Reply to the comments of the reviewers

First of all, we would like to thank the reviewers for their helpful and extremely constructive comments. Our paper has been revised and our responses to the reviewers are now based on the results from the addition of UV spectroradiometric data from all stations through September 2011. To our satisfaction the addition of more than one year of measurements has not changed the main conclusions reached in the first submission of the paper.

The reviewers' comments and our responses are as follows:

Reply to the comments of Reviewer No 1.

General remarks of Reviewer No 1:

'For the last two years of the data record, Figure 1 shows a large increase in ozone, large decrease in spectral irradiance at 305 nm, noticeable decreases in AOD, and noticeable increase in cloudiness. These obvious changes are not being discussed. What is the explanation for these changes? Is it possible that they are an artifact of the data processing? For example, are these changes apparent in the datasets of all stations or is it possible that an incorrect dataset of one station or an isolated event had a large effect on the average?
Like the second Referee (S. Diaz), I would like to see some discussion whether or not the observed changes are representative for stations in all geographic regions (Canada, Europe, Japan) discussed in the paper. For example, I would have expected reductions in AOD for Europe and Japan in response to stricter air pollution laws, but such a reduction would be less obvious for the sparsely populated regions of Canada (excluding Toronto).'
Reply:
Following the common comment of both reviewers, we have included Figures 2a, 2b and 2c which show that the interannual variability over Canada, Europe and Japan of the UV time series under study, are similar to their average seen in Figure 1. Figures 1, 2 and Table 3 show that the earlier conclusions were not an artifact of data processing but appear to be robust when the dataset was subdivided to individual regions. Details on the interannual variability of UV, AOD and cloud fraction are discussed in the revised Section 3.
Another common comment of both reviewers was the improvement of the abstract, which has been fully revised. We note here that the AOD trend individually for Toronto is -3.5% yr^{-1} and all stations show similar decreasing trends in AOD.

The revised abstract reads now as follows:
'This study examines the long term variability of UV solar irradiances at 305nm and 325nm over selected sites in Canada, Europe and Japan. Site selection was restricted to the availability of the most complete UV spectroradiometric datasets during the

period 1990–2011. The analysis includes the long-term variability of total ozone, aerosol optical depth and cloud fraction at the sites studied. The results, based on observations and modeling, suggest that over Canada, Europe and Japan the period under study can be divided into three sub-periods of scientific merit: The first period (1991–1994) is the period perturbed by the Pinatubo volcanic eruption, during which excess volcanic aerosol has enhanced the "conventional" amplification factor of UV-B at ground level by an additional factor that depends on solar elevation. The increase of the UV-B amplification factor is the result of enhanced scattering processes caused by the injection of huge amounts of volcanic aerosols during the perturbed period. The second period (1995–2006) is characterized by a 0.14% yr^{-1} increase in total ozone and an increasing trend in spectral irradiance by 0.94% yr^{-1} at 305nm and 0.88% yr^{-1} at 325nm. That paradox was caused by the significant decline of the aerosol optical depth by more than 1% yr^{-1} (the 'brightening' effect) and the absence of any statistically significant trend in the cloud fraction. The third period (2007–2011) shows statistically significant evidence of a slowdown or even a turning point in the previously reported upward UV-B trends over Canada, Europe and Japan.'

<u>Specific comments of Reviewer No 1:</u>

'P 28546, L 10: The statement 'The second period is characterized by a UVB increase caused by the synergy of ozone decline…' is contradictory with the following statement (P 28550, L 11): 'It is interesting to note here that total ozone at the sites studied had a long term increasing trend after the volcanically perturbed period.' Figure 1 indicates that total ozone is increasing after the Pinatubo period. The first statement provided in the abstract is therefore incorrect and needs to be changed.
P 28546, L 13: Regarding 'During this second period, the long term variability is the brightening of +0.94%yrˆ(−1) and +0.88%yrˆ(−1) at the wavelengths 305nm and 325nm respectively.' The numbers (percent per year) suggest a trend, not a variability. Change to: 'During the second period, the trend in spectral irradiance is 0.94%/yr at 305 nm and +0.88%/yr at 325nm.'

