

Assessing the response of shortwave cloud radiative effect to changes in water vapour continuum absorption

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Research Article

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Abstract

There are large differences in currently available shortwave (SW) water vapour continuum models. We add a three-layer conceptual clouds into a one-dimensional (1D) radiative convective equilibrium (RCE) model and use to study the impact of water vapour continuum on SW cloud radiative effect (CRE). An atmospheric profile with temperature and water vapor volume mixing ratio at 512 vertical levels between 1000 and 0.01hPa is constructed using the python code konrad. The tropospheric temperature profile is adjusted to a moist adiabat at a prescribed surface temperature of 288K up to the tropopause temperature of 175K while the stratospheric temperature profile is kept constant at this tropopause temperature. We use the ECMWF radiation scheme ('ecRad') for radiative transfer calculations in the 1D RCE model. Three water vapour continuum models are analysed: MT_CKD 4.2, MT_CKD 2.5 and CAVIAR. Each of these continuum models is used to train ecRad gas-optics tables. The present-day observed TOA, surface and atmospheric SW CREs obtained using the 1D RCE with idealised distinct simultaneous low-, mid-, and high-level clouds are comparable to those from observational analysis in the tropical region. The current uncertainties in SW water vapour continuum does not have a significant impact on SW CREs irrespective of the vertical cloud structure. TOA and surface SW CREs differ by only 0.1 W m^{-2} ($\sim 0.2\%$) while atmospheric CRE differ by only 0.2 W m^{-2} ($\sim 3.2\%$).

1. Introduction

The Earth's radiation balance is strongly regulated by clouds. In the shortwave (SW) spectral region, clouds reflect solar radiation back to space and thus radiatively cool the Earth. Clouds radiatively warm the Earth in the longwave (LW) spectral region because they trap outgoing longwave radiation. The impact of clouds on the Earth's radiation budget is usually quantified using the concept of cloud radiative effect (CRE). CRE is defined as the difference between net radiative fluxes (either at the-top-of-the-atmosphere or at the surface) in all-sky and clear-sky conditions (e.g., Ramanathan et al., 1989). Conventionally, negative CRE is ascribed to the cooling effects of clouds. Clouds have a net cooling effect on the Earth's climate and surface because the global annual mean (negative) SW CRE at the top-of-the-atmosphere (TOA) and the surface are larger than their (positive) LW CRE (Loeb et al., 2018, Wild et al., 2019). In this study, we focus on the CRE in the shortwave spectral region.

There are significant differences amongst the current estimates of global annual mean SW CRE from comprehensive climate models (e.g., Wild et al., 2020). Globally and for present-day climate, the annual mean TOA shortwave CRE amongst the individual 38 comprehensive climate models analysed by Wild et al (2020) ranges from -41 to -60 W m^{-2} while the annual mean surface SW CRE ranges from -43 to -63 W m^{-2} . We remark that there are important deviations of SW CRE from the global annual conditions. For example, shortwave CRE depends on different cloud classes (e.g., vertical cloud structure, cloud type), geographic locations and seasonal effects (Collow et al., 2016; Oreopoulos et al., 2017; Hill et al., 2018; L'Ecuyer et al., 2019; Li et al., 2021; Dommo et al., 2023).

The inter-model discrepancies in the estimated SW CRE have been attributed mostly to differences in cloud properties (e.g., cloud fraction, cloud optical properties) considered by different atmospheric models and/or how cloud layers are treated in the radiative transfer schemes of these models (Jahangir et al., 2021 and associated references). However, the computation of radiative fluxes (required for CRE estimation) must account for water vapour continuum absorption (e.g., Rädcl et al., 2015). At the moment, the water vapour continuum in the SW spectral region has not been constrained. The background of a good number of currently available SW water vapour continuum models and the disagreements between their strengths are detailly discussed in the literature (for example, Menang, 2025; Menang et al., 2025) and will thus not be repeated here. Despite its importance in the calculation of radiative fluxes, the impact of the current discrepancies in water vapour continuum on SW CRE has been largely ignored. In their study of the radiative impact of the water vapour continuum at visible and near-infrared wavelengths, Rädcl et al. (2015) found out that their computed global mean TOA and surface SW CREs for present-day climate are in reasonable agreement with estimates from other studies. Rädcl et al. (2015) did not investigate the impact of the continuum on the CRE. However, since their study showed that the continuum has a relatively significant impact computed global mean radiative fluxes for present-day climate, this implies that the continuum could possibly have an impact on their estimated CRE.

