The Importance of Condensing Versus Noncondensing Greenhouse Gases for Earth's Habitability

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1 Abstract

It is well known that greenhouse gases are important for maintaining Earth's habitability (ability to maintain liquid water on its surface). Recently Lacis et al. (2010) demonstrated, using global climate model experiments, that carbon dioxide, a noncondensing greenhouse gas on Earth is the primary greenhouse gas that controls Earth's surface temperature and hence its habitability. However, it is still unknown whether habitability can be maintained without condensing greenhouse gases, i.e. water vapor. The goal of this project is to quantify the impact of condensing versus noncondensing greenhouse gases using a global climate model in aqua planet conditions, where there is no land processes and no ocean heat transport. We performed two perturbation experiments. First, we zeroed out noncondensing greenhouse gases including carbon dioxide, nitrous oxide, methane

and ozone in order to reproduce Lacis et al's results using our model. Second, we zeroed out water vapor, the only condensing greenhouse gas, by disabling surface evaporation. Third, we have investigated the response due to a higher albedo of .8. Fourth, we have allowed 1% of water to exist in the atmosphere. In all experiments, the surface temperature evolution was quantified to understand the maintenance of Earth's habitability. We found out that when we zero out the noncondensing greenhouse gases, we reach a snowball Earth in 155 years. However, when we zero out water vapor, we still maintain temperatures above freezing in the tropics. We further found that decreasing the ocean mixed layer depth to only 50m accelerates the temperature evolution but does not change the final climate state. Finally, transition to snowball Earth, when we zero out condensing greenhouse gases, happens only when we raise the ice albedo to 0.8.

2 Introduction

It was long thought that solar radiation is the main source for maintaining the current Earth's surface temperature. In 1824, Joseph Fourier argued for the existence of the greenhouse effect [1]. Eunice Newton Foote in 1856 and John Tyndall in 1859 gave an ample evidence through experimental observations for the existence of the greenhouse effect [2]. Other scientists like Svante Arrhenius, in 1896, predicted global warming as a result of doubling the noncondensing greenhouse gas CO_2[3]. The term "Greenhouse effect" was first formulated by Nils Gustaf Ekhom in 1901[4].

"Greenhouse effect" refers to the role of the atmosphere in warming the planet's surface to a temperature above what it would be if we neglected the atmosphere's role in radiating back to the surface [5]. According to Wien's Law, Earth receives short wave radiation from the sun in the form of ultraviolet and visible radiation. Meanwhile, it emits long wave radiation (infrared radiation) back to space proportional to its temperature following the Stefan-Boltazmann law. Additionally, Earth reflects about 30% of the incoming short wave radiation[6]. Energy conservation without the atmosphere implies

$$(1-\alpha)SW = \sigma T_s^4. \tag{2.1}$$

According to (2.1) the surface temperature is about 255K if SW is $\approx$ 240 W/m^2. This temperature doesn't match the observed value of 288K. Thus, we expect the atmosphere to play an important role in absorbing and emitting radiation. This atmospheric role is usually represented by emissivity- the effectiveness of a body to emit energy in the form of thermal radiation. Taking the emissivity into account, the outgoing long wave radiation is reduced such that part of this radiation will manage to escape to space, the other part will stay to warm the surface (See Figure 1, Earth's radiation Budget). Thus, we obtain the following two equation for energy conservation [7]:

$$\epsilon\sigma T_A^4 + (1-\alpha)SW = \sigma T_s^4 \quad \text{(Surface)} \tag{2.2a}$$

$$(1-\alpha)SW = \epsilon\sigma T_A^4 + (1-\epsilon)\sigma T_s^4 \quad \text{(TOA)} \tag{2.2b}$$

Solving both equations for the surface temperature yields T_s = 288K when ϵ =.78 (See Figure 2). Therefore, greenhouse effect warms the surface temperature.

On Earth, Greenhouse gases can be divided into two groups. Water (H_2O) represents condensing greenhouse gases while carbon dioxide (CO_2), methane (CH_4), ozone (O_3) and nitrous oxide (N_2O) represent the non-condensing greenhouse gases. It has been proven recently by Lacis et al [8] that CO_2 is the primary knob for maintaining Earth's surface temperature. In this paper we use a general circulation model to investigate habitability conditions by quantifying the impact of condensing vs. non condensing greenhouse gases on Earth's temperature.

We perform two perturbation experiments and we test their sensitivity to different values of ice albedo and amount of water vapor in the atmosphere. The first is to zero out noncondensing greenhouse gases to reproduce Lacis et al's results using our model. In the second experiment, we zero out the condensing greenhouse gas H_2O by controlling surface evaporation. Moreover, We investigate the impact of ocean mixed layer depth on the response of other terrestrial parameters. In both experiments, the surface temperature evolution is quantified to understand the maintenance of Earth's habitability.

3 Methods

We have used a global climate model that simulates solutions to equations governing conservation of energy, mass, momentum, and water. We assume aqua planet conditions where the ocean is global and still. Hence, no topography, no land processes, and no ocean heat transport. First, we reproduced Lacis's results on a 250m ocean mixed layer depth model by zeroing out non condensing greenhouse gases and investigating the response of surface temperature, cloud cover, sea ice cover, column water vapor, and planetary albedo. We ran the model until we adhered energetic equilibrium by reaching zero Top of Atmosphere (TOA) net flux. Second, we zeroed out the only condensing greenhouse gas H_2O with an ocean mixed layer of 250m depth. We have also investigated the response of the previous parameters with ocean mixed layer depth of 50m. Third, we performed the same experiments with ice albedo of .8. Fourth, we investigated the response of the aforementioned parameters by allowing 1% of water vapor to exist in the atmosphere. Each experiment was done separately, and the models' output was analyzed through Matlab.

4 Results

To understand the effect of noncondensing greenhouse gases on Earth's habitability, we tested the response of different terrestrial parameters by zeroing out non condensing greenhouse gases in a global climate model with 250 m of ocean mixed layer depth. The ice albedo of this model is set to be .65. As shown in figure 3, surface temperature and column water vapor drop rapidly to below the freezing point of water within the first 10 - 20 years. Planetary albedo and cloud cover increase over time similar to Lacis's results. Sea ice cover reaches 100% (snowball Earth) within 155 years in contrast to Lacis's model which reaches 45% of sea ice cover by the time they maintain equilibrium on the model. Snowball Earth hypothesis was first proposed by Kirschivink et. al [9] where they suggested that Earth was covered by ice from the poles to the equator in two extreme cooling events in the time period between 2.4 billion and 580 million years ago. In figure 4, we can see the local effect of removing all the non condensing greenhouse gases from the atmosphere on the annual mean surface temperature. Within 155 years, temperature drops to 10 - 25 below 0 ^{o}C. On the other hand, when water was removed from the atmosphere, sea ice cover reached only about 43% suggesting the existence of a habitable region which is shown to exist between 30 ^{o} north and 30 ^{o} south (See Figure 5 and 6). The E-folding time scales for surface temperature and column water vapor are summarized in Table 1.

Figures 7 and 8 confirm the previous results with ocean mixed layer depth of only 50 m. Figure 7 shows a snowball Earth condition within 29 years of removing all the non-condensing greenhouse gases. However, in case of removing condensing greenhouse gases with 50m of ocean mixed layer depth, habitability is maintained between 30 ^{o} north and 30 ^{o} south (See Figures 9 and 10) similar to the case of deeper ocean. Thus, we can deduce that the transition to snowball Earth condition happens only when noncondensing greenhouse gases are zeroed out even with a shallower ocean. The E-folding time scales for surface temperature and column water vapor are summarized in Table 2.

Performing the same experiments with higher ice albedo of .8, we find that when we zero out noncondensing greenhouse gases with 250m of ocean mixed layer depth, cloud cover and planetary albedo increase over time. Surface temperature reaches about -50 ^{o}C within 31 years. Sea Ice cover reaches 100% within 29 years (see Figure 11 and 12) similar to the case of a shallower ocean with ice albedo of .65. On the other hand, when we zeroed out condensing greenhouse gases, we noticed that sea ice cover reaches 100% within 65 years. Other parameters like cloud cover and column water vapor behave in an expected way - they drop instantaneously to almost zero and they maintain absolute zero within 21 years. Surface temperature drops rapidly to -50 ^{o}C within 59 years (see Figure 13 and 14). We deduce that with higher ice albedo, zeroing out noncondensing greenhouse gases and condensing greenhouse gases will lead to a snowball Earth within a specific period of time (as described above). The E-folding time scales for surface temperature and column water vapor are summarized in Table 3. The e-folding estimate for the surface temperature in the case of zeroing out non condensing greenhouse gases is not applicable because, as it is shown in figure 11, the decrease in surface temperature is accelerating and therefore not exponentially decaying.

Testing the high albedo with a shallower ocean depth of 50m, we zeroed out noncondensing greenhouse gases which results in speeding up the transition to snowball Earth condition. Sea ice cover reaches 100% in 8 years. Surface temperature drops to about -48 ^{o}C within 7 years (see Figure 15 and 16). Furthermore, when the condensing greenhouse gas (water) was zeroed out, snowball Earth was maintained within 15 years. Surface Temperature drops to about -50 ^{o}C within 13 years. We deduce that shallower ocean with higher ice albedo further accelerates transition to snowball Earth in the absence of condensing and noncondensing greenhouse gases (see Figure 17 and 18). The E-folding time scales for surface temperature and column water vapor are summarized in Table 4. The e-folding estimate for the surface temperature in the case of zeroing out non condensing greenhouse gases is not applicable because, as it is shown in figure 15, the decrease in surface temperature is accelerating and therefore not exponentially decaying. Summary of the previous results is shown in Figure 21.

Finally we tested the sensitivity of the response of the previously mentioned terrestrial parameters to a small fraction of water in the atmosphere. Instead of zeroing it out, we have decreased condensing greenhouse gases to 1% with ice albedo of .65 and ocean mixed-layer of depth 250m. As a result, we found out that surface temperature increase slowly over time specifically over the range of 44-100 years. Column water vapor shows the same behavior where it exhibits a very slow increase between year 31-100. Planetary albedo acts almost like a constant; it barely changes its value over the span of 100 years. Cloud cover decrease slowly over time. TOA net flux reaches almost 0 within 86 years. Sea ice cover shows initial increase to reach a peak of 1.244% at year 13 but then drops to 0% at year 61(see Figure 19). As shown in Figure 20, temperatures above freezing exist between 77 ^{o} north and 77 ^{o} south. The E-folding time scales for surface temperature and column water vapor are summarized in Table 5.

5 Discussion

By comparing our first results of zeroing out non condensing greenhouse gases to those by Lacis et. al's model, very similar results were obtained confirming that noncondensing greenhouse gases (the major contribution comes from CO_2) are the most important factor in maintaining Earth's surface temperature. We also notice that transition to snowball Earth condition by zeroing out condensing greenhouse gases happens only when we raise the ice albedo to .8. Otherwise, we have maintained a habitable region around the equator. The overall results claim that zeroing out water from the atmosphere has less impact on habitability but we know that habitability in general depends on water. Thus, we restrict our attention here to temperature-based habitability where we define any region of temperature above the freezing point of water - 0 ^{o}C -to be habitable and regions of temperature below that point to be inhabitable.

