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Overvåking av ozonlaget og naturlig ultrafiolett stråling: Årsrapport 2014.
Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2014.

Summary – sammendrag

This is an annual report describing the activities and main results of the monitoring programme "Monitoring of the atmospheric ozone layer and natural ultraviolet radiation" for 2014. The ozone layer was below the long-term mean in spring 2014, but increased in April/May and was close to normal rest of the year. A clear decrease in total ozone above Norway during the period 1979-1997 stopped after 1998 and the ozone layer above Norway now seems to have stabilized.

Rapporten presenterer måledata for totalozon og UV-stråling over norske målestasjoner i 2014. For Oslo, Andøya og Ny-Ålesund er trenden i totalozon beregnet for perioden 1979-2014. Ozonlaget over Norge var relativt tynt våren 2014, men det tok seg opp i april/mai, og verdiene var tilnærmet normale resten av året. Den klare reduksjonen av ozonlaget over Norge i perioden 1979-1997 stoppet opp i 1998, og ozonlaget over Norge ser nå ut til å ha stabilisert seg.

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 amount of stratospheric ozone decreased dramatically during the 1980s and 1990s. The main reason 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 revised 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". Five years later the programme was extended to "Monitoring of the atmospheric ozone layer and natural ultraviolet radiation". NILU - Norwegian Institute for Air Research has been responsible for the operation and maintenance of the monitoring programme since 1990. NILU has long experience in ozone monitoring, and has been carrying out numerous stratospheric ozone research projects since 1979.

Due to economic constraints, the monitoring program has been varying over the years with respect to the number of locations and instrumental data reported. Until 2012, three sites were included in the programme: Oslo (60°N), Andøya (69°N) and Ny-Ålesund (79°N). In 2013 Andøya was excluded 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 2014. It also includes total ozone trend analyses for the period 1979-2014 and UV measurements in Oslo, at Andøya and in Ny-Ålesund since 1995.

Total ozone
The monthly mean total ozone above Oslo was low in March and April, around 14% and 8% below normal, respectively. For the other months, the monthly average values were within a ±6% margin compared to the 1979-1989 average. At Andøya the ozone values in February and March were on average 12% below the long-term mean, but for the remaining months the ozone values were higher than or close to normal. The highest values were measured in May and August, with values 7% above normal. Similar to Andøya, Ny-Ålesund had very low total ozone values in February and March (roughly 14% below the long-term mean). However, in April the stratospheric circulation pattern changed and ozone rich air moved towards Ny-Ålesund. This resulted in April average ozone values as much as 12% above the 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: -6.4%/decade annually and -11.4%/decade during the spring months. For the period 1998-2014, the ozone situation seems to have stabilized and no significant trends have been observed at any of the three locations. However, large inter-annual ozone variations are observed, mainly related to stratospheric circulation and temperatures. Consequently, a calculated trend must be relatively large to be classified as significant.

Recent studies indicate signs of ozone recovery in most parts of the world. However, there is still uncertainty related to this recovery, particularly in Arctic 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, 160 mW/m^2, occurred 15 July. This is equivalent to a UV index (UVI) of 6.4. At Andøya the highest UV index in 2014 was 4.8 (observed 25 July), whereas the highest UVI in Ny-Ålesund, 3.2, was observed 19 June. These maximum values are not exceptional. In Ny-Ålesund and at Andøya the integrated annual UV-doses in 2014 were close to the 1994-2014 average. However, in Oslo the 2014 integrated UV-dose was the second highest recorded during the 20 years of observations. The high UVI in Oslo was mainly caused by the high frequency of cloudless days in the summer, especially in July 2014. In addition, the total ozone above Oslo was 3.5% below the long-term ozone mean in 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, the 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. The catalytic cycles producing ozone in the stratosphere are temperature-dependent and more efficient at lower temperatures. On the other hand a colder stratosphere might extend the time period over which Polar Stratospheric Clouds (PSCs) are present in winter and early spring and, as a result, might increase polar ozone

depletion. Furthermore, climate change may alter the strength of the stratospheric circulation and with it the distribution of ozone in the stratosphere.

The atmospheric concentrations of the three long-lived 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 2014

- **In 2014 the ozone values above Norway were close to the long-term means most of the year, except from low values in late winter/early spring.**
- **The annual integrated UV-doses in Ny-Ålesund and at Andøya in 2014 were close to the 1994-2014 average. However, in Oslo the 2014 annual UV-dose was the second highest value registered since 1994. This was mainly caused by the exceptionally sunny conditions in the summer 2014.**
- **At all Norwegian monitoring stations a significant stratospheric ozone decease was recorded for the period 1997-1997. For the period 1998-2014 there is no significant trend in the ozone layer above Norway.**
- **Meteorological variability has a large impact on ozone and can give considerable year-to-year variations in total ozone.**

2. Norwegian ozone measurements in 2014

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 the Italian Brewer ozone data 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 with absent 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, Canada, calibrate Brewer instrument no. 42 (Oslo) and no. 104 (Andøya) against a reference instrument, last time in the summer 2014. 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 yearly compared against a European travelling reference spectro-radiometer QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe; Gröbner et al., 2010). The Norwegian Radiation Protection Authority coordinate this calibration.

In the following sections, results from the ground-based ozone measurements in Oslo, at Andøya and in Ny-Ålesund are described, while in Chapter 4 satellite measurements from the sites are presented.

2.1 Total ozone in Oslo

In Oslo total ozone is primarily recorded with the Brewer MKV Spectrophotometer (#042) 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 high solar zenith angles.

Figure 1a illustrates the daily total ozone values from Oslo in 2014. 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 2014 are based on Brewer direct-sun (DS) measurements when available.

In 2014 direct-sun measurements were performed on 162 out of 365 days. During overcast days or days where the minimum solar zenith angle was larger than 72°, the ozone values

were calculated from the global irradiance (GI) method (Stamnes et al., 1991). The Brewer GI method was used on 195 days. Under heavy cloud conditions (low CLT; cloud transmittance) the Brewer GI retrievals give too high ozone values. Thus, a CLT dependent correction was applied to all GI data before inclusion in the Oslo data series. In 2014 there were in total 8 days without Brewer DS or GI measurements. On days with absent 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. However, heavy clouds and bad weather conditions will also introduce large uncertainty to the GUV data. Thus, GUV ozone data were only retrieved on 4 out of 8 days with missing Brewer data. A summary of instruments and frequency of inclusion in the 2014 Oslo ozone series is given in Table 1. Even if total ozone was retrieved from the GUV instrument on 361 out of 365 days, only 4 of the measurements were used in the 2014 time series since the Brewer measurements were considered as more accurate.

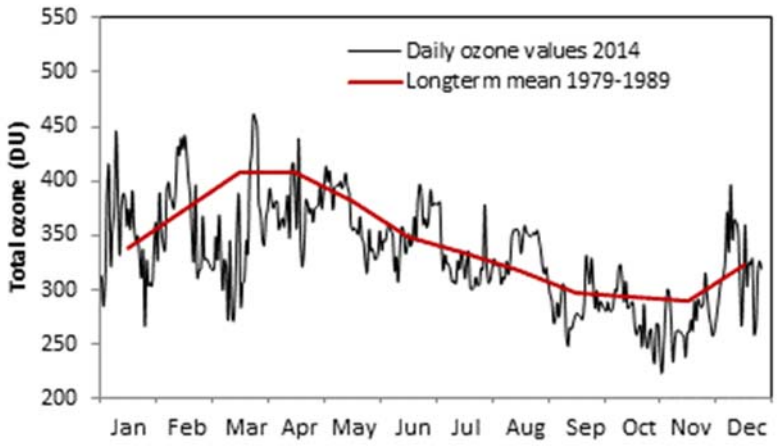

Figure 1a: Daily total ozone values measured at the University of Oslo in 2014. The red curve shows the long-term monthly mean values from 1979-1989.

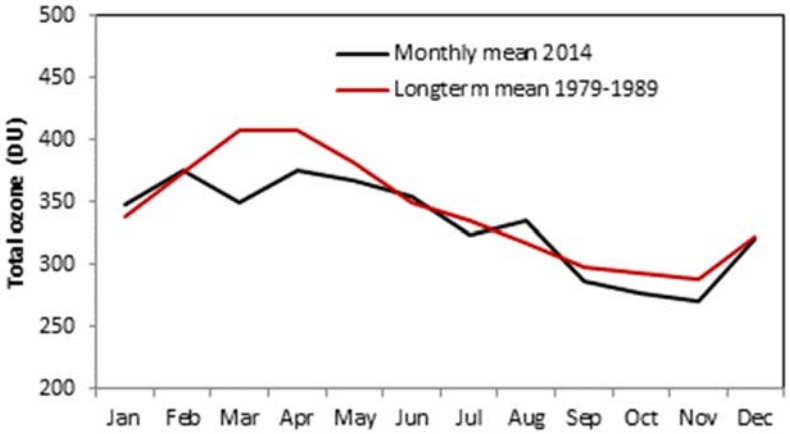

Figure 1b: Monthly mean ozone values for 2014. The red curve shows the long-term monthly mean values from 1979-1989.

