8

Observations of the solar UV irradiance and ozone column at Svalbard

BH Petkov[1], V Vitale[1], GH Hansen[2], TM Svendby[2], PS Sobolewski[3], K Láska[4], J Elster[5], A Viola[1], M Mazzola[1], A Lupi[1]

1 Institute of Atmospheric Sciences and Climate (ISAC), Italian National Research Council (CNR), Via Gobetti 101, I-40129 Bologna, Italy
2 NILU - Norwegian Institute for Air Research, Atmosphere and Climate Department, Instituttveien 18, 2007 Kjeller, Norway
3 Institute of Geophysics Polish Academy of Sciences, Department of Atmospheric Physics, Ksiecia Janusza 64, 01-452 Warsaw, Poland
4 Department of Geography, Faculty of Science, Masaryk University, Kotlářská 2, CZ-611 37 Brno, Czech Republic
5 Centre for Polar Ecology, Faculty of Science, University of South Bohemia, Na Zlaté Stoce 3, 37005 České Budějovice and Institute of Botany CAS, CZ-379 82 Třeboň

Corresponding author: Boyan H Petkov, b.petkov@isac.cnr.it

Keyword: Arctic environment, solar UV irradiance, ozone column, ozone profiles, Arctic upper atmosphere

Introduction

Solar UV radiation reaching the Earth's surface (from about 295 to 400 nm) is able to impact the chemical reactions in the troposphere, and all biological cycles (Bischof et al. 1998; Björn 2002; Cadet et al. 2005; Laglera and Van Den Berg, 2007; Raso et al. 2017). Since the intensity of the UV-B irradiance (wavelengths less than 315 nm) observed at the ground strongly depends on the ozone column, the behaviour of these two parameters is usually jointly studied. Due to its absorption capacity the ozone significantly affects the thermal regime of the stratosphere, where the concentration of this component reaches maximum values (Brasseur and Solomon 2005) and hence, the variations in ozone column can be considered as an important indicator of stratospheric dynamical processes. On the other hand, the atmospheric ozone acts as a reliable shield for all life on the Earth, protecting the organisms from harmful UV-C (100 – 280 nm) and a fraction of UV-B (280 – ~315 nm) irradiance. Svalbard is located in a region where the typical harsh polar climate is disturbed by the Gulfstream, which transports warm water masses from the tropics. As a result, the role of dynamical processes in the atmosphere tends to enhance the variability of the atmospheric transmittance and thus, the variability of the solar radiation reaching the surface. In this context, the study of solar UV irradiance and ozone column behaviour in the region of Svalbard could contribute to our knowledge about the Arctic environment and lead to deeper understanding of climatic variability.

Figure 1. The geographic position of the stations measuring solar UV irradiance and ozone column at Svalbard. The pink dashed curves outline a sector over which the distribution of the daily erythemal doses were reconstructed from the measurements performed at the stations (see Fig. 6).

Instrumentation and summary of existing data and achieved results

Irregular observations of ozone column in Svalbard (74° – 81°N, 10° – 35°E) have been performed since 1950 (either Longyearbyen or Ny-Ålesund, see Fig. 1) and continuously since 1991 in Ny-Ålesund (78°56'N, 11°55'E). Most of the historical ozone observations by means of Dobson spectrophotometer #8 between 1950 and 1968 were re-evaluated and the results were published in the recent past (Vogler et al. 2006). The 1985-1993 Dobson measurements in Longyearbyen are not usable for long-term trend studies due to insufficient quality-control routines, and only in 1995, the Dobson spectrophotometer was moved to Sverdrup Station in Ny-Ålesund, and observations under controlled conditions continued until 2005. Ozone profile measurements by means of ozone sondes were started in Ny-Ålesund by Alfred Wegener Institute in 1988 and are still continuing on a weekly basis. In 1991, a SAOZ UV/Vis spectrometer working on the basis of the Differential Optical Absorption Spectroscopy (DOAS) technique and providing total ozone around sunrise and sunset, was taken into operation in Ny-Ålesund to observe the ozone column behaviour from mid-February until early May and from August to end of October. The SAOZ instrument excellently complements the standard total ozone observation techniques (Dobson, Brewer photo-spectrometers, multi-wavelength filter instruments) which rely on solar zenith angles (SZA) typically less than 80° and it is especially suited to detect stratospheric ozone destruction in later winter/early spring at high latitudes (e.g., Pommereau et al., 2013). In 1995, researchers from Norwegian Institute for Air Research (NILU) established a 5-channel filter instrument (GUV-541, Biospherical Instruments, San Diego) at Sverdrup Station in Ny-Ålesund to monitor UV irradiance and total ozone with 1 min temporal resolution at SZA < 75°. A team from the Italian Institute of Atmospheric Sciences and Climate at the National Research Council (ISAC-CNR) has performed combined UV/ozone measurements since 2008 (with two major gaps in 2011 and 2013) by means of the own-made UV-RAD radiometer aimed to work in the harsh conditions of the polar regions (Petkov et al. 2006; Vitale et al. 2011). In 2005, Italian researchers from the Institute of Acoustics and Sensors "Orso Mario Corbino" (IDASC-CNR) started also operation of a Brewer spectrometer at Ny-Ålesund (Rafanelli et al. 2009). The last two instrument calibrations were in 2015 and 2018, respectively, while regular observations supervised by ISAC-CNR commenced in spring 2017.

