

# **Clear Sky Absorption of Solar Radiation by the Average Global Atmosphere**

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## **Abstract**

The author has analyzed shortwave (SW) absorption of the annual average global atmosphere (AGA) in the clear sky conditions utilizing spectral analysis methods. A modified zenith angle has been used in calculating the average zenith values for five atmospheric models covering three climate zones of the Earth. The absorption flux value of  $67.71 \text{ Wm}^{-2}$  of this study is very close to the value of  $69 \text{ Wm}^{-2}$  found in the energy balance analysis based on the observational data. It means that the absorption due to the aerosols would be  $1.29 \text{ Wm}^{-2}$ , which is close to the values  $1.6 - 2.4 \text{ Wm}^{-2}$  calculated in different studies for aerosol absorption in the atmosphere. This result shows that there is no excessive absorption in the clear sky conditions when calculating annual global value. When the effective global zenith value of 51.38 degrees has been applied to the one dimensional (1D) model in the modified mid-latitude atmosphere corresponding to the AGA conditions, the results are similar to the results based on the five different atmospheric models applied in three climate zones of the Earth. The 1D model has been applied for finding basic relationships in SW absorption phenomenon. One result is that the contribution of water is 77.2 % and ozone's contribution is 19.5 %. The results are comparable to the traditional radiation transfer models developed for SW absorption calculations.

**Keywords:** Solar radiation absorption, Shortwave absorption, Zenith angle, Anomalous absorption, Earth's energy balance.

## **1 Introduction**

The objectives of this paper are to calculate the absorption of solar radiation by the average global atmosphere of the year 2005 (AGA) in the clear sky conditions using spectral analysis methods and to analyze the effects of altitude, the contribution of GH gases, and the effects of a zenith angle on the magnitude of the SW absorption.

Table 1 includes the acronyms and definitions used repeatedly in this paper and they are

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the same as used by Ollila [1].

Clear sky is indicated by the subscript<sub>b</sub>, cloudy atmosphere by the subscript<sub>c</sub>, and all-sky atmosphere by the subscript<sub>a</sub>.

The absorption of solar radiation by the atmosphere and by the surface determines the total energy input in the Earth's energy balance. The author has analyzed several studies of the shortwave (SW) fluxes published during the years 1995 and 2012. The values of the SW fluxes of this study [1] are depicted in Figure 1.

Table 1: List of symbols, abbreviations and definitions of the terms.

<b>Acronym</b>	<b>Definition</b>
AGA	Average global atmosphere
GH	Greenhouse
SW	Shortwave radiation
LW	Longwave radiation
TOA	Top of the atmosphere
SWin	Average incident solar radiation flux at TOA
Ag	Upward LW surface flux absorbed by the atmosphere
Ed	Downward LW flux emitted by the atmosphere
Rp	SW flux reflected by air
Rt	Total reflected SW flux into space
Rs	SW flux reflected by the surface
Sa	Total SW flux absorbed in the atmosphere
Sb	Incoming SW flux absorbed by clear air
Sd	Incoming SW flux reaching the surface
Ss	SW flux absorbed by the surface
Sx	Incoming SW flux ( $S_x = S_{Win} - R_p$ )

There are differences in the total solar irradiance flux values according to the different measurement systems. Kopp and Lean [2] report a value of  $1360.8 \pm 0.5 \text{ Wm}^{-2}$  and Fröhlich [3] reports the value, which is about  $4.5 \text{ Wm}^{-2}$  greater. The value of  $1360.8$  would mean the average incident solar radiation flux  $S_{Win} = 1360.8/4 = 340.2 \text{ Wm}^{-2}$  and the value of Fröhlich[3] would be  $341.3 \text{ Wm}^{-2}$ . The author has used the flux value of  $342 \text{ Wm}^{-2}$ , which is the same value as in his earlier studies [1, 4] making the results of this study directly comparable.

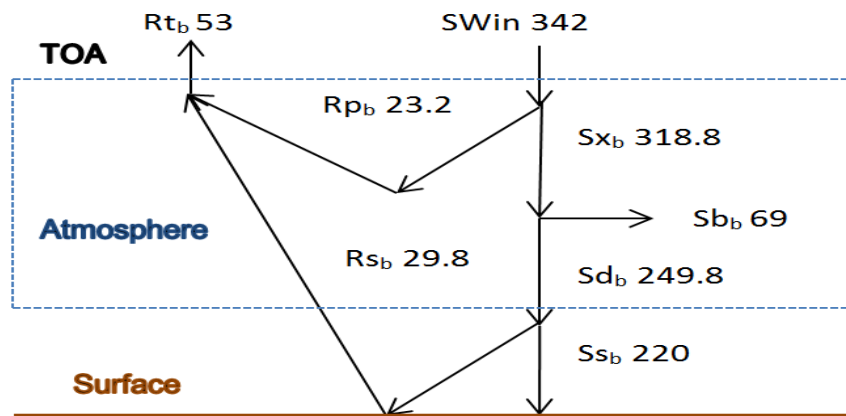


Figure 1: Schematic flow diagram of Earth's shortwave energy fluxes of the clear sky according to Ollila[1]. The flux values are stated in  $\text{Wm}^{-2}$ .

