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Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2011

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Monitoring of the atmospheric ozone layer and natural ultraviolet radiation

Rapport
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Annual report 2011

Author(s): T.M. Svendby, C.L. Myhre, K. Stebel, K. Edvardsen,
Y. Orsolini (all NILU), A. Dahlback (UiO)

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Preface

The ozone layer was discovered in 1913 by the French physicists Charles Fabry and Henri Buisson. The properties of ozone were then explored in detail by the British meteorologist G. M. B. Dobson, who developed a simple spectrophotometer (the Dobson instrument) that could be used to measure stratospheric ozone from the ground. Between 1928 and 1958 Dobson established a worldwide network of ozone monitoring stations, which formed the basis of the ozone network we have today.

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 the countries signed a treaty, The Montreal Protocol, with the aim of phasing out and finally stop the release of ozone depleting substances (ODS). Due to its widespread adoption and implementation it has been hailed as an example of exceptional good international cooperation which has been of large importance for our environment.

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

The Norwegian Institute for Air Research (NILU) 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 Climate and Pollution 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. Dr. Cathrine Lund Myhre is responsible for the monitoring program and was the main author of the annual report previous seven years. Prof. Arne Dahlback at the University of Oslo (UiO) is responsible for ozone measurements in Oslo. Kåre Edvardsen (NILU) is in charge of the UV measurements, whereas Kerstin Stebel (NILU) has analyzed lidar data at Andøya Rocket

Range and SAOZ ozone data at Ny Ålesund. Dr. Yvan Orsolini (NILU) has long experience in stratospheric circulation and has done extensive analyses of the special 2011 winter/spring ozone episode. Dr. Tove Svendby (NILU) is responsible for data submission to The World Ozone Data Centre (http://www.msc-smc.ec.gc.ca/woudc/) and is involved in the analysis of both ground based data, satellite observations and writing of the report.

Acknowledgment
A project jointly financed by The Norwegian Space Centre (Norsk Romsenter, http://www.romsenter.no/) and NILU put us in a position where we can 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.

Kjeller, August 2012

Cathrine Lund Myhre
Project leader and senior scientist, NILU

Contents

1. Summary

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 were further intensified when the Antarctic ozone hole was discovered in the mid 1980's (Farman et al., 1985).

In 1987 the Montreal Protocol was signed in order to reduce the production and use of these ozone-depleting substances (ODS). This international agreement has later been revised several times. Currently, 196 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 been declining slowly for most compounds. The ODS are expected to be back to pre-1980 levels around year 2050. In the stratosphere the peak was reached somewhat later, but measurements indicate that a small ODS decline has taken place in the stratosphere as well.

Without the Montreal protocol the ozone layer would probably have been dramatically destroyed. There are recent studies indicating that large ozone depletions in the Polar Regions would have become a year-round phenomena and ozone hole conditions would have developed also in the tropics, with full collapse of the ozone layer around the year ~2060. For mid-summer the study predicated an increase in the UV radiation of 5-10% for the year 2000 and a UV index (UVI) around 15 within year 2040 in Scandinavian regions. In 2065 the UVI would exceed a value of 30. UV-radiation at such high levels would cause serious damage to ecosystems and humans.

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 and detect other eventual changes in the ozone layer, possibly related to other factors than ODS, like climate change.

MAIN CONCLUSIONS FROM THE MONITORING PROGRAMME 2011

- **2011 was a year with generally low ozone values above Norway.**
- **In spite of low ozone values in 2011 the annual UV doses were not above normal. This was due to long periods with cloudy weather in the summer.**
- **A massive ozone loss was observed in the Arctic and most parts of Norway in the winter/spring 2011. The loss was caused by low stratospheric temperatures, vortex isolation, and halogen-driven chemistry, combined with weak transport of ozone from lower latitudes.**
- **The decrease in annual values of total ozone during the period 1979-1997 was 5.8%/decade at both Oslo and Andøya, with the strongest decrease, as large as 8,4 %/decade during the spring months.**
- **Since 1998 there has not been significant changes in the ozone layer trend above Norway, even with the low values in 2011.**
- **Meteorological variability has large impact on ozone and can give considerable year-to-year variations in total ozone.**

The national monitoring programme

The Climate and Pollution Agency (the former Norwegian Pollution Control Authority) established the programme "Monitoring of the atmospheric ozone layer" in 1990, which at that time included measurements of total ozone only. In 1995 UV measurements were also included in the programme. The Norwegian Institute for Air Research (NILU) is responsible for the operation and maintenance of the monitoring programme. NILU carried out different research projects which comprised monitoring of the ozone layer 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 analyzed. In 2011 the monitoring programme included measurements of total ozone and UV at three locations: Oslo (60°N), Andøya (69°N) and Ny-Ålesund (79°N). In addition some ozone profile (lidar) measurements have been performed at Andøya. The lidar measurements terminated in June 2011 due to lack of funding, thus only a few ozone profiles are available. This report summarises the activities and results of the monitoring programme during the year 2011. It includes trend analyses of total ozone for the period 1979-2011 for Oslo and Andøya and comments on the expected ozone recovery at northern latitudes. Further, total yearly UV doses for 2011 at Oslo, Andøya and Ny-Ålesund are included. The Norwegian UV network was established in 1994/95 and consisted until 2006 of nine 5-channels GUV instruments located from 58°N to 79°N. From 2006 to 2009 the instrument at Ny-Ålesund was excluded from the network, but it was included again in 2010. As a part of the 2011 monitoring programme NILU has been responsible for the daily operation of three GUV instruments located in Oslo, Andøya and Ny-Ålesund.

Total ozone

For the year 2011 the monthly mean ozone layer in Oslo and at Andøya was below the long term mean the whole year, particularly in February, March and April. In March the ozone layer was as much as 14% and 17% below the 1979-1989 average values in Oslo and at Andøya, respectively. In Ny-Ålesund a massive ozone loss was observed within the arctic vortex in March 2011, resulting in values 40 percent below the long-term mean.

The Arctic stratospheric winter temperatures in 2010/11 were fairly low, which enabled formation of polar stratospheric clouds (PSCs) between mid-December 2010 and early April 2011. This initiated chemical processes leading to massive ozone loss. Another possible contribution to the low ozone values was the disturbance of normal stratospheric transport of ozone from lower latitudes to the Arctic stratosphere.

The colourful mother of pearl clouds are polar stratospheric clouds(PSCs) observed above Lillestrøm in January 2005. (Geir Braathen, NILU.)

In spite of the low ozone values in 2011 our monitoring programme and trend analyses indicate that the minimum ozone levels over Norway were reached in the mid 1990s and that the ozone layer now is in a recovery phase. During the period 1979-1997 the annual average ozone layer above Oslo decreased by 5.8 % and as much as 8.4 % during spring. For Andøya the

decrease was similar. For the period 1998-2011 the ozone situation seems to have stabilized and no significant trends have been observed.

Recent global ozone data indicate that there are signs of ozone recovery in most of the world. However there is some uncertainty related to the recovery, particularly at high latitudes in the Northern Hemisphere, the Arctic region. The uncertainty is caused by the high natural variability in this region, and the influence of factors like decreasing temperatures in the stratosphere, which is partly due to the increase of greenhouse gases in the troposphere.

There are several available dataset with satellite ozone measurements over Norway. This is a great benefit and provides increased information on spatial ozone distribution. Comparisons of ground based measurements and satellite data in Oslo and at Andøya show good agreement during the summer, whereas the deviations are larger in the autumn and winter months. Also, there is fairly large deviation between individual satellites. Even if the satellite ozone data have improved significantly the last years, they can not replace the more reliable ground based network.

UV measurements

The highest UV dose rate in Oslo, 170 mW/m^2 occurred 29 June. This is equivalent to a UV index of 6.8. At Andøya the highest UV index, 4.6, was observed 12 June and at Ny-Ålesund an UV index of 2.4 was observed 13 June. In spite of the low ozone values in 2011 the annual UV levels were not above normal. This was mainly due to many overcast days in the summer 2011, especially in the southern part of Norway.

Further monitoring needs

To predict the future development of the ozone layer with acceptable confidence, longer data series and improved understanding of atmospheric processes and dynamics are needed. Long term monitoring is a fundamental basis in ozone studies, in combination with global modelling tools. In particular Arctic ozone is of national and international concern and needs to be monitored carefully. There are long time series with ozone observations at Svalbard that has not yet been fully analysed. These data would provide valuable information about the development of the ozone situation in the Arctic spring from 1991 until today, and would also be valuable for future ozone predictions.

2. Ozone measurements in 2011

Total ozone, i.e. the amount of ozone in a column from the ground to the top of the atmosphere, is measured on a daily basis in Oslo (60°N) and at Andøya (69°N). The ozone measurements are retrieved from Brewer spectrophotometers at both locations, except for periods with polar night at Andøya. The ozone profile at 8-45 km was also measured at Andøya until June 2011[1], providing information about the ozone altitude distribution during clear weather conditions. In addition we are analyzing total ozone data from various satellites to get a more complete description of the ozone situation in Norway and the Arctic region. Ground based total ozone measurements have also been performed at Svalbard/Ny-Ålesund from 1990 until today. The data analyses were excluded from the national monitoring programme from 2003 to 2010, but are now included in the programme again.

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 2011. The Brewers are also regularly calibrated against standard lamps in order to check the stability of the instruments. All the calibrations have indicated that both Brewer instruments have been stable during the years of operation. Calibration reports are available on request.

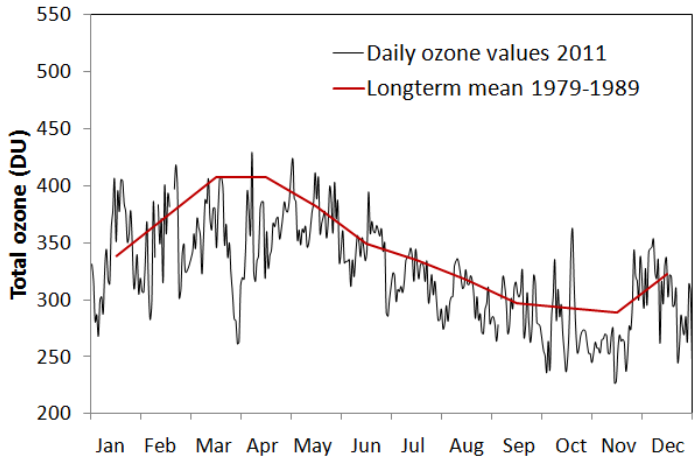

Figure 1a: *Daily total ozone values measured at the University of Oslo in 2011. The red curve shows the long-term monthly mean values from 1979-1989.*

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

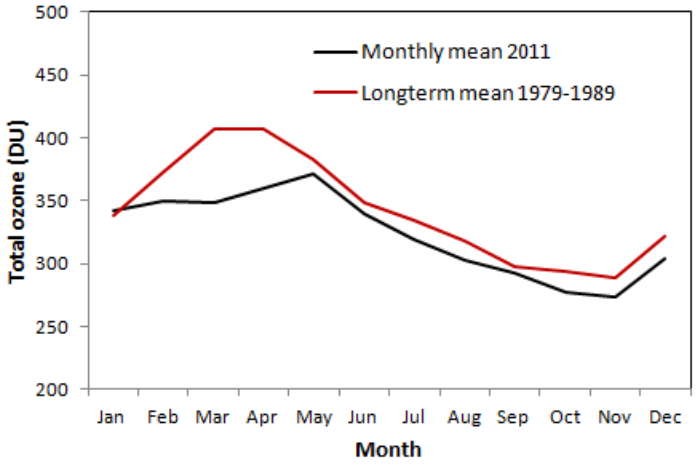

Figure 1b: *Monthly mean ozone values for 2011. The red curve shows the long-term monthly mean values from 1979-1989.*

2.1 Total ozone in Oslo

Figure 1a illustrates the daily total ozone values from Oslo in 2011. The black curve shows the daily measurements, whereas the red curve shows the long-term monthly mean values for the period 1979-1989. The total ozone values in 2011 are based on Brewer direct sun (DS) measurements when available. In 2011 direct sun measurements were performed 195 out of 365 days. During overcast days or days where the minimum solar zenith angle was larger than

[1] These measurements terminated from this month due to lack of funding.

