NILU report 19/2025

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual report 2024

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Overvåking av ozonlaget og naturlig ultrafiolett stråling
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Short summary (English)
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 2024 was characterized by high total ozone values most of the year, especially in the Arctic stations in March. For Ny-Ålesund, 2024 showed the highest annual average total ozone value since systematic ground-based ozone measurements started in 1997.

Short summary (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. 2024 var karakterisert ved høye ozonverdier mesteparten av året, spesielt ved de arktiske stasjonene i mars måned. I Ny-Ålesund var den årlige middelverdien av totalozon i 2024 den høyeste siden systematiske bakkemålinger startet i 1997.

Keywords
Stratospheric ozone, UV radiation, Measurements and observations, Montreal protocol
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Contents

Summary

The current report summarises activities and results from the Norwegian monitoring program on the atmospheric ozone layer and natural UV radiation in 2024. The report includes analyses of total ozone column trends from Oslo and Kjeller, at Andøya and in Ny-Ålesund for the period 1979-2024 and UV measurements for the period 1995-2024. The report also gives an overview of total ozone measurements and UV data from the Trollhaugen station in Antarctica from 2015 to 2024, funded by the Norwegian Ministry of Climate and Environment. The current report builds on “Monitoring of the atmospheric ozone layer and natural ultraviolet radiation, Annual Report 2023” (Svendby et al., 2024), extended with recent updates and studies from 2024.

Main conclusions from the monitoring programme 2024

- **In winter 2024, atmospheric waves weakened the polar vortex and enhanced the transport of ozone toward the poles. This resulted in high total ozone values in spring 2024, which persisted into the summer.**
- **In Ny-Ålesund and at Andøya the monthly mean total ozone values in March 2024 were 13% and 8% above the 1979-2024 average values, respectively.**
- **At Kjeller, the monthly average total ozone values for June and July were the highest recorded since ground-based observations began in Oslo/Kjeller in 1979.**
- **Annual total ozone means at Kjeller, Andøya, and Ny-Ålesund were 1.6%, 3.7%, and 6.2% above the long-term means, respectively. For Ny-Ålesund, this represents the highest annual average value since systematic ground-based ozone measurements started in 1997.**
- **At all Norwegian monitoring stations, a significant stratospheric ozone decrease was recorded for the period 1979 to 1997. For the period 1998 to 2024, there were no significant trends in the ozone layer above Norway.**
- **In general, low annual total UV doses were recorded at the three Norwegian stations in 2024, largely caused by high annual average ozone values**
- **Meteorological variability has a large impact on ozone and UV and can give considerable year-to-year variations.**

Total 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 and usually breaks down during spring. However, in 2024 this polar vortex was weaker than normal and for the Arctic as a whole, the ozone column in March 2024 reached the highest values since the start of the satellite era in 1979 (Newman et al., 2024). The elevated ozone levels were primarily due to enhanced ozone concentrations in the lower stratosphere, driven by persistent upward-propagating planetary wave events and two major sudden stratospheric warmings (SSWs)[1]. These wave events

[1] Sudden Stratospheric Warming (SSW) is a rapid increase in temperature in the stratosphere, particularly over the polar regions, disrupting the usual westerly winds. It can have significant impacts on weather patterns, including shifting the polar vortex and influencing surface weather conditions.

weakened the polar vortex, warmed the stratosphere, and enhanced poleward transport of ozone, resulting in cumulative (stepwise) ozone increases throughout the 2023-2024 winter (Newman et al., 2024; Butler et al., 2025). Exceptionally high total ozone persisted into the summer, and the ozone anomalies also extended beyond the Arctic, influencing the Northern Hemisphere (NH) mid-latitudes.

In 2024 the annual total ozone means at Kjeller, Andøya, and Ny-Ålesund were 1.6%, 3.7%, and 6.2% above the 1979-1989 reference values[2] (also called long-term means), respectively. For Ny-Ålesund, this represents the highest annual average value since the systematic ground-based ozone measurements started in 1997. The monthly mean total ozone column in Ny-Ålesund was especially high in March, i.e. 13.2% above the long-term mean for this month. High total ozone values were also recorded further south. In June and July, the monthly mean total ozone values at Kjeller were 383 Dobson units (DU)[3] and 360 DU, which are 10% and 7% above the long-term means, respectively. These are the highest June and July values measured in Oslo or Kjeller since the start in 1979. Also, at Andøya a record high total ozone average for July was measured, i.e. 337 DU, which is 4% above the long-term mean for July.

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 242 DU was measured 10 December 2024, which was 25% below the long-term mean of 299 DU for December. At Andøya, the minimum ozone value measured by the ground-based instruments was also 242 DU (26 October), ~14% below the long-term mean of 301 DU for this month.

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. 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 UV index (UVI) is a number on a scale from 0 to 11+ that describes the intensity of the UV radiation. A UVI value above 5 is classified as “high” and sunburn will likely occur without sun protection. The highest noon average UVI at Kjeller in 2024 was 6.2, measured on 26 June. UVI values between 6 and 7 are not very unusual in Southern Norway on sunny days in late June and early July. At Andøya, the highest noon average UVI in 2024 was 4.5, observed on 16 June. In Ny-Ålesund, a maximum noon average UVI of 2.5 was observed on 22 June. These peak UVI values at Andøya and Ny-Ålesund are typical for low and high Arctic latitudes, respectively.

In 2024, the annual integrated UV dose at Kjeller was 362.8 kJ/m^2, which was the 18^h highest annual UV dose measured in Oslo or Kjeller since 1995, roughly 14% below the maximum value from 2018. At Andøya, the annual UV dose of 249.5 kJ/m^2 was only ranked as the 15th highest since 1996, despite nice weather and relatively high UV levels in July. The annual UV dose at Andøya was around 11% below the maximum value

[2] Ideally, the period prior to 1980 should serve as a reference for total ozone columns unaffected by CFCs. However, due to lack of reliable Norwegian ground-based measurements from the 1970s, data from the period 1979-1989 are used.

[3] 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”.

from 1997, but 1% above the mean value for the period 1996-2024. In Ny-Ålesund the annual UV dose in 2024 was 186.4 kJ/m^2, which was ~9% below the 1996-2024 average. This dose was the 6th lowest (24th highest) value measured since 1995 and was 19% below the peak value from year 2009. In general, the low annual integrated UV doses were partly caused by high annual average ozone values at all stations. In addition, cloudiness strongly influences the amount of UV radiation that reaches the ground.

Trend analyses indicate that the annual average UV dose has increased by 2-3% per decade in Oslo/Kjeller from 1995 until 2024. Contrary to Oslo/Kjeller, trends of around -1% per decade have been registered at Andøya and Ny-Ålesund. 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 CFCs contain chlorine (Cl), which might react with ozone (O_3) in the stratosphere and destroy ozone molecules. 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 CFCs. However, HFCs, the second-generation replacements for CFCs, are increasing in concentration, even if current levels remain low.

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. Another very important ODS is N_2O, which currently is the most significant ozone-depleting substance being emitted (UNEP, 2024a). Thus, ambitious actions to reduce N_2O is critical for achieving both climate goals and the recovery of the ozone layer.

Coupling of stratospheric ozone and climate

The expected future recovery of stratospheric ozone might be affected by climate change (WMO, 2022). 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 assume full compliance with the Montreal Protocol and are based on baseline estimates 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 is 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, and 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 2024, % per decade	0.7 (±1.0)	-0.1 (±1.2)	0.1 (±1.8)
Annual average total ozone 2024, DU (rank*)	348.4 (6)	356.7 (2)	364.8 (1)
UV			
Annual UV dose 2024, kJ/m^2 (rank**)	362.8 (18)	249.5 (15)	186.4 (24)

*"Rank" indicates how the annual average total ozone was in 2024 compared to other years.
**"Rank" indicates how high the UV dose was in 2024 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 tropical 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 convert it back to O_2, leading to ozone destruction. The Cl and NO radicals mainly originate from stratospheric CFCs and N_2O, respectively.
- Ozone that is formed in the tropical stratosphere is transported to polar regions. The largest transport of ozone rich air from equatorial to polar regions takes place during the winter season, when the temperature gradient is largest. This causes maximum stratospheric ozone values over Norway in March and April.
- From May to October the ozone layer over Norway gradually decreases 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 (Steinbrect et al., 1998). Also, winds in the stratosphere move ozone-rich or ozone-poor air around.
- Some years the winter polar vortex (a cold stratospheric cyclone) 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) are formed. Chemical reactions on the PSC particle surfaces can convert chlorine-containing substances (e.g. CFCs) to highly reactive chlorine gas ClO, which destroys ozone in the presence of sunlight.

1 Norwegian ozone measurements in 2024

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. 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 observatory.

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 SAOZ instrument in Ny-Ålesund runs side-by-side with a Brewer spectrophotometer operated by the Institute of Polar Sciences, National Research Council of Italy, and a relatively 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 B for more details). In addition, NILU analyses total ozone data from various satellites to obtain 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)[3].

Since Brewer is the world standard reference instrument and the Brewer direct sun (DS)[4] are considered the most accurate, we normally select these measurements on sunny days. The SAOZ instrument is the preferred instrument when the solar zenith angles are large in Ny-Ålesund, whereas Brewer global irradiance (GI)[5] and GUV are used on cloudy days. For each day we have selected the observations that are considered most accurate.

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). In 2024, direct sun measurements were performed on 196 out of 366 days. During overcast days or days where the minimum solar zenith angle was larger than 75°, the ozone values were calculated with the Brewer global irradiance (GI) method (Stamnes et al., 1991). The Brewer GI method was used on 97 days. On days with missing or uncertain Brewer measurements, e.g. in winter when Brewer occasionally can be covered by snow, total ozone was 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 70 days in 2024. A summary of instrument frequency in the data set is given in Table 1. In 2024, there were three days without ozone measurements, caused by heavy clouds.

As seen from Figure 1 there can be large day-to-day fluctuations in total ozone. 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 (see solid red line in Figure 1), but in 2024 a minimum ozone value of 242 DU was measured 10 December. This is 25% below the long-term mean for December. On 10 January another seasonal ozone minimum of 252 DU was measured, 26% below the long-term January mean. However, the ozone layer reached a normal level a few days later.

The monthly mean total ozone values in 2024 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 2024 were above normal most of the year, except from March and December. In June and July, the monthly average ozone values were 383 DU and 360 DU, which are 10% and 7% above the long-term

[4] Direct sun (DS) measurement means that an instrument is pointing directly towards the sun and measure radiation from the solar beam.

