Using seasonal variations to estimate earth's response to radiative forcing

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Abstract

By looking at how the changed solar radiation over the annual seasons affect the two hemispheres it is possible to get an estimation of how the climate system reacts to changes in the radiation balance. The inertia in both northern hemisphere (NH) and southern hemisphere (SH) is about the same, but the temperature change in response to radiation change is much larger in NH than in SH. This implies a large negative feedback in the SH. Based on daily temperature data from ECMWF, a climate model with only three parameters is created. It is shown that this model can simulate the temperature response to the changes in solar irradiance (radiation per area) fairly well. If it is assumed that the energy exchange between NH and SH can be neglected, it is possible to calculate how the hemispheres react to changes in radiation forcing. If IPCC's assumption of forcing efficacy is used, a 3.7W/m^2 of greenhouse gas forcing, that is the climate sensitivity, should correspond to about 5.1W/m^2 of solar forcing. This model shows that 5.1W/m^2 of radiation forcing would give approximately 0.5°C higher temperatures on the NH and approximately 0.2°C on the SH. It is also shown that temperatures response after the Mount Pinatubo eruption is completely in line with what would be excepted with the simple climate model.

1 Introduction

Understanding how earth responds to a change in incoming radiation from the sun is essential to understanding how earth will react to increase level of so called greenhouse gases. This study uses the fact that nature conducts a continuous experiment in changing earth's radiation balance. During the northern hemisphere (NH) winter, southern hemisphere (SH) receives increased solar radiation, and vice versa.

In this experiment I have used an average of the 2 meter temperature from ECMWF's ERA-interim reanalysis [1] which provides, amongst others, daily gridded temperature data for complete earth starting at 1979. This temperature is compared to the change in solar irradiance (radiation per area) to the two hemispheres.

I have assumed that the solar irradiance is in average 338 W/m^2 and that albedo is 0.3. This means that the average energy inflow on earth is in average 338*0.7=237 W/m^2.

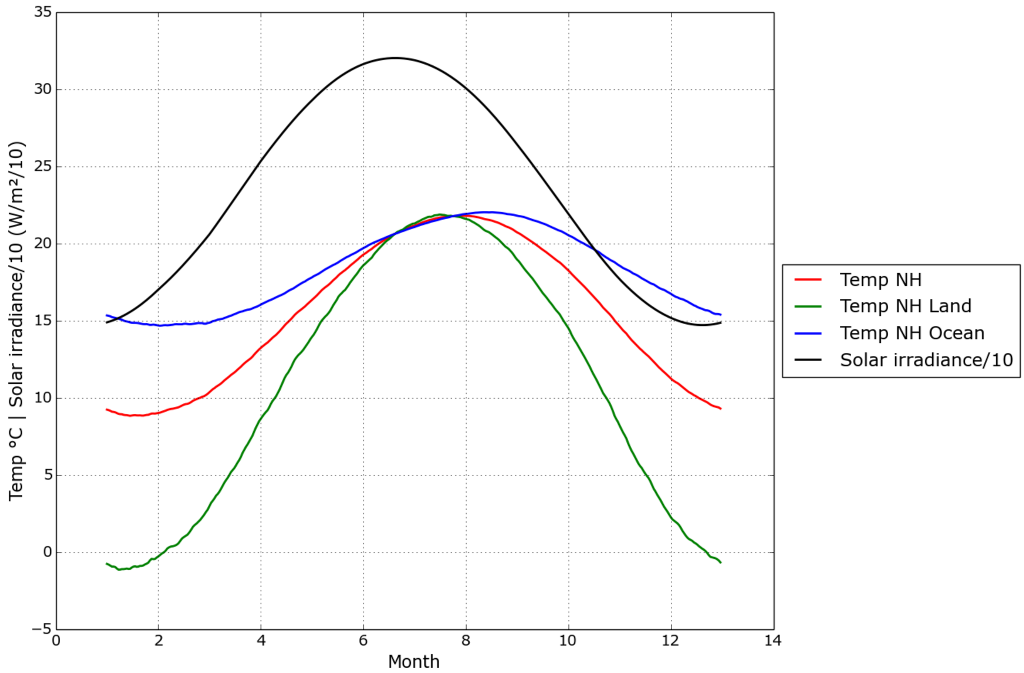


Figure 1: Solar irradiance scaled down to 1/10th and average temperature (ECMWF) 1979-2013 for northern hemisphere.

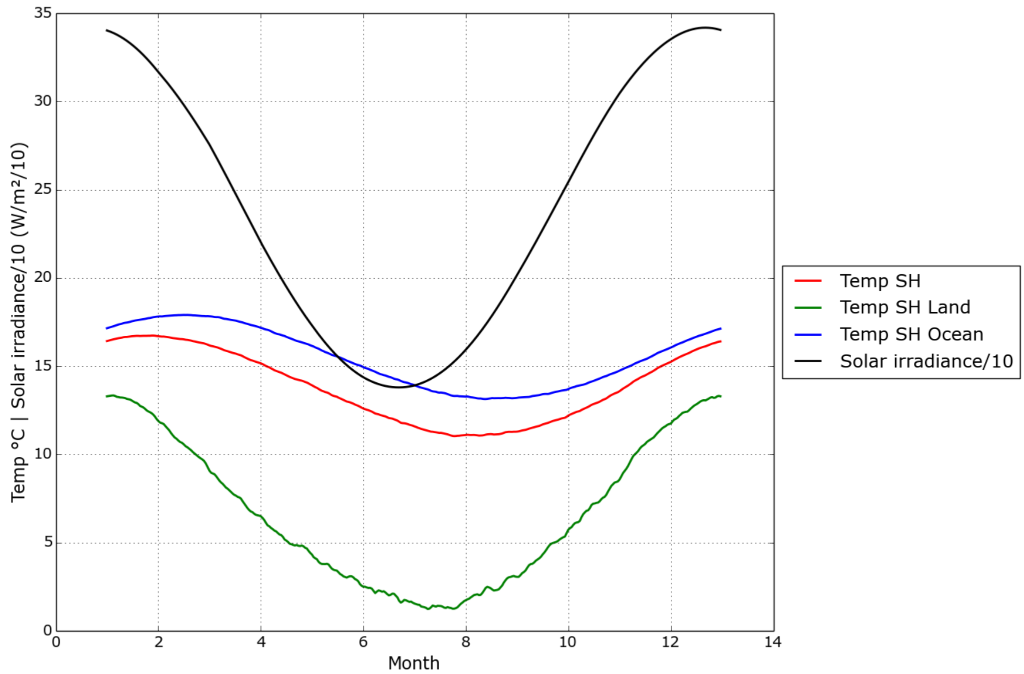


Figure 2: Solar irradiance scaled scaled down to 1/10th and average temperature (ECMWF) 1979-2013 for southern hemisphere.

