American Journal of Climate Change, 2019, 8, 61-76
http://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

The Role of Clouds in Global Radiation Changes Measured in Israel during the Last Sixty Years

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How to cite this paper: Paudel, I., Cohen, S. and Stanhill, G. (2019) The Role of Clouds in Global Radiation Changes Measured in Israel during the Last Sixty Years. *American Journal of Climate Change*, **8**, 61-76.
https://doi.org/10.4236/ajcc.2019.81004

Received: July 7, 2018
Accepted: January 27, 2019
Published: February 2, 2019

Abstract

An analysis of global radiation measurements and fractional cloud cover observations made in the Israel Meteorological Service's network of climate stations demonstrated a significant decrease in the transmittance of solar radiation through the atmosphere during the last 60 years. The major cause was the reduced transparency of clouds. Under completely overcast skies with complete cloud cover transmission in the industrialized central coastal region decreased from 0.41 in the mid-20th century to 0.21 in the first decade of the 21st century. Under cloudless skies the reduction in the transmission of global radiation was less, from 0.79 to 0.71, and not statistically significant. Similar but somewhat smaller changes were observed in the less industrialized central hill region. Multi-linear analysis showed that since 1970, 61% of the measured decline in global radiation was attributable to changes in fractional cloud cover but only 2% to the marked increase in local fuel combustion; there was no statistically significant interaction between the two parameters.

Keywords

Cloud Transmission, Fractional Cloud Cover, Dimming and Brightening, Direct and Indirect Aerosol Effects, Fossil Fuel Combustion

1. Introduction

The first reports of widespread and significant changes in the solar irradiance at the Earth's surface [1] [2] emphasized the causal role of anthropogenic aerosols, a conclusion supported by a study linking population density with changes in global radiation, $E_{g\downarrow}$ [3].

In the present study we examine the effect of the fractional sky cover and the transmissivity of clouds, a major factor influencing $E_{g\downarrow}$, based on the changes measured in Israel during the last 60 years.

The importance of clouds was apparent in an analysis of $E_{g\downarrow}$ measurements in Israel's industrialized central coastal plain which showed that the trend in global dimming was smaller during cloudless days and seasons than during all sky conditions [4].

Over the Eastern Mediterranean a simulation study of radiation transfer during the 1983 to 2013 period showed that on an average annual basis the effect of clouds, aerosols and water vapor reduced $E_{g\downarrow}$ by 63 W·m^{-2}, 18 W·m^{-2} and 9 W·m^{-2} respectively, accounting for 70%, 20% and 10% of their combined radiative effect; it should be noted that the simulation used a constant aerosol load [5].

A study of changes in net solar radiation over the entire Mediterranean basin, based on the GEOS-5 climate model processing of satellite data, indicated that between 1970 and 2012 spatial and temporal trends were primarily controlled by variations in cloud optical depth, although the analysis was unable to distinguish between the roles of the extent of cloud cover and cloud radiative properties [6]. There is also evidence from surface observations, satellite measurements and climate model simulations that total cloud in the Mediterranean has decreased since the late 1970's [7] especially in the eastern and central regions and during springtime [8].

On a global scale the onset of global brightening in the 1980's [2] coincided with a reduction in cloud, based on both land and ship based surface observations, satellite measurements (https://isccp.giss.nasa.gov/products/onlineData.html), and Earthshine [9].

A major difficulty in distinguishing between the role of aerosols and clouds as the cause of trends in global radiation is due to their complex interaction [10] [11], (http://www.climatechange2013.org/report/).

In this study we make this distinction using a simple statistical approach to separate aerosol effects on $E_{g\downarrow}$ into the direct effect observable under cloud-free skies and the indirect effects which include the influence of aerosols on the formation, magnitude and duration of clouds as well as on their radiative properties, *i.e.* reflection and absorption of solar radiation.

Our analysis is based on measurements of global radiation and observations of total cloud cover made at climate stations in Israel during the 60-year period 1954-2014, supplemented with data of total fuel consumption since 1970 used as a proxy measure to quantify the effects of local emissions of anthropogenic aerosols.

