Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual Report 2022

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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 2022 was characterized by annual average total ozone values slightly below “normal”.

NORWEGIAN TITLE

Overvåking av ozonlaget og naturlig ultrafiolett stråling: Årsrapport 2022.

KEYWORDS

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UV radiation
UV-stråling

Measurements and observations
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Montreal protocol
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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 2022 var karakterisert ved ozonverdier litt under langtidsgjennomsnittet.

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Contents

Summary

This report summarises activities and results from the ozone and UV monitoring programme in 2022. It includes total ozone trend analyses for the period 1979-2022 and UV measurements in Oslo and Kjeller, at Andøya and in Ny-Ålesund for the period 1995-2022. 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 2022

- **A strong Arctic polar vortex, which is known to cause low total ozone values, was established in late 2021 and lasted throughout March 2022. Despite the strong vortex the overall ozone loss in 2022 was much smaller than that in 2020 and was to a large extent located in the lower stratosphere at latitudes around 15 km.**
- **The total ozone values were below the long-term means during spring and summer at all stations, but above the long-term mean in the fall. In February the average ozone value in Ny-Ålesund was as much as 12.5% below the long-term mean.**
- **At all Norwegian monitoring stations, a significant stratospheric ozone decrease was recorded for the period 1979 to 1997. For the period 1998 to 2022, there were no significant trends in the ozone layer above Norway.**
- **The annual integrated UV dose at Kjeller in 2022 was the second highest ever registered. At Andøya and in Ny-Ålesund the annual UV doses were slightly below the 1995 to 2022 average.**
- **Meteorological variability has a large impact on ozone and UV and can give considerable year-to-year variations.**

Total ozone

Past emissions of chlorine-containing substances such as chlorofluorocarbons (CFCs) resulted in substantial depletion of stratospheric ozone. Ozone destruction in Polar regions occurs within a cold stratospheric cyclone, the polar vortex, which forms over the North Pole every year during winter. The polar vortex was very cold from December 2021 to March 2022, providing favourable conditions for Polar Stratospheric Cloud (PSC) formation and ozone-destroying species such as chlorine monoxide (ClO). However, the overall ozone loss in 2022 was considerable smaller than in the record year 2020 and was to a large extent located in the lower stratosphere (15 to 20km). Altogether, the below-average ozone concentrations in the lower stratosphere after mid-February 2022 contributed to low total ozone values over Norway in the spring.

The total ozone values remained low at all Norwegian stations throughout the summer, and in June 2022 the total ozone values were 3 to 8% below the long-term means. Usually, such deviations in summer are caused by dynamical conditions in the upper-troposphere-lower stratosphere (UTLS) region, where a high tropopause altitude correlates with reduced total ozone. Certain weather conditions, like stable high-pressure systems favour this situation. In total, the 2022 annual ozone averages were 1.1%, 4.6%, and 2.7% below the long-term means at Kjeller, Andøya, and in Ny-Ålesund, respectively.

Because of atmospheric circulation, the ozone layer above Norway is normally thickest in late winter and spring, whereas the lowest values occur in October to November. At Kjeller, a minimum ozone value of 240 Dobson units (DU) was measured 30 October 2022. This is 18% below the long-term mean for October. At Andøya, the minimum ozone value measured by the ground-based instruments was

230 DU (19 October), which is ~19% below the long-term mean for this month. Also, a spring-time ozone minimum of 281 DU was measured 11 March, ~31% below the long-term average March value. In Ny-Ålesund a local minimum ozone value of 293 DU was measured the same day (11 March). This is 31% below the long-term average value for March in Ny-Ålesund.

The monitoring programme and trend analyses show that minimum average ozone levels over Norway were reached in the mid-1990s. During the period 1979 to 1997, the annual average ozone layer above Oslo and Andøya decreased by 5-6%/decade and as much as 8% per decade during spring. For Ny-Ålesund, the decrease was even larger: 6%/decade for annual means and 11% per 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 2022 was 6.8, measured on 30 June. However, a peak UVI of 7.3 was measured on 1 July. UVI values around 7 are not very unusual in Southern Norway on sunny days in late June and early July. At Andøya, the highest noon average UV index in 2022 was 4.7, observed on 28 June. In Ny-Ålesund, a maximum noon average UVI of 2.8 was observed on 5 July, but a peak value of 3.3 was registered the same day. The values from Andøya and Ny-Ålesund are typical for low and high Arctic latitudes, respectively.

In 2022, the annual integrated UV dose at Kjeller was 403.9 kJ/m^2, which is the 2nd highest annual UV dose measured in Oslo or Kjeller since 1995 and roughly 4% below the maximum value from 2018. At Andøya, where the summer 2022 was characterized by relatively many cloudy days, the annual integrated UV dose was the 11th lowest registered, around 15% below the maximum value from 1997 and 4% below the long-term mean value. In Ny-Ålesund 2022 was a below average year when it comes to integrated UV doses. The annual dose of 200.7 kJ/m^2 is the 7th lowest value measured in Ny-Ålesund and is around 13% below the peak value from year 2009 and 3% below the 1996 to 2022 mean value.

Trend analyses indicate that the annual average UV dose has increased by 2.8% per decade in Oslo and Kjeller from 1995 until 2022. Contrary to Oslo/Kjeller, trends of -1.5% per decade and -1.0% per 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, stratospheric ozone decreased dramatically. The main reason for this decrease was anthropogenic release of ozone depleting substances (ODSs), especially chlorofluorocarbons (CFCs). The Montreal Protocol was signed by several countries in 1987, with the goal of eliminating and preventing the emission of ODSs. This international treaty has 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.

Signs of ozone recovery are visible, but it should be noted 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 11% from the peak value in the 1990s (WMO, 2022). Therefore, it is crucial to follow the development of the ozone layer 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 production of CFC-11 from Eastern China, strongly inconsistent with the Montreal Protocol agreement and illegal under Chinese law. 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 pre2013 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 (WMO, 2022).

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. A decrease in stratospheric temperature slows down the gas-phase ozone destruction reactions, leading to less depletion and higher ozone column values. 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) (WMO, 2022; von der Gathen et al., 2021). Chemical reactions on the PSC particle surfaces can transform passive halogen compounds into active chlorine and bromine, and consequently destroy ozone. 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: 2022 (WMO, 2022), Northern Hemisphere total ozone is expected to return to 1980 abundances around 2035, Southern Hemisphere (60°S to 35°S) around 2045, whereas the Antarctic ozone hole is expected to gradually close and return to 1980 values around 2065. The Arctic springtime total ozone is expected to return to 1980 values around 2045, but substantial ozone loss will occur in cold winters and springs while ODS concentrations are well above natural levels. These projections are based on full compliance with the Montreal Protocol and the baseline estimate of the future evolution of GHGs (SSP2-4.5).

The national monitoring programme

To follow up the Montreal Protocol at the national level, the Norwegian Environment Agency established the programme "Monitoring of the atmospheric ozone layer" in 1990. The climate and environmental research institute NILU has been responsible for the operation and maintenance of the monitoring programme. Three sites are included in the programme: 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). When referring to time series where both the Oslo and Kjeller sites are included, this is referred to as Oslo/Kjeller

The present report belongs one 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), since they are also strong greenhouse gases, an activity closely related to the total ozone and UV monitoring programme presented in this report.

Summary of total ozone and UV key results, standard deviations in parentheses:

Ozone	**Oslo/Kjeller**	**Andøya**	**Ny-Ålesund**
Annual total ozone trend 1979 to 1997, % per decade	-5.9 (±2.0)	-5.2 (±2.0)	-5.9 (±2.2)
Annual total ozone trend 1998 to 2022, % per decade	0.4 (±1.2)	-0.7 (±1.2)	-0.5 (±1.8)
UV			
Annual UV dose 2022, kJ/m^2 (rank*)	403.9 (2)	236.7 (16)	2000.7 (21)

*"Rank" indicates how high the UV dose was in 2022 compared to other years. UV has been measured since 1995/1996.

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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 natural solar depletion processes.
- 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 2022

Total ozone is measured 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 and Tromsø and in Ny-Ålesund since 1990. Additional measurements outside the program, but relevant to this report, are performed in Antarctica at the Norwegian Trollhaugen station.

The ozone measurements are retrieved from Brewer spectrophotometers at Kjeller and Andøya, whereas a SAOZ (Systeme d'Analyse par Observation Zenitale) instrument is one of the standard ozone instruments in Ny-Ålesund. The SOAZ instrument runs side-by-side with a Brewer spectrophotometer operated by the Institute of Polar Sciences, National Research Council of Italy, and a newly installed Pandora spectrometer (2020) operated by NILU in the frame of the SIOS infrastructure development. At all the three Norwegian sites GUV (Ground-based UltraViolet) filter radiometers provide total ozone values on days without Brewer and SAOZ measurements (see Appendix for more details). In addition, NILU analyses total ozone data from various satellites to get a more complete description and understanding of the ozone situation in Norway and the Arctic and Antarctic regions. The total ozone column, frequently denoted as the ozone layer thickness, is expressed in terms of Dobson Units (DU[1])

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

1.1 Total ozone at Kjeller

The total ozone column at Kjeller is primarily recorded with the Brewer MKV Spectrophotometer (B042). The total ozone values in 2022 have been based on Brewer direct sun (DS)[2] measurements when available. In 2022, direct sun measurements were performed on 216 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 (GI) method (Stamnes et al., 1991). The Brewer GI method was used on 136 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 12 days with missing Brewer data in 2022. A summary of instrument frequency in the data set is given in Table 1. In 2022, there was only one day without ozone measurements, caused by heavy clouds at Kjeller.

