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ORIGINAL PAPER

The effect of the differences in near-infrared water vapour continuum models on the absorption of solar radiation

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Abstract

There are currently significant disagreements in the strength of the water vapour continuum in the near-infrared region. To understand the effects of these disagreements on the absorption of solar radiation, line-by-line radiative transfer calculations were performed from 2000 to 10,000 cm^{-1} (1–5 μm) for three standard atmospheres; tropical, mid-latitude summer and sub-arctic winter atmospheres. These calculations were carried out at a solar zenith angle of 60° using line parameters from HITRAN (HIgh-resolution TRANsmission). Three currently available water vapour continuum models were selected for this study; versions 2.5 and 3.2 of the semi-empirical MT_CKD (Mlawer-Tobin-Clough-Kneizys-Davies) model and the laboratory-measured CAVIAR (Continuum Absorption at Visible and Infrared Wavelengths and its Atmospheric Relevance) model. The differences between the contributions of both MT_CKD models to near-infrared absorption and heating are modest for all three atmospheres. The additional absorption due the CAVIAR model more than doubles those due to both MT_CKD models for the tropical and mid-latitude summer atmospheres. For both atmospheres, the extra heating of the CAVIAR model is up to a factor of 5 more than those of the MT_CKD models. For the sub-arctic winter atmosphere, the differences between the extra absorption and heating of the CAVIAR and those of both MT_CKD models are relatively less. Thus, an update of the MT_CKD model from version 2.5 to 3.2 has a relatively small impact on near-infrared spectrally integrated absorbed solar fluxes and heating rates. But their contributions to the calculations of these quantities differ significantly from that of the much stronger CAVIAR model.

1 Introduction

Water vapour is the major absorber of solar radiation at near-infrared wavelengths and thus plays a very important role in the quantification of the Earth's radiation budget (e.g., Trenberth et al. 2009). Since the amount of water vapour in the atmosphere depends on temperature, this short-wave absorption gives an extra positive feedback in climate change (e.g., Held and Soden 2000). The absorption spectrum of water vapour under atmospheric conditions consist of both a large number of individual narrow absorption lines and a background continuous absorption spectrum, called the continuum, that varies smoothly (i.e., with little structure) with wavenumber. The water vapour continuum is present in both bands and windows, but its absorption has a larger impact in windows where line absorption is weaker. Thus, the water vapour continuum is important in understanding atmospheric radiative fluxes (e.g., Paynter and Ramaswamy 2011) as well as in remote sensing applications, such as, those that use near-infrared windows for satellite-based measurements (e.g., O'Dell et al. 2018). The water vapour continuum is made up of two components: the self-continuum, which results from the interaction between water vapour molecules only and the foreign-continuum, which results from the interaction of water vapour molecules with other gaseous molecules (principally nitrogen and oxygen in the Earth's atmosphere because of their high abundances). Any water vapour continuum model used in this work is the total continuum; it comprises of both self- and foreign- continua.

The widely used semi-empirical MT_CKD (Mlawer-Tobin-Clough-Kneizys-Davies) water vapour continuum model (Clough et al. 2005; Mlawer et al. 2012) for

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atmospheric radiative transfer calculations in the near-infrared is updated quite frequently (referred to as "MT_CKD model" hereafter). Thus, many different versions of the MT_CKD model exist. This work will focus on two versions of the MT_CKD model; version 2.5 (MT_CKD 2.5; Mlawer et al. 2012), which is arguably the most widely used version and version 3.2, the most recent update (MT_CKD 3.2; http://rtweb.aer.com/continuum_frame.html). The MT_CKD model was developed using measurements in the mid- and far-infrared (Mlawer et al. 2012). Thus, this continuum model was only extrapolated to the near-infrared. However, in the 2500 cm^{-1} window, measurements were used to "correct" and "strengthened" the MT_CKD 2.5 model in an ad hoc way (see Mlawer et al. 2012 for details). More recently, optical-feedback-cavity enhanced absorption spectroscopic and cavity ring-down spectroscopic laboratory measurements in four near-infrared windows carried out in Grenoble, France have been used to adjust the MT_CKD 3.2 model in the near-infrared (Lechevallier et al. 2018 and associated references). Note that near-infrared measurements have been used to validate both the MT_CKD 2.5 model (e.g., Ptashnik et al. 2011, 2012; Reichert and Sussmann 2016; Campargue et al. 2016) and MT_CKD 3.2 model (e.g., Lechevallier et al. 2018; Vasilchenko et al. 2019; Elsey et al. 2020). At near-infrared windows between 2000 and 10,000 cm^{-1} (1 and 5 µm), the MT_CKD 3.2 model is stronger than the MT_CKD 2.5 model (by up to a factor of 3), except in the 2500 cm^{-1} window where the MT_CKD 2.5 model is stronger (see Fig. 1). It should be noted that any uncertainties associated with either the MT_CKD 2.5 model or MT_CKD 3.2 model is not stated in the literature.

