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# Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

## Annual Report 2016



# COLOPHON

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## Project manager for the contractor

Tove Marit Svendby

## Contact person in the Norwegian Environment Agency

Camilla Fossum Pettersen

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## Author(s)

T.M. Svendby, G.H. Hansen, K. Stebel, A. Bäcklund (all NILU), A. Dahlback (UiO)

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## Summary - sammendrag

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 the 1979-1989 average. There are large inter-annual variations and in 2016 there were relatively low values at all the three Norwegian stations, especially in February/March.

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 en videre reduksjon og ozonverdiene stabiliserte seg på et nivå ~2% lavere enn 1979-1989 middelet. Det er imidlertid store årlige fluktuasjoner, og i 2016 var det gjennomsnittlige ozonlaget relativt tynt, spesielt i februar og mars.

## 4 emneord

Stratosfærisk ozon, UV-stråling, Målinger og observasjoner, Montreal-protokollen

## 4 subject words

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

## Front page photo

Kjetil Tørseth

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# 1. Summary

The amount of stratospheric ozone decreased dramatically during the 1980s and 1990s. 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 stop 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.

Even if we can see signs of ozone recovery today, 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. It is also important to detect possible changes in the ozone layer related to factors other than ODSs, like climate change.

## ***The national monitoring programme***

In 1990, the Norwegian Environment Agency established the programme “Monitoring of the atmospheric ozone layer”. 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). After 2013 Andøya has been omitted from 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.

This report summarises the activities and results of the monitoring programme in 2016. It also includes total ozone trend analyses for the period 1979-2016 and UV measurements in Oslo, at Andøya and in Ny-Ålesund since 1995. 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.

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 (e.g. Myhre et al., 2016) includes monitoring and analysis of ozone depleting substances (ODSs), an activity which is closely related to the total ozone and UV monitoring programme presented in this report.

## ***Total ozone***

Total ozone values above Oslo, Andøya and Ny-Ålesund were record low in February 2016. It was a strong reminder that, despite political regulations of CFCs in place, the possibility of severe ozone depletion in the Arctic will exist for decades to come. In Oslo, a seasonal minimum value of 222 DU was measured on 1 February, which is almost 41% below normal February values. The situation was similar at Andøya and in Ny-Ålesund where minimum

ozone values of 255 DU and 241 DU were measured in February, which are 31% and 38% below long-term February mean values, respectively.

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. In spite of the record low February ozone values, the absolute ozone minima in 2016 were measured in the fall. In Oslo, the minimum ozone value was 218 DU, measured on 14 October 2016. This is about 26% below the long-term mean for October. At Andøya the minimum ozone value was 242 DU, measured 26 October (15% below normal), whereas a minimum value of 225 DU was measured in Ny-Ålesund 22. October, which is 18% below the October long-term mean.

Our monitoring programme and trend analyses indicate 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 -5.8%/decade and as much as -8.4%/decade during spring. For Ny-Ålesund the decrease was even larger: -7.0%/decade for annual means and -11.7%/decade during the spring months. For the period 1998-2016 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 values (i.e. the reference level, before ODSs had significant influence on stratospheric ozone destruction).

Recent studies indicate signs of ozone recovery in most parts of the world. However, there is still uncertainty related to this recovery, particularly in the Polar region. The uncertainty is caused by the high natural ozone fluctuations in this region (varying ozone transport from lower latitudes), plus the influence of climate factors, e.g. decreasing stratospheric temperatures related to the increase of atmospheric greenhouse gas concentrations.

#### ***UV measurements***

The highest 2016 UV index (UVI) in Oslo was 6.4, measured 25 June 2016. 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 2016 was 4.3 (observed 29 May), whereas the highest UVI in Ny-Ålesund, 2.5, was observed 8 July. These values are typical for low and high Arctic latitudes, respectively. In 2016 the UV-doses in Oslo were in general above the long-term mean. For the 1995-2016 period as a whole, 2016 was the year with the fifth highest yearly integrated UV-dose in Oslo. Only 2014 and 1995-1997 had higher UV values. This can partly be explained by low ozone values during the summer 2016. Under clear-sky conditions, a 1% ozone decrease will give a corresponding 1% increase of the UV-dose. At Andøya and in Ny-Ålesund the yearly integrated UV-doses in 2016 were slightly below their long-term means.

#### ***Satellite ozone observations***

For Norway and the Norwegian Arctic, the use of satellite data provides valuable information on spatial distribution of ozone and UV radiation. Satellites also make it possible to investigate the geographical extent of low ozone episodes during spring and summer and thereby discover enhanced UV intensity on a regional level. Thus, satellite observations are complementary to ground based observations, and both provide valuable information.

Comparisons of ground based measurements and satellite data in Oslo show good agreement during the summer, whereas the differences are slightly larger in the spring, autumn and winter months. This is caused by weak instrumental signals during periods with low sun. At

Andøya and in Ny-Ålesund the satellite measurements are normally a few percent lower than the ground based measurements. Also, monthly mean ozone values retrieved from two different satellites might differ significantly.

### ***Coupling of stratospheric ozone and climate***

For several decades, the ozone layer has been threatened by the release of man-made ozone depleting substances (ODSs). The expected future recovery of stratospheric ozone might be affected by climate change. While the Earth's surface is expected to continue warming in response to the net positive radiative forcing from greenhouse gas increases, the stratosphere is expected to cool. A decrease in stratospheric temperature will slow down the gas-phase ozone destruction reactions, leading to less depletion and higher ozone column. Furthermore, climate change may alter the strength of the stratospheric circulation and with it the distribution of ozone in the stratosphere. Chemistry-climate model simulations used in the last Assessment reports (WMO, 2014), predict that the total column ozone concentrations at Northern Hemisphere latitude most likely will reach their pre-1980 values around year 2030. However, more recent analyses presented, e.g., at the 10<sup>th</sup> Ozone Research Managers' meeting at WMO in 2017, conclude that the recovery is slower than expected and that it may take at least 20 more years before the pre-1980 level will be reached.

The atmospheric concentrations of the three greenhouse gases, CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, have increased significantly due to human activities since 1750 and are expected to continue increasing in the 21st century. These continuing increases have consequences for ozone amounts. However, there is a very complex coupling between stratospheric ozone and climate drivers, and the net effect of increased N<sub>2</sub>O and CH<sub>4</sub> on total ozone is uncertain.

#### **MAIN CONCLUSIONS FROM THE MONITORING PROGRAMME 2016**

- The Total ozone values in Norway were record low in February 2016 (between 13% and 27% below the long-term average).
- The ozone situation normalized towards the end of spring, but most months in 2016 had average ozone values below the long-term mean.
- At all Norwegian monitoring stations a significant stratospheric ozone decrease was recorded for the period 1979-1997. For the period 1998-2016 there were no significant trends in the ozone layer above Norway.
- The annual integrated UV dose in Oslo in 2016 was the fifth highest value registered since 1995. This was caused by many cloudless days in the summer, combined with relatively low ozone values.
- Meteorological variability has a large impact on ozone and can give considerable year-to-year variations in total ozone.

## 2. Norwegian ozone measurements in 2016

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 1994 and 1990, respectively. The ozone measurements are retrieved from Brewer spectrophotometers in Oslo and at Andøya, whereas a SAOZ (Système d'Analyse par Observation Zenitale) instrument has been 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 (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 the ozone layer, is expressed in terms of Dobson Units (DU<sup>1</sup>)

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 4.

### 2.1 Total ozone in Oslo

In Oslo total ozone is primarily recorded with the Brewer MKV Spectrophotometer (B042) located at Blindern. Figure 1a illustrates the daily total ozone values from Oslo in 2016. 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 2016 are based on Brewer direct-sun (DS) measurements when available.

In 2016 direct-sun measurements were performed on 175 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 175 days. In the summer 2016 there were some problems with the Brewer standard lamp, which resulted in 13 days without Brewer measurements. On days without 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. Thus, GUV ozone data were used on the 13 days with missing Brewer data. For the remaining three days no ozone was retrieved due to bad weather conditions. A summary of instruments and frequency of inclusion in the 2016 Oslo ozone series is given in Table 1. Even if total ozone

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<sup>1</sup> 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”.

was retrieved from the GUV instrument on 333 out of 366 days, only 13 of the measurements were used in the 2016 time series since the Brewer measurements were considered as more accurate.

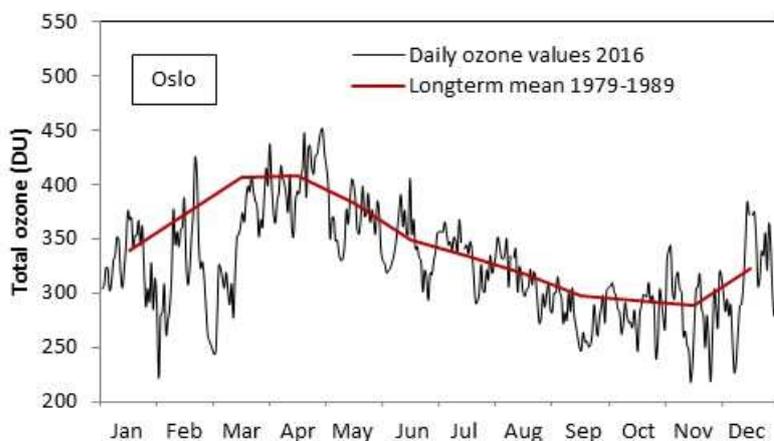


Figure 1a: Daily total ozone values measured at the University of Oslo in 2016. The red curve shows the long-term monthly mean values from 1979-1989.

