Anonymous Referee #1

General comments:

In general, I miss some estimation and discussion of the uncertainties of the derived results, particularly in estimated derived from the “homogenized” and reconstructed data.

In the revised manuscript, the uncertainty of the daily erythemal doses used in trend calculations have been calculated for the data categories: reconstructed (1983-1995, 2002-2004), measured by a prototype of SL biometer (1996-2001), and KZ biometer (2005-2016). See p.5, l.18-21*;* p.6-7, l.19-l.7 *and Table 1.*

In some parts the discussion is not very clear and should be improved and clarified with some more details. *More detailed description of the trend methodology and data preparation are included in the revised manuscript*

I miss in the introduction (and possibly on results) section some discussion on reconstruction methods and their uncertainties citing relevant studies appeared in the last 10 years, as for example:

*This part is added to the main text (*p.4, l.16-26*) using the reviewer's list of most important studies. Moreover, a performance of the proposed reconstruction model is compared to the study using similar proxies for UV attenuation in the atmosphere (*p.5, l.19-21*).*

I consider the title too long: A possible alternative: “Trends in erythemal doses at the Polish Polar Station, Hornsund, Svalbard, based on homogenized measurements (1996-2016) and reconstructed data (1983-1995)” *OK. The title has been changed according the reviewer's suggestion.*

Although I have tried to mark some of the language errors in the technical comments section, I suggest that the language should be checked again and improved. This will make the paper easier to read.

We have tried to improve the language, for example the manuscript has been read by a foreign speaker.

Specific comments:

1, 27: I would suggest using the term severe ozone loss (or depletion) instead of “ozone hole”.

OK. Change according the reviewer's suggestion.

3, 18: Please check this sentence: “Albedoground =0.9”?

New sentence is “Albedo$_{GROUND}$ is assumed equal to 0.9 for snow depth larger than 32 cm”

3, 24: Why there is no plot shown for the first period? The correction factors are very large and it would be good to see them in a graph as for the second period, together with the respective standard deviations. Are there any indications in the literature for such rapid deterioration of the sensitivity of RB instruments in five years?

New Figure 3 is added showing the instrument deterioration. In fact, the deterioration appeared much smaller ~35% in the period 1996-2001. The previously mentioned deterioration rate (~250%) was erroneously calculated. WMO report (Instrument to Measure Solar Ultraviolet Radiation Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance", WMO, Rep. No. 164, 2008) stated that the well maintained broadband instrument could lost its stability maximally up to 5% between yearly intercomparisons. Thus, the loss of about 10% per year after two years of stable behavior (1996-1997) seems possible in a harsh polar environment. p. 4, l.1-6.

3, 27: How large can be the effect of aerosols at that latitude? This can be estimated with the model for the extreme climatological aerosol data of the Cimel. Then it can be inferred whether aerosols are responsible for the differences, or simply the selection of clear-sky data at high SZAs during spring and autumn months.

The extreme aerosols optical depth (AOD) for each month (March-September) are determined from 2.5 and 97.5 percentiles of the daily AOD values in selected month by Cimel measurements (2004-2016). These values are used in radiative model simulations to calculate the daily dose uncertainty due to unknown AOD in period prior Cimel measurements. Uncertainty (~7%) of the annual correction factor ACF for the period 1996-2007 is found. See p.4, l.7-14, and Figure 4.

4, 2: I find too risky to relay the calculation of trends on data which come from an instrument with such large deterioration. Moreover, for such large year-to-year differences, monthly ACFs would have been

In fact, the year-to-year deterioration appeared smaller that discussed in the previous manuscript. It is around ~9% per year, i.e. 9/12% per month. The yearly ACF is derived using mostly from April-June data (i.e. period with many cloudless days). Thus, the July, August, and September value could be underestimated of ~ 0.75%, 1.5%, and 2.25%, respectively, after application of the proposed yearly ACF. The trend calculation for each calendar month (March-September) is not affected by ACF changes within the year. Only the yearly trend could be affected. Taking into account a participation of monthly mean doses for these months in the yearly dose (i.e., 23%, 12%, 4% for July, August, and September, respectively, see new Table 1) it could be estimated that using the yearly ACF would provide less than ~1% underestimation of the yearly dose. Thus, using yearly rate of the instrument deterioration instead of the monthly rate affects only slightly trend estimates of the yearly sums of erythemal daily doses..

4, 10: Please mention that by using daily averages for the proxies, it is assumed implicitly that any diurnal variation of erythemal irradiance due to these proxies is not taken into account. Of course, this adds to the uncertainty of the estimated daily doses.

We discuss the problem in the revised paper:

"We have no variability of sunshine duration throughout a day. Using the daily values adds additional uncertainties to modeled values as a duration of clear-sky conditions near local noon is decisive for daily doses." p.5, l. 12-13

4, 17: Please specify where the default aerosol optical depth of 0.16 is coming from.

In the revised paper, we explain that "

"The same procedure was used for the first period (1996-2001) of the UV monitoring at Hornsund but constant aerosols of AOD at 340 nm equal to 0.16 was assumed. During that period there were no Cimel sunphotometer observations. Thus, for the 1996-2001 calibration, we select AOD value representing the mean AOD value found for the period 2004-2016" p. 3, l.28-30.

4, 25-26: If model (3) explains less than half (45%) of the CMF variance then the reconstructed daily doses by (2) should be very uncertain, despite the highly significant regression coefficients. Please elaborate on this in the text, because if the above argument is true, then the results presented later are questionable.

We agree that the explained variability of the reconstructed data is low. However, the root mean square error of the reconstructed data of ~ 15% (see Table 1) is comparable with performance of previous reconstruction models (e.g. Lindfors et al., 2003 for Sodankyla, Rieder at al., 2008 for Sonnblick). Moreover, the proposed Monte-Carlo procedure to calculate the trend error takes into account the uncertainty of the reconstructed daily doses.

5, 21: I suggest drawing on these figures the linear regressions for the whole period and the observations period with different types of lines, to support the discussion of the linear trends.

New Figure 6 is prepared and lines are drawn for the 1983-2016 and 1996-2016 periods.

6, 2: Please mention whether the negative trends in April-May are statistically significant?

In the revised manuscript we have: "The statistically significant decline at 2σ level of about 1% /yr is revealed in May, June, and in the yearly sum for the observed 1996-2016 data (with the 2002-2004 gap)." p.8, l.8-11.

6, 4: Please make clear that by "short period" you mean the period after 1996.

*It has been defined. See response to the previous (*6.2*) problem.*

6, 7: It is not clear how the weights were derived and used. Do I understand correctly that the total ozone data and the sun shine duration data were weighted with weights derived from the measured monthly erythemal doses? Moreover, is the yearly dose derived from the 12 months of only from March to September? Please make this section clearer.

In the revised paper the ozone effects are discussed using different approach without the above mentioned weighting. The daily doses from radiative model simulations for clear-sky conditions are used to calculate the yearly sum of the daily erythemal doses. The clear-sky data are compared with the original (modeled and measured) to discuss the cloud and ozone/albedo forcing of the UV.

The yearly sum of daily doses are taken from March-September data because of small intensity in UV radiation in February and October and polar night between end of October and mid February. p 7. l.22-24.

6, 10: Isn't there a circular effect? The data used for the reconstruction were based on TUV calculations which used the measured total ozone, and were adjusted by the CMF which was derived by sunshine duration to account for cloud effects. Therefore, FD_TYD includes already the measured total ozone and the measured sunshine duration, and here it is regressed again against total ozone FD_TO3 and the sunshine duration FD_SUN_DUR. Please explain and clarify the discussion if I got it wrongly.

In the revised paper, the different method is proposed to search for clouds and ozone/albedo impact on UV. The results by radiative transfer model for clear-sky conditions are examined in the period 1983-2016. Regression using FD_TYD as a linear function of FD_TO3 and FD_SUN_DUR has been rejected.

6, 14-15: This statement (full ozone recovery in 2016) is a bit strong, as the data presented are weighted averages of ozone. As it is not clear (see previous comment) how the weights are derived and applied, this should be written more carefully.

Problem of the ozone recovery is not discussed in the revised manuscript. We only say that

"The stratospheric ozone changes appear as less important driver of the UV long-term variability in the whole analyzed period. Figure 8 shows the long-term (1979-2016) pattern of the total ozone mean (using SBUV merged data) for the period May-August at Hornsund, Barrow, and Resolute, i.e. in the part of the year with naturally high UV radiation (~ 80% of total yearly sum). The ozone forcing on the surface UV at these sites appears weak (within the ± 1% range) since 1983 (i.e. at the beginning of the reconstructed data)." p.9, l.16-22.

7, 7: Please mention the statistical significance of the linear trends.

We define significance of the trend in the revised paper: "The statistically significant decline at 2σ level of about -1% per year is revealed in May, June, and in the yearly sum for the observed 1996-2016 data (with the 2002-2004 gap). The trend analyses applied to the combined observed (1996-2001 & 2005-2016) and reconstructed data (2002-2004) show statistically significant decline only in May of ~ -1%/yr." p.8, l.8-11.

17, 6: Please mention the type of filter used for the smoothing.

We explain in the revised manuscript: "Figure 8. Smoothed time series (by LOWES smoother, Cleveland, 1979) of annual fractional deviations……." p.22

Technical comments:

The reviewer suggestions (below) are included in the revised manuscript"

4, 5-6: replace "a cloud cover" by "the cloud cover" and "a sunshine" by "the sunshine"
5, 3: Replace "models (2)" with "model (2)" (singular)
5, 25-27: replace "the trendless" by "a trendless", "the decrease/increase" by "a decrease/increase" and "the turning point" with "a turning point"
5, 30: Replace "The" with "A"
6, 1-2: Delete "The" (Negative trends +/-1% ...)
6, 13: Replace "provides" with "suggests"
6, 22: Replace "by the instrument sensitivity lost" with "by deterioration of the instrument's sensitivity"
11, 1: Specify what the bold numbers denote.
14, 10 "monthly doses for the period"; use plural (periods)

Anonymous Referee #2

General comments: The use of sunshine duration and snow depth data for reconstructing long term time series of UV have also been used by other authors, e.g. Lindfors et al. I miss a more extensive reference list. The calibration constants shown in Figure 2, shows that the instrument used in the period after 2004 has been quite stable, considering the harsh environment. The older instrument shows very high annual drift (factor 2.5 over 5 years). I miss some uncertainty estimates for the measurements series and reconstructed time series.

