MILJØ-
DIREKTORATET

NILU Norsk institutt for luftforskning
Norwegian Institute for Air Research

UiO : Universitetet i Oslo

RAPPORT

M-201/2014

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2013

Preface

Stratospheric ozone plays an important role in the life cycle on Earth due to its ability to absorb UV radiation from the sun. In the mid 1970's scientists discovered that compounds containing chlorine and bromine (CFCs and halons) were capable of destroying the ozone layer (Molina and Rowland, 1974). The attention and debate about the ozone destruction was further intensified when the Antarctic ozone hole discovered in the mid 1980's.

The release of CFC-gases started around 1950 and increased drastically up to the 1980s. In 1987 a number of countries signed The Montreal Protocol, with the aim of phasing out and finally stop the release of ozone depleting substances (ODS). In the wake of this treaty it is important to follow the development of the ozone layer in order to verify whether the Montreal Protocol and its amendments work as expected. For this, we need daily ground based measurements at a large number of sites distributed globally. It is the duty of every industrialised nation to follow up with national monitoring programmes.

In 1990 the Norwegian Environment Agency (the former Climate and Pollution Agency) established the programme "Monitoring of the atmospheric ozone layer". Originally, the programme only included measurements of total ozone, but in 1995 UV measurements were also included in the programme.

NILU - The Norwegian Institute for Air Research is responsible for the operation and maintenance of the monitoring programme. The purpose of the programme is to:

- Provide continuous measurements of total ozone and natural ultraviolet radiation reaching the ground.
- Provide data that can be used for trend analysis of both total ozone and natural ultraviolet radiation.
- Provide information on the status and the development of the ozone layer and natural ultraviolet radiation.
- Notify the Norwegian Environment Agency when low ozone/high UV episodes occur.

Personnel and institutions
Several persons and institutions are involved in the operation and maintenance of the monitoring programme and provided valuable contributions to this report. Prof. Arne Dahlback at the Department of Physics, University of Oslo, is performing total ozone and UV measurements in Oslo. Dr. Kåre Edvardsen (NILU) is responsible for the UV measurements and Brewer data at Andøya, Dr. Kerstin Stebel (NILU) is involved in SAOZ analyses in Ny-Ålesund, whereas Dr. Cathrine Lund Myhre is involved in measurements of Ozone Depleting Substances. Dr. Tove Svendby is responsible for the monitoring programme and the overall data analysis.

Acknowledgment
Projects jointly financed by The Norwegian Space Centre (Norsk Romsenter, http://www.romsenter.no/) and NILU makes it possible to explore relevant ozone satellite observations and use these data in the National monitoring programme of ozone and UV radiation. Norsk Romsenter is highly acknowledged for their support.

All the individuals at Andøya Rocket Range and Ny-Ålesund who have been responsible for the daily inspections of the GUV radiometers, SAOZ and Brewer instruments are also highly acknowledged. A special thanks to Bjørn Johnsen at The Norwegian Radiation Protection Authority (NRPA) for generously lending us a GUV instrument when the Andøya GUV was in for repair. Finally, we are grateful for financial support from the Ministry of Climate and Environment, which made it possible to continue the ozone and UV measurements at Andøya.

Kjeller, June 2014

Tove Marit Svendby
Project leader and senior scientist, NILU

Contents

1. Summary

In 1987 a number of countries signed The Montreal Protocol, with the aim of phasing out and stop the release of ozone depleting substances (ODS). This international treaty has later been revised several times. Currently, 197 parties have ratified the protocol and 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 and since then the concentrations have declined slowly for most compounds. With a continuing decrease in stratospheric ODS loading, the Community Climate Model (CCM) projections suggest that the global annual averaged total ozone column will return to pre 1980 levels around the middle of the 21st century.

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 different 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 2013. In addition, it includes total ozone trend analyses for the period 1979-2013 and UV measurements in Oslo, at Andøya and in Ny-Ålesund from 1995 to 2013.

Total ozone
In 2013 the total ozone column over Norway was relatively high all year. In Oslo the ozone level was 7% below the long-term mean in October, but the November average value was corresponding high. In total, the 2013 annual ozone mean in Oslo was close to the long-term average. At Andøya all monthly mean values in 2013 were within ±6% compared to the long-term mean. The largest negative deviation was seen in October (-5.3%), whereas the largest positive deviation occurred in March (+6.0%). In Ny-Ålesund the ozone level was high all year. In July and August the monthly mean values were as much as 12% above than the 1979-1989 average. The high Ny-Ålesund values can partly be assigned the fact that GUV ozone values in general are higher than the satellite retrieved ozone values that were used for calculating the ozone long-term mean for the 1979-1989 period. The annual mean ozone values at Andøya and in Ny-Ålesund were around 2% and 6% above "normal", respectively.

Our monitoring programme and trend analyses indicate that the 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 1998-2013, 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 winds and temperatures. Consequently, the 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 tropospheric greenhouse gas concentration. During winters with very low stratospheric temperatures, the formation of ozone depleting Polar Stratospheric Clouds (PSCs) will increase and result in low ozone values.

UV measurements

The highest UV dose rate in Oslo, 157 mW/m^2, occurred 25 June. This is equivalent to a UV index (UVI) of 6.3. At Andøya the highest UV index in 2013 was 4.7 (observed 30 June), whereas the highest UVI in Ny-Ålesund, 2.7, was observed 1 June. These maximum values are close to normal. In Oslo and at Andøya the integrated annual UV-doses in 2013 were close to the 1994-2013 average. However, in Ny-Ålesund the 2013 integrated UV-dose was the lowest value ever recorded during the 12 years of observations. The low UVI was mainly caused by the high frequency of cloud cover during the summer. In addition, the total ozone in Ny-Ålesund was high all summer. Under clear sky conditions an 1% ozone increase will give a corresponding 1% reduction of the UV-dose. Nevertheless, a thick cloud cover will have an even larger effect on UVI.

Satellite ozone observations

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.

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 seem to be underestimated by a few percent. Also, the monthly mean ozone values retrieved from two different satellites can differ significantly (up to 15%). This demonstrates the importance of validation against high quality ground based observations.

For Norway and the Norwegian Arctic region 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.

Satellite observations are carried out in the context of different research projects and continuation of this useful supplement to ground based monitoring is dependent on funding from other sources than the National monitoring programme of ozone and UV radiation.

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). Now the expected future recovery of stratospheric ozone might be modified by the effect of climate change. While the Earth's surface is expected to continue warming in response to the net positive radiative forcing from greenhouse gas increase, the stratosphere is expected to cool. A colder stratosphere might extend the time period over which 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. Additionally, the catalytic cycles producing ozone in the stratosphere are temperature dependent and more efficient at lower temperatures.

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. An increase in greenhouse gases, as previously discussed, will lower stratospheric temperatures and thus influence PSC formation and stratospheric circulation. In addition, increased concentrations of N_2O will enhance the catalytic loss mechanism for ozone in the stratosphere. Also, the oxidation of CH_4 in the stratosphere will increase water vapour and ozone losses in the HOx catalytic cycle in the stratosphere. 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 2013

- **In 2013 the ozone values above Norway were higher or close to the long-term mean all year.**
- **The annual integrated UV-doses in Oslo and at Andya in 2013 were close to the 1994-2013 average. However, in Ny-Ålesund the 2013 UV-dose was the lowest value ever recorded. The low UV-dose was caused by cloudy conditions and high ozone values during the summer.**
- **The decrease in annual values of total ozone during the period 1979-1997 was 5.8%/decade in both Oslo and at Andøya, with the strongest decrease, as large as 8.4 %/decade during the spring months.**
- **In Ny-Ålesund the annual total ozone decrease during the period 1979-1997 was 6.4%/decade. For the spring months the ozone decline was as high as 11.4%/decade.**
- **Since 1998 there has not been significant trends in the ozone layer above Norway.**
- **Meteorological variability has large impact on ozone and can give considerable year-to-year variations in total ozone.**

2. Ozone measurements in 2013

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 the mid 1990s. The ozone measurements are retrieved from Brewer spectrophotometers in Oslo and at Andøya, whereas a SAOZ (Systeme d'Analyse par Observation Zenitale) instrument is the standard ozone instrument in Ny-Ålesund. In addition GUV (Ground-based UltraViolet) filter radiometers are located at all three sites and can fill in ozone data gaps on days with absent Brewer and SAOZ measurements. We are also analysing 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 2013. The Brewers are also regularly calibrated against standard lamps in order to check the stability of the instruments. Calibration reports are available on request.