At the Polish Polar Station in Hornsund (77°00'N, 15°33'E, see Fig.1), operated by the Institute of Geophysics, Polish Academy of Sciences, solar irradiance measurements, including UV were started in 1996, using an own-made radiometer very similar to Robertson Berger UV meter SL501 A and continued until 2002. In 2005, the instrument was replaced with a Kipp & Zonen UVS-AE-T UV radiometer, supplied by a CM11 pyranometer; these instruments have continued observations until present. In 2017, a new K&Z UVS-E-T UV radiometer was taken into operation, to take over from the old instrument after an adequate overlap time.

At the Russian station in Barentsburg, a filter ozonometer M-124, operated by a research team from the Main Geophysical Observatory, St. Petersburg, Russia, carries out ozone column measurements. At the beginning of March 2018, a recently developed UFOS spectroradiometer, providing the solar UV spectral irradiance was established at the station.

A K&Z UVS-E-T UV radiometer was set up at the new Czech Research Station (Julius Payer House) in Longyearbyen (78°13'N, 15°39'E) in the summer of 2017 to observe the erythemally weighted solar irradiance.

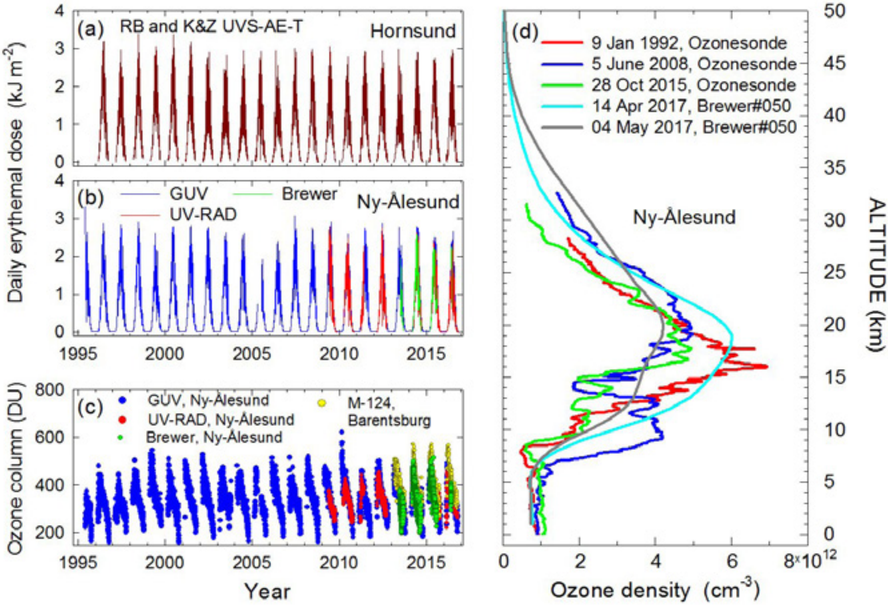

Figure 2. Data-sets, available from the measurements performed at Svalbard. Panels (a) and (b) show time patterns of the daily erythemal dose observed at Hornsund and Ny-Ålesund respectively, while the ozone column behaviour is shown in (c). Several profiles of the ozone density registered over Ny-Ålesund are given in (d). The instruments providing the corresponding data are indicated in each of the panels.