It is evident from figure 1 and 2 that temperature lags the sun in time. This is probably due to an inertia from the time it takes to heat up oceans and lakes. Therefore the land will heat up faster than the ocean. But the system reacts fairly quickly, since the maximum temperature is reached already after about a month after the solar irradiance has reached its maximum. It is interesting to note that the inertia is about the same in both NH and SH, but the temperature swing is much larger in the NH. This implies that there is a large negative feedback in the SH that tries to stabilize the temperature.

If instead the temperature is plotted as a function of the solar irradiance there is a clear evidence of a hysteresis in the system (figure 3 and 4). This hysteresis is a result of the inertia described above.

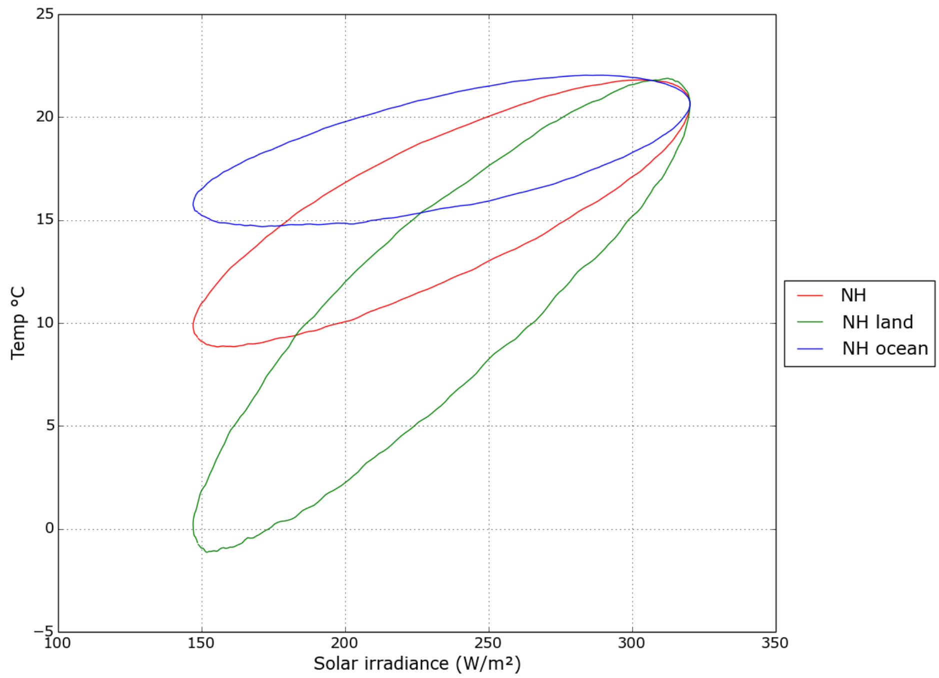


Figure 3: Solar irradiance to NH as a whole vs temperature for northern hemisphere.

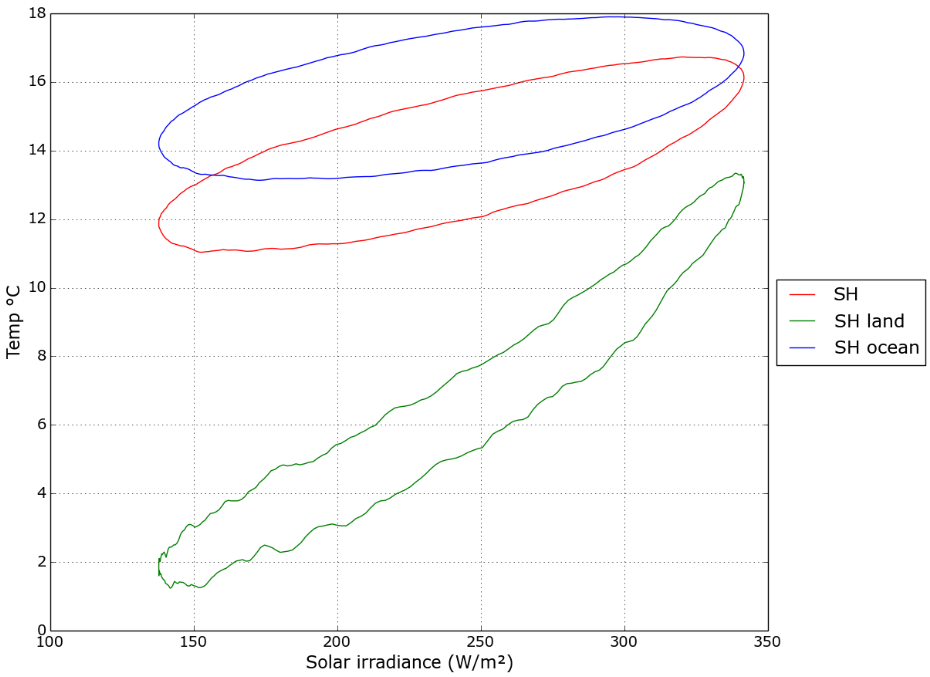


Figure 4: Solar irradiance to SH as a whole vs temperature for southern hemisphere.