In this work, we add conceptual clouds to a single-column radiative-convective equilibrium (RCE) model and use it to estimate the uncertainties in SW CRE resulting from the differences in the strengths of currently available water vapour continuum models. We are motivated to use this rather simple model for our analyses because Kluft et al. (2025) has shown that using plausible idealized cloud properties, a single-column RCE model can produce present-day global annual mean TOA CREs that are in good agreement with those estimated from satellite observations. The atmospheric profile of this RCE model is constructed using konrad (Dacie et al., 2019; Kluft et al., 2019). We use the offline version of the ECMWF (European Centre for Medium-Range Weather Forecasts) radiation code ('ecRad'; Hogan and Bozzo, 2018) for radiative transfer calculations in this RCE model. We selected versions 2.5 and 4.2 of the widely-used semi-empirical MT_CKD (Mlawer–Tobin–Clough–Kneizys– Davies) continuum model (Mlawer et al., 2012, 2023, 2024) and the CAVIAR (Continuum Absorption at Visible and Infrared Wavelengths and its Atmospheric Relevance) continuum model (Paynter et al., 2009, Ptashnik et al., 2011, 2012, 2019, Keith Shine, 2023, personal communication) for this study. We analyse the MT_CKD 2.5, MT_CKD 4.2 and CAVIAR models because of the currently available water vapour continuum models only the strengths these three differ in the shortwave spectral region (Menang, 2025). As discussed in Menang (2025), the relatively older MT_CKD 2.5 model is analysed because some models still use it. Menang (2005) also explains why we the most recent MT_CKD 4.3 is not analysed. The methodology used for this work is described in section 2. The results are presented in section 3. Finally, the summary and conclusions are given in section 4.

2. Methods

2.1. Atmospheric model

As stated in Section 1, we quantify the impact of water vapour continuum on SW CRE with an atmospheric profile constructed using konrad, a Python-based one-dimensional RCE model (Dacie et al., 2019; Kluft et al., 2019). This konrad-constructed atmospheric model has 512 vertical levels of temperature and water vapor volume mixing ratio between 1000 and 0.01 hPa. The model's surface temperature is fixed to a prescribed value of 288 K, which is the current average surface temperature of the Earth. We adjust the tropospheric temperature profile to a moist adiabat that corresponds to the prescribed surface temperature up to the tropopause temperature of 175 K. The stratospheric temperature profile is equilibrated into a radiative equilibrium by representing it as an isothermal layer with the tropopause temperature of 175 K. This approach conforms with the RCE assumption (e.g., Jeevanjee, 2023) and reduces the computational burden (e.g., Kluft et al., 2025). The reduced total solar irradiance was set to 551.58 Wm^{-2} and the zenith angle to 42.05° , resulting in an insolation of 409.6 Wm^{-2} , the annual mean value in the tropics (Kluft et al., 2019). We fix the surface albedo of the model to 0.20. The relative humidity profile and concentration of the gases in the atmospheric column follow Menang et al. (2025).

Uniform 150hPa-thick vertical layers of clouds at three levels (low-, mid- and high-level) are prescribed into this atmospheric profile. A low-level cloud is introduced between 950 and 800 hPa, a mid-level cloud is prescribed between 750 and 600 hPa and a high-level cloud is introduced between 300 and 150 hPa. Figure 1 shows a plot of these three vertical conceptual cloud layers as a function of cloud fraction (the cloud fractions the cloud layers shown in this figure are given in Table 1). The three cloud layers do not extend across pressure boundaries as shown in Fig. 1. We introduce various configurations of the cloud layers into the atmospheric profile (see Section 2.3).

