

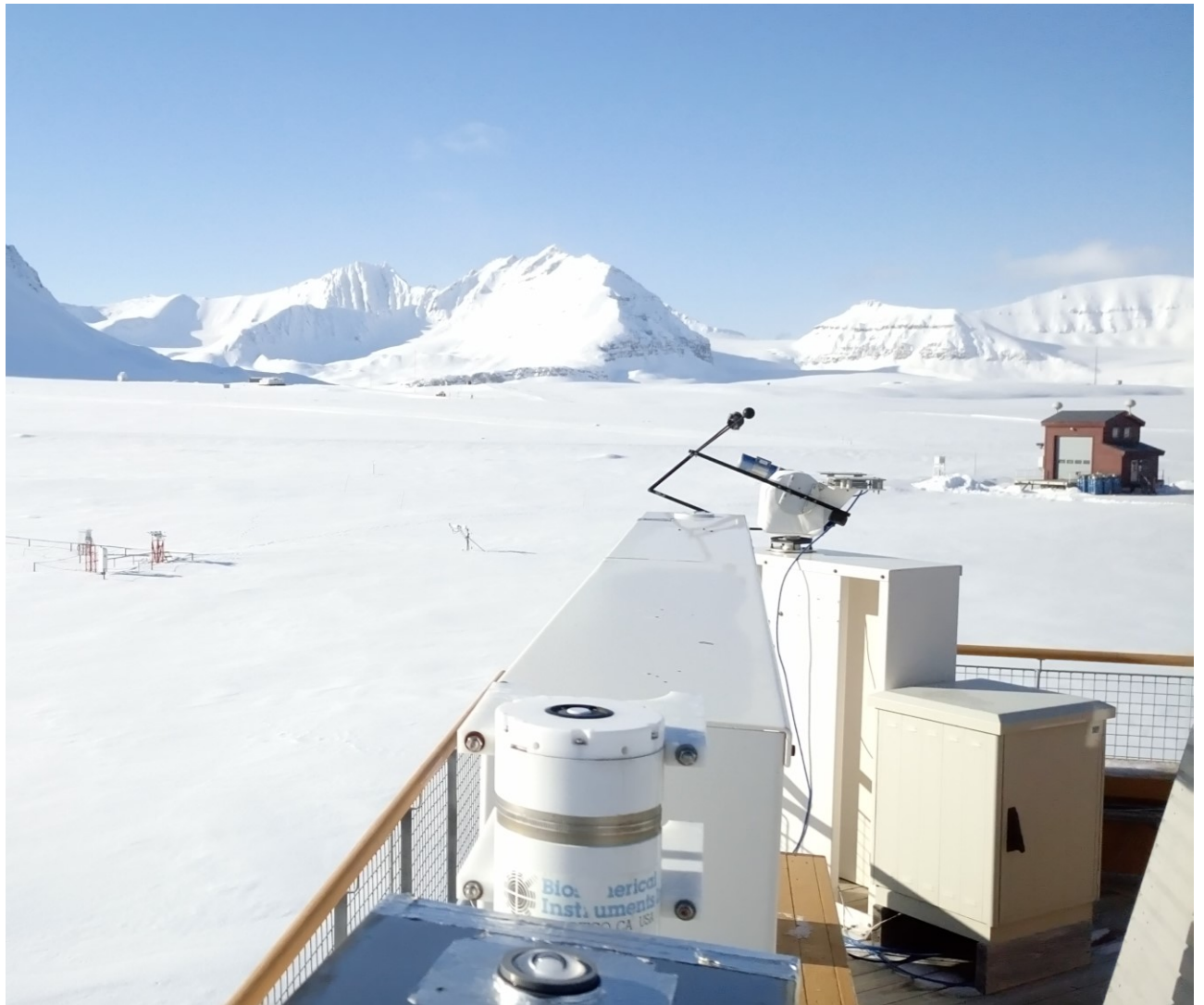
Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual Report 2018

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ABSTRACT This report summarizes the results from the Norwegian monitoring programme on stratospheric ozone and UV radiation measurements. The ozone layer has been measured at three locations since 1979: in Oslo, 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. 2018 was characterized by low summer ozone values in Oslo and a record high annual integrated UV-dose.		
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ABSTRACT (in Norwegian) Denne rapporten presenterer resultatene fra det norske måleprogrammet for totalozon og UV-stråling. Ozonlaget har blitt målt ved tre stasjoner siden 1979: i Oslo, 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 pre-1980 nivået. Mest karakteristisk for 2018 var de lave totalozon-verdiene over Oslo i sommermånedene og den rekordhøye årlige integrerte UV-dosen.		
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Contents

Summary	3
1 Norwegian ozone measurements in 2018.....	6
1.1 Total ozone in Oslo	6
1.2 Total ozone at Andøya	8
1.3 Total ozone in Ny-Ålesund	10
2 Ozone measurements and trends 1979-2018	12
2.1 Background: WMO/UNEP reports	12
2.2 Trends for Oslo 1979-2018	12
2.3 Trends for Andøya/Tromsø 1979-2018	15
2.4 Trends for Ny-Ålesund 1979-2018	17
2.5 The overall Norwegian ozone situation in 2018	19
2.6 Ozone and UV measurements at Troll	22
3 Satellite observations of ozone.....	24
3.1 Satellite ozone observations 1979-2018.....	24
4 The 5th IPCC assessment report: Climate and Ozone interactions	27
5 UV measurements and levels.....	30
5.1 UV measurements in 2018.....	30
5.2 Annual UV doses 1995-2018.....	34
6 Appendix: Instrument description.....	36
7 References	37

Summary

This report summarises activities and results from the ozone and UV monitoring programme in 2018. It includes total ozone trend analyses for the period 1979-2018 and UV measurements in Oslo, at Andøya and in Ny-Ålesund for the period 1995-2018. The report also gives an overview of total ozone measurements and UV data from the Troll Station in Antarctica, which started up in 2007. The Antarctic activity is funded by the Norwegian Antarctic Research Programme and the Ministry of Climate and Environment.

Total ozone

The 2017/2018 winter started with very low stratospheric temperatures and Polar Stratospheric Cloud (PSC) formation, which caused significant ozone depletion in December 2017 and January 2018. However, in early February 2018 a major stratospheric warming occurred, with inflow of ozone-rich air from lower latitudes. The total ozone measurements from the Norwegian stations reflect these dramatic changes in mid-winter. In Oslo the data reveal periods of low ozone from mid-January to mid-February. Measurements from Andøya and Ny-Ålesund show the ozone-depletion period in January and early February, before total ozone values almost doubled within a few days. Due to the polar night the ground based Ny-Ålesund measurements started too late to catch the depletion phase, but satellite observations indicate this dramatic increase. As a result, the February and March monthly ozone means were significantly above the long-term average at all three stations. Total ozone in Oslo, at Andøya and in Ny-Ålesund were 3.9%, 12.9%, and 11.9% above the long-term February means, respectively. In Southern Norway, persistent high-pressure systems dominated the weather most of the spring and summer 2018. Such high-pressure systems are often associated with low ozone values. This was also the case for Oslo, where the monthly average ozone layer was below the long-term mean all months from April to August.

Due to stratospheric circulation, the ozone layer above Norway is normally thickest in late winter and spring, whereas the lowest values occur in October/November. However, in 2018 the situation was slightly different. In Oslo, the minimum ozone value was 226 DU, measured on 19th December 2018. This is about 30% below the long-term mean for the season. Both at Andøya and in Ny-Ålesund the minimum 2018 ozone values were registered 3rd February 2018, just before the major stratospheric warming occurred. The ozone values were 219 DU and 228 DU this day, respectively, which are 41% below the February long-term means for Andøya and Ny-Ålesund.

The monitoring programme and trend analyses show that minimum ozone levels over Norway were reached in the mid-1990s. During the period 1979-1997, the annual average ozone layer above Oslo and Andøya decreased by - 5.7%/decade and as much as -8.1%/decade during spring. For Ny-Ålesund, the decrease was even larger: - 6.9%/decade for annual means and -11.2%/decade during the spring months. Since 1998 no further ozone decrease has been observed at any of the three Norwegian sites, and the 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 destruction).

UV measurements

The highest 2018 UV index (UVI) in Oslo was 6.2, measured on 1st July. Such an UVI is common in Southern Norway during sunny days in late June and early July, and people with a typical Nordic skin-type get sunburnt after approximately 20 minutes if no sun protection is used. At Andøya, the highest UV index in 2018 was 4.7 observed on 5th July, whereas the highest UVI in Ny-Ålesund, 2.7, was observed 3rd June. These values are typical for low and high Arctic latitudes, respectively. In 2018, the annual integrated UV-doses at Andøya and in Ny-Ålesund were relatively modest. Cloudy weather condition during parts of the summer is the main explanation. In Oslo, however, an annual UV-dose of 416 kJ/m² was measured in 2018. This is the highest annual UV-dose registered in Oslo and the first

time the value exceeds 400 kJ/ m². The high UV-dose was caused by sunny weather and low ozone in the summer 2018.

MAIN CONCLUSIONS FROM THE MONITORING PROGRAMME 2018

- The total ozone values in Norway were low in January 2018, but correspondingly high in February and March 2018 (between 4% and 13% above the long-term mean in February/March). **The sudden ozone increase was due to stratospheric dynamics.**
- The ozone values in Oslo were below normal from April to August, closely related to the stable high pressure system over Southern Norway during spring and summer 2018
- At all Norwegian monitoring stations a significant stratospheric ozone decrease was recorded for the period 1979-1997. For the period 1998-2018 there are no significant trends in the ozone layer above Norway.
- The annual integrated UV-dose in Oslo 2018 was the highest ever registered. This was caused by the exceptional sunny weather and many cloudless days in spring and summer 2018, combined with relatively low ozone values.
- **Meteorological variability has a large impact on ozone and UV and can give considerable year-to-year variations**

Ozone Depleting Substances (ODSs)

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

Today we can see signs of ozone recovery, but it is still crucial to follow the development of the ozone layer in order to verify that the Montreal Protocol and its amendments work as expected. A recovery of the stratospheric ozone layer depends on a sustained reduction of CFC-11, which is the most important ODS and contributes one quarter of all chlorine reaching the stratosphere. Recent monitoring results and studies have shown that the rate of decline of atmospheric CFC-11 concentrations has slowed down by about 50% after 2012. This is most likely related to increased CFC-11 emission from China, strongly inconsistent with the Montreal Protocol agreement. This demonstrates the importance of maintaining good monitoring networks, both to detect possible changes related to ODSs, but also to detect possible effects of climate change on the ozone layer.

Coupling of stratospheric ozone and climate

The expected future recovery of stratospheric ozone might be affected by climate change. In general, a decrease in stratospheric temperature will slow down the gas-phase ozone destruction reactions, leading to less depletion and higher ozone column. However, there is a possible exception in the polar regions where lower stratospheric temperatures lead to more favourable conditions for the formation of Polar Stratospheric Clouds (PSCs). Furthermore, climate change may alter the strength of the stratospheric circulation and with it the distribution of ozone in the stratosphere. According to recent

analyses from Scientific Assessment of Ozone Depletion: 2018 (WMO, 2018) Northern Hemisphere total ozone is expected to return to 1980 abundances in the 2030s, Southern Hemisphere mid-latitudes ozone to return around mid-century, whereas the Antarctic ozone hole is expected to gradually close and return to 1980 values in the 2060s. However, there is a very complex coupling between stratospheric ozone and climate drivers, and the net effect of increased N₂O and CH₄ on total ozone is uncertain.

The national monitoring programme

To follow up the Montreal Protocol, the Norwegian Environment Agency established the programme “Monitoring of the atmospheric ozone layer” in 1990. NILU - Norwegian Institute for Air Research has been responsible for the operation and maintenance of the monitoring programme. Until 2012, three sites were included in the programme: Oslo (60°N), Andøya (69°N) and Ny-Ålesund (79°N). Since 2013 only Oslo and Ny-Ålesund have been a part of the programme, but financial support from The Ministry of Climate and Environment has made it possible to continue the operation of ozone and UV measurements at Andøya.

The present report belongs to a series of four annual reports covering national monitoring of atmospheric composition in the Norwegian rural background environment. The other three reports focus on monitoring of 1) particulate and gaseous phase of inorganic constituents, particulate carbonaceous matter, ground level ozone and particulate matter, 2) persistent organic pollutants and heavy metals, and 3) greenhouse gases and aerosol properties. The latter report (Myhre et al., 2018) includes monitoring and analysis of ozone depleting substances (ODSs), an activity closely related to the total ozone and UV monitoring programme presented in this report.

