The effect of atmospheric pressure on Snowball Earth deglaciation

Nicholas Edkins and Roger Davies

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The Effect of Atmospheric Pressure on Snowball Earth Deglaciation

Nicholas Edkins[1,a)] and Roger Davies[1,b)]

[1]*University of Auckland, Auckland, New Zealand*

[a)]Corresponding author: nedk437@aucklanduni.ac.nz
[b)]r.davies@auckland.ac.nz

Abstract. The most common explanation for the escape from a Snowball Earth state involves, among other factors, a strong greenhouse effect caused by a large partial pressure of CO2. This leads to an increase in surface pressure, which most models do not account for. With a higher surface pressure, pressure broadening increases, and convection reaches a deeper layer, both of which result in higher surface temperatures. The latter mechanism, which has not previously been reported, is found to be a greater source of warming than pressure broadening in the normal range of CO2 partial pressures at the point of deglaciation.

INTRODUCTION

The term 'Snowball Earth' describes two global glaciation events in the Neoproterozoic era – the Sturtian, 720 Mya, and the Marinoan, 635 Mya – during which the Earth's surface was ice-covered from the poles to latitudes near or at the equator [1]. From here on, 'Snowball Earth' refers to either of these events.

A commonly proposed scenario for the end of these glaciations involves a very large greenhouse effect caused by the build-up of CO_2 in the atmosphere to high levels, with the CO_2 partial pressure (pCO_2) reaching on the order of tenths of a bar. Ordinarily, the amount of atmospheric CO_2 is determined by a balance between volcanic outgassing (a source) and silicate weathering (a sink). However, silicate weathering is temperature-dependent and would practically cease under Snowball conditions [2], while the volcanic outgassing rate would likely remain close to its present value, allowing for a large accumulation of CO_2 in the atmosphere [3].

Assuming that the amounts of the non-CO_2 gases remain constant, the increased pCO_2 would result in increased surface pressure. As noted and modeled by Hu et al. [4], this would mean increased pressure broadening of the CO_2 absorption lines, which would increase CO_2 absorption and therefore increase the surface temperature. As a result, the amount of CO_2 required for deglaciation (the 'deglaciation threshold') is reduced. Most other Snowball Earth models do not account for pressure broadening, which means that the deglaciation threshold is commonly overestimated.

However, increasing the surface pressure has another consequence that has been neglected thus far. It effectively 'lowers the floor', allowing more space for convection to move into. To illustrate this, compare Fig. 1a and Fig. 1b. The temperature profiles for pressures less than 1 bar will be the same in both cases, since the vertical distribution of greenhouse gases is the same for each. But convection continues from the 1 bar level down to the surface in Fig. 1b, allowing a higher surface temperature to be reached; this is 'convective deepening'.

In the new area between 1 bar and the surface in Fig. 1b, the presence of greenhouse gases is important only insofar as they enable convection. The actual greenhouse effect from gases in this region will be small, because the temperature profile is dominated by convection.

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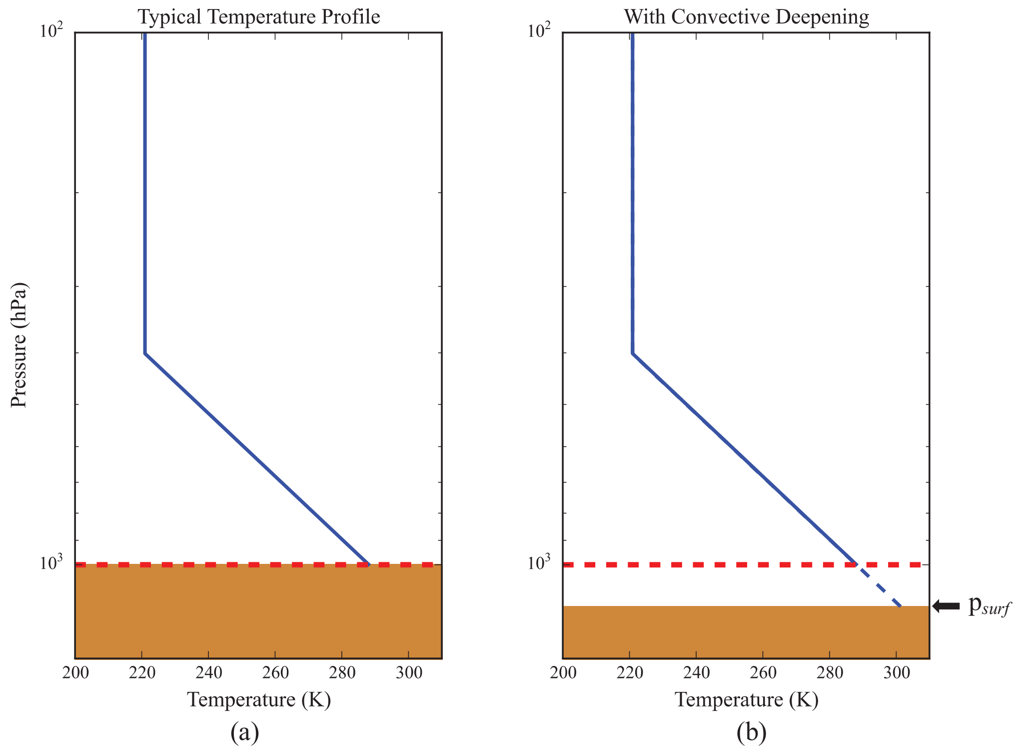