We select observation-based cloud properties that represent typical conditions in the tropics since the RCE is a simplification of the tropical atmosphere (e.g., Kluft et al., 2019). These cloud properties are listed in Table 1.

Table 1
Cloud properties selected for this study. The sources of these properties are given in the text.

Quantity	Value
Low-level cloud fraction	0.35
Mid-level cloud fraction	0.12
High-level cloud fraction	0.25
Low-level liquid cloud mass mixing ratio	$1.4867 \times 10^{-5} \text{ kg kg}^{-1}$
Mid-level liquid cloud mass mixing ratio	$6.1263 \times 10^{-6} \text{ kg kg}^{-1}$
Mid-level ice cloud mass mixing ratio	$3.0875 \times 10^{-7} \text{ kg kg}^{-1}$
High-level ice cloud mass mixing ratio	$3.7803 \times 10^{-5} \text{ kg kg}^{-1}$
Liquid cloud effective radius	$10 \mu\text{m}$
Ice cloud effective radius	$50 \mu\text{m}$

The low-, mid- and high-level cloud fractions are taken from Konsta et al. (2022), Guo et al., (2020) and Wright et al. (2020) respectively. The liquid cloud and ice cloud mass mixing ratios are obtained from the input ERA5 reanalysis data (Hersbach et al., 2020) for ecRad practical exercises (<https://confluence.ecmwf.int/display/ECRAD/ecRad+practical>). This ERA5 reanalysis data consists of a slice through the atmosphere from the North Pole to the South Pole at 5°E at 12 UTC on 1 July 2019. From this ERA5 data, we select tropical latitudes with substantial amount of the corresponding cloud type (based on cloud vertical structure here) and obtain the mass mixing ratios by averaging values over the cloud layers only (and not the entire atmospheric column). The low-level liquid cloud mass mixing ratio is the average over the low cloud layer at 10°S. This ERA5 low cloud layer is shown in Fig. 2. Figure 2 shows that the ice cloud mass mixing ratio for this low-level cloud is zero as expected. This figure also shows the liquid and ice cloud effective radii from the ERA5 dataset at 10°S, which is used in this work.

The mid-level liquid and ice cloud mass mixing ratios are the averages over the mid cloud layer 15°N (not shown here). The high-level ice cloud mass mixing ratio is the average over the high cloud layer at 10°N (not shown here). We assume that the mass mixing ratios are distributed uniformly in a corresponding idealized cloud layer.

2.2. Radiative transfer model

Radiative transfer calculations in the single-column RCE model are performed using the offline version of the ECMWF radiation scheme ('ecRad'; Hogan and Bozzo 2018). We use the ECMWF correlated k -distribution software tool ('ecCKD'; Hogan and Matricardi 2022) to train ecRad gas-optics tables with

each of the water vapour continuum models selected for this work (MT_CKD 4.2, MT_CKD 2.5 and CAVIAR models). Details on the generation of these correlated k -distribution gas-optics models are given in Menang et al. (2024, 2025). We calculate the all-sky fluxes using the two-stream Tripleclouds solver (Shonk and Hogan, 2008) with the *exponential-random* cloud overlap scheme (Hogan and Illingworth, 2000). We compute the cloud overlap parameter during ecRad runs from the overlap decorrelation length as stated in Hogan (2022). The overlap decorrelation length prescribed in ecRad was calculated as a function of latitude following Shonk et al. (2010). Calculations with MT_CKD 4.2 are taken as reference in this work.

