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Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2015.

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. However, there are large inter-annual variations and in 2015 the average ozone level was close to the 1979-1989 average values at all three Norwegian stations.
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 2015 var den gjennomsnittlige ozontykkelsen relativ høy og nær 1979-1989-nivået ved alle de tre norske stasjonene.

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

Content

1. Summary

The ozone layer plays an important role for life on Earth due to its ability to absorb Ultraviolet Radiation (UV) from the sun. The amount of stratospheric ozone decreased dramatically during the 1980s and 1990s. The main reasons for this decrease was anthropogenic release of ozone depleting substances (ODS), especially chlorofluorocarbons (CFCs). In 1987 a number of countries signed The Montreal Protocol, with the aim of phasing out and stop the release of ODS. This international treaty has later been amended several times, and the effective regulations have reduced the use and emissions of ODS significantly. The total amount of ODS 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 ODS, 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). In 2013 Andøya was removed from the programme, but due to financial support from The Ministry of Climate and Environment it has been possible to continue the operation and analysis of ozone and UV measurements at Andøya.

This report summarises the activities and results of the monitoring programme in 2015. It also includes total ozone trend analyses for the period 1979-2015 and UV measurements in Oslo, at Andøya and in Ny-Ålesund since 1995. For the first time, the report also includes total ozone measurements from Troll Station in Antarctica, which were started up in 2007. This activity is funded by the Norwegian Antarctic Research Program and the Ministry of Climate and Environment.

Total ozone
Total ozone above Oslo was record high in January, around 20% above the 1979-1989 seasonal average. For the other months there were only minor deviations compared to the 1979-1989 mean values for Oslo. At Andøya the ozone values in February and June were 9% and 8% above the 1979-1989 seasonal averages, respectively, but for the remaining months total ozone was close to the 1979-1989 mean. In Ny-Ålesund the total ozone values were within ±5% compared to the 1979-1989 averages all month. However, the ozone values in 2015 were in general high and above the 1979-1989 average all months except from June and July. For the latter months the total ozone values were ~2% below the average 1979-1989 summer ozone values.

Chemically induced loss of ozone was minimal in spring 2015 because of a minor "sudden stratospheric warming" event in early January, which caused lower stratospheric temperatures to rise above the critical temperature for the formation of ozone-destroying

chlorine species. In addition there was larger-than-usual vertical transport of ozone-rich air from higher altitudes into the lower stratosphere.

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 1998-2015 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 1979-1989 average.

Recent studies indicate signs of ozone recovery in most parts of the world. However, there is still uncertainty related to this recovery, particularly in Polar regions. 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 UV dose rate in Oslo, 162 mW/m^2, was measured 2 July 2015. This is equivalent to a UV index (UVI) of 6.5. At Andøya the highest UV index in 2015 was 4.0 (observed 1 July), whereas the highest UVI in Ny-Ålesund, 2.6, was observed 9 July. In Oslo and at Andøya the integrated annual UV-doses in 2015 were among the lowest values recorded during the 21 years of observations. This was caused by the large number of cloudy days during the summer, combined with high summer ozone values. The relatively high integrated UVI in Ny-Ålesund, on the other hand, was mainly caused by many cloudless days in late May and early June. In addition, the average total ozone values in Ny-Ålesund was ~2% below the 1979-1989 average in June and July. Under clear-sky conditions, a 1% ozone decrease will give a corresponding 1% increase of the UV-dose.

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 are highly necessary.

Comparisons of ground based measurements and satellite data in Oslo show good agreement during the summer, whereas the differences are larger in the autumn and winter months. 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 occasionally differ significantly (up to 15%).

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 1980 values before year 2030.

The atmospheric concentrations of the three greenhouse gases, CO_2, CH_4, and N_2O, 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_2O and CH_4 on total ozone is uncertain.

MAIN CONCLUSIONS FROM THE MONITORING PROGRAMME 2015

- **In 2015 the ozone values above Norway were close to the 1979-1989 average most of the year. In Oslo the mean January ozone value was the highest January value measured since 1979.**
- **At all Norwegian monitoring stations a significant stratospheric ozone decrease was recorded for the period 1979-1997. For the period 1998-2015 there was no significant trend in the ozone layer above Norway. However, signs of ozone recovery are evident in most parts of the world.**
- **The annual integrated UV doses in Oslo and at Andøya in 2015 were among the lowest values registered since 1995. This was mainly caused by many cloudy days, combined with relatively high summer ozone values.**
- **At all Norwegian monitoring stations a significant stratospheric ozone decease was recorded for the period 1979-1997. For the period 1998-2015 there was no**

2. Norwegian ozone measurements in 2015

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 and 1994, respectively. The ozone measurements are retrieved from Brewer spectrophotometers in Oslo and at Andøya, whereas a SAOZ (Systeme d'Analyse par Observation Zenitale) instrument has been the standard ozone instrument in Ny-Ålesund. In 2014 NILU and CNR-IDASC, Italy, signed an agreement that gives NILU access to Italian Brewer total ozone data in Ny-Ålesund as well. 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. 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.

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 2015. In addition the Italian Brewer no. 50 (Ny-Ålesund) was calibrated by IOS in 2015. The Brewers are also regularly calibrated against standard lamps in order to check the stability of the instruments. Calibration reports are available on request.

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 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. This instrument was originally a Brewer MKIV single-monochromator, but 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.

Figure 1a illustrates the daily total ozone values from Oslo in 2015. 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 2015 are based on Brewer direct-sun (DS) measurements when available.

In 2015 direct-sun measurements were performed on 160 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 199 days. In 2015 there were in total 6 days without Brewer DS or GI 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. GUV ozone data were retrieved on 3 out of 6 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 2015 Oslo ozone series is given in Table 1. Even if total ozone was retrieved from the GUV instrument on 332 out of 365 days, only 3 of the measurements were used in the 2015 time series since the Brewer measurements were considered as more accurate.

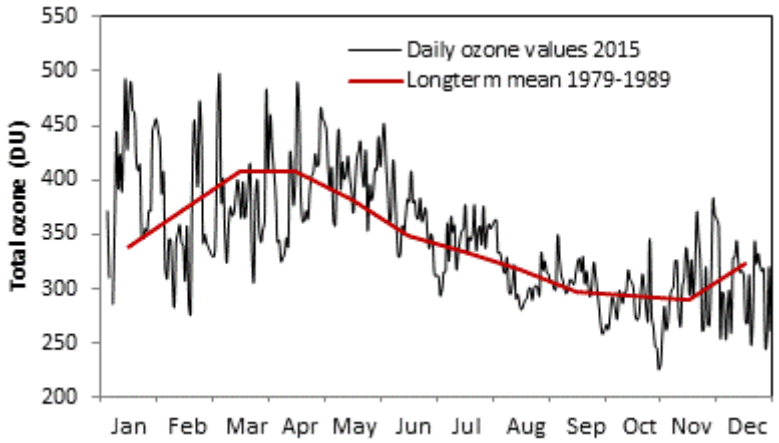

Figure 1a: Daily total ozone values measured at the University of Oslo in 2015. The red curve shows the long-term monthly mean values from 1979-1989.

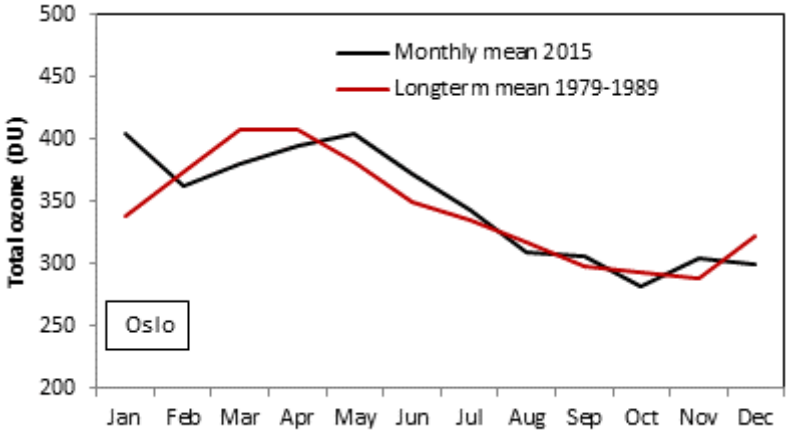

Figure 1b: Monthly mean ozone values for 2015. The red curve shows the long-term monthly mean values from 1979-1989.

Table 1: Overview of total ozone instruments in Oslo and the number of days where the various instruments were used in the 2015 time series

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	160
2	Brewer instrument, global irradiance method	199
3	GUV-511 instrument	3
	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 2015 was 226 DU[1], measured on 30 October. This is about 23% below the long-term mean for October. In January 2015 the ozone values were exceptional high, and a maximum value of 493 DU was measured on 14 January, which is almost 50% above normal January values.

The monthly mean total ozone values in 2015 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 January was significantly higher than normal, whereas the values in March and April were below normal. Section 3.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2015.

2.2 Total ozone at Andøya

The Andøya ozone measurements are no longer a part of the national monitoring programme, but direct 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, 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. 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.

