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Atmospheric Trends Above Finland: II Troposhere and Stratosphere

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Abstract

Long-term meteorological monitoring activities at Sodankylä (67°N, 26°E) in Northern Finland are discussed. Observed time series of surface temperature, radiosoundings, solar radiation, and ozone, are described in more detail and availability of short-term or campaign-based records of other data are summarized. The trends found in the data are discussed and references to earlier analyses on the data sets are given. Data from Jyväskylä and Jokioinen (Finland) are found to agree well with the observed trends in long-term radiosonde data of Sodankylä. The long-term measurements suggest that changes in the atmosphere may occur in a stepwise manner. Here we report enhanced cooling of lower stratosphere as observed above Finland during the recent decade. For the time period January 1991 until December 1997 the observed cooling according to Sodankylä radiosondes has reached (-0.58 ± 0.11) K/year at 50 hPa, (-0.52 ± 0.14) K/year at 70 hPa and (-0.45 ± 0.15) K/year at 100 hPa air pressure level. Recent stratospheric cooling has been accompanied by decrease in ozone partial pressure which has reached (-2.2 ± 1.4) %/ year at the level of 50 hPa for spring season according to the ozone sonde data of 1988-1997. The annual decrease of ozone in the lower stratosphere layer of 150 to 50 hPa has been (-1.3 ± 0.8) % / year according to the balloonborne ECC sonde data, while the measurements by Brewer spectrophotometer suggest that total column ozone for the same period has decreased by (-1 ± 0.1) % / year.

Key words: Ozone, temperature, radiosoundings

1. Introduction

Despite of the impressive development of satellite based remote sensing of the atmosphere, the ground-based meteorological measurements still provide the most important source of information for climate studies due to their long time span and comparable easiness of maintaining calibration of instruments over extended periods (*IPCC,* 1996). However, due to changes in locations and instruments, the data records have to be checked before analysing. The records of the Sodankylä Meteorological Observatory have been critically evaluated and homogenized. Especially ozone sonde, radiosonde and spectral UV-B radiation records belong among the longest homogeneous time series in the Arctic, where the data sets otherwise tend to be sparse and discontinuous (*Weatherhead*, 1998).

Meteorological observations, including surface temperature measurements at Sodankylä, date back to 1858, when a station equipped with barometers and thermometers was established by the Finnish Society of Sciences and Letters (*Heino*, 1994). The station was operational with some minor gaps until 1879. The continuous record of temperature and other regular meteorological observations at Sodankylä starts in 1908. The observations were first made at Sodankylä village and since 1914 at the Sodankylä Geophysical Observatory, about 6 kilometers south of the center of Sodankylä. In the year 1949, the Finnish Meteorological Institute (FMI) established its own observatory in the vicinity of the Geophysical Observatory and the observations continued there. The year 1949 marks also the start of radiosonde observations. In this case there is a break in homogeneity in 1958 when the present sounding times, three hours earlier than original ones, were adopted throughout the WMO network. Another factor affecting homogeneity of the radiosounding records is the relatively fast development of sensors (*Gaffen*, 1997). Solar radiation measurements were added to the routines of the meteorological observatory in 1957. The data consists of measurements of global, diffuse, and reflected radiation, and radiation balance. Solar radiation data from Sodankylä among other stations has been recently analysed by e.g. *Heino* (1994), *Heikinheimo et al.* (1996) and *Venäläinen and Heikinheimo* (1997). A regular ozone monitoring program was established in 1988 involving both column ozone and ozone vertical profile measurements. The ozone data from Sodankylä have been used in numerous studies of the polar ozone layer (e.g. *Kyrö et al.*, 1992; von der Gathen et al., 1995; *Rex et al.*, 1997; *Kivi et al.*, 1998; *Knudsen et al.*, 1998), some studies have been based exclusively on these data (e.g. *Taalas and Kyrö*, 1992; *Kyrö et al.*, 1993). Tropospheric and surface ozone data have been analyzed, e.g., in studies by *Taalas et al.* (1993); *Mikkelsen et al.* (1994) and *Rummukainen et al.* (1996). In the following chapters we present an overview of availability of meteorological data from Sodankylä and a more detailed analysis of the long-term changes of solar radiation, temperature and ozone. Data of vertical distribution of ozone and temperature in this study is obtained by balloon borne instruments. We use additional radiosonde data from two other Finnish stations (Jyväskylä and Jokioinen) for comparison of the observed trends found in the Sodankylä data. Data analysis of measurements in stratosphere and tropoposhere (current paper) follows the I part (*Ulich et al.,* 1999) of atmospheric trend studies above Finland, which deals with the measurements in the ionosphere.

2. Availability of atmospheric data from Sodankylä

Atmospheric data measured at Sodankylä ranges from regular long-term observations to shorter instrumental records obtained during research campaigns. The availability of atmospheric data at the Sodankylä site is summarized in Table 1, together with the starting year of each instrumental record.