2.3. Cloud vertical structure and calculation of SW CRE

As mentioned in Section 1, SW CRE depends on individual cloud classes (or categories) such as, cloud type, cloud regime (weather state), cloud vertical structure and cloud phase as well as how frequently the classes occur (Oreopoulos et al., (2016, 2017); Matus and L’Ecuyer, 2017; Stephens et al., 2018). CRE components estimated based on these different cloud classes are broadly consistent since they are related through common cloud features. Thus, choosing only one of these cloud classes is sufficient for our study. Here we focus only on the SW radiative effects of cloud vertical structure. Within the vertical cloud structure category, we limit our investigation to four vertical cloud structure representation: single-layer low-level clouds, single-layer high-level clouds, distinct simultaneous low- and high-level clouds, and distinct simultaneous low-, mid-, and high-level clouds. Using satellite observations, Hill et al. (2018) reported that these four cloud vertical structure classes are the most frequent in southern West Africa (from $5^\circ - 10^\circ\text{N}$ and $8^\circ\text{W} - 8^\circ\text{E}$ and during June – September 2006–2010), a typical tropical region that is suitable for this study.

We calculate both the TOA and surface SW CREs using the standard definition of CRE (Ramanathan et al., 1989; Allan, 2011; Hill et al., 2018):

$$\text{SW CRE} = \left(F_{SW}^{allsky\downarrow} - F_{SW}^{allsky\uparrow} \right) - \left(F_{SW}^{clrsky\downarrow} - F_{SW}^{clrsky\uparrow} \right)$$

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where $F_{SW}^{allsky\downarrow}$ and $F_{SW}^{allsky\uparrow}$ are, respectively, the all-sky SW downward and upward fluxes computed by the RCE model, while $F_{SW}^{clrsky\downarrow}$ and $F_{SW}^{clrsky\uparrow}$ are the SW downward and upward fluxes computed by repeating the RCE model calculations without clouds (clear-sky conditions). However, since $F_{SW}^{allsky\downarrow}$ and $F_{SW}^{clrsky\downarrow}$ are equal at the TOA (they are both the incoming solar radiation), the SW CRE at TOA is simply $F_{SW}^{clrsky\uparrow} - F_{SW}^{allsky\uparrow}$. The atmospheric SW CRE is computed by subtracting the SW CRE at the surface from the SW CRE at the TOA.

3. Results and discussion

3.1. Three cloud layers configuration

Table 2 shows the TOA, surface and atmospheric SW CREs for the distinct simultaneous low-, mid-, and high-level clouds configuration computed with MT_CKD 4.2, MT_CKD 2.5 and CAVIAR continuum models. These computations were carried out at the current Earth’s average surface temperature of 288 K. The TOA and surface SW CREs are negative because the increased atmospheric opacity due to clouds enhances reflectance of incoming solar radiation to space compared to clear skies and reduces the transmitted SW flux towards the surface far exceeding any difference in surface upward fluxes. The presence of clouds enhances atmospheric absorption of solar radiation leading to a positive atmospheric SW CRE. The increase in atmospheric absorption due to absorptive liquid droplets and ice crystals in the clouds leads to a reduction in water vapor absorption below the cloud because of reduction in solar irradiance transmission (Oreopoulos et al., 2017). However, the positive values of SW CRE obtained here shows that the absorption by cloud particles is greater than the reduced water vapour absorption. The SW CRE values given in Table 2 are comparable to observed cloud radiative effects reported by previous analyses in the tropical region, where the cloud properties for this study are taken from (Collow et al., 2016; Hill et al., 2018; Dommo et al., 2023). The atmospheric CRE given in Table 2 are much smaller than the TOA and surface CREs because enhanced SW atmospheric absorption in the presence of clouds is small and most of the shortwave extinction is manifested mostly in increased scattering and reduced transmission (Hill et al., 2018). This small additional absorption by clouds in the atmospheric column is responsible for the slightly larger values of surface SW CRE compared to TOA SW CRE (Oreopoulos et al., 2017).

This study thus shows that present-day observed TOA, surface and atmospheric SW CREs in the tropical region can be reproduced from calculations using a one-dimensional RCE model in which idealised distinct simultaneous low-, mid-, and high-level clouds have been added to it (with average typical cloud properties of the tropics). Our work thus complements and extends that of Kluft et al. (2025) which focussed on the analyses of global TOA CRE using a single-column RCE model.

Table 2
TOA, surface and atmospheric SW CREs for MT_CKD 4.2, MT_CKD 2.5 and CAVIAR continuum models. These CREs are computed with distinct clouds introduced simultaneously at three vertical levels stated in the text. All calculations are at 288 K, the current average surface temperature of the Earth.

