Peer-Reviewed Term Project

SIO 217a Atmospheric and Climate Sciences I

Mari Masdal, Jonas Coyet, Morven Muilwijk & Nikolai Aksnes

2013

Index

1 Introduction

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

15 Theory
16
17 The model to be reproduced is a contour graph
18 of the daily average insolation at the top of the
19 atmosphere as a function of season and
20 latitude. The insolation is the measure of solar
21 radiation energy received on a given surface
22 area and recorded during a given time.
23
24 *Figure 1* was what we were going to end up
25 with prior to taking into account the volcanic
26 effects. The vertical axis illustrates the latitude
27 with the South Pole at the bottom, equator at
28 the middle and the North Pole at the top. At the
29 horizontal axis we have months starting with
30 January and ending with December. The lines
31 throughout the figure are lines of constant solar
32 flux. The black areas represent periods of no
33 solar insolation, which exist at the North Pole
34 when you have polar nights in the winter
35 months and equivalently at the South Pole in
36 the summer months. The maximum values of
37 the solar flux are also found at the North and
38 South Pole as the lines represent a daily
39 average of insolation giving the poles high
40 values as they have sun all day long (North
41 Pole has midnight sun in June-July and the
42 South Pole in January-December).
43
44 The seasonal and latitudinal variations in
45 temperature are driven primarily by variations
46 of insolation and average solar zenith angle. [i]
47 The figure we were to reproduce was the plot
48 of the daily average insolation which is given
49 by equation (1). Where S is the mean solar flux
50 calculated by (2), the squared mean earth-sun

51 distance is calculated in (3), and Z the solar
52 zenith angle calculated in (5).
53
54 The mean solar flux (S) per unit area at the
55 mean position of Earth is measured for a
56 surface that is perpendicular to the solar beam.
57 Since the approximation that Earth is spherical
58 is not completely correct, most of the surface is
59 inclined at an oblique angle to the solar beam.
60 The solar zenith angle is therefore defined as
61 the angle between the local normal to Earth´s
62 surface and a line between a point on the
63 surface of the Earth and the sun.
64
65 The solar zenith angle depends on the latitude,
66 season and time of day. The season can be
67 expressed in terms of the declination angle of
68 the sun, which is the latitude of the point on
69 the surface of Earth directly under the sun at
70 noon. This angle varies seasonally because of
71 the tilt of the Earth on its axis of rotation and
72 the rotation of the Earth around the sun. This
73 angle would always be 0° if the Earth were not
74 tilted. Also, the season depends on the average
75 sun-earth distance which slightly varies during
76 the year.
77
78 The hour angle represents the time of the day
79 and is defined as the longitude of the sub solar
80 point relative to its position at noon. The hour
81 angle is zero at solar noon (when the sun is at
82 its highest elevation) and increases by 15° for
83 every hour before or after solar noon. [ii]*Figure*
84 *2* gives an illustration of the different inputs to
85 the solar zenith angle.
86
87 The effect of volcanic eruptions on
88 insolation

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

95 The greenhouse effect increases due to the
96 emission of CO_2 from the volcanoes. However,
97 the amounts of water vapor and carbon dioxide
98 emitted by volcanoes are negligibly small
99 compared with the atmospheric reservoir size
100 of these gases, and therefore their climate

101 impact is insignificant. Also, this small amount
102 of global warming caused by eruption-
103 generated greenhouse gasses are offset by the
104 far greater amount of global cooling caused by
105 the particles in the stratosphere from the
106 eruption, which is called the haze effect.[iii]

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

123 One of the largest registered effects on climate
124 due to volcano eruptions came from the
125 eruption of Mount Pinatubo in the Philippines
126 in 1991. The Pinatubo eruption produced the
127 largest sulfur oxide cloud in this century. The
128 emission of SO_2 was calculated to be
129 approximately 20,000,000 tones.[v] The average
130 global mean temperatures dropped by approx.
131 0.5° C for a period of 1-3 years.