As seen from Figure 1 there can be 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 and November, and in 2022 a minimum ozone value of 240 DU was measured 30 October. This is ~18% below the long-term mean for October. However, such an ozone value in October and November is not dramatic and will occur most years.

The monthly mean total ozone values in 2022 are shown in Figure 1 (red dashed line), compared to the long-term monthly mean values for the period 1979 to 1989 (red line). As seen from the figure, the monthly average ozone values in 2022 are below normal during spring and summer, and above normal in winter and late fall. Section 2.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2022.

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[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”.

[2] Direct sun (DS) measurement means that an instrument is pointing directly towards the sun and measure radiation from the solar beam. Global irradiance (GI) measurement means that the instrument measures radiation from all directions through a horizontal window/dome, i.e., both the direct and scattered radiation.

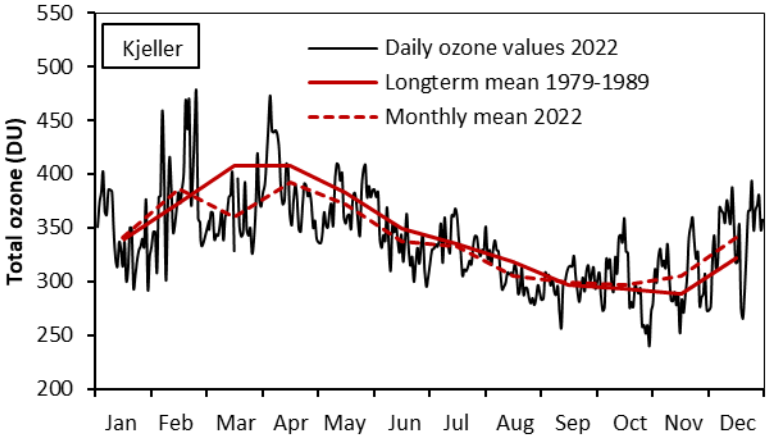

Figure 1: Daily total ozone values measured at Kjeller in 2022 (black curve). The red curve shows the long-term monthly mean values from Oslo 1979 to 1989. The red dashed line is monthly mean ozone values in 2022.

Table 1: Overview of total ozone instruments at Kjeller and the number of days where the various instruments were used in the 2022 time series.

Priority	Method	Total days with observations
1	Brewer #42 instrument, direct sun measurements	216
2	Brewer #42 instrument, global irradiance method	136
3	GUV-511 instrument	12
	Missing days	1

1.2 Total ozone at Andøya

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, 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 and 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 2022, but a significant drift in the standard lamp revealed instrumental problems. The Brewer was checked by the International Ozone Service Inc. (IOS) Canada in the summer 2022 and a preliminary instrument repair was done. However, the drift continued in the following months, causing less reliable measurements. Because of the drift and uncertain data quality, Brewer DS data for 2022 have been omitted from the Andøya time series this year. Instead, GUV total ozone data are more extensively used. A post-processing of the 2022 Brewer data can hopefully be performed in late 2023 after the instrument has been inspected by IOS.

The GUV instrument ran without major problems in 2022, but there is still an unresolved problem with the communication between the detector and the PC. This problem started in 2018, and it is resulting in occasional interruptions and shorter periods (~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 resolved. Despite these challenges there were no days without GUV measurements due to technical problems in 2022. On eight days total ozone values were not accepted due to heavy clouds or large data uncertainty. In addition, total ozone was not retrieved during the polar night period (Nov to Jan) and the weeks shortly before and after the polar night season.

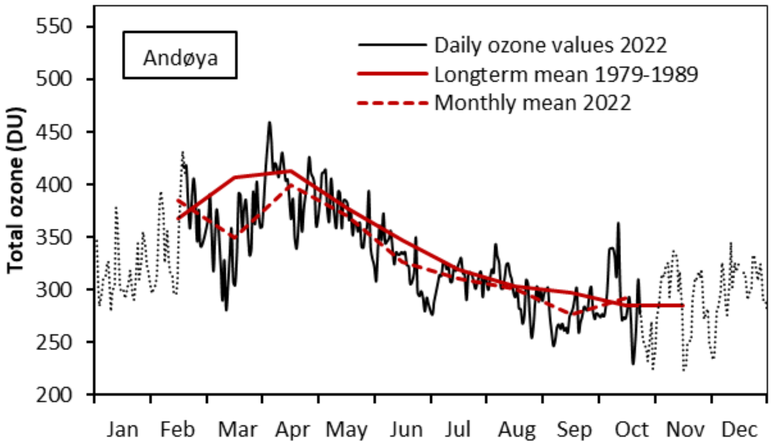

Figure 2: Daily total ozone values measured at ALOMAR, Andøya, in 2022 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989, whereas the red dashed line is monthly mean ozone values in 2022. The black dotted line represents GOME2 satellite measurements.

Table 2 gives an overview of the different instruments and methods used at Andøya in 2022. As mentioned above Brewer DS was not used in 2022. Instead, Brewer GI provided daily ozone values on 150 days, whereas GUV was used 91days.

Figure 2 shows daily ozone values from Andøya in 2022. The lowest ozone values normally occur in October and November (Figure 2), and in 2022 the minimum ozone value measured by the ground-based instruments was 230 DU (19 October). This is ~19% below the long-term October mean. Also, a spring-time ozone minimum of 281 DU was measured 11 March, which is ~31% below the long-term mean value for March.

Monthly mean ozone values at Andøya in 2022 are shown by the red dashed line in Figure 2. 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 2022 shows that the total ozone column was below normal all year, except from February and October.

Table 2: Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2022.

Priority	Method	Total days with observations
1	Brewer #104 instrument, direct sun measurements	0
2	Brewer #104 instrument, global irradiance method	150
3	GUV-541 instrument	91
	Missing days (except polar night period)	8

1.3 Total ozone in Ny-Ålesund

Ny-Ålesund is at a high latitude (79°N), which normally makes it more challenging to obtain reliable ozone measurements due to weak solar radiation or 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 uses 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°. During this period a GUV-541 multi-filter radiometer is used for ozone measurements in Ny-Ålesund. In early 2020 a new Pandora UV/visible spectrometer was put into operation, and the data from this instrument has for the first time been used in the total ozone series from Ny-Ålesund.

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 (B50) instrument set up at the Sverdrup station, which are valuable as quality assurance of the other ground-based instruments. Unfortunately, there were some technical problems with B50 back in 2019. Even if the Brewer has been running without major interruptions the last couple of years, it was decided to omit these ozone data until the instrument has been inspected by IOS.

Both the SAOZ, GUV, and the Pandora instruments worked satisfactorily in 2022. On one out of 365 days, the GUV measurements were missing due to power failures at the Sverdrup station. Table 3 gives an overview of the different instruments and measurement methods used for the 2022 total ozone time series in Ny-Ålesund. No ground-based ozone measurements were performed during the polar night period and the period just before and 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 2022.

Priority	Method	Total days with observations
1	Brewer #50 instrument	0
2	Pandora	63
3	SAOZ instrument	77
4	GUV-541 instrument	102
	Missing days (except polar night period)	1

Figure 3 shows daily ozone values from Ny-Ålesund in 2022. 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. However, a local minimum ozone value was measured 11 March (same as Andøya). This day an ozone value was 293 DU, i.e., 31% below the long-term mean for March.

Monthly mean total ozone values in Ny-Ålesund 2022 are shown in Figure 3. Comparison between the 2022 values and the long-term 1979 to 1989 monthly means demonstrate that the 2022 values were below the long-term mean all months except from August and October.

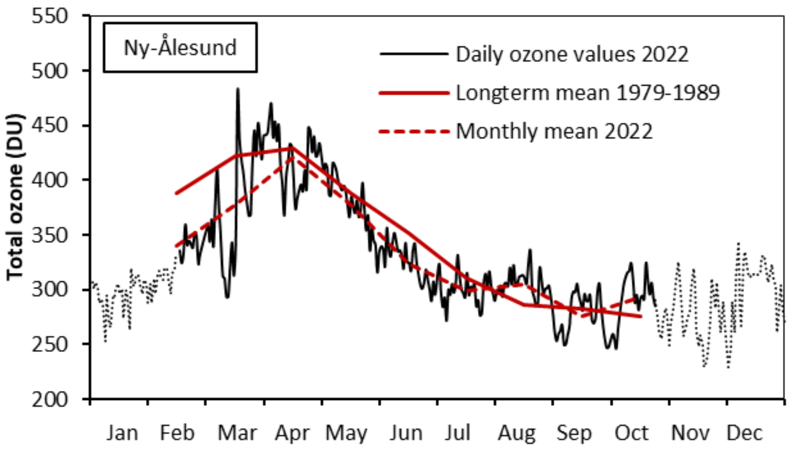

Figure 3: Daily total ozone values measured in Ny-Ålesund in 2022 by the SAOZ, GUV, and Pandora instruments (black curve). The red line is the long-term monthly mean values from 1979 to 1989, whereas the dashed red line is monthly mean values for 2022. The black dotted line represents GOME2 satellite measurements.