Summary of total ozone and UV key results:

Ozone	Oslo	Andøya	Ny-Ålesund
Annual ozone trend 1979-1986, %/decade	-5.7 (±2.0)	-5.7 (±2.0)	-6.9 (±2.2)
Annual ozone trend 1987-2018, %/decade	0.4 (±1.6)	0.7 (±1.6)	0.2 (±2.0)
UV			
Annual UV-dose 2018, kJ/m ² (rank*)	415.7 (1)	225.7 (18)	183.8 (22)

*“Rank” indicates how high the UV-dose was in 2018 compared to other years. UV has been measured since 1995/1996.

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Annual Report 2018

1 Norwegian ozone measurements in 2018

Total ozone is measured on a daily basis in Oslo (60°N), at Andøya (69°N) and in Ny-Ålesund (79°N). The daily ground-based ozone measurements in Oslo started in 1978, whereas modern ground-based ozone observations have been performed at Andøya/Tromsø and in Ny-Ålesund since 1990. The ozone measurements are retrieved from Brewer spectrophotometers in Oslo and at Andøya, whereas a SAOZ (**Systeme d'Analyse par Observation Zenitale**) instrument is the standard ozone instrument in Ny-Ålesund together with an Italian Brewer instrument. At all the three Norwegian sites GUV (Ground-based UltraViolet) filter radiometers are installed and can fill in ozone data gaps on days without Brewer and SAOZ measurements (see Appendix for more details). In addition to the ground-based measurements we also analyse total ozone data from various satellites to get a more complete description and understanding of the ozone situation in Norway and the Arctic region. The total ozone values, frequently denoted as ozone layer thickness, is expressed in terms of Dobson Units (DU¹)

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

1.1 Total ozone in Oslo

In Oslo, total ozone is primarily recorded with the Brewer MKV Spectrophotometer (B042) located at Blindern, University of Oslo. Figure 1a illustrates the daily total ozone values from Oslo in 2018. The black curve shows the daily measurements, whereas the red curve shows the long-term monthly mean values for the period 1979-1989 (frequently denoted as “normal” in the current report). The total ozone values in 2018 are based on Brewer direct-sun (DS) measurements when available.

In 2018, direct-sun measurements were performed on 207 out of 365 days. During overcast days or days where the minimum solar zenith angle was larger than 72°, the ozone values were calculated with the Brewer global irradiance (Brewer GI) method (Stamnes et al., 1991). The Brewer GI method was used on 153 days. In 2018, the Brewer instrument ran without major technical problems or stops. On days with missing Brewer measurements, ozone can normally be retrieved from the GUV-511 instrument, which is located next to the Brewer instrument at the University of Oslo. Altogether, GUV data were used to complete the ozone time series on 3 days with missing Brewer data. A summary of instruments and frequency of inclusion in the 2018 Oslo ozone series is given in Table 1. Even if total ozone was retrieved from the GUV instrument on 347 out of 365 days, only 3 of the measurements were used in the 2018 time series since the Brewer measurements are considered as more accurate.

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

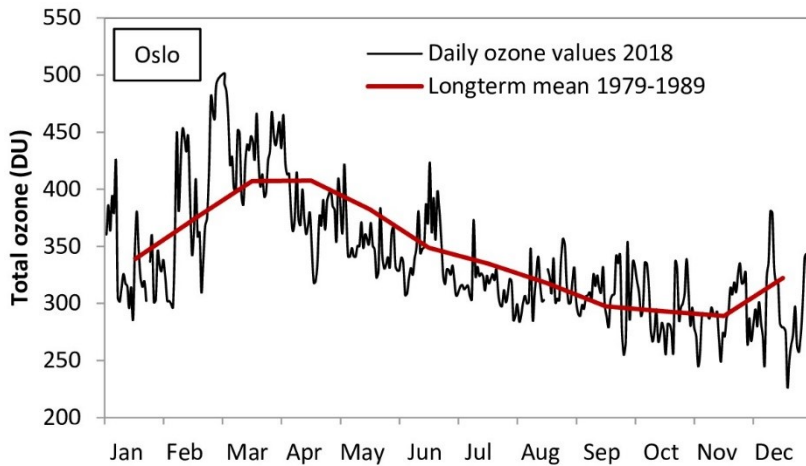


Figure 1a: Daily total ozone values measured at the University of Oslo in 2018. The red curve shows the long-term monthly mean values from 1979-1989.

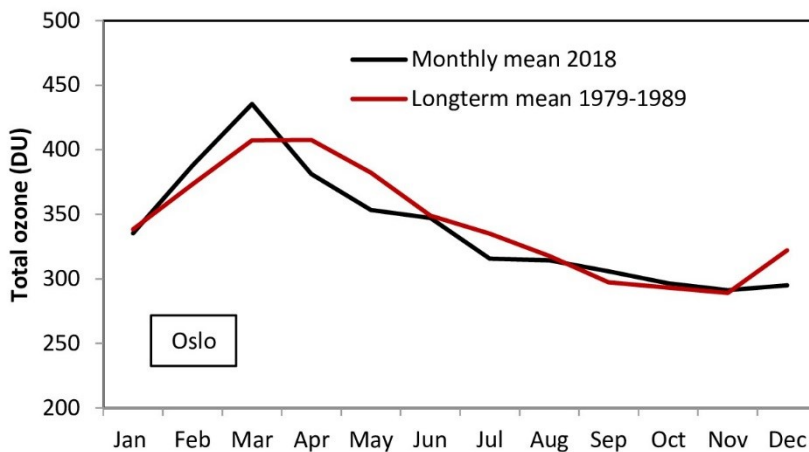


Figure 1b: Monthly mean ozone values for 2018. The red curve shows the long-term monthly mean values from 1979-1989.

Table 1: Overview of total ozone instruments in Oslo and the number of days where the various instruments were used in the 2018 time series

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	207
2	Brewer instrument, global irradiance method	153
3	GUV-511 instrument	3
	Missing days	2

As seen from Figure 1a there are large day-to-day fluctuations in total ozone, particularly during winter and spring. The rapid ozone variations are typically caused by stratospheric circulation and changes in tropopause height. The lowest ozone values normally occur in October/November, but in 2018 the lowest ozone values were registered in December. The minimum ozone value in 2018 was 226 DU, measured on 19 December. This is about 30% below the long-term mean for December.

The monthly mean total ozone values in 2018 are shown in Figure 1b, where the measurements are compared to the long-term monthly mean values for the period 1979-1989. As seen from the figure, the average ozone values during winter and early spring were above normal. In April the situation changed, and from late spring throughout the summer the ozone layer was below the long-term mean most of the time. Section 2.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2018.

1.2 Total ozone at Andøya

Total ozone monitoring at Andøya is not a part of the national programme, but financial support from the Ministry of Climate and Environment has made it possible to continue the measurements. This has been of great importance since the Tromsø/Andøya ozone time series started back in 1935 and is among the longest in the world.

At Andøya the total ozone values are based on Brewer direct-sun (DS) measurements when available. For overcast days and days when the solar zenith angle is larger than 80° (sun lower 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 inhibited by bad weather conditions.

The Andøya Brewer instrument ran without major interruptions and problems in 2018. However, after 2015 a significant drift has been registered in the internal standard lamps, which makes it crucial with comprehensive post-processing of all ozone data.

The GUV instrument also ran without major problems in 2018. The Andøya GUV was sent to BSI (USA) for repair in 2016, but 2018 was a less problematic year and ozone was retrieved all days except for the polar night period and one summer day with a heavy cloud cover. However, it is a challenge that all the GUV instruments in the Norwegian network are getting old and broken parts cannot necessarily be replaced. The GUV instrument at Andøya is experiencing problems with the communication between the detector and the PC, resulting in occasional interruptions and shorter periods (minutes to hours) without data logging. The reason for these interruptions is not clear.

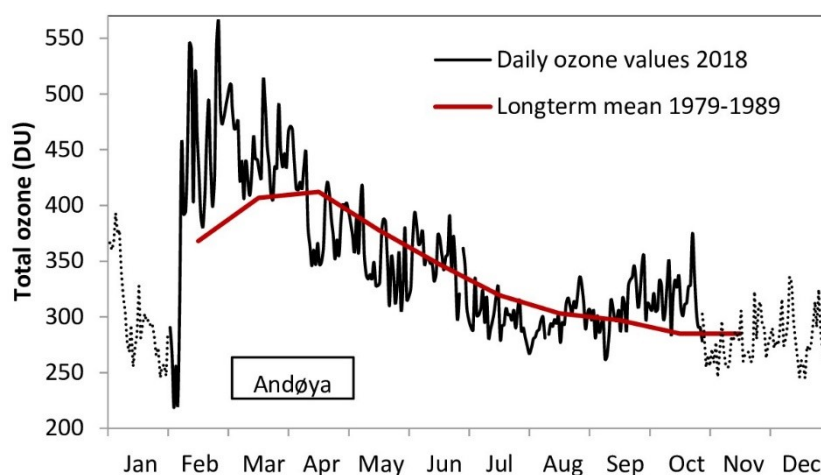


Figure 2a: Daily total ozone values measured at ALOMAR, Andøya, in 2018 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989. The dotted line represents GOME2 satellite measurements.

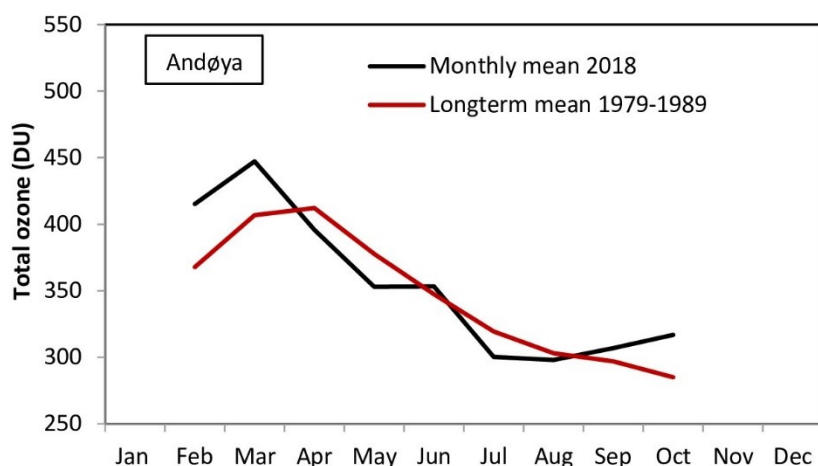


Figure 2b: Monthly mean total ozone values for 2018 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

Table 2 gives an overview of the different instruments and methods used at Andøya in 2018. Brewer DS was available on 154 days, whereas Brewer GI provided the daily ozone value on 70 days. In total, there were 15 days with missing Brewer data in 2018 (related to technical issues and/or heavy cloud cover), and 13 of these days GUV total ozone data served as replacements for Brewer data. The GUV instrument also works satisfactorily when the solar signal is weak. This makes it possible to extend the time series and perform ozone measurements shortly after/before the polar night season. In total, there was only two days with missing ozone observations at Andøya in 2018 (27th June and 9th August), caused by bad weather conditions resulting in ozone values with unacceptably high uncertainty.

Figure 2a shows daily ozone values from Andøya in 2018. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989. In addition, GOME2 satellite data is included for the polar night period (winter), shown as a dotted line in Figure 2a. The lowest ozone values at Andøya normally occur in October and November, however, in 2018 the minimum ozone value was recorded 3 February. This day the ozone value was as low as 219 DU, which is 41% below the long-term February mean. The ozone values were low most part of January.

Table 2: Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2018.

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	154
2	Brewer instrument, global irradiance method	70
3	GUV instrument	42
	Missing days (except polar night period)	2

Monthly mean ozone values at Andøya in 2018 are shown in Figure 2b. For January, November, and December (polar night) there are not sufficient data to calculate monthly means from the ground based instruments. Comparison between the long-term mean and monthly mean ozone values in 2018 shows that the total ozone column was high during winter (except January), spring and fall. For the summer period, the ozone values were below normal most of the time.

1.3 Total ozone in Ny-Ålesund

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

NILU's instrument in Ny-Ålesund is located at 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 (see Appendix)

In addition to the SAOZ instrument, a GUV-541 multi-filter radiometer is used for ozone measurements when the UV radiation becomes stronger in the spring, summer and early fall. These measurements give important contributions to the ozone time series from Ny-Ålesund. NILU has also access to Brewer measurements at the Italian research station, which are valuable for the quality assurance of the SAOZ and GUV ozone data.

Comparisons between Brewer and GUV ozone measurements revealed a seasonal difference in total ozone. For the period 2013 - 2018, the GUV measurements were on average 3-4% higher than the Brewer values. Consequently, a seasonal correction is applied to the GUV data.

