Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual Report 2021

Tove M. Svendby[1], Georg H. Hansen[1], Leonie Bernet[1], Are Bäcklund[1], Anne-Cathrine Nilsen[1], Dorothea Schulze[1], Bjørn Johnsen[2]

1) NILU – Norwegian Institute for Air Research, Norway

2) DSA Norwegian Radiation and Nuclear Safety Authority, Norway

NILU report 25/2022

<table>
<tr><td>NILU report 25/2022
Norwegian Environment Agency
M-2335 | 2022</td><td>ISBN: 978-82-425-3094-3
ISSN: 2464-3327</td><td>CLASSIFICATION:

A – Unclassified (open report)</td></tr>
<tr><td>DATE

24.08.2022</td><td>SIGNATURE OF RESPONSIBLE PERSON

Ole-Anders Braathen (sign.)
Deputy director</td><td>NUMBER OF PAGES

45</td></tr>
<tr><td colspan="2" rowspan="2">TITLE

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual Report 2021</td><td>PROJECT LEADER

Wenche Aas</td></tr>
<tr><td>NILU PROJECT NO.

Proj.no. O-113007/O-113008/O-121002</td></tr>
<tr><td colspan="2">AUTHOR(S)
Tove M. Svendby, Georg H. Hansen, Leonie Bernet, Are Bäcklund, Anne-Cathrine Nilsen, Dorothea Schulze, Bjørn Johnsen</td><td>QUALITY CONTROLLER

Kjetil Tørseth</td></tr>
<tr><td colspan="2">REPORT PREPARED FOR

Norwegian Environment Agency
Contact person: Gunnar Skotte</td><td>CONTRACT REF.

Contract no. 17078061/21087006</td></tr>
<tr><td colspan="3">ABSTRACT

This report summarizes the results from the Norwegian monitoring programme on stratospheric ozone and UV radiation measurements. The ozone layer has been measured at three locations since 1979: In Oslo/Kjeller, Tromsø/Andøya and Ny-Ålesund. The UV-measurements started in 1995. The results show that there was a significant decrease in stratospheric ozone above Norway between 1979 and 1997. After that, the ozone layer stabilized at a level ~2% below pre-1980 level. The year 2021 was characterized by low total ozone values in June and July, whereas “normal” ozone values were measured during winter and spring.</td></tr>
<tr><td colspan="3">NORWEGIAN TITLE

Overvåking av ozonlaget og naturlig ultrafiolett stråling: Årsrapport 2021.</td></tr>
<tr><td colspan="3">KEYWORDS

Stratospheric ozone / Stratosfærisk ozon — UV radiation / UV-stråling — Measurements and observations / Målinger og observasjoner — Montreal protocol / Montreal-protokollen</td></tr>
<tr><td colspan="3">ABSTRACT (in Norwegian)

Denne rapporten presenterer resultatene fra det norske måleprogrammet for totalozon og UV-stråling. Ozonlaget har blitt målt ved tre stasjoner siden 1979: i Oslo/Kjeller, Tromsø/Andøya og Ny-Ålesund. UV-målinger startet i 1995. Resultatene viser at det var en signifikant ozonreduksjon over Norge i perioden 1979 til 1997. Deretter stanset reduksjonen og ozonverdiene stabiliserte seg på et nivå ~2% lavere enn verdiene før 1980. Året 2021 var karakterisert ved lave ozonverdier i sommermånedene, spesielt i juni og juli, mens det var normale ozonverdier vinteren og våren 2021.</td></tr>
<tr><td>PUBLICATION TYPE: Digital document (pdf)</td><td colspan="2">COVER PICTURE: Tove Svendby, 2019</td></tr>
</table>

Citation: Svendby, T.M., Hansen, G.H., Bernet, L., Bäcklund, A., Nilsen, A.C., Schulze, D., Johnsen, B. (2022). Monitoring of the atmospheric ozone layer and natural ultraviolet radiation. Annual Report 2021 (NILU report 25/2022; Norwegian Environment Agency M-2335|2022). Kjeller: NILU.

NILU’s ISO Certifications: NS-EN ISO 9001 and NS-EN ISO 14001. NILU’s Accreditation: NS-EN ISO/IEC 17025.

Contents

Summary

This report summarises activities and results from the ozone and UV monitoring programme in 2021. It includes total ozone trend analyses for the period 1979-2021 and UV measurements in Oslo/Kjeller, at Andøya and in Ny-Ålesund for the period 1995-2021. The report also gives an overview of total ozone measurements and UV data from the Trollhaugen Station in Antarctica. The Antarctic activity is funded by the Norwegian Ministry of Climate and Environment.

MAIN CONCLUSIONS FROM THE MONITORING PROGRAMME 2021

- **A strong Arctic polar vortex, which often results in low total ozone values, was established in late 2020, but a sudden stratospheric warming in early 2021 prevented severe chemical ozone loss during winter and spring.**
- **The total ozone values were below long-term means in June and July 2021. At Kjeller and Andøya, the total ozone values were 4-7% below normal during these summer months.**
- **At all Norwegian monitoring stations, a significant stratospheric ozone decrease was recorded for the period 1979-1997. For the period 1998-2021, there are no significant trends in the ozone layer above Norway.**
- **The annual integrated UV dose at Kjeller in 2021 was the fourth highest ever registered. At Andøya the situation was opposite, where one of the lowest annual integrated UV doses was recorded. This was mainly caused by many cloudy days during the summer 2021.**
- **Meteorological variability has a large impact on ozone and UV and can give considerable year-to-year variations.**

Total ozone

The overall ozone situation in 2021 was very different from the previous year. In 2020, the total ozone columns over the northern polar regions were very low in winter and spring due to an exceptionally cold and persistent stratospheric polar vortex, which provided ideal conditions for the formation of polar stratospheric clouds (PSCs) and chemical ozone destruction from chlorine (Cl).

By mid-November 2020, the stratospheric temperatures in Arctic were low enough for PSC formation, and the activation of chlorine started in late November 2020. If these cold conditions had persisted until end of January 2021, the situation would probably have become the same as in spring 2020. Instead, a major "Sudden Stratospheric Warming" (SSW) in early January 2021 warmed the stratosphere to temperatures at which active chlorine cannot be maintained. ClO-concentrations subsequently declined to near-zero at the end of January 2021, which halted further chemical ozone loss and resulted in "normal" total ozone values over Norway during the rest of winter and spring 2021.

Despite "normal" ozone values in the spring 2021, the summer months were characterized by ozone values below the long-term average. In June and July 2021, the total ozone values above Kjeller and Andøya were 4-7% below the long-term means. Low ozone values were also measured in Ny-Ålesund in June. In total, the 2021 annual ozone averages were 1.7%, 3.4%, and 0.5% below the long-term means at Kjeller, Andøya, and in Ny-Ålesund, respectively. Usually, such deviations in summer are caused by dynamical conditions in the upper-troposphere-lower stratosphere (UTLS) region, where a high altitude of the tropopause correlates with reduced total ozone. Certain weather conditions, like stable high-pressure systems favour this situation.

Because of atmospheric circulation, the ozone layer above Norway is normally thickest in late winter and spring, whereas the lowest values occur in October/November. At Kjeller, a minimum ozone value of 224 DU was measured 24 October 2021. This is 24% below the long-term mean for October. Also, a

springtime ozone minimum of 292 DU was measured at Kjeller on 20 March, which is ~28% below the long-term ozone mean for March. At Andøya, the minimum ozone value in 2021 was measured 24 October. This day an ozone value of 222 DU was recorded, which is 24% below the long-term October mean. The lowest ozone value in Ny-Ålesund in 2021 was 241 DU and was measured 28 September. This is 15% below the long-term ozone mean value for September. The minimum values at Kjeller and Andøya were most probably caused by so-called ozone mini-holes due to a very high tropopause.

The monitoring programme and trend analyses show that minimum average ozone levels over Norway were reached in the mid-1990s. During the period 1979-1997, the annual average ozone layer above Oslo and Andøya decreased by 5-6%/decade and as much as 8%/decade during spring. For Ny-Ålesund, the decrease was even larger: 6%/decade for annual means and 11%/decade during the spring months. The pronounced ozone decreases were partly influenced by special meteorological conditions and very low ozone values in the Mid 1990s. Since 1998, no further ozone decrease has been observed at any of the three Norwegian sites, and the annual average ozone layer has stabilized at a level ~2% below the pre-1980 level (i.e. the reference level, before the ozone depleting substances had significant influence on stratospheric ozone chemistry).

UV measurements

The highest noon average UV index (UVI) at Kjeller in 2021 was 6.3, measured on 16 July. However, a peak UVI of 7.4 was measured on 27 June. UVI values around 7 are not very unusual in Southern Norway on sunny days in late June and early July and people with a typical Nordic skin type can get sunburnt after ~20 minutes if no sun protection is used. At Andøya, the highest noon average UV index in 2021 was 4.9, observed on 4 July. In Ny-Ålesund, a maximum noon average UVI of 2.9 was observed on 6 July, but a peak value of 3.2 was registered on 1 June. The values from Andøya and Ny-Ålesund are typical for low and high Arctic latitudes, respectively.

In 2021, the yearly integrated UV dose at Andøya was 233.0 kJ/m^2, which is among the lowest doses registered since the start in 1996. This is in stark contrast to the high UV dose registered in 2020, which was ~12% higher than the 2021 value. The low 2021 dose was mainly related to a summer with many cloudy days. Contrary to Andøya, the integrated UV dose at Kjeller was relatively high in 2021. Kjeller had an annual dose of 388.5 kJ/m^2, which is the 4^{th} highest value registered. Ny-Ålesund had an annual integrated dose of 211.4 kJ/m^2, which is the 13^{th} highest observation and 9% below the maximum value from 2000.

Trend analyses indicate that the annual average UV dose has increased by 2.2%/decade in Oslo/Kjeller from 1995 until today. Contrary to Oslo/Kjeller, negative trends of -1.8%/decade and -1.5%/decade have been registered at Andøya and Ny-Ålesund, respectively. However, none of these trend results are statistically significant.

Ozone Depleting Substances (ODSs)

During the 1980s and 1990s, the amount of stratospheric ozone decreased dramatically. The main reason for this decrease was anthropogenic release of ozone depleting substances (ODSs), especially chlorofluorocarbons (CFCs). In 1987, a number of countries signed The Montreal Protocol, with the aim of phasing out and stopping the release of ODSs. This international treaty has later been amended several times, and the effective regulations have reduced the use and emissions of ODSs significantly. The total amount of ODSs in the stratosphere reached a maximum in the late 1990s. Since then, the concentrations have declined slowly for most compounds.

Today we can see signs of ozone recovery, but one should keep in mind that the current equivalent effective stratospheric chlorine (EESC) level for polar winter conditions, which is the most appropriate measure of ozone depletion potential, has only declined by 9% from the peak value in the 1990s (WMO, 2018). It is therefore crucial to follow the development of the ozone layer in order to verify that the Montreal Protocol and its amendments work as expected. A recovery of the stratospheric ozone layer depends on a sustained reduction of CFC-11, which is the most important ODS and contributes one quarter of all chlorine reaching the stratosphere. Monitoring results and studies have shown that the rate of decline of atmospheric CFC-11 concentrations slowed down by about 50% after 2012, largely attributed to illegal production of CFC-11 from Eastern China, strongly inconsistent with the Montreal Protocol agreement. However, recent studies show that these regional emissions of CFC-11 have substantially declined from 2017 to 2019, and global CFC-11 emissions in 2019 were back to pre-2013 levels. This demonstrates the importance of maintaining good monitoring networks, both to detect possible changes related to ODSs, but also to detect possible effects of climate change on the ozone layer.

Coupling of stratospheric ozone and climate

The expected future recovery of stratospheric ozone might be affected by climate change. An increase in greenhouse gases will warm the troposphere and cool the stratosphere, and in general a decrease in stratospheric temperature will slow down the gas-phase ozone destruction reactions, leading to less depletion and higher ozone column. However, there is a possible exception in the polar regions where lower stratospheric temperatures and increased stratospheric water vapour leads to more favourable conditions for the formation of Polar Stratospheric Clouds (PSCs). Furthermore, climate change may alter the strength of the stratospheric circulation and with it the distribution of ozone in the stratosphere. According to analyses from Scientific Assessment of Ozone Depletion: 2018 (WMO, 2018), Northern Hemisphere total ozone is expected to return to 1980 abundances in the 2030s, Southern Hemisphere mid-latitude ozone to return around mid-century, whereas the Antarctic ozone hole is expected to gradually close and return to 1980 values in the 2060s. These projections are based on full compliance with the Montreal Protocol and the baseline estimate of the future evolution of GHGs.

The national monitoring programme

To follow up the Montreal Protocol, the Norwegian Environment Agency established the programme "Monitoring of the atmospheric ozone layer" in 1990. NILU - Norwegian Institute for Air Research has been responsible for the operation and maintenance of the monitoring programme. Three sites are included in the programme: Oslo/Kjeller (60°N), Andøya (69°N) and Ny-Ålesund (79°N). In late June 2019, the ozone and UV monitoring instruments at Blindern, Oslo, were moved to NILU (Kjeller) to ensure a continuation of the measurements.

The present report belongs to a series of four annual reports covering national monitoring of atmospheric composition in the Norwegian rural background environment. The other three reports focus on monitoring of 1) particulate and gaseous phase of inorganic constituents, particulate carbonaceous matter, ground level ozone and particulate matter, 2) persistent organic pollutants and heavy metals, and 3) greenhouse gases and aerosol properties. The latter report includes monitoring and analysis of ozone depleting substances (ODSs), an activity closely related to the total ozone and UV monitoring programme presented in this report.

Summary of total ozone and UV key results:

Ozone	**Oslo/Kjeller**	**Andøya**	**Ny-Ålesund**
Annual total ozone trend 1979-1996, %/decade	-5.9 (±2.0)	-5.2 (±2.0)	-5.9 (±2.2)
Annual total ozone trend 1997-2021, %/decade	0.4 (±1.2)	-0.6 (±1.2)	-0.4 (±2.0)
UV			
Annual UV dose 2021, kJ/m^2 (rank*)	352.6 (4)	233.0 (19)	211.4 (13)

*"Rank" indicates how high the UV dose was in 2021 compared to other years. UV has been measured since 1995/1996.

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual Report 2021

OZONE PRODUCTION, DESTRUCTION AND TRANSPORT

- Stratospheric ozone is produced continuously, especially in topical areas at ~40 km altitude. Here, the strong solar radiation can split oxygen molecules (O_2) and form ozone (O_3).
- Solar radiation can also split O_3 molecules and thereby contribute to ozone destruction. In addition, several radicals such as Cl, NO, and OH can react with ozone and bring it back to O_2.
- Ozone that is formed in the tropical stratosphere is transported to polar regions. In the winter the temperature gradient is largest, which also leads to the largest transport of ozone rich air from equatorial to polar regions. This causes maximum stratospheric ozone values over Norway in March and April.
- From May to October the ozone layer over Norway will gradually decrease due to the depletion processes described above
- The ozone layer can also change from one day to the next due to meteorological variations. Under e.g. high pressure situations, the ozone layer can be pushed to the side and to higher altitudes, which locally results in a reduced total ozone column.
- Some years the winter polar vortex is exceptionally strong and persistent and can prevent ozone rich air to reach the polar region. These years we often observe severe ozone depletion. The vortex is also associated with a cold stratosphere, and at temperatures below -78°C polar stratospheric clouds (PSCs) is formed. These clouds can initiate ozone destruction.

1 Norwegian ozone measurements in 2021

Total ozone is measured on a daily basis at Kjeller (60°N), at Andøya (69°N) and in Ny-Ålesund (79°N). The daily ground-based ozone measurements at Blindern (Oslo) started in 1978, but in June 2019 the instruments were moved to NILU, Kjeller, to secure a continuation of the measurements. Modern ground-based ozone observations have been performed at Andøya/Tromsø and in Ny-Ålesund since 1990. The ozone measurements are retrieved from Brewer spectrophotometers in Oslo/Kjeller and at Andøya, whereas a SAOZ (Systeme d'Analyse par Observation Zenitale) instrument is the standard ozone instrument in Ny-Ålesund together with a Brewer instrument operated by the Institute of Polar Sciences, National Research Council of Italy. In 2020, a new Pandora spectrometer was installed in Ny-Ålesund in the frame of the SIOS infrastructure development. At all the three Norwegian sites GUV (Ground-based UltraViolet) filter radiometers are installed and can fill in ozone data gaps on days without Brewer and SAOZ measurements (see Appendix for more details). In addition to the ground-based measurements we also analyse total ozone data from various satellites to get a more complete description and understanding of the ozone situation in Norway and the Arctic region. The total ozone values, frequently denoted as ozone layer thickness, are expressed in terms of Dobson Units (DU[1])

In the following sections, results from the ground-based total ozone measurements in Oslo/at Kjeller, at Andøya and in Ny-Ålesund as well as from Trollhaugen Station, Antarctica, are described, while satellite measurements from the Norwegian and Arctic sites are presented in Chapter 3.