The Fourier transform spectrometer measurements of self-continuum and foreign-continuum in near-infrared windows reported, respectively, by Ptashnik et al. (2011, 2012) were used to produce the CAVIAR (Continuum Absorption at Visible and Infrared Wavelengths and its Atmospheric Relevance) water vapour continuum model (henceforth referred to as "CAVIAR model"). The CAVIAR model is basically the MT_CKD 2.5 model in which its self- and foreign-continuum coefficients at some near-infrared wavelengths have been modified using the measurements of Ptashnik et al. (2011, 2012). The uncertainties of this continuum model are quoted as 15–25% in the windows centred at about 2500 cm^{-1} and 4700 cm^{-1} and 25–30% in the windows centred at about 6300 cm^{-1} and 8000 cm^{-1}. The CAVIAR model is stronger than both the MT_CKD 2.5 and MT_CKD 3.2 models (by more than an order of magnitude at some wavenumbers) at near-infrared windows between 2000 and 10,000 cm^{-1} (see Fig. 1). However, the difference between the CAVIAR and MT_CKD 3.2 models is smaller than that between the CAVIAR and MT_CKD 2.5 models, except in the 2500 cm^{-1} window as Fig. 1 shows. Although

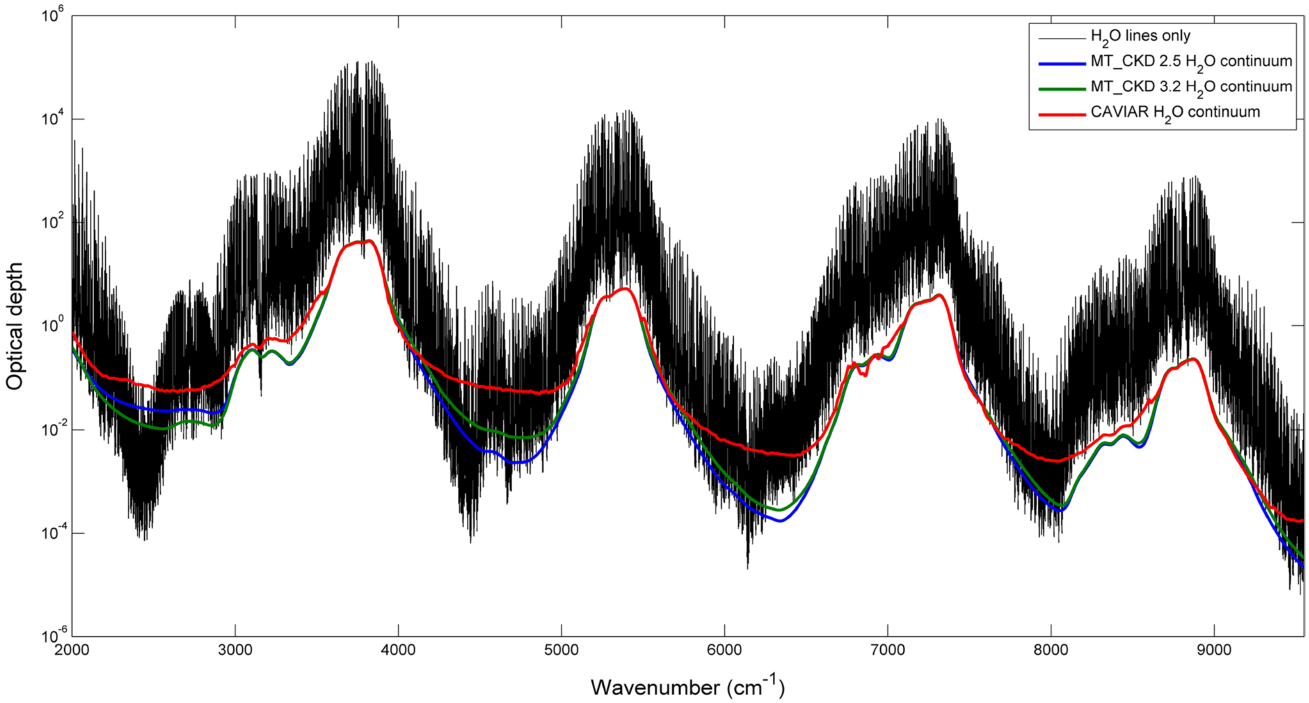

Fig. 1 Atmospheric optical depths due to the MT_CKD 2.5 (blue), MT_CKD 3.2 (green) and CAVIAR (red) models between 2000 and 10,000 cm^{-1} for a standard tropical atmosphere. The optical depth of the water vapour absorption lines only is shown in black. The calculations were carried out using the Mitsel et al. (1995) line-by-line radiative transfer model and absorption line parameters were taken from HITRAN

the most recent revision of the MT_CKD model brings it into a better agreement with the CAVIAR model in most near-infrared windows between 2000 and 10,000 cm^{-1}, the difference between the strengths of these models is still significant. Thus, it is important to assess how differences in the strength of recent near-infrared water vapour continuum models affect the calculations of absorption of solar radiation (and other radiative transfer calculations).

