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Evidence of a possible turning point of UVB increase over Canada, Europe and Japan

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Abstract

This study examines the UV variability at 305 nm and 325 nm over selected sites in Canada, Europe and Japan. Site selection was based by the availability of UV spectroradiometric datasets longer than 15 yr. The analysis of UV variability was conducted in combination to total ozone, aerosol optical depth and cloud variability. The results suggest that the period with the longest available spectral measurements of UV irradiances over Canada, Europe and Japan can be divided into three sub-periods of scientific merit: the first period is the period perturbed by the Pinatubo volcanic eruption for which it is shown that excess volcanic aerosol might have enhanced by an additional 6 % the "conventional" (+18 %) amplification factor of UVB at ground level. The second period is characterized by a UVB increase caused by the synergy of ozone decline and tropospheric aerosol decline (brightening effect) during which overhead cloudiness remained without statistically significant trends. During this second period, the long term variability is the brightening of +0.94 % yr^{-1} and +0.88 % yr^{-1} at the wavelengths 305 nm and 325 nm respectively. The third period, which refers to the last 4–5 yr, might provide for the first time significant statistical evidence indicating the slowdown of the upward trends observed before, over the sites studied where UVB sites seem to have passed maximum UVB exposure levels since about 2006.

1 Introduction

The world "avoided" following the success of the Montreal Protocol (Zerefos et al., 2009a) and signs for recovery of ozone in the Northern Hemisphere (Zanis et al., 2006; Chipperfield et al., 2007; Harris et al., 2008; WMO, 2011) point to the consequence that, other factors remaining constant, harmful UV-B doses should level off or decrease their upward trends (Zerefos, 2002). Instead, the 2011 WMO/UNEP Ozone Assessment and a recent paper (den Outer et al., 2010), reported the continuation through 2005 of upward trends in UV-B and particularly for Europe, they found a range from +0.3 % yr^{-1} to +0.6 % yr^{-1} with about 2/3 being attributed to decreasing of cloudiness and aerosol optical depth and 1/3 to the ozone decline. Trends in cloudiness and aerosols are different in different places on earth (Wild, 2009; Wild et al., 2009; Cermak et al., 2010) and their long term effects vary in different parts of the solar spectrum (Zerefos et al., 2009b). Using the longest available time series of spectral UV measurements (e.g. Fioletov et al., 2001, 2004) and updating the results through 2010, we provide here tentative evidence that we may have passed maximum UV-B exposure levels over various sites in Europe, Canada and Japan located at northern latitudes from 25° N to 60° N. The results pertained to 305 nm and 325 nm at stations with spectroradiometric data covering more than 15 yr of records. The results are supported by observations of other atmospheric variables affecting the UV irradiance at the earth's surface, namely, clouds, ozone, aerosols. Both observations and model results support the evidence of excess UV-B amplification factors during the excessive injection of the volcanic aerosol in the stratosphere (Pinatubo period), the post Pinatubo brightening period and the most recent four years which present signs of passing max UV exposure as discussed in the text

2 Data sources and methodology

We have decided to select the most complete, with the longest available time series of spectroradiometric data set in the 20-yr period of study (1990–2010). We used 12 spectroradiometers listed in Table 1. In addition, to spectral UV and total ozone, this study includes the analysis of time series of aerosol optical depth (AOD) at 550 nm and cloud cover from satellite data for the period 1990–2010. In the case of AOD, two overlapping data sets have been used: (1) for the period 2000–2010, the Terra AOD experiment (Levy et al., 2007) from the MODerate-resolution Imaging Spectroradiometer (MODIS), used to investigate possible AOD trends over the last decade and the NASA Global Aerosol Climatology Project (GACP) (Mishchenko et al., 2007), used in order to investigate the effect of the Pinatubo volcanic eruption. Similarly, cloudiness data for the period 1990–2006 were taken from the NASA International Satellite Cloud Climatology Project (ISCCP), (Rossow and Schiffer, 1999) and for the period 2000–2010 cloud fraction and cloud optical depth from MODIS/Terra satellite.