Continuum model	SW CRE (W m^{-2})		
	TOA	Surface	Atmospheric
MT_CKD 4.2	-64.7	-71.0	+ 6.3
MT_CKD 2.5	-64.7	-71.0	+ 6.3
CAVIAR	-64.8	-70.9	+ 6.1

Table 2 shows that the uncertainty in the characterising water vapour continuum absorption in the shortwave spectral region has a relatively more significant impact on the atmospheric SW CRE than on the TOA and surface SW CREs. Differences in the strength of the two MT_CKD models do not have any impact on the SW cooling of clouds at the TOA and surface as well as the SW warming of clouds within the atmosphere as shown in Table 2. This is because the reduction of net SW fluxes by clouds computed with the two MT_CKD models at the TOA and surface are not significantly different to reflect in the computed CRE.

Compared to calculations with MT_CKD 4.2, calculations with the stronger CAVIAR model leads to very small increase (by 0.1 W m^{-2} or $\sim 0.2\%$) and decrease (by 0.1 W m^{-2} or $\sim 0.1\%$) in SW cooling of clouds at the TOA and surface respectively. With respect to MT_CKD 4.2, calculations with CAVIAR leads to a reduction in both all-sky and clear-sky upward SW radiation at the TOA, but the reduction in clear-sky upward flux is relatively more significant. This leads to an increase in cooling of clouds for computations with CAVIAR. This reduction in upward flux at the TOA with CAVIAR is because clear-sky shortwave atmospheric absorption due to CAVIAR is larger than that due to MT_CKD 4.2 (Menang, 2025). Calculations with CAVIAR also leads to a reduction in both all-sky and clear-sky downward and upward SW fluxes at the surface. The reduction in surface clear-sky downward flux is relatively more significant, and this slightly reduces the SW cooling of clouds at the surface as Table 2 shows. This reduction in surface SW cooling with the corresponding increase in TOA cooling by clouds results in a slight decrease in atmospheric SW CRE estimated with CAVIAR. Computations with the CAVIAR continuum model leads to reduction of 0.2 W m^{-2} ($\sim 3.2\%$) in atmospheric SW CRE relative to that computed with MT_CKD 4.2 (Table 2). Hence, computations with the stronger CAVIAR model lead to a slight reduction in SW warming of clouds in the atmospheric column.

3.2. Other vertical cloud layers configurations

The TOA, surface and atmospheric SW CREs for the single-layer low-level clouds, single-layer high-level clouds and distinct simultaneous low- and high-level clouds computed with MT_CKD 4.2, MT_CKD 2.5 and CAVIAR continuum models are shown in Table 3. For these three vertical cloud structure configurations, the TOA and surface SW CREs are negative while the atmospheric SW CRE is positive (as was the case with the three simultaneous layers of clouds discussed in Section 3.1). Tables 2 and 3 show that the SW CRE depends on the numbers of vertical cloud layers in the atmospheric column. An increase in the number of cloud layers increases the water path and optical depth of the clouds (Hill et al., 2018). Thus, the simultaneous three-layer clouds configuration, which is likely to be most optically thickest clouds considered in this work, has the largest SW CRE, followed by the simultaneous two-layer clouds configuration (Tables 2 and 3). Compared to calculations with clouds at three levels in the atmospheric column (Section 3.1), Table 3 also shows that the low- and high-level clouds account for most the SW CRE.

Table 3 shows that the differences in the strength of the water vapour continuum absorption in shortwave spectral region also have a small and negligible impact on the SW CRE for these three vertical

cloud structure configurations. For these configurations, both the absolute and percentage differences in the SW CRE are equal to those for the three-layer clouds configuration discussed in Section 3.1.

Table 3

As in Table 2, but computations are carried out when a single-layer low-level clouds, a single-layer high-level clouds and distinct simultaneous low- and high-level clouds are prescribed into the atmospheric profile.