[5] 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.

means, respectively. These are the highest June and July values measured in Oslo or at Kjeller since the start in 1979. Section 2.5 provides a broader discussion of the ozone situation in Norway in 2024.

Table 1: Overview of instruments and methods used in the total ozone time series from Kjeller in 2024. Numbers in parentheses show the total days with measurements available from each instrument. In 2024 the time series included 196 Brewer DS values, 97 Brewer GI values and 70 GUV values.

Priority	Method	Total days with observations
1	Brewer #42 instrument, direct sun measurements	196 (196)
2	Brewer #42 instrument, global irradiance method	97 (340)
3	GUV-511 instrument	70 (357)
	Missing days	3

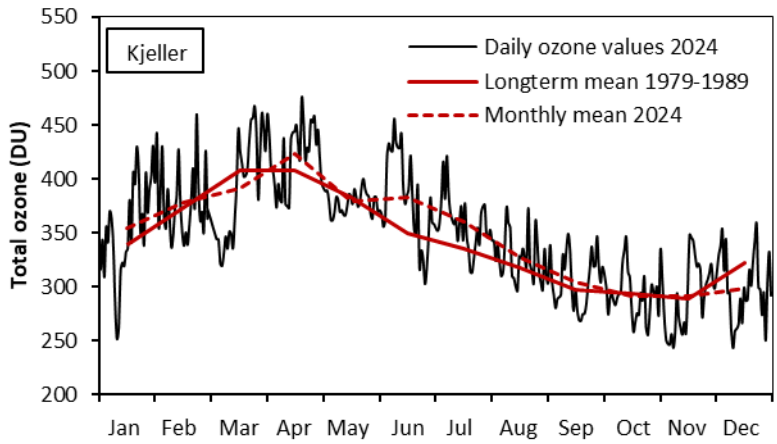

Figure 1: Daily total ozone values at Kjeller in 2024 (black). The red curve shows the long-term monthly mean values from Oslo 1979-1989. The red dashed line is monthly mean ozone values in 2024.

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 larger than 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.

Both the Brewer and GUV instruments at Andøya ran without major interruptions in 2024. There were two days without total ozone retrievals, both days caused by heavy clouds and large data uncertainty. In addition, ozone was not retrieved during the polar night period and the weeks shortly before and after the polar night season (28 October to 14 February). Table 2 gives an overview of the different instruments and methods used at Andøya in 2024. Brewer DS data were used on 147 days, Brewer GI provided daily ozone values on 105 days, whereas GUV was used 2 days with absent GI measurements.

Table 2: Overview of instruments and methods used in the total ozone time series from Andøya in 2024. Numbers in parentheses show the number of days with measurements available from each instrument between 15 February and 27 October (256 days). In 2024 the final ozone time series included 147 Brewer DS values, 105 Brewer GI values and 2 GUV ozone values.

Priority	Method	Total days with observations
1	Brewer #104 instrument, direct sun measurements	147 (173)
2	Brewer #104 instrument, global irradiance method	105 (250)
3	GUV-541 instrument	2 (253)
	Missing days (except dark period, 28 Oct - 14 Feb)	2

Figure 2 shows daily ozone values from Andøya in 2024. The lowest ozone values normally occur in October and November (Figure 2). The minimum ozone value measured by the ground-based instruments in 2024 was 242 DU, measured 26 October. This is ~14% below the long-term October mean. The GOME-2B satellite also registered low ozone values during the polar night period, with a minimum of 228 DU on 9 January 2024. It is also worth mentioning the high ozone values measured from mid-March to early April, with values up to 540 DU on 26 March. A broader description of this is given in Chapter 2.5.

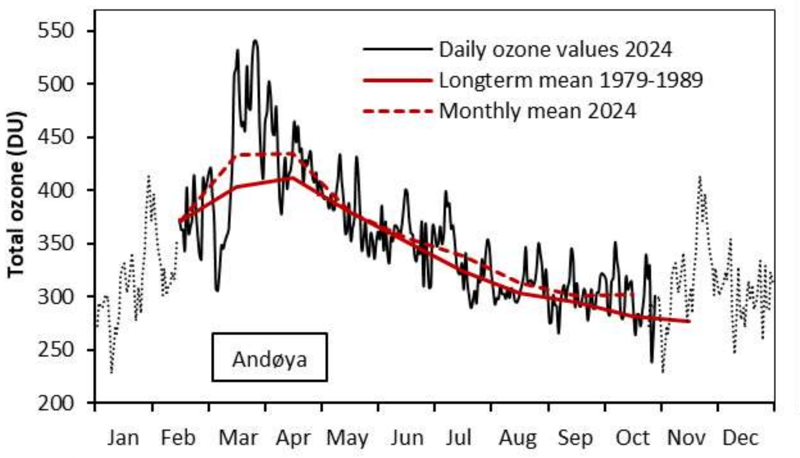

Figure 2: Daily total ozone values measured at ALOMAR, Andøya, in 2024 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989, whereas the red dashed line is monthly mean ozone values in 2024. The black dotted line represents GOME-2B satellite measurements.

Monthly mean ozone values at Andøya in 2024 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 2024 shows that the 2024 values were above normal all year, except from May. Like Kjeller, the monthly average total ozone for July (337 DU) was the highest July average value registered since the systematic ground-based ozone measurements started in Tromsø/Andøya in 1995.

1.3 Total ozone in Ny-Ålesund

Ny-Ålesund is a high latitude site (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, e.g., the Brewer and GUV instruments, are based on UV absorption techniques, the SAOZ instrument uses radiation from the visible part of the solar spectrum. The latter 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 Pandora UV/visible spectrometer was put into operation. The data from this instrument has become an important add on to the total ozone series from Ny-Ålesund.

NILU's total ozone monitoring instruments in Ny-Ålesund are all located at the observation platform of the Sverdrup Station of the Norwegian Polar Institute (see Appendix B for more details). In addition, NILU has access to data from an Italian Brewer (B50) instrument installed side-by-side with the NILU instruments at the Sverdrup station. There have been some technical challenges with B50 the last few years, but the problem was identified and resolved by the International Ozone Services (IOS) in July 2023. The Italian Brewer measurements are currently used as a backup and data quality assurance.

All the ozone monitoring instruments worked satisfactorily in 2024. Altogether there were two days without measurements (except for the polar night period) caused by harsh measuring conditions one day in early March and late October. Table 3 gives an overview of the different instruments and measurement methods used for the 2024 total ozone time series in Ny-Ålesund. For the regular time series, 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. However, for the first time, Brewer total ozone measurements were analysed from the moon light. These moon measurements, marked as yellow diamonds in Figure 3, can be performed on clear days close to full moon. Thus, there are relatively few days with moon measurements during the winter season.

Figure 3 shows daily ozone values from Ny-Ålesund in 2024. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989. Due to lack of ground-based ozone measurements in Ny-Ålesund in the 1970s and 1980s, data from TOMS (Total ozone Mapping Spectrometer) satellite instrument is used to calculate the 1979-1989 reference. Total ozone values during winter (November to mid-February) are not achievable due to absence of sunlight, but similar to Andøya, GOME-2B satellite data have been used to indicate the ozone values for the polar night period, shown by the dotted line in Figure 3. Also, Brewer moon measurements are shown in Figure 3. Like in Oslo and Andøya, the lowest ozone values in Ny-Ålesund normally occur in October and November. However, in 2024 no extremely low ozone values were recorded. Instead, it was registered very high total ozone values in March, with a maximum of 542 DU on 17 March, which is 28% above the long-term mean for March. In total, 2024 showed the highest annual average value since systematic ground-based ozone measurements began in 1997.

Table 3: Overview of instruments used in the total ozone time series from Ny-Ålesund in 2024. Numbers in parentheses show the number of days with measurements available from each instrument between 17 February and 24 October (251 days). In 2024 the final ozone time series included 69 Pandora, 86 SAOZ and 94 GUV ozone values.

Priority	Method	Total days with observations
1	Brewer #50 instrument	0 (108)
2	Pandora	69 (69)
3	SAOZ instrument	86 (144)
4	GUV-541 instrument	94 (237)
	Missing days (except dark period, 25 Oct - 16 Feb)	2

Monthly mean total ozone values in Ny-Ålesund 2024 are shown in Figure 3 (red dashed line). Comparison between the 2024 values and the long-term 1979 to 1989 monthly means demonstrate that the 2024 values were above the long-term mean all months except from February.

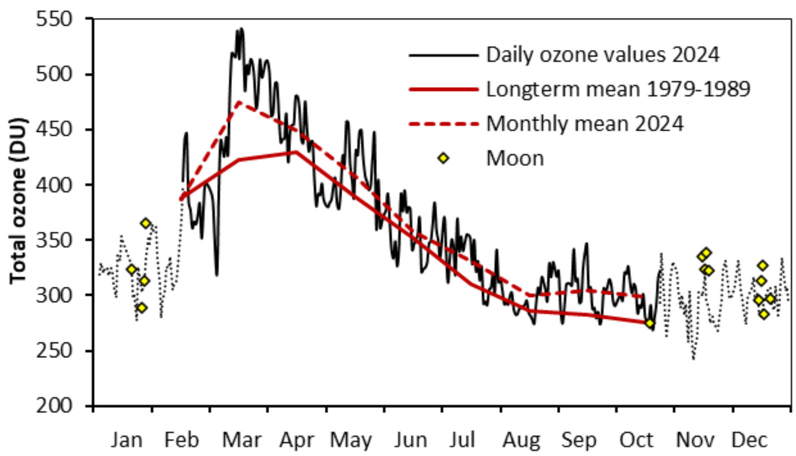

Figure 3: Daily total ozone values measured in Ny-Ålesund in 2024 by the Panora, SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 to 1989, whereas the dashed red line is monthly mean values for 2024. The black dotted line represents GOME-2B satellite measurements. Yellow diamonds show Brewer moon neasurements.

2 Ozone measurements and trends 1979 to 2024

2.1 Background: WMO/UNEP reports and global highlights

Since the early 1990s, the World Meteorological Organisation (WMO) and United Nations Environment Programme (UNEP) have published assessment reports on 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 declined by 11.5% from the 1993 peak value. Total bromine 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 to 1980 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 (35°N to 60°N) 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 2066. 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 the ODS concentrations are well above natural levels. It should be mentioned that the uncertainty range of ozone recovery is relatively wide. For Antarctica the range of ozone recovery spans from years 2049 to 2077, caused by modelled differences in meteorology and dynamical variability (WMO, 2022). The recovery dates also vary with climate scenario: in higher GHG scenarios (SSP3-7.0, SSP5-8.5), the return occurs up to 15 years earlier. For the Arctic springtime total column ozone, the range of recovery years are 2029–2051 (WMO, 2022).

