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Long-term trends in, and the spatial variation of, global irradiance in Israel‡

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ABSTRACT

An analysis of 130 station-years of global irradiance measurements made in Israel during the last 40 years showed a significant decrease of 20%. In absolute terms, the reduction, averaging -0.88 W m^{-2} per year, was the same at Bet Dagan in the central coastal plain as at Jerusalem in the central hill region. The decline in irradiance was greater in winter than in summer, in the northern Jordan Rift Valley than in the southern Negev and under overcast compared with clear sky conditions. The cause of the decline could not be attributed to an increase in cloud cover, as analysis of 4 long-term series of daytime observations showed that small reductions in cloud cover had occurred. Possible reasons for the reduction in atmospheric transmissivity are discussed and the increase in emissions of anthropogenic aerosols within Israel and from the upwind regions of SE Europe is considered the most probable.

1. Introduction

Global irradiance, $K\downarrow$, is generally considered to be a conservative climatic element showing only minor interannual and spatial variation, especially in areas and seasons of high irradiance (Robinson, 1964).

Recently, however, evidence has been accumulating which indicates that significant long-term changes in $K\downarrow$ have occurred in many of the areas where long-term series of measurement have been studied (Abakumova, 1980; Idso, 1972; Ohmura and Lang, 1989; Petrosianz, 1989; Russak, 1990; Sekihara, 1973; Stanhill, 1995; Stanhill and Kalma, 1995; Stanhill and Moreshet, 1992a, b), 1994, and Stiet, 1992): although other studies have shown no significant change (Anon, 1980; Dirmhirn, Farkas and Zeiner, 1992; Stanhill and Kalma, 1994; De Bruin, Van den Hurk and Walgraven, 1995).

A study of 3 pyranometer measurement series in Israel (Stanhill and Moreshet, 1992b) showed that a highly significant decrease in $K\downarrow$, averaging 1.4 W m^{-2} per year between 1956 and 1987, had occurred at a site in the central coastal plain downwind of the greater Tel-Aviv connurbation and increasingly exposed to pollution from passing motor traffic. No significant change in $K\downarrow$ measured at Jerusalem in the central hill region was found between 1954 and 1979; nor was there any evidence of a trend in a short measurement series from Quidron, an uninhabited site on the Dead Sea shore, during the period 1982–1990.

The difference in the results found at these three sites suggested that the cause of the reduction in atmospheric transmissivity in the central coastal plain was locally generated pollution as no changes in the extent of cloud cover were observed at this site and a high correlation was found

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between the density of passing motor traffic and irradiance on both a yearly and a daily basis. However, a recent comparison of three pairs of short measurement series made in Israel during the 1960s and 1980s at rural sites in the upper, central and lower Jordan Valley showed a considerable reduction in $K\downarrow$ had occurred at all three sites, comparable in magnitude with that reported for the central coastal plain (Cohen and Stanhill, 1996).

In this paper, all available measurements of $K\downarrow$ in Israel have been analyzed to determine the current magnitude of the interannual change and extent of the spatial differences.

This study is dedicated to the memory of Dov Ashbel on the centenary of his birth. Ashbel, the doyen of Israeli climatologists, was the first to measure solar irradiance in Israel.

2. Measurement methods

The measurement analyzed in this study are daily totals made with radiometers meeting the WMO requirements for Class One or Class Two pyranometers. Measurements made prior to 1981 have been converted to the World Radiometric Reference (WRR) scale introduced in January 1981 and are expressed in the recommended SI units (WMO, 1983).

In the earlier years the mean daily totals were derived from integrated chart recordings, and, in more recent years, from data logged totals of the continuously measured pyranometer outputs. Details of the coordinates of the pyranometer sites, the period of measurement, instrumentation and sources of the data are given in Table 1.

The irradiance measurements considered in this study do not constitute a homogeneous data set. They comprise a collection of individually processed data sets of different durations which were obtained with different models of pyranometers independently calibrated.