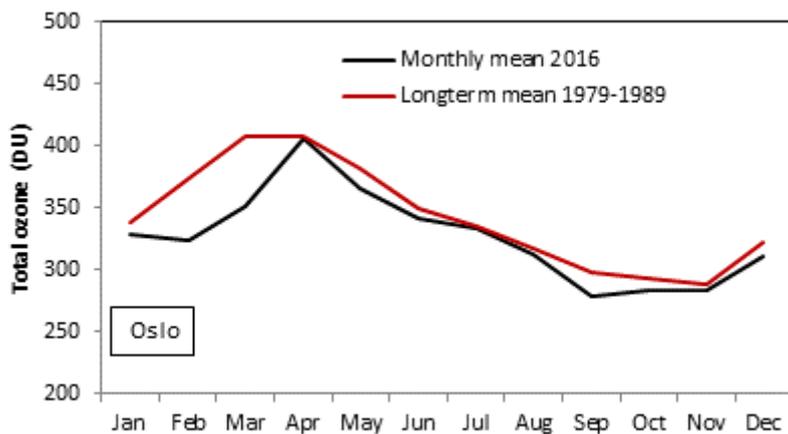


Figure 1b: Monthly mean ozone values for 2016. The red curve shows the long-term monthly mean values from 1979-1989.

Table 1: Overview of total ozone instruments in Oslo and the number of days where the various instruments were used in the 2016 time series

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	175
2	Brewer instrument, global irradiance method	175
3	GUV-511 instrument	13
	Missing days (due to bad weather)	3

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 and November. The minimum ozone value in 2016 was 218 DU, measured on 14 October. This is about 26% below the long-term mean for October. 2016 was a very special year due to exceptionally low ozone values in February and March. In Oslo a minimum value of 222 DU was measured on 1 February, which is almost 41% below normal February values.

The monthly mean total ozone values in 2016 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 value in February and March were significantly lower than normal, i.e. ~13% below normal, whereas the values were close to normal rest of the year. Section 3.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2016.

## 2.2 Total ozone at Andøya

The Andøya ozone measurements are no longer a part of the national monitoring 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 the second 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 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. 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.

The Andøya Brewer instrument ran without major interruptions in 2016. However, it was registered a significant drift in the internal standard lamps last year, which made it crucial with comprehensive post-processing of all ozone data. Both Brewer DS and GI had to be standard-lamp-corrected prior to publication. Also the GUV instrument at Andøya had some technical problems in 2016. In late fall 2015 it was discovered that the 320 nm channel in Andøya GUV no. 9276 failed. Thus, for a short period total ozone and UV were retrieved from alternative retrieval algorithms where the 320 nm channel was excluded. A spare instrument, GUV no. 9278, was borrowed from the Norwegian Radiation and Protection Authority. This instrument was used from 18 March to December 2016. Meanwhile GUV no. 9276 was sent to BSI (USA) for repair.

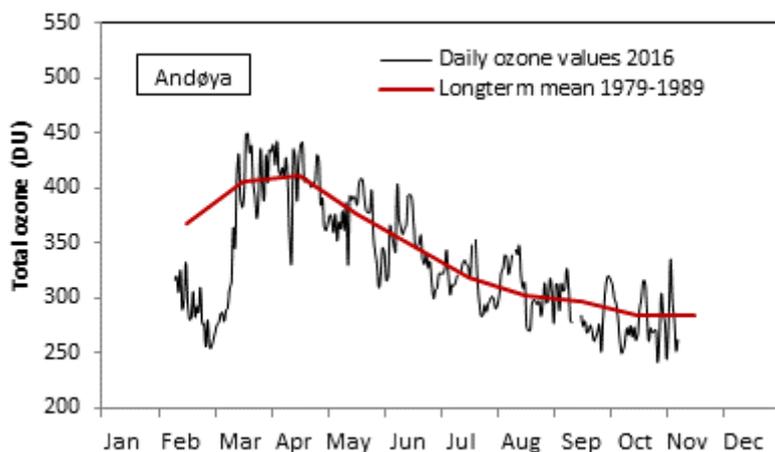


Figure 2a: Daily total ozone values measured at ALOMAR, Andøya, in 2016 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989.

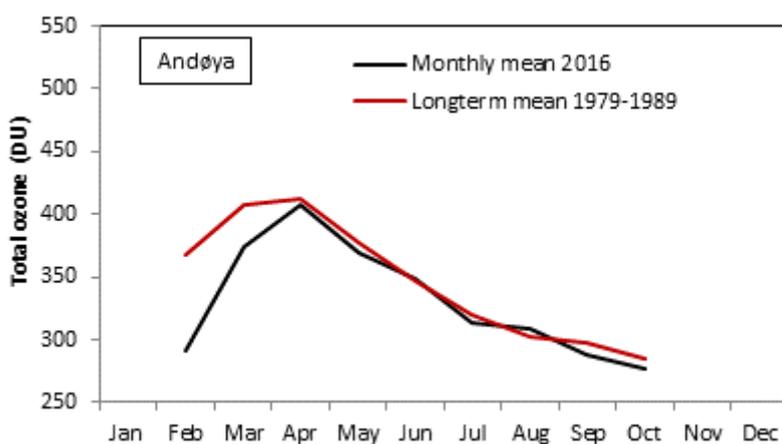


Figure 2b: Monthly mean total ozone values for 2016 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

Table 2 gives an overview of the different instruments and methods used at Andøya in 2016. Brewer DS was used on 147 days, whereas Brewer GI provided the daily ozone value on 69 days. In total, there were 12 days with missing Brewer data in 2016 where GUV total ozone values were used as replacements. The GUV instrument also works satisfactory 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, GUV measurements were used on 50 days in 2016. In addition, on 6 days bad weather conditions resulted in ozone values with unacceptably high uncertainty.

Figure 2a shows daily ozone values from Andøya in 2016. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989. The lowest ozone values at Andøya normally occur in October and November, and the minimum ozone value in 2016 was 242 DU, measured 26 October. This was about 15% below the long-term mean for October. On 29 February, total ozone reached a relative minimum of 255 DU, which is 31% below average February values.

Monthly mean ozone values at Andøya for 2016 are shown in Figure 2b. For January, November, and December (polar night) there were not sufficient data to calculate monthly means. Comparison between the long-term mean and monthly mean ozone values in 2016 shows that the total ozone column was very low in February and March (21% and 8% below the long-term means for February and March, respectively). During the rest of the year the ozone values were close to normal (within  $\pm 3\%$ ).

Table 2: Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2016.

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	147
2	Brewer instrument, global irradiance method	69
3	GUV instrument	50
	Missing days (except polar night period)	6

## 2.3 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 instruments are based on UV absorption techniques, e.g. the Brewer and GUV instruments, the SAOZ instrument 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  $\sim 85^\circ$ . 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 up in the fall 1990 and have continued until the present time with a few exceptions (see Appendix)

In addition to SAOZ, 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 Italian Brewer measurements, which are valuable for evaluating SAOZ and GUV ozone data.

Comparisons between Brewer and GUV ozone measurements revealed a seasonal difference in total ozone. For the period 2013 - 2015 the GUV measurements were on average 4-5% higher than the Brewer values. Consequently, a seasonal correction has been applied to the entire GUV ozone time series. The adjustment of GUV total ozone data had small impact on the overall ozone trend, since most summer ozone measurements after 1998 are based on the GUV instrument and consequently all measurements have been adjusted equally. Also, the SAOZ ozone data were adjusted by  $\sim 5\%$  for the years 2012-2016 to account for changes in the retrieval algorithms.

Both the SAOZ and GUV instruments worked satisfactorily in 2016 and there were none days of missing data due to technical problems or bad weather conditions. Table 3 gives an overview of the different instruments and methods used for the 2016 ozone series in Ny-Ålesund. No 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 2016.

Priority	Method	Total days with observations
1	SAOZ instrument	84
2	GUV instrument	166
	Missing days (except polar night period)	0

Figure 3a shows daily ozone values from Ny-Ålesund in 2016. 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. Similar to Oslo and Andøya, the lowest ozone values in Ny-Ålesund normally occur in October and November, and the minimum ozone value in 2016 was 225 DU, measured on 22 October. This value is 18% below the long-term mean for October. In addition it was measured an ozone value of 241 DU 25 February, i.e. 38% below normal values for February.

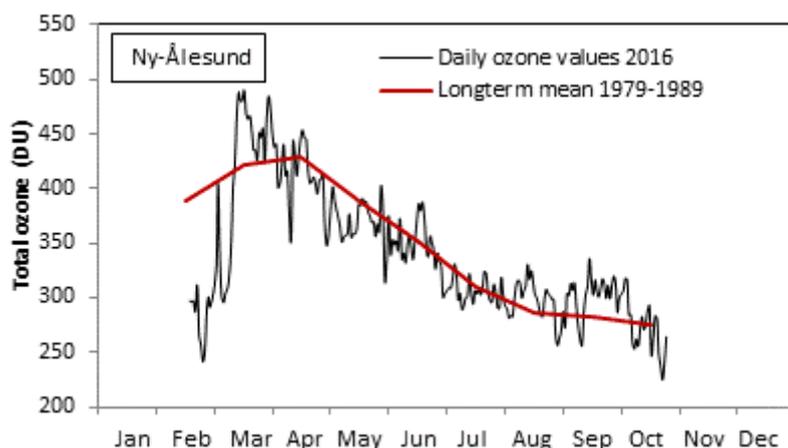


Figure 3a: Daily total ozone values measured in Ny-Ålesund in 2016 by the SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 - 1989.

Monthly mean total ozone values in Ny-Ålesund 2016 are shown in Figure 3b. Comparisons between the monthly mean 2016 ozone values and the long-term monthly means show that the average ozone layer in Ny-Ålesund was exceptionally thin in February 2016, with 27% below normal. Late spring and early summer were also associated with low ozone values (1-4% below the long-term means), but the situation reversed in late summer/fall. In September 2016 the average ozone value was 7% higher than the long-term September mean.