72°, the ozone values were calculated from the global irradiance (GI) method (Stamnes et al., 1991). The Brewer GI method was used 159 days. During days with heavy clouds (low CLT) the Brewer GI retrieval gives too high ozone values. Thus, a CLT dependent correction was applied to all GI data before inclusion in the Oslo data series. In 2011 there were totally 12 days without Brewer DS or GI measurements, caused by bad weather conditions, instrument calibration or technical problems. These days the ozone values were usually retrieved from the GUV-511 instrument, which is located next to the Brewer instrument at the University of Oslo. The GUV data were harmonized with respect to the Brewer DS measurements before including them in the 2011 ozone time series. February 19 and 20 no ground based ozone observations were available in Oslo due to instrumental problems.

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 2011 was 227 DU, measured 14 November. This is more than 20% below the long-term mean for November. In the end of March there were a few days where the ozone values in Oslo were around 35% below the long-term mean. This ozone loss coincided with the "ozone holes" observed in the Arctic in spring 2011 (see chapter 3.5).

The monthly mean total ozone values for 2011 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 2011 ozone values were below the long-term mean all months, except for January where the monthly average ozone value was 1% higher. Section 3.4 gives a broader discussion and interpretation of the ozone situation in Norway in 2011.

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

From April to September 2011 there were 5 days without total ozone observations at Andøya. In addition there was a period with polar night when reliable ozone measurements only could be achieved from lidar. Table 1 gives an overview of the different instruments and methods that were used at Andøya in 2011.

Table 1: *Overview of instruments and methods applied for retrieval of the total ozone at Andøya in 2011.*

Priority	Method	Total days with observations
1	Brewer instrument, direct sun measurements	84
2	Brewer instrument, global irradiance method	142
3	GUV instrument	45
	Lidar (measurements during the Polar night)	7

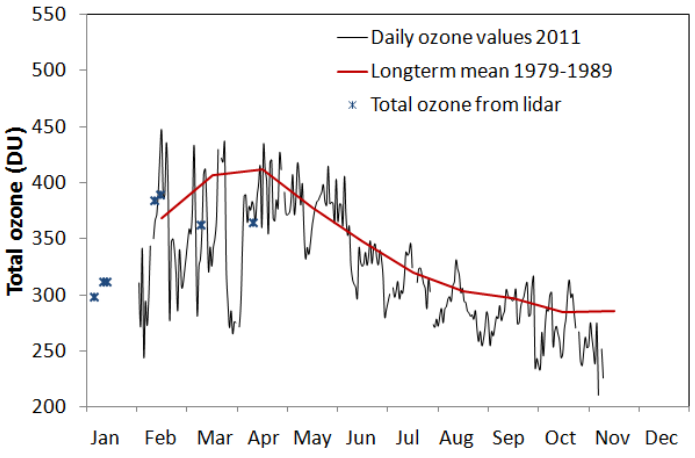

Figure 2a: *Daily total ozone values measured at ALOMAR, Andøya, in 2011 by the Brewer/GUV instruments (black curve) and the LIDAR instrument (blue stars). The red line is the long-term monthly mean values from 1979-1989.*

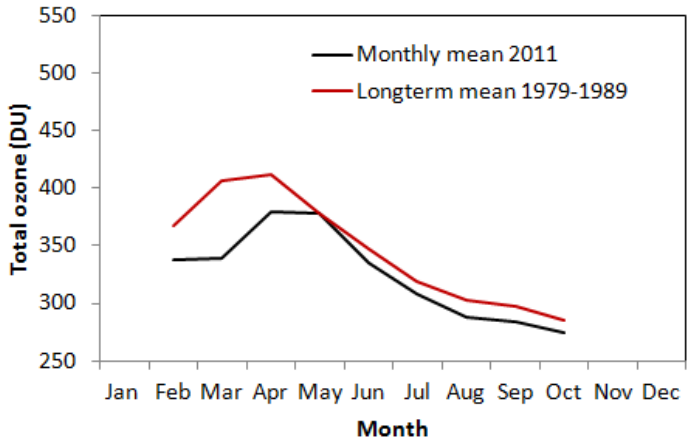

Figure 2b: *Monthly mean total ozone values for 2011 (black curve) compared to the long-term monthly mean values for the period from 1979-1989 (red curve).*

Figure 2a) shows daily ozone values from Andøya in 2011. 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 values during the polar night (mid November to mid February) were occasionally retrieved from the ozone lidar at ALOMAR. These measurements are indicated by blue stars. The lidar data give a good picture of the ozone variation during the winter months when Brewer and GUV measurements not are achievable. The lowest ozone values at Andøya normally occur in October and November, and the minimum ozone value in 2011 was 210 DU, measured 11 November. This is more than 25% below the long-term mean for November

Monthly mean ozone values at Andøya for 2011 are shown in Figure 2b). For January, November, and December (polar night) there are not sufficient data to calculate monthly means. Comparison between the long-term mean and monthly mean ozone values for 2011 shows that the ozone values were low the whole year. The month of May is the only exception, where the monthly average ozone value was equal to the long-term mean. March sticks out as an extreme month where the monthly mean ozone value was about 70 DU lower than normal. Also in February and April the ozone values were far below the long-term average. As indicated by the blue stars in Figure 2a, the ozone values at Andøya were also low in January. However, only three lidar measurements were performed this month, which is not enough data to calculate a representative monthly mean value for this month.

2.3 Total ozone column observations in Ny-Ålesund

For the winter season 2010/11 record high ozone loss was retrieved from measurements within the Systeme d'Analyse par Observation Zenitale (SAOZ) network. The network consists of eight zenith sky visible spectrometer distributed in the Arctic region. NILU's instrument in Ny-Ålesund is located at the observation platform of the Sverdrup Station of the Norwegian Polar Institute. Measurements were started up in 1990 and were continued until the present time with a few exceptions, one of which was repair and maintenance of the instrument during winter 2010/11 at LATMOS/CNR. Until 2002 total ozone column observations from Ny-Ålesund were funded and reported to Klif (see Høiskar et al., 2003). These 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%. Here, we report the observations made during 2011. Homogenization of all data (V2 data version) and time-series analysis of data from all years is ongoing and will be reported to Klif in 2013.

Total ozone columns derived from the SAOZ instrument are shown in Figure 3 (left panel). As described in section 3.5 the period with low total ozone columns around the end of March, going down to 263 DU during sun-rise measurements on March 31 2011, is evident in the observations.

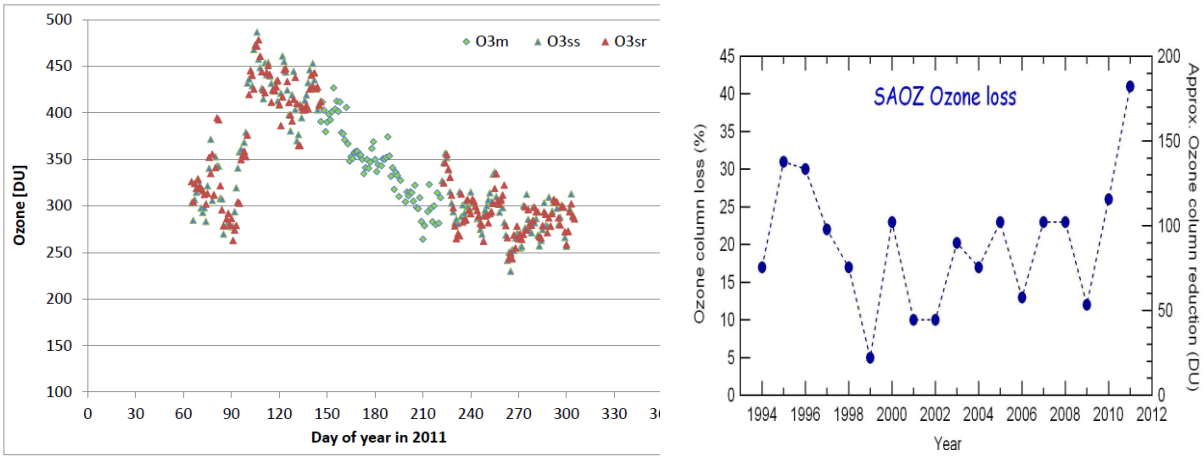

Figure 3: *Left panel: Total ozone column during 2011 above Ny-Ålesund derived from SAOZ observation. The brown and blue triangles mark the sun-rise and sun-set values, respectively. During summer month the values are complemented by observations from the GUV instruments (noon-values). Right panel: Ozone loss derived from the SAOZ network (Image from Goutail et al., 2011).*

Using the whole SAOZ network, chemical ozone reduction can be deduced from a comparison between ground-based total ozone measurements and a 3D model simulation in which ozone is considered as a passive tracer. The method allows determining the period of ozone destruction and the amplitude of the cumulative loss (see poster from Goutail et al., 2011, for more details). In 2010/11 record high ozone loss was observed in the Arctic vortex. The total ozone reduction within the polar vortex was as high as 41% ± 3% or ~165 DU.

Loss rates were estimated as 0.2% per day until mid-February, and 0.8% per day between February 20 and March 20. A comparison of ozone column losses during spring 2011 with earlier winters is shown in Figure 3 (right panel, *Image from Goutail et al., 2011*), clearly illustrating the uniqueness of this Arctic winter season 2010/11.

2.4 Stratospheric ozone-profile measurements made in 2011 by means of the ozone lidar at ALOMAR (69°N, 16°E)

2.4.1 Lidar measurements

Ozone profile measurements utilizing a stratospheric ozone lidar started during winter 1994/95 at the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR, Andøya, 69°16'N, 16°00'E, 380 m a.s.l.). The lidar was built as a classical Differential Absorption Lidar (DIAL) operating at two wavelength 308 nm (ozone absorption is strong) and 353 nm (weak ozone absorption). The system was upgraded with a daylight receiver and new receiving electronics, in 1998 and 2008, respectively. Operations were terminated end of June 2011 due to lack of funding.

The instrument was used to monitor stratospheric ozone, temperatures, and Polar Stratospheric Clouds (PSCs). Ozone density profiles were derived with the DIAL method. The retrieval used for the data analysis is described in Hansen et al. (1997). During night-time conditions typically two hours of measurements were needed for the retrieval of an ozone profiles in the height range between 8 and 45 km. The data contributed to the NDACC, the Network of Detection of Atmospheric Composition Change (see www.ndacc-lidar.org).

In 2011 measurements have been performed on seven days during clear sky night-time conditions. No funding has been available for daylight operations (the need for alignment of the system makes daytime operation more person-intensive). In total seven quality controlled ozone profiles have been retrieved from the observations. The specific days are summarized in Table 2.

***Table 2**: Overview over days with stratospheric ozone profiles retrieved in 2011.*

Month	Ozone profiles
January	04, 10, 12
February	10, 14
March	11
April	05
May – June	no daylight measurements

2.4.2 Stratospheric temperatures (from ECMWF data) and polar stratospheric cloud observations during winter 2010/11

Polar stratospheric clouds (PSCs) have been monitored with the ozone lidar since 1994/95. PSCs occur in different compositions and physical shapes. They form when the temperature in the stratosphere drops below 195K during the polar winter. Originally they were classified according to their occurrence above (type I) and below (type II) the water ice frost point (T_{ice}). Type I PSCs were later on sub-classified into non-spherical solid particles (type Ia) and spherical liquid particles (type Ib). Besides the actual temperatures, an important factor steering PSC formation is the temperature history of the air mass.

Chemical reactions occurring on the PSC surfaces can transform passive and innocuous halogen compounds (e.g. HCl and HBr) into active chlorine and bromine (e.g. ClO and BrO). Under sunlit conditions these active species react with ozone through catalytic cycles and thereby cause rapid ozone destruction.

Stratospheric temperatures during the last 15 winter seasons at around 20 km altitude above Andøya are shown in the left panel of Figure 4. The data are retrieved from the European Centre of Medium Range Weather Forecast (ECMWF). The green line shows temperatures during winter 2010/11 (the data stop in early January due to end of funding). Dates on which the ozone lidar at ALOMAR has been operated are marked with black symbols "+". Measurements made during days where PSCs have been observed are indicated by red symbols. Only on 4 January 2011, PSC measurements utilizing the ozone lidar were made. The averaged backscatter profile (at 353 nm) of this PSC observation is shown in the right panel of Figure 4.

