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Evaluation of the ECHAM family radiation codes performance in the representation of the solar signal

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Abstract

Solar radiation is the main source of energy for the Earth's atmosphere and in many respects defines its composition, photochemistry, temperature profile and dynamics. The magnitude of the solar irradiance variability strongly depends on the wavelength making difficult its representation in climate models. Due to some deficiencies of the applied radiation codes several models fail to show a clear response in middle stratospheric heating rates to solar spectral irradiance variability, therefore it is important to prove reasonable model performance in this respect before doing multiple model runs. In this work we evaluate the performance of three generations of ECHAM (4, 5 and 6) radiation schemes by comparison with the reference high resolution libRadtran code. We found that both original ECHAM5 and 6 solar radiation codes miss almost all solar signal in the heating rates in the mesosphere. In the stratosphere ECHAM5 code reproduces only about a half of the reference signal, while representation of ECHAM6 code is better – it maximally misses about 17 % in the upper stratosphere. On the basis of the comparison results we suggest necessary improvements of the ECHAM family codes by inclusion of available parameterizations of the heating rate due to absorption by oxygen (O_2) and ozone (O_3). Both codes with the introduced parameterizations represent the heating rate response to the spectral solar irradiance variability simulated with libRadtran much better without substantial increase of computer time. The suggested parameterizations are recommended to apply in the middle atmosphere version of the ECHAM-5 and 6 models for the study of the solar irradiance influence on climate.

1 Introduction

Although solar ultraviolet radiation (SUV) comprises only a couple of percent of the total solar irradiance (TSI), it plays a crucial role, largely defining the structure of the middle atmosphere. While the radiation in visible and infrared spectral ranges of the solar spectrum propagates through the atmosphere without significant absorption, almost all solar ultraviolet irradiance below 300 nm is absorbed by ozone and oxygen above the troposphere and represents the main source of energy in these regions. Furthermore, the SUV is strongly modulated by the solar rotational and 11 yr solar cycles. Whereas the variability of TSI during 11 yr solar activity cycle is around 0.1 %, SUV variations can be more than 10 times higher. Moreover, recent measurements by the SORCE (SOLar Radiation and Climate Experiment) suggest a SUV variability significantly higher than all previous estimates (Ermolli et al., 2103 and references therein).

Changes in SUV irradiance lead to significant ozone, temperature, and zonal wind responses in the stratosphere and mesosphere, which has been shown in many modeling and observation data analysis studies (Hood and Soukharev, 2012; Austin et al., 2008; Gray et al., 2010; Haigh et al., 2010; Shapiro et al., 2013). The SUV is not considered as a direct radiative forcing for troposphere and surface, since it does not reach these altitudes, but there are indirect effects of solar irradiance variability, which are communicated downward in the so-called “top-down” mechanism: the modulation of stratospheric temperatures leads to dynamical feedbacks by affecting Brewer–Dobson circulation and hence the stratosphere-troposphere exchange, resulting in decadal climate changes in the lower atmosphere (Solomon et al., 2007; Gray et al., 2010; Ermolli et al., 2013).

A comprehensive study of the entangled possible effects of solar variability requires chemistry-climate models (CCMs), the main instruments which are capable to take into account many atmospheric chemical, dynamics and temperature feedbacks. To this end, CCMs should contain a correct representation of radiative transfer in the atmosphere. Accurate codes for radiative transfer solution exist, e.g. LibRadtran (Mayer and Kylling, 2005), but they are too computationally expensive to be commonly used in global models. Therefore, different parameterizations have been designed to provide a compromise between accuracy and efficiency. Since most CCMs arise from global circulation models (GCMs), which are primarily tropospheric models, their radiation schemes carefully treat the longwave part of the spectrum, whereas the representation of the solar irradiance is coarse, approximating the entire UV/visible spectral range by 1 or 2 spectral bands and not considering wavelengths shorter then ∼ 250 nm. The evaluation of the radiation codes performed in the framework of SPARC CCMVal-2 project (Forster et al., 2011; SPARC CCMval, 2010) have shown that only a few CCM radiation codes are capable of reproducing the magnitude and vertical profile of heating rate differences between solar minimum and maximum, which in turn directly depends on the treatment of the spectral resolution in the codes.