Table 1: Overview of total ozone instruments in Oslo and the number of days where the various instruments were used in the 2014 time series

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	162
2	Brewer instrument, global irradiance method	195
3	GUV-511 instrument	4
	Missing days (due to bad weather)	4

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, and the minimum ozone value in 2014 was 224 DU[1], measured on 1 November. This is about 23% below the long-term mean for November. On 12 March, the ozone value in Oslo reached a relative minimum of 271 DU, which is 33% below normal March values.

The monthly mean total ozone values in 2014 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 ozone values in March and April 2014 were significantly lower than normal. Section 3.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2014.

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, 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".*

In May 2013 a problem with the 380 nm channel was discovered on the GUV 9276 instrument at Andøya. The instrument was sent to Biospherical Instruments, USA, for repair. Meanwhile a spare instrument, GUV 9280, from The Norwegian Radiation Protection Authority (NRPA) was installed. This spare instrument was used until 24 March 2014.

The Brewer instrument also had some technical problems in 2014. The communication between the instrument and PC was frequently interrupted, and the internal Hg lamp tests occasionally failed. Installation of a new connection cable improved the stability of the instrument significantly. However, the technical problems resulted in less Brewer ozone measurements from Andøya in 2014 than normal.

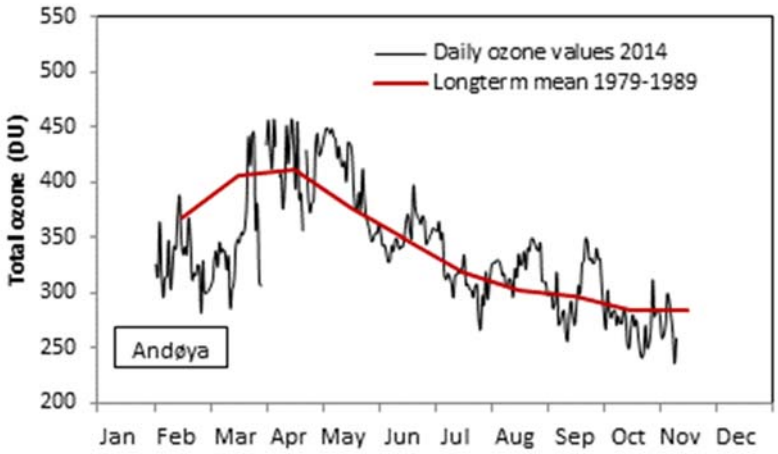

Figure 2a: Daily total ozone values measured at ALOMAR, Andøya, in 2014 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989.

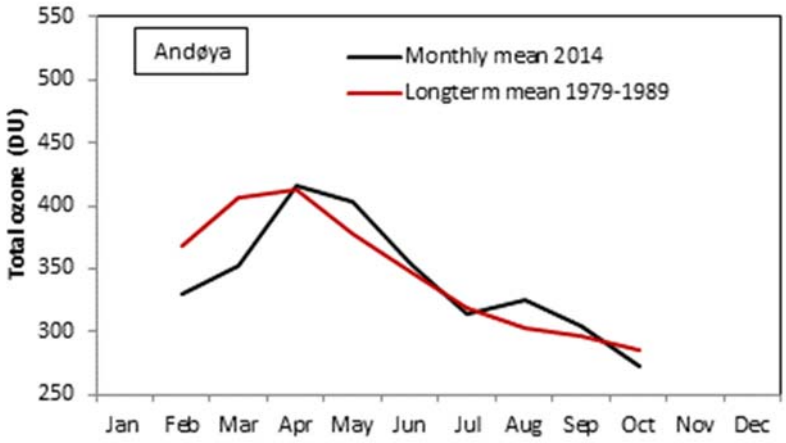

Figure 2b: Monthly mean total ozone values for 2014 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

Table 2 gives an overview of the different instruments and methods used at Andøya in 2014. The ozone lidar at Andøya is no longer in regular operation, and consequently no ozone

measurements were performed during winter. Due to the GUV and Brewer problems described above, there were 15 days without ozone measurements in 2014.

Figure 2a shows daily ozone values from Andøya in 2014. The black curve illustrates the daily ozone values, whereas the red curve shows the long-term monthly mean values for the years 1979-1989. Total ozone from early November to mid February was not achievable due to low solar radiation. The lowest ozone values at Andøya normally occur in October and November, and the minimum ozone value in 2014 was 236 DU, measured 8 November. This was about 17% below the long-term mean for October. On 26 February, total ozone reached a relative (winter) minimum of 282 DU, which is 23% below average February values.

Monthly mean ozone values at Andøya for 2014 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 2014 shows that the ozone layer was close to normal most months, except February and March. The largest deviation was found in March, where the average ozone value was 13% below the long-term mean.

Table 2: Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2014.

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	66
2	Brewer instrument, global irradiance method	123
3	GUV instrument	46
	Missing days (except polar night period)	15

2.3 Total ozone in Ny-Ålesund

Ny-Ålesund is located at a high northern latitude (79º N), which makes it more challenging to obtain reliable ozone measurements due to weak solar radiation, 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. 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. Thus, total ozone data from Ny-Ålesund are missing from mid-February until mid-March 2014.

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 getting stronger in the 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 indicate that the GUV ozone data might be too high during summer. New comparisons between GUV and a high-quality Brewer spectrophotometer indicate the same. This is described in more detail in Section 2.3.1

Due to the SAOZ failure and repair in early 2014, less SAOZ measurements than normal are included in the 2014 ozone time series. Table 3 gives an overview of the different instruments and methods used for the 2014 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 2014.

Priority	Method	Total days with observations
1	SAOZ instrument	96
2	GUV instrument	141
	Missing days (~10 days in February)	13

Figure 3a shows daily ozone values from Ny-Ålesund in 2014. 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 2014 was 261 DU, measured 23 October. This is 5% below the long-term mean for October. A seasonal ozone minimum of 291 DU was reached on 1 March, which is 31% below normal March values.

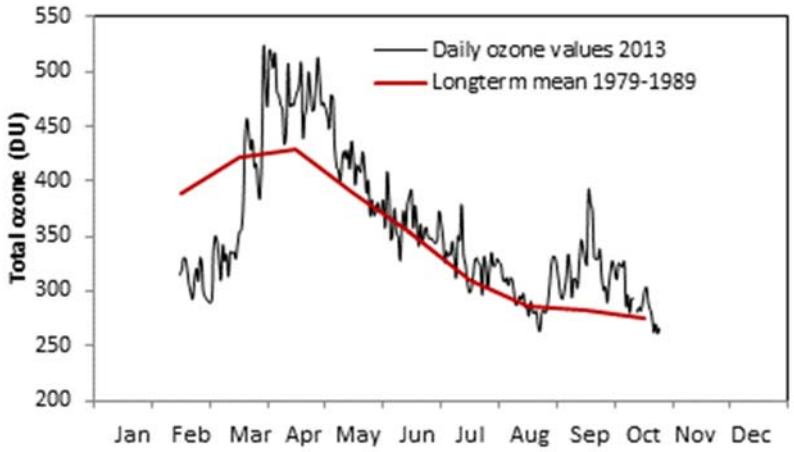

Figure 3a: Daily total ozone values measured in Ny-Ålesund in 2014 by the SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 -1989.

Monthly mean ozone values in Ny-Ålesund 2014 are shown in Figure 3b. Comparison between the long-term mean and monthly mean ozone values 2014 shows that the ozone values were above the long-term mean from April and throughout the year. Similar to Andøya, the ozone values were low in February and March. It should be noted that the summer ozone measurements are based on the GUV instrument, which might overestimate ozone by a few percent (see Section 2.3.1).