[1] *The Dobson unit (DU) is a unit of measurement of total-column ozone in the Earth's atmosphere. One Dobson unit refers to a layer of gas that would be 10 µm thick under standard temperature and pressure. The ozone layer in Norway normally varies between 240 and 550 DU, depending on the season. An ozone value of less than 220 DU defines an "ozone hole".*

The Andøya Brewer instrument had some technical problems in 2015. The communication between the instrument and PC was frequently interrupted, and the internal Hg lamp tests occasionally failed. We also detected a large drift in the internal standard lamp. A new Brewer measurement schedule was selected to overcome the problem. However, the technical problems resulted in less Brewer ozone measurements from Andøya in 2015 than desired.

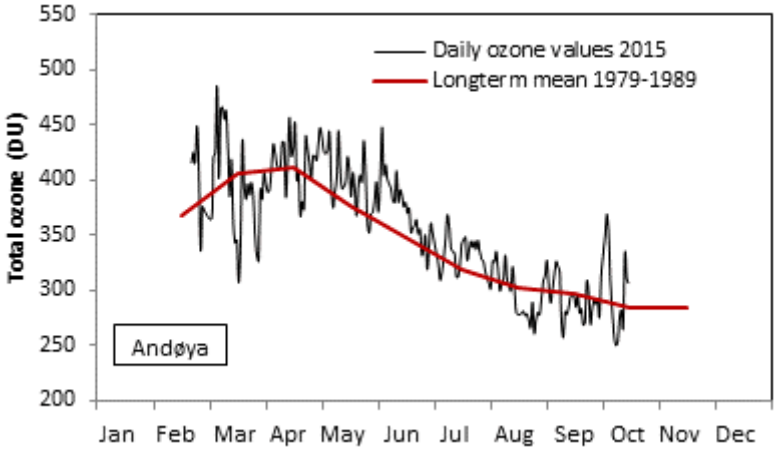

Figure 2a: Daily total ozone values measured at ALOMAR, Andøya, in 2015 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989.

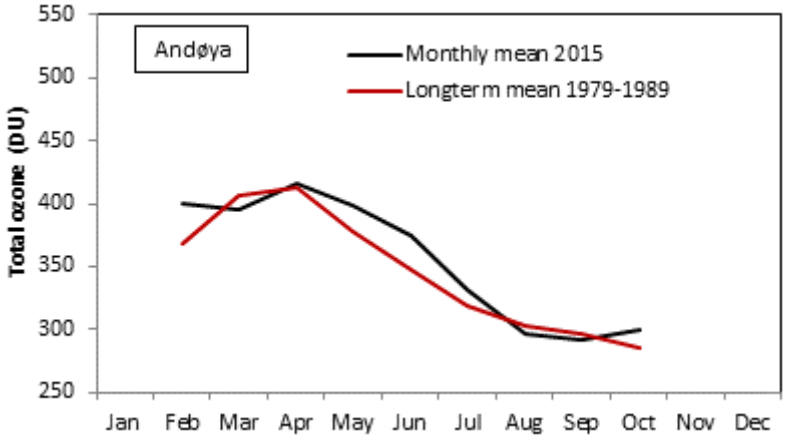

Figure 2b: Monthly mean total ozone values for 2015 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

Table 2 gives an overview of the different instruments and methods used at Andøya in 2015. Due to the Brewer problems described above, there were altogether 38 days in 2015 where the GUV instrument had to replace Brewer ozone measurements. In addition, on 8 days bad weather conditions resulted in ozone values with unacceptably high uncertainty, mainly in February and October when the solar radiation is low.

Figure 2a shows daily ozone values from Andøya in 2015. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989. From late October to mid-February total ozone cannot be measured with the available instrumentation due to too large solar zenith angles. The lowest ozone values at Andøya normally occur in October and November, and the minimum ozone value in 2015 was 250 DU, measured 7 October. This was about 12% below the long-term mean for October. On 16 March, total ozone reached a relative minimum of 307 DU, which is 24% below average March values.

Monthly mean ozone values at Andøya for 2015 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 2015 shows that the ozone layer was close to normal most months (within ±5%), except February and June. The largest deviation was found in February, where the average ozone value was 9% above the long-term mean.

Table 2: Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2015.

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	141
2	Brewer instrument, global irradiance method	56
3	GUV instrument	38
	Missing days (except polar night period)	8

2.3 Total ozone in Ny-Ålesund

Ny-Ålesund is located at a high northern latitude (79° N), which 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 > ca. 85°. At 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 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 (sun rise /sun set). 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%.

In addition to SAOZ, a GUV-541 multi-filter radiometer is used for ozone measurements when the UV-radiation is becoming stronger in late spring, summer and early fall. These measurements give important contributions to the ozone time series from Ny-Ålesund. Comparisons between SAOZ and GUV data during overlapping measuring periods has previously indicated that the GUV ozone data might be too high during summer.

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. B50 was installed in Ny-Ålesund in 1997, but unfortunately total ozone data for the entire period 1997-2014 is not available. However, from July 2013 and most parts of 2014 Brewer total ozone data are accessible and suitable for an inter-comparison to the Norwegian ozone measurements. The Brewer instrument was calibrated by IOS Canada in the summer 2015, which has insured high quality ozone measurements.

Comparisons between Brewer and GUV ozone measurements revealed a seasonal difference in total ozone. For the summer 2013 and 2014 the GUV measurements were on average 4-5% higher than the Brewer values. Consequently, a seasonal correction was 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 were adjusted equally. Also, the SAOZ ozone data were adjusted by ~5% for the years 2012-2015 to account for changes in the retrieval algorithms.

Both the SAOZ and GUV instruments worked satisfactorily in 2015 and there were only 4 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 2015 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 2015.

Priority	Method	Total days with observations
1	SAOZ instrument	90
2	GUV instrument	157
	Missing days (~10 days in February)	4

Figure 3a shows daily ozone values from Ny-Ålesund in 2015. 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 2015 was 244 DU, measured 18 October. This is 11% below the long-term mean for October

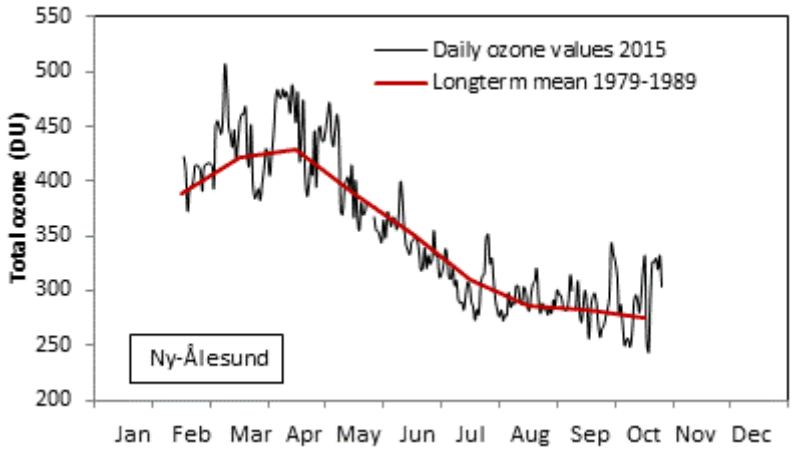

Figure 3a: Daily total ozone values measured in Ny-Ålesund in 2015 by the SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 -1989.

Monthly mean total ozone values in Ny-Ålesund 2015 are shown in Figure 3b. Comparison between the long-term mean and monthly mean ozone values 2015 shows that the ozone values were close to the long-term mean in all months.

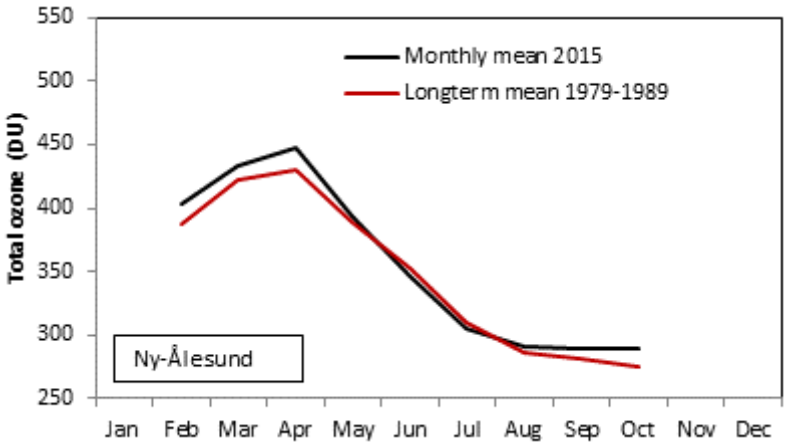

Figure 3b: Monthly mean total ozone values for 2015 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

3. Ozone measurements and trends 1979-2015

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 before 2030 in mid-latitudes and the Arctic, and somewhat later for the Antarctic region.

The 2014 assessment report also emphasizes that changes in CO_2, N_2O, and CH_4 will have an increasing influence on the ozone layer as ODS concentrations decline. 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 1979-2015

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 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 The World Ozone Data Centre.

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 2015. 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 – 2015 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) 1998-2015. 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 (1σ) in percent/decade. A trend larger than 2σ 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.