2. Measurements and Data Processing

2.1. Global Radiation

Measurements of $E_{g\downarrow}$ were made with regularly calibrated thermopile pyranometers at the 23 sites in Israel shown in **Figure 1**; the number of sites increased from two in the early 1950's to more than ten in the 1990's. The mean annual values of $E_{g\downarrow}$ for all available sites together with their inter-site variation, as

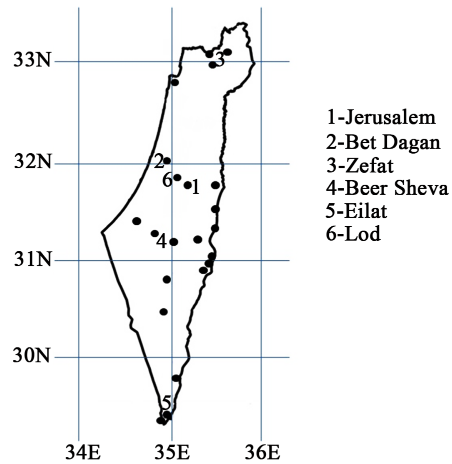


Figure 1. Location of climate stations providing data used in study. Cloud observation sites indicated by number, global radiation measurement sites shown by (●). The three adjacent sites operating in Jerusalem are shown as one site.

represented by the standard error, varied between 248 ± 6 W·m^{-2} in the first decade of measurement to 225 ± 4 W·m^{-2} in the last decade. Measurements of $E_{g\downarrow}$ were subject to the quality control procedures recommended by the World Meteorological Organization and have been corrected to the current World Radiometric Reference scale [12].

In addition to mean annual values of $E_{g\downarrow}$ three series of mean monthly values normalized to their extra-terrestrial values, *i.e.* as Clearness Indices CI [13] were analyzed. In the central coastal plain the measurements were made at the Israel Meteorological Service's Observatory at Lod airport until 1964 and subsequently at its new site at Bet Dagan some 10 km NW. Measurements in the central hill region were made at three sites in Jerusalem less than one km apart. The third group of monthly CI values analyzed consisted of measurements made before 1961 at sites in the central coastal plain, central hill region and northern Negev.

Additional details of the $E_{g\downarrow}$ measurements made before 1995 can be found in Stanhill and Ianetz [14].

2.2. Cloud

Observations at 08, 14 and 20 Israel Standard Time, were analyzed as mean monthly values after conversion from oktas to fraction of sky covered C. Six stations in the Israel Meteorological Service's climate station network were selected to represent the five major climate regions on the basis of completeness and quality of the observations and the data was subject to the quality control procedures recommended by the World Meteorological Organization. Locations of the stations are shown in Figure 1.

2.3. Aerosol Load

In the absence of land based or satellite observations covering the 60-year period under study, national statistics of monthly values of total fuel consumption in units of TOE, thousand tons of oil equivalent F, were used as a proxy for the anthropogenic aerosols emitted by local fossil fuel combustion. The data is available from the Central Bureau of Statistics at http://www.cbs.gov.il/energy/new.enr.nach.eng.new.huz.html.

After 2000 measurements of aerosol optical depth, AOD were available from the MODIS Terra satellite for a 1˚ pixel centered on Israel (http://giovanni.gsfc.*nas*a.gov/giovanni/#service=ArAvTs&starttime=2000-03-01100.00:00Z&endtime+2016-04-30T23:59Z&bbox+39.6948.31.5857,35.4858,32.4866&data=MOD008).

3. Results

3.1. Trends in Global Radiation, Cloud and Primary Fuel Consumption

Annual mean values of global radiation averaged for all available sites are presented in **Figure 2(a)** in units of W·m^{-2}, of cloud cover as the mean of five representative sites in units of fractions of sky cover in **Figure 2(b)**, and of total national fossil fuel consumption (F) in units of $\log_{10}$ Tons of Oil Equivalent, TOE, in **Figure 2(c)**. For ease of comparison the changes were also shown as normalized anomalies in **Figure 2(d)**. The trends in global radiation ($E_{g\downarrow}$)and clouds (C) were significant at $P < 0.01$ as determined by the non-parametric Mann-Kendall test used to eliminate the effect of auto correlation common to climate series [15]. Parametric analysis by linear regression yielded the following relationships with year of measurement, N.