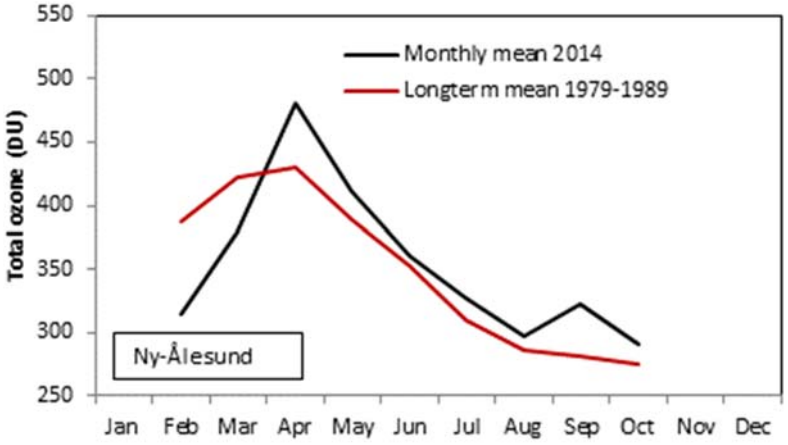

Figure 3b: Monthly mean total ozone values for 2014 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).

2.3.1 Italian Brewer measurements 2014

As stated above, comparisons between SAOZ and GUV data during overlapping measuring periods have indicated that GUV ozone data are too high during the summer. Comparisons between GUV and satellite observations have also indicated such an overestimate of GUV total ozone.

In October 2014 CNR-IDASC, Italy, and NILU signed a scientific agreement that gives 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 onward Brewer total ozone data are accessible and suitable for a preliminary inter-comparison to the Norwegian ozone measurements. Figure 4 shows GUV and Brewer ozone measurements in 2014.

Figure 4 shows that GUV values are above those from the Brewer instrument most of the year. On average, GUV ozone values are 15 DU (~4.2%) higher than Brewer ozone. This is in line with our expectations. It should be noted that B50 has not undergone calibration since 2009 and that the Brewer data shown in Figure 4 possibly need minor corrections. The Italian Brewer instrument will be calibrated by IOS Canada in summer 2015, and a final inter-comparison between Brewer and GUV will be performed after this calibration. Until then, GUV data and trend analyses are presented without corrections. An adjustment of GUV total ozone data will probably have a small impact on trend analyses, since most summer ozone measurements after 1998 are based on the GUV instrument and consequently all measurements will be adjusted equally.

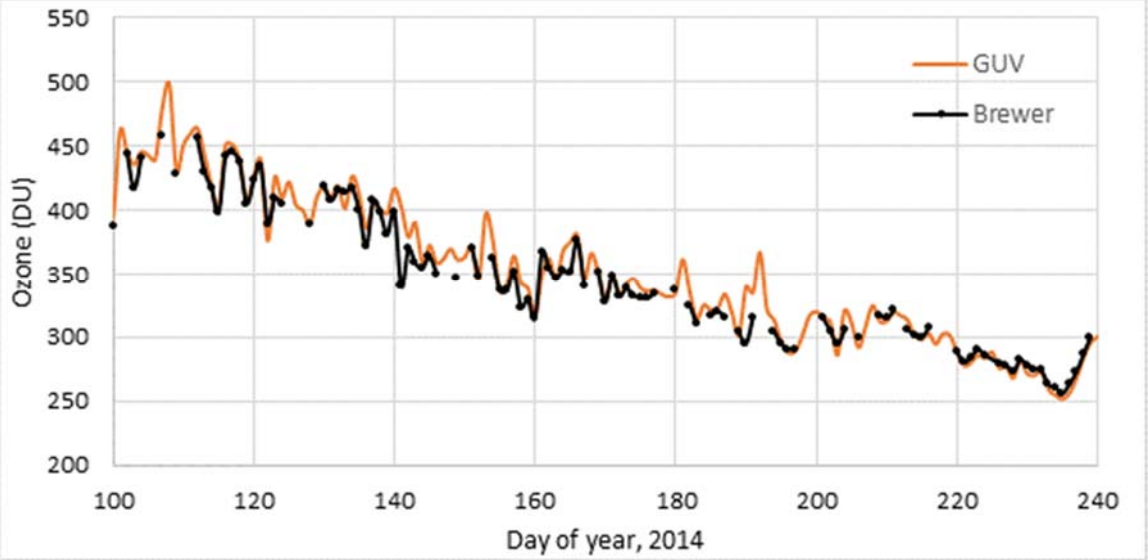

Figure 4: Comparison between GUV and Brewer ozone measurements in Ny-Ålesund 2014

3. Ozone measurements and trends 1979-2014

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 of ten to fifteen years ago.

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 mid-century in mid-latitudes and the Arctic, and somewhat later for the Antarctic ozone hole.

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 trend, 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 1979-2014

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 5a shows the variations in monthly mean ozone values in Oslo for the period 1979 to 2014. 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 – 2014 we have removed the seasonal variations by subtracting the long-term monthly mean ozone value from the data series, shown in Figure 5b. Next, we have divided the time series into two periods: 1) 1978-1997, and 2) 1998-2014. 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.

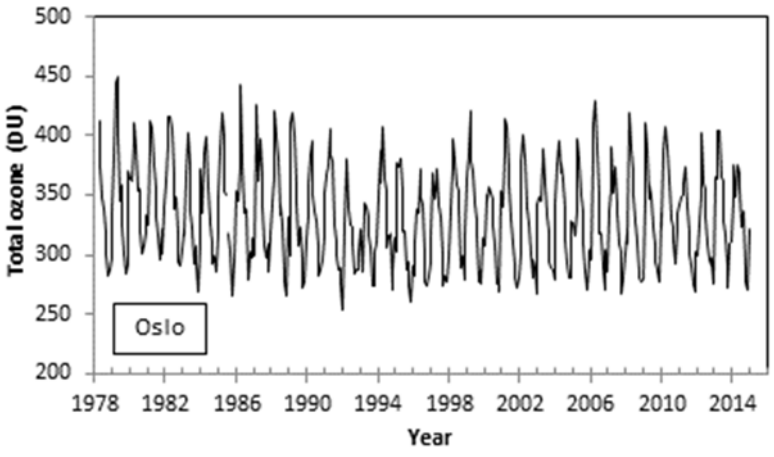

Figure 5a: Time series of monthly mean total ozone in Oslo 1979-2014.

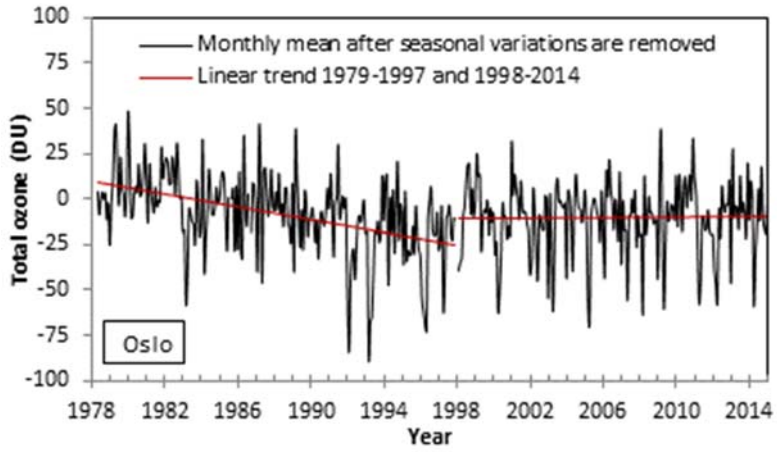

Figure 5b: Variation in total ozone over Oslo for the period 1979–2014 after the seasonal variations have been removed. Trend lines are marked in red.

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 1998-2014 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. For the spring period there is an ozone decline of -0.8% /decade during the last 17 years, whereas the trend is +1.3%/decade for the fall. The annual ozone trend from 1998 to 2014 is close to zero.

Table 4: Percentage changes in total ozone (per decade) for Oslo for the period 1.1.1979 to 31.12.2014. 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) 1998-2014*
Winter (Dec - Feb)	-6.2 (2.4)	0.4 (2.4)
Spring (Mar - May)	-8.4 (1.4)	-0.8 (2.0)
Summer (Jun - Aug)	-3.4 (1.1)	-0.5 (1.1)
Fall (Sep - Nov)	-4.3 (1.0)	1.3 (1.4)
Annual (Jan - Dec):	-5.8 (1.0)	0.1 (1.1)

3.3 Trends for Andøya 1979-2014

The Brewer instrument has been in operation at Andøya since 2000. In the period 1994 to 1999 the instrument was located in Tromsø, approximately 130 km North 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 6a shows variation in the monthly mean ozone values at Andøya from 1979 to 2014. The extreme February 2010 value is seen as a high peak in the plot. The variations in total ozone at Andøya for the period 1979–2014, after removing the seasonal variations, are shown in Figure 6b 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 sun. Simple linear regression lines have been fitted to the data in b. Similar to the Oslo site we have chosen to divide the ozone time series into two periods: 1) 1979-1997, and 2) 1998-2014. The results of the trend analyses are summarized in Table 5. Comparison of Figure 5b and Figure 6b shows that the trend patterns at Andøya have many similarities to the Oslo trend pattern.