The ocean and land comparison with solar irradiance is only valid if the ocean/land is equally distributed over the hemisphere and if there is neglectable energy flow between ocean and land. This is definitely not the case on SH due to the very small amount of land. And this is very clear from figure 4 where SH land has a very uneven shape. Therefore the SH ocean/land data will be ignored from this point in this study. In NH the amount of ocean is about 60% and is somewhat equally distributed. The NH land and ocean are therefore included as examples but the values calculated from these have much higher uncertainty than the values for the hemispheres as a whole.

The solar irradiance has been calculated as a function of the solar declination and the distance to the sun.

2 A simple climate model

Based on these measurements from ECMWF, I will now create a simple climate model that simulates the temperature with solar irradiance as input. The assumption is that the temperature is a linear function of solar irradiance, but that the temperature is also low pass filtered (figure 5) to achieve the inertia in the system.

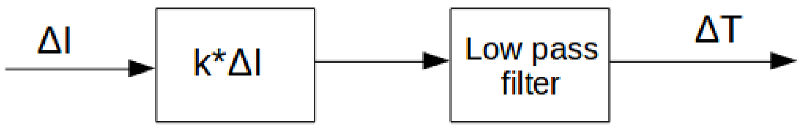


Figure 5: Flowchart for simple climate model. ΔI is change in solar irradiance, and ΔT is change in temperature.

The climate model can now be defined as:

- A temperature offset: T_{offset}(°C). This is an offset to be able to convert from delta temperatures to absolute temperatures.
- A linear factor between temperature and irradiance: k (°Cm^2/W). Defines the temperature response to a change in irradiance when the system has reached equilibrium.
- A filter value for the low pass filter: k_{filter}. Defines the inertia in the system. Higher value gives lower inertia, that is, decrease the delay between temperature response and irradiance change.

First the temperature without filter can be calculated:

$$T_{without\_filter} = T_{offset} + k * \Delta I \tag{1}$$

As filter I have used a very simple filter defined as:

$$T_n = T_{n-1} + k_{filter} * (T_{without\_filter} - T_{n-1}) \tag{2}$$

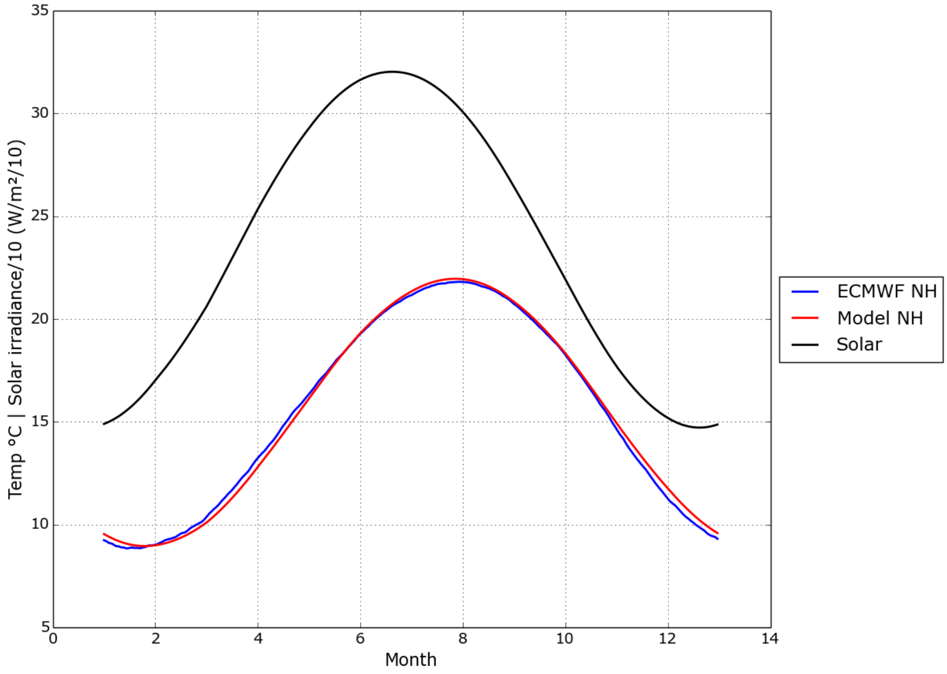
n is here the number of days since the simulation started. A higher value of k_{filter} will make system respond quicker to changes (lower inertia).

By adjusting these three parameters I have tried to see how well this very simple climate model can simulate the measured temperatures for the two hemispheres and also NH land and NH ocean. The following parameters have been empirically tried out to give a reasonable similar result to the measurements:

	T$\mathbf{T_{offset}}$ (°C)	**k** (°Cm^2/W)	$\mathbf{k_{filter}}$
NH	15.7	0.093	0.023
SH	13.8	0.035	0.021
NH land	11	0.15	0.030
NH ocean	18.5	0.065	0.015

Table 1: Empirically defined climate model parameters

Below are shown simulations of the 4 different models and how well they correlate with measured temperatures.