2 Ozone measurements and trends 1979 to 2022

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 most recent, “Scientific Assessment of Ozone Depletion: 2022”, was published in October 2022 (WMO, 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 2022 report concludes that the actions taken under the Montreal Protocol have led to decreases in the atmospheric abundance of ozone-depleting substances (ODSs). By 2020, the chlorine entering the stratosphere from ODSs has declined by 11.5% from the 1993 peak value. Total bromine has decreased by 14.5% between the 1999 peak and 2020.

Earlier measurements showed that total column ozone declined over most of the globe during the 1980s and early 1990s. The 2022 assessment report concludes that the near global (60°S to 60°N) total column ozone has remained relatively unchanged since 1997, roughly 2% below the 1964 to1980 average. However, the upper stratospheric ozone has increased by 1 to 2%/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 (WMO, 2022).

According to the 2022 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 around 2035, Southern Hemisphere (60°S to 35°S) around 2045, whereas the Antarctic ozone hole is expected to gradually close and return to 1980 values around 2065. The Arctic springtime total ozone is expected to return to 1980 values around 2045, but substantial ozone loss will occur in cold winters or springs as long as ODS concentrations are well above natural levels.

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 has recently been published (Bernet et al., 2023).

As mentioned above, stratospheric ODS concentrations have declined slowly the last 20 to 25 years. The most important ODS is CFC-11, and the 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 CFC-11 emissions from unreported 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. Still, uncertainties in CFC emissions from banks (substances already produced) and gaps in the observing network are too large to determine whether all unexpected emissions now have ceased. Some unexplained emissions are likely occurring as leaks of feedstocks or by-products during manufacture of other compounds (WMO, 2022).

2.2 Trends for Oslo/Kjeller 1979 to 2022

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, and 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 very similar, and the relocation of the instrument will have very small impact on the total ozone values and trend calculations.

Figure 4a shows the variations in monthly mean ozone values above Oslo/Kjeller for the period 1979 to 2022. 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.

To make ozone trend analyses for the period 1979 to 2022 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 to 1997, and 2) 1998 to 2022. 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 and the major Mt. Pinatubo volcanic eruption in 1991 (Solomon et al., 1999; Chipperfield et al., 2017). 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. The second time period (1998-2022) 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[3]) 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 also be large to be classified as statistically significant.

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[3] 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.

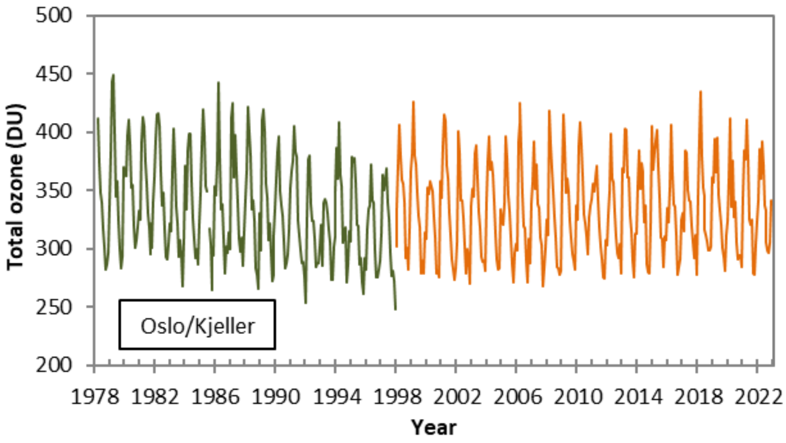

Figure 4a: *Time series of monthly mean total ozone in Oslo and at Kjeller 1979 to 2022. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements.*

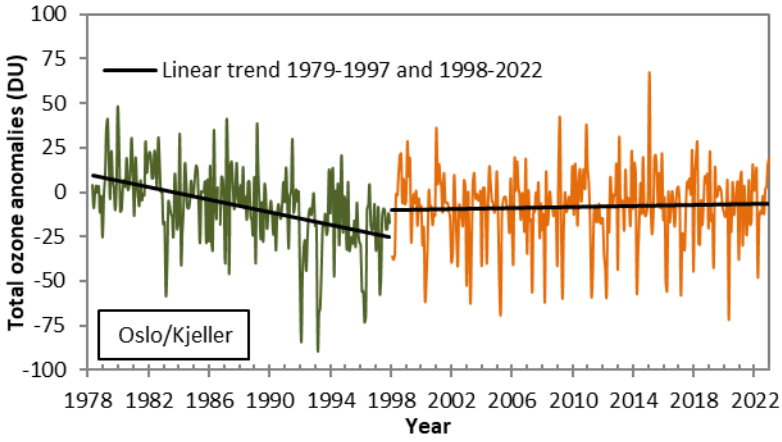

Figure 4b: *Variation in total ozone over Oslo/Kjeller for the period 1979 to 2022 after the seasonal variations have been removed. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements. Trend lines are marked as black lines.*

A large ozone decrease occurred during the 1980s and first half of the 1990s (Table 4). In the period 1979 to 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 to 2022 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. There is a statistically significant ozone increase of 1.7%/decade for the fall period September to November (Table 4). For the winter season December to February, it is also observed a positive ozone trend over the last decades, but the change is not statistically significant. The annual ozone trend from 1998 to 2022 is 0.4% /decade.

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 01.01.1979 to 31.12.2022. 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 1979-1997 (%/decade)	Trend 1998-2022 (%/decade)
Winter (Dec – Feb)	-6.0 (2.3)	1.6 (1.4)
Spring (Mar – May)	-8.0 (1.3)	-0.2 (1.0)
Summer (Jun – Aug)	-3.5 (1.0)	-0.9 (0.6)
Fall (Sep – Nov)	-4.2 (1.0)	1.7 (0.7)
Annual (Jan – Dec):	-5.9 (1.0)	0.4 (0.6)

2.3 Trends for Andøya/Tromsø 1979 to 2022

Total ozone measurements in Tromsø started back in 1935, which makes this time series one of the longest in the world. Total first measurements were performed with a Fery spectrograph (1935-1939) and Dobson no. 14 from 1939 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 and Atlantic Arctic. Thus, for trend study purposes the Tromsø and Andøya total ozone time series can be considered as one series and is denoted Tromsø/Andøya.

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 to 1994.

Figure 5a shows the variation in the monthly mean ozone values at Andøya from 1979 to 2022. The variations in total ozone, after removing the seasonal cycle, are shown in Figure 5b, together with the annual trends. November to 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 to 1997, and 2) 1998 to 2022. 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 2022, no significant trends have been found for any sesons. The annual ozone trend from 1998 to 2022 is -0.7%/decade.

Table 5: Percentage changes in total ozone (per decade) at Andøya for the periods 1) 1979-1997, and 2) 1998- 2022. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	Trend 1979-1997 (%/decade)	Trend 1998-2022 (%/decade)
Spring (Mar – May)	-7.5 (1.5)	-1.6 (1.0)
Summer (Jun – Aug)	-3.4 (1.0)	-0.9 (0.6)
Fall (Sep – Oct)	-3.4 (1.1)	1.2 (0.7)
Annual (Mar – Oct)	-5.2 (1.0)	-0.7 (0.6)

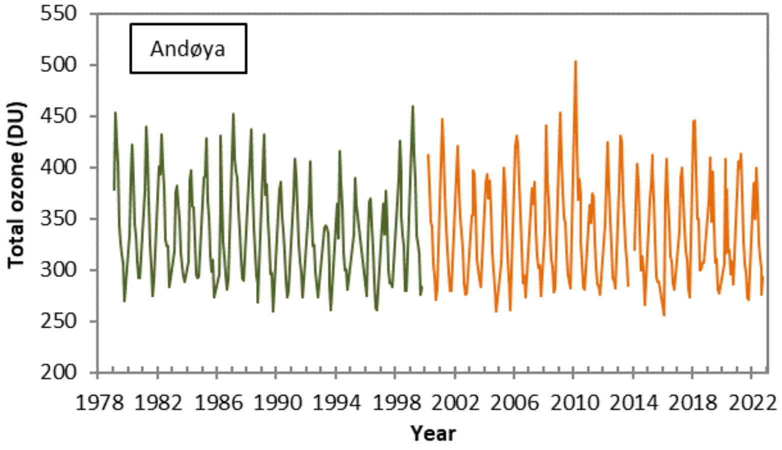

Figure 5a: Time series of monthly mean total ozone at Andøya and Tromsø 1979 to 2022. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya.