1.1 Total ozone at Kjeller

Total ozone has been measured at Blindern, University of Oslo, for more than 40 years. Due to retirement of key personnel at the Department of Physics, University of Oslo, it was decided to move all the instruments to NILU, Kjeller, in the end of June 2019. The station at Kjeller is located ~18 km east of Blindern, and it is assumed that the ozone column above Oslo and Kjeller are more or less the same. In Oslo/Kjeller total ozone is primarily recorded with the Brewer MKV Spectrophotometer (B042). Figure 1a illustrates the daily total ozone values measured in 2021. The black curve shows the daily measurements, whereas the red curve shows the long-term monthly mean values for the period 1979-1989 (frequently denoted as “normal” in the current report). The total ozone values in 2021 are based on Brewer direct-sun (DS) measurements when available.

In 2021, direct-sun measurements were performed on 215 out of 365 days. During overcast days or days where the minimum solar zenith angle was larger than 72°, the ozone values were calculated with the Brewer global irradiance (Brewer GI) method (Stamnes et al., 1991). The Brewer GI method was used on 146 days. On days with missing Brewer measurements, total ozone is retrieved from the GUV-511 instrument which is located next to the Brewer. Altogether, GUV data were used to complete the ozone time series on 4 days with missing Brewer data in 2021. A summary of instrument frequency in the data set is given in Table 1. In 2021 there were no days without measurements.

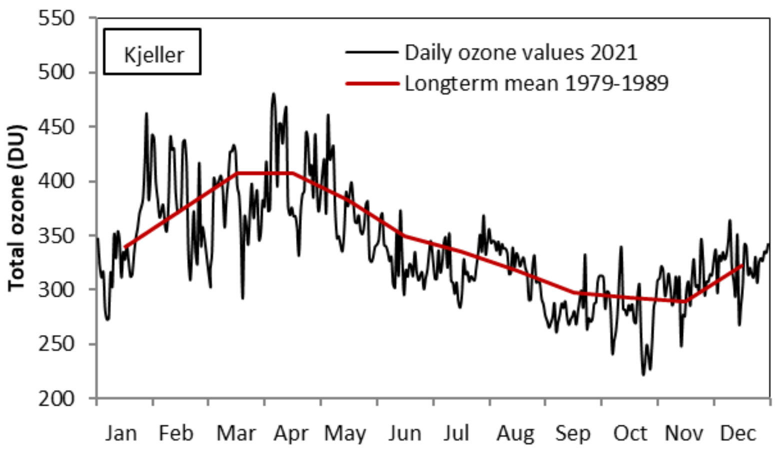

Figure 1a: Daily total ozone values measured at Kjeller in 2021. The red curve shows the long-term monthly mean values from Oslo 1979-1989.

[1]The Dobson unit (DU) is a unit of measurement of total-column ozone in the Earth's atmosphere. One Dobson unit refers to a layer of gas that would be 0.01 mm thick under standard temperature and pressure. The ozone layer in Norway normally varies between 240 and 550 DU, i.e. 2-6 mm, depending on the season. An ozone value of less than 220 DU defines an “ozone hole”.

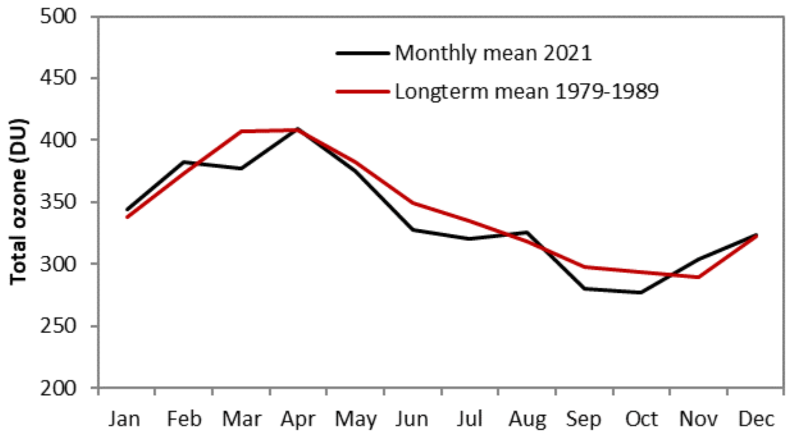

Figure 1b: Monthly mean ozone values at Kjeller in 2021. The red curve shows the long-term monthly mean values from 1979-1989.

Table 1: Overview of total ozone instruments at Kjeller and the number of days where the various instruments were used in the 2021 time series

Priority	Method	Total days with observations
1	Brewer #42 instrument, direct sun measurements	215
2	Brewer #42 instrument, global irradiance method	146
3	GUV-511 instrument	4
	Missing days	0

As seen from Figure 1a there are large day-to-day fluctuations in total ozone, particularly during winter and spring. The rapid ozone variations are typically caused by stratospheric circulation and changes in tropopause height. The lowest ozone values normally occur in October/November, and in 2021 a minimum ozone value of 224 DU was measured 24 October. This is 24% below the long-term mean for October. Also a spring time ozone minimum of 292 DU was measured 20 March, which is ~28% below the long-term mean value for March.

The monthly mean total ozone values in 2021 are shown in Figure 1b (black line), compared to the long-term monthly mean values for the period 1979-1989 (red line). As seen from the figure, the monthly average ozone values in 2021 are below normal most of the year, except for the winter months and August. Section 2.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2021.

1.2 Total ozone at Andøya

Total ozone measurements in Tromsø started back in 1935, which makes the Tromsø/Andøya time series one of the longest in the world. At Andøya the total ozone values are based on Brewer direct-sun (DS) measurements when available. For overcast days and days when the solar zenith angle is larger than 80° (sun less than 10° above the horizon), the ozone values are based on the Brewer global irradiance (GI) method. As in Oslo, a GUV instrument provides ozone data when the Brewer instrument is out of order or Brewer measurements are inhibited by bad weather conditions. From about 1

December until 10 January, the sun is below the horizon, thus not allowing ozone measurements with these instruments. Also, the total ozone measurements are more uncertain when the solar zenith angle is above 82°, and in the first weeks before/after the polar night, the ozone measurements are often rejected due to large standard deviation in the measurements.

The Andøya Brewer instrument ran without major interruptions in 2021, but a significant drift in the standard lamp started early in the year. Due to the Covid-19 pandemic, Brewer was not calibrated and checked by IOS Canada in summer 2021 and the exact reason for the instrument drift is not known. Because of the drift and uncertain data quality, Brewer data for the period May-August 2021 are preliminarily omitted from the Andøya time series. Instead GUV total ozone data are used. A post-processing of the 2021 Brewer data will be performed in 2022/2023 after the instrument has been inspected by the International Ozone Service Inc.

The GUV instrument ran without major problems in 2021. However, since 2018 the GUV instrument at Andøya has been experiencing some problems with the communication between the detector and the PC, resulting in occasional interruptions and shorter periods (several minutes) without data logging. The reason for these interruptions is not clear. A new PC, new cables, and a new controller has been installed, but the problem is still not completely gone. Despite this trouble there were only two days without GUV measurements due to technical problems in 2021. On one additional day total ozone was not retrieved due to heavy clouds and large data uncertainty. In addition, total ozone was not retrieved during the polar night period (Nov-Jan).

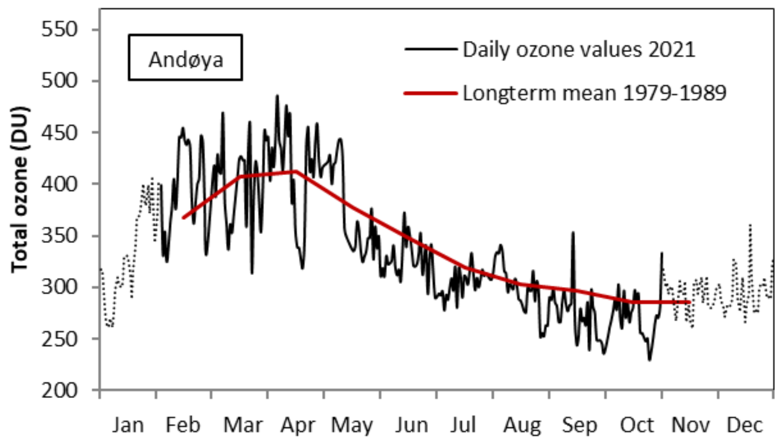

Figure 2a: Daily total ozone values measured at ALOMAR, Andøya, in 2021 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989.The dotted line represents GOME2 satellite measurements.

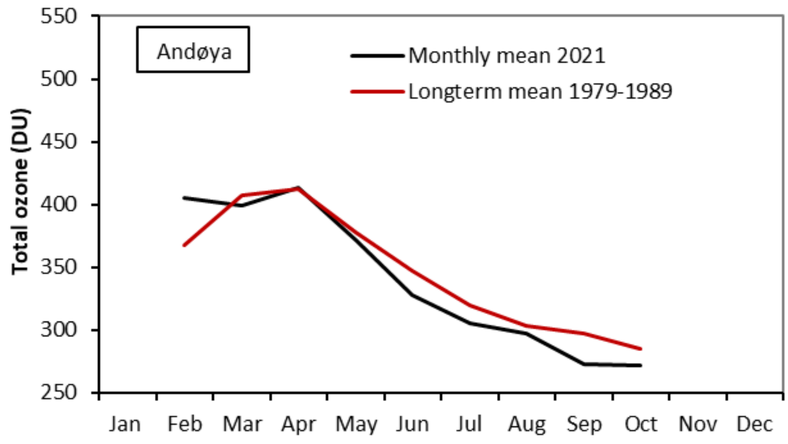

Figure 2b: Monthly mean total ozone values at Andøya in 2021 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

Table 2 gives an overview of the different instruments and methods used at Andøya in 2021. Brewer DS was used 66 days, Brewer GI provided the daily ozone values on 76 days, whereas GUV was used 126 days. In total, there were 3 days with missing data in 2021: two days related to technical issues and one day caused by heavy clouds and unacceptably high uncertainty.

Figure 2a shows daily ozone values from Andøya in 2021. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989. In addition GOME2 satellite data are included for the polar night period (winter), shown as a dotted line in Figure 2a. The lowest ozone values at Andøya normally occur in October and November, and in 2021 the minimum ozone value was measured 24 October. This day the ozone value was 222 DU, which is 24% below the long-term October mean.

Table 2: Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2021.

Priority	Method	Total days with observations
1	Brewer #104 instrument, direct sun measurements	66
2	Brewer #104 instrument, global irradiance method	76
3	GUV-541 instrument	126
	Missing days (except polar night period)	3

Monthly mean ozone values at Andøya in 2021 are shown in Figure 2b. For January, November, and December (polar night) there are not sufficient data to calculate monthly means from the ground based instruments. Comparison between the long-term mean and monthly mean ozone values in 2021 shows that the total ozone column was above normal in February, close to normal in March-May, and below normal the rest of the year.

1.3 Total ozone in Ny-Ålesund

Ny-Ålesund is located at a high northern latitude (79°N), which normally makes it more challenging to obtain reliable ozone measurements due to weak solar radiation/large solar zenith angles, especially during spring and fall. Whereas most ozone monitoring instruments are based on UV absorption techniques, e.g. the Brewer and GUV instruments, the SAOZ instrument measuring total ozone in Ny-Ålesund is based on radiation from the visible part of the solar spectrum. This requires a long pathway through the atmosphere, and ozone retrievals can only be made at solar zenith angles larger than ~85°. In Ny-Ålesund, this excludes measurements between approximately 1 May and 15 August, as the sun never settles below 5° elevation during this period.

In addition to the SAOZ instrument, a GUV-541 multi-filter radiometer is used for ozone measurements when the UV radiation becomes stronger in the spring, summer and early fall. These measurements give important contributions to the ozone time series from Ny-Ålesund.

In early 2020 a new Pandora UV/visible spectrometer monitoring both total ozone and NO_2 was put into operation as part of the SIOS-InfraNord project. The Pandora instrument provides data for both the sun and the moon as a light source, thus potentially providing data also during the polar night. Currently, the instrument is still in a commissioning phase mode, but is envisaged to be in routine operation mode from 2022. Data will be provided to the SIOS (Svalbard Integrated Arctic Earth Observing System) Data Management System, but also be available for other projects.

NILU's instruments in Ny-Ålesund are all located at the observation platform of the Sverdrup Station of the Norwegian Polar Institute. SAOZ measurements started in the fall 1990, GUV measurements in 1995, and have continued until the present time with a few exceptions (see Appendix).

NILU has also access to data from an Italian Brewer instrument set up at the Sverdrup station, which are valuable for the quality assurance of the SAOZ and GUV ozone data. There were some technical problems with the Brewer in 2019, and in 2020 and 2021 a Brewer calibration was not possible due to travelling restrictions under Covid-19. Even if the Brewer ran without major interruptions the summer 2021, it was decided that the quality-controlled GUV ozone data should be used in the 2021 time series.

Both the SAOZ and GUV instrument worked satisfactorily the whole year. One out of 365 days GUV measurements were missing due to power failures at the Sverdrup station. This day Brewer total ozone was used. In 2021 there were no days with absent ozone measurements due to heavy clouds and bad weather conditions.
Table 3 gives an overview of the different instruments and measurement methods used for the 2021 total ozone time series in Ny-Ålesund. No ground-based ozone measurements were performed during the polar night period and the days just before/after the polar night, i.e. from 25. October to 16. February.

Table 3: Overview of instruments and methods applied for retrieval of the total ozone in Ny-Ålesund 2021.

Priority	Method	Total days with observations
1	Brewer #50 instrument	1
2	SAOZ instrument	102
3	GUV-541 instrument	140
	Missing days (except polar night period)	0

Figure 3a shows daily ozone values from Ny-Ålesund in 2021. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989, calculated from TOMS (Total ozone Mapping Spectrometer) satellite data. Total ozone values during winter (November to mid-February) are not achievable due to absence of sunlight, but similar to Andøya, GOME2 satellite data have been used to indicate the ozone values for the polar night period, shown by the dotted line in Figure 3a. Similar to Oslo and Andøya, the lowest ozone values in Ny-Ålesund normally occur in October and November. The lowest ozone value in 2021 was 241 DU, measured 28 September 2021. This is 15% below the long-term mean for September.

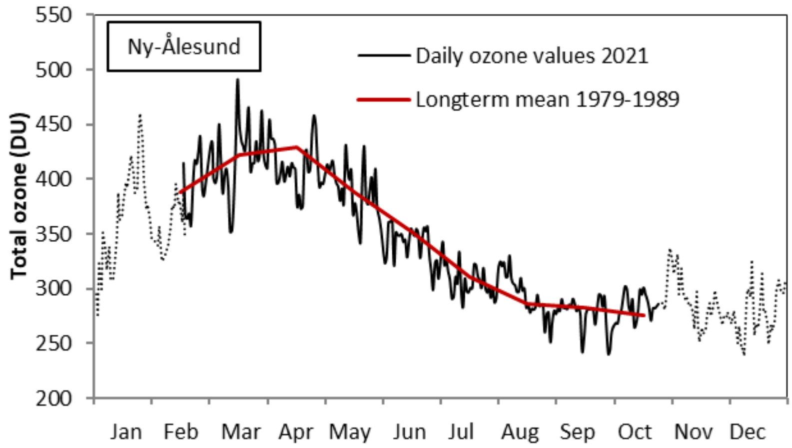

Figure 3a: Daily total ozone values measured in Ny-Ålesund in 2021 by the SAOZ, GUV, and Brewer instruments (black curve). The red line is the long-term monthly mean values from 1979 - 1989. The dotted line represents GOME2 satellite measurements.

Monthly mean total ozone values in Ny-Ålesund 2021 are shown in Figure 3b. Comparison between the 2021 values and the long-term 1979-1989 monthly means demonstrate that the 2021 values were close to normal throughout the year, except a couple of weeks in April with somewhat lower values.

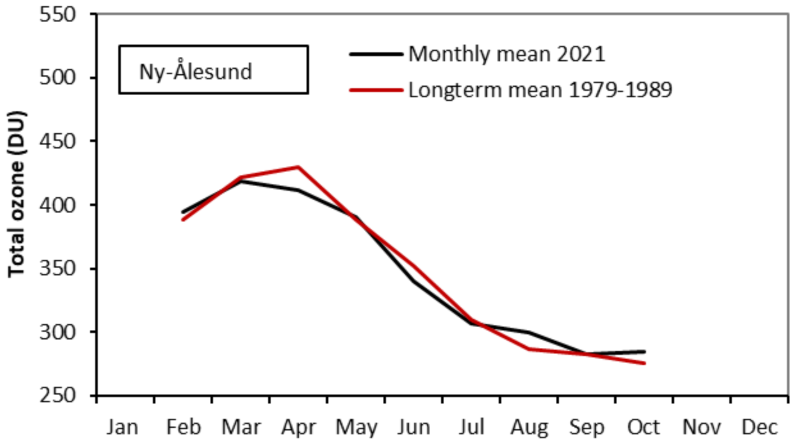

Figure 3b: Monthly mean total ozone values for 2021 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

2 Ozone measurements and trends 1979-2021

2.1 Background: WMO/UNEP reports

Since the early 1990s, the World Meteorological Organisation (WMO) and United Nations Environment Programme (UNEP) have published assessment reports of ozone depletion every four years. The last one, "Scientific Assessment of Ozone Depletion: 2018", was published in October 2018 (WMO, 2018). The 2022 Ozone Assessment will be submitted to the WMO Ozone Secretariat in December 2022. The reports summarize the current knowledge and status of the ozone layer, ozone recovery, UV changes, and development of relevant trace gases (e.g. halocarbons, chlorine and bromine) in the atmosphere.