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

145 The ship measurement studies concluded that
146 in the equatorial region, months after the
147 eruption, the aerosol optical thickness
148 increased from 0.1 to 0.3 at 500nm.
149 Wavelength dependency also changed. The

150 solar flux insolation decreased with 1.4%-4.1%
151 compared to that before the eruption.[vi]

152 The 2010 eruption of Eyjafjallajökull on
153 Iceland caused a lot of attention in the media
154 due to the large ash cloud it produced and the
155 enormous disruption to air travel across
156 western and northern Europe. However, the
157 eruption was relatively small compared to
158 other large eruptions. Later studies have shown
159 that the Iceland eruption had nearly no effect at
160 all on climate and solar insolation. The ash
161 cloud was spread over a large area, but was
162 relatively short lived (weeks) and had therefore
163 had negligible impact on local or global
164 climate. The main reason that the Iceland
165 eruption did not have any impact on longer
166 timescales is that the amount of sulfur emitted
167 was very small from this particular volcano.
168 The sulfur emission was approx. 3000 tons a
169 day for a few days, compared to 20 million
170 tons for the Pinatubo eruption. Since we now
171 know that the greatest cooling effect from
172 volcanoes come from the conversion of sulfur
173 dioxide to sulfate aerosols that reflect sunlight,
174 we understand why the Iceland eruption had
175 little impact on insolation, both locally and as a
176 global average. This shows that relatively large
177 volcano eruptions do not necessarily have an
178 impact on climate, as this is primarily
179 dependent on the amount of sulfur in the
180 eruption. For our study of impact on averaged
181 insolation the Iceland eruption does not do any
182 impact at all. *Figure 7*shows the spreading of
183 the ash cloud after the 2010 eruption. [viiviii]
184
185 **Combining the effect of volcanoes in our**
186 **model**
187
188 Reproduction of the model given in the task is
189 shown in *Figure 8* and the calculations and
190 MATLAB codes are given in the appendix.
191
192 In our insolation model our only variables are
193 any possible local changes in insolation or a
194 change in global average albedo. There are no
195 studies that directly connect the amount of
196 sulfur emitted by the volcano and the change
197 in albedo. We know that the haze effect gives a
198 cooling effect, which means an increase in
199 albedo and decrease in insolation. If we
200 neglect any other effects that might change the
201 surface temperature or albedo, such as the
202 short-lived ash cloud or the small increase in

203 greenhouse effect, we can assume that all
204 change in insolation is due to the increase in
205 sulfur aerosols. We have found two ways to
206 implement this effect into our insolation
207 model. The first way is to look at the change in
208 global mean surface temperature over a longer
209 timescale of 1-3 years, and from this calculate
210 a change in global albedo. In this model we
211 have averaged the effect over a long timescale
212 and over the planet's surface area. Another
213 way of looking at the effect is using
214 measurements of change in insolation and
215 atmospheric optical depth in the local areas
216 affected by the plume taken from ships during
217 the years after the eruption. We have applied
218 these two methods below.
219
220 Since the eruption of Eyafjallajökull had such
221 a little impact on the average insolation and
222 climate, we will demonstrate the effect that a
223 sulfur rich volcano eruption has by applying
224 the Pinatubo eruption to our model. We only
225 make a model for the Pinatubo, since the
226 eruption of El Chichon also was sulfur rich and
227 therefore give a similar but smaller result.
228

Pinatubo effect in our model as a local
229
change
230
231
232 As explained earlier measurements taken from
233 ships showed an approx. local decrease in solar
234 insolation of 1.4%-4.1% compared to with that
235 before the eruption. By adjusting our model by
236 this percentage reduction in the regional band
237 between 15 degrees S and 15 degrees N we can
238 see the effects off the volcano. See *Figure 9*.
239

Pinatubo effect in our model as global
240
average
241
242
243 The Pinatubo eruption led to a decrease in
244 global mean temperature of approximately
245 0.5°C. If we assume the effect is averaged over
246 the global surface area we can use a simplified
247 climate model and find what a change in
248 albedo would give in terms of temperature
249 change. Assuming we have a perfect
250 atmosphere in equilibrium (steady-state) with
251 the earth surface, transparent for incoming
252 shortwave radiation, absorbing and emitting
253 longwave radiation perfectly and the earth

