The Runaway Greenhouse in a Cloudy Column

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1 Introduction

1.1 What is a Runaway Greenhouse

The Runaway Greenhouse refers to a process in which the liquid reservoir of a volatile greenhouse gas completely evaporates due to a positive greenhouse feedback. In our case the volatile greenhouse gas is water vapor.

1.2 Motivation

Previous studies on the Runaway Greenhouse did not include the effects of clouds or assumed either a constant fractional cloud cover [1,2,3] or investigated the influence of cloud cover exemplarily for a single temperature (but different pressure levels) [4]. The results of two more recent studies [5,6] conducted with GCMs indicate that the total cloud cover tends to decrease as the average surface temperature increases. This effect may prevent the system from attaining a new equilibrium: The reduced cloud cover tends to decrease the albedo and therefore leads to a positive feedback, which is supposed to outweigh the negative longwave feedback associated with a reduced cloud cover [6]. Hence the cloud-albedo feedback may play a very important role in assessing critical values for the necessary forcing to destabilize the climate. More precisely we would like to know:

- **Do clouds have an influence on the critical solar irradiance for the onset of a Runaway Greenhouse ?**
- **What is the influence of the cloud albedo?**

1.3 Method

We use a single-column version of the general circulation model ECHAM6 with 95 atmospheric layers. An ensemble of three runs is performed for both clear-sky conditions (CSC, clouds are present but transparent to radiation) and full sky-conditions (FSC, clouds affect radiation). In order to have comparable control climates the surface-albedo is increased to 0.27 for CSC. The column is located at the equator and the time-averaged total solar irradiance (TSI) is varied between 1120 Wm^{-2} and 1800 Wm^{-2}. Hence, the TSI averaged over a year (TSI_{ann}) (at the equator) varies between experiments from 343 Wm^{-2} to 552 Wm^{-2}. The column is isolated to the side such that there is no horizontal energy transport. The runs end either after 50 years or once the mixed layer ocean or an atmospheric layer reaches 383 K.

2 Results

2.1 The influence of clouds on the critical solar irradiance

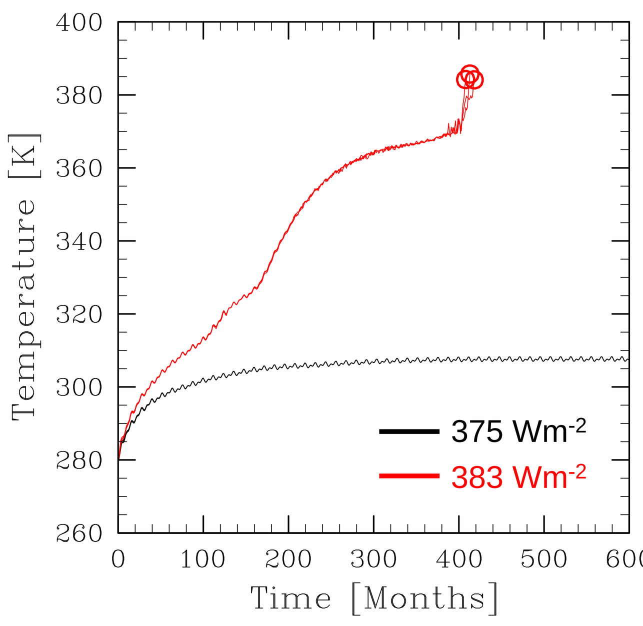

Fig. 1a: Temperature of the lowest atmospheric level for runs with CSC and a TSI_{ann} of 375 Wm^{-2} (black lines) and 383 Wm^{-2} (red lines). Circles indicate that the runs are terminated, because boiling temperature is attained.