As for Oslo, the ozone layer above Andøya declined significantly from 1979 to 1997. This decline was evident for all seasons. The negative trend for the spring season was 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 2014. For the latter period an ozone increase of 0.3%/decade is observed during spring, the summer trend is zero, whereas the annual trend for the period 1998-2014 is 0.7%/decade. None of these trend results are significant at either 1σ or 2σ significance level.

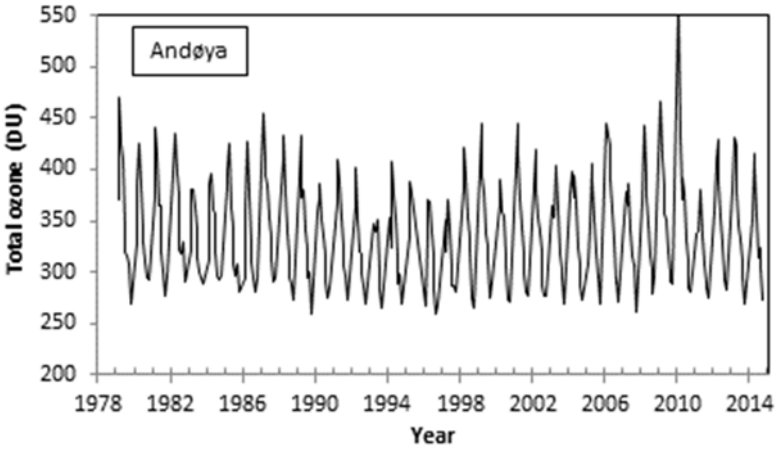

Figure 6a: Time series of monthly mean total ozone at Andøya/Tromsø 1979–2014.

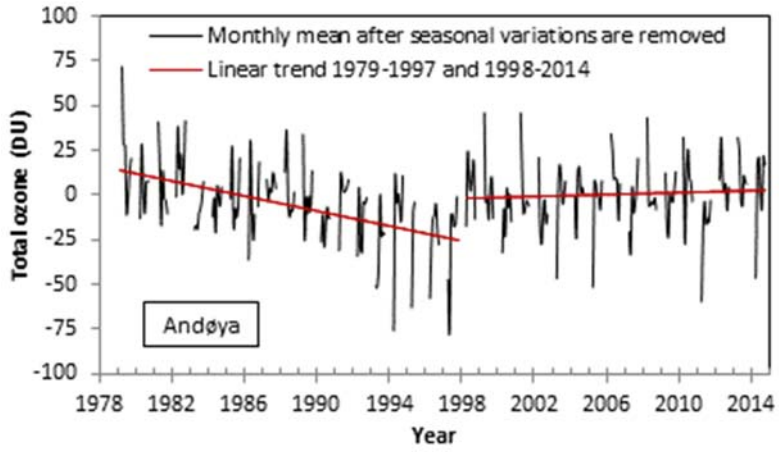

Figure 6b: Variations in total ozone at Andøya for the period 1979–2014 after the seasonal variations are removed. Only data for the months March–September are included.

Table 5: Percentage changes in total ozone (per decade) at Andøya for the periods a) 1979-1997, and 2) 1998- 2014. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant. Data from the Brewer and GUV instruments have been used in this study.

Season	*Trend (%/decade) 1979-1997*	*Trend (% /decade) 1998-2014*
Spring (Mar - May)	-8.4 (1.5)	0.3 (2.0)
Summer (Jun - Aug)	-2.8 (0.9)	0.0 (1.1)
Annual (Mar - Sep)	-5.8 (1.0)	0.7 (1.2)

3.4 Trends for Ny-Ålesund 1979-2014

The first Arctic ozone measurements started in Svalbard 65 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 instruments require 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 7a and Figure 7b 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 23 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.

As seen from Figure 7b and Table 6 the trend pattern in Ny-Ålesund has many similarities to the Oslo and 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 -11.3%/ decade, whereas the negative trend for the summer months was only -1.0%/ decade. The annual trend in total ozone was -6.5%/ decade during these years. In contrast, no significant trends have been observed for the second period from 1998 to 2014. During these years an ozone increase of 0.7%/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 1.2%/decade. None of these results are significant to a 2σ significance level, but there might be indications of a positive development of the ozone layer.

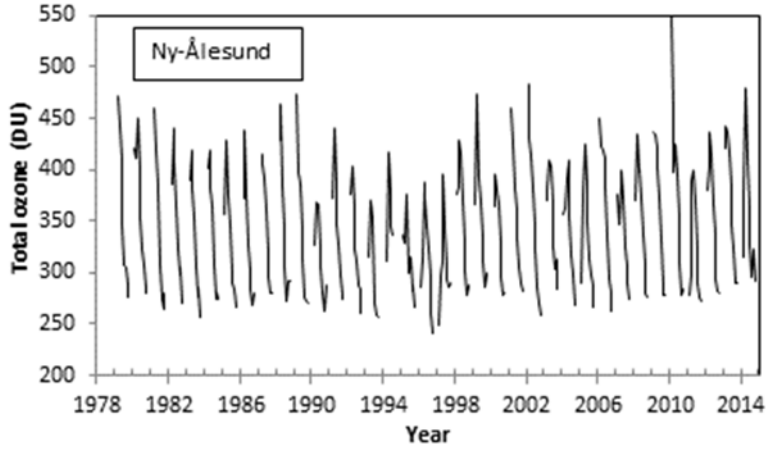

Figure 7a: Time series of monthly mean total ozone at Ny-Ålesund 1979–2014.

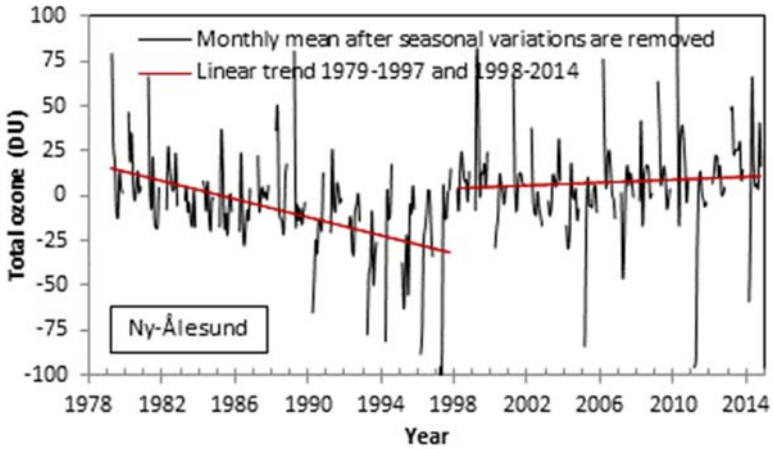

Figure 7b: Variations in total ozone at Ny-Ålesund for the period 1979–2014. Only data for the months March–September are included.

Table 6: Percentage changes in total ozone (per decade) in Ny-Ålesund for the periods a) 1979-1997, and 2) 1998-2014. The numbers in parenthesis give the uncertainty (1σ). A trend larger than 2σ is considered significant.

Season	*Trend (%/decade) 1979-1997*	*Trend (% /decade) 1998-2014*
Spring (Mar - May)	-11.3 (1.8)	0.7 (2.7)
Summer (Jun - Aug)	-1.0 (1.3)	1.6 (1.4)
Annual (Mar - Sep)	-6.5 (1.1)	1.2 (1.6)

3.5 The overall Norwegian ozone situation 2014

As described in Chapter 2, low ozone values were measured at all the three Norwegian stations in March 2014. At Andøya and Ny Ålesund the February ozone values were also significantly lower than normal. However, the low winter ozone values were not representative for the entire Arctic. Figure 8 shows a map of Arctic total ozone on March 12, 2014, from WOUDC and Environment Canada, based on a combination of ground based measurements and satellite observations. It reveals that on this day the stratospheric vortex with reduced stratospheric total ozone was centered over Western Eurasia, while the rim with strongly elevated levels of total ozone usually surrounding the vortex is seen in the North-American and Pacific sector of the Arctic. Results from the 2014 MATCH campaign indicate that the vortex persisted until end of March with substantial ozone depletion taking place (von der Gathen, personal comm., 2014). Moreover, a persisting dynamical anomaly affecting total ozone was observed over Europe; this may be responsible for the particularly low total ozone values in the Baltic region in Figure 8.