In fact, the instrument deterioration in the period 1996-2001 appeared much smaller about 35% (not

2.5 as it was previously mentioned). We add new Figure (new Fig. 3) showing the loss of instrument sensitivity in this period.

We discuss some important studies on the UV reconstruction models (the beginning of section 4). Moreover, a performance of the proposed reconstruction model is compared to the previous study (Lindfors et al., 2003) using similar proxies for UV attenuation in the atmosphere.

"The model setup is almost similar to that used by Lindords et al. (2003) for UV daily doses reconstruction for Sodankylä. However, our model provides RMS error ~15% for estimates of the daily erythemal dose. Lindords et al. (2003) found RMS error of ~23%." p.5, 19-21.

A reference to Fig5.b is missing in the paper. *Figure 5 has been replaced by Fig.7., which illustrates changes if UV radiation due to combined ozone and albedo effects (simulation by radiative transfer model for clear sky conditions)*. We *think that new Figure illustrates better impact on cloudiness on surface UV at Hornsund*.

Figure 5b: If I have understood correctly, the curves in Figure 5b are showing the yearly deviation (residuals) from the mean for the whole period, which means that the two curves labelled "Observed" and "Model" are showing the relative differences in yearly UV doses from their respective means. It would be interesting discussing the differences between real UV observations and modeled UV data. *There are not such curves in new Fig.7. Previous "modeled" curves were obtained with the regression model applied to the weighted data (Eq. 5 in the previous manuscript) that was criticized by the reviewers. The differences between the observed and modeled data (based on cloud modification factor defined by Eq. 2) are shown in new Table 1.* p.13

The curve labeled "Observed" is in fact a combination of reconstructed, and measured with gaps complemented with reconstructed UV data, for the whole period 1983-2016. A distinction would be appropriate, e.g. by changing the legend "Observed" to "Combined Observed and Modelled", or adding a curve with UV observations alone. *We decide to delete previous Fig.5 as it combined results of two regression models (previous Eq.2 and Eq.5) and it was difficult to find out meaning of the modeled data. Moreover, the second model was not correctly defined and it was rejected.*

Otherwise, one may think the two curves were completely independent on each other. It would also be informative for a reader to see the fractions of the monthly or yearly doses that actually were based on measurements (and not substituted with modelled data). *The monthly and yearly doses in the 1996-2001 and 2005-2015 periods are derived from almost every day UV measurements, so the gap existed only for period March 2002 up to April 2005. In the revised paper we calculated trends for both the 1996-2016 time series with the data holes filled by the modeled data and for the time series comprising only observations.*

Furthermore (figure 5b), it appears strange that the two curves labelled “Observed” and “Model” are distinctively different for periods where UV observation are missing (1983-1995 and 2002-2004), considering that both are modelled, taking the same input parameters. An explanation would be helpful for the reader. *The both curves were modeled by different models; previous Eq. 2 for cloud modification factor and previous Eq.5 for yearly sum of daily doses variability. We do not follow this concept in the revised paper. We explain the long-term cloud effects on surface UV in much simpler way.*

Minor comments:

Page 1, line 27: “The ozone hole over the Arctic was observed only once in 2011” Even though the ozone layer was record low in the Arctic in 2011, large negative anomalies in total ozone has happened before and after 2011, e.g. in winter 2016/17, see e.g. “State of the Climate 2016”, section J: page S151-S154. http://www.ametsoc.net/sotc2016/Ch05_Arctic.pdf. Please, consider a reformulation.

We add a statement according the reviewer's comment. “However, severe ozone losses appeared occasionally over the Arctic, e.g. in 2011 (Garcia, 2011; Bernhard et al., 2013) and in 2016 (http://www.ametsoc.net/sotc2016/Ch05_Arctic.pdf).” p.1, l.25-28.

Page 2, line 29-31: “During the two years of its operation …”. A reader may first believe the instrument was operating only for two years. The meaning is likely rather “During 2006 and 2007 the instrument was calibrated. *We change the text according the reviewer's comment*. p.2, l 28-29.

Page 3 line 4: “Biometer” is normally associated with another brand of erythemal UV radiometers; the Solar Light Co. UV-Biometer. Please, consider using the wording UV-radiometer instead, for all instances of “biometer”. *“Biometer” has been replaced by “UV-radiometer” in the revised manuscript.*

Page 3 line 18, There should likely be a comma instead of a dot (.) after “>32 cm*”. OK. It has been removed.*

Section 5 Results and section 6 Discussion and Conclusion: Please, consider restructuring, or moving overlapping information. Example: page 6 lines 1-5 is restated on page 7 lines 4-9.

In the revised paper in section 7 (Discussion and Conclusion) we state that “The linear trend calculation by a standard least-squares fit applied to the measured (1996-2016 with the 2002-2004 gap) data shows statistically significant declining tendency in the monthly mean of daily doses (May and June), and in the yearly sum of the erythemal doses. However, such declining tendency are forced by two-three years of high positive fractional deviations of the erythemal doses around 2000.” p 9, l.7-9. *We cut details of the trend (overlapping information) but focus on a source of such trend behavior.*

Information on page 6-13 could be moved to the materials section.

This part of text has been deleted as it concerns the models' results not used in the revised manuscript. Information on page 6 lines 17-24 could be moved to the Discussions section. *OK. Now this part appears in the Discussion section.*

Page 7 line 14: Belsk should probably be Hornsund. *We change the text according the reviewer's comment*.

Page 14, legend to Figure 3d:

"Monthly doses" are probably monthly mean daily doses. *We change the text according the reviewer's comment*.

Anonymous Referee #3

In general, I feel the paper could be strengthened by discussion of the uncertainties in the results. This might require additional calculations that address sensitivities in the derived results to assumptions in the corrections. *The basic difference between the previous and revised manuscript is using a special Monte-Carlo procedure of generation hypothetical time series of daily erythemal doses accounting for various uncertainties for different data categories: reconstructed data, measured by the SL prototype, and measured by KZ instrument (see new section 5). The trend values are derived averaging sample of linear slopes derived by a standard least-squares fit applied to each Monte-Carlo time series.*

Uncertainty bars would be very beneficial for the trend analysis discussion. The discussion of the approach to homogenize the observed data for 20 years from the high-latitude station is of benefit.

The uncertainty bar appear in the revised manuscript (see new Fig. 6, p.20*). Moreover, the model-observation differences are shown in new Tab.1*. (p.13)

General comments on instrument correction/calibration:

I do not find in the discussion of the Annual Correction Factor, for the 5 year time period from 1996 to 2001, why the ACF value is so large and reaches a factor of 2.5 over five years. Is that a typical degree of instrument degradation for the Robertson-Berger UV meter? I also miss how sensitive the ACF value is to assumed AOD value of 0.16 and to assumption of no dependency on solar zenith angle.

New Figure is added showing the instrument deterioration. In fact, the deterioration appeared much smaller ~35% in the period 1996-2001. The previously mentioned deterioration rate (~250%) was erroneously calculated. WMO report (Instrument to Measure Solar Ultraviolet Radiation Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance", WMO, Rep. No. 164, *2008) stated that the well maintained broadband instrument could lost its stability maximally up to 5% between yearly intercomparisons. Thus, the loss of about 10 per year after two years of stable behavior (1996-1997) seems possible in a harsh polar environment.*

The extreme aerosols optical depth (AOD) for each month (March-September) are determined from 2.5 and 97.5 percentiles of the daily AOD values in selected month by Cimel measurements (2004-2016). These values are used in radiative model simulations to calculate the daily dose uncertainty due to unknown AOD in period prior Cimel measurements. Uncertainty (~7%) of the annual correction factor ACF for the period 1996-2007 is found. See Figure 4. p.18.

Additionally, please clarify what is the time period over which an assumed AOD of 0.16 is assumed: is it 1996-2001 (p.3, l.30) or 2004-2014 (p.4, l.16).

In the revised manuscript we explain that "… for the 1996-2001 calibration, we select AOD value representing the mean AOD value found for the period 2004-2016" p.3., l 30. *We used this value also if there were no observations of AOD because of bad weather.*

"daily observed aerosol optical depth (AOD) at 340 nm by the collocated Cimel sunphotometer or AOD equal to 0.16, i.e., equal to long-term (2004-2016) monthly means of AOD at 340 nm, for days without CIMEL measurements " p.5, l. 9-10.

I think more discussion of this result and the implication of the degree to which the trend analysis of the long-term record will be subsequently affected by derived ACF factor is required because there is an obvious knee-bone" around 2006 in the erythemal dosage time series in Figures 4 and 5b. A sensitivity analysis to incremental changes in assumed AOD could be performed at the very least to provide some uncertainty around the ACF value. also I do not find if (and how) uncertainty in the ACF is propagated into the coefficients derived from the linear regression analysis.

As mention before, the trend are calculated using a novel trend method accounting for data uncertainties depending on data collection periods: 1983-1995 for reconstructed data, 1996-2001 for the SL prototype, 2002-2004 for the reconstructed data, and since 2005 up to the end of data for KZ data..

An empirical factor, a function of sunshine duration, is applied to account for clouds. Clouds, due to their temporal and spatial variability, and changing optical properties as a function of low (predominantly water) and high (predominantly ice) altitude will be difficult to proxy model well.

Previous paper shows that the combined cloud effects on UV could be parameterized using proxies and solar duration appeared one of possible proxies (see introduction to section 4).