We have used the MODIS/Terra AOD for the period 2000–2010 with a spatial resolution of 1° × 1° around each of the ground based monitoring stations, listed in Table 1. For retrieving information on AOD during and after the Pinatubo eruption and its effect on UV irradiance levels we have used the NASA/GACP data on AOD at 550 nm. As NASA/GACP AOD data accuracy increases to areas near large water bodies such as oceans, seas and lakes, where the surface reflectance is often low, we have used the 2.5° × 2.5° square degree resolution for eight out of the twelve spectroradiometric stations that are near water bodies and a 5° × 5° resolution for the remaining four. In order to test the accuracy of the time series created as averages pertaining at each station from the NASA/GACP data, the corresponding MODIS/Terra data for the overlapping period (2000–2006) have been used, to calculate correlation between the common-period data sets, showing that the differences between any of the data sets are not significant at the 99 % confidence level in accordance with the results of Geogdzhayev et al. (2004). Similarly, the cloud fraction and cloud optical depth products from MODIS and the cloud fraction product from NASA/ISCCP cloud data, have been used. The NASA/GACP AOD data were obtained from the webpage http://gacp.giss.nasa.gov/. The NASA/ISCCP cloud data were obtained from the webpage http://isccp.giss.nasa.gov/. The MODIS/Terra AOD and cloud data were obtained from the webpage http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_MONTHLY_L3.

UV irradiance measurements at 305 nm and 325 nm and total column ozone data for the stations in Canada and Japan were obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) operated by Environment Canada, Toronto, Ontario, Canada under the auspices of the World Meteorological Organization (www.woudc.org). European UV irradiance data were obtained from the European UV Database (http://www.ozone.fmi.fi/uvdb). Monthly means of daily UV irradiance doses were calculated for each station.

For the statistical linear trend analysis we have followed the procedure described in Reinsel (2002) and Newchurch et al. (2003). The statistical linear trend model analysis used here can be described by the equation:

$$Y_\mathrm{t} = \alpha \mathrm{Tr}_\mathrm{t} + \beta_1[\mathrm{QBO\ terms}]_\mathrm{t} + \beta_2[\mathrm{cld\ term}]_\mathrm{t} + \beta_3[\mathrm{solar\ cycle\ term}]_\mathrm{t} + N_\mathrm{t} \quad (1)$$

Where: Y_t are the monthly deseasonalized UV data, Tr_t is a linear trend term QBO terms are used to describe the QBO effect (2 terms, equatorial zonal wind at 30 and 50 hPa), the cld term to describe the cloud cover effect, and the solar cycle term to describe the effect of the 11-yr solar cycle (using the F10.7 cm solar radio flux density as proxy). Finally, N_t is the unexplained noise term. The statistical model is autoregressive AR(1), and the term N_t satisfies:

$$N_\mathrm{t} = \phi N_{\mathrm{t}-1} + \varepsilon_\mathrm{t}. \quad (2)$$

The ε_t residuals, after removing the autoregressive component $\phi N_{\mathrm{t}-1}$, are the residuals used to compute the cumulative sums of residuals (CUSUM).

In order to account for the cloud cover effect, a unified index was constructed based on the homogenization of the deseasonalized NASA/ISCCP cloud data to the MODIS/Terra cloud data during their common period. The MODIS/Terra deseasonalized series were used from 2000 until the end of the stations records. The cloud cover term was used as pertaining to the geographic area of the UV time series. Note that the aerosol optical depth has not been used in this statistical model.

3 Results and discussion

Figure 1 shows the deseasonalized departures from the 1990–2010 monthly mean anomalies averaged over all stations of total ozone 305 nm, 325 nm UV irradiances, the AOD and cloud fraction. On top of the figure is the QBO time series plotted for comparison. The gray vertical zone swiping the composite time series was drawn to indicate the period when the Pinatubo eruption had significant effects in both total ozone and the AOD values (Granier et al., 1992; Zerefos et al., 1994). Noteworthy here is the perturbation introduced by the Pinatubo aerosol in the well-known anti-correlation between UV-B and total ozone (Zerefos et al., 1994) which will be discussed later.

As it appears from figure 1 the significant excursion of UV at 305 nm and not at 325 nm during the perturbed period from Pinatubo, is definitely related to the combined effect of reduced ozone overhead and the increase of volcanic aerosols in the lower stratosphere. Moreover, the lower stratosphere aerosol continues to decline after the end of the volcanic perturbation. It is interesting to note here that total ozone at the sites studied had a long term increasing trend after the volcanically perturbed period. More interesting thought is the long term increase in both 305 nm (ozone dependent) and 325 nm (almost independent of ozone). Both increases must be related to the overall aerosol decrease as well as to the fact that clouds do not present any significant trends. We therefore observe for the case of 305 nm of two competing factors affecting its levels reaching the ground: total ozone increasing which would have an effect of reducing 305 nm and aerosols decreasing which would have a positive effect to both UVB and UVA since a major factor which is cloudiness do not present any significant long term variability. Following the above arguments, we would expect, for the case of 305 nm (and UVB in general), that a turning point of the long term increasing trends in this part of the spectrum would be found with our data sets.