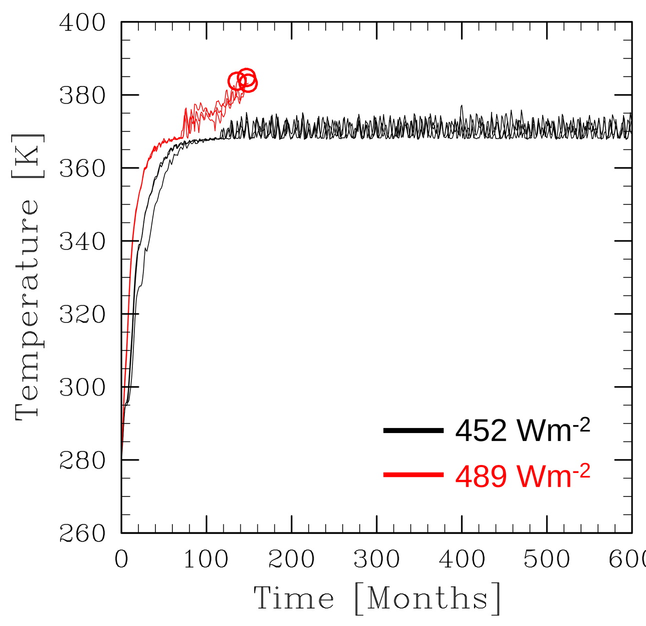

Fig. 1b: Temperature of the lowest atmospheric level for runs with FSC and a TSI_{ann} of 452 Wm^{-2} (black lines) and 489 Wm^{-2} (red lines). Circles indicate that the runs are terminated, because the boiling temperature is attained.

The experiments with CSC (Fig. 1a) show that an equilibrium may be attained for a TSI_{ann} of 375 Wm^{-2}, but a Runaway Greenhouse occurs for all initial conditions for a time averaged TSI_{ann} of 383 Wm^{-2}. Hence the critical solar constant for CSC lies between 375 Wm^{-2} and 383 Wm^{-2}.

For FSC (Fig. 1b) equilibrium may be attained for a TSI_{ann} of 452 Wm^{-2} with surface temperatures in the 360 K's. For a TSI_{ann} of 489 Wm^{-2} the atrmospheric temperature of all experiments exceeds 383 K and hence a Runaway Greenhouse may occur. Simulations with TSI_{ann} between 452 Wm^{-2} and 489 Wm^{-2} have been conducted but the results were inconclusive with ensemble members terminating the runs and others exceeding atmospheric temperatures of 383 K.

The difference in critical solar irradiance between runs with CSC and FSC implies thus that clouds play an important role in preventing the column from going into a Runaway Greenhouse for a large range of TSI.

2.2 The influence of the cloud albedo on the radiative balance

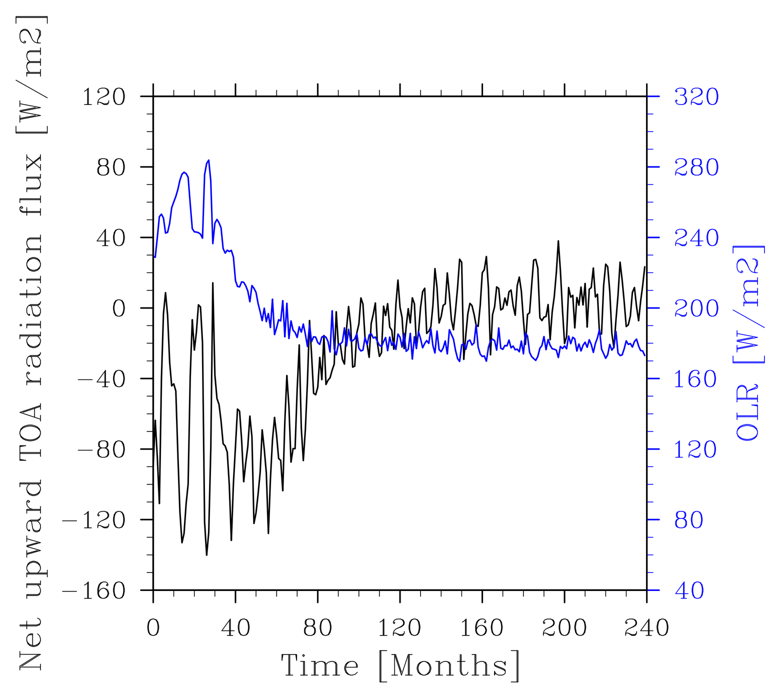

Fig. 2a: The net upward top of the atmosphere (TOA) radiation flux (black) and the outgoing longwave radiation (OLR) (blue) plotted as a function of time for one of the runs with FSC and a TSI_{ann} of 452 Wm^{-2} (first 20 years).