$$E_{g\downarrow} = -0.49 \pm 0.055N + 1205.8, R^2 = 0.56, P < 0.001\,(1955\text{ - }2013)$$

$$C = -0.000803 \pm 0.000255N + 1.895, R^2 = 0.23, P < 0.08\,(1955\text{ - }2013)$$

$$F = 165 \pm 23N - 32150,$$
$$R^2 = 0.91, P < 0.0001\,(1970\text{ - }2013)$$

There was no significant difference between trends in $E_{g\downarrow}$ measured at Bet Dagan and in Jerusalem [16]; trends in C differed between the stations; an increase was observed at the two hill stations until 2000 after which all stations showed a decrease which was statistically significant ($P > 0.05$) at two of the lowland sites.

3.2. Relationships between Mean Annual Values of Global Radiation, Clouds and Fuel Consumption in Israel

Analysis of variation of the multi-linear relationship between $E_{g\downarrow}$, C and F over the 1970 to 2013 period for which data for all parameters was available indicated that the relationship of $E_{g\downarrow}$ to C and F was highly significant while the interaction between C and F was not. After removing the interaction term the coefficient of determination was 0.25. Replacing F with $\log_{10}F$ raised the value of R^2 to 0.31; justifications for the use of a logarithmic scale for fossil fuel consumption are discussed in Section 4.1.3.

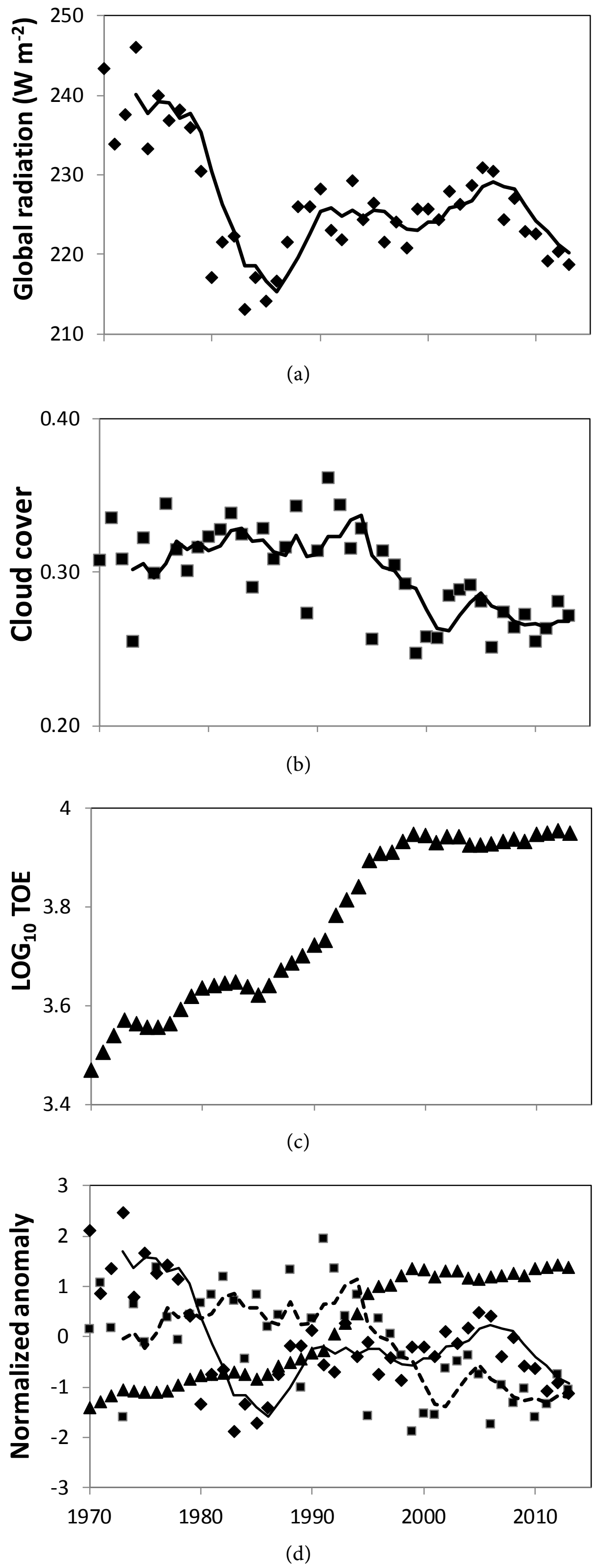


Figure 2. Annual values of global radiation, cloud cover and primary fuel consumption. (a) Global radiation; (b) Cloud cover and (c) Primary fuel consumption; (d) Shows data presented in (a), (b) and (c) as normalized anomalies. The solid lines represent five year running means of global radiation and cloud cover.