6 Conclusions

Greenhouse effect is important in maintaining Earth's habitable surface temperature. Zeroing out noncondensing greenhouse gases always leads to a Snowball Earth and therefore they are the primary knob in maintaining Earth's surface temperature. However, zeroing out condensing greenhouse gases with ice albedo of .65 does not lead to transition to Snowball Earth because we have temperatures above freezing in the tropics. Raising the ice albedo to .8 guarantees maintaining snowball Earth -even faster- for zeroing out condensing greenhouse gases and noncondensing greenhouse gases. Having a shallower ocean speeds up the transition to snowball Earth in case of zeroing out non condensing greenhouse gases but doesn't affect -for the most part- our results for the case of zeroing out condensing greenhouse gases.

7 Acknowledgements

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Table 1: Table of e-folding time scales for 250m mixed layer ocean depth with ice albedo of .65

Variable	zero non-cond. GHG	zero cond. GHG
Surface temperature	30.760 yr	15.49 yr
Column water vapor	13.883 yr	0.271 yr

Table 2: Table of e-folding time scales for 50m mixed layer ocean depth with ice albedo of .65

Variable	zero non-cond. GHG	zero cond. GHG
Surface temperature	9.208 yr	6.739 yr
Column water vapor	3.297 yr	0.260 yr

Table 3: Table of e-folding time scales for 250m mixed layer ocean depth with ice albedo of .8

Variable	zero non-cond. GHG	zero cond. GHG
Surface temperature	NA	90.009 yr
Column water vapor	18.904 yr	0.2675 yr

Table 4: Table of e-folding time scales for 50m mixed layer ocean depth with ice albedo of .8

Variable	zero non-cond. GHG	zero cond. GHG
Surface temperature	NA	31.847 yr
Column water vapor	3.261 yr	0.249 yr

Table 5: Table of e-folding time scales for 250m mixed layer ocean depth with ice albedo of .65 with condensable greenhouse gases decreased to 1%

Variable	1% of cond. GHG
Surface temperature	16.689 yr
Column water vapor	18.587 yr

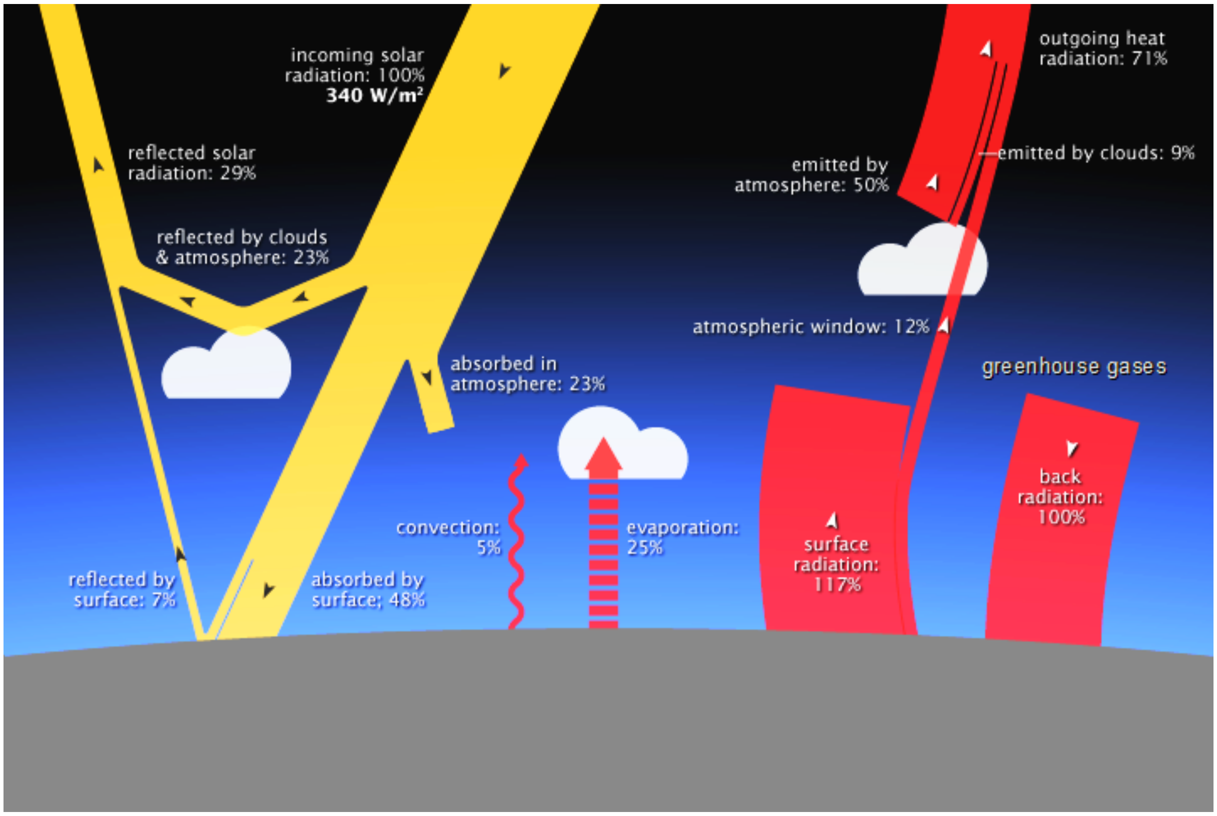

Figure 1: NASA illustration by Robert Simmon, adapted from Trenberth et al. 2009, using CERES flux estimates provided by Norman Loeb. See https:earthobservatory.nasa.govfeaturesEnergyBalance

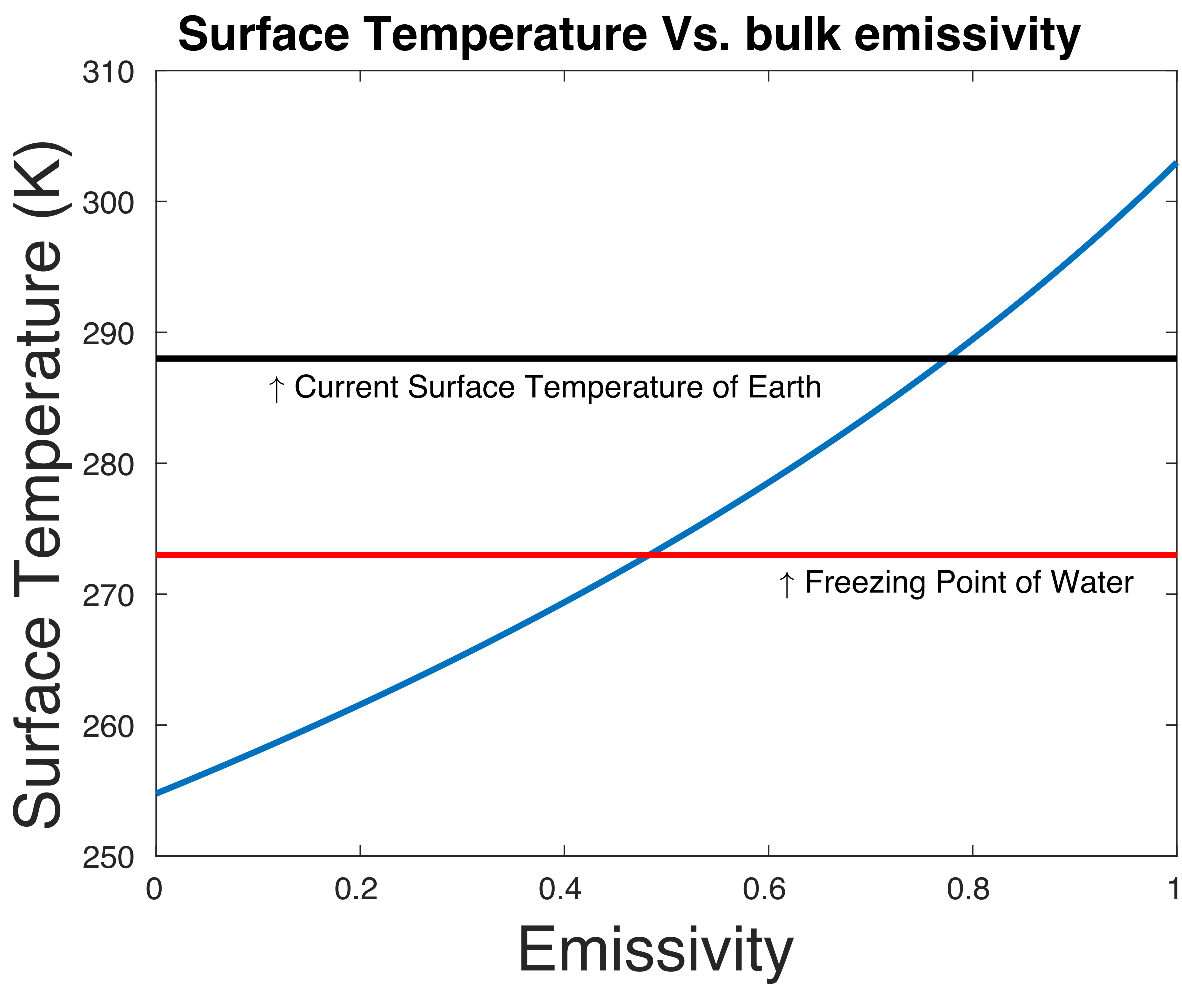

Figure 2: Surface temperature Vs. emissivity. When emissivity = 0 (no atmosphere), the surface temperature = 255K which doesn't match the realistic value of the observed 288K. When emissivity equal to .78, the observed global mean value of surface temperature is maintained. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

