MILJØ-DIREKTORATET

NILU

UiO : Universitetet i Oslo

RAPPORT

M13-2013

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2012

Preface

Ozone is one out of many gases in the stratosphere. Although the concentration of ozone is relatively low it plays an important role for life on Earth due to its ability to absorb ultraviolet radiation (UV) from the sun. In the course of the last 25 years we have often heard about "*the depletion of the ozone layer"* and the co-called "*ozone hole"*, resulting from anthropogenic release of compounds containing chlorine and bromine (CFCs and halons).

The release of CFC-gases started around 1950 and increased drastically up to the 1980s. In 1987 a number of countries signed a treaty, 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 have given valuable contributions to this report. Prof. Arne Dahlback at the University of Oslo (UiO) has been responsible for the ozone measurements at the Department of Physics, UiO. Kåre Edvardsen (NILU) has analyzed UV measurements and Brewer data at Andøya and Kerstin Stebel (NILU) has retrieved SAOZ ozone data from Ny-Ålesund. Cathrine Lund Myhre was responsible for the monitoring programme until December 2012. After that Tove Svendby took over as project leader and is now responsible for the monitoring programme and 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.

Kjeller, September 2013

Tove Marit Svendby
Project leader and senior scientist, NILU

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1. Summary

In 1987 the Montreal Protocol was signed in order to reduce the production and use of ozone-depleting substances (ODS). This international agreement has later been revised several times. Currently, 197 nations have ratified the protocol and effective regulations have reduced the use and emissions of ODS significantly. The total amount of ODS in the troposphere reached a maximum around 1995 and since then the concentration has declining slowly for most compounds. In the stratosphere the ODS peak was reached a few years later, and measurements indicate that a small ODS decline has taken place in the stratosphere as well. 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 economical constraints the monitoring program has been varying in the course of the years with respect to the number of locations and instrumental data reported. In 2012 the monitoring programme included measurements of total ozone and UV at three locations: Oslo (60°N), Andøya (69°N) and Ny-Ålesund (79°N). Previous years ozone profile (lidar) measurements were performed at Andøya, but these measurements terminated in June 2011 due to lack of funding. This report summarises the activities and results of the monitoring programme in 2012. In addition it includes total ozone trend analyses for the period 1979-2012 and UV measurements in Oslo, at Andøya and in Ny-Ålesund from 1995 to 2012.

Total ozone
The monthly mean total ozone above Oslo was below the long-term mean from January to March as well as in December 2012. In March and December 2012 the ozone layer was as much as 14% below the 1979-1989 average. In late spring the ozone amount increased and remained at a level close to the long-term mean until November 2012. At Andøya and in Ny-Ålesund no long-lasting ozone decline was observed in 2012. The monthly mean ozone values were slightly above the long-term mean most of the year and contrary to Oslo the annual average ozone values were higher than normal. For Oslo the annual ozone mean in 2012 was about 5% below the long-term mean, whereas the annual values at Andøya and in Ny-Ålesund were around 1% and 2% 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 1998-2012 the ozone situation seems to have stabilized and no significant trends have been observed at any of the three locations. However, large interannual ozone variations are observed, mainly related to stratospheric winds and temperatures. Consequently, the calculated trend must be relatively large to be classified as significant. When the variations are significantly larger than the resulting straight line trend, the choice of start and end points can change the result considerably.

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 PSCs will increase and result in low ozone values.

UV measurements

The highest UV dose rate in Oslo, 173 mW/m^2 occurred 22 June. This is equivalent to a UV index of 6.9. At Andøya the highest UV index in 2012 was 4.7 (observed 24 June), whereas the highest UVI in Ny-Ålesund, 3.0, was observed 16 June. Due to many overcast days in Oslo in the summer 2012 the annual UV-dose was relative low. Only in 1998 and 2007 lower integrated annual UV-doses were measured. In Ny-Ålesund the 2012 UV-level was higher than previous 2-3 years. This was caused by many cloudless days during the summer. Under clear sky conditions an 1% ozone increase will give a corresponding 1% reduction of the UV-dose. However, a thick cloud cover will have a much larger effect on UV and can easily reduce the UVI in Oslo from a value of 6 to a value of 1 during noon in the summer.

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, at Andøya and in Ny-Ålesund show relatively good agreement during the summer, whereas the differences are larger in the autumn and winter months. 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 man made release of 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 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. 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. Today the current anthropogenic emission of N_2O from human activities destroys more stratospheric ozone than the current emission of any ODS. Finally the oxidation of CH_4 in the stratosphere will increases water vapour and ozone losses in the HOx catalytic cycle in the stratosphere. This demonstrates the complex coupling between stratospheric ozone and climate change.

MAIN CONCLUSIONS FROM THE MONITORING PROGRAMME 2012

- **In 2012 the ozone values above Norway were close to the long-term mean, except from the ozone winter values in Oslo which were lower than normal.**
- **The annual integrated UV-dose in Oslo was below normal in 2012, whereas it was relatively high in Ny-Ålesund. This was mainly caused by long periods with overcast days in Oslo, contrary to Ny-Ålesund which had many clear summer days.**
- **The decrease in annual values of total ozone during the period 1979-1997 was 5.8%/decade in both Oslo and 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 trend 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 2012

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 and in Ny-Ålesund since the mid 1990s. The ozone measurements are retrieved from Brewer spectrophotometers in Oslo and at Andøya, whereas a SAOZ instrument is the standard ozone instrument in Ny-Ålesund. In addition GUV instruments are located at all three sites and can fill in ozone data gaps on days with absent Brewer and SAOZ measurements. We are also analyzing 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 June 2012. The Brewers are also regularly calibrated against standard lamps in order to check the stability of the instruments. Calibration reports are available on request.

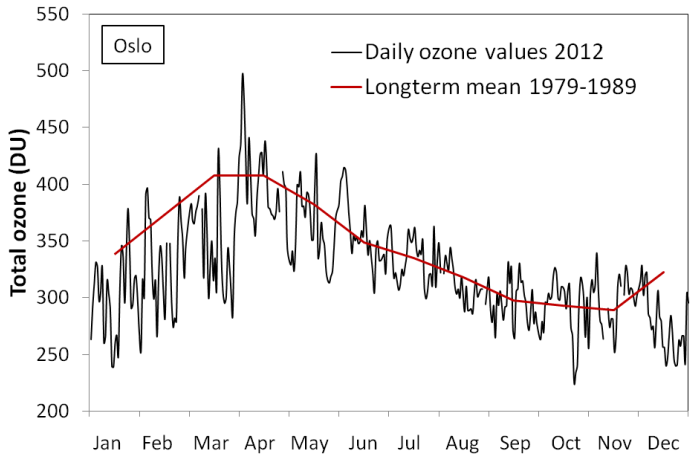

Figure 1a: *Daily total ozone values measured at the University of Oslo in 2012. The red curve shows the long-term monthly mean values from 1979-1989.*

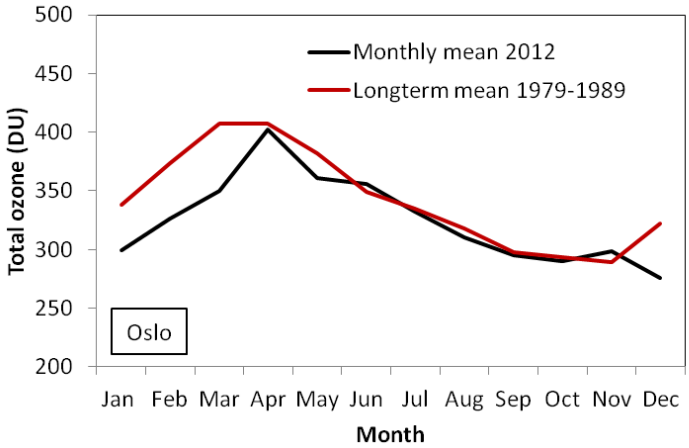

Figure 1b: *Monthly mean ozone values for 2012. The red curve shows the long-term monthly mean values from 1979-1989.*

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 2012. 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 2012 are based on Brewer direct sun (DS) measurements when available. In 2012 direct sun measurements were performed 151 out of

366 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 207 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 2012 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 2012 Oslo ozone series, are summarized in Table 1. Even if total ozone was retrieved from the GUV instrument 350 out of 366 days, none of the measurements were used in the 2012 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 2012 time series

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	151
2	Brewer instrument, global irradiance method	207
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 2012 was 223 DU, measured 22 October. This is about 23% below the long-term mean for October. On the 27 March the ozone value in Oslo reached a relative minimum, with 285 DU which is around 30% below normal. Five days later the ozone value reached the 2012 maximum value of 496 DU. Such rapid ozone variations are typically related to stratospheric winds and changes in tropopause height.

The monthly mean total ozone values for 2012 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 2012 ozone values were far below normal in January, February, March and December. For the other months the monthly average ozone values were close to normal. Section 3.5 gives a broader discussion and interpretation of the ozone situation in Norway in 2012.

2.2 Total ozone at Andøya

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-541 instrument will also provide ozone data when the Brewer instrument is out of order or Brewer measurements are prevented by bad weather conditions.