Changes in CO_2, N_2O, and CH_4 will have an increasing influence on the ozone layer in the future. A recent report from UNEP (2024a) emphasizes the importance on N_2O on the ozone layer. Nitrous oxide is the most significant ODS currently being emitted to the atmosphere, as its anthropogenic emissions are increasing, and the Montral Protocol has succeeded in controlling emissions of long-lived halogenated ODSs. Also, emissions of CO_2 and methane will affect future evolution of the stratospheric ozone layer through chemical, radiative and dynamic feedback mechanisms, and the net effect on the ozone layer strongly depends on which greenhouse gas pathway is followed (Butler et al., 2016). Figure 4 shows the predicted development of the ozone layer based on the SSP2-4.5 scenario, which is a "middle of the road" emission scenario and assumes that the world follows a path with social, economic, and technological development like past trends. For this pathway N_2O will be the main ODS towards the end of this century, whereas CO_2 and methane will lead to higher ozone and outweigh the ozone decrease from ODSs and result in a global-average return to 1980 ozone levels around 2060.

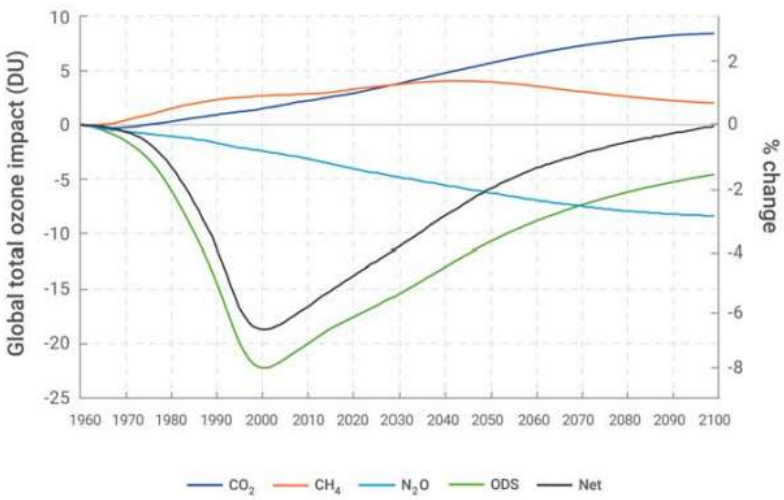

Figure 4: Changes in global-average total column ozone due to separate impacts of carbon dioxide, methane, nitrous oxides and long-lived halogenated ozone depleting substance, 1960–2100, relative to 1960 (From Figure 4.11 in UNEP, 2024a).

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, from 2012 to 2019 the rate of decline slowed down due to unreported production in China (Rigby et al., 2019). 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).

It should also be mentioned another uncertainty regarding total ozone recovery. In the publication by Ferreira et al. (2024), it is described what can happen when satellites burn up in the atmosphere on re-entry from space: aluminium in spacecraft materials forms aluminium oxide nanoparticles that can catalyse chlorine activation and, in turn, deplete stratospheric ozone. Overall, the study highlights satellite debris as a long-lived ozone risk that should be followed carefully.

2.2 Trends for Oslo/Kjeller 1979 to 2024

The total ozone time series from Oslo/Kjeller consists of ground-based measurements with Dobson no. 56, Brewer no. 42, and GUV-511. In 2019, the Brewer and GUV instruments were moved to Kjeller (NILU), approximately 18 km east of the original site at the University of Oslo (see Appendix A for more details).

Figure 5a shows the variations in monthly mean ozone values above Oslo/Kjeller for the period 1979 to 2024. 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 (see information box “Ozone production, destruction and transport”). During summer there will be a gradual depletion of the ozone layer.

To make ozone trend analyses for the period 1979 to 2024 we have removed the seasonal variations by subtracting the long-term monthly mean ozone values from the data series, shown in Figure 5b. Next, we have divided the time series into two periods: 1) 1978 to 1997, and 2) 1998 to 2024. For the first time period the ozone measurements were entirely derived from the Dobson instrument and reflect a period when a gradual decline in stratospheric ozone was observed at most mid- and high-latitude stations. This decrease was intensified by the major Mt. Pinatubo volcanic eruption in 1991 and the cold Arctic winters in 1996 and 1997 (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 (1998-2024) 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[6] (1σ) 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.

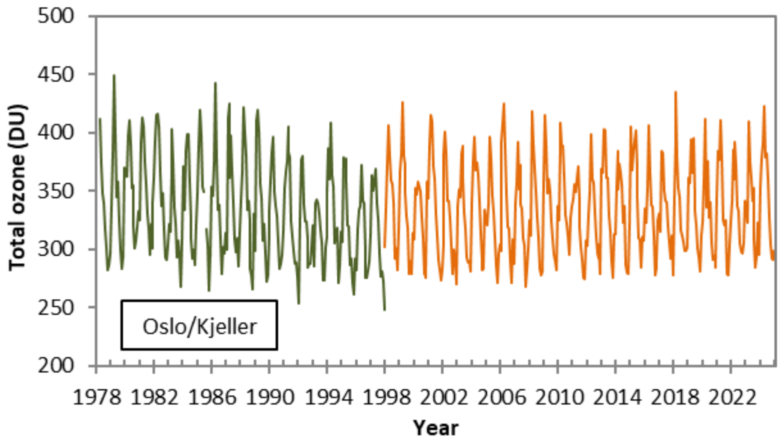

Figure 5a: Time series of monthly mean total ozone in Oslo and at Kjeller 1979 to 2024. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements.

[6] 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.

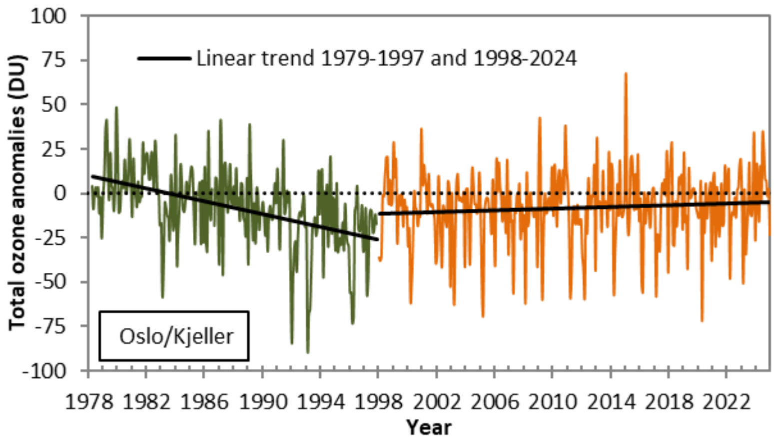

Figure 5b: Variation in total ozone over Oslo/Kjeller for the period 1979 to 2024 after the seasonal variations have been removed. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements. Trend lines are marked as black lines.

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 2024 the picture is different. There are substantial year-to-year fluctuations, and it is difficult 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 +1.8%/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 2024 is +0.7% /decade.

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 01.01.1979 to 31.12.2024. 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 1998-2024 (%/decade)
Winter (Dec – Feb)	-6.0 (2.3)	1.4 (1.2)
Spring (Mar – May)	-8.0 (1.3)	0.3 (0.9)
Summer (Jun – Aug)	-3.5 (1.0)	-0.1 (0.6)
Fall (Sep – Nov)	-4.2 (1.0)	1.8 (0.6)
Annual (Jan – Dec):	-5.9 (1.0)	0.7 (0.5)

2.3 Trends for Andøya/Tromsø 1979 to 2024

The total ozone time series from Tromsø consists of ground-based measurements with Brewer no. 104 and GUV-541. In 2000, the two instrument were moved to Andøya, approximately 130 km West-southwest of Tromsø (see Appendix A for more details)

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 6a shows the variation in the monthly mean ozone values at Andøya and Tromsø from 1979 to 2024. The variations in total ozone, after removing the seasonal cycle, are shown in Figure 6b, together with the annual trends. November to February are not included in the trend analysis due to lack of data and uncertainties in ozone retrieval during the period with low solar elevation. Simple linear regression lines have been fitted to the data in Figure 6b. Similar to the Oslo site we have divided the ozone time series into two periods: 1) 1979 to 1997, and 2) 1998 to 2024. The results of the trend analyses are summarized in Table 5. Comparison of Figure 5b and Figure 6b 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 2024, there is an ozone increase of +1.4%/decade for the fall, but no significant trends for the other seasons. The annual ozone trend from 1998 to 2024 is close to zero.

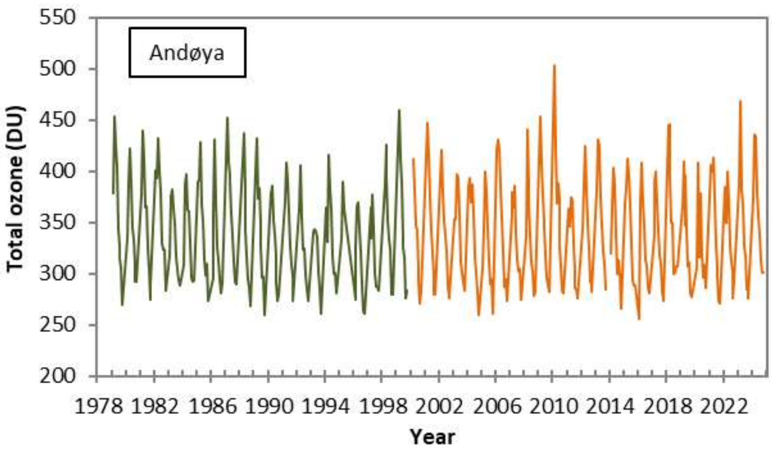

Figure 6a: Time series of monthly mean total ozone at Andøya and Tromsø 1979 to 2024. The green line represents total ozone from Tromsø, the orange line represents measurements at Andøya.