Reply to both comments:

The revised text in the abstract reads now as follows:
'The second period (1995–2006) is characterized by a 0.14% yr^{-1} increase in total ozone and an increasing trend in spectral irradiance by 0.94% yr^{-1} at 305nm and 0.88% yr^{-1} at 325nm. That paradox was caused by the significant decline of the aerosol optical depth by more than 1% yr^{-1} (the 'brightening' effect) and the absence of any statistically significant trend in the cloud fraction.'

'P 28546, L 20: Provide a reference for the 'world avoided' scenario here, for example: P. A. Newman, L. D. Oman, A. R. Douglass, E. L. Fleming, S. M. Frith, M. M. Hurwitz, S. R. Kawa, C. H. Jackman, N. A. Krotkov, E. R. Nash, J. E. Nielsen, S. Pawson, R. S. Stolarski, and G. J. M. Velders (2009): What would have happened to

the ozone layer if chlorofluorocarbons (CFCs) had not been regulated?, Atmos. Chem. Phys., 9, 2113–2128, available at: www.atmos-chem-phys.net/9/2113/2009/'

Reply:

The proposed reference of Newman et al. (2009) has been added.

'P 28547, L2: Regarding '…with about 2/3 being attributed to decreasing of cloudiness and aerosol optical depth and 1/3 to the ozone decline….': While this statement is consistent with the conclusions reached by den Outer et al. (2010), it is inconsistent with the ozone record shown in Figure 1, which shows an increase roughly between 1994 and 2009. This inconsistency needs to be explained.'

Reply:

The sentence has been rewritten as: 'The 2011 WMO/UNEP Ozone Assessment and a recent paper by den Outer et al. (2010) reported the continuation through 2005, of upward trends in UV-B over Europe. They found these upward trends to range between +0.3%yr^{-1} and +0.6%yr^{-1} of which 2/3 they have attributed to the combined decrease of cloudiness and aerosol optical depth and 1/3 to the past long-term ozone change through 2005.'

'P 28547, L22 ff.: Two overlapping datasets are mentioned. The enumeration starts with dataset '(1)' but dataset (2) is not mentioned, albeit it could be the GACP dataset. This should be clarified and also the period of the second aerosol dataset should be provided.'

Reply:

We clarify the issue in the revised paragraph 2 of the revised Section 2, which reads now as follows:

'In addition to spectral UV solar irradiances and total ozone, this study includes the analysis of time series of aerosol optical depth (AOD) at 550nm and the cloud fraction from satellite data for the period 1990–2011. In the case of AOD, two overlapping data sets have been used: (1) for the period 1990–2006, the NASA/GACP, Global Aerosol Climatology Project (Mishchenko et al., 2007a) and (2) for the period 2000–2011, the Terra AOD experiment (MODIS) from the MODerate-resolution Imaging Spectroradiometer (Levy et al., 2007). The MODIS/Terra AOD data were taken at a spatial resolution of $1^o \times 1^o$ around each of the ground based monitoring stations, listed in Table 1.'

'P 28548, L1: Better describe what is meant with 'cloudiness data' from ISCCP. Is it cloud fraction and cloud optical depth as in the case of the MODIS? If it is a different cloud parameter, how were the two datasets combined? Is there the risk that there is a bias between the two datasets that could be misinterpreted as a real change in optical depth or cloud fraction? (Figure 1 indicates that the two datasets are indeed consistent, but this should also be mentioned in the text.)'

Reply:

By the term 'cloudiness data' from ISCCP we meant cloud fraction and not cloud optical depth. We now use the correct term throughout the whole study which is

‘cloud fraction’. Both data sets are consistent with each other, since the deseasonalized monthly time series of cloud fraction from ISCCP and from MODIS during their common period 2000-2006, are highly correlated ($r \approx +0.6$, confidence level >99.9%). The correlation coefficients calculated separately for the different geographical regions of the study were found to be also highly significant (+0.6 for Canada, +0.7 for Europe, and +0.7 for Japan). This has been described in Section 2 which was revised accordingly.

‘P 28548, L9: What is the accuracy of ‘NASA/GACP AOD data’ for land and water pixels?’