The 2018 report concludes that the actions taken under the Montreal Protocol have led to decreases in the atmospheric abundance of ozone-depleting substances (ODSs). By 2016, the chlorine entering the stratosphere from ODSs has declined by 12% from the 1993 peak value. Total bromine has decreased by 15% since 1998.

Earlier measurements showed that total column ozone declined over most of the globe during the 1980s and early 1990s. The 2018 assessment report concludes that the global (60°S-60°N) total column ozone has remained relatively unchanged since 1997, remaining roughly 2% below the 1964-1980 average. However, the upper stratospheric ozone has increased by 1-3%/decade since 2000. Climate models suggest that this increase can be explained by comparable contributions from declining ODS abundances and upper stratospheric cooling caused by carbon dioxide increases.

According to the 2018 Ozone Assessment, it is likely that total column ozone will recover toward the 1980 benchmark levels over most of the globe under full compliance with the Montreal Protocol. Northern Hemisphere total ozone is expected to return to 1980 abundances in the 2030s, Southern Hemisphere mid-latitudes ozone around mid-century, whereas the Antarctic ozone hole is expected to gradually close and return to 1980 values in the 2060s.

The last assessment report also emphasizes that changes in CO_2, N_2O, and CH_4 will have an increasing influence on the ozone layer as ODS concentrations decline. These gases impact both chemical cycles and stratospheric circulation. This is described in more detail in Chapter 4. Studies of long-term ozone trends, presented in the next sections, are essential in the assessment of possible ozone recovery and for gaining more information about atmospheric processes. A detailed trend analysis for Oslo, Andøya, and Ny-Ålesund using a more advanced multiple linear regression is in preparation for publication (Bernet et al., 2022).

As mentioned above, stratospheric ODS concentrations have declined slowly the last 20+ years. The most important ODS is CFC-11, which contributes one quarter of all chlorine reaching the stratosphere. A recovery of the stratospheric ozone layer depends on a sustained reduction of CFC-11. The rate of decline of atmospheric CFC-11 concentrations was constant from 2002 to 2012. However, after 2012 the rate of decline slowed down by about 50% (Montzka et al., 2018). The same pattern was also evident from the CFC-11 measurements performed at the Zeppelin observatory. This was explained by an increase in CFC-11 emissions caused by unreported new production in China (Rigby et al., 2019), strongly inconsistent with the Montreal Protocol agreement to phase out global CFC production by 2010. A more recent study from Park et al. (2021) indicates that the CFC-11 emissions in eastern China returned to pre-2013 levels in 2019, which probably avoided a substantial delay in the ozone layer recovery.

2.2 Trends for Oslo 1979-2021

Total ozone measurements using the Dobson spectrophotometer (No. 56) were performed on a regular basis in Oslo from 1978 to 1998. The complete set of Dobson total ozone values from Oslo is available at The World Ozone Data Centre, WOUDC (https://woudc.org/data.php). Since the summer of 1990, Brewer instrument no. 42 has been in operation. The entire set of Brewer DS measurements from Oslo and Kjeller is also available at WOUDC.

At the end of June 2019 the Brewer instrument no. 42 was moved from Blindern in Oslo to NILU, Kjeller, ~18 km east of Blindern. The stratospheric ozone climatology above Blindern and Kjeller are more or less the same, and the move of the instrument is assumed to have no significant impact on the total ozone values and trend calculations.

Figure 4a shows the variations in monthly mean ozone values in Oslo/Kjeller for the period 1979 to 2021. The large seasonal variations are typical for stations at high latitudes. This is a dynamic phenomenon and can be explained by the springtime transport of ozone from the source regions in the stratosphere above the equator.

In order to make ozone trend analyses for the period 1979 – 2021 we have removed the seasonal variations by subtracting the long-term monthly mean ozone values from the data series, shown in Figure 4b. Next, we have divided the time series into two periods: 1) 1978-1997, and 2) 1998-2021. For the first time period, the ozone measurements were entirely derived from the Dobson instrument and reflect a time period when a gradual decline in stratospheric ozone was observed at most mid- and high-latitude stations. This decrease was intensified by the cold Arctic winters in 1996 and 1997 (Solomon et al., 1999) and the major Mt. Pinatubo volcanic eruption in 1991. Also, the stratospheric chlorine level reached a maximum around 1995-1997 (WMO, 2018). Thus, 1998 is a natural starting point for studying total ozone recovery. In Oslo the second time period (1998-2021) is based on Brewer measurements, with inclusion of some GUV measurements. For the two time periods, simple linear regression lines have been applied to the data to derive trends in the ozone layer above Oslo/Kjeller. The results are summarized in Table 4. The numbers in the table represent seasonal and annual percentage changes in total ozone (per decade) for the two time periods. The numbers in parenthesis give the uncertainty (1σ[2]) in percent/decade. A trend larger than 2σ is considered as significant. In winter and spring, the ozone variability is relatively large and the corresponding ozone trend must be large in order to be classified as statistically significant.

[2] Sigma (σ) represents a confidence interval. The 1σ interval means that it is 68.3% certain that the trend is between calculated trend ± 1σ value. The 2σ value represents a 95.4% confidence interval.

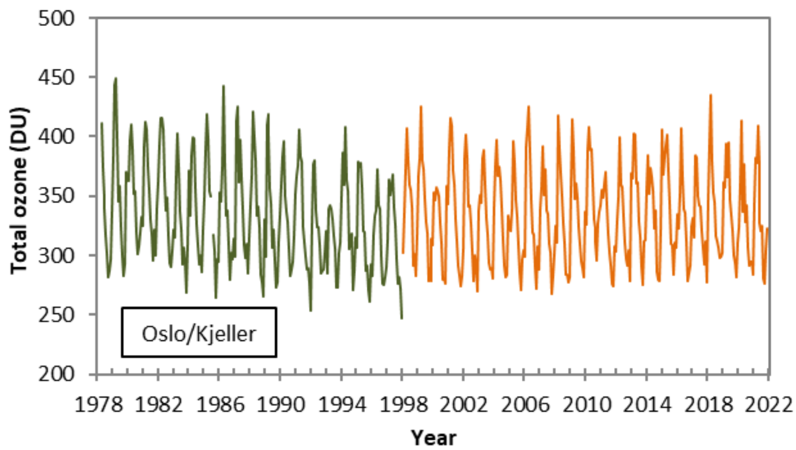

Figure 4a: Time series of monthly mean total ozone in Oslo and at Kjeller 1979-2021. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements.

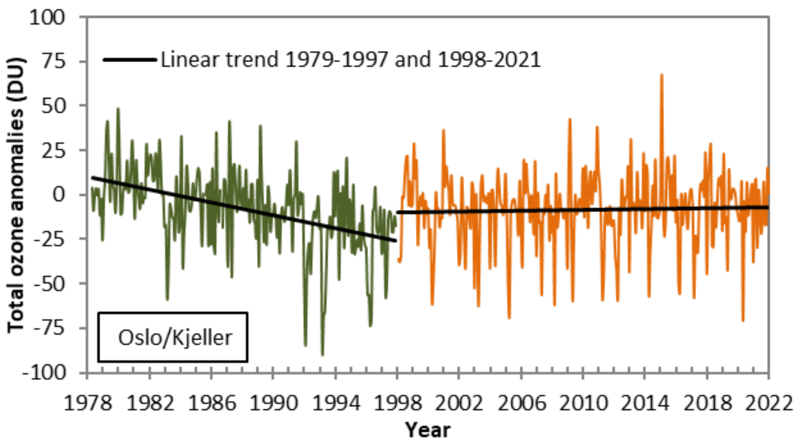

Figure 4b: Variation in total ozone over Oslo/Kjeller for the period 1979–2021 after the seasonal variations have been removed. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements. Trend lines are marked as black lines.

The second column in Table 4 indicates that a large ozone decrease occurred during the 1980s and first half of the 1990s. In the period 1979-1997 there was a significant decline in total ozone for all seasons. For the winter and spring, the decrease was as large as -6.0 %/decade and -8.0 %/decade, respectively. The negative ozone trend was less evident for the summer, but nevertheless it was significant at a 2σ level.

For the period 1998-2021 the picture is different. There are substantial year-to-year fluctuations, and it is hard to draw definite conclusions about trends. Multiple linear regression would be required to separate the recovery signal from other natural ozone variability. Still, the simple regression analysis gives a good indication of the status of the ozone layer for recent years. As seen from the last column in Table 4, there is a statistically significant ozone increase of 1.6%/decade for the fall period September to November. For all other seasons the changes in total ozone are relatively small and close to zero. The annual ozone trend from 1998 to 2021 is 0.4% /decade.

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 1.1.1979 to 31.12.2021. The numbers in parenthesis represent the uncertainty (1σ). Data from the Dobson, Brewer and GUV instruments have been used in this study. A trend larger than 2σ is considered as significant.

Season	Trend (%/decade) 1979-1997	Trend (%/decade) 1998-2021
Winter (Dec – Feb)	-6.0 (2.3)	1.5 (1.5)
Spring (Mar – May)	-8.0 (1.3)	0.0 (1.1)
Summer (Jun – Aug)	-3.5 (1.0)	-0.8 (0.6)
Fall (Sep – Nov)	-4.2 (1.0)	1.6 (0.8)
Annual (Jan – Dec):	-5.9 (1.0)	0.4 (0.6)

2.3 Trends for Andøya/Tromsø 1979-2021

Total ozone monitoring started in Tromsø back in 1935 (a Fery spectrograph until 1939, and Dobson no. 14 from 1939), and measurements were performed on a routine basis until 1972. In 1985 Dobson instrument no. 14 was put into operation again, but unfortunately the instrument was not properly inter-compared with other Dobson instruments until 1990.

An automated Brewer instrument (B104) was installed in Tromsø in 1994 and operated at this site until fall 1999, in parallel with Dobson no.14. In 2000, the Brewer instrument was moved to Andøya, approximately 130 km West-southwest of Tromsø, while Dobson observations were terminated. Studies have shown that the ozone climatology is very similar at the two locations (Høiskar et al., 2001), and the two datasets are considered equally representative for the ozone values at 70° in the European/ Atlantic Arctic. Thus, for trend study purposes the Tromsø/Andøya total ozone time series can be considered as one series.

To avoid periods of missing data and possible influences of missing inter-comparison, and to make the total ozone time series as homogeneous as possible, total ozone values from the satellite instrument TOMS (onboard the Nimbus 7 satellite) have been used for the period 1979-1994.

Figure 5a shows the variation in the monthly mean ozone values at Andøya from 1979 to 2021. The variations in total ozone, after removing the seasonal cycle, are shown in Figure 5b, together with the annual trends. November – February months are not included in the trend analysis due to lack of data and uncertainties in ozone retrieval during the period with low solar elevation. This includes removal of, e.g., the ozone peak value in February 2010 and the low ozone values in early February 2018. Simple linear regression lines have been fitted to the data in Figure 5b. Similar to the Oslo site we have divided the ozone time series into two periods: 1) 1979-1997, and 2) 1998-2021. The results of the trend analyses are summarized in Table 5. Comparison of Figure 4b and Figure 5b shows that the trend patterns at Andøya have many similarities to the Oslo trend pattern.

As for Oslo, the ozone layer above Andøya declined significantly from 1979 to 1997. This decline was evident for all seasons. The negative trend for the spring season was -7.5%/decade, whereas the negative trend for the summer months was -3.4%/decade. The yearly trend in total ozone was -5.2%/decade. For the second period from 1998 to 2021, no significant trends have been found. The annual ozone trend from 1998 to 2021 is -0.6%/decade.

Table 5: Percentage changes in total ozone (per decade) at Andøya for the periods 1) 1979-1997, and 2) 1998- 2021. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	*Trend (%/decade) 1979-1997*	*Trend (%/decade) 1998-2021*
Spring (Mar – May)	-7.5 (1.5)	-1.4 (1.1)
Summer (Jun – Aug)	-3.4 (1.0)	-0.8 (0.7)
Fall (Sep – Oct)	-3.4 (1.1)	1.2 (0.8)
Annual (Mar – Oct)	-5.2 (1.0)	-0.6 (0.6)

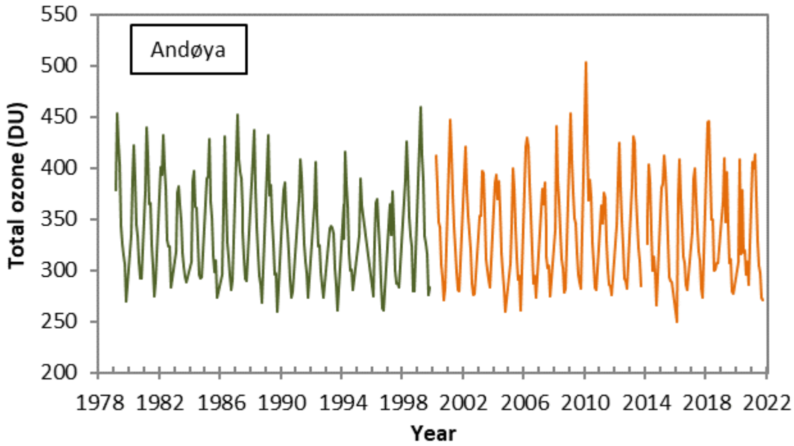

Figure 5a: Time series of monthly mean total ozone at Andøya/Tromsø 1979–2021. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya.

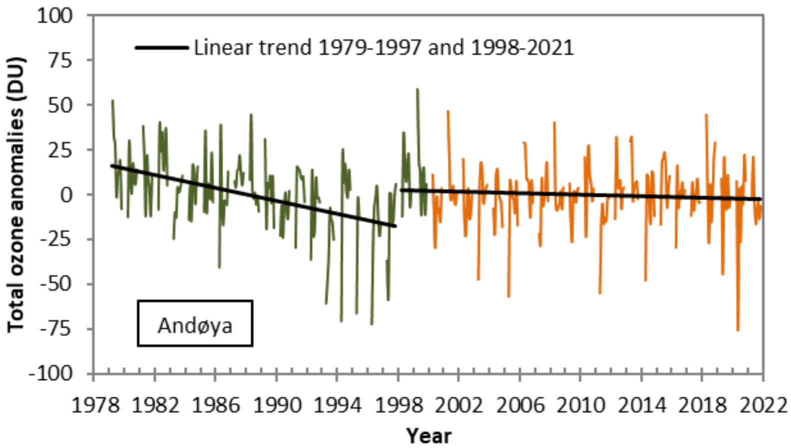

Figure 5b: Variations in total ozone at Andøya for the period 1979–2021 after the seasonal variations are removed. Only data for the months March–October are included. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya. The trends are marked as black lines.

2.4 Trends for Ny-Ålesund 1979-2021

The first Arctic ozone measurements started in Svalbard in 1950, when a recalibrated and upgraded Dobson instrument (D8) was sent to Longyearbyen, and Søren H.H. Larsen was the first person who performed ozone measurements in Polar regions (Henriksen and Svendby, 1997). Larsen studied the annual ozone cycle, and his measurements were of great importance when Gordon M.B. Dobson and his co-workers started ozone observations in Antarctica (Halley Bay) some years later.

Regular Dobson ozone measurements were performed at Longyearbyen until 1966. The data series from 1950 to 1962 has been reanalyzed and published by Vogler et al. (2006). In 1966, the Dobson instrument was moved to Ny-Ålesund and measurements continued until 1968. As in Tromsø, measurements were discontinued after technical failures and they didn't resumed until August 1984, now again in Longyearbyen. The measurements continued until 1993, but unfortunately without appropriate quality assurance and calibration. In 1994, the instrument was once again moved to Ny-Ålesund and operations were taken over by the Norwegian Polar Institute. There they continued – with interruptions – until fall 2005. A major reason for the final termination of the Dobson measurements was the requirement of a substantial amount of manual operation. In parallel with the Dobson instrument, the more automatic SAOZ and GUV instruments were put into operation in Ny-Ålesund in 1991 and 1995, respectively. Since 2014 we have also had access to Italian Brewer measurements.

The ozone measurements presented in Figure 6a and Figure 6b are based on a combination of Dobson, Brewer, SAOZ, GUV and satellite measurements. For the years 1979 to 1997 the monthly mean ozone values are entirely based on TOMS Nimbus 7, Meteor-3, and SBUV overpass data. For the last 24 years, only ground-based measurements have been used to calculate the mean values: Dobson and Brewer data are included when available, SAOZ data are the next priority, whereas GUV data are used when no other ground-based measurements are available. Due to the optimal operation mode of the SAOZ instrument around 90° solar zenith angle, the period of performing acceptable ozone measurements is almost as long in Ny-Ålesund as at Andøya, although the site is 10° further north.

As seen from Figure 6b and Table 6, the trend pattern in Ny-Ålesund is similar to the Oslo and Andøya trend patterns. A massive ozone decline was observed from 1979 to 1997, especially during winter and spring. The negative trend for the spring season was as large as -10.8%/decade, whereas the negative trend for the summer months was "only" -2.4%/decade. The annual trend in total ozone column was -5.9%/decade during this early period. For the second period 1998-2021 no significant trends have been observed. The trend for fall is +1.4%/decade, whereas a negative trend of -0.9%/decade is found for the summer months. Figure 6b also shows that a slightly positive trend for the last two decades is reduced (reversed) because of the occasional years with a strong polar vortex and substantial ozone depletion (e.g. 2005, 2011, 2016, and 2020).