However, more than 85% of the data analyzed in this study were measured with pyranometers which were regularly calibrated against secondary standard pyrheliometers or pyranometers which were themselves calibrated against national or internationally maintained standard radiometers. Also, in accordance with WMO recommendations (WMO, 1983), the outer hemispheres of the pyranometers were regularly cleaned, in most cases on a daily basis.

A homogeneous data set covering the southern half of the country has recently become available from the Negev Radiation Survey in which the same model of Class One pyranometer was used to measure $K\downarrow$, as well as the diffuse and direct components, for a number of years starting in 1989. The same calibration and data processing procedures were followed at all 6 stations. The methods used and results obtained have been described by Faiman et al. (1990, 1992, 1993).

3. Results

The mean monthly values of $K\downarrow$ presented in Table 2 are based on all complete months of data available since 1970, i.e., months with at least 26 days of measurements. The annual totals for all complete years are listed in Table 3.

3.1. Long-term trends

Annual values of $K\downarrow$ measured at the Israel Meteorological Services pyranometer station at Bet Dagan, in the central coastal plain, provide the longest single measurement series in Israel. Statistical analysis showed a highly significant ($p=0.001$), linear ($r=-0.758$) mean annual decrease of 28.63 MJ m^{-2} per year. In relative terms this represents an annual reduction of 0.41% of the mean annual irradiance (6.909 GJ m^{-2}) over the 1963–1994 period analyzed. Extending this series to include measurements made with the same pyranometer and by the same authority between 1958 and 1962 at Lod, 8 kms east of Bet Dagan, increases the mean loss in irradiance over the 39-year period to 36.29 MJ m^{-2} or 1.15 W m^{-2} per year and the correlation coefficient to $r=-0.846$.

The small decrease in annual values of $K\downarrow$ measured by Ashbel at Jerusalem in the central hill region during the 25 years between 1954 and 1979 was not statistically significant. However, when extended to include all 38 yearly values now available from the three series of Jerusalem measurements listed in Table 1, a highly significant ($p=0.001$), linear ($r=-0.712$), annual decrease averaging 28.33 MJ m^{-2}, was derived. This decrease is similar to that at Bet Dagan although

Table 1. *Details of global irradiance measurements in Israel made after 1970 and used in analyses*

Region and site	Coordinates E	N	MSL, m	Data Period	Instrumentation	Source
Coastal plain						
Bet Dagan	34°49′	32°00′	30	1970–1987	Tt–E_2	1
				1991–4	Tt–E_1	1
Hill region						
Jerusalem						
Climatology Dept. HU	35°14′	31°46′	789	1971–9	Tt–E_1	2
Israel Phys. Lab. HU	35°11′	31°46′	780	1971–6, 1980–7	Tt–E_3	3
Earth Sci. Lab. HU	35°11′	31°46′	785	1990–4	Tt–E_3	1
Arad	35°12′	31°15′	585	1990–2	Tt–E_3	4
Sede Boqer	34°46′	30°50′	470	1983–1992	Tt–E_3	4, 5
Jordan Rift Valley						
Huleh	35°35′	33°11′	70	1986–1994	Tt–Mg	6
Tabgha	35°27′	32°52′	−208	1986–1994	S_i–L	7
Jericho	35°27′	31°51′	−260	1981–1990	Tt–E_2	1
Quidron	35°27′	31°40′	−395	1982–9	Tt–Mg	8
Sedom	35°23′	31°02′	−390	1973–9	Tt–E_2	1
	35°24′	31°04′	−395	1989–1991	Tt–E_3	4
Yotvata	35°03′	29°53′	80	1990–2	Tt–E_3	4
Eilat	34°57′	29°32′	12	1982–1994	Tt–E_3	4
Negev						
Beersheba	34°45′	31°15′	315	1982–1994	Tt–E_3	9

Instrumentation: Tt — thermopile pyranometer; E_1 — Eppley 180° pyrheliometer and chart recorder; E_2 — Eppley black and white pyranometer and chart recorder; E_3 — Eppley Precision Spectral pyranometer and data logger; Mg — Kipp CM11 pyranometer and data logger; S_i–L — Licor 200 SA silicon photovoltaic cell pyranometer and data logger. At Beersheba, a chart recorder was used before 1988.