254 acting like a perfect black body. Then a simple
255 climate model with one atmosphere, and
256 albedo of 0.31 would give us a surface
257 temperature of T=303K. This is too high
258 because of the assumptions we have made, but
259 we can use the model to connect deltaT to
260 deltaα. By our calculations from below we get
261 an increase of 1.4988% in the albedo for a 0.5°
262 decrease in temperature. See *Figure 10* and
263 calculations. The pattern here is exactly the
264 same as in figure 8, only the values associated
265 with them have changed.
266
267 **Conclusion**
268
269 We can conclude that we successfully have
270 reproduced the insolation figure and that we
271 can show the effect from sulphur rich volcano
272 eruptions in our model. As we can see from
273 figure 9 the daily average insolation will
274 slightly decrease in the band close to the
275 equator. In our model the insolation have
276 decreased evenly between -15°<latitude<15°.
277 It might be more realistic if the effect
278 decreased as one approaches -15° or 15°
279 latitude, as by now the model states that the
280 effect suddenly goes from 3% decrease in
281 insolation to 0% at the edge of the ash cloud.
282 According to figure 10 we can see that the
283 daily average insolation decreased more in
284 high insolation areas compared to lower
285 insolation regions. This is due to the fact that
286 the albedo is set to be 1.5 % lower globally,
287 and so the effect have greater impact on higher
288 insolation values.
289
290 By comparing figure 9 and 10 we can see how
291 the two models differ from each other. The
292 model with a local effect will give us a lower
293 value of insolation at the equatorial regions,
294 compared to the insolation in the same region
295 for the model with a global effect. Still, the
296 global model spreads the decrease in insolation
297 over the whole planet, though the change in
298 insolation for this model is drastically reduced
299 when looking at the low insolation regions.
300 Therefore, the conclusion is that the two
301 models give somewhat the same average effect
302 for the total decrease in insolation, which
303 indicates that both models seem reasonable.

SIO 217a Atmospheric and Climate Sciences

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°< ϕ < 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:

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

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

$$F_{atm} = \sigma T_{atm}^4 \tag{8}$$

$$F_{surf} = \sigma T_{surf}^4 \tag{9}$$

Our simplified model states that:

$$F_s = F_{atm} \tag{10}$$
$$F_{surf} = 2 F_{atm} \tag{11}$$

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

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

$$\alpha_p = 1 - \frac{\sigma T_{surf}^4}{0{,}5 S_0} \tag{12}$$

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%.
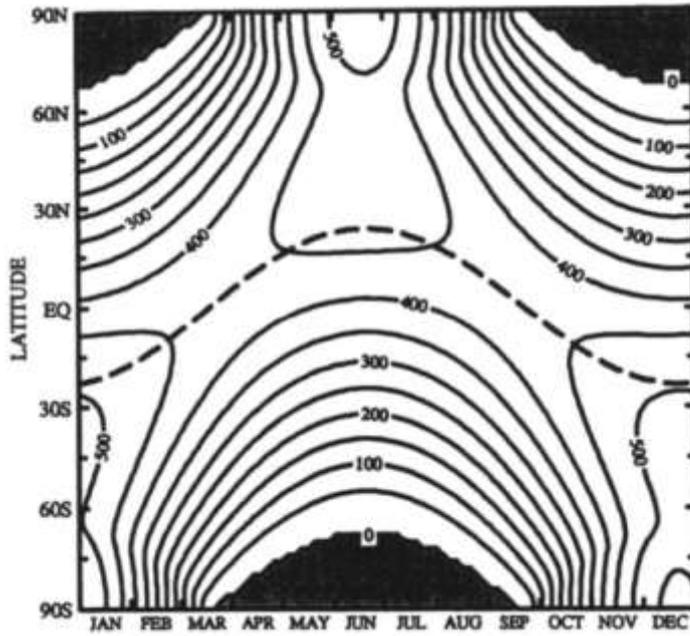
Appendix II - Figures

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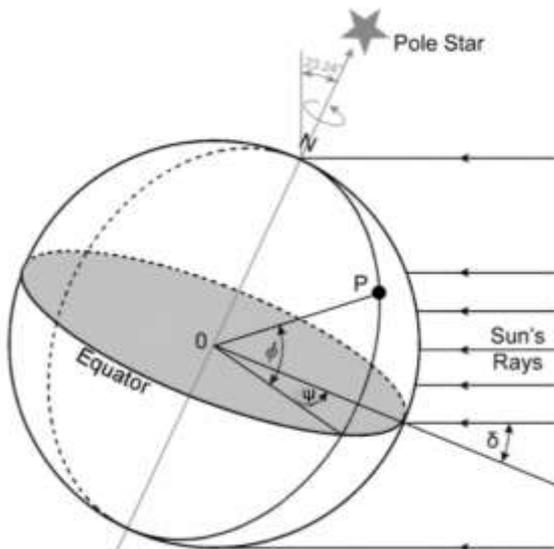