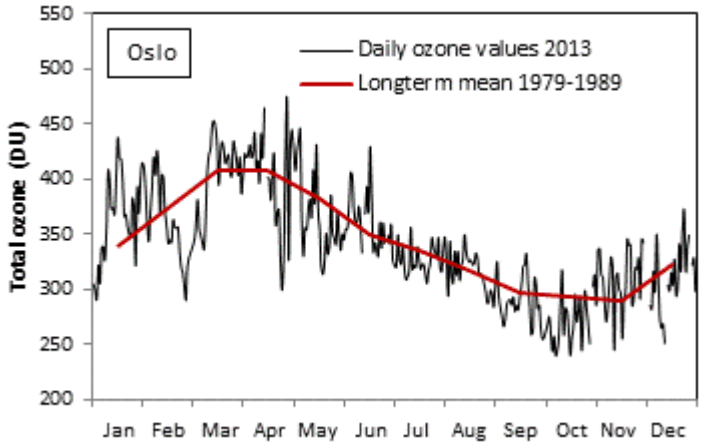

Figure 1a: *Daily total ozone values measured at the University of Oslo in 2013. The red curve shows the long-term monthly mean values from 1979-1989.*

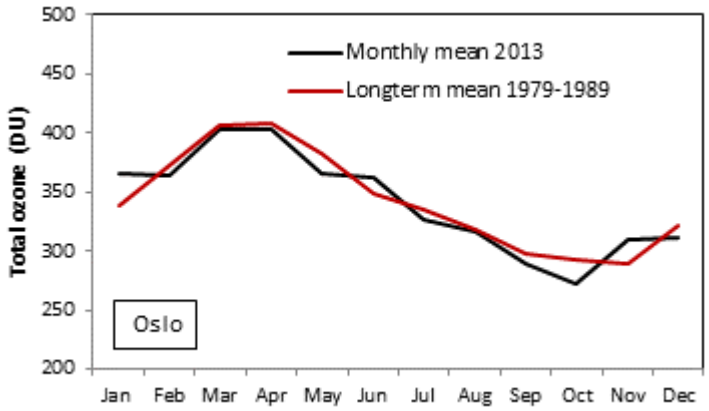

Figure 1b: *Monthly mean ozone values for 2013. The red curve shows the long-term monthly mean values from 1979-1989.*

The GUV instruments are yearly calibrated against a European travelling reference spectro-radiometer QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe; Gröbner et al., 2010).

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

2.1 Total ozone in Oslo

Figure 1a illustrates the daily total ozone values from Oslo in 2013. 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 2013 are based on Brewer direct sun (DS)

measurements when available. In 2013 direct sun measurements were performed 169 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 188 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 2013 there were totally 8 days without Brewer DS or GI measurements, all related by bad weather conditions. 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, it was decided to also exclude GUV measurements these 8 days. A summary of instruments and frequency of inclusion in the 2013 Oslo ozone series, are summarized in Table 1. Even if total ozone was retrieved from the GUV instrument 349 out of 365 days, none of the measurements were used in the 2013 time series since the Brewer measurements were considered as more accurate.

Table 1: Overview of total ozone instruments in Oslo and the number of days where the various instruments were used in the 2013 time series

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	169
2	Brewer instrument, global irradiance method	188
3	GUV-511 instrument	0
	Missing days (due to bad weather)	8

As seen from Figure 1a) there are large day-to-day fluctuations in total ozone, particularly during winter and spring. The lowest ozone values normally occur in October and November, and the minimum ozone value in 2013 was 240 DU[1], measured 6 October. This is about 18% below the long-term mean for October. On the 27 February the ozone value in Oslo reached a relative minimum of 290 DU, which is around 22% below normal. However, there were no dramatic long lasting periods of low ozone values in 2013. The rapid ozone variations observed in the winter/spring are typically caused by stratospheric winds and changes in tropopause height.

The monthly mean total ozone values in 2013 are shown in Figure 1b) and compared to the long-term monthly mean values for the period 1979-1989. As seen from the figure the 2013 ozone values in Oslo were close to normal all months. Section 3.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2013.

[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”.

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 MK III, which allow ozone measurements at higher solar zenith angles than the Oslo instrument. A GUV instrument will also provide ozone data when the Brewer instrument is out of order or Brewer measurements are prevented by bad weather conditions.

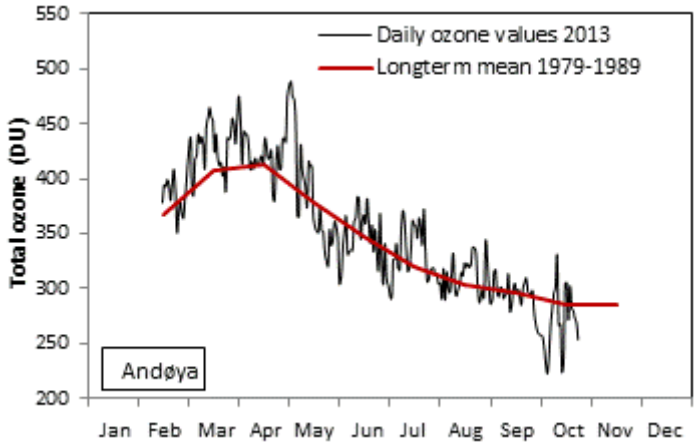

Figure 2a: *Daily total ozone values measured at ALOMAR, Andøya, in 2013 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989.*

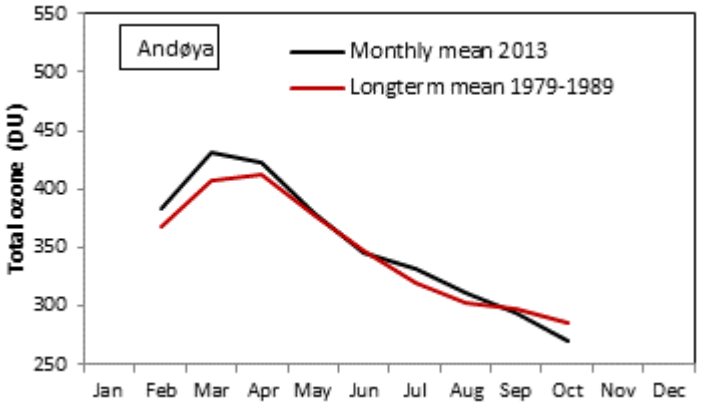

Figure 2b: *Monthly mean total ozone values for 2013 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).*

In May 2013 it was discovered a problem with the 380 nm channel 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 instrument had not previously been used for ozone measurements and the data had to be homogenized with respect to the Brewer GI data before inclusion in the Andøya ozone time series.

Table 2 gives an overview of the different instruments and methods that were used at Andøya in 2013. The ozone lidar at Andøya is no longer in operation, and consequently none ozone measurements were performed during winter.

Figure 2a) shows daily ozone values from Andøya in 2013. 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 weak solar radiation. The lowest ozone values at Andøya normally occur in

October and November, and the minimum ozone value in 2013 was 223 DU, measured 4 October. This was about 22% below the long-term mean for October. Monthly mean ozone values at Andøya for 2013 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 2013 shows that the ozone layer was close to normal all months. The largest deviations were found in March and October, where the monthly averages deviated by +6% and -5% from the long-term means, respectively.

Table 2: *Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2013.*

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	73
2	Brewer instrument, global irradiance method	144
3	GUV instrument	34
	Missing days (except polar night period)	0

2.3 Total ozone in Ny-Ålesund

Ny-Ålesund is located at a high northern latitude (79ºN), 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. Also, in early October 2013 it was discovered a temperature failure in the SAOZ instrument, caused by a broken electronic card. The instrument was sent to LATMOS, France, for repair, and this resulted in roughly 20 days without SAOZ ozone measurements in the fall 2013.

The SAOZ instrument is a zenith sky UV-visible spectrometer where ozone is retrieved in the Chappuis bands (450-550 nm) twice per day (sun rise /sun set). Data from the instrument contribute to the Network of Detection of Atmospheric Composition Change (NDACC). An ozone intercomparison 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 have been included in the 2013 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. Both the GUV and SAOZ instrument should ideally be compared to a well-calibrated and accurate ozone spectrophotometer (e.g. a Brewer instrument). Due to the SAOZ breakdown in the fall 2013, more GUV measurements than normal are included in the 2013 ozone time series. However, the GUV instrument at Ny-Ålesund also experienced a temperature failure in October 2013. The instrument was sent to NILU/Kjeller for repair. Consequently, there are neither SAOZ

nor reliable GUV ozone measurements available after 14. October 2013. Table 3 gives an overview of the different instruments and methods used for the 2013 ozone series in Ny-Ålesund. No ozone measurements were performed during periods with polar night.

Table 3: *Overview of instruments and methods applied for retrieval of the total ozone in Ny-Ålesund 2013.*

Priority	Method	Total days with observations
1	SAOZ instrument	68
2	GUV instrument	181
	Missing days (~10 days in October)	11

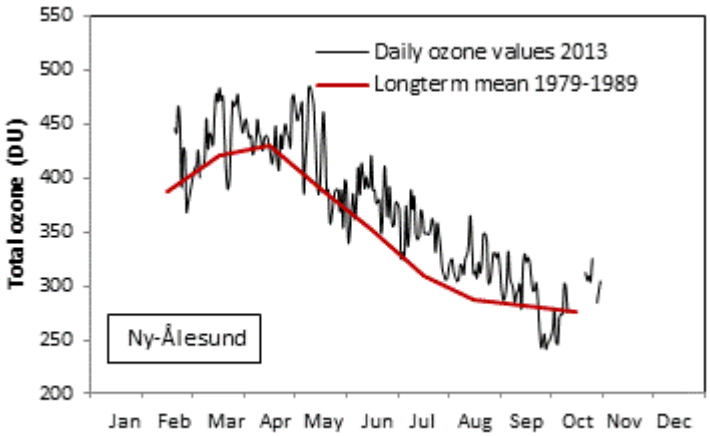

Figure 3a: *Daily total ozone values measured in Ny-Ålesund in 2013 by the SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 -1989.*

Figure 3a shows daily ozone values from Ny-Ålesund in 2013. 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 2013 was 242DU, measured 28 September. This is about 14% below the long-term mean for September.