The total absorption of the incoming solar radiation  $S_a$  by the atmosphere has stayed as a research target for decades. The observational value of  $S_{b_b}$  in the clear sky conditions can be determined indirectly by measuring the energy fluxes  $SW_{in}$ ,  $S_{s_b}$ ,  $R_{t_b}$  and  $R_{s_b}$ . The problem has been that the theoretical absorption calculation models utilizing radiative transfer models have produced values which are considerably lower than the observations especially for cloudy sky. Cess et al. [5] have estimated that the difference is even  $25 \text{ Wm}^{-2}$  at the global annual level in cloudy sky conditions. This discrepancy between the models and observations has been called anomalous or enhanced or excess SW absorption. In the latest regional calculations the excess absorption has been in the limits of measurement errors [6].

This study does not cover the cloudy sky SW absorption. There have been conflicting results about whether there is excess absorption in clear skies. Some studies like Valero and Bush [7], Ackerman et al. [8] and Ramana et al. [9] show that the clear sky SW absorption based on the radiation transfer models and observations match in the boundaries of measurement accuracies. Reno et al.[10] have prepared a comprehensive study about the clear sky models. One of the conclusions is that simple models are comparable to more complicated models. The studies referred above [6-9] are based on the local measurement arrangements and not on the calculations for the annual average global atmosphere.

When the incoming solar light transmits through the cloudless atmosphere, air molecules cause Rayleigh scattering. The scattering phenomena causes reflection of light in the atmosphere and it has an effect of the total albedo of the Earth as indicated in Fig.1. In this study the scattering and albedo changes has not been studied, because these effects have been included in the reflected flux  $R_{p_b}$  caused by clear air.

The calculation method used in this study is the spectral analysis utilizing the Spectral Calculator, which is available on the Internet. This application is provided by Gats Inc. [11]. Molecules emit and absorb radiation only at certain frequencies or wavenumbers, thereby creating changes in their quantum energy levels. This produces a unique spectrum for each gas molecule species. According to Kirchhoff's law, the absorptivity is the compliment of transmittance: absorptivity = 1- transmittance.

The Spectral Calculator tool produces the transmittance values only; the absorptivity values can easily be calculated using the relationship above. The absorption lines appear as dips in the transmittance spectrum lines. Each line has a width and a depth, which are determined by the quantum mechanical properties of the molecule in question.

The spectrum of a gas molecule can be calculated using the basic physical laws, but it is not accurate enough for practical calculations. The collection of line parameters for a group of absorption lines is called a line list; the list has been derived by fitting laboratory spectra measured in various conditions. In this way, each absorption line is specified by a set of parameters. Using this data, an absorption line can be calculated for a given concentration, temperature and pressure. HITRAN [12] is probably the most comprehensive and commonly used line list for atmospheric applications and it is available when using the Spectral Calculator tool.

In order to simulate the transmittance spectrum of a gas mixture over a given spectral range, the absorption lines of each gas must be calculated. The complete spectrum is the product of the individual, absorption-line spectra. The individual line spectra cannot be directly summarized in the case of overlapping frequencies.

The algorithms that calculate molecular spectra in this way are known as line-by-line (LBL) models, and they produce the most accurate values for molecular absorption. The Spectral Calculator tool uses LBL modelling for the molecular transmission and emission calculations. In actual calculations Spectral Calculator uses Linepak<sup>TM</sup> algorithms, which Gordley et al. have described in detail [13]. Many international research institutes, including NASA, use Linepak<sup>TM</sup> software for spectral calculations, which proves the correctness and validity of Spectral Calculator.

Calculating the spectrum in a complicated path, like through the planetary atmosphere, requires special arrangements. Spectral Calculator divides the path into segments, which are approximated by constant temperature, pressure and gas concentrations. The transmittance spectrum of the whole path is the product of individual spectra of the segments. These calculations may become computationally very intensive and, therefore, Spectral Calculator has been designed to maximize efficiency without losing accuracy.

The Spectral Calculator tool offers an opportunity for individual researchers to calculate and analyze the absorption phenomenon. Atmospheric path calculations are possible from a minimum height of 1 km to a maximum height of 600 km. Six different atmospheric models are readily available: U.S. standard, tropical, mid-latitude summer, mid-latitude winter, polar summer and polar winter. The atmospheric models differ mainly in their temperature and humidity profiles. Users can modify the GH concentration profiles by scale factors and the temperature by offset changes.

This calculation method does not cover the absorption caused by aerosols in the atmosphere. The aerosols have both warming and cooling effects in the atmosphere. The total radiative forcing of aerosols according to IPCC [14] in its latest report is  $-0.27 \text{ Wm}^{-2}$  (direct effects) and  $-0.55 \text{ Wm}^{-2}$  (cloud effects). There is also warming effect of aerosols due to the absorption in the atmosphere. Hatzianastassiou et al. [15] have calculated that in the clear sky conditions this flux is  $1.6 \text{ Wm}^{-2}$ . Stier et al. [16] have found that six models give the flux values between  $1.78 - 2.38 \text{ Wm}^{-2}$ .