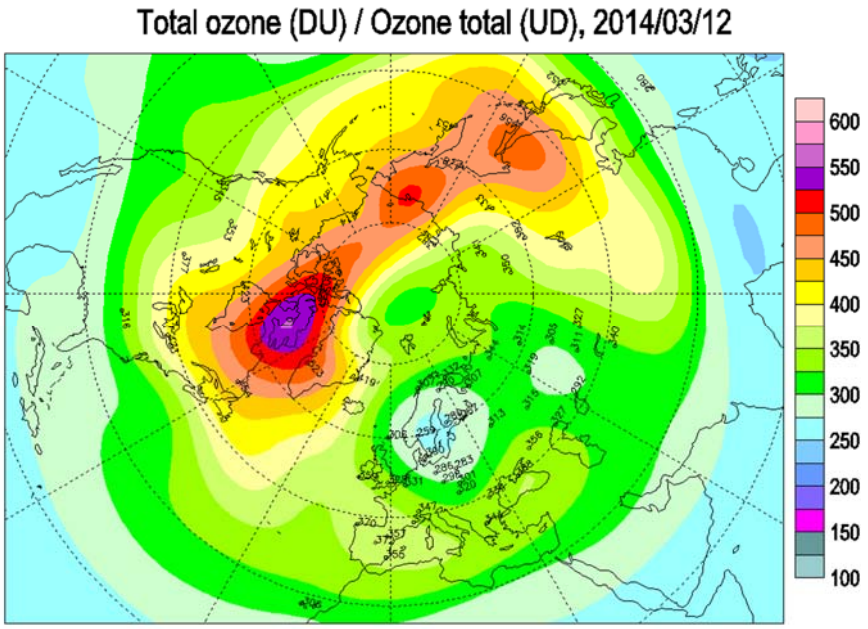

Figure 8: Total ozone from WOUDC and Environment Canada 12. March 2014. The map is based on ground based measurements and satellite observations (http://exp-studies.tor.ec.gc.ca/e/ozone/Curr_allmap_g.htm)

High pressure systems are normally associated high tropopause and low ozone values. On 11 March 2014, the day before the local ozone minimum in Oslo, the air pressure at Blindern was 1023 hPa. This was the highest pressure measured at Blindern in 2014.

The "high ozone area" seen in Figure 8 moved towards Svalbard and Northern Norway in April 2014. This explains why the April ozone values in Ny-Ålesund are very high (Figure 3a and b), whereas the Oslo values remain low.

Table 7 summarizes the ozone situation for Norway 2014 and gives the percentage difference between the monthly mean total ozone values in 2014 and the long-term monthly mean values at the three Norwegian sites. As mentioned above, the ozone level above Oslo was low in March and April, i.e. around 14% and 8% below normal, respectively. For the other months, the ozone values were within ±6% compared to the long-term mean. At Andøya the ozone values in February and March were low (10% and 13% below the long-term mean, respectively), but for the remaining months the total ozone was relatively high. In both May and August the monthly mean ozone values were roughly 7% higher than normal. In Ny-Ålesund, February ozone values were exceptionally low, as much as 19% below normal. Note that the February mean ozone value in Ny-Ålesund is based on measurements from the second half of February only. Thus, the average value is not necessarily representative for the entire month. From April and throughout 2014 all monthly mean ozone values in Ny-Ålesund were higher than normal. The September value was exceptionally high with 14% above the 1979-1989 average. As noted in Section 2.3, the high Ny-Ålesund values can partly be assigned the fact that GUV and SOAZ ozone values in general are higher than the satellite retrieved ozone values that are used for calculating the ozone long-term mean for the 1979-1989 period.

Table 7: Percentage difference between the monthly mean total ozone values in 2014 and the long-term mean for Oslo, Andøya, and Ny-Ålesund.

Month	Oslo (%)	Andøya (%)	Ny-Ålesund (%)
January	2.9		
February	0.5	-10.2	-19.0
March	-14.3	-13.3	-10.0
April	-8.0	0.8	11.8
May	-3.8	6.6	5.7
June	1.6	1.6	2.4
July	-3.5	-1.7	5.3
August	5.6	7.1	3.6
September	-3.7	2.4	14.4
October	-5.7	-4.5	5.9
November	-6.5		
December	-0.6		

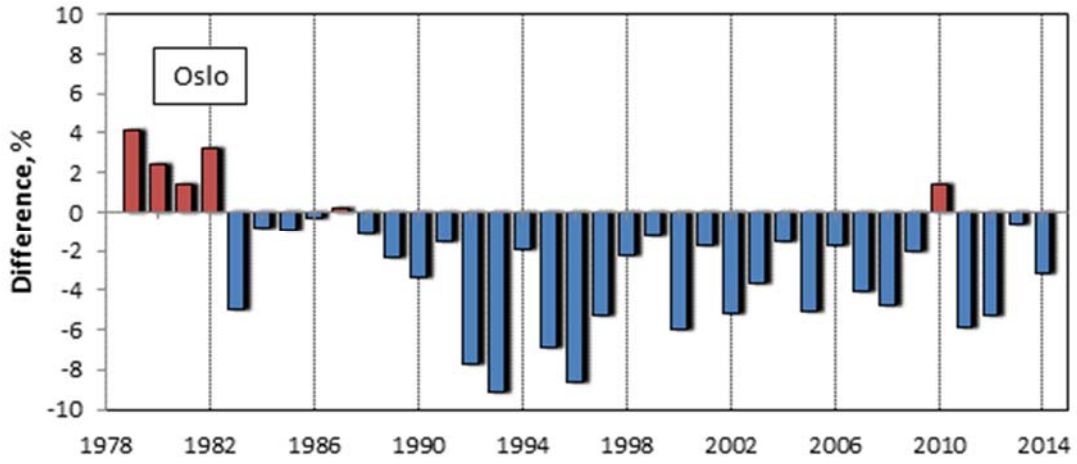

Figure 9: Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean 1979-1989.

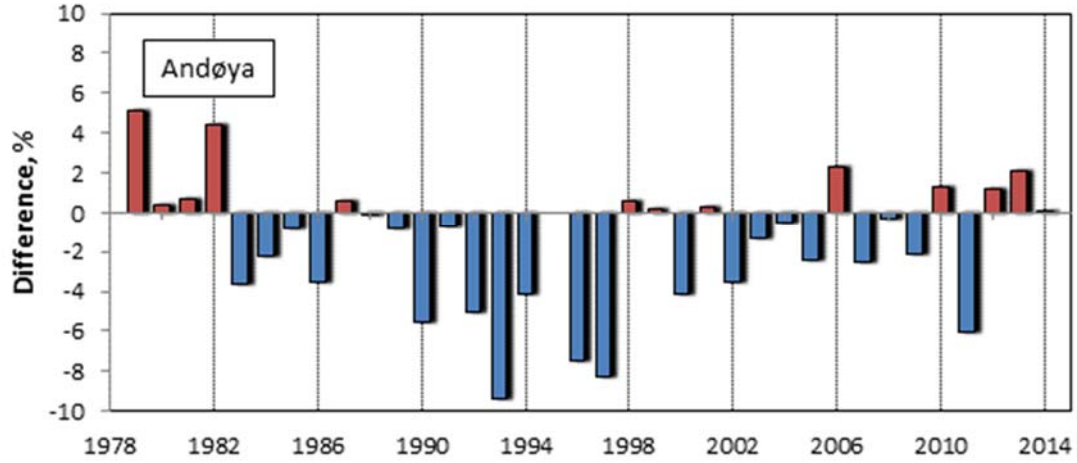

Figure 10: Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean1979-1989 for the months March-October.

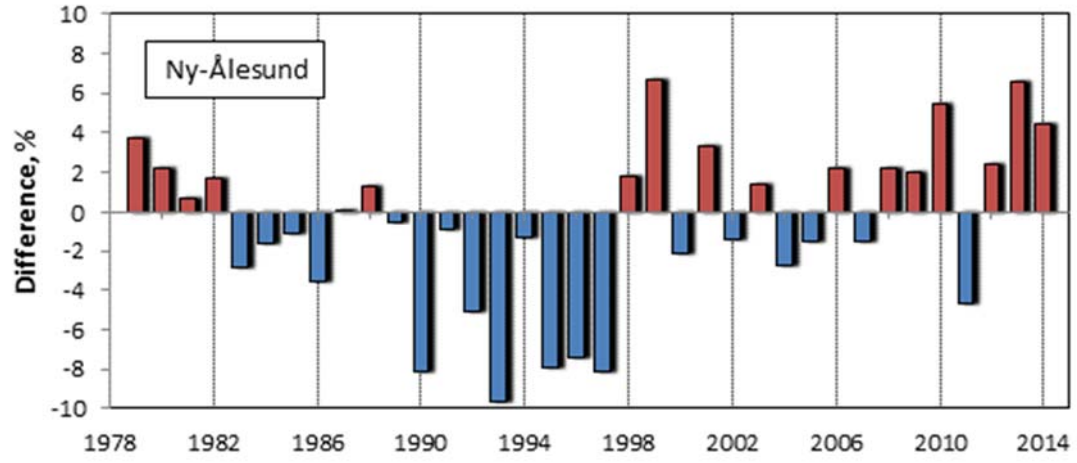

Figure 11: Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean 1979-1989 for the months March-October.