Except from a short SAOZ computer failure in March 2018 (resulting in 4 days with missing data), both the SAOZ and GUV instrument worked satisfactorily the whole year. Table 3 gives an overview of the different instruments and methods used for the 2018 ozone series in Ny-Ålesund. No ground based ozone measurements were performed during the polar night period.

Table 3: Overview of instruments and methods applied for retrieval of the total ozone in Ny-Ålesund 2018.

Priority	Method	Total days with observations
1	Brewer#50 instrument	96
2	SAOZ instrument	75
3	GUV instrument	69
	Missing days (except polar night period)	1

Figure 3a shows daily ozone values from Ny-Ålesund in 2018. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989, calculated from TOMS (Total ozone Mapping Spectrometer) satellite data. Total ozone values during winter (November to mid-February) are not achievable due to absence of sunlight, but similar to Andøya GOME2 satellite data have been used to indicate the ozone values for the polar night period, shown by the dotted line in Figure 3a. Similar to Oslo and Andøya, the lowest ozone values in Ny-Ålesund normally occur in October and November. However, 2018 was an exception regarding minimum values. Similar to Andøya, the minimum ozone value in 2018 was recorded 3 February. The

value was 228 DU, which is 41% below the long-term mean for February. It should be noted that this ozone value was measured/modelled from GOME2 satellite data.

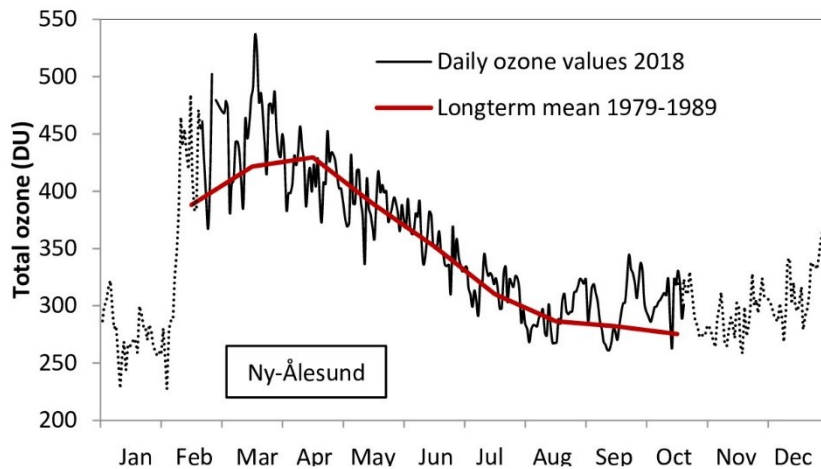


Figure 3a: Daily total ozone values measured in Ny-Ålesund in 2018 by the Brewer, SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 - 1989. The dotted line represents GOME2 satellite measurements.

Monthly mean total ozone values in Ny-Ålesund 2018 are shown in Figure 3b. Comparison between the monthly mean 2018 ozone values and the long-term monthly means shows that the average ozone layer in Ny-Ålesund was high during winter, spring and fall, and close to the long-term mean during the summer. The largest deviation was found in February 2018 where the average ozone value was 12% above the long-term February mean. It should be noted that the low ozone values in early February, as recorded by GOME2, is not included in the monthly mean values.

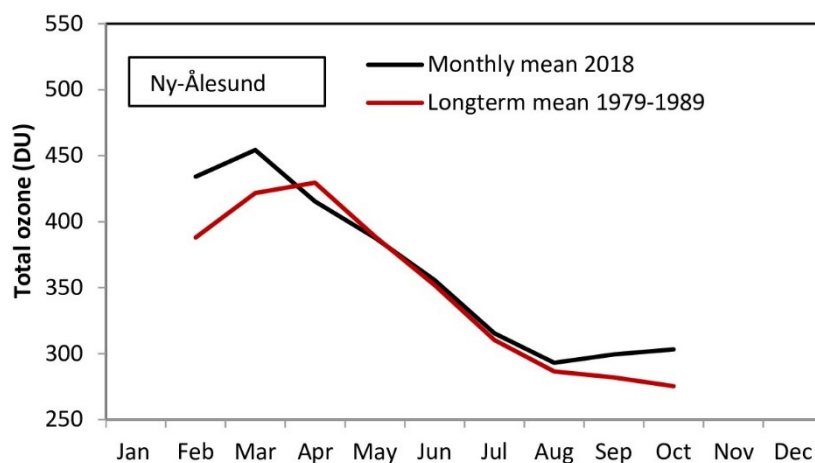


Figure 3b: Monthly mean total ozone values for 2018 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

2 Ozone measurements and trends 1979-2018

2.1 Background: WMO/UNEP reports

Since the early 1990s, the World Meteorological Organisation (WMO) and United Nations Environment Programme (UNEP) have regularly published assessment reports of ozone depletion. The last report, “Scientific Assessment of Ozone Depletion: 2018”, was published in October 2018 (WMO, 2018). The report summarizes 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 report concludes that the actions taken under the Montreal Protocol have led to decreases in the atmospheric abundance of ozone-depleting substances (ODSs). By 2016, the chlorine entering the stratosphere from ODSs has declined by 12% from the 1993 peak value. Total bromine has decreased by 15% since 1998.

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

According to the 2018 Ozone Assessment, it is likely that total column ozone will recover toward the 1980 benchmark levels over most of the globe under full compliance with the Montreal Protocol. Northern Hemisphere total ozone is expected to return to 1980 abundances in the 1930s, Southern Hemisphere mid-latitudes ozone to return around mid-century, whereas the Antarctic ozone hole is expected to gradually close and return to 1980 values in the 2060s.

The 2018 assessment report also emphasizes that changes in CO₂, N₂O, and CH₄ will have an increasing influence on the ozone layer as ODS concentrations decline. These gases impact both chemical cycles and stratospheric circulation. This is described in more detail in Chapter 4. Studies of long-term ozone trends, presented in the next sections, are essential in the assessment of possible ozone recovery and for gaining more information about atmospheric processes.

As mentioned above, the stratospheric ODS concentrations have started to decline. The most important ODS is CFC-11, which contributes one quarter of all chlorine reaching the stratosphere. A recovery of the stratospheric ozone layer depends on a sustained reduction of CFC-11. The rate of decline of atmospheric CFC-11 concentrations was constant from 2002 to 2012. However, after 2012 the rate of decline has slowed down by about 50% (Montzka et al., 2018). The same pattern is also evident from the CFC-11 measurements performed at the Zeppelin observatory. This suggests an increase in CFC-11 emission caused by unreported new production in China (Rigby et al., 2019), strongly inconsistent with the Montreal Protocol agreement to phase out global CFC production by 2010.

2.2 Trends for Oslo 1979-2018

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 at the University of Oslo. The entire set of Brewer DS measurements from Oslo is also available at WOUDC.

Overlapping measurements of Dobson and Brewer total ozone in Oslo from 1990 to 1998 have shown that the two instruments agree well, but there is a systematic seasonal variation in the difference between the two instruments. Thus, a seasonal correction function has been applied to the entire Dobson ozone time series from 1978 to 1998. The homogenized Oslo time series has been used in all ozone analyses presented in this report.

Figure 4a shows the variations in monthly mean ozone values in Oslo for the period 1979 to 2018. The large seasonal variations are typical for stations at high latitudes. This is a dynamic phenomenon and can be explained by the springtime transport of ozone from the source regions in the stratosphere above the equator.

In order to make ozone trend analyses for the period 1979 – 2018 we have removed the seasonal variations by subtracting the long-term monthly mean ozone values from the data series, shown in Figure 4b. Next, we have divided the time series into two periods: 1) 1978-1997, and 2) 1998-2018. For the first time period, the ozone measurements were entirely derived from the Dobson instrument and reflect a time period when a gradual decline in stratospheric ozone was observed at most mid and high latitude stations. The second period is based on Brewer measurements, with inclusion of some GUV measurements. For the two time periods, simple linear regression lines has been applied to the data to derive trends in the ozone layer above Oslo. 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 ($1\sigma^2$) in percent/decade. A trend larger than 2σ is considered as significant. In winter and spring, the ozone variability is relatively large and the corresponding ozone trend must be large in order to be classified as statistically significant.

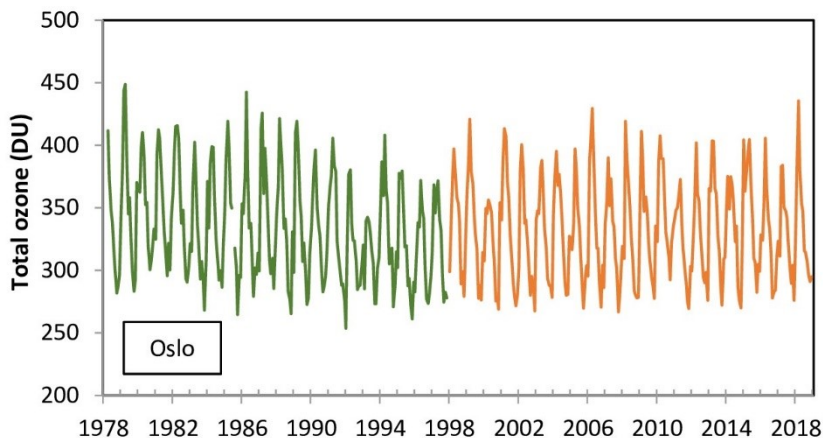


Figure 4a: Time series of monthly mean total ozone in Oslo 1979-2018. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements.

² Sigma (σ) represents a confidence interval. The 1σ interval means that it is 68.3% certain that the trend is between calculated trend $\pm 1\sigma$ value. The 2σ value represents a 95.4% confidence interval.

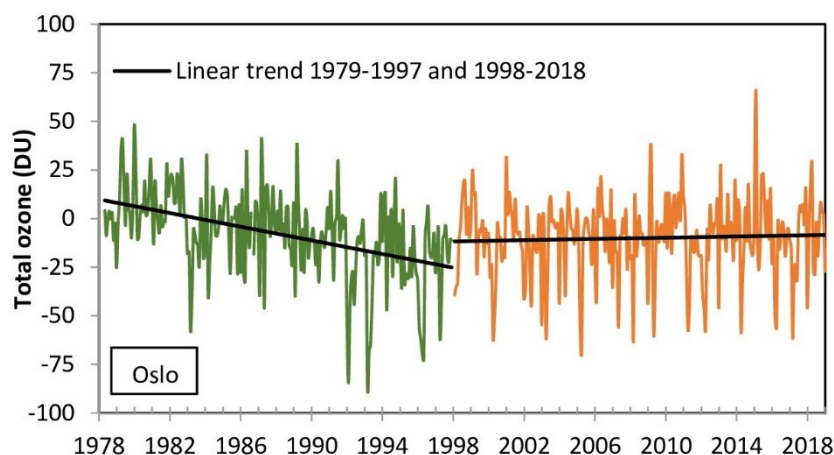


Figure 4b: Variation in total ozone over Oslo for the period 1979–2018 after the seasonal variations have been removed. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements. Trend lines are marked as black lines.

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

For the period 1998-2018 the picture is different. There are substantial year-to-year fluctuations and it is hard to draw definite conclusions about trends. Still, the regression analysis gives a good indication of the status of the ozone layer for recent years. As seen from the last column in Table 4, there is a statistical significant ozone increase of 2.0% /decade for the fall period September to November. For all other seasons the changes in total ozone are relatively small and close to zero. The annual ozone trend from 1998 to 2018 is 0.4% /decade.

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 1.1.1979 to 31.12.2018. The numbers in parenthesis represent the uncertainty (1σ). Data from the Dobson, Brewer and GUV instruments have been used in this study. A trend larger than 2σ is considered as significant.

Season	Trend (%/decade) 1979-1997	Trend (%/decade) 1998-2018
Winter (Dec – Feb)	-6.0 (2.3)	0.5 (1.9)
Spring (Mar – May)	-8.0 (1.3)	0.0 (1.4)
Summer (Jun – Aug)	-3.4 (1.0)	-0.1 (0.8)
Fall (Sep – Nov)	-4.2 (1.0)	2.0 (1.0)
Annual (Jan – Dec):	-5.7 (1.0)	0.4 (0.8)

2.3 Trends for Andøya/Tromsø 1979-2018

Total ozone monitoring started in Tromsø back in 1935 and measurements were performed on a routinely basis until 1972. In 1985 the old 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 autumn 1999, in parallel with Dobson no.14. In 2000, the Brewer instrument was moved to Andøya, approximately 130 km West-southwest of Tromsø, while Dobson observations were terminated. Studies have shown that the ozone climatology is very similar at the two locations (Høiskar et al., 2001), and the two datasets are considered equally representative for the ozone values at 70° in the European/ Atlantic Arctic. Thus, for trend study purposes the Tromsø/Andøya total ozone time series can be considered as one series.