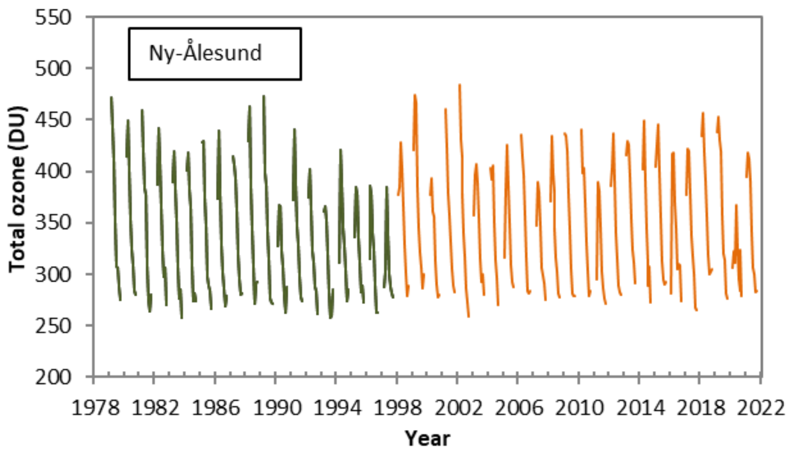

Figure 6a: Time series of monthly mean total ozone at Ny-Ålesund 1979–2021. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments.

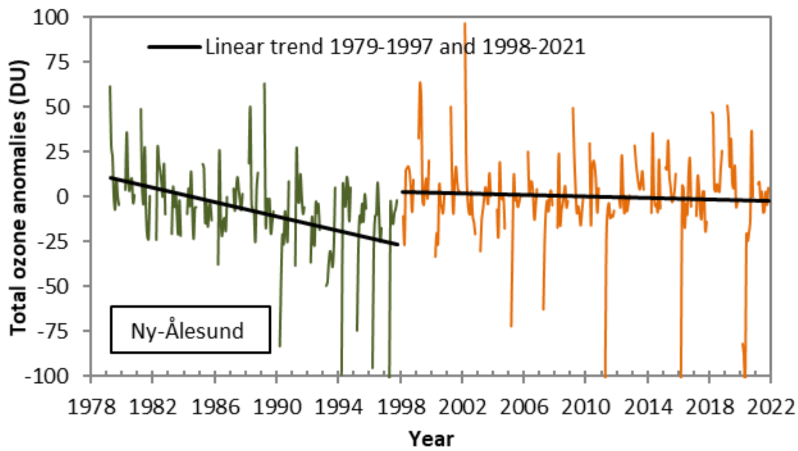

Figure 6b: Variations in total ozone at Ny-Ålesund for the period 1979–2021. Only data for the months March–October are included. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments. Trends for the two periods are marked as black lines.

Table 6: Percentage changes in total ozone (per decade) in Ny-Ålesund for the periods 1) 1979-1997, and 2) 1998- 2021. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	*Trend (%/decade) 1979-1997*	*Trend (%/decade) 1998-2021*
Spring (Mar – May)	-10.8 (1.7)	-0.7 (1.8)
Summer (Jun – Aug)	-2.4 (1.2)	-0.9 (0.7)
Fall (Sep – Oct)	-1.2 (1.0)	1.4 (1.0)
Annual (Mar – Oct)	-5.9 (1.1)	-0.4 (1.0)

2.5 The overall Norwegian ozone situation in 2021

The overall ozone situation in 2021 was very different from that in 2020. Total ozone columns over the northern polar regions were exceptionally low in winter and spring of 2020 (Lawrence et al., 2020). The average total ozone value for February to April 2020 was ~100 DU below the mean of measurements between 1979 and 2019, and the lowest value since the start of satellite measurements in 1979. The low total ozone values were caused by an exceptionally strong, cold, and persistent stratospheric polar vortex, which provided ideal conditions for the formation of polar stratospheric clouds (PSCs) and chemical ozone destruction (Goutail et al., 2020; Manney et al., 2020; Wohltmann et al., 2020). The chemical processes that drive ozone depletion in the polar stratosphere are initiated at temperatures below ~195 K (−78°C) at 15 to 25 km altitude. These low temperatures lead to the formation of PSCs, which act as a catalyst to transform inactive forms of chlorine-containing substances into active, ozone-destroying chlorine species such as chlorine monoxide (ClO).

As mentioned above the situation in 2021 was in stark contrast to that of 2020. By mid-November 2020 the stratospheric temperatures in Arctic were low enough for PSC formation, and the activation of chlorine started in late November 2020. If these cold conditions had persisted until January, this could have led to large Arctic ozone depletion in spring 2021 similar to that observed in spring 2020. Instead, a major “Sudden Stratospheric Warming” (SSW) in early January 2021 warmed the stratosphere to temperatures at which active chlorine cannot be maintained. ClO concentrations subsequently declined to near-zero at the end of January 2021 as ClO was converted back to inactive forms of chlorine (Bernhard et al., 2022). The rapid drop in ClO halted further chemical ozone loss this winter and spring, and the early termination of chemical ozone loss in the lower stratosphere led to “normal” total ozone values over Norway most of the year 2021. An analysis of all SAOZ observations inside the Arctic polar vortex concluded that the cumulated ozone loss of the 2020/2021 winter was approximately 11%, in contrast to more than 30% in 2020 (Goutail et al., 2021).

Total ozone maps from WOUDC and Environment Canada, based on ground-based measurements and satellite observations, are shown in Figure 7 and demonstrate the difference between the ozone situation in 2020 and 2021. The upper figure shows the severe ozone depletion in the spring 2020, where the Arctic ozone column on 1 April 2020 was more than 50% below normal. The lower figure shows the situation from 1 April 2021 where the total ozone values were close to normal.

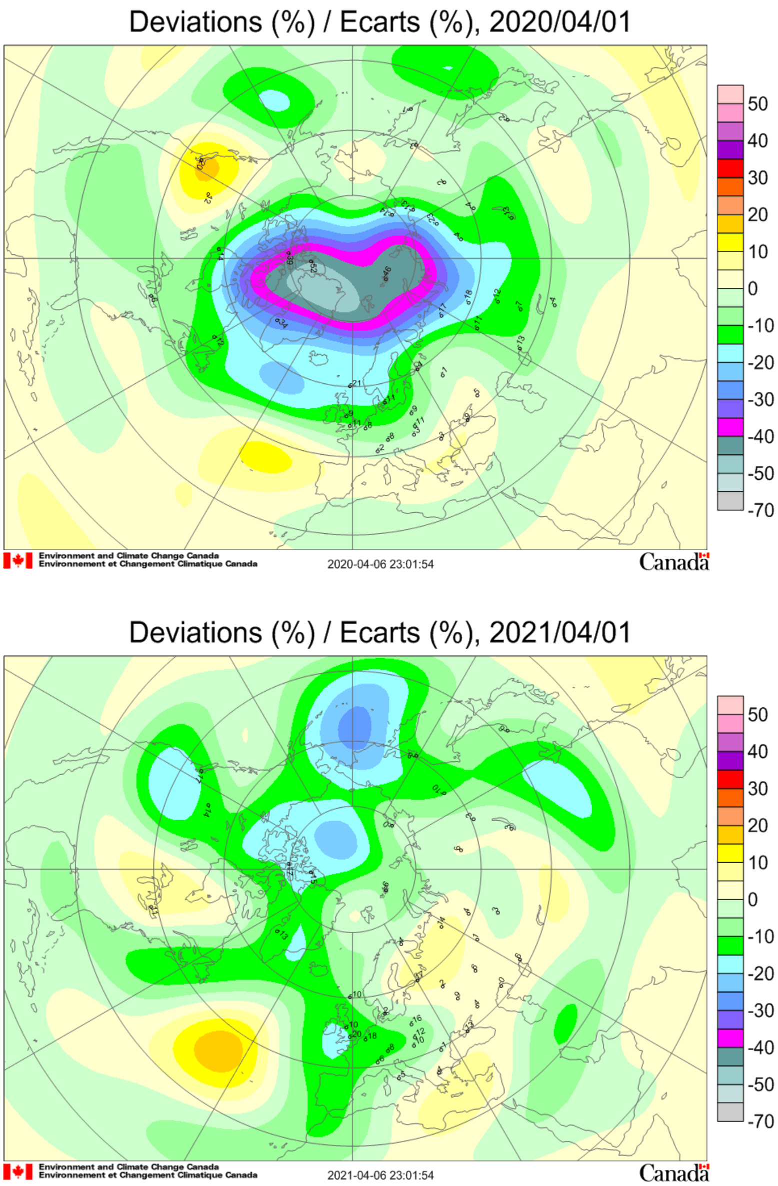

Figure 7: Total ozone from WOUDC and Environment Canada: 1 April 2020 (top) and 1 April 2021 (bottom). The maps are based on ground-based measurements and satellite observations (http://exp-studies.tor.ec.gc.ca/e/ozone/Curr_allmap_g.htm)

Table 7 summarizes the ozone situation for Norway in 2021 and gives the percentage difference between the monthly mean total ozone values in 2021 and the long-term monthly mean values at the three Norwegian sites. As seen from Table 7, 2021 was characterized by high or normal values in winter and spring, whereas the ozone layer was below normal in early summer. At all stations the average August values were higher (relative to long-term means) than the two previous and subsequent months.

Table 7: Percentage difference between the monthly mean total ozone values in 2021 and the long-term 1979-1989 average for Oslo/Kjeller, Andøya, and Ny-Ålesund.

Month	Kjeller (%)	Andøya (%)	Ny-Ålesund (%)
January	1.8		
February	2.3	9.4	1.7
March	-7.3	-1.0	-0.8
April	0.5	0.2	-4.2
May	-1.8	-1.9	0.4
June	-6.3	-6.8	-3.4
July	-4.3	-5.9	-1.2
August	1.9	-2.3	4.6
September	-5.8	-7.5	0.2
October	-5.7	-3.6	3.3
November	5.1		
December	0.3		

Figure 8, Figure 9 and Figure 10 show the percentage difference between yearly mean total ozone and the long-term yearly mean 1979-1989. The low values in 1992/1993 are partly related to the eruption of the Mount Pinatubo volcano at the Philippines in 1991.

Comparison of Figure 8, Figure 9 and Figure 10 shows that the ozone patterns at the three Norwegian sites have several similarities. At all sites high ozone values were measured in the end of the 1970s and in 2010, 2013 and 2015. Moreover, all sites had very low ozone values 1990-1997, in 2011 (roughly 6% below the long-term mean), and in 2020 (4-9% below the long-term mean). In the winter/spring of 1997, 2011 and 2020 there was a very strong and persistent polar vortex. This is clearly reflected by the low annual average total ozone values these years (Figure 10). In 2021 the annual ozone means were 1.7%, 3.4%, and 0.5% below the long-term means at Kjeller, Andøya, and Ny-Ålesund, respectively.

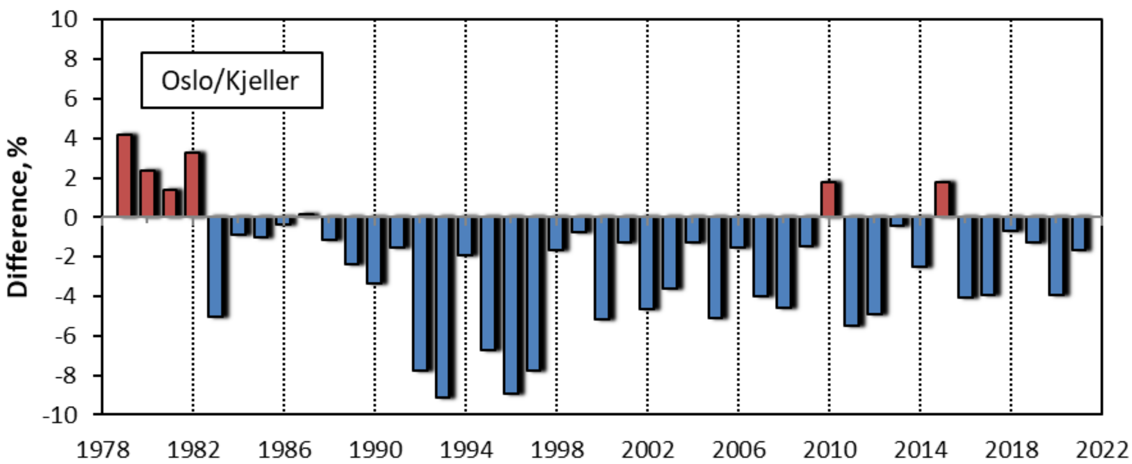

Figure 8: Percentage difference between yearly mean total ozone in Oslo/Kjeller and the long-term yearly mean 1979-1989.

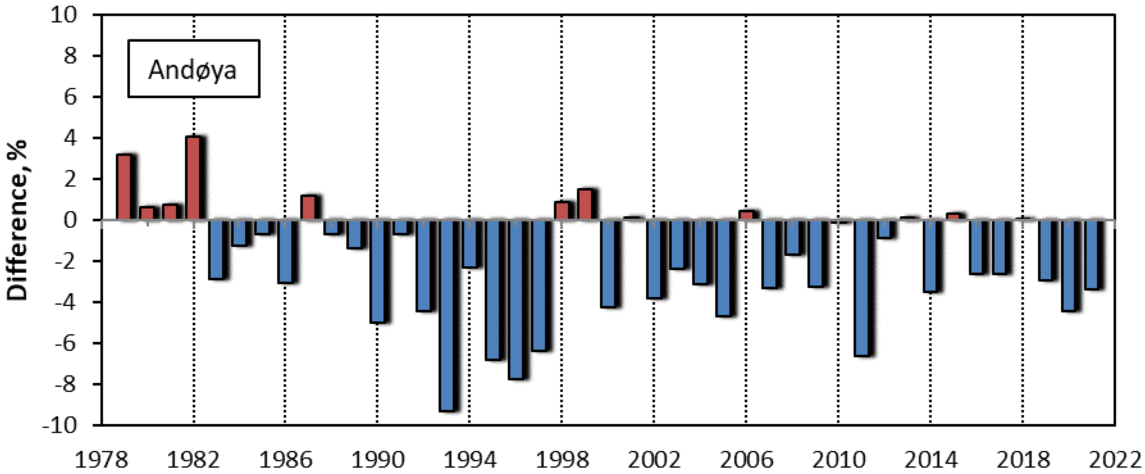

Figure 9: Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean1979-1989 for the months March-October.

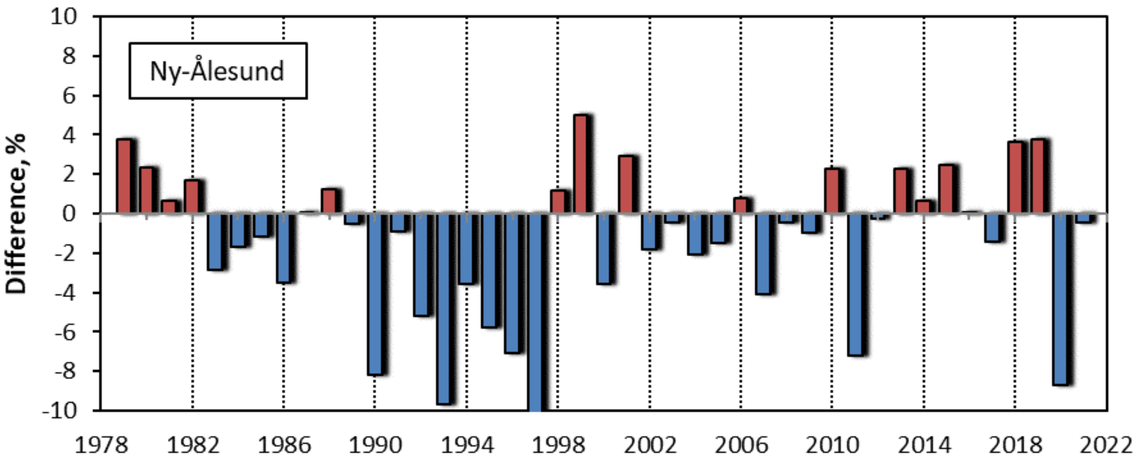

Figure 10: Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.

2.6 Ozone and UV measurements at Trollhaugen

In austral summer 2006/2007, NILU established an atmospheric monitoring station at the Norwegian Troll Station (72°01'S, 2°32'E, 1270 m a.s.l.). During the first years of operation the atmospheric station was located close to the main building of Troll, which caused frequent episodes of local pollution. In January 2014, the atmospheric monitoring station was moved uphill and about 2 km further away (to Trollhaugen), virtually eliminating the local pollution problem.

The instrumentation includes a NILU-UV instrument, which is NILU's own version of a six-channel broadband filter radiometer for the measurement of UV and visible radiation, comparable to the GUV filter instrument used in the Norwegian ozone and UV monitoring network. A detailed description of the instrument is given in Høiskar et al. (2003). Measurements of the first year of operation were published in Hansen et al. (2009). An analysis of total ozone measurements from Troll/Trollhaugen 2007-2018 has been published by Sztipanov et al., 2020.