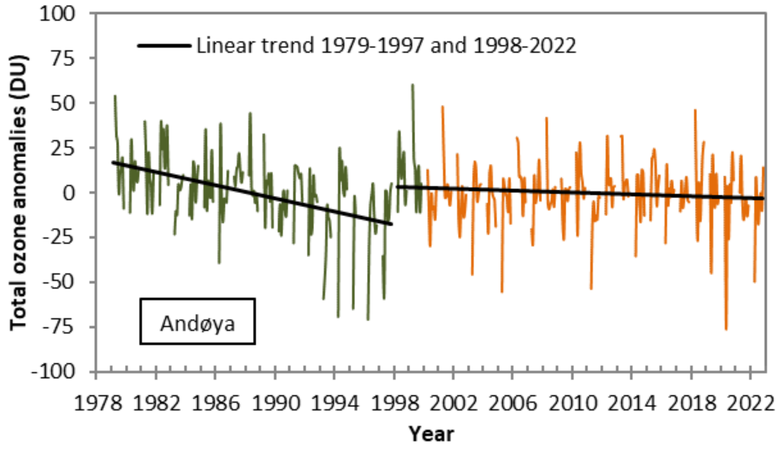

Figure 5b: Variations in total ozone at Andøya for the period 1979 to 2022 after the seasonal variations are removed. Only data for the months March to October are included. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya. The trends are marked as black lines.

2.4 Trends for Ny-Ålesund 1979 to 2022

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 pioneer to perform 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.

Following this, regular Dobson ozone measurements were performed in 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 resume 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 the fall 1990 and in 1995, respectively. Since 2014 we have also had access to Italian Brewer measurements, and in 2020 a Pandora spectrometer was installed in Ny-Ålesund.

The ozone measurements presented in Figure 6a and Figure 6b are based on a combination of Dobson, Brewer, Pandora, 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 satellite overpass data due to lack of ground-based measurements. 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, Pandora and SAOZ data are used when Brewer/Dobson measurements are absent, 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 1998-2022 no significant trend is observed. The trend for fall is +1.0%/decade, whereas a negative trend of -1.1%/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., in 2005, 2011, 2016, and 2020).

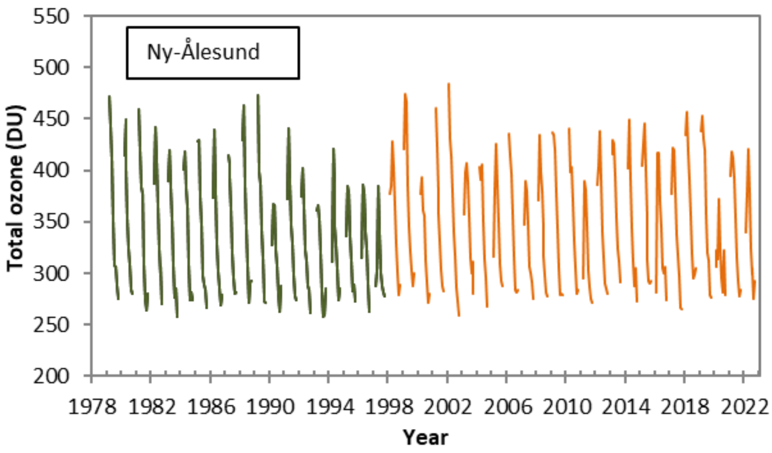

Figure 6a: Time series of monthly mean total ozone at Ny-Ålesund 1979 to 2022. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments.

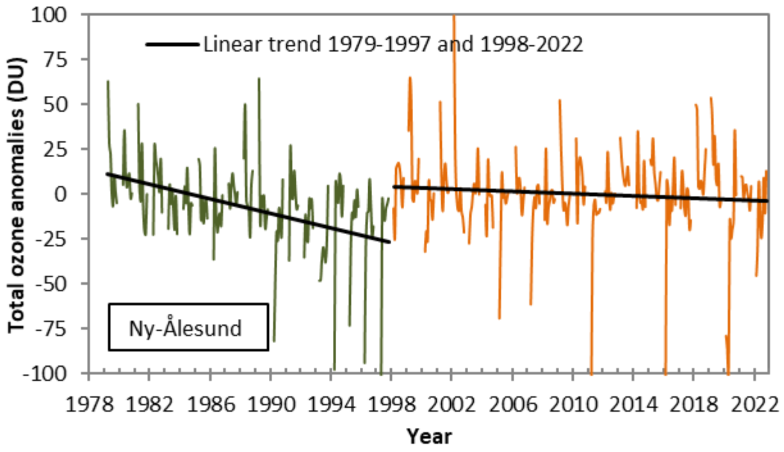

Figure 6b: Variations in total ozone at Ny-Ålesund for the period 1979 to 2022. Only data for the months March to October are included. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments. Trends for the two periods are marked as black lines.

Table 6: Percentage changes in total ozone (per decade) in Ny-Ålesund for the periods 1) 1979 to 1997, and 2) 1998 to 2022. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	Trend 1979-1997 (%/decade)	Trend 1998-2022 (%/decade)
Spring (Mar – May)	-10.8 (1.7)	-0.8 (1.6)
Summer (Jun – Aug)	-2.4 (1.2)	-1.1 (0.7)
Fall (Sep – Oct)	-1.2 (1.0)	1.0 (1.0)
Annual (Mar – Oct)	-5.9 (1.1)	-0.5 (0.9)

2.5 The overall Norwegian ozone situation in 2022

Past emissions of chlorine-containing substances such as chlorofluorocarbons (CFCs) have caused substantial chemical depletion of stratospheric ozone. The chemical ozone destruction in Polar regions occurs within a cold stratospheric cyclone, the polar vortex, which forms over the North Pole every year during winter (WMO, 2022). The polar vortex in 2021 and 2022 was colder than usual from December 2021 to March 2022, providing favourable conditions for PSC formation and ozone-destroying species such as chlorine monoxide (ClO).

From late February through March 2022, ozone in the lower stratosphere dropped more rapidly than the mean (Bernhard et al., 2023), consistent with the above average ClO concentrations formed during that period. However, the overall ozone loss in 2022 was much smaller than that in 2020 and was to a large extent located in the lower stratosphere. All in all, below-average ozone concentrations in the lower stratosphere after mid-February 2022 contributed to below-average total ozone columns in the Arctic in February and March 2022. This is seen from the low total ozone values in Ny-Ålesund in February and March (see Table 7)

As seen from Table 7, 2022 was characterized by relatively low total ozone values during the spring and summer and higher ozone values later in the season (fall and winter). At all stations the average March values were very low compared to the long-term means.

Table 7: Percentage difference between the monthly mean total ozone values in 2022 and the long-term 1979 to 1989 average for Oslo/Kjeller, Andøya, and Ny-Ålesund. Red numbers are positive differences, whereas blue numbers represent negative differences.

Month	Kjeller (%)	Andøya (%)	Ny-Ålesund (%)
January	0.9		
February	3.4	3.8	-12.5
March	-11.7	-13.3	-10.4
April	-3.8	-3.0	-2.1
May	-2.8	-2.3	-2.8
June	-3.4	-7.3	-8.0
July	-0.7	-4.1	-3.6
August	-4.3	-1.2	6.4
September	0.6	-6.3	-2.3
October	1.1	3.9	6.4
November	5.5		
December	5.9		

Figure 7, Figure 8 and Figure 9 show the percentage difference between yearly mean total ozone and the long-term yearly mean 1979 to 1989. The low values in 1992 and 1993 are partly related to the eruption of the Mount Pinatubo volcano at the Philippines in 1991 (Svendby and Dahlback, 2004).

Comparison of Figure 7, Figure 8 and Figure 9 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 to 9% below the long-term mean). In the winter and 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 9). In 2022 the annual ozone means were 1.1%, 4.6%, and 2.7% below the long-term means at Kjeller, Andøya, and Ny-Ålesund, respectively.

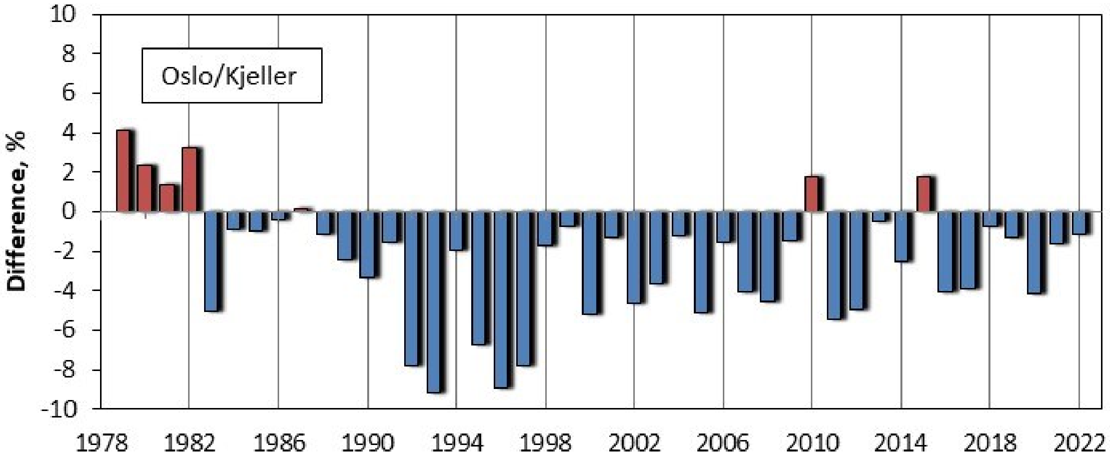

Figure 7: Percentage difference between yearly mean total ozone in Oslo/Kjeller and the long-term yearly mean 1979 to 1989. Red numbers represent positive differences, whereas blue numbers are negative differences.