Figure 2 presents the available data-sets together with some examples of ozone profiles provided by ozone sondes and Brewer spectrophotometer (Umkehr measurements); these data were subjects of different studies performed by the corresponding research teams. The NILU Annual reports summarise measurements of surface UV radiation and ozone column at Ny-Ålesund (e. g. Svendby et al., 2017), while the observations performed at Hornsund were presented by Sobolewski and Krzyścin (Krzyścin and Sobolewski, 2001 and Sobolewski and Krzyścin, 2004-2005). Weather variability at Svalbard as a parameter strongly impacting surface UV radiation was examined by Láska et al. (2013). Large short-period ozone column variations characterised by hourly time-scales were observed at Ny-Ålesund and were a subject of an in-depth study (Petkov et al., 2012) to exclude the hypothesis that they could be a result of measurement errors. In addition, it was concluded that these short-period oscillations can be a manifestation of the evolution of a 6-dimensional stationary chaotic system (Petkov et al., 2015), that assumes a deterministic character of the ozone variations, and hence, the possibility to predict them within daily time intervals.

The impact of strong ozone depletion events observed in the Arctic on ozone column at lower latitudes were studied (Hansen et al., 1997; Hansen and Chipperfield, 1999; Petkov et al., 2014), and the results indicate that the processes in polar areas are able to affect UV radiation over highly populated lower-latitude regions. The variability in ozone density, air temperature and wind velocity over Svalbard were investigated by examining the 21-year data-set of ozone sonde measurements performed at Ny-Ålesund through the principal component analysis applied to two data-sets representing short-period (composed by harmonics with periods $P < 1$ year) and long-period ($P > 1$ year) oscillations (Petkov et al., 2018). The obtained Empirical Orthogonal Functions (EOF), which were assumed to represent the vertical profiles of amplitudes attributed to specific harmonics composing both kind of variations exhibited layered structure expressed by wave-like forms up to 25 km altitude. One of the important features of the EOF height distributions was the extremely low tropospheric values of the amplitudes characterising the long-period harmonics, composed by the Quasi-Biennial Oscillations, El Niño-Southern Oscillations etc. that usually are detected in the behaviour of atmospheric parameters over the world. These findings depict the Svalbard troposphere as being a comparatively closed system with respect to these global variations. The wave-like behaviour of some EOF components that compose the short- and long-period variations in the studied parameters was characterised by fluctuations from negative to positive values, whose changes in the amplitude sign were interpreted as changes in the phases of the corresponding components. This occurrence assumes height levels where the amplitudes of some spectral harmonics become close to zero and hence, the corresponding variations vanish. In addition, a response of the short-period ozone variations to particular atmospheric events, like the strong ozone depletion over Arctic in the spring 2011 and solar eclipses, was registered and such a response was expressed by modifications in the amplitude frequency characteristics of the corresponding oscillations.

Recent activity on harmonisation of UV and ozone studies at Svalbard.

The above presented results led to the idea of uniting the efforts of different research teams active in UV irradiance and atmospheric ozone research, and integration of the existing Svalbard stations in a network that would be able to provide more comprehensive information for scientists working on climatic and biological issues in the Arctic and for validation of satellite data. The project "UV Intercomparison and Integration in a High Arctic Environment (UV-ICARE)" (RIS 10871, https://www.researchinsvalbard.no/project/8626) aimed at making the first step toward the creation of such a network, starting with an intercomparison campaign of the instruments from 17 to 23 April, 2018. Considering the Brewer spectrophotometer as a reference device, it was found that the values of erythemally weighted solar UV irradiance provided by the different instruments agree within ±3% deviation for SZA < 75°, within ±5% for 75° < SZA < 80° and ±7 – 10% for SZA > 80°. With regard to ozone column measurements, the GUV, UV-RAD and Brewer radiometers showed less than ±3% differences between each other. These results demonstrate a satisfactory agreement between the different devices, bearing in mind that they are characterised by quite different spectral selection techniques and electronic equipment.

