The effect of chosen extraterrestrial solar spectrum on clear-sky atmospheric absorption and heating rates in the near infrared

AIP Proceedings

The effect of chosen extraterrestrial solar spectrum on clear-sky atmospheric absorption and heating rates in the near infrared

Kaah P. Menang and Keith P. Shine

Citation: AIP Conference Proceedings **1531**, 520 (2013); doi: 10.1063/1.4804821
View online: http://dx.doi.org/10.1063/1.4804821
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1531?ver=pdfcov
Published by the AIP Publishing

The Effect of Chosen Extraterrestrial Solar Spectrum on Clear-sky Atmospheric Absorption and Heating Rates in the Near Infrared

Kaah P. Menang and Keith P. Shine

Department of Meteorology, University of Reading, PO Box 243, Reading, RG6 6BB, UK

Abstract: The extraterrestrial solar spectrum (ESS) is an important component in near infrared (near-IR) radiative transfer calculations. However, the impact of a particular choice of the ESS in these regions has been given very little attention. A line-by-line (LBL) transfer model has been used to calculate the absorbed solar irradiance and solar heating rates in the near-IR from 2000-10000 cm^{-1}(1-5 μm) using different ESS. For overhead sun conditions in a mid-latitude summer atmosphere, the absorbed irradiances could differ by up to about 11 Wm^{-2} (8.2 %) while the tropospheric and stratospheric heating rates could differ by up to about 0.13 K day^{-1} (8.1 %) and 0.19 K day^{-1} (7.6 %). The spectral shape of the ESS also has a small but non-negligible impact on these factors in the near-IR.

Keywords: Extraterrestrial solar spectrum, Radiative transfer, Absorbed solar irradiance, Solar heating rates.
PACS: 42.68.Ay, 92.60.Vb

INTRODUCTION

Solar radiation is the principal source of energy that drives the Earth's climate and weather. Its interaction with the Earth-atmosphere system, leads to its absorption by atmospheric gases and radiative heating of the atmosphere. This quantification of these processes requires knowledge of the extraterrestrial solar spectrum ESS [1]. In the near-IR, ESS with different absolute levels, resolutions and consequently different amount of solar energy available at the top-of-the-atmosphere (TOA), have been derived over the years. Thus, the interaction of solar radiation as given by different ESS with the Earth-atmosphere system may be different. Despite these efforts, the ESS variation in this spectral region is still quite poorly observed [2]. Menang et al. [3] have recently produced a high-resolution ESS ("CAVIAR ESS") in the near-IR from 2000-10000 cm^{-1} (1-5μm). The CAVIAR ESS is based on a Langley analysis of ground-based sun-pointing measurements using a calibrated high-resolution (0.03 cm^{-1}) Fourier Transform Spectrometer (see [4] for the instrument configuration) made by the National Physical Laboratory as part of the UK consortium "Continuum Absorption by Visible and Infrared radiation and its Atmospheric Relevance" (CAVIAR). The analysis has been shown to be capable of reproducing the fine resolution features of the solar spectrum seen in limited spectral regions in earlier measurements.

Since the Langley technique fails in spectral regions with strong atmospheric absorption (notably the near-IR bands of water vapour), the CAVIAR spectrum is filled in with other available spectrum in these regions. A comparison of the CAVIAR ESS with those of [5] ("Fontenla ESS"), [6] ("Kurucz-modelled ESS") and [1] ("Thuillier ESS"), confirms that there are some significant differences between them, both in terms of the fine structure in the ESS, but also in the absolute level of the ESS. It is important that the impact of these ESS on near-IR absorption and heating rates should be assessed.

Using both LBL and broadband radiative transfer calculations under all-sky, [7] have shown that the choice of ESS has a significant impact on heating rates and atmospheric temperatures in the ultra-violet. In a similar study but in a broader region (ultra-violet to near-IR), [8] have also arrived at the same conclusion as [7]. However, none of these studies is dedicated to the near-IR, which contains over 50% of available solar energy.

In this paper, the changes in the clear-sky absorbed solar irradiance and heating rates in the near-IR as a result of using the four ESS stated above in line-by-line (LBL) radiative transfer calculations will be presented. In addition to their absolute levels, the effect of their spectral variation and fine structure on atmospheric absorption and heating rates will also be discussed.