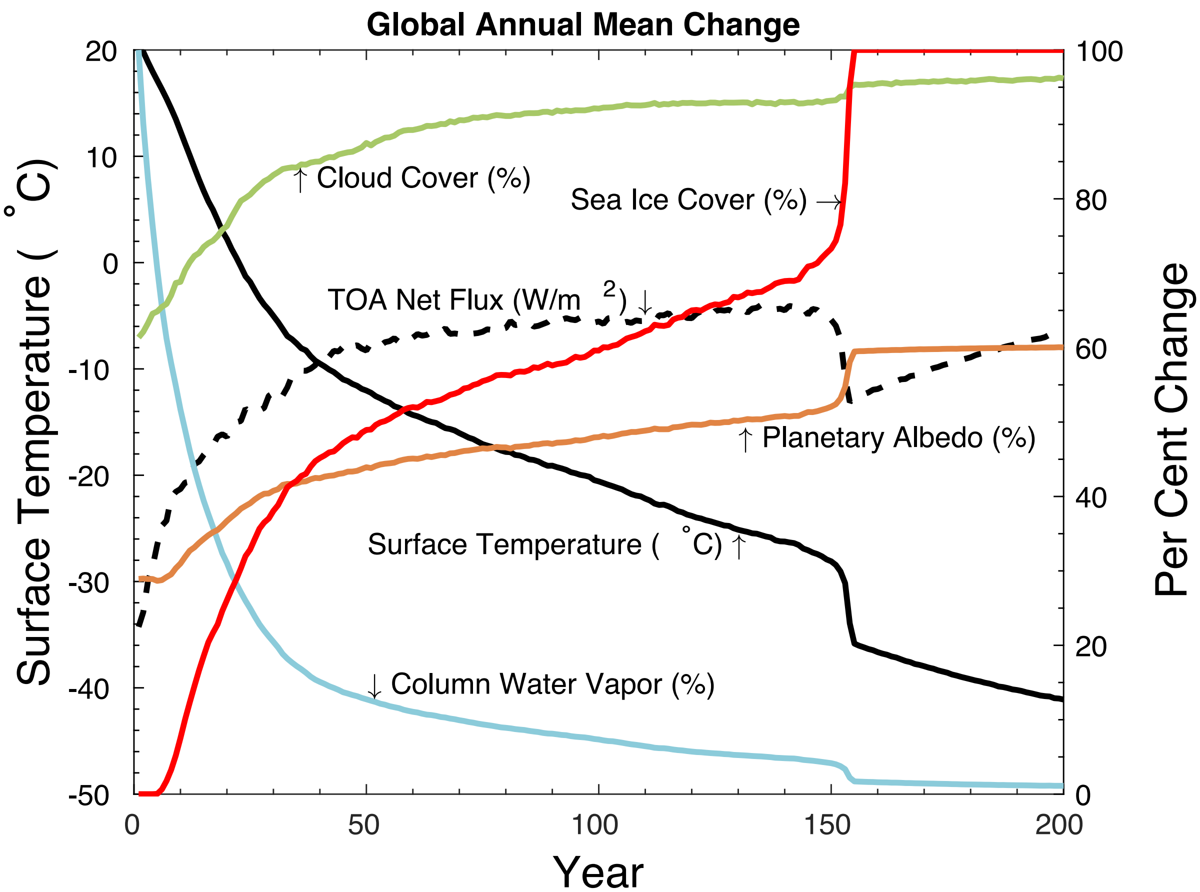

Figure 3: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out non condensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .65 with a mixed layer depth of 250m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

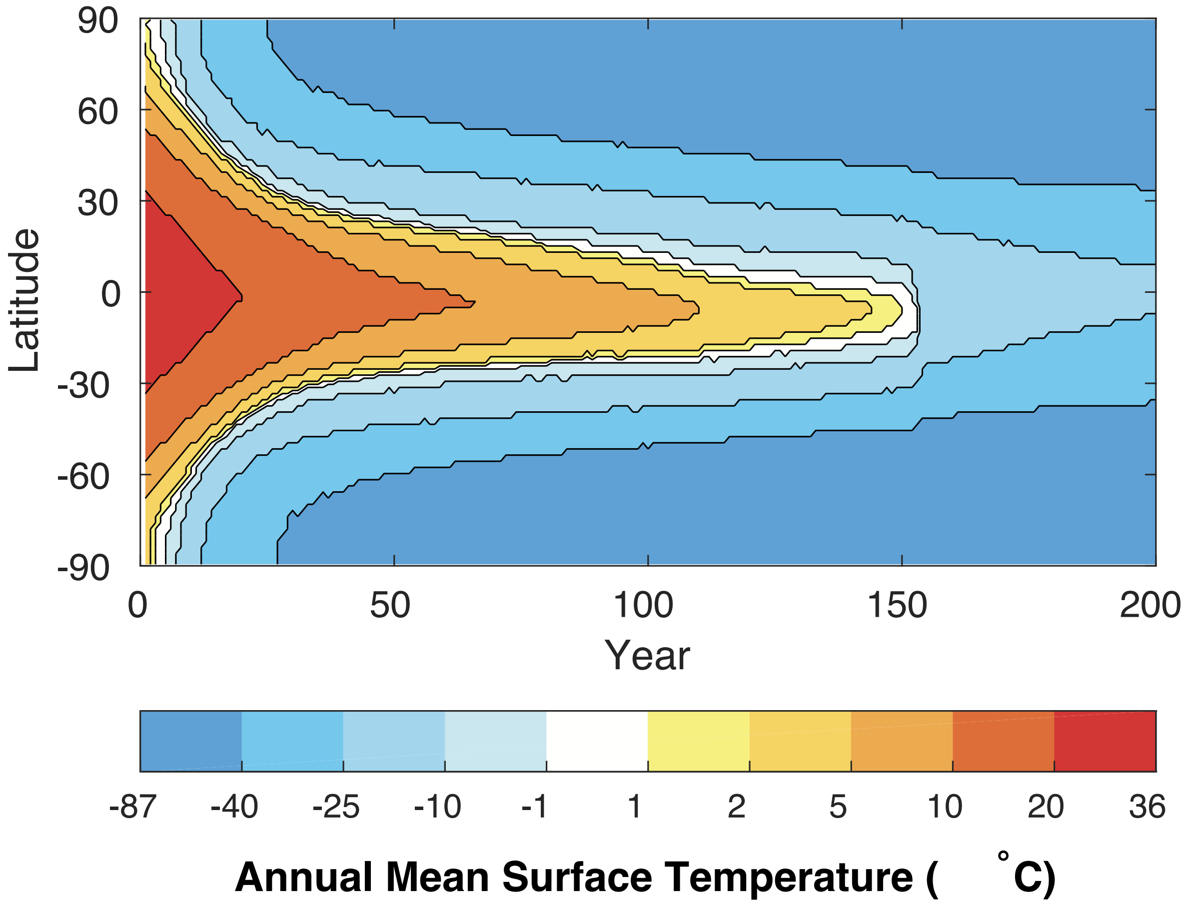

Figure 4: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out noncondensing greenhouse gases. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

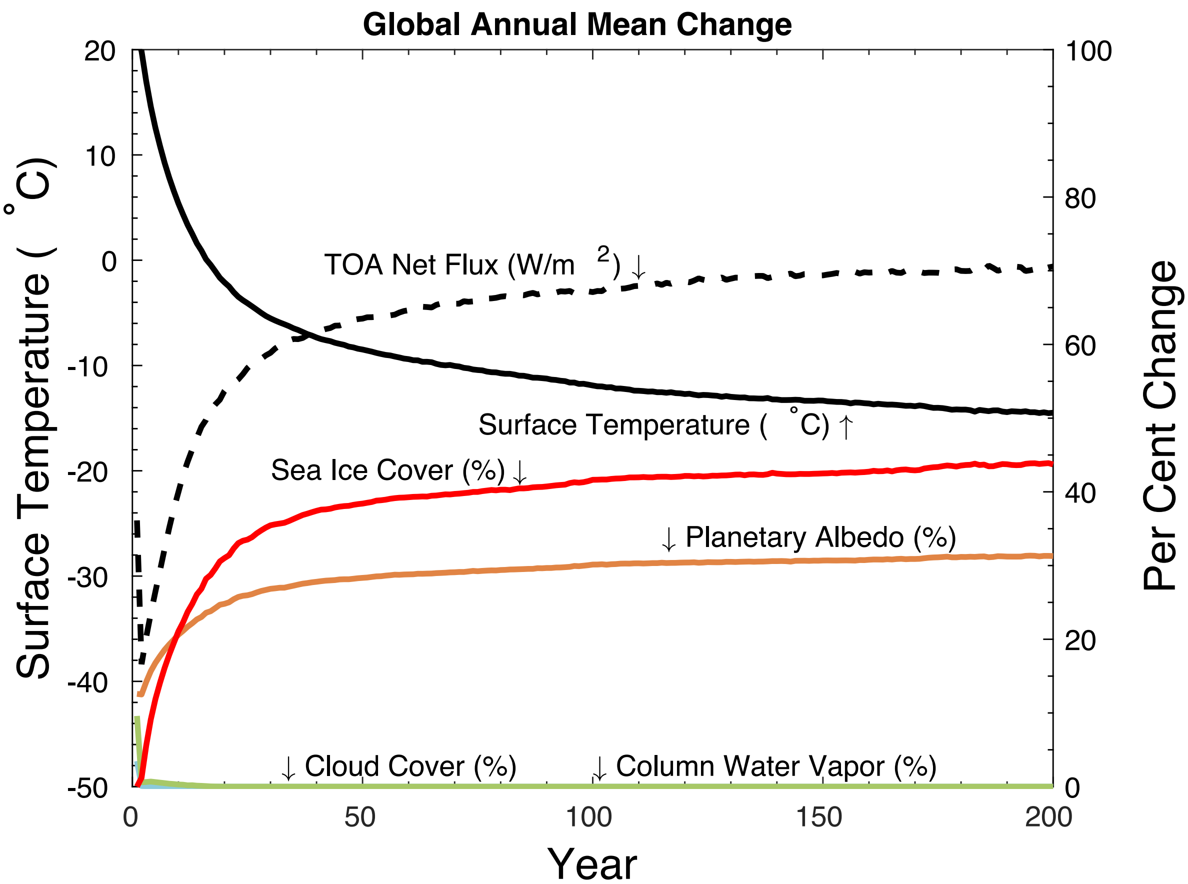

Figure 5: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out condensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .65 with a mixed-layer depth of 250m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

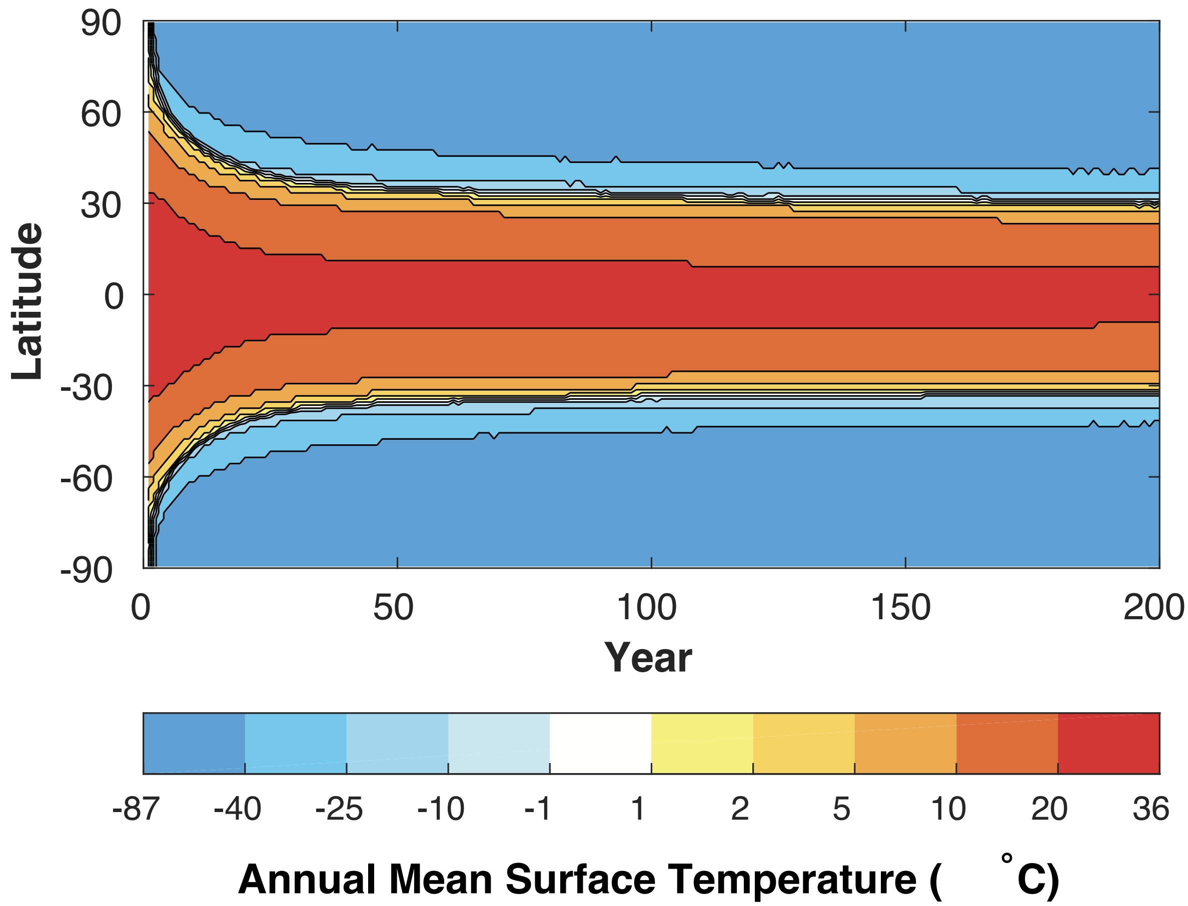

Figure 6: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out condensing greenhouse gases with ice albedo of .65 and ocean mixed-layer of depth 250m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