In summary the expected value of total SW flux absorbed by the GH gases in the atmosphere would be  $69 - 1.6 \dots 2.4 = 66.6 \dots 67.4 \text{ Wm}^{-2}$  caused by the GH gases in annual average global atmosphere.

Another good reason for studying SW absorption is that the variation of SW absorption value according to different studies has been more than the total anthropogenic radiative

forcing of  $2.29 \text{ Wm}^{-2}$  since 1750 [14].

## **2 Calculation Method of the Annual Average Global Absorption**

### **2.1 General Conditions of Shortwave Absorption Calculations**

The author has applied three climate zones or belts of the Earth in the absorption calculations. The common definitions for these belts are: the tropical belt between 23.5 degrees North and South, the mid-latitudes from 23.5 degrees to 60 degrees and the Polar Regions between 60 and 90 degrees. By applying these definitions, the calculations utilizing the belt areas yield weighting factors of 0.399, 0.467 and 0.134 for the zones. These weighting factors have been used in combining the results of different climate zones into the annual global average (AGA) value.

The Spectral Calculator supports these climate zones by offering five atmospheric models originally produced by Ellingson et al.[17]. These are tropical, mid-latitude summer, mid-latitude winter, polar summer and polar winter. Each atmospheric model contains a temperature profile, a pressure profile, and GH concentration profiles from the surface up till 600 km. In this study the author has used these five temperature and pressure profiles of the Spectral Calculator and the altitude of 120 km for each climate zone. The five GH gas profiles of the three climate zones have been modified by scale factors to yield the GH gas concentrations [18] of the year 2005 at the surface:  $\text{CO}_2$  379 ppm,  $\text{CH}_4$  1.774 ppm, and  $\text{N}_2\text{O}$  0.319 ppm. The scale factor modifies the gas concentration profile in question over the whole altitude. The concentrations of other gases like CO are the same as used by Spectral Calculator.

Miskolczi [19] has calculated from TIGR (The Thermodynamic Initial Guess Retrieval) climatological balloon observation library and from NOAA (National Oceanic and Atmospheric Administration) data that the total precipitable water amount in the average global atmosphere is 2.6 cm. The average profile for water by combining the five climate zones resulted in a total content of water in the troposphere of 2.694 prcm (precipitable water in centimeters) as can be seen in Table 2.

Table 2: The water concentration profiles of the five climate zones, U.S. Standard Atmosphere 76 and the AGA. The unit prcm means total precipitable water.

<b>Alt</b>	<b>Tropical</b>	<b>Mid-Lat. Summer</b>	<b>Mid-Lat. North</b>	<b>Polar Summer</b>	<b>Polar Winter</b>	<b>USST 76</b>	<b>AGA</b>
.	$\text{g/m}^3$	$\text{g/m}^3$	$\text{g/m}^3$	$\text{g/m}^3$	$\text{g/m}^3$	$\text{g/m}^3$	$\text{g/m}^3$
m							
0	18.489	13.767	3.486	8.930	1.202	5.857	12.037
1	12.756	9.183	2.488	5.944	1.201	4.171	8.264
2	9.136	5.841	1.795	4.169	0.940	2.885	5.756
3	4.656	3.275	1.198	2.686	0.681	1.792	3.122
4	2.189	1.890	0.659	1.693	0.410	1.096	1.607
5	1.496	1.000	0.380	0.998	0.200	0.640	0.999
6	0.847	0.609	0.210	0.539	0.098	0.379	0.571
7	0.469	0.369	0.085	0.290	0.054	0.210	0.316
8	0.250	0.210	0.035	0.130	0.011	0.120	0.166
9	0.120	0.120	0.016	0.038	0.008	0.046	0.082
10	0.050	0.064	0.007	0.011	0.005	0.018	0.037
11	0.017	0.022	0.002	0.003	0.002	0.008	0.013
prcm	4.122	2.946	0.862	2.096	0.421	1.429	2.694

The most important GH gas in SW absorption calculations is water like in LW calculations. That is why, it is important to use the right value for water content. Some researchers have used the U.S. Standard Atmosphere 1976 (USST 76) as an average global atmosphere. The water content of this atmosphere is only about 55 % of the real the AGA value causing a massive error in the total absorption of the atmosphere. Finally, the water profile of each climate zone was adjusted by a scale factor of 0.965 to produce the AGA value to be 2.6 prcm. This means that the water profiles of climate zones are actually very accurate, because the area-weighted sum of the profiles is only 4.5 % too big.

The ozone concentration profiles vary according to the climate zones and altitudes as shown in Table 3 but the real profiles of Spectral Calculator are more accurate above the troposphere. The 1D model utilizes the ozone profile of the mid-latitude summer (MLS). This profile has not been adjusted, because it is very close to the AGA value. The difference in the total ozone amount of the atmosphere between these two profiles is only 0.5 %.

Table 3: The ozone concentration profiles of the five climate zones. The concentration is in the unit of volume mixing ratio (vmr).

