd.50601

Kvíderová J, Elster J, Komárek J (2019) Ecophysiology of Cyanobacteria in the Polar Regions. In Mishra et al (eds) Cyanobacteria, from basic science to applications, Academic Press, pp. 227 – 302. https://doi.org/10.1016/B978-0-12-814667-5.00014-3

Lakkala K, Redondas A, Meinander O, Thölix L, Hamari B, Almansa AF, Carreno V, García RD, Torres C, Deferrari G, Ochoa H, Bernhard G, Sanchez R, De Leeuw G (2018) UV measurements at Marambio and Ushuaia during 2000–2010. Atmos. Chem. Phys., 18, 16019–16031, https://doi.org/10.5194/acp-18-16019-2018

Lawrence ZD, Perlwitz J, Butler AH, Manney GL, Newman PA, Lee SH, Nash ER (2020). The remarkably strong Arctic stratospheric polar vortex of winter 2020: Links to record-breaking Arctic oscillation and ozone loss. Journal of Geophysical Research, https://doi.org/10.1029/2020JD033271

Madronich S, McKenzie RL, Björn L, Caldwell MM (1998) Changes in biologically active ultraviolet radiation reaching the Earth's surface. J. Photochem. Photobiol. B. 46, 5–19. https://doi.org/10.1016/S1011-1344(98)00182-1

Manney GL, Santee M, Rex M, et al. (2011) Unprecedented Arctic ozone loss in 2011. Nature 478: 469–475. https://doi.org/10.1038/nature10556

Manney GL, Livesey NJ, Santee ML, Froidevaux L, Lambert A, Lawrence ZD, Millán LF, Neu JL, Read WG, Schwartz MJ, Fuller RA (2020) Record-Low Arctic Stratospheric Ozone in 2020: MLS Observations of Chemical Processes and Comparisons With Previous Extreme Winters. Geophys Res Lett 47Ю e2020GL089063. https://doi.org/10.1029/2020GL089063

Mckinlay AF, Diffey BL (1987) A reference action spectrum for ultraviolet induced erythema in human skin. CIE J 6: 17–22

Molina MJ, Rowland FS (1974) Stratospheric sink for chlorofluoromethanes: chlorine atom catalysed destruction of ozone. Nature 249: 810 – 814. https://doi.org/10.1038/249810a0

NASA (USA National Aeronautics and Space Administration) (https://ozonewatch.gsfc.nasa.gov/), last accessed in September 2021

Petkov B, Vitale V, Tomasi C, Bonafé U, Scaglione S, Flori D, Santaguida R, Gausa M, Hansen G, Colombo T (2006) Narrow-band filter radiometer for ground-based measurements of global UV solar irradiance and total ozone. Appl Opt 45:4383–4395

Petkov B, Vitale V, Gröbner J, Hülsen G, De Simone S, Gallo V, Tomasi C, Busetto M, Barth VL, Lanconelli C, Mazzola M (2012) Short-term variations in surface UV-B irradiance and total ozone column at Ny-Ålesund during the QAARC campaign, Atmospheric Research, 108: 9–18. https://doi.org/10.1016/j.atmosres.2012.01.006

Petkov BH, Vitale V, Tomasi C, Siani AM, Seckmeyer G, Webb AR, Smedley ARD, Casale GR, Werner R, Lanconelli C, Mazzola M, Lupi A, Busetto M, Diémoz H, Goutail F, Köhler U, Mendeva BD, Josefsson W, Moore D, Bartolomé ML, González JRM, Mišaga O, Dahlback A, Tóth Z, Varghese S, De Backer H, Stübi R, Vaníček V (2014) Response of the ozone column over Europe to the 2011 Arctic ozone depletion event according to ground-based observations and assessment of the consequent variations in surface UV irradiance. Atmos Envir 85: 169–178. https://doi.org/10.1016/j.atmosenv.2013.12.005

Petkov BH, Vitale V, Hansen GH, Svendby TM, Sobolewski PS, Láska K, Elster J, Viola A, Mazzola M, Lupi A (2019) Observations of the solar UV irradiance and ozone column at Svalbard, In Orr et al (eds) SESS report 2018, Longyearbyen, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 170–183. https://doi.org/10.5281/zenodo.4778491

Petkov B, Vitale V, Di Carlo P, Mazzola M, Lupi A, Diémoz H, Fountoulakis I, Drofa O, Mastrangelo D,·Casale GR, Siani AM (2021) The 2020 Arctic ozone depletion and signs of its effect on the ozone column at lower latitudes. Bull of Atmos Sci & Technol. 2: 8, https://doi.org/10.1007/s42865-021-00040-x

Seckmeyer G, Bais A, Bernhard G, Blumthaler M, Booth CR, Lantz K, McKenzie RL (2005) Instruments to Measure Solar Ultraviolet Radiation, Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance. WMO-GAW Report No.164

Solomon S, Garcia RR, Rowland FS, Wuebbles DJ (1986) On the depletion of Antarctic ozone. Nature 321: 755–758. https://doi.org/10.1038/321755a0

Solomon S, Portmann RW, Thompson DWJ (2007) Contrasts between Antarctic and Arctic ozone depletion, PNAS, v. 104, 445–449. https://doi.org/10.1073/pnas.0604895104

Svendby TM, Johnsen B, Kylling A, Dahlback A, Bernhard GH, Hansen GH, Petkov B, Vitale V (2021) GUV long-term measurements of total ozone column and effective cloud transmittance at three Norwegian sites. Atmos Chem Phys 21:7881–7899, https://doi.org/10.5194/acp-21-7881-2021

Weber M, Arosio C, Feng W, Dhomse SS, Chipperfield MP, Meier A, Burrows JP, Eichmann K-U, Richter A, Rozanov A (2021) The unusual stratospheric Arctic winter 2019/20: Chemical ozone loss from satellite observations and TOMCAT chemical transport model. Journal of Geophysical Research: Atmospheres, 126, e2020JD034386, https://doi.org/10.1029/2020JD034386

WMO (2010) Instruments to measure solar Ultraviolet Radiation Part 3: Multi-channel filter instruments. GAW Report No 190, WMO/TD-No. 1537, Edited by Seckmeyer G, Bais A, Bernhard G, Blumthaler M, Johnsen B, Lantz K, McKenzie R, Diaz S, Disterhoft P, Jalkanen L, Kazantzidis A, Kiedron P, Petkov B, Sinclair C, Wilson C. World Meteorological Organization, Geneva, Switzerland