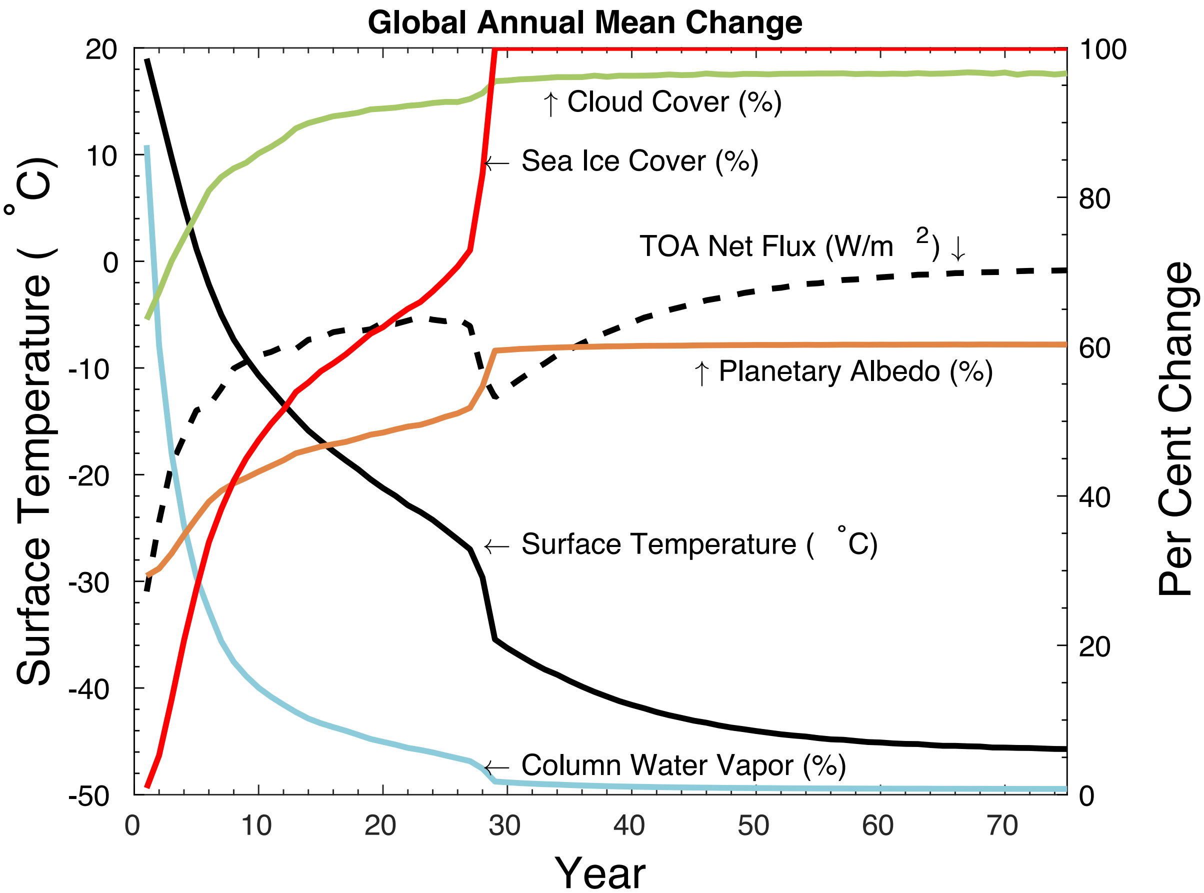

Figure 7: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out noncondensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .65 with a mixed-layer depth of 50m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

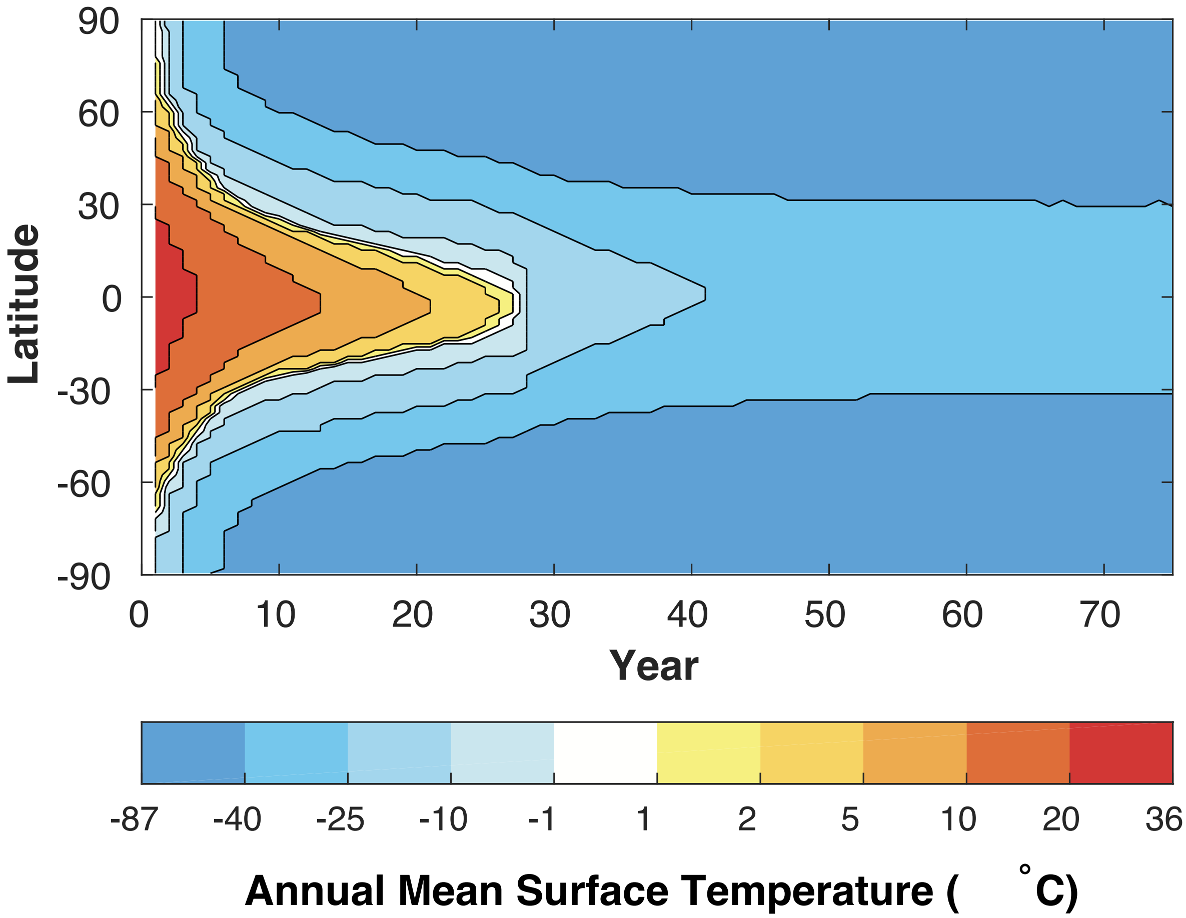

Figure 8: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out noncondensing greenhouse gases with ice albedo of .65 and ocean mixed-layer of depth 50m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

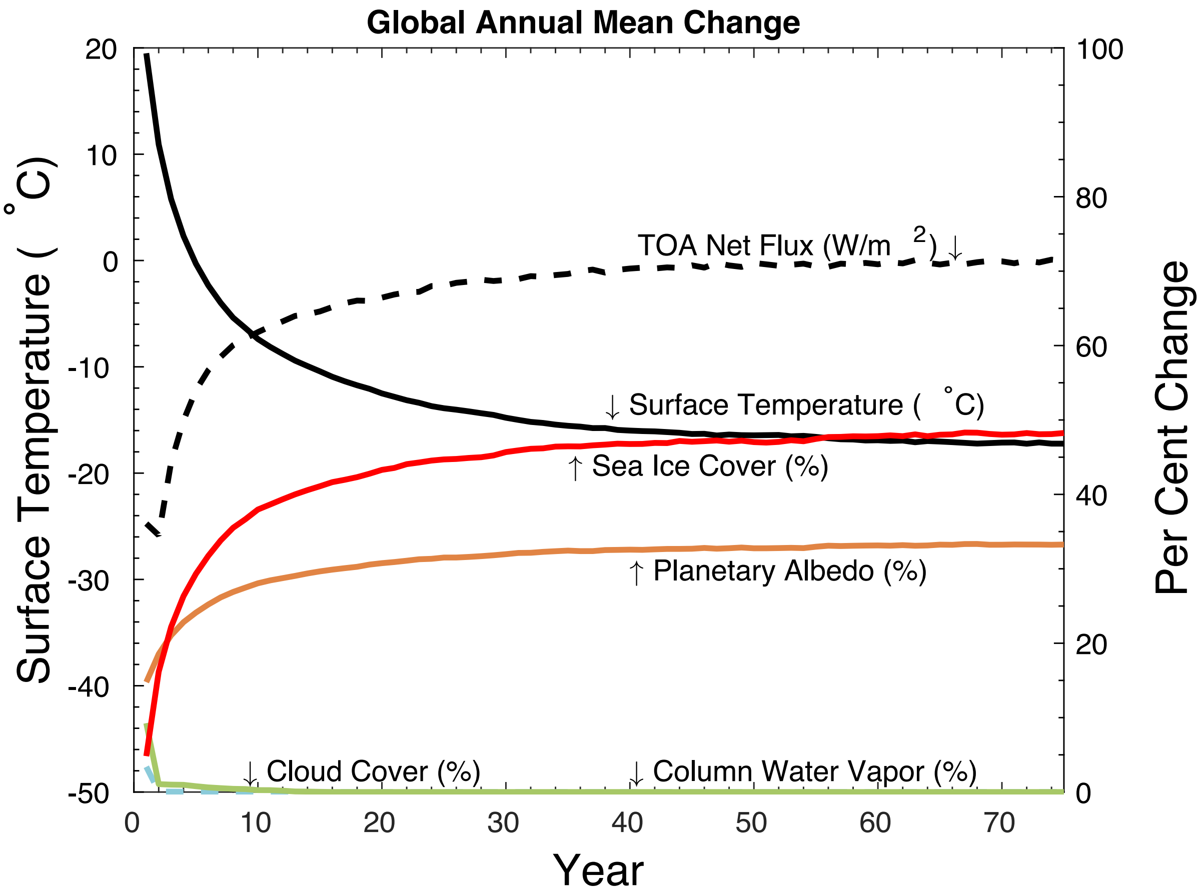

Figure 9: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out condensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .65 with a mixed-layer depth of 50m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