<b>Alt. km</b>	<b>Tropical</b>	<b>Mid-lat. Winter</b>	<b>Mid-lat. Summer</b>	<b>Polar Winter</b>	<b>Polar Summer</b>	<b>AGA</b>
0	2,87E-08	2,78E-08	3,02E-08	1,80E-08	2,41E-08	2,77E-08
1	3,15E-08	2,80E-08	3,34E-08	2,07E-08	2,94E-08	3,02E-08
2	3,34E-08	2,85E-08	3,69E-08	2,34E-08	3,38E-08	3,24E-08
3	3,50E-08	3,20E-08	4,22E-08	2,77E-08	3,89E-08	3,57E-08
4	3,56E-08	3,57E-08	4,82E-08	3,25E-08	4,48E-08	3,89E-08
5	3,77E-08	4,72E-08	5,51E-08	3,80E-08	5,33E-08	4,49E-08
6	3,99E-08	5,84E-08	6,41E-08	4,45E-08	6,56E-08	5,18E-08
7	4,22E-08	7,89E-08	7,76E-08	7,25E-08	7,74E-08	6,33E-08
8	4,47E-08	1,04E-07	9,13E-08	1,04E-07	9,11E-08	7,65E-08
9	5,00E-08	1,57E-07	1,11E-07	2,10E-07	1,42E-07	1,07E-07
10	5,60E-08	2,37E-07	1,30E-07	3,00E-07	1,89E-07	1,42E-07
11	6,61E-08	3,62E-07	1,79E-07	3,50E-07	3,05E-07	1,97E-07
20	1,40E-06	2,90E-06	2,00E-06	3,70E-06	2,10E-06	2,10E-06
30	9,30E-06	6,10E-06	7,00E-06	5,40E-06	5,70E-06	7,50E-06
50	2,80E-06	2,75E-06	2,80E-06	2,60E-06	2,50E-06	2,75E-06
60	1,10E-06	1,00E-06	1,30E-06	9,50E-07	1,20E-06	1,12E-06
70	3,00E-07	3,20E-07	4,00E-07	5,00E-07	4,00E-07	3,50E-07
80	3,30E-07	2,30E-07	2,00E-07	1,30E-07	1,80E-07	2,52E-07
90	5,20E-07	8,00E-07	7,50E-07	8,00E-07	9,00E-07	6,84E-07
100	4,00E-07	4,00E-07	4,00E-07	4,00E-07	4,00E-07	4,00E-07
110	5,00E-08	5,00E-08	5,00E-08	5,00E-08	5,00E-08	5,00E-08
120	5,00E-10	5,00E-10	5,00E-10	5,00E-10	5,00E-10	5,00E-10

The range of wavelengths utilized in absorption calculation has been from 0.21 micrometers ( $\mu\text{m}$ ) to 5.5  $\mu\text{m}$ . A user cannot execute the calculation over the whole wavelength range with one calculation operation because the Spectral Calculator maximizes the calculation accuracy. If the whole wavelength range could be calculated by one operation only, the line number in the LBL method would grow over calculation capacity of the tool. In this case 38 separate calculations are needed for one absorption calculation to cover the selected wavelength range. Each calculation produces a list of absorption values varying from 403 to 564 wavelength points.

At TOA the value of SW flux  $S_{x_b}$  moving downwards in the atmosphere is the same as  $S_{W\text{in}} = 342 \text{ Wm}^{-2}$ . When the flux  $S_{x_b}$  moves forward in the atmosphere, its value does not decrease only because of absorption by air but because air reflects solar insolation back into space. The balance value of  $S_{x_b}$  is  $S_{W\text{in}} - R_{p_b} = 318.8 \text{ Wm}^{-2}$ . The author has assumed in his earlier study [1] that this reflection is proportional to the mass of air. In the SW absorption calculations the author has used the average value  $(342 + 318.8)/2 = 330.4 \text{ Wm}^{-2}$  for  $S_{x_b}$ . The author's analysis later on considers the possible errors caused by this choice.

## 2.2 Calculation of Zenith Angles of the Climate Zones

The calculation method of the Spectral Calculator uses a zenith angle as supplied by a user. The basic challenge in calculating the annual average global SW absorption is the calculation of zenith angles for the selected climate zones. A zenith angle varies continuously depending on the geographical place, the time of year and the time of day. The average values of zenith angles are needed for each climate zone. In order to keep the amount of the calculations limited, the author has used the following choices.

The tropical zone was divided into three zones of equal area each having the midpoint latitudes 3.819, 11.529, 19.46 degrees. In the same way the mid-latitudes were divided into three equal zones having the midpoint latitudes 28.588, 39.463, and 52.623 degrees. Because the area of the polar zone is only 13.4 % of the Earth's area, it was divided into two zones having the midpoint latitudes 64.45 and 79.49 degrees. The seasonal variation of the sun's position has been calculated for the 15<sup>th</sup> day of each month and then calculating the annual average value. The variation of a zenith angle according to the time of a day was calculated at one hour intervals. These choices mean that there are eight geographical areas having the midpoint latitude degrees as specified above and the longitudes with  $\pm 7.5$  degrees. In square meters the area varies from 700 000 km<sup>2</sup> in the polar zone to 1 500 000 km<sup>2</sup> in the mid-latitude zone.