The ozone and UV measurements at the Trollhaugen Station are not part of the Norwegian ozone and UV monitoring program, but are funded by the Norwegian Ministry of Climate and Environment. One of the goals of these measurements is to compare the development at high Southern latitudes with the situation in the Arctic. After 15 years of operation, the data set also gives valuable information about the long-term stability of the instrument. Unfortunately, NILU-UV no. 015 suffered a major technical failure in April/May 2015, and it had to be replaced with NILU-UV no. 005 in November 2015.

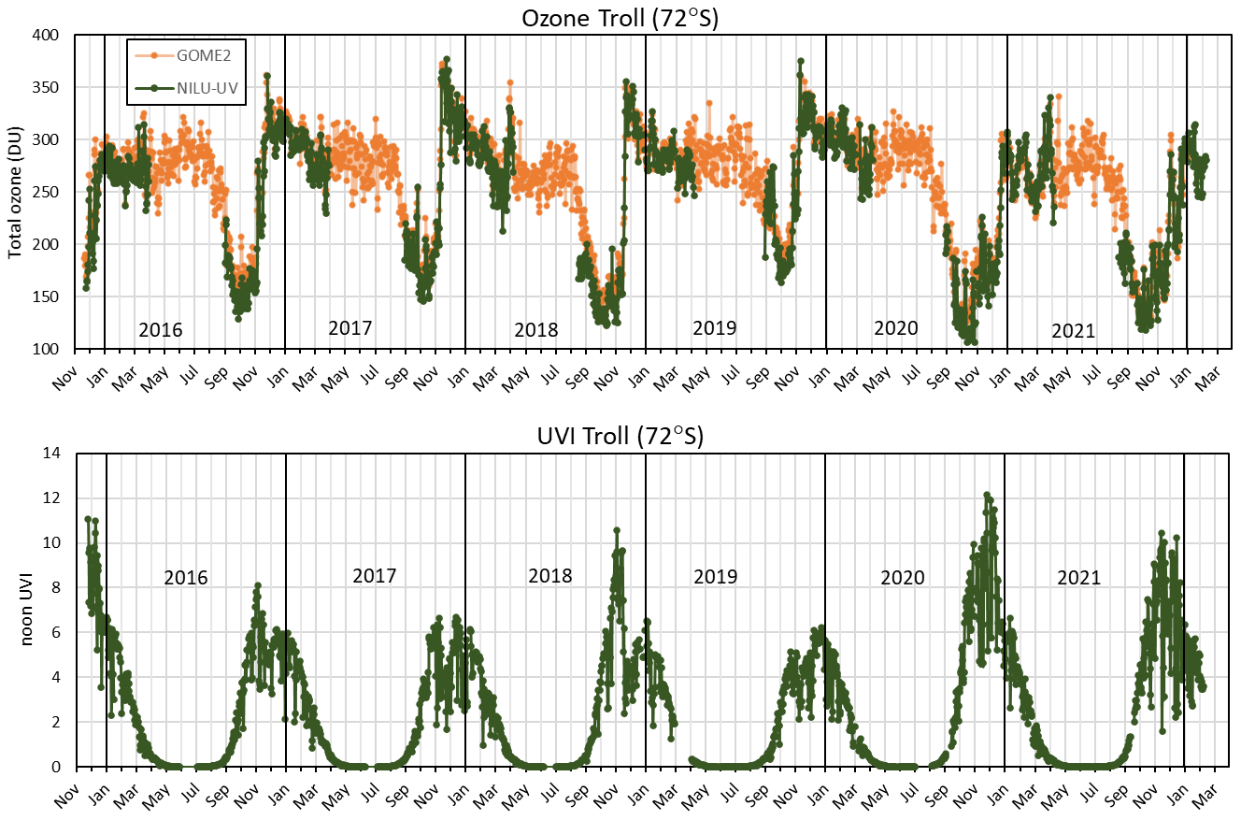

Figure 11: Upper panel: Total ozone from NILU-UV and GOME-2A from November 2015 to February 2021. Lower panel: Noon time UVI from NILU-UV 2015-2021

Figure 11, upper panel, shows NILU-UV total ozone values from Trollhaugen (green) and total ozone values from GOME-2a (orange) at the Sanae station about 190 km northwest of Troll. As seen, the Trollhaugen ground-based and satellite data are in good agreement.

In contrast to 2019, when unusual weather patterns in the upper atmosphere over Antarctica limited ozone depletion in September and October and resulted in the smallest ozone hole observed since 1982[3], the Antarctic ozone holes both in 2020 and in 2021 were strong and long-lasting. In fact, the lowest values recorded in 2020 were close to the all-time lows of the years 1990 and 2000, and during several days in November and December the depletion was the most severe ever recorded at this station. The Antarctic polar vortex did not break up until end of December in both years (Copernicus, 2021).

As mentioned above the austral spring/summer 2021 was another year with severe Antarctic ozone depletion, although not as dramatic as in 2020. A minimum ozone value of 118 DU was measured by the NILU-UV instrument on 10 October 2021.

[3] https://www.nasa.gov/feature/goddard/2019/2019-ozone-hole-is-the-smallest-on-record-since-its-discovery

The low total ozone values in the late austral spring season caused high UV levels in 2021, with a maximum UVI peak of 12.7 at the Trollhaugen station on 20 December 2021. This is an extremely high UVI, similar to the values normally measured in tropical regions during summer. This peak UVI value only lasted for a few minutes, and the highest noon UVI (1h average) was “only” 10.5 and was measured 18 November 2021.

The situation in 2020 and 2021 clearly shows that stratospheric ozone hole formation in Antarctica remains an environmental issue almost 40 years after its discovery and 30 years after the implementation of international regulatory measures. The CFC load in the stratosphere is still high, and depending on the meteorological conditions future ozone holes may remain severe for decades to come. However, the timing of the recovery of the ozone hole will probably not be significantly affected by increases in GHG concentrations. There are no substantial differences between Antarctic total ozone columns at the end of this century for the various GHG scenarios (WMO, 2018).

3 Satellite observations of total ozone

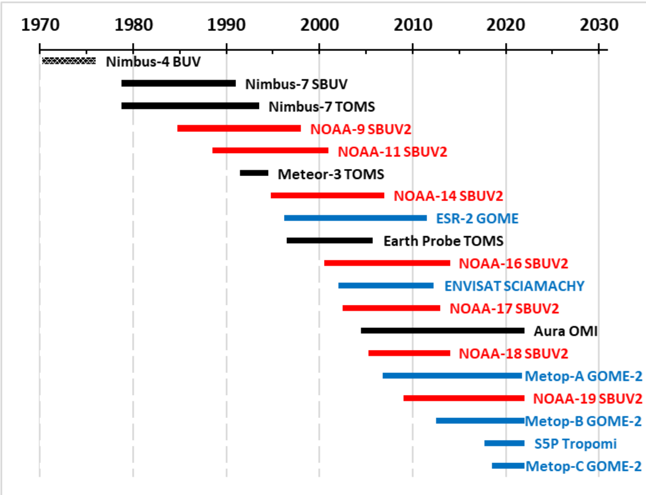

Figure 12: An overview of the most common satellites and their instruments measuring ozone from space since the beginning of the 1970's. NASA satellites are marked in black, ESA and EUMETSAT are in blue, whereas NOAA satellites are marked in red.

The amount and distribution of ozone in the stratosphere varies greatly over the globe and is mainly controlled by two factors: the fact that the maximum production of ozone takes place at approximately 40 km height in the tropical region, and secondly the large-scale stratospheric transport from the tropics towards the mid- and high latitudes. In addition, there are small-scale transport and circulation patterns in the upper troposphere/lower stratosphere (UTLS) region determining the daily ozone levels. Thus, observing ozone fluctuations over just one spot is not sufficient to give a precise description of the ozone situation in a larger region. Satellite observations are filling these gaps. However, satellite observations rely on proper ground-based monitoring as satellites have varying and unpredictable life times, and calibration and validation rely upon high-quality ground-based observations. Thus, satellite observations are complementary to ground-based observations, and both are highly necessary.

Observations of the seasonal, latitudinal, and longitudinal ozone distribution from space have been performed since the 1970s using a variety of satellite instruments. The American institutions NASA (National Aeronautics and Space Administration) and NOAA (National Oceanic and Atmospheric Administration) started these observations. In 1995, ESA (The European Space Agency) started their monitoring programme as the GOME instrument was launched on the ERS-2 platform/satellite. Figure 12 gives an overview of the various ozone measuring satellites and their time of operation.

3.1 Satellite total ozone observations 1979-2021

In the course of the last 43 years several satellites have provided ozone data for Norway. The most widely used instruments have been TOMS (onboard Nimbus-7 satellite), TOMS (onboard Meteor-3), TOMS (on Earth Probe), GOME I (on ESR-2), GOME-2 (on MetOp), SCIAMACHY (on Envisat), and OMI (onboard Aura). In the 1980s TOMS and SBUV instruments onboard the Nimbus 7 satellite were the only reliable ozone instruments in space, but in recent decades overlapping ESA and NASA satellite products have been available. Moreover, different ozone retrieval algorithms have been used over the years, which have gradually improved the quality of and confidence in ozone data derived from satellite measurements. Corrections for instrumental drift and increased knowledge of ozone absorption cross sections as well as latitude-dependent atmospheric profiles have improved the data quality, especially in the Polar regions.

The monthly mean ozone values from ground-based (GB) measurements and satellites are analysed for the full period 1979-2021. Figure 13 and Table 8 show the percentage GB-satellite deviation from Oslo/Kjeller (upper panel), at Andøya (centre panel) and in Ny-Ålesund (lower panel) for different satellite products. Monthly mean ozone values are calculated from days where simultaneous ground based and satellite data are available.

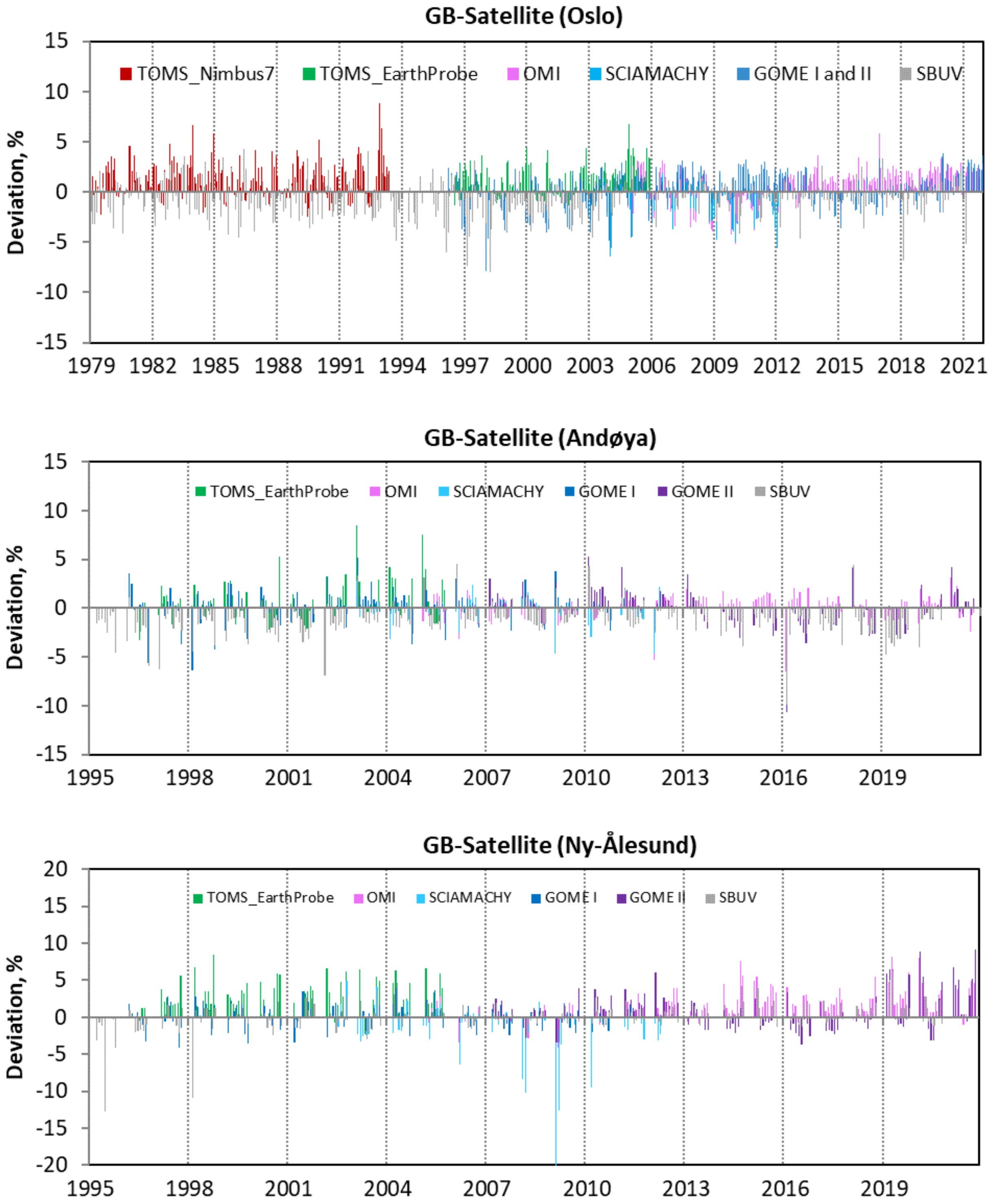

Figure 13: Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2021 (Oslo/Kjeller) and 1995-2021 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo/Kjeller, middle panel: Andøya, lower panel: Ny-Ålesund.

Table 8 gives an overview of the average deviations between ground-based ozone measurements and various satellite data products, together with standard deviations and variances for Oslo/Kjeller, Andøya and Ny-Ålesund. From this table, it is difficult to draw any conclusion as to which satellite instrument performs best compared to ground-based measurements. In Oslo/Kjeller and Andøya all GB-Satellite mean values are within ±1.3%, and the standard deviation is less than 2.1%. In Ny-Ålesund the GB-satellite deviations are generally slightly higher, but all satellite instruments (except SCIAMACHY) have a GB-satellite standard deviation below 2.5%. In general there is a good agreement between ground-based total ozone measurements and satellite retrievals.

Table 8: Average deviations in % between ground-based and satellite retrieved monthly mean ozone values from Oslo, Andøya and Ny-Ålesund. Standard deviation and variance are also included.

		Oslo/Kjeller			
Instrument	**Period**		**Mean**	**St. Dev**	**Variance**
TOMS (Nimbus 7)	Nov-78	May-93	1.3	1.9	3.5
TOMS (Earth probe)	Jul-96	Dec-05	1.3	1.5	2.3
OMI	Oct-04	Dec-21	0.6	1.9	3.7
GOME I	Mar-96	Jul-11	-0.5	2.1	4.5
GOME II	Jan-07	Dec-21	0.6	1.6	2.5
SCIAMACHY	Jul-02	Apr-12	-0.6	1.8	3.2
SBUV	Nov-78	Dec-20	-0.6	1.7	2.9
		Andøya			
Instrument	**Period**		**Mean**	**St. Dev**	**Variance**
TOMS (Earth probe)	Jul-96	Dec-05	0.8	2.0	4.0
OMI	Oct-04	Dec-21	0.2	1.3	1.8
GOME I	Mar-96	Jul-11	0.2	1.7	3.0
GOME II	Jan-07	Dec-21	-0.2	1.9	3.7
SCIAMACHY	Jul-02	Apr-12	-0.1	1.3	1.6
SBUV	Nov-78	Dec-20	-1.3	1.6	2.6
		Ny-Ålesund			
Instrument	**Period**		**Mean**	**St. Dev**	**Variance**
TOMS (Earth probe)	Jul-96	Dec-05	2.7	2.3	5.2
OMI	Oct-04	Dec-21	1.4	2.2	5.0
GOME I	Mar-96	Jul-11	0.1	1.7	2.9
GOME II	Jan-07	Dec-21	0.8	2.5	6.0
SCIAMACHY	Jul-02	Apr-12	-1.2	3.5	12.2
SBUV	Nov-78	Dec-20	0.1	2.0	3.9

4 The IPCC assessment reports: Climate and Ozone interactions

IPCC's 6th Assessment Report (AR6) addresses the most up-to-date physical understanding of the climate system and brings together the latest advances in climate science. The first part of AR6, *Climate Change 2021: The Physical Science Basis,* was published in August 2021 (IPCC, 2021).

Changes of the ozone layer will affect climate through the influence on the radiative balance and the stratospheric temperature gradients. In turn, climate change will influence the evolution of the ozone layer through changes in transport, chemical composition, and temperature (IPCC, 2013; 2021). Climate change and the evolution of the ozone layer are coupled and understanding of the processes involved is very complex as many of the interactions are non-linear.

Radiative forcing[4] (RF) is a useful tool to estimate the relative climate impacts due to radiative changes. The influence of external factors on climate can be broadly compared using this concept. Ozone is not emitted directly into the atmosphere but is formed by photochemical reactions. Tropospheric ozone RF is largely attributed to anthropogenic emissions of methane (CH_4), nitrogen oxides (NOx), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs), whereas stratospheric ozone RF is affected by ozone depletion from halocarbons.