I cannot understand how the sunshine duration, as a proxy of clouds, is found to be highly statistically significant (*it means that there is strong linear dependence between the proxy and UV radiation, i.e. long sunshine duration corresponds to higher doses and zero/short duration means small UV doses)*, when this approach is found to explain only 45% of the cloud modification? (*it means that other factors are also important i.e., cloud transparency, period of the day with cloudless condition as noon conditions are decisive for the dose value*)

What was the criteria that was used to select sun duration as the best regressor for clouds? *We add paragraph (introduction to section 4. Data Reconstruction) providing some details of previous papers focusing on UV modeling. The sun duration was among the regressors used to explain UV variability. There were better set of the regressors (global solar radiation, diffusive component of solar radiation, etc.) but only sunshine duration was available at Hornsund. Of course, it provide a large uncertainty of the reconstructed doses but the trends were calculated taking into the data uncertainty.*

The correlation coefficient of greater than 0.9 is reported when regressing modeled and measured erythemal doses (Fig 3). I do not find the sigma (uncertainty in the regression best fit line) reported.

We add following statement: "*Slope by an ordinary least squares least-squares fit is 0.99 ± 0.02 (1σ), i.e., it also supports a perfect correspondence between measured and modeled daily doses",* P.5, 28-30.

What uncertainty is assumed/applied for the observed daily erythemal dose in the regression? While standard linear regression does not allow for uncertainties in the regressor, a somewhat related approach called Orthogonal distance regression (ODR) does. I find that clarification and additional discussion about the uncertainty in the proxy model regression to derive the cloud modification factor is required. An assessment of the propagation of this uncertainty into trend analysis would be helpful. Perhaps an ODR approach could contribute to an improved understanding of the sensitivity in the derived scaling coefficients to uncertainties in the modeled erythemal dose.

In the revised manuscript, trends are estimated using Monte-Carlo approach taking into account uncertainties in the reconstructed (see new Table 1) and measured data (different values for the measurements by the prototype for the period 1996-2001, and KZ instrument for the period 2005-2016) . New section 5 (Monte-Carlo method for trend estimates) explains the methodology used.

If I understand correctly, a second proxy model of total yearly dose of erythemal radiation is derived from a linear regression of the fractional deviation in yearly dose, where the model contribution in this fractional deviation comes from another multiple linear regression proxy model incorporating sunshine duration. I am not aware of "nested" multiple linear regression proxy models in general. Is this a commonly applied approach and are their references that can be cited as examples? I would feel that the uncertainties from the first proxy model would propagate into uncertainties in the second proxy model (and likely not in a linear fashion due to the nonlinear behavior between clouds, ozone, surface albedo and radiation). Some discussion and acknowledgement of the potential pitfalls of this approach would be helpful in the paper.

The second proxy model was used to find out sources of the long-term variability in UV radiation at Hornsund. We propose much simpler approach in the revised manuscript to solve this task. We use simulations by radiative transfer model to find combined effects of total ozone/albedo changes on surface UV. The clear-sky time series is compared to all-sky series to reveal cloud forcing on UV. Thus, parts of manuscript dealing with the performance of second proxy model have been deleted.

General comments on trend analysis: The proxy model (Eq.2) will be sensitive to clouds, as discussed in the paper. An underlying change in cloud fractions, cloud type (altitude, thermodynamic phase) over long time periods will manifest in the observed surface UV but will not be captured by the proxy model. Therefore, I find that ascribing behavior in long-term trends using the described approach somewhat dangerous, in particular given the large amount of uncertainties inherent in the approach for empirical cloud modification. The analysis that the conclusions are drawn from should really contain uncertainty bars to guide the interpretation of the concluding statements regarding trends in ozone and cloudiness.

We are aware of difficulties to estimate trends based on data having different sources and thus variable uncertainties. Simple approach of using only one ordinary least-square linear fit to all or parts of data, provides inappropriate estimate of the trend uncertainty. We propose a novel method to deal with the problem. Statistical analysis of the Monte-Carlo trend sample allows to determine the trend significance based on performance of many hypothetical time series having properties of the original time series.

List of basic changes and/or improvements

1. The manuscript tile is changed to “ Trends in erythemal doses at the Polish Polar Station, Hornsund, Svalbard, based on the homogenized measurements (1996-2016) and reconstructed data (1983-1995). It was according to the referee #1 suggestion.
2. A trend estimate in the revised manuscript is based on new model (description is in new section 5) to account for different uncertainties in different data periods (1983-1995 for reconstructed data, 1995-2001 for measurements by not commercial instrument, and 2004-2016 for measurements by standard Kipp and Zonen radiometer). Trend values and their significances are determined from a statistical analysis of the Monte-Carlo sample of linear slopes and corresponding slope errors.
3. A correction factor time series for the first measurement period (1996-2001) is prepared (new Fig. 3) to discuss the instrument deterioration. It appears much lower (35%) than that erroneously shown in previous manuscript (~250%).
4. Regression lines are drawn in new Fig. 6 (Previous Fig. 4)
5. The sources of the annual UV variability are quantified in much simpler way by analyses of the long-term pattern of the clear-sky and all-sky yearly sums of daily erythemal doses. Previous, i.e., the second regression model built to search for such sources, was criticized by referrers, and it has been deleted. New Fig. 7 has replaced previous Fig. 5
6. A short review of the UV reconstruction models used by other authors has been added (beginning of section 4). Performance of the proposed model has been discussed (see new Tab. 1) and a comparison with the reconstructed model by Lindfors et al. (2003) using the same proxy (relative sunshine duration) supports that our model behaves as a typical UV reconstruction model.
7. New Fig. 4 has been added showing the range of the erythemal UV for cases with extreme aerosols loading, i.e. between 2.5% and 97.5% of aerosols optical depth distribution.

Trends in ~~the surface UV radiation~~erythemal doses at the Polish Polar Station, Hornsund, Svalbard ~~(77°00’ N, 15°33’ E),~~ based on the homogenized ~~time series of broad-band~~ measurements (1996-2016) and reconstructed data (1983-1995)

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Abstract. Erythemal daily doses measured at the Polish Polar Station, Hornsund (77°00’N, 15°33’E), for the period 1996-2001 and 2005-2016 are homogenized using yearly calibration constants derived from the comparison of observed doses for cloudless conditions with the corresponding doses calculated by radiative transfer (RT) simulations. Modeled all-sky doses are calculated by the multiplication of cloudless RT doses by the empirical cloud modification factor dependent on the daily sunshine duration. An all-sky model is built using daily erythemal doses measured in the period 2005-2006-2007. The model is verified by comparisons with the 1996-1997-1998 and 2009-2010-2011 measured data. The daily doses since 1983 (beginning of the proxy data) are reconstructed using the all-sky model with the historical data of the column ozone from ~~the~~ satellite measurements (SBUV merged ozone data set), the snow depth (for ground albedo estimation), and the observed daily sunshine duration at the site. Trend analyses of the monthly and yearly time series comprising of the reconstructed and observed doses do not reveal statistically significant trend~~ only in March (~1%/yr)~~ in the period 1983-2016. The trends based on the observed data only (1996-2001 and 2005-2016) show declining ~~tendencies during spring (March-April-May) of ~1%/yr.~~tendency (-1%/yr) in the monthly mean of daily erythemal doses in May and June, and in the yearly sum of daily erythemal doses. An analysis of sources of the yearly dose variability since 1983 provides that cloud cover changes are a basic driver of the long-term UV changes at the ~~location~~site.

1- Introduction

The importance of the solar UV radiation on human health and ecosystems is widely discussed in the literature since the ozone hole discovery in the early 1980s (e.g. WMO, 2014). The Montreal Protocol was signed by UN countries in 1987 to protect the ozone layer, which acts as a shield against the solar UV. Since 1980 especially large ozone depletion was observed every year in the late winter and spring, the so-called ozone hole, over Antarctica (e.g. WMO, 2014). However, ~~the~~severe ozone ~~hole~~losses appeared ocassionally over the Arctic~~ was observed only once~~, e.g. in 2011 (Garcia, 2011; Bernhard et al., 2013) and in 2016 (http://www.ametsoc.net/sotc2016/Ch05_Arctic.pdf). The ozone downward trend and the increase of the surface UV in the Arctic was observed in 1990s (Fioletov et al., 1997; Newmann et al., 1997; Gurney, 1998).

The amount of column ozone and its vertical distribution have been measured using a ground-based and satellite network. Nowadays, the ozone distribution over the whole globe is available for scientific purposes. The surface UV radiation in the UV-B range also depends on the Sun’s elevation, cloud/aerosol characteristics, and the surface albedo, which are widely variable from site to site. There are a limited number of ground-based stations measuring erythemaly effective doses continuously for longer than 20 years. These include only 5 northernmost stations above 70° N: Alert (82.5° N, 62.31° E), Ny-Ålesund (78.92° N, 11.92° E), Hornsund (77.0° N, 15.33° E), Resolute (74.72° N, 94.98° W, and Barrow (71.32° N, 156.68° W). The algorithm to calculate the surface UV using the satellite data (total ozone, ground-reflectivity) over high-latitude regions sometimes failed due to the fact that the observed high reflectivity surfaces might be erroneously classified as high ground-albedo (from snow and ice cover) or cloud effect (Tanskanen et al. 2007). It is crucial to examine the UV variability over the Arctic regions, especially for high latitudinal coastal sites, because of rich and diverse ecosystems located in this area (Hessen et al, 2001). It is anticipated that anthropogenic climate effects will be the most pronounced in high latitudinal regions (Taalas et al., 2000; IPCC 2014).

Maintaining homogeneity of long-term UV time series (20+yr) taken from various instruments is a challenging task especially for remote sites. In this paper, we propose a method for the UV data homogenization applicable for any remote Arctic site like the Polish Polar Station Hornsund (Section ~~2 and~~ 3). Next, we reconstruct the UV doses dating back to 1983 when the observations of proxies for the UV variability started at Hornsund (Section 4). Finally, we search for linear trends ~~in~~and their uncertainty using a Monte-Carlo approach (Section 5) applied to monthly and yearly doses (Section ~~5) separately for the periods comprising both~~6) based on the reconstructed and observed data (1983-2016) and ~~for~~ the observed data only (1996-2016 with the 2002-2004 gap).