Data sources: For further details, see *Acknowledgments* and *References*.

1. A. Manes, Research and Development Division, Israel Meteorological Service, Bet Dagan.
2. The late D. Ashbel, Climatology Department, H.U., Jerusalem.
3. S. Suraqui, Israel Physics Laboratory, Jerusalem.
4. D. Faiman et al., 1990, 1992, 1993.
5. A. Zangvil, Blaustein Institute for Desert Research, Ben-Gurion University, Sede Boqer.
6. M. Meron, Migal Galilee Technology Center, Kiryat Shemona.
7. M. Rom, Mekorot Water Company, Upper Nazareth.
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9. A. Kudish and A. Ianetz, 1992, A. Kudish, Chemical Engng. Department, Ben-Gurion University, Beersheba.

relatively slightly less because of the greater irradiance at Jerusalem.

The plot of all annual totals of $K\downarrow$ measured in Israel against year of measurement (Fig. 1A) shows considerable year-to-year variation in the long term trend even after applying a five-year running mean as a filter. One reason could be the changing number of stations contributing records each year (Fig. 1B) which compounds spatial with secular variation.

The individual annual sums of $K\downarrow$ listed in Table 3, together with the corresponding measurements made before 1970 (tabulated in Stanhill, 1970), were related to the year of measurement, YR, in the form of annual averages for all sites $\bar{K}\downarrow$, yielding the following highly significant ($p=0.001$), linear ($r=-0.829$), relationship

$$\bar{K}\downarrow = 70.646 \text{ GJ m}^{-2} - 0.0321 \text{ YR}.$$

The annual decline in irradiance 32.07 ± 3.46 MJ m^{-2}, was equivalent to -1.02 W m^{-2} or -0.47% per year over the

Table 2. *Mean global irradiance (MJ m^{-2} day^{-1}) measured from 1970*

Site	Huleh	Tabgha	Bet Dagan	Jerusalem	Quidron	Beersheba	Eilat
January	7.63	7.61	10.07	11.30	9.56	10.19	12.67
February	9.87	9.94	12.81	14.38	12.83	12.95	15.62
March	15.16	14.74	17.48	18.88	17.20	17.36	19.81
April	20.84	20.08	21.82	22.86	21.00	22.37	23.38
May	23.85	21.80	25.16	27.16	24.20	25.38	25.27
June	27.23	25.89	27.63	29.21	26.87	28.07	28.15
July	26.80	25.11	26.83	28.83	26.90	27.25	27.45
August	24.24	22.85	24.56	26.51	24.50	25.15	25.54
September	20.35	19.54	20.90	22.65	20.94	21.54	22.13
October	15.05	14.36	16.05	17.51	15.92	16.52	17.73
November	10.13	10.04	11.66	12.58	11.69	12.12	13.98
December	7.01	6.83	9.18	10.42	9.34	9.73	12.09
Annual sum (GJ m^{-2})	6.345	6.056	6.828	7.381	6.730	6.964	7.423
Kt	0.56	0.53	0.59	0.64	0.58	0.60	0.64

41-year period 1954–1994. The addition of a quadratic term to the relationship did not increase its statistical significance.

The seasonal pattern of global irradiance in Israel has also undergone a small but consistent secular change with an increase in the fraction of annual irradiance occurring in early summer and a decrease in midwinter, leading to a slightly larger intra-annual range.

Averaged over the Jerusalem, Bet Dagan and Beersheba series, the mean fraction of annual irradiance measured in January decreased by 6% after 1970 compared with the mean fraction measured prior to 1970. The fraction in May increased by 3%; there was no change in the spring and autumn (Fig. 2).

Secular changes in atmospheric transmissivity are demonstrated in Fig. 3 in which $K\downarrow$, expressed as K_t, i.e., global irradiance as a fraction of extraterrestrial irradiance, has been related to observation of mean daytime cloud cover c, observed at 08, 14 and 20 h, and expressed in oktas, i.e. $\frac{1}{8}$s of the sky vault covered by cloud. 94 pairs of monthly means of $K\downarrow$ measurements and c observations made before 1962 at three sites in the central coastal plain and hill regions and in the Negev (Stanhill, 1962) were compared with a similar sized data set gathered after 1990: although data from the same sites were not available for the two periods the same climatic regions were represented.