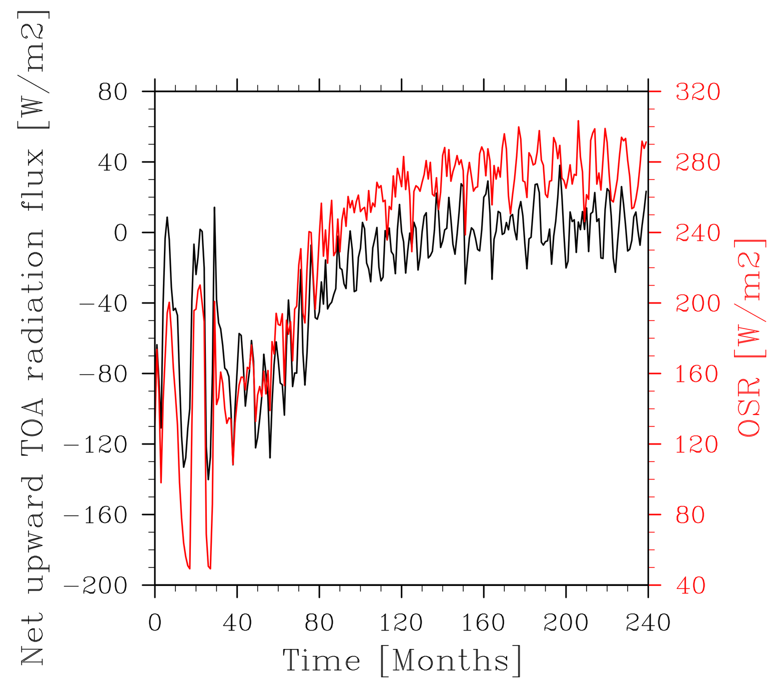

Fig. 2b: The net upward top of the atmosphere (TOA) radiation flux (black) and the outgoing shortwave radiation (OSR) (red) plotted as a function of time for one of the runs with FSC and a TSI_{ann} of 452 Wm^{-2} (first 20 years).

Figures 2a and 2b show the OLR, the OSR and the radiative imbalance for one of the runs with FSC and a TSI_{ann} of 452 Wm^{-2} . As expected from previous studies on the Runaway Greenhouse, the OLR decreases as the surface temperature increases due to increasing infrared absorption by water vapor. The OSR decreases strongly for short periods during the first 40 months, which leads to a strong radiative imbalance at the TOA, which contributes to the initial increase of surface temperature. Eventually the albedo and hence the OSR show a strong increase (see also Fig. 4) which restores the radiative balance of the column. Since the surface albedo is constant, the cloud albedo feedback is therefore the crucial mechanism to restore equilibrium at high temperatures.