The amount of solar radiation absorbed by the Earth depends on the solar zenith angle ( $z$ ), which is the angle the sun makes with the perpendicular to the surface. When the sun is low in the sky (almost in the horizon), a lot of the sunlight is reflected and the absorption is also greater, because the sunlight must travel a longer path through the atmosphere. The TOA incident solar radiation per unit ground area, or insolation  $I$ , is the product of  $SW_{in}$  and the cosine of the solar zenith angle  $z$ :

$$I = SW_{in} * \cos(z) \quad (1)$$

In the calculations over a certain area on the Earth, some calculation basis is needed for the average zenith angle. Cronin [20] summarizes three choices for zenith angle calculations which are simple average, daytime-weighted and insolation-weighted zenith angles. The simple average includes the dark half of the planet, which would correspond to a sun that is near setting being about 15 degrees above the horizon. The daytime-weighted zenith angle is widely used, which corresponds to a sun having a zenith angle of 60 degrees and it makes the insolation according to equation (1) to be  $\frac{1}{2}$  of the  $SW_{in}$ . Cronin [20] also introduces so called insolation-weighted zenith cosine of the zenith angle, which makes the insolation even smaller. According to Cronin, the insolation-weighted zenith angle is more accurate for a cloudy sky but for a clear sky the daytime-weighted zenith could be more accurate. It looks like that there is no scientific prove, what method could be the best choice.

The author introduces another way to calculate so called effective zenith angle for a defined area on the Earth, which is represented in Figure 2.



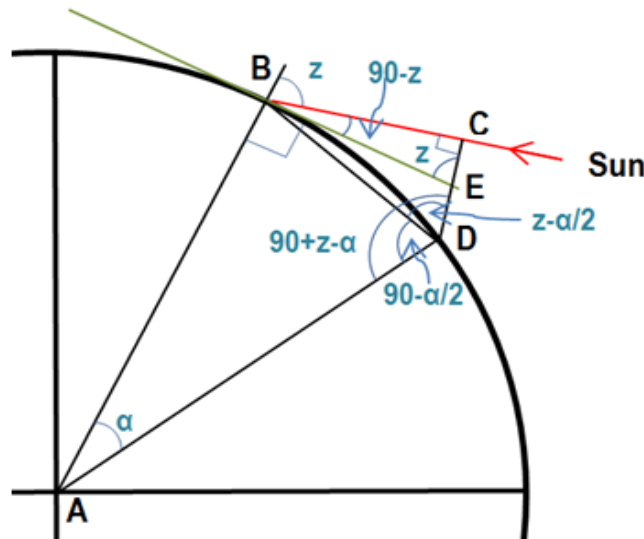


Figure 2: The schematic picture for defining the effective solar angle  $z$ .

According to Fig. 2, the line segment  $BE = S_{x_b} * \cos(z)$  and the line segment  $BD$  is

$$BD = S_{x_b} * \cos(z-\alpha/2) \tag{2}$$

where  $\alpha$  is the angle formed by latitudes and  $BD$  is calculated by applying the trigonometric formulas in the quadrangle  $ABCD$ . The line segment  $BD$  corresponds more accurately to the real area, which is between defined latitudes rather than the line segment  $BE$ .

The author has used the application of PV Education[21] which can be used through Internet for calculating the zenith angles for the defined eight geographical areas. This application utilizes so called PSA algorithm developed by al Blanco-Muriel et al.[22] which is accurate to within 0.5 minutes in zenith angle calculation for the year 1999-2015. The zenith angles of the sun traveling across the sky were averaged for one day. The zenith angles have been modified according to Equation (2) by weighting the noon time values in a way that the total angle  $\alpha/2$  remains the same. The summary of the effective zenith angles  $z_e$  have been depicted in Table 4.

Table 4: The summary of the effective zenith angles  $z_e$  and the effective global zenith angle  $z_a$  in degrees.

Climate zone	Lowest zone	Middle zone	Highest zone	Average
Polar winter	79.77		82.860	81.32
Polar summer	61.69		72.250	66.97
Mid-latitude winter	55.41	63.620	73.430	64.15
Mid-latitude summer	38.39	43.150	48.590	43.38
Tropical	39.35	40.370	43.120	40.95
Effective global zenith angle, $z_a$				51.38

The zenith angle  $z_a$  has been calculated utilizing the geographical weighting factors.

### 3 Absorption Calculation Results

#### 3.1 The Average Global Shortwave Absorption

Using the effective zenith values for each climate zone, the absorption calculations were carried out. The results are depicted in Table 5.

Table 5: The SW absorption in different climate zones without aerosol absorption.

Climate zone	Absorption, $\text{Wm}^{-2}$
Polar winter	9.91
Polar summer	80.36
Mid-latitude winter	39.41
Mid-latitude summer	84.06
Tropical	82.89
The average global absorption	67.71

The total SW absorption according to these calculations is  $67.71 \text{ Wm}^{-2}$ . This value is  $0.71 \text{ Wm}^{-2}$  and 1 % greater than the value of  $67 \text{ Wm}^{-2}$  which was calculated to be the expected value. This result means that there is no excessive absorption of SW insolation.