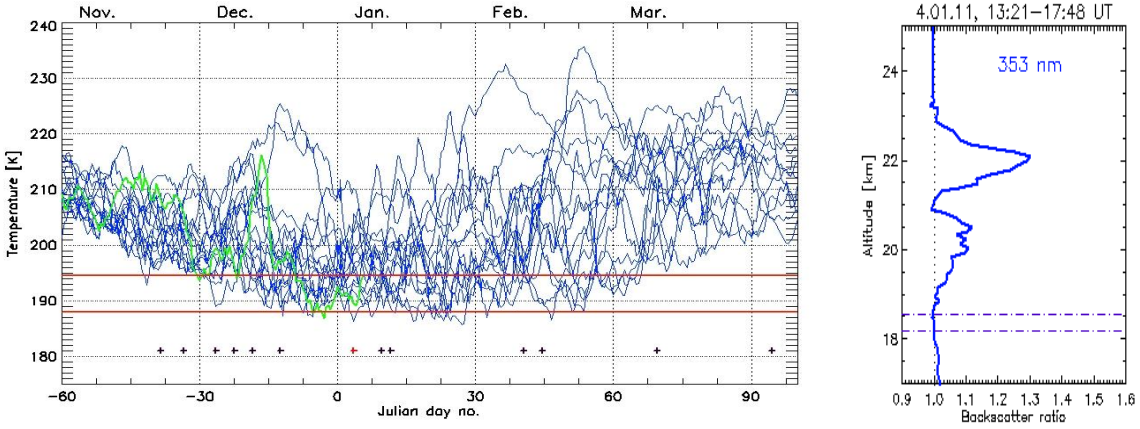

Figure 4: *Left panel: Stratospheric temperatures at an altitude of ca. 20 km for the years between 1995/96 and 2010/11 (data from ECMWF). The temperature development during winter 2010/11 is highlighted in green. The two vertical red lines indicate roughly the temperature thresholds needed for PSC type I (NAT) and II (ice) formation. Days with lidar observations are marked with black "+" symbols, PSCs observed by lidar are indicated by red "+" symbols. Right panel: Polar stratospheric cloud observations in January 2011. Shown is the averaged backscatter profile (at 353 nm). The dashed dotted horizontal lines indicate the normalization range used for the data analysis.*

In the Arctic winter 2010/11 stratospheric temperatures were low enough for PSC formation between mid-December 2010 to early April 2011. The region with low stratospheric temperatures was centered in the European Arctic during end of December and the first and only PSC observation utilizing the ozone lidar during this winter was made 4 January, 2011. After that there was no more match between operations of the lidar (clear night-sky conditions) and low enough stratospheric temperatures (location of the cold pool/polar vortex).

The lidar observations document the large inter-annual variability in PSC occurrence at the northern Scandinavian observatory. An overview of days on which PSCs have been observed with help of the ozone lidar during the last 16 winters is shown in Table 3. PSCs have been measured between 1 December (in 2002) and 21 February (in 2005). The numbers of days on which PSCs have been seen vary between zero (winter 1998/99, 2001/02, 2003/04 and

2006/07) and 12 (in early 1996). Very different stratospheric winters have occurred in recent years: warm winters with very low PSC formation potential (1998/99, 2001/02, and 2005/06, and 2008/09) and very cold winter with long periods of temperatures low enough for PSCs to form (1994/95, 1995/96, 2009/10, and 2010/11).

Table 3: *List of days with PSCs seen by means of the ozone lidar at ALOMAR.*

Winter	December	January	February
1995/96	-	5, 7, 9, 11, 17, 18, 23, 24	12, 13, 16, 17
1996/97	-	7, 16, 19	9/10
1997/98	-	16/17	-
1998/99	-	-	-
1999/00	21	21, 22, 26, 29	6
2000/01	-	21, 23	-
2001/02	-	-	-
2002/03	1, 2, 3, 4, 5, 7, 16, 25	9	5
2003/04	-	-	-
2004/05	-	5, 6, 24	7, 13, 14, 15, 20, 21
2005/06	6, 19, 20, 29, 31	6, 9	-
2006/07	-	-	-
2007/08	-	14, 17, 18, 21, 22, 23	4
2008/09	15	-	-
2009/10	-	14, 15, 20, 21, 22	-
2010/11	-	4	-

2.4.3 Ozone profile measurements from lidar and ozone sondes

The development of the stratospheric ozone layer above Andøya and surrounding areas until early summer 2011 is illustrated in Figure 5. The profile measurements are combinations of lidar observations at Andøya and ozone sonde launches at Sodankylä in Finland. For comparison stratospheric ozone profiles in 2010 is shown (Figure 5, right panel).

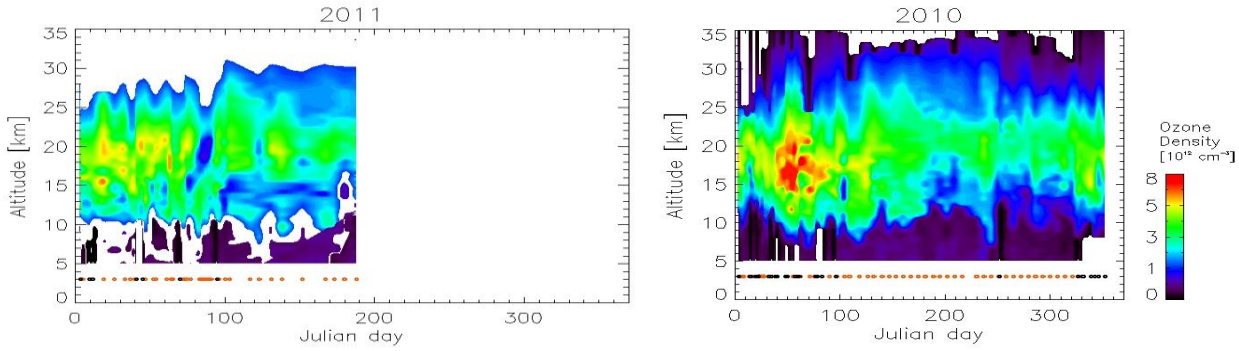

Figure 5: *Development of the stratospheric ozone layer in spring 2011 (left panel) and 2010 (right panel), derived from profiles measured by the ALOMAR ozone lidar and ozone sondes launched in Sodankylä, Finland (courtesy to the Finnish Meteorological Institute). The black dots at the bottom of the plot mark the times when lidar measurements were performed, while the red dots mark days where data from ozone sondes launched from Sodankylä were used. Between the individual measurements the data were linearly interpolated and smoothed with a one-week median filter.*

The lidar measurements document the large inter-annual variability in spring-time ozone depletion in the Arctic. During winter 2009/10 largely enhanced ozone values were observed in February with total ozone values - retrieved from ozone lidar observations - reaching up to 550 DU on February 26. In contrast the ozone values in 2010/2011 were clearly lower than average, in particular during a period end of March 2011. This is visualized by the blue shaded area at about 20 km altitude in Figure 5. During Julian days 80-90 the ozone column densities were as low as $1.5 \cdot 10^{12}$ cm^{-3}. For more explanation of this unusual Arctic winter see section 3.5.

3. Ozone measurements and trends for 1979–2011

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.

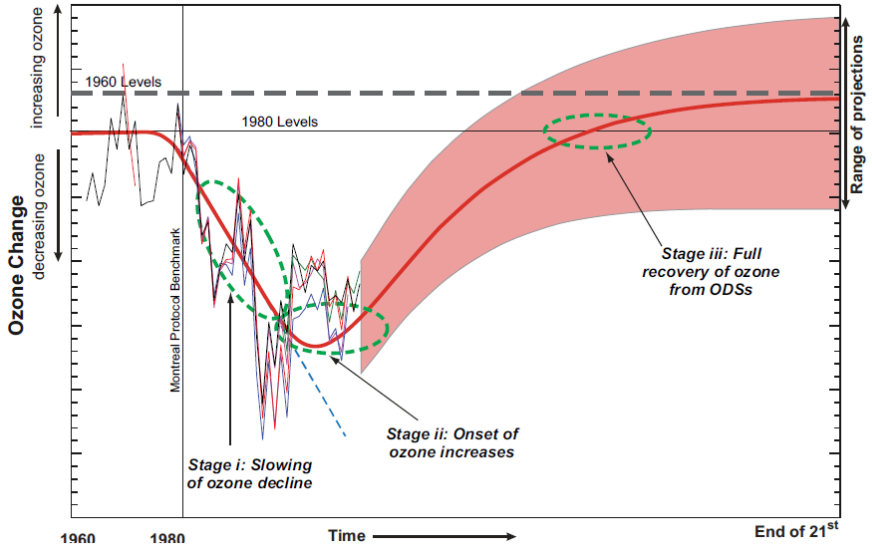

***Figure 6**: Total ozone at latitudes 60°N to 60°S for the period 1960 to 2100 (the x-axis is not to scale). The thick red line is a representation of the ozone amounts observed to date and projected for the future. The red-shaded region represents the model results predicted for the future. The 1980 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 6 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 the years the stratospheric temperatures are low, exemplified with the different situations in spring 2010 (record high ozone values) and the record minimum levels in winter 2011 (not a part of the WMO report).

According to the 2011 Assessment report (WMO, 2011) the Antarctic springtime ozone column does not yet show a statistically significant increasing trend. Year-to-year variability, due to meteorology, is much larger than the response to the small ODS decreases within the Antarctic vortex. Model simulations show that greenhouse gas changes have had, and will continue to have, a small impact on the ozone hole compared to the effect of ODS changes. In spring and early summer, Antarctica will continue to experience elevated surface UV levels the next decades. There are also some evidences that the Antarctic ozone hole has affected the surface climate in the Southern Hemisphere. Climate models demonstrate that the ozone hole is the dominant driver of the observed changes in surface winds over the Southern Hemisphere mid and high latitudes during austral summer. These changes have contributed to the observed warming over the Antarctic Peninsula and cooling over the high plateau. The changes in the winds have also been linked to regional changes in precipitation, increases in sea ice around Antarctica, warming of the Southern Ocean, and a local decrease in the ocean sink of CO_2.

In Arctic 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 2011 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.

The broad red-shaded area in Figure 6 which represents the range of future ozone predictions, illustrates the uncertainty in many factors affecting the ozone layer. Stratospheric halogen loading is expected to remain the most important factor affecting future stratospheric ozone, and their future trends are connected with uncertainty. One important ODS group is the HCFCs (chlorine containing halocarbons replacing CFCs). At the 2007 Meeting of the Parties to the Montreal Protocol, the parties agreed on a nearly full phase-out of HCFCs in developing countries within 2030. Many of these compounds are still increasing significantly, which is also evident from our measurements at Zeppelin (Myhre et al., 2012). Another uncertainty factor is the future concentrations of the long-lived greenhouse gases nitrous oxide (N_2O) and methane (CH_4). Natural ozone loss in the absence of chlorine is primarily due to the reactions involving nitrogen (NO_x) and hydrogen (HO_x) radicals. NO_x and HO_x levels are controlled by the amount of N_2O, H_2O, and CH_4. CH_4 and N_2O are both increasing due to human activity. Also anthropogenic enhancements of stratospheric sulphate aerosols, from increased surface sulphur emissions and possible geo-engineering actions, are important for the future ozone level. According to WMO (2011) the additional stratospheric sulphate aerosols from a possible geo-engineering action would have large impacts on the future evolution of stratospheric ozone, as sulphate aerosols act as PSCs and can initiate massive ozone loss. Finally, better understanding of atmospheric dynamics and circulation is likely to improve future ozone predictions. In total, the increase in greenhouse gas emissions and subsequent changes in climate, including cooling of the stratosphere, is an overarching theme linking many of the factors that will affect the future ozone layer. According to the assessment report it will be challenging to attribute ozone increases to the decreases in ODSs during the next few years because of natural variability, observational uncertainty, and the confounding factors mentioned.

Studies of long-tem trends of ozone, as presented in the sections 3.2 and 3.3, are essential in the assessment of the ozone recovery.