From 20 February to 10 April 2012 the Brewer instrument at Andøya had technical failure. To complete the 2012 time series total ozone was instead retrieved from the GUV instrument, which is less accurate than the Brewer instrument. This substitute has added additional uncertainty to the 2012 spring values. The GUV measurements were also used during a few days where Brewer GI retrievals were prevented due to bad weather conditions. Table 2 gives an overview of the different instruments and methods that were used at Andøya in 2012. The ozone lidar at Andøya is no longer in operation, and consequently none ozone measurements were performed during periods with polar night.

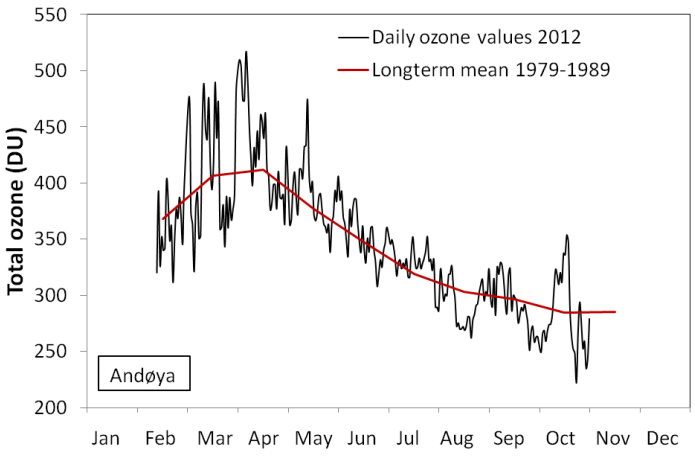

Figure 2a: *Daily total ozone values measured at ALOMAR, Andøya, in 2012 by the Brewer and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979-1989.*

Figure 2a) shows daily ozone values from Andøya in 2012. 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 2012 was 222 DU, measured 23 October. This was about 22% below the long-term mean for October.

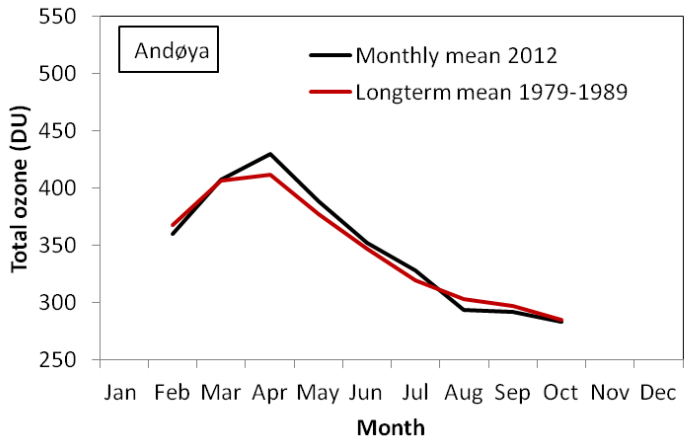

Figure 2b: *Monthly mean total ozone values for 2012 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).*

Monthly mean ozone values at Andøya for 2012 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 for 2012 shows that the ozone values were close to normal all months. The most "extreme" months were April, where the 2012 average was about 4% above the long-term mean, and August where the 2012 mean value was about 3% below normal.

Table 2: *Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2012.*

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	49
2	Brewer instrument, global irradiance method	135
3	GUV instrument	79
	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 (Systeme d'Analyse par Observation Zenitale) 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. From 1990 to 2002 total ozone column observations from Ny-Ålesund were funded and reported to the Norwegian Environment Agency (see Høiskar et al., 2003). From 2003 to 2010 the station was excluded from the monitoring programme, but the measurements were included again from 2011.

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). For ozone there is a consistency between stations of about 3%.

In addition to SAOZ, a GUV-541 multi-filter radiometers 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 2012 ozone time series from Ny-Ålesund. Preliminary comparisons between SAOZ and GUV data during overlapping measuring periods indicate that the GUV ozone data might be too high during summer. Homogenization of SAOZ and GUV data from all years, plus comparisons to other available ozone data will be studied and reported to the Norwegian Environment Agency next year.

Table 3 gives an overview of the different instruments and methods that have been used for the 2012 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 2012.*

Priority	Method	Total days with observations
1	SAOZ instrument	144
2	GUV instrument	104
	Missing days (except polar night)	0

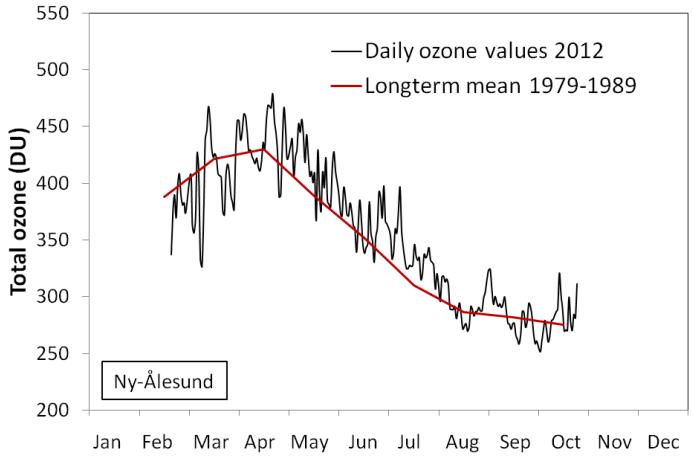

Figure 3a: *Daily total ozone values measured in Ny-Ålesund in 2012 by the SAOZ and GUV instruments (black curve). The red line is the long-term monthly mean values from 1979 -1989.*

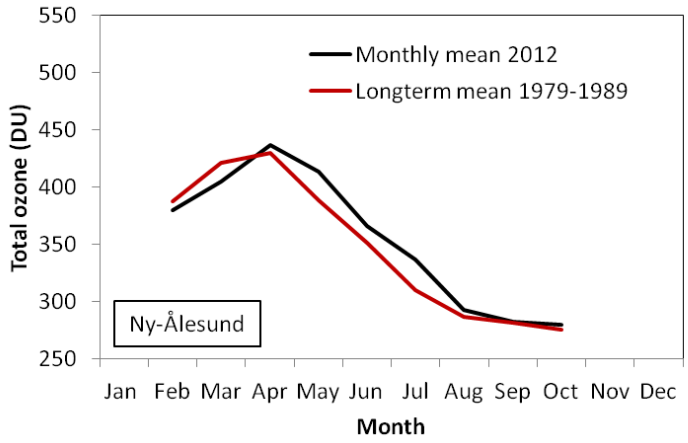

Figure 3b*: Monthly mean total ozone values for 2012 (black curve) compared to the long-term monthly mean values for the period 1979-1989 (red curve).*

Figure 3a shows daily ozone values from Ny-Ålesund in 2012. 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 satellite data. The ozone pattern in Ny-Ålesund is fairly similar to Andøya, but has slightly higher ozone values in spring and lower values in fall. 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 2012 was 251 DU, measured 1 October. This is about 8% below the long-term mean for October.

Monthly mean ozone values in Ny-Ålesund for 2012 are shown in Figure 2b). For January, November, and December (polar night) there is not possible to achieve data from our instruments. Comparison between the long-term mean and monthly mean ozone values for 2012 shows that the ozone values were slightly below the long-term mean in February and March, whereas the monthly mean average was higher than normal from April to August. It should be kept in mind that all ozone summer measurements are based on the GUV instrument, which might overestimate ozone by a few percent (see Section 4.2).

3. Ozone measurements and trends 1979–2012

3.1 Background

3.1.1 Status of the ozone layer

Since the beginning of the 1990s the World Metrological Organisation (WMO) and 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). This report summarizes 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 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.

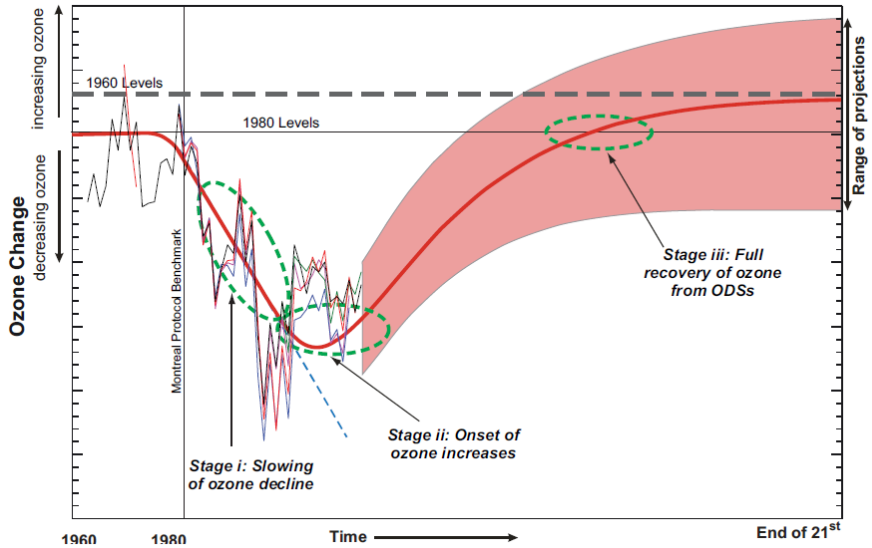

***Figure 4**: Total ozone at latitudes 60°N to 60°S for the period 1960 to 2100 (the x-axis is not to scale). The thick red line is a representation of the ozone amounts observed to date and projected for the future. The red-shaded region represents the model results predicted for the future. The 1980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

Figure 4 is taken from the 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 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 previous 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. This region also exhibits 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 2012 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 will also be strongly influenced by changes in stratospheric winter temperatures during the next years, and 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-tem ozone trend, presented in the next sections, are essential in the assessment of possible ozone recovery and to gain more information about atmospheric processes.