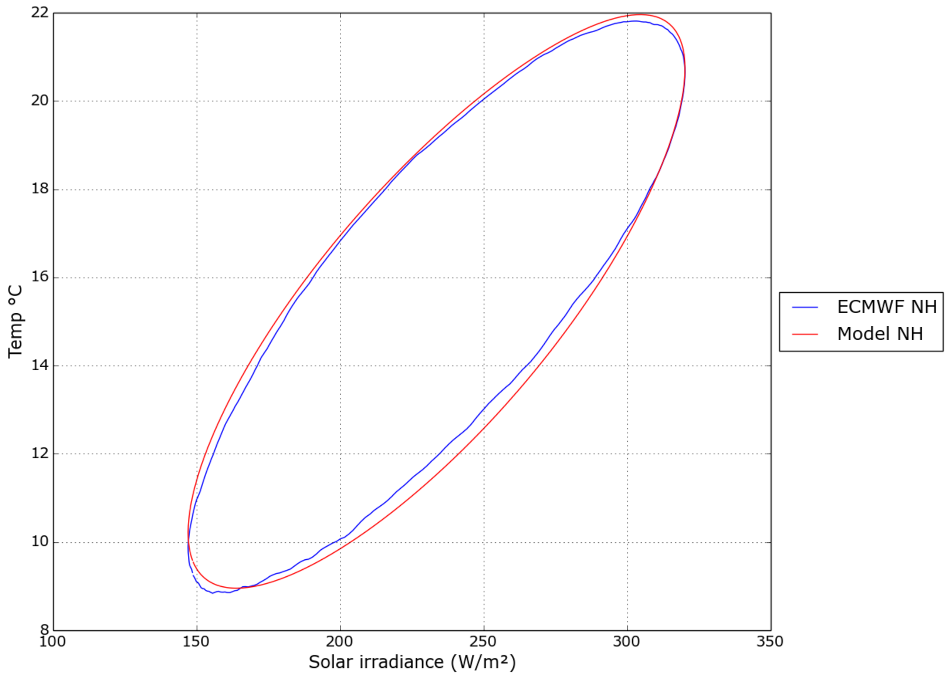


Figure 6: Simulation of northern hemisphere.

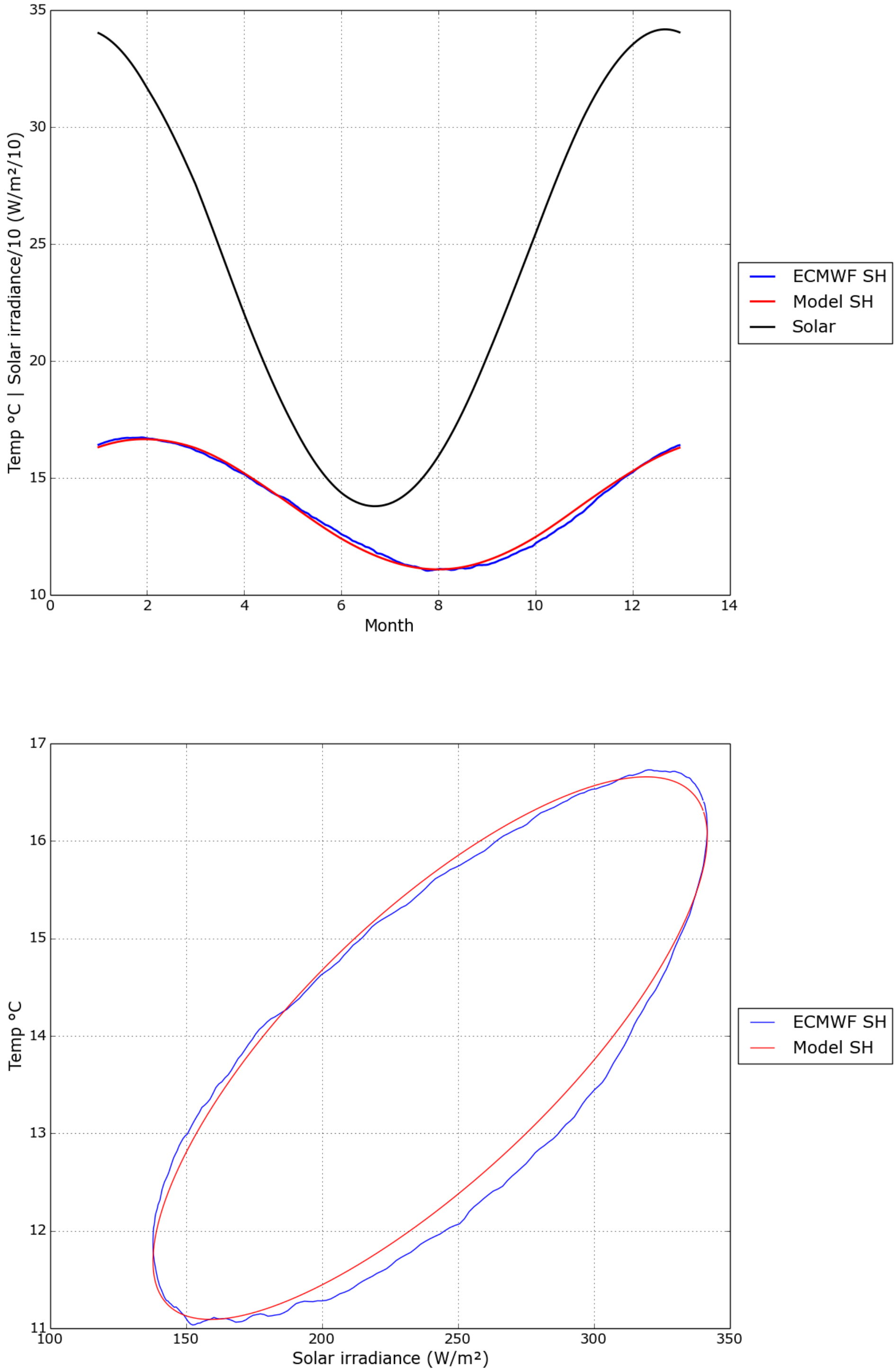


Figure 7: Simulation of southern hemisphere.

