FINLAND

1. GROUND BASED OBSERVATIONS

1.1 Column measurements of ozone and other gases/variables relevant to ozone loss

The discovery of the Antarctic "ozone hole" in the mid 1980's initiated several ozone monitoring activities also at northern high latitudes. In Finland, ozone column monitoring has been carried out by the Finnish Meteorological Institute at Sodankylä (67.4°N, 26.6°E) since 1988 and at Jokioinen (60.5°N, 23.3°E) since 1994. At both stations an automated system based on Brewer spectrophotometer is continuously operated. Since November 2012 this monitoring programme has taken place in close cooperation with the COST Action ES1207: A EUropean BREWer NETwork – EUBREWNET.

At Sodankylä Arctic research centre (FMI-ARC) wintertime ozone columns are also monitored with a SAOZ spectrophotometer which is operated in cooperation with CNRS-Paris already since 1990. The SAOZ measurements also provide NO_2 and OClO column amounts. This instrument works at large solar zenith angles and is thus capable of measurements during the wintertime at high latitudes. Multiyear ozone measurements from both stations have shown large inter-annual variations, in addition significant ozone loss has been observed in the Arctic stratospheric vortex during several years since early 1990's.

Total ozone columns have been measured during 2012–2013 in Helsinki using a NASA owned Pandora spectrometer. Measurements will be continued again in 2014 in Helsinki and a new FMI Pandora instrument will be implemented to Kuopio.

1.2 Profile measurements of ozone and other gases/variables relevant to ozone loss

Ozone soundings have been carried out since 1989 at Sodankylä where balloon ozone sensor measurements are carried out regularly throughout the year, while in Jokioinen these measurements are conducted during winter and spring when chemical ozone depletion is expected.

Another long-term initiative at FMI-ARC related to stratospheric ozone is the measurements of polar stratospheric cloud (PSC) properties. PSCs play an essential role in chlorine activation and subsequent ozone depletion. PSCs are generally divided in two types based on their optical parameters, type II are large particles of primarily water ice, type I are typically smaller particles of nitric acid trihydrate or supercooled ternary solution droplets. At Sodankylä these stratospheric cloud particles have been observed during stratospheric campaigns since 1991/1992 by lidar and since 1994 by aerosol backscatter sondes.

At Sodankylä, since December 2002, stratospheric humidity is monitored in winter months using Cryogenically cooled Frost point Hygrometer (CFH) and FLASH-B hygrometers developed at the Central Aerological Observatory of RosHydromet. Already earlier, in January 1996 an Arctic dehydration event was recorded and investigated at Sodankylä using NOAA/CMDL hygrosonde, a predecessor of CFH.

The national meteorological institutes in Finland (FMI) and Argentina (SMN) started a joint ozone research program in 1987, including regular ozonesonde measurements at Marambio (64.1°S, 56.4°W), Antarctica. In 1988 routine ozone soundings were started at Marambio. Recently FMI and SMN have started Aerosol optical depth and radionuclide measurements at Marambio.

1.3 UV measurements

1.3.1 Broadband measurements

FMI operates SL501 broadband instruments at six sites in Finland. These instruments provide on-line information on the erythemal irradiance that is published through the internet along with the UV-Index forecast.

1.3.2 Narrowband filter instruments

FMI cooperates with Argentina and Spain on Antarctic ozone and UV. In 1999 the collaboration was extended to include UV radiation research. The established UV monitoring network consists of NILU-UV instruments in Marambio, Belgrano and Ushuaia, and a travelling reference. Continuous multifilter UV time series are available from Sodankylä since 2002. One NILU-UV radiometer has been used to measure UV radiation of a reference field within a large field experiment of FUVIRC (Finnish Ultraviolet International Research Center) and one measure at the roof of the sounding station. One NILU-UV, in Helsinki, has been acquired for campaign use.

1.3.3 Spectroradiometers

FMI has monitored the spectral UV irradiance with Brewer instruments in Jokioinen (Mark III since 1995) and Sodankylä (Mark II since 1990). A second Brewer spectroradiometer, Mark III, has been installed in Sodankylä in 2012. Additionally, a Bentham DM150 has been acquired for campaign use, as well as, more recently, one diode array spectroradiometer SP-J1009 for monitoring the spectral irradiance on a vertical surface following the solar azimuth, and another for monitoring the direct spectral irradiance at Jokioinen. In 2012, a portable ASD field spectrometer was acquired.