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

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

As for Oslo, the ozone layer above Andøya declined significantly from 1979 to 1997. This decline was evident for all seasons. The negative trend for the spring season was -8.1%/decade, whereas the negative trend for the summer months was -2.9%/decade. The yearly trend in total ozone was -5.7%/decade. For the second period from 1998 to 2018, no significant trends have been found, except September-October. For these two months total ozone has increased by 3.1%/decade. For the other seasons, the ozone trends are essentially zero. The annual ozone trend from 1998 to 2018 is 0.7%/decade.

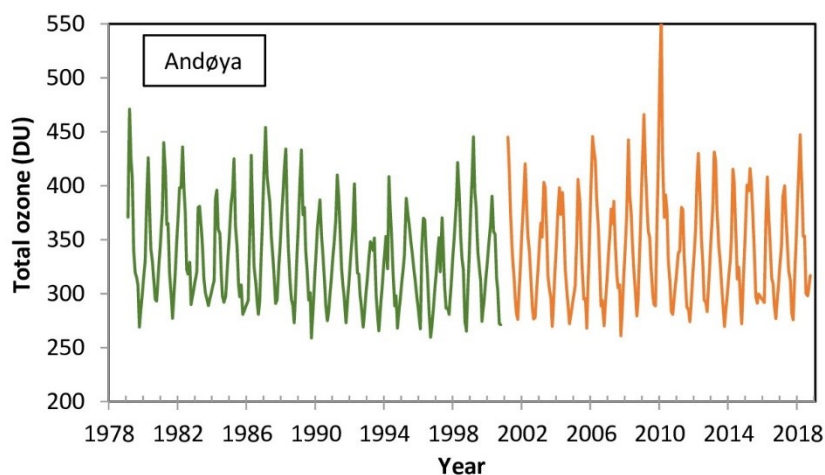


Figure 5a: Time series of monthly mean total ozone at Andøya/Tromsø 1979–2018. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya.

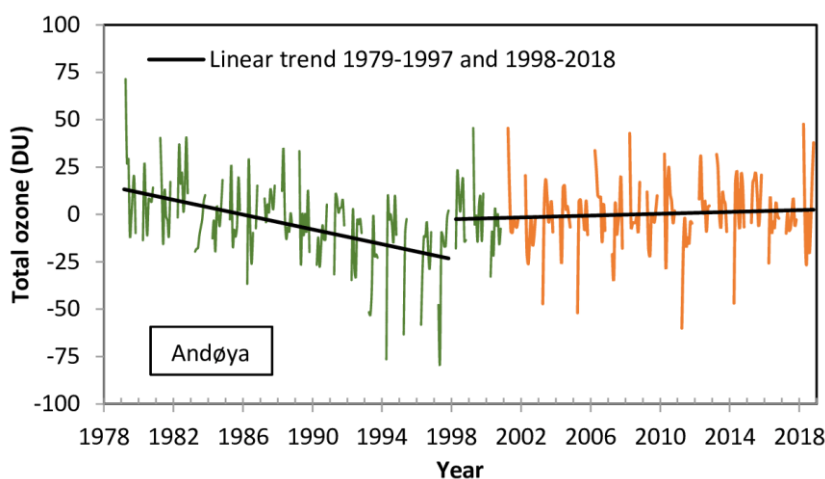


Figure 5b: Variations in total ozone at Andøya for the period 1979–2018 after the seasonal variations are removed. Only data for the months March–October are included. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya. The trends are marked as black lines.

Table 5: Percentage changes in total ozone (per decade) at Andøya for the periods a) 1979-1997, and 2) 1998- 2018. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	Trend (%/decade) 1979-1997	Trend (% /decade) 1998-2018
Spring (Mar – May)	-8.1 (1.5)	0.2 (1.3)
Summer (Jun – Aug)	-2.9 (0.9)	-0.1 (0.8)
Autumn (Sep – Oct)	-4.9 (1.3)	3.1 (1.0)
Annual (Mar – Oct)	-5.7 (1.0)	0.7 (0.8)

2.4 Trends for Ny-Ålesund 1979-2018

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

Regular Dobson ozone measurements were performed at Longyearbyen until 1966. The data series from 1950 to 1962 has been reanalyzed and published by Vogler et al. (2006). In 1966, the Dobson instrument was moved to Ny-Ålesund, and measurements continued until 1968. As in Tromsø, there were no measurements until the early 1980s. They resumed in August 1984, now again in Longyearbyen, where they continued until 1993, but without appropriate quality assurance and calibration. In 1994, the instrument was once again moved to Ny-Ålesund and operations taken over by the Norwegian Polar Institute. There they continued – with interruptions – until autumn 2005. A major reason for the final termination of the Dobson measurements was the requirement of a substantial amount of manual operation time. In parallel with the Dobson instrument, the more automatic SAOZ and GUV instruments were put into operation in Ny-Ålesund in 1991 and 1995, respectively, and since 2003, they have been the basis for ozone measurements at Ny-Ålesund. Since 2014 we have also had access to Italian Brewer measurements.

The ozone measurements presented in Figure 6a and Figure 6b are based on a combination of Dobson, Brewer, SAOZ, GUV and satellite measurements. For the years 1979 to 1991 the monthly mean ozone values are entirely based on TOMS Nimbus 7 and Meteor-3 overpass data. For the last 27 years, only ground-based measurements have been used: Dobson and Brewer data are included when available, SAOZ data are the next priority, whereas GUV data are used when no other ground-based measurements are available.

As seen from Figure 6b and Table 6, the trend pattern in Ny-Ålesund is similar to the Oslo and Andøya trend patterns. A massive ozone decline was observed from 1979 to 1997, especially during winter and spring. The negative trend for the spring season was as large as -11.2%/decade, whereas the negative trend for the summer months was somewhat smaller; -2.6%/decade. The annual trend in total ozone was -6.9%/decade during this early period. For the second period 1998-2018 no significant trends have been observed. The trend for spring and fall is around 1%/decade, whereas a negative trend of -1.1%/decade is found for the summer months. The annual trend for the period 1998-2018 is as small as 0.2%/decade.

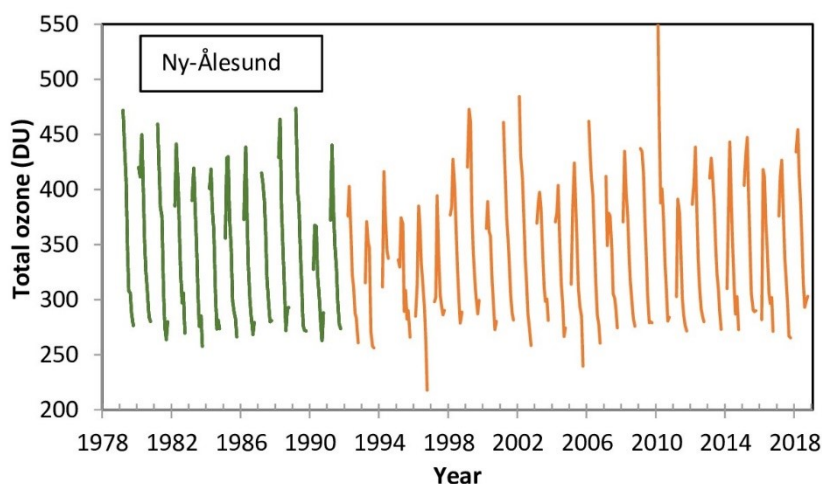


Figure 6a: Time series of monthly mean total ozone at Ny-Ålesund 1979–2018. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments.

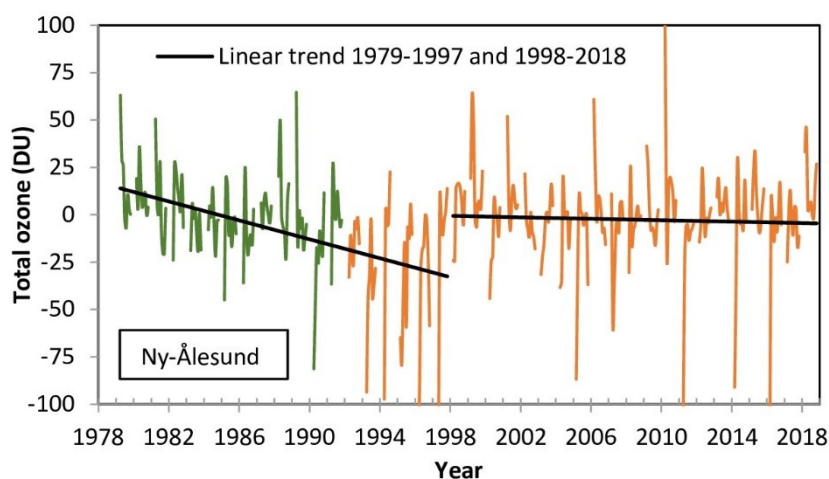


Figure 6b: Variations in total ozone at Ny-Ålesund for the period 1979–2018. Only data for the months March–October are included. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments. Trends for the two periods are marked as black lines.

Table 6: Percentage changes in total ozone (per decade) in Ny-Ålesund for the periods a) 1979–1997, and b) 1998–2018. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	Trend (%/decade) 1979–1997	Trend (%/decade) 1998–2018
Spring (Mar – May)	-11.2 (1.8)	0.8 (1.8)
Summer (Jun – Aug)	-2.6 (1.3)	-1.1 (0.8)
Autumn (Sep – Oct)	-3.7 (1.9)	1.1 (1.3)
Annual (Mar – Oct)	-6.9 (1.1)	0.2 (1.0)

2.5 The overall Norwegian ozone situation in 2018

The 2017/2018 winter started very cold, with low stratospheric temperatures and PSC displayed already in December 2017 and continuing in January 2018. However, in early February 2018 a major stratospheric warming occurred, first splitting and then gradually dissolving the Arctic stratospheric vortex. Although the two remnants of the vortex existed until end of March, the European sector was dominated by the inflow of ozone-rich air from lower latitudes (see Figure 7). The SAOZ network determined an integrated ozone reduction until 10 February, 2018 of 19%, which is a medium-sized value in the 25-year series of this monitoring network (Goutail et al., 2018).

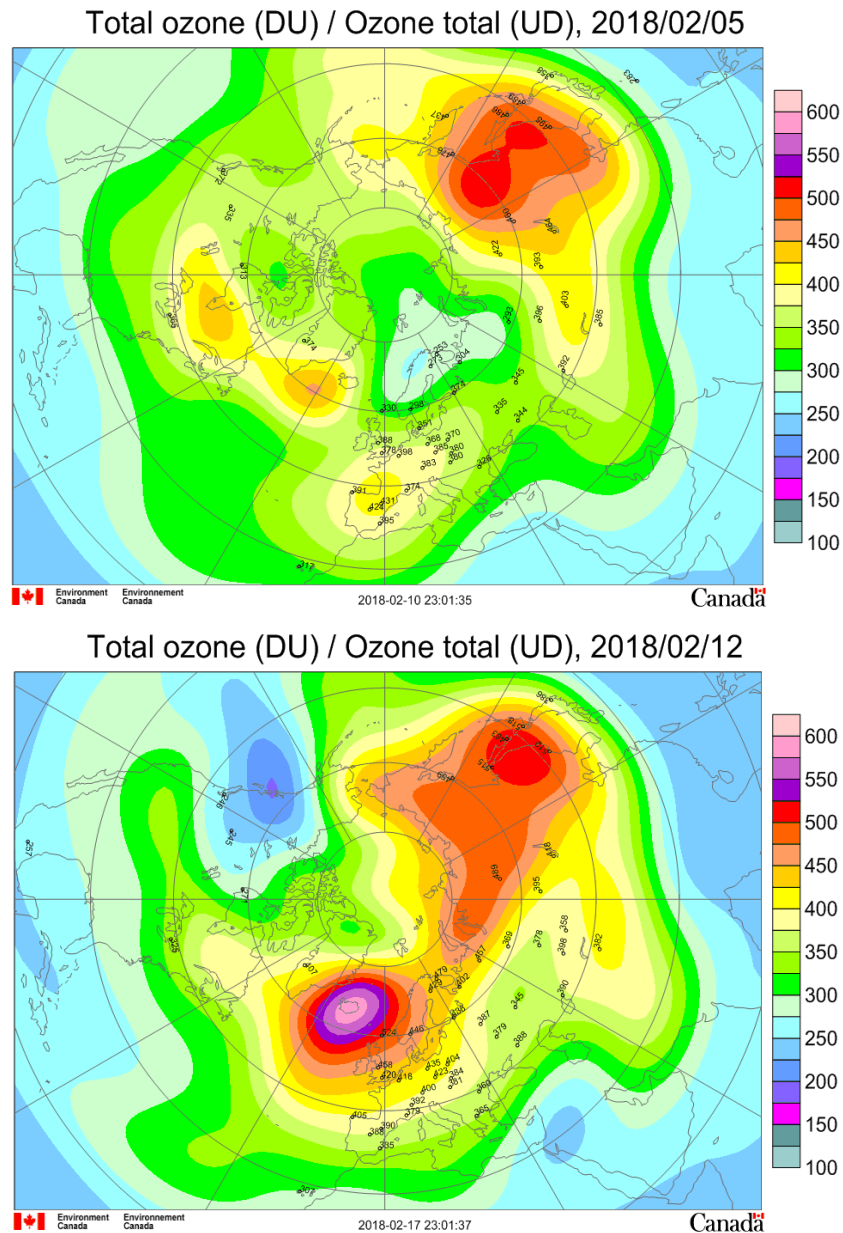


Figure 7: Total ozone from WOUDC and Environment Canada February 5 and 12, 2018. The maps are based on ground based measurements and satellite observations (http://exp-studies.tor.ec.gc.ca/e/ozone/Curr_allmap_q.htm)