As was pointed out by Forster et al. (2011), a good representation of the solar signal can be obtained by increasing the number of spectral intervals. However, such an approach implies an increase of computational costs, which is a sensitive issue for already numerically expensive global CCMs (Nissen et al., 2007; Kubin et al., 2011). Nissen et al. (2007) increased the number of spectral intervals in ECHAM-5 from 6 to 49 and found out that it improves the accuracy of solar variability induced changes in heating rates by 20 % in comparison to 6-band scheme, while the CPU time taken by parameterization was increased by roughly factor of 8. Another way is to apply the parameterisations for the missed extra heating due to solar UV enhancement based on Beer–Lambert law (Strobel, 1978; Nicolet, 1985; Zhu, 1994). This method has been already used in MAECHAM-4 (Egorova et al., 2004) and CMAM (Fomichev et al., 2004) in order to parameterize the solar signal in missing and/or underrepresented spectral intervals and demonstrated good accuracy combined with very good efficiency. The most recent way to obtain satisfying results even with relatively small number of spectral intervals is to use a completely different approach of incorporating non-gray gaseous absorption based on the so-called "correlated k-distribution" method (e.g. Fu and Liou, 1992). This method exploits the cumulative probability of the absorption coefficient in a spectral interval to replace wavenumber as an independent variable. Such a code is a part of ECHAM6, but its performance in respect to solar UV influence has not been checked which limits its application for solar-climate studies.

In this paper we evaluate the performance of the ECHAM family radiation codes in reproducing the heating rate response to SUV variability through the detailed comparison with the reference libRadtran code. We demonstrate the weaknesses of the ECHAM family solar radiation codes and suggest possible ways to improve their performance.

2 Description of the original ECHAM solar radiation codes

ECHAM is a family of atmospheric general circulation models developed by the Max Planck Institute for Meteorology (MPI-M) in Hamburg, Germany. The original ECHAM model branched from an early release of the ECMWF (European Center for Medium Range Weather Forecasts) model to enable climate studies (Simmons et al., 1989). It covered only the lower part of the atmosphere up to the 25 hPa level. Therefore, its solar radiation scheme (Fouquart and Bonnel, 1980) inherited by ECHAM was quite crude with respect to shortwave part of spectrum, namely it had only one band covering the UV and visible parts of the solar spectrum (250–680 nm), considered only absorption by O_3 and used TSI as input, i.e. change of the TSI was equally distributed among all spectral bands, and high shortwave variability was missed. The weakness of this scheme in representing the solar signal was demonstrated several times in standalone form (Solomon et al., 2007; Forster et al., 2011) and within CCMs (Egorova et al., 2004; Cagnazzo et al., 2007; Nissen et al., 2007): basically it has almost negligible radiative response to solar irradiance changes due to the lack of wavelength dependence within the broad band. This scheme had been used in ECHAM until it was upgraded by Cagnazzo et al. (2007) for ECHAM5 by extending the number of spectral intervals from 1 in UV/VIS to 3 with 2 covering the UV range (Table 1) and switching to SSI as input. This allowed reproducing about half of the reference heating rate differences (Forster et al., 2011). However, this scheme still does not contain any O_2 absorption. Since ECHAM5 code (E5) is the direct extension of the ECHAM4 code (E4), the further discussion will refer only to ECHAM5 code.

One of the main improvements of ECHAM6 compared to previous versions was adaptation of another solar radiation scheme, namely the Rapid Radiation Transfer model optimized for general circulation modeling studies (E6) (Stevens et al., 2013).

This scheme is ~ 10 times faster than previous schemes, it uses the correlated k-distribution method, and solar irradiance is calculated over a prescribed number of pseudo wavelength or g-points regarding to the absorbing features of certain wavelengths. Quadrature is performed over 112 g-points in the shortwave part of the spectrum, which then are grouped to 14 bands with 3 bands in UV (Table 1). The model has three UV spectral bands and considers oxygen absorption. However, the lowest wavelength boundary is 200 nm (Iacono et al., 2008), so that important features such as the solar Lyman-α (121.6 nm) line and part of the Schumann–Runge oxygen absorption band are not taken into account.