2 UV and ancillary data

The erythemal UV measurements at Hornsund were carried out since 1996 up to 2001 by an improved version (with temperature stabilization) of the classic Robertson-Berger UV meter. This was a prototype of the presently widely used broadband Solar Light Model 500 (denoted SL 500) radiometer produced by Solar Light Co. RB meter was designed in the early 1970s to measure erythemal solar irradiation as its spectral ~~characteristics~~characteristic resembled that of the human skin (McKinlay and Diffey, 1987). The prototype was designed in the Institute of Geophysics (IG), Polish Academy of Sciences (PAS), Belsk, in the late 1980s and since then took part in the UV monitoring at the Central Geophysical Laboratory, IG PAS, Belsk, Poland. It was moved to the Hornsund observatory in 1995 and put into regular UV monitoring in 1996 (Krzyścin and Sobolewski, 2001) that lasted up to autumn 2001. Since spring 2004, a new UV broadband meter Kipp and Zonen UVS-AE-T (Fig. 1) has been installed at Hornsund and started continuous UV monitoring in April 2005. ~~During the two years of its operation (~~In spring 2006~~-~~ and 2007~~)~~, it was calibrated by the IG PAS substandard Kipp & Zonen UVS-AE-T (No. 616), which was frequently ~~calibrated against~~adjusted to the Belsk's Brewer spectrophotometer (Sobolewski and Krzyścin, 2006). There were logistical difficulties with the calibration of the Hornsund meter by a higher-level standard (e.g. the Brewer spectrophotometer) as the station could by reached only by snowmobiles (in spring), helicopters or ships (in summer). Thus, we decided to apply radiative transfer (RT) model simulations for clear-sky conditions to calibrate ~~the~~ output of the ~~biometer~~UV-radiometer during cloudless days and perform a homogenization of the past UV data.

The following ancillary data routinely measured at Hornsund is used in the model simulations: snow depth~~, cloud fractions by low-, mid-, and high-level clouds~~, aerosols characteristics (aerosols optical depth, single scattering albedo from the Cimel Sunphotometer observations since 2004), and the sunshine duration (by a Campbell-Stokes recorder).

3 Data Homogenization

8. Clear-sky conditions over the Hornsund observatory were identified by the examination of the 1-minute erythemal irradiation daily pattern. The smoothness of the pattern and the steady increase (before local noon) and decrease (after local noon) of the irradiances provided a criterion for cloudless day. The Tropospheric Ultraviolet-Visible (TUV) RT model by

Madronich (1993) is implemented to calculate hypothetical clear-sky daily dose for the selected cloudless days. The TUV input consists of the column ozone amount (taken from the site overpasses by the Solar Backscatter Ultraviolet (SBUV) instrument onboard the NOAA satellites, aerosols characteristics from the AERONET database~~ (aerosol optical depth, single scattering albedo of aerosols, and asymmetry factor).~~. The ground albedo in UV range is approximated by a local formula:

$$Albedo_{\mathrm{GROUND}} = 0.1 + Depth_{\mathrm{SNOW}}/40, \qquad (1)$$

where $Depth_{\mathrm{SNOW}}$ is the measured snow depth in cm, ~~for $Depth_{\mathrm{SNOW}}$ >32 cm.~~ $Albedo_{\mathrm{GROUND}}$ ~~=~~is assumed equal to 0.9~~.~~ for snow depth larger than 32 cm. Equation (1) was found experimentally, to have the best agreement with the measured daily doses in the period when the UV data at Hornsund were calibrated by the IG PAS substandard (2006-2007).

For each year (2005-2016) ratios between the modeled and observed daily doses were averaged to provide the annual correction factor, which is ~~consequently ~~applied to ~~the~~all measured ~~all-sky ~~daily doses. The annual correction factor (ACF) was calculated separately for selected ranges of the noon solar zenith angle (SZA); SZA≤60°, 60°<SZA≤70°, 70°<SZA≤80°, and SZA > 80~~°.~~°, in the period March-June when many cloudless days were found. Figure 2 shows ACF time series (2005-2016) for four SZA ranges. It is worth noting that ACF oscillates in the range 0.95-1.05 for SZA≤60°, 60°<SZA≤70°. There is a much larger ACF variability of ~0.75-1.35 for noon SZA>80° (~~February – 15 ~~early March~~, October~~), i.e. for a period with a weak UV intensity when the solar UV is dominated by the diffusive component related to aerosol characteristics, which sometimes is not well parameterized in the RT model. All time series shown in Fig.2 are trendless. It seems that the ~~biometer's~~instrument sensitivity to the UV radiation is constant since 2005, i.e. there is no need to use any correction for the instrument aging and ACF=1.

The same procedure was used for the first period (1996-2001) of the UV monitoring at Hornsund but constant aerosols of AOD at 340 nm equal to 0.16 was assumed~~ (~~. During that period there were no Cimel sunphotometer observations~~ in that period).~~. Thus, for the 1996-2001 calibration, we select AOD value representing the mean AOD value found for the period 2004-2016. Moreover, only one ACF value was calculated regardless of SZA. Figure 3 shows yearly ACF values for the period 1996-2001. It is seen that almost linear instrument deterioration of ~10% per year appeared after two years (1996-1997) of its stable behavior. The prototype instrument operated without any maintenance since 1997. Thus, it seems that the instrumental drift appeared due to increasing humidity level inside the instrument. Following ACF values~~ were ~~, which were derived from model-observation comparisons for clear-sky days, are applied to the observed (uncorrected) daily ~~dose~~doses: 1.~~00~~01 (1996), 0.99(1997), 1.~~20(1997), 1.40~~10(1998), 1.~~79 (1998), 1.80 (~~20(1999), ~~2.00 ~~1.26(2000), ~~and 2.50 ~~1.35(2001).

~~4 Data Reconstruction~~

~~Reconstruction of the erythemal daily doses is based on a regression model using proxies for the cloud attenuations i.e. a cloud cover observed by the technical staff and a~~The uncertainty of UV observations by the prototype instrument induced by unknown aerosols AOD in ACF calculations could be estimated using extreme AOD monthly values in RT simulations, i.e. 2.5 and 97.5 percentiles of AOD values taken from all Cimel measurements in a selected month for the period 2004-2016. Figure 4 shows the differences between clear-sky erythemal daily doses calculated in 1996 for extreme high (2.5 percentile) and extreme low (97.5 percentile) AOD monthly values. Actual snow cover and satellite total ozone were used in these simulations. Because the AOD variability range depends on month, we found that the uncertainty level varies between 2-7%. Further in calculations we select 7% as a characteristic of the instrument's uncertainty induced by no precise information of aerosols loading in ACF calculations for the period 1996-2001.

4 Data Reconstruction

Past variations of the surface erythemal radiation in periods without UV measurements could be retrieved from statistical and radiative transfer modelling using various proxies to describe attenuation of UV radiation in the atmosphere (e.g. Lindfors and Vuilleumier, 2005; Koepke et al., 2006; Lindfors et al., 2007; Rieder et al., 2008). Global solar radiation, cloud cover, solar zenith angle, and the sunshine duration were usually used as proxies to construct empirical formulas to determine cloud attenuation of UV radiation. Junk et al. (2007) applied an advanced statistical technique, artificial neural network, to find out the most effective combination of proxies for surface UV estimation. It appeared that global solar radiation, solar zenith angles, and diffusive part of global solar radiation were essential proxies for UV reconstruction giving 1-2 percent bias and ~ 3-4% root mean square (RMS) error relative to the measured daily erythemal dose. Bilbao et al (2011) found that RMS error of ~4-9%, when only global solar irradiance and SZA were used to parameterize 10-minute erythemal doses. For some sites, only the sunshine duration was possible as a cloud attenuation proxy and it yielded 5-6% bias and RMS errors of order 20% for the reconstructed daily doses (Lindfors and Vuilleumier, 2005).

Here reconstruction of the erythemal daily doses is derived using hypothetical clear-sky erythemal daily doses from a radiative transfer model simulation using following input parameters: total ozone (for satellite overpasses), albedo (retrieved from snow depth), and aerosol optical depth at 340 nm (from collocated CIMEL sunphotometer measurements). The cloud attenuations due to clouds are derived from an empirical formula based on the daily sunshine duration measured by a Cambell-Stokes recorder. Model's regression parameters were determined using the 2005-2006-2007 daily erythemal doses (by Kipp and Zonen UV~~-biometer-~~radiometer). The model is verified using the 1996-1997-1999 data (output of SL 500 prototype) and 2009-2010-2011 (output of Kipp and Zonen ~~biometer~~UV-radiometer).

A semi-empirical model is built to reproduce the measured daily doses (erythemal Jm^{-2}) for the period 2006-2007-2008.

$$\cancel{Dose}\,DOSE_{\text{MOD}}(t) = CMF\,(t)\ \text{x}\ \cancel{Dose}DOSE_{\text{CLEAR-SKY}}(t)\,, \qquad (2)$$

where $\cancel{Dose_{\text{CLEAR}}}DOSE_{\text{CLEAR-SKY}}$ (t) is a hypothetical clear-sky daily dose in day t from the radiative transfer model simulations (TUV) with the following input:

- the daily total ozone (TO_3) from the station satellite overpasses (SBUV merged data set)
- the snow albedo according ~~formula (~~to Eq.1~~)~~ with the snow depth from the station meteorological data
- daily observed aerosol optical depth (AOD) ~~values~~at 340 nm by the collocated Cimel sunphotometer or ~~the~~AOD equal to 0.16, i.e., equal to long-term (2004-~~2014~~2016) monthly means of AOD at 340 nm~~ (0.16) if there were no~~, for days without CIMEL measurements ~~at the station.~~

CMF is an empirical cloud modification factor (CMF) used to parameterize an attenuation of hypothetical clear-sky daily doses by clouds. ~~Various combinations~~We have no variability of ~~regressors (explaining variables) were examined using standard multi-linear regression to reproduce observed erythemal doses. These included~~ the ~~cloud cover (by total, low-, mid-, and high-level clouds), cloud types identified by an observer (every 3 h), and the measured daily relative~~ sunshine duration ~~(the sunshine~~throughout a day. Using the daily values adds additional uncertainties to modeled values as a duration ~~divided by the pertaining day length). The time series~~ of ~~these regressors were available since 1983.~~ clear-sky conditions near local noon is decisive for daily doses.