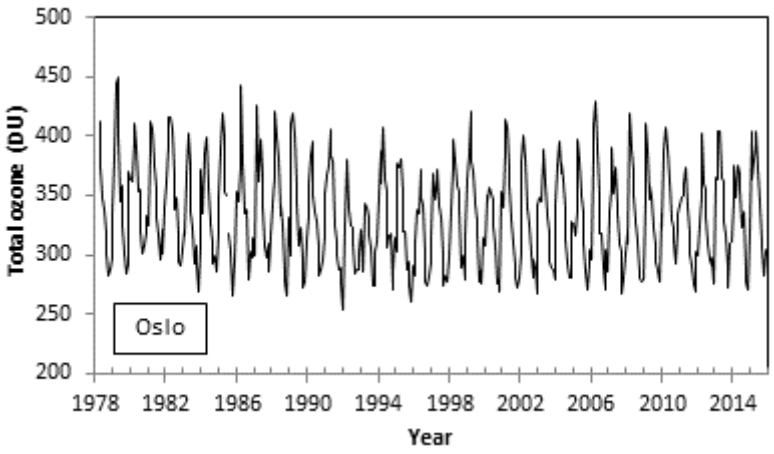

Figure 4a: Time series of monthly mean total ozone in Oslo 1979-2015.

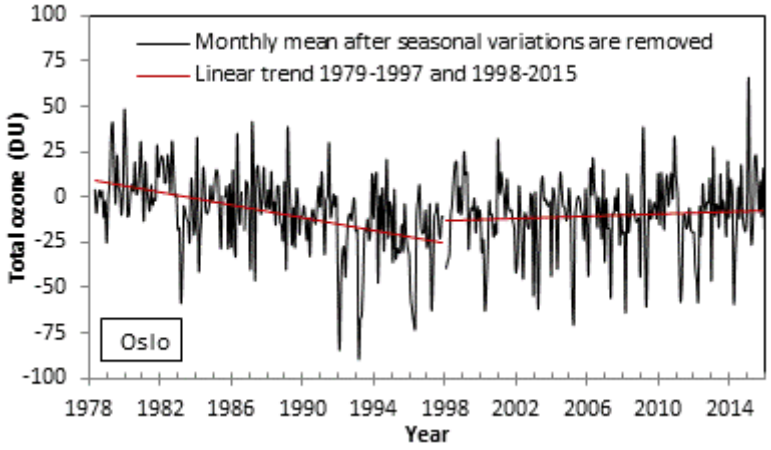

Figure 4b: Variation in total ozone over Oslo for the period 1979-2015 after the seasonal variations have been removed. Trend lines are marked in red.

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 2σ level.

For the period 1998-2015 the picture is different. There are substantial annual fluctuations and one should be cautious to draw definite conclusions about trends. Nevertheless, 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 neither 1σ nor 2σ levels. However, for all seasons there is a small (or zero) ozone increase for the last 18 years. The largest increase is for the winter season December-February, where an ozone increase of 2.2% /decade is measured. The annual ozone trend from 1998 to 2015 is 0.9% /decade.

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 1.1.1979 to 31.12.2015. The numbers in parenthesis represent the uncertainty (1σ). Data from the Dobson and Brewer instruments have been used in this study. A trend larger than 2σ is considered as significant.

Season	*Trend (%/decade) 1979-1997*	*Trend (% /decade) 1998-2015*
Winter (Dec - Feb)	-6.2 (2.4)	2.2 (2.3)
Spring (Mar - May)	-8.4 (1.4)	0.0 (1.9)
Summer (Jun - Aug)	-3.4 (1.1)	0.1 (1.0)
Fall (Sep - Nov)	-4.3 (1.0)	1.8 (1.2)
Annual (Jan - Dec):	-5.8 (1.0)	0.9 (1.1)

3.3 Trends for Andøya 1979-2015

The Brewer instrument B104 has been in operation at Andøya since 2000. In the period 1994 to 1999 the instrument was located in Tromsø, approximately 130 km Northeast of Andøya. 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. For the time period 1979–1994 total ozone values from the satellite instrument TOMS (onboard Nimbus 7 satellite) have been used for the trend studies.

Figure 5a shows variation in the monthly mean ozone values at Andøya from 1979 to 2015. The variations in total ozone at Andøya for the period 1979–2015, after removing the seasonal variations, are shown in Figure 5b together with the annual trends. October – 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 chosen to divide the ozone time series into two periods: 1) 1979-1997, and 2) 1998-2015. 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. In contrast, no significant trends have been observed for the second period from 1998 to 2015. For the latter period an ozone increase of 0.7%/decade is observed during spring, the summer trend is 0.5%/decade, whereas the annual trend for the period 1998-2015 is 1.0%/decade. None of these trend results are significant at either 1σ or 2σ significance level.

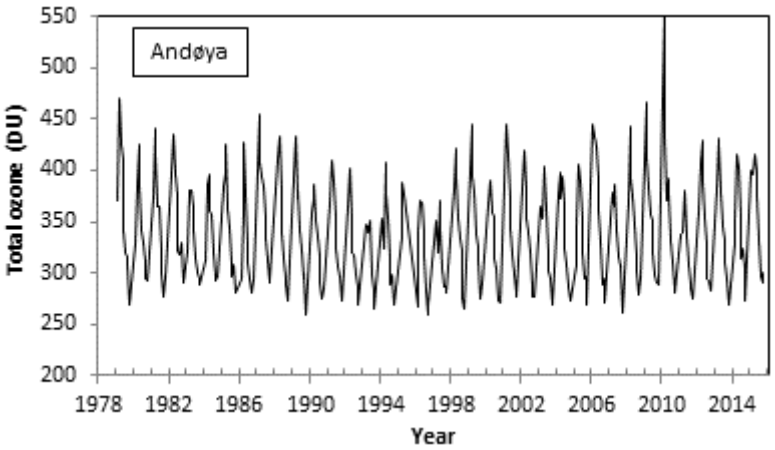

Figure 5a: Time series of monthly mean total ozone at Andøya/Tromsø 1979-2015.

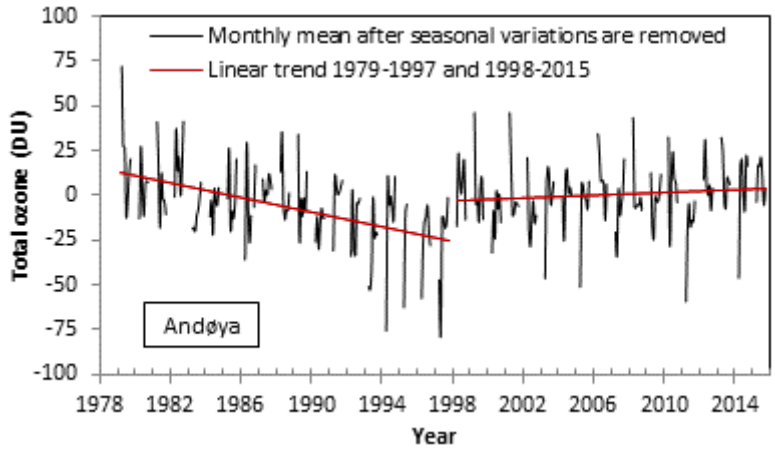

Figure 5b: Variations in total ozone at Andøya for the period 1979-2015 after the seasonal variations are removed. Only data for the months March-September are included.

Table 5: Percentage changes in total ozone (per decade) at Andøya for the periods a) 1979-1997, and 2) 1998- 2015. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	*Trend (%/decade) 1979-1997*	*Trend (% /decade) 1998-2015*
Spring (Mar - May)	-8.4 (1.5)	0.7 (1.8)
Summer (Jun - Aug)	-2.8 (0.9)	0.5 (1.0)
Annual (Mar - Sep)	-5.8 (1.0)	1.0 (1.1)

3.4 Trends for Ny-Ålesund 1979-2015

The first Arctic ozone measurements started in Svalbard 66 years ago. In 1950 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 Svalbard until 1962. The data have been reanalyzed and published by Vogler et al. (2006). After 1962 only sporadic measurements were performed in Longyearbyen, but after the instrument was moved to Ny-Ålesund in 1994 more systematic measurements took place. However, the Dobson instrument requires manual operation and it soon became more convenient to replace the manual instrument with the more automatic SAOZ and GUV instruments.

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 24 years only ground based measurements are 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. Also data from the Italian Brewer no. 50 have been included for 2013 and 2014. Unfortunately, the Brewer data from 2015 were not accessible due to problems with data connection and termination of the Italian Arctic research program.

As seen from Figure 6b and Table 6 the trend pattern in Ny-Ålesund has many similarities to the Andøya trend series. 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 -1.6%/ decade. The annual trend in total ozone was -7.0%/ decade during these years. For the second period 1998-2015 no significant trends have been observed. During these years an ozone increase of 0.1%/decade is observed for the spring months, and a trend of -1.6%/decade is found for the summer months. The annual trend for the period 1998-2014 is -0.4%/decade. None of these results are significant at a 2σ significance level.