1.4 Calibration activities

FMI is operating dark room UV calibration facilities both in Jokioinen and Sodankylä. FMI has participated in several UV measurement comparison campaigns, where it has been established that the quality of Finnish Brewer measurements is high and steady. The Brewer instrument of Jokioinen served as one of the core instruments of the QUASUME project (Quality Assurance of Spectral Ultraviolet Measurements in Europe). The European reference spectroradiometer developed in the project and now hosted by the WMO World Calibration Center for UV radiation in Davos is invited for auditing visits to both observatories on a regular basis. FMI is also responsible for the calibration of the Antarctic NILU-UV travelling reference instrument and for its data quality assurance. Brewer total ozone measurements in Jokioinen and Sodankylä are calibrated by annual visits of a travelling Brewer standard instrument or by visiting the Regional Brewer Calibration Center for Europe (RBCC-E) at Tenerife.

1.5. Measurement and validation campaigns

The Arctic research center at FMI has become an important site for ozone validation campaigns. In 2006 and 2007 major ozone campaigns were organised in Sodankylä by NASA, ESA and FMI, aiming to achieve < 1% total ozone measurement accuracy in both ground based and satellite based platforms. Sub-percent accuracy is needed for reliable monitoring of the effects of Montreal protocol. FMI Arctic Research Centre (FMI-ARC) also participated in the EUMETSAT EPS campaign in 2007, which involved ozone soundings and groundbased measurements.

FMI has also hosted international intercomparison campaigns of lightweight hygrosondes in 2004 and 2010. The LAPBIAT Atmospheric Sounding Campaign in January-March 2010 involved a large set of stratospheric measurements by applying various measurement techniques. In 2011 FMI organised the CEOS Nordic Ozone Intercomparison campaign. The goal of the campaign was to characterize Brewer and Dobson spectrophotometer accuracy. FMI stations at Sodankylä and Jokioionen have participated in ozonesonde Match campaigns during each Arctic winter, including winter 2013/2014.

2. SATELLITE OBSERVATIONS AND DATA PRODUCTS

FMI has a strong participation in several satellite instruments that are targeted for monitoring ozone in the atmosphere (GOMOS/Envisat, OSIRIS/Odin, OMI/EOS-Aura, GOME-2/METOP-A, METOP-B). The GOMOS stellar occultation instrument onboard the ESA's Envisat satellite operated from March 2002 to April 2012. High vertical resolution ozone profiles that cover the altitude range from upper troposphere to lower thermosphere during years 2002-2012 have been analysed at FMI. FMI participates in ensuring the GOMOS data quality and in improving the data processing as a member of the ESA's GOMOS quality working group. The full reprocessing of GOMOS data was performed by ESA in 2012. Recently the algorithm for processing GOMOS bright limb data have been developed at FMI and daytime GOMOS ozone profiles are made available through the ESA SPIN project.

The GOMOS data 2002–2012 have been used to continue SAGE II solar occultation time series of ozone 1984–2005 in the stratosphere. The trend analysis of the time series shows that negative ozone trend observed in 1984 – 1997 has changed to positive at mid-latitudes and tropics. In particular positive ozone trend is now seen around 40 km. These results are part of the international SI2N project (Past changes in vertical distribution of ozone) and will be included in WMO 2014 ozone assessment. In addition, GOMOS data plays an important role in the ESA's climate change initiative for developing essential climate variable (ECV) of ozone. FMI participates in developing the ECV dataset of high resolution ozone profiles using GOMOS data.
The OSIRIS instrument onboard the Swedish small satellite Odin has measured ozone profiles since 2001. The work is ongoing to combine OSIRIS, GOMOS and SAGE II observations to study the changes of ozone in high latitudes.