The total ozone measurements from the Norwegian stations reflect these dramatic changes in mid-winter depending on the beginning of observations: While the Oslo data reveal periods of low ozone from mid-January to mid-February, the Andøya measurements only catch a glimpse of the ozone-depletion period before mid-February, before total ozone almost doubled within a few days due to the split and moving-away of the vortex remnants. The Ny-Ålesund measurements started too late to catch the depletion phase, but satellite observations indicate the same dramatic rise as at Andøya. As a result, the February and March monthly mean ozone values are significantly above the long-term average at all three stations.

Table 7 summarizes the ozone situation for Norway 2018 and gives the percentage difference between the monthly mean total ozone values in 2018 and the long-term monthly mean values at the three Norwegian sites. As mentioned above, the ozone levels were high in all parts of Norway in February and March (between 3.9 and 12.9% above normal February/March values in Oslo, Andøya and Ny-Ålesund, respectively), but below long-term averages in April and May. Throughout summer and autumn, the situation changed to persistent higher-than-average values in Ny-Ålesund, mostly lower-than-average values in Oslo, and considerable month-to-month variation at Andøya.

Table 7: Percentage difference between the monthly mean total ozone values in 2018 and the long-term 1979-1989 average for Oslo, Andøya, and Ny-Ålesund.

Month	Oslo (%)	Andøya (%)	Ny-Ålesund (%)
January	-0.9		
February	3.9	12.9	11.9
March	6.9	9.9	7.7
April	-6.5	-4.0	-3.3
May	-7.6	-6.5	-0.3
June	-0.5	1.7	1.1
July	-5.9	-6.0	1.6
August	-1.2	-1.7	2.3
September	2.9	3.4	6.1
October	1.1	11.1	10.1
November	0.7		
December	-8.4		

Figure 8, Figure 9 and Figure 10 show the percentage difference between yearly mean total ozone and the long-term yearly mean for the period 1979-1989. The low values in 1983 and 1992/1993 are partly related to the eruption of the El Chichón volcano in Mexico in 1982 and the Mount Pinatubo volcano at the Philippines in 1991.

Comparison of Figure 8, Figure 9 and Figure 10 shows that the ozone patterns at the three Norwegian sites have several similarities. At all sites high ozone values were measured in the end of the 1970s and in 2010, 2013 and 2015. Moreover, all sites had record-low ozone values in 1993 (around 9% below the long-term mean), in 2011 (roughly 6% below the long-term mean), in 2016 and 2017. In 2018 the annual ozone means were 0.8% and 2.8% above the long-term means at Andøya and in Ny-Ålesund, respectively, whereas the annual mean was 1.3% below the long-term mean in Oslo. The low annual

mean ozone value in Oslo was to a large extent caused by the exceptional weather situation from late spring throughout the summer. High-pressure systems are often associated with a high tropopause. In this situation the lower stratospheric ozone will normally be transported horizontally or shifted vertically, leading to reduced total ozone values.

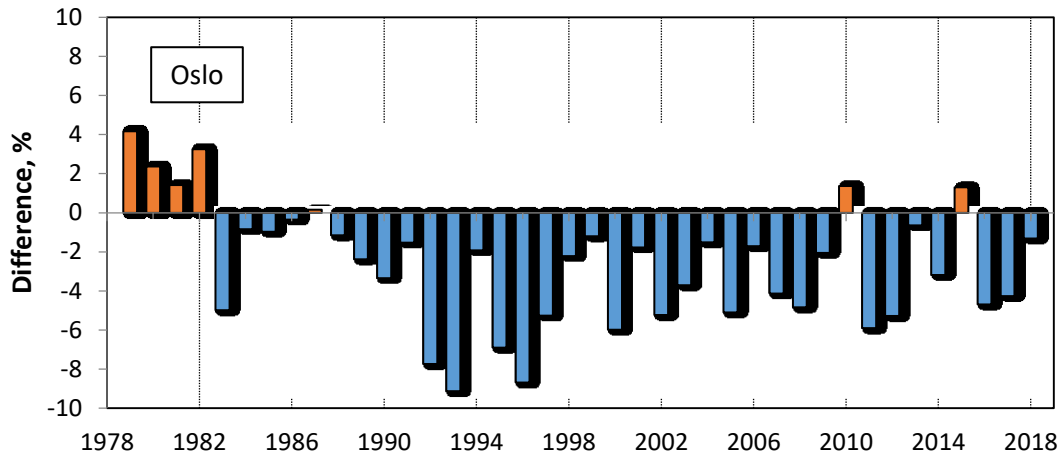


Figure 8: Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean 1979-1989.

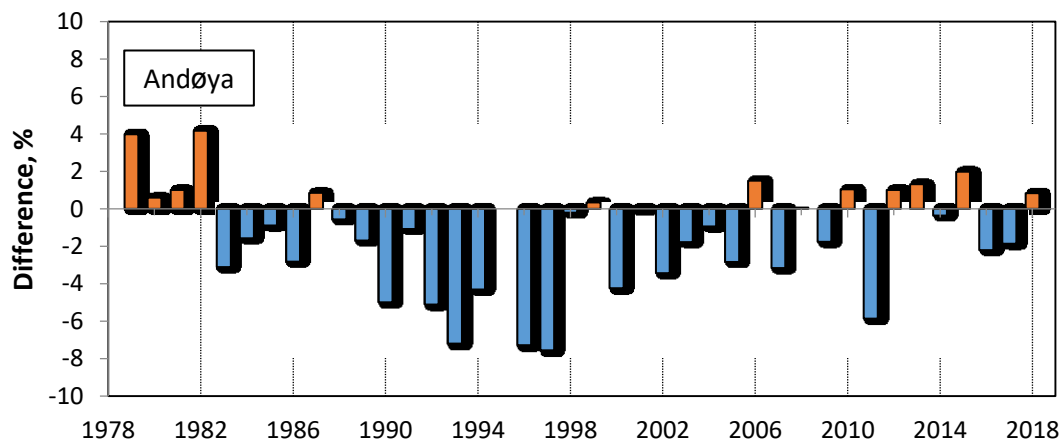


Figure 9: Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean 1979-1989 for the months March-October.

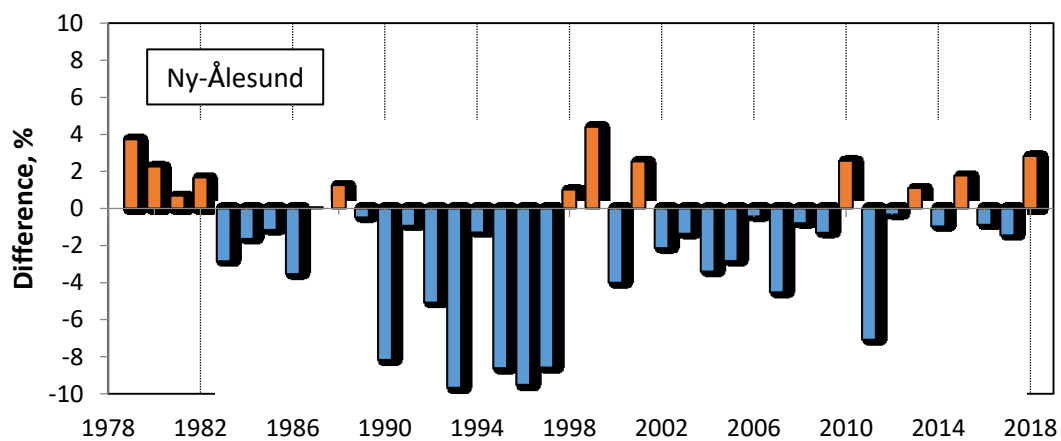


Figure 10: Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.

2.6 Ozone and UV measurements at Troll

In austral summer 2006/2007, NILU established an atmospheric monitoring station at the Norwegian Troll Station (72°01'S, 2°32'E, 1270 m a.s.l.). During the first years of operation the atmospheric station was located close to the main building of Troll, which caused frequent episodes of local pollution. In January 2014, the atmospheric monitoring station was moved uphill and about 2 km further away. The instrumentation originally includes the NILU-UV instrument no. 015, which is NILU's own version of a six-channel broadband filter radiometer for the measurement of UV and visible radiation, comparable to the GUV filter instrument used in the Norwegian ozone and UV monitoring network. A detailed description of the instrument is given in Høiskar et al. (2003). Measurements of the first year of operation were published in Hansen et al. (2009).

The ozone and UV measurements at the Troll Station are not part of the Norwegian ozone and UV monitoring program, but funded by the Norwegian Ministry of Climate and Environment and the Norwegian Antarctic Research Programme. A major goal of these measurements is to compare the development at high Southern latitudes with the situation in the Arctic as given by respective measurements in Ny-Ålesund. After 11 years of operation, the data set also gives valuable information about the long-term stability of the instrument. Unfortunately, NILU-UV no. 015 suffered a major technical failure in April/May 2015, and it had to be replaced with NILU-UV no. 005 in November 2015.

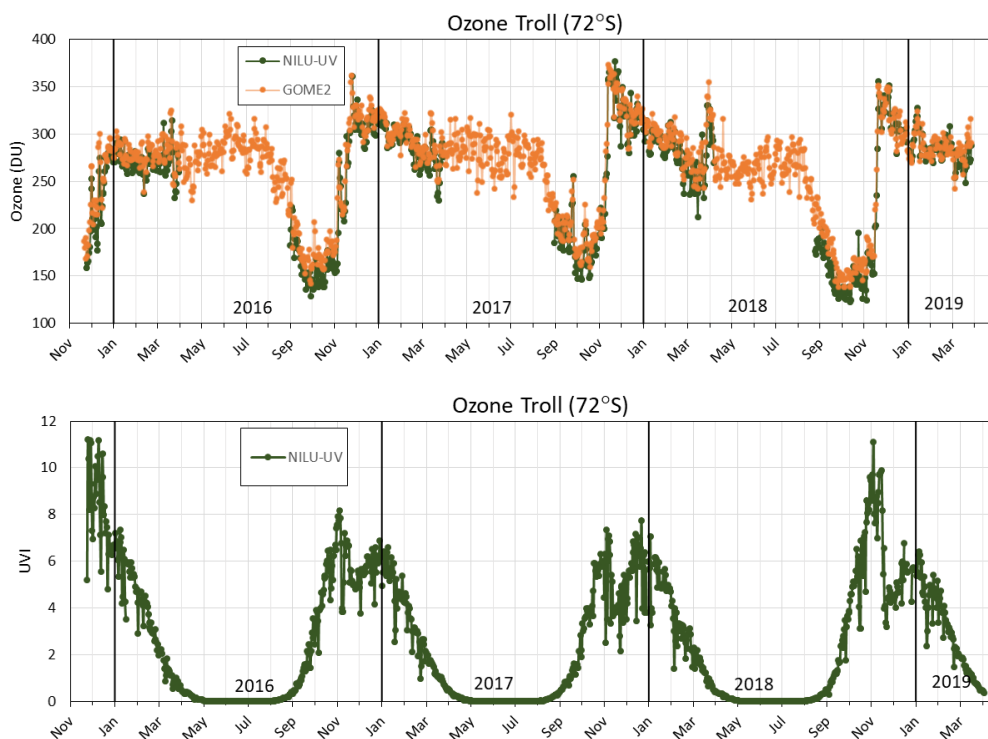


Figure 11: Upper panel: Total ozone from NILU-UV and GOME-2 from November 2015 to March 2019. Lower panel: UVI from NILU-UV 2015-2019

Figure 11, upper panel, shows NILU-UV total ozone values from Troll (green) and total ozone values from GOME-2 (orange) at the Snae station close to Troll. As seen, the ground based and satellite data are in good agreement.