FIGURE 1. Idealized present Earth atmosphere with a) surface pressure = 1 bar, and b) surface pressure = 1.2 bar. The surface is at the top of the brown area.

VALIDATING THE MODEL FOR THE PRESENT EARTH

To quantitatively investigate the convective deepening mechanism, a radiative-convective model was developed. The longwave radiative transfer was provided by PRRTM_LW, which is the planetary version of RRTM [5]. It was necessary to use the planetary version because the cold temperatures and high CO_2 partial pressures encountered in the process of Snowball Earth deglaciation are outside the range for which RRTM is validated.

To determine whether the radiative-convective model worked correctly, it was first necessary to set the parameters to their values for the present Earth and ensure that the output matched observations. Globally averaged values of the observed vertical mixing ratio profiles of water vapor, carbon dioxide, and ozone were calculated using the BDBP database [6]. The observed global average vertical profile of cloud fraction was obtained from MISR, and an optical depth was assigned to each cloud level, with an additional ice cloud added at 18.3 km, following Radley [7]. The lapse rate was set at 5.7 K/km. Although this is lower than the usual 6.5 K/km used by Manabe and Wetherald [8], it agrees with Kuhn [9] and more modern data. The planetary albedo was assumed to be 0.3. Lacis and Hansen's [10] parameterizations were used to calculate the shortwave absorption.

With these parameters, the modeled global average surface temperature was 288.4 K, which agrees well with the observed value. This confirmed that the model was able to replicate the climate of the present-day Earth.

MODELING THE SNOWBALL EARTH

In order to use the same model to simulate Snowball Earth conditions, parameters from Hu et al. were adopted. Hu et al. was chosen for replication because it is the only radiative-convective model of the Snowball Earth known to account for pressure broadening, which allows for a comparison of the relative magnitudes of pressure broadening and convective deepening.

The planetary albedo was set at 0.62. The dry adiabatic lapse rate of 9.8 K/km was applied. The vertical profile of relative humidity was determined using Manabe and Wetherald's method, with a surface relative humidity of 80%. The CO_2 was well mixed, and no ozone was included. Cloud longwave radiative forcing was accounted for through a constant reduction of the clear-sky OLR by 15.6 Wm^{-2}.

To calculate the effect of pressure broadening, Hu et al. increased the surface pressure while keeping the CO_2 mixing ratio constant. This increases pressure broadening, as they stated, but also allows convection to extend further downward, assuming that the tropopause pressure remains fixed. They attributed all of the subsequent increase in surface temperature to pressure broadening. In our model, the warming effects of pressure broadening and convective deepening can be separated and compared.

ISOLATING THE CONVECTIVE DEEPENING EFFECT

To isolate the effect of convective deepening, three different model setups were used at each value of CO_2 mixing ratio, as shown for a mixing ratio of 0.2 in Fig. 2. Run 1 included no pressure effects. Relative to Run 1, Run 2 had increased pressure broadening as well as convective deepening. Run 3 included only convective deepening; the pressure broadening was the same as in Run 1, since both contained the same gas at the same pressure. The equilibrium surface temperature in each case is shown in Fig. 3.