The final relationship was,

$$E_{g\downarrow} = (-116.2 \pm 81.4)C - (31.97 \pm 15.1)\log_{10} F + 381.6 \pm 74.2,$$
$$R^2 = 0.31, P < 0.001$$

After normalization to the mean annual extra-terrestrial value of solar radiation, 360 W·m^{-2}, the relationship for clearness index *CI*, illustrated in Figure 3(a), is

$$CI = (-0.371 \pm 0.26)C - (0.102 \pm 0.048)\log_{10} F + 1.219 \pm 0.24,$$
$$R^2 = 0.31, P < 0.001$$

3.3. Relationships between Mean Monthly Values of Global Radiation, Clouds and Fuel Consumption

The multi-linear analyses of monthly values were based on $E_{g\downarrow}$ measurements from Bet Dagan as this was the only site with an almost complete series of monthly values for the 1970-2013 period analyzed. The use of data from this site as a proxy for the national mean is justified by the highly significant correlation between the two series ($P < 0.01$) and the near unity of their slope, 1.004. Values of $E_{g\downarrow}$ were converted to CI to remove the major effect of seasonal variation in Sun-Earth geometry. As was the case with the annual values, analysis of variance of the multi-linear relationship indicated that the interaction between cloud cover and fossil fuel consumption was not significant, $R^2 = 0.003$, $P > 0.23$. After eliminating this term stepwise regression indicated that cloud and local fossil fuel consumption together accounted for almost two thirds of the inter-monthly variation in *CI* ($R^2 = 0.63$) with clouds accounting for 0.61 of the variation and fossil fuel consumption only adding another 0.02 to the coefficient of variation. The multi-linear relationship for monthly values, illustrated in Figure 3(b), was

$$CI = (-0.511 \pm 0.034)C - (0.0606 \pm 0.023)\log_{10} F + 0.920 \pm 0.062$$
$$R^2 = 0.63, P < 0.0001$$

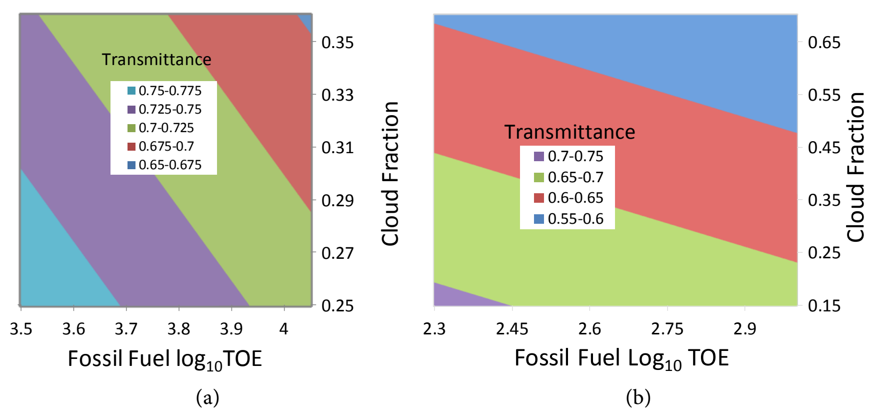


Figure 3. Relationship between global radiation transmittance at Bet Dagan, average cloud cover and national primary fuel consumption, 1970-2009 based on equations listed in Sections 3.2 and 3.3. (a) Annual mean values (Yearly); (b) Monthly mean values (Monthly).