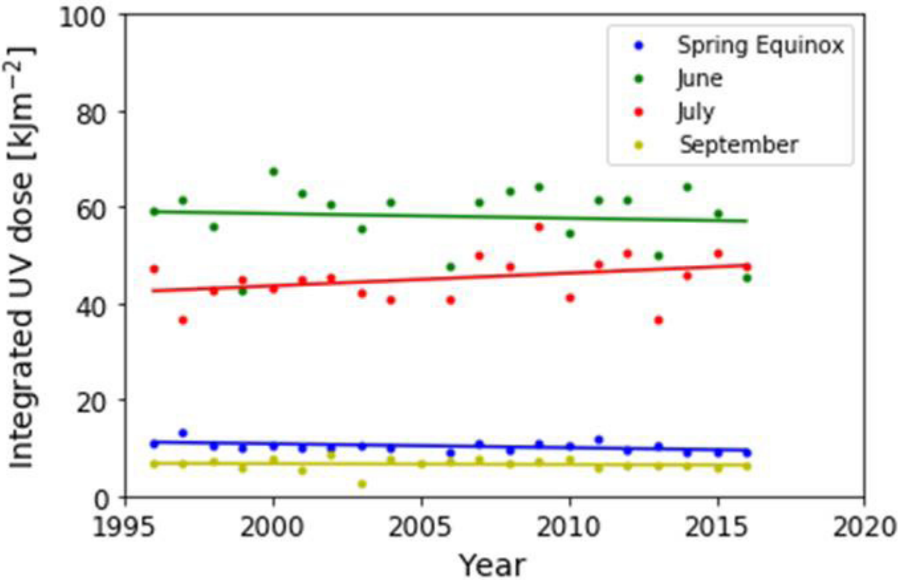

Figure 3. Integrated UV doses from Ny-Ålesund during selected periods: spring equinox±10 days (blue), monthly doses from June (green), July (red) and September (yellow). June and July values for 2005 are missing.

Another important task for the establishment of the new network was a re-analysis of the available data-sets that would help us to outline better the long-term features of the observed parameters and hence, to have a realistic idea about their evolution. As a part of such studies the trends derived from the GUV erythemal dose data series from 1996 to 2016 (except 2005 due to missing observations during summer) has been investigated, both on an annual basis (including days 60 to 285), and on a monthly and seasonal basis (G. Hansen, personal communication). During these two decades, the annual dose decreased by 1.6%, but the trend is not significant at a 2-s level. Figure 3 shows the trends for selected sub-sets exhibiting a negative trend in most of the months and seasons with an exception. The strongest negative trend of -8.1%/decade was found around spring equinox (±10 days), while in June the trend presented a lower negative value of -1.7%/decade followed by clearly positive trend of 5.8 %/decade in July. The September trend again is negative,with a value of -2.5 %/decade. As one does not see similarly large trends in the total ozone data, the cause has to be hidden in the other parameters: cloud cover and albedo (snow coverage). It is imaginable that a reduced snow cover during spring and autumn may explain the decrease of UV doses in these two seasons, while the marked increase in the summer must be due to reduced cloud coverage, possibly also decreased turbidity (less aerosols). Such a hypothesis should be investigated in detailed studies of these parameters.

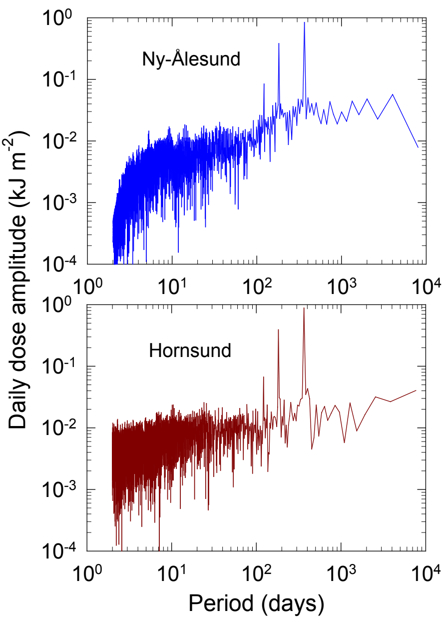

Figure 4. Spectra of the GUV and UV-RAD erythemal daily doses time patterns given in Fig. 2 (a) and (b), respectively.

Two erythemal dose data series registered at Hornsund and Ny-Ålesund (by GUV radiometer), which are shown in Figs. 2 (a) and (b) respectively, cover more than 20-year observational period. Assuming that the two partial series yielded by Robertson Berger and Kipp & Zonen radiometers at Hornsund within different periods are optimally homogenized, the two sequences offer the opportunity for a statistical long-term comparison. Figure 4 exhibits the spectra of the two time-series derived through the Lomb-Scargle periodogram approach (Lomb 1976; Scargle 1982). These spectra indicate very similar features: (i) both time-series are dominated by annual, semi-annual and 4-month harmonics, which are assumed to be modulated by the variations in the incoming solar radiation and (ii) both spectra contain a continuum-like band of harmonics with periods $P < 120$ days that are assumed to express the impact of the local environ-