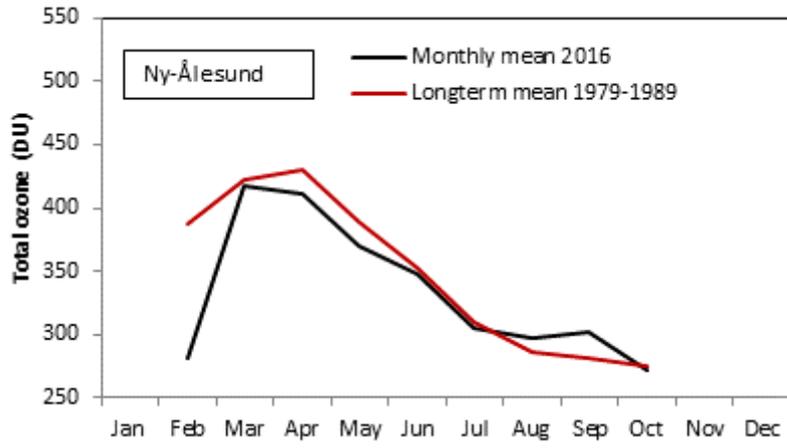


Figure 3b: Monthly mean total ozone values for 2016 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

## 3. Ozone measurements and trends 1979-2016

### 3.1 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: 2014”, was published in December 2014 (WMO, 2014). 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 2012, the combined chlorine and bromine levels had declined by about 10-15% from the peak values in the late 1990s.

Earlier measurements showed that total column ozone declined over most of the globe during the 1980s and early 1990s. The 2014 assessment report concludes that total column ozone has remained relatively unchanged since 2000, with indications of a small increase in recent years, as expected. In the upper stratosphere, there is a clear ozone increase in recent years, which climate models suggest can be explained by comparable contributions from declining ODS abundances and upper stratospheric cooling caused by carbon dioxide increases.

According to the 2014 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. This recovery is expected to occur around 2030 in mid-latitudes and the Arctic, and somewhat later for the Antarctic region.

The 2014 assessment report also emphasizes that changes in CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> will have an increasing influence on the ozone layer as ODS concentrations decline. This is described in more detail in Chapter 5. 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.

### 3.2 Trends for Oslo 1979-2016

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 (<http://www.msc-smc.ec.gc.ca/woudc/>). 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 has also been submitted to 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 2016. 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 - 2016 we have removed the seasonal variations by subtracting the long-term monthly mean ozone value from the data series, shown in Figure 4b. Next, we have divided the time series into two periods: 1) 1978-1997, and 2) 1998-2016. For the first time period the ozone measurements were entirely derived from the Dobson instrument and reflect a time period where a gradual decline in stratospheric ozone was observed at most mid and high latitude stations. The second period has been based on Brewer measurements, with inclusion of some GUV measurements. For the two time periods, simple linear regression lines have been fitted to the data to describe 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 ( $1\sigma$ ) in percent/decade. A trend larger than  $2\sigma$  is considered 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 statistical significant.

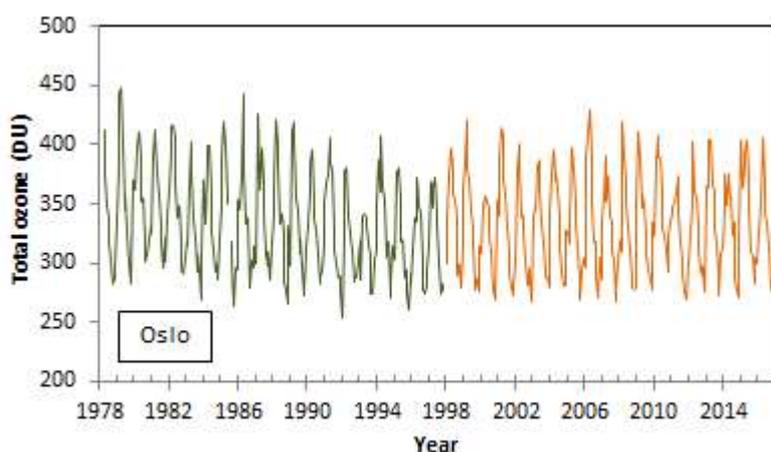


Figure 4a: Time series of monthly mean total ozone in Oslo 1979-2016. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements.

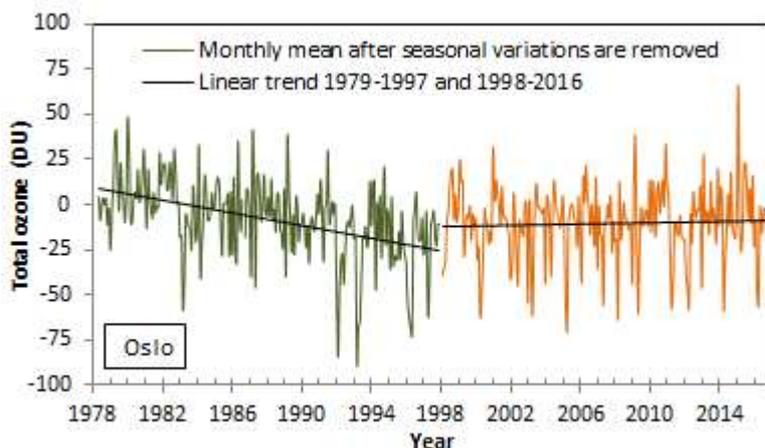


Figure 4b: Variation in total ozone over Oslo for the period 1979-2016 after the seasonal variations have been removed. The green line represents measurements performed with the Dobson instrument, whereas the orange line represents Brewer measurements. Trend lines are marked as black lines.

The second column in Table 4 indicates that a large ozone decrease occurred during the 1980s and first half of the 1990s. For 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  $-6.2\%/decade$  and  $-8.4\%/decade$ , respectively. The negative ozone trend was less evident for the summer, but nevertheless it was significant to a  $2\sigma$  level.

For the period 1998-2016 the picture is different. There are substantial annual 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 none of the trend results are significant to  $2\sigma$  levels. For all seasons the change in total ozone are relatively small: in winter and fall there is  $-1\%/decade$  ozone increase for the past 19 years, for the other seasons the trend is essentially zero. The annual ozone trend from 1998 to 2016 is  $0.5\%/decade$ .

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 1.1.1979 to 31.12.2016. The numbers in parenthesis represent the uncertainty ( $1\sigma$ ). Data from the Dobson and Brewer instruments have been used in this study. A trend larger than  $2\sigma$  is considered as significant.

Season	Trend (%/decade) 1979-1997	Trend (% /decade) 1998-2016
Winter (Dec - Feb)	-6.2 (2.4)	1.4 (2.2)
Spring (Mar - May)	-8.4 (1.4)	-0.2 (1.7)
Summer (Jun - Aug)	-3.5 (1.1)	-0.1 (0.9)
Fall (Sep - Nov)	-4.3 (1.0)	1.3 (1.2)
Annual (Jan - Dec):	-5.8 (1.0)	0.5 (1.0)

### 3.3 Trends for Andøya/Tromsø 1979-2016

Total ozone monitoring started up 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 Southwest of Tromsø. 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 Andøya. 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 variation in the monthly mean ozone values at Andøya from 1979 to 2016. The variations in total ozone at Andøya for the period 1979-2016, after removing the seasonal variations, 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. 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) 1998-2016. 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 as large as -8.4%/decade, whereas the negative trend for the summer months was -2.8%/decade. The yearly trend in total ozone was -5.8%/decade. For the second period from 1998 to 2016, no significant trends have been observed, except from September-October. For these two months the ozone level increased by 2.6%/decade. For the other seasons an ozone increase of 0.2%/decade is observed during spring, the summer trend is 0.3%/decade, whereas the annual trend for the period 1998-2016 is 0.8%/decade. None of these trend results are significant at either  $1\sigma$  or  $2\sigma$  significance level.

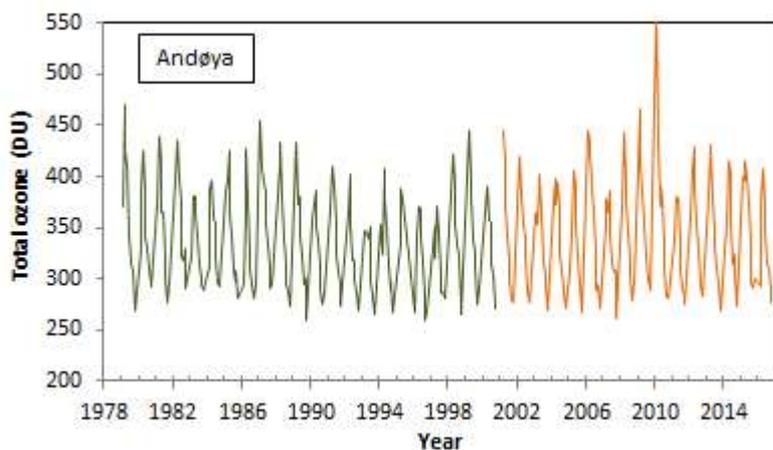


Figure 5a: Time series of monthly mean total ozone at Andøya/Tromsø 1979-2016. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya.

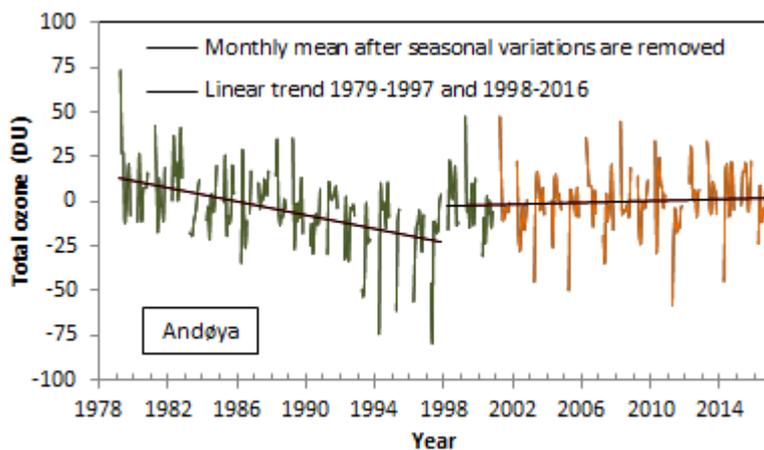


Figure 5b: Variations in total ozone at Andøya for the period 1979-2016 after the seasonal variations are removed. Only data for the months March-October are included. The green line represents total ozone from Tromsø, whereas the orange line represents measurements at Andøya. The trends are marked as black lines.