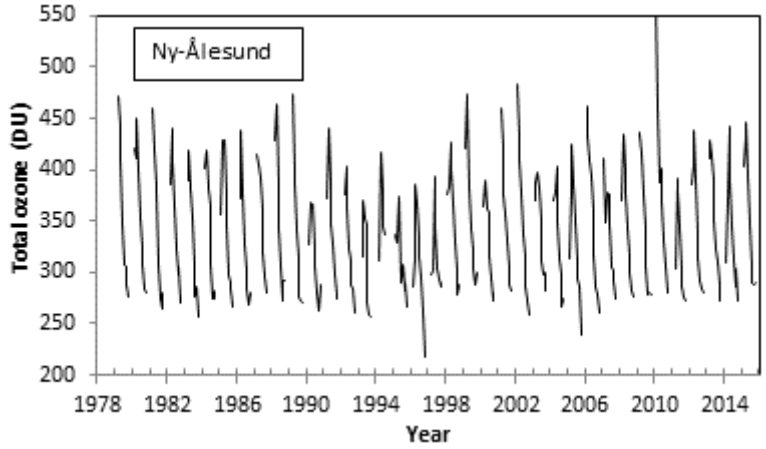

Figure 6a: Time series of monthly mean total ozone at Ny-Ålesund 1979-2015.

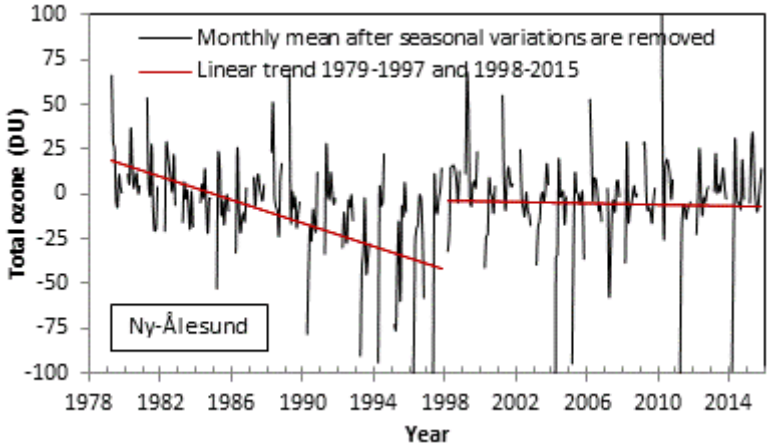

Figure 6b: Variations in total ozone at Ny-Ålesund for the period 1979-2015. Only data for the months March-September are included.

Table 6: Percentage changes in total ozone (per decade) in Ny-Ålesund for the periods a) 1979-1997, and 2) 1998-2015. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	*Trend (%/decade) 1979-1997*	*Trend (% /decade) 1998-2015*
Spring (Mar - May)	-11.7 (1.8)	0.1 (2.4)
Summer (Jun - Aug)	-1.6 (1.2)	-1.6 (1.0)
Annual (Mar - Sep)	-7.0 (1.1)	-0.4 (1.4)

3.5 The overall Norwegian ozone situation 2015

As seen from the Figures in Chapter 2, there were no episodes of long lasting ozone decline over Norway in 2015. Most of the year the ozone values were higher or close to normal at all the Norwegian sites. In January 2015 the ozone layer above Oslo was exceptionally thick, and on January 14 an ozone value of 493 DU was measured. This is almost 50% higher than the average January ozone value. Figure 7 shows a map of Northern Hemisphere total ozone deviation this day. The map is from WOUDC and Environment Canada, based on a combination of ground based measurements and satellite observations. The high-ozone area covering Oslo is clearly seen on the map.

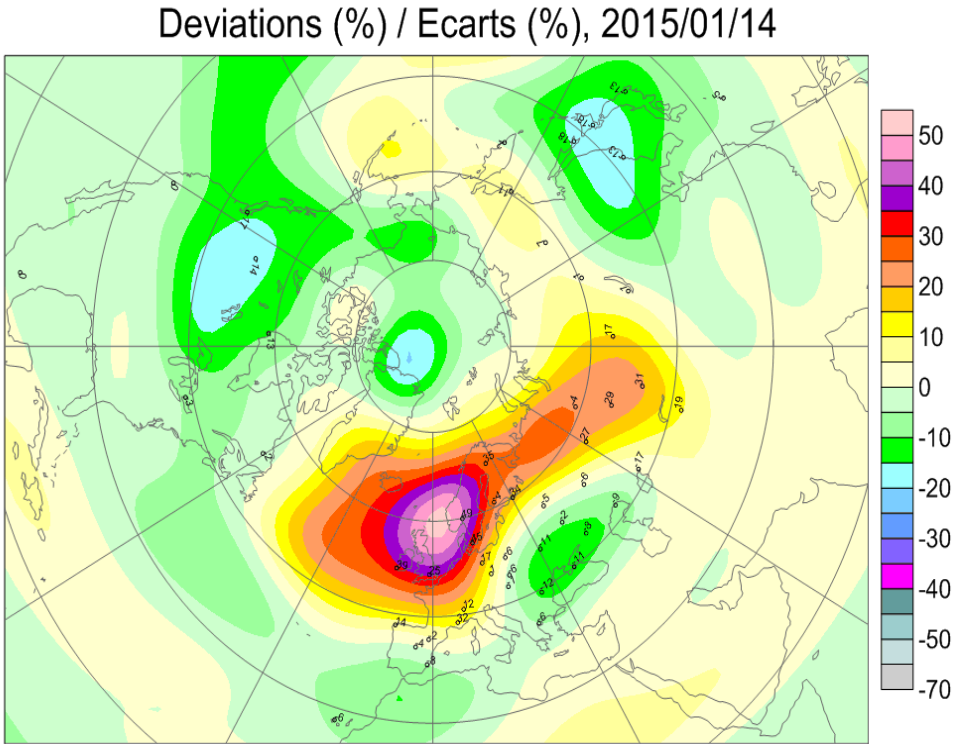

Figure 7: Total ozone deviation from WOUDC and Environment Canada 14. January 2015. The map is based on ground based measurements and satellite observations (http://exp-studies.tor.ec.gc.ca/e/ozone/Curr_allmap_g.htm)

For the Arctic as a whole the ozone values in in winter/spring 2015 were also higher than normal. Chemically induced loss of ozone was minimal in the spring because of a minor "sudden stratospheric warming" (SSW) event in early January, which caused lower stratospheric temperatures to rise above the critical temperature for formation of ozone-destroying chlorine species. A second reason for the high ozone concentrations observed in 2015 was larger-than-usual transport of ozone-rich air into the lower stratosphere from higher altitudes (Manney et al., 2015).

The Arctic interannual ozone variability is large, exemplified by the different situations in spring 2015 compared to 2011. This is related to dynamical effects that influence vortex size and longevity, transport of ozone into the lower stratosphere, and stratospheric chemistry via its sensitivity to temperature (WMO, 2014).

Table 7 summarizes the ozone situation for Norway 2015 and gives the percentage difference between the monthly mean total ozone values in 2015 and the long-term monthly mean values at the three Norwegian sites. As mentioned above, the ozone level above Oslo was record high in January, i.e. around 20% above normal. For the other months, the ozone values were within ±7% compared to the long-term mean. At Andøya the ozone values in February and June were fairly high (9% and 8% above the long-term mean, respectively), but for the remaining months the total ozone was within ±5% compared to the long-term mean. In Ny-Ålesund the ozone values were close to normal all months (within ±5%). In general the ozone values were above normal, except from June and July where the values were ~2% below the long-term summer ozone average in Ny-Ålesund.
It should be noted that the December monthly mean in Oslo was 7% below the long-term average. At the high latitude stations, continuous displays of polar stratospheric clouds were observed from around 12 December, indicating an early strong onset of the 2015/16 polar vortex. This will be dealt with in more detail in the 2016 report.

Table 7: Percentage difference between the monthly mean total ozone values in 2015 and the long-term mean for Oslo, Andøya, and Ny-Ålesund.

Month	Oslo (%)	Andøya (%)	Ny-Ålesund (%)
January	19.5		
February	-2.7	8.9	4.1
March	-6.5	-2.8	2.7
April	-3.2	0.9	4.1
May	5.8	5.5	1.3
June	6.7	7.6	-1.6
July	2.6	3.9	-1.6
August	-2.5	-1.9	1.4
September	3.0	-1.9	2.4
October	-3.6	-5.1	5.4
November	5.5		
December	-7.1		

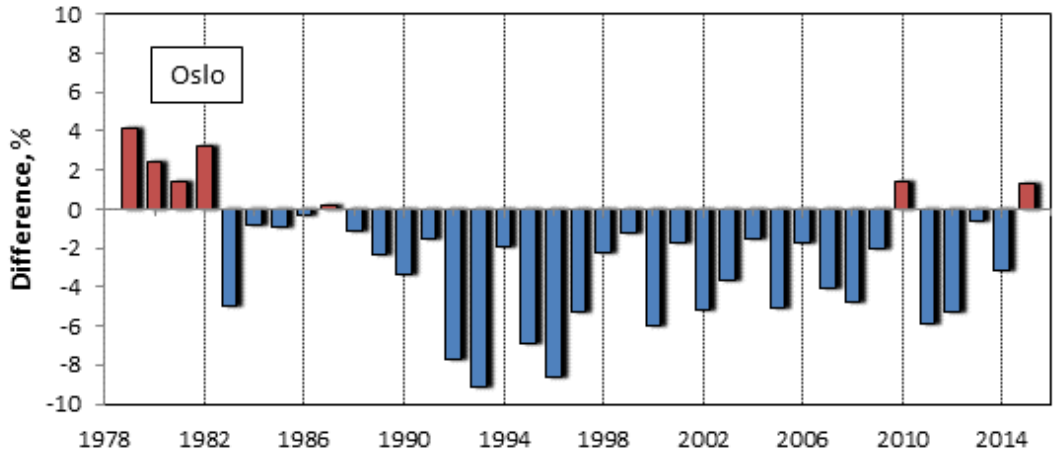

Figure 8: Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean 1979-1989.