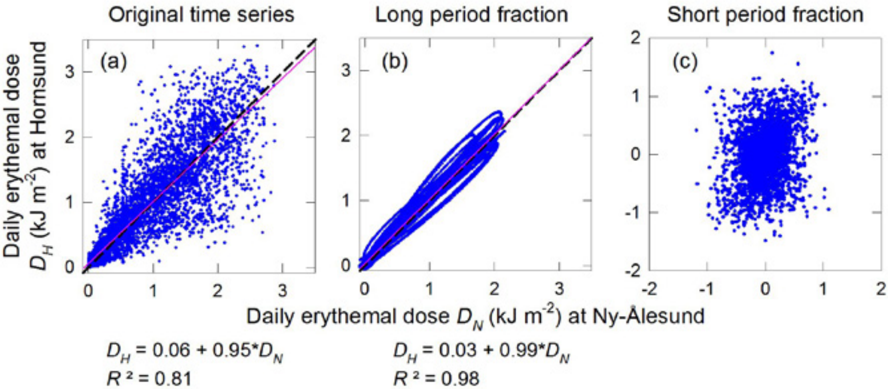

Figure 5. Comparison of daily erythemal doses (left panel) and their long-, and residual short-period components (middle and right panels, respectively) observed at Hornsund and Ny-Ålesund. Diagonals (black dashed lines) and regression lines (in pink) are shown for measured and long period values. Analytical regression dependencies with the corresponding coefficient of determinations R2 are given below.

mental conditions (cloud cover, aerosol loadings, surface albedo etc.) on the atmospheric transmittance. These findings led to the idea to separate both long-period (P > 120 days) and short-period (P < 120 days) spectral components and compare to each other all three time series: originally measured, short- and long-period fractions, obtained at each of the stations. Figure 5 shows scatter plots of these three datasets demonstrating that the values, which correspond to the long-period series (Fig. 5 (b)) are highly correlated with an axis offset of about 1%, a slope of 0.99, and a correlation coefficient of 0.98 that confirms the intuitively assumed circumstance about the similar effects of the incoming solar radiation, stratospheric ozone field and seasonal effects (snow cover) on the measurements at both stations. In contrast, the scatter plot of erythemal dose values representing the short-period time series (Fig. 5 (c)) exhibits a lack of linear dependence. It is seen that the short-period components reveal a larger variability at Hornsund than at Ny-Ålesund and, at the same time, they spread as much as the long-term component, varying within a ±2 kJ m^{-2} interval, which emphasizes the great influence of local conditions. The comparison between originally measured time series at both stations demonstrated in Fig. 5. (a) shows a good correlation and high significance that assumes a dominant role of the long-period component.

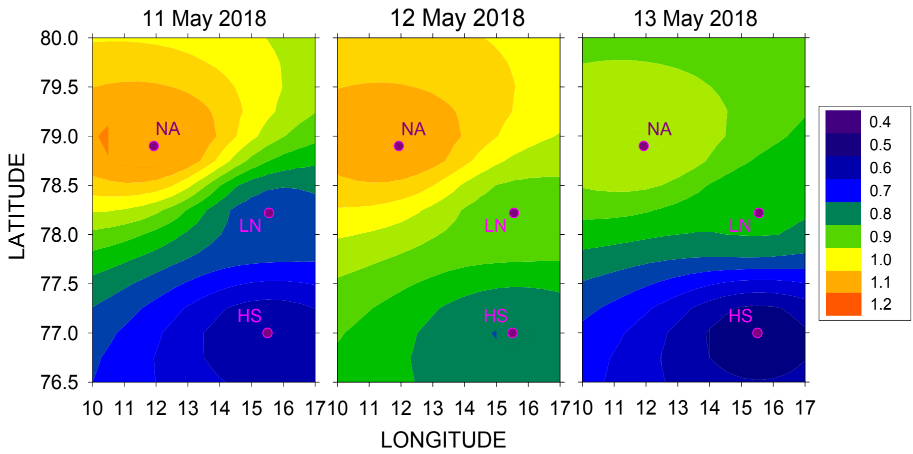

Figure 6. Erythemal dose distribution over the sector shown in Fig. 1 and obtained through the interpolation procedure presented in the text. The colour scale indicates the daily erythemal dose in kJ m-2 and the positions of the three stations, Ny-Ålesund (NA), Longyearbyen (LN) and Hornsund (HS), whose data were used for the reconstruction are also indicated.