3.1.2 What would have happened to the ozone layer without the Montreal protocol?

In 2009 it was published a comprehensive and interesting paper in the journal *Atmospheric Chemistry and Physics* that investigates the broad effects and consequences if chlorofluoro-carbons had not been regulated through the Montreal protocol (Newman et al., 2009). Newman and his co-workers uses a state of the art radiation-chemical-dynamical model to simulate a future world were the ozone depleting substances (ODS) never were regulated. In their study they allowed the ODSs to grow at a rate of 3% per year. This is a modest growth as the annual CFC production rate up to 1974 was as high as 12-17%. Their simulations showed that 17% of the globally-averaged column ozone would be destroyed by 2020, and 67% would be destroyed by 2065 in comparison to 1980. Large ozone depletions in the polar region would become year-round rather than just seasonal and very large temperature decreases were found in the stratosphere in the tropics in response to circulation changes and decreased shortwave radiation absorption by ozone. This led to heterogonous chemical destruction of ozone also in the tropical region similar to the present processes occurring in Antarctica. The result was a full collapse in the tropical ozone approaching zero by the year 2058. In response to the dramatic ozone changes, ultraviolet radiation would increase substantially globally: For mid-summer an UV increase of 5-10% was calculated for the year 2000 and later a UV index around 15 was reached within the year 2040 and exceeding a value of 30 by the year 2065 (see Table 9 at page 36 for description of UV index.) The UV increase would more than double the erythemal dose in the summer mid latitudes by 2060.

3.2 Trends for Oslo 1979 – 2011

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 instrument is yearly calibrated by the International Ozone Services, Canada, and the calibrations reveal that and the instrument has been stable during the 22 years of operation. The entire set of Brewer DS measurements from Oslo was re-evaluated and submitted to The World Ozone Data Centre in 2010.

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 (see Figure 7).

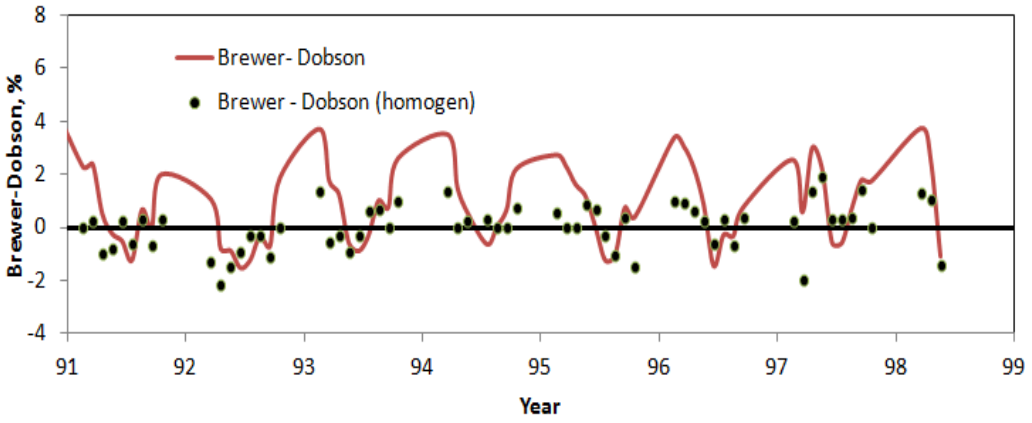

Figure 7: Monthly mean percentage difference between Brewer and Dobson 1991-1998. The red curve shows the original difference whereas the black dots represent the percentage difference after a seasonal correction factor is applied to the Dobson data.

There is an ongoing process coordinated trough WMO assessing the Brewer/Dobson differences and recommendations for data analysis (http://igaco-o3.fmi.fi/ACSO/). For the Oslo site we have chosen a common approach, i.e. applied a seasonal correction function to all Dobson measurements. As indicated by the red line in Figure 7 the Dobson values are too low during winter and too high during summer compared to Brewer. Thus, a seasonal correction function is applied to the entire Dobson ozone time series from 1978 to 1998. Differences between monthly mean Brewer and ozone corrected Dobson data are visualized by the black dots in Figure 7. The homogenized Oslo time series is used in all ozone analyses presented in this report

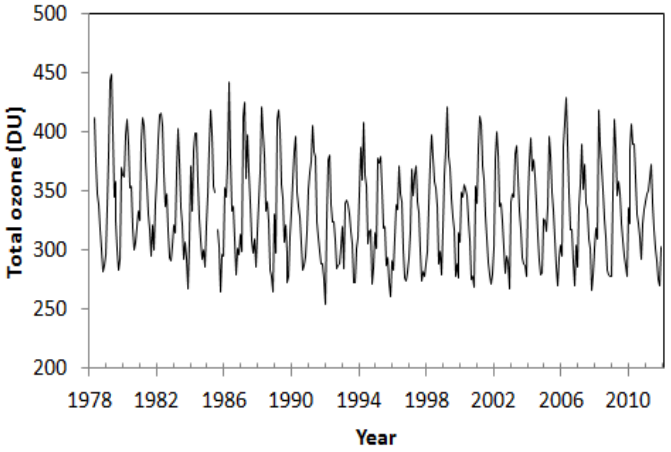

Figure 8a: *Time series of monthly mean total ozone in Oslo 1979-2011.*

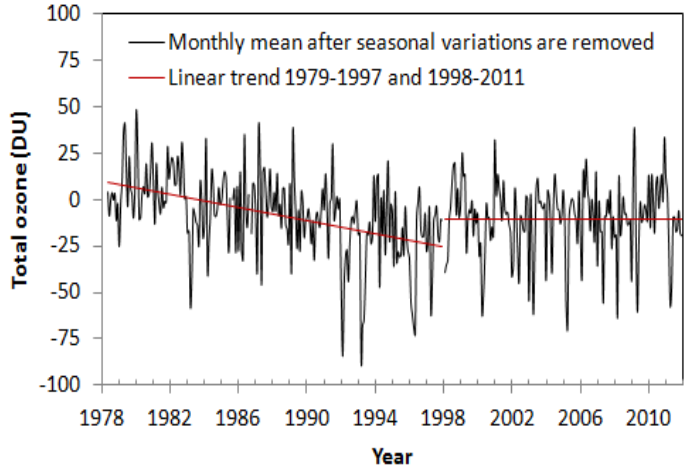

Figure 8b: *Variation in total ozone over Oslo for the period 1979–2011 after the seasonal variations have been removed. Trend lines are including in red.*

Figure 8a shows the variations in monthly mean ozone values in Oslo for the period 1979 to 2011. 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 trends analyses for the period 1979 - 2011 we have removed the seasonal variations by subtracting the long-term monthly mean ozone value from the data series, shown in Figure 8b. Next, we have divided the time series into two periods: 1) 1978-1997, and 2) 1998-2011. For the first time period the ozone measurements are 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 is based on Brewer measurements, with some additional 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 1998-2011 the picture is different. This is a shorter time period, only including 14 year, and due to 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 2.2% /decade during the last 14 years, whereas the ozone trend is correspondingly positive (1.9%/decade) for the fall. The total ozone was very low most of 2011, which has strongly affected the 1998-2011 trend results. For example, the ozone winter trend from 1998-2010 was as large as 4.5%/ decade. When 2011 was included in the trend analysis the positive winter trend decreased to 1.0%/ 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 2011 is close to zero.

Table 4: *Percentage changes in total ozone per year for Oslo for the period 1.1.1979 to 31.12.2011. 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) 1998-2011
Winter (Dec – Feb)	-6.2 (2.4)	1.0 (3.2)
Spring (Mar – May)	-8.4 (1.4)	-0.3 (2.9)
Summer (Jun – Aug)	-3.4 (1.1)	-2.2 (1.5)
Fall (Sep – Nov)	-4.3 (1.0)	1.9 (1.8)
Annual (Jan – Dec):	-5.8 (1.0)	0.1 (1.5)

3.3 Trends for Andøya 1979 – 2011

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.

Figure 9a shows the variations in the monthly mean ozone values at Andøya from 1979 to 2011. 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 1979-2011, after removing the seasonal variations, are shown in Figure 9b together with the annual trends. October – February months are not included in the trend analysis due to lack of data and uncertain ozone values during seasons with low sun. Simple linear regression lines have been fitted to the data in Figure 9b. Similar to the Oslo site we have chosen to divide the ozone time series into two periods: 1) 1979-1997, and 2) 1998-2011. The results of the trend analysis are summarized in Table 5. Comparison of Figure 8b and Figure 9b shows that the trend patterns from Andøya have many similarities to the Oslo trend pattern.

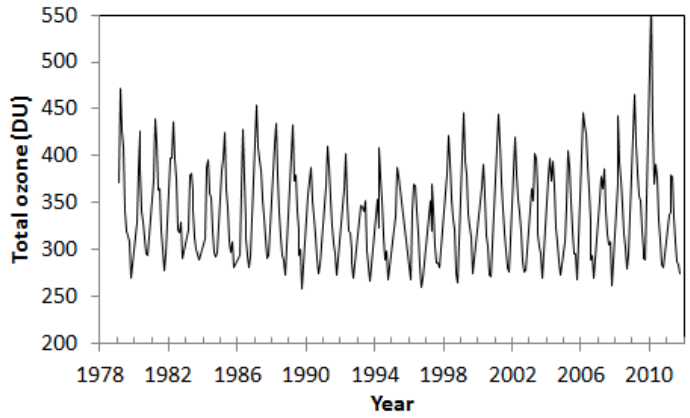

Figure 9a: *Time series of monthly mean total ozone at Andøya/Tromsø 1979–2011.*

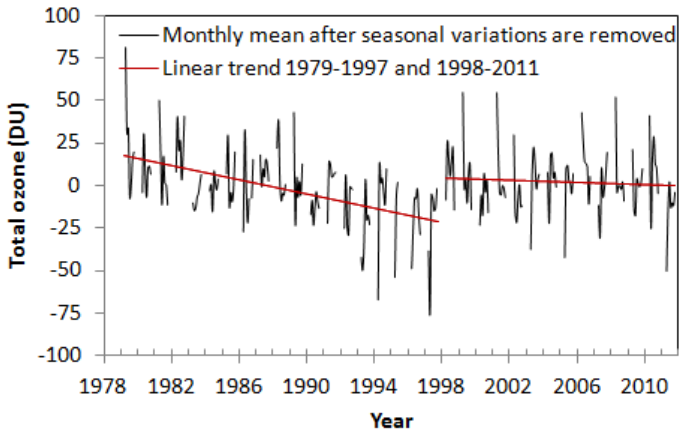

Figure 9b: *Variations in total ozone at Andøya for the period 1979–2011 after the seasonal variations are removed. Only data for the months March–September are included.*

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 2011. For this period an ozone decrease of 2.3%/decade was observed for the spring, whereas a trend of -1.0%/decade was found for the summer months. The annual trend for the period 1998-2011 was -1.0% /decade. However, these results are not significant at neither 1σ nor 2σ significance level.

Table 5: *Percentage changes in total ozone per decade at Andøya for the periods a)1979-1997, and 2) 1998-2011. The numbers in parenthesis gives the uncertainty (1σ). A trend larger than 2σ is considered to be significant. Data from the Dobson and Brewer instruments have been used in this study, in addition to a few GUV data.*

Season	Trend (% /decade) 1979-1997	Trend (% /decade) 1998-2011
Spring (Mar – May):	-8.4 (1.5)	-2.3 (2.6)
Summer (Jun – Aug):	-2.8 (0.9)	-1.0 (1.6)
Annual (Mar – Sep):	-5.8 (1.0)	-1.0 (1.6)

3.4 The ozone situation above Norway 2011

Figure 10 (Oslo) and Figure 11 (Andøya) show the percentage difference between yearly mean total ozone and the long-term yearly mean for the period 1979 to 2011. 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.

The Figure shows that the low ozone values in the 1990's contribute strongly to the observed negative trends in total ozone above Oslo. It is also worth mentioning that the values for the last 14 years are more negative than presented in previous ozone reports. This is related to the update of the Dobson ozone series (see Figure 7). All Dobson winter values have been increased to harmonize Brewer DS measurements. This has resulted in overall higher ozone winter values for the years 1979-1989, which represent the long–term ozone reference period. During the last 20 years only 2010 had an above normal annual mean ozone value. As seen from
Figure 10 the annual mean in 2011 was almost 6% below the long-term mean.