Table 5: Percentage changes in total ozone (per decade) at Andøya for the periods a) 1979-1997, and 2) 1998- 2016. The numbers in parenthesis give the uncertainty ( $1\sigma$ ). A trend larger than  $2\sigma$  is considered significant.

Season	Trend (%/decade) 1979-1997	Trend (% /decade) 1998-2016
Spring (Mar - May)	-8.4 (1.5)	0.2 (1.6)
Summer (Jun - Aug)	-2.9 (0.9)	0.3 (0.9)
Autumn (Sep - Oct)	-5.0 (1.3)	2.6 (0.7)
Annual (Mar - Oct)	-5.8 (1.0)	0.8 (0.9)

## 3.4 Trends for Ny-Ålesund 1979-2016

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 have 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. 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 discontinuing the measurements was the requirement of a substantial amount of manual operation. In parallel with the Dobson instrument, the more automatic SAOZ and GUV instruments were put into operation in Ny-Ålesund in 1991 and 1995, respectively, and since 2003, they have been the basis for ozone measurements at Ny-Ålesund.

The ozone measurements presented in Figure 6a and Figure 6b are based on a combination of Dobson, 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 25 years only ground-based measurements have been used: Dobson 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 -11.7%/decade, whereas the negative trend for the summer months was only -2.6%/decade. The annual trend in total ozone was -7.0%/decade during these years. For the second period 1998-2016 no significant trends have been observed. No ozone change is observed for the spring months, a negative trend of -1.6%/decade is found for the summer months, whereas an ozone increase of 0.9%/decade is observed for the fall. The annual trend for the period 1998-2016 is -0.3%/decade. None of these results are significant at a  $2\sigma$  significance level.

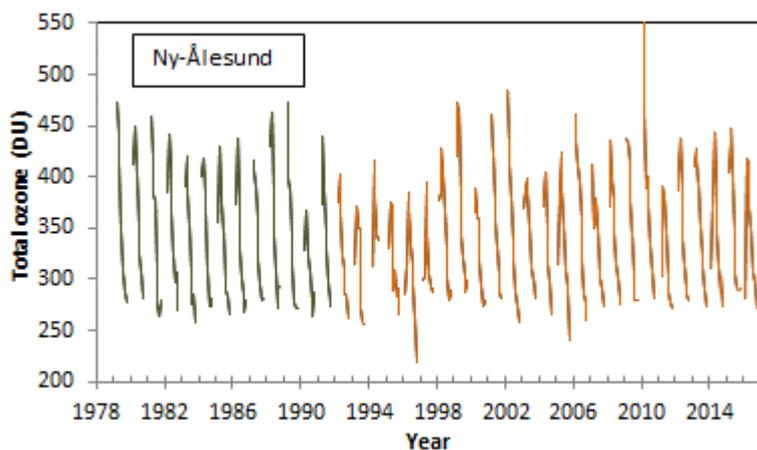


Figure 6a: Time series of monthly mean total ozone at Ny-Ålesund 1979-2016. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments.

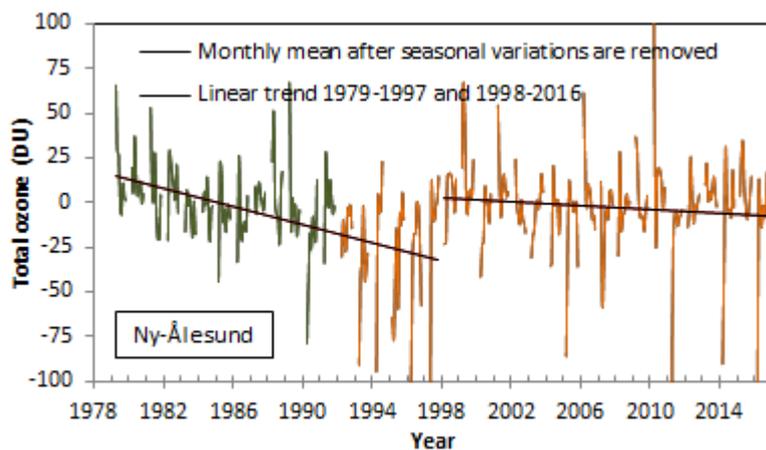


Figure 6b: Variations in total ozone at Ny-Ålesund for the period 1979-2016. Only data for the months March-October are included. The green line represents total ozone data from satellite, whereas the orange line represents measurements from ground-based instruments. Trends for the two periods are marked as black lines.

Table 6: Percentage changes in total ozone (per decade) in Ny-Ålesund for the periods a) 1979-1997, and 2) 1998-2016. The numbers in parenthesis give the uncertainty ( $1\sigma$ ). A trend larger than  $2\sigma$  is considered significant.

Season	Trend (%/decade) 1979-1997	Trend (% /decade) 1998-2016
Spring (Mar - May)	-11.7 (1.8)	0.0 (2.2)
Summer (Jun - Aug)	-2.6 (1.3)	-1.6 (0.9)
Autumn (Sep - Oct)	-3.8 (1.9)	0.9 (1.3)
Annual (Mar - Oct)	-7.0 (1.1)	-0.3 (1.2)

## 3.5 The overall Norwegian ozone situation 2016

The 2015/2016 winter was one of the coldest in the Arctic stratosphere observed so far, and for long periods the coldest region was located in the European Arctic, including Norway. German scientists operating several lidars at the ALOMAR Observatory (Andøya) recorded an up to 12 km thick layer of Polar Stratospheric Clouds (PSCs) through most of January 2016. The clouds were also observed by eye in Tromsø on any clear-sky occasion from mid-December 2015, throughout January 2016 and, periodically, in February 2016. The situation changed fundamentally around 10 March, with a major stratospheric warming which dissolved the stratospheric vortex and mixed the already massively ozone-depleted air inside the vortex with surrounding ozone-rich air masses. Without this early major warming, one would have faced ozone depletion of the same scale as during the onset of the Antarctic ozone hole in the early 1980s and even more than in the record winter of 2010/2011 (Manney and Lawrence, 2016). 2016 was a strong reminder that, despite political regulations of CFCs in place, the possibility of severe ozone depletion also in the Arctic will exist for decades to come (e.g., Pommereau et al., 2013). Although there has been no detailed analysis of this, it is rather probable that the low ozone values throughout spring and early summer in Norway were influenced by the strong depletion prior to the vortex break-up in March, combined with the displacement of the vortex far away from the geographical North Pole during its final phase.

Figure 7 shows a map of Northern Hemisphere total ozone on 1 March, 2016. The map is from WOUDC and Environment Canada, based on a combination of ground-based measurements and satellite observations. The low-ozone area covering Scandinavia is clearly seen on the map.

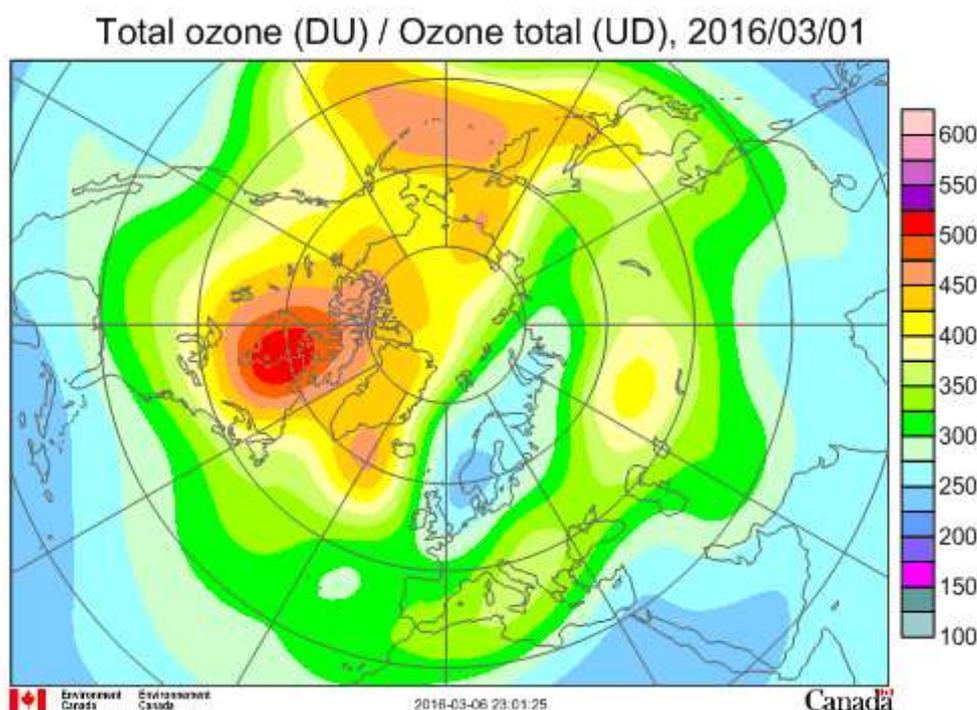


Figure 7: Total ozone from WOUDC and Environment Canada 1. March 2016. The map is based on ground based measurements and satellite observations ([http://exp-studies.tor.ec.gc.ca/e/ozone/Curr\\_allmap\\_g.htm](http://exp-studies.tor.ec.gc.ca/e/ozone/Curr_allmap_g.htm))

Table 7 summarizes the ozone situation for Norway 2016 and gives the percentage difference between the monthly mean total ozone values in 2016 and the long-term monthly mean values at the three Norwegian sites. As mentioned above, the ozone levels were record-low in all parts of Norway in February 2016 (-13.3%, -20.7% and -27.4% below normal in Oslo, Andøya and Ny-Ålesund, respectively). In Oslo the situation of low ozone values continued in March (average total ozone ~14% below the long-term mean). Even if the situation normalized towards the end of spring, all months in 2016 had average total ozone values below the long-term mean. At Andøya the ozone situation was similar to Oslo: most months had average ozone values below the long-term mean. During summer the situation normalized with, e.g., an average ozone value of -2% above normal in August. In Ny-Ålesund the ozone values were below normal in winter, spring and the first part of the summer. The situation changed in the fall, and in September the average total ozone was 7% above normal.

