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Atmospheric Chemistry and Physics Discussions

Clear sky UV simulations in the 21st century based on ozone and temperature projections from Chemistry-Climate Models

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Abstract

We have used total ozone columns and vertical profiles of ozone and temperature from 11 coupled Chemistry-Climate Models (CCMs) to project future solar ultraviolet radiation levels at the surface in the 21st century. The CCM simulations are used as input to a radiative transfer model for the simulation of the corresponding future UV irradiance levels under cloud free conditions, presented here as time series of monthly erythemal irradiance received at the surface during local noon covering the period 1960 to 2100. Starting from the first decade of the 21st century, the surface erythemal irradiance decreases globally as a result of the projected ozone recovery, at rates which are larger in the first half of the 21st century, compared to the period up to 2100. The magnitude of these decreases varies with latitude and is more pronounced at areas where ozone has been depleted most considerably after 1980. Over midlatitudes surface erythemal irradiance decreases between 5 and 15% by 2100 relative to 2000, while at the southern high latitudes these changes are twice as much. Climate change may affect future cloudiness, surface reflectivity and tropospheric aerosol loading, the effects of which are not included in this study. Therefore, the actual changes in future UV radiation are likely to change accordingly in the areas affected.

1 Introduction

Stratospheric ozone depletion has been one of the first priority environmental concerns in the past three decades, due to the consequent increases in solar ultraviolet radiation reaching the earth's surface (e.g., Herman et al., 1999; Kerr et al., 2003), and related skin cancer risks (e.g., Slaper et al., 1996). Observations suggest that the concentrations of the ozone depleting substances in the atmosphere have started to decrease as a result of the measures taken under the Montreal Protocol and its Amendments and Adjustments (WMO, 2007). Future levels of surface UV radiation will depend on the evolution of various factors, known to influence the propagation of solar UV radiation in

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the atmosphere. Some of these factors, such as ozone, clouds and surface reflectivity are included in the standard output products of coupled Chemistry-Climate Models (CCMs) (e.g., Eyring et al., 2006, 2007), whereas the prediction of future aerosol levels and their optical characteristics, that are very important in the attenuation of UV radiation, is a topic of ongoing research. Under clear skies, the most important factor affecting UV radiation is stratospheric ozone, followed by tropospheric ozone and aerosols, and to a lesser extent, by SO_2, NO_2 and other trace gases in urban atmospheres. The effects of ozone depend on its column abundance, but also on its vertical distribution and the corresponding temperature at each level (Lapeta et al., 2000; Kazantzidis, 2004; McKenzie et al., 2003). Prediction of future surface UV levels can be achieved through radiative transfer model calculations using the above-mentioned factors as input (Bais et al., 2007). Erythemally weighted irradiance (McKinlay and Diffey, 1987) represents a broad spectral region in the ultraviolet and as it provides a direct link to the harmful biological effects of UV radiation, it was chosen as a suitable parameter to quantify future UV levels.

In order to simulate surface erythemal irradiance fields in the 21st century, we use here monthly mean total ozone and zonal-mean vertical profiles of ozone and temperature as projected by the CCMs taking part in the CCM Validation Activity (CCMVal) for WCRP's (World Climate Research Programme) SPARC (Stratospheric Processes and their Role in Climate project). All irradiance simulations have been done assuming clear skies, since, at present, no usable information on the future levels of the other UV influencing factors is available.

2 Methodology and data

Total column ozone as well as zonal-mean ozone and temperature profiles used for the UV calculations are taken from the CCMVal reference simulations for the future ("REF2") (Eyring et al., 2005a, 2005b, 2007). The CCMVal standard output of these reference simulations did not include information on clouds. Greenhouse Gases (GHGs)

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in the simulations follow the IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emission Scenarios). (IPCC, 2002) A1B (medium) scenario and surface halogens are prescribed according to the Ab scenario of (WMO, 2003). Sea Surface Temperatures (SST) and Sea Ice Concentrations in the CCM simulations are taken from coupled atmosphere-ocean model projections using the same GHG scenario. REF2 includes only anthropogenic forcings, while natural forcings such as solar variability and external triggering of the quasi biennial oscillation (QBO) are not included. However, AMTRAC and E39C models include future solar forcing and E39C includes also an externally forced QBO. The eleven CCMs considered in this study are listed in Table 1, and further details are given in the listed reference for each model. For two models, there are differences from the description of the runs as given in Eyring et al. (2007): (a) the run from CCSRNIES model has been extended through 2100, and (b) the MRI model group provided new runs with improved transport of chemical species, extended through 2099.