Reply:

‘Statistical comparisons of NASA/GACP AOD at 550nm with ship-borne sun-photometer AOD data at 550nm have shown significant correlations. It has been found that the ensemble-averaged NASA/GACP AOD at 550nm overestimates the ensemble-averaged sun-photometer data only by about 3.6% with a random error of about 0.04 (Mishchenko et al., 2007b and references therein).’ This has been described in Section 2 which was revised accordingly.

Reference: Mishchenko, M. I., Geogdzhayev, I. V., Cairns, B., Carlson, B. E., Chowdhary, J., Lacis, A. A., Liu, L., Rossow, W. B., Travis, L. D., Past, present, and future of global aerosol climatologies derived from satellite observations: A perspective, Journal of Quantitative Spectroscopy & Radiative Transfer, 106, 325–347, doi:10.1016/j.jqsrt.2007.01.007, 2007b.

‘Section 2 first discusses AOD data, then briefly mentions cloudiness data, before returning to AOD data and repeating some information on cloud data. The section should be restructured such that all parameters are discussed separately, e.g. first AOD, then cloudiness, then ozone, then QBO, etc. Of course a different sequence could be chosen.’

Reply:

The whole Section 2 has been revised to address all the comments of the reviewer. Please see the revised Section 2.

‘P 28549, L1: I assume the UV datasets had some gaps. How were these gaps treated when calculating monthly means and what is the uncertainty of monthly means caused by missing data?’

Reply:

Monthly means from daily UV solar irradiances were calculated at each station only if 14 daily summaries were available for each month. In order to avoid uncertainties introduced by missing values, monthly data have been deseasonalized and averaged as follows: First, we deseasonalized the monthly mean data at each station by subtracting the long-term monthly mean pertaining to the same calendar month. Next, we calculated the averages over each geographical region separately (Canada, Europe and Japan) by averaging the deseasonalized data of the stations belonging to each region. Finally, the overall deseasonalized averages of all stations were obtained by averaging

the three regional deseasonalized averages over Canada, Europe and Japan. This has been described in Section 2 which was revised accordingly.

'Equation (1): The equation and its arguments should be discussed in much greater detail. For example: How were UV data deseasonalized?'

Reply:

As mentioned in our previous reply, monthly UV data were deseasonalized at each station by subtracting the long-term monthly mean pertaining to the same calendar month. Next, we calculated the averages over each geographical region separately (Canada, Europe and Japan). Finally, the overall deseasonalized averages of all stations were obtained by averaging the three regional deseasonalized averages over Canada, Europe and Japan. Please see the revised text, where the deseasonalization is now described in detail.

'Was Eq. (1) evaluated separately for each station or were monthly averages from individual stations averaged over all stations to calculate Y_t?'

Reply:

Equation (1) was evaluated for the stations average but also for each individual region described in the revised text.

If so, how was the problem addressed that not all stations have data for the entire period discussed in the paper (see Table 1)?

Reply:

UV data at each station were deseasonalized by subtracting the long-term monthly mean pertaining to the same calendar (see revised Table 1). Missing months were filled-in by their long-term monthly mean.

'Was the averaging done consistently for Y_t and the other terms of Eq. (1)?'

Reply:

Yes, it was done in a consistent manner. For more details please see the revised text.

'What exactly are the 'QBO terms', 'cld term', and 'solar cycle term'? Explicit equations for these terms should be provided. If the authors feel that the flow of the paper would suffer from additional equations, these could be put into an appendix.'

Reply:

These terms refer to the proxy data time series that were used in Eq. (1) in order to identify the effect of the various terms. They are just used as proxies, so no explicit equations are necessary, in view also of the time scales we are interested here. More details are given in the text.

'The statement 'the cld term to describe the cloud cover effect' is too vague.'

Reply:

The 'cld term' refers to the cloud cover data from the satellites used in order to construct a proxy for cloud cover to be used in our statistical model. Please see the

reply to the relevant comment below for details in the construction of this proxy, namely the 'unified index'. As mentioned in response to the comment above, a more detailed description is now included in the text. Moreover, in our approach we assumed linear relationship between cloud cover and UV, as we are interested in changes in time scales longer than days or months. The results for the average of the European stations show a response of about -8% in 305nm for a 10% change in the cloud cover variability, which is in agreement with den Outer et al.