Figure 9, Figure 10 and Figure 11 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 9, Figure 10 and Figure 11 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 and 2013. 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 2014 did not differ dramatically from the annual average long-term means. In Oslo, the annual ozone mean was 3% below normal, at Andøya it was close to normal, whereas the annual mean at Ny-Ålesund was around 4% above the long-term mean.

4. Satellite observations of ozone

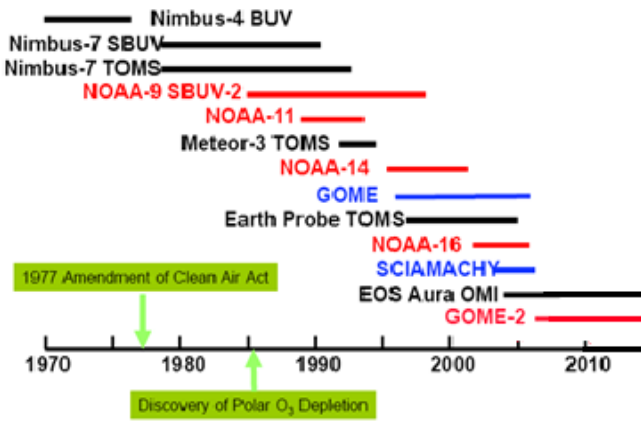

Figure 12: An overview of the various satellites and their instruments measuring ozone from space since the beginning of the 1970's (Figure from NASA).

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 1979-2014

In the course of the last 35 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 region.

The monthly mean ozone values from ground-based (GB) measurements and satellites are analysed for the full period 1979-2014. Figure 13 shows the percentage of 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.

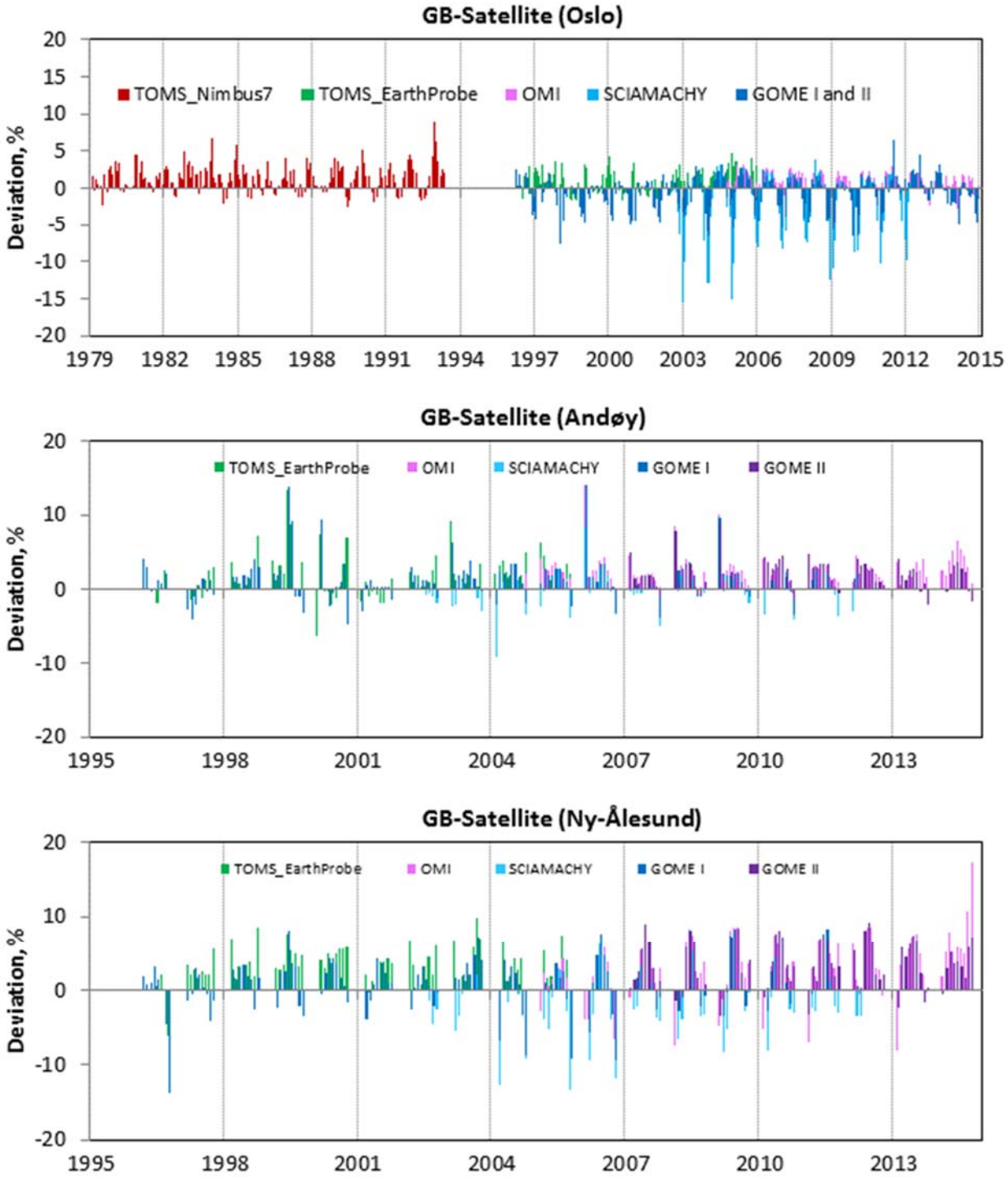

Figure 13: Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2014 (Oslo) and 1995-2014 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, middle panel: Andøya, lower panel: Ny-Ålesund.

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 the ozone. For Andøya all mean satellite values are lower than the ground based observations. The same is the case in Ny-Ålesund, except from SCIAMACHY which has a large negative bias during early spring and late fall which gives an overall annual average ozone value higher than the ground based mean value. For Ny-Ålesund, all satellite retrieved ozone values are lower than the ground based measurements during summer. As seen from Figure 13 (lower panel), the GB measurements are typically 6-7% higher during the summer months. This might be partly caused by overestimated GUV and SAOZ ozone values, but can also be attributed to uncertain satellite retrievals at high latitudes. Comparison to other ground based instruments, preferably Dobson or Brewer measurements, will give a better insight to this problem.

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-14	0.90	1.36	1.86
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-14	0.50	1.97	3.89
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	Oct-14	2.70	2.02	4.07
GOME 1	Mar-96	Jul-11	1.42	2.78	7.74
GOME 2	Jan-07	Dec-14	1.93	1.98	3.94
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	3.26	2.57	6.60
OMI	Oct-04	Dec-14	3.01	4.44	19.70
GOME 1	Mar-96	Jul-11	1.18	3.78	14.30
GOME 2	Jan-07	Dec-14	3.21	3.34	11.15
SCIAMACHY	Jul-02	Apr-12	-0.67	4.86	23.61

There are also clear seasonal variations in the deviations between GB ozone and satellite retrieved ozone values, especially in Oslo and Ny-Ålesund. For example, SCIAMACHY systematically overestimated ozone values during periods with low sun. 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. 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 as high as 19.7%, whereas GB-GOME II has a variance of 11.2%. This might indicate that GOME II is more accurate 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 14 (IPCC, 2013). The estimates represent changes in energy fluxes, caused by various drivers, in 2011 relative to 1750. This figure is slightly more complex than the corresponding representations in previous IPCC reports (e.g. IPCC, 2007), since it shows how emitted compounds affect the atmospheric concentration of other substances.

The total radiative forcing estimated from ozone changes is 0.35 W/m^2, with RF due to tropospheric ozone changes of 0.40 W/m^2, and due to stratospheric ozone changes of –0.05 W/m^2. The overall RF best estimates for ozone is 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 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 PSCs. These ice clouds are formed when stratospheric temperature drops below -78ºC. Chemical reactions occurring on the PSC 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.