Radiation Processes in the Atmosphere and Ocean (IRS2012)
AIP Conf. Proc. 1531, 520-523 (2013); doi: 10.1063/1.4804821

CLEAR-SKY ABSORPTION

This study was carried out for an overhead Sun and a cloudless and aerosol-free mid-latitude summer (MLS) atmosphere with a surface albedo of zero. The calculations were carried out in the 2000-10000 cm^{-1} band and 4200-10000 cm^{-1} (2.4-5 μm) sub-band (to match the spectral regions of earlier ESS). The total absorbed solar irradiance, $\boldsymbol{F_{absorbed}}$, was obtained from the difference between the net solar irradiance arriving at the top of atmosphere and Earth's surface. Under clear-sky conditions, scattering is negligible in the near-IR.

For an overhead Sun, the SSI arriving at the surface, $\boldsymbol{F_{\nu S}}$ is given by:

$$F_{\nu S} = F_{\nu 0} \exp(-\tau_\nu), \tag{1}$$

where $\boldsymbol{F_{\nu 0}}$ is the SSI at the TOA and $\boldsymbol{\tau_\nu}$ is the atmospheric optical depth. The net surface irradiance is the integrated, $\boldsymbol{F_{\nu S}}$ and $\boldsymbol{\tau_\nu}$ was calculated from 2000-10000 cm^{-1} using a LBL code developed by [9], at a very high resolution of 0.001 cm^{-1}. Other inputs to the LBL calculations were; the first seven gases of the molecular spectroscopic database of [10]; H_2O, CO_2, O_3, N_2O, CO, CH_4 and O_2, which are the gases responsible most of clear-sky absorption in the near-IR and the continua of [11] for H_2O, CO_2, O_3 and O_2. Table 1 shows the absorbed solar irradiance calculated using the CAVIAR, Fontenla, Kurucz-modelled and Thuillier ESS from both 2000-10000 cm^{-1} and 4200-10000 cm^{-1} spectral regions.

TABLE (1). Absorbed solar irradiance obtained using the CAVIAR, Fontenla, Kurucz-modelled and Thuillier ESS from 2000-10000 cm^{-1} and 4200-10000 cm^{-1} for a MLS atmosphere and overhead Sun.

Extraterrestrial solar spectrum	Absorbed irradiance from 2000-10000 cm^{-1} (Wm^{-2})	Absorbed irradiance from 4200-10000 cm^{-1} (Wm^{-2})
CAVIAR	149.26	116.87
Fontenla	157.09	123.12
Kurucz-modelled	157.29	122.93
Thuillier	-	127.35

From Table 1, the absorbed solar irradiance obtained using the CAVIAR solar spectrum is less than those obtained using the other solar spectra in both spectral regions. These differences are up to about 8 Wm^{-2} (5.1 %) from 2000-10000 cm^{-1} and about 11 Wm^{-2} (8.2 %) from 4200-10000 cm^{-1}.

In order to study the effect of the shapes of ESS on clear-sky absorption, the Kurucz-modelled and Thuillier ESS were chosen (because they are widely-used) in turn as a reference to normalise the other solar spectra to it. After normalising one spectrum to another, the two solar spectra have equal integrated SSI but their spectral shapes (and hence spectral absolute levels) are different. The difference in absorbed solar irradiance obtained using the reference and normalised solar spectra gives an indication of the effect of the spectral shape on absorption. Differences of up to about 1.3 Wm^{-2} in the absorbed solar irradiance were obtained from 2000-10000 cm^{-1}, which is about 0.8 % of the maximum solar irradiance absorbed in this spectral region (see Table 1). From 4200-10000 cm^{-1}, differences of up to about 1.2 Wm^{-2} were obtained, representing about 1 % of the maximum absorbed solar irradiance in this spectral region (see Table 1).

The effect of the fine spectral structure on atmospheric absorption was studied by applying a running average through 5 cm^{-1}, 15 cm^{-1} and 50 cm^{-1} to the CAVIAR, Fontenla, Kurucz-modelled and Thuillier ESS. Both the original and smoothed spectra were used to calculate the absorbed solar irradiance. These calculations showed that the absorbed solar irradiances could differ by only up to 0.1 W m^{-2} as a result of changes in the structure of the solar spectra.