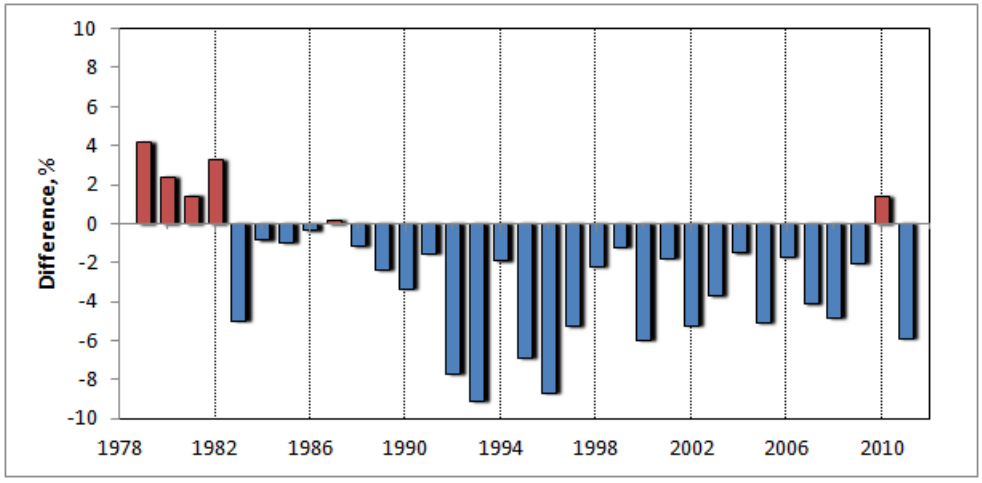

Figure 10: *Percentage difference between yearly mean total ozone in Oslo and the long-term yearly mean for 1979-1989.*

The percentage difference between yearly mean total ozone and the long-term yearly mean at Andøya is shown in Figure 11. For 2011 the yearly mean ozone value was 6.0% below the long-term yearly mean value for the period 1979–1989. This is similar to the yearly mean difference found in Oslo. Comparison of Figure 10 and Figure 11shows that the ozone patterns in Oslo and at Andøya have several similarities. At both sites high ozone values were measured in the end of the 1970s and in 2010. Also, both sites had record low ozone values in 1993 (9% below the long-term 1979-1989 mean) and low ozone values in 2011 (about 6% below the long-term yearly mean value for the period 1979-1989).

Table **6** gives the percentage difference between the monthly mean total ozone values for 2011 and the long-term monthly values. Both Oslo and Andøya are listed in the table. Again the ozone situations were similar in Oslo and at Andøya in 2011, where the ozone values in general were low throughout the year. In particular February, March and April were consider-

able below the long-term mean. In Oslo and at Andøya the ozone levels were as much as 14.1% and 16.5% below the long-term mean in March. In 2010 the opposite situation occurred with very high ozone values in February and March, especially at Andøya.

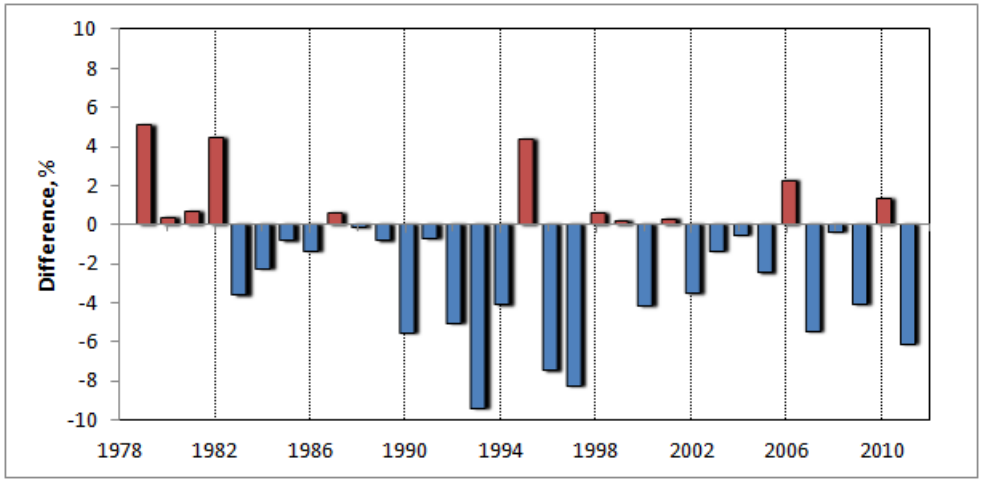

Figure 11: *Percentage difference between yearly mean total ozone at Andøya and the long-term yearly mean for 1979-1989 for the months March-September.*

Table 6: *Percentage difference between the monthly mean total ozone values for 2011 and the long-term mean for Oslo and Andøya.*

Month	Oslo (%)	Andøya (%)
January	0.9	
February	-6.7	-8.2
March	-14.1	-16.5
April	-11.5	-7.8
May	-2.5	0
June	-2.7	-3.5
July	-5.2	-3.4
August	-5.1	-5.0
September	-2.0	-4.2
October	-6.2	-3.8
November	-6.7	
December	-5.9	

As will be described in the next chapter the low ozone values observed in the winter/spring 2011 was a result of weak ozone transport and halogen-induced ozone depletion. The polar stratospheric vortex[2] leads to chemical ozone destruction when air masses, quasi-isolated in the polar vortex, are illuminated by sunlight. Sunlight initiates the formation of active chlorine and bromine compounds (e.g. HCl and HBr) by heterogeneous chemistry on polar

[2] During the winter there is no sunlight in the Arctic and so the lower stratosphere becomes very cold. Thermal gradients around the Arctic cold pool give rise to an enormous cyclone that is referred to as the polar stratospheric vortex. It is in the core of the polar vortices that winter- and springtime ozone depletion occur.

stratospheric clouds (PSC). The active chlorine and bromine reacts with ozone and results in severe ozone depletion. The PSCs are fundamental for the chemical ozone destructions observed in Antarctica and the Arctic. There are two main types of PSCs, called PSC I and PSC II. The approximate threshold formation temperature for type I is 195 K (-78°C) and for type II 188 K (-85°C) and the first Arctic observation of PSC type II, which consist of relatively pure water crystals, was in 2005.

As described in 3.1.1 a colder upper stratosphere is a suggested feedback to the increased level of greenhouse gases in the troposphere, and the concentrations of water vapour will likely increase due to enhanced methane concentrations. Thus, it is important to detect signs of climate changes and their influence on the occurrence of PSCs and particularly the abundance of PSC type II. However, ozone observations the latest years clearly manifest the great variability of the ozone layer over Northern regions (WMO, 2011; Weatherhead and Andersen, 2006).

3.5 Total ozone loss during the Arctic winter and spring 2010/11

In 2011, the Arctic ozone reached a record low driven by cold temperatures, vortex isolation, weak ozone transport from lower latitudes, and halogen-driven chemical loss. Ozone columns were as much as 40% lower than their long-term averages. The Arctic ozone deficit first appeared in late January and reached a maximum in late March before the breakdown of the polar vortex in early April. Figure 12 (left panel) shows that the O_3 column measured by the GOME-2 satellite instrument on 30 March 2011 is in excellent agreement with model results from the Oslo chemical transport model, CTM2 (middle panel). It also shows in the right panel, the modeled column O_3 loss inferred from the difference between a full chemistry model run and a run without ozone-depleting chemistry north of 60°N. By 30 March 2011, the average O_3 loss north of 60°N is ~65 DU, while the vortex average loss (within the black solid line) is ~93DU.

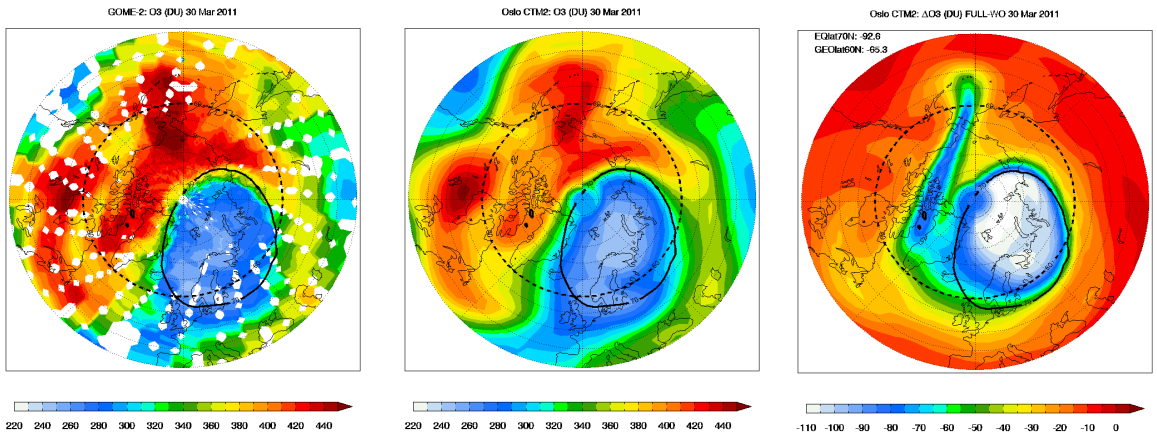

Figure 12: *O3 column on 30 March 2011 as observed by the GOME-2 satellite instrument (left) and modelled by Oslo CTM2 (middle), and the corresponding column O_3 loss (right) calculated as a difference between the full chemistry run and the run without chemistry north of 60°N. Black solid line is the 70°N equivalent latitude marking the vortex edge, while black dashed line is drawn at 60°N (Adapted from Isaksen, I., et al., to be submitted, 2012).*

While halogen-induced ozone depletion was record high for the Arctic, it appears that dynamics was important in setting the scene for the low ozone amount (Balis et al., 2011). The respective roles of transport and chemical loss during 2010 and 2011 are compared in

Figure 13, in simulations with the CTM2. The top panel of Figure 13 shows modelled column ozone averaged north of 60°N through January, February and March 2010 (dotted line) and 2011 (full line) in simulations with no ozone-depleting chemistry north of 60°N. It is seen that, in 2010, ozone is replenished more efficiently at high latitudes than in 2011. This replenishment results from both isentropic mixing and from transport by the Brewer-Dobson circulation, i.e. a global transport of ozone away from the tropics and towards polar latitudes driven by a temperature gradient. This indicates that the lack of transport into the high latitudes played an important role in the ozone deficit in 2011. The lower panel in Figure 13 shows this large relative difference in transport to high latitudes in 2010 vs. 2011 (dotted line), and also the absolute contribution of heterogeneous chemistry to ozone loss in 2011 (full line, sign reversed). While the chemical loss in 2011 was much higher than in 2010, the relative weakness of transport into the very stable and narrow vortex was the dominating factor.

In the first part of the winter, pronounced polar stratospheric cooling and vortex intensification were a response to the weakened planetary wave flux from the troposphere into the stratosphere. The lessening of the wave flux seemed to originate from the interaction of a blocking high in the North Pacific with the planetary wave trough over the Far East. This evolution follows the typical amplification of the positive phase of the Western Pacific teleconnection pattern (Orsolini et al, 2009). The origin of the anomalous steady cooling in February and March that lead to the exceptionally strong vortex and to ozone depletion, remains unclear, although recent studies indicate an important role for the sea surface temperatures and the circulation anomalies over the North Pacific.

The vortex broke down late and abruptly in early April, when a record-size low-latitude intrusion displaced the vortex, and remained long-lived as part of the summer polar anticyclone[3].

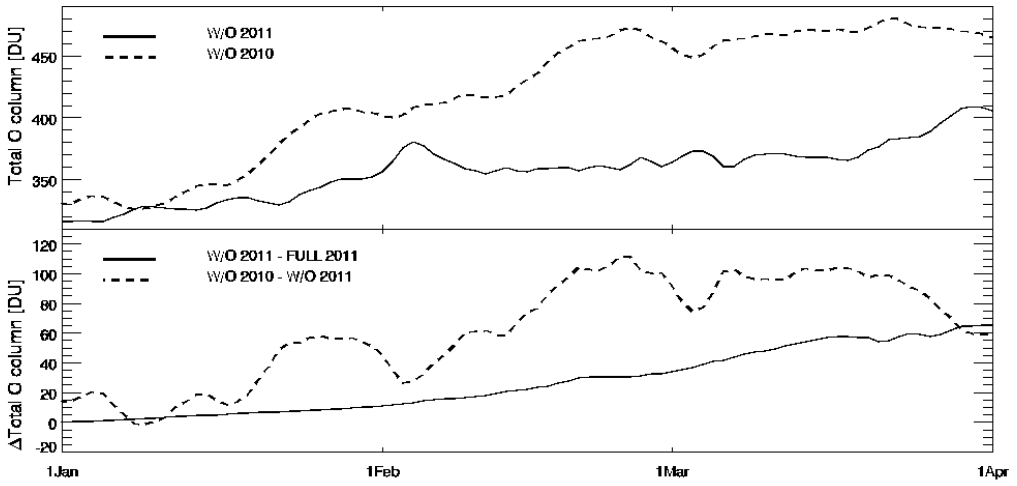

Figure 13: *Modelled average column ozone north of 60°N for January, February and March 2010 (upper panel, dotted line) and 2011 (upper panel, full line) in simulations with no ozone-depleting chemistry north of 60°N. Relative difference in transport in 2010 compared to 2011 (lower panel, dotted line), and absolute ozone loss from heterogeneous chemistry in 2011 (lower panel, full line) (adapted from Isaksen, I., et al., to be submitted, 2012).*

[3] Large-scale circulation of winds around a region of high atmospheric pressure

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 Arctic 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 (SatLuft) started in October 2007 and ended late 2010. Another project (SatMonAir) started in 2012. Some results from the activities within the ongoing SatMonAir project are included in this report.