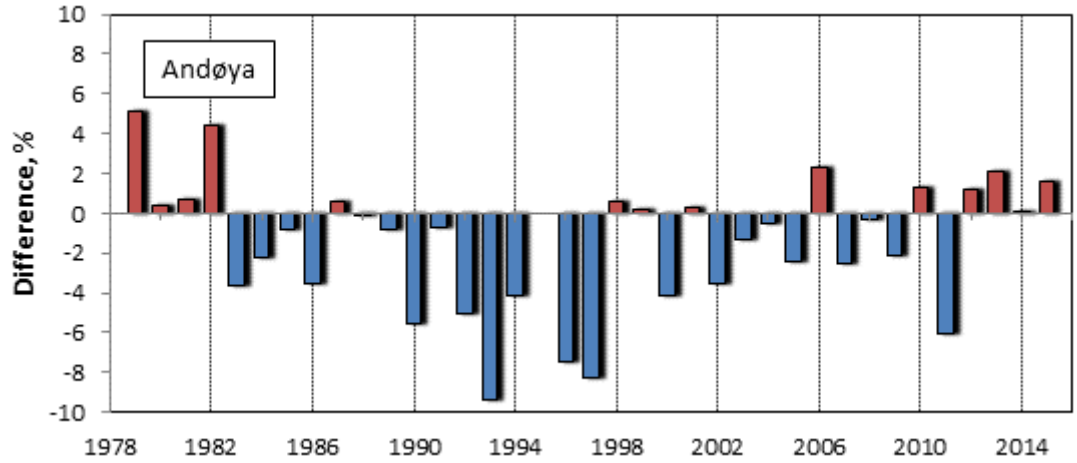

Figure 9: Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean1979-1989 for the months March-October.

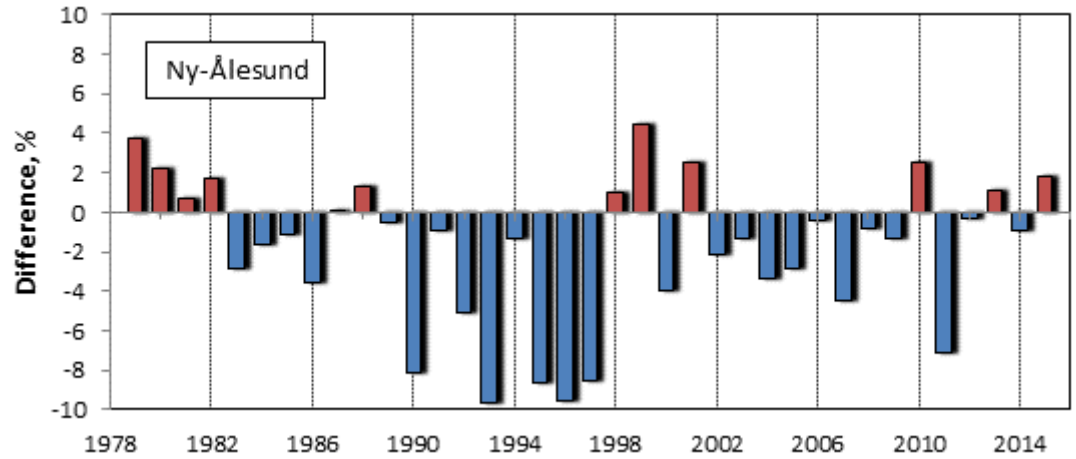

Figure 10: Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.

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) and in 2011 (roughly 6% below the long-term mean).

The annual mean ozone values in 2015 do not differ dramatically from the annual average long-term means. In Oslo, at Andøya and in Ny-Ålesund the annual ozone means are 1.3%, 1.6%, and 1.8% above the long-term means, 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, it was moved uphill and about 2 km further away; this dramatically improved air quality conditions. The instrumentation 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. 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 9 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, which however did not happen before November 2015.

The only (short horizontal distance) data set the NILU-UV data can be compared with are satellite-borne data of the OMI/AURA instrument. However, also the OMI data have increased uncertainty at large solar zenith angles (SZA), though not as large as multi-wavelength moderate-bandwidth filter instruments such as GUV and NILU-UV. The only dataset without SZA dependence are ozonesonde data, and the closest site to Troll with regular ozonesonde launches is the German Neumayer Station, about 400 km northwest of Troll.

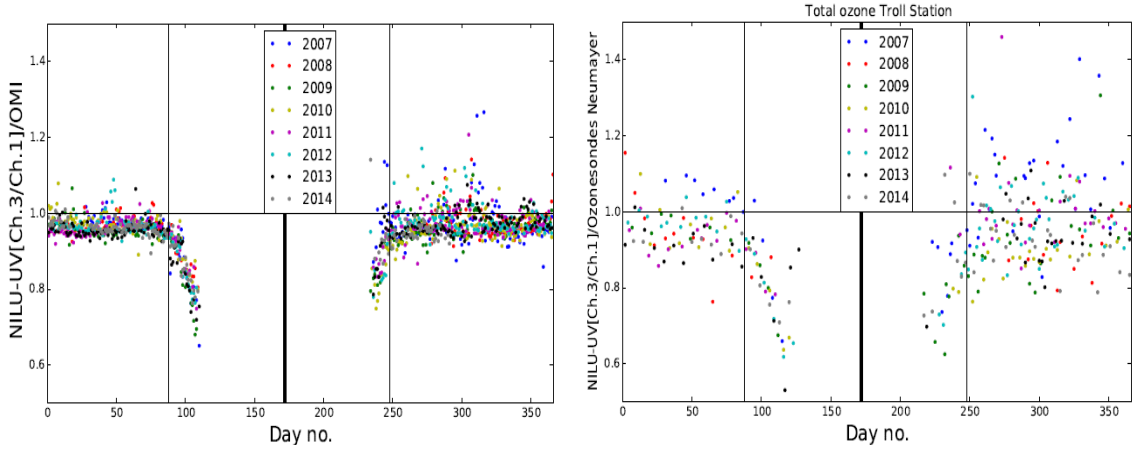

Figure 11: Ratio of NILU-UV to OMI/AURA (left panel) and of NILU-UV to ozonesondes at Neumayer Station (right panel) total ozone column, using the Channel 3/Channel 1 wavelength pair of the NILU-UV instrument. Vertical lines mark the austral winter solstice and the period around it not considered in the calculation of monthly means.

Figure 11, left panel, shows the ratio between the NILU-UV total ozone values, derived from the channel 3/channel 1 wavelength pair, and the OMI/AURA values for all years. Data derived from this channel pair have turned out to be most stable both within a year and from year to year. The figure shows that the average discrepancy between the two data sets is approximately 5% before day 88 and after day 248. In between these dates, the ratio between the two data series deviates much more and increasingly with increasing solar zenith angle. However, this is not a symmetric feature; before austral winter solstice, the deviation occurs earlier and more gradual than after solstice. Moreover, the scattering in the deviations is significantly larger after winter solstice. These features also occur when one compares the NILU-UV data with total ozone derived from ozonesondes at Neumayer Station (only soundings where the sonde reached an altitude of more than 28 km were considered).

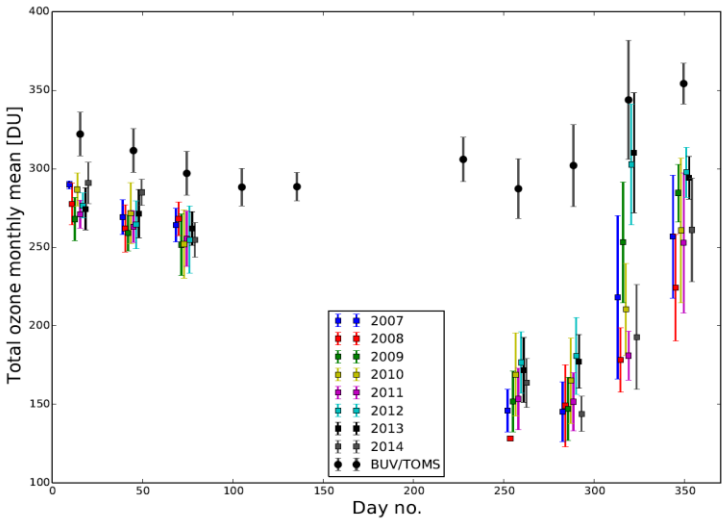

Figure 12: Monthly mean total ozone as measured with the Troll Station NILU-UV instrument, including the standard deviation of daily values considered (shown as error bars). BUV/TOMS monthly means: based on 1970 - 1981 satellite measurements

The ratios based on the same NILU-UV channel pair are shown in the right panel of Figure 11. The overall scattering of the ratios is about twice as large compared to the NILU-UV vs. OMI data set, probably due to the considerable horizontal distance between the two measurement sites (ca. 400 km). Based on the above comparisons, NILU-UV data taken between 30 March (day 89) and 5 September (day 248) are not considered. Figure 12 shows monthly means and standard deviation of total ozone derived as measured by the NILU-UV. For comparison,

monthly means from pre-ozone-hole conditions in the period 1970 – 1981 as measured by the BUV and TOMS satellite instruments are depicted as well.