CLEAR-SKY SOLAR HEATING RATES

The solar heating rates obtained using the CAVIAR (H_C), and its differences with those from Kurucz-modelled (H_K) and Fontenla (H_F) ESS from 2000-10000 cm^{-1} and 4200-10000 cm^{-1} are shown in Figure 1. The difference between H_C with that calculated using the Thuillier ESS (H_T) from 4200-10000 cm^{-1} is also shown.

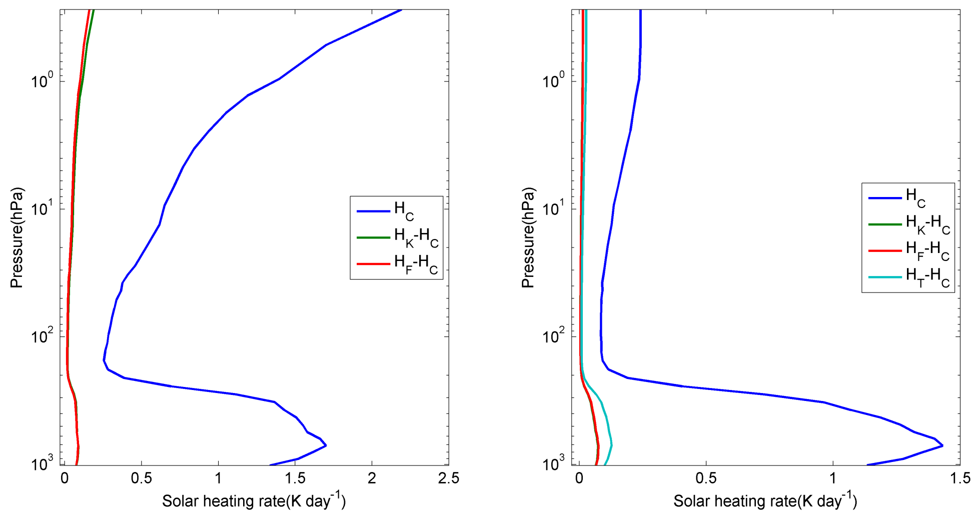

FIGURE 1: H_C, and the difference H_K- H_C and H_F- H_C from 2000-10000 cm^{-1}(left) and H_C, and the differences H_K- H_C, H_F- H_C and H_T- H_C from 4200-10000 cm^{-1}.

The variation of the tropospheric heating rates with altitude in both spectral regions is similar as it is driven by the strength of the near-IR bands of water vapour and the vertical distribution of water vapour, but with the heating rate in the narrower spectral region being lower. We also observe that there is a significant increase in the stratospheric heating rates from 2000-10000 cm^{-1} compared to the region 4200-10000 cm^{-1}, due to heating produced by strong CO_2 absorption bands at 2300 cm^{-1} (4.3 µm) and 3500 cm^{-1} (2.8 µm).

Figure 1 shows that H_C is smaller than those calculated using the other solar spectra in both spectral regions. H_K and H_F are almost equal in both spectral regions. From 2000-10000 cm^{-1}, differences of up to about 0.09 K day^{-1} (5.3 %) in the troposphere and up to about 0.19 K day^{-1} (7.6 %) in the stratosphere were obtained when different ESS were used. From 4200-10000 cm^{-1}, we obtained differences of up to about 0.13 K day^{-1} (8.1 %) in the troposphere and about 0.03 K day^{-1} (10 %) in the stratosphere. The absolute difference in the stratosphere from 4200-10000 cm^{-1} is lower than that obtained from 2000-10000 cm^{-1} because of the absence of the strong CO_2 absorption bands discussed above.

The effect of the shape of the ESS (using the normalisation method described above) on heating rates is shown in Figure 2. H_{Cnorm} is the heating rate obtained by using normalized (to wavelength-integrated Kurucz-modeled ESS) CAVIAR ESS.