3.2 Trends for Oslo 1979 – 2012

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.

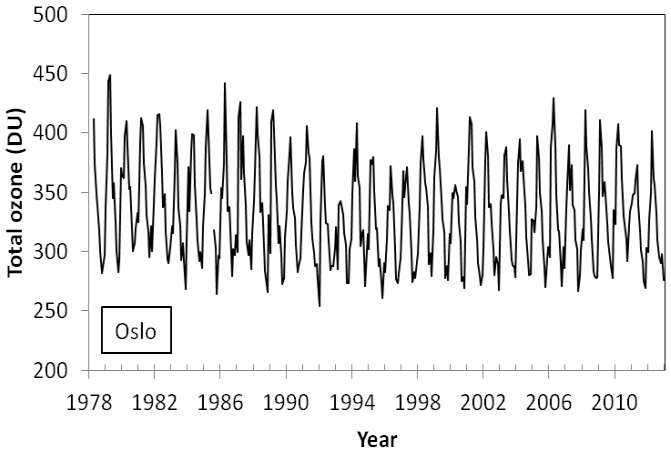

Figure 5a: *Time series of monthly mean total ozone in Oslo 1979-2012.*

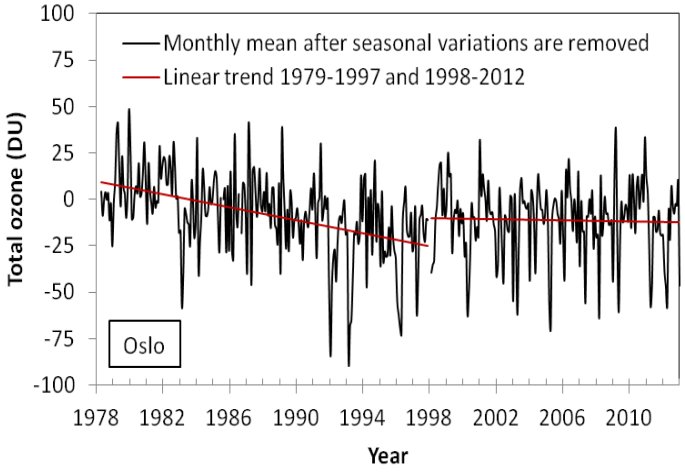

Figure 5b: *Variation in total ozone over Oslo for the period 1979–2012 after the seasonal variations have been removed. Trend lines are marked in red.*

Figure 5a shows the variations in monthly mean ozone values in Oslo for the period 1979 to 2012. The large seasonal variations are typical for stations at high latitudes. This is a dynamic phenomenon and is 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 – 2012 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) 1998-2012. 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 gives the uncertainty (1σ) in percent/decade. A trend larger than 2σ is considered to be 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 1998-2012 the picture is different. There are substantial annual fluctuations 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 months there is an ozone decline of -1.6% /decade during the last 15 years, whereas the ozone trend is correspondingly positive (+2.3%/decade) for the fall. The total ozone was very low most of 2011 and the winter 2012, which has strongly affected the 1998-2012 trend results. For example, the ozone winter trend from 1998-2010 was as large as +4.5%/ decade. When 2011 and 2012 was included in the trend analysis the positive winter trend turned to a negative value of -0.9%/ decade. This clearly demonstrates how trend results can be affected by extreme values in the start and/or end of a short regression period. As seen from Table 4 the annual ozone trend from 1998 to 2012 is close to zero.

Table 4: *Percentage changes in total ozone per year for Oslo for the period 1.1.1979 to 31.12.2012. 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) 1998-2012
Winter (Dec – Feb)	-6.2 (2.4)	-0.9 (3.0)
Spring (Mar – May)	-8.4 (1.4)	-0.8 (2.5)
Summer (Jun – Aug)	-3.4 (1.1)	-1.6 (1.3)
Fall (Sep – Nov)	-4.3 (1.0)	2.3 (1.6)
Annual (Jan – Dec):	-5.8 (1.0)	-0.5 (1.4)

3.3 Trends for Andøya 1979–2012

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 (Total ozone Mapping Spectrometer) have been used for the trend studies.

Figure 6a shows variation in the monthly mean ozone values at Andøya from 1979 to 2012. The extreme February 2010 value and the record low 2011 spring values are seen as high and low peaks in the plot. The variations in total ozone at Andøya for the period 1979–2012, 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) 1998-2012. The results of the trend analyses are summarized in Table 5. Comparison of Figure 5b and Figure 6b shows that the trend patterns from Andøya have many similarities to the Oslo trend pattern.

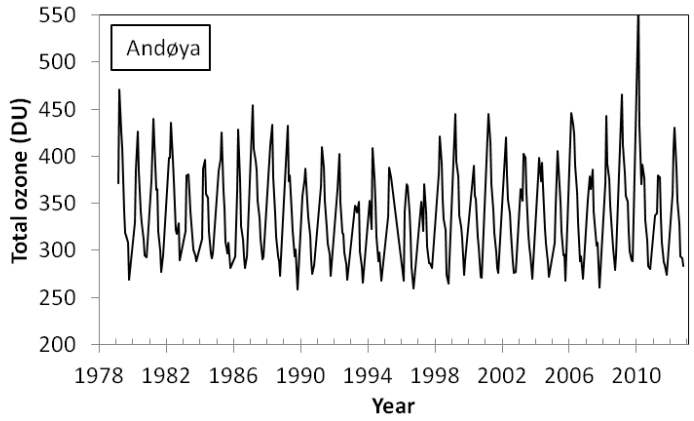

Figure 6a: *Time series of monthly mean total ozone at Andøya/Tromsø 1979–2012.*

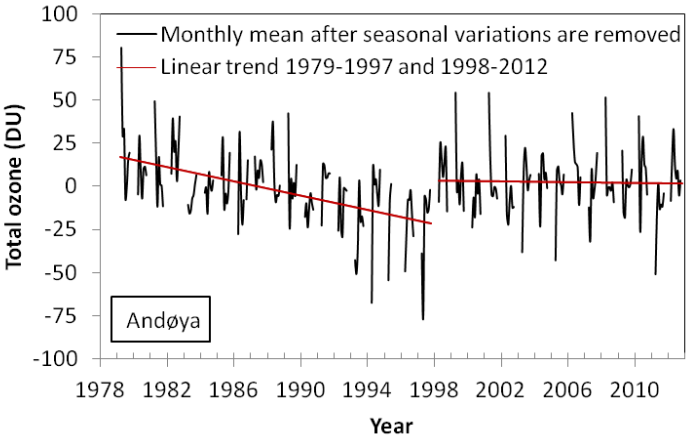

Figure 6b: *Variations in total ozone at Andøya for the period 1979–2012 after the seasonal variations are removed. Only data for the months March–September are included.*

Similar to 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 2012. For this period an ozone decrease of -0.7%/decade was observed for the spring, whereas a trend of -0.8%/decade was found for the summer months. The annual trend for the period 1998-2012 was -0.2% /decade. None of these results 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- 2012. The numbers in parenthesis gives the uncertainty (1σ). A trend larger than 2σ is considered to be significant. Data from the Brewer and GUV instruments have been used in this study.*

Season	Trend (% /decade) 1979-1997	Trend (% /decade) 1998-2012
Spring (Mar – May):	-8.4 (1.5)	-0.7 (2.4)
Summer (Jun – Aug):	-2.8 (0.9)	-0.8 (1.4)
Annual (Mar – Sep):	-5.8 (1.0)	-0.2 (1.5)

3.4 Trends for Ny-Ålesund 1979 – 2012

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).

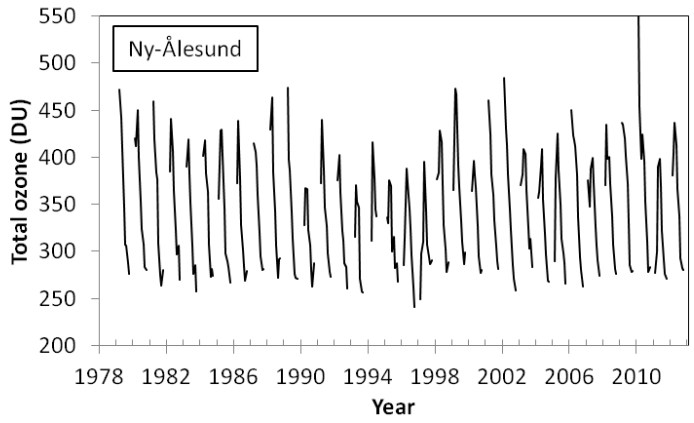

Figure 7a: *Time series of monthly mean total ozone at Ny-Ålesund 1979–2012.*

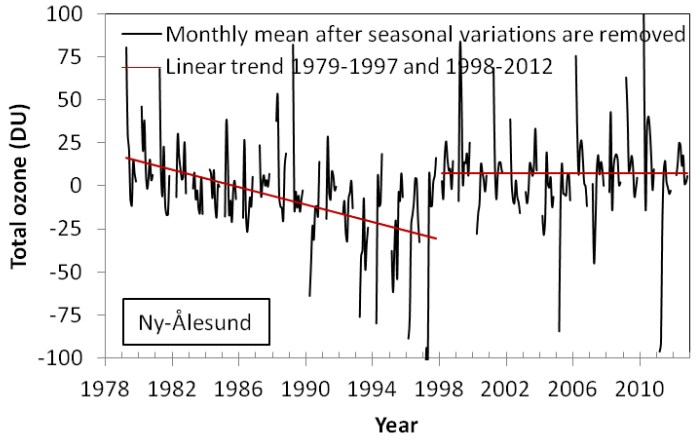

Figure 7b: *Variations in total ozone at Ny-Ålesund for the period 1979–2012. Only data for the months March–September are included.*