The ozone and UV measurements in Figure 11 reveal that the Antarctic ozone depletion at the Troll Station increased in 2018 compared to the preceding two years, both in terms of minimum total ozone

and duration of the depletion. Total ozone reached minimum values of about 120 DU several times, and latest around 1 November, thus causing a maximum UV index of more than 11.

The Antarctic ozone hole was slightly above average size in 2018, but at the same time it was smaller than expected for the weather conditions³. Colder-than-average temperatures in the Antarctic stratosphere created ideal conditions for ozone destruction, but declining levels of ozone depleting chemicals prevented the hole from growing as large as it might have been 20 years ago. Chlorine levels in the Antarctic stratosphere have fallen about 11% from the peak year. The ozone hole reached an average area of 22.9 million square kilometers in 2018, almost three times the size of the United States. It ranks 13th largest out of 40 years of satellite observations.

This underlines that the Antarctic ozone issue is not a historical event yet and that it largely depends on dynamical conditions, not only the level of ODSs in the stratosphere.

³ <https://earthobservatory.nasa.gov/images/144239/ozone-hole-is-big-but-tempered-by-cfc-reductions>

3 Satellite observations of ozone

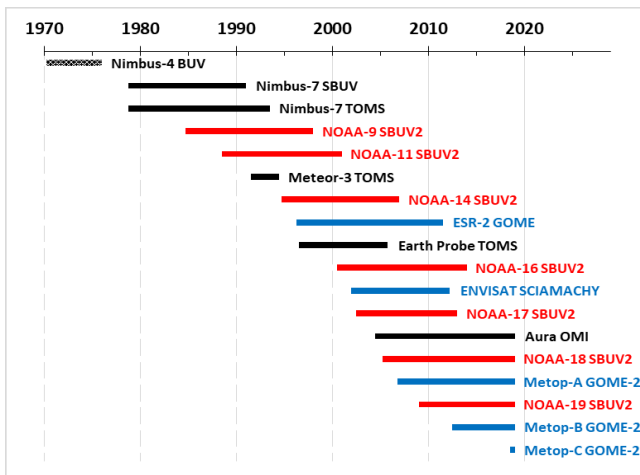


Figure 12: An overview of the most common satellites and their instruments measuring ozone from space since the beginning of the 1970's. NASA satellites are marked in black, ESA and EUMETSAT are in blue, whereas NOAA satellites are marked in red.

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

rely upon high quality ground-based observations. Thus, satellite observations are complementary to ground-based observations, and both are highly necessary.

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

3.1 Satellite ozone observations 1979-2018

In the course of the last 40 years several satellites have provided ozone data for Norway. The most widely used instruments have been TOMS (onboard Nimbus-7 satellite), TOMS (onboard Meteor-3), TOMS (on Earth Probe), GOME I (on ESR-2), GOME-2 (on MetOp), SCIAMACHY (on Envisat), and OMI (onboard Aura). In the 1980s TOMS Nimbus 7 was the only reliable satellite-borne ozone instrument 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 1979-2018. Table 8 shows the percentage GB-satellite deviation in Oslo (upper panel), at Andøya (centre panel) and in Ny-Ålesund (lower panel) for different satellite products. Monthly mean ozone values are calculated from days where simultaneous ground based and satellite data are available.

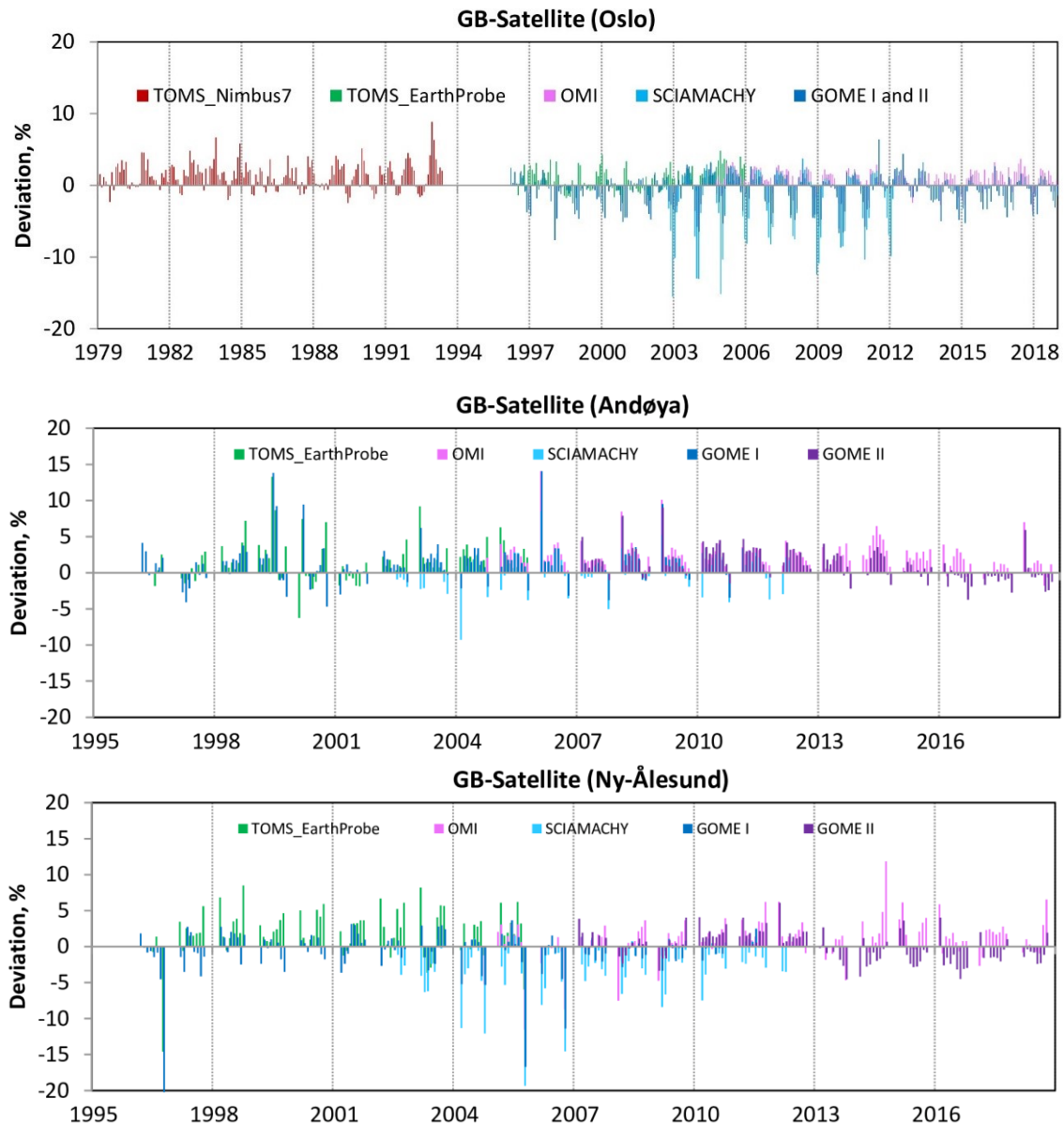


Figure 13: Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2018 (Oslo) and 1995-2018 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, middle panel: Andøya, lower panel: Ny-Ålesund.

Table 8 gives an overview of the average deviations between ground-based ozone measurements and various satellite data products, together with standard deviations and variances for Oslo, Andøya and Ny-Ålesund. For Oslo, ozone values from TOMS and OMI seem to be slightly underestimated, whereas GOME I and SCIAMACHY tend to overestimate total ozone. For Andøya all mean satellite values are lower than the ground based observations, especially the OMI values. The analysis for Ny-Ålesund gives a similar result as Oslo: TOMS and OMI seem to underestimate total ozone, whereas GOME I and SCIAMACHY tend to overestimate ozone. The SCIAMACHY overestimate is to a large extent caused by a large negative bias during early spring and late fall, i.e. at large solar zenith angles even at noon. This contributes strongly to an overall annual average ozone value higher than the ground-based mean value.

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

Oslo					
Instrument	Period		Mean	St. Dev	Variance
TOMS (Nimbus 7)	Nov-78	May-93	1.35	1.88	3.53
TOMS (Earth probe)	Jul-96	Dec-05	0.96	1.60	2.56
OMI	Oct-04	Dec-18	0.90	1.43	2.05
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-18	0.00	2.05	4.19
SCIAMACHY	Jul-02	Apr-12	-2.07	4.43	19.63
Andøya					
Instrument	Period		Mean	St. Dev	Variance
TOMS (Earth probe)	Jul-96	Dec-05	1.71	2.86	8.18
OMI	Oct-04	Dec-18	2.28	2.10	4.39
GOME I	Mar-96	Jul-11	1.42	2.78	7.74
GOME II	Jan-07	Dec-18	1.07	2.26	5.11
SCIAMACHY	Jul-02	Apr-12	0.30	2.37	5.61
Ny-Ålesund					
Instrument	Period		Mean	St. Dev	Variance
TOMS (Earth probe)	Jul-96	Dec-05	2.00	3.33	11.08
OMI	Oct-04	Dec-18	0.89	2.72	7.39
GOME I	Mar-96	Jul-11	-0.72	3.30	10.88
GOME II	Jan-07	Dec-18	0.02	2.07	4.30
SCIAMACHY	Jul-02	Apr-12	-2.95	3.60	12.95

There are clear seasonal variations in the deviations between GB ozone and satellite retrieved ozone values, especially in Oslo and Ny-Ålesund. As mentioned above, SCIAMACHY systematically overestimated ozone values during periods with low solar elevation. This gives a high standard deviation and variance for the GB-SCIAMACHY deviation for Oslo and Ny-Ålesund. The high SCIAMACHY winter values are visualized by the light blue columns/lines in Figure 13, and for Oslo the variance is as high as 19.6%. In contrast, the OMI ozone values are relatively close to the Brewer measurements in Oslo all year, giving a variance of only 2.1% (see Table 8). The GB-OMI variance in Ny-Ålesund is 7.4%, whereas GB-GOME II has a variance of 4.3%. This might indicate that GOME II is slightly better than OMI at high latitudes.

4 The 5th IPCC assessment report: Climate and Ozone interactions

Changes of the ozone layer will affect climate through the influence on the radiative balance and the stratospheric temperature gradients. In turn, climate change will influence the evolution of the ozone layer through changes in transport, chemical composition, and temperature (IPCC, 2013). 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 forcing⁴ (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. Revised global-average radiative forcing estimates from the 5th IPCC assessment report (AR5) are shown in Figure 14 (IPCC, 2013). The estimates represent changes in energy fluxes, caused by various drivers, in 2011 relative to 1750. This figure is slightly more complex than the corresponding representations in previous IPCC reports (e.g. IPCC, 2007), since it shows how emitted compounds affect the atmospheric concentration of other substances.

The total radiative forcing estimated from ozone changes is 0.35 W/m^2 , with RF due to tropospheric ozone changes of 0.40 W/m^2 , and due to stratospheric ozone changes of -0.05 W/m^2 . The overall RF best estimates for ozone are identical with the range in AR4 (previous IPCC report). 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 (NO_x), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs), while stratospheric ozone RF is dominated by ozone depletion from halocarbons.

In total, Ozone-Depleting Substances (ODS; Halocarbons) cause an ozone RF of -0.15 W/m^2 . On the other hand, tropospheric ozone precursors (CH_4 , NO_x , CO , NMVOC) produce ozone with a RF of 0.50 W/m^2 , some of which is in the stratosphere. This is slightly larger than the respective value from AR4. There is also robust evidence that tropospheric ozone has a detrimental impact on vegetation physiology, and therefore on its CO_2 uptake, but there is a low confidence on quantitative estimates of the RF owing to this indirect effect.

Stratospheric ozone is indirectly affected by climate change through changes in dynamics and in the chemical composition of the troposphere and stratosphere (Denman et al., 2007). An increase in the greenhouse gases, especially CO_2 , will warm the troposphere and cool the stratosphere. In general, a decrease in stratospheric temperature reduces ozone depletion leading to higher ozone column. However, there is a possible exception in the polar regions where lower stratospheric temperatures lead to more favourable conditions for the formation of more Polar Stratospheric Clouds (PSCs). 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. This is of particular importance in the Arctic region. It should also be mentioned that ozone absorbs UV radiation and provides the heating responsible for the observed temperature profile above the tropopause. Changes in stratospheric temperatures, induced by changes in ozone or greenhouse gas concentrations will alter dynamic processes.