Line-by-line (LBL) radiative transfer calculations have been used to study the impacts of different continuum models on shortwave absorption (e.g., Paynter and Ramaswamy 2011, 2012; Ptashnik et al. 2012; Chesnokova et al. 2013). Paynter and Ramaswamy (2011) investigated the effects of four water vapour continuum models; their empirically constructed BPS (Baranov-Paynter-Serio), CKD 2.4 (Clough-Kneizys-Davies; Clough et al. 1989) and MT_CKD (versions 1.1 and 2.5) models on clear-sky LBL calculations in three standard atmospheres. They found that at a solar zenith angle of 30°, these continuum models agree to within 1% in their contribution to shortwave absorption by water vapour. In a follow-up study, Paynter and Ramaswamy (2012) examined the impact of the prescribed continuum model on the global clear-sky radiation budget. All continuum models adopted by Paynter and Ramaswamy (2011) were also used in this study, except the MT_CKD 1.1 model. Paynter and Ramaswamy (2012) showed that the different continuum formulations resulted in up to about 0.8% differences in the globally averaged shortwave absorption (which is relatively higher than the differences in the longwave). Both Paynter and Ramaswamy (2011) and Paynter and Ramaswamy (2012) also examined the effect on continuum on clear-sky shortwave heating rates of the troposphere. The heating rates due to the different water vapour continuum models agreed to within the uncertainties of the BPS continuum model. Ptashnik et al. (2012) studied the contributions of the CAVIAR and MT_CKD 2.5 models to the LBL calculated clear-sky absorption of solar radiation in the near-infrared region between 2000 and 10,000 cm^{-1} for a tropical atmosphere and overhead Sun. Their results show that the contribution of the CAVIAR model to near-infrared water vapour absorption is two times that due to the MT_CKD 2.5 model. Paynter and Ramaswamy (2011, 2012) and Ptashnik et al. (2012) also looked at the effects of the individual contributions of both the self- and foreign-continua to radiative fluxes, but as stated above the focus of this work is on the total continuum. Chesnokova et al. 2013 showed, for standard winter and summer atmospheres in Western Siberia, Russia, that when compared to the CAVIAR model, the MT_CKD 2.4 model overestimates total clear-sky surface shortwave fluxes by more than 2 W m^{-2}.

The focus of this study is to investigate how differences in three recent total water vapour continuum formulations (MT_CKD 2.5, MT_CKD 3.2 and CAVIAR) influence clear-sky radiative transfer calculations of atmospheric absorption and tropospheric heating rates in the near-infrared region from 2000 to 10,000 cm^{-1} (1–5 μm). The absorption (and heating) due to water vapour only was considered in the calculations. The contributions of other gases will not significantly affect the results of this study because water vapour is the major absorber in this spectral region. In Sect. 2, the specifications of the LBL radiative transfer calculations will be described. The findings from this work are presented in Sect. 3. Section 4 summarises.

2 Line-by-line radiative transfer calculations

The LBL calculations were carried out using the Mitsel et al. (1995) code at a spectral resolution of 0.001 cm^{-1}. The absorbed solar fluxes and heating rates were computed for three standard 50-level atmospheric atmospheres (with the top-of-the-atmosphere at 120 km); tropical (TROP), mid-latitude summer (MLS) and sub-arctic winter (SAW) atmospheres (Anderson et al. 1986).

The calculations were performed for clear-sky conditions and zero surface albedo at a solar zenith angle of 60°. Rayleigh scattering was also ignored in these calculations. The water vapour absorption line parameters were taken from the 2016 version of HITRAN (Gordon et al. 2017). For each atmosphere, the calculations were carried out both with and without the water vapour continuum absorption. Where required, the water vapour continuum absorption was represented successively by the MT_CKD 2.5, MT_CKD 3.2 and CAVIAR models. The water vapour optical depths were calculated for the layers of interest in the atmosphere in the spectral interval 2000–10,000 cm^{-1}. The solar irradiance at the top-of-the-atmosphere used here was taken from the calculations of Kurucz (1995) at a spectral resolution of 0.1 cm^{-1}. The absorbed solar fluxes and heating rates were computed using the modelled optical depths and solar spectral irradiance in the standard way (e.g., Liou 2002). The absorbed solar fluxes were calculated in the atmospheric layer between the surface and 120 km while the heating rates were calculated for each layer of the atmosphere from the surface to 18 km. The contribution of the water vapour continuum to absorption and heating is the difference between the calculations when that continuum is taken into consideration and when it is not.