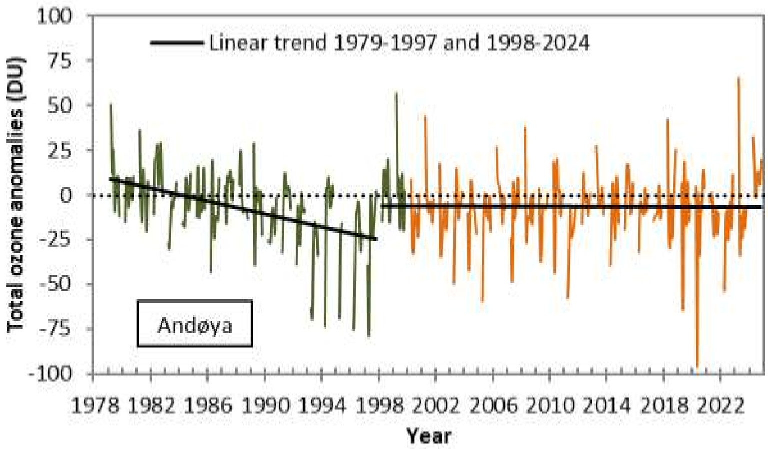

Figure 6b: Variations and trends in total ozone at Andøya for the period 1979 to 2024 after the seasonal variations are removed. Only data for the months March to October are included. The green line represents total ozone from Tromsø, whereas orange line represents measurements at Andøya.

Table 5: Percentage changes in total ozone at Andøya for the periods 1) 1979-1997, and 2) 1998- 2024. Numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is statistically significant.

Season	Trend 1979-1997 (%/decade)	Trend 1998-2024 (%/decade)
Spring (Mar – May)	-7.5 (1.5)	-0.4 (1.0)
Summer (Jun – Aug)	-3.4 (1.0)	-0.6 (0.6)
Fall (Sep – Oct)	-3.4 (1.1)	1.4 (0.7)
Annual (Mar – Oct)	-5.2 (1.0)	-0.1 (0.6)

2.4 Trends for Ny-Ålesund 1979 to 2024

The time series of daily total ozone values in Ny-Ålesund is composed of data from various instruments and measurement techniques. The history and installation of the various instruments is described in Appendix A.

The ozone measurements presented in Figure 7a and Figure 7b 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 26 years, only ground-based measurements have been used to calculate the mean values: Dobson, Brewer and/or Pandora data are included when available, SAOZ data are used in the spring and fall, whereas GUV data are used under cloudy conditions and 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 7b 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 large decrease in winter and spring is consistent with ozone depletion caused by PSC formation in winter, where chemical reactions on the PSC particle surface can convert CFCs into reactive chlorine that destroys ozone. The annual trend in total ozone column was -5.9%/decade during this early period. For the second period 1998-2024 the seasonal trends are much smaller. A non-significant statistical trend of +1.4%/decade is estimated for the fall, whereas a non-significant statistical trend of -1.0%/decade is found for the summer months. Figure 7b also shows that the annual trend for the period 1998-2024 is close to zero, i.e. +0.1%/decade. It can be mentioned that the 1979-1989 total ozone average for Ny-Ålesund is calculated from TOMS satellite data, which normally is 1-2% lower than the ground-based measurements (see Chapter 3).

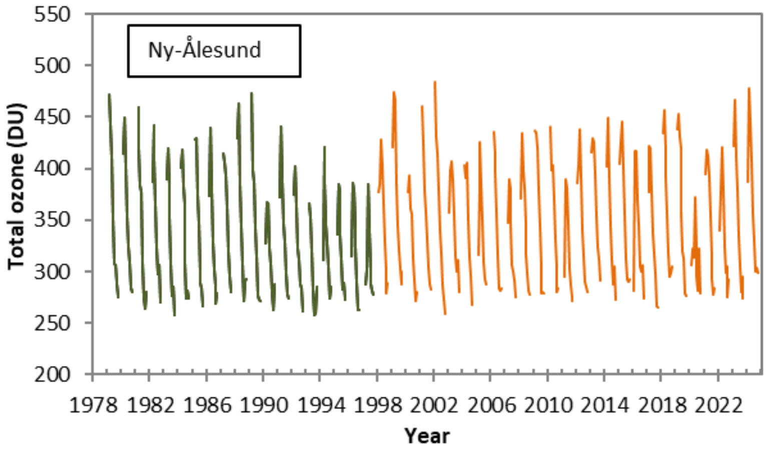

Figure 7a: Time series of monthly mean total ozone at Ny-Ålesund 1979 to 2024. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments.

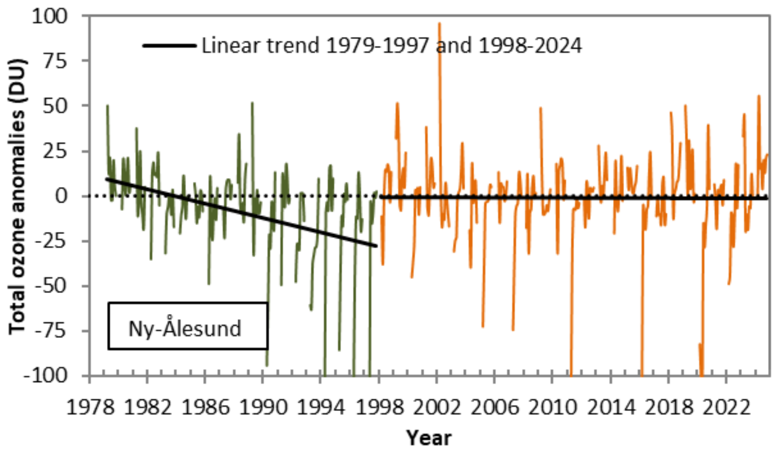

Figure 7b: Variations in total ozone at Ny-Ålesund for the period 1979 to 2024. Only data for the months March to October are included. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments. Trends for the two periods 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 2024. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered statistically significant.

Season	Trend 1979-1997 (%/decade)	Trend 1998-2024 (%/decade)
Spring (Mar – May)	-10.8 (1.7)	0.4 (1.5)
Summer (Jun – Aug)	-2.4 (1.2)	-1.0 (0.6)
Fall (Sep – Oct)	-1.2 (1.0)	1.4 (0.8)
Annual (Mar – Oct)	-5.9 (1.1)	0.1 (0.9)

2.5 The overall Norwegian ozone situation in 2024

As seen from Figure 1 to Figure 3 the ozone layer above Norway was relatively thick in 2024, especially at Andøya and Ny-Ålesund. For the Arctic as a whole (63°N- 90°N), the ozone column in March 2024 reached a record high of 477 DU - the highest since the start of the satellite era in 1979 (Newman et al., 2024). This was 14.5% (60 DU) above the 1979–2023 average of 416 DU. The elevated ozone levels were primarily due to enhanced ozone concentrations in the lower stratosphere (up to ~20 km altitude), driven by persistent upward-propagating planetary wave events. These wave events weakened the polar vortex, warmed the stratosphere, and enhanced poleward transport of ozone to the Arctic, resulting in cumulative (stepwise) ozone increases throughout the 2023-2024 winter (Newman et al., 2024). Exceptionally high total ozone persisted into the summer, with an Arctic average of 417 DU in May 2024, which also was a record over the 1979–2024 period. The ozone anomalies also extended beyond the Arctic, influencing the Northern Hemisphere (NH) mid-latitudes.

The high 2024 ozone values can be seen from the positive and red numbers in Table 7. At Andøya and in Ny-Ålesund, the March values were 8.0% and 13.2% above the long-term March mean values, respectively. For Ny-Ålesund this is the highest March value that has been registered after the SOAZ measurements started in 1990. Similarly, Andøya noted a new record for July, and at Kjeller it was measured the highest June and July averages since 1979. From June to September the ozone values were above the long-term means at all the Norwegian stations.

Figure 8, Figure 9 and Figure 10 show the percentage difference between yearly mean total ozone and the long-term yearly means 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).

Table 7: Percentage difference between the monthly mean total ozone values in 2024 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	4.6		
February	1.2	0.5	-0.1
March	-3.9	8.0	13.2
April	3.7	5.0	3.6
May	-0.9	-0.3	4.7
June	9.7	1.2	1.1
July	7.4	4.0	6.5
August	2.5	2.7	4.6
September	2.4	2.0	7.6
October	-0.5	6.9	8.5
November	0.8		
December	-7.3		

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 (before the CFC related ozone depletion was evident) and in 2010, 2013, 2015, and 2024. 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 10). The Ny-Ålesund station was at the core of the strong polar vortex in the winter and spring 2020, which caused more severe ozone depletion at this station compared to Oslo and Andøya. In 2024 the annual ozone means were 1.6%, 3.7%, and 6.2% above the long-term means at Kjeller, Andøya, and Ny-Ålesund, respectively. For Ny-Ålesund, this represents the highest annual average value since the systematic ground-based ozone measurements started in 1997.

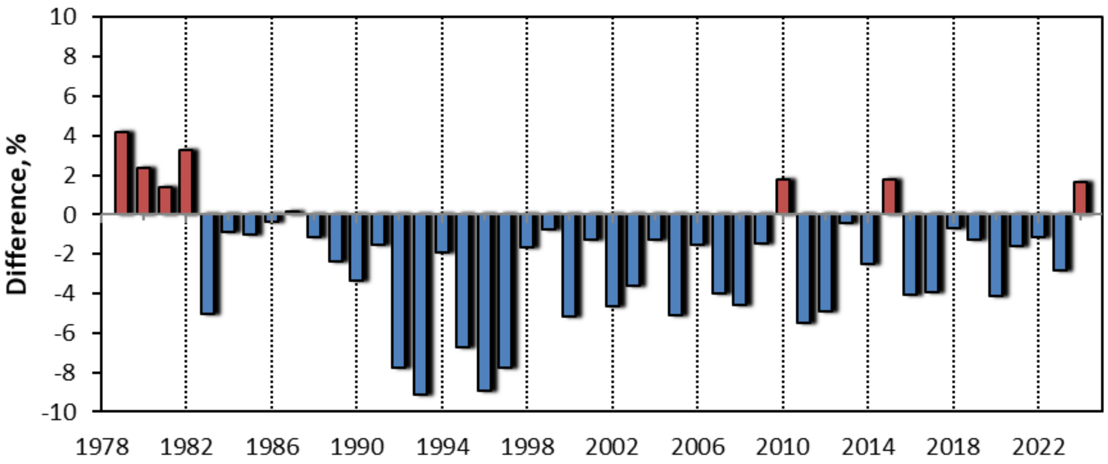

Figure 8: *Percentage difference between yearly mean total ozone in Oslo/Kjeller and the long-term yearly mean 1979 to 1989. Red numbers represent positive differences, whereas blue numbers are negative differences.*