The Dutch-Finnish OMI instrument onboard the NASA's EOS-Aura satellite has measured total ozone columns since 2004. FMI is hosting the OMI UV surface irradiance processing and archiving facility which includes level 2 data, gridded level 2 data and level 3 data. The improvement and validation of the UV products are continued. In addition, local maps of total ozone columns and UV irradiance together with other atmospheric constituents covering Central and Northern Europe are processed at FMI. These Very Fast Delivery (VFD) products exploit the Direct Broadcast antenna at Sodankylä, Northern Finland. These products are available in the Internet (omivfd.fmi.fi) within 15 min after the overpass of the satellite. Presently similar real time ozone products are being developed for OMPS instrument on-board NASA/NOAA Suomi NPP satellite.

FMI is responsible of developing, distributing and archiving of the UV-radiation product of GOME-2. This is done within the EUMETSAT's Satellite Application Facility project of ozone and atmospheric chemistry, O3M-SAF (http://o3msaf.fmi.fi).

3. RESULTS FROM OBSERVATIONS AND ANALYSIS

FMI has developed quality control (QC) and quality assurance (QA) practices that are suitable for many kinds of UV instruments. At FMI, at the moment, only Brewer UV measurements are considered to have a sufficient quality for assessment of long-term changes. The QC/QA procedures of the Brewers include daily maintenance, laboratory characterizations, calculation of long-term spectral responsivity, data processing and quality assessment. Methods for the cosine correction, the temperature correction and calculation of long-term changes in spectral responsivity were implemented. The Sodankylä spectral time series is among the longest in Europe. No statistically significant spectral UV changes were found for the SZA interval 63°-65° at Sodankylä during 1990-2011. However, record high UV levels were observed in summer 2011 at both Jokioinen and Sodankylä, were the UV index 7 and 6, correspondingly, were measured for the first time. The ratio of UV-B irradiance at 305 nm to UV-A irradiance at 324 nm exceeded the 1990-2010 average by 16% in summer 2011. At Jokioinen, however, the 18-year time series shows a positive trend of nearly 5% per decade in the monthly sum of erythemal UV radiation in July, the main holiday season in the country.

The UV albedo of Arctic snow has been quantified in Sodankylä, also in relation to UV absorbing aerosols, including volcanic ash, dust and soot, deposited on snow. The effective snow grain size is the main factor to determine snow albedo, but various environmental parameters can influence the spectral UV albedo, too, and the UV absorbing impurities may decrease albedo the more the shorter the wavelength.

Ozonesonde observations have been conducted in Sodankylä since 1989. These data along with the data from other Arctic stations have been analysed. It was seen that during the recent decades the largest ozone changes in the stratosphere and troposphere have occurred in the late winter/spring period. The observed negative trend in the stratosphere prior to 1996-1997 can be attributed to the combined effect of chemical and dynamical changes, while the observed increase since then is primarily due to the dynamical changes. In the troposphere, trends have been positive regardless of the chosen time period. This may be related to the long-term changes in Arctic oscillation as it regulates the transport of ozone and its precursors from industrialized regions towards the pole and it may also modulate stratosphere-troposphere exchange. Continuation of ozonesonde observations is planned to detect possible changes in high-latitude tropospheric and stratospheric ozone.

Water vapour changes in the UTLS have a large impact on the climate system. Yet the accurate measurements of the UTLS water vapour remain a technological challenge. FMI has hosted two major field campaigns of comparison of light-weight instruments capable of water vapour measurements in the upper troposphere and lower stratosphere. The campaigns has led to a better understanding of the accuracy of the in situ instruments and contributed to significant improvement of the technology. In addition, the data has provided a unique opportunity to study meteorological and microphysical processes in the lower stratosphere and upper troposphere, including processes related to PSC formation and redistribution of water vapour in the Arctic lower stratosphere.

Recently, changes in the vertical distribution of ozone have been analysed with the combined analysis of GOMOS and SAGE-II data. Several studies have been dedicated to the evolution of ozone and other trace gases during sudden stratospheric warmings, to influence of planetary waves on shaping ozone profiles, and to influence of energetic particle precipitation on the chemical composition of the middle atmosphere.