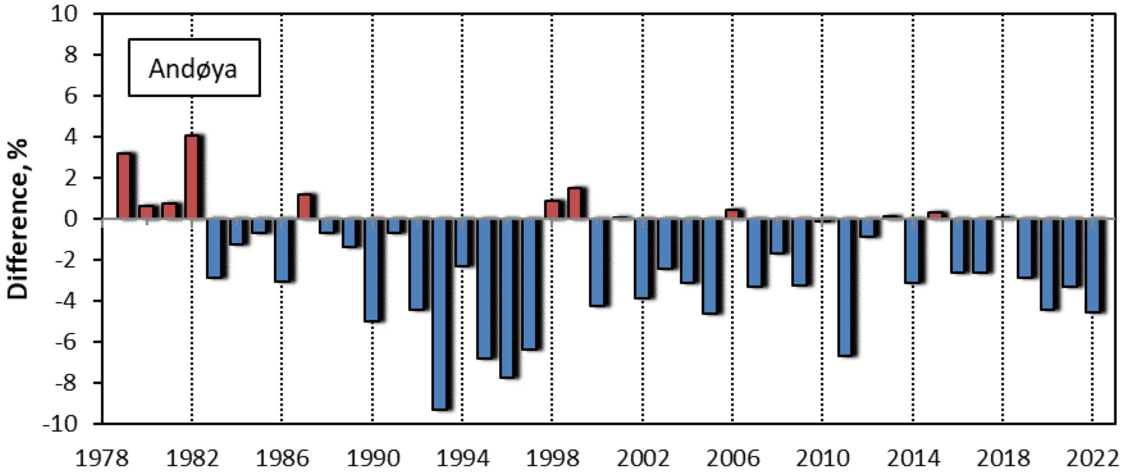

Figure 8: Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean1979 to 1989 for March to October.

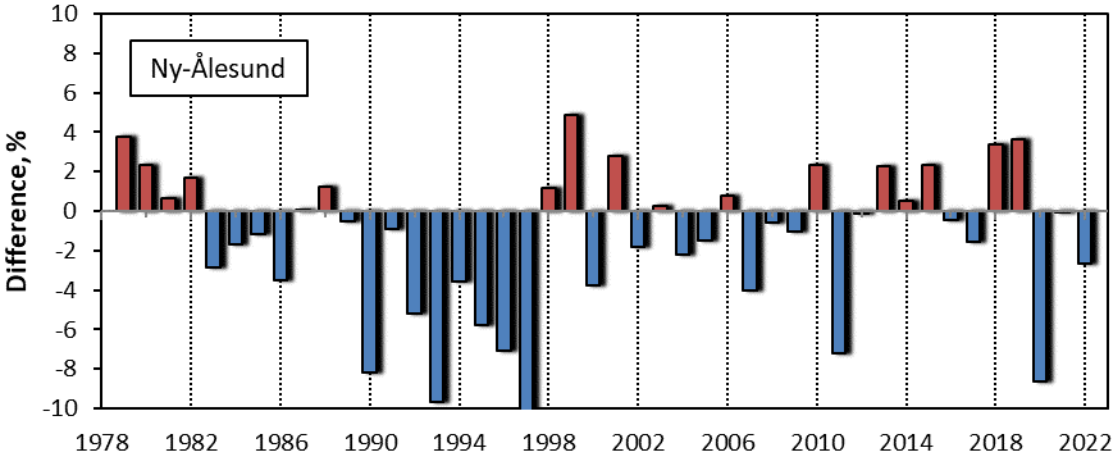

Figure 9: Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.

2.6 Ozone and UV measurements at Trollhaugen

In the Southern Hemisphere 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 problem of local pollution.

The station is equipped with a NILU-UV instrument (Høiskar et al., 2003), which is a six-channel broadband filter radiometer for measuring UV and visible radiation. The instrument is similar to the GUV filter instrument used in the Norwegian ozone and UV monitoring network. The NILU-UV instrument no. 015 operated from 2007 to 2015, when it was replaced by NILU-UV instrument no. 005 due to a major technical failure. In 2022, a new Pandora instrument was installed at Troll as part of the TONe (Troll Observing Network) infrastructure project, which aims to strengthen research within Antarctica.

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 16 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 10, 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.

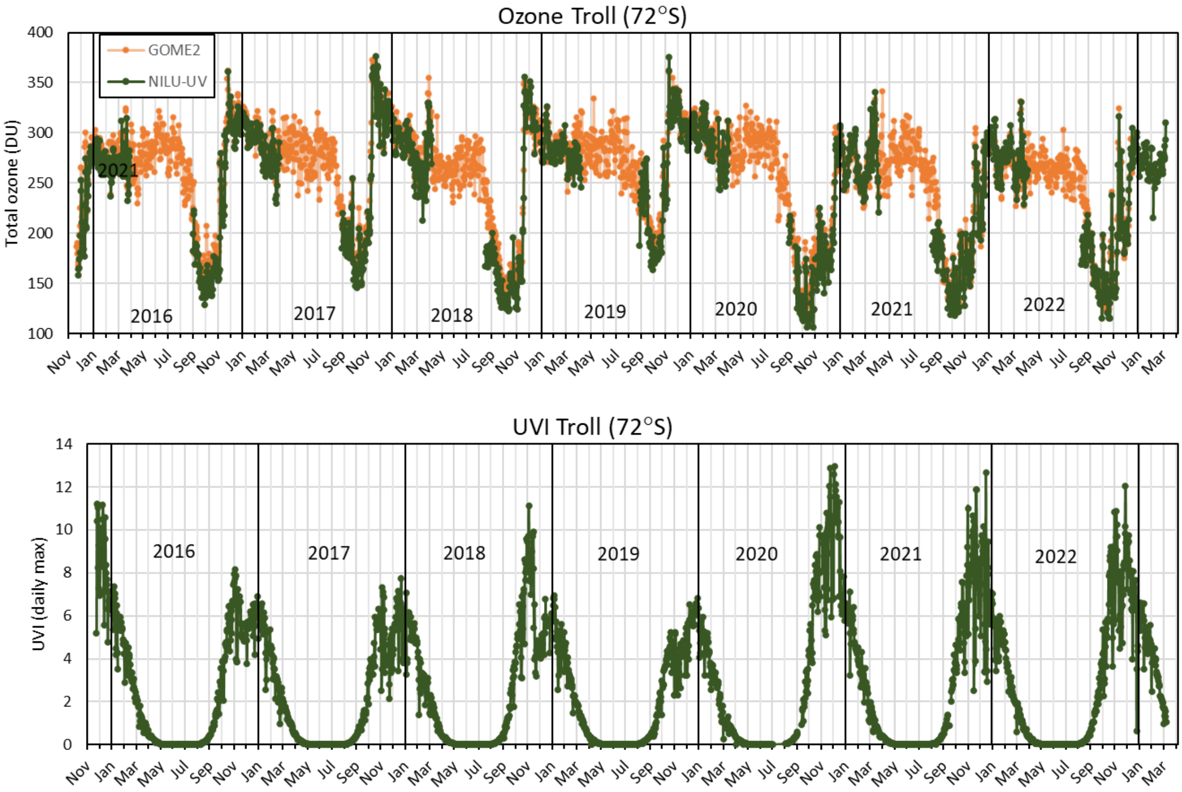

Figure 10: Upper panel: Total ozone from NILU-UV and GOME-2A from November 2015 to February 2022. Lower panel: Noon time UVI from NILU-UV 2015-2022

In 2022, the Antarctic ozone hole reached its annual maximum size in early October before starting to shrink (https://ozonewatch.gsfc.nasa.gov/SH.html). The 2022 ozone hole was similar in size and persistence to the ones in 2021 and 2020, due to a strong and long-lasting polar vortex these years. A minimum ozone value of 115 DU was measured by the NILU-UV instrument on 25 October 2022.

The low total ozone values in November/December caused high UV levels in 2022, with a maximum UVI peak of 12.0 at the Trollhaugen station on 12 December 2022. This is an extremely high UVI, like 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 around midday) was “only” 10.1 and was measured 11 November 2022.