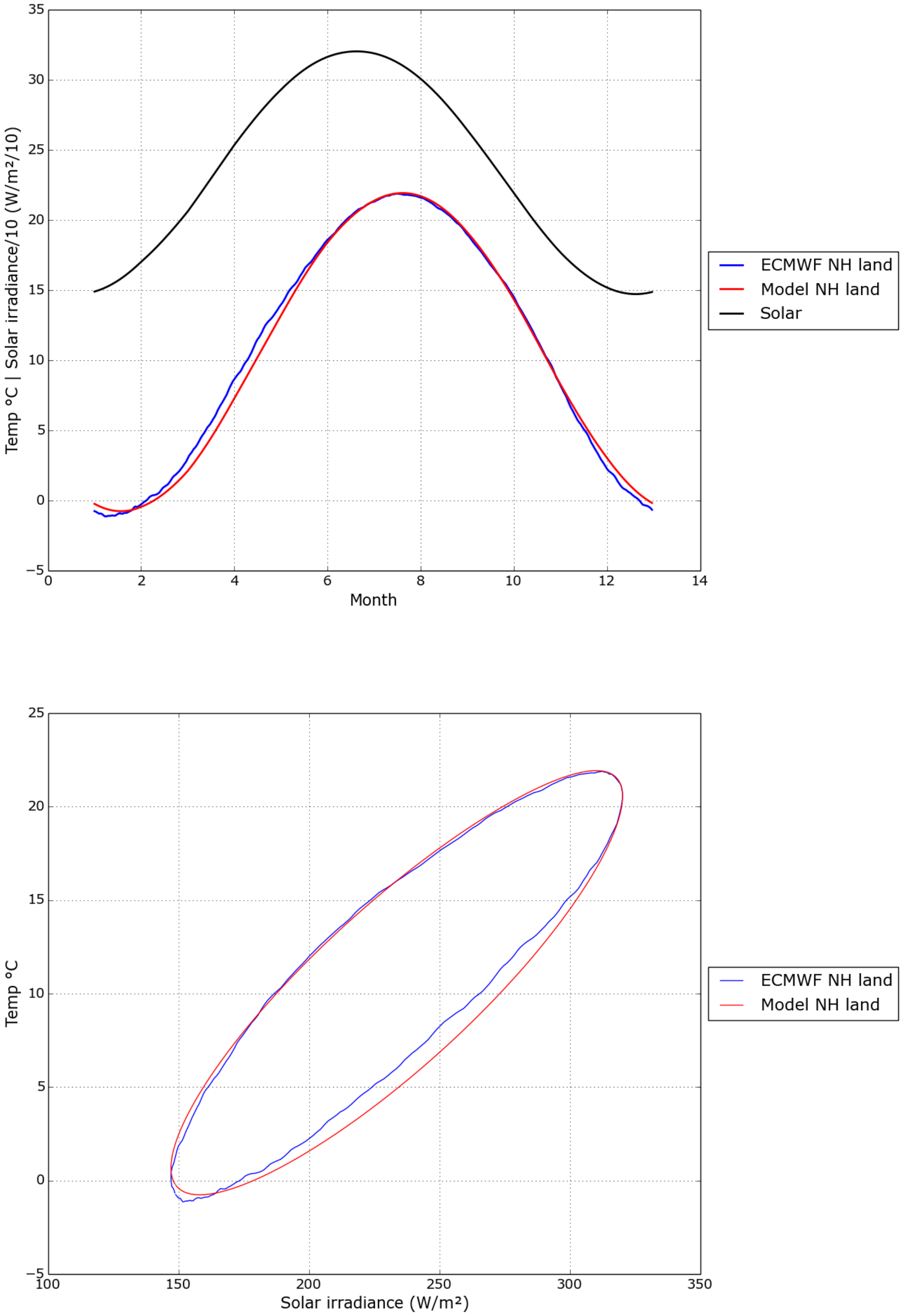
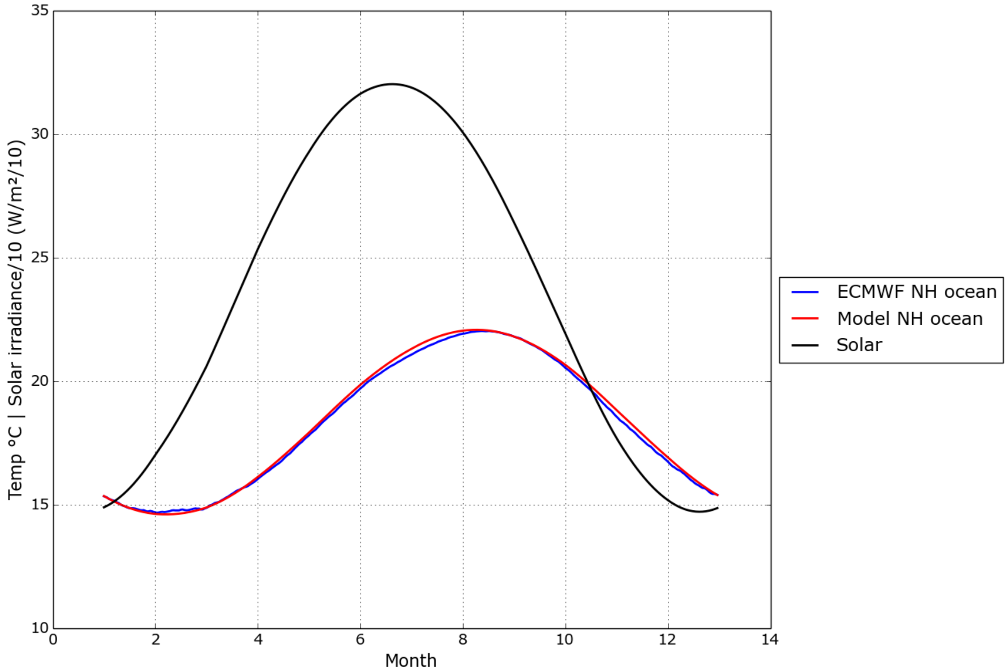


Figure 8: Simulation of northern hemisphere only land.