The effects of the Antarctic ozone hole are very obvious in the second half of the year, but also the austral summer (January-March) ozone levels are affected, even if the NILU-UV data have a systematic offset of, at most, 5% which would account for 16 DU, while the observed offset is between 30 and 50 DU. With regard to the austral spring/summer monthly means, there is very strong ozone depletion in September and October in all years, while the situation is much more variable especially in November, but also in December. Figure 13 gives a high-resolution view of this period, emphasizing that there is a marked transition around day 310, with relatively stable ozone hole conditions before and large intra- and inter-annual variability after this date. While in 2008 and 2011 ozone-hole conditions prevailed until the end of the calendar year, they changed to extra-vortex conditions in 2012 and 2013. During the other years, the station was obviously located close to the vortex edge, which swept back and forth overhead Troll Station. With these large variations on short and annual time scale, trend studies from a single site are not meaningful. Taking into account regional-scale satellite observations, there were indications of a gradual recovery of the Antarctic ozone layer. However, conditions in 2014 and even more in 2015 stated a return to ozone depletion as severe as in the early 2000s.

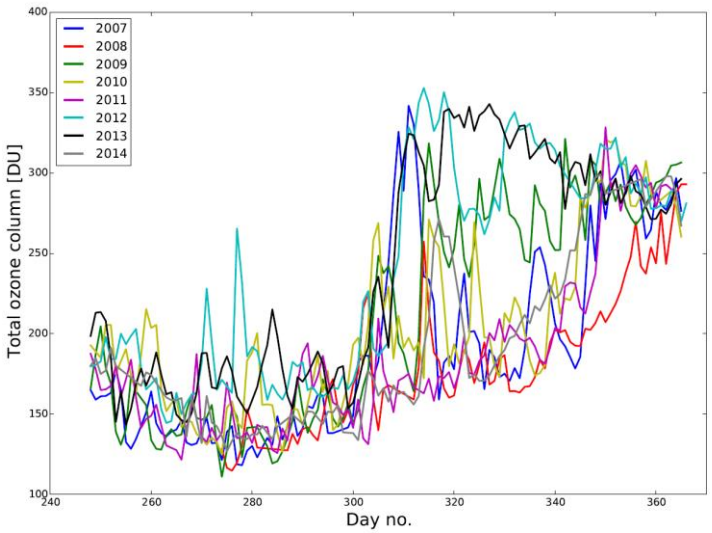

Figure 13: Daily total ozone data during the "ozone hole season" as observed by NILU-UV for all years 2007 - 2014.

4. Satellite observations of ozone

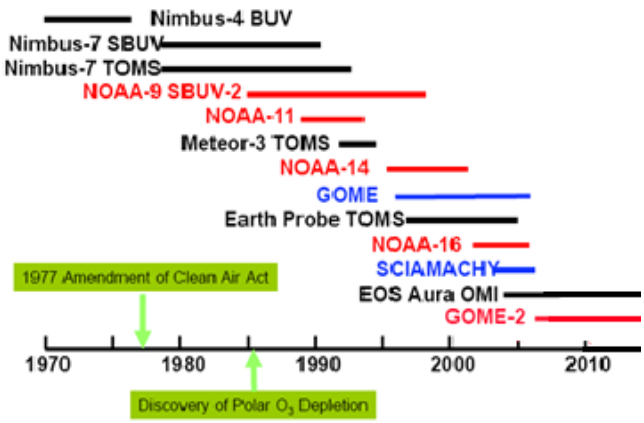

Figure 14: An overview of the various satellites and their instruments measuring ozone from space since the beginning of the 1970's (Figure from NASA).

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 14 gives an overview of the various ozone measuring satellites and their time of operation.

4.1 Satellite ozone observations 1979-2015

In the course of the last 36 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 1979-2015. Figure 15 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.

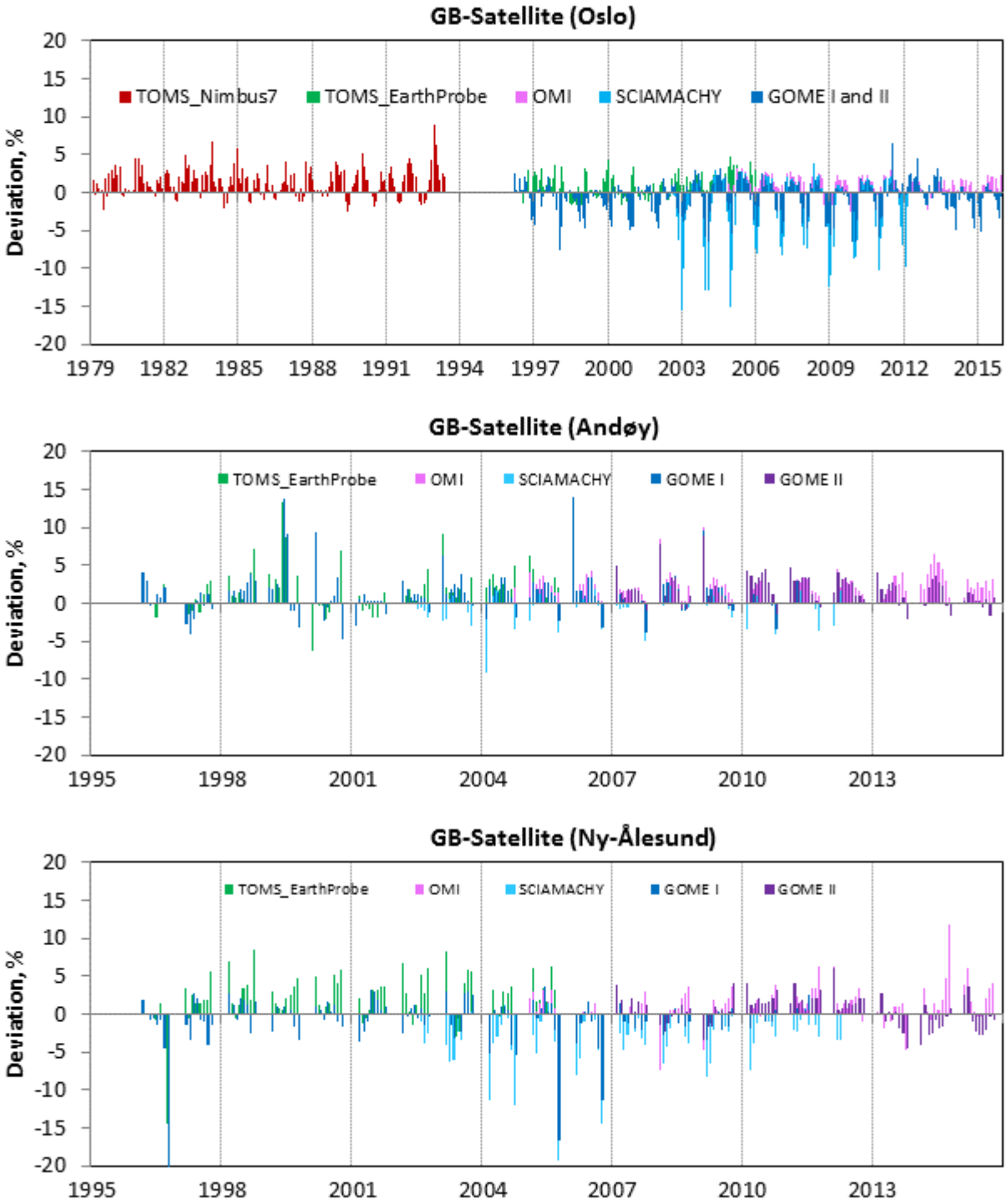

Figure 15: Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2015 (Oslo) and 1995-2015 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, middle panel: Andøya, lower panel: Ny-Ålesund.

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-15	0.88	1.39	1.94
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-15	0.31	2.03	4.13
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-15	2.66	1.94	3.77
GOME 1	Mar-96	Jul-11	1.42	2.78	7.74
GOME 2	Jan-07	Dec-15	1.74	1.97	3.86
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-15	0.89	2.90	8.41
GOME 1	Mar-96	Jul-11	-0.72	3.30	10.88
GOME 2	Jan-07	Dec-15	0.40	2.03	4.11
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 15, 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 1.9% (see Table 8). The GB-OMI variance in Ny-Ålesund is 8.4%, whereas GB-GOME II has a variance of 4.1%. This might indicate that GOME II is slightly better than OMI at high latitudes.

5. 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 forcing[2] (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 16 (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 (NOx), 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 ozone RF of –0.15 W/m^2. On the other hand, tropospheric ozone precursors (CH_4, NOx, CO, NMVOC) cause ozone 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

[2] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere. It is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Wm^{-2} and positive radiative forcing tends to warm the surface. A negative forcing tends to cool the surface.

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 (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.