4.1 Short introduction to ozone observations from space

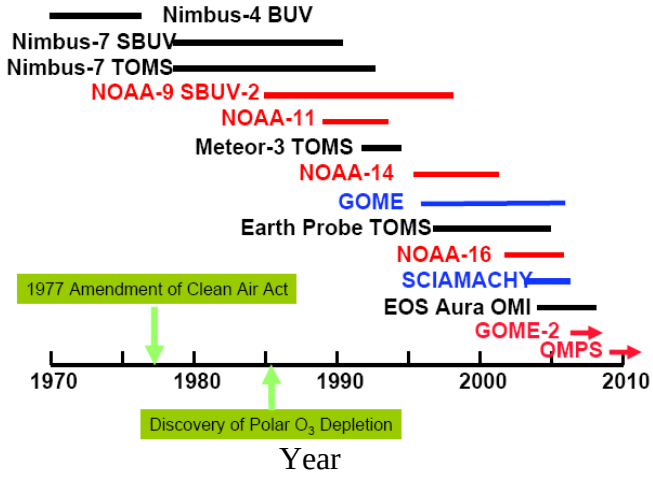

Figure 14: *An overview of the various satellites and their instruments measuring ozone from space since the beginning of 1970's (Figure from NASA).*

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 patterns 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 on 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.

4.2 Satellite ozone observations above the Norwegian sites from 1978–2011

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). Figure 14 shows the life time of the

various satellites. In the 1980s TOMS-Nimbus 7 was the only 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 section 3.5 we describe the special ozone situation in the spring 2011, where very low ozone values were measured until the beginning of April. Figure 15 (left panel) and Figure 15 (right panel) show the Scandinavian/Arctic ozone situation 1st April 2011 and 1st April 2010, respectively. The ground based Brewer ozone values for Oslo and Andøya are marked in the figures (blue numbers) along with the OMI ozone value at the same locations (black numbers). As seen from the two figures the colours are very different. In the beginning of April 2010 the Arctic ozone level was close to the long term mean, whereas the large 2011 ozone depletion is visualized by the light blue colours in Figure 15 (left panel). Comparisons between Brewer and OMI data over Oslo and Andøya show that the satellite values differs by some Dobson Units from the ground based measurements. Ozone can exhibit some variations within short distances and an OMI satellite pixel of 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 the "ozone hole" and how ozone rich/poor air moves. As a part of the SatMonAir project spatial correlation, standard deviation and bias between satellite products (plus comparisons to ground based measurements) will be studied in more detail.

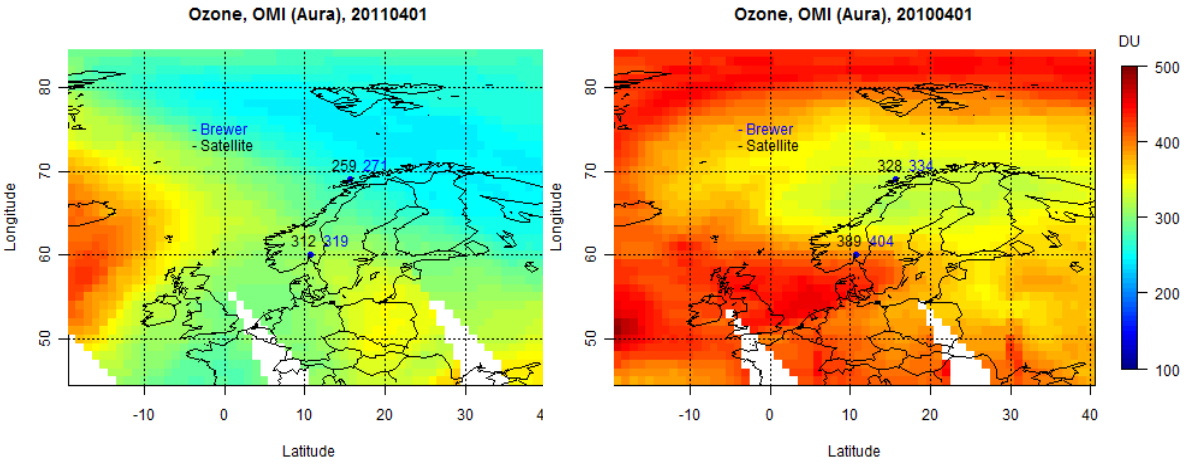

Figure 15: *Ozone maps over Scandinavia and the Arctic 1st April 2011 (left panel) and 1st April 2010 (right panel). The numbers above Oslo and Andøya represent satellite observations (black) and ground based Brewer observation (blue numbers).*

With respect to the monthly mean ozone values, there might be relatively large differences between the ground based measurements and the satellite data, and also between the various satellite data for overlapping time periods. There are both seasonal and systematic differences between the various satellite products.

The monthly mean ozone values from ground based (GB) measurements and satellites are analysed for the full period 1979-2011. Figure 16 shows the percentage GB-Satellite deviation at Oslo (upper panel) and at Andøya (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 deviation between the different satellite retrievals 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.

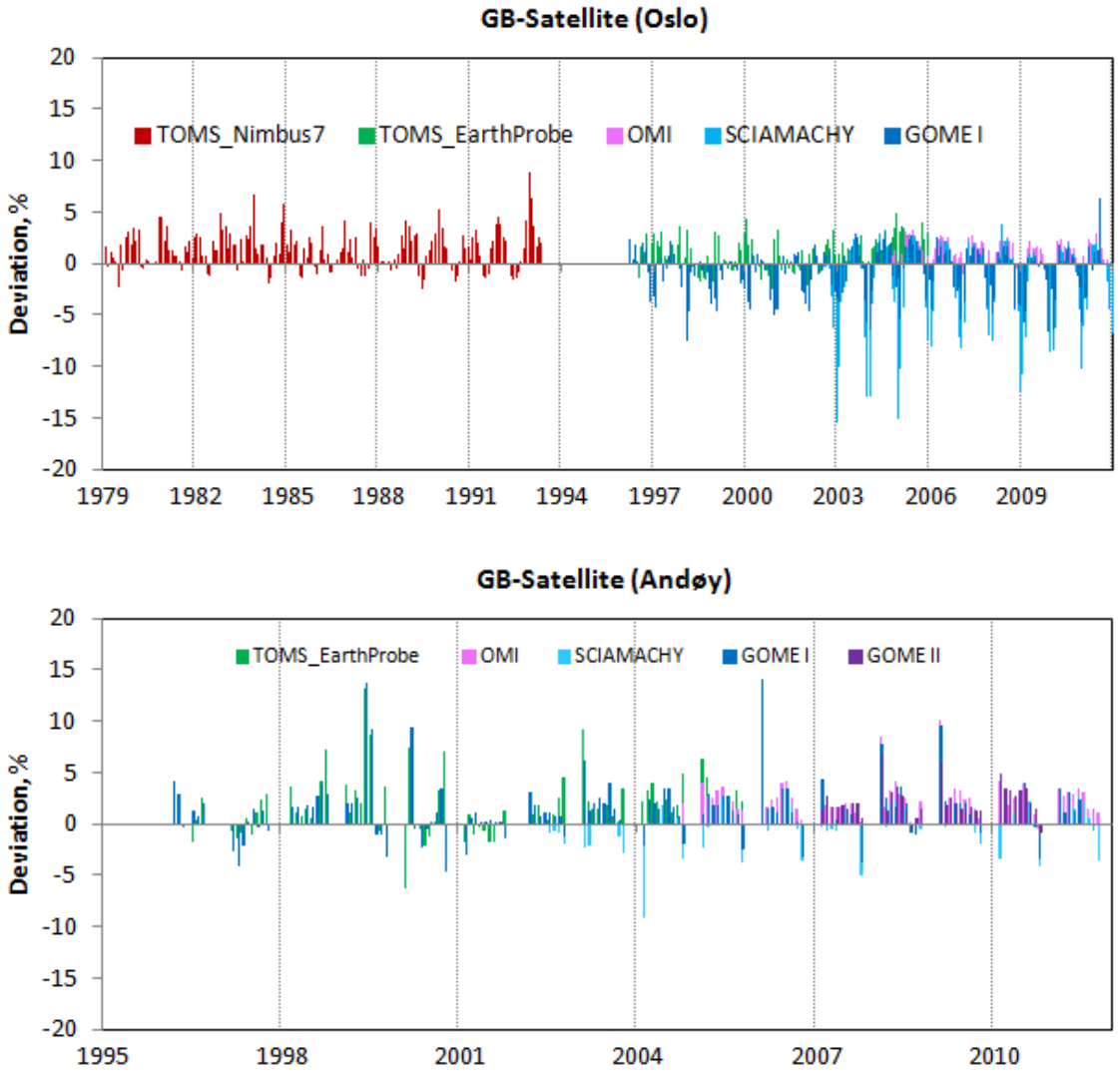

Figure 16: *Difference between ground based (GB) and satellite retrieved monthly mean ozone values from 1979 to 2011 for Oslo and 1995-2011 for Andøya. Deviations (GB minus satellite values) are given in %. Upper panel: Oslo, lower panel: Andøya.*

Table 7 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 and Andøya. For Oslo, ozone retrieved 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. There are also clear seasonal variations in the deviations between GB ozone and satellite retrieved values, especially in Oslo. For example, SCIAMACH systematically overestimates ozone values in December, January and February. This gives a very high

standard deviation and variance for the GB-SCIAMACHY deviation in Oslo. The high SCIAMACHY winter values are visualized by the light blue columns/lines in Figure 16 (upper panel). In contrast the OMI ozone values are close to the Brewer measurements in Oslo all year, giving a variance of only 1.9 (see Table 7). For Andøya the BG-SCIAMACHY variance is much smaller 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.

Table 7: *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-11	1.03	1.39	1.94
GOME I	Mar-96	Jul-11	-0.85	2.42	5.84
GOME II	Jan-07	Dec-11	1.22	1.42	2.00
SCIAMACHY	Jul-02	Dec-11	-2.03	4.42	19.54
Andøya					
Instrument	**Period**		**Mean**	**St. Dev**	**Variance**
TOMS (Earth probe)	Jul-96	Dec-05	1.71	2.86	8.18
OMI	Oct-04	Oct-11	2.67	2.20	4.82
GOME 1	Mar-96	Jul-11	1.42	2.78	7.74
GOME 2	Jan-07	Dec-11	2.16	1.55	2.41
SCIAMACHY	Jul-02	Dec-11	0.30	2.37	5.62

One aim of the SatLuft and 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 7 it seems like the ozone data from TOMS and OMI have similar mean and standard deviation and are most suited for further trend studies, especially in southern Norway. However, a series of new satellite retrieval versions will also be investigated before any conclusions are drawn.

5. The 4th IPCC report: 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[4] 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 17 (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).

