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Peer-Reviewed Term Project

SIO 217a Atmospheric and Climate Sciences I

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Introduction

Volcanic eruptions affect the climate in several ways over different timescales. There is a small warming effect due to an increased greenhouse effect, a cooling effect due to sulfur aerosols over a longer timescale and local covering effects due to ash clouds. The topic assigned was to reproduce Fig. 12.3 by using Eqn.12.1-3 from the book "Thermodynamics of Atmospheres & Oceans" by Curry & Webster. We were to show the effect of the recent volcanic eruption in Iceland in this model and compare to the Pinatubo and El Chichon eruptions.

Theory

The model to be reproduced is a contour graph of the daily average insolation at the top of the atmosphere as a function of season and latitude. The insolation is the measure of solar radiation energy received on a given surface area and recorded during a given time.

Figure 1 was what we were going to end up with prior to taking into account the volcanic effects. The vertical axis illustrates the latitude with the South Pole at the bottom, equator at the middle and the North Pole at the top. At the horizontal axis we have months starting with January and ending with December. The lines throughout the figure are lines of constant solar flux. The black areas represent periods of no solar insolation, which exist at the North Pole when you have polar nights in the winter months and equivalently at the South Pole in the summer months. The maximum values of the solar flux are also found at the North and South Pole as the lines represent a daily average of insolation giving the poles high values as they have sun all day long (North Pole has midnight sun in June-July and the South Pole in January-December).

The seasonal and latitudinal variations in temperature are driven primarily by variations of insolation and average solar zenith angle. [i] The figure we were to reproduce was the plot of the daily average insolation which is given by equation (1). Where S is the mean solar flux calculated by (2), the squared mean earth-sun distance is calculated in (3), and Z the solar zenith angle calculated in (5).

The mean solar flux (S) per unit area at the mean position of Earth is measured for a surface that is perpendicular to the solar beam. Since the approximation that Earth is spherical is not completely correct, most of the surface is inclined at an oblique angle to the solar beam. The solar zenith angle is therefore defined as the angle between the local normal to Earth´s surface and a line between a point on the surface of the Earth and the sun.

The solar zenith angle depends on the latitude, season and time of day. The season can be expressed in terms of the declination angle of the sun, which is the latitude of the point on the surface of Earth directly under the sun at noon. This angle varies seasonally because of the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun. This angle would always be 0° if the Earth were not tilted. Also, the season depends on the average sun-earth distance which slightly varies during the year.

The hour angle represents the time of the day and is defined as the longitude of the sub solar point relative to its position at noon. The hour angle is zero at solar noon (when the sun is at its highest elevation) and increases by 15° for every hour before or after solar noon. [ii]*Figure 2* gives an illustration of the different inputs to the solar zenith angle.

The effect of volcanic eruptions on insolation

Ash clouds can block sunlight and darken the skies visibly, resulting in reduced solar heating. However, such effects are typically short-lived and geographically limited. There is no large effect on a global scale or longer timescale.

The greenhouse effect increases due to the emission of CO_2 from the volcanoes. However, the amounts of water vapor and carbon dioxide emitted by volcanoes are negligibly small compared with the atmospheric reservoir size of these gases, and therefore their climate impact is insignificant. Also, this small amount of global warming caused by eruption-generated greenhouse gasses are offset by the far greater amount of global cooling caused by the particles in the stratosphere from the eruption, which is called the haze effect.[iii]

It is not necessarily the volume of debris and aerosols emitted in the eruption that is the most important criteria to measure its effect on the atmosphere but the amount of sulfur rich gases appears to be more important. Sulfur combines with water vapor in the stratosphere to form dense clouds of dense sulfuric acid droplets (H_2SO_4) [iv]. These sulfuric acids or sulfate aerosols scatter efficiently the visible part of the solar spectrum; their presence increases the optical depth of the atmosphere and therefore the atmospheric albedo. So after large eruptions with large emissions of sulfur the mean reflectivity of earth increases, decreasing the mean global temperature, which can be seen in *Figure 3* and *4*.

One of the largest registered effects on climate due to volcano eruptions came from the eruption of Mount Pinatubo in the Philippines in 1991. The Pinatubo eruption produced the largest sulfur oxide cloud in this century. The emission of SO_2 was calculated to be approximately 20,000,000 tones.[v] The average global mean temperatures dropped by approx. 0.5° C for a period of 1-3 years.

The aerosol cloud from the Pinatubo spread meridional over time after the eruption, creating a band around the equator from approximately 15 degrees South to 15 degrees North. This is the area where the insolation is directly affected, and in this region ship measurements were also taken. *Figure 5*shows the spreading of the cloud mapped by the TOMS satellite(Data courtesy of Gregg Bluth and Arlin Krueger, NASA Goddard Space Flight Center). *Figure 6* shows the change in integrated stratospheric optical depth in this region over time.