In both data sets the relationships were highly significant, $p=0.001$, with correlation coefficients of $r=-0.749$ and -0.895, respectively, for the pre-1962 and post-1990 data sets. No statistical advantage was obtained by adding a quadratic term to the relationship, in both cases this was very small and did not significantly differ from zero.

The intercepts and slopes of the two equations, representing the transmissivity of clear sky and cloud cover, respectively, were different for the two periods. Before 1962, the extrapolated value for the mean transmissivity under cloudless conditions [$c=0$], was 0.772 ± 0.042; after 1990 it was 0.729 ± 0.037, 6% less. Over the 30-year period the transmissivity per unit cloud cover decreased from -0.033 ± 0.003 to -0.058 ± 0.003 Kt per oktas, i.e., by 76%. Extrapolation to overcast conditions [$c=6$], yielded a transmissivity of 0.574 for the early measurements and 0.381 for the current ones, a reduction of 33%, more than 5 times the reduction in transmissivity estimated for cloudless conditions.

The data shown in Fig. 3 indicates that the degree of cloud cover had decreased between the years sampled. For the pre-1962 years (open squares), 54% of the plotted points represent cloud cover values greater than 3 oktas. For the post-1990 years, only 24% of the plotted points (filled squares) have cloud covers greater than 3 oktas.

This conclusion was supported by the results of an analysis of long-term series of cloud cover

Table 3. *Annual global irradiance (GJ m^{-2} yr^{-1}) measured in Israel since 1970*

		Jerusalem												
	Bet Dagan	(1)	(2)	(3)	Arad	Sede Boqer	Huleh	Tabgha	Jericho	Quidron	Sedom	Yotvata	Eilat	Beersheba
1970	7.624													
1971	7.076	7.738	7.305											
1972	7.037	7.892	7.598											
1973	7.300	8.177	7.796								7.400			
1974	7.008	7.652	7.398											
1975	7.136	8.107	7.461											
1976	6.985	7.997												
1977	7.117	7.907												
1978	7.180	7.702												
1979	6.899	7.639												
1980	6.672													
1981	6.917		6.972						7.019					
1982	6.348												7.532	6.383
1983	6.221					7.243				6.697			7.744	6.283
1984	6.464					7.160			7.074	6.778			7.675	
1985	6.184					7.218				6.516				
1986		7.169	6.702			6.916								6.858
1987	6.437		6.565					6.210	6.997					7.105
1988		6.423						5.834	6.539					
1989							6.072		6.748	6.984	7.063		7.517	7.337
1990				7.462	7.556	7.610	6.518	6.067		6.862	6.984	7.642	7.4847	7.286
1991	6.715			7.173	7.358	7.236	6.188	6.015			6.811	7.402	7.175	7.264
1992	6.518				7.232	7.128	6.664	5.966				7.315	7.178	6.987
1993	6.827			7.261			7.036						7.143	7.167
1994	6.678			7.099			6.901						7.166	7.036

Jerusalem series are (1) Givat Washington, HU, (2) Israel Physics Laboratory, (3) Earth Sciences Laboratory, HU. For further details, see Table 1.