Table 1.
a) Long-term monitoring of atmospheric species at Sodankylä

Type of observation/instrument	record starts in
Routine weather observations	1908 (1858)
Radiosoundings of P, T, RH%	1949
Solar radiation: global, diffuse, reflected, radiation balance, sunshine hours	1957
SO_2	1972
O_3 column, Brewer spectrophotometer	1988
O_3 vertical profile, ozone sondes	1988

b) Availability of atmospheric data for a shorter than 10-years period.

Type of observation/ instrument	record starts in
O_3 column, SAOZ spectrophotometer	1990
NO_2 column, SAOZ	1990
UVB/UVA radiation, Brewer	1990
UVB/UVA radiation, SL500/501	1990
Aerosol vertical profile, aerosol lidar	1991
Aerosol vertical profile, aerosol sondes	1994
OClO column, SAOZ	1995
Surface ozone, Dasibi 1008 AH, ECC ozone sonde	1995
O3 vertical profile, microwave radiometer	1996
Atmospheric electricity: -current density, electric field, electrical +/– conductivity	1998 (1993)

3. Solar radiation

The continuous series of solar radiation measurements at Sodankylä starts from August 1957, although before that, during 1952-1957, total incoming radiation was measured (*Meteorological yearbook of Finland*, 1966). The global, diffuse, and reflected components of solar radiation have been observed with a Moll-Gorczynski type of pyranometer and the radiation balance with a Suomi-Franssila radiation balance instrument (*Meteorological Yearbook of Finland*, 1982, 1993). Since the same type of instrumentation has been used, and the location of the measurements has not been shifted, the solar radiation record is considered homogeneous, except for a small shift of about 2 % since 1981, when the present World Radiometric Reference Scale was introduced (*Heino*, 1994). In general we observe a decreasing trend for global radiation (Figure 1). This tendency is consistent with the earlier findings e.g. by *Russak* (1990), *Stanhill and Moreshet* (1994) and *Heikinheimo et al.* (1996). *Russak* (1990) found a decrease of 6.3 % in annual mean global irradiance over Tõravere in Estonia corresponding to years 1955-1988. The trend was attributed to changes in cloudiness (increase by 11%) and decrease of incoming direct solar energy (14.4 %). *Heikinheimo et al.* (1996) calculated decrease of mean annual global solar irradiance of 8.7 % and 11.2 % above Jokioinen and Sodankylä respectively based on the data of the period from 1958 to 1992. They concluded that the trend in irradiance was caused mainly by increase in cloudiness, since the contribution from increased aerosol concentrations was about 1%. The most striking feature in the recent Sodankylä record is the marked increase in global radiation since early nineties. In the same time the amount of sunshine hours has increased and the diffuse component of radiation has decreased slightly (Figure 1). The cloudiness has decreased during the post-Pinatubo period since 1991 by (-1 ± 0.3)% per year (cloudiness is not shown on the graph). Similar minima followed by recovery can be found also in earlier data attributable to El Chichón eruption in April 1982.