Table 7: Percentage difference between the monthly mean total ozone values in 2016 and the long-term mean for Oslo, Andøya, and Ny-Ålesund.

Month	Oslo (%)	Andøya (%)	Ny-Ålesund (%)
January	-2.9		
February	-13.2	-20.7	-27.4
March	-13.8	-8.1	-0.8
April	-0.4	-1.0	-4.2
May	-4.2	-2.1	-4.9
June	-2.2	0.2	-1.3
July	-0.5	-1.8	-1.5
August	-1.7	2.1	3.5
September	-6.6	-3.0	7.0
October	-3.4	-2.9	-1.5
November	-1.7		
December	-3.3		

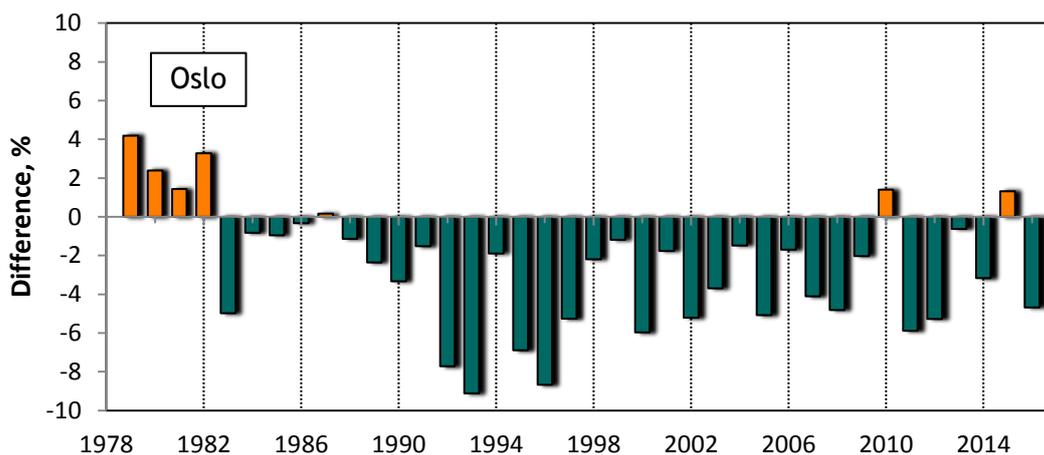


Figure 8: Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean 1979-1989.

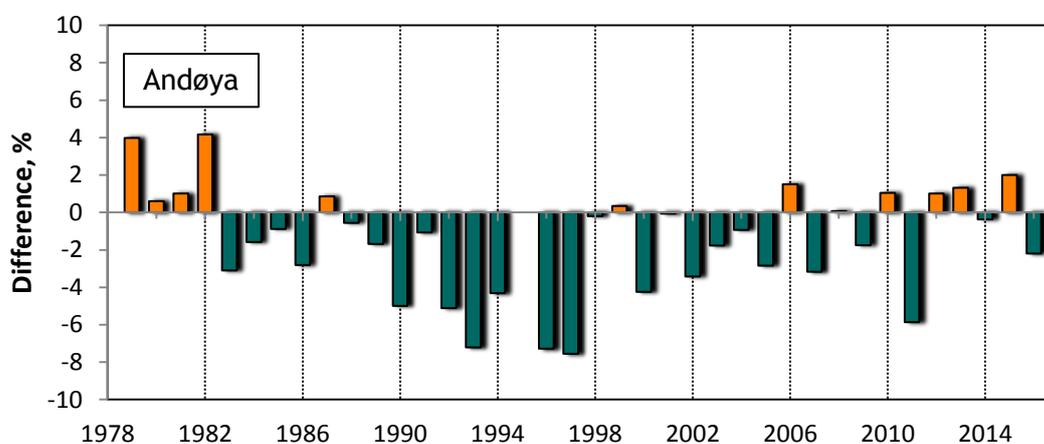


Figure 9: Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean 1979-1989 for the months March-October.

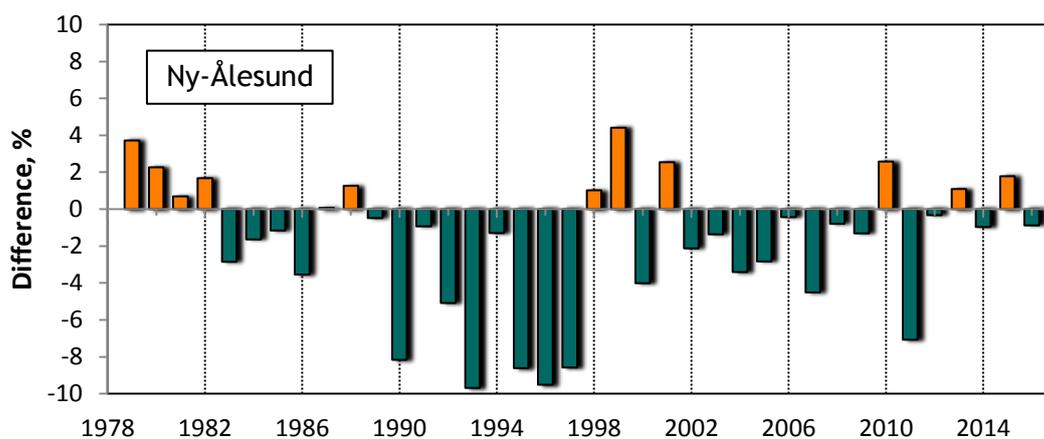


Figure 10: Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.

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 at 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) and in 2016. For 2016 the annual ozone means were 4.7%, 2.1%, and 0.9% below the long-term means in Oslo, at Andøya and in Ny-Ålesund, respectively.

### 3.6 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 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 Troll Station are not part of the Norwegian ozone and UV monitoring program, but funded by the Norwegian Ministry of Climate and the 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 10 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.

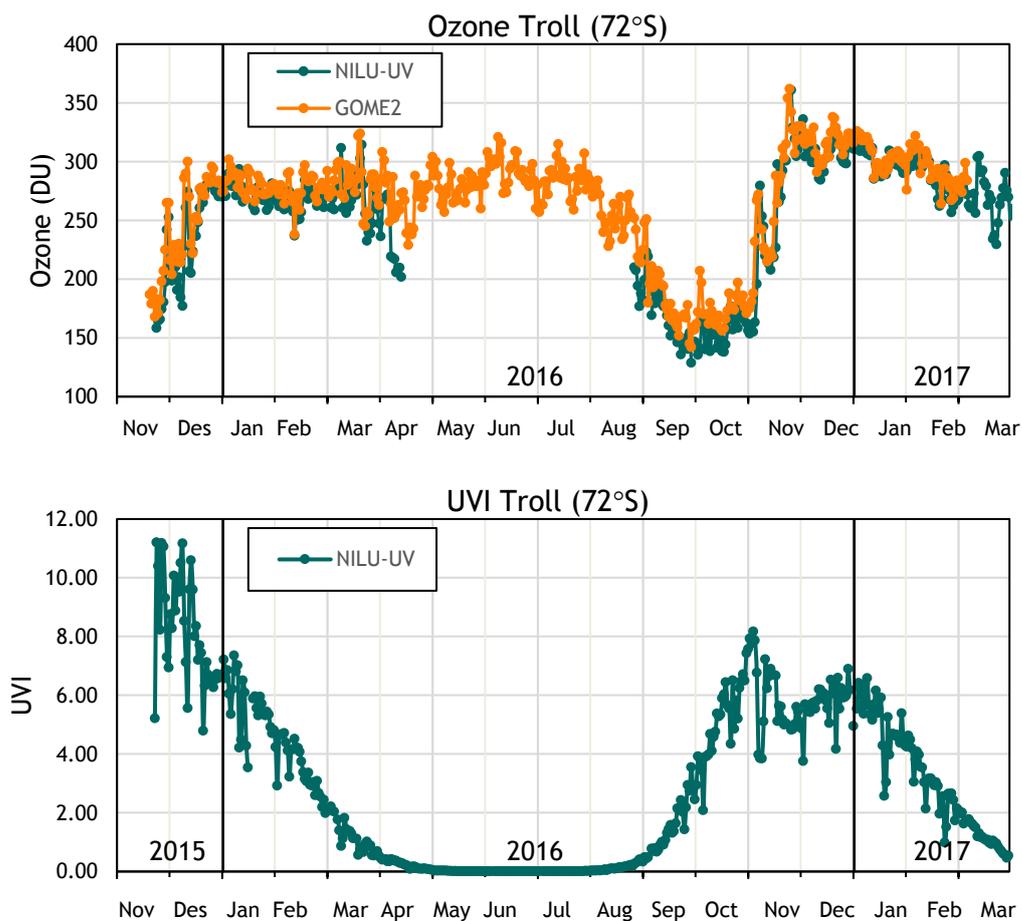


Figure 11: Upper panel: Total ozone from NILU-UV and GOME-2 from November 2015 to March 2017. Lower panel: UVI from NILU-UV 2015-2017

The ozone and UV measurements in Figure 11 reveal that at the Troll Station Antarctic ozone depletion was of moderate scale in 2016, both with respect to the lowest total ozone values measured (ca. 135 DU) and the duration of the ozone hole season. The latter parameter is particularly important for UV levels at the station. In 2016, the ozone layer already started to recover in early November, i.e., long before Austral summer solstice. This resulted in moderate maximum UV index (UVI) values of about 8 in early November. In contrast, in 2015 the ozone layer recovery only took place from early December, resulting in maximum UV indices of more than 11 in that year.