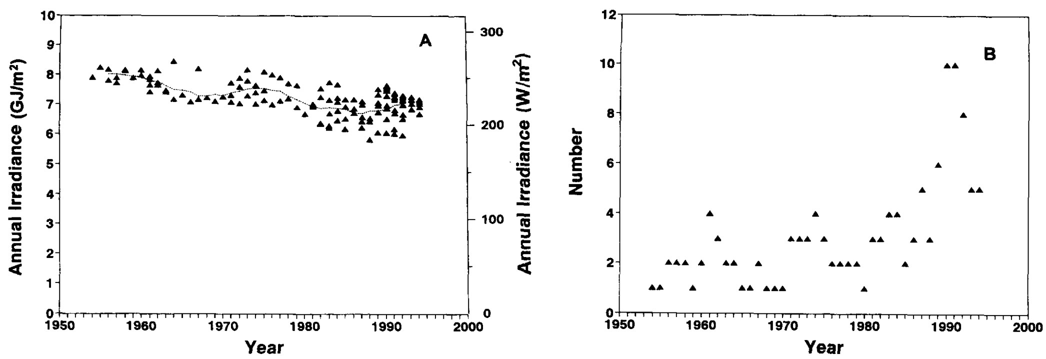

Fig. 1. (A) Annual sums of global irradiance measured in Israel. The line represents the five years running mean of the average of all annual totals for each year. (B) The growth in number of pyranometer stations with complete years of data.

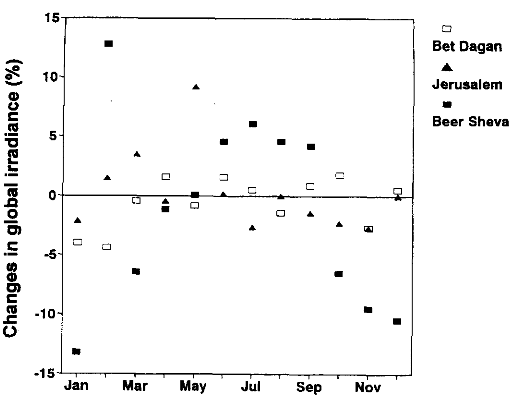

Fig. 2. Changes in seasonal distribution of global irradiance at Jerusalem (▲), Bet Dagan (□) and Beersheba (■). The percent change between mean monthly values measured before and after 1970 expressed as fractions of annual totals.

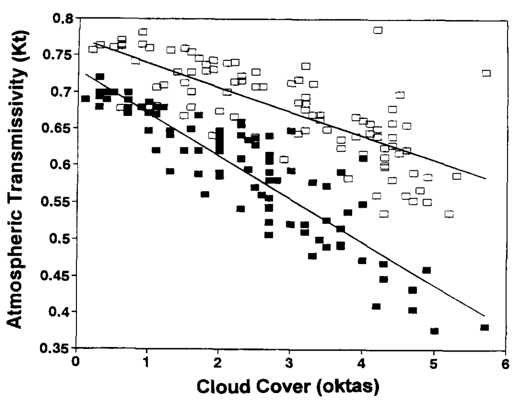

Fig. 3. Relationships between atmospheric transmissivity, Kt, and total daytime cloud cover in oktas c, measured and observed before 1962 (□) and after 1990 (■). Points represent individual monthly values and the lines the statistically fitted linear relationship.

observations taken at 4 climatological stations representing the major climatic regions of Israel, which showed that small *reductions* in cloud cover had occurred at all four sites. Averaged over the three daytime hours of observation 08, 14 and 20 h, the linear decrease in annual mean cloud cover, over the period 1964–1993, was greatest at Beersheba in the northern Negev (34°40′E, 31°15′N, 315 m MSL), averaging −0.022 oktas per year, and this trend was statistically significant at $p=0.05$. At Ramat David in the inland Emeq Valley (35°11′E, 32°40′N, 49 m MSL), the average annual decrease over the same period, −0.0177 oktas per year, was also statistically significant at $p=0.05$. At Kfar Blum in the northern Jordan Rift Valley (35°36′E, 33°10′N, 75 m MSL) the decrease in cloud cover over the period 1967–1989 was less, −0.009 oktas per year, and not statistically significant. The average decrease over the period 1964–1993, at Bet Dagan in the central coastal plain (34°49′E, 32°00′N, 30 m MSL) was very small, −0.001 oktas per year, and not statistically significant.

A similar seasonal pattern in the trends was found in all four series. The long-term decreases in cloud cover were greatest in April, ranging between −0.04 oktas per year at Ramat David, to −0.002 at Bet Dagan, with secondary maximums occurring between September and December at the different stations. In February and May cloud cover either slightly increased or showed no change. 90% of the changes in cloud cover for individual months and at the individual hours of observations were not statistically significant.