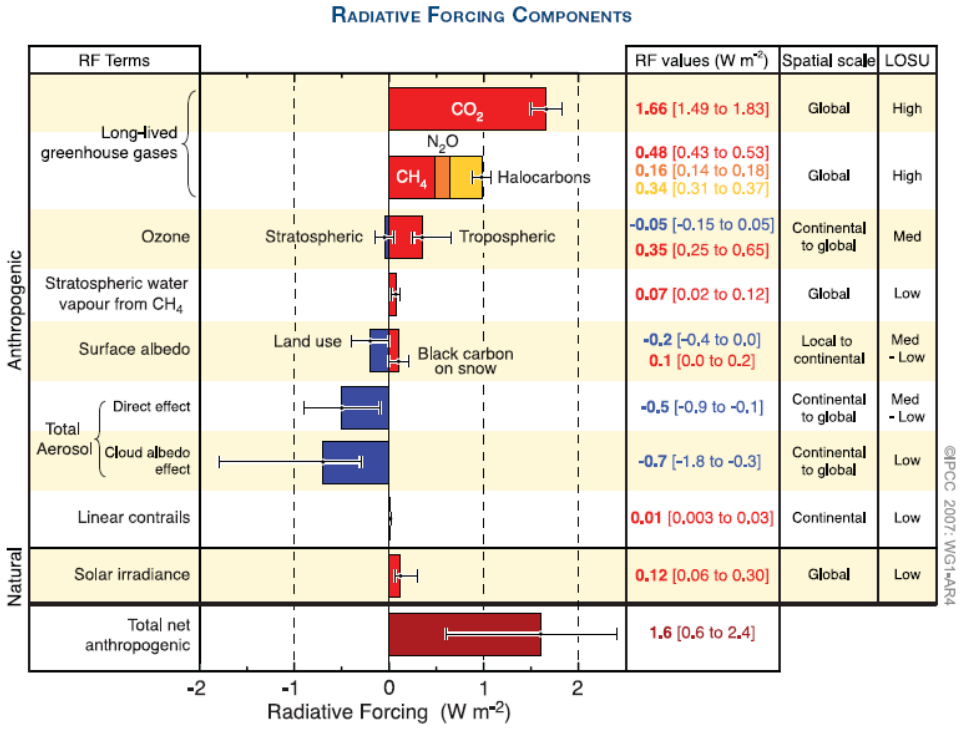

Figure 17: *Global-average radiative forcing estimates for important anthropogenic agents and mechanisms as greenhouse gases, aerosol effects, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU).*

[4] 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 3.1of 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, cools 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 PSC conditions and possible formation of more PSCs. This is of particular importance in the Arctic region (WMO, 2007). Moreover, ozone absorbs UV radiation. Absorption of UV radiation 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 is observed. 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 one of the most important. Other sources are volcanoes, natural and anthropogenic biomass burning and air crafts. 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 17.

The evolution of stratospheric ozone over the next few decades will depend on natural, and human-caused factors such as stratospheric halogen loading. The evolution of ozone will also depend on changes in many stratospheric constituents: it is expected that the reduction of ozone-depleting substances in the 21st century will cause ozone to increase via chemical processes. However, this increase could be strongly affected by temperature changes (due to greenhouse gases), other chemical changes (e.g., due to water vapour) and transport changes. According to model studies presented in the last IPCC report (Denman et al., 2007) Antarctic ozone development follows mainly the behavior of chlorine and bromine compounds. The peak depletion is expected to have occured around the year 2000 followed by a slow increase. Most models predict that Antarctic ozone amounts will increase to 1980 levels close to the time when modelled halogen amounts decrease to 1980 values, which is in the year 2065. Increased atmospheric fluxes of chlor-fluor-carbons (CFCs) have recently been reported which may point to a still later recovery. The various models do not predict consistent values for minimum arctic column ozone. However, all the models predict that the Arctic ozone will recover earlier than the Antarctic ozone, mainly explained by circulation differences combined with a reduction in stratospheric temperatures.

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 18. 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/.

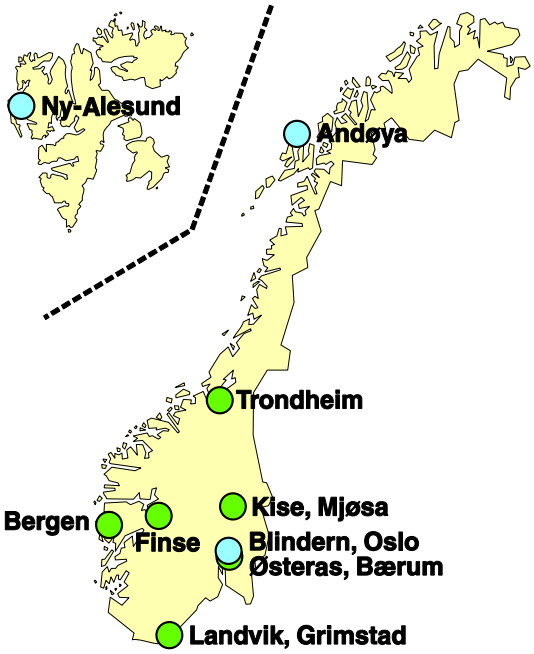

Figure 18: *Map of the stations included in the Norwegian UV network. The stations marked with blue are operated by NILU on behalf of The Norwegian Pollution Control Authority (SFT), whereas the Norwegian Radiation Protection Authority operates the stations marked with green.*

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)[5]. 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, including 16 NILU-UVs, 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 2011 is given in Table 8.

6.1 UV measurements in 2011

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

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

Table 8: *Number of days with more than 2 hours of missing GUV data in 2011 and 2010. Days where the sun is below the horizon (polar night) are not included.*

Station	Technical problems	
	2011	2010
Oslo	1	3
Andøya	12	4
Ny-Ålesund	1	0

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, 2002). Table 9 shows the UV-index scale with the recommended protections at the different levels. The recommendations are based on a moderate light skin type, typical for the Nordic population.

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

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

Figure 19 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, 169.9 mW/m^2, was observed 29 June at 11:05 UTC and is equivalent to a UV index of 6.8. 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 2011 was 4.6, equivalent to a dose rate of 115.5 mW/m^2, observed 12 June at 10:50 UTC. The highest UVI value in Ny-Ålesund was 2.4, or 61.2 mW/m^2, and was measured 13 June at 11:01 UTC. The maximum UVI in Oslo was observed during clear sky conditions and quite low total ozone values, i.e. 297 DU (normal ~ 340 DU). At Andøya the ozone column was exactly the same as in Oslo (297 DU versus normally ~ 350 DU) and was also measured during clear sky conditions. At Ny-Ålesund the maximum UVI was observed during clear sky conditions and a total ozone column of 348 DU, slightly under the normal of ~360 DU. For UV-levels corresponding to the maximum value of 6.8 in Oslo, people with a typical Nordic skin type get sunburnt after approximately 20 minutes if no protection is used.

Figure 20 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 20 (right panel) the cloud transmission in Ny-Ålesund was above 100% the first part of the day. This was caused by high albedo 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 and afternoon, with a few scattered clouds around noon. Such clouds tend to enhance the UV-radiation due to scattering of radiation towards the ground. Oslo had the cloudiest day, but between 09:00 and 13:00 UTC it was fairly clear sky.

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

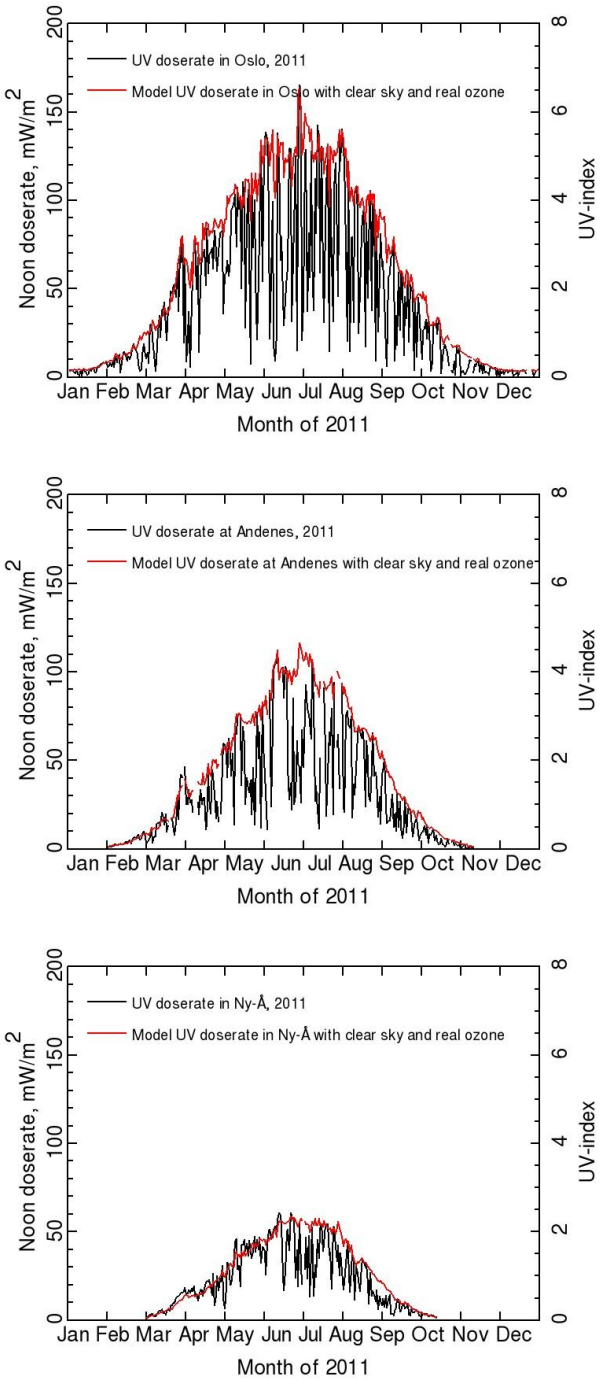

Figure 19: *Hourly averaged UV dose rate measured at noon (between 10:30 and 11:30 UTC) in 2011. Upper panel: Oslo. Mid panel: Andøya. Lower panel: Ny-Ålesund.*

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.

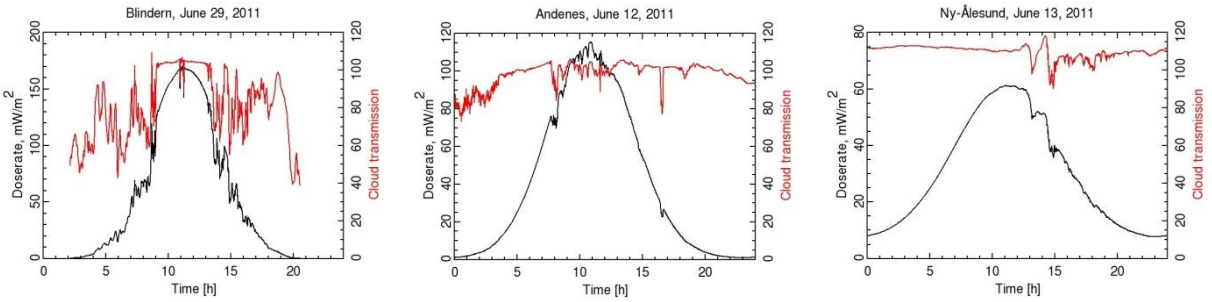

Figure 20: *UV dose rates (left axis, black curves) and cloud transmission (right axis, red curves) during the days of maximum UVI in Oslo (left panel), Andøya (middle panel) and Ny-Ålesund (right panel). A cloud transmission of 100% represents clear sky conditions, whereas cloud transmissions of 20-30%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

Monthly mean noon UV indices for Oslo, Andøya and Ny-Ålesund in 2011 are compared in Figure 21. As expected, the monthly mean UVI in Oslo were significantly higher than the values observed at Andøya and Ny-Ålesund. If the cloud and ozone conditions at all three sites were similar during the summer, the UV-radiation would be highest in Oslo due to higher solar elevation most of the day.