Each model provided the simulated monthly mean total ozone columns in different latitude-longitude reslution and the pertaining vertical distribution of ozone and temperature as zonal monthly means at the same latitudes as for total ozone. Therefore, for total ozone, we calculated first the zonal mean from the monthly means for each model as a function of time and latitude, which were then interpolated linearly to 5° latitude intervals. For the ozone and temperature profiles, the zonal monthly means were also linearly interpolated to 5° latitude intervals, same as for total ozone. E39C has the upper boundary centered at 10 hPa whereas all other models are middle atmosphere CCMs. For E39C we used standard atmospheric ozone and temperature profiles from the AFGL model atmospheres (Anderson et al., 1986) for the appropriate latitude and season above 10 hPa, scaled to match the total ozone column in each grid. Then the radiative transfer model calculations were performed over the appropriate latitudes.

For the UV radiation calculations we used the UVSPEC model of the LibRadTran package (Mayer and Kylling, 2005) with the DISORT solver running with 6 streams (Stamnes and Swanson, 1981; Stamnes et al., 1988). Surface UV reflectivity was set

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to 0.05, except for the polar regions where it was set to 0.7. For the aerosol optical depth, the default profile by Elterman (1968) was used. This profile results in a columnar optical depth of 0.38 at 340 nm, which is certainly not appropriate for all locations and for the future atmospheres, but is more realistic than assuming aerosol free atmosphere. We should note that there is no quantitative information on the evolution of changes in the tropospheric aerosol loading in the 21st century, an issue that was not addressed in the CCMVal simulations used here. Nevertheless, any differences in surface UV irradiance that would arise from the use of another aerosol profile would have been practically the same for all years, as long as the profile and the resulting optical depth are kept constant throughout the period of study. As far as it concerns the stratosphere, the CCMVal REF2 runs apply fixed sulfate aerosols conditions from 1999 (volcanic free). In this study we are primarily concerned with relative changes in erythemal irradiance throughout the 21st century; hence the changes induced by the constant aerosols are canceled out.

Based on the input data described above (monthly means for ozone and temperature), the erythemal irradiance for the solar zenith angle corresponding to the local noon of the 15th of each month was calculated for all latitudes. All results are presented here as departures (in %) from the corresponding monthly means of the 10-year average of the period 1996 through 2005. Although it would be more meaningful to normalize with the 10-year average of the 1980s, corresponding to pre-ozone depletion conditions, not all CCMs provided data for the period before 2000 for their runs under the REF2 scenario. For the models that provided data starting in year 2000 (E39C, GEOSCCM, and, MAECHAM4CHEM), we calculated the 6-year average from 2000 through 2005. In the case of multiple model simulations the ensemble average was calculated (AMTRAC, E39C, CMAM and WACCM).

In this study we focus on the relative changes of surface UV irradiance in the future rather than in absolute values, the main reason being the difference in absolute total ozone estimates among the CCMs for details see Eyring et al. (2007). Moreover, as the effects from major factors that influence UV radiation, such as clouds, aerosol and

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surface reflectivity are not included in the calculations, it is more realistic to demonstrate the relative effect from changes in ozone, the only parameter that is taken into account.

3 Results and discussion

Figure 1 shows zonal averages of erythemal irradiance departures for the latitude belts of 70° N–55° N, 55° N–25° N, 25° N–25° S, 25° S–55° S, and 55° S–70° S (top to bottom), representing the high and the middle latitudes of the two hemispheres and the tropics. Each line corresponds to the calculation based on the ozone prediction from each different model, as annual mean, in order to eliminate the short term variability caused by the seasonal variations of ozone.