Global-average radiative forcing estimates from the 5th IPCC assessment report (AR5) are shown in Figure 14 (IPCC, 2013). The estimates represent changes in energy fluxes caused by various drivers in 2011 relative to 1750. It shows how emitted compounds affect the atmospheric concentration of other substances. In AR5 the total radiative forcing from ozone changes was estimated to 0.35 W/m^2, with a RF due to tropospheric ozone increase of 0.40 W/m^2, and due to stratospheric ozone depletion of –0.05 W/m^2. In AR6 the radiative forcing from total ozone changes (both tropospheric and stratospheric) for the period 1750-2019 has increased to 0.47 W/m^2. The increased ozone RF in AR6 is partly caused by improved knowledge on pre-industrial emissions. There is no tropospheric-stratospheric separation of RF in AR6, but the tropospheric ozone RF is clearly dominating. It is interesting to note that Skeie et al. (2020) have reported a small positive RF of 0.02 W/m^2 for stratospheric ozone change. This is caused by an ozone depletion in the upper stratosphere, which contributes a *positive* radiative forcing.

In AR5 it was estimated that the emissions of Ozone-Depleting Substances (ODS; Halocarbons), with a subsequent stratospheric ozone loss, caused an ozone RF of –0.15 W/m^2. The assessment of RF from ODSs in AR6 indicates that the quantification of these terms may be more uncertain than the formulations in AR5. Thus, no such quantification is included in AR6.

Stratospheric ozone is indirectly affected by climate change through changes in dynamics and in the chemical composition of the troposphere and stratosphere (Denman et al., 2007). An increase in greenhouse gases, especially CO_2, will warm the troposphere and cool the stratosphere. In general, a decrease in stratospheric temperature reduces ozone depletion leading to a higher ozone column. However, there is a possible exception in the polar regions where lower stratospheric temperatures and increased stratospheric water vapour lead to more favourable conditions for the formation of more Polar Stratospheric Clouds (PSCs) (von der Gathen et al., 2021). These ice clouds are formed

[4] Radiative forcing (RF) or climate forcing is the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space. Positive radiative forcing means Earth receives more incoming energy from sunlight than it radiates to space. This net gain of energy will cause warming. Conversely, negative radiative forcing means that Earth loses more energy to space than it receives from the sun, which produces cooling. RF is expressed in Wm^{-2}.

when stratospheric temperature drops below -78ºC. Chemical reactions occurring on PSC particle surfaces can transform passive halogen compounds into active chlorine and bromine and cause massive ozone destruction. This is of particular importance in the Antarctic region. It should also be mentioned that ozone absorbs UV radiation and provides the heating responsible for the observed temperature inversion above the tropopause (creating the stratosphere). Changes in stratospheric temperature distribution, induced by changes in ozone or greenhouse gas concentrations will alter atmospheric dynamics.

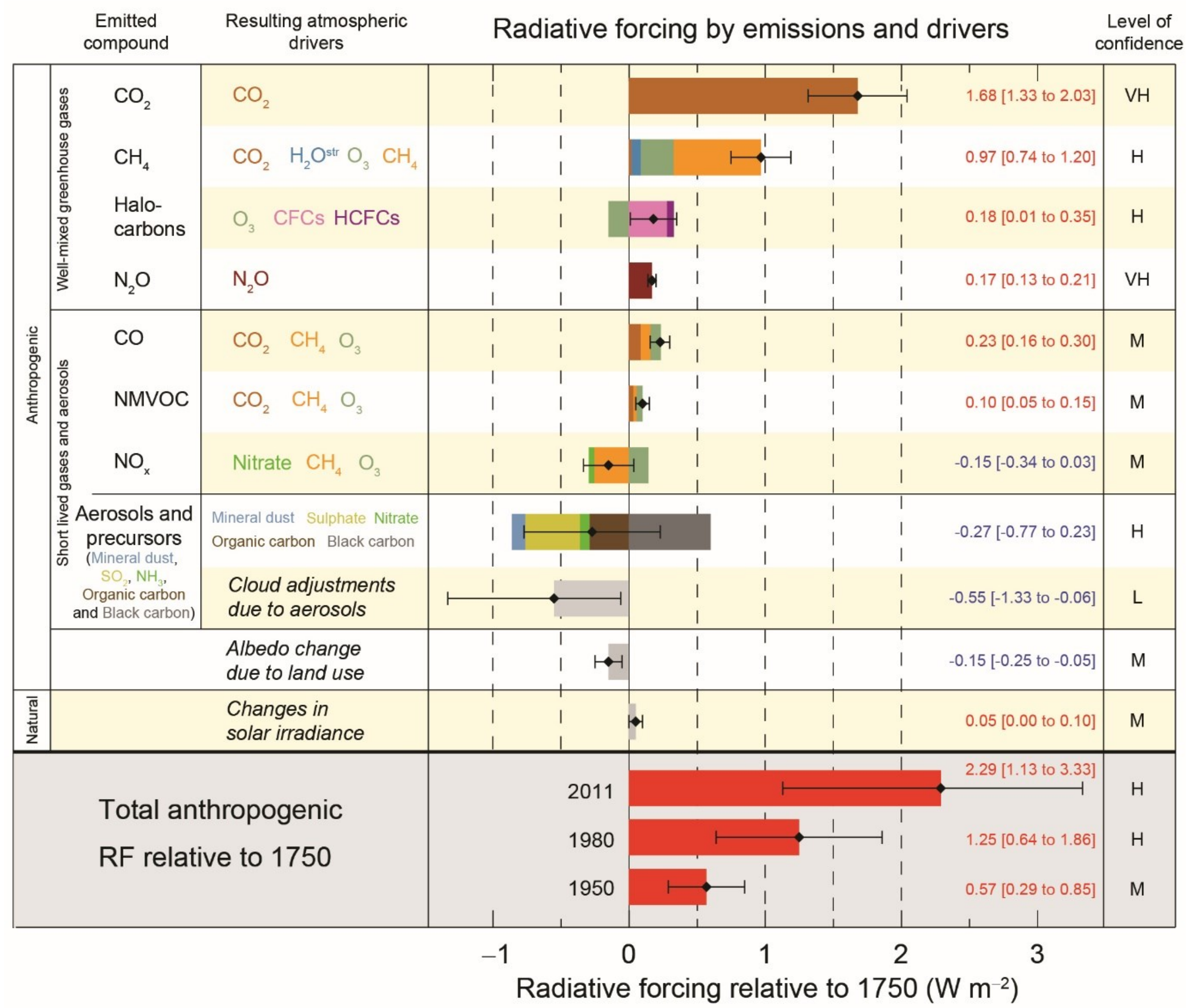

Figure 14: Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change. Values are global average radiative forcing, partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – very high, H – high, M – medium, L – low, VL – very low).

A long-term increase in stratospheric water content has been observed since the second half of the 20th century at the long-term observation site in Boulder (USA) (Oltmans et al., 1995; Lossow et al., 2018). The water vapour trends in the stratosphere is a widely discussed issue with satellite data indicating both positive and negative trends, depending on altitude range and data set selection (e.g. Hegglin et al, 2014; Lossow et al., 2018). Nevertheless, a recent study by Konopka et al. (2022) suggests that stratospheric water vapour increased in the northern hemisphere after 2000. An increase in stratospheric water vapor will influence the total ozone column, as stratospheric water vapour is among the main sources of OH in the stratosphere[5]. OH is one of the key species in the chemical cycles influencing ozone levels. There are several sources for stratospheric water, where CH_4 is the most important. Other water vapour sources are volcanoes and aircrafts, as well as natural and anthropogenic biomass burning which indirectly can influence stratospheric moisture content through cloud mechanisms (Andreae et al., 2004). The latter mechanism has gained further importance in recent years following the extended and severe forest and bushfire events in both boreal and tropical/sub-tropical regions (e.g. Peterson et al., 2018). In a recent publication, Solomon et al. (2022) hypothesize that severe biomass burning events like the extreme bushfires in Australia in austral summer 2019/2020 may slow the recovery of the ozone layer. In the 5th IPCC report it was estimated that the increase in stratospheric water vapour resulting from anthropogenic emissions of methane (CH_4) had a positive radiative forcing of 0.07 W/m^2 (see Figure 14). In AR6 an adjusted value of RF = 0.05 W/m^2 is estimated for stratospheric water vapor produced by CH_4 oxidation.

The overall impact of methane on ozone is very complex. According to AR5 increased total ozone concentrations from increased methane emissions are contributing a radiative forcing of 0.24 W/m^2. A study from Thornhill et al. (2021), referred to in AR6, indicates that the methane induced RF on total ozone might be slightly lower. One mechanism is that methane reacts with chlorine and converts active chlorine (Cl) to a reservoir species (HCl). In this way, stratospheric methane can prevent ozone destruction.

The evolution of stratospheric ozone in the decades to come will to a large extent depend on the stratospheric halogen loading. Halocarbons play a double role in the ozone-climate system. They are greenhouse gases and contribute to a strong positive radiative forcing of 0.41 W/m^2 (IPCC, 2021). In addition, chlorine and bromine containing compounds play a key role in ozone destruction processes. Since ozone itself is an important greenhouse gas, less ozone normally means a negative radiative forcing. In total, the negative RF due to ozone depletion from halocarbons will to some extent outweigh the positive RF they have induced. The positive RF from all halocarbons has increased since AR5, with a reduced RF from CFCs but an increased RF from most of their substitutes (e.g. HFCs).

Finally, nitrous oxide (N_2O) is considered as a key species that influences ozone concentrations. The photochemical degradation of N_2O in the middle stratosphere leads to ozone-depleting NOx, but in AR5 the impact of N_2O on ozone RF was set to zero. This was due to insufficient quantification of the N_2O influence and particularly the vertical profile of the ozone change (IPCC, 2013, Supplementary Material). According to AR6 increased nitrous oxide leads to ozone depletion in the upper stratosphere which will make a positive, but very small, contribution to the direct radiative forcing.

[5] *In the stratosphere, water vapour is oxidized by exited O atoms to produce OH (H20 + O(1D) -> 2OH). Next, the hydroxyl radical OH can react with O3, resulting in a loss of ozone.*

5 UV measurements

The Norwegian UV network was established in 1994/95 and consists of nine 5-channel GUV instruments located from 58°N to 79°N, as shown in Figure 15. NILU is responsible for the daily operation of three of the instruments located at Kjeller (60°N), at Andøya (69°N), and in Ny-Ålesund (79°N). The Norwegian Radiation and Nuclear Safety Authority (DSA) is responsible for the operation of the measurements performed in Trondheim, Bergen, Kise, Landvik, Finse, and Østerås. On-line data from the UV network are shown at https://uvnett.dsa.no/.

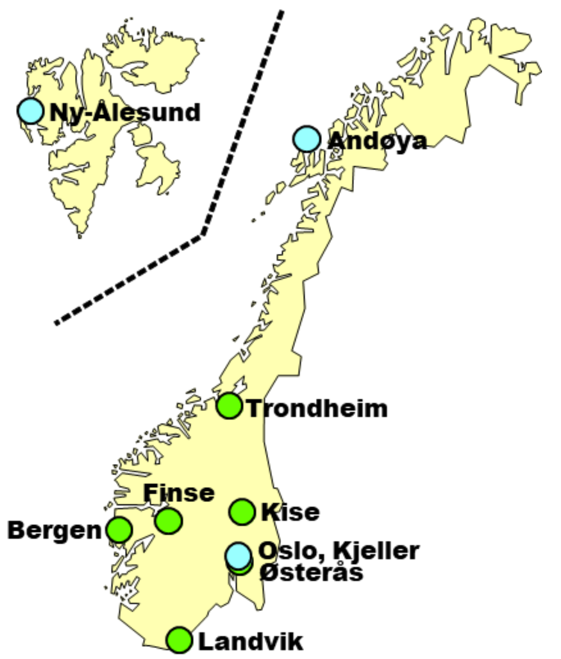

Figure 15: Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas DSA operates the stations marked with green.

This annual report includes results from Oslo/Kjeller, Andøya and Ny-Ålesund. Together with the Brewer instrument described in Section 1.1, the GUV instrument was moved from Blindern to Kjeller end of June 2019. The new station is located ~18km east of Blindern. It could also be mentioned that the GUV instrument in Ny-Ålesund was omitted from the monitoring programme for the period 2006-2009, but was included again in 2010. This resulted in gaps in the original UV time series from Ny-Ålesund. However, the GUV instrument has been logging continuously since 1995 and the measurements from 2006-2009 have been reanalysed and included in the UV time series.

The GUV instruments are normally easy to maintain and have few interruptions due to technical problems. However, the instruments have been in operation for 27 years and technical failures have occurred more frequently in recent years. Fortunately, the instruments at Kjeller, Andøya and Ny-Ålesund ran without major problems in 2021, except for some unknown stops/interruptions at Andøya that normally last for a few minutes or hours. The reason for these problems is still not fully known.

5.1 UV measurements in 2021

The UV dose rate is a measure of the total biological effect of UVA and UVB radiation (UV irradiance weighted by the CIE action spectra[6]). The unit for dose rate is mW/m^2 but is often given as a UV index (also named UVI). A UV index of 1 is equal to 25 mW/m^2. The concept of UV index is widely used for public information concerning sunburn potential of solar UV radiation. At Northern latitudes the UV indices typically vary between 0 – 7 at sea level, but can range up to 18 in Equatorial regions and high altitudes (WHO, 2009).

Table 9 shows the UV index with recommended sun protection at the different UV levels. The recommendations are based on a moderate light skin type, typical for Nordic population.

[6] CIE (Commission Internationale de l'Éclairage) action spectrum is a reference spectrum for UV induced erythema in human skin.

Figure 16 shows the UV dose rates measured at local noon (± 0.5 hour) at Kjeller (top), Andøya (middle) and in Ny-Ålesund (bottom) in 2021. The black curves in Figure 16 represent the UV measurements whereas the red curves are model calculations employing the measured ozone values, clear sky, and a surface albedo of 0.05. The black dotted lines represent modelled UVI for "normal" total ozone values and clear sky. The highest noon-time UV dose rate at Kjeller, 156.9 mW/m^2, was observed on 16 July 2021 and is equivalent to a UV index of 6.3. However, a peak UVI as high as 7.4 was observed on 27 June.

At Andøya the highest noon average UVI in 2021 was 4.9, equivalent to a dose rate of 122.0 mW/m^2 (observed on 4 July).

The highest noon average UVI in Ny-Ålesund in 2021 was 2.9, registered on 6 July, equivalent to 71.9 mW/m^2. The overall maximum UVI measured this year was 3.2 (observed on 1 June). Note that the modelled values (red curve) often are lower than the measured UV dose rates in the spring. This is caused by the low albedo used in the model simulations. Snow/ice in Ny-Ålesund from January to May will enhance the UV level significantly.

At all the Norwegian stations the maximum noon UVI values in 2021 were observed during days with relatively low ozone values. For these days of maximum UV, the total ozone columns at Kjeller, Andøya, and in Ny-Ålesund were 15%, 13%, and 6% below the long-term seasonal mean ozone values, respectively.

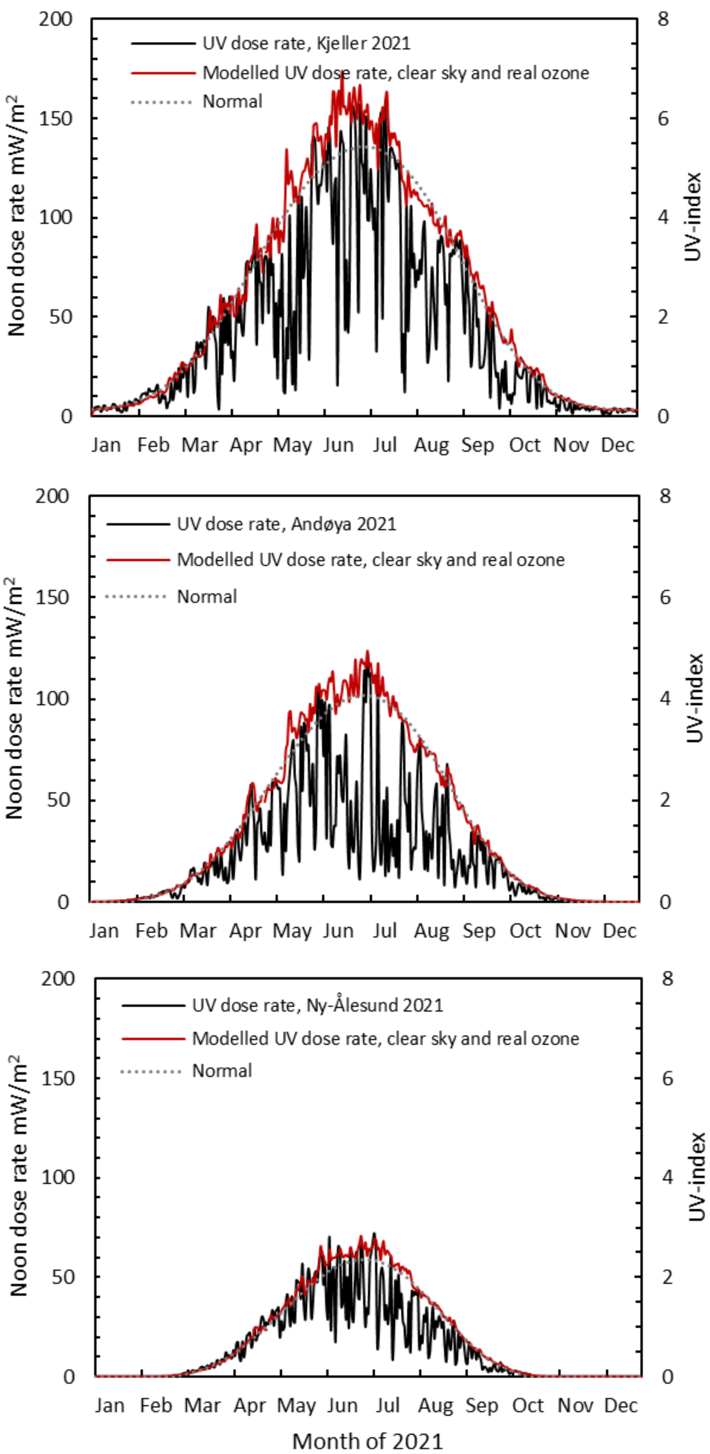

Figure 16: Hourly averaged UV dose rate measured at local noon (± 0.5 hour) in 2021. Upper panel: Kjeller. Middle panel: Andøya. Lower panel: Ny-Ålesund.