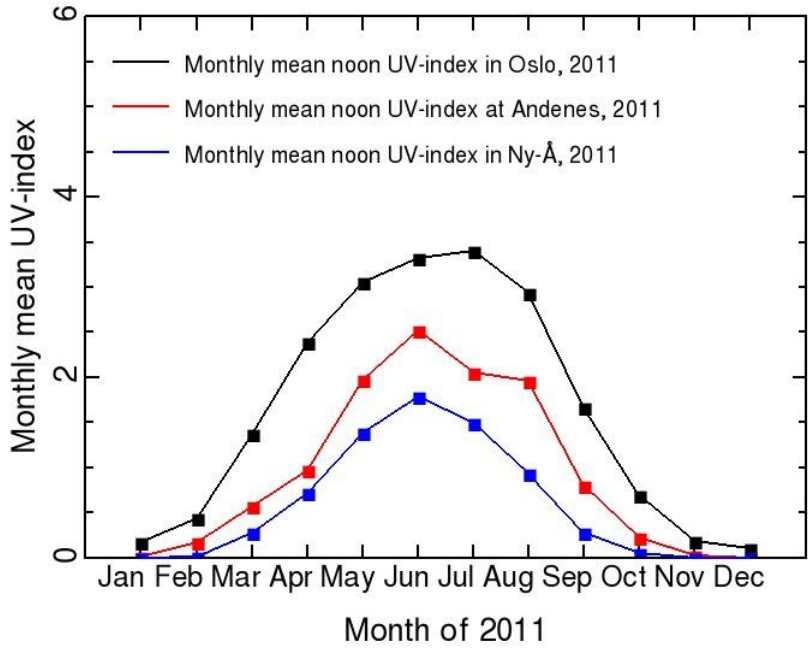

Figure 21: *Monthly mean UV indices in 2011 measured with the GUV instruments located in Oslo, Andøya and Ny-Ålesund.*

6.2 Elevated UV levels during the ozone hole episode in winter/spring 2011

As described in section 3.5 massive ozone loss was observed over Northern regions in winter and spring 2011. In January and February the solar intensity is fairly weak and enhanced UVI due to ozone depletion is not critical. In contrast, low ozone values in March and April might give elevated UVI under clear sky conditions that can influence living organisms and humans.

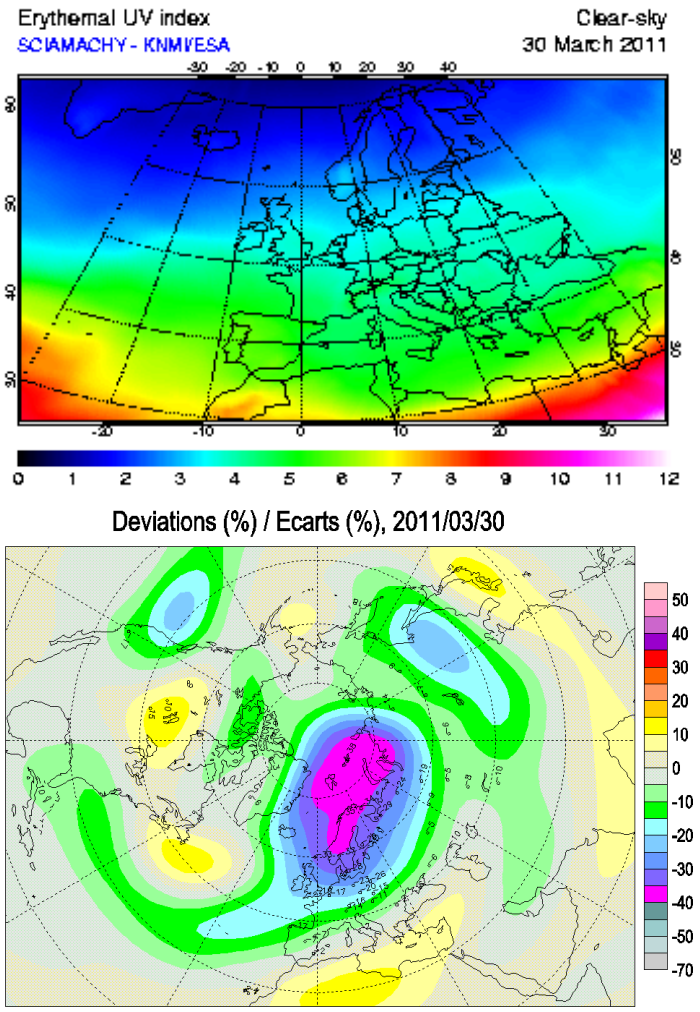

Figure 22: *Upper panel: European erythemal UV index from SCIAMACHY the 30 March 2011. Lower panel: Percentage deviation in total ozone the same day. (Map from the World Ozone and Ultraviolet Radiation Data Centre.)*

On 30 March 2011, during the Arctic ozone loss episode, it was cloudless conditions in Southern Norway and the UV index over Oslo and surrounding areas was as much as 65% higher than normal. At Finse, which is located at high altitude (1222 m a.s.l), the UV index was as high as 5.3 in the end of March, whereas an UV index of 3.2 would have be measured under clear sky conditions and pre 1990 ozone values.

Satellite data are crucial in determining the geographical extend of the low ozone and high UV episodes. Figure 22 (upper panel) shows the European erythemal UV index retrieved from SCIAMACHY on 30 April 2011, where the enhanced UVI in the southern part of Norway is visualized by the light blue colour. The lower panel shows the deviation in ozone from daily long term mean. This map is prepared by the World Ozone and Ultraviolet Radiation Data Centre. The map shows that Norway, including Svalbard, and Sweden experienced ozone values that were 35-40% below the long term mean values on 30 March 2011.

6.3 Annual UV doses 1995–2011

Annual UV doses for the period 1995–2011 are shown in Table 10 for the GUV instruments in Oslo, at Andøya and in Ny-Ålesund. Annual UV doses for 2005 are not included in the Table as there were large gaps in the data set caused by a calibration campaign. The uncertainty in the daily UV doses is estimated to ±5 % at a 2σ level (Johnsen et al., 2002). For

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

In 2011 the UV-doses in Oslo and Ny-Ålesund were relative low in spite of the low ozone values that were measured most parts of the year (see section 3.5). This can be explained by many overcast days during the summer. As shown in Figure 19 (upper panel) there were many days where the UV index in Oslo was below 2, even in June, July and August. On the other hand 2011 had the fourth highest annual UV level at Andøya, the years 1995-2011 taken into account. The low ozone values and relatively cloudless conditions, especially in June, are the main reasons for the relatively high UV-levels at Andøya.

A graphical illustration of the yearly integrated UV-dose is shown in Figure 23 to illustrate yearly fluctuations.

Table 10: *Annual integrated UV doses (in kJ/m^2) for Oslo, Andøya and Ny-Ålesund for the period 1995 – 2011.*

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

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

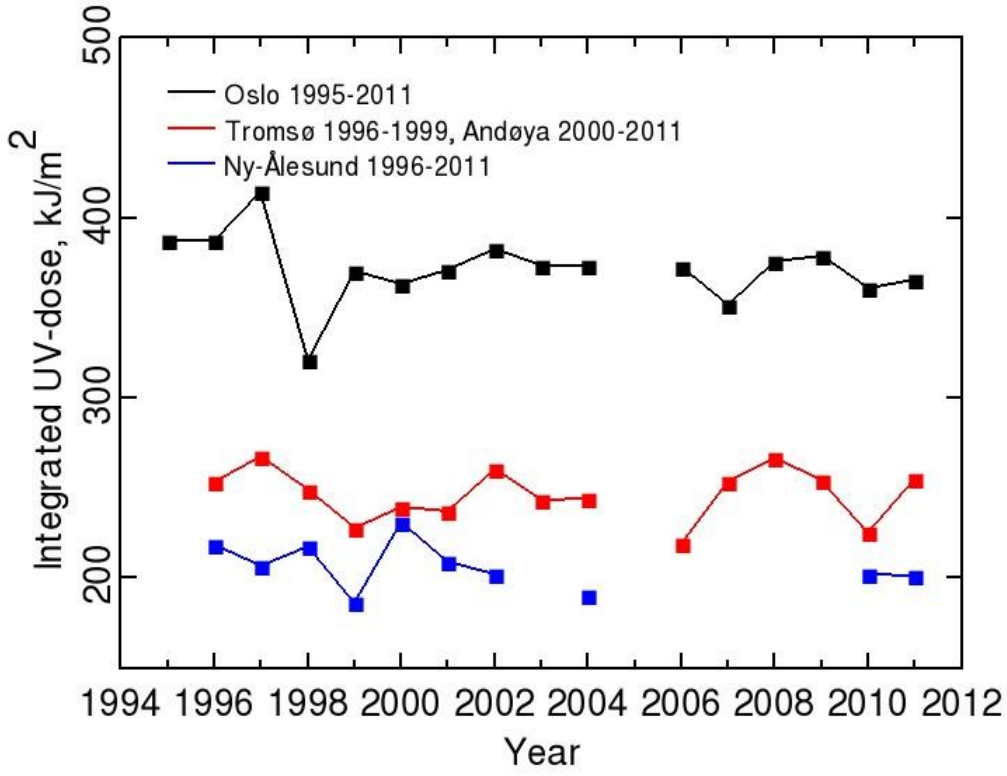

Figure 23: *Annual integrated UV doses (in kJ/m^2) at Oslo, Tromsø/Andøya and Ny-Ålesund for the period 1995 – 2011.*

7. Long term changes in UV and coupling to changes in ozone, pollution and aerosols

Global dimming is a process where atmospheric aerosols reduce the radiation received by the earth surface through scattering and absorption of solar radiation. Understanding of global dimming is of crucial important in the investigation of climate change; because aerosol dimming may mask the temperature rise at the surface caused by the increase of greenhouse gases. A study presented in Science in May 2005 (Wild et al., 2005) shows that the surface levels of total solar radiation from 1990 to present has increased. In a work from Kvalevåg et al. (2009) data from the monitoring program is used for studying the effect of human-induced changes in the surface erythemally weighted ultra-violet radiation (UV-E) since 1750. In addition to the effect of changes in ozone, they also investigated the effect of changes in SO_2, NO_2, the direct and indirect effects of aerosols, albedo changes and aviation-induced contrails and cirrus. The results showed an increase of surface UV-E in polar regions, most strongly in the Southern Hemisphere. Furthermore, the study demonstrated an extensive surface UV-E reduction over most land areas; a reduction up to 20% since 1750 was found in some industrialized regions. Based on the work, it was argued that SO_2, NO_2, ozone, and direct and indirect effects of aerosols have reduced surface UV-E by up to 15–20%, during the industrial era. The strongest reduction was seen over South East Asia, Europe and North America.

It has previously been indicated that pollutants could mask expected increase of UV from stratospheric ozone depletion, especially through UV absorption by black carbon over urban areas. The publication from Kvalevåg et al. (2009) showed that this has occurred over most land regions through the time period 1750-2000. This UV-dimming has similarities with the dimming of total solar radiation at the surface. Changes in ozone, aerosols, pollution and clouds influence the UV level and long-term changes in the solar radiation received at the earth surface. An implication of this study is that future changes in UV radiation clearly depend on a complex mixture of factors, among them ozone and atmospheric pollutants. This links health, UV radiation, air pollution, and climate change. It is therefore important to continue UV and ozone monitoring activities in the future to observe and investigate long-term variations of ground level solar radiation.

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KLIMA- OG FORURENSNINGS-DIREKTORATET

Klima- og forurensningsdirektoratet
Postboks 8100 Dep, 0032 Oslo
Besøksadresse: Strømsveien 96
Telefon: 22 57 34 00
Telefaks: 22 67 67 06
E-post: postmottak@klif.no
Internett: www.klif.no

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Overvåking av ozonlaget og naturlig ultrafiolett stråling: Årsrapport 2011.

Monitoring of the atmospheric ozone layer and natural ultraviolet radiation: Annual report 2011.

Sammendrag – summary

Rapporten presenterer måledata for totalozon, vertikalfordelingen av ozon og UV-stråling over norske målestasjoner i 201|. For Oslo og Andøya er trenden i totalozon beregnet for perioden 1979-2011. Ozonverdiene over Norge var generelt lave i hele 2011. 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 2011.
2011 was a year with generally low ozone values above Norway. A clear decrease in the ozone layer above Norway during the period 1979-1997 stopped after 1998 and the ozone layer above Norway seems now 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

Statlig program for forurensningsovervåking

Klima- og forurensningsdirektoratet
Postboks 8100 Dep,
0032 Oslo
Besøksadresse: Strømsveien 96

Telefon: 22 57 34 00
Telefaks: 22 67 67 06
E-post: postmottak@klif.no
www.klif.no

Om Statlig program for forurensningsovervåking

Statlig program for forurensningsovervåking omfatter overvåking av forurensningsforholdene i luft og nedbør, skog, vassdrag, fjorder og havområder. Overvåkingsprogrammet 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. Klima- og forurensningsdirektoratet er ansvarlig for gjennomføringen av overvåkingsprogrammet.

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