3 Validation

To demonstrate the capabilities of the original codes we performed calculations with stand-alone versions of E5 and E6 for the tropical standard atmosphere, with solar zenith angle equal to 10° and for solar minimum and maximum conditions. To validate the original schemes we compare all our calculations to the reference code LibRadtran (Mayer and Kylling, 2005), which has shown high accuracy in a number of intercomparison studies. For the 120–440 nm range LibRadtran considers more than 16 000 wavelengths resolving in detail all relevant spectral features. Figure 1 shows the input information that we used to simulate solar variability: the solar irradiance changes, i.e. the relative difference between the irradiances during solar maximum and minimum conditions, and resulting solar-induced ozone changes. Irradiance spectrum for solar minimum and maximum conditions was calculated with Code for Solar Irradiance (Shapiro et al., 2010) following the approach presented in Shapiro et al. (2011). The solar minimum and maximum conditions correspond to sunspot numbers equal 0 and 120, respectively. We note that the spectral profile of the solar irradiance variability on the 11 yr time scale yielded by the approach presented in Shapiro et al. (2011) agrees well with other reconstructions (Ermolli et al., 2013). Figure 1 shows that the solar irradiance variability is a very sophisticated function of wavelength. Resulting ozone changes were estimated from a composite of observational data (Soukharev and Hood, 2006; Austin et al., 2008; SPARC CCMVal, 2010).

Figure 2 illustrates the heating rates calculated by original E5 and E6 schemes and by LibRadtran for solar maximum conditions and heating rate differences between solar maximum and minimum caused only by the solar irradiance changes. Figure 2 shows that both schemes highly underestimate heating rate response in the mesosphere. E5 first band covers Schumann–Runge bands (SRB) but since it does not take into account any oxygen absorption it misses all solar response in the high altitudes and underestimates absolute values up to 5 K day^{-1} in the upper mesosphere. E6 considers absorption by oxygen and shows adequate absolute values in the mesosphere, but its shortest wavelength limit is only 200 nm and therefore the radiative heating in Lyman-a line (LYA) and most part of SRB, important for mesosphere, are also missed.

First band in E5, which contains also Herzberg continuum and part of Hartley band, is reproduced well in the upper stratosphere, but the contribution from the second E5 band containing Hartley (HAR) and Huggins (HUG) bands is highly underestimated. In total, E5 reproduce about a half of solar signal compare to the reference model, which is consistent with previous comparison studies (Forster et al., 2011; SPARC CCMval, 2010). E6 in the middle atmosphere shows much better performance. It misses only about 0.08 K day^{-1} in the upper stratosphere due to underestimation in HAR. Underestimation of both schemes in HAR-HUG bands can be explained by a high spectral inhomogeneity of the solar irradiance variability in these regions (see Fig. 1), which is smoothed in integrated fluxes. In case if higher UV variability suggested by SORCE (Ermoli et al., 2013) is correct, absolute values of missed solar signal in heating rates would be respectively higher, providing more discrepancy to all feedbacks related to solar irradiance changes.

Also it should be noted that underestimation of solar signal in both schemes takes place while the absolute values in the same areas are overestimated. In E5 it is about 2 K day^{-1} in the altitude of maximum heating due to overestimation in the same band which underestimates solar signal. In E6 there is 12 % shift within all altitudes lower than 65 km, which can be the the results of the fact that this scheme was adjusted to another LBL model which could differ from LibRadtran.

4 Implementation of the parameterizations

To improve the representation of the solar signal we have implemented the parameterizations of the heating rates in the spectral regions, where we have found problems in the previous section. All parameterizations use the same approach based on Strobel (1978), deriving heating rates H from the atmosphere transmissivity of O_2 and O_3, using integrated fluxes of the solar radiation F as well as the ozone and oxygen number ($[O_2][O_3]$) and column (N_2, N_3) density. For LYA we used parameterization of Nicolet (1985)

$$H_{\text{lya}} = [O_2]\sigma_{\text{lya}} F_{\text{lya}} T_{O_2,\text{lya}}, \tag{1}$$

where mean LYA absorption cross-section $\sigma_{\text{lya}} = 1.725 \times 10^{-18}/N_2^{0.1175}\ \text{cm}^2$ and transmissivity $T_{O_2,\text{lya}} = \exp(-2.115 \times 10^{18} N_2^{0.8855})$.