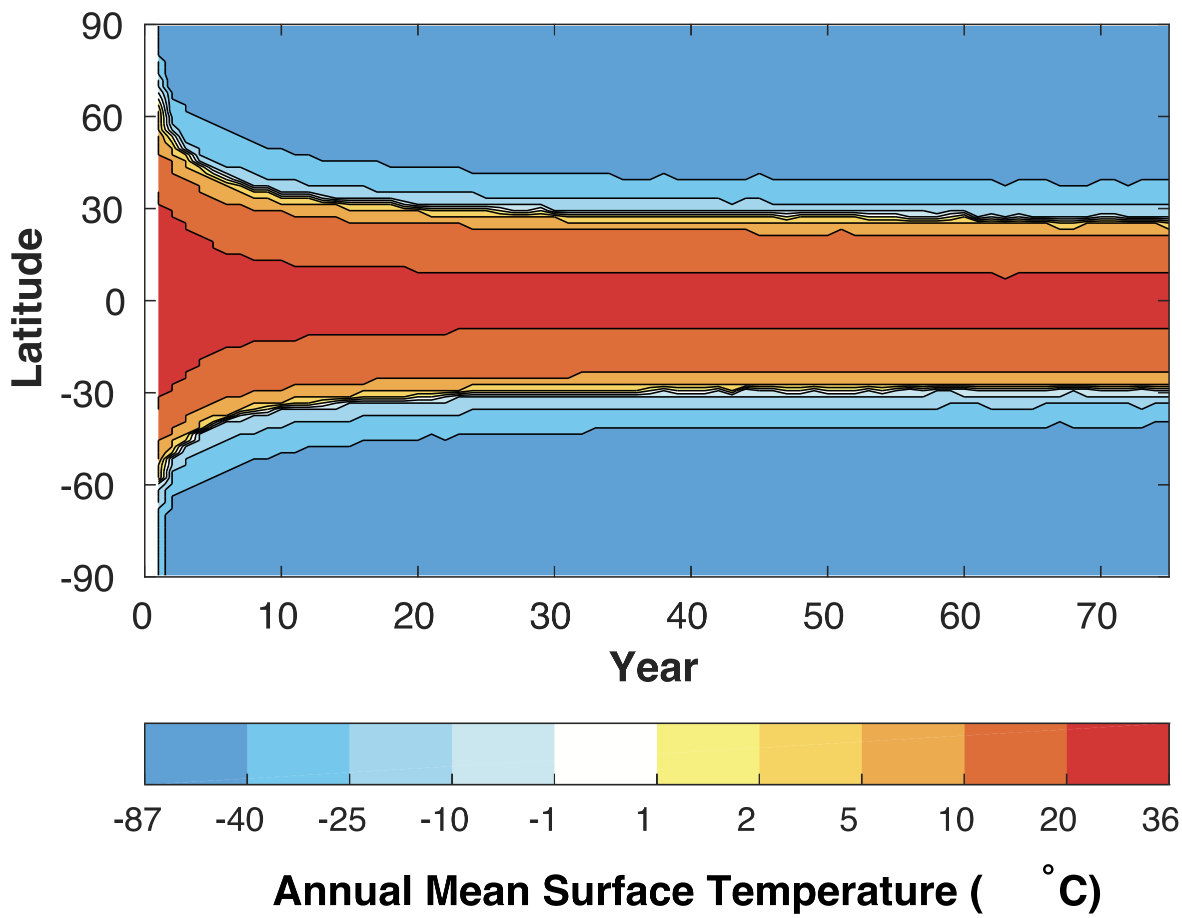

Figure 10: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out condensing greenhouse gases with ice albedo of .65 and ocean mixed-layer of depth 50m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

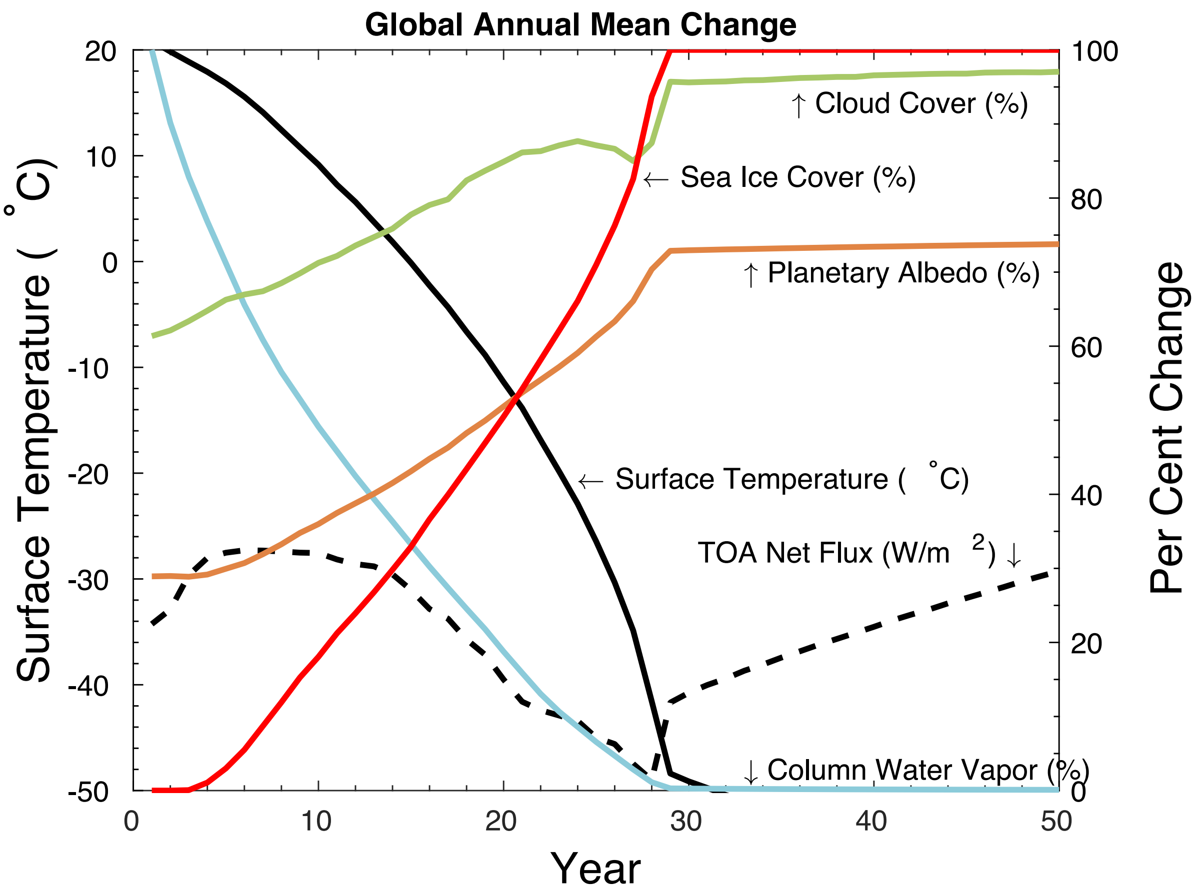

Figure 11: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out noncondensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .8 with a mixed-layer depth of 250m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

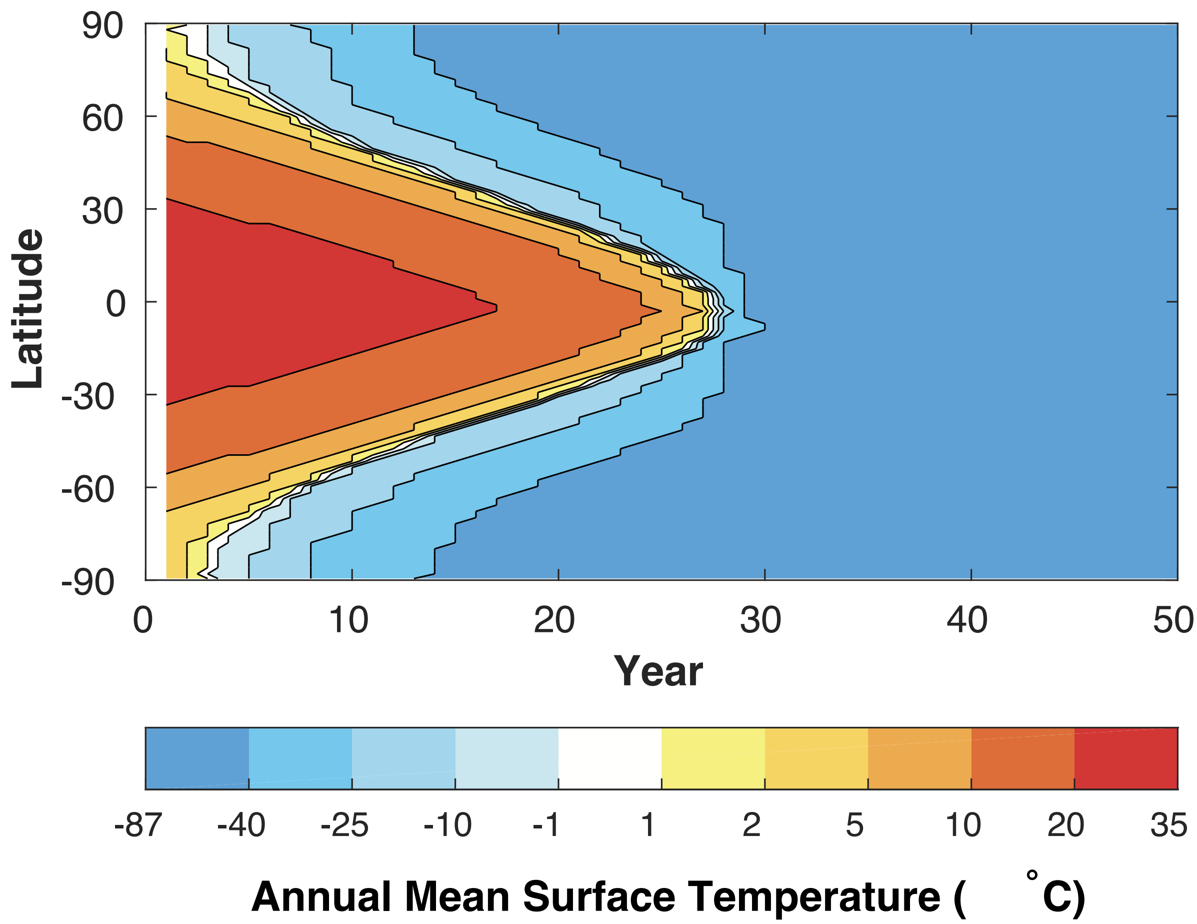

Figure 12: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out noncondensing greenhouse gases with ice albedo of .8 and ocean mixed-layer of depth 250m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