The ship measurement studies concluded that in the equatorial region, months after the eruption, the aerosol optical thickness increased from 0.1 to 0.3 at 500nm. Wavelength dependency also changed. The solar flux insolation decreased with 1.4%-4.1% compared to that before the eruption.[vi]

The 2010 eruption of Eyjafjallajökull on Iceland caused a lot of attention in the media due to the large ash cloud it produced and the enormous disruption to air travel across western and northern Europe. However, the eruption was relatively small compared to other large eruptions. Later studies have shown that the Iceland eruption had nearly no effect at all on climate and solar insolation. The ash cloud was spread over a large area, but was relatively short lived (weeks) and had therefore had negligible impact on local or global climate. The main reason that the Iceland eruption did not have any impact on longer timescales is that the amount of sulfur emitted was very small from this particular volcano. The sulfur emission was approx. 3000 tons a day for a few days, compared to 20 million tons for the Pinatubo eruption. Since we now know that the greatest cooling effect from volcanoes come from the conversion of sulfur dioxide to sulfate aerosols that reflect sunlight, we understand why the Iceland eruption had little impact on insolation, both locally and as a global average. This shows that relatively large volcano eruptions do not necessarily have an impact on climate, as this is primarily dependent on the amount of sulfur in the eruption. For our study of impact on averaged insolation the Iceland eruption does not do any impact at all. *Figure 7*shows the spreading of the ash cloud after the 2010 eruption. [vii][viii]

Combining the effect of volcanoes in our model

Reproduction of the model given in the task is shown in *Figure 8* and the calculations and MATLAB codes are given in the appendix.

In our insolation model our only variables are any possible local changes in insolation or a change in global average albedo. There are no studies that directly connect the amount of sulfur emitted by the volcano and the change in albedo. We know that the haze effect gives a cooling effect, which means an increase in albedo and decrease in insolation. If we neglect any other effects that might change the surface temperature or albedo, such as the short-lived ash cloud or the small increase in greenhouse effect, we can assume that all change in insolation is due to the increase in sulfur aerosols. We have found two ways to implement this effect into our insolation model. The first way is to look at the change in global mean surface temperature over a longer timescale of 1-3 years, and from this calculate a change in global albedo. In this model we have averaged the effect over a long timescale and over the planet’s surface area. Another way of looking at the effect is using measurements of change in insolation and atmospheric optical depth in the local areas affected by the plume taken from ships during the years after the eruption. We have applied these two methods below.

Since the eruption of Eyafjallajökull had such a little impact on the average insolation and climate, we will demonstrate the effect that a sulfur rich volcano eruption has by applying the Pinatubo eruption to our model. We only make a model for the Pinatubo, since the eruption of El Chichon also was sulfur rich and therefore give a similar but smaller result.

Pinatubo effect in our model as a local change

As explained earlier measurements taken from ships showed an approx. local decrease in solar insolation of 1.4%-4.1% compared to with that before the eruption. By adjusting our model by this percentage reduction in the regional band between 15 degrees S and 15 degrees N we can see the effects off the volcano. See *Figure 9*.

Pinatubo effect in our model as global average

The Pinatubo eruption led to a decrease in global mean temperature of approximately 0.5°C. If we assume the effect is averaged over the global surface area we can use a simplified climate model and find what a change in albedo would give in terms of temperature change. Assuming we have a perfect atmosphere in equilibrium (steady-state) with the earth surface, transparent for incoming shortwave radiation, absorbing and emitting longwave radiation perfectly and the earth acting like a perfect black body. Then a simple climate model with one atmosphere, and albedo of 0.31 would give us a surface temperature of T=303K. This is too high because of the assumptions we have made, but we can use the model to connect deltaT to deltaα. By our calculations from below we get an increase of 1.4988% in the albedo for a 0.5° decrease in temperature. See *Figure 10* and calculations. The pattern here is exactly the same as in figure 8, only the values associated with them have changed.

Conclusion

We can conclude that we successfully have reproduced the insolation figure and that we can show the effect from sulphur rich volcano eruptions in our model. As we can see from figure 9 the daily average insolation will slightly decrease in the band close to the equator. In our model the insolation have decreased evenly between -15°<latitude<15°. It might be more realistic if the effect decreased as one approaches -15° or 15° latitude, as by now the model states that the effect suddenly goes from 3% decrease in insolation to 0% at the edge of the ash cloud. According to figure 10 we can see that the daily average insolation decreased more in high insolation areas compared to lower insolation regions. This is due to the fact that the albedo is set to be 1.5 % lower globally, and so the effect have greater impact on higher insolation values.

By comparing figure 9 and 10 we can see how the two models differ from each other. The model with a local effect will give us a lower value of insolation at the equatorial regions, compared to the insolation in the same region for the model with a global effect. Still, the global model spreads the decrease in insolation over the whole planet, though the change in insolation for this model is drastically reduced when looking at the low insolation regions. Therefore, the conclusion is that the two models give somewhat the same average effect for the total decrease in insolation, which indicates that both models seem reasonable.

Appendix I - Formulas used in our calculations

REPRODUCTION OF MODEL

The daily average insolation:

$$F_{TOA}^{SW} = S\left(\frac{\bar{d}}{d}\right)^2 \cos(Z) \tag{1}$$

Where;
S = the mean solar flux (typically 1370 W/m²
d = Earth-sun distance
$\bar{d}$ = average value of Earth-sun distance=150 x 10^{11} m
Z = solar zenith angle

The mean solar flux:

$$S = \frac{L_0}{4\pi\bar{d}^2} \tag{2}$$

The squared mean earth-sun distance by expansion of a Fourier series:

$$\left(\frac{\bar{d}}{d}\right)^2 = \sum_{n=0}^{2} a_n \cos(n\varphi_d) + b_n \sin(n\varphi_d) \tag{3}$$

Where a and b are Fourier coefficients (see table 1) and φ_d is depending on the day number d_n as:

$$\varphi_d = \frac{2\pi d_n}{365} \tag{4}$$

The zenith angle Z can be found from the following relation:

$$\cos(Z) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(\psi) \tag{5}$$

Where ϕ is the latitude (-90°$< \phi < 90°$), δ is the solar declination angle and ψ is the hour angle (see figure 2). The solar declination is also found from an expansion of Fourier series:

$$\delta = \sum_{n=0}^{3} a_n \cos(n\varphi_d) + b_n \sin(n\varphi_d) \tag{6}$$

The hour angle ψ is defined as 0° at noon and increases by 15° for each hour before or after noon.