The situation the last three years clearly shows that stratospheric ozone hole formation in Antarctica remains an environmental issue almost 40 years after its discovery and 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. The timing of the recovery of the ozone hole may also be affected by anthropogenic climate change (WMO, 2022)

3 Satellite observations of total ozone

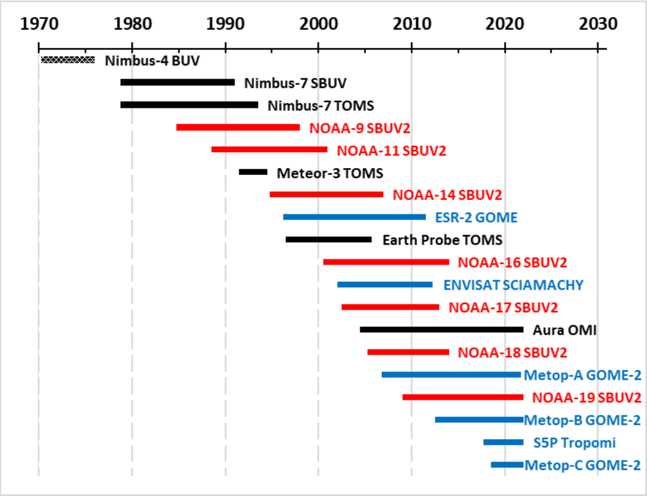

Figure 11: An overview of the most common satellites and their instruments measuring ozone from space since the beginning of the 1970's. NASA satellites are marked in black, ESA and EUMETSAT are in blue, whereas NOAA satellites are marked in red.

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 and 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 lifetimes, 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.

Since the 1970s, satellite instruments have been used to observe how ozone varies with season, latitude, and longitude. NASA and NOAA initiated these observations. ESA, the European space agency, joined the monitoring programme in 1995 when it launched the GOME instrument on the ERS-2 satellite. Figure 12 shows the different satellites that measure ozone and their operating periods.

3.1 Satellite total ozone observations 1979 to 2022

Over the last 43 years several satellites have provided ozone data above 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 to 2022 (Figure 12 and Table 8). Monthly mean ozone values are calculated from days where simultaneous ground- based and satellite data are available. In recent years, after the ground-based instruments were automated, simultaneous measurements are made almost every day (except for polar night periods).

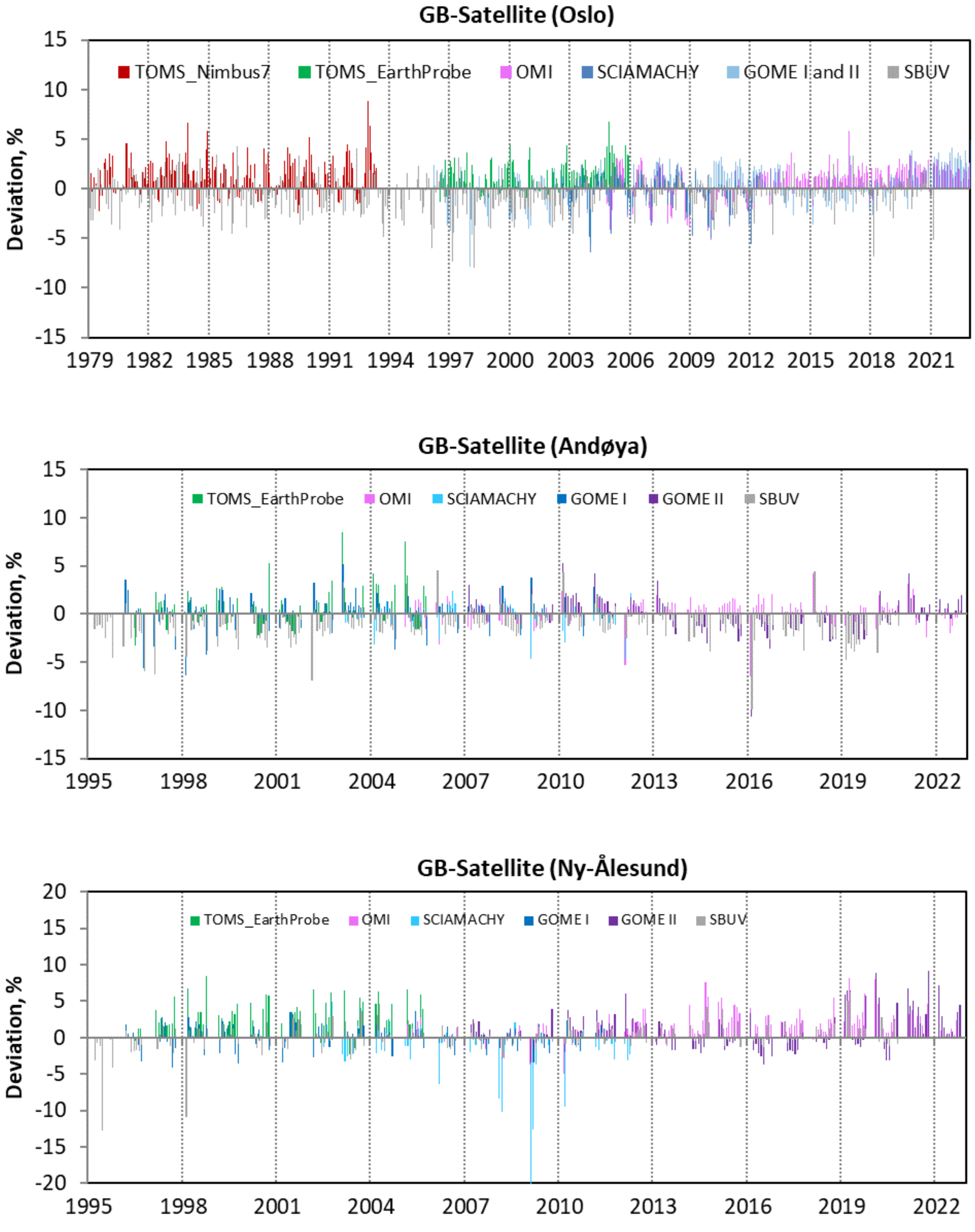

Figure 12: Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2022 (Oslo and Kjeller) and 1995 to 2022 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo and Kjeller, middle panel: Andøya, lower panel: Ny-Ålesund.

From Table 8 it is difficult to conclude 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-22	0.7	1.9	3.6
GOME I	Mar-96	Jul-11	-0.5	2.1	4.5
GOME II	Jan-07	Dec-22	0.8	1.7	2.8
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-22	0.1	1.3	1.7
GOME I	Mar-96	Jul-11	0.2	1.7	3.0
GOME II	Jan-07	Dec-22	-0.2	1.9	3.5
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-22	1.4	2.2	4.7
GOME I	Mar-96	Jul-11	0.1	1.7	2.9
GOME II	Jan-07	Dec-22	0.9	2.5	6.10
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

The 6th Assessment Report (AR6) from The Intergovernmental Panel on Climate Change (IPCC) 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 in the ozone layer thickness 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, 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 6th IPCC assessment report (AR6) are shown in Figure 13 (IPCC, 2021). The estimates represent changes in energy fluxes caused by various drivers in 2019 relative to 1750. It shows how emitted compounds affect the atmospheric concentration of other substances. In AR5 (IPCC, 2013) the total radiative forcing from ozone changes was estimated to 0.35 watt per square meter (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 to 2019 was 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.

As seen from Figure 13 (grey bars) emissions CFC + HCFC + HFC have caused a positive RF and an increased surface temperatures in 2019 compared to preindustrial times. At the same time emission of CFCs have resulted in ozone loss and a subsequent negative ozone RF, seen by the green bar in the Figure. Figure 13 also shows that changes in CH_4, NOx, NMVOCs and CO have contributed to increased ozone concentration (tropospheric and stratospheric) and an overall positive ozone RF.

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 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 leads to more favourable conditions for the formation of more Polar Stratospheric Clouds (PSCs) (von der Gathen et al., 2021). These ice clouds are formed when

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[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 W/m^2.

stratospheric temperature drops below -78°C. Chemical reactions occurring on PSC particle surfaces can transform passive halogen compounds into active chlorine and bromine and cause massive ozone destruction.