3.4. Relationships between Monthly Values of Normalized Global Radiation and Cloud Cover

3.4.1. Central Coastal Plain-Bet Dagan

A comparison of the clearness index CI with observations of fractional cloud cover C is shown in **Figure 4**. The data is equally well fitted by the linear equation,

$$CI = -0.471C + 0.756, R^2 = 0.51$$

as by the quadratic equation

$$CI = -0.087C^2 - 0.405C + 0.744, R^2 = 0.51$$

both relationships are highly significant ($P < 0.01$) and by extrapolation yield similar values for cloudless skies (*i.e.* $C = 0$), $CI = 0.76$ and 0.74 respectively, as well as for overcast, completely cloud covered skies (*i.e.* $C = 1$), $CI = 0.28$ and 0.25 respectively.

Time trends during the entire 1956 to 2013 period of measurement were examined by repeating the linear analyses for each of 10 successive periods of six years, this period was selected to provide sufficient data to yield statistically highly significant relationships ($P < 0.01$). The parameters of the linear regressions together with extrapolated values of normalized $E_{g\downarrow}$ for both cloudless and completely overcast skies, are presented in **Table 1**. The slopes of the relationships S, that is the decrease in transmission per unit increase in cloud, were highly significant and inversely related to the mid-year of measurement Y by the equation:

Table 1. Linear relationships between normalized global radiation and cloud cover.

Period	Slope	Intercept	R^2	Sky transmission	
				Cloudless	Overcast
CENTRAL COASTAL PLAIN, BET DAGAN. 1956-2013					
1956-1961	−0.377	0.79	0.63	0.79	0.41
1962-1967	−0.439	0.759	0.51	0.76	0.32
1968-1973	−0.482	0.779	0.77	0.78	0.3
1974-1979	−0.541	0.789	0.74	0.79	0.25
1980-1985	−0.424	0.708	0.58	0.71	0.28
1986-1991	−0.544	0.775	0.71	0.78	0.23
1992-1997	−0.536	0.761	0.66	0.76	0.23
1998-2003	−0.518	0.731	0.61	0.73	0.21
2004-2009	−0.548	0.78	0.64	0.78	0.23
2010-2013	−0.564	0.773	0.58	0.77	0.21
1956-2013	−0.471	**0.756**	**0.51**	**0.76**	**0.28**
CENTRAL HILL REGION, JERUSALEM. 1954-2014					
1954-1963	−0.336	0.774	0.96	0.77	0.44
1968-1975	−0.241	0.732	0.48	0.73	0.49
1986-1995	−0.431	0.722	0.85	0.72	0.29
1996-2005	−0.388	0.75	0.89	0.75	0.36
2006-2014	−0.475	0.776	0.91	0.78	0.3
THREE SITES, 1953-1961 (for details see Stanhill, 1962)					
1953-1961	−0.262	0.771	0.56	0.77	0.51
THREE SITES, 1992-1994 (for details see Stanhill and Ianetz, 1997)					
1992-1994	−0.464	0.729	0.8	0.73	0.27

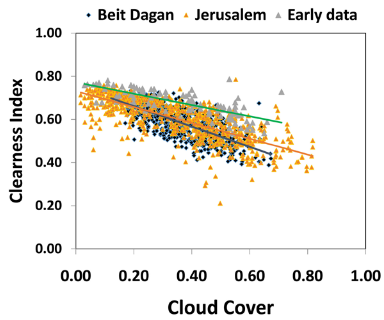


Figure 4. Relationships between monthly values of normalized global radiation and fractional cloud cover at Bet Dagan, Jerusalem and at three early measurement sites.

$$S = -0.00275Y + 4.967, R^2 = 0.617, P < 0.01$$

The intercepts of the relationships, that is, the transmission of completely clear, cloudless skies, also decreased with the mid-year of measurement but the decrease was small and not statistically significant.

3.4.2. Central Hill Region-Jerusalem

The results of a comparison of monthly measurements of *CI* and observations of *C* made at three sites in Jerusalem between 1954 and 2014 are presented in Table 1. The relationships are only available for five periods of varying duration and are based on measurements made at three different although adjacent sites which were equipped with different pyranometers which were calibrated with different pyrheliometers.