4. THEORY, MODELLING, AND OTHER RESEARCH

The modelling activities related to middle atmospheric ozone includes the use of a global 3D chemistry transport model of the stratosphere and mesosphere (FinROSE-ctm), a climate model covering the middle atmosphere (MAECHAM) and a model of the ionosphere (Sodankylä Ion Chemistry model). The modelling work includes both studies of long term trends of stratospheric ozone and water vapour utilizing reanalysed meteorological data (ECMWF reanalysis data) as well as process studies (PSC, chlorine activation, ozone loss rates). It has been shown, using both chemistry transport models and observations, that in the Northern Hemisphere the amount of springtime ozone has a large impact on the surface UV radiation, which extends into the following summer. The studies are also focused on impacts of ozone depletion and recovery on surface climate, which are shown to be significant in the Southern Hemisphere. These results add to the increasing number of evidence that the stratosphere plays an important role in climate change and call for a better representation of the stratosphere in models used for climate studies, in particular for a wider use of chemistry-climate models (CCMs), which include stratospheric ozone chemistry. FMI participated in the preparation of the SPARC assessment of CCMs (CCMVal-2, http://www.atmosp.physics.utoronto.ca/SPARC/ccmval_final/index.php). Furthermore, FMI contributes to the ozone assessment 2014.

The scientific use of satellite measurements is increasingly important. In addition, the impact of solar proton events on the stratosphere and mesosphere is studied. In this study the unique night time ozone profile measurements of GOMOS are used. GOMOS data are also used for studying turbulence and gravity waves in the stratosphere.

FMI has developed models for reconstruction of the past UV time series as well as for assessment of the future UV levels. These data are essential for assessment of the long-term changes in surface UV. FMI has participated in multidisciplinary research projects that aim at better understanding of the effects of increased UV exposures on human health, terrestrial and aquatic ecosystems, or materials.

FMI coordinates the research project UVEMA exploring the Effects of UV radiation on MAterials. The study focuses on rubber compounds, natural fibre composites and carbon fibres provided by the industrial partners of the project. A program of long-term outdoor material testing has been set up at seven European sites, including Jokioinen Observatory and Arctic Research Centre at Sodankylä. Prevailing UV radiation and weather conditions are being monitored alongside with the program at each station. Exposed material samples will be investigated in respect of various properties: colour, quality/coarseness of the surface and compression/flexural/tensile strength. As an outcome, more reliable estimates for the useful life-time of the materials are to be gained.

5. DISSEMINATION OF RESULTS

5.1 Data reporting

FMI has participated in the Global Atmospheric Watch (GAW) programme since 1994. Within the program, FMI maintains the Pallas-Sodankylä GAW station and conducts an extensive research programme related to atmospheric aerosols. Within this twin GAW station surface and boundary layer measurements are done in FMI clean air site of Pallas while upper air measurements, UV and Ozone monitoring takes place at Sodankylä (fmiarc.fmi.fi). In upper air research Sodankylä functions as an auxiliary station in the global Network of Detection of Atmospheric Composition Change (NDACC). The total ozone values are reported to the WOUDC on a daily basis both from Jokioinen and from Sodankylä.

FMI maintains the European UV Database (EUVDB). EUVDB is a regional WMO database containing some two million UV spectra (uvdb.fmi.fi/uvdb/). The UV spectra of the two Finnish Brewer instruments are submitted to EUVDB. The UV time series of FMI are used to yearly update the UV-radiation chapter of the NOAA Arctic Report Card: http://www.arctic.noaa.gov/reportcard/.

Regular ozone soundings have been performed at Marambio since 1988, the ozone data is sent to two international databases at the World Ozone and Ultraviolet Data Centre (WOUDC, Toronto, www.woudc.org) and the Norsk institutt for luftforskning (NILU, Oslo, www.nilu.no/nadir/). Furthermore, the UV measurements are available at polarvortex.org. Both the ozone and UV measurements are used in scientific publications, and form a significant contribution to the WMO ozone bulletins (www.wmo.ch).

5.2 Information to the public

FMI provides a 2-day global forecast of the UV Index (http://www.fmi.fi/uvi). The forecast, which is published on the internet, includes contour maps of the local solar noon maximum clear sky maximum UV Index. Additionally, local clear sky UVI forecasts are provided for several sites in Finland and globally. The Finnish broadband UVI measurements are also incorporated in near-real-time on the web page. Several newspapers, radio channels and TV publish the forecasted or measured values during April to August. FMI has actively participated in increasing the awareness of general public on the health effects of UV radiation. Ozone depletion has a large public interest due to related health (UV) and environmental issues. The unprecedented stratospheric conditions and severe ozone loss in the spring of 2011 triggered a wide interest in the Finnish media.