Figure 2: Definition of hour angle ψ, declination angle δ and latitude angle φ[ix]
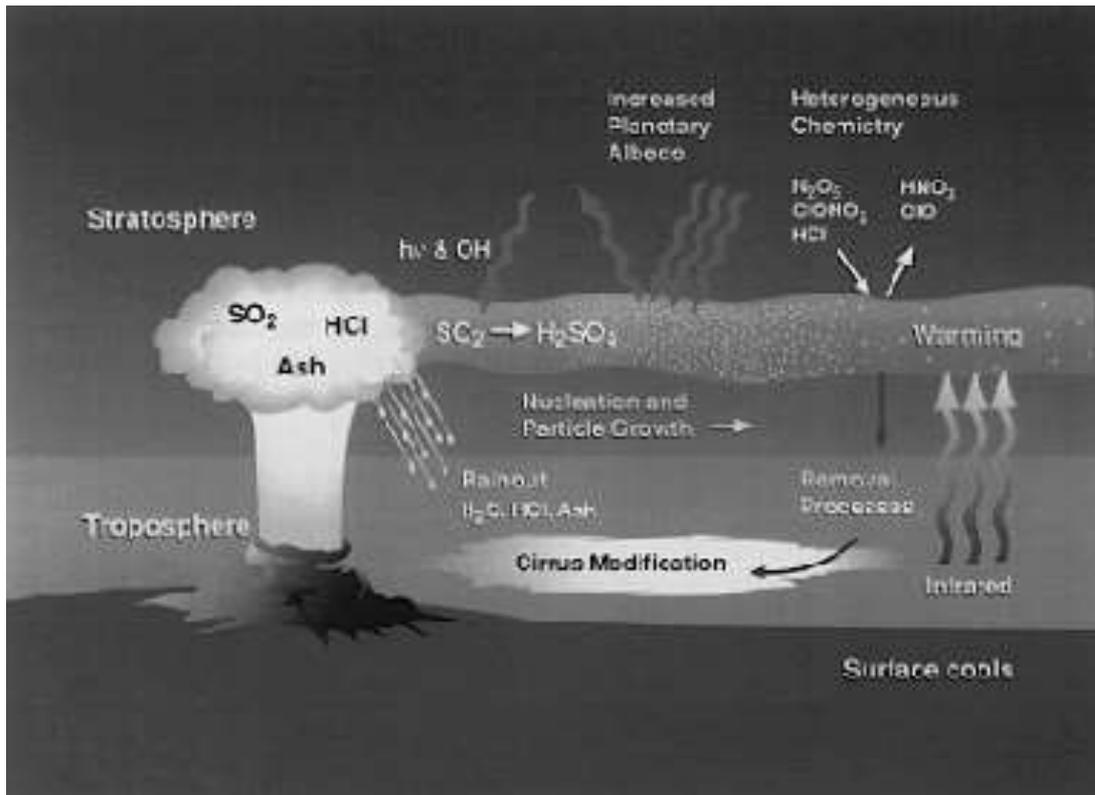*Source: www.itacenet .org*

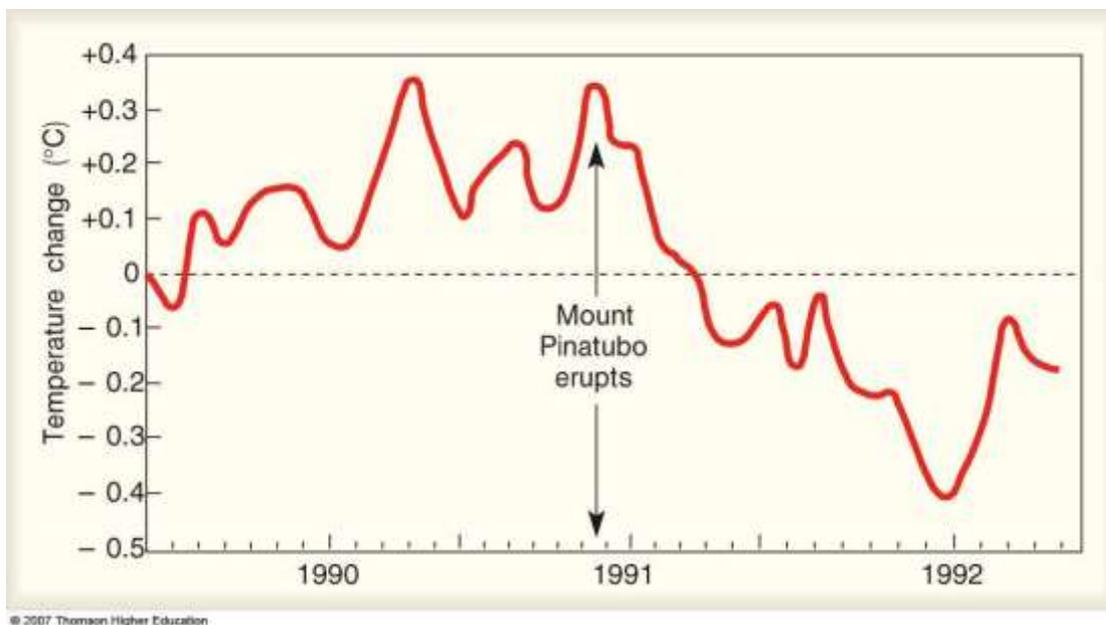*Figure 3:Effect of sulfur on solar insolation*
Source www.iagos.org