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, SOAZ, GUV and satellite measurements. For the years 1979 to 1994 the monthly mean ozone values are entirely based on TOMS Nimbus 7 and Meteor-3 overpass data. For the latest 20 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 2012. During this period an ozone decrease of -1.9%/decade was observed for the spring months, whereas a trend of

+1.2%/decade was found for the summer months. The annual trend for the period 1998-2012 was -0.7% /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- 2012. The numbers in parenthesis gives the uncertainty (1σ). A trend larger than 2σ is considered to be significant.*

Season	Trend (% /decade) 1979-1997	Trend (% /decade) 1998-2012
Spring (Mar – May):	-11.4 (1.8)	-1.9 (3.3)
Summer (Jun – Aug):	-1.0 (1.3)	1.2 (1.6)
Annual (Mar – Sep):	-6.4 (1.1)	-0.7 (2.0)

3.5 The overall ozone situation for Norway 2012

The ozone pattern and month-to-month variations at the three Norwegian sites were slightly differently in 2012. The overall Norwegian ozone picture was not as dramatic as in 2011, when record low ozone values in March and April contributed to low values throughout the rest of the year. In spite of low ozone values in Oslo in January-March 2012, the weather frontal systems changed in April and resulted in ozone values close to the long term-mean rest of the year. Figure 8 shows a map from WOUDC 15 March 2012 illustrating ozone deviations at the Northern Hemisphere. This day the ozone decline in Southern Norway was 20-25%, whereas insignificant reductions where measured at Andøya and Ny-Ålesund. This was a typical situation winter and early spring 2012.

Figure 9, Figure 10 and Figure 11 show the percentage difference between yearly mean total ozone and the long-term yearly mean for all years from 1979 to 2012. The low values in 1983 and 1992/1993 are 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.

For Oslo the annual ozone mean in 2012 was about 5% below the long-term mean. As explained above the low ozone average was caused by the unusual low values during the winter months. Contrary to Oslo, the annual average ozone values at Andøya and in Ny-Ålesund were above the long-term mean in 2012: around 1% and 2% for the two stations, respectively.

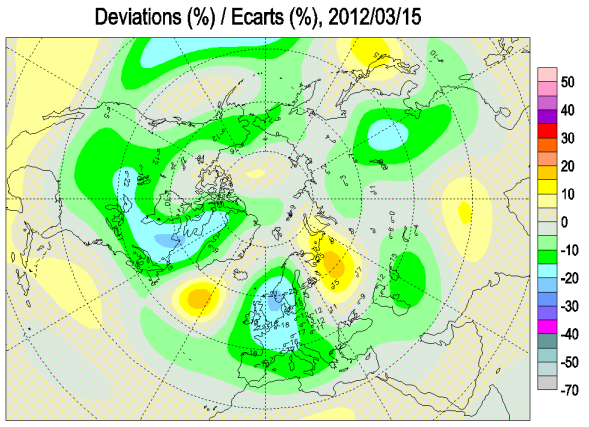

Figure 8: *Deviation from normal ozone values 15 March 2012 (map from WOUDC).*

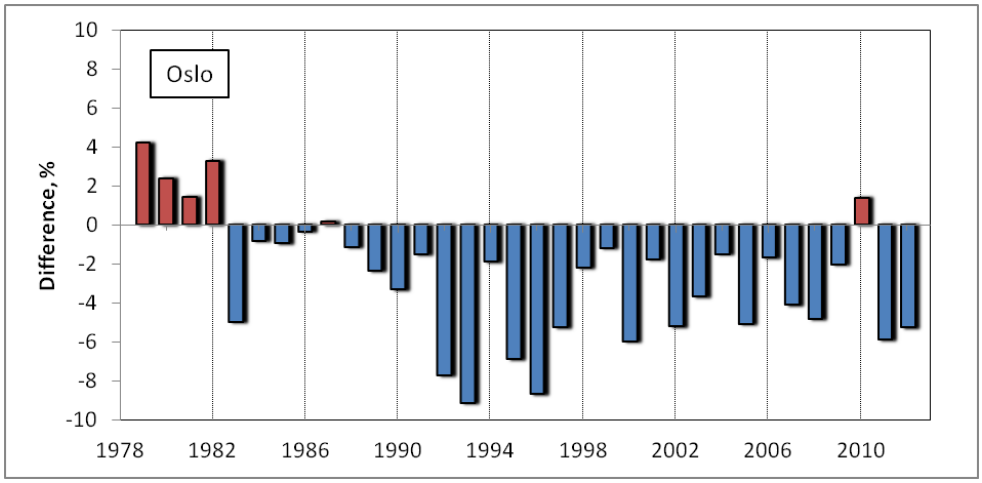

Figure 9: *Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean for 1979-1989.*

Table 7 gives the percentage difference between the monthly mean total ozone values for 2012 and the long-term monthly mean values for the three Norwegian sites. For Oslo the ozone level was as large as 14% below "normal" in March and December. Only June and November 2012 had values above the long-term average. At Andøya all the 2012 values were within ±5% compared to the long-term mean. The largest negative deviation was seen in August (-2.9%), whereas the largest positive deviation occurred in April (+4.3%). In Ny-Ålesund the ozone level was fairly high most of the year. In August the monthly mean value was as much as 8.5% 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, which have been used for calculating the ozone long-term mean for the 1979-1989 period. This will be described in more detail in Section 4.

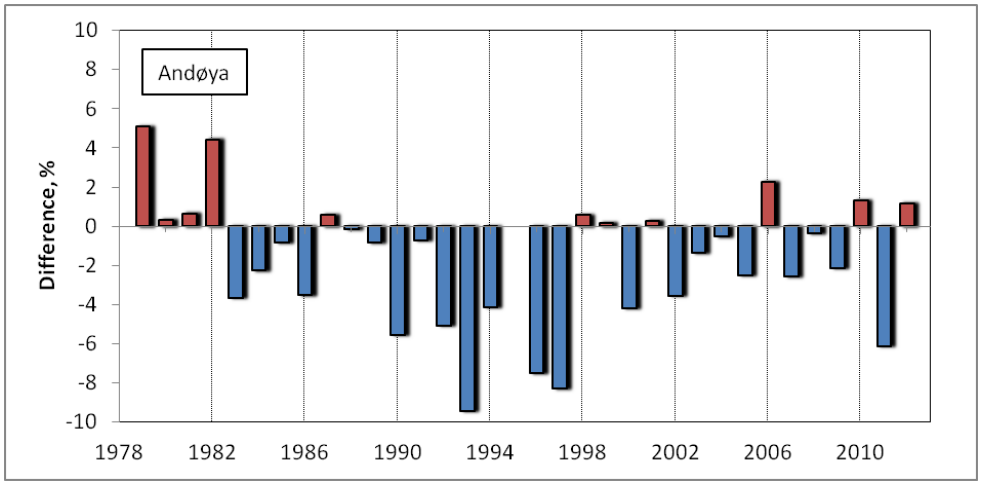

Figure 10: *Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean for 1979-1989 for the months March-October.*

Again, comparison of Figure 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 in the end of the 1970s and in 2010. Also, all sites had record low ozone values in 1993 (around 9% below the long-term 1979-1989 mean) and low ozone values in 2011 (roughly 6% below the long-term yearly mean).

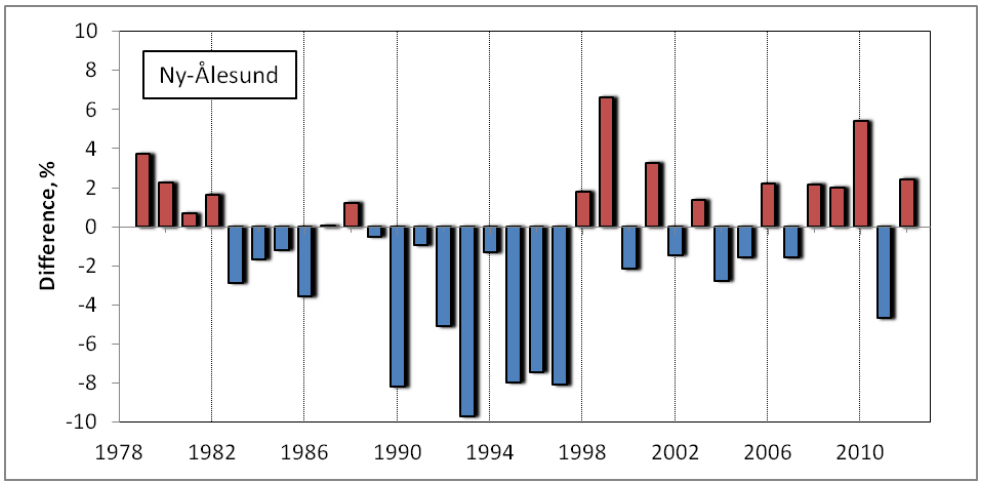

Figure 11: *Percentage difference between yearly mean total ozone in Ny-Ålesund and the long-term yearly mean value (1979-1989 average). Ozone values from March to October are included in the calculations.*

Table 7: *Percentage difference between the monthly mean total ozone values in 2012 and the long-term mean for Oslo, Andøya, and Ny-Ålesund.*

Month	Oslo (%)	Andøya (%)	Ny-Ålesund (%)
January	-11.4		
February	-12.6	-2.1	-2.0
March	-14.1	0.2	-4.0
April	-1.4	4.3	1.7
May	-5.6	2.8	6.3
June	2.0	1.5	4.0
July	-0.9	2.7	8.5
August	-2.4	-2.9	2.2
September	-0.8	-1.7	0.3
October	-1.1	-0.6	1.7
November	3.2		
December	-14.4		

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 projects jointly financed by The Norwegian Space Centre (NRS, Norsk Romsenter) and NILU we are in a good position to explore and utilize ozone satellite observations in the National monitoring of the ozone and UV radiation. One project (SatMonAir) was funded in 2012, whereas a follow-up project (SatMonAir II) started in 2013. Some results from the activities within the SatMonAir projects are included in this report.