## 4. Satellite observations of ozone

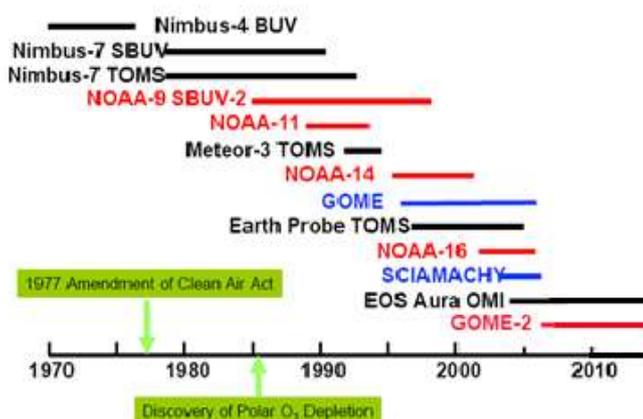


Figure 12: An overview of the various satellites and their instruments measuring ozone from space since the beginning of the 1970's (Figure from NASA).

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, and later ESA (The European Space Agency) initiated their ozone programmes. Figure 12 gives an overview of the various ozone measuring satellites and their time of operation.

### 4.1 Satellite ozone observations 1979-2016

In the course of the last 37 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 1979-2016. Figure 13 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.

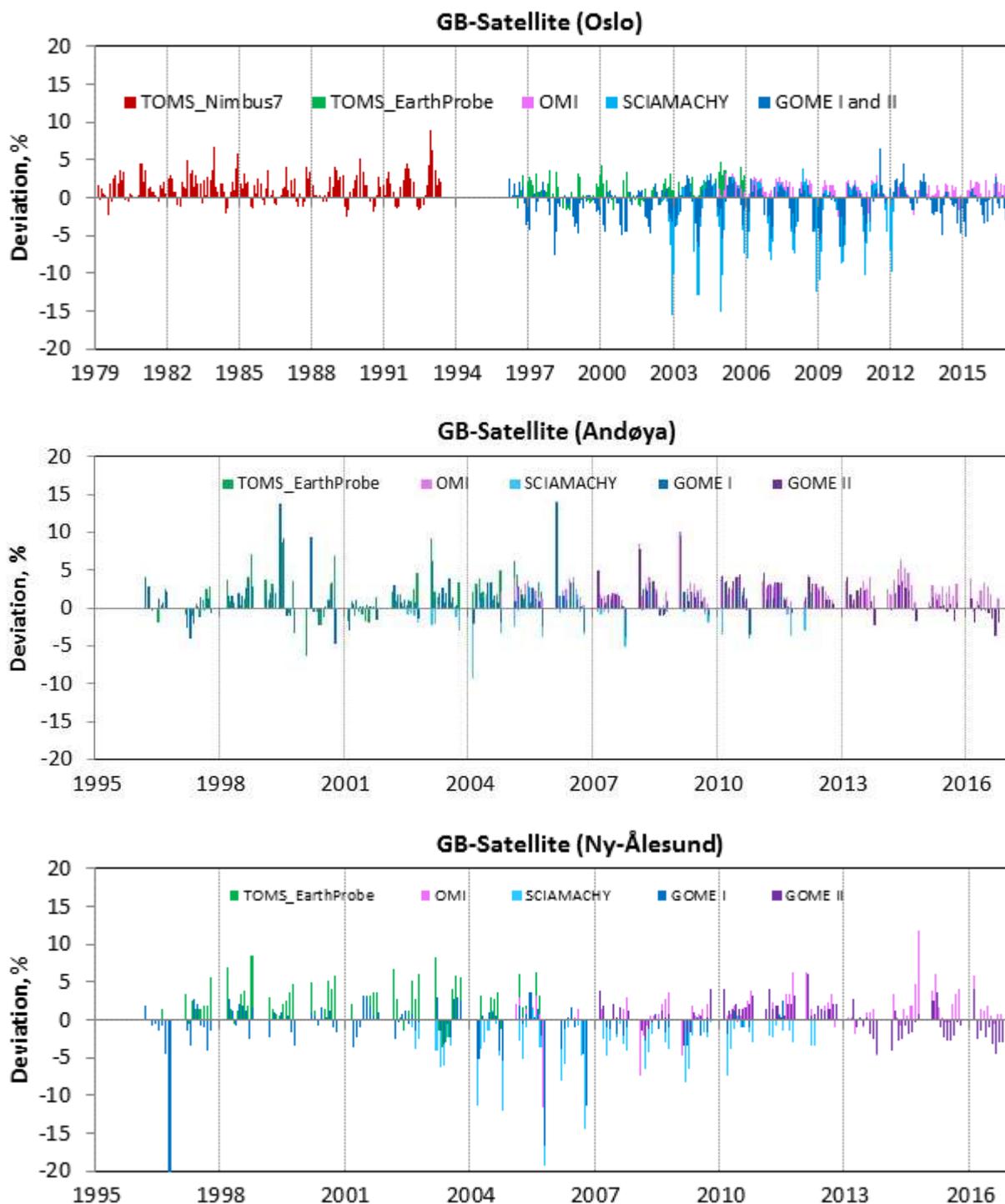


Figure 13: Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2016 (Oslo) and 1995-2016 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, middle panel: Andøya, lower panel: Ny-Ålesund.

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, OMI and GOME II 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, OMI and GOME II 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. 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-16	0.89	1.40	1.95
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-16	0.17	2.07	4.27
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-16	2.51	2.06	4.23
GOME 1	Mar-96	Jul-11	1.42	2.78	7.74
GOME 2	Jan-07	Dec-16	1.40	2.19	4.81
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-16	0.91	2.83	8.00
GOME 1	Mar-96	Jul-11	-0.72	3.30	10.88
GOME 2	Jan-07	Dec-16	0.17	2.17	4.71
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 close to the Brewer measurements in Oslo all year, giving a variance of only 1.95% (see Table 8). The GB-OMI variance in Ny-Ålesund is 8.0%, whereas GB-GOME II has a variance of 4.7%. This might indicate that GOME II is slightly better than OMI at high latitudes.

## 5. The 5<sup>th</sup> 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 forcing<sup>2</sup> (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 5<sup>th</sup> 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  $0.35 \text{ W/m}^2$ , with RF due to tropospheric ozone changes of  $0.40 \text{ W/m}^2$ , and due to stratospheric ozone changes of  $-0.05 \text{ W/m}^2$ . 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 ( $\text{CH}_4$ ), nitrogen oxides ( $\text{NO}_x$ ), carbon monoxide ( $\text{CO}$ ) 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 ozone RF of  $-0.15 \text{ W/m}^2$ . On the other hand, tropospheric ozone precursors ( $\text{CH}_4$ ,  $\text{NO}_x$ ,  $\text{CO}$ , NMVOC) cause ozone a RF of  $0.50 \text{ W/m}^2$ , 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  $\text{CO}_2$  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  $\text{CO}_2$ , will warm the troposphere and cool the stratosphere. In general, a decrease in stratospheric temperature reduces ozone depletion

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<sup>2</sup> 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  $\text{Wm}^{-2}$ .

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  $-78^{\circ}\text{C}$ . 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 (WMO, 2011). 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.