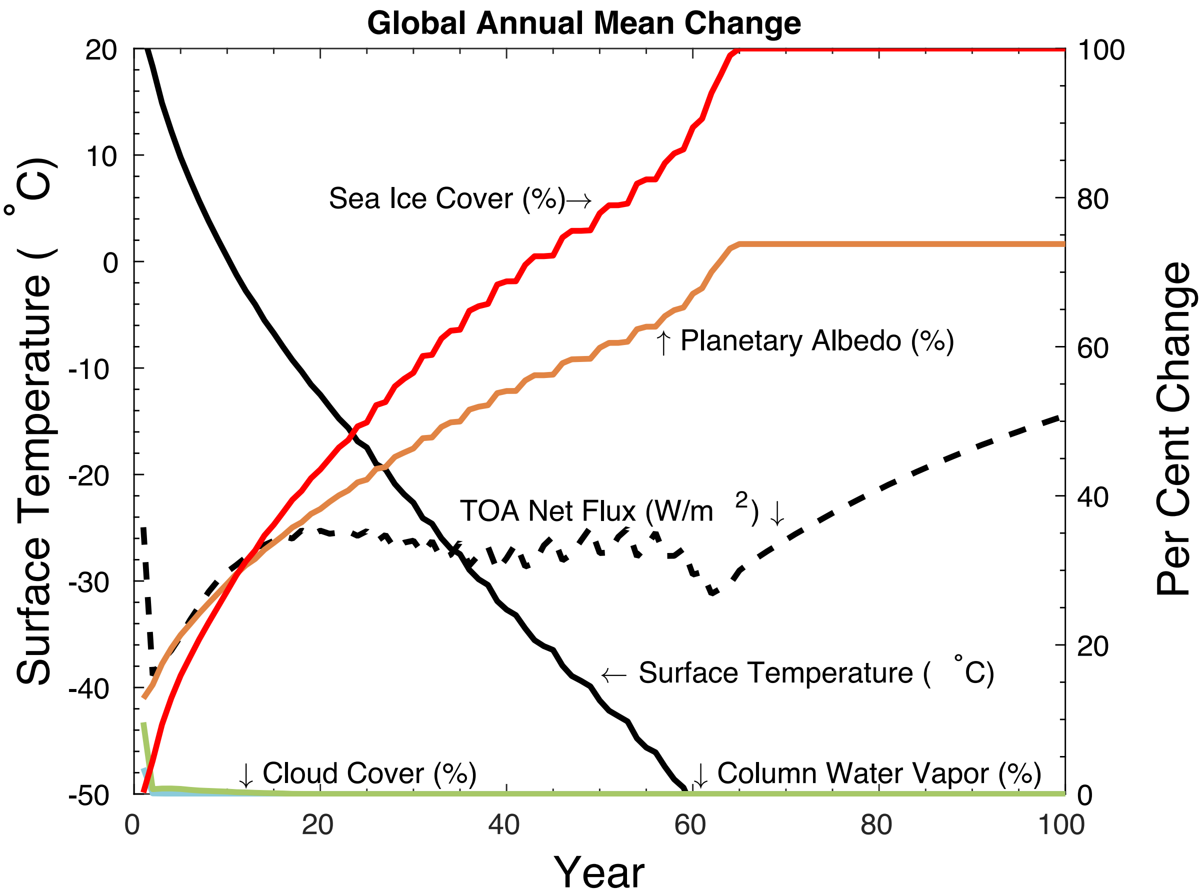

Figure 13: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out condensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .8 with a mixed-layer depth of 250m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

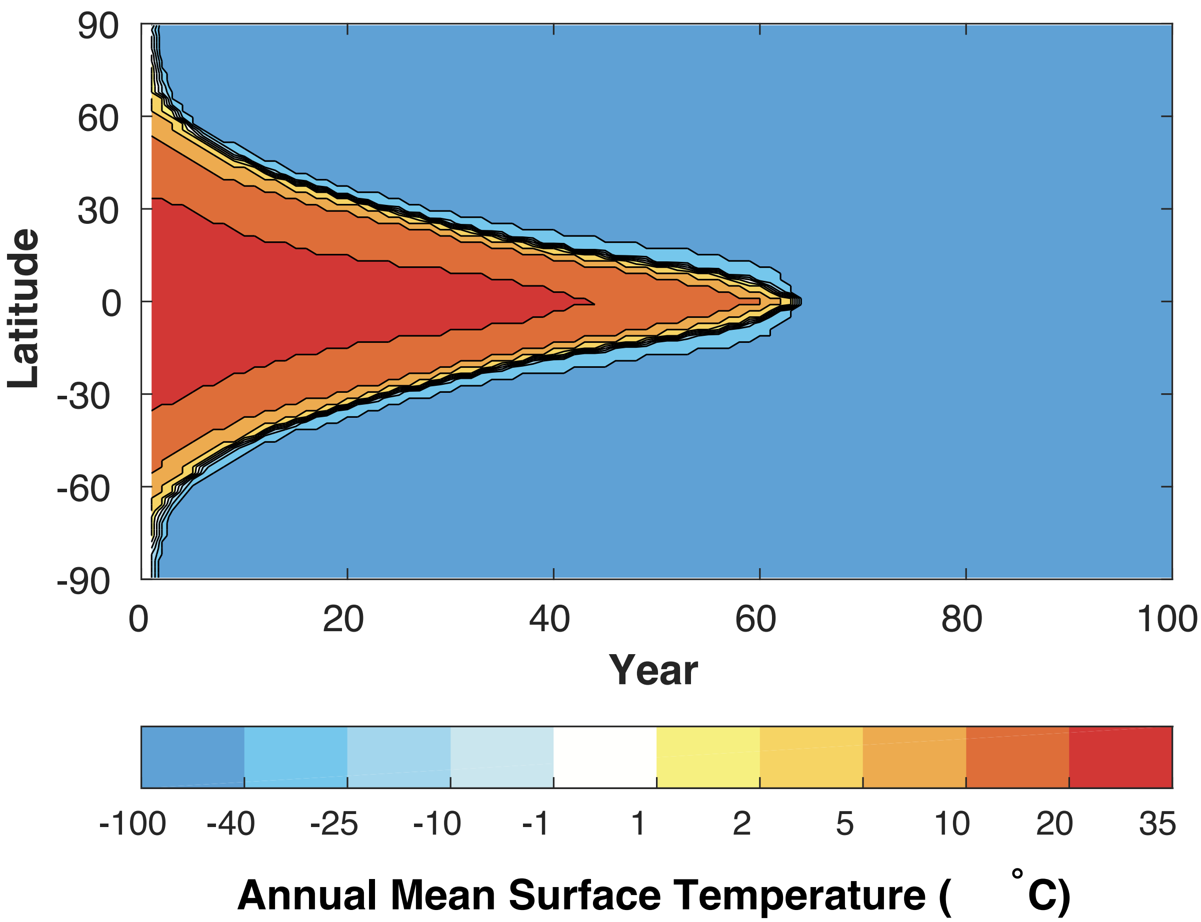

Figure 14: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out condensing greenhouse gases with ice albedo of .8 and ocean mixed-layer of depth 250m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

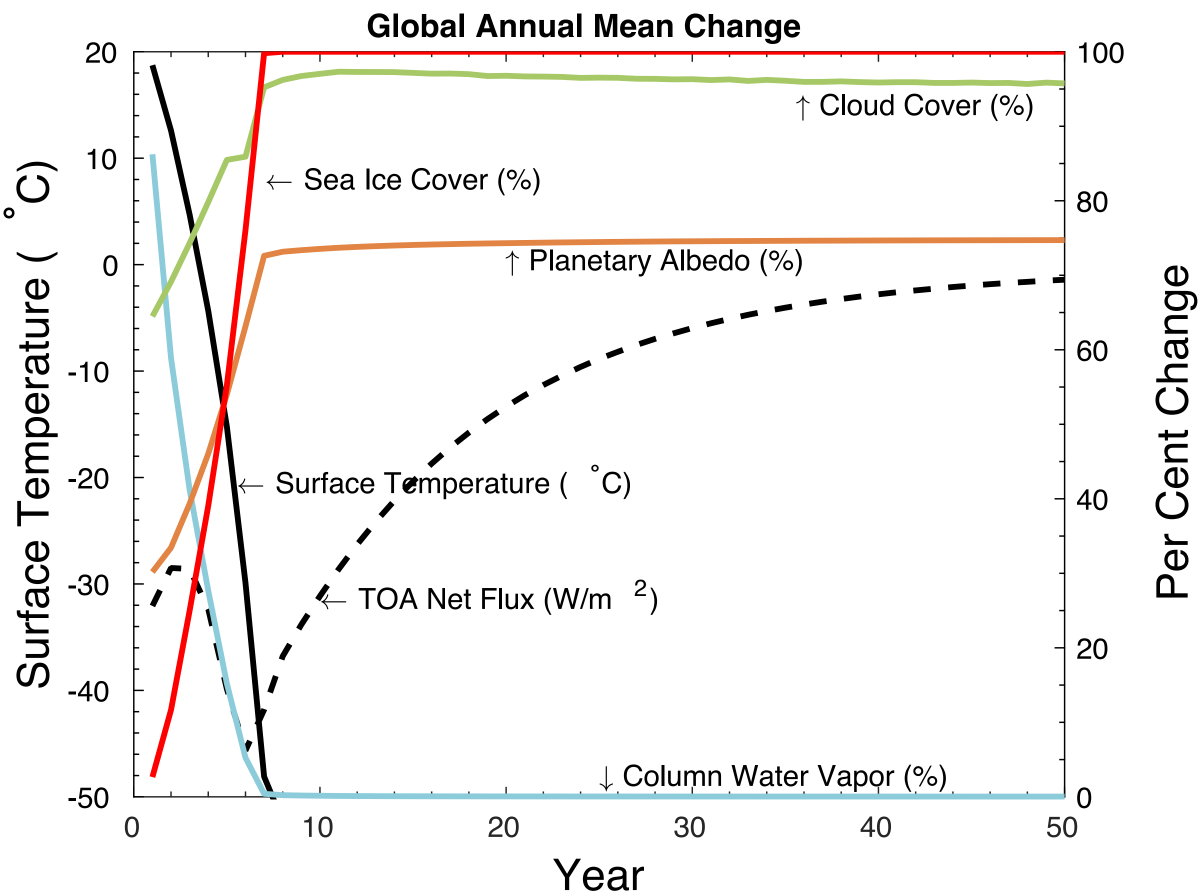

Figure 15: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out noncondensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .8 with a mixed-layer depth of 50m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