The overall impact of methane on ozone is very complex. One mechanism is the temperature change mentioned above. Another mechanism is that methane can react with chlorine and convert active chlorine (Cl) to a reservoir species (HCl). In this way, stratospheric methane will affect the efficiency of chlorine-driven ozone loss (IPCC/TEAP, 2005)

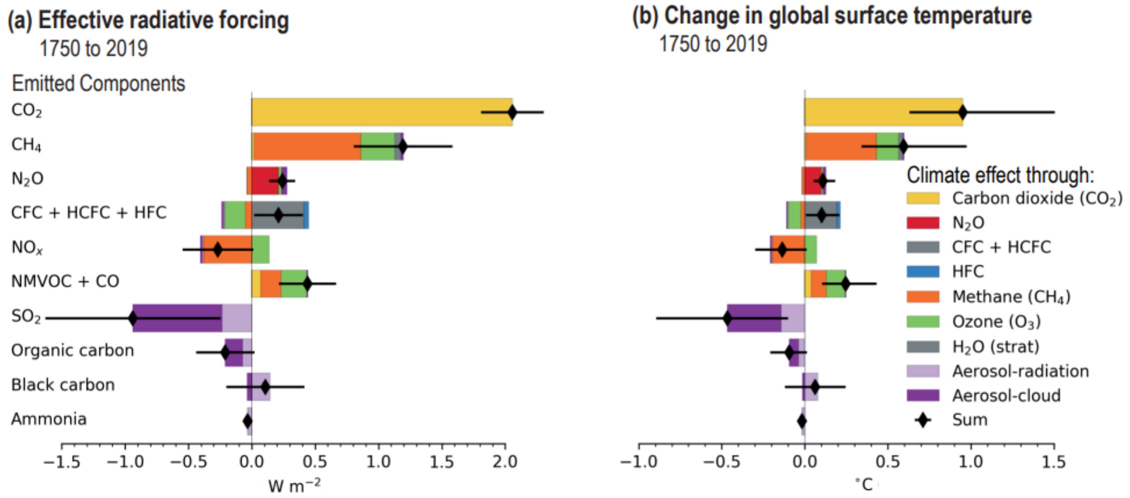

Figure 13: Contribution to (a) effective radiative forcing (RF) and (b) global surface temperature change from component emissions for 1750–2019 based on Coupled Model Intercomparison Project Phase 6 (CMIP6) models (Figure from IPCC, 2021)

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 trend 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 vapour will influence the total ozone column, as stratospheric water vapour is among the main sources of hydroxyl radicals (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 biogenic 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) hypothesizes that severe biomass burning events like the extreme bushfires in Australia in austral summer 2019/2020 may slow the recovery of the ozone layer.

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/m² (IPCC, 2021). In addition, chlorine and bromine containing compounds play a key role in ozone destruction

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[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 O_3, resulting in a loss of ozone.*

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 as a key species influencing ozone concentrations. The photochemical degradation of N_2O in the middle stratosphere leads to ozone-depleting NO_X, but in the last IPCC reports the impact of N_2O on ozone RF is close to zero. This is due to insufficient quantification of the N_2O influence and particularly the vertical profile of the ozone change. According to AR6 increased nitrous oxide might lead to ozone depletion in the upper stratosphere which will make a positive, but very small, contribution to the direct radiative forcing.

5 UV measurements

The Norwegian UV network was established in 1995 and consists of nine 5-channel GUV instruments located from 58°N to 79°N, as shown in Figure 14. 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 14: 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 Kjeller station is located ~18 km east of the initial site of Blindern. The GUV instrument in Ny-Ålesund was omitted from the monitoring programme for the period 2006 to 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 to 2009 have been reanalysed and included in the UV time series.

GUV instruments are usually easy to maintain and have few data gaps due to technical problems. However, the instruments are quite old and have been running for nearly 30 years. Replacement instruments (GUVis) will gradually be purchased and implemented in the UV network to ensure measurements in the future. A new GUVis is planned to be installed at Kjeller in September/October 2023. In 2022, the instruments at Kjeller, Andøya and Ny-Ålesund worked well, except for some short and unexplained interruptions at Andøya. The cause of these problems is still unclear.

5.1 UV measurements in 2022

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 and 7 at sea level but can range up to 18 in Equatorial regions and high altitudes (WHO, 2009).

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

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.

Figure 15 shows the UV dose rates measured at local noon (± 0.5 hour) at Kjeller (top), Andøya (middle) and in Ny-Ålesund (bottom) in 2022. The black curves in Figure 15 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, 169.4 mW/m^2, was observed on 30 June 2022 and is equivalent to a UV index of 6.8. However, a peak UVI as high as 7.3 was observed on 1 July.

At Andøya the highest noon average UVI in 2022 was 4.7, equivalent to a dose rate of 117.6 mW/m^2 (observed on 28 June). A peak UVI of 5.2 was observed on 3 July.

The highest noon average UVI in Ny-Ålesund in 2022 was 2.8, registered on 5 July, equivalent to 70.4 mW/m^2. The peak UVI measured this year was 3.3 (observed on the same day). 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.

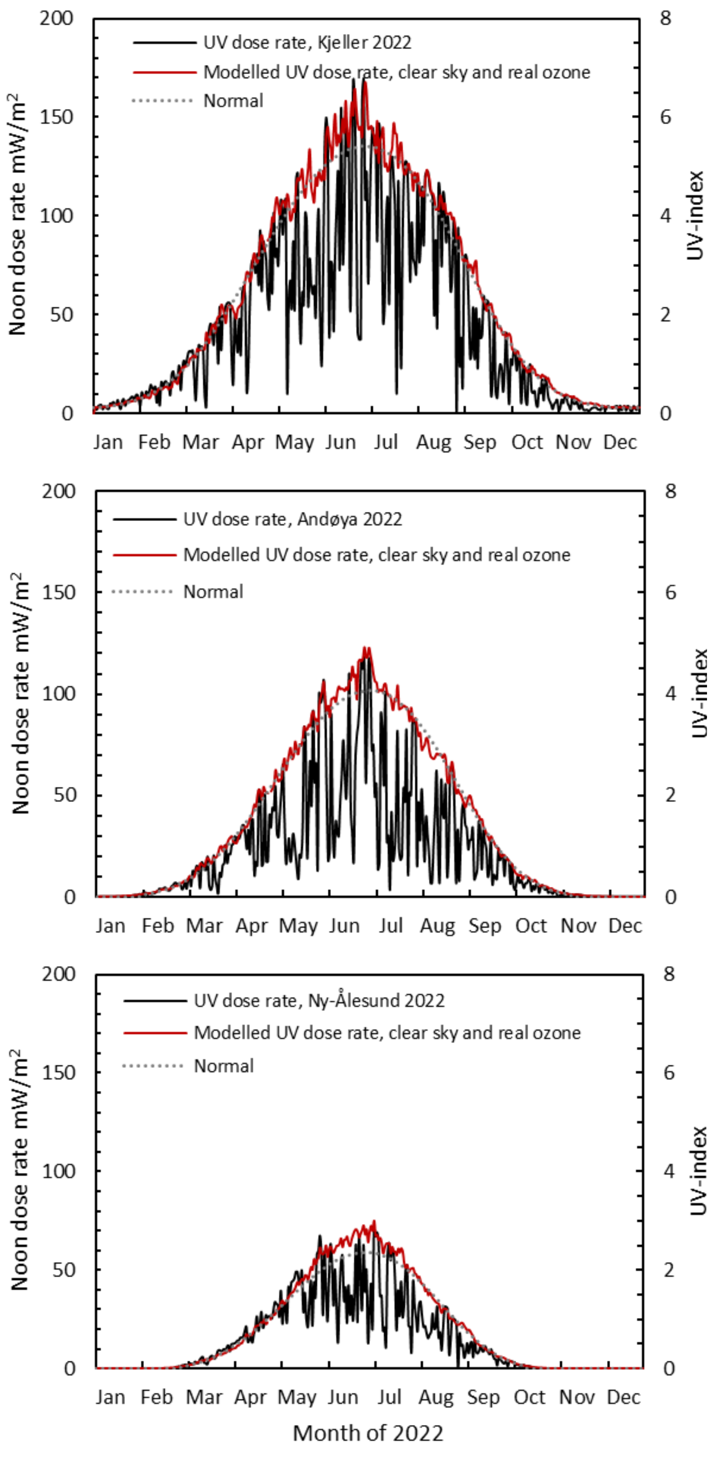

Figure 15: Hourly averaged UV dose rate measured at local noon (± 0.5 hour) in 2022. Upper panel: Kjeller. Middle panel: Andøya. Lower panel: Ny-Ålesund.

At all the Norwegian stations the maximum noon UVI values in 2022 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 17%, 18%, and 13% below the long-term seasonal mean ozone values, respectively.

For UV levels corresponding to the maximum UVI value of 6.8 at Kjeller, people with a typical Nordic skin type get sunburnt after approximately 20 minutes if no sun protection is used.

Figure 16 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	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.
9		
8		
7	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+).
6		
5	Moderate	Protection may be necessary. Clothes, a hat and sunglasses give good protection. Don't forget the sunscreen!
4		
3		
2	Low	No protection is necessary.
1		

As seen from Figure 16 (red curves), the cloud transmittances were close to or above 100% during the periods of maximum UVI. The "noisy" red curve and high cloud transmittance in Ny-Ålesund (Figure 16, right panel) indicates occurrence of scattered clouds. These 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 of 120% in the middle of the day.

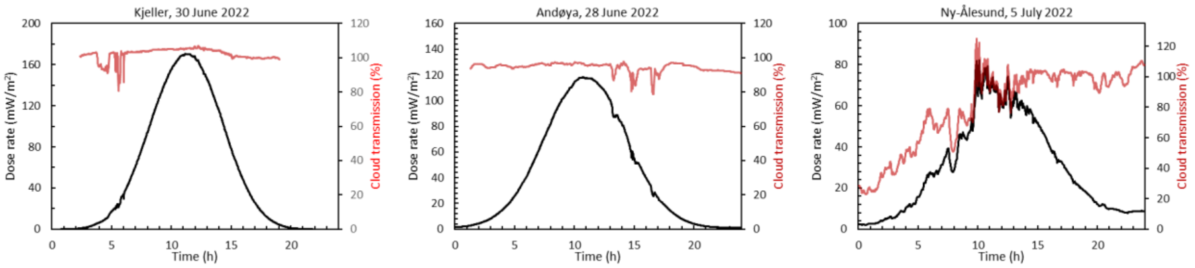

Figure 16: UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI at Kjeller (left panel), Andøya (middle panel) and Ny-Ålesund (right panel) in 2022. A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions 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. In Mediterranean and other lower-latitude countries 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 deep and long-lasting in 2022, and a UVI close to 12 was measured at Trollhaugen in December 2022.