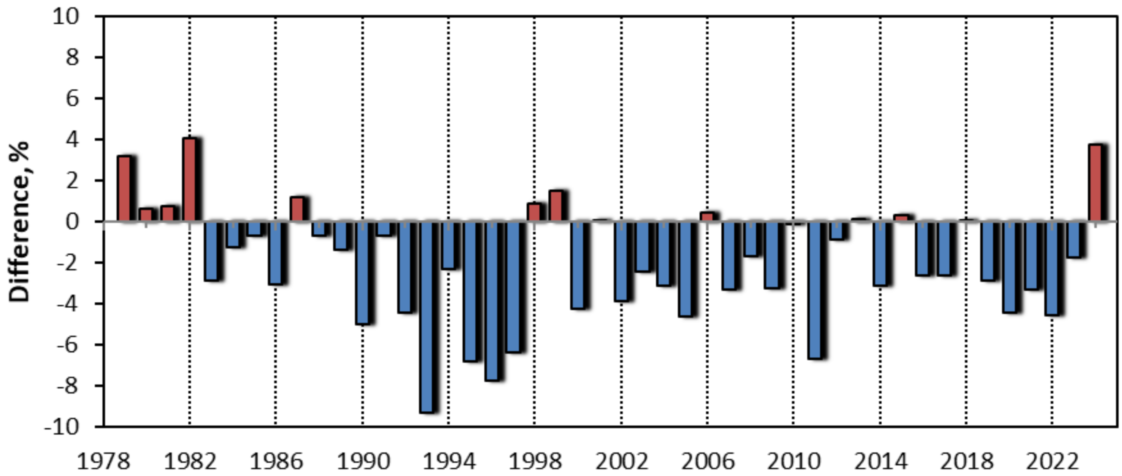

Figure 9: *Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean1979 to 1989 for March to October.*

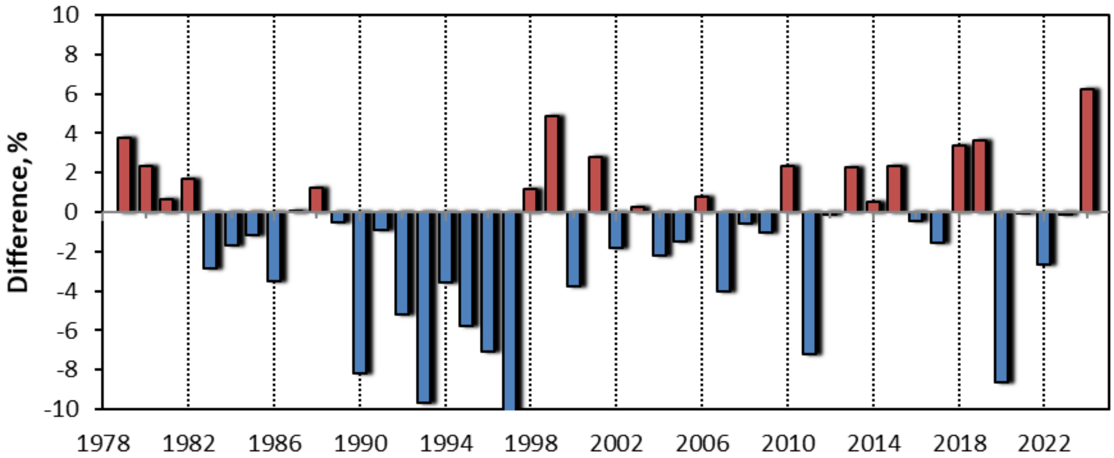

Figure 10: *Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.*

2.6 Ozone and UV measurements at Trollhaugen

In 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 Trollhaugen 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 18 years of operation, the data set also provides valuable information about the long-term stability of the instrument. With the additional Pandora instrument installed, measurements can also be performed during the polar night, as the Pandora is set up to measure moonlight in addition to sunlight.

Figure 11, upper panel, shows NILU-UV total ozone values from Trollhaugen (black) and total ozone values from GOME-2B (green) at the SANAE station about 190 km northwest of Troll. The seasonal cycle with total ozone values far below 220 DU (ozone hole) is seen from September to November every year. In 2024, Trollhaugen was included in the Global Atmosphere Watch Programme (GAW), which automatically provides easy access to OMI overpass data (https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMDOAO3/), represented by orange dots in Figure 11. As seen from the figure, ground-based and satellite data are in good agreement.

There are several studies showing that the actions taken under the Montreal Protocol to reduce ODSs are working and that we currently can see signs of ozone recovery in Antarctica (Solomon et al., 2016; Wang et al., 2025). In 2024, the average extent of the ozone hole was 20 million km^2, making it the 7th smallest ozone hole since regulation of ozone-harming chemicals began in the early 1990s (https://ozone.unep.org/2024-ozone-hole-ranked-7th-smallest-recovery-began). The red line in Figure 12, provided CAMS/ECMWF, shows that the Antarctic ozone hole in 2024 was smaller than the 2022 and 2023 ozone holes most of the time.

A minimum ozone value of 125 DU was measured by the NILU-UV instrument 28 September 2024, but due to Antarctic winter/spring with low solar elevation in September, the UV index was relatively modest. The total ozone values gradually increased from late September until mid-November; however, a new ozone decrease was recorded on 25 November, with a total ozone value of 165 DU, which caused a UVI peak of 10.4 at Trollhaugen on this day. An UVI value above 10 is classified as "very high". The high UVI levels lasted for about 10 days, before the ozone hole closed and the total ozone values started to increase.

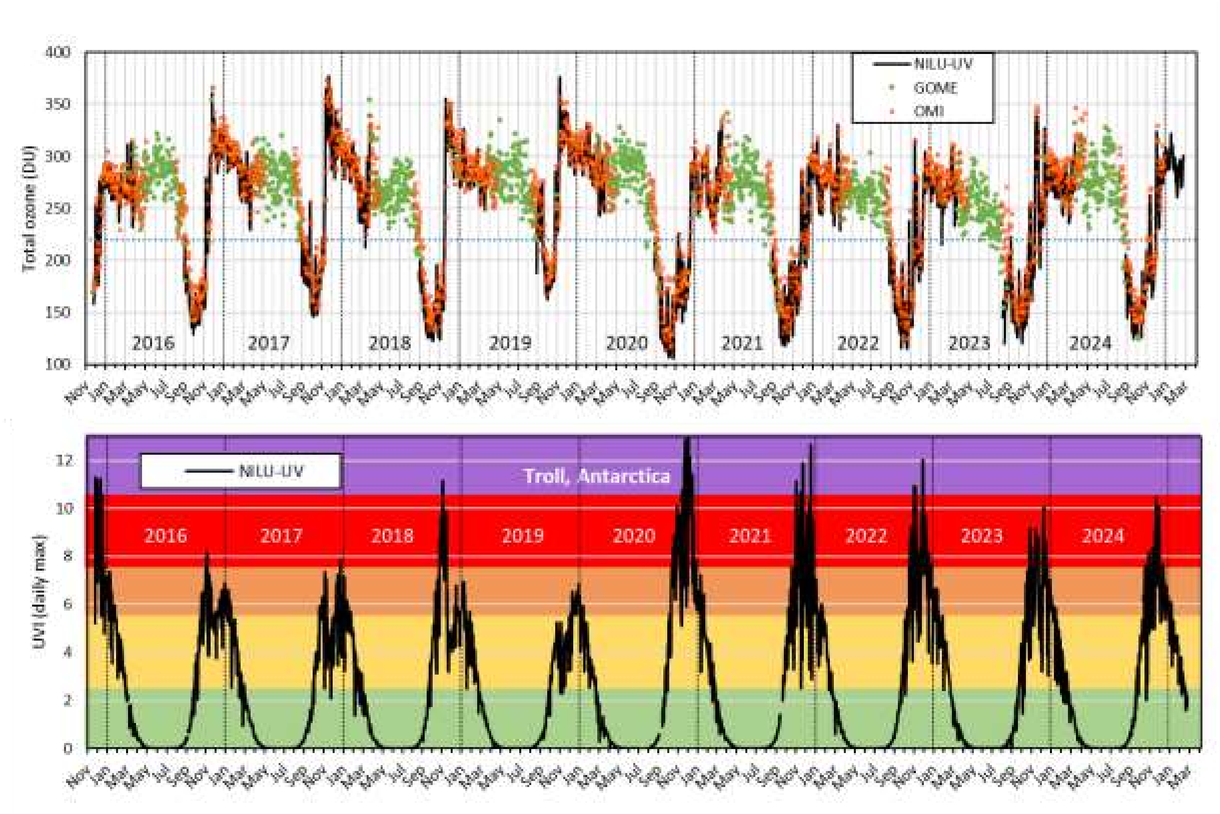

Figure 11: Upper panel: Total ozone from NILU-UV and OMI (at Trollhaugen) and GOME-2B (at SANAE) from November 2015 to March 2025. Lower panel: Noon time UVI from NILU-UV for the same period. The green, yellow, orange, red, and ultraviolet colours represent the UVI categories low, moderate, high, very high, and extreme, respectively.

The previous years from 2020-2023 witnessed large and long-lived ozone holes over Antarctica, and there are several reasons for this. In a paper from Yook et al. (2022) it was concluded that the main drivers of the large ozone holes in 2020 and 2021 were due to two distinct and extraordinary events, namely the Australian wildfires in late 2019 and early 2020, and the eruption of La Soufriere on the Caribbean Island in April 2021. From these events large amounts of aerosol were injected into the stratosphere, which enhanced ozone depletion. These events, combined with unusually weak stratospheric wave activity and strong polar vortices in both years, resulted in large and very persistent Antarctic ozone holes in 2020 and 2021.

The large Hunga Tonga-Hunga Ha'apai volcanic eruption in 2022, which injected several million tons of water vapor into Earth's atmosphere, is believed to explain a record early onset of the 2023 ozone hole in Antarctica (Fleming et al., 2024). The 2023 ozone hole also persisted longer than normal, not breaking up until late December. The long duration of the ozone hole was attributed to weaker planetary-scale wave activity[7] in late spring, which resulted in stronger-than-average circumpolar westerlies and colder-than-average temperatures in the stratosphere (Blunden and Boyer, 2024).

[7] Planetary waves are large-scale oscillations in the atmosphere that arise due to the Earth's rotation and the variation of the Coriolis force with latitude. They are typically generated in the troposphere and can propagate upward into the stratosphere where they can interact with the polar vortex and disturb it.