Vertical cloud structure configuration	Continuum model	SW CRE (W m^{-2})		
		TOA	Surface	Atmospheric
Single-layer low-level clouds	MT_CKD 4.2	-30.8	-35.5	+ 4.7
	MT_CKD 2.5	-30.8	-35.5	+ 4.7
	CAVIAR	-30.8	-35.4	+ 4.6
Single-layer high-level clouds	MT_CKD 4.2	-30.0	-32.0	+ 2.0
	MT_CKD 2.5	-30.0	-32.0	+ 2.0
	CAVIAR	-30.1	-31.9	+ 1.9
Distinct simultaneous low- and high-level clouds	MT_CKD 4.2	-55.3	-61.1	+ 5.9
	MT_CKD 2.5	-55.3	-61.1	+ 5.9
	CAVIAR	-55.3	-61.0	+ 5.7

4. Summary and conclusion

Discrepancies in estimated shortwave (SW) cloud radiative effect (CRE) have been attributed to factors such as differences in cloud properties and treatment of cloud layers in radiative transfer schemes in models. Accounting for water vapour continuum absorption is crucial in atmospheric radiative transfer calculations. The water vapour continuum has not been properly constrained in the shortwave spectral region. In this work, we have added conceptual clouds into a single-column radiative-convective equilibrium (RCE) model and use it to investigate the impact of the disagreements in the strengths of water vapour continuum absorption in the shortwave spectral region on SW CRE.

We use the python code konrad to create a 512-level atmospheric profile of temperature and water vapor volume mixing ratio between 1000 and 0.01 hPa. To conform with the RCE assumption, the tropospheric temperature profile is adjusted to follow a moist adiabat that corresponds to the prescribed surface temperature of 288 K up to the tropopause temperature of 175 K. The stratospheric temperature profile is kept constant at the tropopause temperature of 175 K. We perform radiative transfer calculations in this single-column RCE model using the offline version of the ECMWF radiation scheme ('ecRad'). We add uniform 150 hPa-thick vertical layers of clouds at four configurations into the RCE model: single-layer low-level clouds, single-layer high-level clouds, distinct simultaneous low- and high-level clouds, and distinct simultaneous low-, mid-, and high-level clouds. The cloud properties are taken from observations

of typical conditions in the tropics. We select the MT_CKD 4.2, MT_CKD 2.5 and CAVIAR water vapour continuum models for our analysis. The correlated k -distribution gas-optics tables for ecRad are trained with each of these continuum models.

This work shows that a single-column RCE model with conceptual distinct simultaneous low-, mid-, and high-level clouds prescribed into it can simulate TOA, surface and atmospheric SW CREs that are comparable to those obtained from observations in the tropical region. The low- and high-level clouds account for most of the SW CRE.

For all the vertical cloud configuration considered in this study, differences in the MT_CKD continuum models have no impact on computed SW CREs. TOA and surface SW CREs calculated with the CAVIAR continuum model is only $\sim 0.1 \text{ W m}^{-2}$ (only up to 0.2%) different from those calculated with MT_CKD 4.2. The atmospheric SW CRE computed with the CAVIAR continuum model is only $\sim 0.2 \text{ W m}^{-2}$ ($\sim 3.2\%$) less than that computed with MT_CKD 4.2.

Thus, compared to other factors such as differences in cloud properties implemented in atmospheric models (e.g., Jahangir et al., 2021), the uncertainty in characterising water vapour continuum absorption in the shortwave spectral region is not a major contributor to the inter-model discrepancies in estimated shortwave cloud radiative effects.

Declarations

Competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Author contributions

The conception, design, material preparation, data collection and analysis of the study were performed by the author. The author wrote all versions of the manuscript.

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Data availability

The MT_CKD and CAVIAR continuum data sets is available at https://github.com/AER-RC/MT_CKD_H2O and <http://www.met.reading.ac.uk/caviar/home/data.php> respectively. The ERA5 reanalysis data used here can be downloaded from <https://confluence.ecmwf.int/display/ECRAD/ecRad+practical>. The offline version of the ECMWF radiation code ('ecRad') is available at <https://github.com/ecmwf-ifs/ecrad>. The model konrad (v1.0.2) is available at <https://zenodo.org/records/7438306>.