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

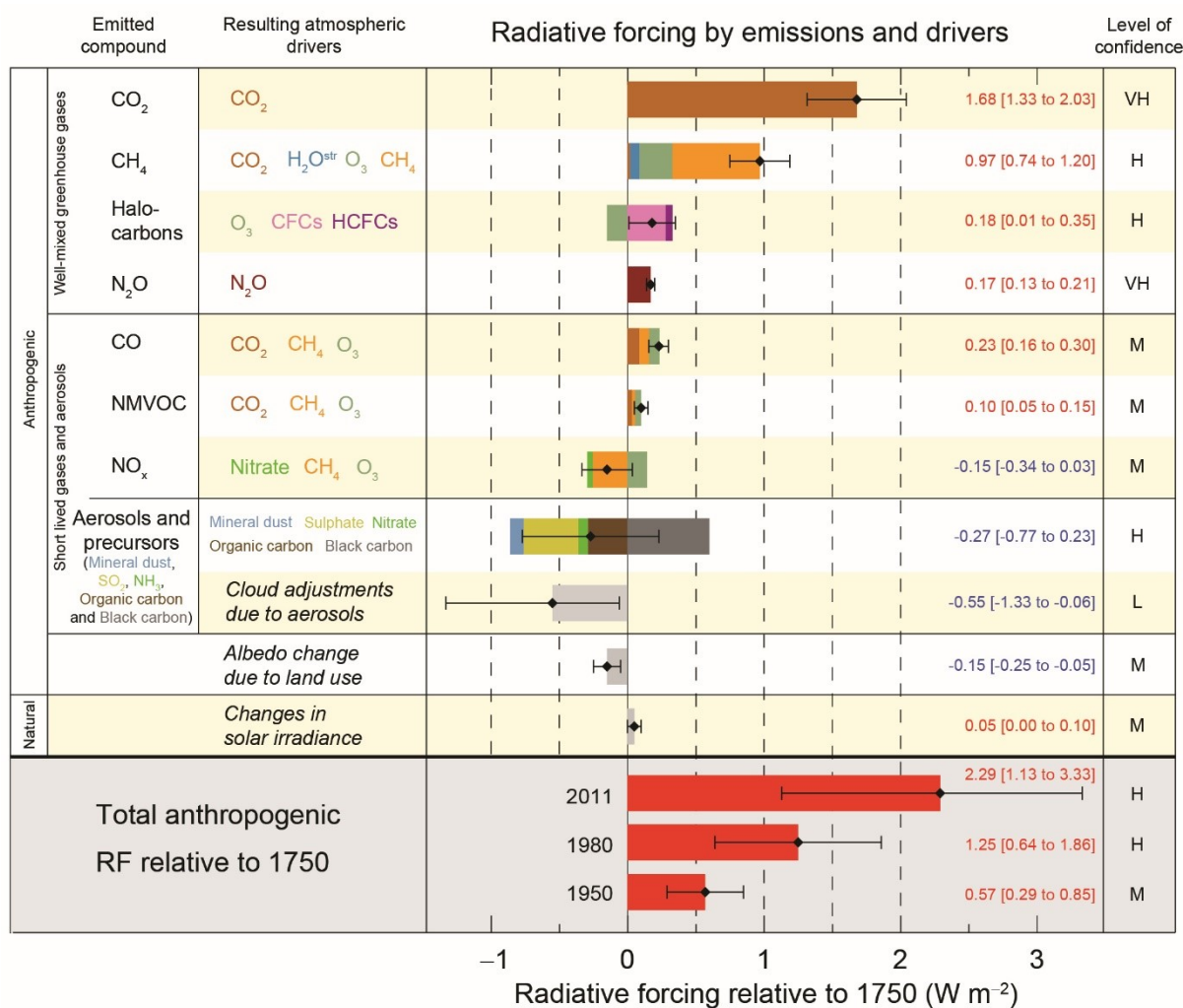


Figure 14: Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change. Values are global average radiative forcing, partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative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

A long-term increase in stratospheric water content has been observed since the second half of the 20th century at the only long-term observation site in Boulder (USA). This would influence the total ozone column, as stratospheric water vapour is among the main sources of OH in the stratosphere⁵. OH is one of the key species in the chemical cycles influencing ozone levels. There are several sources for stratospheric water, where CH₄ is the most important. Other water vapour sources are volcanoes and aircrafts, as well as natural and anthropogenic biomass burning which indirectly can influence on stratospheric moisture through cloud mechanisms (Andreae et al., 2004). In the 5th IPCC report it is estimated that the increase in stratospheric water vapour resulting from anthropogenic emissions of methane (CH₄) has a positive radiative forcing of 0.07 W/m² (see Figure 14). This is consistent with the results from AR4. However, water vapour trends in the stratosphere is a widely discussed issue with satellite data indicating both positive and negative trends, depending on altitude range and data set

⁵ In the stratosphere, water vapour is oxidized by excited O atoms to produce OH (H₂O + O(1D) → 2OH). Next, the hydroxyl radical OH can react with O₃, resulting in a loss of ozone.

selection (e.g., Hegglin et al, 2014; Dessler et al., 2014). The impact of methane on ozone is very complex, but according to AR5 increased ozone concentrations resulting from increased methane emission attributes to a radiative forcing of 0.24 W/m^2 . One mechanism is that methane reacts with chlorine and converts active chlorine (Cl) to a reservoir species (HCl) that does not directly destroy ozone. In this way, stratospheric methane can prevent ozone destruction.

The evolution of stratospheric ozone in the decades to come will, to a large extent, depend on the stratospheric halogen loading. Halocarbons play a double role in the ozone-climate system. They are greenhouse gases and contribute to a strong positive radiative forcing of 0.36 W/m^2 (IPCC, 2013). 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 means a negative radiative forcing. In total, the positive RF from halocarbons has outweighed the negative RF from the ozone depletion that they have induced. The positive RF from all halocarbons is similar to the value in AR4, with a reduced RF from CFCs but increases from many of their substitutes (HFCs).

Finally, nitrous oxide (N_2O) is considered as a key species that influences ozone concentrations. The photochemical degradation of N_2O in the middle stratosphere leads to ozone-depleting NO_x , but unlike in AR4 (IPCC, 2007) the N_2O influence on RF of ozone has been set to zero in AR5. This is due to insufficient quantification of the N_2O influence and particularly the vertical profile of the ozone change (IPCC, 2013, Supplementary Material).

5 UV measurements and levels

The Norwegian UV network was established in 1994/95 and consists of nine 5-channel GUV instruments located from 58°N to 79°N, as shown in Figure 15. NILU is responsible for the daily operation of three of the instruments, located in Oslo (60°N), at Andøya (69°N) and in Ny-Ålesund (79°N). The Norwegian Radiation Protection Authority (NRPA) 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 <http://uv.nilu.no/> and at <http://www.nrpa.no/uvnett/>.

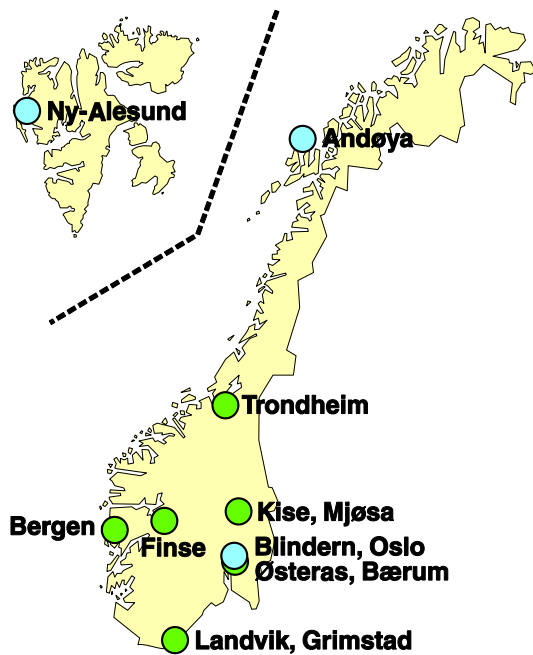


Figure 15: Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas the Norwegian Radiation Protection Authority operates the stations marked with green.

This annual report includes results from Oslo, Andøya and Ny-Ålesund. The GUV instrument in Ny-Ålesund was omitted from the monitoring programme for the period 2006-2009, but was included again in 2010. This resulted in gaps in the original UV time series from Ny-Ålesund. However, the GUV instrument has been logging continuously since 1995 and the measurements from 2006-2009 have been reanalysed and included in the UV time series.

The GUV instruments are normally easy to maintain and have few interruptions due to technical problems. However, the instruments have been in operation for 24 years and technical failures have occurred more frequently in recent years. Fortunately, the instruments at Blindern, Andøya and Ny-Ålesund ran without major problems in 2018, except for some unknown stops/interruptions that normally last for a few minutes or hours. The reason for these problems is still not known, but switching detector cable seems to help in some situations. Also, the temperature controller for the Blindern GUV broke down in the summer 2018, but this was repaired without lack of data.

5.1 UV measurements in 2018

The UV dose rate is a measure of the total biological effect of UVA and UVB radiation (UV irradiance weighted by the CIE action spectra⁶). The unit for dose rate is mW/m², but is often given as a UV index (also named UVI). A UV index of 1 is equal to 25 mW/m². The concept of UV index is widely used for public information concerning sunburn potential of solar UV radiation. At Northern latitudes the UV indices typically vary between 0 – 7 at sea level, but can range up to 20 in Equatorial regions and high altitudes (WHO, 2009). Table 9 shows the UV-index scale with recommended protections

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

at the different levels. The recommendations are based on a moderate light skin type, typical for Nordic population.

Figure 16 shows the UV dose rates measured at local noon (± 0.5 hour) in Oslo, at Andøya and in Ny-Ålesund in 2018. The highest noon UV dose rate in Oslo, 154.6 mW/m^2 , was observed on 1st July and is equivalent to a UV index of 6.2. The black curves in Figure 16 represent the measurements whereas the red curves are model calculations employing the measured ozone values and clear sky. At Andøya the highest noon UV index in 2018 was 4.7, equivalent to a dose rate of 117.2 mW/m^2 , observed on 5th July. The highest UVI noon value in Ny-Ålesund was 2.7 or 67.1 mW/m^2 , measured on 3rd July.

At all the Norwegian stations the highest noon UVI values in 2018 were observed during days with relatively low ozone values. In Oslo, at Andøya and in Ny-Ålesund the total ozone columns were 11%, 9% and 6% below the long-term seasonal mean ozone values, respectively.

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

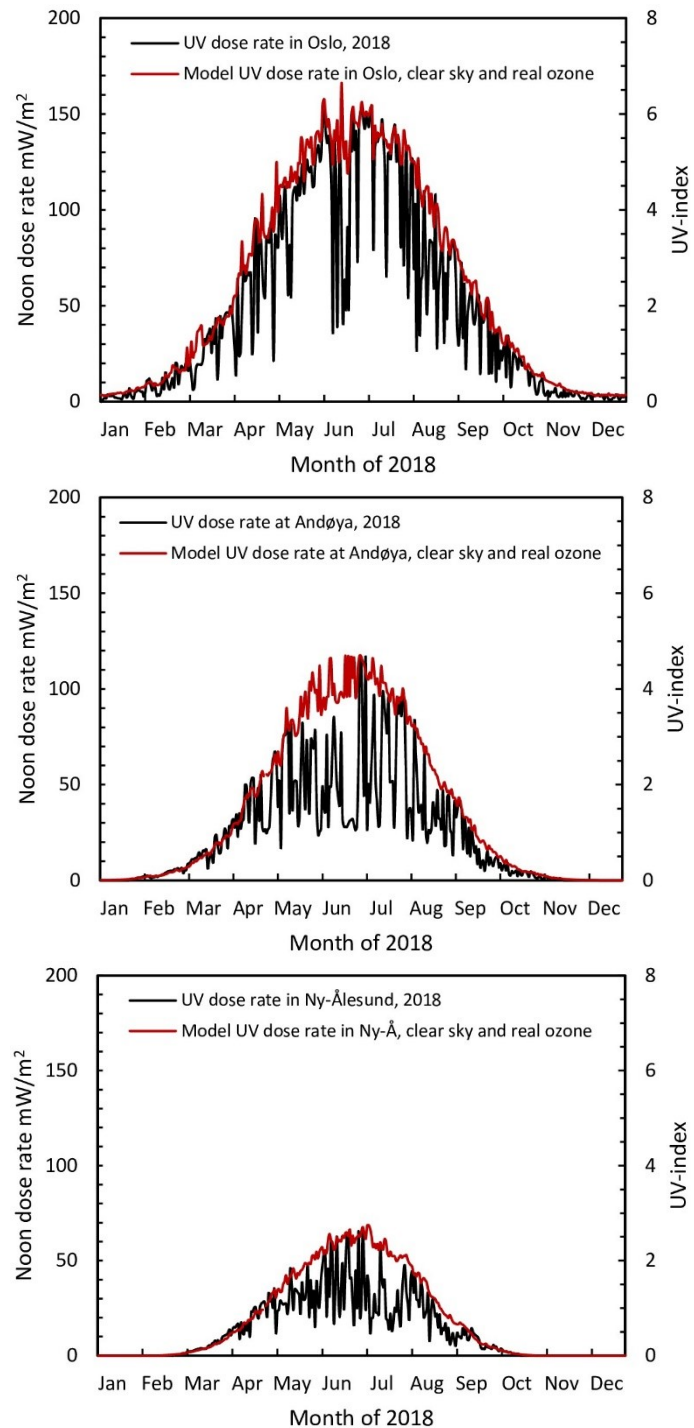


Figure 16: Hourly averaged UV dose rate measured at local noon (± 0.5 hour) in 2018. Upper panel: Oslo. Mid panel: Andøya Lower panel: Ny-Ålesund.