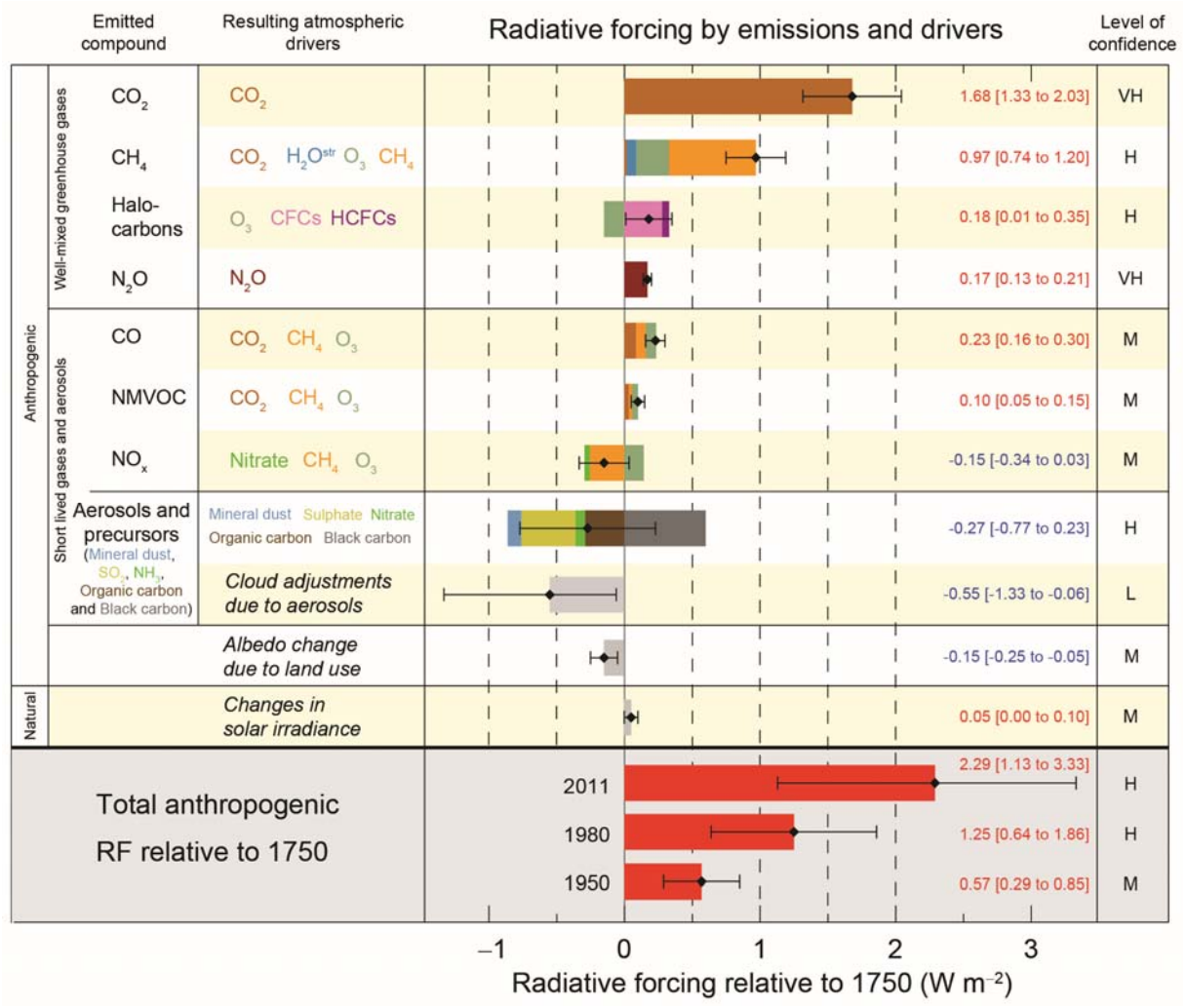

Figure 14: Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change. Values are global average radiative forcing, partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative 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 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 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^2.

The evolution of stratospheric ozone in the next 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 15. 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 at 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/.

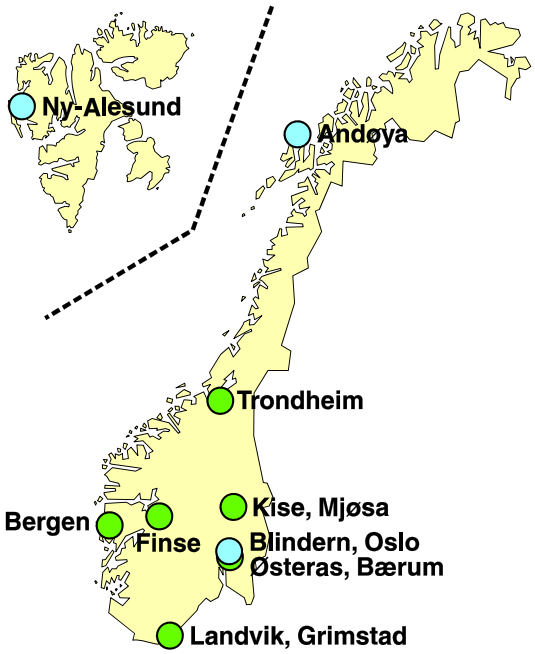

Figure 15: Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas the Norwegian Radiation Protection Authority operates the stations marked with green.

This annual report includes results from Oslo, Andøya and Ny-Ålesund. Due to lack of funding, 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 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 at Andøya and in Ny-Ålesund both had technical failures in the fall 2013 and needed repair (see Chapter 2). Fortunately, a spare instrument was available at Andøya. The GUV failure in Ny-Ålesund occurred late in the season and the repaired instrument was reinstalled in early spring 2014. Thus, the missing Ny-Ålesund GUV data add insignificant uncertainty to the calculated annual UV dose in 2014.

6.1 UV measurements in 2014

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

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

radiation. At Northern latitudes the UV indices typically vary between 0 – 7 at sea level, but can range up to 20 in Equatorial regions and high altitudes (WHO, 2009). Table 9 shows the UV-index scale with 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 16 shows the UV dose rates measured at noon (averaged between 10:30 and 11:30 UTC) for Oslo, Andøya and Ny-Ålesund. The highest UV dose rate in Oslo, 159.6 mW/m^2, was observed on July 15, at 11:32 UTC 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 UV index in 2014 was 4.8, equivalent to a dose rate of 119.2 mW/m^2, observed twice July 25, first at 10:43, and then 11:00 UTC. The highest UVI value in Ny-Ålesund was 3.2 or 78.9 mW/m^2, and was measured June 19, at 10:44 UTC. The maximum UVI in Oslo was observed during scattered cloud conditions and at a normal total ozone value, i.e. 336 DU (normal ~ 335 DU). At Andøya the ozone column was only 262 DU when the maximum UVI was measured. This is far below the normal of ~ 320 DU, and was also measured during scattered cloud conditions. In Ny-Ålesund the maximum UVI was observed during partly cloudy conditions and a total ozone column of 357 DU, close to the normal of ~352 DU. 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 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 (left and middle panel) both Oslo and Andøya had scattered clouds all day. This 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 a few scattered clouds in the morning, but around noon the sky got more cloudy. Towards the evening the sky got clearer, but still with a few clouds that resulted in some fluctuations in the cloud transmission. As seen in the data from Ny-Ålesund (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.

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.

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 8.

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, as may occur during the spring, may also give rise to large fluctuations in the

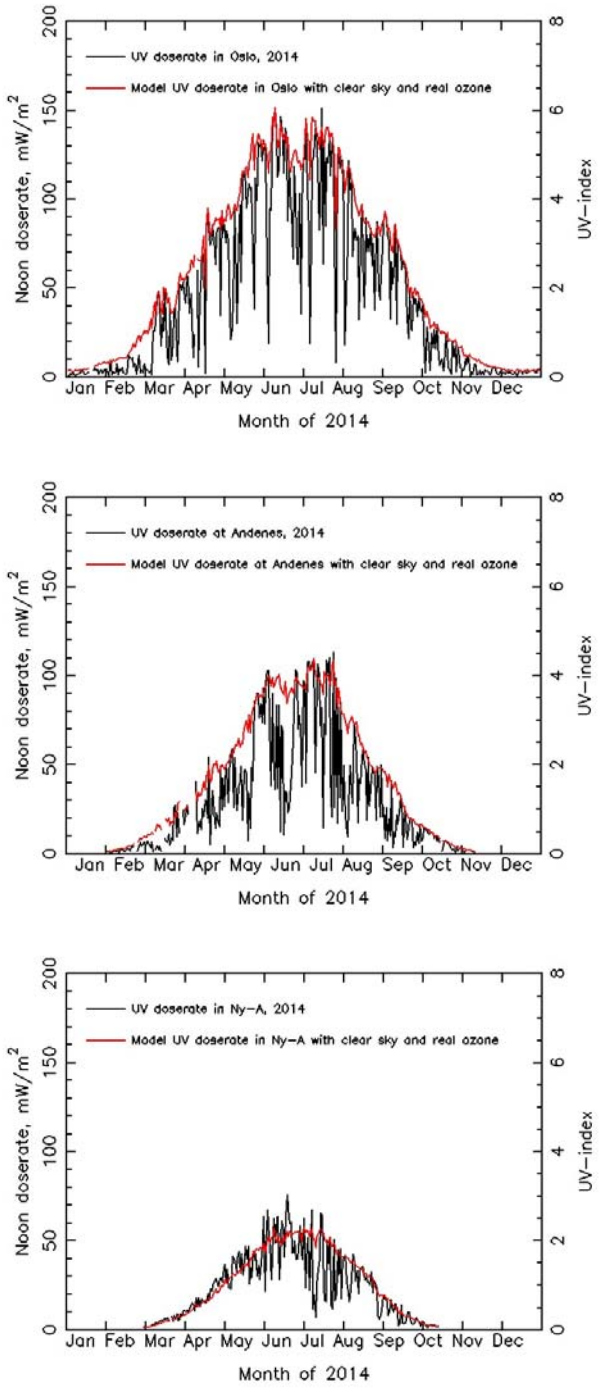

Figure 16: Hourly averaged UV dose rate measured at noon (between 10:30 and 11:30 UTC) in 2014. Upper panel: Oslo. Mid panel: Andøya Lower panel: Ny-Ålesund.