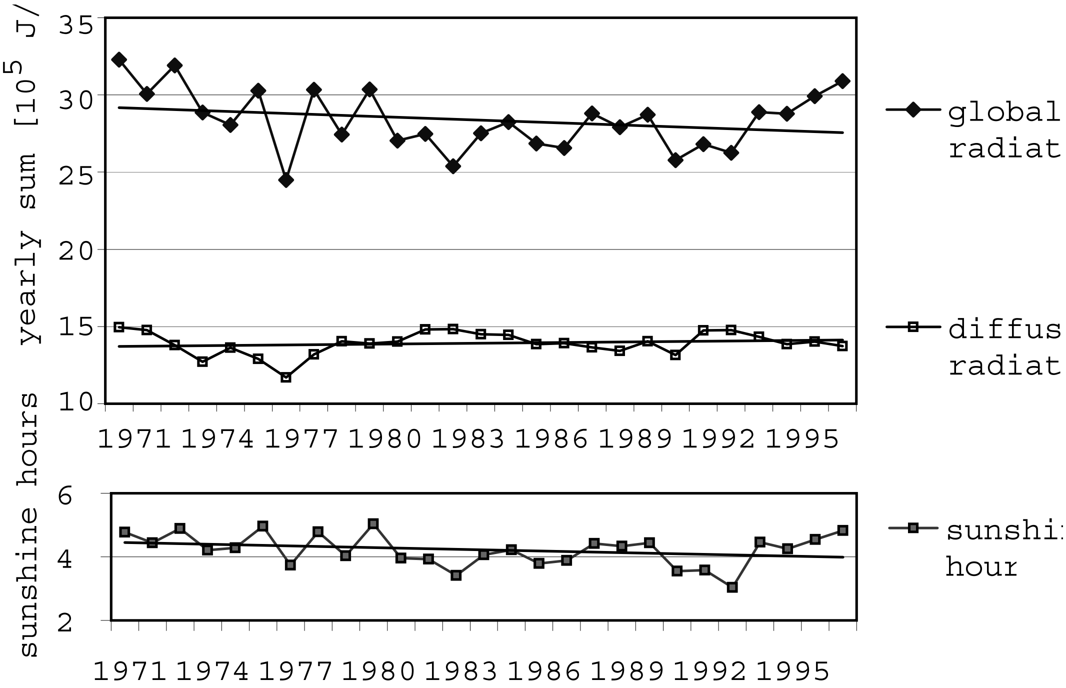

Fig. 1. Temporal development of yearly global and diffuse radiation, and sunshine hours at Sodankylä since 1971.

4. *90-year continuous record of surface temperature*

In Figure 2 we present the continuous part of the Sodankylä surface temperature (measured 2 m above the ground) record as yearly mean temperatures. The record shows warming of the surface layer until the late 30ies and a successive cooling until mid-80s. During the nineties the mean temperature has stayed above the long-term mean value of -0.1. The temperature time series were calculated using the method given in *Heino* (1994) and tested for homogeneity according to the Standard Normal Homogeneity Test (*Alexandersson*, 1986; *Alexandersson and Moberg,* 1997). The possible inconsistency in Sodankylä mean temperatures does not exceed 0.1 K (*Tuomenvirta,* private communication).

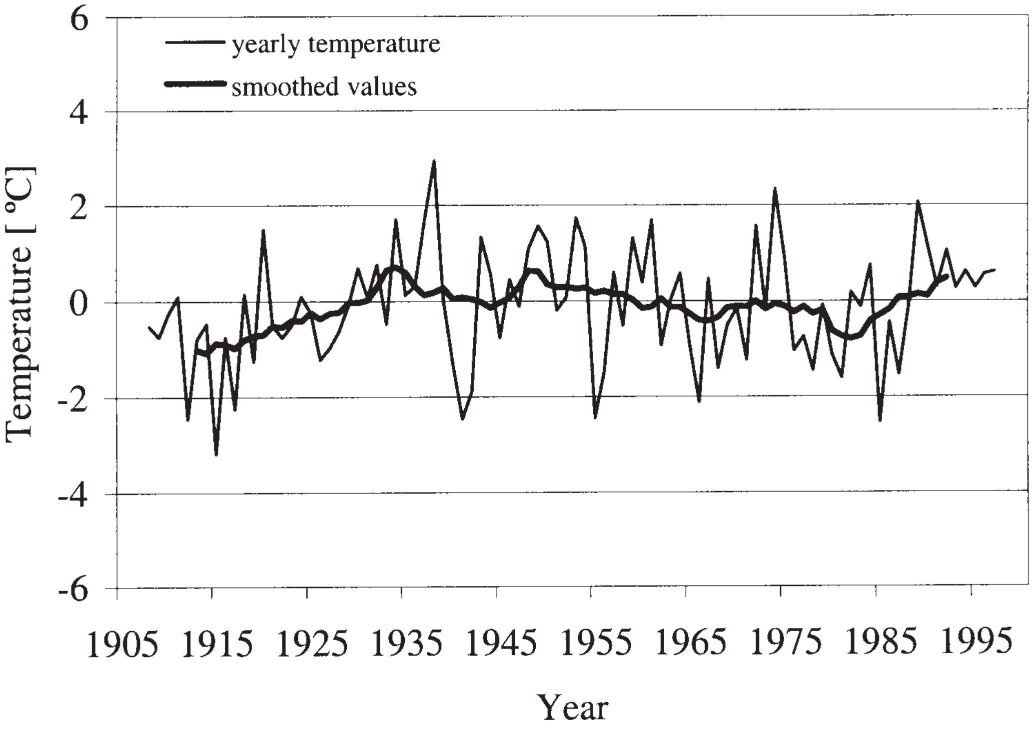

Fig. 2. Temporal development of mean annual surface temperature at Sodankylä since year 1908. Data of the Finnish Meteorological Institute.

5. *Radiosonde observations of vertical temperature profile*

In this study trends of radiosonde temperatures in troposphere and lower stratosphere were calculated for Sodankylä for the period of 1958-1998. As shown in table 2 radiosondes show warming of the lower troposphere although statistically not significant and cooling of the lower stratosphere. Long- term stratospheric cooling over Jokioinen (60° N) was similar to that observed over Sodankylä (67° N), the corresponding trends at 50 hPa level for years 1965-97 were (-0.07 ± 0.02) K/year and (-0.08 ± 0.02), respectively. These results are consistent with earlier findings by *Taalas et al.* (1996), where data of the period of 1958-1994 was analysed. Also in this study additional radiosonde data was treated for lag error correction as in analysis *by Taalas et al.* (1996). However, here the trend calculations did not include the radiosoundings performed at noon, in order to avoid uncertainties raising from daytime radiation corrections of RS18/21 sondes (*Luers and Eskridge*, 1998).