For UV levels corresponding to the maximum UVI value of 6.3 at Kjeller, people with a typical Nordic skin type get sunburnt after approximately 20 minutes if no sun protection is used.

Figure 17 shows the atmospheric conditions during the days of maximum UVI at Kjeller, at Andøya and in Ny-Ålesund. A cloud transmission (red curve) of 100% represents clear sky conditions. The cloud transmission can exceed 100% if the surface albedo is large and/or there are reflecting clouds in the sky that do not block the solar disc.

Table 9: UV index together with the recommended protection.

UV-Index	Category	Recommended protection
11+	Extreme	Extra protection is definitively necessary. Avoid the sun and seek shade.
10 9 8	Very high	Extra protection is necessary. Avoid the sun between 12 PM and 3 PM and seek shade. Use clothes, a hat, and sunglasses and apply sunscreen with high factor (15-30) regularly.
7 6	High	Protection is necessary. Take breaks from the sun between 12 PM and 3 PM. Use clothes, a hat, and sunglasses and apply sunscreen with high factor (15+).
5 4 3	Moderate	Protection may be necessary. Clothes, a hat and sunglasses give good protection. Don't forget the sunscreen!
2 1	Low	No protection is necessary.

As seen from Figure 17 (red curve, left panel) Kjeller had fairly clear sky on 16 July, probably with some haze or thin clouds early in the morning. This is evident from the relatively straight red curve and cloud transmission close to 100% after 8:00. At Andøya it was also clear sky most of the day, but thin clouds appeared in the afternoon and reduced the cloud transmission from 100% to ~80%. In Ny-Ålesund it was cloudy in the morning but cleared up around noon. The peak UVI just before noon was caused by scattered clouds This is seen from the "noisy" red curve in Figure 17 (right panel) and high cloud transmission around noon. The scattered clouds result in multiple reflections between the clouds, and between the ground and the clouds, which may enhance the UVI beyond clear-sky values. In Ny-Ålesund the cloud transmittance (CLT) had a peak value around 120% in the middle of the day. Such a high CLT is caused by both scattered clouds and snow/ice in the surroundings which enhance the UV.

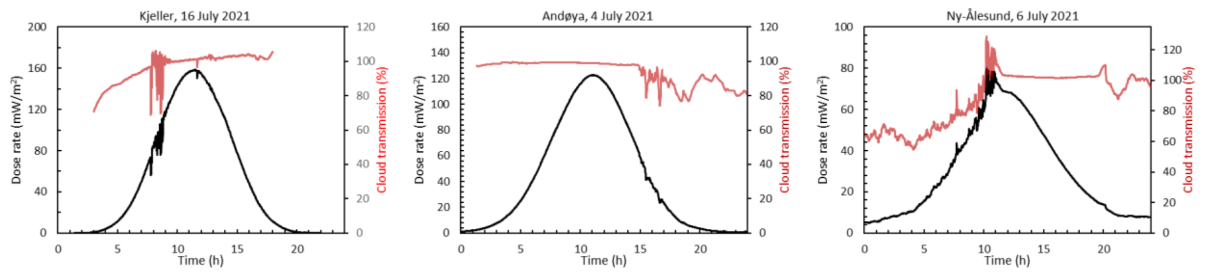

Figure 17: UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI at Kjeller (left panel), Andøya (middle panel) and Ny-Ålesund (right panel) in 2021. A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30% represent heavy clouds.

In Norway the highest UV dose rates generally occur in early summer in southern alpine locations with fresh snow, such as Finse. Here the UV indices at noon can reach 9. Many Norwegian citizens visit Mediterranean and other lower-latitude countries during holidays, and here the UV indices may easily become twice as high as in Norway. Also at the Trollhaugen station in Antarctica, the UVI can exceed 11 during ozone hole periods in November/December (Antarctic spring and early summer). As described in Section 2.6 the Antarctic ozone hole was exceptionally deep and long-lasting in 2021, and a UVI close to 12 was occasionally measured at Trollhaugen in early December 2021.

The seasonal variation in observed UV dose rate is closely related to the solar elevation. Consequently, the highest UV levels normally occur during the summer months when the solar elevation is highest. Also, the occurrence of fresh snow in late May and early June can enhance the UV-level and give exceptionally high UV values. In addition to the solar zenith angle, UV radiation is influenced by clouds, total ozone, aerosols, and surface reflectance (albedo). Day-to-day fluctuation in cloud cover is the main explanation for large daily variations in UV radiation. However, rapid changes in the total ozone column may also give rise to large fluctuations in the UV radiation. In general, the UV radiation in Ny-Ålesund is strongly enhanced during spring due to the high albedo from snow and ice surfaces that surround the measurement site.

Monthly integrated UV doses for Kjeller, Andøya and Ny-Ålesund in 2021 are compared in Figure 18. As expected, the monthly UV doses at Kjeller (60°N) were higher than the values observed at Andøya (69°N) and in Ny-Ålesund (79°N). If the cloud cover, albedo and ozone conditions are the same at all three sites, the UV radiation will be highest at Kjeller due to higher solar elevation at mid-day. Similar, the UV doses at Andøya will normally be higher than the doses in Ny-Ålesund. Thus, it is worth noting that the integrated UV dose at Andøya in June 2021 was below the Ny-Ålesund value. This was a result of many cloudy days at Andøya the summer 2021. As seen from Figure 16 (middle panel) the measured UV doses were far below the modelled clear-sky values in June.

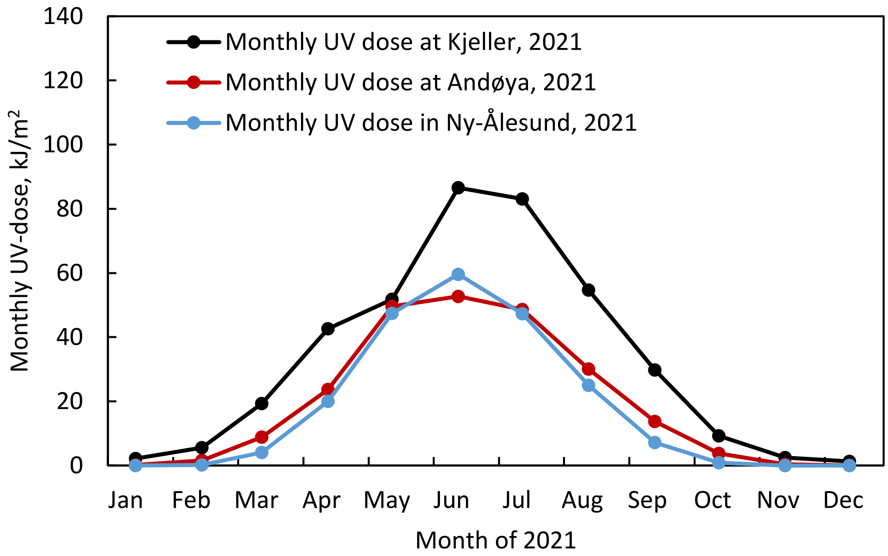

Figure 18: Monthly integrated UV doses (in kJ/m^2) in 2021 measured with the GUV instruments located at Kjeller, Andøya and in Ny-Ålesund.

5.2 Annual UV doses 1995-2021

Annual UV doses for the period 1995–2021 are shown in Table 10 for the GUV instruments in Oslo/Kjeller, at Andøya and in Ny-Ålesund. The UVI time series have been reanalysed using a statistical method from Bjørn Johnsen (DSA). Gaps in GUV measurements have been complemented with modelled values, based on cloud modification factors derived from synoptic cloud observations and pyranometer data from AWI (in Ny-Ålesund), from met.no at Blindern (for Kjeller GUV), and from Sortland (for Andøya GUV).

Uncertainty in the daily UV doses is estimated to ±5 % at a 2σ level (Johnsen et al., 2002). For periods with missing measurements, there is an additional uncertainty in annual integrated UV doses of ±1.6 % for all stations and years, except for Andøya where the uncertainty is ±2 % for 2000, and ±5 % for 2001 and 2011 when more than 12 days of measurements were missing. Also, all the annual integrated UV doses in 2005 and 2019, when calibration campaigns were arranged, have additional uncertainties of around ±5 %.

Table 10: Annual integrated UV doses (in kJ/m²) for Oslo/Kjeller, Andøya and Ny-Ålesund for the period 1995 – 2021.

Year	Oslo/Kjeller (kJ/m²)	Andøya (kJ/m²)	Tromsø (kJ/m²)*	Ny-Ålesund (kJ/m²)
1995	375.3			
1996	373.9		224.8	215.7
1997	400.9		247.4	215.0
1998	313.8		238.8	217.4
1999	355.3		224.5	184.2
2000	352.6	244.7		231.8
2001	359.7	231.5		211.3
2002	372.0	254.6		214.9
2003	364.0	247.8		184.3
2004	367.6	240.3		201.7
2005	367.4	248.0		210.0
2006	367.1	222.3		184.4
2007	354.9	254.7		218.7
2008	373.5	259.7		210.5
2009	367.7	259.6		230.4
2010	353.6	232.0		201.4
2011	355.7	256.6		217.1
2012	357.4	233.2		212.5
2013	360.0	245.8		179.4
2014	386.8	254.0		212.6
2015	357.2	223.3		214.8
2016	374.0	230.7		189.7
2017	359.1	264.7		207.2
2018	422.1	228.5		184.3
2019	359.1	252.7		203.6
2020	403.5	266.2		212.4
2021	388.5	233.0		211.4

*The GUV instrument at Andøya was operating in Tromsø during the period 1996 – 1999. The instrument in Oslo was moved to Kjeller in July 2019

The annual integrated UV doses in 2021 were not extreme in one or the other way. Compared to other years, the annual integrated UV dose at Kjeller was the one that stood out the most. The 2021 value of 388.5 kJ/m^2 was the 4th highest annual UV dose measured in Oslo/Kjeller since 1995. This is ~8% below the maximum value measured in 2018. At Andøya, where the summer 2021 was characterized by many cloudy days, the annual integrated UV dose was the 8th lowest registered, almost 17% below the maximum value from 1997 and 12% below the value from 2020. In Ny-Ålesund 2021 was an average year when it comes to UV doses. The annual dose of 211.4 kJ/m^2 is the 13th highest value measured in Ny-Ålesund and is around 9% below the peak value from year 2000.

Graphical presentations of the annual integrated UV doses from 1995 to 2021 are shown in Figure 19. For Oslo/Kjeller there is an increase of 2.2%/decade in the annual UV dose. For Andøya and Ny-Ålesund there is a negative trend of -1.8%/decade and -1.5%/decade, respectively.

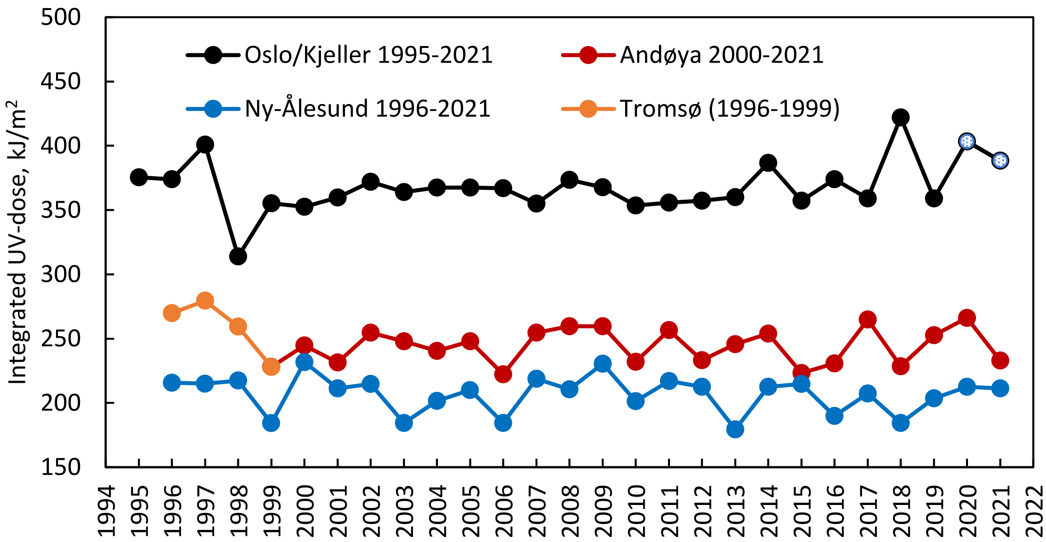

Figure 19: Annual integrated UV doses (in kJ/m^2) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995–2021.

The trend results (though not significant at a 2σ level) are related to changes in both ozone, cloudiness and albedo. It is worth noting that the UV trend at Andøya for the period 2000-2021 is close to zero. The negative UV trend of -1.8%/decade from 1996-2021 is caused by the high UV values measured the first few years when the GUV was located in Tromsø. At Andøya, the instrument is placed at the ALOMAR Observatory on the Ramnan Mountain ~400 m a.s.l. which is often covered by convective clouds approaching from the nearby ocean.

6 Appendix: Instrument description

The Norwegian ozone measurements are retrieved from Brewer spectrophotometers in Oslo/Kjeller and at Andøya, whereas a SAOZ **(**Systeme d'Analyse par Observation Zenitale) instrument is the standard ozone instrument in Ny-Ålesund. At all the three Norwegian sites GUV (Ground-based UltraViolet) filter radiometers are installed and can fill in ozone data gaps on days without Brewer and SAOZ measurements. Reidar Lyngra at Andøya Rocket Range is responsible for the daily inspection of the Brewer and GUV at ALOMAR, whereas staff at the Norwegian Polar Institute are doing daily inspections of the instruments at the Sverdrup station in Ny-Ålesund.

In the end of June 2019 the GUV and Brewer instruments at Blindern were moved to Kjeller and located at the roof of the NILU building (60.0°N, 11.1°E). This movement was due to the retirement of Prof. Arne Dahlback, Department of Physics, University of Oslo, and the decision of terminating total ozone and UV related activities at the department of Physics, UiO.

Brewer

In Oslo and at Kjeller, total ozone is primarily recorded with the Brewer MKV Spectrophotometer (B042). This instrument, which was installed at Blindern in 1990, was originally a Brewer MKIV single-monochromator. In 1998, the instrument was upgraded to the new MKV type with extended UV scanning range. This made the instrument more suitable for measurements at large solar zenith angles.

At Andøya, the total ozone values are based on Brewer direct-sun (DS) measurements when available, as in Oslo/Kjeller. For overcast days and days where the solar zenith angle is larger than 80° (sun lower than 10° above the horizon), the ozone values are based on the Brewer global irradiance (GI) method. The Brewer instrument at Andøya (B104) is a double monochromator MKIII, which allows ozone measurements at higher solar zenith angles than the Oslo instrument.

Every year the International Ozone Services (IOS), Canada, calibrate Brewer instrument no. 42 (Oslo/Kjeller) and no. 104 (Andøya) against a reference instrument, last time in May 2022. The Brewer instruments are also regularly calibrated against standard lamps in order to check the stability of the instruments. Calibration reports are available on request.

In October 2014, CNR-IDASC, Italy, and NILU signed a scientific agreement that give NILU access to the Italian Brewer (B50) measurements in Ny-Ålesund. The Brewer instrument was calibrated by IOS Canada in the summer 2015 and 2018, to ensure high quality ozone measurements. Unfortunately there have been some problems with B50 the last two years:

- In November 2018 IOS Canada (Volodya Savastiouk) made a visit to Ny-Ålesund to repair Brewer. The instrument had probably been subjected to a shock which displaced the diffraction grating.
- The Brewer Power supply broke in April 2019. A new one was installed by NILU in August 2019.
- In September 2019 it was discovered a problem with the thermostat which resulted in very high temperatures in the Brewer. The thermostat was disconnected to let Brewer operate without heaters. This is OK at moderate temperatures, but Brewer is switched off during the coldest periods.