2.3 The effect of the clouds on the albedo

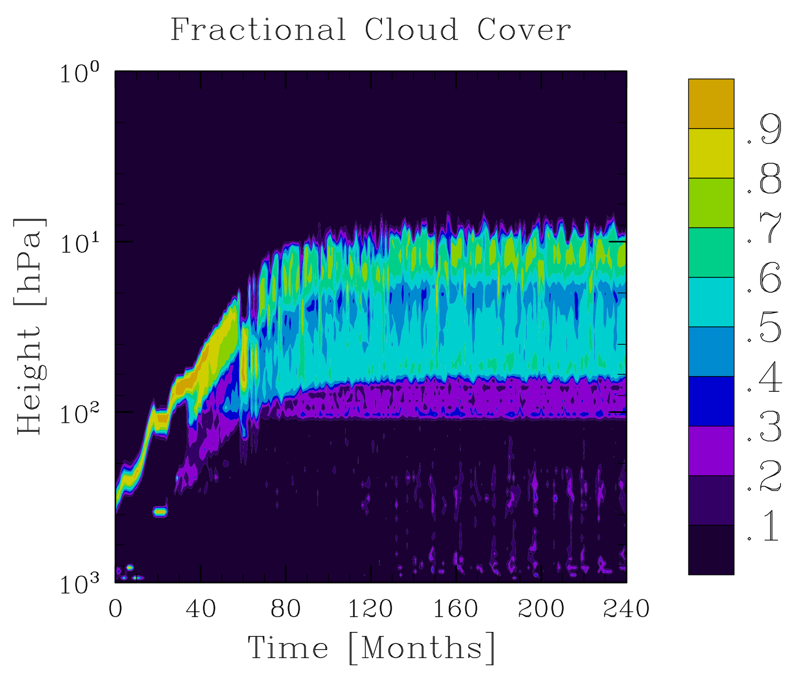

Fig. 3: Fractional cloud cover as a function of height and time for one of the runs with FSC and a TSI_{ann} of 452 Wm^{-2} (first 20 years).

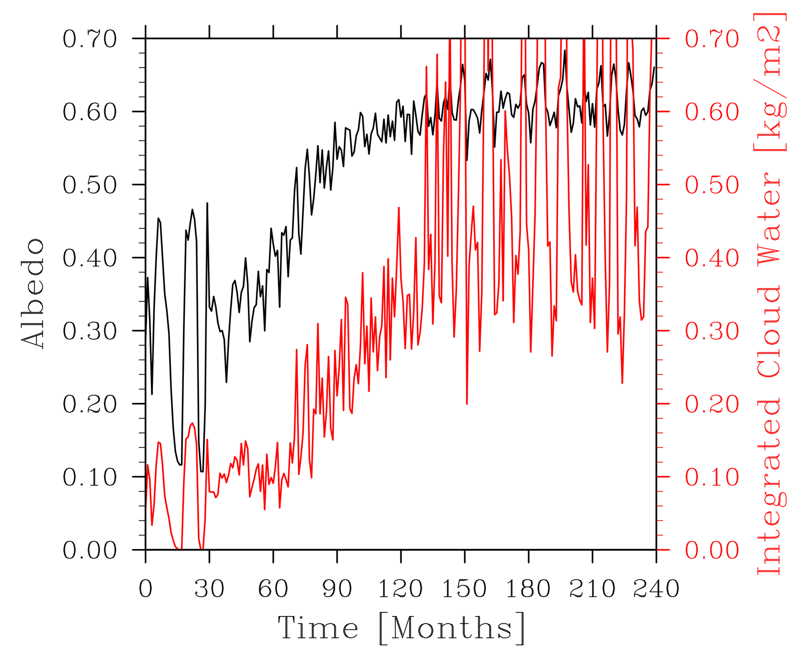

Fig. 4: Evolution of the albedo (black) and of the integrated cloud water (red) in one of the runs with FSC and a TSI_{ann} of 452 Wm^{-2} (first 20 years).

Even though the cloud profile changes markedly with time, a main feature of Fig. 3 is that clouds are always present and that the total (integrated) cloud cover does not vary strongly with time. So the increase in cloud albedo cannot be attributed to an increase in cloud cover. From Fig. 4 it becomes clear that it is the increase in cloud water which causes the albedo to increase. Hence the cloud albedo is increasing due to thicker clouds.

3 Conclusions

1. **Clouds have an influence on the critical solar strength for a Runaway Greenhouse.**
2. **The cloud albedo feedback is the crucial mechanism to restore the equilibrium of the column at high temperatures.**
3. **The cloud albedo is markedly higher at high temperatures due to thicker clouds.**

References:

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