A trend of decreasing *CI* was found for completely overcast skies, $S = -0.00298Y + 6.28$, $R^2 = 0.546$, $P > 0.15$ which, although non-significant, was similar to the trend found in the Central coastal plain, as was the much smaller change in the transmission of completely cloud free, clear skies.

3.4.3. Early Observations at Three Sites

A highly significant linear relationship between the 94 monthly values of *CI* and observations of *C* measured between 1953 and 1961 is presented in Table 1 made at three sites in the central coastal plain and hill regions and in the northern Negev. The value for clear sky transmission found was similar to that of the longer series from the coastal plain and hill regions, but transmission of cloud covered skies derived from those early observations was much larger.

A comparison of the relationship between 1953 and 1961 with that derived from a group of measurements made at matched sites between 1992 and 1994 [14] showed the reduction in transmission; during the early period change in transmission per unit increase of cloud cover was −0.262, 40 years later it was −0.464.

3.5. Relationship between Annual Values of $E_{g\downarrow}$ Transmission and Local Fossil Fuel Combustion

Under overcast sky conditions *CI* was highly significantly inversely related to the fossil fuel combust ion (F in units of MTOE) both on logarithmic and linear scales as shown in Figure 5(a) and Figure 5(b). The relationships at Bet Dagan were

$$CI_{cloud} = -0.1574\log_{10} F + 0.8349,\ R^2 = 0.732$$

$$CI_{cloud} = -0.0114F + 0.3135, R^2 = 0.697$$

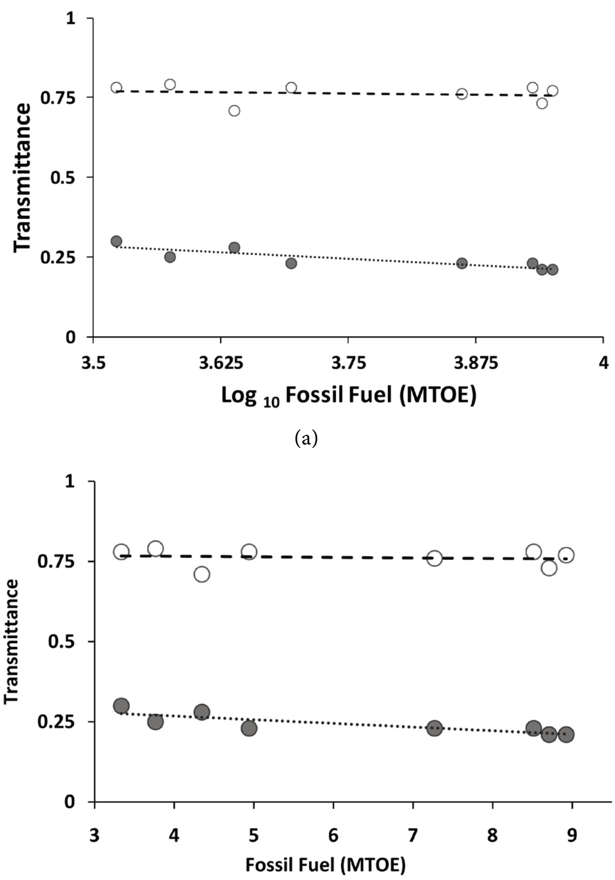
Under cloudless skies the relationships were not statistically significant:

$$CI_{clear} = -0.2811\log_{10} F + 0.8608, R^2 = 0.019$$

$$CI_{clear} = -0.0017\text{MTOE} + 0.7728, R^2 = 0.019$$

Over the 1970-2013 period the relationship $CI_{cloud} = -0.0114F + 0.3135$, on a unit area basis (total area 20,770 km^2) indicates that the combustion of each unit TOE, by definition equivalent to 41.868 GJ, reduced $E_{g\downarrow}$ by an average of 4.1 W·m^{-2}.

Under cloudless conditions both the log and linear relationships indicate much smaller effects of fuel combustion which were not statistically significant.



(b)

Figure 5. Relationships between mean annual values of global radiation transmittance at Bet Dagan under cloud covered (●) and clear sky (○) conditions and local fuel consumption, Israel 1970-2013. (a) Fuel consumption on logarithmic scale; (b) Fuel consumption on linear scale.