N	a_n	b_n
0	0,006918	0
1	-0,399912	0,070257
2	-0,006758	0,000907
3	-0,002697	0,001480

Table 1: Fourier coefficients

MODIFICATIONS DUE TO VOLCANIC EFFECTS

Given a change of 0.5 degrees Celsius in mean global surface temperature, we may calculate the change in albedo with our simplified climate model. The incoming solar radiation is given by:

$$F_s = 0{,}25 S_0 (1 - \alpha_p) \qquad (7)$$

Where α_p is the albedo. From Stefan Boltzmann's law we have:

$$F_{atm} = \sigma T_{atm}^4 \qquad (8)$$

$$F_{surf} = \sigma T_{surf}^4 \qquad (9)$$

Our simplified model states that:

$$F_s = F_{atm} \qquad (10)$$
$$F_{surf} = 2F_{atm} \qquad (11)$$

And so we can combine equation (7)-(11) and solve for the change in albedo due to a decreased global temperature:

$$F_s = \frac{F_{surf}}{2} = \frac{\sigma T_{surf}^4}{2} = 0{,}25 S_0 (1 - \alpha_p) \qquad \rightarrow$$
$$\alpha_p = 1 - \frac{\sigma T_{surf}^4}{0{,}5 S_0} \qquad (12)$$

The change of 0.5° in temperature gives from eq. (12) a variation in albedo as:

$$T_{surf} = 303\ K \rightarrow \alpha_p = 0{,}30231$$
$$T_{surf} = 302{,}5\ K \rightarrow \alpha_p = 0{,}30691$$

Which corresponds to a change in albedo of 1.5%.

Appendix II - Figures

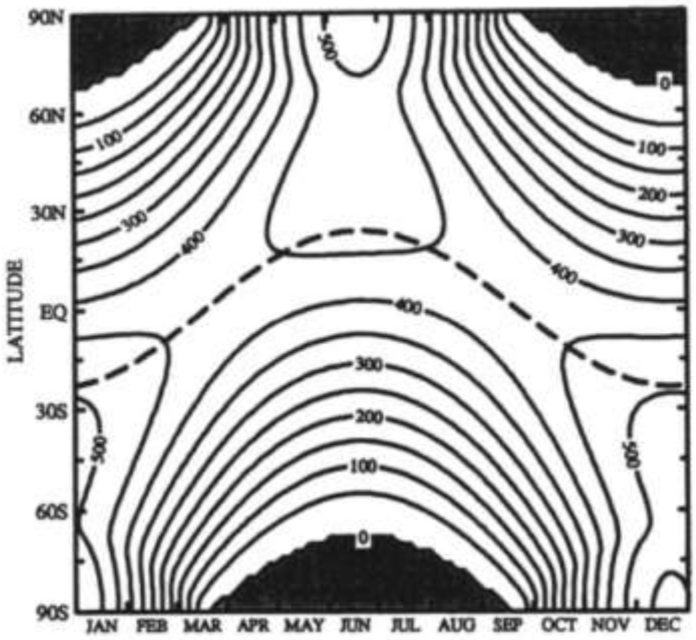

Figure 1: Daily average insolation from figure 12.3 in"Thermodynamics of Atmospheres and Oceans" by Curry & Webster

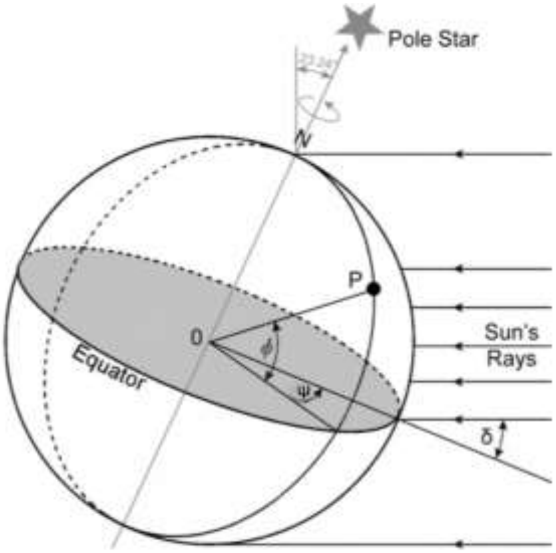

Figure 2: Definition of hour angle ψ, declination angle δ and latitude angle ϕ[ix]
Source: www.itacenet .org