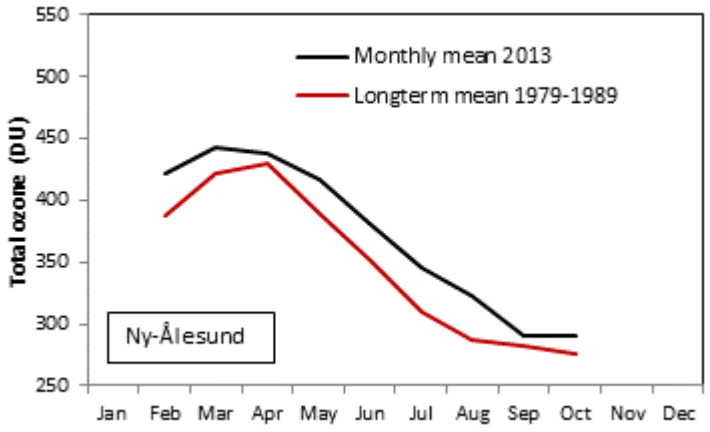

Figure 3b*: Monthly mean total ozone values for 2013 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).*

Monthly mean ozone values in Ny-Ålesund for 2013 are shown in Figure 2b). Comparison between the long-term mean and monthly mean ozone values for 2013 shows that the ozone values were above the long-term mean all months. It should be kept in mind that a large fraction of the ozone measurements is based on the GUV instrument, which might overestimate ozone by a few percent (see Section 4.2).

3. Ozone measurements and trends 1979–2013

3.1 Background

3.1.1 Status of the ozone layer

Since the beginning of the 1990s the World Metrological Organisation (WMO) and United Nations Environment Programme (UNEP) have regularly published assessment reports of ozone depletion. The last report, "Scientific Assessment of Ozone Depletion: 2010", was published in March 2011 (WMO, 2011). A new report will available in spring 2014. These reports summarize the current knowledge and status of the ozone layer, ozone recovery, UV changes, development of relevant trace gases (e.g. halocarbons, chlorine and bromine) in the atmosphere. The most relevant conclusions in the 2011 report are briefly summarised in this section.

Recovery of the ozone layer is a process beginning with a decrease in the rate of decline, followed by a levelling off and finally an increase in ozone driven by the changes in the concentrations of ozone-depleting substances.

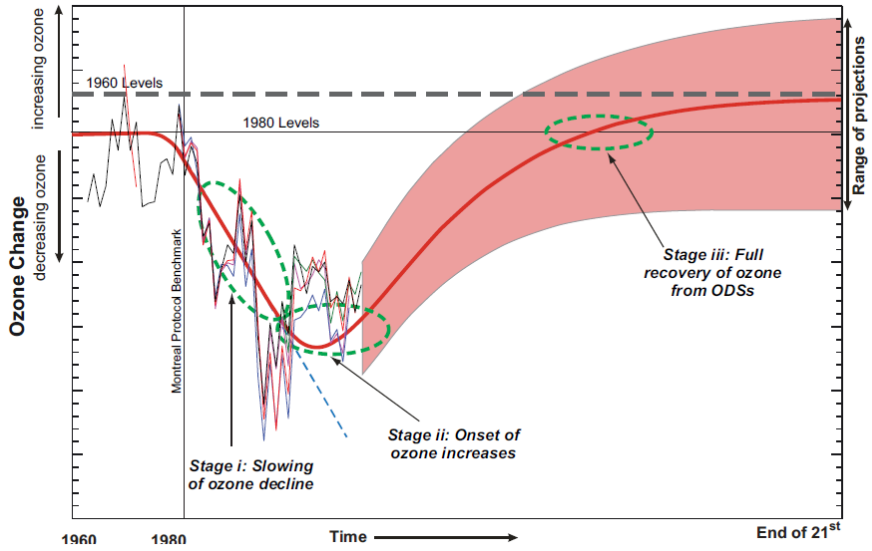

***Figure 4**: Total ozone at latitudes 60°N to 60°S for the period 1960 to 2100 (the x-axis is not to scale). The thick red line is a representation of the ozone amounts observed to date and projected for the future. The red-shaded region represents the model results predicted for the future. The 1980 ozone level benchmark is shown as the horizontal line. The dashed thick grey line represents the 1960 levels. The three stages of decline, onset of ozone increase, and recovery are shown by dashed green ellipses (Figure from WMO, 2011).*

Figure 4 is taken from the 2011 assessment report and shows a schematic diagram of the temporal evolution of global ozone amounts beginning with pre-1980 values. This represents a time before significant ozone depletion occurred due to emission of anthropogenic ozone depleting substances (ODS). The thin black curve represents ground based observations averaged over 60°S-60°N, whereas the thin coloured curves represent various satellite observations. The thick red line is a representation of the ozone amounts observed to date and projections for the future, where three stages of ozone decline, levelling off, and recovery are marked by the green dashed ellipses. The red-shaded region represents the model predictions

for the future. It is worth noting that the range is rather large and that both an under-recovery and a “super-recovery” are possible. Because of factors other than ODSs, the ozone levels in the future could easily go above the values that were present in the 1980s or even the 1960s ("super-recovery"). This is not recovery from the influence of ODSs but due to other factors, primarily changes in CO_2. Therefore, the term "super-recovery" differs from references to recovery from ODS-forced ozone depletion.

The 2006 Assessment (WMO, 2007) showed that the globally averaged total ozone column stopped declining around 1996, meeting the first criteria in the stage of recovery. The next decades the ozone layer is expected to increase as a result of continued decrease in ODSs. According to the last Assessment report (WMO, 2011) the total global ozone amount has not started to increase yet, but has been fairly stable the last years. The average total ozone for the period 2006–2009 remain at the same level as for the 1996-2005 period, i.e. roughly 3.5% and 2.5% below the 1964–1980 averages for 90°S–90°N and 60°S–60°N, respectively.

The most dramatic ozone depletion has occurred in the Polar Regions. These regions also exhibit the highest level of natural variability, which makes the predictions of recovery more uncertain. In Antarctica the ozone layer continues to reach very low levels from September to November. In the Arctic and at high northern latitudes the situation is more irregular as severe springtime ozone depletion usually occurs in years where the stratospheric temperatures are low, exemplified with the different situations in spring 2012 (high ozone values) and the record minimum levels in spring 2011 (not a part of the WMO report).

In the Arctic region the rate of recovery will partially depend on possible dynamical and temperature changes the coming decades, both in the stratosphere as well as the troposphere. The Arctic winter and springtime ozone loss between 2007 and 2013 has been variable, but has remained in a range comparable to the values prevailing since the early 1990s. Model predictions indicate that the evolution of ozone in the Arctic is more sensitive to climate change than in the Antarctic. The projected strengthening of the stratospheric circulation in Arctic is expected to increase lower stratospheric ozone transport and speed up the return to 1980 levels.

The ozone levels in the Arctic and high northern latitudes might also be influenced by changes in stratospheric winter temperatures during the next years. Lower stratospheric temperatures will possibly result in delayed recovery or record low ozone observations due to formation of PSCs. Considerably longer data series and improved understanding of atmospheric processes and their effect on ozone are needed to estimate future ozone levels with higher confidence.

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 – 2013

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.

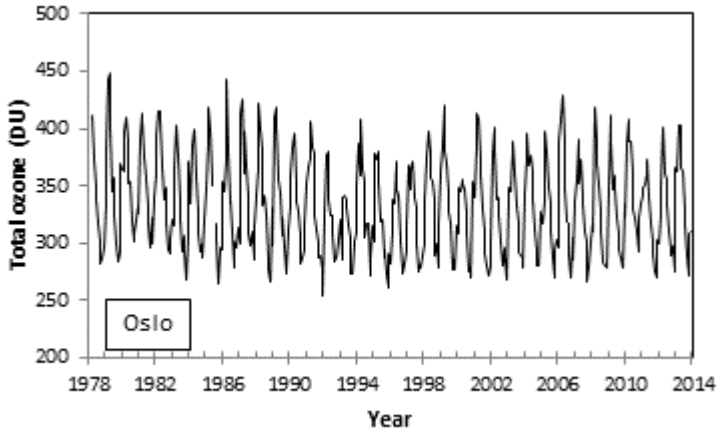

Figure 5a: *Time series of monthly mean total ozone in Oslo 1979-2013.*

Figure 5a shows the variations in monthly mean ozone values in Oslo for the period 1979 to 2013. 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.

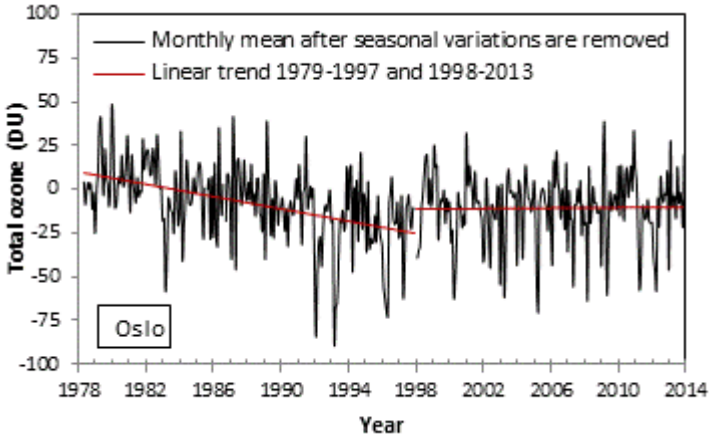

Figure 5b: *Variation in total ozone over Oslo for the period 1979–2013 after the seasonal variations have been removed. Trend lines are marked in red.*

In order to make ozone trend analyses for the period 1979 – 2013 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) 1998-2013. 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.

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 1998-2013 the picture is different. There are substantial annual fluctuations and one should be cautious to draw any 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 a 2σ level. For the summer period there is an ozone decline of -1.1% /decade during the last 16 years, whereas the trend is +2.2%/decade for the fall. The annual ozone trend from 1998 to 2013 is close to zero.