Finally, the relative sunshine duration (in percent of the polar day durations, $SUN\_DUR(t)$, was selected as ~~the best~~single UV regressor, and the following formula was obtained by standard least-squares approach:

$$CMF(t) = 1.0324\,[SUN\_DUR(t)]^{0.1951}\,, \qquad (3)$$

~~Model (3) explains ~ 45% of CMF variance.~~ The regression coefficients (1.0324, 0.1951) are found highly statistically significant at the 99% confidence level. Model (3) explains ~ 45% of CMF variance. ~~It appeared that~~ Table 1 shows the ~~cloud fractions~~monthly bias and ~~types were not good predictors due to~~ RMS errors of the ~~large variability of cloud types with different optical properties. Moreover, cloud observations at~~model (3) performance for March –September in the ~~station were taken every 3 h and~~ period 2005-2016. The model setup is almost similar to that used by Lindords et al. (2003) for UV daily doses reconstruction for Sodankylä. However, our model provides RMS error ~ 15% for estimates of the ~~closest observation to~~ daily erythemal dose. Lindords et al. (2003) found RMS error of ~23%.

To determine how model (2) uncertainty influences trend estimates for the ~~noon was 12 GMT, i.e. approximately 1 h after~~whole period 1983-2016, we propose a Monte-Carlo methodology to derive the ~~local noon.~~ trend value and its uncertainty based on a hypothetical bootstrap sample (N=10,000) of the linear trend coefficients and their errors (see section 5).

Model (2) with CMF defined by Eq. (3) performs almost perfectly (see Fig.~~3a~~5a). The model-observation correlation coefficients exceed 0.9 and the smoothed pattern of scattered data obtained by LOWESS (locally weighted scatterplot smoothing, Cleveland, 1979) matches the 1-1 line (perfect agreement line - diagonal of the square). Slope by an ordinary least squares least-squares fit is 0.99 ± 0.02 (1σ), i.e., it also supports a perfect correspondence between measured and modeled daily doses.

The regression coefficient of ~~models~~model (2) was computed using the multi-linear least-squares fit to the observed 2005-2006-2007 daily doses. Comparisons of the modeled data to the observed ones taken in different periods will provide a kind of the model's verification and will support a correctness of the calibration constants applied to total UV data (Section 3). Figure ~~3b~~5b and Figure ~~3c~~5c show the comparisons for the period 2009-2010-2011 and 1996-1997-1998, respectively. The model-observation correlation coefficients are high (~0.95) ~~and~~with linear slopes close to 1. Moreover, the smoothed patterns of scattered data points match the 1-1 line (perfect agreement line) throughout the whole range of the data variability.

The model-observation agreement appears even better for the monthly averages of daily erythemal doses (Fig.~~3d~~5d) for three periods together: 1996-1997-1998, 2005-2006-2007, and 2009-2010-2011. Here the correlation coefficient is equal to ~0.99 and the linear regression line has the slope of 1.002~~. Thus, the~~+0.009 (1σ). The simple parameterization of cloud effects on the surface erythemal dose by Eq. (3) could be used for a reconstruction of the long-term UV variability at Hornsund. Moreover, almost the same model performance was found for the periods with the UV observations done by different instruments: 1996-1997-1998 (SL 500 prototype), 2005-2006-2007 (model's built period) and 2009-2010-2011 (Kipp and Zonen UVS-AE-T radiometer). It supports the data homogeneity of the UV observations by different ~~biometers~~UV-radiometer since 1996.

~~5 Results~~

~~The monthly mean erythemal doses from the UV observations (1996-2001, and 2005-2016) and reconstructed by the model (2) for the period 1983-1995, and the period 2002_2004 is used to estimate the long-term variability and linear trends for the whole 1983-2016 period and for the 1996-2016 period (with the gap in the period 2002-2004) using only the ground-based data.~~

5 Monte-Carlo method for trend estimates

We propose a Monte-Carlo procedure to estimate linear trend that accounts for various uncertainties of the daily doses throughout the examined period. The monthly and yearly trend values and their significance are derived averaging linear regression coefficients and their errors taken from a standard least-squares linear regression applied to a large number (N=10,000) of hypothetical erythemal UV time series. These time series were randomly generated for the period 1983-2016. Random representatives are generated taking into account specific uncertainty of the UV data for selected periods with different data categories, i.e.,

- for the period 1983-1995 and 2001-2004, we use the reconstructed data, based on model (2), adjusted for the model (2) uncertainty, $DOSE_{\mathrm{MOD,\ Adjusted,\ n}}(t)$. To the modeled value we add a random component, $RAN_{\mathrm{n}}(Mean(t), SD(t))$, being n-th value taken from normal distribution with mean value, $Mean(t)$, and standard deviations $SD(t)$, which allows to account for possible variations of the hypothetical daily dose around its original value:

$$DOSE_{\mathrm{MOD,\ Adjusted,\ n}}(t) = DOSE_{\mathrm{MOD}}(t) + RAN_{\mathrm{n}}(Mean(t), SD(t)), \qquad \mathrm{n}=\{1, \dots, \mathrm{N}=10000\} \qquad (4)$$

  where $Mean(t)$ and $SD(t)$ are monthly mean value and pertaining standard deviation calculated from differences between the measured daily doses, $DOSE_{\mathrm{OBS}}(t)$, in the period 2005-2016, and modeled doses, $DOSE_{\mathrm{MOD}}(t)$, for the calendar month corresponding to t value (see Table 1).

- for the period 1996-2001 and 2005-2016 we use the Monte-Carlo set of the potential representatives of the observed time series that is also adjusted for the observation uncertainty, $DOSE_{\mathrm{OBS\ Adjusted,\ n}}(t)$. In the former period, the data uncertainty was larger than that in the latter period because of using a non-commercial instrument and less precise ACF calculation to account for the instrument deterioration.

$$\mathrm{DOSE}_{\mathrm{OBS\ Adjusted,\ n}}(t) = \mathrm{DOSE}_{\mathrm{OBS}}(t) + RAN_{\mathrm{n}}(0, SD_k), \qquad k=\{1, 2\}, \qquad \mathrm{n}=\{1, \dots, \mathrm{N}=10000\} \qquad (5)$$

  where SD_1 and SD_2 are the 1-sigma uncertainties of the daily erythemal UV measurements in the period 1996-2001 and 2005-2016, respectively. We assume that our SL prototype had an uncertainty level similar to the commercial SL UV-radiometer. Hülsen and Grobner (2007) found 11.2% and 7.2% uncertainty (at 2 sigma level) for typical SL and KZ instruments, respectively. Finally, the uncertainty of UV daily doses by the SL prototype is calculated as 13.2% taking into account 7% uncertainty induced by an assumption of a constant AOD value in the ACF calculation for the period 1996-2001 (Section 3).

10,000 hypothetical representatives of daily erythemal doses values for each day in the March-September subperiod of the period 1983-2016 were generated. Next these daily doses were averaged to produce the monthly mean of daily doses and a standard least-square linear fit was applied to each hypothetical monthly series to obtain a linear slope and its standard error. To check a hypothesis of statistical significance of the trend value at 2 sigma confidence level, we calculate a number of cases with the absolute value of the slope larger than the twice standard error of the pertaining slope. The trend is statistically significant at 2 sigma level if at least 95% of slopes fulfil this condition. The number of Monte-Carlo time series was determined by testing the stability of the mean slope and it's 2-sigma slope error when changing number of series between 1,000 and 15,000. A larger number than about 10,000 did not introduce any further changes in the statistical characteristics of the slope sample. Thus N=10,000 samples are selected for further statistical analyses.

6 Results

Monthly means of daily erythemal doses show significant intra-year variability (Tab.1) with the late spring early summer maximum. Therefore, to compare trend values in selected months, the trend analyses are applied to departures of the monthly mean of daily doses from pertaining the long-term monthly mean (2005-2016) in percent of the long-term monthly mean. The yearly sum of erythemal doses are calculated as a sum of the daily doses between 1st March and 30th September as earlier, and later doses are small or zero because of high solar zenith angles and polar night (between 29th October and 11th February). Similarly, to the monthly means of daily doses, the yearly sum is converted to the normalized departures relative to the mean yearly sum in the period 2005-2016.

Figure 46 illustrates the time series of the monthly (March-September) and yearly ~~fractional deviations, *FD_DOSE*(*t*), i.e. deviations~~normalized departures from the long-term (~~1996~~2005-2016) monthly means~~, <*DOSE*(*t*)>, in percent~~ and a yearly sum of daily doses. The regression lines show the long-term ~~means: ~~tendency in the 1983-2016 period and in the shorter period (1996-2001 and 2005-2016) when only the results of measurements were taken into account.

~~*FD_DOSE*(*t*) = (*DOSE*(*t*) - <*DOSE*(*t*)>) / <*DOSE*(*t*)>*100% , (4)~~

There are large year-to-year fluctuations in the monthly fractional deviations in the range between -40% and 40%. ~~The smoothed data patterns show: an increasing tendency throughout the whole period in March and April, the trendless behavior in July and September, the increase/decrease in May and June with the turning point around 1996, the decrease/increase in August with the turning point around 1998. Yearly sums of the erythemal daily doses show increasing tendency of about 1% per year up to ~1996 and afterward a leveling off. ~~The linear fit to the normalized departures in the 1983-2016 period reveals a slightly increasing tendency in the yearly sums and in all examined monthly means (excluding May with trendless behavior). The observed data for the 1996-2001 and 2005-2016 periods show a declining tendency in April, May, June, and throughout the whole year but an increasing tendency in March, August, and September. Statistical significance of the trend results is shown in Tab.2.