The above results led to the idea for a reconstruction of the erythemal dose distribution over a region of Svalbard. Since the measured doses at two points placed at a distance of 230 km, like Hornsund and Ny-Ålesund are highly correlated, according to Fig. 5 (a), it can be assumed that an interpolation of the data from several stations over a grid covering an area around these stations so that the distance of each grid point to the closest station does not exceed 200 km, could give a realistic surface distribution of the doses. To perform such an interpolation, the sector outlined by 76°30'N – 80°00'N and 10°00' – 17°00'E that is shown in Fig. 1 by pink curves was covered by a grid with 15' resolution along the latitude and 30' along the longitude. The interpolation was performed by applying the Shepard (1968) approach that determines the erythemal daily dose D_{ij} at each grid-point (*i*,*j*) located at latitude *i* and longitude *j*, as weighted average using the inverse square of the distance d_{ij}^{s} between the grid-point (*i*,*j*) and station S as weight:

$$D_{ij} = \frac{\sum_{S} D_S \left(d_{ij}^{s}\right)^{-2}}{\sum_{S} \left(d_{ij}^{s}\right)^{-2}}$$

where D_S is the dose measured at station S. The distance d_{ij}^{s} (in km) was determined by applying the Lambert (1942) formula to the World Geodetic System 1984 spheroid (WGS84, 2000). A similar approach was applied by Petkov et al. (2014) to study the effect of the 2011 Arctic ozone depletion on the mid-latitude ozone column. Figure 6 shows three examples of dose distribution maps obtained for 11, 12 and 13 May 2018, respectively, over the chosen sector using the measurements performed at Ny-Ålesund, Hornsund and Longyearbyen. This example indicates that the Northwest part of Svalbard was exposed to more intense solar UV irradiance than the Southeast areas during the 3-day period considered.

The observations performed on Svalbard allow also us to gain information about the altitude characteristics of the variations in the ozone density. Besides ozone vertical profiles derived from ozone sondes, which were already presented above displaying features of ozone variation up to 25 km, the Brewer Umkehr measurements give the possibility to extract the vertical ozone distribution up to 50 km altitude as Fig. 2 (d) shows, though with less vertical resolution. Such an enlargement of the observational range, together with the satellite measurements allows a more profound study of the effects produced on the upper atmosphere by the solar particle fluxes, which are much more intensive over the polar areas (Jackman and Fleming 2000; Randall et al. 2005; Damiani et al. 2008; Mironova and Usoskin 2014). Figure 7 exhibits ozone density time series at different heights for the period March – May 2017 extracted from the Umkehr measurements at Ny-Ålesund. It can be seen that in the upper stratosphere the ozone was characterised by a comparatively deep minimum occurring in the middle of April, while below about 30 km, where the maximum of ozone density is usually registered (about 20 km), such a minimum occurred nearly two weeks later.

The achieved results help to outline the main features of the surface UV irradiance and ozone behaviour at Svalbard but, on the other hand, they assume a variety of unanswered questions that need additional study in the future. Some of these issues are:

The trends in the erythemal doses and ozone evolutions need to be studied in-depth including all available data-sets and compared with results found in other atmospheric parameters by other research groups working at Svalbard.

In the discussion of Figs. 4 and 5 it was mentioned that the short-period variations in the erythemal doses registered at Hornsund and Ny-Ålesund are strongly affected by the impact of local or regional environmental conditions. A detailed study of these variations, taking into account the measurements performed at other Svalbard stations, is expected to provide important information about the intensity of the atmospheric processes in the archipelago. Figure 4 indicates that the spectra of these variations follow a power law behaviour that reveals a complex nature of the dynamical system containing the erythemal dose as a component. The main features of this system could be outlined by examining the dose variations together with the evolution of other environmental factors.

- The dose distribution maps should be examined more carefully considering large observational data-sets that could help to find possibly typical patterns giving information about the exposure of Svalbard to solar UV radiation. This information would be important for biological and chemical studies. In addition, a comparison with satellite data provided by operating space-borne devices like Ozone Monitoring Instrument (OMI), Global Ozone Monitoring Experiment 2 (GOME-2) or completed missions like Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), should be performed in order to have an idea about the reliability of the applied method and obtained results.

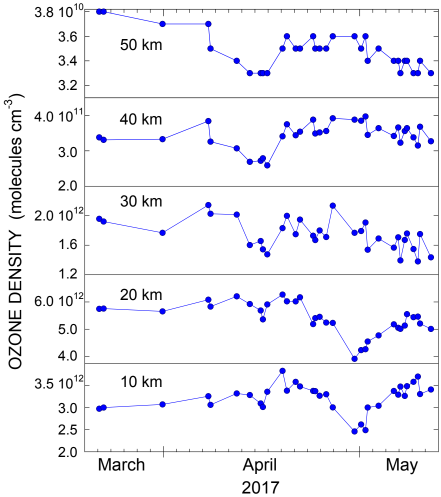

Figure 7. Time patterns of the ozone density derived from the Umkehr Brewer measurements at different altitude levels indicated in each of the panels. The blue circles correspond to the times when the ozone profiles were retrieved.