Table 4: *Percentage changes in total ozone per decade for Oslo for the period 1.1.1979 to 31.12.2013. The numbers in parenthesis gives the uncertainty (1σ) in percent. Data from the Dobson and Brewer instruments have been used in this study. A trend larger than 2σ is considered to be significant.*

Season	Trend (% /decade) 1979-1997	Trend (% /decade) 1998-2013
Winter (Dec – Feb)	-6.2 (2.4)	-0.5 (2.6)
Spring (Mar – May)	-8.4 (1.4)	0.0 (2.2)
Summer (Jun – Aug)	-3.4 (1.1)	-1.1 (1.2)
Fall (Sep – Nov)	-4.3 (1.0)	2.2 (1.4)
Annual (Jan – Dec):	-5.8 (1.0)	0.2 (1.3)

3.3 Trends for Andøya 1979–2013

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 2013. The extreme February 2010 value is seen as a high peak in the plot. The variations in total ozone at Andøya for the period 1979–2013, 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 Figure 6b. Similar to the Oslo site we have chosen to divide the ozone time series into two periods: 1) 1979-1997, and 2) 1998-2013. 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.

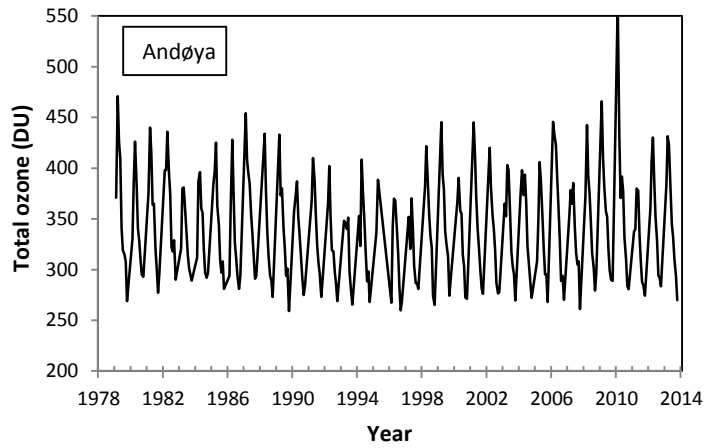

Figure 6a: *Time series of monthly mean total ozone at Andøya/Tromsø 1979–2013.*

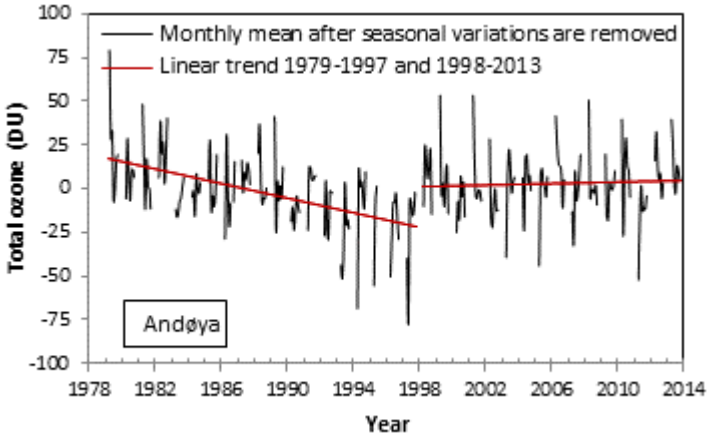

Figure 6b: *Variations in total ozone at Andøya for the period 1979–2013 after the seasonal variations are removed. Only data for the months March–September are included.*

As for Oslo, the ozone layer above Andøya declined significantly from 1979 to 1997. This decline is 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 were observed for the second period from 1998 to 2013. For the latter period an ozone increase of 0.5%/decade was observed during spring, whereas a trend of -0.4%/ decade was found for the summer months. The annual trend for the period 1998-2013 was 0.5%/decade. None of these trends are significant at either 1σ or 2σ significance level.

Table 5: *Percentage changes in total ozone per decade at Andøya for the periods a) 1979-1997, and 2) 1998- 2013. The numbers in parenthesis gives 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) 1998-2013
Spring (Mar – May):	-8.4 (1.5)	0.5 (2.2)
Summer (Jun – Aug):	-2.8 (0.9)	-0.4 (1.3)
Annual (Mar – Sep):	-5.8 (1.0)	0.5 (1.4)

3.4 Trends for Ny-Ålesund 1979 – 2013

The first Arctic ozone measurements started in Svalbard more than 60 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).

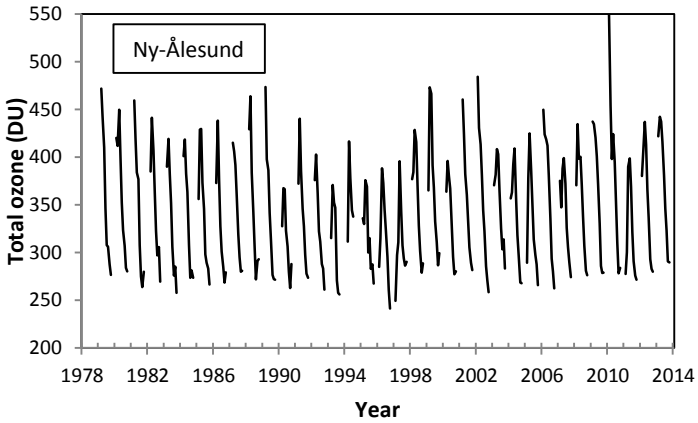

Figure 7a: *Time series of monthly mean total ozone at Ny-Ålesund 1979–2013.*

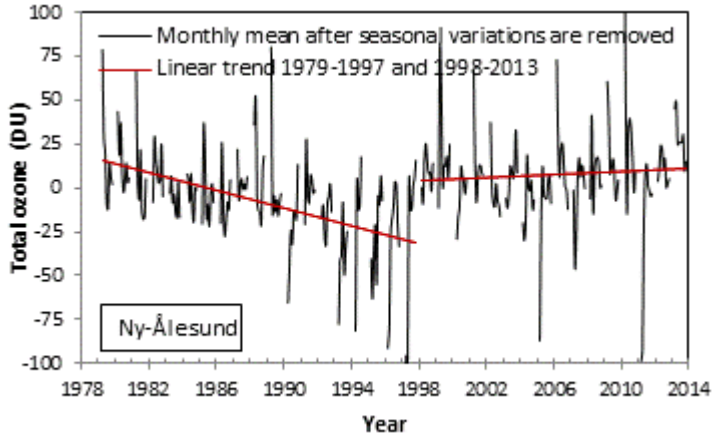

Figure 7b: *Variations in total ozone at Ny-Ålesund for the period 1979–2013. Only data for the months March–September are included.*

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 latest 22 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 -11.4%/decade, whereas the negative trend for the summer months was only -1.0%/decade. The annual trend in total ozone was -6.4%/decade during these years. In contrast, no significant trends were observed for the second period from 1998 to 2013. During this period an ozone decrease of -0.1%/decade was observed for the spring months, whereas a trend of

+2.3%/decade was found for the summer months. The annual trend for the period 1998-2013 was 0.6% /decade. None of these results are significant at either 1σ or 2σ significance level.

Table 6: *Percentage changes in total ozone per decade in Ny-Ålesund for the periods a) 1979-1997, and 2) 1998- 2013. The numbers in parenthesis gives the uncertainty (1σ). A trend larger than 2σ is considered significant.*

Season	Trend (% /decade) 1979-1997	Trend (% /decade) 1998-2013
Spring (Mar – May):	-11.4 (1.8)	-0.1 (3.0)
Summer (Jun – Aug):	-1.0 (1.3)	2.3 (1.5)
Annual (Mar – Sep):	-6.4 (1.1)	0.6 (1.9)

3.5 The overall ozone situation for Norway 2013

No long lasting periods of low ozone values were observed at the three Norwegian sites in 2013. In Oslo and at Andøya the monthly mean ozone values were close to normal all months, whereas the monthly mean ozone values in Ny-Ålesund were above the long-term mean.

Figure 8, Figure 9 and Figure 10 show the percentage difference between yearly mean total ozone and the long-term yearly mean for all years from 1979 to 2013. The low values in 1983 and 1992/1993 are most likely related to the eruption of the El Chichón volcano in Mexico in 1982 and the Mount Pinatubo volcano at the Philippines in 1991. Also, the low ozone values in 2011 can clearly be seen.