Erythemal irradiance under cloud-free skies is decreasing after the first two decades of the 21^{st} century, with higher rates at the high latitudes of both hemispheres, reflecting the projected ozone recovery for the next few decades (Eyring et al., 2007). The changes in erythemal irradiance in the tropics are smaller in absolute value but still negative. The highest UV levels are seen in the period 1990–2010, when the simulated ozone has reached its minimum. The negative departures of irradiance in the 1980s and early 1990s show that total ozone, as simulated by the CCMs, had not reached its minimum until early 2000s.

The magnitudes of the calculated changes in erythemal irradiance vary significantly, as a result of differences in the predicted ozone columns from the CCMs. After the first quarter of the 21st century the calculated changes start to diverge among the models, and especially after 2050 when only four models (two with multiple runs) are available. The projected reduction of erythemal irradiance towards 2100 ranges between 5% and 15% for midlatitudes and is only a few percent in the tropics. At the southern high latitudes the reductions are about two times larger, ranging between about ~10% and 25%.

The evolution of the zonal-mean erythemal irradiance at the two southernmost latitude belts for the months October–November is seen in Fig. 2. During this season the

Antarctic ozone hole reaches its maximum in area coverage as well as in intensity. The interannual variability of all models is larger at these latitudes. In the 55°–75° S belt, the erythemal irradiance changes become negative for all models after about 2020, and they continue to decrease reaching on the average −25% on year 2100. At the southernmost belt (75°–90° S) the departures become negative for all models about 10 years later and are larger in magnitude (∼−40% in 2100). During this season, the variability in the other latitude belts (not shown here) is much smaller, i.e. similar to the annual patterns presented in Fig. 1. All these changes in erythemal irradiance reflect the corresponding changes in the simulated ozone fields.

In Fig. 3 the relevant changes in surface erythemal irradiance for the northern high and polar latitudes and for late winter – early spring months (March–April) are presented. Again the inter-annual variability of each model is large (larger in the MRI runs) mainly in the polar region, but nevertheless smaller than in the southern hemisphere (note the different ordinates between Figs. 2 and 3). The pronounced negative course that may be attributed to the predicted ozone recovery is seen here since about the mid 2020s, earlier than in the southern hemisphere. These changes are about half in magnitude compared to the changes in the southern hemisphere (Fig. 2).

In the case of multiple model simulations, the variability of the ensembles is larger in the polar regions between the individual runs of each model, mainly in the late winter – early spring months such as October in the Southern and March in the Northern hemisphere. This variability, which becomes much smaller when calculating annual or seasonal averages, remains large until about the mid 2030s and is reduced afterwards, the individual simulations merging to each other. Still, the spread of the ensembles, even in the case of CMAM (which is forced by different SSTs) is smaller than the differences from model to model.

Figure 4 shows the seasonal and latitudinal variability of decadal averages of clear-sky erythemal irradiance changes (%) from the 1996–2005 average for the 2010s and the 2090s. These changes are an ensemble of the changes calculated from the different CCMs. The number of models entering each ensemble depends on the length of each model's simulation. In the 2010s the changes are small, in the order of 1–2% and only in the southern hemisphere spring there are signs of greater reductions. In the 2090s, reductions in erythemal irradiance are seen over the entire globe. These are smallest in the tropical region (the order of a few percent) and become more pronounced as we move poleward. The Antarctic region exhibits the largest reductions (up to 47%) in the austral spring period. All these negative changes are a result of the projected recovery of the ozone layer.

In all calculations presented here we have used total ozone data together with the vertical ozone and temperature distribution as provided by the models. However, even if the analysis is performed using only the total ozone information from each model, i.e. using constant profiles from AFGL scaled to match the total ozone, the difference is very small outside the polar regions. In the polar regions, it is of the order of a few percent, reflected mostly in the year to year variability of each model. The negative correlation between total ozone and UV irradiance reaching the ground is so high, that total ozone might be viewed as the most important component in predicting future UV irradiance levels under clear skies and constant aerosol loading.