Trying to quantify these arguments, we have calculated trend estimates and tested them for significance, based on Eq. (1) restricted to the period 1995–2010. We note here that the time series for both the cloud fraction and for the QBO do not present any significant trends throughout the past 20 yr period. If these terms are not used in Eq. (1) then the results of 305 nm and 325 nm UV irradiances averaged over all stations display an increase of (0.55 % ± 0.03 %) yr^{-1} and (0.44 % ± 0.05 %) yr^{-1} respectively, while average ozone levels increased by (+0.13 % ± 0.02 %) yr^{-1}. Similarly, AOD levels appear to decline by about 1 % yr^{-1} during the same period 1995–2010. A summary of the results can be found in Table 2.

The observed trend at 305 nm is the result of changes introduced by ozone, aerosols and clouds. An estimate of the long term trend at 305 nm, which can be attributed to the ozone increase, can be estimated by the difference in the observed trends at 305 nm minus the trend at 325 nm, since the longer wavelength is almost not depended on ozone variability. By a simple difference of the trends, it can be inferred that aerosol together with cloudiness trends increased UV-B radiation trend and since cloudiness had no significant trend, a large part of the observed positive trend in UV can be attributed to the significant decrease of the aerosol trend.

To clarify the issue, we have applied radiative transfer model calculations with the LibRadtran package in order to quantify the individual effects of ozone and AOD on the UVB irradiance (Mayer and Kylling, 2005). Ozone and AOD, have been used as radiative transfer model inputs in order to calculate model derived irradiances at 305 nm for all stations during the period 2000–2010 using the MODIS/Terra satellite AOD data and the ground-based ozone measurement data. Deseasonalized UVB retrieved results showed a –5 % change in the UVB levels from 2005 to 2010 under cloudless conditions (Fig. 2). This change is a result of the ozone positive change and the competing AOD factor decrease (upper and middle panels of Fig. 2). Separating the effects, we found a –6.2 % change due to the observed ozone increase for the last 5 yr. The calculation for the aerosol case shows a +3 % increase of UVB from 2000–2010, and a +1.8 % increase from 2005–2010. The total UVB decreasing tendency during the 2006–2010 period, shown also in Fig. 1, can be tentatively proposed to be the result of the competing tendencies of the factors affecting UVB i.e. ozone and aerosols, provided that the year-to-year cloud variability is insignificant. A minor point to make for this last 4-yr period is that the cloud optical depth (MODIS/Terra) shows a small negative trend in the opposite direction of the negative UVB tendency seen in Fig. 1.

Trying to explore more on whether a slowdown in UV trends has occurred in the last years of the record, we have examined the rate of change in UV records in the course of

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the last 5 yr, that is after the period examined by den Outer et al. (2010). The procedure of the statistical trend analysis described in Sect. 2, Eq. (1) was applied, using as base period the January 1995 through December 2005. As discussed in Sect. 2, the AOD was purposely left out from the terms of Eq. (1), in order to quantitatively prove its effect (together with ozone for UV at 305 nm) in the calculated UV trends. Following the Eqs. (1) and (2), the residual series (ε_t) from the model estimates for the full period beyond 2005 have been created until the end of the record. We followed Newchurch et al. (2003, their Appendix B) to calculate the 95 % confidence limits due to the statistical model uncertainty and the unexplained noise (due to unresolved fluctuations). The CUSUM procedure can assess the systematic departure of UV (at either wavelength) from the trend line calculated for 1995–2005 and extended after 2005 (i.e. linear trend forecast), and negative CUSUM indicates a smaller change in the UV increasing rate in comparison to the base period. Statistical significance can be assessed by comparison to the 95 % confidence limits and the results are presented in Fig. 3.