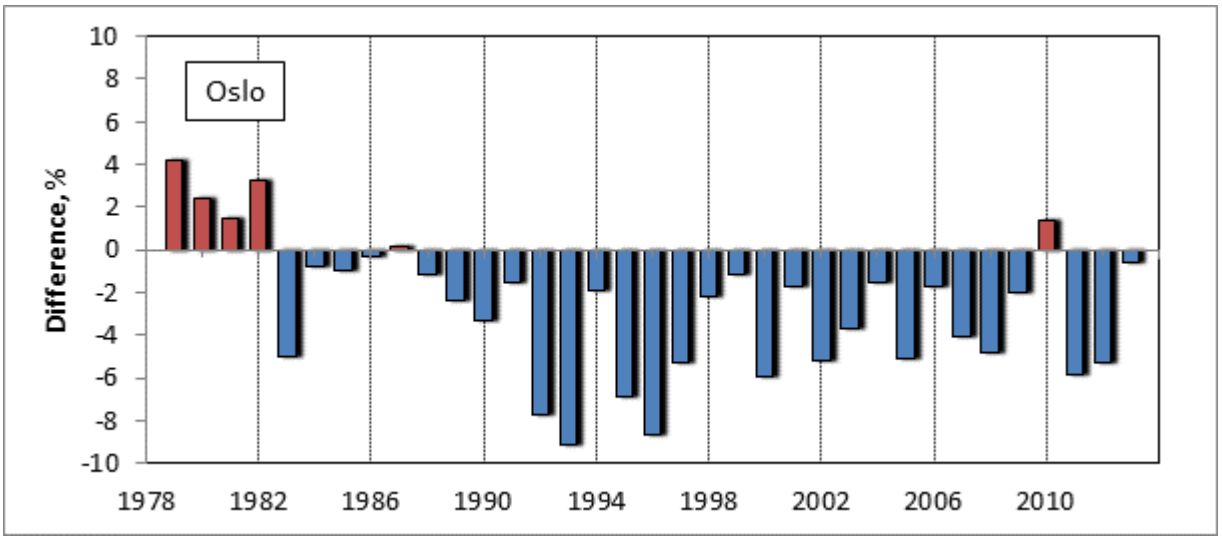

Figure 8: *Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean for 1979-1989.*

Table 7 gives the percentage difference between the monthly mean total ozone values for 2013 and the long-term monthly mean values for the three Norwegian sites. For Oslo the ozone level was about 7% below "normal" in October, but the November average value was corresponding high. As seen from Figure 8 the 2013 yearly mean was very close to zero in

2013. At Andøya all monthly mean values in 2013 were within ±6% compared to the long-term mean. The largest negative deviation was seen in October (-5.3%), whereas the largest positive deviation occurred in March (+6.0%). In Ny-Ålesund the ozone level was high all year. In July and August the monthly mean values were as much as 12% above than the 1979-1989 average. As noted in Section 2.3 the high Ny-Ålesund values can partly be assigned the fact that GUV ozone values in general are higher than the satellite retrieved ozone values that have been used for calculating the ozone long-term mean for the 1979-1989 period.

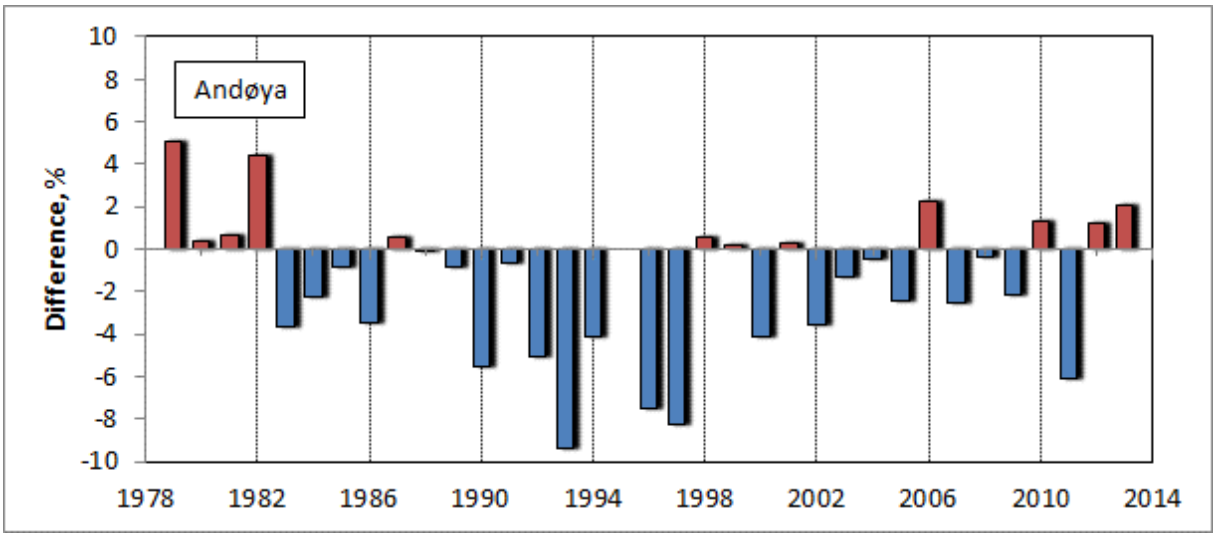

Figure 9: *Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean for 1979-1989 for the months March-October.*

Again, comparison of Figure 8, Figure 9 and Figure 10 shows that the ozone patterns at the three Norwegian sites have several similarities. At all sites high ozone values were measured in the end of the 1970s and in 2010 and 2013. Also, 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).

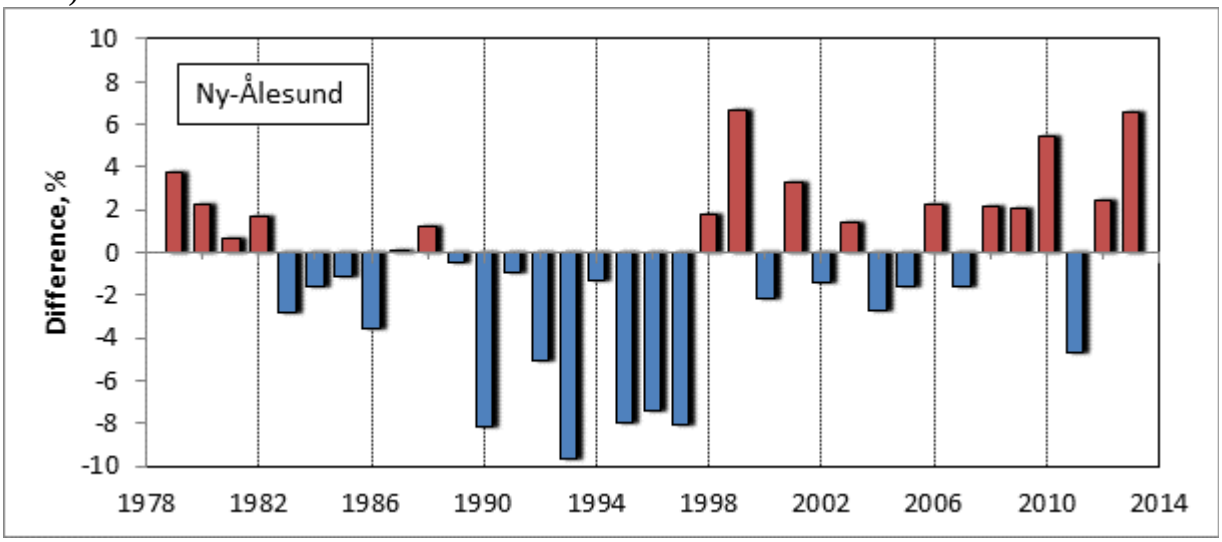

Figure 10: *Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean value (1979-1989 average). Ozone values from March to October are included in the calculations.*

Table 7: *Percentage difference between the monthly mean total ozone values in 2013 and the long-term mean for Oslo, Andøya, and Ny-Ålesund.*

Month	Oslo (%)	Andøya (%)	Ny-Ålesund (%)
January	8.0		
February	-2.6	4.1	8.7
March	-0.9	6.0	4.9
April	-1.1	2.6	1.8
May	-4.3	0.3	7.0
June	3.7	-0.7	8.3
July	-2.3	4.1	11.5
August	-0.6	2.5	12.7
September	-3.0	-1.1	3.1
October	-7.1	-5.3	5.2
November	6.9		
December	-3.6		

The annual mean ozone values were also high in 2013, and the values at Andøya and in Ny-Ålesund were around 2% and 6% above long-term mean, respectively.

4. Satellite observations of ozone above Norway and the Norwegian Arctic region

Satellites can never replace our ground based ozone monitoring network, but they give a very important contribution to the global ozone mapping. For Norway and the Norwegian Arctic region the use of satellite data will provide 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. Based on a project, SatMonAir II, jointly financed by The Norwegian Space Centre (NRS, Norsk Romsenter) and NILU we were in a good position to explore and utilize ozone satellite observations in the National monitoring of the ozone and UV radiation in 2013. Some results from the activities within the SatMonAir II project are included in this report.

4.1 Short introduction to ozone observations from space

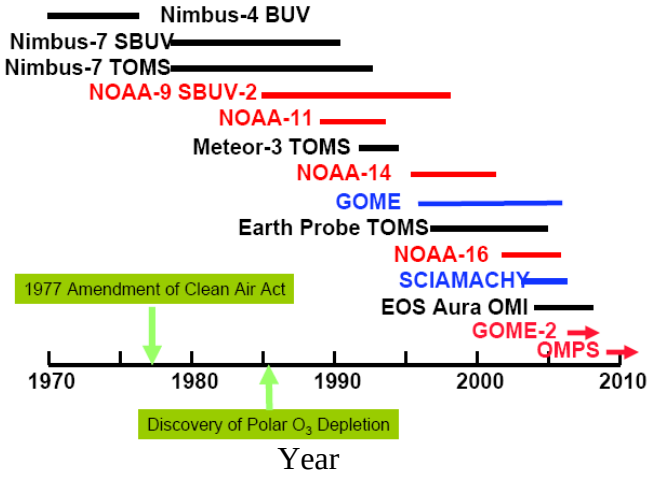

Figure 11: *An overview of the various satellites and their instruments measuring ozone from space since the beginning of 1970's (Figure from NASA).*

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 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 1970's 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 11 gives an overview of the various ozone measuring satellites and their time of operation.

4.2 Satellite ozone observations above the Norwegian sites 1979–2013

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 the last decades overlapping ESA and NASA satellite products have been available. Also, different ozone retrieval algorithms have been used over the years, which have gradually improved the quality and confidence in the ozone data. Corrections for instrumental drift and increased knowledge of ozone absorption cross sections and latitude dependent atmospheric profiles have improved the data quality, especially in the Polar region.

There might be relative large differences between ground based measurements and satellite retrieved data on a day-to-day basis. In addition there are often differences between the various satellite ozone products for overlapping time periods. The differences have regional, seasonal and systematic nature.