Table 2. Trends per pressure level in K/decade together with standard deviation (std) of 00 UT radiosoundings at Sodankylä (67° N) for 1958-1998.

altitude [hPa]	surface	850	700	500	400	300	200	150	100	70	50
trend [K/decade]	0.10	0.02	0.01	-0.10	-0.16	-0.23	-0.25	-0.31	-0.42	-0.55	-0.65
std	0.16	0.10	0.10	0.09	0.07	0.06	0.14	0.13	0.13	0.13	0.14

Sodankylä temperature data since 1991 shows clear increase of lower stratospheric cooling between 100 and 50 hPa, which may be explained by radiative effects of the recent enhance ozone decrease (*Pawson et al*., 1998). For the time period January 1991 until December 1997 the observed cooling has been (-0.58 ± 0.11) K/year at 50 hPa, (-0.52 ± 0.14) K/year at 70 hPa and (-0.45 ± 0.15) K/year at 100 hPa air pressure level. Radiosonde data has also been used to study the occurrence of sufficiently cold temperatures (T<195K) for polar stratospheric cloud (PSC) formation e.g. by *Taalas et al.* (1996) and *Taalas and Kyrö* (1994). These clouds are of special interest, as chemical reactions on PSC particles play a major part in the depletion of the ozone layer (e.g. *Carslaw et al.,* 1998). Figure 3 shows the temporal development of the occurrence of temperaturees which allow PSC formation grouped by winters (December-March). During the period prior to 1982 these events occurred in 3 % of all winter radiosondings, while the mean for the recent period (1982/83-1998/99) has reached 11 %. Finally, we have studied the long term changes in tropopause height using data from three Finnish radiosonde stations, Sodankylä, Jokioinen, and Jyväskylä for the period of 1965-1997. Changes in tropopause height were studied here, because it is one of the meteorological factors which contribute to changes of daily total ozone column. The tropopause was defined as the lowest level at which lapse rate decreases to 2 K/km or less, which is in accordance with *WMO* (1992) criteria. As shown in Figure 4 similar features are evident in the data of all Finnish stations. There is a pronounced increase in tropopause height since the observed minimum in 1985. The linear trend calculated over the whole period of Sodankylä observations is (+4.1 ± 2.8) gpm/year, which gives 135 gpm increase in average tropopause altitude. The linear trend for the same period according to Jokioinen data is considerably smaller, (+0.5 ± 0.2) gpm/year (Figure 4).

6. *Balloon-borne measurements of ozone vertical distribution*

The Sodankylä ozone sonde record (1988 to present) is the longest in the European sector of the Arctic. By the end of 1997, the ozone sonde database comprised 640 quality controlled soundings (*Kyrö et al.,* 1998). The quality control routines developed at Sodankylä for European ozone sonde campaign have been adopted for the whole Sodankylä ozone sonde time series. These include automated routines inspecting the key quality parameters such as correction factor (ratio of Brewer or TOMS total