Based on these calculations it is possible to specify a 1D climate model for calculation of SW absorption. The graphical presentation of the absorption calculations using the 1D AGA model is depicted in Figure 3.

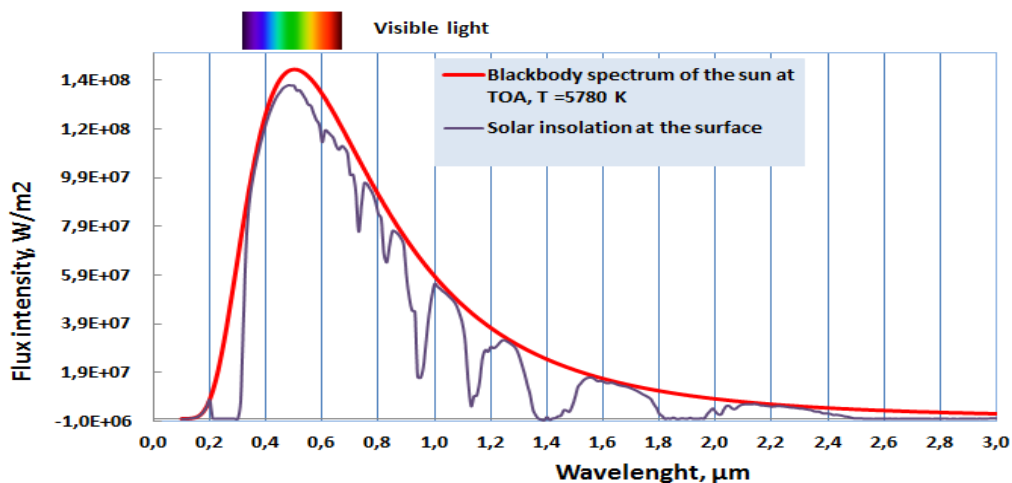


Figure 3: The absorption of shortwave insolation in the average global atmosphere (AGA) conditions using 1D model without aerosol absorption.

In this case the author has selected the mid-latitude summer (MLS) climate zone in the Spectral Calculator to be the basis. MLS has the same GH gas composition as specified earlier, which is the AGA climate. The water content must be multiplied by the scale factor 0.88266, because now the modified MLS water profile must alone produce the

AGA value of 2.6 prcm. The temperature off-set is -6.0 °C bringing the surface temperature to 15 °C and adjusting the whole profile with the same value. The zenith angle is 51.38 degrees. Using these specifications, the SW absorption based on the 1D model and modified mid-latitude climate corresponding to the average global atmosphere (AGA), is 67.67 Wm<sup>-2</sup>. It is only 0.06 % smaller than the value of 67.71 Wm<sup>-2</sup> calculated for five atmospheric models over three climate zones and combined according to the areal weighting factors. This result means that the applied calculation methods are consistent.

### 3.2 Analyses Based on the 1D Shortwave Model

The first analysis is to find out if the average insolation value of 330.4 Wm<sup>-2</sup> for S<sub>x<sub>b</sub></sub> has been justified. As noticed before, when the flux S<sub>x<sub>b</sub></sub> moves forward in the atmosphere, its value does not decrease only because of absorption by air, but the air also reflects solar insolation back into space. The author carried out absorption calculations using the 1D model. The descending values of S<sub>b<sub>x</sub></sub> flux were calculated based on the air mass in the atmosphere assuming that the reflection is directly proportional to the air mass. The results are shown in Table 6.

Table 6: The SW absorption in altitude zones starting calculation from TOA without aerosol absorption.

Altitude zone, km	Insolation, Wm <sup>-2</sup>	SW absorption, Wm <sup>-2</sup>
0 – 0.6	319.566	3.787
0.6 – 2.0	322.009	9.650
2.0 – 7.3	327.865	25.402
7.3 - 11	334.378	8.441
11 - 25	339.069	6.180
25 - 50	341.711	12.154
50 - 120	341.999	2.178
Average absorption		67.792

These results are also depicted in Figure 4.

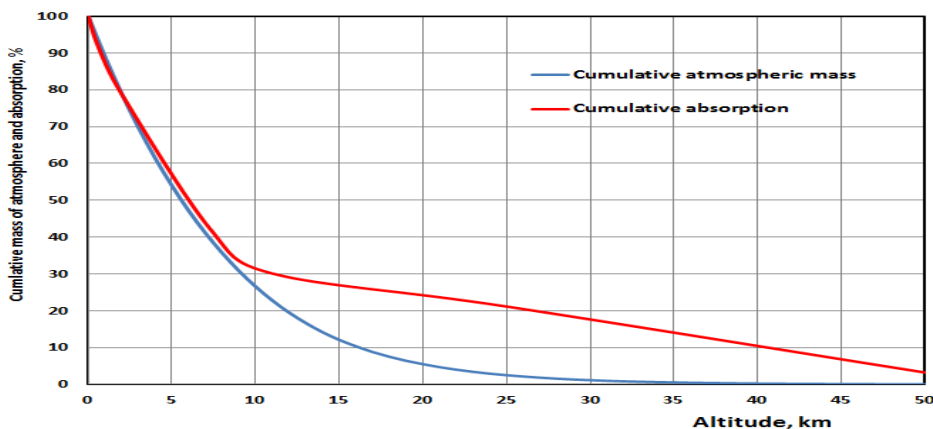


Figure4: The air mass and shortwave absorption as a function of altitude calculated from TOA to the surface without aerosol absorption. The calculations started from TOA at 120 km.