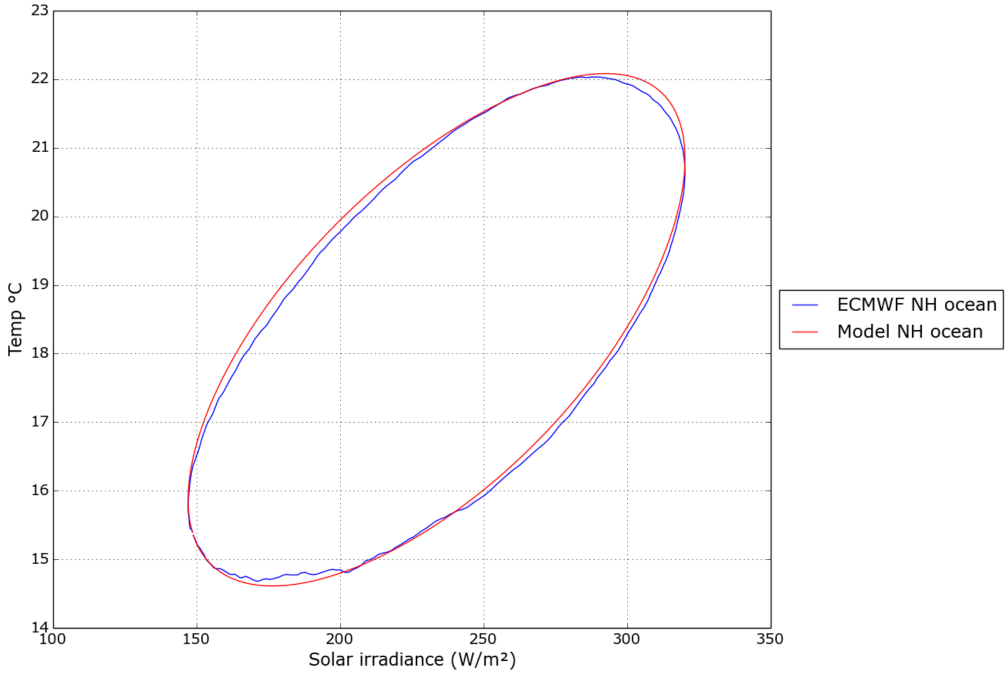


Figure 9: Simulation of northern hemisphere only ocean.

In all simulations the model has been run 20 years and only the last year is shown. The climate model is stable no matter what the start temperature is. In figure 10 is shown all 20 years for SH and the start temperature was set to 0°C.

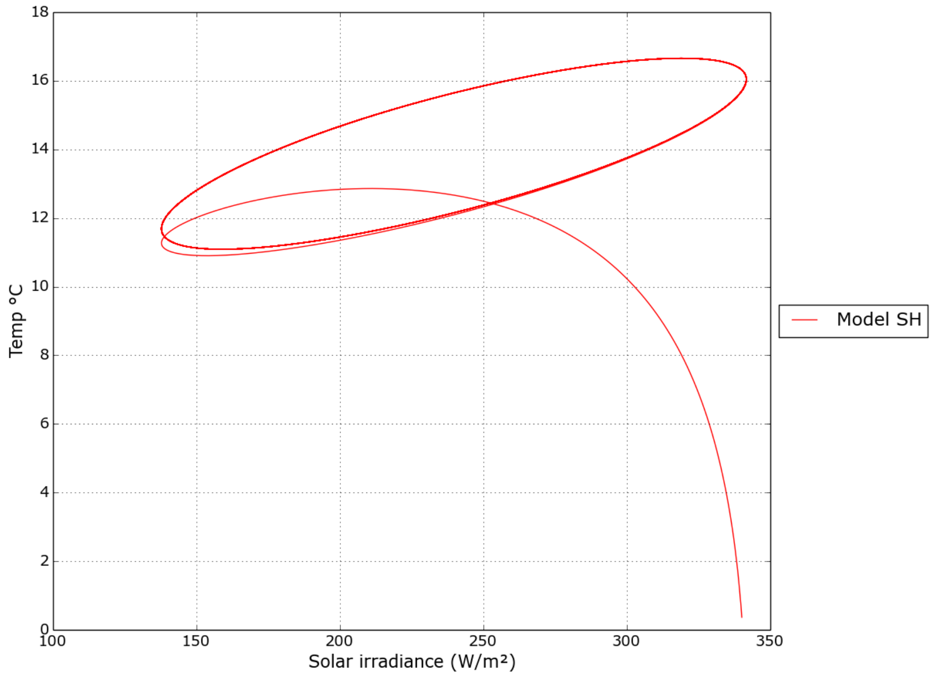


Figure 10: Stability of the climate model. The system has stabilized already after a couple of years.

By looking at figure 6 to 9 it is clear that this simple model simulates the temperature response fairly well. It is therefore assumed that this simple model can be used to estimate how the two hemispheres would react to increased radiation forcing from the greenhouse gases.

3 Climate sensitivity

According to the IPCC, a doubling of the amount of carbon dioxide will result in an increased radiation through the tropopause towards earth by $3.7\mathrm{W/m^2}$ [2]. But in the IPCC AR4 report [3] the efficacy of greenhouse gases has been described as higher than the efficacy of solar short wave radiation. That means that a certain amount of forcing from greenhouse gases will generate higher temperatures than if the same forcing came from the sun. If the IPCC AR4 report is correct, the efficacy of greenhouse gases is about 1.1 and the efficacy of solar radiation is about 0.8. Using these efficacy numbers, a forcing of $3.7\mathrm{W/m^2}$ from greenhouse gases will correspond to about $5.1\mathrm{W/m^2}$ from the sun. But another study [4] finds that the relationship should be reversed, that is, greenhouse gases has lower efficacy than solar radiation.

By using the simple climate model described in the previous chapter it is possible to calculate how earth's temperature will change if the solar radiation forcing is changed. Please note that this calculation assumes that the energy flow in-between the hemispheres can be neglected compared to the large change in irradiance to the hemispheres. If there is a considerable energy flow in-between the hemispheres, the climate sensitivity will increase.

Since the low pass filter only will delay changes, it is only the linear factor k in equation 1 that will affect the temperature response at equilibrium. I have used both solar forcing of $3.7\mathrm{W/m^2}$ and $5.1\mathrm{W/m^2}$ to illustrate the difference between different assumptions of efficacy. The forcing temperature response has been calculated in table 2.

	Solar forcing $3.7W/m^2$	**Solar forcing $5.1W/m^2$**
NH	0.34°C	0.47°C
SH	0.13°C	0.18°C
NH land	(0.55°C)	(0.77°C)
NH ocean	(0.24°C)	(0.33°C)
Global (average NH & SH)	0.23°C	0.32°C

Table 2: Temperature response to $3.7W/m^2$ and $5.1W/m^2$ solar forcing. Land/Ocean values have much higher uncertainty.