For the UV 305 nm departures (upper panels), the station average shows large negative CUSUM of residuals, which exceeds the 95 % confidence limit, thus indicating that the positive trend seen in 305 nm UV records until the end of the 2005s ($0.94 \pm 0.07\,\%\,\mathrm{yr}^{-1}$ for the base period 1995–2005) is beginning to slowdown. In the case of 325 nm UV departures (bottom panels), the station average shows large negative CUSUM of residuals, exceeding the 95 % cl., indicating a slowdown of the trend of the previous period ($0.88 \pm 0.04\,\%\,\mathrm{yr}^{-1}$ for 1995–2005).

Going back to the first volcanically perturbed period seen in Fig. 1 and Table 2 we note the following: a significant 8 % ozone loss and a disproportionately increase in UV-B by about 25 %, the 325 nm UV remaining within its expected range. The well-known anti-correlation between UV-B and total ozone (i.e. the amplification factor) is significantly enhanced compared to any other time period in the series. Application of the LibRadtran package (Mayer and Kylling, 2005) showed that an 8 % reduction in total column ozone, introduces an approximately 18 % increase in 305 nm irradiance levels at a solar zenith angle of 63 degrees. Using the same columnar AOD and a different aerosol-property profile scenario (urban for lower troposphere and extreme volcanic aerosol for higher altitudes), the calculation leads to an additional 6 % (24 % in total) enhancement to the calculated 305 nm irradiance levels reaching the ground. Therefore, it is probable that the excess UV-B levels during the volcanically perturbed period are the result of enhanced scattering processes caused by the injection of huge amounts of volcanic aerosols. Summarizing the above findings, we can say that over the sites studied the UVB irradiances long-term variability can be divided into three sub-periods which are characterized by different physical processes which affect the interannual variation of UVB. The first period is the period perturbed by the Pinatubo volcanic eruption for which it is shown that excess volcanic aerosol might have enhanced by an additional 6 % the "conventional" (+18 %) amplification factor of UVB at ground level. The second period is characterized by a UVB increase caused by the synergy of ozone decline and tropospheric aerosol decline (brightening effect) during which overhead cloudiness remained without statistically significant trends. During this second period, the long term variability is the brightening of +0.94 % yr^{-1} and +0.88 % yr^{-1} at the wavelengths 305nm and 325nm respectively. The third period, which refers to the last 4–5 yr, might provide for the first time significant statistical evidence indicating the slowdown of the upward trends observed before, over the sites studied where UVB sites seem to have passed maximum UVB exposure levels since about 2005–2006.

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References

Cermak, J., Wild, M., Knutti, R., Mishchenko, M. I., and Heidinger, A. K.: Consistency of global satellite-derived aerosol and cloud data sets with recent brightening observations, Geophys. Res. Lett., 37, L21704, doi:10.1029/2010GL044632, 2010.

Chipperfield, M. P., Fioletov, V. E., Bregman, B., Burrows, J., Connor, B. J., Haigh, J. D., Harris, N. R. P., Hauchecorne, A., Hood, L. L., Kawa, S. R., Krzyscin, J. W., Logan, J. A., Muthama, N. J., Polvani, L., Randel, W. J., Sasaki, T., Staehelin, J., Stolarski, R. S., Thomason, L. W., and Zawodny, J. M.: Global ozone: past and present. Chapter 3 in Scientific Assessment of Ozone Depletion: 2006, Global Ozone Research and Monitoring Project–Report No. 50, 572 pp, World Meteorological Organization, Geneva, Switzerland, 2007.

den Outer, P. N., Slaper, H., Kaurola, J., Lindfors, A., Kazantzidis, A., Bais, A. F., Feister, U., Junk, J., Janouch, M., and Josefsson, W.: Reconstructing of erythemal ultraviolet radiation levels in Europe for the past 4 decades, J. Geophys. Res., 115, D10102, doi:10.1029/2009JD012827, 2010.

Fioletov, V. E., McArthur, L. J. B., Kerr, J. B., and Wardle, D. I.: Long-term variations of UV-B irradiance over Canada estimated from Brewer observations and derived from ozone and pyranometer measurements, J. Geophys. Res., 106, 23009–23027, doi:10.1029/2001JD000367, 2001.

Fioletov, V. E., Kimlin, M. G., Krotkov, N., McArthur, L. J. B., Kerr, J. B., Wardle, D. I., Herman, J. R., Meltzer, R., Mathews, T. W., and Kaurola, J.: UV index climatology over the United States and Canada from ground-based and satellite estimates, J. Geophys. Res., 109, D22308, doi:10.1029/2004JD004820, 2004.