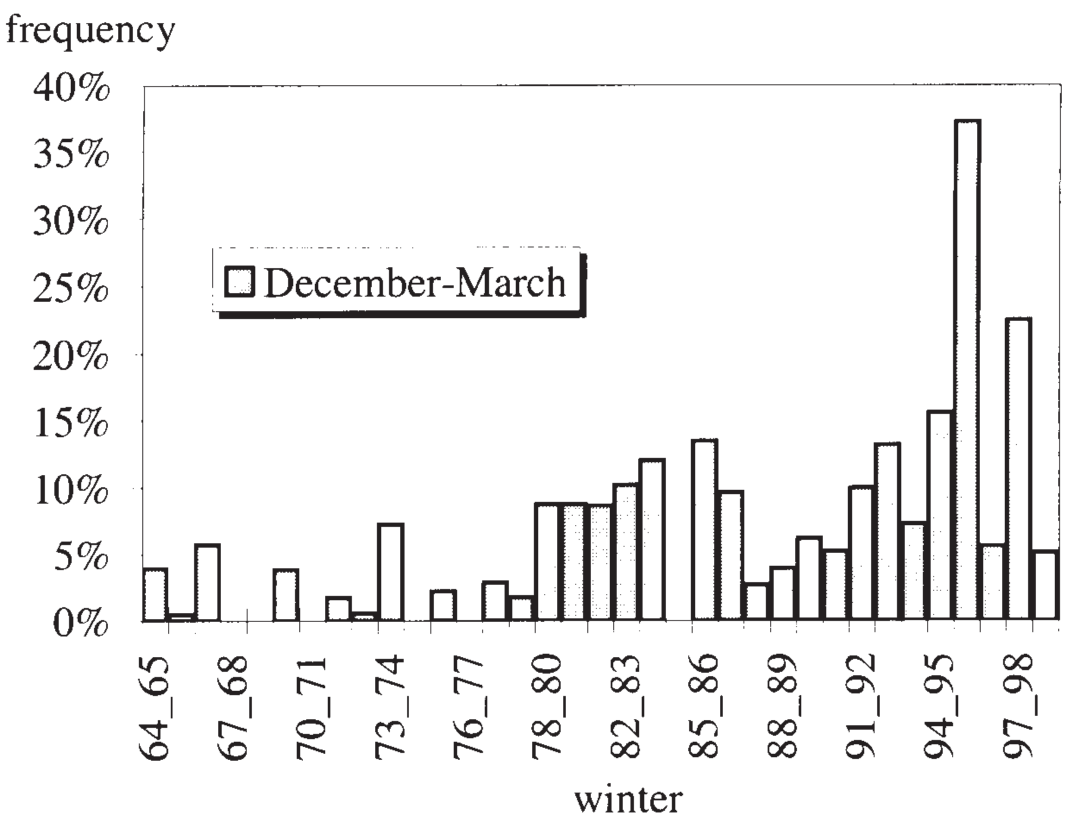

Fig. 3. Occurrence of temperatures below type I PSC threshold values at 50 hPa (below 195 K) for winter seasons (DJFM), according to radiosonde observations at Sodankylä during 1964/65-1998/99.

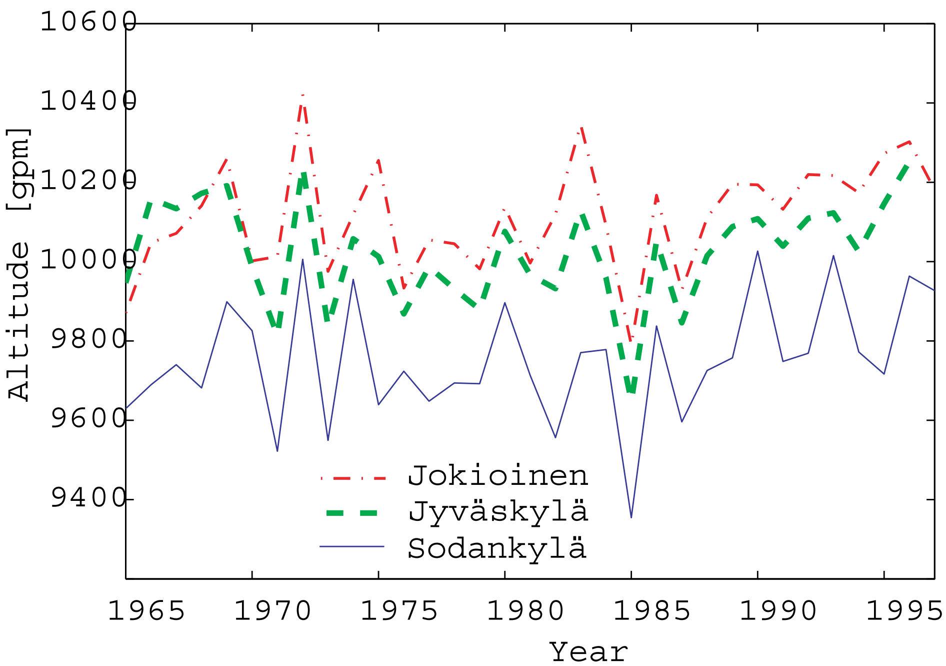

Fig. 4. Long-term observations of tropopause height of Finnish radiosonde stations Sodankylä (67° 22′ N, 26° 39′ E), Jyväskylä(62° 24′ N, 25° 39′ E) and Jokioinen (60° 49′ N, 23° 30′ E).