3 Results

3.1 Near-infrared absorption

The clear-sky near-infrared absorption due to the different water vapour continuum models as a function of wavenumber for the TROP, MLS and SAW atmospheres are shown in Fig. 2.

Figure 2 shows that all the water vapour continuum models contribute relatively more to absorption in the atmospheric windows than in the bands between 2000 and 10,000 cm^{-1} for all atmospheres. The water vapour continuum contributes relatively very little to absorption in the bands because they have been saturated by water vapour spectral lines. In this spectral region, the CAVIAR model generally contributes more to absorption in all windows than both the MT_CKD 2.5 and MT_CKD 3.2 models for all atmospheres as Fig. 2 shows. Although the strengths of the CAVIAR model in the windows centred at about 2500 cm^{-1} and 4700 cm^{-1} are approximately the equal (see Fig. 1), Fig. 2 shows that most of the contribution to absorption occurs in the window between 4000 and 5000 cm^{-1} for all atmospheres. This is because the top-of-the-atmosphere solar irradiance in the 4700 cm^{-1} window is about a factor of 3 higher than that in the 2500 cm^{-1} window (Ptashnik et al. 2012).

Compared with the calculations using only water vapour lines (that is, the ‘no continuum’ case), the increase in near-infrared absorbed solar fluxes due to the MT_CKD 2.5, MT_CKD 3.2 and CAVIAR models for the three atmospheres used in this work are shown in Table 1.

Table 1 The contribution of the MT_CKD 2.5, MT_CKD 3.2 and CAVIAR models to water vapour absorption of solar radiation in the near-infrared from 2000 to 10,000 cm^{-1} for different atmospheres

Continuum model	Standard atmosphere		
	TROP	MLS	SAW
No Continuum	94.2	93.8	61.5
MT_CKD 2.5	3.0	2.9	1.5
MT_CKD 3.2	3.6	3.5	1.8
CAVIAR	7.7 (± 1.9)	7.5 (± 1.9)	2.6 (± 0.7)

The initial absorption calculated without the continuum (using only water vapour lines) is included for reference. All calculations were carried out using HITRAN2016 at a solar zenith angle of 60°. All values are in W m^{-2}

Table 1 shows that the extra near-infrared absorptions due to all three water vapour continuum models are smaller for the SAW atmosphere than the TROP and MLS atmospheres. The absorption for the SAW atmosphere is smaller because its column water vapour amount (0.43 g cm^{-2}) is lower than in the other two atmospheres (4.24 g cm^{-2} and 3.02 g cm^{-2} for TROP and MLS atmospheres, respectively). This table also shows that according to all three models, the amounts of absorbed solar fluxes by the water vapour continuum for the TROP atmosphere are almost equal to those for the MLS atmosphere. This is probably a reflection of the column