Future UV levels are likely to be affected by other factors influenced by climate change, such as cloudiness, aerosols and surface albedo. Therefore the predicted changes towards the middle of the 21^{st} century due only to ozone trends may change substantially, even reverse in sign, depending on season and latitude. According to the Fourth Assessment Report (AR4) of the IPCC (Meehl et al., 2007 and in particular their Fig. 10), cloud cover is predicted to decrease by the end of the 21st century in most of the low and middle latitudes of both hemispheres. This would result in further increases in surface UV radiation at these regions. The opposite is expected at high latitudes and at a few low-latitude regions where cloud cover is predicted to increase. This is supported by preliminary results (not shown here) from an ongoing study on the long term effects of clouds on future surface UV irradiance derived from results of the General Circulation Models used in the IPCC AR4.

A decrease in surface reflectivity in the high to polar latitudes of both hemispheres due to reduction of ice covered areas e.g., Comiso et al., 2008; Overland and Wang, 2007) would result in a decrease of surface UV radiation over these areas, enhancing the projected decrease in surface erythemal irradiance due to ozone.

In conclusion, the projected recovery of the ozone layer during the 21st century in conjunction with the expected changes in other UV influencing factors due to climate changes are expected to modify accordingly the erythemal solar irradiance at the earth's surface leading in general to decreases in areas where the ozone depletion has been most pronounced, like the Antarctica. The magnitude of the UV predictions is associated with large uncertainties due to uncertainties in the projections of all the involved parameters. These uncertainties will become smaller as more quantitative information on the effects of climate change become available.

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Table 1. A summary of the Climate Chemistry Models used in this study. (For details and references see Eyring et al., 2007).

Name of Model	Domain /resolution	No/Type of model runs	Period of simulation	References
AMTRAC	48L, 0.0017 hPa	3×REF2	1990–2099	(Austin and Wilson, 2006; Austin et al., 2006)
CCSRNIES	T42, 34L, 0.01 hPa	1×REF2	1980–2100	(Akiyoshi et al., 2004; Shiogama et al., 2005; Kurokawa et al., 2005)
CMAM	T32, 71L, 0.0006 hPa	3×REF2	1960–2099	(de Grandpré et al., 2000; Beagley et al., 1997)
E39C	T30, 39L, 10 hPa	3×SCN2	2000–2019	(Dameris et al., 2006; Dameris et al., 2005)
GEOSCCM	55L, 0.01 hPa	1×REF2	2000–2099	(Stolarski et al., 2006; Pawson et al., 2008, in press)
MAECHAM4/CHEM	T30,39L, 0.01 hPa	1×REF2	2000–2019	(Manzini et al., 2003; Steil et al., 2003)
MRI	T42,68L, 0.01 hPa	1×REF2	1980–2080	(Shibata et al., 2005; Shibata and Deushi, 2005)
SOCOL	T30,39L, 0.01 hPa	1×REF2	1980–2050	(Rozanov et al., 2005; Egorova et al., 2005)
ULAQ	26L, 0.04 hPa	1×REF2	198–2050	(Pitari et al., 2002)
UMSLIMCAT	64L, 0.01 hPa	1×REF2	1980–2019	(Tian and Chipperfield, 2005)
WACCM (v.3)	66L, 4.5×10^{-6} hPa	3×REF2	1980–2050	(Garcia et al., 2007)