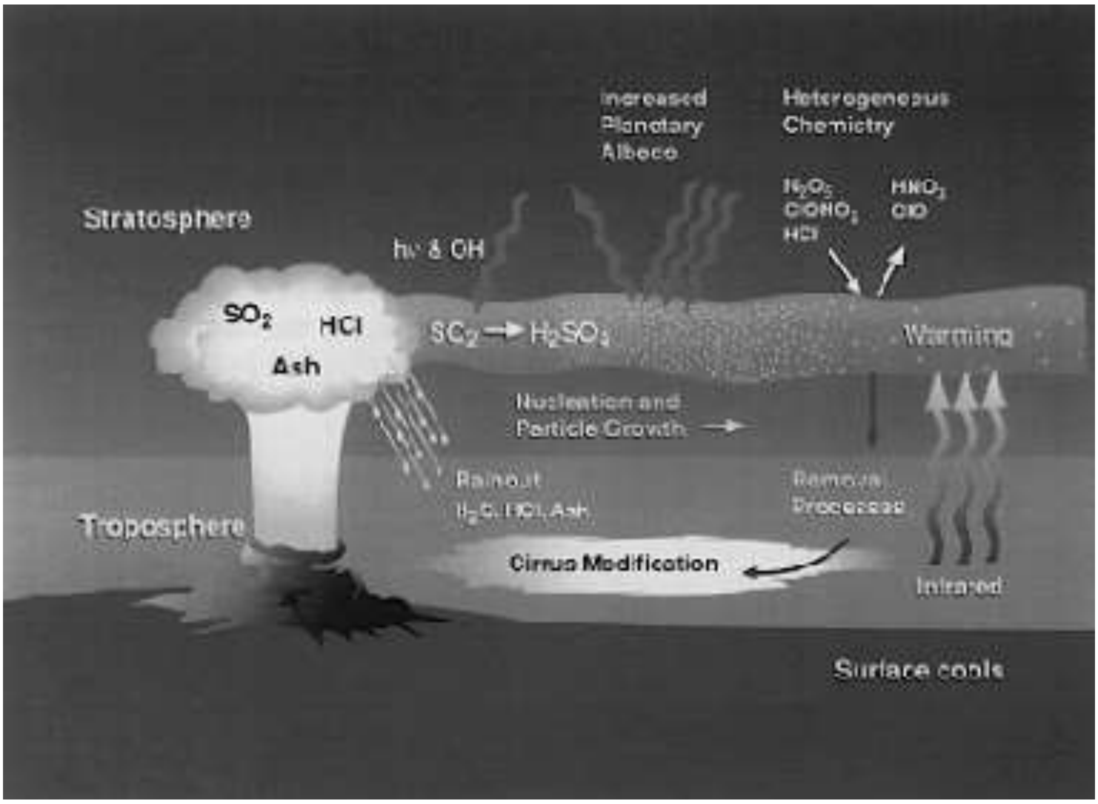

Figure 3:Effect of sulfur on solar insolation
Source www.iagos.org

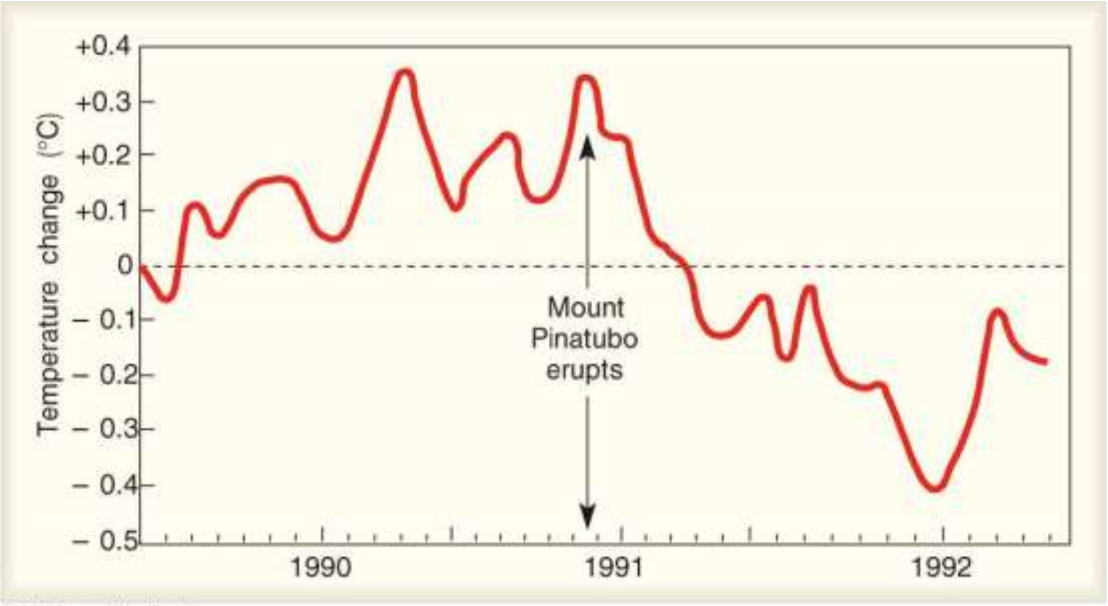

Figure 4: Effect from Pinatubo on global average temperature
Source: http://apollo.lsc.vsc.edu/classes/met130/notes/chapter16/graphics/temp_pinatubo.jpg