Table ~~1 shows the ~~2 presents statistical characteristics of the Monte-Carlo trend estimates. The mean linear trend ~~values by~~ coefficients and their mean standard errors together with pertaining range of estimates (between minimum and maximum of the slope and standard deviation) were derived by examining all slopes and their errors obtained by an ordinary least-~~squares regression.~~square fit to each of the Monte-Carlo representative of the original time series. The trends are calculated for the period 1983-2016 (both observed and reconstructed data~~) and~~), for the period 1996-2016 ~~taking into account only the~~(with observed data~~.~~ for the 1996-2001 and 2005-2016 periods, and the reconstructed one for the period 2002-2004), and for the period with the UV measurements only (with the gap for the period 2002-2004). The statistically significant ~~(at 2σ level) positive trend is ~~decline at 2σ level of about -1%/yr is revealed in May, June, and in the yearly sum for the observed 1996-2016 data (with the 2002-2004 gap). The trend analyses applied to the combined observed (1996-2001 & 2005-2016) and reconstructed data (2002-2004) show statistically significant decline only in May of ~ -1% /yr.

To find sources of the long-term UV variability at Hornsund, we analyze also time series of yearly (March-September) sum of hypothetical clear-sky daily doses by RT simulations (using total ozone, aerosols, and snow albedo as model's input), and the pertaining yearly cloud modification factor (i.e., actual yearly sum divided by the corresponding clear-sky value). Figure 7a shows the yearly sum of daily doses values, for clear-sky and all-sky conditions (in kJm^{-2}), and CMF (in dimensionless unit). Figure 7b illustrates long-term variability of the normalized departures (% of the long term mean values for the period 2005-2015). About 10% increase of the yearly sum of all-sky daily erythemal doses and a slight decline in the clear-sky yearly sums due to the combined total ozone/albedo changes could be found ~~only in March (~1% per year) for the 1983-2016 period. The negative trends ~1% per year are calculated in April, May, and June for the shorter period (since 1996). It seems~~in the 1980s and 1990s. Thus, it could be estimated that ~~the negative trend in April was caused by two extremely high positive fractional deviations (~30-40%) at the beginning of time series (1996 and 1997) and the trend in shorter period does not correspond with an ~~increasing ~~tendency found in the whole data period. ~~cloud transparency and/or declining cloud cover should force ~10% an increase of yearly sums. The clear-sky UV forcing at Hornsund appears weak in the 21st century and UV follows mostly changes in cloud characteristics.

~~To find sources of the long-term behavior of total yearly dose, $TYD(t)$, we calculate the corresponding pattern for total ozone and the relative sunshine duration for the same period. The explained variables are weighted using the monthly weights according to participation of the monthly doses in $TYD(t)$, i.e. {0.02,0.10,0.21,0.27,0.22,0.12,0.04} for each month since March up to September, respectively. A multivariate regression of the TYD fractional deviations, $FD\_TYD(t)$, on the fractional deviations of the weighted total ozone, $FD_W\_TO_3(t)$, and the weighted relative sunshine duration, $FD_W\_SUN\_DUR(t)$ is found as follows,~~

~~$FD\_TYD(t) = -3.0304 - 0.7498\ FD_W\_TO_3(t) + 0.5017\ FD_W\_SUN\_DUR(t)$, (5)~~

~~The Model (5) explains 63% of the total variance (Fig5.a) and provides that cloudiness changes were the dominant the factor of TYD variability. TO_3 changes induced $FD\_\ TYD(t)$ variability in the range ~1%. It is worth mentioning that the weighted pattern of annual TO_3 values shows full recovery of ozone in 2016. Clouds caused $FD\_\ TYD(t)$ increase of ~ 3% in the period 1983-1996 and 2008-2016, and a decrease of ~3% in the period 1996-2003.~~

~~Previous studies showed that the sunshine duration was a worse proxy for a parameterization of the cloud attenuation when compared to the total solar (300-3000nm) radiation. It does not reflect basic cloud characteristics such as cloud fractions and the cloud optical thickness (Koepke et al., 2006). The total solar radiation was measured at Hornsund in some disjoined periods since 1983 but the data was not calibrated by a higher-ranking instrument. Thus, we decided to use only sunshine duration data to parameterize the cloud effects since 1983 at Hornsund. Sunshine duration measurements by a Campbell-Stokes instrument seem to be less influenced by the instrument sensitivity lost and its calibration is very simple as during cloudless conditions the sunburn track should appear throughout the whole day.~~

~~6~~

7 Discussion and Conclusions

A procedure for the examination of the UV data homogeneity is proposed based on RT simulations for clear-sky conditions. It allows introducing the yearly calibration coefficient showing the instrument sensitivity ~~lost~~loss (1996-2001) and stable behavior in the period of measurements by the Kipp and Zonen UVS-AE-T ~~biometer~~instrument (2005-2016). For all-sky conditions, the regression model is built using 3-year data (2005-2006-2007) and comparisons of the modeled data with earlier (1996-1997-1998) and later (2009-2010-2011) data shows the same ~~behavior~~model performance as for the model building period that supports the data homogeneity and its usefulness for the long-term trend analysis. The regression model allows the UV dose reconstruction since 1983, i.e. in the period when the daily total ozone (from the satellite observations) and the sunshine duration data, which represented a proxy for the cloud effects on surface UV, were both available. The reconstruction model is also used to fill the data gaps in the UV observing period (since 1996).

Previous studies showed that the sunshine duration was a worse proxy for a parameterization of the cloud attenuation when compared to the global solar radiation. Using global solar irradiance is more appropriate to parameterize cloud effects on UV (Koepke et al., 2006). However, this variable was measured at Hornsund in some disjointed periods since 1983 but the pyranometer data were not calibrated by a higher-ranking instrument. Sunshine duration measurements by a Campbell-Stokes instrument seem to be less influenced by deterioration of the instrument's sensitivity, and its calibration is very simple as during cloudless conditions the sunburn track on a recorded cart should appear throughout the whole day.

Analyses of the yearly sums of daily erythemal doses at Hornsund reveal a non-statistically significant trend in the period 1983-2016. Two phases of the long-term behavior of total yearly doses could be identified, i.e. a positive tendency in total yearly doses in the period 1983-2000 and afterward a leveling off. The linear trend calculation by a standard least-squares fit applied to the measured ~~monthly means~~ (1996~~-2001 and 2005~~-2016~~)~~ with the 2002-2004 gap) data shows ~~apparent~~statistically significant declining tendency in ~~April,~~ monthly means of daily doses (May~~,~~ and June), and ~~July.~~in the yearly sum of the erythemal doses. However, ~~these trends are influenced~~such declining tendency is forced by two-three years of high positive fractional deviations of the erythemal doses ~~at the beginning of the shorter time series.~~around 2000. Longer time series (since 1983) do not show any sign of the declining tendency~~,~~ starting around 1996. Bernhard et al. (2011) analysis of the monthly trends at Barrow (Alaska) for the period 1990-2010 revealed statistically significant trend only in October (decline of about -1% per year) when the UV intensity was rather weak without the erythemal risk.

The stratospheric ozone ~~effect on the surface UV appeared~~changes appear as a ~~secondary source~~less important driver of the UV long-term variability ~~causing the long-term oscillations~~ in the ~~range of ±1% in the~~whole analyzed period~~ 1983-2016. Such total ozone pattern is not unique in the Arctic.~~. Figure ~~6~~8 shows the long-term (1979-2016) pattern of the total ozone mean (using SBUV merged data) for the period May-August at ~~Belsk~~Hornsund, Barrow, and Resolute, i.e. in the ~~period~~part of the year with naturally high UV radiation~~.~~ (~ 80% of total the yearly sum). The ozone forcing on the surface UV at these sites ~~is~~appears weak (within the ± 1% range) since 1983 (i.e. at the beginning of the ~~1990s.~~ reconstructed data). Cloud effects are the basic source of the UV variability at Hornsund. ~~Here the relative sunshine duration was used~~The albedo variations are also important as ~~the proxy explaining the cloud effects. It allows to identify, for example, a decrease~~~ 5% decline in ~~cloudiness~~the clear-sky modelled values in the ~~period~~ 1980s and 1990s (Fig.7b), i.e. during the ozone declining period,~~1983-2000 but the corresponding increase in the total yearly doses~~ seems to be ~~larger than that inferred from the proxy pattern. Evidently, the cloud optical thickness should be also responsible for the yearly UV variability~~forced by declining snow albedo.

It seems that the excessive UV radiation will be unlikely over the Arctic during the 21st century as prolonged decrease of ozone will not be possible due to the declining tendency in the concentration of the ozone-depleting chemicals in the stratosphere, anticipated intensification of the Brewer-Dobson circulation loading higher amount of ozone into the Arctic stratosphere (WMO, 2014). The downward UV tendency in the Arctic will ~~by~~ also be induced by the increase in the cloudiness, and the lowering of the ground albedo due to the snow and sea-ice melting (e.g. Bais et al., 2015).

A continuation of UV measurements at Hornsund seems to be necessary as it is located in a region vulnerable to climate changes with the local climate strongly dependent on the heat arriving with the Gulf Stream. A projection of the weakening of the Atlantic Meridional Overturning Circulation (Boulton et al., 2014) will lead to the surface cooling at the location. It can not be excluded that high reflectivity areas (sea-ice and snow) will extend over west Svalbard and the present climatic contrast between west (warm) and east (cold) part of Svalbard will disappear. Any projection for erythemal irradiance by the end of the 21st century is the most uncertain for this part of the Arctic.