UV-radiation. In general, the UV-radiation in Ny-Ålesund is strongly enhanced during spring due to the high albedo from snow and ice that surrounds the measurement site.

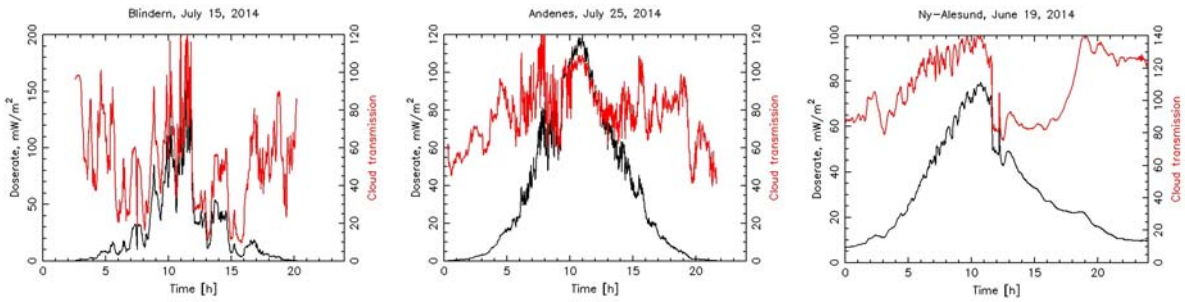

Figure 17: UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel). A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30%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

Monthly integrated UV doses for Oslo, Andøya (Andenes) and Ny-Ålesund in 2014 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 and ozone conditions at all three sites had been similar during the summer, the UV-radiation would be highest in Oslo due to higher solar elevation most of the day. In July 2014 it was very sunny in Oslo, which is seen by the high July UV-dose in Figure 18. In addition, the average total ozone value in July 2014 was -3.5% below the long-term mean in Oslo. This can partly explain the UV peak in July. Similarly, July was the most sunny month with lowest ozone values at Andøya. In Ny-Ålesund, June was the month with most sunshine and least total ozone during the summer.

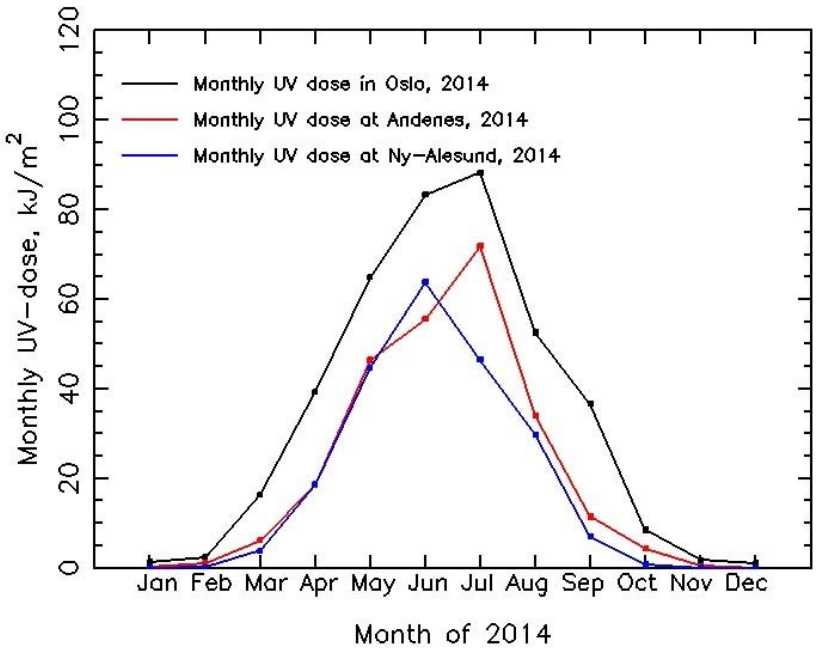

Figure 18: Monthly integrated UV doses (in kJ/m^2) in 2014 measured with the GUV instruments located in Oslo, at Andøya and in Ny-Ålesund.

6.2 Annual UV doses 1995-2014

Annual UV doses for the period 1995–2014 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 – 2014.

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

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

In 2014 the UV-doses in Oslo during summer were in general above normal. July had the highest monthly UV dose of 2014, with UVI between 5 and 6 several days. As shown in Figure 16 (upper panel) there were also some days in the beginning and end of July where the noon UV index in Oslo was as low as 1. This was caused by heavy clouds. When we study the period

from 1995-2014, it should be noted that 2014 was the year with second highest yearly integrated UV dose in Oslo.

At Andøya, there was a period with less clouds and high UVI from late May to early June. However, July had the highest integrated UVI the whole month taken into account. In Ny- Ålesund the highest UV doses were measured in June and late May. Later in the season lower albedo and cloudier conditions became more frequent, which kept the UVI below 2 most days.

A graphical presentation of the yearly integrated UV-doses from 1995 to 2014 is shown in Figure 19. This clearly illustrates yearly fluctuations. No significant UV trends can be detected at any of the three sites.

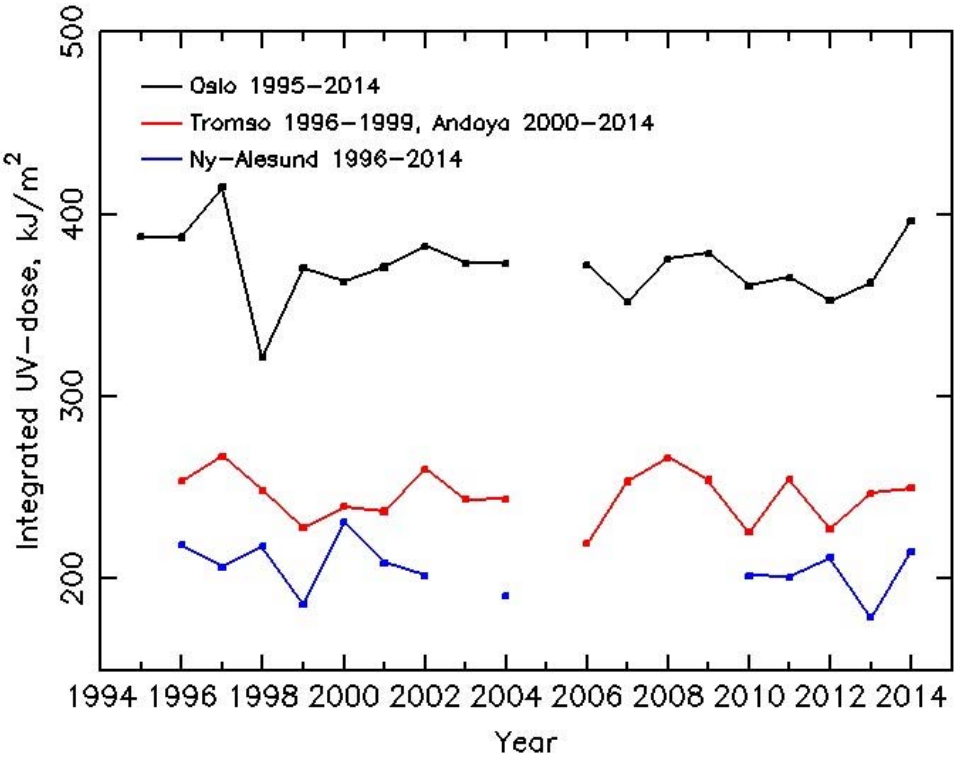

Figure 19: Annual integrated UV doses (in kJ/m^2) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995–2014.

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