3.2. Spatial variation

The only spatial comparison of long-term measurements possible is between the central coastal plain and central hill region series, i.e., between the extended Bet Dagan and Jerusalem measurements between 1956 and 1994. The mean difference between annual sums measured at Jerusalem and Bet Dagan was $0.502\ \mathrm{GJ\ m^{-2}}$. The interannual variation in this spatial difference was large, with a standard deviation of $\pm 0.290\ \mathrm{GJ\ m^{-2}}$. The spatial difference was not significantly related to the year of measurement confirming the similarity in the long-term trends for the two series previously reported.

There was a clear seasonal trend in the differences between $K\downarrow$ measured at Jerusalem and Bet Dagan. Maximum differences, around 10%, were found in the three midwinter months, December to February, with the least differences between March and September (Table 3). A similar seasonal trend was found in the somewhat smaller spatial differences measured between 1956 and 1969 (Stanhill, 1970).

A greater spatial variation was found in recent years. The annual sums for 1989–1992 of all the stations listed in Table 3 shows a range of $1.4\ \mathrm{GJ\ m^{-2}}$ between the maximum irradiance — $7.5\ \mathrm{GJ\ m^{-2}\ yr^{-1}}$ — measured in the arid southern Negev — and the minimum sums around $6.1\ \mathrm{GJ\ m^{-2}\ yr^{-1}}$ measured at the two northern Jordan Rift Valley pyranometer stations. Averaged for these 4 years, and expressed as the standard deviation of all the measurements, spatial variation in $K\downarrow$ was $\pm 0.48\ \mathrm{GJ\ m^{-2}\ yr^{-1}}$.

Confining attention to the more homogeneous data set measured at the 6 pyranometer stations of the Negev Radiation Survey, indicates a much smaller spatial variation over the southern, arid half of the country. Averaged over the 2 years 1990, 1991, the maximum annual sum of irradiance ($7.52\ \mathrm{GJ\ m^{-2}}$) was measured at Yotvata 40 km north of the Red Sea in the Aravah Rift Valley, and the minimum ($6.89\ \mathrm{GJ\ m^{-2}}$) at Sedom 395 m below sea level to the south of the Dead Sea. Excluding this latter station reduces the range from 8.6% to 3.9% of the averages.

The recent measurements show greater spatial differences on a seasonal basis than for annual sums. Comparing the maximum values at Yotvata, with the minimum values in the Huleh Valley, both measured with Class One pyranometers during the three years 1989–1992, shows an annual difference of 14%. The difference rose to 41% in the two midwinter months, January and February, falling to 2% during the three midsummer months, June, July and August.

4. Discussion

The major finding, derived from the results of the two long-term measurement series as well as that of the complete national data base, is of a large and statistically significant decline in global irradiance over the last 40 years.

The decline in $K\downarrow$ can be highlighted by the fact that the pooled data presented in Fig. 1A show that annual sums of $K\downarrow$ greater than $8.0\ \mathrm{GJ\ m^{-2}}$ were no longer measured after 1975 while sums less than $7.0\ \mathrm{GJ\ m^{-2}}$ were never reported before that year. Nor were annual sums of irradiance less than $6.0\ \mathrm{GJ\ m^{-2}}$ recorded before 1985.

The decline in $K\downarrow$ is greater in winter than summer, and is more widespread than previously described (Stanhill and Moreshet, 1992b). It appears to be greatest in the area of least irradiance, i.e., the northern Jordan Valley (Cohen and Stanhill, 1996) but in recent years the decline is also apparent from measurements in the areas with most irradiance, i.e., the arid Negev including the Aravah valley (Table 3).

Indirect evidence supporting the finding of a decline in solar irradiance in Israel is available from four independent sources.

These are as follows.

(a) The statistically significant reductions in maximum and diurnal air temperature range found at four climate stations in the Jordan Valley during the last 50 years (Cohen and Stanhill, 1996). Diurnal air temperature range, in particular, is known to be highly and positively correlated with $K\downarrow$ (Bristow and Campbell, 1984; McVicar et al., 1992; Meinke et al., 1995). Reductions in maximum temperature and diurnal range have also been reported for Tel-Aviv and Jerusalem (Jaffe, 1991), and for all of Turkey (Turkes, Sumer and Kilic, 1996).