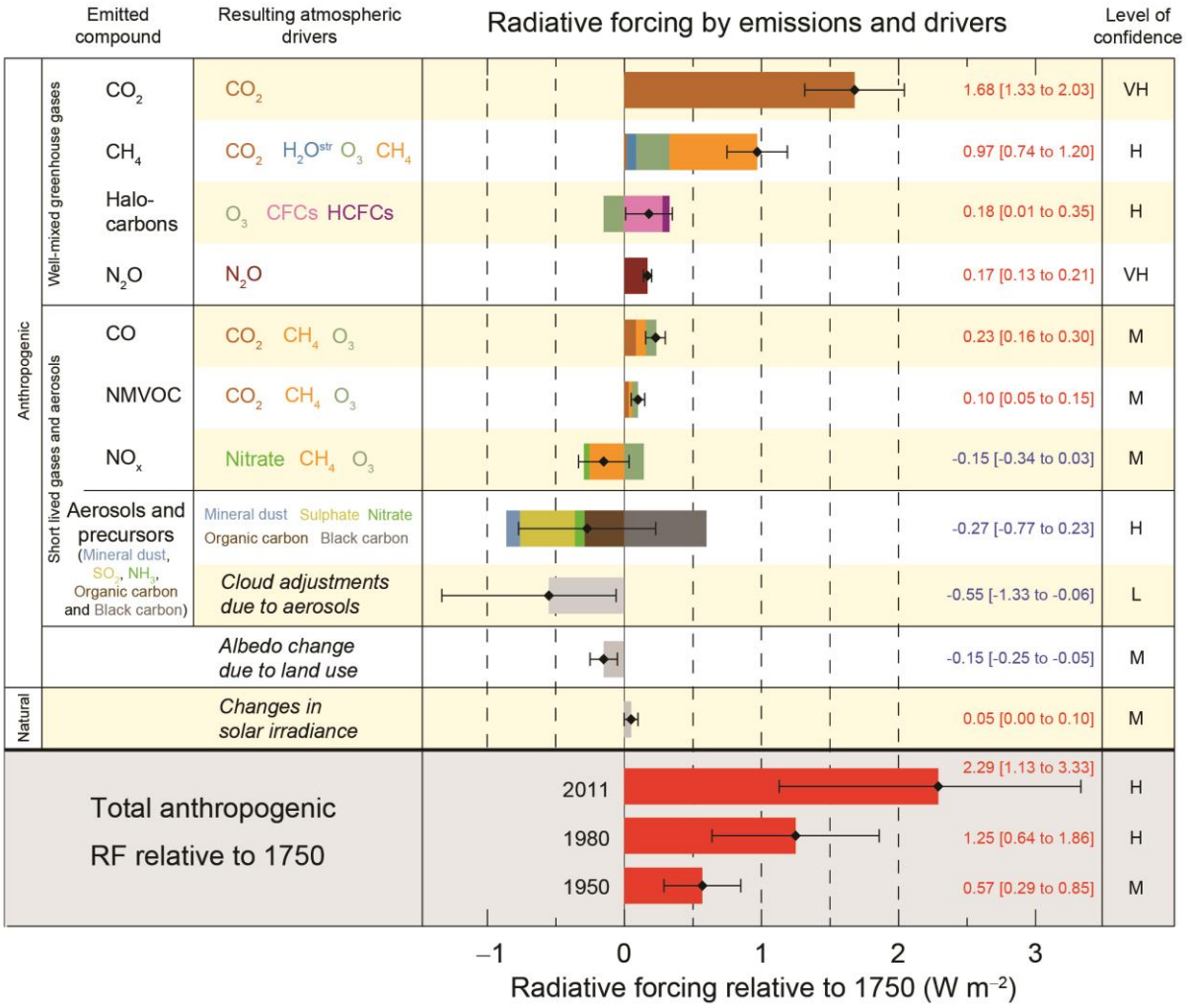

Figure 16: Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change. Values are global average radiative forcing, partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative 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 stratosphere. OH is one of the key species in the chemical cycles regulating ozone

levels. There are several sources for stratospheric water, where CH_4 is the most important. Other water vapour sources are volcanoes and aircrafts, as well as natural and anthropogenic biomass burning which indirectly can influence 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 (CH_4) has a positive radiative forcing of 0.07 W/m^2 (see Figure 16). 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^2.

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 regulates ozone concentrations. The photochemical degradation of N_2O in the middle stratosphere leads to ozone-depleting NOx, 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).

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 17. NILU is responsible for the daily operation of three of the instruments, located at Oslo (60°N), Andøya (69°N) and 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/.

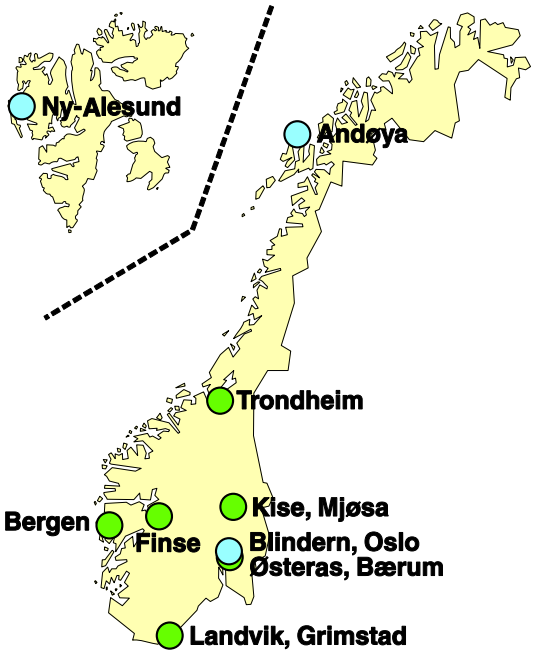

Figure 17: Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas the Norwegian Radiation Protection Authority operates the stations marked with green.

This annual report includes results from Oslo, Andøya and Ny-Ålesund. The GUV instrument in Ny-Ålesund was omitted from the monitoring programme in the period 2006-2009, but was included again in 2010. In 2013, Andøya was excluded from the programme, but the measurements have continued due to direct financial support from the Ministry of Climate and Environment.

The GUV instruments are normally easy to maintain and have few interruptions due to technical problems. However, the instruments have been in operation for 20 years, and technical failures have occurred more frequently in recent years. The instruments in Ny-Ålesund and at Andøya were out of order several weeks in 2014 and were sent to Kjeller and BSI (USA), respectively, for repair. In 2015 both instruments ran without major problems most of the time.

6.1 UV measurements in 2015

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[3]). The unit for dose rate is mW/m^2, but is often given as a UV index (also named UVI). A UV index of 1 is equal to 25 mW/m^2. The concept of UV index is widely used for public information concerning sunburn potential of solar UV radiation. At Northern latitudes the UV indices typically vary between 0 – 7 at sea level, but

[3] *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.

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

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

Figure 18 shows the UV dose rates measured at noon (averaged between 10:30 and 11:30 UTC) for Oslo, Andøya and Ny-Ålesund. The highest noon UV dose rate in Oslo, 161.7 mW/m^2, was observed on July 2 and is equivalent to a UV index of 6.5. The black curves in Figure 18 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 2015 was 4.0, equivalent to a dose rate of 100.1 mW/m^2, observed July 1. The highest UVI noon value in Ny-Ålesund was 2.6 or 64.6 mW/m^2, and was measured July 9. However, a UVI peak value of 2.9 was observed in Ny-Ålesund the day before. In Oslo the highest noon averaged UVI was observed during a clear day with relatively low ozone values, i.e. 294 DU (normal ~335 DU). At Andøya the ozone column was 334 DU (close to normal) during the day of maximum UVI. This day the sky was covered with thin and scattered clouds. In Ny-Ålesund the maximum UVI was observed during a relatively clear day with total ozone column of 291 DU, roughly 20 DU below normal value.

For UV levels corresponding to the maximum UVI-value of 6.5 in Oslo, people with a typical Nordic skin type get sunburnt after approximately 20 minutes if no sun protection is used.

Figure 19 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 19 (red curve, left panel) Oslo had clear sky all day 2 July. A cloudless sky in combination with low ozone values resulted in high UVI this day. At Andøya there were some scattered clouds during the day of maximum UVI in 2015. This is seen by the "noisy" red curve in Figure 19 (middle panel). 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.

In Ny-Ålesund there were some clouds early in the morning and evening, but around noon the sky was clear. As seen from Figure 19 (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.

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.