Please note that the climate sensitivity for NH land and ocean is probably not as accurate as the NH as a whole due to that the land/ocean is not evenly distributed over the hemisphere. The land/ocean values are just displayed as examples that the oceans seem to have lower climate sensitivity. This is also evident on the southern hemisphere where the ocean comprises about 81% of the area, and the climate sensitivity is therefore considerably lower. The reason why the ocean seems to have so much lower climate sensitivity is probably due to the oceans have a strong negative feedback where more clouds are formed when the temperature rises.

Another unknown factor is the change of albedo during the seasons. If the albedo increases with increased solar declination, the seasonal changes in solar irradiance will be even greater, and this implies even lower climate sensitivity. But the albedo can also be a feedback to changing temperature, and in this case the albedo shall not be adapted for. Therefore the albedo has been ignored in this study, and therefore it is an uncertainty factor.

4 Mount Pinatubo eruption

In June 15th 1991 a large volcanic eruption occurred in Mount Pinatubo in the Philippines. This eruption lowered the NH temperatures for several years, see figure below.

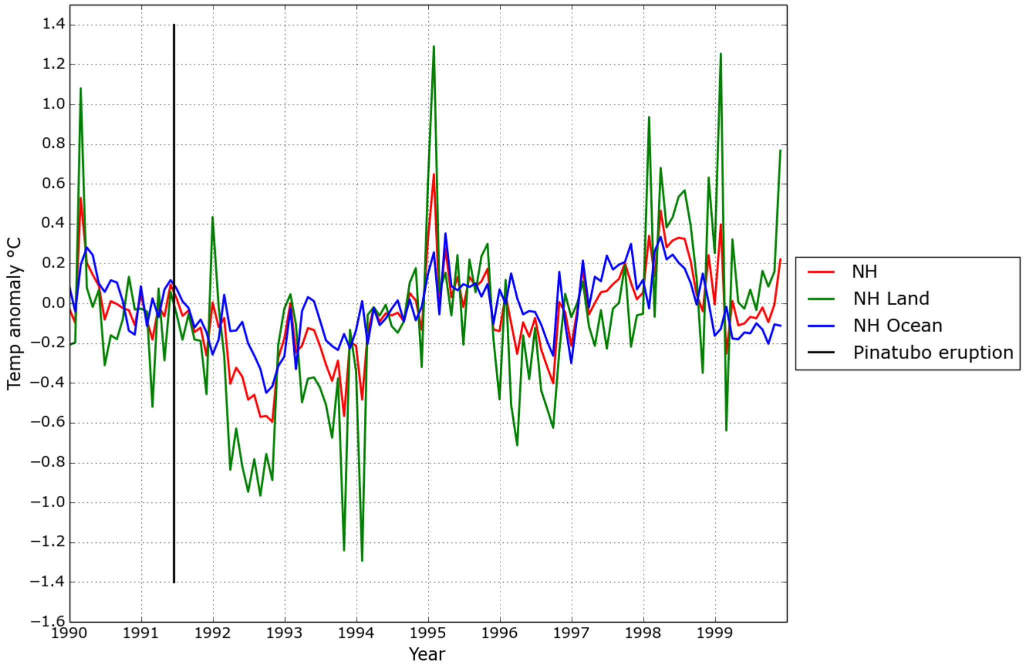


Figure 11: Monthly temperature anomalies for NH in the 1990s. The Pinatubo eruption occurred on June 15th 1991. Data from ECMWF [1].

The Pinatubo eruption, and other volcanic eruptions, is another of nature's big experiment in changing the energy balance of earth. After the eruption the temperatures over land was lowered much more than over the oceans, but when the temperatures returned they did that equally fast for ocean and land. This indicates that the inertias over land and ocean are similar, and that there is a big negative feedback over the oceans which is not present over land. There are of course other natural variations that occur at the same time, like the temperature spike in beginning of 1993, but the overall impression is that the temperatures behave in a way that the simple climate model from previous chapter has predicted.

Below is an attempt to create a simplified Pinatubo forcing model. Please note that there is no scientific data supporting this model, except from the temperature profile after the eruption.

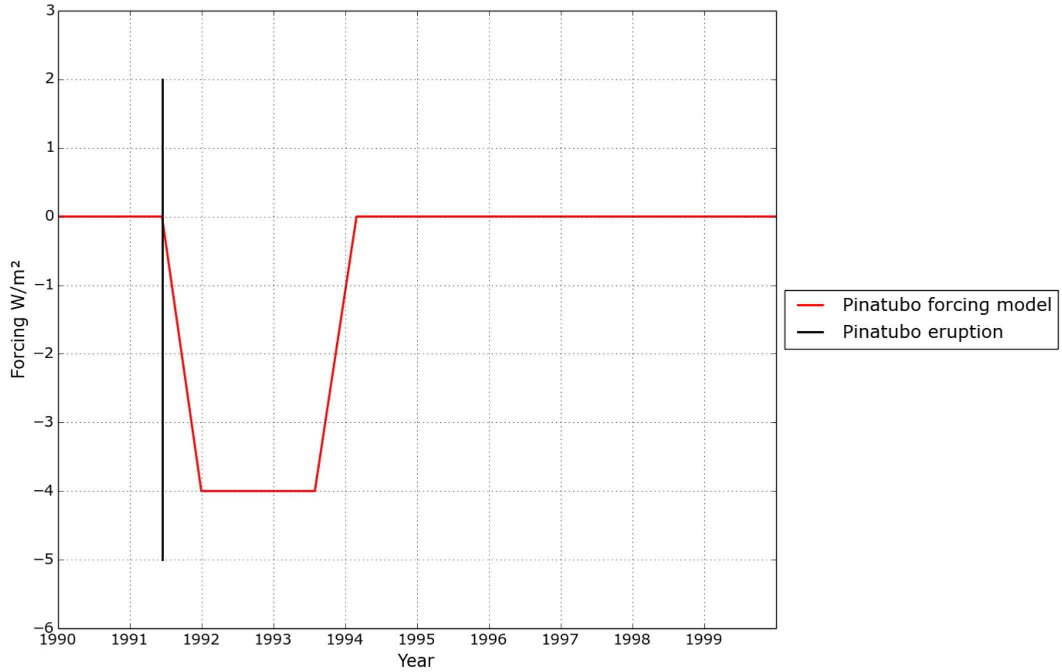


Figure 12: Simplified model of forcing after Pinatubo eruption.