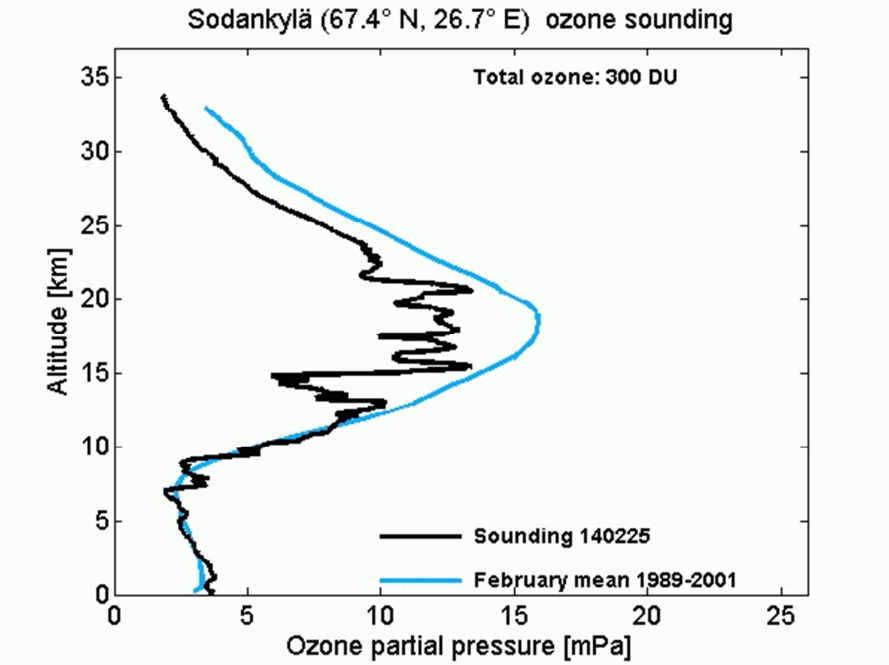

Figure 1. Ozone sounding at Sodankylä in February 2014. The ozone soundings have been made on regular basis in an effort to study Arctic stratospheric and tropospheric ozone changes. Results of the ozone soundings have been made publicly available through the FMI web site.

The major scientific results are published in international refereed journals and are also presented at relevant international conferences. Popularized information is distributed through press releases and interviews. Information about research activities, remote sensing projects as well as measurements and analysis results are available through FMI web pages, http://www.fmi.fi. FMI-ARC observations and analyses are available at http://fmiarc.fmi.fi.

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6. PROJECTS AND COLLABORATION

The major national funding organisations are the Academy of Finland and Tekes, the Finnish Funding Agency for Innovation. Both of them have partially funded the ozone research in Finland in addition to FMI. FMI collaborates with Finnish universities on atmospheric modelling and developing data retrieval methods and assimilation techniques for the satellite instruments.

A list of projects related to UV and ozone research:

- SAARA 2009–2012 (Studies of the Changing Antarctic Atmosphere using Soundings, Remote Sensing and Modelling: A Bi-polar Approach)
- MIDAT 2010–2013 (Middle atmosphere dynamics and chemistry in climate change)
- ASTREX (Advanced Analyses of Stratosphere- Troposphere Exchange)
- UTLS WaVa (Arctic upper troposphere lower stratosphere water vapour)
- COOL (Aerosol intervention technologies to cool the climate: costs, benefits, side effects, and governance)
- FUVIRC (Finnish Ultraviolet International Research Center, http://fmiarc.fmi.fi/fuvirc/fuvirc_hs)
- UVEMA (Effects of UV radiation on Materials, uvema.fmi.fi/)
- MACC-II (EU project, FMI participating in task related to UV-radiation)
- O3M-SAF (EUMETSAT's Satellite application facility on ozone and atmospheric chemistry)
- IGACO-O3/UV secretariat (WMO and GAW-ozone)
- ACSO (Absorption cross sections of ozone, IGACO-O3/UV activity)
- Ozone_cci (ESA Climate Change Initiative)
- EUBREWNET (EUropean BREWer NETwork, COST Action ES1207 for the years 2012-2017 whose main objective is to establish a coherent network of European Brewer Spectrophotometer stations to harmonise and develop approaches, practices and protocols to achieve consistency in quality control, quality assurance and coordinated operations.)
- SI2N (Past changes in vertical distribution of ozone, SPARC, IO3C, IGACO-O3, NDACC initiative)
- PP-TROPOMI (Processor prototype studies for TROPOMI, Tekes funded)
- SPIN (ESA funded project, GOMOS ozone data and time series)