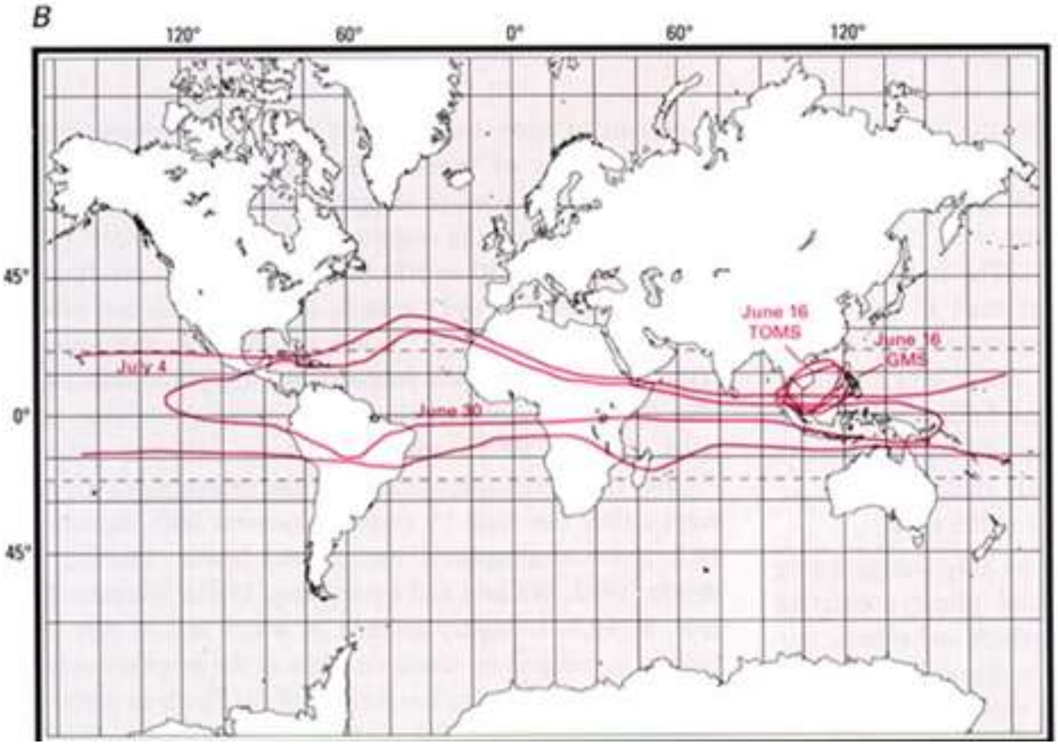

Figure 5: Spreading of the sulfuracid cloud around equator 1 year after eruption.

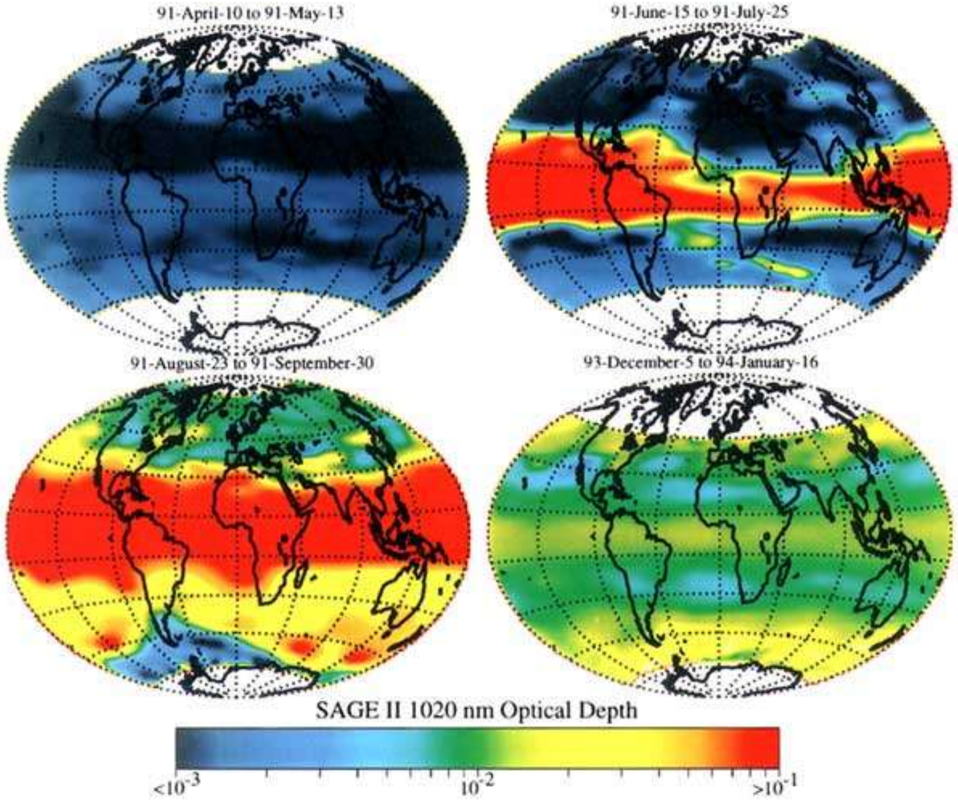

Figure 6:Change in optical depth in the sulfuracid cloud given by time after Pinatubo eruption. Source: http://pubs.usgs.gov/pinatubo/self/fig6.jpg

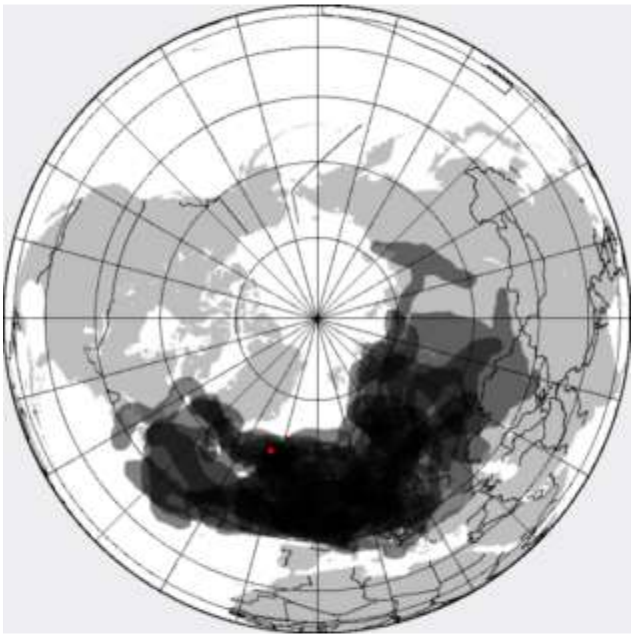

Figure7: Spreading of the ash cloud after the 2010 eruption in Iceland
Source: http://upload.wikimedia.org/wikipedia/commons/b/b1/Eyjafjallaj%C3%B6kull_volcanic_ash_composite.png