(b) The significant reduction in visibility observed during daylight hours at Lod airport in the central costal plain over the 1940–1971 period documented by Manes et al. (1974). Less well-documented but widely accepted is the virtual disappearance of Mt. Hermon (elevation 2769 m MSL and 100 km downwind), once a prominent feature of the Haifa landscape (Oliphant, 1887).

(c) The increase in the diffuse, and the decrease in the direct solar beam component of $K\downarrow$ measured in the central coastal plain (Stanhill and Moreshet, 1992b).

(d) The reduction in evaporation from Lake Kinneret and the Dead Sea, two large water bodies in the Jordan Rift Valley, as shown by a comparison of early and recent estimates (Cohen and Stanhill, 1996).

Before discussing the causes of this decline in $K\downarrow$ the reliance that can be placed in the measurements analyzed will be touched upon. Until recently, the accuracy attainable for routine measurements of $K\downarrow$ with careful maintenance and regular calibration was assessed as 5% (WMO, 1961, 1983; BMO, 1982); currently the goal for continuous measurements with Class One pyranometers has been set at 2% (WMO, 1991).

There is every reason to suppose that the two long-term measurement series, as well as those from Beersheba and Quidron, and the Negev Radiation Survey series met the lower of these standards, indicating that the measured decline in irradiance is instrumentally as well as statistically significant, exceeding by three-fold the uncertainty in measurement.

Moreover, the non-homogeneity in the measurements reviewed, i.e., the variety of pyranometers used, variety of authorities responsible for the measurements and their calibration and the number of series, makes the possibility that a similar and consistent error in calibration was the cause of the decline in $K\downarrow$ exceedingly unlikely.

4 mechanisms could, either singly or in combination, be responsible for the loss of irradiance at the earth's surface found in this study.

The first, a reduction in the sun's output, can be excluded as on an annual basis, the measured changes in the extraterrestrial flux observed by satellite are cyclic and at least one order of magnitude less than the long-term trends measured at the surface. Another reason is that the surface changes in $K\downarrow$ are not latitudinally uniform as would be expected if caused by changes at the top of the atmosphere (Stanhill and Moreshet, 1992a and 1994).

The second mechanism, a decrease in global irradiance reflected from the earth's surface $K\uparrow$, could only be of secondary significance in the local context. While under extreme conditions, such as a change from snow to water cover, reductions of $K\uparrow$ under conditions of significant cloud cover and/or turbidity can substantially reduce $K\downarrow$ (Hisdal, 1982; Gardner, 1987), this is not so for Israeli conditions where the maximum local change in surface reflectivity $K\uparrow/K\downarrow$ to be expected, is from values typical of desert cover, $K\uparrow/K\downarrow=0.35$, to those for a high-rise, urban landscape, $K\uparrow/K\downarrow=0.15$. With an annual value of atmospheric transmissivity around $\mathrm{Kt}=0.6$ (Table 2, Fig. 3), this change would only reduce the total downward flux of $K\downarrow$ by 3%, i.e. by $\frac{1}{7}$ of the measured decrease.

The 3rd and 4th mechanisms refer to changes in the radiative characteristics of the atmosphere; respectively, to increases in the reflection of the atmosphere to space and in the absorption of solar irradiance by the atmosphere. Both such increases could be affected by increases in the extent, duration as well as in the reflectivity and absorptivity of cloud cover as well as by changes in the aerosol load. The results presented show that changes in the extent and duration of cloud cover can be excluded as the cause of the significant decrease in atmospheric transmissivity.

Although changes in the radiative properties of the atmosphere apart from cloud cover have not been monitored in Israel, it is possible to calculate their mean values and the size of the changes needed to account for the observed decline in $K\downarrow$. To do so requires values of the upwelling reflected global radiation both at the top of the atmosphere $K_a\uparrow$, and at its base, i.e., at the earth's surface $K_s\uparrow$.