Harris, N. R. P., Kyrö, E., Staehelin, J., Brunner, D., Andersen, S.-B., Godin-Beekmann, S., Dhomse, S., Hadjinicolaou, P., Hansen, G., Isaksen, I., Jrrar, A., Karpetchko, A., Kivi, R., Knudsen, B., Krizan, P., Lastovicka, J., Maeder, J., Orsolini, Y., Pyle, J. A., Rex, M., Vanicek, K., Weber, M., Wohltmann, I., Zanis, P., and Zerefos, C.: Ozone trends at northern mid- and high latitudes - a European perspective, Ann. Geophys., 26, 1207–1220, doi:10.5194/angeo-26-1207-2008, 2008.

Geogdzhayev, I. V., Mishchenko, M. I., Liu, L., and Remer, L.: Global two-channel AVHRR aerosol climatology: Effects of stratospheric aerosols and preliminary comparisons with MODIS and MISR retrievals, J. Quant. Spectrosc. Radiat. Transfer, 88, 47–59, doi:10.1016/j.jqsrt.2004.03.024, 2004.

Granier, C. and Brasseur, G.: Impact of Heterogeneous Chemistry on Model Predictions of Ozone Changes, J. Geophys. Res., 97, 18015–18033, 1992.

Levy, R. C., Remer, L. A., Mattoo, S., Vermote, E. F., and Kaufman, Y. J.: Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance, J. Geophys. Res., 112, D13211, doi:10.1029/2006JD007811, 2007.

Mayer, B. and Kylling, A.: Technical note: The libRadtran software package for radiative transfer calculations – description and examples of use, Atmos. Chem. Phys., 5, 1855–1877, doi:10.5194/acp-5-1855-2005, 2005.

Mishchenko, M. I., Geogdzhayev, I. V., Rossow, W. B., Cairns, B., Carlson, B. E., Lacis, A. A., Liu, L., and Travis, L. D.: Long-term satellite record reveals likely recent aerosol trend, Science, 315, 1543, doi:10.1126/science.1136709, 2007.

Newchurch, M. J., Yang, E.-S., Cunnold, D. M., Reinsel, G. C., Zawodny, J. M., and Russell III, J. M.: Evidence for slowdown in stratospheric ozone loss: First stage of ozone recovery, J. Geophys. Res., 108, 4507, doi:10.1029/2003JD003471, 2003.

Reinsel, G. C.: Trend analysis of upper stratospheric Umkehr ozone data for evidence of turnaround, Geophys. Res. Lett., 29, 1451, doi:10.1029/2002GL014716, 2002.

Rossow, W. B. and Schiffer, R. A.: Advances in understanding clouds from ISCCP, B. Am. Meteorol. Soc., 80, 2261–2287, 1999.

WMO/UNEP: Scientific Assessment of Ozone Depletion: 2010, Geneva, 2011.

Wild, M.: Global dimming and brightening: A review, J. Geophys. Res., 114, D00D16, doi:10.1029/2008JD011470, 2009.

Wild, M., Trüssel, B., Ohmura, A., Long, C. N., König-Langlo, G., Dutton, E. G., and Tsvetkov, A.: Global dimming and brightening: An update beyond 2000, J. Geophys. Res., 114, D00D13, doi:10.1029/2008JD011382, 2009.

Zanis, P., Maillard, E., Staehelin, J., Zerefos, C., Kosmidis, E., Tourpali, K., and Wohltmann, I.: On the turnaround of stratospheric ozone trends deduced from the reevaluated Umkehr record of Arosa, Switzerland, J. Geophys. Res., 111, D22307, doi:10.1029/2005JD006886, 2006.

Zerefos, C. S.: Long-term ozone and UV variation at Thessaloniki, Greece, Phys. Chem. Earth, 27, 455–460, 2002.

Zerefos, C. S., Tourpali, K., and Bais, A. F.: Further studies on possible volcanic signal to the ozone layer, J. Geophys. Res., 99, 25741–25746, 1994.

Zerefos, C. S., Contopoulos, G., and Skalkeas, G.: Twenty years of Ozone Decline. Proceedings of the Symposium for the 20th Anniversary of the Montreal Protocol, 470 pp., Springer Science+Business Media B. V., 2009a.