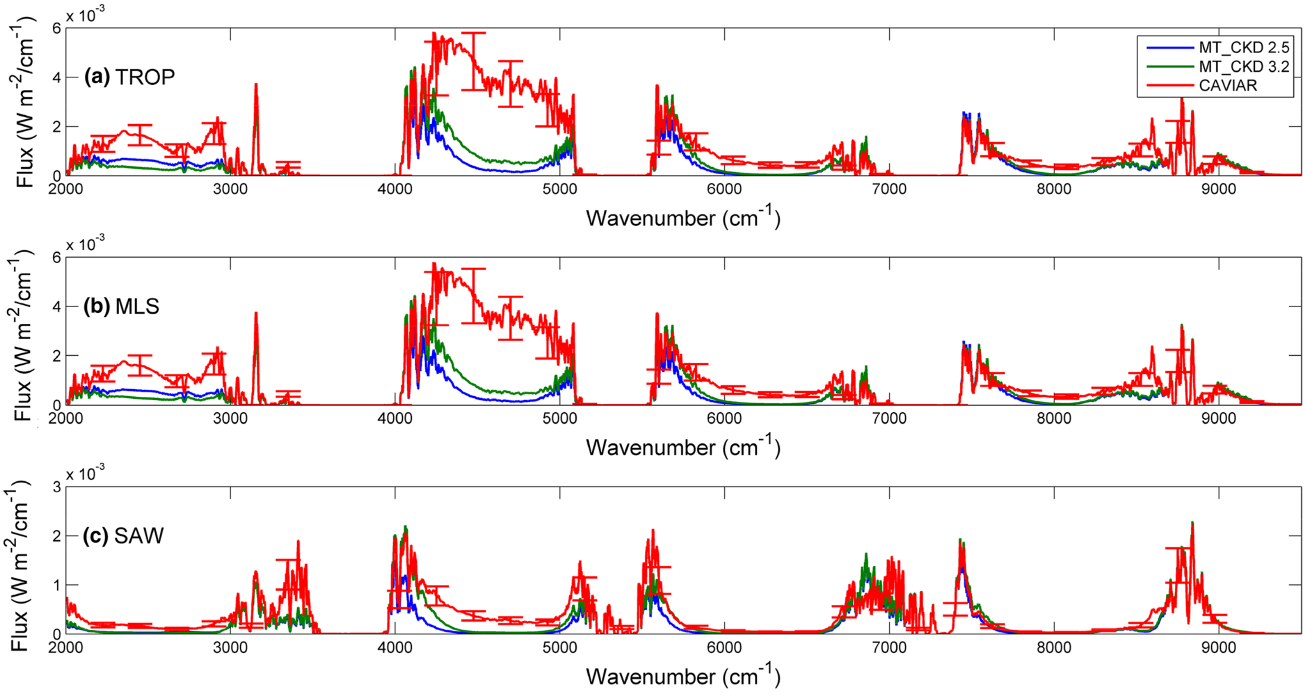

Fig. 2 The spectral variation of near-infrared clear-sky absorption between 2000 and 10,000 cm^{-1} of the MT_CKD 2.5, MT_CKD 3.2 and CAVIAR models for (**a**) TROP, (**b**) MLS and (**c**) SAW atmospheres. These calculations were carried at a solar zenith angle of 60° using HITRAN (version 2016). A running average through 15 cm^{-1} has been applied to these absorbed fluxes. Note that the uncertainty on the CAVIAR model is indicated at selected and not all wavenumbers in this spectral region

water vapour amounts for these two humid atmospheres used for this work; that of the TROP atmosphere is not much higher than that of the MLS atmosphere (as stated above). Another reason why the absorbed solar fluxes for the TROP and MLS atmospheres are almost equal is that a cut off of the calculations at 10,000 cm^{-1} leads to a considerable loss of water vapour absorption above 10,000 cm^{-1} in the TROP atmosphere.

An update of the MT_CKD model from version 2.5 to version 3.2 has a small effect on the additional absorption of solar radiation by water vapour continuum in the spectral region 2000–10,000 cm^{-1} for all three atmospheres as Table 1 shows. The water vapour absorption due these two models agree to within only 0.6 W m^{-2} for the TROP and MLS atmospheres and to within only 0.3 W m^{-2} for the SAW atmosphere. These are very small differences compared to the absorption by water vapour lines only in this spectral region (see Table 1). The extra absorption by the MT_CKD 3.2 model is a factor of only about 1.2 more than that due to the MT_CKD 2.5 model for these atmospheres.

An increase in water vapour absorption of near-infrared solar radiation due to the CAVIAR model is higher than those due to both the MT_CKD 2.5 and MT_CKD 3.2 models for all three atmospheres (see Table 1). This table shows that for the TROP and MLS atmospheres, the absorption due to the CAVIAR model more than doubles those due to both MT_CKD models. For the SAW atmosphere, the absorption due the CAVIAR model is higher than those due to the MT_CKD 2.5 and MT_CKD 3.2 by factors of about 1.7 and 1.4, respectively. Thus, for the relatively moist TROP and MLS atmospheres, the contribution of the much stronger CAVIAR model (see Fig. 1) to spectrally integrated near-infrared absorbed solar fluxes by water vapour is significantly higher than those of both MT_CKD models. When the lower limit of the relatively large uncertainties associated the CAVIAR model (see Sect. 1) are taken into account, the contribution of this model to integrated near-infrared absorption by water vapour is still higher than those due to the MT_CKD 2.5 and MT_CKD 3.2 models by factors of about 1.6 and 2.0, respectively, for the TROP and MLS atmospheres.

3.2 Tropospheric heating rates

Figure 3 shows the heating rates owing to the MT_CKD 2.5, MT_CKD 3.2 and CAVIAR models for the TROP atmosphere in the spectral region 2000–10,000 cm^{-1}. Also shown in this figure is the heating rate due to the water vapour lines only (that is, the ‘no continuum’ case). The corresponding heating rates for the MLS and SAW atmospheres are shown in Figs. 4 and 5.