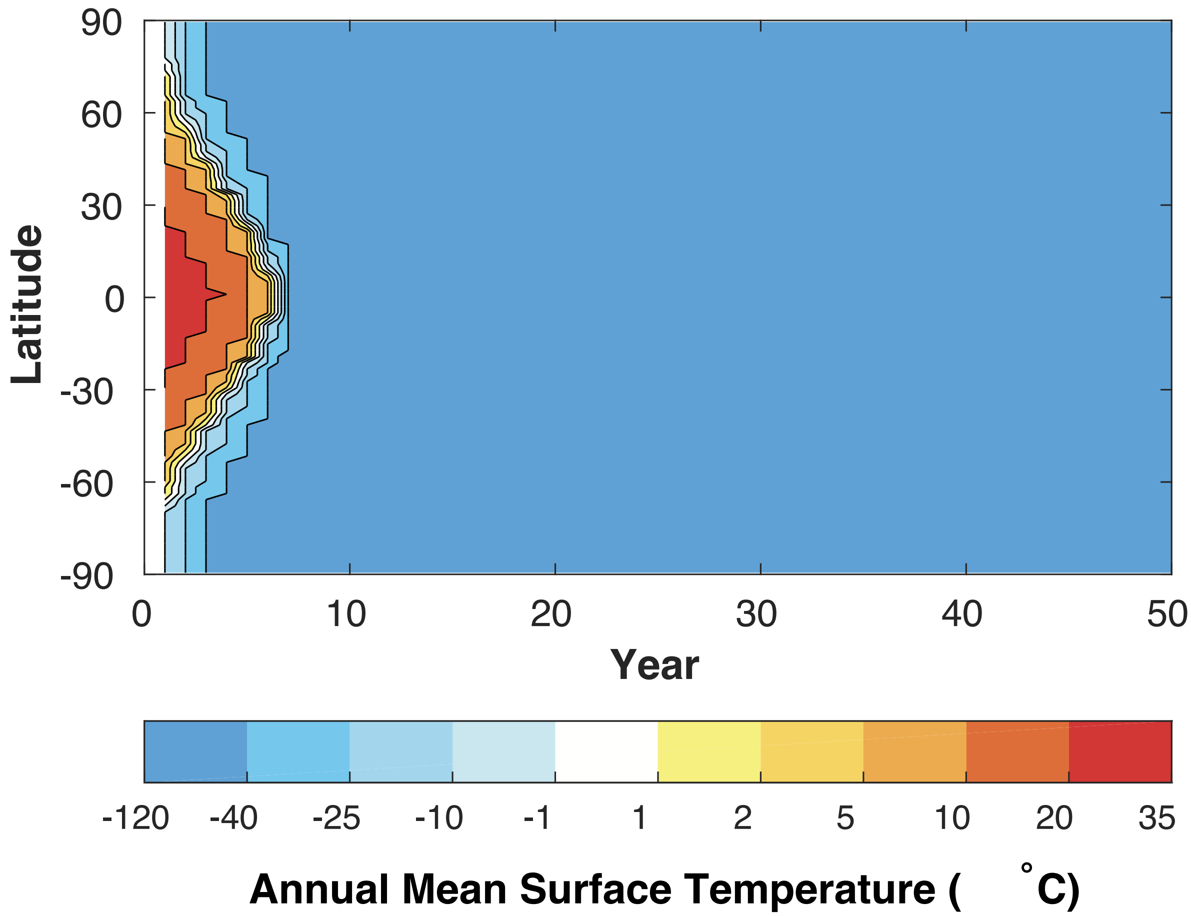

Figure 16: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out noncondensing greenhouse gases with ice albedo of .8 and ocean mixed-layer of depth 50m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

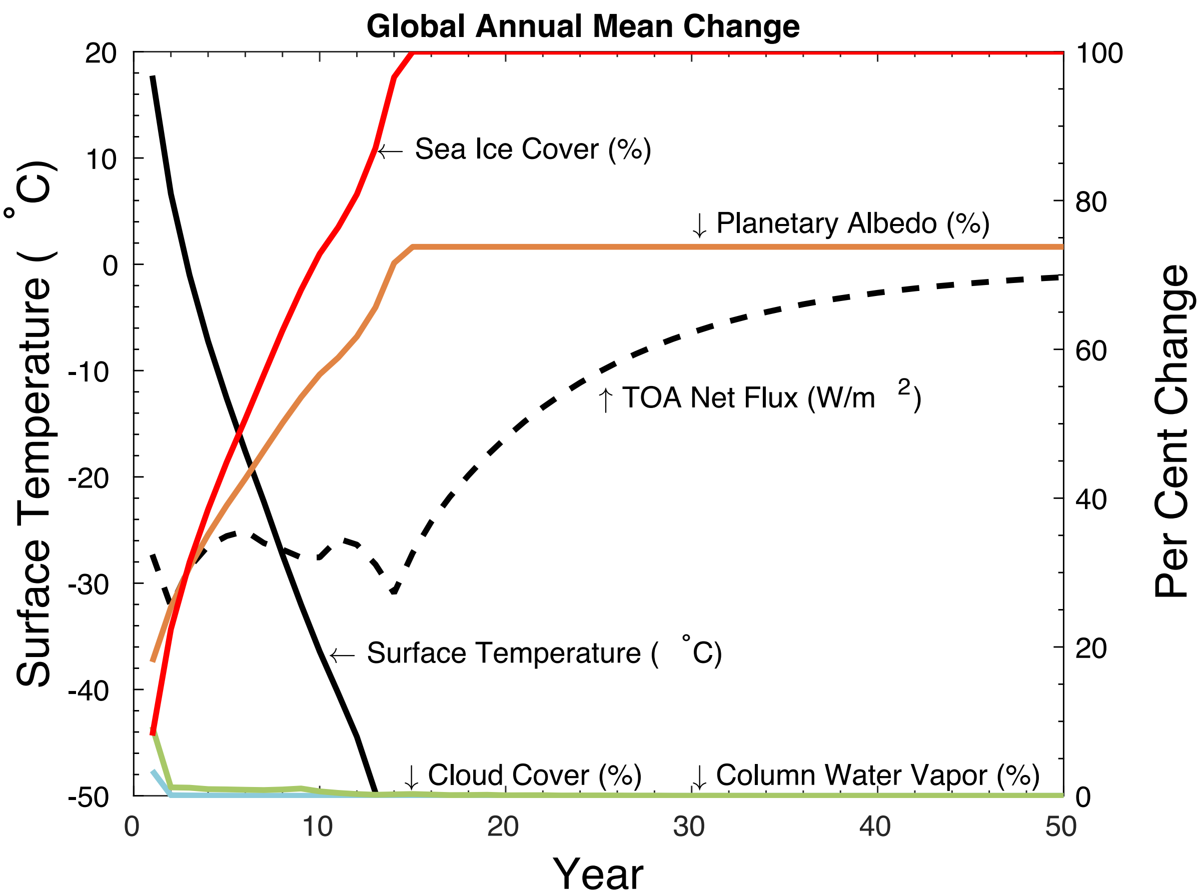

Figure 17: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out condensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .8 with a mixed-layer depth of 50m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

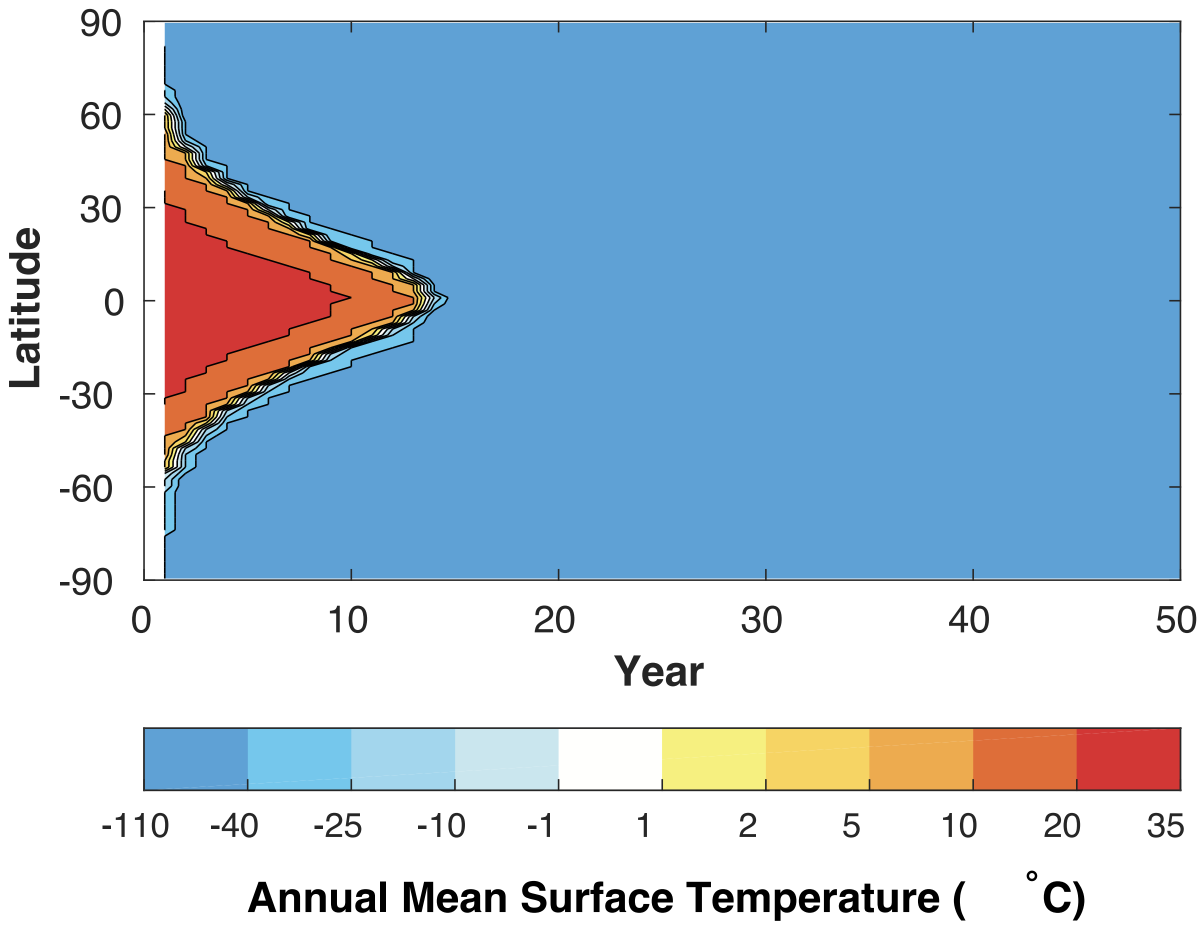

Figure 18: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out condensing greenhouse gases with ice albedo of .8 and ocean mixed-layer of depth 50m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