Zerefos, C. S., Eleftheratos, K., Meleti, C., Kazadzis, S., Romanou, A., Ichoku, C., Tselioudis, G., and Bais, A.: Solar dimming and brightening over Thessaloniki, Greece, and Beijing, China, Tellus, 61B, 657–665, doi:10.1111/j.1600-0889.2009.00425.x, 2009b.

Table 1. Mid-latitude stations with long series of accessible spectral UV data analysed in this study.

Canada	Latitude	Longitude	Data used	Instruments	Data source
Churchill	58.75	−94.07	1992–2010	Brewer MKII	WOUDC
Edmonton/Stony Plain	53.55	−114.1	1992–2010	Brewer MKII	WOUDC
Saturna Island	48.78	−123.13	1990–2010	Brewer MKII, MKIV	WOUDC
Toronto	43.78	−79.47	1990–2010	Brewer MKII	WOUDC
Europe					
Jokioinen	60.81	23.49	1996–2010	Brewer MKIII	FMI
Lindenberg	52.21	14.12	1995–2010	Brewer MKIV, Spectro 320D	DWD
Hradec Kralove	50.18	15.83	1994–2009	Brewer MKIV	EUVDB
Reading	51.44	−0.94	1992–2010	Optronics, Bentham	WOUDC
Thessaloniki	40.63	22.95	1992–2010	Brewer MKII, MKIII	AUTH
Japan					
Sapporo	43.05	141.33	1991–2010	Brewer MKII, MKIII	WOUDC
Tateno	36.05	140.13	1990–2010	Brewer MKII, MKIII	WOUDC
Naha	26.2	127.67	1991–2010	Brewer MKII, MKIII	WOUDC

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Table 2. Amplitude [i.e. (max-min)/2] of atmospheric parameters during 1991–1993 (volcanic period) and during 1995–2010 (non-volcanic period). The right column shows the trends from 1995 to 2010 in % per year. Values in brackets refer to statistical significance of each trend.

	Amplitude (%)		Trend per year (%)
	1991–1993	1995–2010	1995–2010
Ozone	7.9	5.2	+0.13 ± 0.02 (99 %)
305 nm	25.7	19.0	+0.55 ± 0.02 (99 %)
325 nm	6.3	10.6	+0.44 ± 0.05 (99 %)
AOD (GACP)	71.4	56.2	−1.00 ± 0.39 (95 %)
AOD (MODIS)	–	37.8	−2.23 ± 0.37 (99 %)
Clouds (ISCCP)	10.5	9.1	+0.10 ± 0.08 (–)
Clouds (MODIS)	–	10.9	+0.06 ± 0.13 (–)