'I realize that some of that information is provided in the works by Reinsel (2002) and Newchurch et al. (2003), but these papers do not discuss UV radiation, and therefore, their methods are not identical to the method used in this manuscript.'

Reply:

Use of equation (1) for UV data was first employed by Fioletov et al., JGR, 2001. They used a simplified form in the sense that they did not including qbo or solar cycle factors. In our case, it was found that the inclusion of these terms reduced the error of the trend as well as the noise. Moreover, the CUSUM technique used in Reinsel and Newchurch et al., is the application of the cumulative sum technique, commonly used in many statistical applications with normally distributed variables (such as UV). In our case it is used on the residual time series (the noise) with the autocorrelation also taken into account. A more detailed description is now included in the revised text.

'P 28549, L16-19: Also this section is not detailed enough. How is the 'unified index' defined? How was it constructed?'

Reply:

We have constructed the 'unified index' proxy using the deseasonalized cloud fraction time series from the NASA/ISCCP and from the MODIS/Terra data sets described in paragraph 4 of the revised Section 2 'Data sources and Methodology'. We tested them for homogeneity during their common period of records (2000–2006), and found no systematic discontinuities. The correlation between the two time series was highly significant (r ~ +0.6), in the overall as well as in individual months, pointing to a linear relation between them. Based on this, we adjusted the NASA/ISCCP time series to the MODIS/Terra, as the latter reaches to the end of our UV records. Please see also the revised text.

'I do not understand the sentence 'The cloud cover term was used as pertaining to the geographic area of the UV time series.' Was a different cloud term used for every station or is there only one term that is representative for the (large!) geographic area covered by the stations?'

Reply:

For every geographic region a cloud fraction time series was used. Even though each region covers a rather large geographic area, we have used satellite data which correspond to the nearest grid point to every individual station, so that the initial cloud fraction time series are used to form regions in exactly the same way as the UV data. Please see the revised text for details.

'P 28549, L 23: Please describe better how data were deseasonalized and averaged. This is related to my question above whether or not Eq. (1) is applied individually to every station or to the average of deseasonalized data of all stations.'

Reply:

First, we deseasonalized the monthly mean data at each station by subtracting the long-term monthly mean pertaining to the same calendar month. Next, we calculated the averages over each geographical region separately (Canada, Europe and Japan) by averaging the deseasonalized data of the stations belonging to each region. Finally, the overall deseasonalized averages of all stations were obtained by averaging the three regional deseasonalized averages over Canada, Europe and Japan.

Eq. (1) was applied to each individually region and to the average of deseasonalized data of all stations.

'Figure 1: QBO is not mentioned in the figure caption. Indicate what the QBO dataset represents and its unit. What cloud parameter is displayed? Is it cloud optical depth, cloud fraction, a combination of both or something else? The terms 'cloud cover' used in the legend and 'total cloudiness' used in the caption are ambiguous. The solar cycle is considered in Eq. (1). I suggest to include this parameter in Figure 1 also.'

Reply:

QBO is now mentioned in the figure caption. The QBO indexes are from the CDAS Reanalysis data and are the zonally averaged winds at 30 and 50 hPa and taken from over the equator (http://www.cpc.ncep.noaa.gov/data/indices/). The units of the zonally averaged winds are meters per second. The cloud parameter which is displayed in Fig. 1 is 'cloud fraction'. We now use the correct term throughout the whole study which is 'cloud fraction'. We decided not to include the solar cycle parameter in Fig. 1 because the solar signal in total ozone is small in amplitude and can be clearly seen only in the tropics.

'P 28550, L 11: I am glad to see that it is stated here that 'total ozone at the sites studied had a long term increasing trend after the volcanically perturbed period.' As discussed above, this (correct!) statement is in conflict to assertions used earlier and later in the paper.'