From Zhu (1994) we used for SRB

$$H_{\text{srb}} = \frac{[O_2] X_{\text{srb}} F_{\text{srb}}}{\left(1 + \frac{4\sigma_{\text{srb}}}{\pi y_{\text{srb}}} N_2\right)^{\frac{1}{2}}} \exp\left(-\frac{\pi y_{\text{srb}}}{2}\left[\left(\left(1 + \frac{4\sigma_{\text{srb}}}{\pi y_{\text{srb}}} N_2\right)^{\frac{1}{2}}\right) - 1\right]\right), \tag{2}$$

where $\sigma_{\text{srb}} = 2.07 \times 10^{-24}\ \text{m}^2$, $X_{\text{srb}} = (N_{2,\text{top}}/N_2)^{0.3}\sigma_{\text{srb}}$ and $y_{\text{srb}} = 0.0152$.

And for HAR and HUG we used

$$H_{\text{har}} = [O_3]\sigma_{\text{har}} F_{\text{har}} \exp(-\sigma_{\text{har}} N_3), \tag{3}$$

$$\begin{aligned} H_{\text{hug}} = \frac{[O_3]}{M N_3} & \left(F_{1,\text{hug}} + (F_{2,\text{hug}} - F_{1,\text{hug}})\right) \exp\left(-\sigma_{\text{hug}} N_3 \exp(-M\lambda_{\text{long}}\right) \\ & - F_{2,\text{hug}} \exp\left(-\sigma_{\text{hug}} N_3 \exp(-M\lambda_{\text{short}})\right)\right), \end{aligned} \tag{4}$$

where $M = 0.01273\,\text{Å}^{-1}$, $(\lambda_{\text{short}}, \lambda_{\text{long}}) = (2805, 3015)\,\text{Å}$, $(\sigma_{\text{har}}, \sigma_{\text{hug}}) = (8.7\times10^{-22}, 1.15\times10^{-6})\,\text{m}^2$ and $F_{1,\text{hug}}$ and $F_{2,\text{hug}}$ are the integrated solar fluxes in the 280.5–305.5 and 305.5–360 nm ranges.

First, we have performed separate tests of these parameterizations which have shown that parameterizations for HAR and HUG are in a good agreement with libRadtran. However, for LYA and SRB according to the test results we have changed σ_{lya} and added altitude dependent x_{srb}. Then, since we use parameterizations to restore only a part of the heating rates variability, we have calculated scaling coefficients for each of the applied parameterization separately for E5 and E6 and implemented them to the original ECHAM codes. Since E5 does not have original absorption by oxygen and therefore underestimates absolute values in the mesosphere, heating parameterizations for LYA and SRB have been added to the original scheme using full flux integrated within specific band in order to improve the scheme in respect to the calculation of the absolute heating rates. However to avoid overestimation in the upper stratosphere, related to the fact that original codes partially treat O_3 absorption in Hartley and Huggins bands, we recommend to use not the full flux, but the difference between solar minimum and maximum. The same should be done for LYA and SRB in E6 to avoid overestimation in the mesosphere, since the absolute values in the mesosphere are already reproduced well. In global models this can be done choosing the year with the lowest SSI in which all extra heating will be equal to zero, and then for calculations in all other years one should use the SSI difference from this “grand minimum” year.

4.1 Changing UV

Figure 3 shows the improvement of the original schemes performance due to implemented parameterizations of O_2 and O_3 absorption calculated under changing UV and constant ozone conditions for tropical standard atmosphere and solar zenith angle equal to 10°. Implemented parameterizations of O_2 absorption allowed us to get very good agreement in solar variability induced heating rate changes with reference model in the mesosphere. And implemented parameterizations of O_3 absorption resulted in a very good agreement in the stratosphere. These parameterizations take negligible computer time compare to the time taken by radiation schemes and another advantage is that the inclusion of these parameterizations does not change much the absolute values of the heating rates and therefore does not require any retuning of the original codes.