The monthly mean ozone values from ground based (GB) measurements and satellites are analysed for the full period 1979-2013. Figure 12 shows the percentage GB-Satellite deviation in Oslo (upper panel), at Andøya (middle 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. The most surprising finding is that the monthly mean ozone deviation between two different satellites can be up to 15%, e.g. in December 2004 where OMI measured 328 DU and SCIAMACHY measured 380 DU, a difference of 52 DU. The ground based Brewer observation was 329 DU this month, which was close to the OMI ozone value.

Table 8 gives an overview of the average deviations between ground-based ozone measurements and various satellite data products, together with standard deviations and variance 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 12 (lower panel), the GB measurements are typically 7-8% higher during the summer months. This might be caused by overestimated GUV ozone values, but can also be attributed to uncertain satellite retrievals at high latitudes. Comparisons to other ground based instruments, preferably Dobson or Brewer measurements, will give a better insight to this problem.

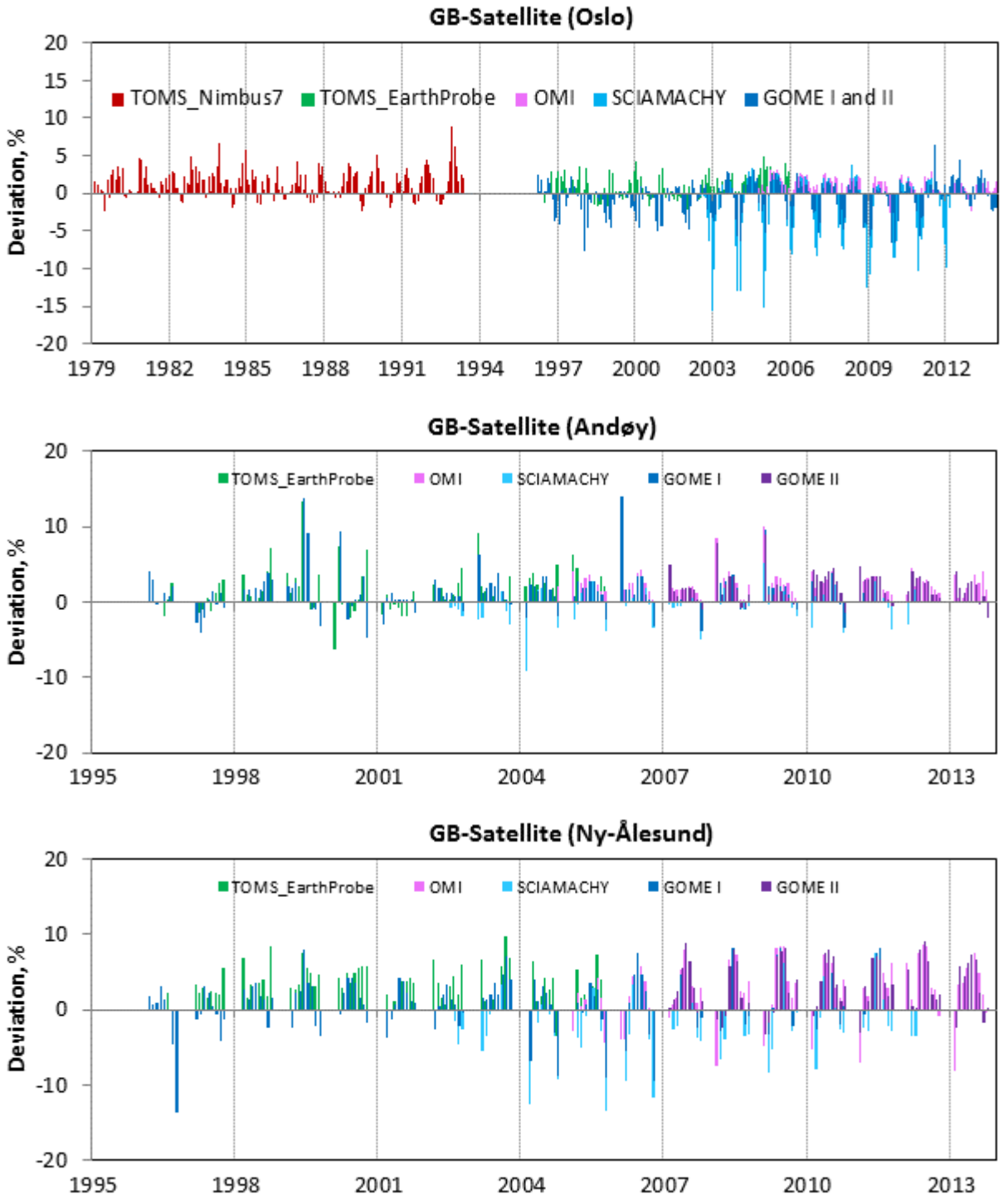

Figure 12: *Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2013 (Oslo) and 1995-2013 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, middle panel: Andøya, lower panel: Ny-Ålesund.*

Table 8: *Average deviations in % between ground based and satellite retrieved monthly mean ozone values from Oslo and Andøya. 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-13	0.96	1.35	1.82
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-13	0.80	1.80	3.24
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-13	2.59	2.02	4.06
GOME 1	Mar-96	Jul-11	1.42	2.78	7.74
GOME 2	Jan-07	Dec-13	2.02	2.00	4.00
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-13	2.55	4.22	17.81
GOME 1	Mar-96	Jul-11	1.18	3.78	14.30
GOME 2	Jan-07	Dec-13	3.15	3.47	12.05
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, SCIAMACH systematically overestimated ozone values during periods with low sun. This gives a very 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 12. In contrast the OMI ozone values are close to the Brewer measurements in Oslo all year, giving a variance of only 1.8 (see Table 8). The GB-OMI variance in Ny-Ålesund is as high as 17.8, whereas GB-GOME II has a variance of 12.1. This might indicate that GOME II is more accurate at high latitudes. It can also be noted that the GB-SCIAMACHY variance is much smaller at Andøya than in Oslo. This is probably caused by the fact that no ground based measurements are performed in December, January and most of November and February. Thus, the months with largest uncertainty and variance are omitted from the comparison.

5. The 5th IPCC report: Climate and Ozone interactions

Changes to 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 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 report (AR5) are shown in Figure 13 (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 IPPC 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 cause ozone RF of 0.50 W/m^2, some of which is in the stratosphere. This is slightly larger than comparing value from AR4. There is also robust evidence that tropospheric ozone has a detrimental impact on vegetation physiology, and therefore on its CO_2 uptake, but there is a low confidence on quantitative estimates of the RF owing to this indirect effect.

Stratospheric ozone is indirectly affected by climate change through changes in dynamics and in the chemical composition of the troposphere and stratosphere (Denman et al., 2007). An increase in the greenhouse gases, especially CO_2, will warm the troposphere and cool the stratosphere. In general a decrease in stratospheric temperature reduces ozone depletion leading to higher ozone column. However, there is a possible exception in the Polar Regions where lower stratospheric temperatures lead to more favourable conditions for the formation of more PSCs. These ice clouds are formed when the stratospheric temperature gets 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

[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.

temperature profile above the tropopause. Changes in stratospheric temperatures, induced by changes in ozone or greenhouse gas concentrations will alter dynamic processes.