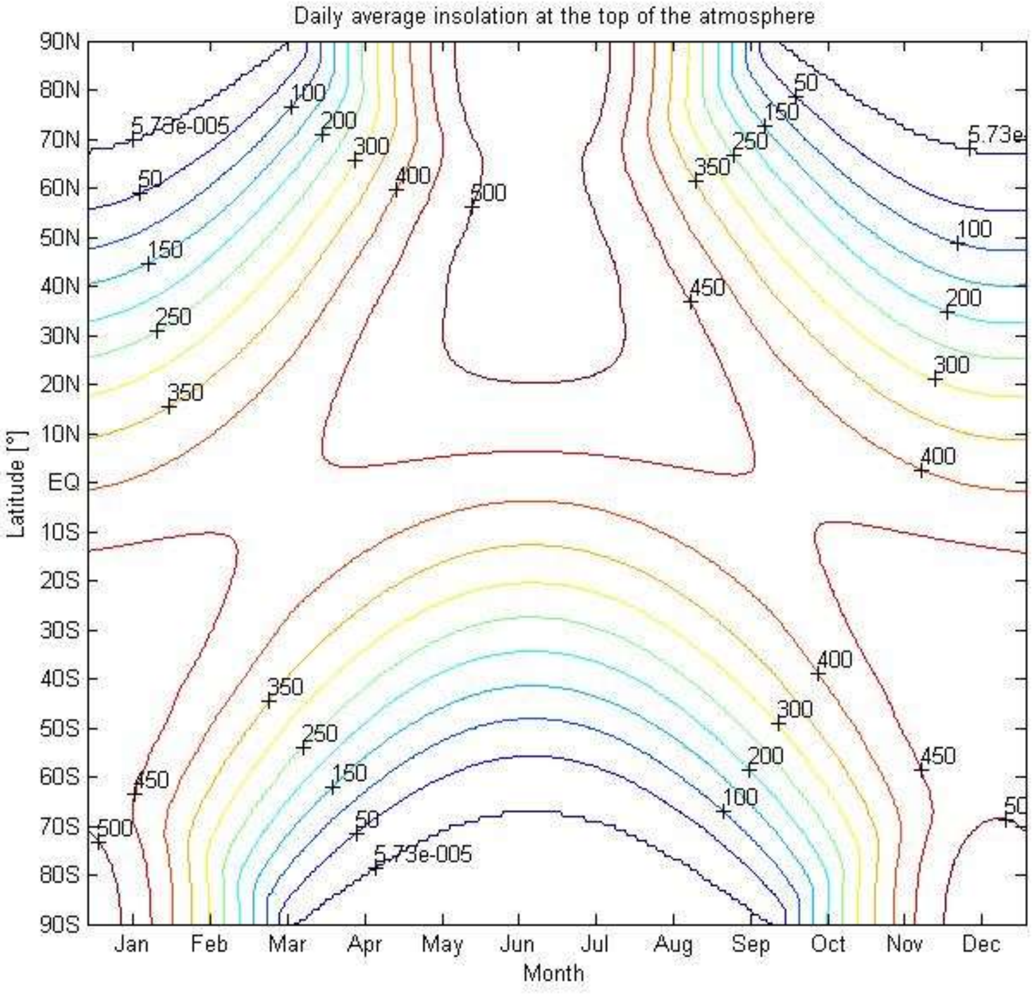

Figure 8: Daily aerage insolation as reproduced from figure 12.3 in "Thermodynamics of Atmospheres and Oceans" by Curry & Webster. The Curve-function values are given in [W/m²]