Results of calculations with 4 other different atmosphere models (midlatitude summer, midlatitude winter, subarctic summer, subarctic winter (McClatchey et. al., 1972)) and 3 solar zenith angles (10, 40, 70°) presented in Fig. 4 have shown that parameterizations work good for all conditions, and applied scaling coefficients do not strongly depend on position of the Sun and latitude and can be used in models with high confidence. It should be noted that for other radiation schemes and other SSI data sets these coefficients will differ and have to be carefully calculated regarding to specific features of each scheme.

4.2 Changing ozone

For previous calculations we have used only changing UV fluxes with constant ozone profile, but the ozone profile can also be modulated by solar irradiance changes and these two features are closely related. To check the parameterization applicability taking into account the ozone feedback we have also calculated the heating rate response to the solar induced ozone changes keeping the UV fluxes unchanged. Results of these calculations are shown in Fig. 5. In this case original codes work well, and since we use irradiance difference to calculate extra heating, we do not affect heating rates by ozone changes, because extra-heating rates in this case are equal to zero. Total heating rate (UV + ozone) also looks good compare to the reference model.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

5 Conclusions

We have evaluated the performance of the ECHAM5 and ECHAM6 radiation codes in the representation of the solar UV variability induced changes in the heating rates. Both schemes have shown high underestimation in the mesosphere, while in the stratosphere ECHAM6 code results are much better than ECHAM5, but still some of the solar signal is missed compared to the reference libRadtran model. We suggested an accurate method to correct revealed problems by the implementation of the parameterizations of extra heating due to oxygen and ozone absorption. This allowed us to get very good agreement with reference model in the representation of solar signal in the mesosphere and stratosphere without significant increase of computational time. This method does not require tuning of the original codes, but it only provides the solar induced addition to original heating rates. Therefore this method is suitable for any other radiation scheme to correct the solar signal in heating rates due to missing or underrepresented spectral intervals. It should be noted that the coefficients of the parameterizations should be re-evaluated regarding to the features of any particular scheme. For more detailed information about implementation please contact the first author.

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Table 1. ECHAM radiation schemes spectral intervals and main absorbers in UV part of spectrum.

Model	SW intervals (nm)	Main absorbers
ECHAM 4	250–680	O_3
ECHAM 5	185–250	O_3
	250–440	
ECHAM 6	200–263	O_3, O_2
	263–345	
	345–441	

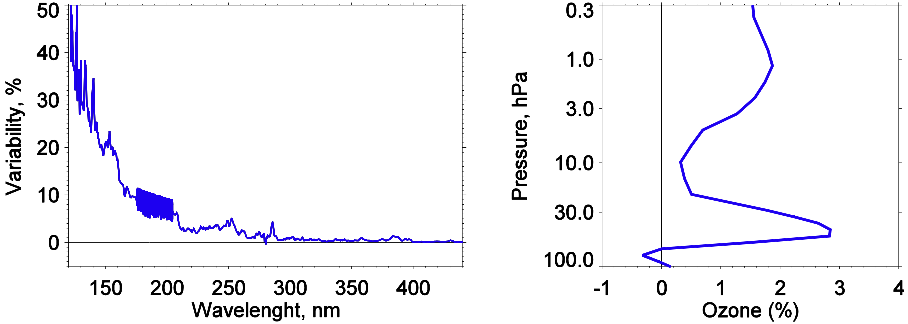

Fig. 1. Variability of solar irradiance in the 120–440 nm wavelength range calculated by COSI (left) and resulting ozone response from a composite of observational data from Soukharev and Hood (2006) and Austin et al. (2008) (right).