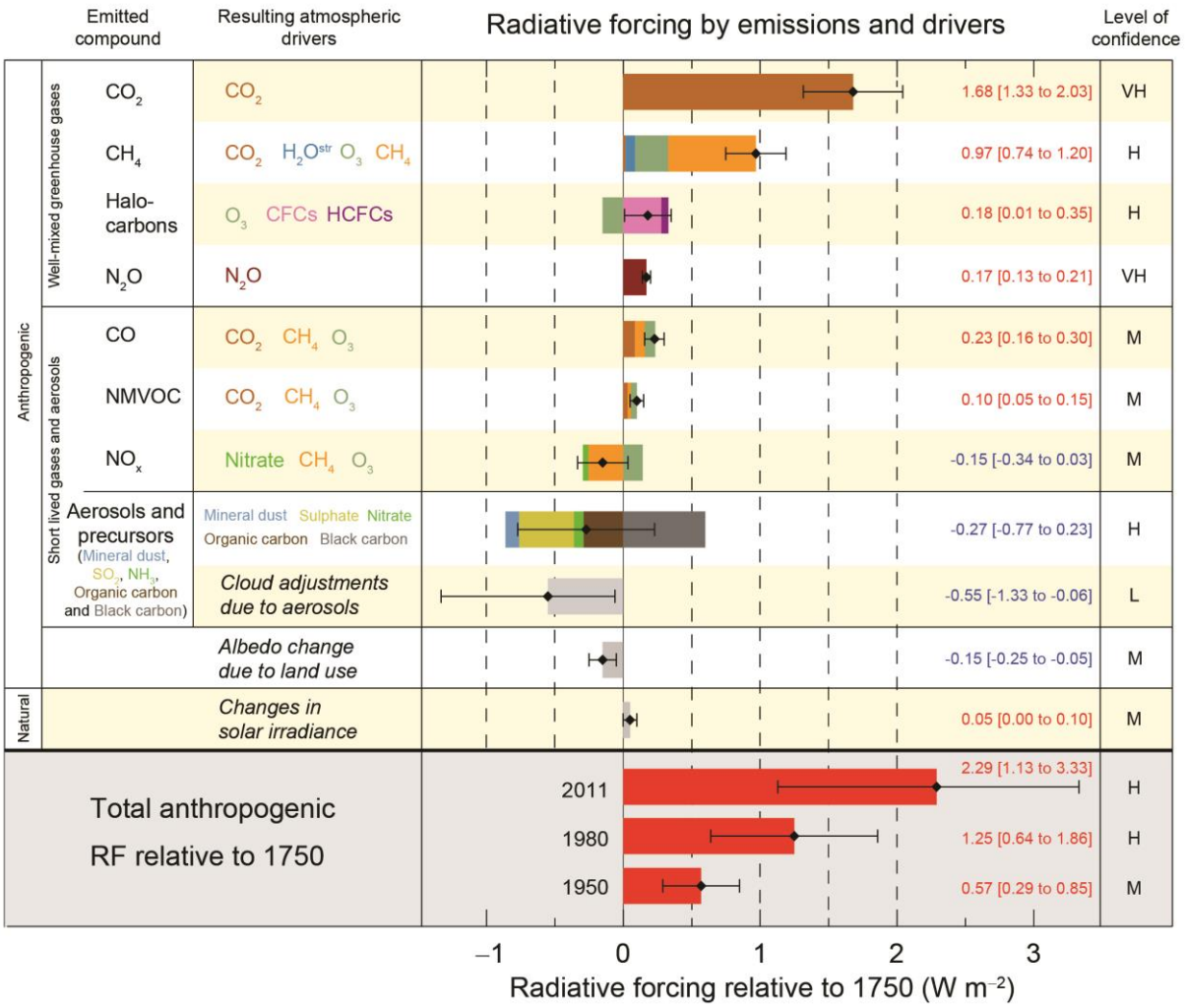

Figure 13: *Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change. Values are global average radiative forcing, partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative 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. This will influence on 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 the 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 13). This is consistent with the results from AR4. 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 over the next decades 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 climate forcer, 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.

Finally, nitrous oxide (N_2O) is considered as a key species that regulates the ozone levels. 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, illustrated in Figure 14. 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 is shown at http://uv.nilu.no/ and at http://www.nrpa.no/uvnett/.

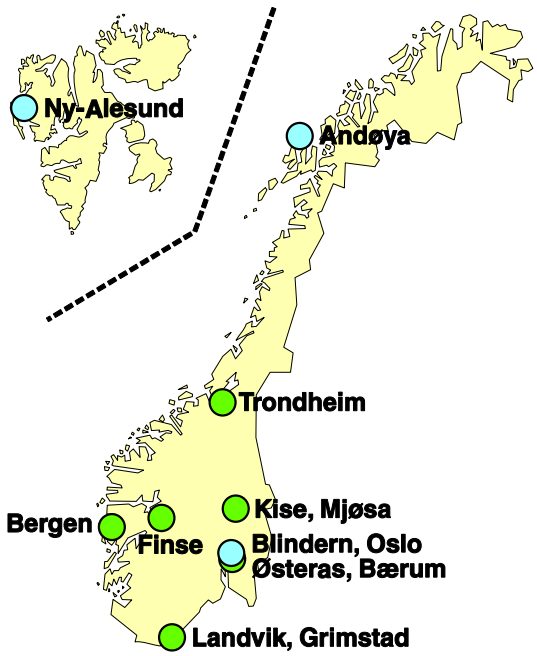

Figure 14: *Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas the Norwegian Radiation Protection Authority operates the stations marked with green.*

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 Norwegian GUV instruments were included in a calibration and inter-comparison campaign in 2005 as a part of the project FARIN (Factors Controlling UV in Norway)[3]. The project, which was financed by The Norwegian Research Council, aimed to quantify the various factors controlling UV radiation in Norway. This includes e.g. clouds, ozone, surface albedo, aerosols, latitude, and geometry of exposed surface. One part of the project was comparison and evaluation of all the UV-instruments in the Norwegian monitoring network. In total 43 UV instruments were compared during the campaign. The three GUV instruments from NILU were set up at NRPA, Østerås, during the campaign and the calibration results were satisfactory.

The GUV instruments are normally easy to maintain and have few interruptions due to technical problems. However, the instrument at Andøya and in Ny-Ålesund had both a serious breakdown in 2013 and needed repair (see Chapter 2 for description). Fortunately, a spare instrument was available at Andøya. The GUV breakdown in Ny-Ålesund occurred late in the season and the missing GUV data add insignificant uncertainty to the calculated annual UV dose. The number of missing days due to technical problems in 2013 (during the measuring season), are given in Table 9.

[3] http://www.nilu.no/farin/

6.1 UV measurements in 2013

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[4]). 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 can range up to 20 in Equatorial regions and high altitudes (WHO, 2009). Table 10 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: *Number of days with more than 2 hours of missing GUV data in 2013 and 2012. Days where the sun is below the horizon (polar night) are not included.*

Station	Technical problems	
	2013	2012
Oslo	6	1
Andøya	1	1
Ny-Ålesund	5	1

Table 10: *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 15 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, 157.1 mW/m^2, was observed June 25 at 11:25 UTC and is equivalent to a UV index of 6.3. The black curves 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 2013 was 4.7, equivalent to a dose rate of 117.4 mW/m^2, observed June 30 at 10:40 UTC. The highest UVI value in Ny-Ålesund was 2.7 or 66.9 mW/m^2, and was measured 1 June at 10:58 UTC. The maximum UVI in Oslo was observed during scattered cloud conditions and slightly higher total ozone value than normal, i.e. 350 DU (normal ~ 340 DU). At Andøya the ozone column was exactly the same as in Oslo (350 DU, equal to normal value) and was also measured during scattered sky conditions. In Ny-Ålesund the maximum UVI was observed during clear cloud conditions and a total ozone column of 341 DU, slightly under the normal of ~360 DU. For UV-levels corresponding to the maximum UVI-value of 6.9 in Oslo, people

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

with a typical Nordic skin type get sunburnt after approximately 20 minutes if no sun protection is used.

Figure 16 shows the atmospheric conditions during the days of maximum UVI in Oslo, at Andøya and in Ny-Ålesund. A cloud transmission of 100% (red curve) represents clear sky conditions. In Ny-Ålesund it was a few scattered clouds in the morning and about 1.5 hours before noon the sky got clearer. Towards the evening a few clouds appeared, showing some fluctuations in the cloud transmission. As seen from Ny-Ålesund in Figure 16 (right panel) a cloud transmission above 100% represents the high albedo from snow and ice in the vicinity of the instrument site, which enhanced the solar radiation detected by the GUV instrument. Both Oslo and Andøya had scattered clouds all day. This will normally create multiple reflection between the clouds, and the ground and clouds, which enhances the UV-radiation at ground.

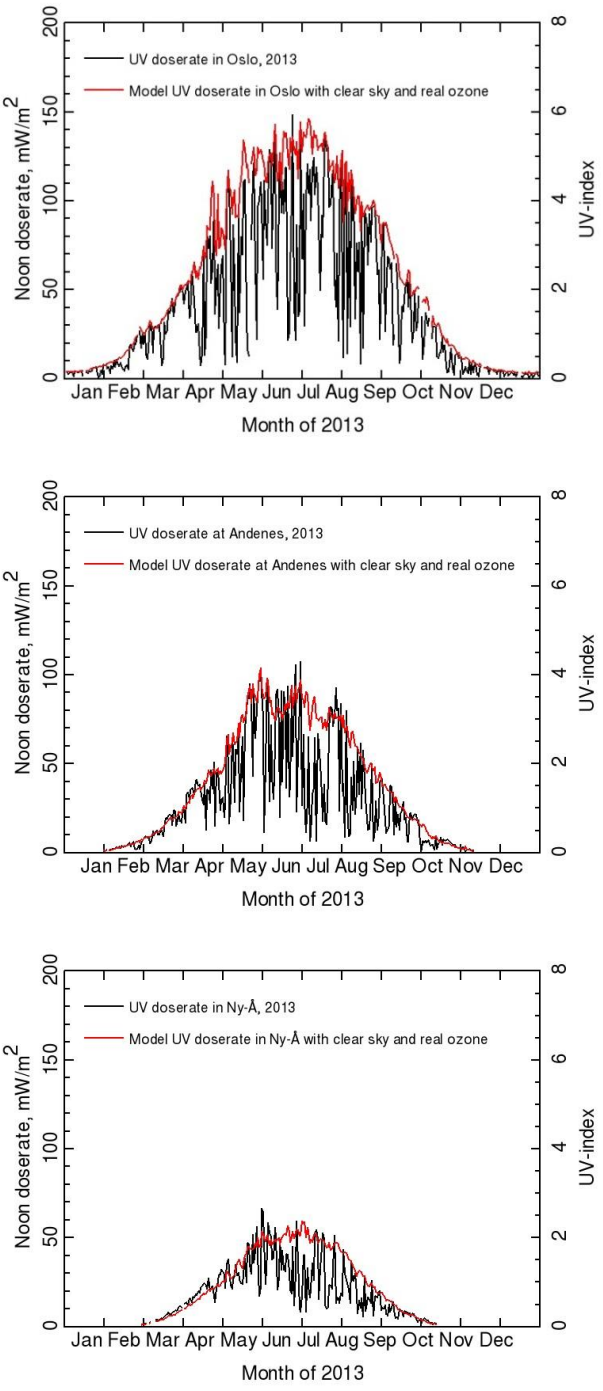

Figure 15: *Hourly averaged UV dose rate measured at noon (between 10:30 and 11:30 UTC) in 2013. Upper panel: Oslo. Mid panel: Andøya Lower panel: Ny-Ålesund.*

Many people from Norway 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 in May and early June. 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 exceptional 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 UV-radiation. In general, the UV-radiation in Ny-Ålesund is largely enhanced during spring due to the high albedo from snow and ice that surrounds the measurement site.