- The variations in ozone density observed in the upper stratospheric layers through the Umkehr Brewer measurements is considered to provide an important information about stratospheric processes and combining our efforts with those made by the research teams studying the upper atmosphere could outline a more comprehensive picture of the Svalbard middle atmosphere dynamics. Moreover, these data could be of great use in satellite validation efforts concerning both running instruments like OMI and GOME-2, and devices included in future space missions as well.
- A comparison of the achieved results about UV irradiance and ozone column with those obtained at other locations could indicate features that are particular for Svalbard that, in turn will outline the specific environmental features. The team presenting this report is also working on measurements of UV and ozone in other geographical regions such as Norway that ranges from Svalbard in the north to less than 60°N latitude, central and south Europe (Czech Republic and Italy) and also in Antarctica. In addition, data from adjacent regions can be also provided for comparison.

Data used and data providers / acknowledgements

The Norwegian ozone and UV measurements at Ny-Ålesund are funded by the Norwegian Environment Agency and the Ministry of Climate and Environment. The GUV instrument calibration is performed by the Norwegian Radiation Protection Agency.

The ozone sonde data at Ny-Ålesund were provided by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, and were partly funded from the European Community's Seventh Framework Programme (FP7/2007 - 2013) under grant agreement № 603557 (StratoClim).

The observational activity at Longyearbyen was supported by the Ministry of Education, Youth and Sports of the Czech Republic, № LM2015078 - CzechPolar2, № CZ.02.1.01/0.0/0.0/16_013/0001708 - ECOPOLARIS and by the institutional long-term research plan № RVO 67985939 of the Institute of Botany CAS References, and by a support of NILU - Norwegian Institute for Air Research, № 270644/E109.

The ozone data from Barentsburg were provided by the Laboratory of Ozone Layer Control at Voeikov Main Geophysical Observatory, St. Petersburg, Russia

The measurement activity at Hornsund is partially supported within statutory activities No 3841/E-41/S/2018 of the Ministry of Science and Higher Education of Poland.

The UV-RAD and Brewer measurements are the result of the ISAC-CNR activity at Ny-Ålesund, supported by CNR and partly by a Great Relevance project funded by MAECI in the frame of the Executive Cooperation programme Italia-Quebec 2017-2019. Data analysis and presented results received support also by the Horizon 2020 European project iCUPE (Integrative and Comprehensive Understanding on Polar Environments), a project of The European Network for Observing our Changing Planet (ERA-PLANET), Grant Agreement n. 689443.

The local network that is currently being established at Svalbard provides space for collecting all above data in a server, which will be integrated with the SIOS database. At the moment, such a storage that contains the data of the different instruments in the format determined by the above providers is accessible via secure copy protocol (scp) at the address uv-icare@skyrad.bo.isac.cnr.it, after identification via password provided under request. A unification of the format allowing more compact data storage and an easier access is one of the aims for the near future.

References

Bischof K, Hanelt D, Tůg H, Karsten U, Brouwer PEM, Wiencke C (1998) Acclimation of brown algal photosynthesis to ultraviolet radiation in Arctic coastal waters (Spitsbergen, Norway). Polar Biol 20:388-395.

Björn LO (2002) Effects of UV-B radiation on terrestrial organisms and ecosystems with special reference to the Arctic. In: Hessen DO (ed) UV radiation and Arctic ecosystems. Springer-Verlag, Berlin, pp 93-121.

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

Cadet J, Sage E, Douki T (2005) Ultraviolet radiation-mediated damage to cellular DNA (review). Mutat Res 571: 3–17.

Damiani A, Storini M, Laurenza M, Rafanelli C (2008) Solar particle effects on minor components of the Polar atmosphere. Ann Geophys 26: 361–370.

Hansen G, Svenøe T, Chipperfield MP, Dahlback A, Hoppe U-P (1997) Evidence of substantial ozone depletion in winter 1995/96 over Northern Norway. Geophys Res Lett 24: 799-802.

Hansen G, Chipperfield MP (1999) Ozone depletion at the edge of the Arctic polar vortex 1996/1997. J Geophys R 104: 1837-1845.