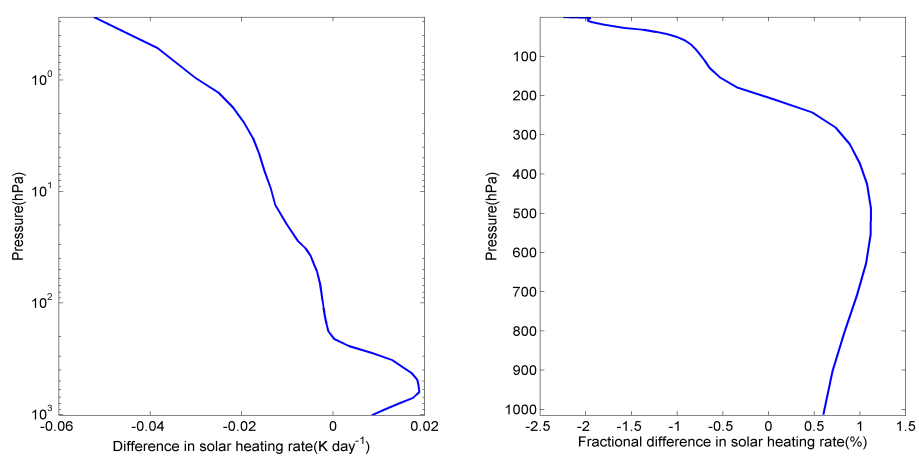

FIGURE 2. Absolute (left) and fractional (right) differences in H_{Cnorm} and H_K from 2000-10000 cm^{-1}. The absolute difference is H_{Cnorm}-H_K while the fractional difference is $(H_{Cnorm}$-$H_K)/H_{Cnorm}$.

Figure 2 shows that the effect of the shape of the ESS is relatively small, increasing the heating rate by only up to about 0.018 K day^{-1} (1%) in the troposphere. In the stratosphere, using the Kurucz-modeled and normalized CAVIAR ESS causes a decrease of up to about 0.05 K day^{-1} (2 %) in the heating rate. The decrease in heating rate in the stratosphere shows that the normalization takes away energy from the strong CO_2 bands influencing stratospheric heating in this spectral region. The effect of the fine spectral structure of an ESS on heating rates was not studied because of the very small effect it had on absorption as discussed above.

CONCLUSIONS

A LBL radiative transfer model has been used to calculate the clear-sky absorbed solar irradiances and heating rates in the near-IR using different ESS. For overhead sun conditions in a mid-latitude summer atmosphere, differences of up to about 11 Wm^{-2} (8.2 %) in absorption were obtained. The differences in the spectral shape of the ESS resulted in smaller differences, of up to about 1.3 Wm^{-2} (0.8 %) in absorption. Tropospheric and stratospheric heating rates could differ by up to about 0.13 K day^{-1} (8.1%) and 0.19 K day^{-1} (7.6 %) respectively between different ESS, but differences in the (normalised) spectral variation of the ESS result in relatively small changes in the heating rates, accounting for a maximum heating of only about 0.018 K day^{-1} (1%) and 0.05 K day^{-1} (2 %) in the troposphere and stratosphere respectively. Although these results show a relatively small effect in the near-IR, they are not negligible. There is a need for further high-spectral resolution measurements of the near-IR ESS, given the differences in existing data sets, and the effect of uncertainty in the ESS for radiative transfer calculations should be further assessed.

ACKNOWLEDGMENTS

We thank Marc Coleman and Tom Gardiner for their contribution to the derivation of the ESS, and Igor Ptashnik for his help and advice in all aspects of this work.

REFERENCES

1. G. Thuillier et al., "Solar Irradiance Reference Spectra", in J. Pap and P. Fox, editors, Solar Variability and its effects on Climate, Geophysical Monograph, **141**, 171-194 (2004).
2. J. W. Harder et al., *Geophys. Res. Lett.* **36**, L07801 (2009).
3. K. P. Menang et al., to be submitted (2012).
4. T. D. Gardiner et al., *Phil. Trans Roy Soc A.* **370**, 2590-2610 (2012).
5. J. M. Fontenla et al., *J. Geophys. Res.* **116**, D20108 (2011).
6. R. L. Kurucz, "The solar irradiance by computation", can be obtained online from http://kurucz.harvard.edu/sun.html.
7. W. Zhong et al., *Geophys. Res. Lett.* **35,** L22813, doi:10.1029/2008GL035993 (2008).
8. Z. Sun et al., "Evaluation of Solar Spectra and Their Effects on Radiative Transfer and Climate Simulation", Solar Power, R. Rugescu (Ed.), ISBN: 978-953-51-0014-0, InTech, (2012).
9. A. A. Mitsel et al., *Atmos. Oceanic Opt.* **8**, 847-850 (1995).
10. L. S. Rothman et al., *J. Quant. Spectrosc. Radiat. Transfer* **110**, 533-572 (2009).
11. E. J. Mlawer et al., *Phil. Trans. Roy. Soc. A.* **370**, 2520-2556 (2012).