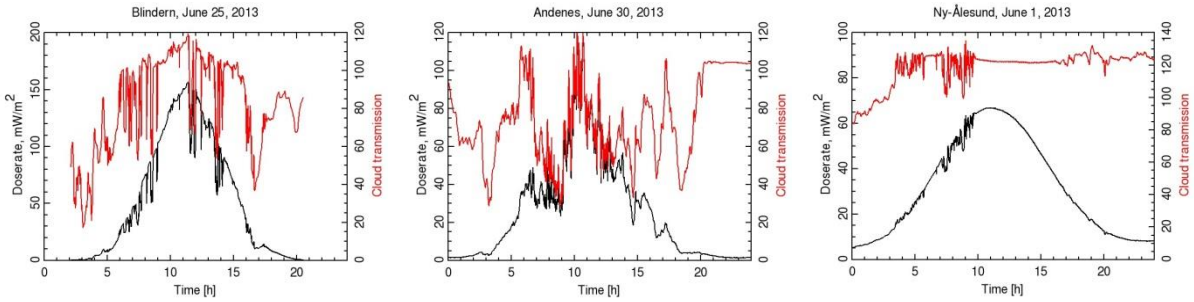

Figure 16: *UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel). A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30% represent heavy clouds.*

Monthly integrated UV doses for Oslo, Andøya (Andenes) and Ny-Ålesund in 2013 are compared in Figure 17. As expected, the monthly UV doses in Oslo were significantly higher than the values observed at Andøya (and Ny-Ålesund), except for May at Andøya, when a longer period of good weather in the north contributed significantly to the UV-dose. If the cloud and ozone conditions at both sites were similar during the summer, the UV-radiation would be highest in Oslo due to higher solar elevation most of the day. In July 2013 the weather was very good in Oslo, which is seen by the high July UV-dose in Figure 17.

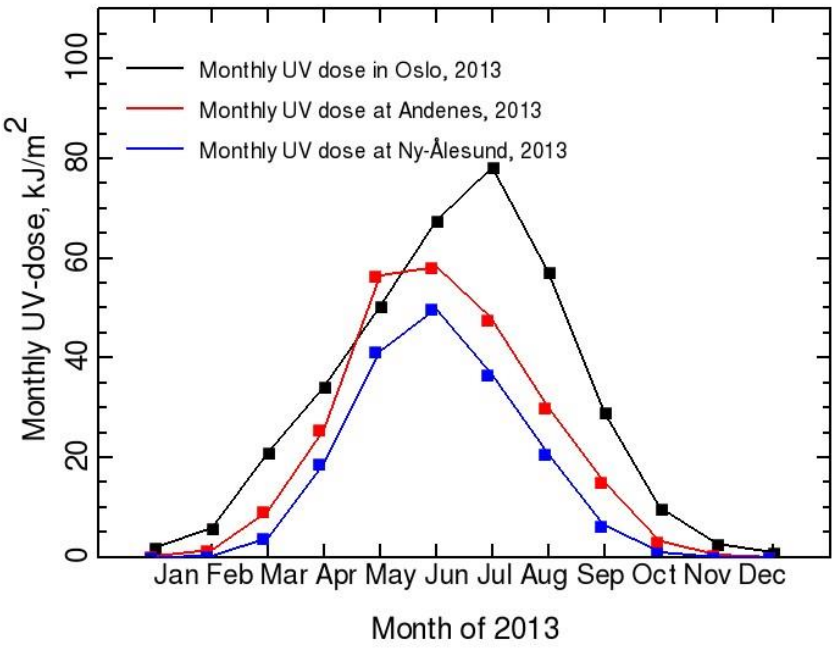

Figure 17: *Monthly integrated UV doses (in kJ/m^2) in 2013 measured with the GUV instruments located in Oslo, at Andøya and in Ny-Ålesund.*

6.2 Annual UV doses 1995 – 2013

Annual UV doses for the period 1995–2013 are shown in Table 11 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 11: *Annual integrated UV doses (in kJ/m^2) for Oslo, Andøya and Ny-Ålesund for the period 1995 – 2013.*

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

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

In 2013 the UV-doses in Oslo during summer were quite varying. Late June and August were fairly overcast with noon UV indices below 4 most days. However, July was less cloudy with UV indices around 4 and 5. July had the highest monthly UV dose of 2013. As shown in Figure 15 (upper panel) there were also some days in July where the noon UV index in Oslo

was as low as 2. For Andøya, the less cloudy periods were in May and July. The less cloudy period in Ny-Ålesund usually appears towards the end of May, giving a noon UV index up to 3.0, but later in the season lower albedo and cloudier conditions keep the UV index under 3.0. It should be noted that the lowest yearly integrated UV dose in Ny-Ålesund for the period 1995-2013 was detected this year.

A graphical presentation of the yearly integrated UV-doses is shown in Figure 18 to illustrate yearly fluctuations. No significant UV trends can be detected at any of the sites.

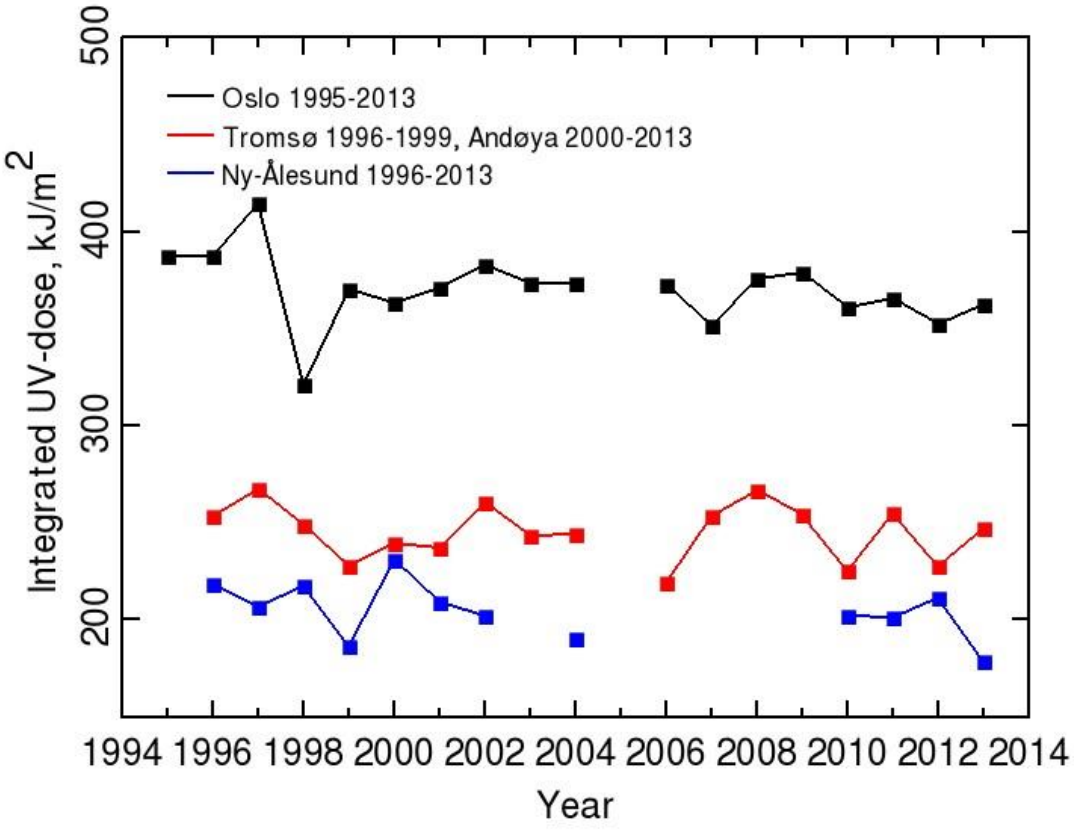

Figure 18: *Annual integrated UV doses (in kJ/m^2) in Oslo, at Andøya/Tromsø and in Ny-Ålesund for the period 1995–2013.*

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Tittel - norsk og engelsk
Overvåking av ozonlaget og naturlig ultrafiolett stråling: Årsrapport 2013.

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2013.

Sammendrag – summary
Rapporten presenterer måledata for totalozon og UV-stråling over norske målestasjoner i 2013. For Oslo, Andøya og Ny-Ålesund er trenden i totalozon beregnet for perioden 1979-2013. Ozonverdiene over Norge var tilnærmet normale 2013. 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.

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 2013. In 2013 the ozone values above Norway were close to the long-term mean at all sites. A clear decrease in the ozone layer above Norway during the period 1979-1997 stopped after 1998 and the ozone layer above Norway now seems to have stabilized.

4 emneord	4 subject words
Stratosfærisk ozon UV-stråling Målinger og observasjoner Montreal-protokollen	Stratospheric ozone UV radiation Measurements and observations Montreal protocol

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Om Statlig program for forurensningsovervåking

Statlig program for forurensningsovervåking omfatter overvåking av forurensningsforholdene i luft og nedbør, skog, vassdrag, fjorder og havområder. Overvåkings-programmet dekker langsiktige undersøkelser av:

- overgjødsling
- forsuring (sur nedbør)
- ozon (ved bakken og i stratosfæren)
- klimagasser
- miljøgifter

Overvåkingsprogrammet skal gi informasjon om tilstanden og utviklingen av forurensningssituasjonen, og påvise eventuell uheldig utvikling på et tidlig tidspunkt. Programmet skal dekke myndighetenes informasjonsbehov om forurensningsforholdene, registrere virkningen av iverksatte tiltak for å redusere forurensningen, og danne grunnlag for vurdering av nye tiltak. Miljødirektoratet er ansvarlig for gjennomføringen av overvåkingsprogrammet.

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