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Figures

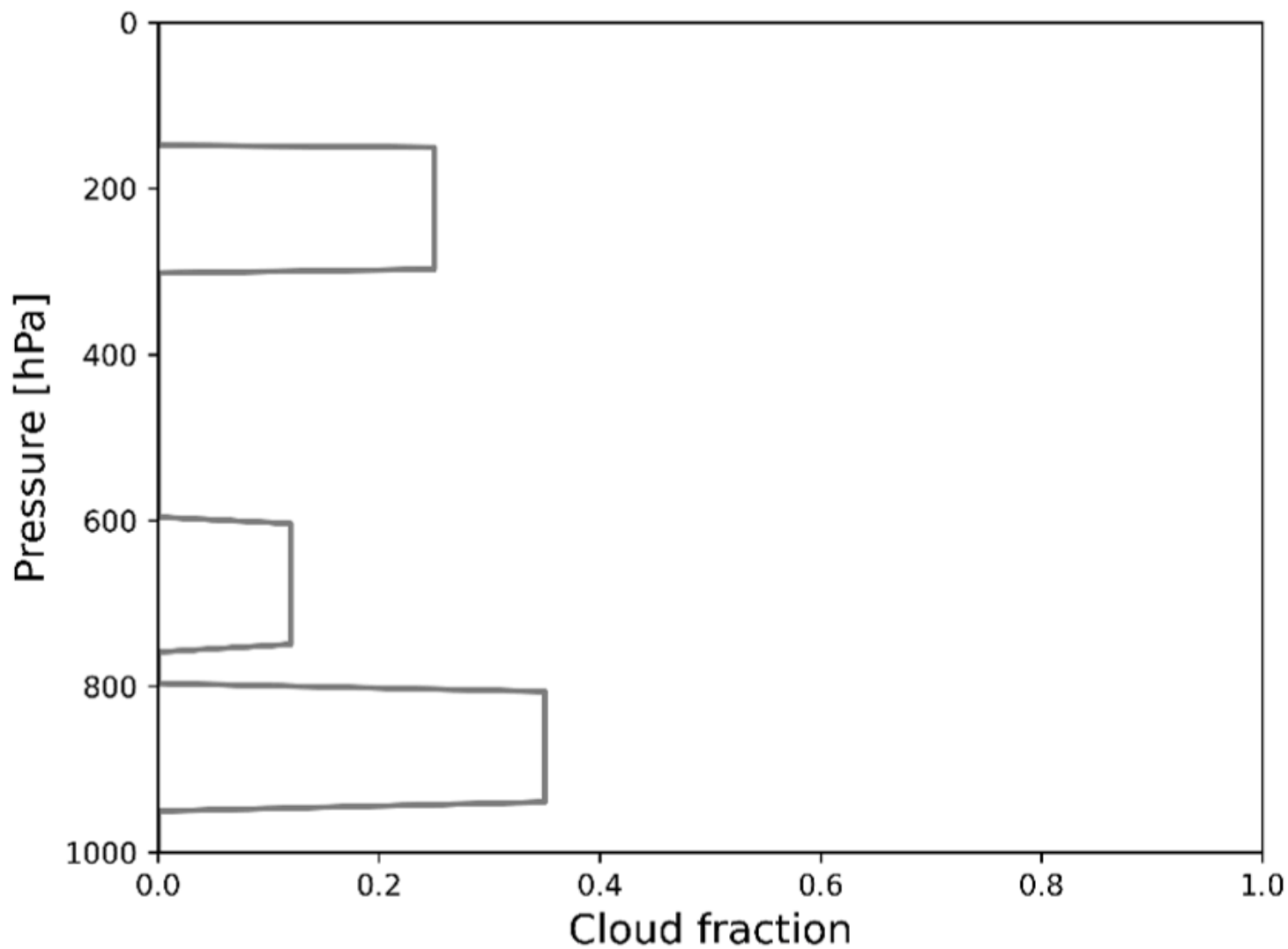


Figure 1

Conceptual low-, mid-, and high- level clouds as a function of cloud fraction defined for this study. These cloud layers have equal vertical thickness of 150 hPa.