'P 28550, L 15: I suggested changing the sentence to: 'The data indicate that spectral irradiance at 305 nm is affected by two competing factors: the increase of total ozone, which reduces spectral irradiance at 305 nm, and the decrease of aerosol optical depth, which increases both UVB and UVA. There is no significant change in cloud optical depth and cloud fraction [use the most appropriate term!]. The effect of clouds on long-term trends in UV irradiance is therefore negligible.'

'P 28550, L 15: I don't understand how the authors can conclude from the 'above arguments' that 'a turning point of the long term increasing trends in this part of the spectrum would be found with our data sets.' A turning point in UVB can only be expected if there was a change in either the trend of ozone or aerosol optical depth.

While Figure 1 supports this conclusion, The 'above arguments' do not mention a change in the trend of either of the two parameters.'

Reply to the three comments:

The discussion on Fig. 1 has been fully revised to address the three comments of the Reviewer. The new text which appears in the revised Section 3 reads now as follows: 'The post-Pinatubo opposite long-term variability of total ozone and AOD, provided us with the unique opportunity to search for any possible leveling of UV-B reaching ground level, as would be expected from the observed positive trend of total ozone as seen in Fig. 1. If AOD and cloud fraction had no trend, UV-B should have started its leveling off and its decrease in time due to the total ozone increase. However, although the cloud fraction is remaining statistically unchanged, AOD with its monotonous decreasing trend, had the effect to delay the leveling or even the decrease of UV-B due to the observed ozone upward trend, up to the last few years of the record. The above discussion is supported by the third time series in Fig. 1, which shows the long-term variability of the difference (in per cent) between the 305nm and the 325nm spectral solar irradiances which is dependent mostly on ozone. The anticorrelation between total ozone and the (305nm–325nm) irradiance difference is highly significant, exceeding 0.8 both on short and on longer time scales. This high anticorrelation emphasizes the role that AOD trends have played, in delaying the long-term UV-B 'recovery' over about half of the northern hemisphere. We emphasize that the (305nm–325nm) difference is about free from the combined effects of changes in aerosol and cloud fraction.'

'P 28550, L 26: I accept that there is no trend in cloud fraction and QBO. It should be explained why the two terms were not used here. Even if there are no trends in these terms, both terms reduce the variability in the regression model such that the residuals would be better represented by random numbers. Use of the two terms would consequently lower the uncertainty of the trend estimate for spectral irradiance at 305 nm and 340 nm. What would be the value of the trends and their uncertainty if the QBO and cloud terms had been included in the calculation? There is also an inconsistency between the trend estimate for spectral irradiance at 305 nm provided in the text (0.55%+/-0.03%)/yr and Table 2 (0.55%+/-0.02%)/yr, which should be resolved.'

Reply:

The QBO and cloud fraction terms had been included in the first calculations. To clarify the issue, we have revised the text as follows (see revised Page 9 Lines 13-17 in the revised Section 3): 'We note here that the time series for cloud fraction and QBO do not have any significant trends throughout the past 20-yr period. If these terms are used in Eq. (1) then the results of 305nm and 325nm UV irradiances averaged over all stations, display increasing rates of (0.37% ± 0.05%) yr^{-1} and (0.55% ± 0.03%) yr^{-1} respectively, while the average ozone levels increased at the rate of (0.1% ± 0.02%) yr^{-1}.'

The inconsistency between the text and the table has been corrected.

'P 28551, L 22: With respect to 'The total UVB decreasing tendency during the 2006–2010 period, shown also in Fig. 1….' I don't see this decreasing tendency in Figure 1. In fact , spectral irradiance at 305 nm increases between 2006 and 2009, and only decreases during the last year. While the end point is indeed smaller than the value for 2006, describing the pattern of that period as 'decreasing tendency' is not justified. What could be said (and what is supported by the CUSUM approach discussed later) is: 'Figure 1 hints that the positive trend in spectral irradiance at 305 nm observed for the 1994 - 2006 period has leveled off in the last five years of the data record'.