ozone to integrated ozone column from contemporoneous sounding), background current, gaps and spurious spikes in the data, and anomalous ozone values as compared with climatological data close to the top of the profile, which is indicative of pump problems. Those soundings which fail to pass the automated QC routine are subjected to individual inspection by experienced scientist. In this study we have calculated the mean profiles for spring (MAM) and winter months (DJF) as shown in Figure 5. Data of ozone profiles obtained both inside and outside polar vortex has been used here. The standard deviations relative to calculated means are the largest around tropopause and dynamically active lowest stratosphere (between 40 and 60 %), while for the rest of the vertical profile the variability is between 10 and 30 percent. Ozone profiles of the spring season are decribed by higher variance in the lowest stratosphere compared to winter profiles. The first profile represents the pre-Pinatubo situation (1988-1991), second and third profile are grouped by 3 years (1991-94 and 1995-97) to obtain an estimation of ozone changes over 9 years of observations at different tropospheric and stratospheric altitude levels. The most striking feature is the ozone decrease of (-2.2 ± 1.4) % per year in springtime at around 50 hPa altitude, however this method does not allow to separate dynamical and chemical factors affecting ozone changes. Using balloonborne ozone sonde data from 35 stations within the Match 1994/95 campaign *Rex et al.* (1997) have shown that during cold stratospheric winters chemical ozone loss in the Arctic lower stratosphere may reach maximum value of 2.7 DU/day in mid-March as integrated over a column from 370 K to 600 K. The work to further analyse vertically resolved ozone trends will be continued in the near future, including analysis of tropospheric ozone trends. The current study suggests that yearly mean ozone has decreased by (-1.3 ± 0.8) %/ year in the lower Arctic stratosphere between 50 and 150 hPa over the period of 1989-1997.

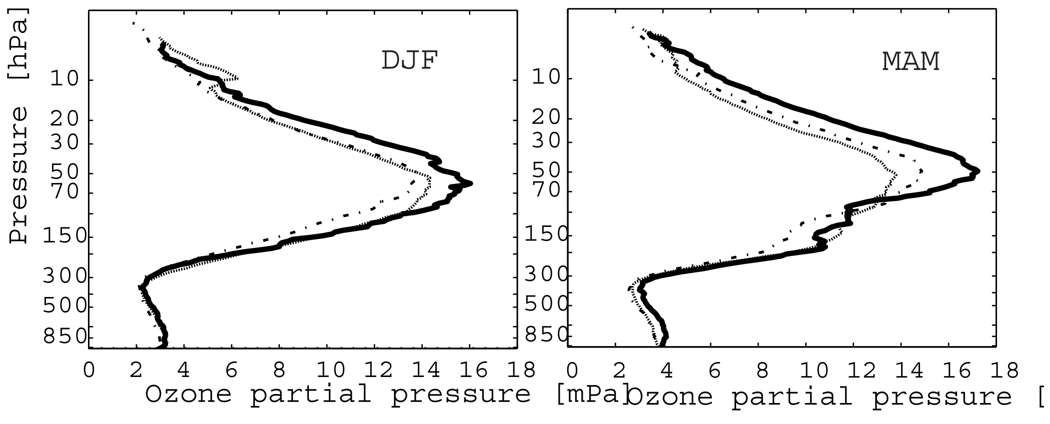

Fig. 5. Seasonal mean profiles of ozone partial pressure [mPa] derived from balloon-borne ozone measurements: winter (DJF) profile is shown on the left panel and spring profile (MAM) on the right panel. The solid line corresponds to the mean profile of pre-Pinatubo period (1988-1991), the line of dots and dashes represents the period of 3 years shortly after Pinatubo eruption (1992-1994), while the mean profile for the latest three years of measurements (1995-1997) is shown by the thin line.

7. *Measurements of total O_3 and NO_2 column*

First measurements of the total ozone column were performed at Sodankylä by a Russian filter ozonometer in 1987. A continuous record, based on Brewer spectrophotometer measurements, started a year later. Brewer direct sun data has been recalculated based on nine intercomparisons with travelling standard Brewer no. 17 and on the daily O_3 and SO_2 ratios recorded on the internal calibration lamp. The zenith measurements have been recalculated using the zenith sky charts developed for the Sodankylä Brewer (*Karhu*, 1995).

The recalculated Brewer total ozone data show a decrease of total column ozone by (-1.0 ± 0.1) % per year corresponding to the data from 1989 until the end of 1997 (Figure 6). In addition to ozone, the Brewer spectrophotometer also gives information on spectrally resolved UV-radiation. Using this spectral responsivity *Masson et al.* (1998) have calculated the time series of the spectral UV-B radiation at Sodankylä from late 1990 to 1997. In their study spectral solar measurements were compared to spectral irradiances calculated using a radiation transfer model both for low and high surface albedo for clear sky midday conditions. Calculated long-term spectral irradiances of Sodankylä Brewer will be used in a trend study (Masson, private communication).