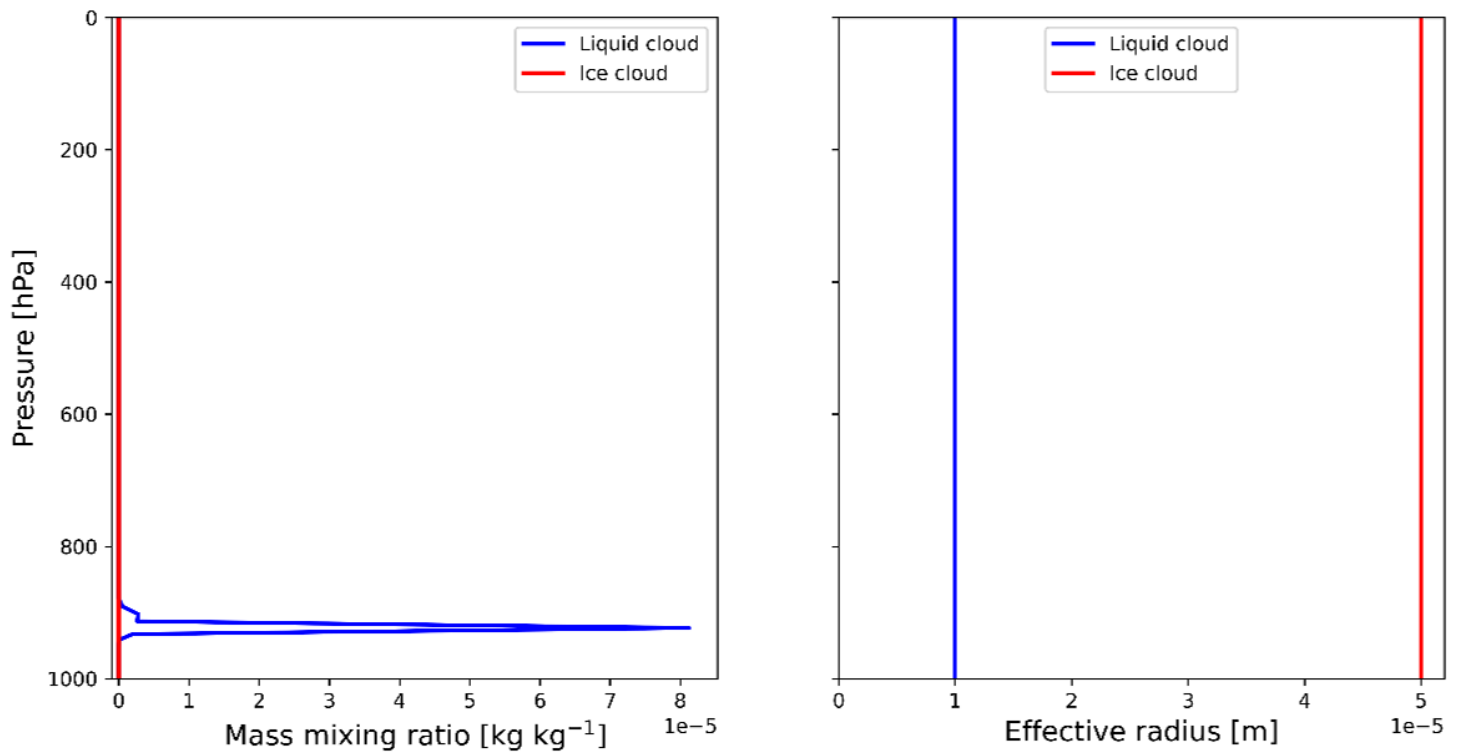


Figure 2

(Left) Liquid and ice cloud mass mixing ratios and (right) liquid and ice cloud effective radii of a low cloud layer at 10°S from the ERA5 dataset described in the text.