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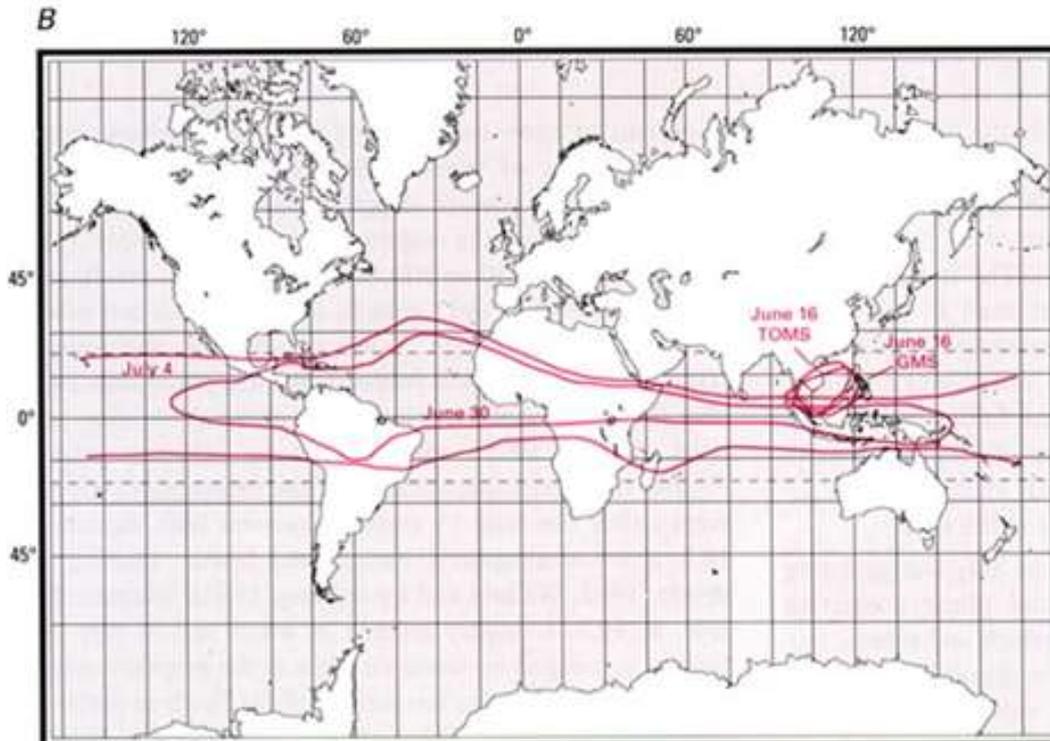*Source: http://apollo.lsc.vsc.edu/classes/met130/notes/chapter16/graphics/temp_pinatubo.jpg*

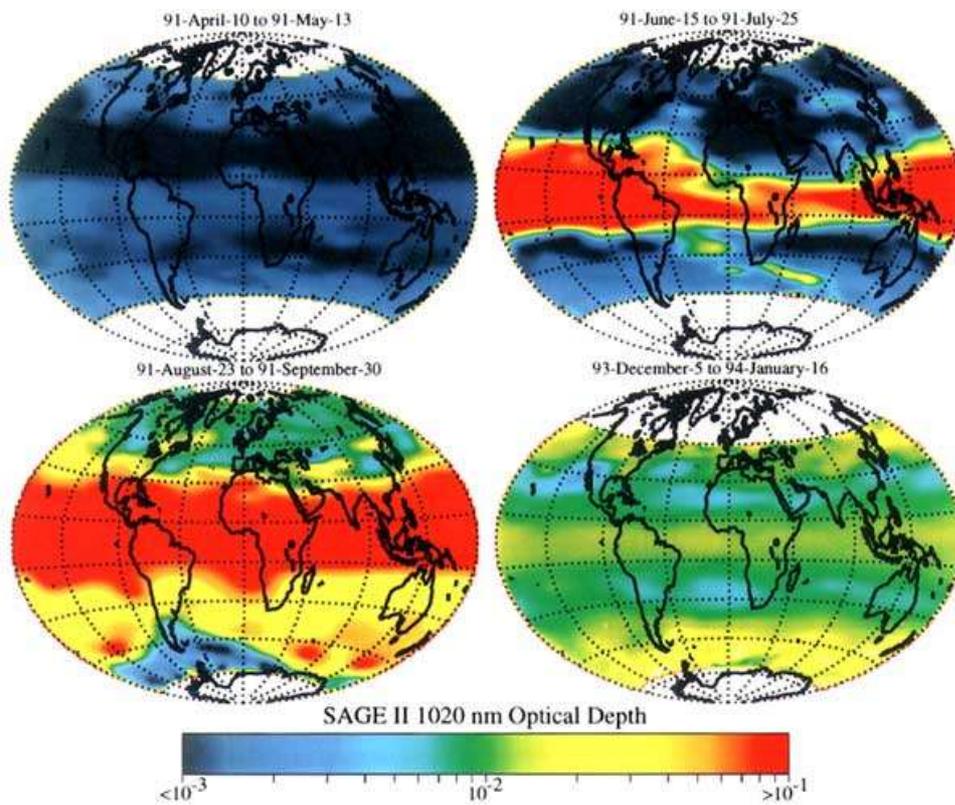*Figure 5: Spreading of the sulfuracid cloud around equator 1 year after eruption.*