The ozone and UV measurements from the last years demonstrate that stratospheric ozone hole formation in Antarctica remains an environmental issue 40 years after its discovery and after implementation of international regulatory measures. The ODS 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), as described in Chapter 2.1.

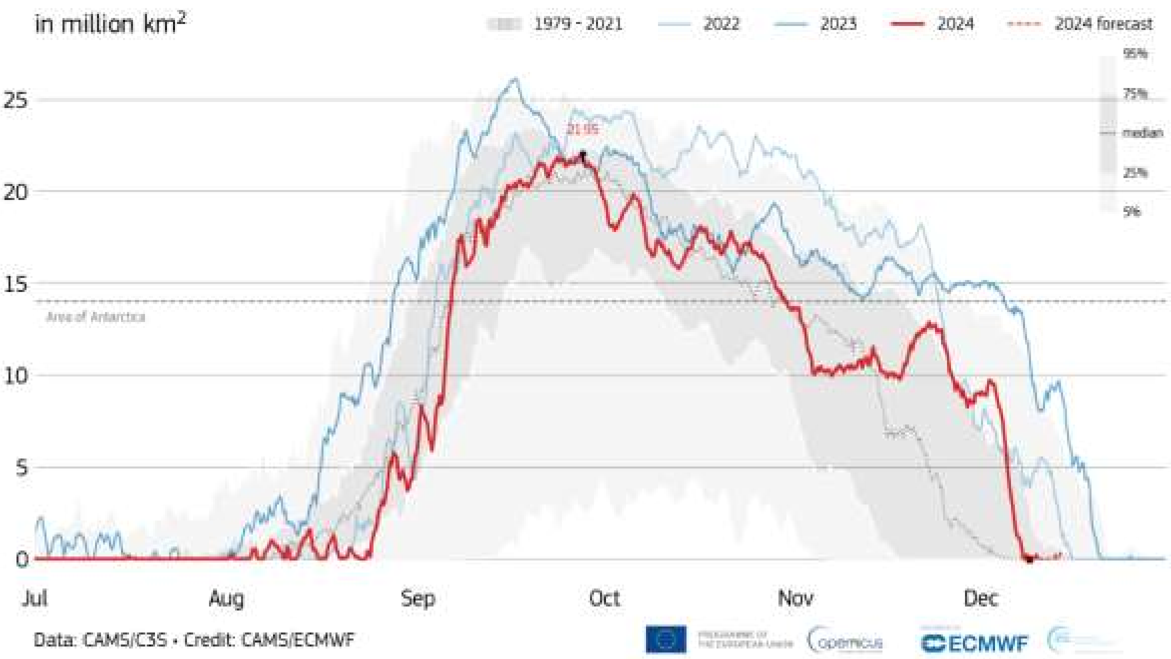

Figure 12: Time series of daily ozone hole area between July and December. The red line shows the data for 2024. The thicker, darker blue line is the evolution of the ozone hole during 2023, and the lighter blue line represents 2022. The grey colours represent the percentile values and the median between 1979 – 2021. (Figure from CAMS/ECMWF; https://atmosphere.copernicus.eu/ozone-hope-2024-one-smallest-ozone-holes-recent-years-closes)

3 Satellite observations of total ozone

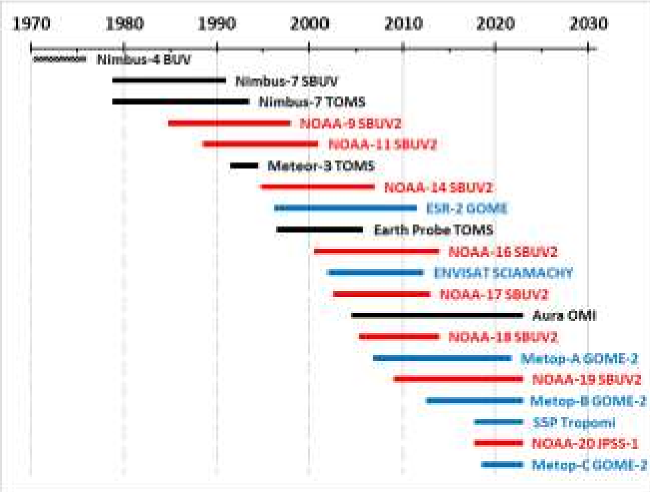

Figure 13: An overview of the most common satellites and their instruments measuring ozone from space since the beginning of the 1970's. NASA satellites are marked in black, ESA and EUMETSAT are in blue, whereas NOAA satellites are marked in red.

The amount and distribution of ozone in the stratosphere vary greatly over the globe and are 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 13 shows the different satellites that measure ozone and their operating periods. In addition to the satellites shown in Figure 13, total ozone is also measured from the Chinese Fen Yun 3 and Gaofen 5 satellites.

3.1 Satellite total ozone observations 1979 to 2024

Over the last 45 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 2024 (Figure 14). 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).

In Oslo/Kjeller and Andøya all GB-Satellite mean values are within ±1.3%, with standard deviation 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 2.7%. In general, there is a good agreement between ground-based total ozone measurements and satellite retrievals. More details about the GB-satellite comparison can be found in Appendix C (Table 10).

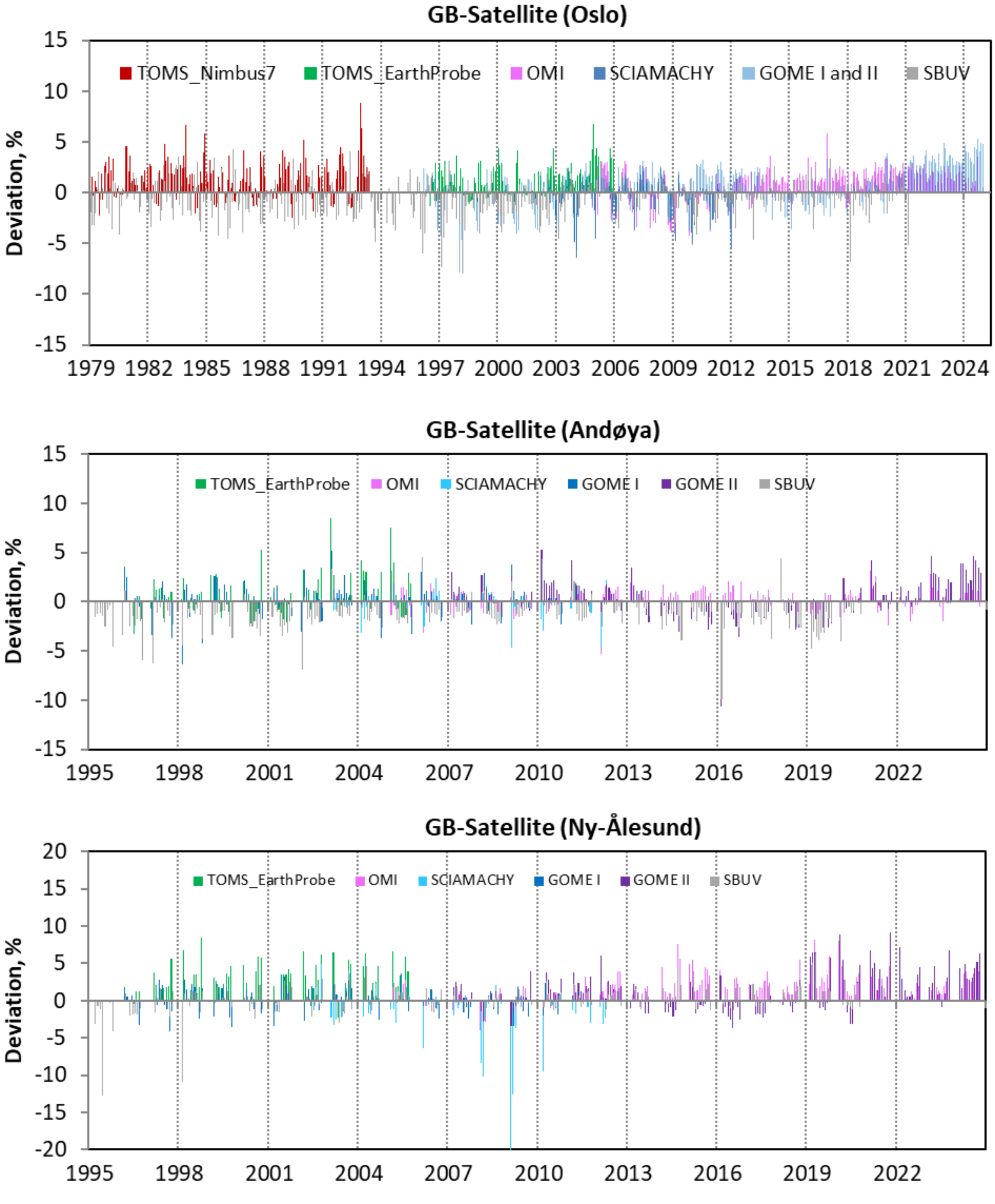

Figure 14: Difference between ground-based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2024 (Oslo/Kjeller) and 1995 to 2024 (Andøya and Ny-Ålesund). Deviations are given in %. Upper panel: Oslo/Kjeller, middle panel: Andøya, lower panel: Ny-Ålesund.

4 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[8] (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. Positive RF implies a warming of the Earth, whereas negative RF leads to cooling. 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 15 (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. As the ozone layer recovers, the negative forcing from stratospheric ozone loss will diminish. This means that over coming decades, the net ozone-related forcing could increase slightly (more positive), unless tropospheric ozone is strongly mitigated. 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 15 (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 Figure 15. Figure 15 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; Tian et al., 2023). An increase in greenhouse gases will warm the troposphere and cool the stratosphere. In general, a decrease in stratospheric

[8] 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.

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 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).