*Data Availability***.** The total ozone overpass data was acquired from the data archive of SBUV merged ozone at ftp://toms.gsfc.nasa.gov/pub/sbuv/MERGED/. The sunshine duration and snow height at Hornsund were available at https://github.com/AtmosIGFPAN/Hornsund_Data. Aerosols optical properties were taken from AERONET database at https://aeronet.gsfc.nasa.gov/new_web/aerosols.html. Finally, the reconstructed and observed erythemal doses at Hornsund for the period 1983-2016 could be found at https://github.com/AtmosIGFPAN/Hornsund_Data.

*Acknowledgments***.** Funding for this study was provided by the Ministry of Science and Higher Education, Republic of Poland, ~~within~~ statutory activity No 3841/E-41/S/2017. We are grateful to ~~the~~ numerous dedicated individuals who ~~have~~had collected meteorological data ~~for~~over many decades.

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Table 1. ~~**Monthly and yearly trend values (% per yr.) with 2 sigma errors of estimate (in parentheses) by a standard least-squares regression for the period 1983-2016 (reconstructed and observed data together) and 1996-2016 (only observed data).**~~**Monthly mean of the daily erythemal doses (in Joules), participation of the monthly sum of daily doses in the yearly (February-October) sum of the daily doses (in %), monthly mean difference between the observed and modelled doses (Bias in Joules) and corresponding root mean square error (RMSE in Joules), monthly mean difference between the observed and modelled doses as a percent of the observed doses (Bias in %) and corresponding root mean square error (RMSE in %). The results are from modelled and observed daily doses at Hornsund for the period 2005-2016.**

Month	Mean [J]	% yearly dose	(Obs-Model) [J]		(Obs-Mod)/Obs [%]	
			Bias	RMSE	Bias	RMSE
March	178	3	17	22	9	14
April	744	10	39	84	6	14
May	1516	21	68	214	4	14
June	1983	27	-6	237	-0	14
July	1627	23	-89	211	-5	15
August	876	12	-44	116	-5	14
September	266	4	-3	46	-1	15

Table 2. The monthly and yearly mean slope of the linear fit and the corresponding standard deviation (in % per year) from 10,000 sample of the hypothetical time series for the period 1983-2016 (modelled & observed data), and 1996-2016 (observed & modeled data), and for the period 1996-2001 and 2005-2016 (observed data only). The minimum and maximum values of the slope and its standard selected from 10,000 simulations are in the parentheses. Numbers in bold font represent statistically significant estimates at 2σ level.

Month	Slope (%/yr)	SD Error (%/yr)
	1983-2016 (modeled & observed)	
March	0.46 (0.31, 0.32)	0.29 (0.27, 0.32)
April	0.23 (0.12, 0.37)	0.28 (0.26, 0.30)
May	-0.04 (-0.19, 0.09)	0.23 (0.20, 0.27)
June	0.05 (-0.08, 0.17)	0.27 (0.24, 0.29)
July	0.16 (0.05, 0.29)	0.29 (0.24, 0.31)
August	0.22 (0.10, 0.35)	0.23 (0.21, 0.25)
September	0.11 (-0.03, 0.27)	0.19 (0.16, 0.22)
Year (III-IX)	0.11 (0.05, 0.17)	0.18 (0.17, 0.19)
	1996-2016 (modeled & observed)	
March	0.20 (0.00, 0.37)	0.71 (0.64, 0.77)
April	-0.46 (-0.63, -0.29)	0.58 (0.52, 0.64)
May	**-0.94** (-1.10, -0.75)	0.42 (0.37, 0.48)
June	-0.98 (-1.17, -0.81)	0.56 (0.50, 0.61)
July	0.03 (-0.15, 0.22)	0.45 (0.41, 0.49)
August	0.59 (0.45, 0.74)	0.44 (0.40, 0.49)
September	0.05 (-0.17, 0.22)	0.40 (0.33, 0.46)
Year (III-IX)	0.40 (-0.48, -0.33)	0.35 (0.33, 0.38)
	1996-2001 : 2005-2016 (observed)	
March	-0.17 (-0.37, -0.00)	0.64 (0.57, 0.75)
April	0.82 (-0.98, -0.64)	0.47 (0.43, 0.51)
May	**-1.10** (-1.28, -0.92)	0.38 (0.34, 0.43)
June	**-1.22** (-1.41, -1.02)	0.50 (0.45, 0.55)
July	-0.78 (-1.11, -0.38)	0.56 (0.47, 0.71)
August	0.48 (0.33, 0.61)	0.44 (0.39, 0.47)
September	0.11 (-0.07, 0.28)	0.42 (0.37, 0.46)
Year (III-IX)	**-0.75** (-0.85, -0.65)	0.32 (0.30, 0.36)

Figure 1. The observing platform at the Polish Polar Station Hornsund (~~77°00’N, 15°33’E~~77º00’N, 15º33’E). (Photo by P. Sobolewski).

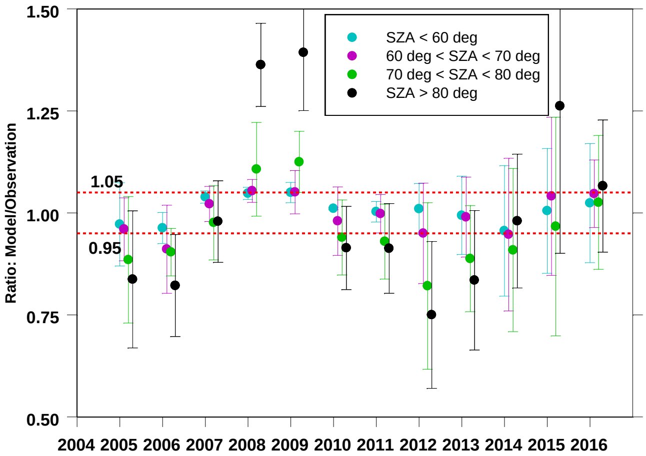

Figure 2. The calibration constants for the Kipp and Zonen UVS-AE-T ~~biometer~~instrument in the period 2005-2016 derived from a comparison of the modeled clear sky doses with the observed ones in cloudless conditions for four solar zenith angle (SZA) ranges

~~9.~~

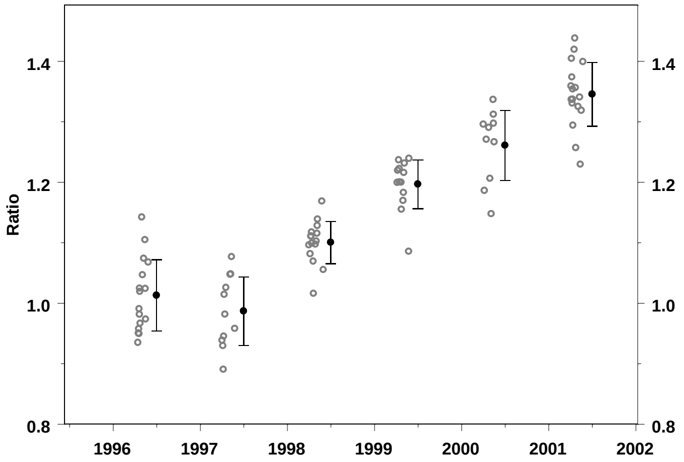

Figure 3. The calibration constants for the prototype of Solar Light instrument in the period 1996-2001 derived from a comparison of the modeled clear-sky doses with fixed aerosols optical depth (0.16 at 340 nm) with the observed ones in cloudless conditions in the March-June period. Full circles and bars represent the mean value and ± 1 standard deviation range in the selected year.

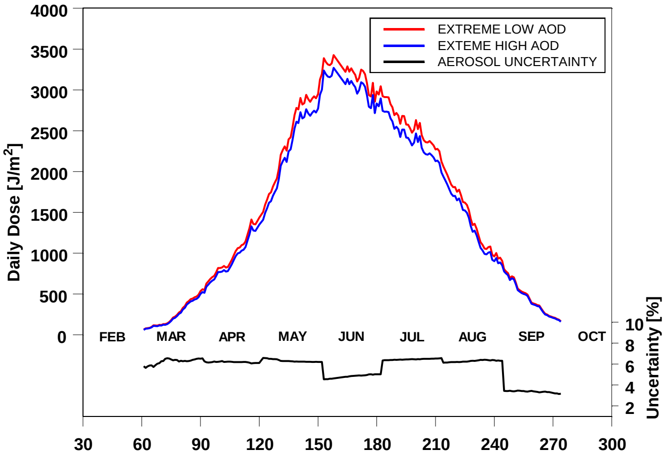

Figure 4. **Radiative model simulations of daily erythemal doses for clear-sky conditions in 1996 using observed total ozone, surface albedo, and extreme high and low aerosols monthly optical thickness derived from all CIMEL sunphotometer measurements at Hornsund in the period 2004-2016. Uncertainty is calculated as difference between the extreme daily doses expressed in percent of the mean daily dose.**