4.1 Short introduction to ozone observations from space

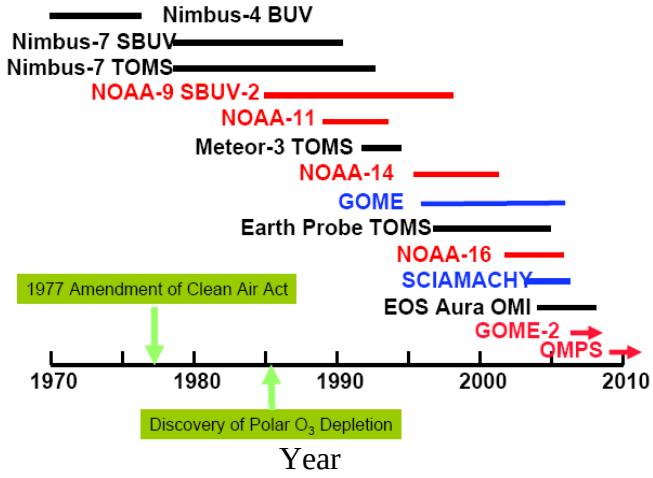

Figure 12: *An overview of the various satellites and their instruments measuring ozone from space since the beginning of 1970's (Figure from NASA).*

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 and NOAA (National Oceanic and Atmospheric Administration) started these observations, and later The European Space Agency initiated their ozone programmes. Figure 12 gives an overview of the various ozone measuring satellites and their time.

4.2 Satellite ozone observations above the Norwegian sites 1979–2012

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), 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.

In 2011 the Arctic ozone situation was extraordinary in winter/spring, where extremely low ozone values were measured until the beginning of April. Figure 13 (left panel) shows the Scandinavian/Arctic ozone situation 1st April 2011, with ozone values down to 250 DU north of 70ºN. As shown in Figure 13 (right panel) the ozone situation was very different 1st April 2012, where ozone values around 500 DU were measured in Arctic regions. The ground based ozone values in Oslo, at Andøya and in Ny-Ålesund are marked in the figures (blue numbers) along with the OMI ozone value at the same locations (black numbers).

Comparisons of Ground based measurements and satellite data over Oslo, Andøya and Ny-Ålesund show that the satellite values normally differs from the ground based measurements. Ozone can exhibit some variations within short distances and a satellite pixel of typically 1x1 degree might have an average value that deviates from the point measurement. On the other hand the satellites give a very good picture of spatial extent of "ozone holes" and how ozone rich/poor air moves. As a part of the SatMonAir projects spatial correlation, standard deviation and bias between satellite products (plus comparisons to ground based measurements) have been studied.

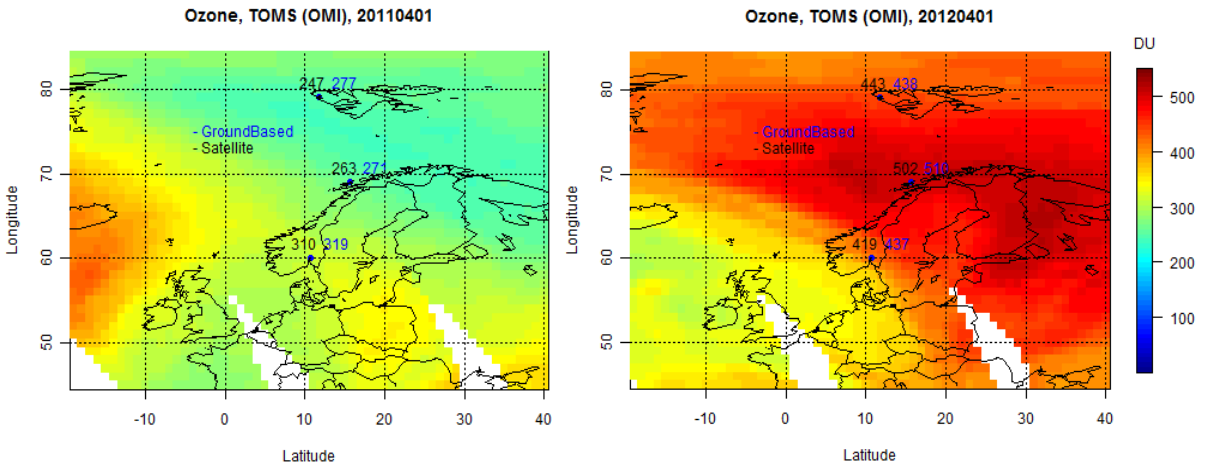

Figure 13: *Ozone maps over Scandinavia and the Arctic 1st April 2011 (left panel) and 1st April 2012 (right panel). The numbers above Oslo, Andøya and Ny-Ålesund represent satellite observations (black) and ground based observation (blue numbers).*

As mentioned above, 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.

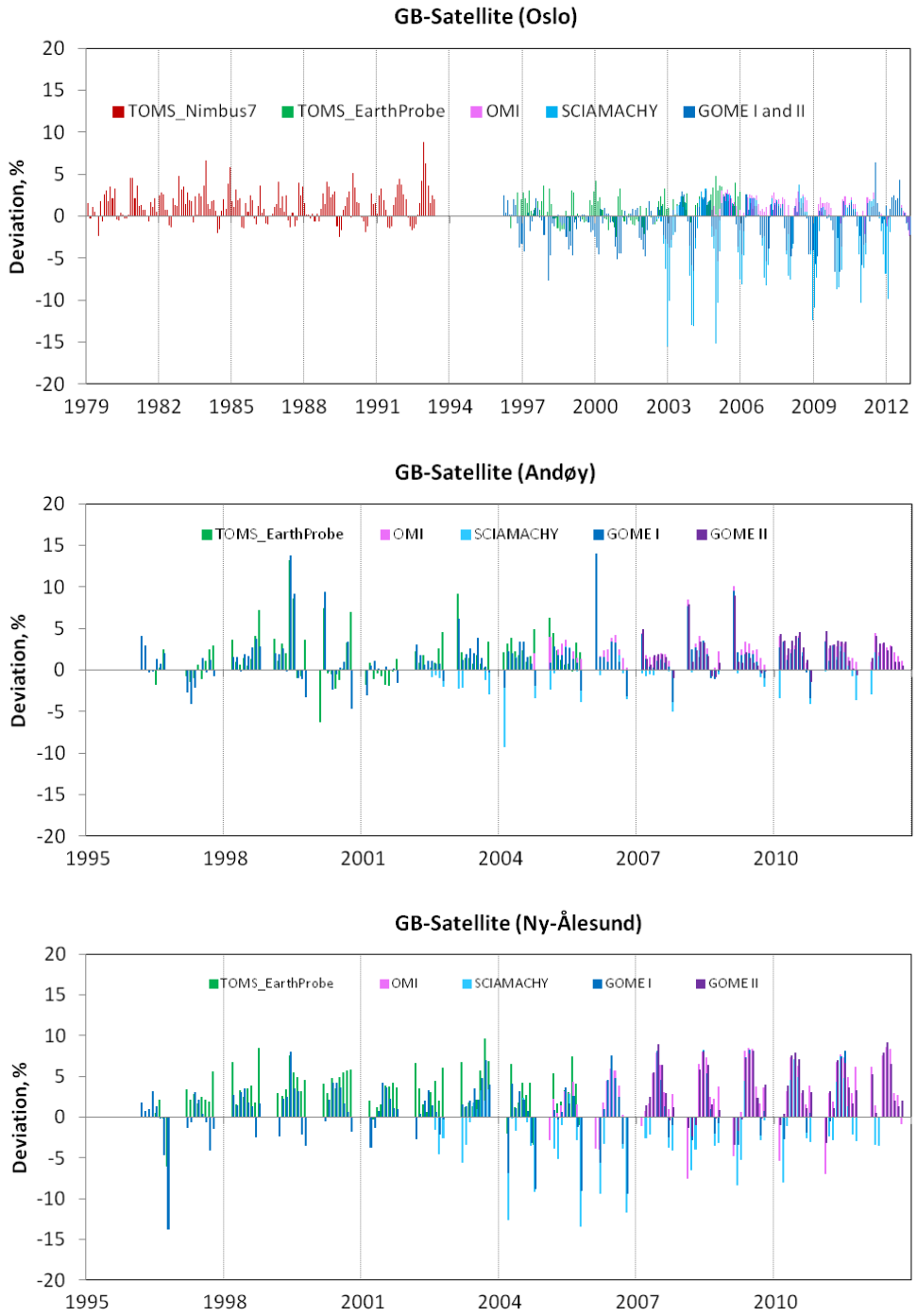

Figure 14: *Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2012 (Oslo) and 1995-2012 (Andøya and Ny-Ålesund). Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, Middle panel: Andøya, Lower panel: Ny-Ålesund.*

The monthly mean ozone values from ground based (GB) measurements and satellites are analysed for the full period 1979-2012. Figure 14 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. This clearly demonstrates the importance of continuous long-term ground based measurements.