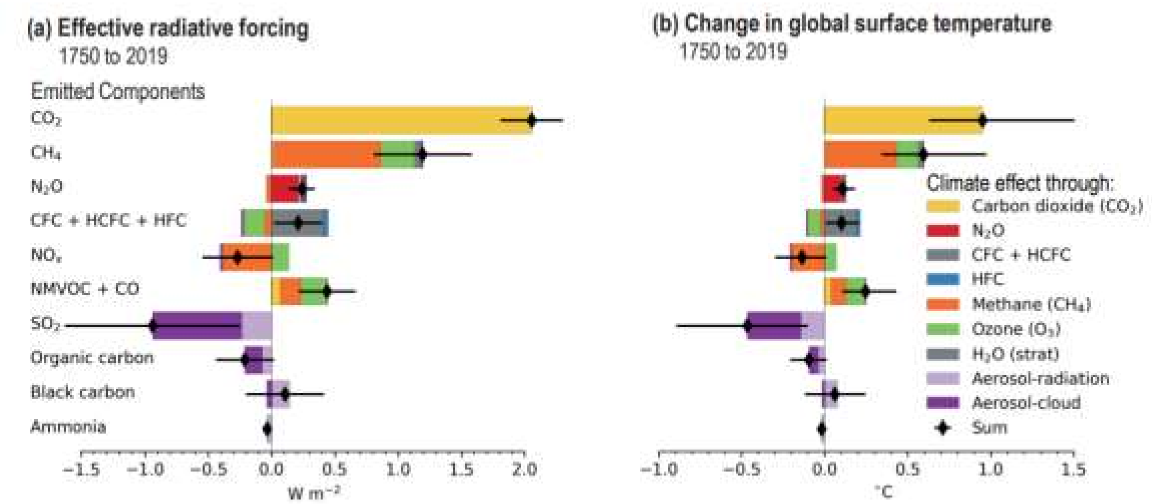

Figure 15: Contribution to (a) effective radiative forcing (RF) and (b) global surface temperature change from component emissions for 1750–2019 based on Coupled Model Intercomparison Project Phase 6 (CMIP6) models (Figure from IPCC, 2021)

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 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[9]. 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

[9] 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.

boreal and tropical/sub-tropical regions (e.g., Peterson et al., 2018). In the publication by Solomon et al. (2022), it is hypothesized 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/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 cooling effect (negative RF) from ozone depletion caused by halocarbons partly offsets the warming effect (positive RF) they produce. Since AR5, the total warming from all halocarbons has increased: the contribution from CFCs has gone down, but this has been more than compensated by increases from their replacements, such as 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.

Although N_2O is not controlled under the Montreal Protocol, its anthropogenic emissions are currently a larger threat to the ozone layer than any other chemicals controlled under the Protocol. Except from the influence on the ozone layer, N_2O is a long-lived greenhouse gas approximately 270 times more powerful than CO_2 per tonne of emission at warming the Earth (UNEP, 2024a). Ambitious actions to reduce N_2O emissions could move the world closer to meeting a wide range of global climate, ozone, environmental and human health goals.

5 UV measurements

5.1 Relationship between ozone, UV and health

The ozone layer is crucial for life on Earth as it absorbs harmful ultraviolet (UV) radiation from the sun. Overexposure to UV radiation can cause skin damage, eye damage, and suppress the immune system. It also interferes with environmental cycles, affecting organisms such as plants and phytoplankton that move nutrients and energy through the biosphere (EPA, 2020). In the report from United States Environmental Protection Agency (EPA), it is estimated that full implementation of the Montreal Protocol is expected to prevent approximately 443 million cases of skin cancer, 2.3 million skin cancer deaths, and 63 million cases of cataracts for people in the United States born in the years 1890–2100.

Despite implementation of the Montreal Protocol, overexposure to UV is still a major concern in many countries, including Norway. Skin cancer was the fourth most frequent type of cancer in Norway in 2019-2023 and compared to the period 2014-2018 the rates for melanoma skin cancer (the most dangerous type of skin cancer) increased by ~10%, whereas non-melanoma skin cancer increased by 24%. The sharp increase is suggested to be largely attributed to sun exposure habits, including the use of tanning beds. Worryingly, Norway ranks second in the world in melanoma mortality rates (NIPH, 2024).

It should be emphasized that a moderate dose of UV radiation also can have advantages, such as vitamin D production in the skin and possible benefits for some autoimmune and allergic conditions (UNEP, 2024b). The balance of harm and benefit from solar exposure differs for various people and can be challenging to determine. One useful tool can be found at https://uv.nilu.no/, where the user can select any location in the world and find the approximate time it will take to obtain the daily vitamin D dose without getting sun burn.

The biological effect of UV is closely related to the energy of the radiation. UV is normally divided into three categories, depending on wavelength (energy) and how harmful the radiation is:

- UVC (100-280 nm) is highly dangerous but almost completely absorbed by the Earth's atmosphere, especially the ozone layer. No UVC will normally reach the ground.
- UVB (280-315 nm) penetrates the top layer of the skin and can cause sunburn and contribute to skin cancer. UVB radiation is absorbed by ozone, thus, the UVB level at the ground is closely linked to the thickness of the ozone layer. A thin ozone layer will give high UVB radiation.
- UVA (315-400 nm) is less energetic than UVB and penetrates deep into the skin. It is associated with skin aging and immune suppression. There are also studies indicating that UVA may contribute to skin cancer (UNEP, 2024b). UVA is hardly absorbed by the ozone layer.

Next, 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[10]). The unit for dose rate is mW/m^2 (milliWatt per square meter) 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). Table 8 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.

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

Table 8: UV index together with the recommended protection (Source: WHO).

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 11 AM and 3 PM and seek shade. Use clothes, a hat, and sunglasses and apply sunscreen with high factor (30+) regularly.
7 6	High	Protection is necessary. Take breaks from the sun between 11 AM and 3 PM. Use clothes, a hat, and sunglasses and apply sunscreen with high factor (30+).
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.

5.2 Norwegian UV network

The Norwegian UV network was established in 1995 and consists of nine 5-channel GUV instruments (described in Appendix B) located from 58°N to 79°N, as shown in Figure 16. 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 16: 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.

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 was installed at Kjeller in the spring 2024. In 2024, the instruments at Kjeller, Andøya and Ny-Ålesund worked well, except for some short and unexplained interruptions at Andøya.

5.3 UV measurements in 2024

Figure 17 shows the UV dose rates measured at local noon (± 0.5 hour) at Kjeller (top), Andøya (middle) and in Ny-Ålesund (bottom) in 2024. The black curves in Figure 17 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 grey dotted lines represent modelled UVI for "normal" total ozone values (i.e. 1979-1989 long-term monthly mean ozone values at the sites) and clear sky. The highest noon-time UV dose rate at Kjeller, 156 mW/m^2, was observed on 26 June 2024 and is equivalent to a UV index of 6.2.

At Andøya the highest noon average UVI in 2024 was 4.5, equivalent to a dose rate of 113 mW/m^2 (observed on 16 July). A peak UVI of 4.7 was observed on 28 June.

The highest noon average UVI in Ny-Ålesund in 2024 was 2.5, registered on 22 June, equivalent to 62 mW/m^2. Note that the modelled values (red curve) often are lower than the measured UV dose rates in the spring and early summer. 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 2024 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 13%, 6%, and 10% below the long-term seasonal mean ozone values, respectively.

For UV levels corresponding to the maximum UVI value of 6.2 at Kjeller, people with a typical Nordic skin type get sunburnt after 20-25 minutes if no sun protection is used.

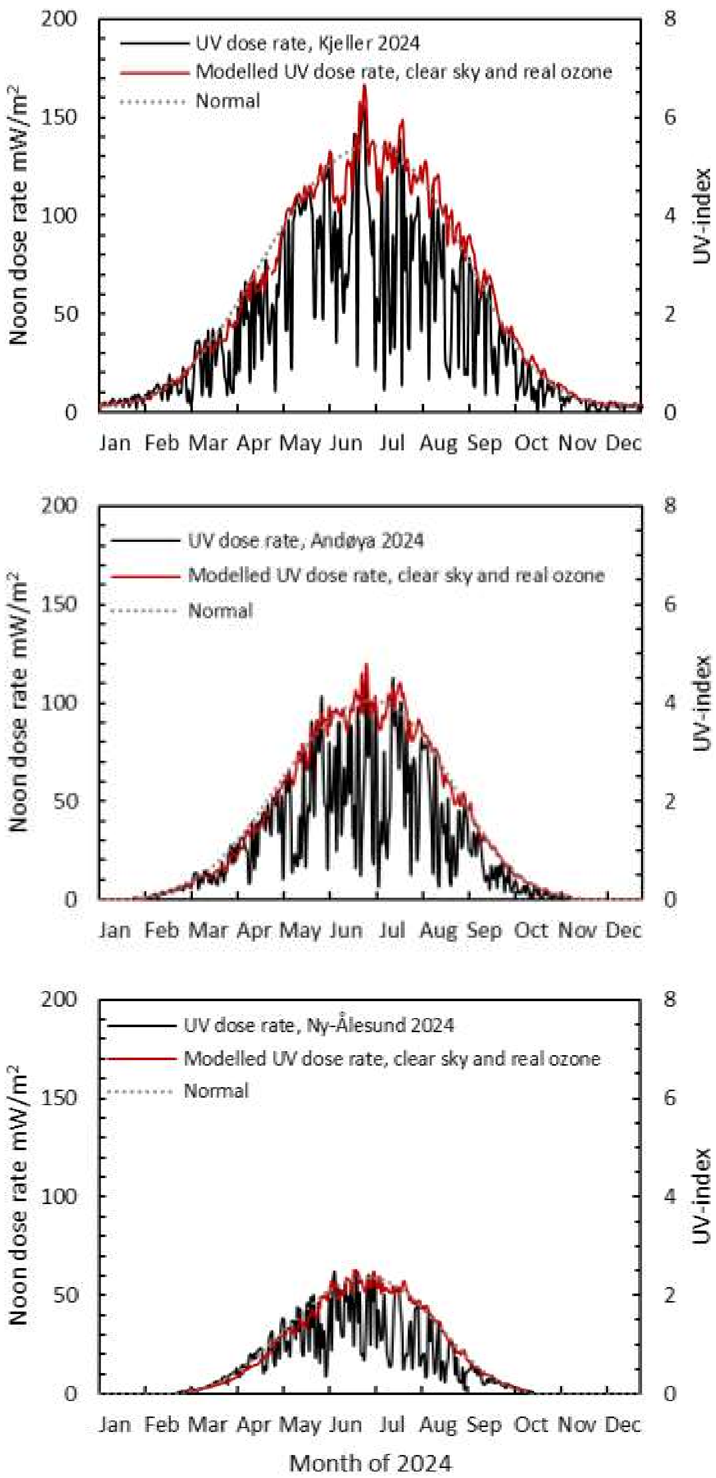

Figure 17: Hourly averaged UV dose rate measured at local noon (± 0.5 hour) in 2024. Upper panel: Kjeller. Middle panel: Andøya. Lower panel: Ny-Ålesund.