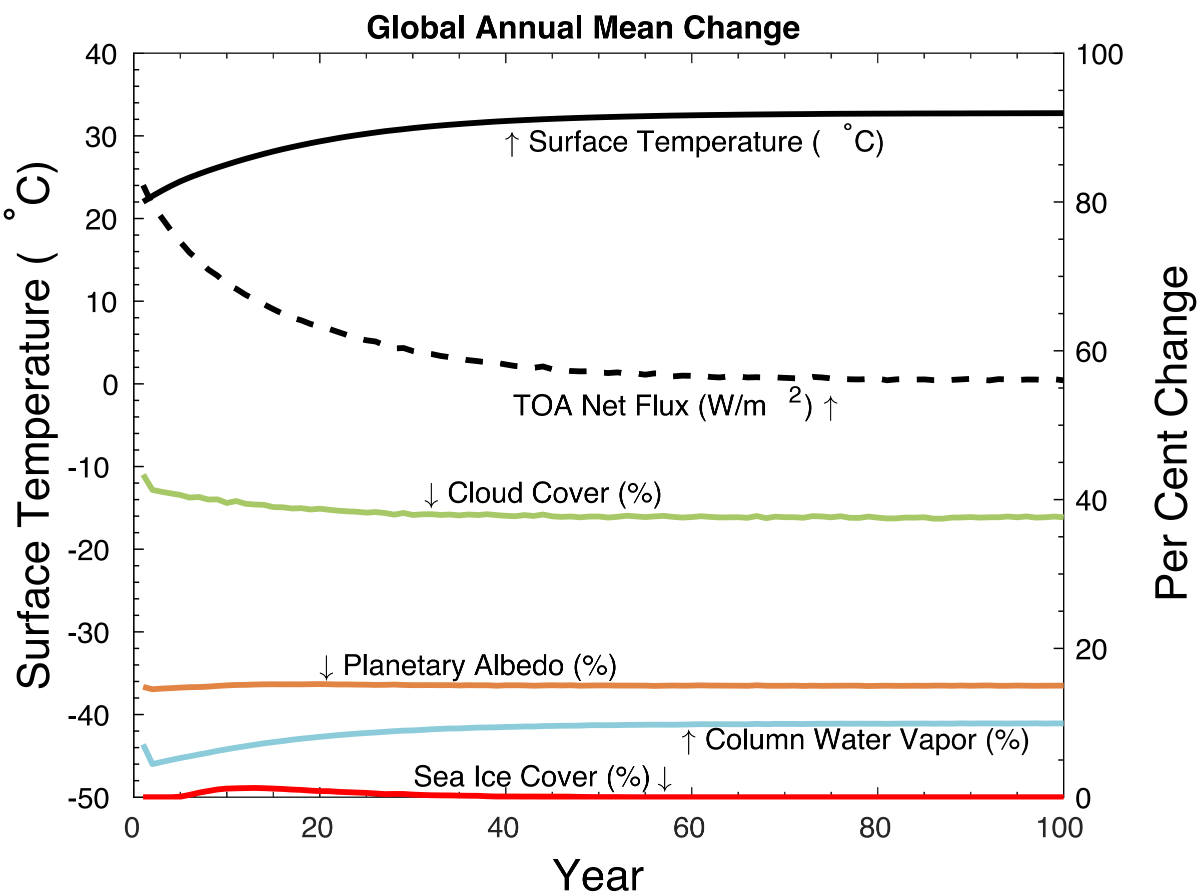

Figure 19: Time evolution of global surface temperature, TOA net flux, column water vapor, planetary albedo, sea ice cover, and cloud cover, after zeroing out condensing greenhouse gases. The model used in this experiment is the GFDL AM2 (Geophysical Fluid Dynamics Laboratory, Princeton, NJ, affiliated with NOAA and Princeton University). The ice albedo for this experiment was considered to be .65 with a mixed-layer depth of 250m. TOA net flux and surface temperature are to be read off to the left hand scale. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

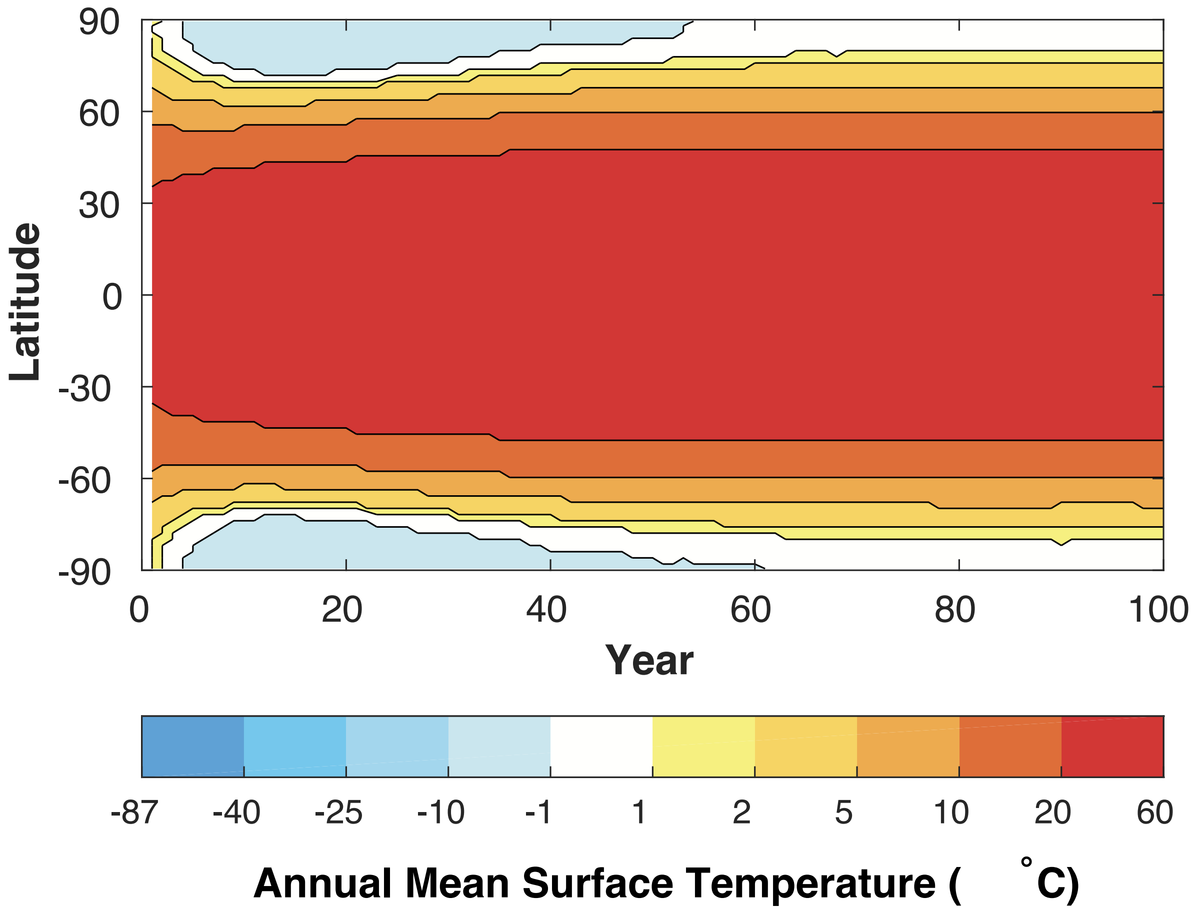

Figure 20: Zonally averaged annual mean surface temperature as a function of latitude and time after zeroing out condensing greenhouse gases with ice albedo of .65 and ocean mixed-layer of depth 250m. MATLAB code can be accessed through https://github.com/myoussef660/Geophysics

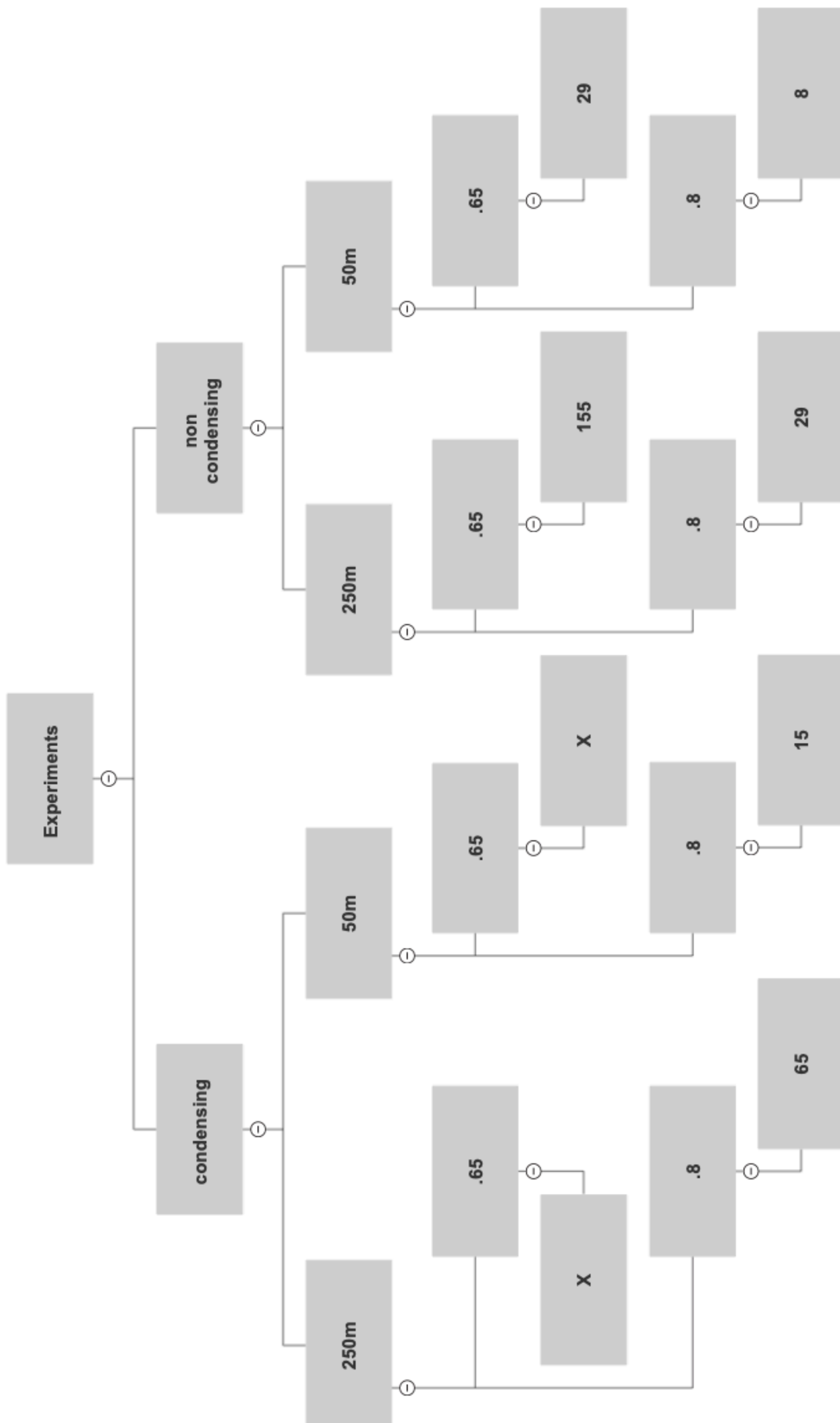

Figure 21: Transition to snowball Earth: Summary of the obtained results. First row shows the two major experiments conducted of zeroing out condensing greenhouse gases and noncondensing greenhouse gases. Second row shows the ocean mixed layer depth. Third and fifth rows show the ice albedo. 4th and 6th rows show the number of years taken to obtain a snowball Earth. The "X" indicate that there is no snowball Earth obtained.

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