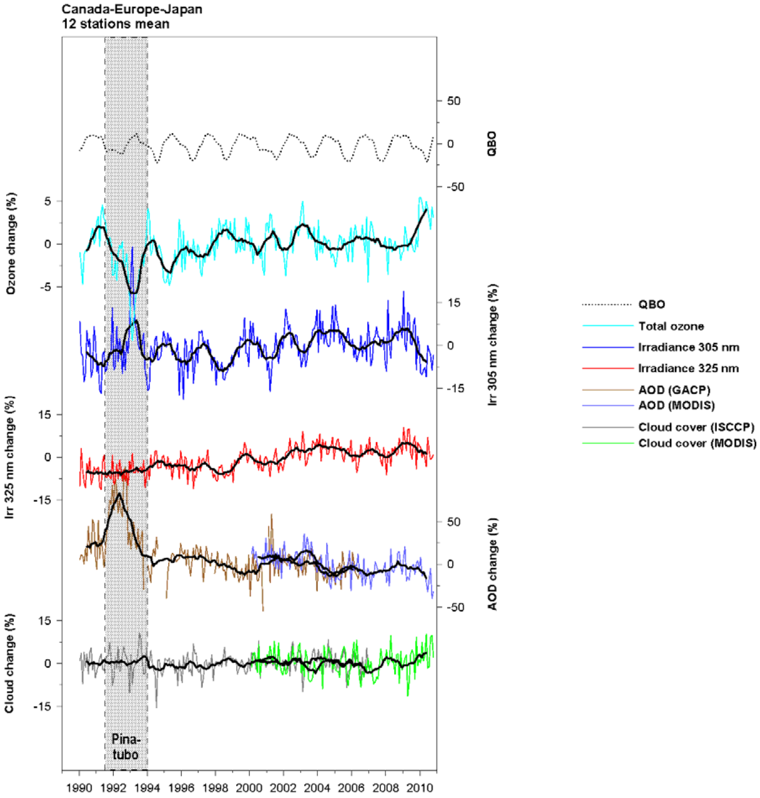


Fig. 1. Changes in percent (%) in total ozone, UV irradiances at 305 and 325 nm, AOD at 550 nm and total cloudiness averaged over 12 regions between 25°–60° N (Churchill, Edmonton/Stony Plain, Saturna Island, Toronto, Jokioinen, Lindenberg, Hradec Kralove, Reading, Thessaloniki, Sapporo, Tateno, Naha). Solid black curves: fits of 12-month running means that have been applied to the data.

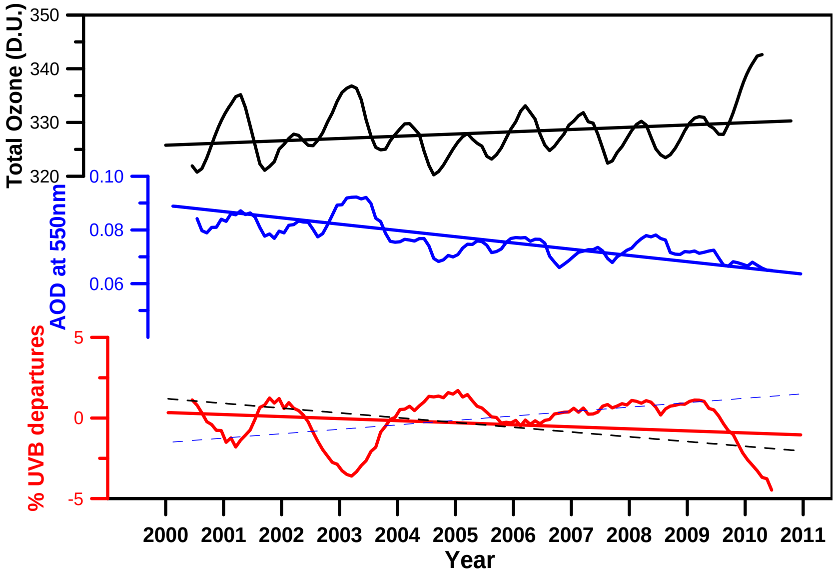
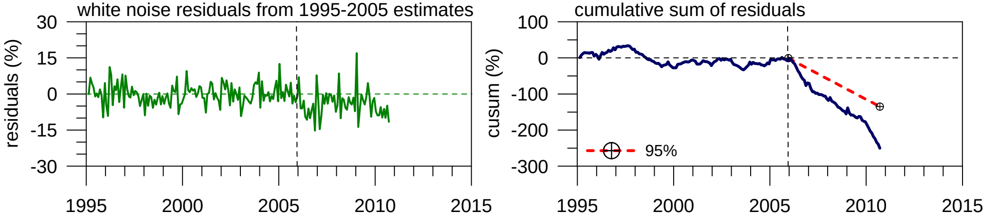


Fig. 2. Up: average Total Ozone (12 month running mean) from ground based measurements of the 12 stations, Middle: average MODIS/Terra AOD (12 month running mean) for the 12 stations. Down: 305 nm irradiance departures (red) calculated with the RT model, dashed lines represent the individual ozone (black) and AOD (blue) contribution.

(a) 305 nm



(b) 325 nm

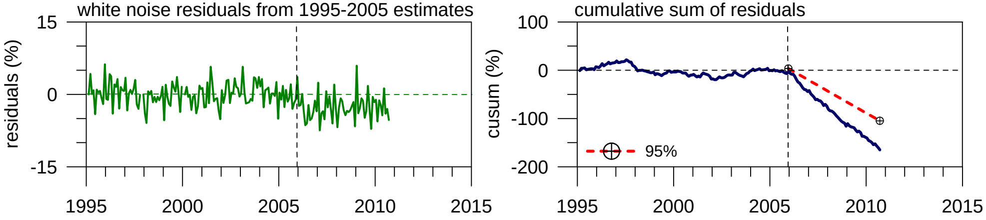


Fig. 3. White noise residuals (left panels) and their CUSUMs (ε_t, right panels) for the station average (as in Fig. 1). The red dotted line indicates the negative part of the 95 % confidence envelope of departures from natural variability and model uncertainty.