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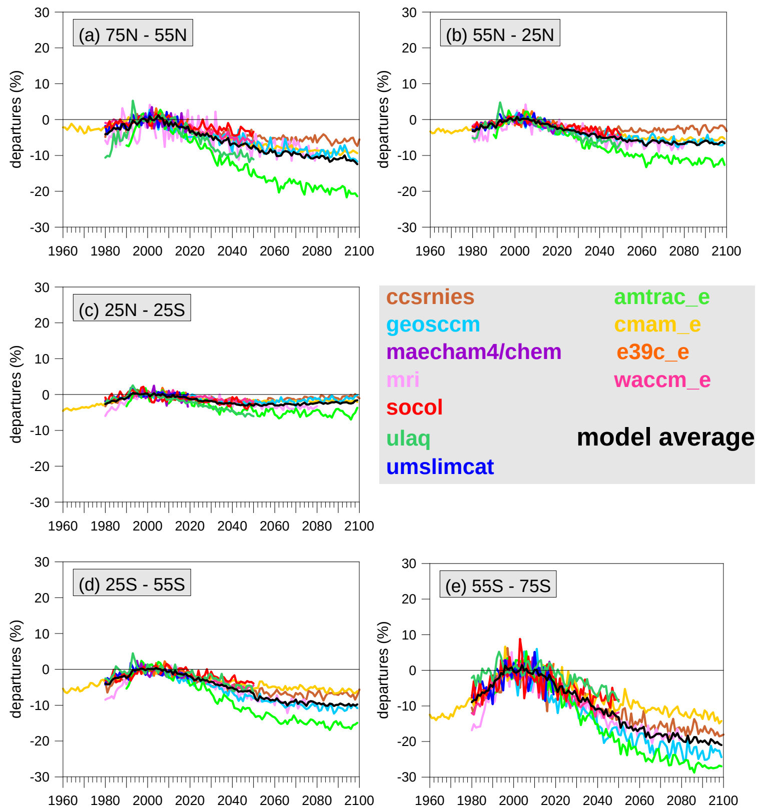

Fig. 1. Annual means of surface erythemal irradiance for five latitude belts. From top left to bottom **(a)** 75° N–55° N, **(b)** 55° N–25° N, **(c)** 25° N–25° S, **(d)** 25° S–55° S and **(e)** 55° S–75° S. The model names (in the corresponding color) are indicated in the center panel. Suffix "_e" indicates ensemble means. The black line represents the model average.

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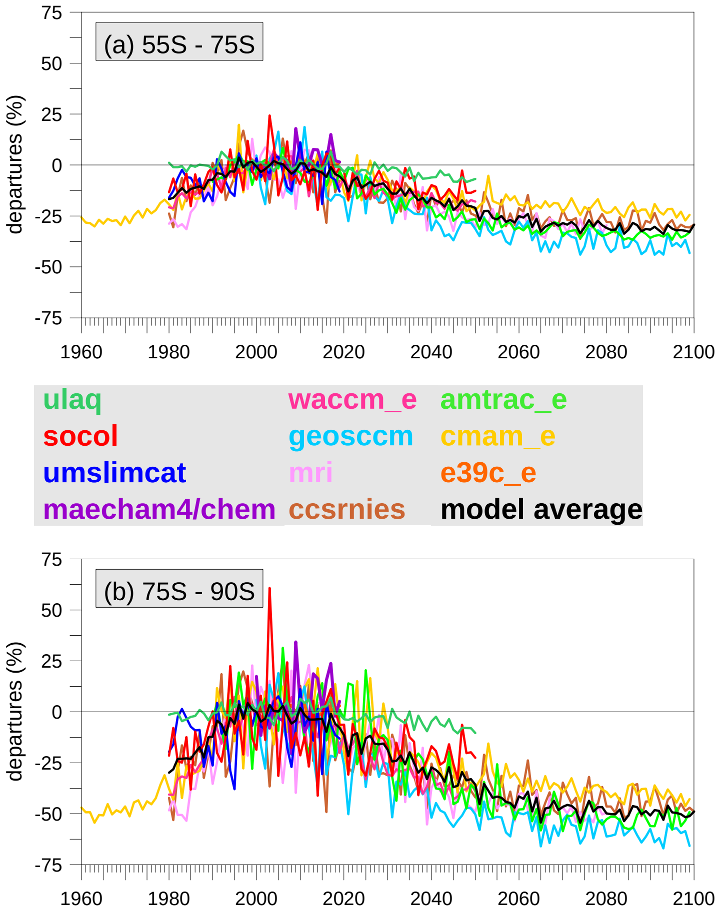

Fig. 2. Average of surface erythemal irradiance for October–November at the two southernmost latitude belts. From top to bottom **(a)** 55° S–75° S and **(b)** 75° S–90° S. Model names as in Fig. 1.