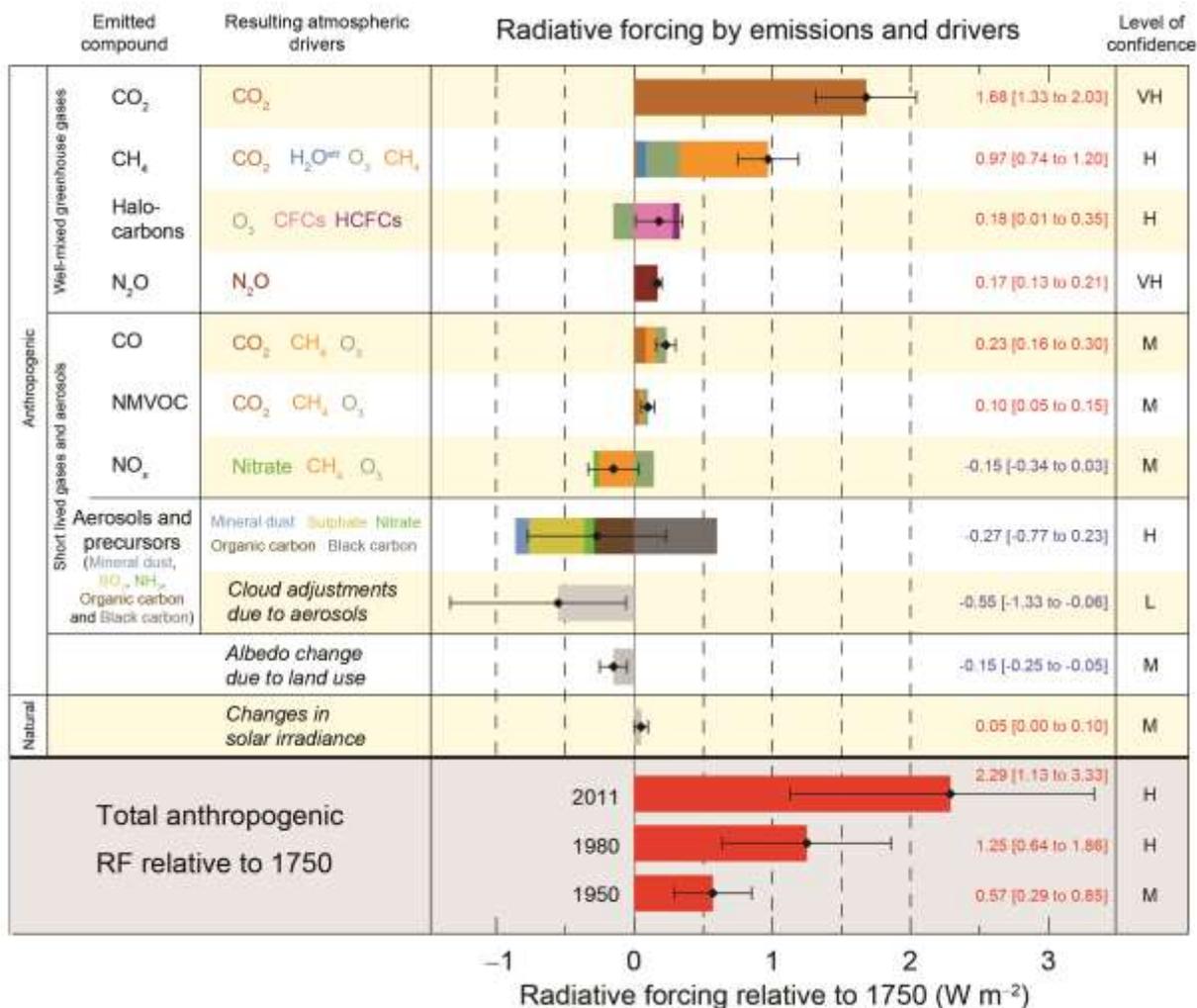


Figure 14: Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change. Values are global average radiative forcing, partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative 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 20<sup>th</sup> 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 stratosphere<sup>3</sup>. OH is one of the key species in the chemical cycles regulating ozone levels. There are several sources for stratospheric water, where CH<sub>4</sub> 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 5<sup>th</sup> IPCC report it is estimated that the increase in stratospheric water vapour resulting from anthropogenic emissions of methane (CH<sub>4</sub>) has a positive radiative forcing of 0.07 W/m<sup>2</sup> (see Figure 14). This is consistent with the results from AR4. However, water vapour trends in the stratosphere are 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; 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<sup>2</sup>. 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<sup>2</sup> (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<sub>2</sub>O) is considered as a key species that regulates ozone concentrations. The photochemical degradation of N<sub>2</sub>O in the middle stratosphere leads to ozone-depleting NO<sub>x</sub>, but unlike in AR4 (IPCC, 2007) the N<sub>2</sub>O influence on RF of ozone has been set to zero in AR5. This is due to insufficient quantification of the N<sub>2</sub>O influence and particularly the vertical profile of the ozone change (IPCC, 2013, Supplementary Material).

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<sup>3</sup> In the stratosphere, water vapour is oxidized by excited O atoms to produce OH (H<sub>2</sub>O + O(1D) → 2OH). Next, the hydroxyl radical OH can react with O<sub>3</sub>, resulting in a loss of ozone.

## 6. 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/>.

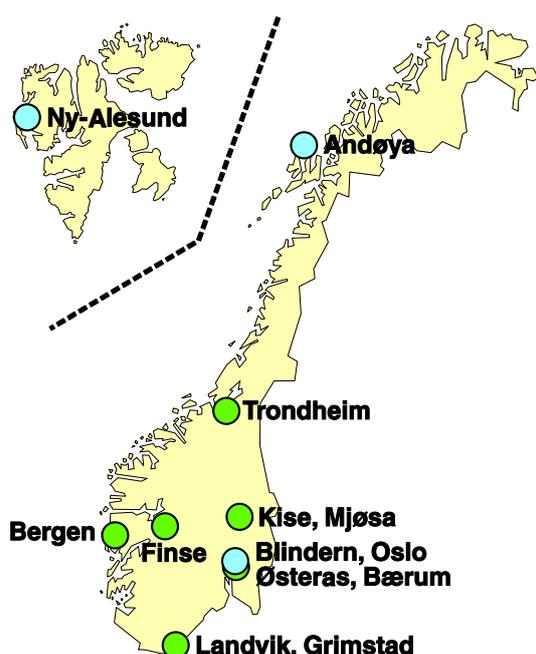


Figure 15: Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas the Norwegian Radiation Protection Authority operates the stations marked with green.

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 has resulted in a gap in the UV time series from Ny-Ålesund.

The GUV instruments are normally easy to maintain and have few interruptions due to technical problems. However, the instruments have been in operation for 21 years, and technical failures have occurred more frequently in recent years. The instrument at Andøya was out of order for several weeks in 2016 and was sent to Biospherical Institute, USA, for repair. During the repair period, a spare GUV instrument was borrowed from the Norwegian Radiation Protection Authority (NRPA).

### 6.1 UV measurements in 2016

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<sup>4</sup>). The unit for dose rate is mW/m<sup>2</sup>, but is often given as a UV index (also named UVI). A UV index of 1 is equal to 25 mW/m<sup>2</sup>. 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

<sup>4</sup> CIE (Commission Internationale de l'Éclairage) action spectrum is a reference spectrum for UV induced erythema in human skin

can range up to 20 in Equatorial regions and high altitudes (WHO, 2009). Table 9 shows the UV-index scale with the recommended protections at the different levels. The recommendations are based on a moderate light skin type, typical for the Nordic population.

Figure 16 shows the UV dose rates measured at local noon ( $\pm 0.5$  hour) in Oslo, at Andøya and in Ny-Ålesund. The highest noon UV dose rate in Oslo,  $160.6 \text{ mW/m}^2$ , was observed on June 25 and is equivalent to a UV index of 6.4. 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 2016 was 4.3, equivalent to a dose rate of  $107.1 \text{ mW/m}^2$ , observed May 29. The highest UVI noon value in Ny-Ålesund was 2.5 or  $63.6 \text{ mW/m}^2$ , measured July 8.

In Oslo the highest noon averaged UVI was observed during a day with relatively low ozone values, i.e. 299 DU (normal  $\sim 351$  DU). At Andøya the ozone column was 300 DU (normal  $\sim 378$  DU), whereas the maximum UVI in Ny-Ålesund was observed during a relatively clear day with total ozone column of 302 DU, roughly 10 DU below normal value.

For UV levels corresponding to the maximum UVI value of 6.4 in Oslo, people with a typical Nordic skin type get sunburnt after approximately 20 minutes if no sun protection is used.

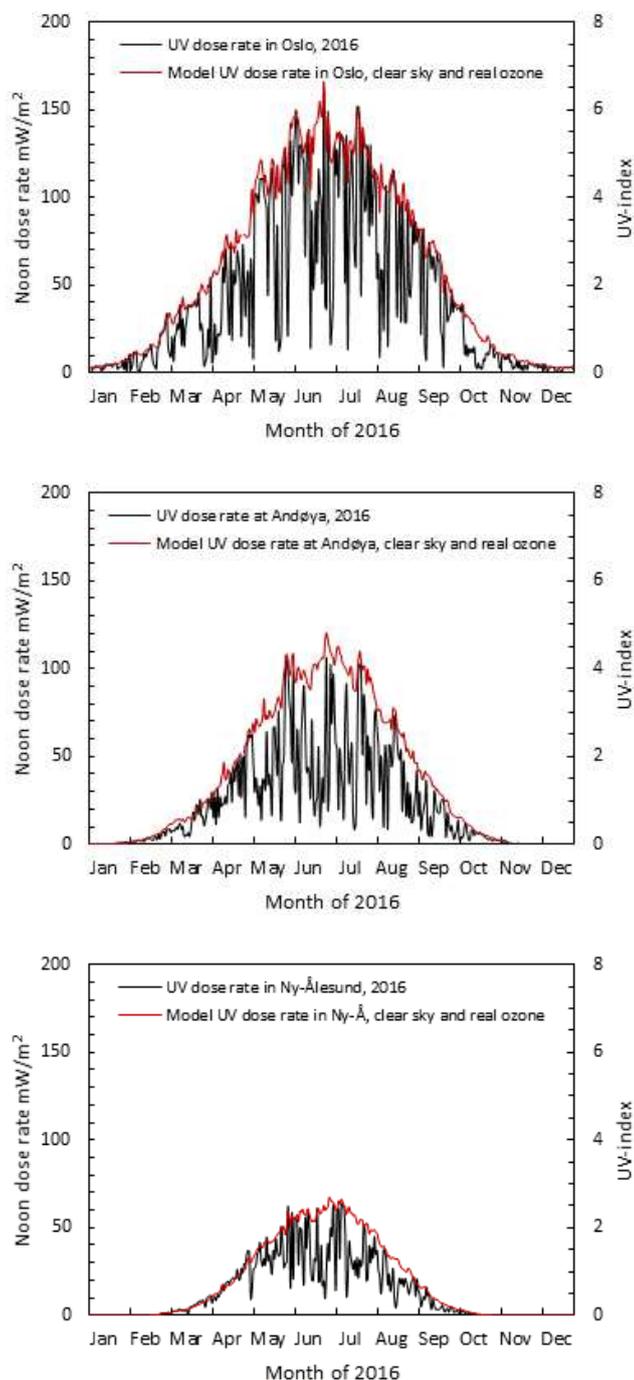


Figure 16: Hourly averaged UV dose rate measured at local noon ( $\pm 0.5$  hour) in 2016. Upper panel: Oslo. Mid panel: Andøya Lower panel: Ny-Ålesund.

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 in Figure 17 (red curve, left panel) Oslo had scattered clouds all day 25 June. This is seen by the “noisy” red curve. The scattered clouds resulted in multiple reflection between the clouds, and between the ground and the clouds. Such conditions will normally enhance the ground level UV-radiation.

At Andøya there were also scattered clouds during the day of maximum UVI in 2016, visualized by the red curve in Figure 17 (middle panel). In the early morning the sky was covered by heavy clouds (cloud transmission below 80%), but these clouds did not affect the noon dose rate.

In Ny-Ålesund there were some clouds early in the morning, but around noon the sky was clear. As seen from Figure 17 (right panel) the cloud transmission is above 100% even when clouds are absent. This is caused by the high albedo from snow- and ice-covered surfaces in the vicinity of the instrument site, which enhance the solar radiation detected by the GUV instrument.