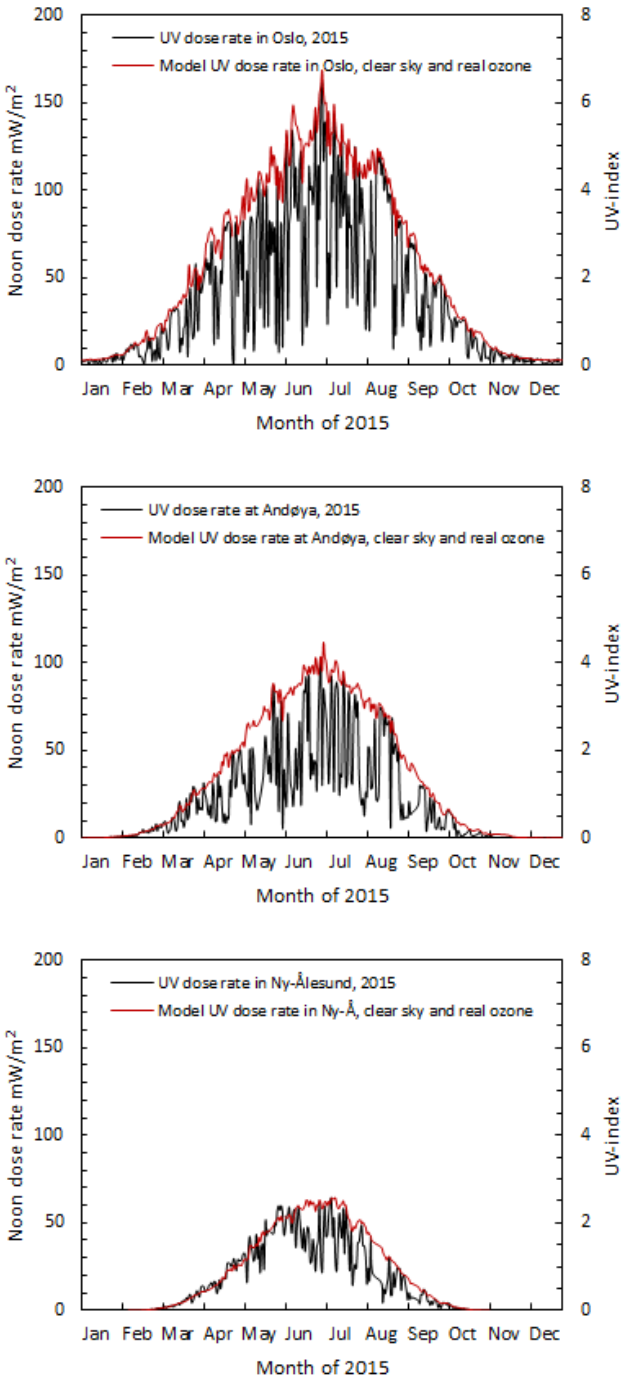

Figure 18: Hourly averaged UV dose rate measured at noon (between 10:30 and 11:30 UTC) in 2015. Upper panel: Oslo. Mid panel: Andøya Lower panel: Ny-Ålesund.

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 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.

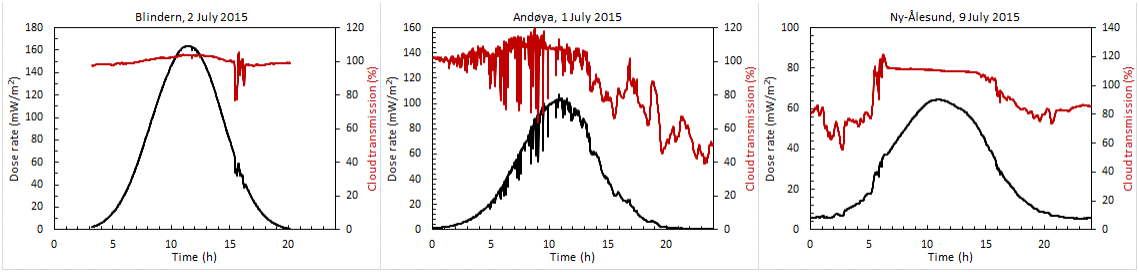

***Figure 19**: UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel) in 2015. A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30% represent heavy clouds.*

Monthly integrated UV doses for Oslo, Andøya and Ny-Ålesund in 2015 are compared in Figure 20. As expected, the monthly UV doses in Oslo were significantly higher than the values observed at Andøya and in Ny-Ålesund. If the cloud, 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. Contrary to 2014, the summer of 2015 was characterized by many overcast days in Oslo and at Andøya. Consequently, the monthly integrated summer UV-doses were significantly lower than the 2014 values. In Ny-Ålesund, however, the UV-doses in May and first parts of June were close to "clear sky values" (see Figure 18, lower panel). This resulted in monthly integrated UV-doses that exceeded the values measured at Andøya these two months. Moreover, total ozone values were lower in Ny-Ålesund than at Andøya in summer 2015. In June the average ozone layer at Andøya was ~8% above the long-term mean, whereas the average ozone in Ny-Ålesund was ~2% below normal. This can explain parts of the high Ny-Ålesund UV-dose compared to the Andøya dose.

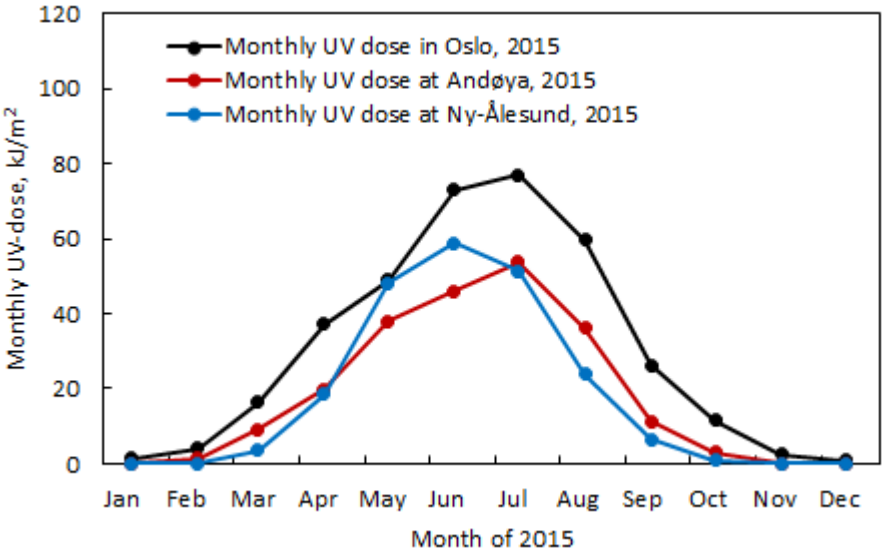

Figure 20: Monthly integrated UV doses (in kJ/m^2) in 2015 measured with the GUV instruments located in Oslo, at Andøya and in Ny-Ålesund.

6.2 Annual UV doses 1995-2015

Annual UV doses for the period 1995–2015 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 ±5 % at a 2σ level (Johnsen et al., 2002). For periods with missing data we have estimated the daily UV doses from a radiative transfer model (FastRt, http://nadir.nilu.no/~olaeng/fastrt/fastrt.html). Normally this gives an additional uncertainty in the annual UV doses of ±1.6 % for all stations and years, except for Andøya where the uncertainty is ±2 % for 2000, ±5 % for 2001, and ±5 % for 2011 where 12 days of measurements were missing.

Table 10: Annual integrated UV doses (in kJ/m^2) for Oslo, Andøya and Ny-Ålesund for the period 1995 - 2015.

Year	Oslo (kJ/m^2)	Andøya (kJ/m^2)	Tromsø (kJ/m^2)*	Ny-Ålesund (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

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

In 2015 the UV doses in Oslo during summer were in general below normal. July had the highest monthly UV dose of 2015, with UVI between 5 and 6 on several days. As shown in Figure 18 (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 we study the period from

1995-2015 it should be noted that 2015 was the year with second lowest yearly integrated UV dose in Oslo. Only 2012 had lower UV values.

At Andøya there were periods with heavy clouds and low UVI in May and June. Thus, July was the month with highest integrated UVI in 2015. In Ny-Ålesund the highest UV doses were measured in late May and early June. Later in the season lower albedo and cloudy conditions became more frequent, which kept the UVI below 2 most days.

A graphical presentation of the yearly integrated UV-doses from 1995 to 2015 is shown in Figure 21. The figure illustrates yearly UV fluctuations. At all three stations a negative UV trend of 3% to 5% has been detected for the past 21 years. However, the trend results are not statistically significant.

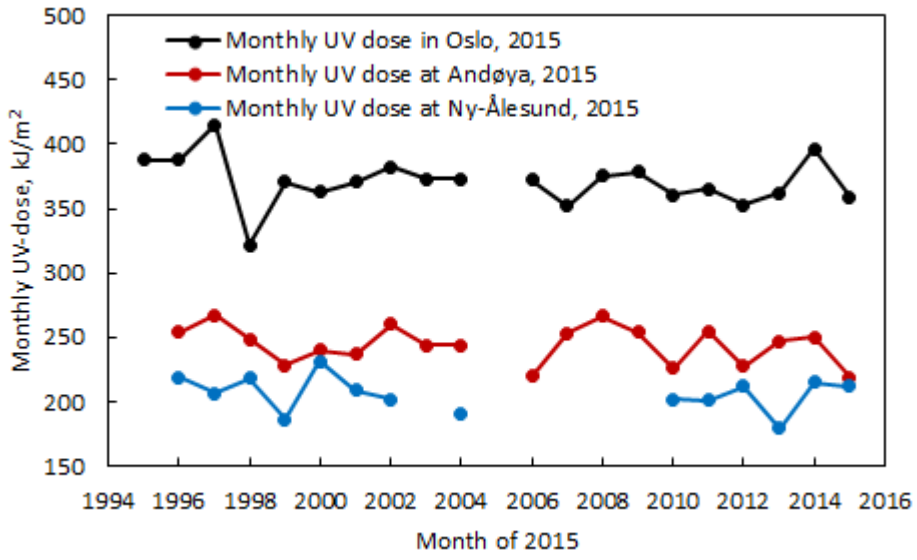

Figure 21: Annual integrated UV doses (in kJ/m^2) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995-2015.

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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.