The seasonal variation in observed UV dose rate is closely related to the Sun's elevation angle. 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 other parameters such as clouds, total ozone, aerosols, and surface reflectance (albedo). Day-to-day fluctuation in cloud cover is the main driver 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 2022 are compared in Figure 17. 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, and the UV doses at Andøya will normally be higher than the doses in Ny-Ålesund. It is, however, worth noting that the integrated UV dose at Andøya in May 2022 was below the Ny-Ålesund value, partly as a result of high albedo (snow) in Ny-Ålesund in May 2022.

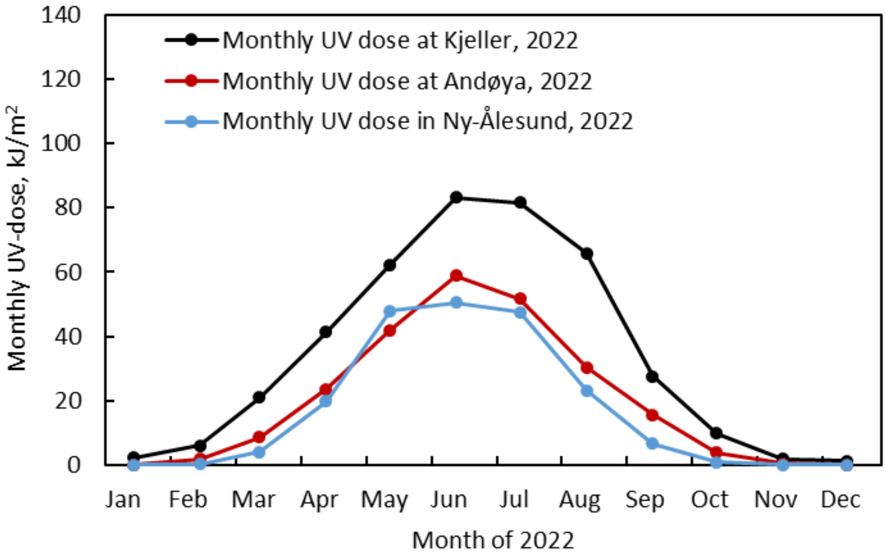

Figure 17: Monthly integrated UV doses (in kJ/m^2) in 2022 measured with the GUV instruments located at Kjeller, Andøya and in Ny-Ålesund.

5.2 Annual UV doses 1995 to 2022

Annual UV doses for the period 1995–2022 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 %.This makes it more difficult to make statistically significant trend estimates of UV doses.

Table 10: Annual integrated UV doses (in kJ/m^2) for Oslo/Kjeller, Andøya and Ny-Ålesund for the period 1995 to 2022.

Year	Oslo/Kjeller (kJ/m^2)	Andøya (kJ/m^2)	Tromsø (kJ/m^2)*	Ny-Ålesund (kJ/m^2)
1995	375.3			
1996	373.9		269.8	215.7
1997	400.9		279.4	214.9
1998	313.8		259.5	217.4
1999	355.3		228.1	184.2
2000	352.6	242.3		218.2
2001	359.7	227.0		211.3
2002	372.0	253.7		214.9
2003	364.0	247.4		179.4
2004	367.6	240.0		201.6
2005	367.4	229.4		207.6
2006	367.1	222.3		184.4
2007	354.9	254.7		218.7
2008	373.5	259.8		210.4
2009	367.7	259.2		230.4
2010	353.6	231.4		201.4
2011	355.7	256.5		217.1
2012	357.4	233.0		212.7
2013	360.0	249.7		179.6
2014	386.8	254.0		212.9
2015	357.2	223.3		215.0
2016	374.0	230.6		190.0
2017	359.1	264.6		207.5
2018	422.1	228.4		184.3
2019	359.1	252.9		203.5
2020	402.3	266.4		212.5
2021	392.1	234.1		213.0
2022	403.9	236.7		200.7

*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 dose at Kjeller was relatively high in 2022. The 2022 value of 403.9 kJ/m^2 is the 2nd highest annual UV dose measured in Oslo/Kjeller since 1995, roughly 4% below the maximum value from 2018, but 9% above the 1996-2022 average. At Andøya, where the summer 2022 was characterized by relatively many cloudy days, the annual integrated UV dose was the 11th lowest registered, around 15% below the maximum value from 1997 and 11% below the value from 2020. In Ny-Ålesund 2022 was a below average year when it comes to integrated UV doses. The annual dose of 200.7 kJ/m^2 is the 7th lowest value measured in Ny-Ålesund and is around 13% below the peak value from year 2009.

Graphical presentations of the annual integrated UV doses from 1995 to 2022 are shown in Figure 18. For Oslo/Kjeller there is an increase of 2.8%/decade in the annual UV dose. For Andøya and Ny-Ålesund there is a negative trend of -1.5%/decade and -1.0%/decade, respectively.

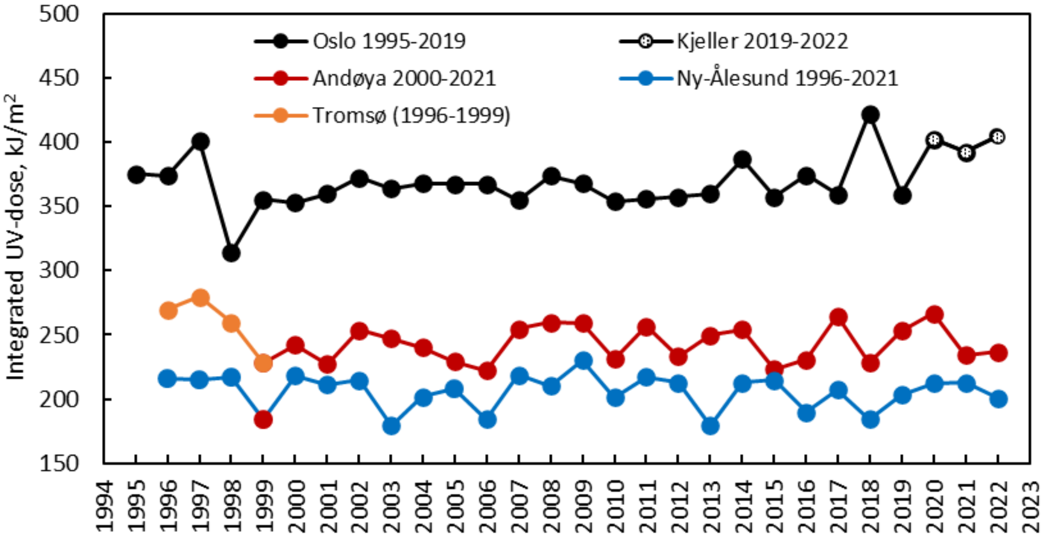

Figure 18: Annual integrated UV doses (in kJ/m^2) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995–2022.

The trends in UV radiation depend on changes in ozone, cloudiness, and albedo. A notable finding is that the UV trend at Andøya is almost zero for the period 2000 to 2022. The negative trend of -1.5%/decade from 1996-2022 may be due to the high UV values measured in the first few years when the GUV was in Tromsø. The instrument is now on the Ramnan Mountain at Andøya, about 400 m above sea level. This location is often affected by convective clouds from the ocean, which lower the UV radiation at the ground. At Oslo/Kjeller, there is also some evidence of higher UV-doses after the instrument moved from Blindern. This suggests that the positive UV trend of 2.8%/decade could be influenced by less clouds or aerosols at the new site at Kjeller.

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.

For these periods the Brewer data must be analysed carefully. If the data deviates from other ozone measurements, including satellite values, the Brewer data are flagged as “uncertain” and omitted from the ozone time series.

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). Data from these three sites are presented in Svendby et al. (2021). 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.

Pandora

NILU's Pandora instrument in Ny-Ålesund is located on the observation platform of the Sverdrup Station of the Norwegian Polar Institute, side-by-side with the SAOZ instrument. Measurements started in 2020. The Pandora instrument is a ground based direct sun DOAS instrument and measures the amount of trace gases (such as O3, NO2, CH2O) in the atmosphere by using the sun's light. The instrument is part of the Pandonia Global Network (PGN), a collaboration between NASA and ESA, which aims to monitor air quality and atmospheric composition worldwide and to validate satellite data from sensors such as Sentinel 5P. Pandora instruments can measure total ozone column with low air mass dependence up to 81.6° solar zenith angle, which is comparable to double Brewer instruments.

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