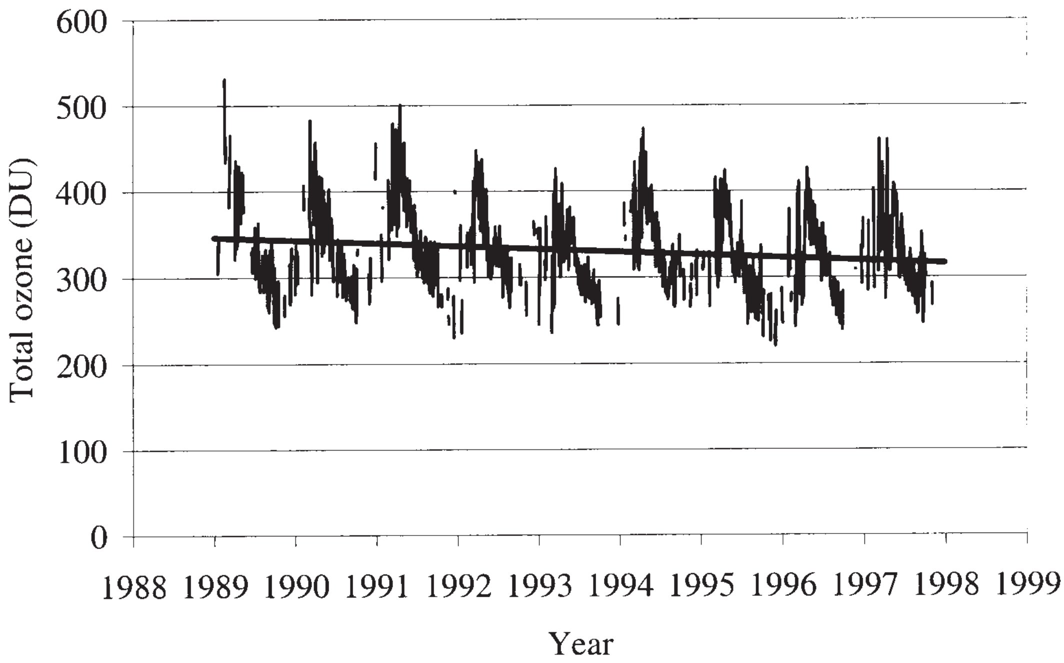

Fig. 6. Recalculated data of daily total ozone observations by Brewer for 1989-1997. Observed ozone decrease during this period is (–1.0 ± 0.1) % per year.

The problem in UV-based total-ozone meters is the lack of sun during polar night and twilight. The winter data is only based on a limited set of moonlight measurements and trend estimates are based mainly on spring, summer and autumn data. At visible spectral range the measurements become possible at larger zenith angles. The SAOZ spectrometer, which uses these techniques, is able to give total ozone and column NO_2 values throughout the year at Sodankylä and corresponding latitudes (*Goutail et al.*, 1994). SAOZ has been operational in Sodankylä since 1990 (Table 1). Possible biases between Brewer and SAOZ instruments were studied in detail by *Kyrö* (1993) and *Høiskar et al.* (1996). Recently *Van Roozendael et al.* (1998) have discussed in detail different contributions for the scatter of SAOZ/Brewer comparisons at Sodankylä. Column ozone measurements by SAOZ distributed in the Arctic were used recently in the study by *Goutail et al.* (1999). They found cumulative total ozone depletion at the end of winter in March of 18± 4% in 1994 and of 32± 4% in 1995 within the polar vortex and of 15± 4% in both years outside the vortex.

The SAOZ time series from 1990 to the end of January 1998 of daily column NO_2 [10^{15} molec cm^{-2}] are shown in Figure 7. NO_2 measurements are important because of its ability convert ClO to $ClONO_2$ in the stratosphere.