4. Discussion

4.1. Accuracy of Measurements

4.1.1. Global Radiation

At the start of the period studied the accuracy of daily values was assessed at 5% [17] and the same value was recently assigned to routine measurements from station networks [12]. The greater accuracy to be expected for the monthly and annual values analyzed in this study is limited by the 0.3% uncertainty in the World Radiometric Reference and the loss of accuracy involved in its transfer by calibration to the pyranometers in routine use. Error terms of 5% and 2% respectively have been estimated for monthly and annual values of $E_{g\downarrow}$ [18] [19].

The spatial representativeness of the mean of values of $E_{g\downarrow}$ measured at individual sites, which was related to the national mean data of cloud cover and fossil fuel consumption to derive the relationships presented in Sections 3.2 and 3.3, was assessed as the standard error of the national means of $E_{g\downarrow}$. Thus, the uncertainty in the areal mean varied between 2.4% for the first decade of measurements to 1.7% in the last decade of the previous century, values similar to the 2% absolute mean error found in a study comparing measurements at 778 sites with that of their surrounding 3˚ grid area [20].

4.1.2. Cloud

In the absence of a local objective measurement series of known accuracy it is not possible to assess the accuracy of the standard subjective synoptic observations of cloud cover used in this study. However the combined effect of between observer variability [21] [22] together with the very limited sampling of diurnal variation represented by three observations suggest that the uncertainty of such observations is considerable. An additional important limitation to the use of the amount of cloud as the metric for normalized global radiation is the variation in the transmission of different cloud types [23]. Even so, previous studies have shown that when compared with global radiation measurements these data can give important insight into cloud interactions with changes in solar radiation [24].

4.1.3. Anthropogenic Aerosol Load

The use of local data of primary fuel consumption as the proxy for aerosol load assumes that the aerosol load produced bears a constant relationship to the advected aerosols. Another limitation is the neglect of changes and trends in the type and composition of the fuels used and in the efficiencies of the combustion processes; changes that can be expected to have led to a reduction in the aerosol emissions per unit ton of oil equivalent. The use of $\log_{10}F$ values in Equations (1) and (2) is justified by the logarithmic sensitivity of cloud properties to aerosol load [25] [26] [27] and is also supported by the fact that the increase in fuel consumption was logarithmic for much of the period examined (**Figure 2(c)**).

4.1.4. Role of Changes in Cloud Characteristics

The values of the cloudiness index for cloudless and cloud covered skies in Israel found in this study as listed in **Table 1** fall within the range reported for sites in the tropics, subtropics, England and Oregon reported on page 35 of a review of the literature on cloud-solar radiation relationships [28]. The observations of C used in this study do not allow the effect of changes in the fraction of the sky covered with cloud to be distinguished from the effect of changes in the transmissivity per unit cloud cover and this explains the lack of a clear inverse relationship between annual values of $E_{g\downarrow}$ and C seen in **Figure 2(a)** and **Figure 2(b)**. However, in the case of monthly values the greater seasonal variation enabled monthly variations in C account for half the variation in CI measured at Bet Dagan and Jerusalem over a 60-year period as shown in **Figure 4**. A similar coefficient of determination R^2 was found in a comparison of monthly values of C and CI based on measurements and observations at three sites in Israel between 1953 and 1961 [29]. Analysis of these early measurements yielded a value of CI during cloudless skies of 0.77, similar to the values measured over the later periods shown in **Table 1**. Under conditions of complete cloud cover CI for the early period was 0.51, considerably higher than the mean values tabulated for the later Bet Dagan and Jerusalem series. At both these sites the trends were similar indicating that cloud transmission had decreased by 0.165 at Bet Dagan and 0.179 at Jerusalem during the 60 years of measurement. This explains the fact that under completely cloud covered skies transmission during the early period of global dimming was greater than during the later period of global brightening.

4.2. Proxy Measurements of Cloud

Replacing the subjective synoptic observations of cloud cover at Bet Dagan with measurements of sunshine duration increased the coefficient of determination in the relationship with normalized global radiation to $R^2 = 0.81$; similar high coefficients of determination were found at five other sites covering a wide range of climates and aerosol emissions. At Bet Dagan and the two other urban sites the transmission of cloud was found to decrease with time [30].