The total SW absorption calculated by this method is  $67.80 \text{ Wm}^{-2}$ , which is only 0.13 % greater than  $67.71 \text{ Wm}^{-2}$ , which was calculated using the average  $Sb_x$  flux value of  $330.4 \text{ Wm}^{-2}$ . It means that the average flux value is a good approximation to be used in SW absorption calculations. Figure 4 shows that SW absorption in the troposphere (below 11km) follows the amount of air mass, which is in the pathway of the solar radiation beam having a zenith angle of 51.38 degrees. The departure of these two curves in the stratosphere originates from the strong absorption by ozone.

Using the 1D model it is easy to calculate the effect of the zenith angle on the absorption. The results are depicted in Figure 5. The effect of zenith angle is rather moderate around the global average value of 51.38 degrees. The effect of the zenith angle starts to increase rapidly, when the angle is growing greater than 80 degrees.

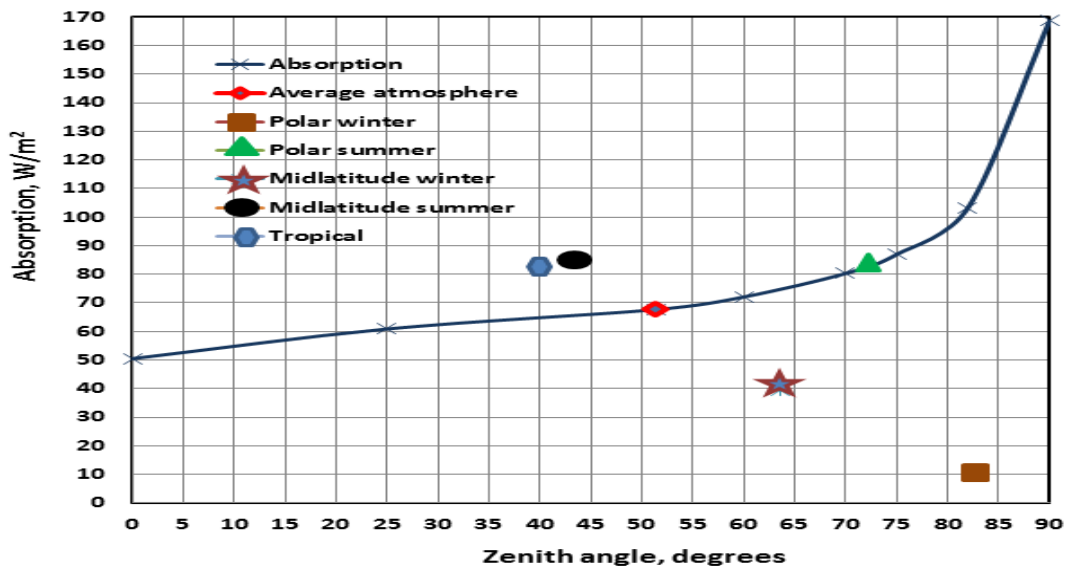


Figure 5: The effect of the zenith angle on the shortwave absorption in the atmosphere.

Using the 1D model, it is easy to derive the contributions of GH gases in the SW absorption. The effect of GH gas can be found by removing the GH gas in question from the atmospheric model in the Spectral Calculator and keeping the GH gases present in the AGA. The results are shown in Table 7.

Table 7: The contributions of GH gases in the SW absorption in the AGA conditions.

GH gas	Absorption change, $\text{Wm}^{-2}$	Contribution, %
H <sub>2</sub> O	52.254	77.2
O <sub>3</sub>	13.192	19.5
CO <sub>2</sub>	1.589	2.3
CH <sub>4</sub>	0.491	0.7
N <sub>2</sub> O	0.127	0.2
CO	0.017	0.0

The strongest absorber is water, having a contribution of 77.2 % and ozone's contribution is of 19.5 %. Ozone's absorption happens in a wavelength range below  $0.35 \mu\text{m}$  while water's main absorption range is above  $0.4 \mu\text{m}$ .

The change of CO<sub>2</sub> concentration from 280 ppm to 560 ppm, which is the calculation basis for the climate sensitivity, is 0.40 Wm<sup>-2</sup> using the 1D model. This change alone would mean essential warming impact, but the situation is not straightforward, because this absorption directly decreases the SW radiation reaching the surface. The net effect can be close to zero. Myhre et al.[23] have calculated the final net radiative forcing effect of -0.06 Wm<sup>-2</sup> (i.e. cooling) for the SW absorption due to the CO<sub>2</sub> concentration change from 280 to 361 ppm.