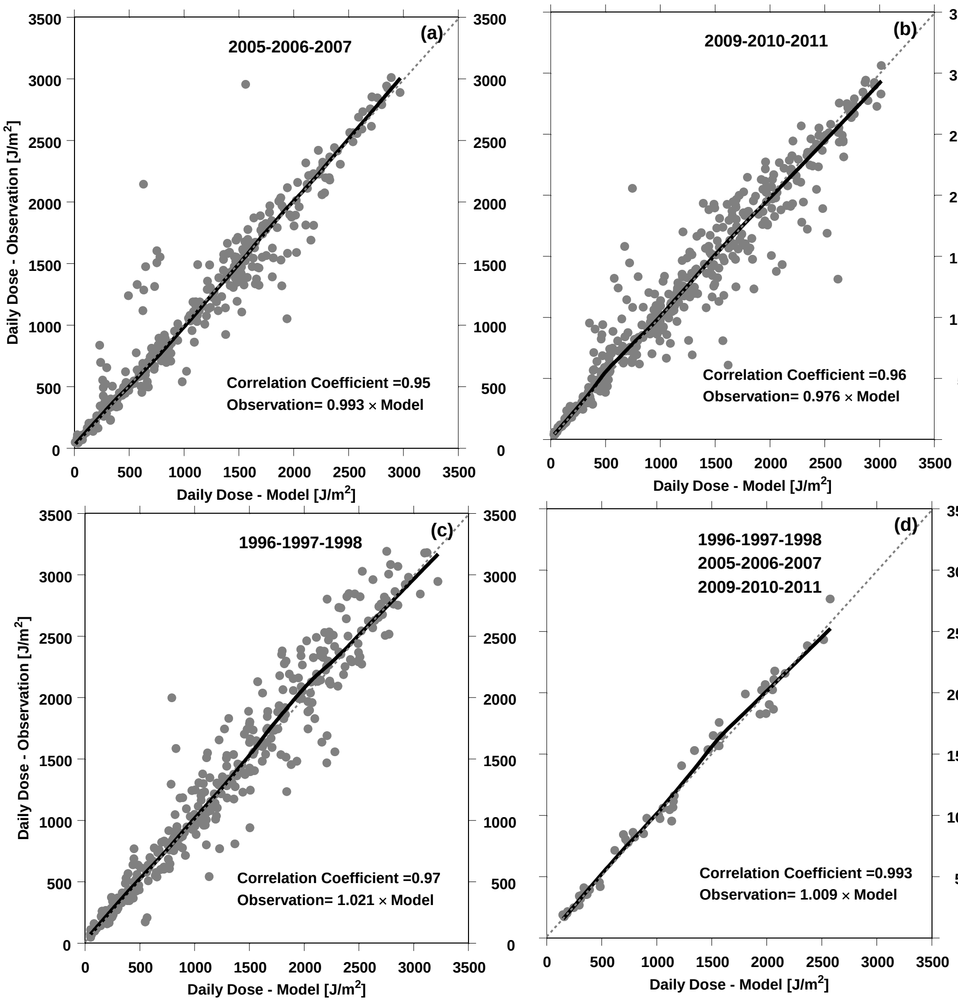

Figure 5. The observed versus modeled erythemal doses: (a) daily doses for the period 2005-2006-2007, (b) daily doses for the period 2009-2010-2011, (c) daily doses for the period 1996-1997-1998, (d) monthly mean daily doses for the ~~period~~periods 1996-1997-1998, 2005-2006-2007, and 2009-2010-2011.

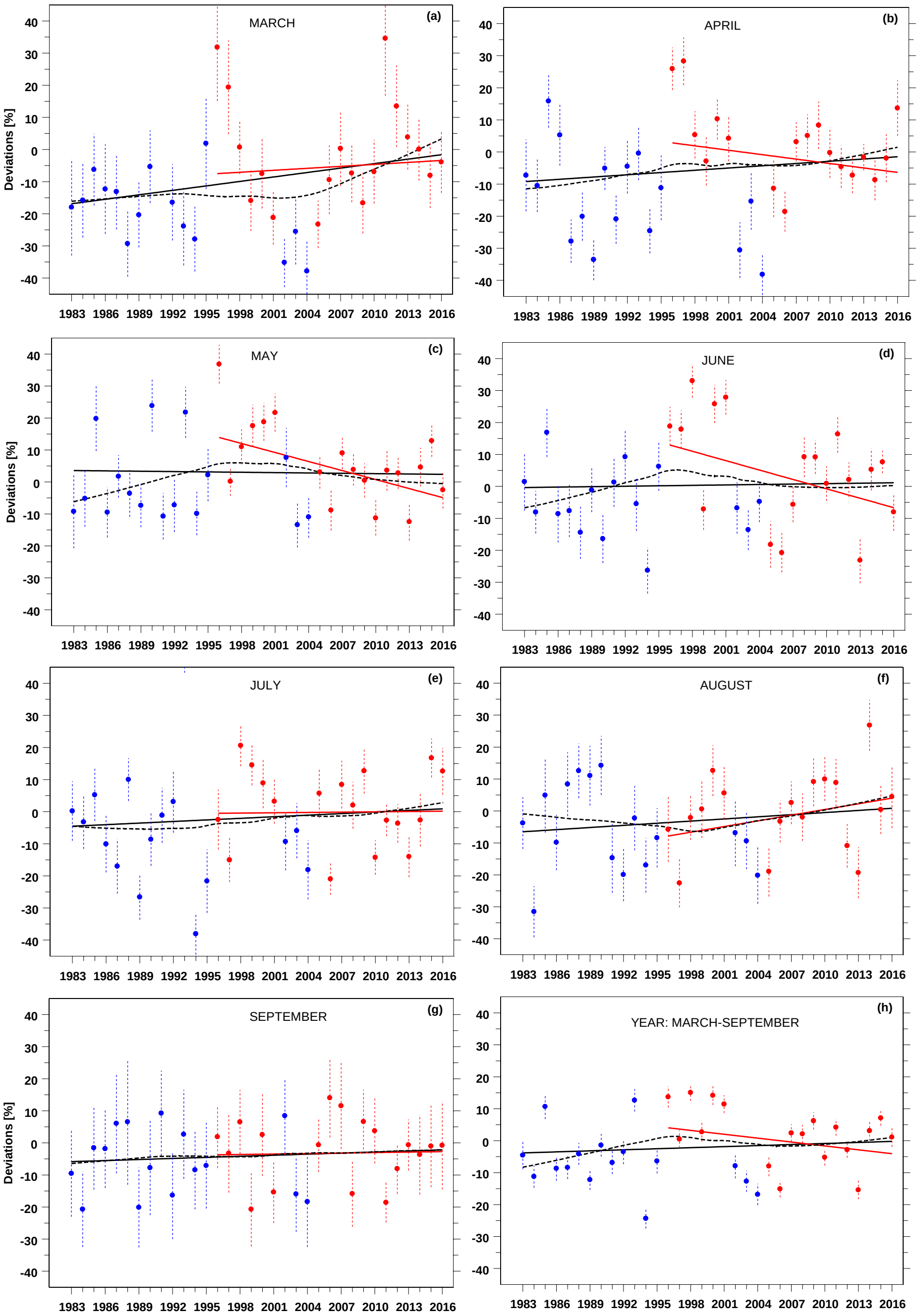

Figure 6. Time series of normalized deviations of monthly means of daily doses and normalized yearly ~~fractional deviations~~sum of ~~erythemal~~daily doses~~ consisting of~~: observed ~~(open~~values (red circles~~) and modeled (full~~), reconstructed values (blue circles~~) data. The solid curve~~). Vertical line shows +/- 1 standard deviation. Straight line represents ~~the smoothed data by the LOWESS low-pass filter.~~ linear regression line. Dashed curve represents smoothed values by LOWES smoother (Cleveland, 1979).

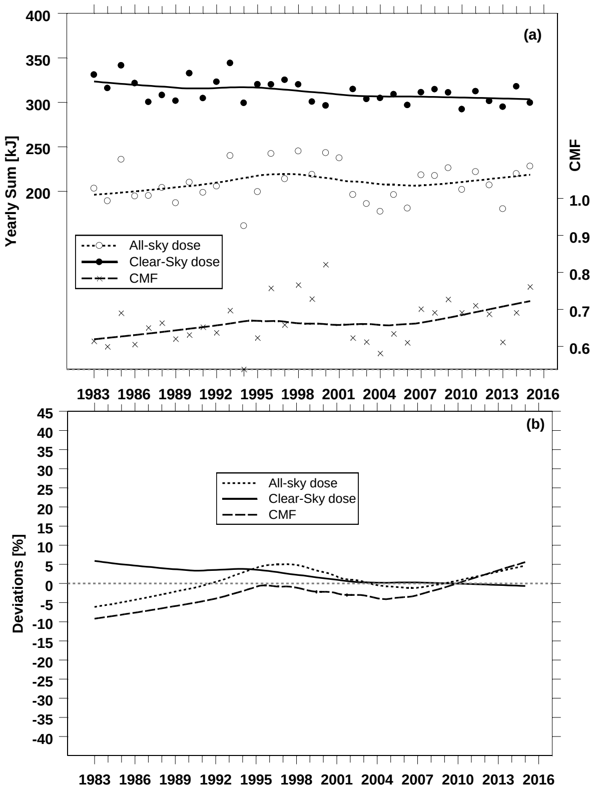

Figure 7. (a) yearly (March-September) daily sum of erythemal doses in the period 1983-2016: modeled clear-sky values (full circles), observed and modeled all-sky values (open circles), and cloud modification factor (CMF, crosses), (b) normalized smoothed deviations (by LOWES smoother, Cleveland, 1979) of the yearly values shown in Fig.7a.

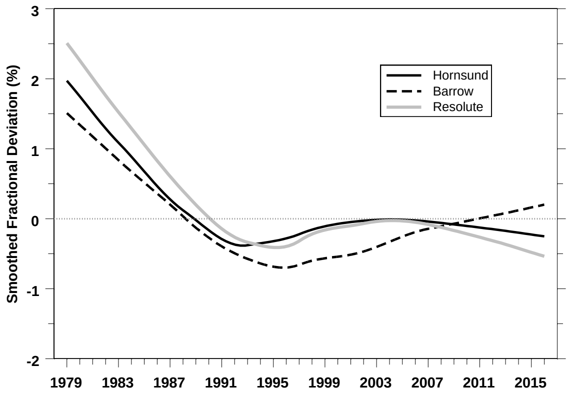

Figure 8. **Smoothed time series (~~1979-2016~~by LOWES smoother, Cleveland, 1979) of ~~the total ozone~~ annual fractional deviations of mean total ozone in period May-August for the period 1979-2016 at ~~Barrow (Alaska, the United States),~~ Hornsund (Svalbard), Barrow (Alaska, United States), and Resolute (Cornwallis Island, Canada~~) averaged over the period May-June-July-August.~~).**