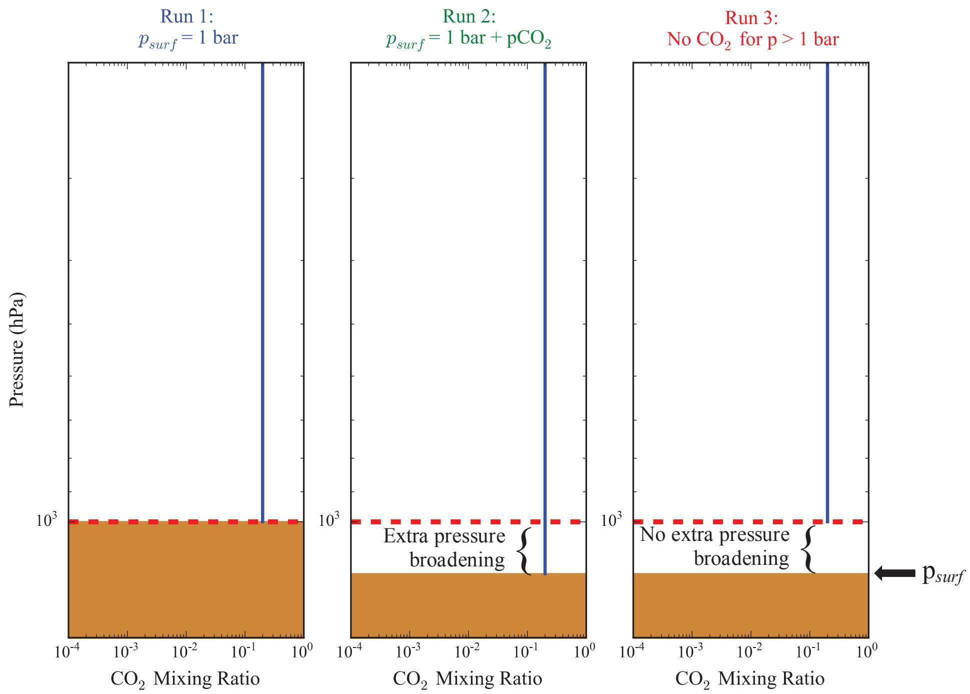

FIGURE 2. A schematic of the three model setups used to isolate the convective deepening effect. Run 1 was the baseline, with no pressure effects. Run 2 had both pressure broadening and convective deepening – this was the setup that best simulated the atmosphere when pCO_2 added significantly to the surface pressure. Run 3 was used to isolate the effect of convective deepening since, relative to Run 1, it had no extra pressure broadening.

THE RELATIVE IMPORTANCE OF CONVECTIVE DEEPENING AND PRESSURE BROADENING

The warming effects of pressure broadening and convective deepening were found to be approximately additive – the total effect was equal to the sum of each of the effects in isolation. This allowed the warming due to pressure broadening to be calculated by subtracting the surface temperature in Run 3 from that in Run 2.

Figure 3 shows that convective deepening contributed more to the surface warming than pressure broadening until about 0.4 bar. Since the convective deepening effect is approximately logarithmic in pCO_2 and the pressure broadening effect is proportional to $(pCO_2)^2$, pressure broadening becomes more important at higher pCO_2. However, for the pCO_2 required for deglaciation, the convective deepening effect is as or more important than pressure broadening (depending on the exact threshold required, which is model-dependent).

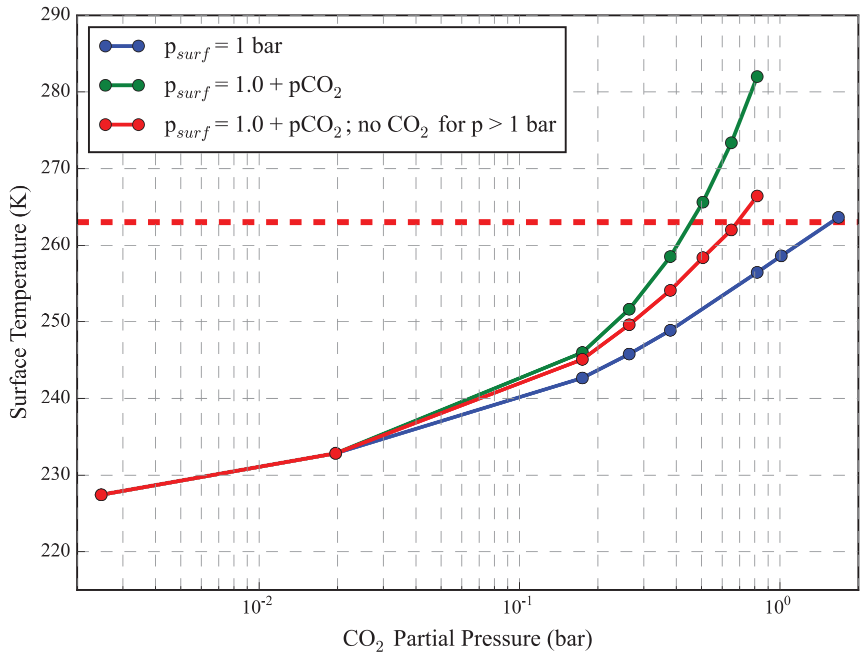

FIGURE 3. The surface temperature, for various CO_2 partial pressures, using each of the model setups in Fig. 2. The difference between the blue and red lines is due to convective deepening, and the difference between the red and green lines is due to pressure broadening. The red dashed line at 263 K shows where the model deglaciates, assuming the equatorial annual average temperature is 10 K greater than the global annual average temperature [4].

CONCLUSION

When large amounts of CO_2 are added to the atmosphere, models must allow for the fact that this will increase the surface pressure. This brings two warming effects into play: pressure broadening and convective deepening. In the range of 0.1 to 0.4 bar of added CO_2, in which most Snowball models deglaciate, convective deepening contributes more to the resultant increase in surface temperature than pressure broadening does.

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