Figures 3, 4, 5 show that the tropospheric heating rates due to all water vapour continuum models are lower for the

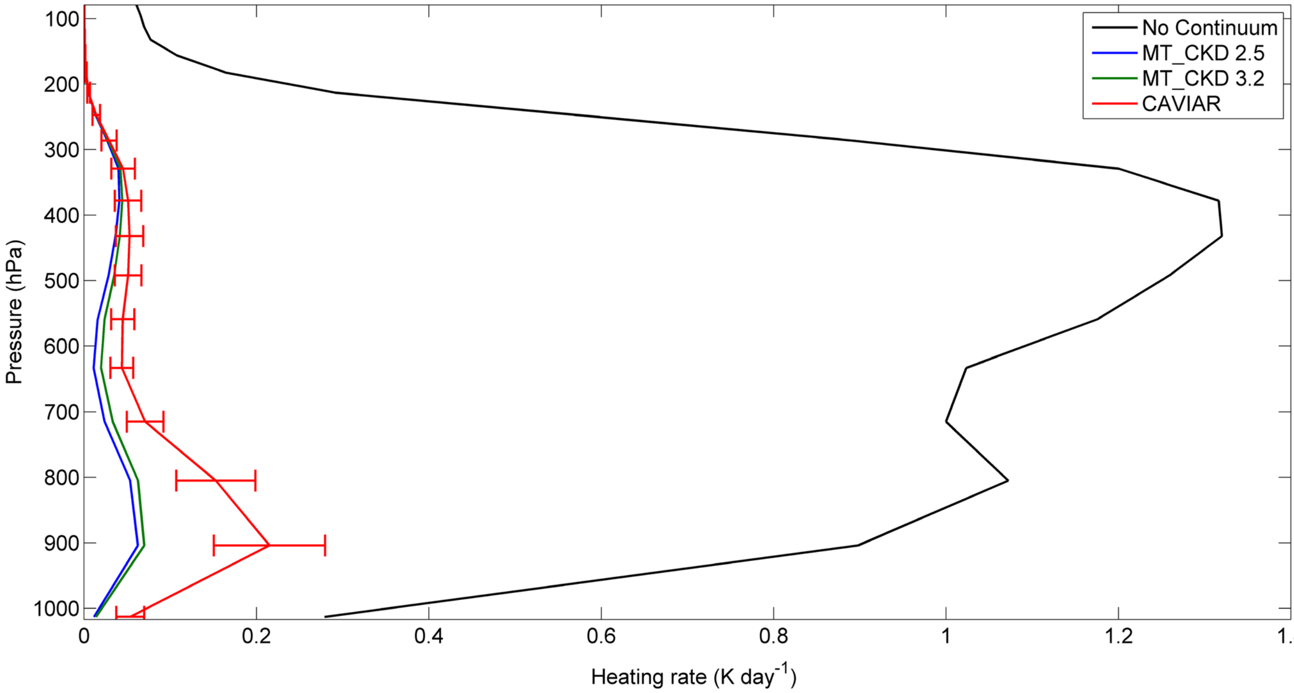

Fig. 3 The clear-sky heating rate due the water vapour lines only (‘no continuum’; black line) and the extra heating due the MT_CKD 2.5 (blue line), MT_CKD 3.2 (green line) and CAVIAR (red line) models in the spectral interval 2000–10,000 cm^{-1} for a TROP atmosphere at a solar zenith angle of 60°. Absorption line parameters from HITRAN2016 were used for all calculations. The uncertainty in the CAVIAR model is given by the error bars