Reply:

The discussion of the model results in Section 3 has been fully revised. It reads now as follows:

'To quantify further the hypothesis of the synergy of solar brightening and ozone upward trends to the overall UV-B variation, we have applied radiative transfer model calculations using the LibRadtran package (Mayer and Kylling, 2005). The radiative transfer model was fed with the ground-based observed ozone and MODIS-AOD at 550nm measurements to calculate irradiances at 305nm for all stations during the period (2000–2011). The model results together with the observations are displayed in Fig. 4. On top of that figure the significant upward trend in total ozone and the downward trend in AOD are dominant. Keeping constant the AOD to its mean value, the calculated effect of ozone on UV-B is shown by curve A. Curve C shows the effect of 'brightening' at 305nm as a result of the reduced AOD and curve B shows the calculated effect on 305nm from the synergy of both ozone and AOD trends. The corresponding best fit modelled curve is also shown for comparison. Curves A and C are respectively best fit to their respective model calculations. All calculations were based on deseasonalized monthly means assuming cloudless conditions. The observed 305nm monthly mean deseasonalized irradiances averaged over Canada, Europe and Japan are shown by the open circles describing the UV-B variability due to the changes in ozone, aerosols and clouds.

The centre of the circle with the two arrows shown in Fig. 4 is the interception of curves A and C which probably marks the starting point of the levelling off, in the upward UV-B trend, which is followed by a decrease in the subsequent few years through September 2011. The model estimates a –1.5% to –2% UV-B decrease from 2007 to 2011 under cloudless conditions. The overall calculated effect of ozone increase on 305nm irradiances, is estimated to be on the order of –4% during 2007-2011. The corresponding effect of AOD at 305nm irradiances was calculated to be on the order of +1.8% increase. These model calculations confirm the statistical results derived from the analysis of observations as discussed previously in connection to Fig. 1.'

'P 28551, L 27: The trend in cloud optical depth during the last year shown in Figure 1 is positive, not negative as stated in the text.'

Reply:

The cloud optical depth has been removed from the discussion of the paper. The sentence has been removed.

'Comparison of Figure 1 and Figure 3. The residuals shown in Figure 3 do not match the pattern of the 305 nm dataset of Figure 1. For example, spectral irradiance is decreasing between 2005 and 2006 in Figure 1 while the residuals don't show a trend for this year. This discrepancy is likely caused by the QBO. It would be helpful to include additional sub-panels in Figure 3 showing spectral irradiance at 305 nm and 325 nm corrected for QBO, solar cycle, and clouds according to Eq. (1). The change (or slowdown) in the UV trend since 2006 suggested by the authors and supported by Figure 3 should become visually obvious in such a figure.'

Reply:

The noise residuals in the left hand panels of Fig. 3 are filtered from QBO, solar cycle and cloud effects for the whole period presented. Moreover, and most importantly, the linear trend for the whole period 1995-2011, but based on the coefficients calculated from 1/1995-12/2005, is removed.

The autocorrelation of the series has also been taken into account with the calculation of ε_t. This later variable is the one plotted in Fig. 3 (left panels), and used to calculate the cusum in the right panels. In Fig. 3, the residuals up to 12/2005 (the last month used to estimate the coefficients) show no trend, as the linear trend removed was calculated for this period. The trend line overplotted is zero.

From 1/2006 on, there is no qbo, cloud or solar effect, but the trend removed is a "ficticious" trend, as it is based on the first period (1995-2005). The residual time series clearly drop below the zero level and on average remain lower until the end of the record, meaning that the upward trend of UV from 1995 to 2006 is too strong for the second period (2006-on), and that the rate of change in UV has become lower (in analogy to the arguments for ozone).

Please see the revised text on Page 10 Line 3 to Page 11 Line 5 which clarifies the issue.

'P 28552, L 26: Radiation amplification factors (RAF) depend on solar zenith angles and ozone. The UV data used in the paper were monthly means of daily doses and there is an annual cycle of SZA. So calculations at SZA = 63 may not be representative.

P 28552, L 29: 'Using the same columnar AOD and a…..' The sentence is somewhat confusing. It should be expressed that, for constant aerosol optical depth, aerosols have a larger effect on UV when they are redistributed from the troposphere to the stratosphere. (I recall that the effect has a large SZA-angle dependence and calculations at 63 may not be appropriate. The RAF for the volcanic aerosol scenario should also be calculated for additional solar zenith angles).'