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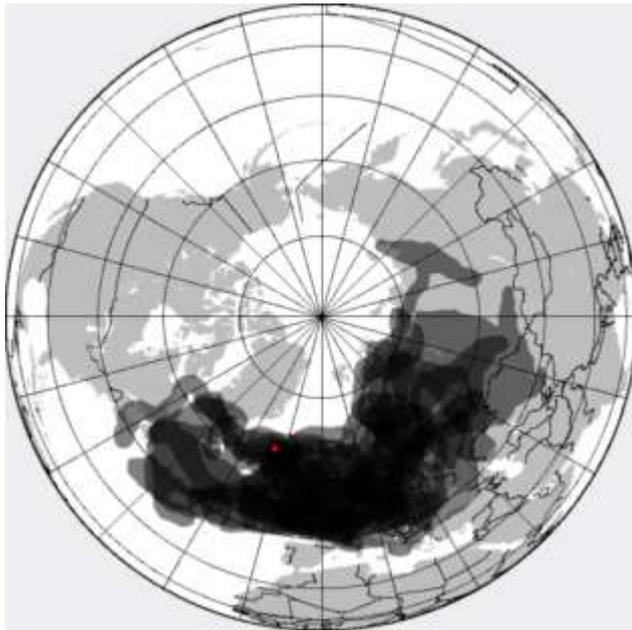*Source: http://pubs.usgs.gov/pinatubo/self/fig6.jpg*

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
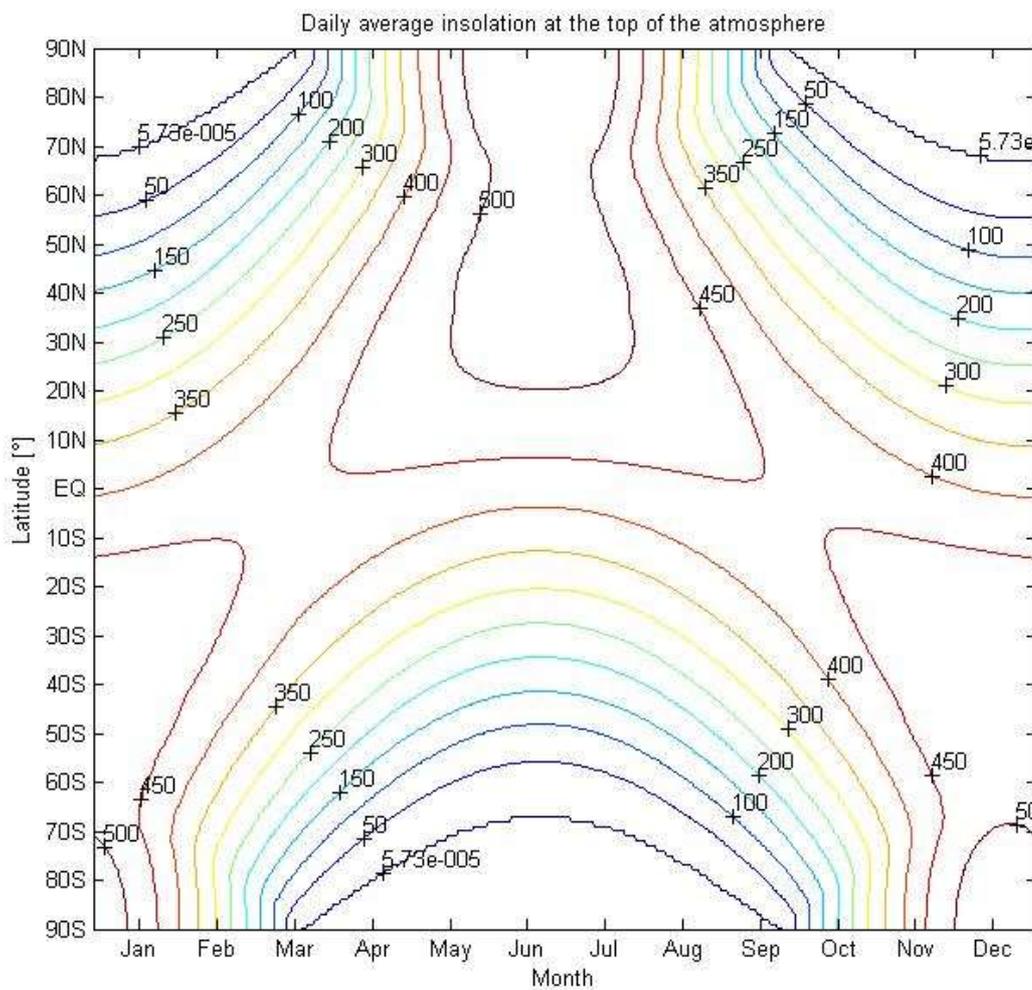