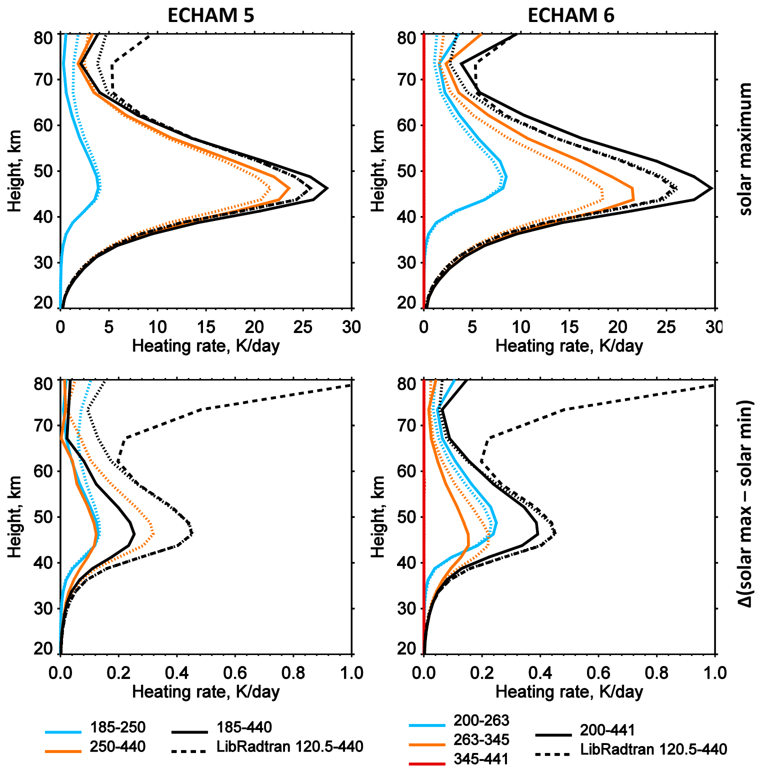

Fig. 2. Shortwave heating rates in $\mathrm{K\,day^{-1}}$ for tropical standard atmosphere and solar zenith angle equal to 10° calculated by E5 (left pictures) and E6 (right pictures). Top panels: absolute values during solar maximum. Bottom panels: differences between minimum and maximum of the 11 yr solar cycle. Solid lines: ECHAM results. Dotted lines: LibRadtran results for the same spectral intervals. Different spectral intervals are designated by colours. Black dashed line: LibRadtran results for 120–440 nm (i.e. including shortest wavelengths > 120 nm).

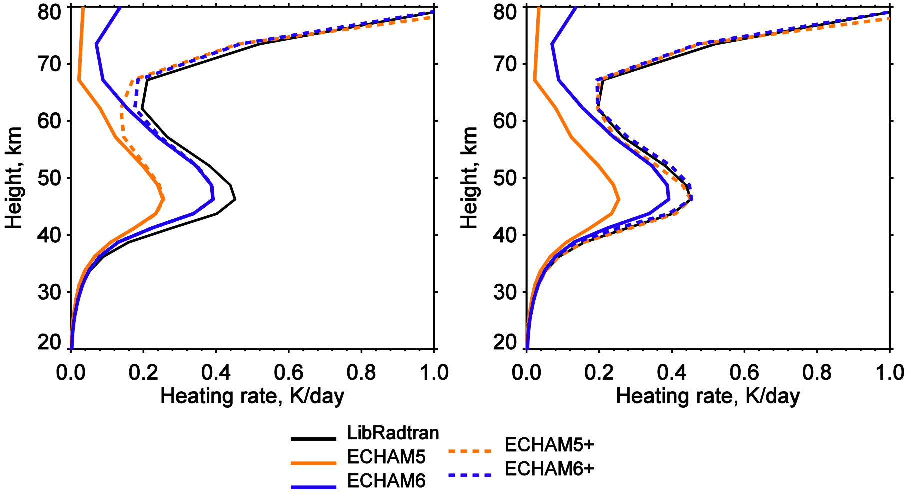

Fig. 3. Shortwave heating differences of the 11 yr solar cycle (solar max minus solar min) in $\mathrm{K\,day^{-1}}$ for tropical standard atmosphere and solar zenith angle equal to 10° in case of UV only variability and constant ozone profile. Coloured solid lines: results from original codes. Black solid line: LibRadtran results for reference. Dashed lines: results from improved parameterizations. Left panel: improvement due to implementation of O_2 absorption parameterization only. Right panel: O_2 and O_3 absorption parameterization.