FMI has participated in several EU funded Arctic and Antarctic research projects including tasks such as stratospheric modelling and measurement campaigns. Sodankylä has participated in all major European stratospheric ozone campaigns.

FMI is coordinating the EUMETSAT Satellite Application Facility on Ozone Monitoring (O3M SAF, o3saf.fmi.fi). O3M SAF is one of the SAFs in EUMETSAT SAF network. SAFs are specialised development and processing centres within the EUMETSAT Application Ground Segment (www.eumetsat.int). O3M SAF is developed in co-operation with Koninklijk Nederlands Meteorologisch Instituut (KNMI), Deutsche Zentrum fur Luft- and Raumfarhrt (DLR), Deutscher Wetterdienst (DWD), Aristotle University of Thessaloniki (LAP), Hellenic National Meteorological Service (HNMS), Danish Meteorological Institute (DMI), Meteo-France (M-F) and Koninklijk Meteorologisch Instituut (KMI).

The purpose of the O3M SAF is to produce a set of near real-time and offline products and validation services. Near real-time products are GOME-2 total ozone and ozone profiles, NO_2 and UV fields. Offline products derived from GOME-2 data are total and/or tropospheric column amounts of ozone, NO_2, BrO, SO_2, HCHO, H_2O, OClO, ozone profiles, aerosol index and UV fields including cloudiness and albedo. The ozone and UV data is validated against ground-based observations of total ozone and UV as well as balloon borne, microwave and lidar observations of the vertical distribution of ozone. An important part of the O3M SAF activities has been related to scientific work to develop radiative transfer calculation methods and other algorithms used for satellite ozone and related data retrieval.

The Satellite Data Centre of FMI-ARC started in 2002. The activities include a processing facility for the GOMOS/Envisat ozone instrument. The FMI-ARC data centre also process part of the OSIRIS/Odin ozone data. Data reception and processing from the EOS-Aura satellite is also going on for Very Fast Delivery products of the total ozone, SO_2, aerosol index and UV irradiance

products, available within 15 min after the overpass of the satellite. The Centre is also responsible of reception of OMI data used in near real time O_3 and UV-products.

IGACO (International Global Atmospheric Chemistry Observations) is a strategy which aims for bringing together ground-based, aircraft and satellite observations of 13 chemical species in the atmosphere. The implementation of IGACO-O3/UV has been organized through the Global Atmospheric Watch (GAW) programme of WMO. Everyday work is coordinated by WMO jointly with a secretariat hosted by the Finnish Meteorological Institute with a Memorandum of Understanding with the WMO. The implementation plan of IGACO-O3/UV was published in 2008 (http://www.igaco-o3.fi/linked/en/IGACO-O3_UV_Implementation_Plan.pdf). During the last years IGACO-O3/UV has concentrated on two activities: ACSO (Absorption Cross Sections of Ozone, http://igaco-o3.fmi.fi/ACSO) and SI2N (SPARC-IO3C-IGACO-O3-NDACC initiative on Past Changes on Vertical Distribution of Ozone, http://igaco-o3.fmi.fi/VDO/).

7. FUTURE PLANS

Although the basic processes related to stratospheric ozone are now believed to be fairly well understood, there remain important research topics related to ozone and UV, such as the interaction between ozone depletion/recovery and climate change and the effects of UV-irradiance on nature, human health, agriculture, and on materials. According to the present understanding the recovery of the ozone layer will take several decades, but the scenarios contain many uncertainties, among which man's behaviour is not the smallest. To verify the existing and coming scenarios it is imperative that the research and monitoring activities will be continued and developed.