Figure 8: Daily aerage insolation as reproduced from figure 12.3 in "Thermodynamics of Atmospheres and Oceans" by Curry & Webster. The Curve-function values are given in [W/m²]
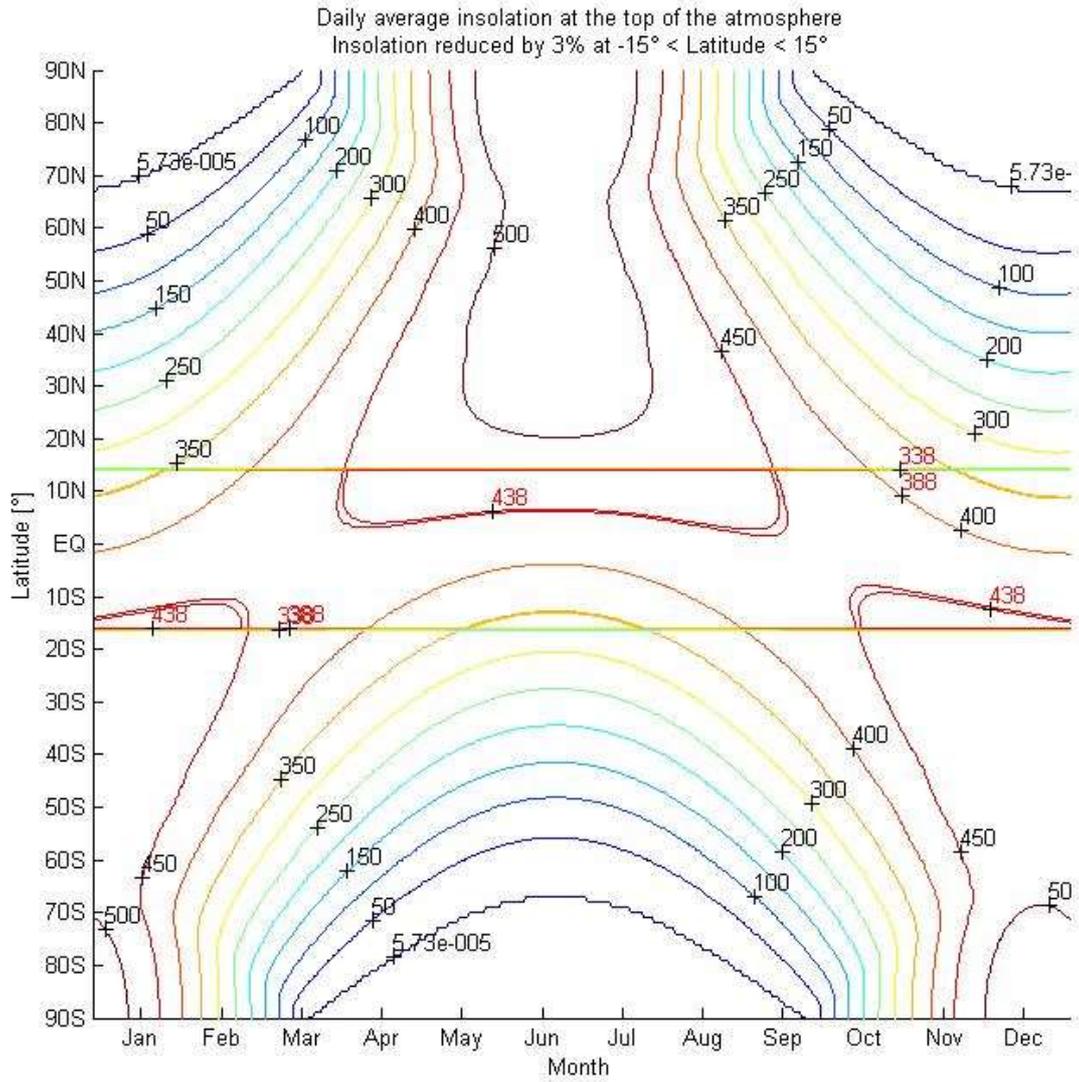
Figure 9: Comparison of the daily average insolation as the insolation is reduced by 3% at (-15° < Latitude < 15°). The Curve-function values are given in [W/m²] The red numbers refers to the affected values.
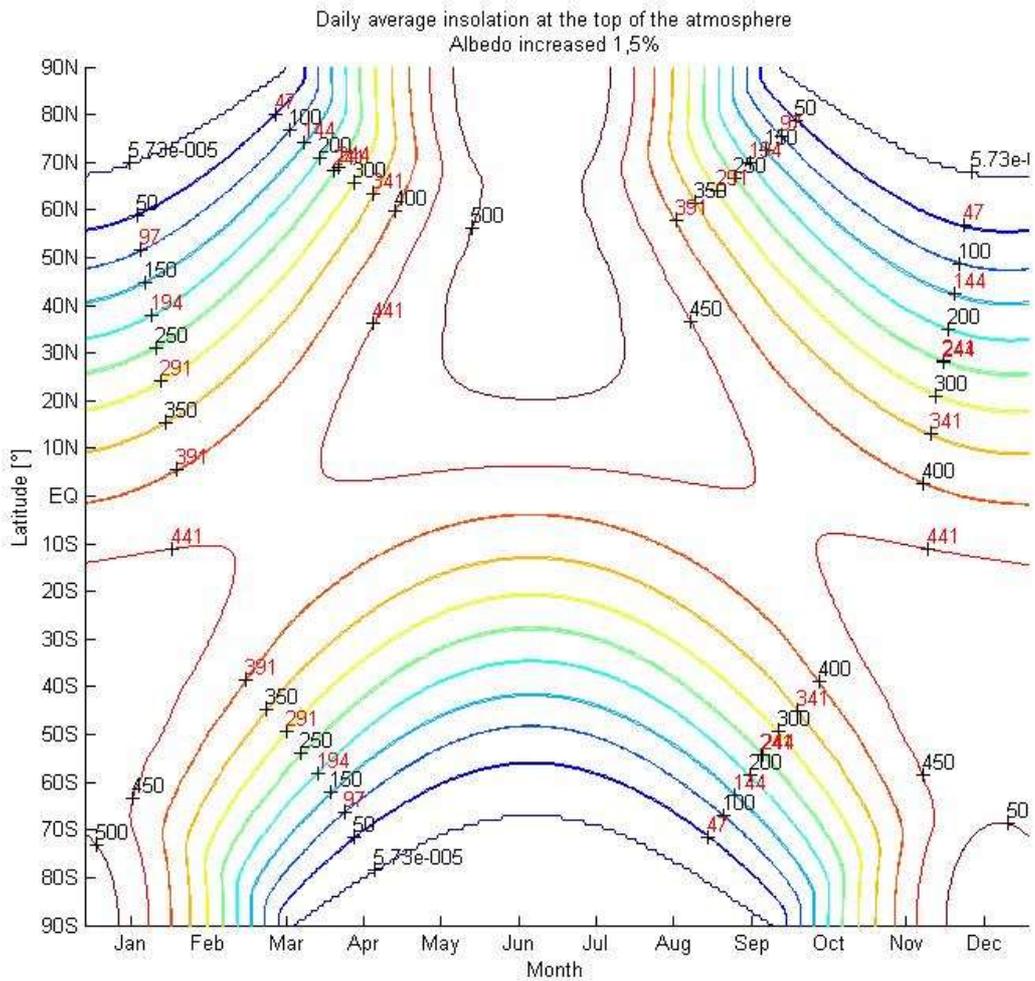
Figure 10: For a global decrease in temperature of 0.5°C the albedo is reduced by ~1.5 %. This figure compares the unaffected atmosphere (black numbers) to the atmosphere affected by the volcano eruption (red numbers).

Apendix III - Matlab coding

```matlab
% 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
```

9

```matlab
%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.
```

10

```matlab
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

[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/