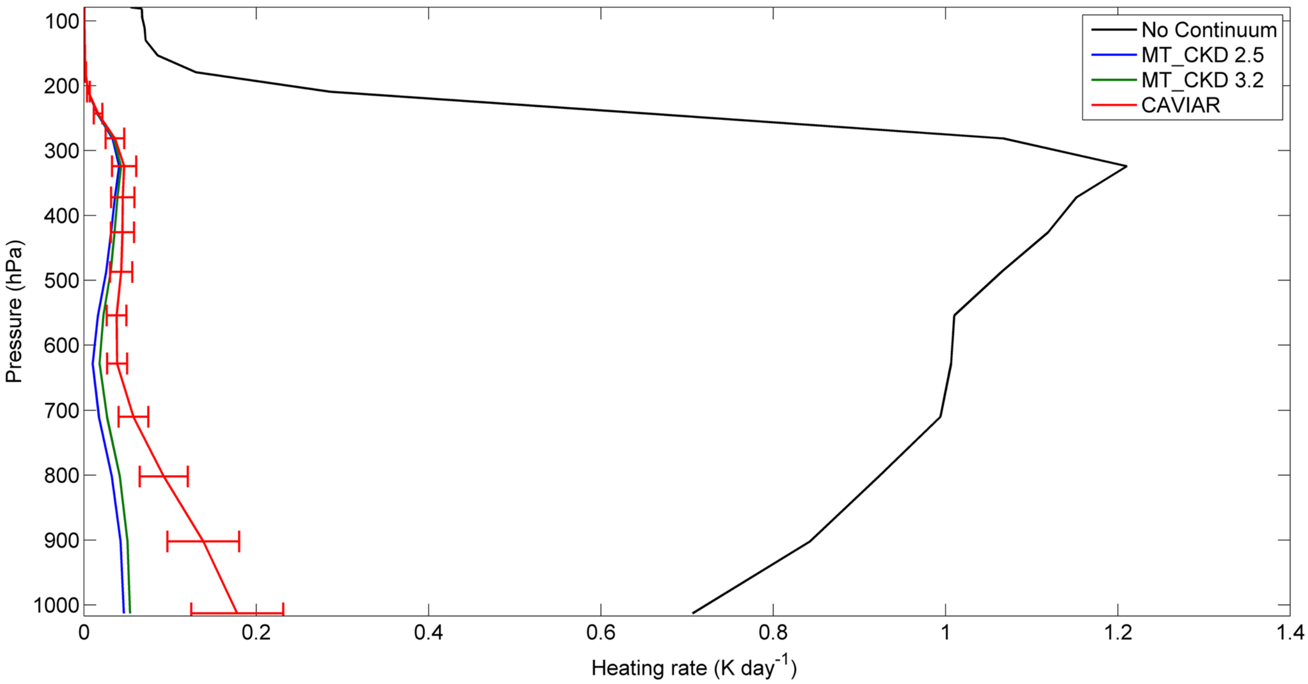

Fig. 4 As in Fig. 3, but for the MLS atmosphere

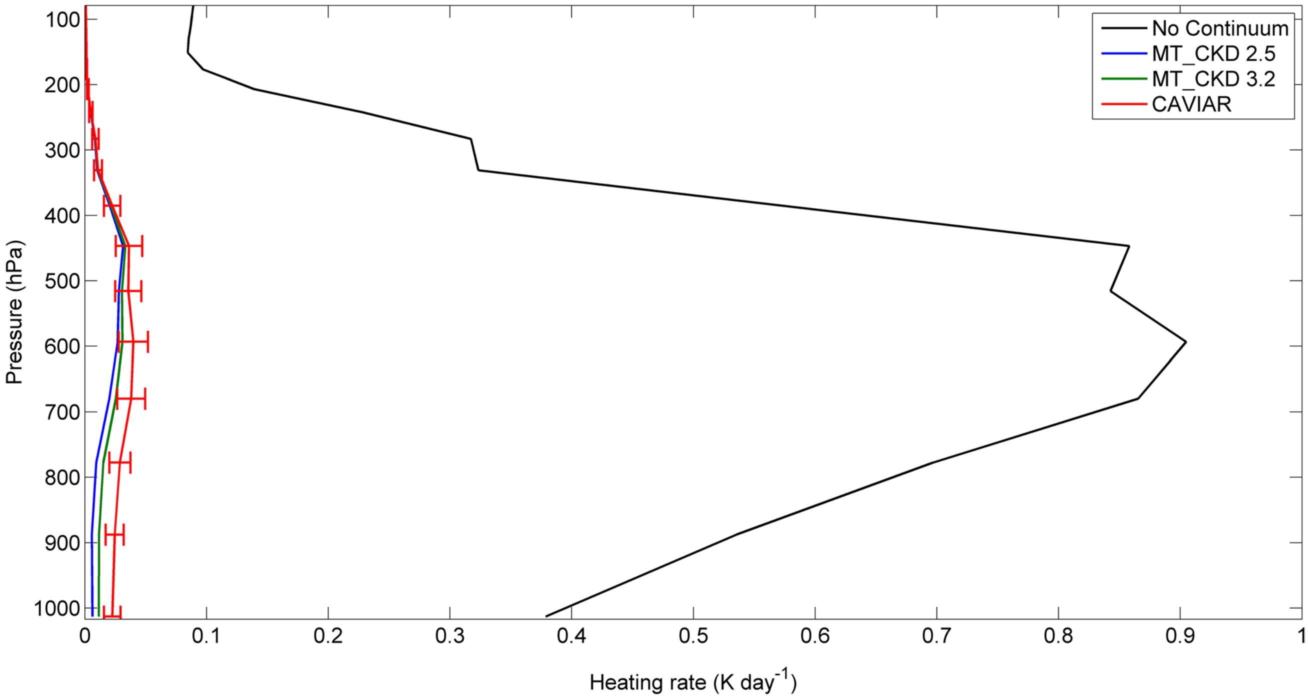

Fig. 5 As in Fig. 3, but for the SAW atmosphere

SAW atmosphere than the TROP and MLS atmospheres. This is because of the lower amount of water vapour in the SAW atmosphere compared to the TROP and MLS atmosphere. The heating rate of the MT_CKD 3.2 model is moderately higher than that of the MT_CKD 2.5 model for all atmospheres considered in this work (see Figs. 3, 4, 5). The extra heating due the MT_CKD 3.2 model is up to a factor of about 2 more than that due to the MT_CKD 2.5 model for all three atmospheres.