Reply to both comments:

Calculations have been performed for various solar zenith angles as suggested. The revised text (last paragraph of the revised Section 3) reads now as follows:

‘Before closing this paragraph we provide here some modelling results on the UV variability during the Pinatubo period. In the volcanically perturbed period seen in Fig. 1 and Table 2, we note a significant 8% ozone loss and a disproportionately increase in 305nm solar irradiance by about 25%, while the 325nm solar irradiance remained within its expected range of variability. The well-known anti-correlation between UV-B and total ozone (i.e. the amplification factor) is significantly enhanced at 305nm (by a factor of 3) compared to any other time period in the series. We have used the LibRadtran package (Mayer and Kylling, 2005) to investigate the role played by the volcanic aerosols in explaining this enhancement. More specific we have calculated the UV irradiance for a constant (8%) ozone decrease and for different aerosol scenarios and various solar zenith angles. The results are solar zenith angle dependent, so they can not directly be compared with the results shown in Fig. 1. This is because data presented in Fig. 1 are monthly means of daily doses, thus representing measurements that have been performed at a variety of solar zenith angles. Our calculations show that for constant aerosol optical depth, aerosols have a larger effect on UV when they are redistributed from the troposphere to the stratosphere, combined with the 8% ozone reduction. Calculations for 45, 60 and 75 degrees of solar zenith angle showed (additional to the ozone related reduction) enhancements of 2%, 5% and 20% respectively when a scenario of urban/extreme volcanic aerosol below/above 2Km respectively is selected, relative to the non-volcanic case.’

‘P 28553, L 12: ‘The second period is characterized by a UVB increase caused by the synergy of ozone decline and tropospheric aerosol decline….’ No, ozone is increasing during this period!’

Reply:

The text has been corrected accordingly.

‘P 28553, L 14: Change ‘During this second period, the long term variability is the brightening of 0.94%/yr and +0.88%/yr at the wavelengths 305nm and 325nm respectively.’ to ‘During the second period, the trend in spectral irradiance is 0.94%/yr at 305 nm and +0.88%/yr at 325nm.’

Reply:

The proposed change has been done.

‘P 28553, L 16: Figure 1 indicates that ‘maximum UVB exposure’ during the last 10 years was in 2009. So the final sentence needs some rewording.’

Reply:

The final sentence has been revised as follows: ‘The third period, which refers to the last 5 yrs, might provide for the first time significant statistical and model-derived evidence, indicating a slowdown of the upward trends observed in the past, over the sites studied where UV-B trends seem to have undergone a turning point most probably after 2007.’

Reply to the Technical corrections of Reviewer No 1:

'P 28549, L 15: change '….residuals (CUSUM).' to '….residuals (CUSUM) in Section 3.'
Reply: The text has been revised to: 'in which the ε_t are the residuals used to compute the cumulative sums of residuals (plotted in Fig. 3), after removing the autoregressive component φN_{t-1}.'. See the revised Section 2.

'P 28550, L 11: Change 'More interesting thought….' to 'More interesting though….'
'P 28550, L 15: Change 'as well as to the fact that' to 'because'
Reply to both comments: The paragraph has been fully revised. See paragraph 3 of the revised Section 3.

'P 28550, L 25: Change '….time series for both the cloud fraction and for the QBO….' to '….time series for cloud fraction and QBO….'
Reply: Done

'P 28551, L 13: Move the reference (Mayer and Kylling, 2005) after 'LibRadtran package'.
Reply: Done

'P 28552, L 23: 'a significant 8% ozone….': Sentence misses a verb.
Reply: The sentence has been revised as follows: 'In the volcanically perturbed period seen in Fig. 1 and Table 2, we note a significant 8% ozone loss and a disproportionately increase in 305nm solar irradiance by about 25%, while the 325nm solar irradiance remained within its expected range of variability.'