GUV

The GUV instruments are produced by Biospherical Instruments Inc., USA, and the Norwegian instruments consist of two different types: GUV-511 operating in Oslo/Kjeller (serial number 9222) and GUV-541 operating at Andøya and in Ny-Ålesund (serial numbers 9276 and 9275, respectively). Every year the GUV's are compared with a travelling GUV reference instrument which is calibrated against the European reference spectro-radiometer QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe; Gröbner et al., 2010). Bjørn Johnsen at The Norwegian Radiation and Nuclear Safety Authority (DSA) coordinates the calibrations and reference measurements. He also calculates annual drift factors for the GUVs. The GUV instruments have also been a part of two major calibration campaign at DSA, the FARIN campaign in 2005 (Johnsen et al., 2008) and the QUASUME campaign in May/June 2019.

On days with absent GUV measurements a gap- filling procedure is used by DSA. Dose-products are reconstructed by modelling, applying total ozone data from overpass satellite data, cloud modification factors from available cloud coverage and pyranometer data, as well as the STRÅNG model from SMHI (http://strang.smhi.se/).

SAOZ

NILU's SAOZ instrument in Ny-Ålesund is located on the observation platform of the Sverdrup Station of the Norwegian Polar Institute. Measurements started in the fall 1990 and have continued until the present time with a few exceptions, one of which was repair and maintenance of the instrument during the winter of 2010/2011 at LATMOS/CNR. In October 2013, a temperature failure of the SAOZ instrument was discovered, caused by a broken electronic card, and the instrument was sent to LATMOS, France, for repair.

The SAOZ instrument is a zenith-sky UV-visible spectrometer where ozone is retrieved from the Chappuis bands (450-550 nm) absorption twice a day (sunrise/sunset). Data from the instrument contribute to the Network of Detection of Atmospheric Composition Change (NDACC). An ozone inter-comparison shows that different SAOZ instruments are consistent within 3%.

The SAOZ instrument is a very robust device, partly because it uses a differential method relative to a reference spectrum, which can be updated when necessary. After the major refurbishment in 2014 it turned out that a new reference spectrum was required. During a visit of G. Hansen at LATMOS in fall 2017 a new reference spectrum from 3 April 2017 was selected. This proved to be satisfactory also for measurements back to 2013. Simultaneously, all observations since 2000 have been re-analyzed with updated analysis parameters, as has been done with all instruments in the SAOZ network. By the end of 2017, the data from the Ny-Ålesund SAOZ were state-of-the-art in line with the other active instruments in this global network.

7 References

Andreae, M.O., Rosenfeld, D., Artaxo, P., Costa, A.A., Frank, G.P., Longo, K.M., Silva-Dias, M.A.F. (2004). Smoking rain clouds over the Amazon. *Science, 303*, 1337-1342.

Bernet, L., Svendby, T., Hansen, G., Orsolini, Y., Kylling, A., Dahlback, A., Goutail, F., Pazmiño, A., Petkov, B. (2022). Total ozone trends at three northern high-latitude stations. *In preparation.*

Bernhard, G. H., Fioletov, V. E., Grooß, J.-U., Ialongo, I., Johnsen, B., Lakkala, K., Manney, G. L., 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.

Bernhard, G. H., Fioletov, V. E., Grooß, J.-U., Ialongo, I., Johnsen, B., Lakkala, K., Manney, G. L., Müller, T.R., Svendby, T. (2022). Ozone and ultraviolet radiation [in "State of the Climate in 2021"]. *Bull. Amer. Meteor. Soc.,* submitted March 2022

Bojkov, R. D. and Balis, D. S. (2001). Characteristics of episodes with extremely low ozone values in the northern middle latitudes 1957−2000. *Ann. Geophys., 19*, 797–807. https://doi.org/10.5194/angeo-19-797-2001.

Copernicus Atmospheric Monitoring Service (2021). *The 2020 Antarctic Ozone Hole Season.* https://atmosphere.copernicus.eu/2020-antarctic-ozone-hole-season, 11 January 2021.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C., Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. In: *Climate Change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, H.L. Miller. Cambridge: Cambridge University Press. pp. 499-587.

Dessler, A. E., Schoeberl, M. R., Wang, T., Davis, S. M., Rosenlof, K. H., Vernier, J.-P. (2014). Variations of stratospheric water vapour over the past three decades. *J. Geophys. Res. Atmos., 119,* 12,588–12,598. https://doi.org/10.1002/2014JD021712.

Goutail, F., Pommereau, J.-P., Pazmino, A., Lefevre, F., Clerbaux, C., Boynard, A., Hadji-Lazaro, J., Chipperfield, M., Feng, W., Van Roozendael, M., Jepsen, N., Hansen, G., Kivi, R., Bognar, K., Strong, K., Walker, K. (2020). Total ozone loss during the 2019/20 Arctic winter and comparison to previous years, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-3571. https://doi.org/10.5194/egusphere-egu2020-3571.

Goutail, F., Pazmino, A., Pommereau, J.-P., Lefevre, F., Godin-Beekmann, S., Hauchecorne, A., Lecouffe, A., Clerbaux, C., Boynard, A., Hadji-Lazaro, J., Chipperfield, M., Feng, W., VanRoozendael, M., Jepsen, N., Hansen, G., Kivi, R., Bognar, K., Strong, K., Walker, K., and Colwell, S.: Evaluation of interannual variability of Arctic and Antarctic ozone loss since 1989, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12805- https://doi.org/10.5194/egusphere-egu21-12805.

Gröbner, J., Hülsen, G., Wuttke, S., Schrems, O., Simone, S. D., Gallo, V., Rafanelli, C., Petkov, B., Vitale, V., Edvardsen, K., Stebel, K. (2010). Quality assurance of solar UV irradiance in the Arctic. *Photochem. Photobiol. Sci., 9*, 384-391.

Hansen, G., Aspmo, K., Berg, T., Edvardsen, K., Fiebig, M., Kallenborn, R., Lunder, C.R., Stebel, K., Schmidbauer, N., Solberg, S., Wasseng, J.H., Yttri, K.E. (2009). Atmospheric monitoring at the Norwegian Antarctic station Troll: Measurement programme and first results. *Polar Research*, *28,* 353-363. https://doi.org/10.1111/j1751-8369.2009.00134x.

Hegglin, M. I., Plummer, D. A., Shepherd, T. G., Scinocca, J. F., Anderson, J., Froidevaux, L.,Funke, B., Hurst, D., Rozanov, A., Urban, J., von Clarmann, T., Walker, K.A., Wange, H.J., Tegtmeier, S., Weigel, K. (2014). Vertical structure of stratospheric water vapour trends derived from merged satellite data. *Nat. Geosci., 7,* 768. https://doi.org/10.1038/ngeo2236

Henriksen, T., Svendby, T. (1997). *Ozonlag, UV-stråling og helse.* Oslo: Department of Physics, University of Oslo.

Høiskar, B.A.K., Braathen, G.O., Dahlback, A., Bojkov, B.R., Edvardsen, K., Hansen, G., Svenøe, T. (2001). *Monitoring of the atmospheric ozone layer and natural ultraviolet radiation. Annual report 2000.* Kjeller: NILU (Statlig program for forurensningsovervåking. Rapport 833/01. TA-1829/2001) (NILU OR, 35/2001).

Høiskar, B.A.K, Haugen, R., Danielsen, T., Kylling, A., Edvardsen, K., Dahlback, A., Johnsen, B., Blumthaler, M., Schreder, J. (2003). Multichannel moderate-bandwidth filter instrument for measurement of the ozone-column amount, cloud transmittance, and ultraviolet dose rates. *Appl. Opt.*, *42*, 3472-3479. https://doi.org/10.1364/ao.42.003472.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. By T.F. Stocker et al. Cambridge: Cambridge University Press.

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. by: Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou. Cambridge: Cambridge University Press. In Press.

Johnsen, B., Mikkelborg, O., Hannevik, M., Nilsen, L.T., Saxebø, G., Blaasaas, K.G. (2002). *The Norwegian UV-monitoring program, period 1995/96 to 2001.* Østerås: Statens strålevern (Strålevern Rapport 2002:4).

Johnsen, B., Kjeldstad, B., Aalerud, T.N., Nilsen, L.T., Schreder, J., Blumthaler, M., Bernhard, G., Topaloglou, C., Meinander, O., Bagheri, A., Slusser, J.R., Davis, J. (2008). Intercomparison and harmonization of UV index measurements from multiband filter radiometers. *J. Geophys. Res. 113, D15206*. https://doi.org/10.1029/2007JD009731.

Lawrence, Z. D., Perlwitz, J., Butler, A. H., Manney, G. L., Newman, P. A., Lee, S. H., Nash, E. R. (2020). The remarkably strong Arctic stratospheric polar vortex of winter 2020: Links to record-breaking Arctic oscillation and ozone loss. *J. Geophys Res. Atmos, 125*, e2020JD033271, https://doi.org/10.1029/2020JD033271.

Konopka, P., Tao, M., Ploeger, F., Hurst, D. F., Santee, M. L., Wright, J. S., & Riese, M. (2022). Stratospheric moistening after 2000. *Geophysical Research Letters*, 49, e2021GL097609. https://doi.org/10.1029/2021GL097609

Lossow, S., Hurst, D. F., Rosenlof, K. H., Stiller, G. P., von Clarmann, T., Brinkop, S., Dameris, M., Jöckel, P., Kinnison, D. E., Plieninger, J., Plummer, D. A., Ploeger, F., Read, W. G., Remsberg, E. E., Russell, J. M., Tao, M. (2018). Trend differences in lower stratospheric water vapour between Boulder and the zonal mean and their role in understanding fundamental observational discrepancies. *Atmos. Chem. Phys., 18,* 8331–8351. https://doi.org/10.5194/acp-18-8331-2018.

Manney, G. L., Livesey, N. J., Santee, M. L., Froidevaux, L., Lambert, A., Lawrence, Z. D. Millan, L. F., Neu, J. L., Read, W. G., Schwartz, M. J., Fuller, R. A. (2020). Record-low Arctic stratospheric ozone in 2020: MLS observations of chemical processes and comparisons with previous extreme winters. *Geophys. Res. Lett., 47,* e2020GL089063. https://doi.org/10.1029/2020GL089063.

Montzka, S. A., Dutton, G. S., Yu, P., Ray, E., Portmann, R. W., Daniel, J. S., Kuijpers, L., Hall, B. D., Mondeel, D., Siso, Nance, J. D., Rigby, M., Manning, A. J., Hu, L., Moore, F., Miller, B. R., Elkins, J. W. (2018). An unexpected and persistent increase in global emissions of ozone-depleting CFC-11. *Nature, 557,* 413-417.

Myhre, C. L., Svendby, T., Hermansen, O., Lunder, C., Platt, S., Fiebig, M., Fjæraa, A. M., Hansen, G., Schmidbauer, N., Krognes, T. (2020). *Monitoring of greenhouse gases and aerosols at Svalbard and Birkenes in 2019 - Annual report.* Kjeller: NILU (NILU report, 16/2020).

Oltmans, S.J., and D.J. Hofmann (1995). Increase in lower-stratospheric water vapor at a midlatitude N.H. site from 1981 to 1994. *Nature, 374,* 146-149.

Park, S., Western, L. M., Saito, T., Redington, A., Henne, S., Fang, X., Prinn, R. G., Manning, A. J., Montzka, S. A., Fraser, P. J., Ganesan, A. L., Harth, C. M., Kim, J., Krummel, P. B., Liang, Q., Mühle, J., O'Doherty, S., Park, H., Park, M-K., Reimann, S., Salameh, P. K., Weiss, R. F., Rigby, M. (2021). A decline in emissions of CFC-11 and related chemicals from eastern China. *Nature, 590*(7846), 433-437. https://doi.org/10.1038/s41586-021-03277-w

Peterson, D.A., Campbell, J.R., Hyer, E.J., Fromm, M.D.,Kablick III, G.P., Cossuth, J.H., DeLand, M.T. (2018). Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke. *npj Clim. Atmos. Sci., 1,* 30. https://doi.org/10.1038/s41612-018-0039-3.

Rigby, M., Park, S., Saito, T., Western, L. M., Redington, A. L., Fang, X. , Henne, S., Manning, A. J., Prinn, R. G., Dutton, G. S., Fraser, P. J., Ganesan, A. L., Hall, B. D., Harth, C. M., Kim, J., Kim, K.-R., Krummel, P. B., Lee, T., Li, S., Liang, Q., Lunt, M. F., Montzka, S. A., Mühle, J., O'Doherty, S., Park, M.-K., Reimann, S., Salameh, P. K., Simmonds, P., Tunnicliffe, R. L., Weiss, R. F., Yokouchi, Y., Young, D. (2019). Increase in CFC-11 emissions from eastern China based on atmospheric observations. *Nature*, *569*, 546-550. https://doi.org/10.1038/s41586-019-1193-4.

Skeie, R. B., Myhre, G., Hodnebrog, Ø., Cameron-Smith, P.J., Deushi, M., Hegglin, M.I., Horowitz, L.W., Kramer, R.J., Michou, M., Mills, M.J., Olivié, D.J., O'Connor, F.M., Paynter, D., Samset, B.H., Sellar, A., Shindell, D., Takemura, T., Tilmes, S., Wu, T. (2020). Historical total ozone radiative forcing derived from CMIP6 simulations. *Npj Clim. Atmos. Sci., 3,* 32, https://doi.org/10.1038/s41612-020-00131-0

Solomon, S. (1991). Stratospheric ozone depletion: A review of concepts and history (1999). *Rev. Geophys., 37,* 275-316, https://doi.org/10.1029/1999RG900008.

Solomon, S., Dube, K., Stone, K., Yu, P., Kinnison, D., Toon, O.B., Strahan, S:E:, Rosenlof, K.H., Portman, R., Davis, S., Randel, W., Bernath, P., Boone, C., Bardeen, C.G., Bourassa, A., Zawada, D., Degenstein, D. (2022). On the stratospheric chemistry of midlatitude wildfire smoke. *Proc. Nat. Acad. Sci., 119,* e2117325119. https://doi.org/10.1073/pnas.2117325119.

Stamnes, K., Slusser, J., Bowen, M. (1991). Derivation of total ozone abundance and cloud effects from spectral irradiance measurements. *Appl. Opt.*, *30*, 4418-4426.

Sztipanov, M., Tumeh, L., Li, W., Svendby, T., Kylling, A., Dahlback, A., Stamnes, J., Hansen, G.H., Stamnes, K. (2020). Ground-based measurements of total ozone column amount with a multichannel moderate-bandwidth filter instrument at the Troll research station, Antarctica. *Appl. Opt., 59*, 97-106. https://doi.org/10.1364/AO.59.000097.

Thornhill, G. D., Collins, W. J., Kramer, R. J., Olivié, D., Skeie, R. B., O'Connor, F. M., Abraham, N. L., Checa-Garcia, R., Bauer, S. E., Deushi, M., Emmons, L. K., Forster, P. M., Horowitz, L. W., Johnson, B., Keeble, J., Lamarque, J.-F., Michou, M., Mills, M. J., Mulcahy, J. P., Myhre, G., Nabat, P., Naik, V., Oshima, N., Schulz, M., Smith, C. J., Takemura, T., Tilmes, S., Wu, T., Zeng, G., and Zhang, J. (2021). Effective radiative forcing from emissions of reactive gases and aerosols – a multi-model comparison. *Atmos. Chem. Phys., 21,* 853–874. https://doi.org/10.5194/acp-21-853-2021.

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.

von der Gathen, P., Kivi, R., Wohltmann, I., Salawitch, R. J., Rex, M. (2021). Climate change favours large seasonal loss of Arctic ozone. *Nat. Commun., 12,* 3886. https://doi.org/10.1038/s41467-021-24089-6

WHO (2009). *Ultraviolet radiation and human health.* Geneva: World Health Organization (Fact Sheet No 305). http://www.who.int/mediacentre/factsheets/fs305/en/index.html.

WMO (2018). *Scientific assessment of ozone depletion: 2018*. Geneva: World Meteorological Organization (Global Ozone Research and Monitoring Project-Report No. 58).

Wohltmann, I., von der Gathen, P., Lehmann, R., Maturilli, M., Deckelmann, H., Manney, G. L., Davies, J., Tarasick, D., Jepsen, N., Kivi, R., Lyall, N., Rex, M. (2020). Near-complete local reduction of Arctic stratospheric ozone by severe chemical loss in spring 2020. *Geophys. Res.Lett., 47,* e2020GL89547. https://doi.org/10.1029/2020GL089547.

NILU – Norwegian Institute for Air Research

NILU – Norwegian Institute for Air Research is an independent, nonprofit institution established in 1969. Through its research NILU increases the understanding of climate change, of the composition of the atmosphere, of air quality and of hazardous substances. Based on its research, NILU markets integrated services and products within analyzing, monitoring and consulting. NILU is concerned with increasing public awareness about climate change and environmental pollution.

NILU's values: *Integrity - Competence - Benefit to society*
NILU's vision: *Research for a clean atmosphere*

NILU – Norwegian Institute for Air Research
P.O. Box 100, NO-2027 KJELLER, Norway

E-mail: nilu@nilu.no
http://www.nilu.no

ISBN: 978-82-425-3094-3
ISSN: 2464-3327

Norsk institutt for luftforskning
Norwegian Institute for Air Research