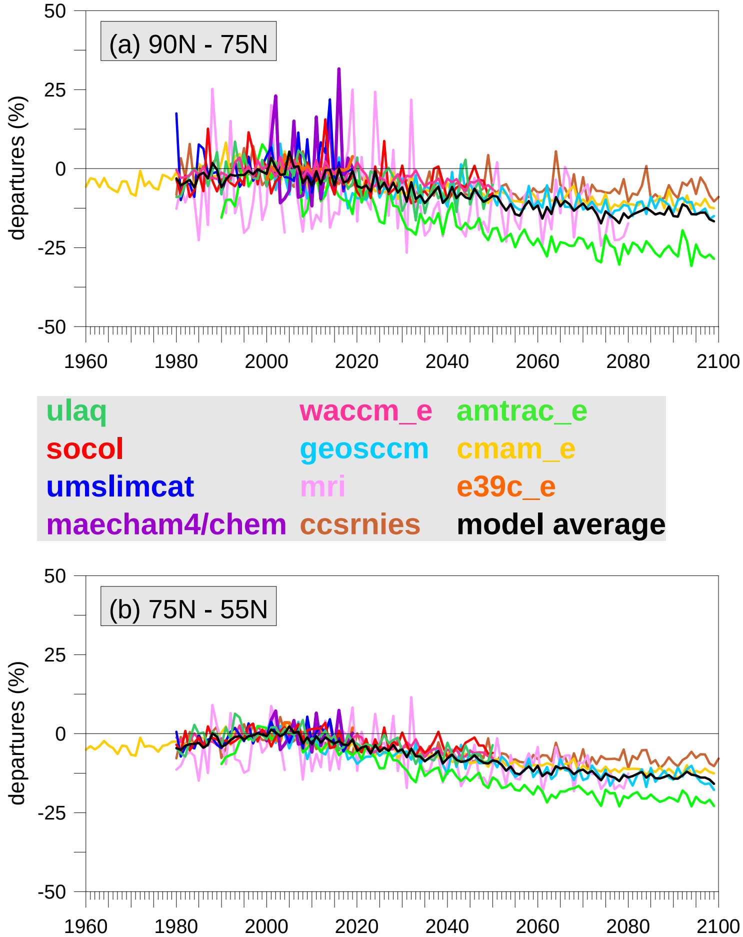

Fig. 3. Average of surface erythemal irradiance for March–April at the two northernmost latitude belts. From top to bottom **(a)** 75° N–90° N and **(b)** 55° N–75° N. Model names as in Fig. 1.

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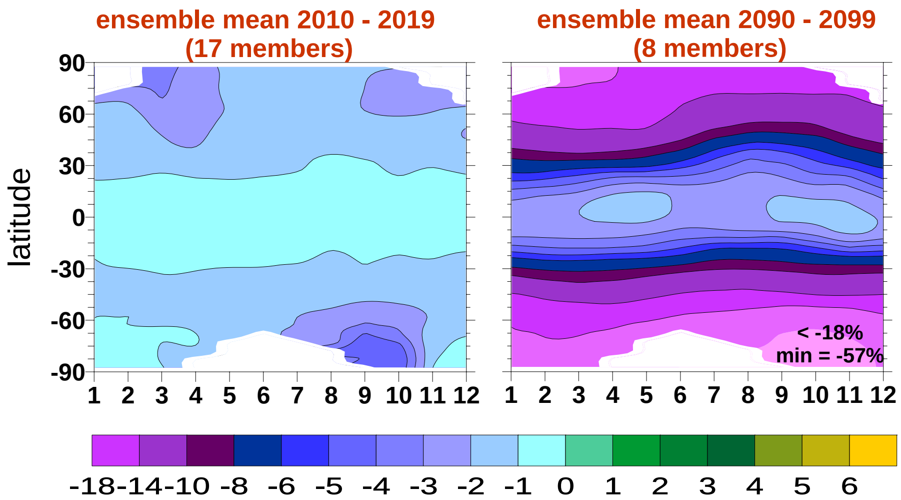

Fig. 4. Decadal averages of clear-sky erythemal irradiance changes (%) with respect to the 1996–2005 average. Calculations refer to local noon values and changes reflect the predicted changes in total ozone by the CCMs. Due to differences in the period of the CCM outputs, the number of models entering each ensemble differs between periods.

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