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-12	0.98	1.40	1.96
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-12	0.91	1.77	3.12
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-12	2.64	2.09	4.36
GOME 1	Mar-96	Jul-11	1.42	2.78	7.74
GOME 2	Jan-07	Dec-12	2.12	2.02	4.10
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-12	2.51	4.18	17.45
GOME 1	Mar-96	Jul-11	1.18	3.78	14.30
GOME 2	Jan-07	Dec-12	3.14	3.45	11.93
SCIAMACHY	Jul-02	Apr-12	-0.67	4.86	23.61

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 seems 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 14 (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.

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 overestimates ozone values during periods with low sun. This gives a very high standard deviation and variance for the GB-SCIAMACHY deviation in Oslo and Ny-Ålesund. The high SCIAMACHY winter values are visualized by the light blue columns/lines in Figure 14. In contrast the OMI ozone values are close to the Brewer measurements in Oslo all year, giving a variance of only 2.0 (see Table 8). The GB-OMI variance in Ny-Ålesund is as high as 17.5, whereas GB-GOME II has a variance of only 11.9. This might indicate that GOME II is more accurate at high latitudes. It can also be noted that the BG-SCIAMACHY variance is much smaller at Andøya than in Oslo. This is probably caused by the fact that no 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.

One aim of the SatMonAir project is to define and construct an integrated satellite data set that is suitable for trend analysis for the Scandinavian region. Based on the analysis and results presented in Table 8 it can be concluded the ozone data from TOMS and OMI have similar mean and standard deviation and are suited for such trend studies, especially in Southern Norway. Figure 15 shows the results from our preliminary satellite trend calculations, focusing on April isolated. Left panel shows trends from 1979-1993, where a large negative trend of 7- 10%/decade is seen most places in Norway. This is in line with trend results presented in Section 3.2 - 3.4. However, for the westerly regions around Iceland, the negative trend is less evident. For the period 1998-2012 no strong satellite retrieved ozone trend is seen in the Arctic regions. For the Svalbard and Andøya area the trend is close to zero, whereas a negative trend of around 3%/decade can be seen around Oslo. For the Bergen region the negative 1998-2012 April trend is somewhat larger and estimated to about 7%/decade.

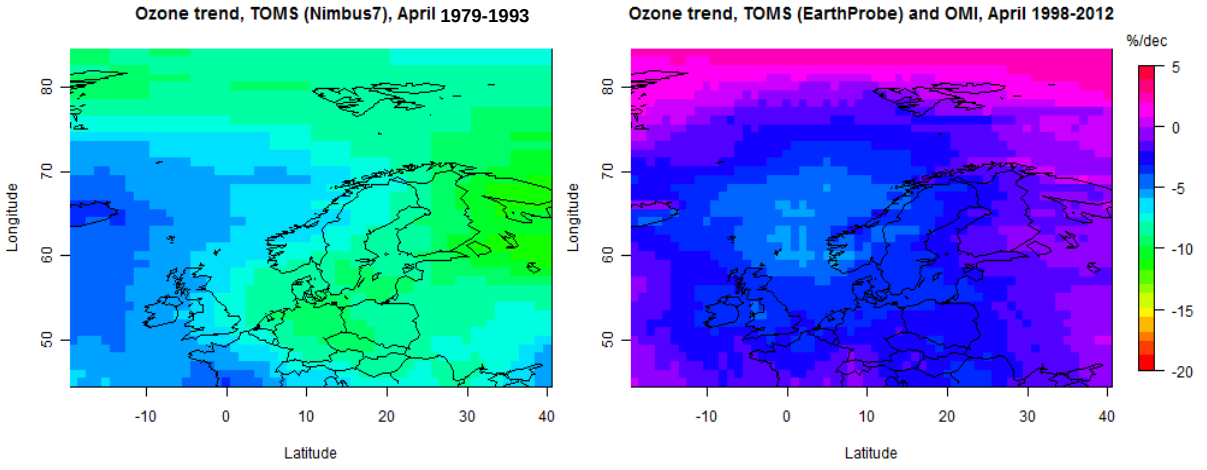

***Figure 15**: April ozone trend (%/decade) calculated from space. Left panel: TOMS Nimbus 7 data 1979-1993. Right panel: TOMS Earth Probe and OMI data 1998-2012.*

5. Coupling of stratospheric ozone and climate

Climate change will affect the evolution of the ozone layer in several ways; through changes in transport, chemical composition, and temperature (IPCC, 2007; WMO, 2007). In turn, changes to the ozone layer will affect climate through the influence on the radiative balance, and the stratospheric temperature gradients. 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[1] 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 4th IPCC are shown in Figure 16 (IPCC, 2007). The estimates are for changes in anthropogenic factors since pre-industrial times. Stratospheric ozone is a greenhouse gas. The change in stratospheric ozone since pre-industrial times has a weak negative forcing of -0.05 W/m^2 with a *medium* level of scientific understanding. This new estimate is weaker than in the previous report where the estimate was –0.15 W/m^2. The updated estimate is based on new model results employing the same data set as in the previous report, where observational data up to 1998 is included. No study has utilized ozone trend observations after 1998 (Forster et al., 2007).

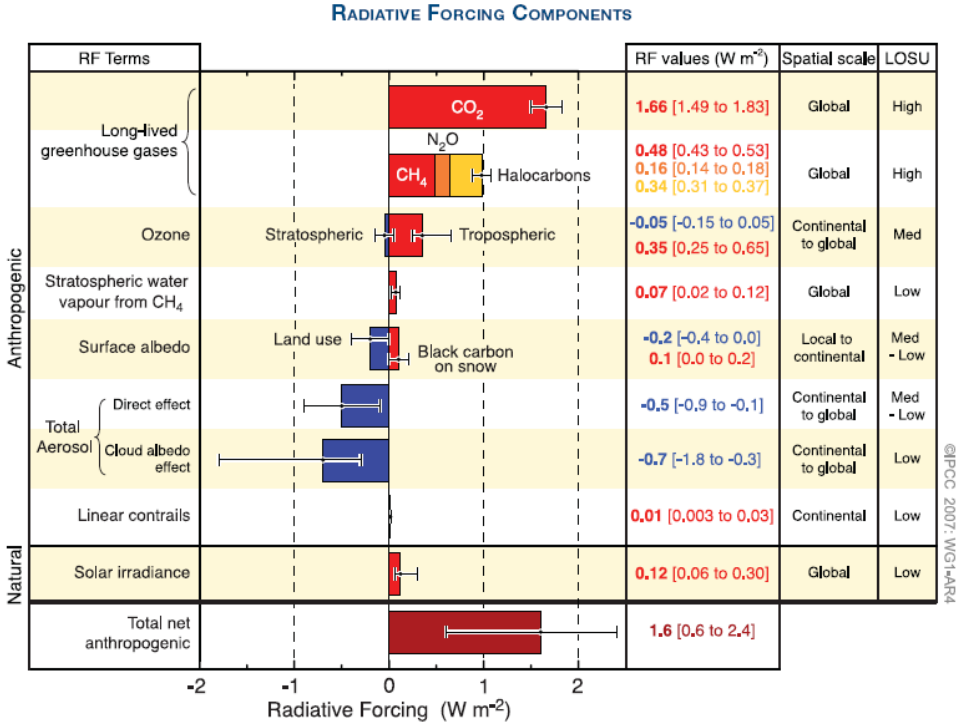

Figure 16: *Global-average radiative forcing estimates for important anthropogenic agents and mechanisms as greenhouse gases, aerosol effects, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU).*

[1] 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.

The temporarily and seasonally non-uniform nature of the ozone trends has important implications for the radiative forcing. Total column ozone changes over mid latitudes is considerable larger at the southern hemisphere (-6%) than at the northern hemisphere (-3%). According to the IPCC report the negative ozone trend has slowed down the last decade, also described in section 3 of this report.

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, 2007). 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.

A long-term increase in stratospheric water content has been observed in the second half of the 20th century. This might have important consequences for the ozone layer 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 4th IPCC report, the increase in stratospheric water vapour resulting from anthropogenic emissions of methane (CH_4) has a positive forcing of 0.07 W/m^2, shown in Figure 16.

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 climate gases and contribute to a strong positive radiative forcing (see Figure 16). 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. The negative forcing due to the net ozone change from 1979 to 1994 has likely counterbalanced more than 30% of the positive forcing due to the increase of well-mixed greenhouse gases in the same period (Hansen et al., 1997). However, if we study radiative forcing related to human activities between 1750 and today (Figure 16), the ozone depleting contribution is small compared with the contribution from all other greenhouse gas increases.