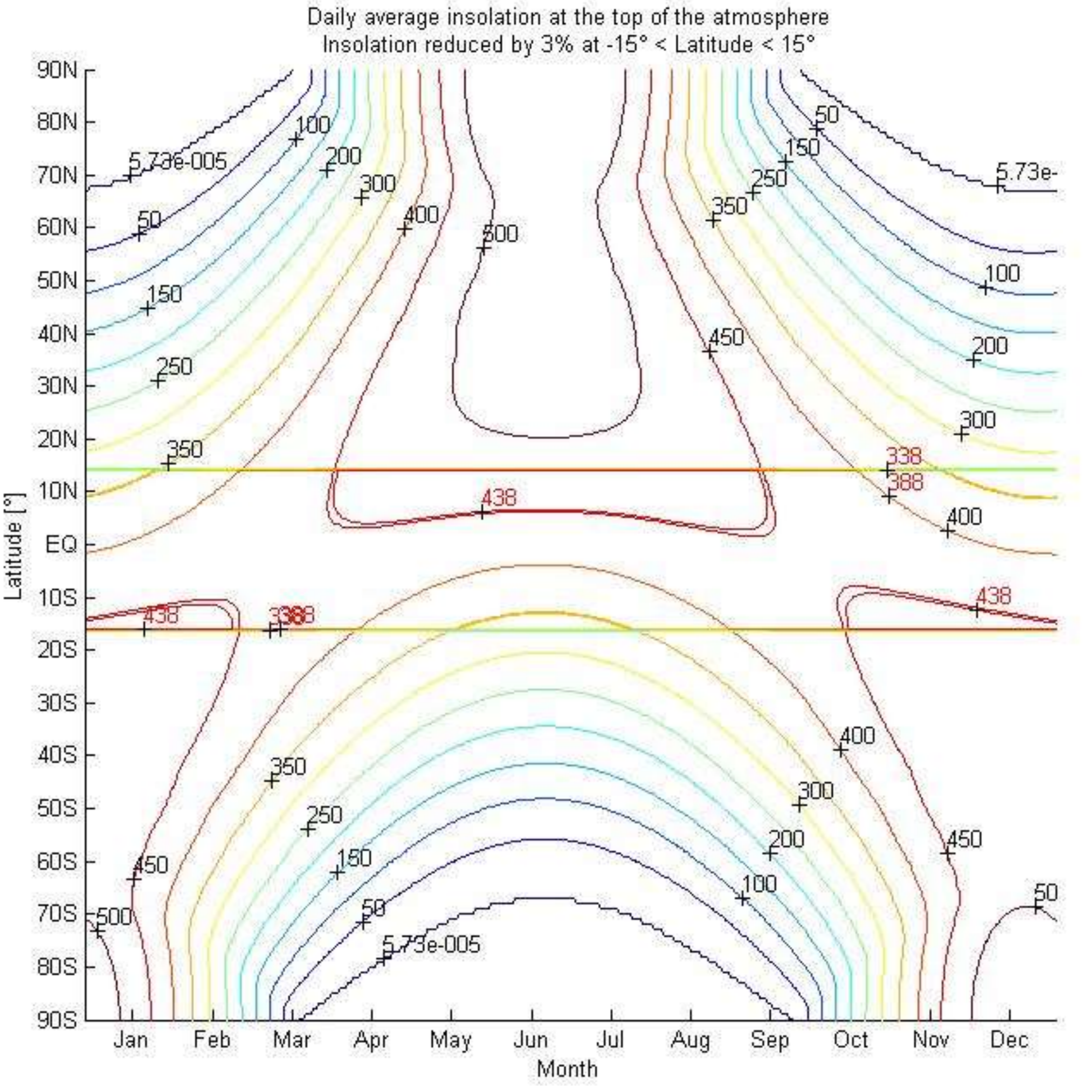

Figure 9: Comparison of the daily average insolation as the insolation is reduced by 3% at (-15° < Latitude < 15°). The Curve-function values are given in [W/m²] The red numbers refers to the affected values.

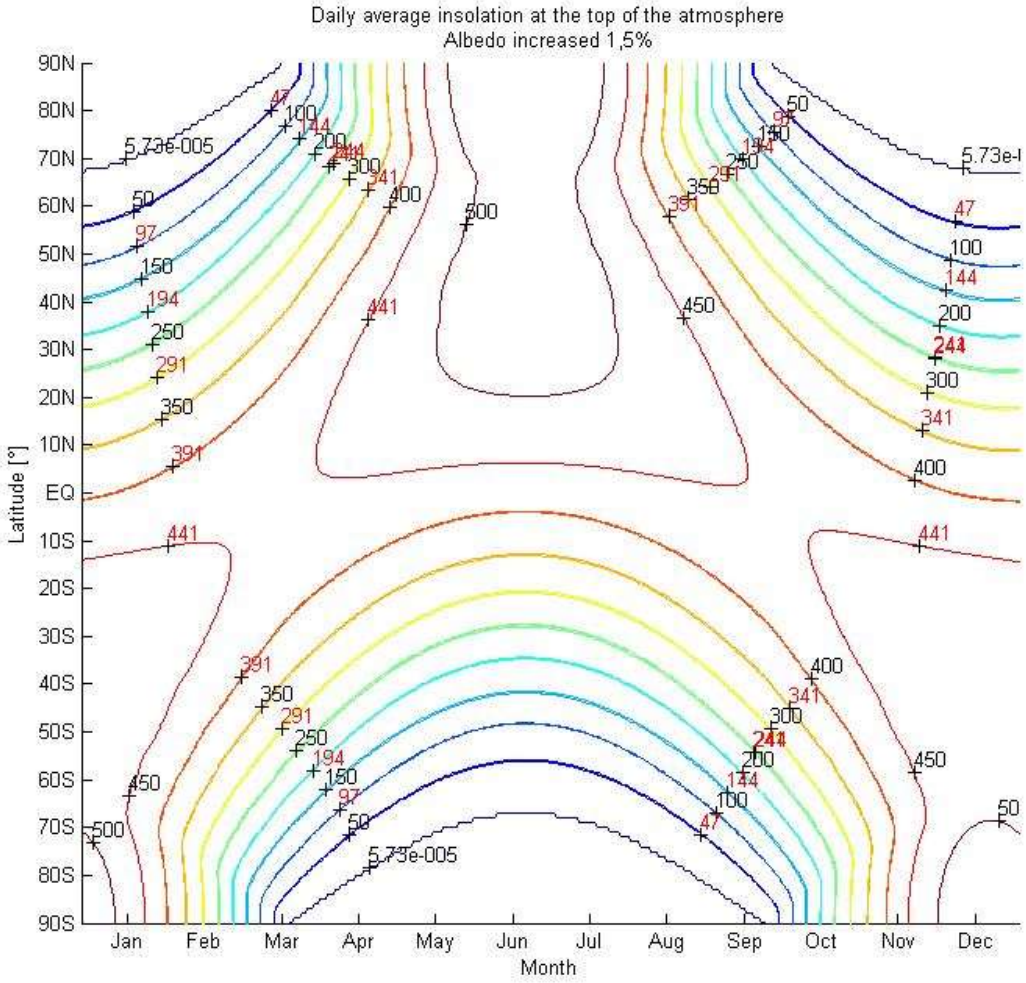

Figure 10: For a global decrease in temperature of 0.5°C the albedo is reduced by ~1.5 %. This figure compares the unaffected atmosphere (black numbers) to the atmosphere affected by the volcano eruption (red numbers).