These results support the SW absorption value of 69 Wm<sup>-2</sup> as represented by Ollila[1]. The author has found a lapse in his original energy balance calculations [1,4] concerning the reflected flux by the air. It was assumed that the reflection is linearly dependent upon the amount of air molecules. Because 38 % of air mass is above the average global cloud top height of 7.3 km, the reflect flux Rp<sub>o</sub> should be 0.38 \* Rp<sub>b</sub> = 8.8 Wm<sup>-2</sup> and not 14.4 Wm<sup>-2</sup>. This error causes three other flux values to change: Rp<sub>a</sub> = 13.7 Wm<sup>-2</sup>, Rc<sub>o</sub> = 91 Wm<sup>-2</sup> and Rc<sub>a</sub> = 67.8 Wm<sup>-2</sup>.

#### 4 Discussion and Conclusion

In this the SW absorption calculations have been carried out in the average global atmosphere (AGA) conditions. The absorption flux value of 67.71 Wm<sup>-2</sup> is very close to the value of 69 Wm<sup>-2</sup> which was used in the energy balance analysis of Ollila [1,4]. This value is based on the study of Zhang et al.[24]. It means that the absorption due to the aerosols would be 1.29 Wm<sup>-2</sup>, which is close to the values 1.6 – 2.4 Wm<sup>-2</sup> calculated in the studies for aerosol absorption in the atmosphere. This result shows that there is no excessive absorption in the clear sky conditions in annual global average level.

The effective zenith value of 51.38 degrees, which is based on slight modification of the mathematical average value, seems to give reliable results. The 1D model applied in the modified mid-latitude atmosphere, corresponding to the AGA conditions, shows similar results as the calculations based on the five different atmospheric models covering the three climate zones of the Earth.

The analysis using the 1D model yields that the average insolation flux value of 330.4 Wm<sup>-2</sup> gives the same results as the more accurate method of changing the flux value according to the altitude. The contribution of water is 77.2 % and ozone's contribution is 19.5 % in the SW absorption. There are not many studies indicating the contributions of GH gases in the SW absorption. Collins et al. [25] have found out that utilizing the updated water vapor spectroscopy in the Community Atmosphere Model 3 (CAM3), the total clear sky absorption is 70.34 Wm<sup>-2</sup>, and the water represents 78.5 % of the total absorption. These values are very close to the values of the 1D model of this study.

The absorption according to the altitude depends on two factors. The absorption by ozone – even though its absolute concentration is low – explains the absorption in the stratosphere. The two potential absorbers – H<sub>2</sub>O and CO<sub>2</sub> – have no absorbing wavelengths below 0.4 μm and therefore ozone alone can effectively absorb SW radiation. In the troposphere the absorption by water has the main role. That is why the absorption seems to follow also the cumulative mass of the troposphere. The other GH gases have minimal effects in the total absorption of SW radiation.

The use of five climate models in describing the real atmosphere creates errors in the absorption calculations. Freckleton et al. [26] have studied the errors caused by the use of limited number of atmospheric profiles. Their conclusion is that three atmospheric zones

reduce the errors of the longwave (LW) absorption calculations of GH gases smaller than the errors of the spectroscopic uncertainties. That is why the use of simplified atmospheric models is a common practice in the LW absorption studies. For example the calculation of radiative forcing effect  $1.68 \text{ Wm}^{-2}$  of  $\text{CO}_2$  [14], which is the most important factor in the global warming according to IPCC, is still based on the vertical profiles of three atmospheric zones only [23]. The reduction of five atmospheric models into 1D model caused an error of 0.13 % in this study.

The accuracy of spectral calculations has been checked using the real atmosphere conditions. The two studies [27, 28] in dry and clear atmosphere conditions show that generally the calculation accuracy is below 1 %. However the question of water vapor continuum is still unclear. The continuum means that the strong absorption bands of water have effects also on the neighboring bands. The continuum effects have been estimated by semi-empirical formulas in the spectral calculation tools.

Spectral Calculator does not use water continuum effects in its atmospheric path calculations. There is a simple way to check the accuracy of the atmospheric spectral calculations carried out by Spectral Calculator. In the clear sky conditions according to the Kirchhoff's rule, the LW downward flux  $E_{d_0}$  emitted by the atmosphere should be the same as the total absorption  $A_{g_0}$  due to the absorption caused by the GH gases. According to the synthesis analysis of Stephens et al. [29], the measured value of  $E_{d_0}$  varies between  $309.2 - 326 \text{ Wm}^{-2}$  in 13 independent studies the average value being  $314.2 \text{ Wm}^{-2}$ . The author [1] has calculated the flux value of  $A_{g_0}$  to be  $310.9 \text{ Wm}^{-2}$  using the Spectral Calculator's formula for water vapor. The conclusion is that Spectral Calculator gives results, which are near to the measured values of the real atmosphere and the difference is in average 1.0 %. This difference is well inside the error margin of  $\pm 10 \text{ Wm}^{-2}$  estimated to be the accuracy of measured LW fluxes [28].

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