Finally, nitrous oxide (N_2O) is another key species that regulates the ozone levels. The photochemical degradation of N_2O in the stratosphere leads to ozone-depleting NOx. Although the past emissions of ODSs (i.e. CFCs) still dominate global ozone depletion, the current emission of N_2O from human activities will destroy more stratospheric ozone than the current emission of any ODS (WMO, 2011). Reduction of future N_2O emissions, one target of the Kyoto Protocol, would enhance the recovery of the ozone layer and would also reduce anthropogenic forcing of the climate system.

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 17. NILU is responsible for the daily operation of three of the instruments, located at Oslo (60°N), Andøya (69°N) and Ny-Ålesund (79°N). The Norwegian Radiation Protection Authority (NRPA) is responsible for the operation of the measurements performed at Trondheim, Bergen, Kise, Landvik, Finse and Østerås. On-line data from the UV network is shown at www.nilu.no and at http://www.nrpa.no/uvnett/.

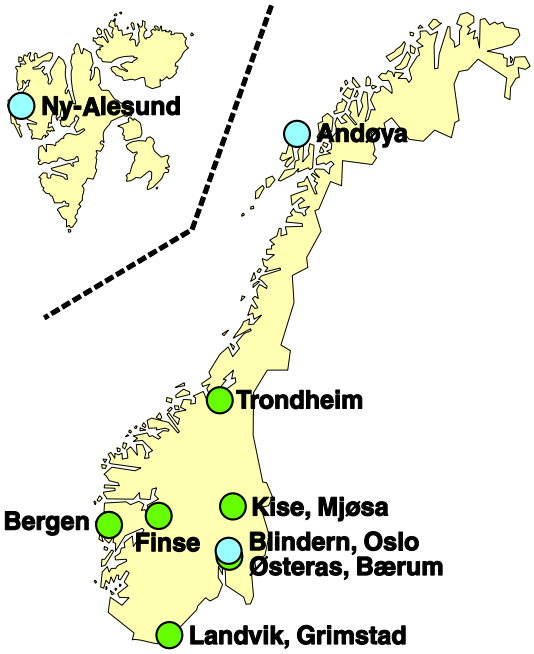

Figure 17: *Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU, whereas the Norwegian Radiation Protection Authority operates the stations marked with green.*

This annual report includes results from Oslo, Andøya and Ny-Ålesund. 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.

The Norwegian GUV instruments were included in a calibration and intercomparison campaign in 2005 as a part of the project FARIN (Factors Controlling UV in Norway)[2]. 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 has been the comparison and evaluation of all the UV-instruments in the Norwegian monitoring network. In total 43 UV instruments were included in 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. The number of missing days due to technical problems in 2012 is given in Table 9.

6.1 UV measurements in 2012

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). 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

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

Table 9: *Number of days with more than 2 hours of missing GUV data in 2012 and 2011. Days where the sun is below the horizon (polar night) are not included.*

Station	Technical problems	
	2012	2011
Oslo	1	1
Andøya	1	12
Ny-Ålesund	1	1

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 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 18 shows the UV dose rates measured at noon (averaged between 10:30 and 11:30 UTC) for Oslo, Andøya and Ny-Ålesund. The highest UV dose rate in Oslo, 173.1 mW/m^2, was observed 22 June at 11:17 UTC and is equivalent to a UV index of 6.9. 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 2012 was 4.7, equivalent to a dose rate of 118.0 mW/m^2, observed 24 June at 10:41 UTC. The highest UVI value in Ny-Ålesund was 3.0, or 75.9 mW/m^2, and was measured 16 June at 11:00 UTC. The maximum UVI in Oslo was observed during scattered cloud conditions and slightly lower total ozone value than normal, i.e. 317 DU (normal ~ 340 DU). At Andøya the ozone column was almost the same as in Oslo (311 DU versus normally ~ 350 DU) and was measured during clear sky conditions. At Ny-Ålesund the maximum UVI was observed during scattered 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 with a typical Nordic skin type get sunburnt after approximately 20 minutes if no sun protection is used.

Figure 19 shows the atmospheric conditions during the days of maximum UVI in Oslo, Andøya and Ny-Ålesund. A cloud transmission of 100% (red curve) represents clear sky conditions. In Ny-Ålesund it was clear sky until noon and a few scattered clouds towards the evening. As seen from Figure 19 (right panel) the cloud transmission in Ny-Ålesund was above 100% the first part of the day. This was caused by high albedo from snow and ice in the vicinity of the instrument site, which enhanced the solar radiation detected by the GUV instrument. At Andøya the day was fairly clear in the morning, with a few scattered clouds around noon. Such clouds tend to enhance the UV-radiation due to scattering of radiation towards the ground. Towards the evening the sky became more and more cloudy. Oslo had scattered clouds all day, and this will normally create multiple reflection which enhances the UV-radiation.

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, the UV radiation is influenced by e.g. 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

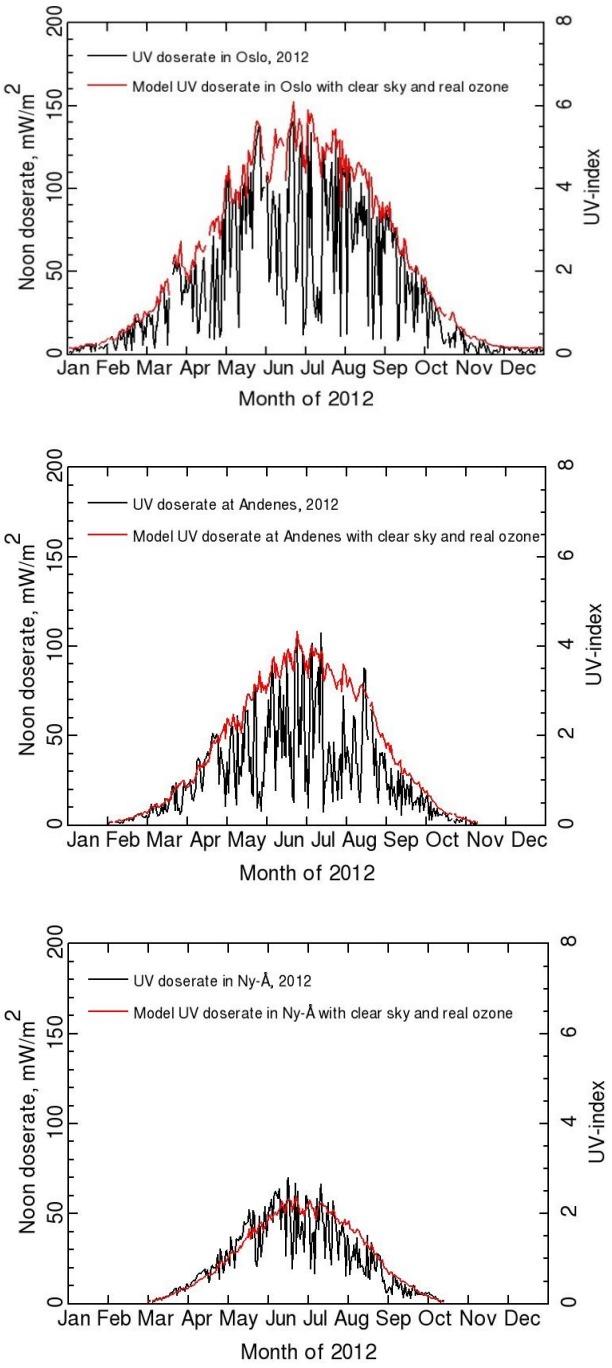

Figure 18: *Hourly averaged UV dose rate measured at noon (between 10:30 and 11:30 UTC) in 2012. Upper panel: Oslo. Mid panel: Andøya Lower panel: Ny-Ålesund.*

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.

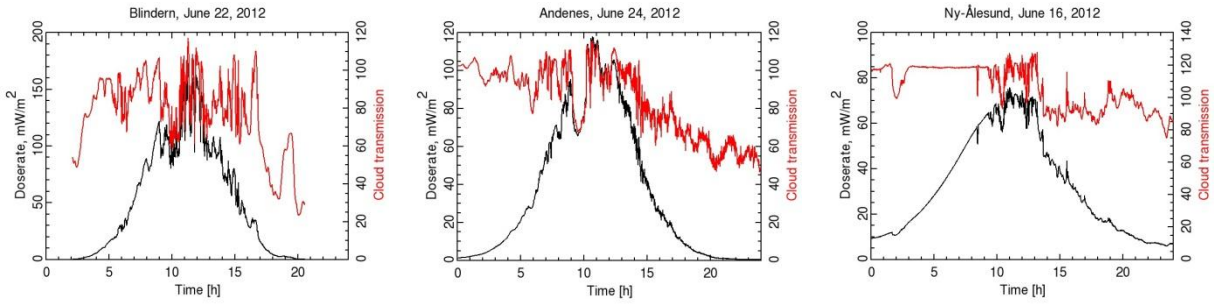

Figure 19: *UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel). A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30%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

Monthly mean noon UV doses for Oslo, Andøya and Ny-Ålesund in 2012 are compared in Figure 20. As expected, the monthly mean UV doses in Oslo were significantly higher than the values observed at Ny-Ålesund, except for June when the midnight sun in Ny-Ålesund contributes 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.