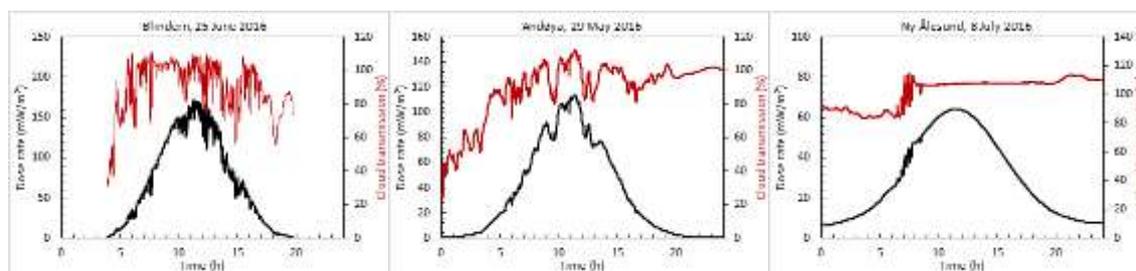


Figure 17: UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel) in 2016. A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30% represent heavy clouds.

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

Many Norwegian citizens visit Mediterranean 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.

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. As mentioned above 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 also influenced by clouds, total ozone, aerosols, and ground reflection (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 2016 are compared in Figure 18. As expected, the monthly UV doses in Oslo were significantly higher than the values observed at Andøya and in Ny-Ålesund. If the cloud cover, albedo and ozone conditions at all three sites were similar during the summer, the UV-radiation would be highest in Oslo due to higher solar elevation most of the day. June 2016 was characterized by many overcast days at Andøya, resulting in a relatively low June UV-dose. This explains why the integrated UV-doses at Andøya and in Ny-Ålesund are equal in June 2016.

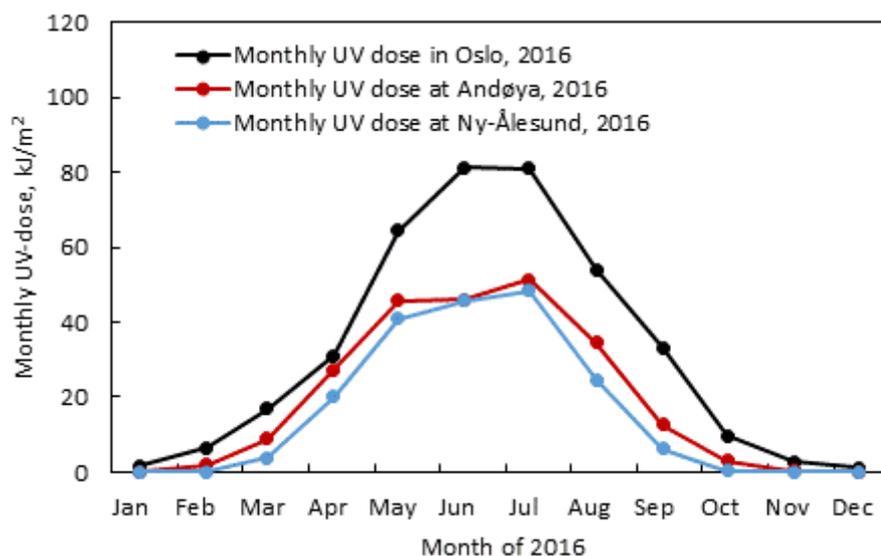


Figure 18: Monthly integrated UV doses (in  $\text{kJ}/\text{m}^2$ ) in 2016 measured with the GUV instruments located in Oslo, at Andøya and in Ny-Ålesund.

## 6.2 Annual UV doses 1995-2016

Annual UV doses for the period 1995-2016 are shown in Table 10 for the GUV instruments in Oslo, at Andøya and in Ny-Ålesund. Annual UV doses for 2005 are not included in the table as there were large gaps in the data set caused by a calibration campaign. The uncertainty in the daily UV doses is estimated to  $\pm 5\%$  at a  $2\sigma$  level (Johnsen et al., 2002). For periods with missing data we have estimated the daily UV doses from a radiative transfer model (FastRt, <https://fastrt.nilu.no/fastrt.html>). Normally this gives an additional uncertainty in the annual UV doses of  $\pm 1.6\%$  for all stations and years, except for Andøya where the uncertainty is  $\pm 2\%$  for 2000,  $\pm 5\%$  for 2001, and  $\pm 5\%$  for 2011 where 12 days of measurements were missing.

Table 10: Annual integrated UV doses (in  $\text{kJ/m}^2$ ) for Oslo, Andøya and Ny-Ålesund for the period 1995 - 2016.

Year	Oslo ( $\text{kJ/m}^2$ )	Andøya ( $\text{kJ/m}^2$ )	Tromsø ( $\text{kJ/m}^2$ )*	Ny-Ålesund ( $\text{kJ/m}^2$ )
1995	387.6			
1996	387.4		253.6	218.5
1997	415.0		267.0	206.5
1998	321.5		248.4	217.7
1999	370.5		228.0	186.1
2000	363.0	239.7		231.0
2001	371.0	237.0		208.6
2002	382.5	260.0		201.8
2003	373.2	243.4		Excluded from the program
2004	373.2	243.7		190.5
2005	No annual UV doses due to gaps in the data caused by a calibration campaign			
2006	372.4	219.4		Excluded from the program
2007	351.8	253.3		Excluded from the program
2008	375.3	266.5		Excluded from the program
2009	378.6	254.1		Excluded from the program
2010	360.5	225.6		201.6
2011	365.2	254.8		200.8
2012	352.6	227.5		211.6
2013	362.4	247.0		178.9
2014	396.4	249.7		215.0
2015	358.9	219.2		213.6
2016	383.7	232.1		190.7

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

In 2016 the UV doses in Oslo during summer were in general above normal. June had the highest monthly UV dose of 2016, with UVI between 5 and 6 on several days. As shown in Figure 16 (upper panel) there were also several days in the summer where the noon UV index in Oslo was as low as 1. This was caused by heavy clouds. When studying the entire 1995-2016

period, 2016 was the year with the fifth highest yearly integrated UV dose in Oslo. Only 2014 and 1995-1997 had higher UV values. At Andøya and in Ny-Ålesund the yearly integrated UV-doses in 2016 were slightly below the 1995-2016 average.

A graphical presentation of the yearly integrated UV-doses from 1995 to 2016 is shown in Figure 19. The figure illustrates yearly UV fluctuations. At all three stations a negative UV trend of 2% to 5% has been detected for the past 22 years. However, the trend results are not statistically significant.

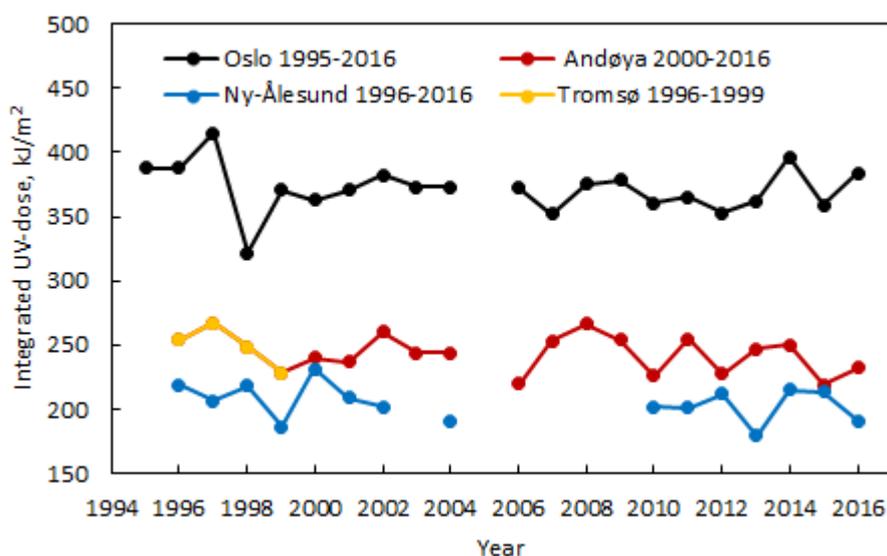


Figure 19: Annual integrated UV doses (in kJ/m<sup>2</sup>) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995-2016.

## 7. 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 the summer 2016. The Brewers 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 the summer 2015, to ensure high quality ozone measurements.

The GUV instruments are compared with the European travelling reference spectroradiometer 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 at the observation platform of the Sverdrup Station of the Norwegian Polar Institute. Measurements started up 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 winter 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 instrument returned to Ny-Ålesund in March 2014, and since then the instrument has been running without major problems.

The SAOZ instrument is a zenith-sky UV-visible spectrometer where ozone is retrieved in the Chappuis bands (450-550 nm) 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%.

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### Norwegian Environment Agency

Telephone: +47 73 58 05 00 | Fax: +47 73 58 05 01

E-mail: [post@miljodir.no](mailto:post@miljodir.no)

Web: [www.environmentagency.no](http://www.environmentagency.no)

Postal address: Postboks 5672 Sluppen, N-7485 Trondheim

Visiting address Trondheim: Brattørkaia 15, 7010 Trondheim

Visiting address Oslo: Grensesvingen 7, 0661 Oslo

The Norwegian Environment Agency is working for a clean and diverse environment. Our primary tasks are to reduce greenhouse gas emissions, manage Norwegian nature, and prevent pollution.

We are a government agency under the Ministry of Climate and Environment and have 700 employees at our two offices in Trondheim and Oslo and at the Norwegian Nature Inspectorate's more than sixty local offices.

We implement and give advice on the development of climate and environmental policy. We are professionally independent. This means that we act independently in the individual cases that we decide and when we communicate knowledge and information or give advice.

Our principal functions include collating and communicating environmental information, exercising regulatory authority, supervising and guiding regional and local government level, giving professional and technical advice, and participating in international environmental activities.