This forcing model has then been run using the climate model from previous chapter, and the result is shown below.

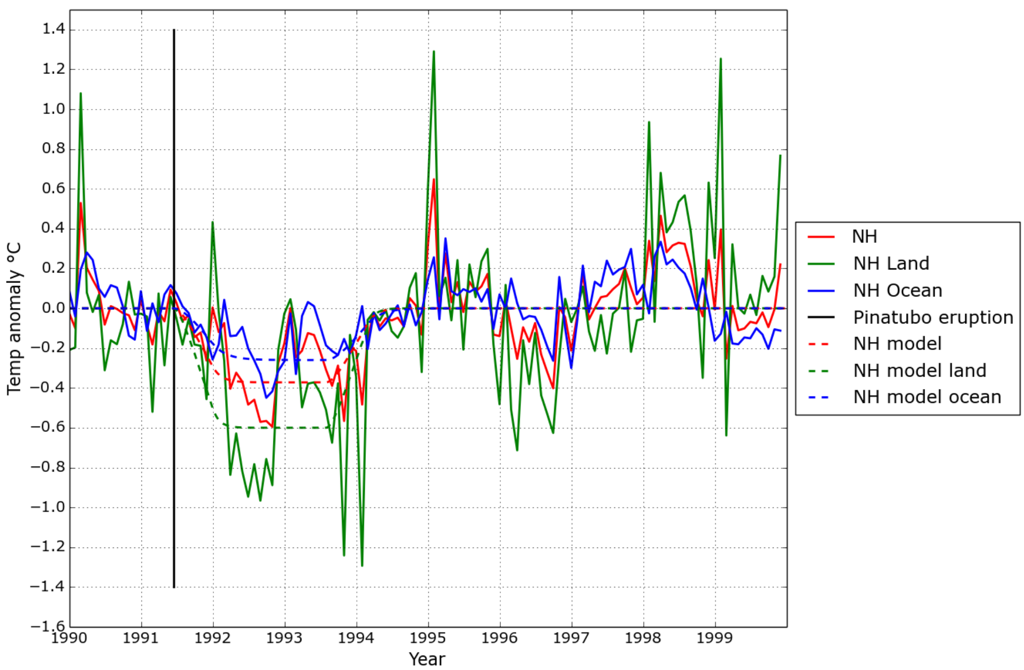


Figure 13: Same as figure 13, but with climate model as dotted lines. The forcing input is from figure 12.

It seems like there is a good correlation in the relation between land and ocean between the model and the measured temperatures. This doesn't prove that the climate sensitivity calculated in previous chapter is correct, but it supports the assumption that the oceans have a large negative feedback. It also supports the assumption that the land and ocean have similar inertia.

5 Conclusion

Since both hemispheres show similar inertia but large differences in temperature response compared to irradiance change, it implies that SH has a large negative feedback when the temperature change. Similar pattern is seen in the difference between ocean and land in NH, where the ocean seems to have a large negative feedback. Also the temperature response after the Pinatubo eruption in 1991 supports the conclusion that oceans have a large negative feedback. Therefore it is reasonable to conclude that rising temperatures over water causes more clouds to form which will hold the temperature change back.

A very simple climate model with only three parameters can simulate the hemispheres temperature response to the seasonal changes in solar irradiance fairly well. By using this climate model, it is possible to estimate the hemispheres temperature response to increased radiative forcing from greenhouse gases. When assuming that the seasonal energy exchange between the hemispheres is neglectable and a doubling of the carbon dioxide level would cause $3.7\mathrm{W/m^2}$ forcing, a climate sensitivity figure can be calculated. This climate sensitivity has in this case been calculated to about 0.5°C for NH and about 0.2°C for the SH if IPCC's assumptions of efficacy is used. In this case it is assumed that $3.7\mathrm{W/m^2}$ of greenhouse forcing corresponds to $5.1\mathrm{W/m^2}$ of solar forcing. But if the efficacy of greenhouse gases is significantly lower as at least one study indicates [4], the climate sensitivity will also be significantly lower.

As further evidence that the simple climate model is correct, is the fact that the temperature response after the Pinatubo eruption is completely in line with what would be excepted with the simple climate model.

The major uncertainty factors in this study are:

- If there is a (to me unknown) seasonal energy exchange between the hemispheres.
- If the efficacy comparison between greenhouse gases and solar radiation is incorrect.
- If the albedo is sensitive to solar declination.

The first factor, if found significant, will increase the climate sensitivity figure, but the other two can significantly decrease the climate sensitivity figure.

The strong negative feedback over the oceans can also explain why the biggest temperature rise during the 20th century occurred on land. But the temperature increase that has been measured is bigger than what would be expected due to the changes in the carbon dioxide levels according to this study. Therefore it is reasonable to assume that natural variations also causes the radiation balance to change and also in this case the land will experience the biggest temperature change.

References

[1] ECMWF ERA-interim reanalysis, http://www.ecmwf.int/en/research/climate-reanalysis/era-interim

[2] IPCC AR4 Chapter 2.3.1 Atmospheric Carbon Dioxide, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-3.html

[3] IPCC AR4 Chapter 2.8.5 Efficacy and Effective Radiative Forcing, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-8-5.html

[4] A comparison of the efficacy of greenhouse gas forcing and solar forcing, R. A. Irvine, 2014