Jackman ChH, Fleming EL (2000) Influence of extremely large solar proton events in a changing stratosphere. J Geophys Res 105: 11659-11670.

Krzyścin JW, Sobolewski PS (2001) The surface UV-B irradiation in the Arctic: Observations at the Polish polar station, Hornsund (77°N, 15°E), 1996-1997. J Atmos Sol-Terr Phys, 63: 321–329.

Laglera LM, Van Den Berg CMG (2007) Wavelength dependence of the photochemical reduction of iron in Arctic seawater. Environ Sci Technol 41: 2296 – 2302.

Lambert WD, 1942. The distance between two widely separated points on the Earth surface. J. Wash. Acad. Sci. 32, 125-130.

Láska K, Chládová Z, Ambrožová K, Husák J (2013) Cloudiness and weather variation in central Svalbard in July 2013 as related to atmospheric circulation. Czech Polar Reports 3: 184-195.

Lomb NR (1976) Least-squares frequency analysis of unequally spaced data. Astroph Space Sci, vol. 39: 447–462.

Mironova IA, Usoskin IG (2014) Possible effect of strong solar energetic particle events on polar stratospheric aerosol: a summary of observational results. Environ Res Lett 9: 1 – 8.

Petkov B, Vitale V, Tomasi C, Bonafè 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. App 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, Atmos Res 108: 9–18.

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 K (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 Environ 85: 169–178.

Petkov BH, Vitale V, Mazzola M, Lanconelli C, Lupi A (2015) Chaotic behaviour of the short-term variations in ozone column observed in Arctic, Commun Nonlinear Sci Numer Simulat 26: 238–249.

Petkov BH, Vitale V, Svendby SM, Hansen GH, Sobolewski PS, Láska K, Elster J, Pavlova K, Viola A, Mazzola M, Lupi A, Solomatnikova A (2018) Altitude-temporal behaviour of atmospheric ozone, temperature and wind velocity observed at Svalbard. Atmos Res 207: 100–110.

Pommereau J-P, Goutail F, Lefèvre F, Pazmino A, Adams C, Dorokhov V, Eriksen P, Kivi R, Stebel K, Zhao X, van Roozendael M (2013) Why unprecedented ozone loss in the Arctic in 2011? Is it related to climate change? Atmos Chem Phys 13: 5299-5308.

Rafanelli C, De Simone S, Damiani A, Myhre CL, Edvardsen K, Svenoe T, Benedetti E (2009) Stratospheric ozone during the arctic winter: Brewer measurements in Ny-Ålesund. Int J Remote Sens 30: 4319-4330.

Randall CE, Harvey VL, Manney GL, Orsolini Y, Codrescu M, Sioris C, Brohede S, Haley CS, Gordley LL, Zawodny JM, Russell III JM (2005), Stratospheric effects of energetic particle precipitation in 2003–2004, Geophys Res Lett 32: L05802.

Raso ARW, Custard KD, May NW, Tanner D, Newburn MK, Walker L, Moore RJ, Huey LG, Alexander L, Shepson PB, Pratt KA (2017) Active molecular iodine photochemistry in the Arctic. PNAS 114: 10053–10058.

Scargle JD (1982) Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. Astrophys J 263: 835–853.

Shepard DA (1968) A two-dimensional interpolation function for irregularly spaced data. In: Proceedings of 1968 23rd ACM National Conference, New York, USA, 517-524.

Sobolewski PS, Krzyścin JW (2004-2005) UV measurements at the Polish Polar Station, Hornsund, calibration and data for the period 2005-2006. Publications of the Institute of Geophysics, Polish Academy of Sciences D-67 (382) Atmospheric Ozone. Solar Radiation.

Svendby TM, Hansen GH, Stebel K, Bäcklund A, Dahlback A (2017) Monitoring of the atmospheric ozone layer and natural ultraviolet radiation. Annual report 2016, NILU OR 31/2017, ISSN: 2464-3327.

Vitale V, Petkov B, Goutail F, Lanconelli C, Lupi A, Mazzola M, Busetto M, Pazmino A, Schioppo R, Genoni L, Tomasi C (2011) Variations of UV irradiance at Antarctic station Concordia during the springs of 2008 and 2009, Antar Sci 23: 389–398.

Vogler C, Brönnimann S, Hansen G (2006) Re-evaluation of the 1950-1962 total ozone record from Longyearbyen, Svalbard. Atmos Chem Phys 6: 4763–4773.

WGS84 (2000) World Geodetic System 1984. Department of Defense, National Imagery and Mapping Agency. Technical Report TR8350.