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 10 during ozone hole periods in November/December (Antarctic Spring and early summer).

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 2024 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, 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 July 2024 was close to the July dose at Kjeller. This was mainly caused by nice and sunny weather in the northern part of Norway, contrary to the cloudy conditions in Southern Norway.

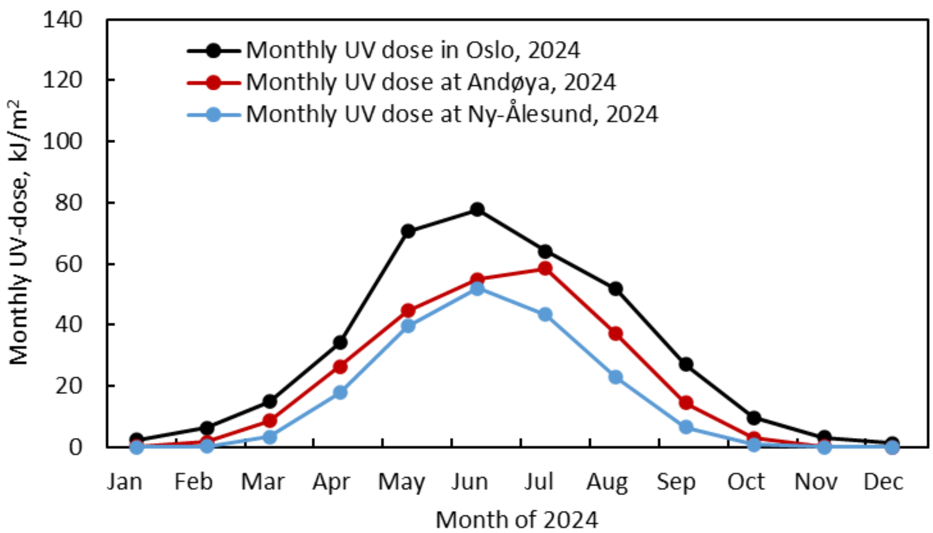

Figure 18: Monthly integrated UV doses (in kJ/m^2) in 2024 measured with the GUV instruments located at Kjeller, Andøya and in Ny-Ålesund.

5.4 Annual UV doses 1995 to 2024

Annual UV doses for the period 1995–2024 are shown in Table 9 for the GUV instruments in Oslo/Kjeller, at Andøya and in Ny-Ålesund. The UVI time series have been processed 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 9: Annual integrated UV doses (in kJ/m²) for Oslo/Kjeller, Andøya and Ny-Ålesund for the period 1995 to 2024.

Year	Oslo/Kjeller (kJ/m²)	Andøya (kJ/m²)	Tromsø (kJ/m²)*	Ny-Ålesund (kJ/m²)
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
2023	393.8	252.0		209.3
2024	362.8	249.5		186.4
1995/96-2024 average	**370.2**	**246.1**		**205.3**

*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

In 2024 the calculations of UV-doses were based on the original measurements without any further adjustments. Fortunately, the instruments at Kjeller, Andøya, and Ny-Ålesund ran without major interruptions in 2024, and the need for data gap-filling was minimal. Thus, the uncertainty in monthly and annual UV doses should still be within ±5 %.

The annual integrated UV dose at Kjeller was relatively low in 2024. The 2024 value of 362.8 kJ/m^2 was the 18th highest annual UV dose measured in Oslo/Kjeller since 1995, roughly 14% below the maximum value from 2018, and 2% below the 1995-2024 average. High ozone values in June and July, combined with many overcast days, were the main reasons for low UV doses at Kjeller. At Andøya, the annual UV dose was only ranked as the 15th highest since 1996 despite the nice weather in July. The annual dose at Andøya was around 11% below the maximum value from 1997, but 1% above the mean value for the period 1996-2024. In Ny-Ålesund the UV dose in 2024 was 186.4 kJ/m^2, which is ~9% below the 1996-2024 average. This dose was the 6th lowest value measured since 1995 and was 19% below the peak value from year 2009. In general, the low annual integrated UV doses were partly caused by high annual average ozone values at all stations.

Graphical presentations of the annual integrated UV doses from 1995 to 2024 are shown in Figure 19. For Oslo/Kjeller there is an increase of 2.6%/decade in the annual UV dose. For Andøya and Ny-Ålesund there is a negative trend of -1.0%/decade and -1.3%/decade, respectively.

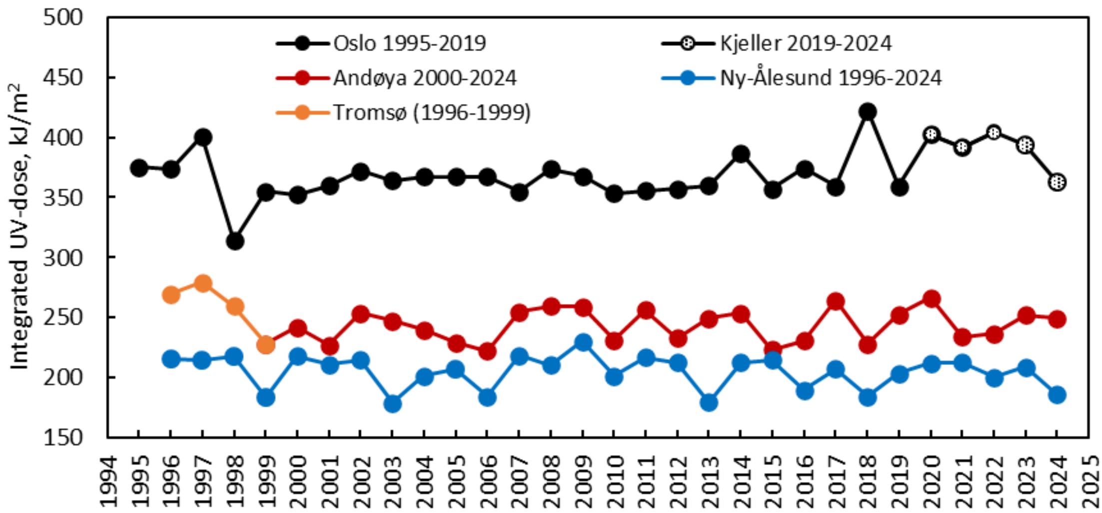

Figure 19: Annual integrated UV doses (in kJ/m^2) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995–2024.

The trends in UV radiation depend on changes in ozone, cloudiness, and albedo. A notable finding is that the UV trend at Andøya is around +1.1%/decade for the period 2000 to 2024. The negative trend of -1.0%/decade from 1996-2024 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 2.6%/decade could be influenced by less clouds or aerosols at Kjeller compared to Blindern.

The current report emphasizes the protective role of the ozone layer in filtering harmful solar radiation, with overexposure linked to skin cancer, cataracts, and ecological impacts. In Norway, skin cancer rates have risen sharply despite the Montreal Protocol's success, highlighting the importance of public awareness and monitoring. The Norwegian UV network, established in 1995, continues to provide long-term measurements, showing clear links between ozone variability, clouds, snow/ice reflectance, and UV levels. Recent data reveal relatively low annual UV doses in 2024, partly linked to high total ozone values. However, long-term observations demonstrate that UV levels can vary significantly from year to year and therefore require continued attention in the future.

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Appendix A
History of Norwegian monitoring sites

NY-ÅLESUND

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 reanalysed 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 did not 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, NILU has also had access to Italian Brewer measurements, and in 2020 a Pandora spectrometer was installed in Ny-Ålesund.

Due to interruptions and sparse ground-based total ozone measurements in Ny-Ålesund in the 1980s and early 1990s, our trend analyses and monthly mean calculations from Ny-Ålesund for the period 1979 to 1997 are entirely based on TOMS Nimbus 7, Meteor-3, and SBUV satellite overpass data.

TROMSØ AND ANDØYA

Total ozone measurements in Tromsø started back in 1935, which makes this time series one of the longest in the world. The 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.

OSLO AND KJELLER

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.

In the end of June 2019, the GUV and Brewer instruments at Blindern (Oslo) 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 Univ. of Oslo. 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.

Appendix B
Instrument description

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 July 2024. Calibration reports are available on request. The Brewer instruments are also regularly calibrated against internal standard lamps (SL) to check the stability of the instruments. From mid-2021 to mid-2023 the SL-measurements from B104 suffered from a severe and unpredictable drift. Fortunately, the problem was resolved by IOS Canada in August 2023.

In October 2014, CNR-IDASC, Italy, and NILU signed a scientific agreement that give NILU access to the Italian Brewer (B050) 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 from 2019 to 2023:

- 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 the Brewer is switched off during the coldest periods.
- In August 2023 IOS Canada made a new visit to Ny-Ålesund to fix a broken solar tracker and to calibrate the B050

For the period 2020-2023 the B050 data should be used with care. 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 GUVs 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/).

Is spring 2024 a new GUVis-3511 radiometer from Biospehrial Instruments Inc. was installed at Kjeller. This is a 19 channels instruments, with wavelengths ranging from 305 to 1640 nm. The GUVis will run in parallel with the old GUV-511 instrument from1993 and eventually replace the old instrument.

SAOZ

NILU’s SAOZ (Systeme d'Analyse par Observation Zenitale) 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 reanalysed 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.

Appendix C
Satellite and Ground-based measurements

Table 10: 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-24	0.7	1.8	3.3
GOME I	Mar-96	Jul-11	-0.5	2.1	4.5
GOME II	Jan-07	Dec-24	1.1	1.8	3.4
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-24	0.2	1.3	1.7
GOME I	Mar-96	Jul-11	0.2	1.7	3.0
GOME II	Jan-07	Dec-24	0.2	2.0	4.2
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-24	1.6	2.1	4.6
GOME I	Mar-96	Jul-11	0.1	1.7	2.9
GOME II	Jan-07	Dec-24	1.1	2.5	6.3
SCIAMACHY	Jul-02	Apr-12	-1.2	3.5	12.2
SBUV	Nov-78	Dec-20	0.1	2.0	3.9

NILU is a Norwegian, nonprofit and independent climate and environmental research institute founded in 1969. We started as an institute for air research but have now expanded to research almost all aspects of how people, climate, and the environment affect each other.

Our goal is to attain a better quality of life for everyone! We contribute to this through our research into the composition of the atmosphere, climate change, air quality, environmental toxins, health effects, sustainable systems, circular economy, and digitalization. Together we enable sustainable solutions for current societal and business challenges.

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