4.3. Role of Changes in Aerosol Load

Trends in the direct and indirect aerosol effects derived from the intercepts and slopes of the relationships between CI and C shown in **Table 1** indicate that the trend in direct aerosol effect was small, −0.003 per decade, and not statistically significant, $P > 0.54$. For the period of 2000 to 2016 covered by satellite measurements this conclusion is supported by the lack of inter-annual change in values of aerosol optical depth at 550 nm measured by MODIS Terra over the 1˚ pixel centered on Israel. The mean monthly values of AOD shown in **Figure 6** indicate that during this century the trend in annual values of AOD was small; the reduction in inter-annual values from 0.32 to 0.30 was dwarfed by the large but irregular intra-annual variation.

By contrast the increase in the indirect aerosol effect over the 60 years was significant. The decrease in cloud transmittance is highlighted by a comparison of the values listed in **Table 1** for the 1953-1961 period skies when complete

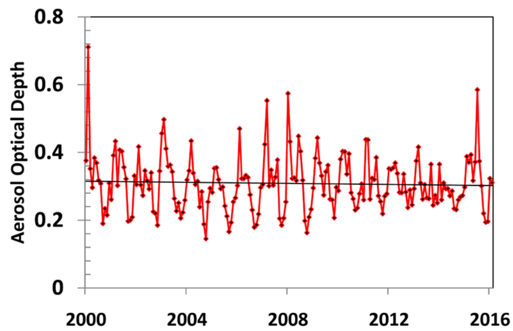


Figure 6. Aerosol Optical Depth at 550 nm measured by MODIS Terra over a 1˚ pixel centered on Israel, mean monthly values during 2000-2016.

cloud covered skies transmitted half of the top of atmosphere irradiance; during the later period only a third was transmitted.

Similar results showing major changes in cloud transmission and minor changes in clear skies were reported in an analysis of high frequency direct and diffuse solar radiation measurements at seven USA sites between 1996 and 2011 [31] and in studies showing the major role of clouds in solar dimming in India [32] and in Iran [33].

4.4. Causes of Changes in Cloud Transmission

The significant relationship between cloud transmission and fossil fuel consumption in Israel during the period under study shown in **Figure 5** indicates anthropogenic contamination of clouds, also referred to as the cloud albedo effect [34] was a cause of the changes in cloud transmission documented in this study. Other possible causes include a change in the diurnal or seasonal distribution of cloud cover [35] [36]; and/or a change in the frequency of different cloud types with their associated radiative properties [37]. Changes in the frequency of the different synoptic situations reaching the Eastern Mediterranean region are known to have occurred during the period covered in this study, they include air masses with very diverse loads of dust and non-anthropogenic aerosols [38] and changes related to Hadley Cell expansion [39]. On a global scale changes in cloud cover were found to be significantly related to changes in solar activity through its effect on the flux of cosmic rays reaching the lower atmosphere [39] [40] suggesting changes in solar emissions could be related to those in cloud cover and global radiation at the Earth's surface.

5. Conclusion

Changes in cloud, both in the fraction of sky covered and in their radiative characteristics, played a major role in determining the global radiation measured in Israel during the last 60 years. Highly significant inverse linear relationships between normalized $E_{g\downarrow}$ and cloud cover indicate that a reduction in cloud transmission occurred in both the central coastal plain and central mountain region with a much smaller change in the transmission of cloudless skies. Analysis by stepwise regression indicated that since 1970 changes in cloud cover accounted for 61% of the changes in $E_{g\downarrow}$ while the major increase in local fossil fuel consumption, serving as a proxy for anthropogenic aerosol emissions, only accounted for an additional 2% of the changes. Although the interaction between cloud cover and fossil fuel consumption is not statistically significant the indirect aerosol effect demonstrated in this study suggests that an important microphysical interaction may exist.

Acknowledgements

We thank Amos Porat, Talia Horowitz and Vera Lybansky of the Israel Meteorological Service who provided the data on cloud cover and global radiation used in this study. The assistance of I. Lynsky of Tel Aviv University who supplied the MODIS measurements is gratefully acknowledged. We also thank Marcel Fuchs for useful discussion of the results presented in this paper.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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