Table 9: UV-index together with the recommended protection.

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

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

As seen from Figure 17 (red curve, left panel) Oslo had clear sky all day 1st July. This is evident from the straight red curve, with cloud transmission constantly around 100%. At Andøya and Ny-Ålesund the sky was cloud-free after noon, but was covered with scattered clouds in the morning. This is seen from the “noisy” red curves in Figure 17 (middle and right panels) the first part of the day. The scattered clouds result in multiple reflections between the clouds, and between the ground and the clouds, which normally enhance the UVI. Around noon the scattered clouds at Andøya did not block the solar disk, resulting in high cloud transmission (CLT above 100%). In the late afternoon heavy clouds covered the sun, and the cloud transmission dropped down to 40-50%. The UV dose rate dropped correspondingly.

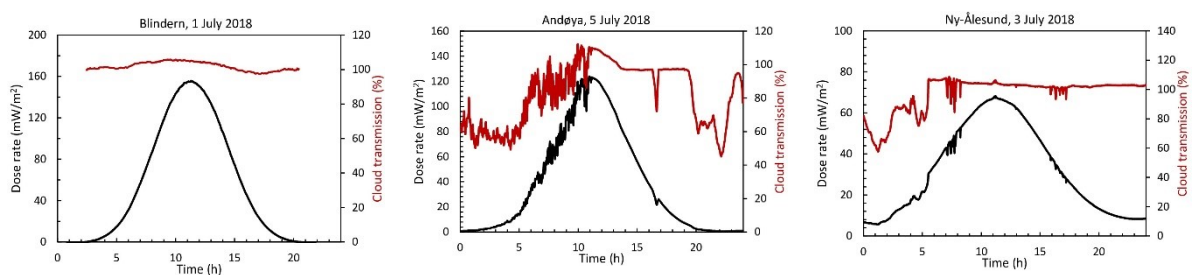


Figure 17: UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel) in 2018. A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30% represent heavy clouds.

In Norway the highest UV dose rates generally occur in the late spring and early summer in southern alpine locations with fresh snow, such as Finse. Here the UV indices at noon can reach 9.

Many Norwegian citizens visit Mediterranean and other lower-latitude countries during holidays, and UV-indices may easily become twice as high as in Oslo under conditions with clear sky and low ozone. Also, at the Troll station in Antarctica the UVI can exceed 11 during ozone hole periods in November/December (Antarctic spring/early summer).

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

Monthly integrated UV doses for Oslo, Andøya and Ny-Ålesund in 2018 are compared in Figure 18. As expected, the monthly UV doses in Oslo were higher than the values observed at Andøya and in Ny-Ålesund. If the cloud cover, albedo and ozone conditions are the same at all three sites, the UV-radiation will be highest in Oslo due to higher solar elevation at mid-day. In May, June and July 2018 the UV-doses in Oslo were far above normal due to the exceptional nice weather in the summer (many cloudless days) and low ozone values. It is also worth noting that the integrated UV-dose at Andøya in June 2018 was lower than the Ny-Ålesund UV-dose, caused by long periods of overcast conditions at Andøya this month.

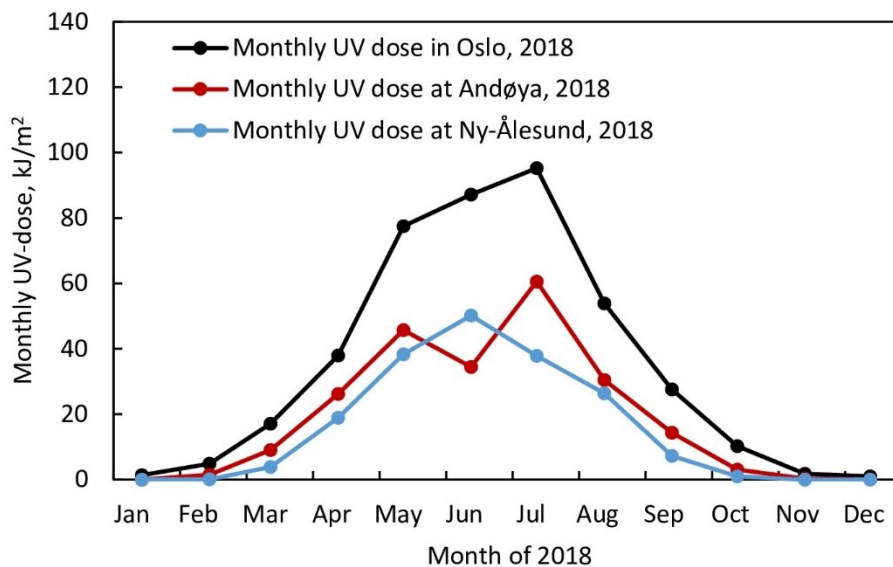


Figure 18: Monthly integrated UV doses (in kJ/m^2) in 2018 measured with the GUV instruments located in Oslo, at Andøya and in Ny-Ålesund.

5.2 Annual UV doses 1995-2018

Annual UV doses for the period 1995–2018 are shown in Table 10 for the GUV instruments in Oslo, at Andøya and in Ny-Ålesund.

The UVI time series have recently been reanalysed, using a statistical method from Bjørn Johnsen (NRPA). Gaps in GUV measurements have been complemented with modelled values, based on cloud modification factors derived from synoptic cloud observations and pyranometer data, as well as derived from the STRÅNG model (<http://strang.smhi.se/>).

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

Table 10: Annual integrated UV doses (in kJ/m^2) for Oslo, Andøya and Ny-Ålesund for the period 1995 – 2018.

Year	Oslo (kJ/m^2)	Andøya (kJ/m^2)	Tromsø (kJ/m^2)*	Ny-Ålesund (kJ/m^2)
1995	373.1			
1996	371.8		224.8	215.8
1997	398.5		247.4	214.7
1998	312.0		238.8	215.1
1999	353.2		224.5	183.8
2000	350.5	235.2		221.2
2001	357.4	220.4		210.9
2002	369.7	255.8		214.8
2003	361.8	237.8		184.3
2004	365.4	238.6		201.4
2005	365.0	229.5		208.1
2006	365.2	221.9		184.4
2007	352.8	254.9		219.0
2008	371.2	260.9		212.9
2009	365.4	256.8		228.7
2010	351.5	229.1		201.5
2011	353.6	254.9		217.0
2012	354.8	233.9		212.5
2013	357.6	245.8		179.5
2014	384.4	252.3		212.7
2015	355.0	224.0		214.6
2016	371.8	228.3		189.8
2017	357.0	260.0		207.5
2018	415.7	225.7		183.8

*The GUV instrument at Andøya was operating in Tromsø during the period 1996 – 1999.

In 2018 the total yearly integrated UV-dose in Oslo was the highest value ever recorded. The dose of 416 kJ/m² is 4.3% higher than the previous record value from 1997. Again, the exceptional nice weather from May to July, with many cloudless days and low ozone values, is the main explanation for the high annual UV-dose. Contrary to Oslo, the annual integrated UV-doses at Andøya and in Ny-Ålesund were relatively modest. Ny-Ålesund had the 2nd lowest integrated UV-dose since the measurements started in 1995, whereas Andøya had the 4th lowest observation. Bad weather condition during parts of the summer is the main explanation.

Graphical presentations of the annual integrated UV-doses from 1995 to 2018 are shown in Figure 19. For Oslo and Andøya there is an increase of 1.5%/decade and 0.7%/decade, respectively, in the annual UV-doses. For Ny-Ålesund there is a negative trend of -2.1%/decade. However, none of the trend results are statistical significant.

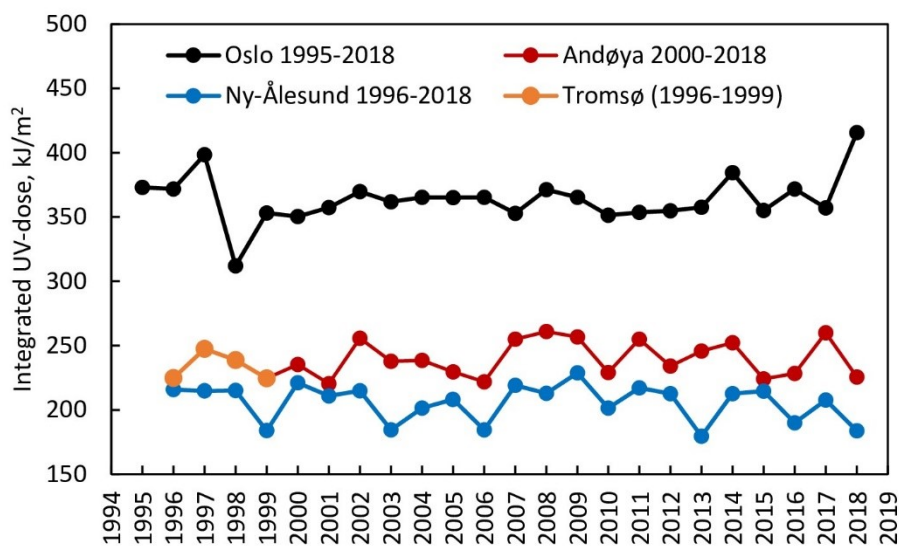


Figure 19: Annual integrated UV doses (in kJ/m²) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995–2018.

The trend results (though not significant at a 2 σ level) are related to changes in both ozone, cloudiness and albedo. It is worth noting that the UV-trend in Oslo from 1995-2017 was close to zero and the current trend of 1.5%/decade is caused by the exceptional high UV level in 2018.

6 Appendix: Instrument description

The Norwegian ozone measurements are retrieved from Brewer spectrophotometers in Oslo and at Andøya, whereas a SAOZ (Système d'Analyse par Observation Zenitale) instrument is the standard ozone instrument in Ny-Ålesund. At all the three Norwegian sites GUV (Ground-based UltraViolet) filter radiometers are installed and can fill in ozone data gaps on days without Brewer and SAOZ measurements.

Every year the International Ozone Services (IOS), Canada, calibrate Brewer instrument no. 42 (Oslo) and no. 104 (Andøya) against a reference instrument, last time in summer 2017. The Brewer instruments are also regularly calibrated against standard lamps in order to check the stability of the instruments. Calibration reports are available on request.

In October 2014, CNR-IDASC, Italy, and NILU signed a scientific agreement that should give NILU access to the Italian Brewer (B50) measurements in Ny-Ålesund. The Brewer instrument was calibrated by IOS Canada in summer 2015, to ensure high quality ozone measurements.

The GUV instruments are compared with the European travelling reference spectro-radiometer QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe; Gröbner et al., 2010) every year. The Norwegian Radiation Protection Authority coordinates this calibration.

In Oslo, total ozone is primarily recorded with the Brewer MKV Spectrophotometer (B042) located at Blindern. 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. 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.

NILU's 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 autumn 2017 a new reference spectrum from 3 April 2017 was selected. This proved to be satisfactory also for measurements back to 2013. Simultaneously, all observations since 2000 have been re-analyzed with updated analysis parameters, as has been done with all instruments in the SAOZ network. By the end of 2017, the data from the Ny-Ålesund SAOZ were state-of-the-art in line with the other active instruments in this global network.

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