Figures 3, 4, 5 also show that the heating due to the CAVIAR model is relatively much higher than those due to both the MT_CKD 3.2 and MT_CKD 2.5 models for all three atmospheres. For the TROP atmosphere, the additional heating of the troposphere owing to the CAVIAR model is up to a factor of about 4 more than that of the MT_CKD 3.2 model and up to a factor of about 5 more than that of the MT_CKD 2.5 model. For the MLS atmosphere, these factors are respectively about 3 and 4 while for the SAW atmosphere the factors are about 2 and 4. As was the case with total absorption (see Sect. 3.1), the significant differences between the CAVIAR and MT_CKD 3.2/MT_CKD 2.5 models in their contribution to near-infrared tropospheric heating is as a result of the differences in the strength of their water vapour continuum (see Fig. 1). It can also be observed from Figs. 3, 4, 5 that within the uncertainties of the CAVIAR model, the extra heating due to this model is still higher than those due to both MT_CKD models in the lower troposphere. In the upper troposphere, the heating rates agree within the uncertainties of the CAVIAR model.

4 Conclusions

Using a high-resolution line-by-line radiative transfer model, this work analysed the influence of water vapour continuum models on the absorption of near-infrared solar radiation and subsequent heating of the trosposphere. The clear-sky model calculations were carried out in the spectral region from 2000 to 10,000 cm^{-1} (1–5 μm), at a solar zenith angle of 60° for three standard atmospheres (TROP, MLS and SAW atmospheres). Three water vapour continuum models were selected for this work; the MT_CKD 2.5, MT_CKD 3.2 and CAVIAR models.

The MT_CKD 2.5 and MT_CKD 3.2 models do not disagree much in their contribution to near-infrared absorption of solar radiation by water vapour for all atmospheres. They agree to within 0.6 W m^{-2} for the TROP and MLS atmospheres and to within 0.3 W m^{-2} for the SAW atmosphere; very small values compared to the absorption by water vapour lines only. An increase in near-infrared water vapour absorption due to the CAVIAR model is much higher than those due to both the MT_CKD 2.5 and MT_CKD 3.2 models for all atmospheres, especially for the TROP and MLS atmospheres where the CAVIAR absorption more than doubles the MT_CKD 2.5/MT_CKD 3.2 absorption.

The extra tropospheric heating in the near-infrared due the MT_CKD 3.2 model is up to about two times as high as that due MT_CKD 2.5 model for all three atmospheres. On the other hand, the tropospheric heating rates of the CAVIAR model are relatively much higher than those of both MT_CKD models. The heating rates of the CAVIAR model are higher by factors of about 3 to 5, with the higher factors for the moist TROP and MLS atmospheres.

Therefore, an update of the MT_CKD model from version 2.5 to 3.2 has a modest effect on the spectrally integrated absorbed solar fluxes and heating rates in the near-infrared. However, the update will probably have a greater impact on spectrally dependent applications such as remote sensing. The significant differences between the CAVIAR model and both MT_CKD models in their contribution to water vapour absorption and tropospheric heating in the near-infrared can be attributed to the differences between their strengths in this spectral region.

Taking into account the uncertainties associated with the CAVIAR model, the absorption and heating of this model are still significantly higher than that of the recently updated MT_CKD (version 3.2) model. These disagreements pose a major challenge in constraining atmospheric absorption of solar radiation (and subsequent atmospheric heating) in the near-infrared. While the uncertainties of the CAVIAR model are relatively large, there are no quoted uncertainties associated with the MT_CKD 3.2 model in the literature. Thus, at the moment, it is difficult to recommend with confidence the appropriate water vapour continuum model to use in near-infrared radiative transfer modelling. To resolve this discrepancy, there is the need for more measurements of near-infrared water vapour continuum absorption.

The results presented in this study have limited applications due to the fact that the calculations take into account only standard atmospheres, a single solar zenith angle, zero albedo, a limited wavenumber range, only water vapour absorption and ignore Rayleigh scattering. An extension of this study that considers the real world atmospheres is thus recommended to understand the impact of recent water vapour continuum formulations on present day and/or future climates (see, for example, Paynter and Ramaswamy (2012, 2014)).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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