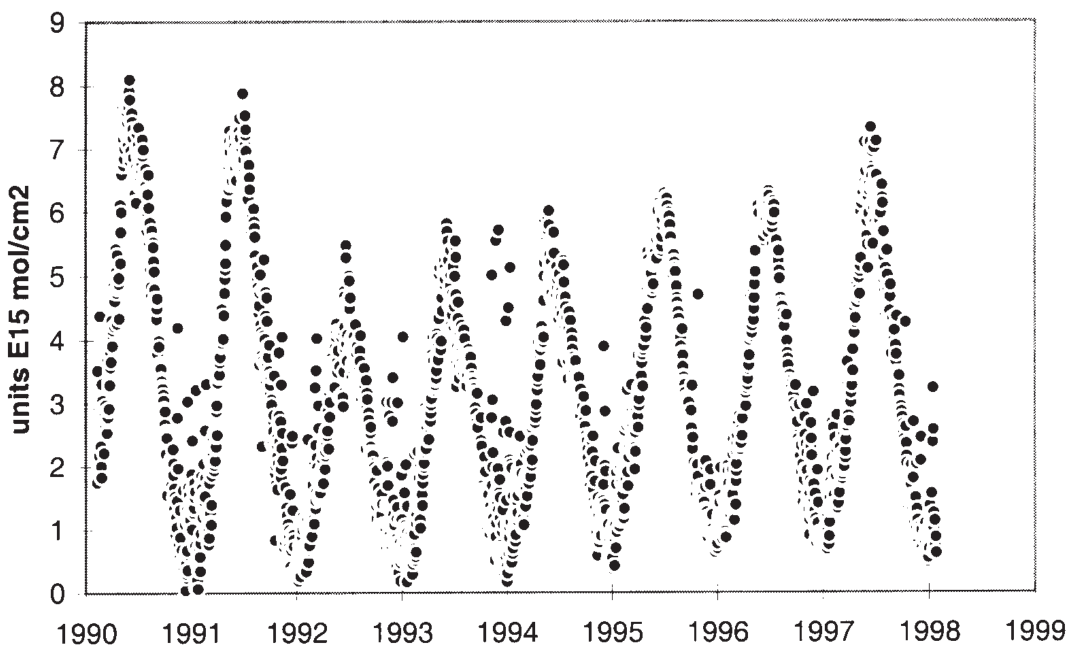

Fig. 7. NO_2 column [10^{15} molec cm^{-2}] as measured by SAOZ at Sodankylä, from January 1990 to January 1998.

Nitrogen dioxide is measured by SAOZ by a differential absorption method in the visible bands between 412 and 515 nm. The instrumental uncertainties of SAOZ are discussed in e.g. *Goutail et al.* (1994) and in an intercomparison study by *Vaughan et al.* (1997). The eruption of Mt. Pinatubo caused 30 % of decrease of NO_2, because of the ability of volcanic aerosols to convert NO_2 into HNO_3 in the lower stratosphere (*Goutail et al.*, 1994). A steady recovery in column NO_2 towards "pre-Pinatubo" values since 1991/1992 is shown in Figure 7. The data are averaged over measurements of the solar zenith angle range from 86° to 91°. Tropospheric pollution events (tropospheric NO_2-rich air arriving to the site) are not filtered out from the data. During the winter, the movements of the polar vortex are reflected in the column ozone and NO_2 data from Sodankylä as air alternatively from the vortex, from the vortex edge and from outside the vortex are sampled. Correlations of column ozone and column NO_2 with meteorological parameters, such as the location relative to the polar vortex and lower stratospheric temperatures, change during the annual cycle. NO_2 seasonal variations at Sodankylä are caused by the inhibition of N_2O_5 formation during the polar day in summer and the absence of N_2O_5 photolysis during winter.

Comparison performed by *Goutail et al.* (1994) showed that NO_2 data from other stations in European Arctic was very similar, while there were large discrepancies between Sodankylä and Zhigansk (66° N, 123° E). This finding was attributable to differences in aerosol loading and different locations relative to artic vortex and thus subsequent differences in temperatures at 30-50 hPa above the two stations.

8. Conclusions and discussion

We have presented a review of long and medium term meteorological measurements from Sodankylä including climatological trends found in the data based on this work and earlier investigations. Also radiosonde data from other Finnish stations (Jyväskylä and Jokioinen) was used in the analysis. Some of the Sodankylä meteorological data sets constitute a unique source of information on the development of important climate parameters over decades. Especially, the records of surface temperature, free tropospheric and lower stratospheric temperatures, solar radiation, ozone soundings and spectral UV-radiation measurements are among the longest in the arctic and boreal region. The data have been quality controlled and temperature and ozone data have been reprocessed to remove known inhomogeneities. The measurements of surface temperatures show warming from the beginning of the record in 1908 till late 30ies, followed by a cooling tendency to mid-80ies and a new warming period during the recent years. From the radiosonde records warming has also been found from the measured lower tropospheric temperatures, while upper troposphere and lower stratosphere have been cooling down.

In general we found that several long-term time series of atmospheric measurements are not well described by linear trends, as changes in the atmosphere may occur in a stepwise manner. This feature is seen for example in enhanced stratospheric cooling which is also evident in hemispheric scale (*Pawson et al.*, 1998) and in revised tendencies of temporal development of solar radiation components and cloudiness during the recent decade. In some cases the changes may be of natural origin, e.g. major volcanic eruptions. For example during the post-Pinatubo period there has been a steady increase in global radiation attributable to observed decrease in cloudiness and possible increase in direct radiation as the diffuse component of radiation has decreased slightly during the most recent period. A steady recovery in column NO_2 towards “pre-Pinatubo” values is observable since 1991/1992, according to measurements by the SAOZ spectrometer. In some cases we may suspect antropogenic influence as in the case of accelerated cooling of lower stratosphere in nineties and reduction of lower stratospheric ozone content. Decrease of total ozone is confirmed both by ground-based spectrometer measurements and by ozone sonde records. For the period of 1989 to 1997 inclusive, the total ozone has decreased by (-1.0 ± 0.1) % per year, while the long-term vertically resolved data suggests, that the ozone decrease has been most intense during the spring season at the altitude region of 70 to 30 hPa (about 18-22 km) around the maximum of the ozone layer. We are planning to extend the vertically resolved ozone trend study to the troposphere and the lowest stratosphere. This study will include a closer look at sources of possible instrumental errors and their impact on ozone trends. The recently calculated spectral UV-B radiation data will also be used for trend studies.

Acknowledgments

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