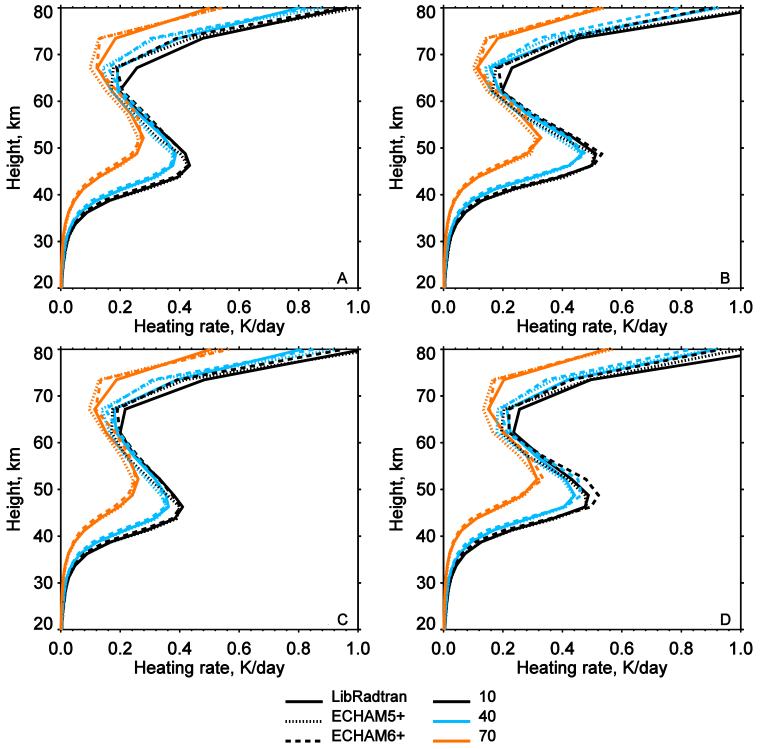

Fig. 4. Shortwave heating rate differences (solar may minus solar min) of the 11 yr solar cycle in $\mathrm{K\,day^{-1}}$ for 4 standard atmospheres: **(A)** – midlatitude summer, **(B)** – midlatitude winter, **(C)** – subarctic summer, **(D)** – subarctic winter. Solid lines: LibRadtran. Dashed lines: E6+ (E6 including corrections to 120 nm). Dotted lines: E5+. Colours: different solar zenith angles (black 10°, blue 40°, orange 70°).

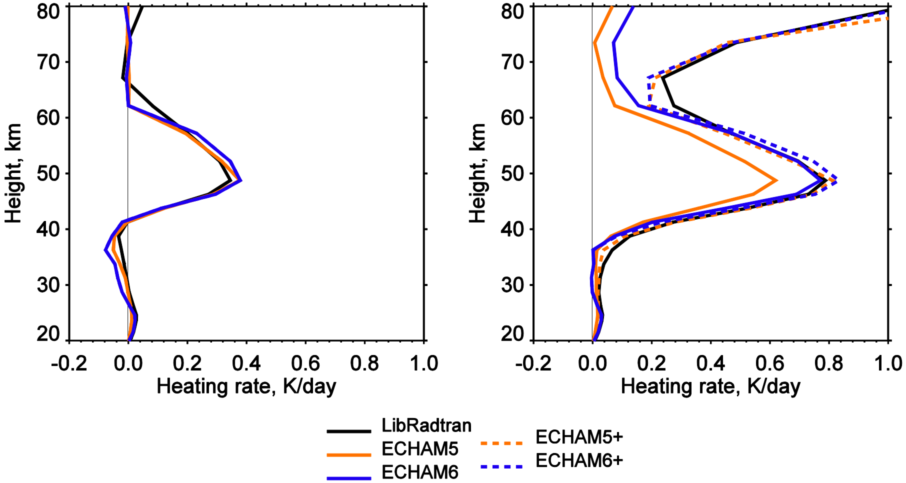

Fig. 5. Shortwave heating rate differences (solar max minus solar min) of the 11 yr solar cycle in $\mathrm{K\,day^{-1}}$ for tropical standard atmosphere and solar zenith angle equal to 10°. Left panel: including only ozone changes. Right panel: UV + ozone changes. Original codes results are denoted by solid lines, improved codes results – by dashed lines.