Apendix III - Matlab coding

```
% Scandi project SIO 217

%%
clc
%Data

Lo=3.92e26;                                       %The luminosity of the sun
d_apogee=152098290000;                            %The point where earth has
the largest distance from the sun
d_perigee=147098290000;                           %The point where earth has
the shortest distance from the sun

%Fourier coefficients
n=[0 1 2 3];
a=[0.006918 -0.399912 -0.006758 -0.002697];
b=[0 0.070257 0.000907 0.001480];

%Mean earth-sun distance
D_mean=(d_apogee+d_perigee)/2;

%Calculate the mean solar flux
S=Lo/(4*pi*D_mean^2)

%Create matrix to save values of F in
M=zeros(181,365);

%Create PHI vector with latitudes
PHI=linspace(-90,90,181);
PHI=PHI*pi/180;

%%

%Loop over days of a year
fori=0:364

%Calculatephi_d
phi_d=2*pi*i/365;

%Calculate delta - the solar declination angle
delta=0;
for j=1:4
        delta=delta+a(j)*cos(n(j)*phi_d)+b(j)*sin(n(j)*phi_d);
end


%Calculate (D/d)^2
dd=(d_perigee+sin((i+1)*pi/(180*2))*(d_apogee-d_perigee))/D_mean;
dd=dd^2;
%     dd=0;
%     forjj=1:3
%         dd=dd+(a(jj)*cos(n(jj)*phi_d))+(b(jj)*sin(n(jj)*phi_d));
%     end


%Loop over latitude
for k=1:181
```

```
%Insolation must be set to zero for each loop through the latitudes
        F_TOA=0;

%Create a loop of 24 hours to sum up the insolation for one day
for t=1:24

%Hour angle - which is zero at noon and increases by 15° for
%each hour before or after that
ho=15*(t-12)*pi/180;

%Zenith angle
cos_Z=sin(PHI(k))*sin(delta)+cos(PHI(k))*cos(delta)*cos(ho);

%Let zenith angle be -90°<Z<90°
ifcos_Z<0
cos_Z=0;
end


%Calculate F_TOA - The total insolation for 24 hours

            F_TOA=F_TOA+S*dd*cos_Z;


end

%Store data in matrix of size 181*365. Also the total insolation
%for one day must be divided by 24 to get the mean value
M(k,i+1)=F_TOA/24;
end

end


% Create contour plot

clevels=0:50:500; %Contour levels for all plots
C=contour(M,clevels);

CLABEL(C);

xlabel('Month')
ylabel('Latitude [°]')
title('Daily average insolation at the top of the atmosphere')




%set(gca,'XTickLabel',['1  ';'100'])
% Alternatively, use a cell array of strings:
set(gca,'XTickLabel',{'1','100'})

set(gca,'XLim',[0 365]);% This automatically sets the
% XLimMode to manual.
% Set XTick so that only the integer values that
% range from 0.5 - 12.5 are used.
```

```
set(gca,'XTick',[18:30:350])  % This automatically sets
% the XTickMode to manual.
% Set the XTickLabel so that abbreviations for the
% months are used.

months = ['Jan';
'Feb';
'Mar';
'Apr';
'May';
'Jun';
'Jul';
'Aug';
'Sep';
'Oct';
'Nov';
'Dec'];
set(gca,'XTickLabel',months)

%Y-axis

set(gca,'YTickLabel',{'90S','80S','70S','60S','50S','40S','30S','20S','10S'
,'EQ','10N','20N','30N','40N','50N','60N','70N','80N','90N'})
set(gca,'YTick',[1:10:181])
```

Appendix IV References

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[i] Curry and Webster, ‘Thermodynamics of Atmospheres and Oceans, Academic Press, San Diego, 1999.

[ii] Hartmann, Global Physical Climatology, Academic Press, San Diego, 2000.

[iii] Jihong-Cole, Volcanos and Climate, John Wiley and Sons Ltd 2010, accessed 11.12.2013 http://www.sdstate.edu/chem/faculty/jihong-cole-dai/upload/Volcanoes-and-Climate-10-1002-wcc-76.pdf

[iv] Geology SDSU Website accessed 11.12.2013 http://www.geology.sdsu.edu/how_volcanoes_work/climate_effects.html

[v] Wikipedia Website, Mount Pinatubo, accessed 11.12.2013 http://en.wikipedia.org/wiki/Mount_Pinatubo

[vi] Hayasaka et al. Changes in stratospheric aerosols and insolation due to Mt. Pinatubo eruption as observed over the western pacific, Geophysical research letter vol. 21 No12. 1994. http://onlinelibrary.wiley.com.pva.uib.no/doi/10.1029/94GL00987/pdf

[vii] University of Iceland Website, eruption of Eyafjalloyokull, accessed 11.12.2013 http://www.iagos.org/lw_resource/datapool/_items/item_163/wmo_iagos_bonadonna.pdf

[viii] USGS website, Volcanos effect on climate, accessed 11.12.2013 http://volcanoes.usgs.gov/hazards/gas/climate.php

[ix] ITACA, Part 1: Solar Astronomy http://www.itacanet.org/the-sun-as-a-source-of-energy/part-1-solar-astronomy/