Reply to the comments of S. Diaz (Referee)

'The manuscript presents results of an important topic for the atmospheric community and should be published in acp. It analysis irradiances in the UVB and UVA at Canada, Europe and Japan for the period 1990-2010 and relates the trends with total ozone column, AOD and cloudiness.
In general, the methodology is appropriate, but I have a couple of comments about it. In the study, the average for all stations is analyzed. I think that analysis showing the results for individual stations should be included in order to evaluate if the observed trend is representative of all stations, or a region, etc.'
Reply:
Our responses are now based on the results from the addition of UV spectroradiometric data from all stations through September 2011. To our satisfaction the addition of more than one year of measurements has not changed the main conclusions reached in the first submission of the paper. Following the common comment of both reviewers, we have included Figures 2a, 2b and 2c which show that the interannual variability over Canada, Europe and Japan of the UV time series under study, are similar to their average seen in Figure 1. Figures 1, 2 and Table 3 show that the earlier conclusions were not an artifact of data processing but appear to be robust when the dataset was subdivided to individual regions. Details on the interannual variability of UV, AOD and cloud fraction are discussed in the revised Section 3.

'Another topic is the use of AOD at 550nm and extrapolate to the AOD, or the effect of aerosols, at 305 and 325nm. The authors should add a paragraph justifying this.'
Reply:
'The relation between AOD monthly values at 550nm from MODIS and at 320nm from ground-based measurements was next checked for correlation in their long-term variability. Unfortunately we had common AOD ground-based data at 320nm and from MODIS at 550nm, with sufficient detail, only at the stations of Thessaloniki 40° N and Lindenberg 52° N. These data sets have been correlated on different time scales. Both on short and on longer time scales the ground-based AOD at 320nm were highly correlated ($r \approx +0.8$) with the satellite AOD at 550nm (see Supplement Fig. S1).'
This has been described in Section 2 which was revised accordingly.

'On other topics: The abstract should be improved. Some points are not clear, particularly when it says '....excess volcanic aerosol might have enhanced by an additional 6%....' Here it should be said that this would be because of the increased in scattering, as explained in page 9, line 15, otherwise it is confusing. Also, in the abstract it should be pointed out the period considered in the analysis.'
Reply:
The revised abstract reads now as follows:
'This study examines the long term variability of UV solar irradiances at 305nm and 325nm over selected sites in Canada, Europe and Japan. Site selection was restricted

to the availability of the most complete UV spectroradiometric datasets during the period 1990–2011. The analysis includes the long-term variability of total ozone, aerosol optical depth and cloud fraction at the sites studied. The results, based on observations and modeling, suggest that over Canada, Europe and Japan the period under study can be divided into three sub-periods of scientific merit: The first period (1991–1994) is the period perturbed by the Pinatubo volcanic eruption, during which excess volcanic aerosol has enhanced the "conventional" amplification factor of UV-B at ground level by an additional factor that depends on solar elevation. The increase of the UV-B amplification factor is the result of enhanced scattering processes caused by the injection of huge amounts of volcanic aerosols during the perturbed period. The second period (1995–2006) is characterized by a 0.14% yr^{-1} increase in total ozone and an increasing trend in spectral irradiance by 0.94% yr^{-1} at 305nm and 0.88% yr^{-1} at 325nm. That paradox was caused by the significant decline of the aerosol optical depth by more than 1% yr^{-1} (the 'brightening' effect) and the absence of any statistically significant trend in the cloud fraction. The third period (2007–2011) shows statistically significant evidence of a slowdown or even a turning point in the previously reported upward UV-B trends over Canada, Europe and Japan.'

'The text needs to be revised. For example, first sentence page 4, repeats part of last sentence page 3.'

Reply:

The text has been revised. See revised paragraph 2 of the revised Section 2 which reads now as follows:

'In addition to spectral UV solar irradiances and total ozone, this study includes the analysis of time series of aerosol optical depth (AOD) at 550nm and the cloud fraction from satellite data for the period 1990–2011. In the case of AOD, two overlapping data sets have been used: (1) for the period 1990–2006, the NASA/GACP, Global Aerosol Climatology Project (Mishchenko et al., 2007a) and (2) for the period 2000–2011, the Terra AOD experiment (MODIS) from the MODerate-resolution Imaging Spectroradiometer (Levy et al., 2007). The MODIS/Terra AOD data were taken at a spatial resolution of $1^o \times 1^o$ around each of the ground based monitoring stations, listed in Table 1.'