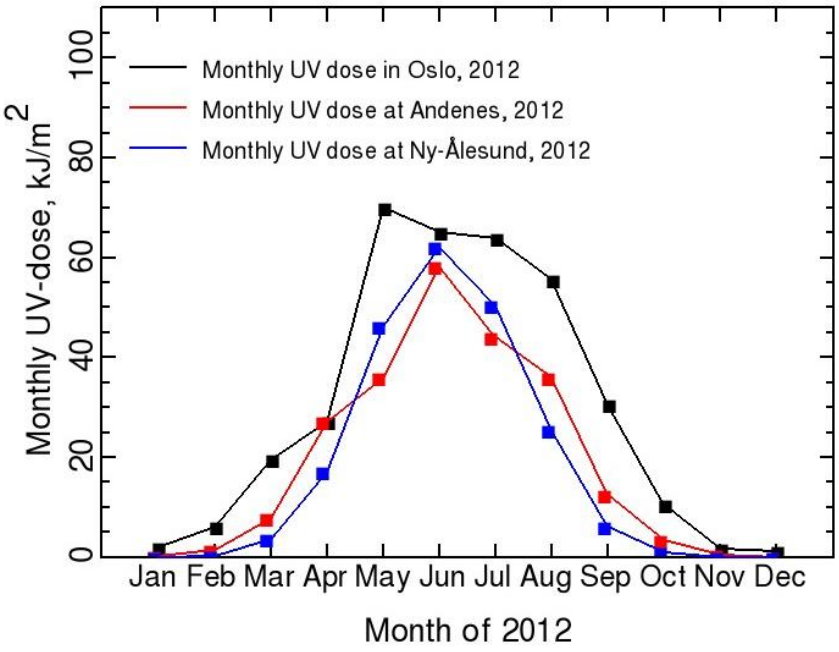

Figure 20: *Monthly mean UV doses (in kJ/m^2) in 2012 measured with the GUV instruments located in Oslo, Andøya and Ny-Ålesund.*

6.2 Annual UV doses 1995 – 2012

Annual UV doses for the period 1995–2012 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 are missing.

In 2012 the UV-doses in Oslo during summer were relative low. This can be explained by many overcast days in June and July. As shown in Figure 18 (upper panel) there were many days during the summer where the UV index in Oslo was below 2. Contrary to Oslo, there were few heavy overcast days in Ny-Ålesund in 2012. Thus, the monthly mean UVI for June is almost equal in Oslo and Ny-Ålesund (see Figure 20).

A graphical illustration of the yearly integrated UV-doses is shown in Figure 21 to show yearly fluctuations.

Table 11: *Annual integrated UV doses (in kJ/m^2) for Oslo, Andøya and Ny-Ålesund for the period 1995 – 2012.*

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

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

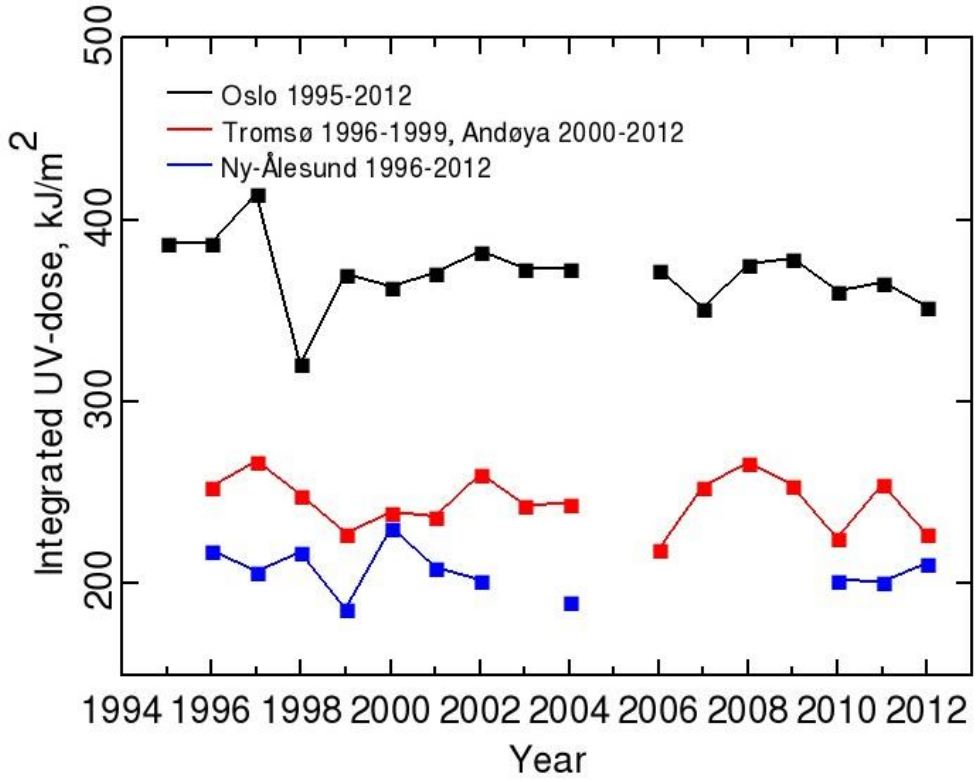

Figure 21: *Annual integrated UV doses (in kJ/m^2) at Oslo, Tromsø/Andøya and Ny-Ålesund for the period 1995–2012.*

7. References

Andreae, M.O., Rosenfeld, D., Artaxo, P., Costa, A.A., Frank, G.P., Longo, K.M., Silva-Dias, M.A.F. (2004*)* Smoking rain clouds over the Amazon. *Science, 303*,1337-1342.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C., Zhang, X. (2007) Couplings between changes in the climate system and biogeochemistry. In: *Climate Change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, H.L. Miller. Cambridge, Cambridge University Press.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R. (2007) Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller. Cambridge, Cambridge University Press.

Gröbner, J., Hülsen, G., Wuttke, S., Schrems, O., Simone, S. D., Gallo, V., Rafanelli, C., Petkov, B., Vitale, V., Edvardsen, K., Stebel, K. (2010) Quality assurance of solar UV irradiance in the Arctic. *Photochem. Photobiol. Sci., 9*, 384-391.

Hansen, J., Sato, M., Ruedy, R. (1997) Radiative forcing and climate response, *J. Geophys. Res., 102*, 6831-6864.

Henriksen, T., Svendby, T. (1997) Ozonlag, UV-stråling og helse. Department of Physics, University of Oslo.

Høiskar, B.A.K., Braathen, G.O., Dahlback, A., Bojkov, B.R., Edvardsen, K., Hansen, G., Svenøe, T. (2001) Monitoring of the atmospheric ozone layer and natural ultraviolet radiation. Annual report 2000. Kjeller (Statlig program for forurensningsovervåking. Rapport 833/01. TA-1829/2001) (NILU OR 35/2001).

Høiskar, B.A., Braathen, G.O., Dahlback, A., Edvardsen, K., Hansen, G., Stebel, K., Svendby, T., Vik, A.F. (2003) Overvåking av ozonlaget og naturlig ultrafiolett stråling. Årsrapport 2002. Kjeller (Statlig program for forurensningsovervåking. Rapport 881/2003) (TA-1972/2003) (NILU OR 33/2003).

IPCC (2007) Summary for policymakers. In: *Climate Change 2007: The physical science basis. contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, H.L. Miller. Cambridge, Cambridge University Press.

Johnsen, B., Mikkelborg, O., Hannevik, M., Nilsen, L.T., Saxebø, G., Blaasaas, K.G. (2002) The Norwegian UV-monitoring program, period 1995/96 to 2001. Østerås, Statens strålevern (Strålevern Rapport 2002:4).

Stamnes, K., Slusser, J., Bowen, M. (1991) Derivation of total ozone abundance and cloud effects from spectral irradiance measurements. *Appl. Opt*., *30*, 4418-4426.

Vogler, C., Bröonnimann, S., Hansen, G. (2006) Re-evaluation of the 1950–1962 total ozone record from Longyearbyen, Svalbard. *Atmos. Chem. Phys., 6*, 4763-4773.

WHO (2009) Ultraviolet radiation and human health. Geneva, World Health Organization (Fact Sheet No 305).
URL: http://www.who.int/mediacentre/factsheets/fs305/en/index.html.

WMO (2007) Scientific assessment of ozone depletion: 2006. Geneva, World Meteorological Organization (Global Ozone Research and Monitoring Project – Report No. 50).

WMO (2011) Scientific assessment of ozone depletion: 2010. Geneva, World Meteorological Organization, (Global Ozone Research and Monitoring Project – Report No. 52).

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Tittel - norsk og engelsk

Overvåking av ozonlaget og naturlig ultrafiolett stråling: Årsrapport 2012.

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2012.

Sammendrag – summary

Rapporten presenterer måledata for totalozon og UV-stråling over norske målestasjoner i 2012. For Oslo, Andøya og Ny-Ålesund er trenden i totalozon beregnet for perioden 1979-2012. Ozonverdiene over Norge var tilnærmet normale 2012, bortsett fra vinterverdiene i Oslo som var lavere enn normalt. 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 2012. In 2012 the ozone values above Norway were close to the long-term mean, except from the ozone winter values in Oslo which were lower than normal. 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	Stratospheric ozone
UV-stråling	UV radiation
Målinger og observasjoner	Measurements and observations
Montreal-protokollen	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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