Measurements of the $K_a\uparrow$ during the period 1985–9 were available from the Earth Radiation Balance Experiment through the courtesy of D. O'Brien (personal communication, 1993). For the area delimited by 35.0° and 37.5°E, and 30.0° and 32.5°N, i.e, the major part of Israel and

Jordan, the average reflectivity at the top of the atmosphere under cloudy conditions, was 0.30, varying seasonally between 0.25 in summer and 0.35 in winter. Clear sky reflectivity averaged 0.25 with a non-seasonal, inter- and intra-annual range of 0.03. Corresponding mean values for the northern hemisphere as a whole during the same period were 0.39 for cloudy skies and 0.25 for clear skies.

Measurements of $K_s\uparrow$ for different land covers in Israel (Stanhill et al., 1966) indicate an areal mean reflectivity at the surface of 0.20. This value was used to calculate the mean atmospheric absorptivity A, expressed as a fraction of the downwelling global irradiance at the top of the atmosphere $K\downarrow\downarrow$, using the simple radiation balance equation

$$A = \frac{(K\downarrow\downarrow - K\downarrow) - (K_a\uparrow - K_s\uparrow)}{K\downarrow\downarrow}$$

For the period of the ERBE measurements, this yields a mean value of 0.24 for atmospheric absorptivity.

To account for the observed 20% decline in $K\downarrow$ over the 1954–1994 period would require an unrealistic doubling of solar reflectivity at the top of atmosphere, i.e., from 0.14 to 0.28. Alternatively, an increase in atmospheric absorptivity from 0.15 to 0.26, is required to explain the observed decline in global irradiance at the surface.

An increase in $K_a\uparrow$ of the magnitude required is unlikely in the absence of any significant increase in cloud cover. Moreover, no time trend was discernible in the admittedly short ERBE measurement series.

The increase required in atmospheric absorptivity could not have come about through the large increases necessary in the extent of cloud cover as small *decreases* in this parameter were observed in Israel over the period during which $K\downarrow$ declined. This leaves changes in solid and gas phase components of the atmosphere radiatively active in the solar spectrum, i.e., suitably sized aerosols or stratospheric ozone, as the direct or indirect causes of an increase in atmospheric absorptivity; the energy absorbed in the atmosphere being dissipated either in endothermic chemical reactions or stratospheric heating.

The modelled geographic distribution of anthrophogenically generated sulphate aerosols in the atmosphere indicates that the global maximum concentration occurs over the central and eastern Mediterranean, giving rise to a mean, negative, radiative forcing of 2 W m^{-2} (Houghton et al., 1995). This same reference states that the indirect effects of these aerosols are equal to their direct effects, giving a total reduction of 4 W m^{-2} from 1850 to the present day (Houghton et al., 1995). A similar value of sulphate cooling for the eastern Mediterranean has been given by Boucher and Lohman (1995). This estimated value is far below the mean *annual* reduction in $K\downarrow$ measured in Israel in the last 40 years, 1.02 W m^{-2}.

This large discrepancy could perhaps be explained by a growth in the size of the anthropogenically generated aerosols, and hence their scattering properties in the short wave, as they cross the Mediterranean with its higher relative humidity especially in the winter months. Direct pyrheliometer observations to test this hypothesis are needed.

Evidence that the hypothetical increase in aerosol concentrations is, at least partially, of local origin and is associated with changes in emissions from motor traffic, has been presented in an earlier study (Stanhill and Moreshet, 1992b). It is also supported by the significant negative relationship found between values of $K\downarrow$ measured in the Tel Aviv radiation network during the different days of the week and the corresponding average number of km travelled during that day. The slope of this relationship was such that each 1% increase in motor traffic was associated with a 0.2% decrease in $K\downarrow$ and extrapolation to zero traffic indicated values of $K\downarrow$ similar to those measured 40 years ago (Stanhill, 1994).

Evidence that aerosols emitted outside and upwind of Israel also contribute to the decreased transmissivity of $K\downarrow$ include the previously discussed modelled geographical distribution of aerosol-induced radiative cooling (Houghton et al., 1995); the reduction of $K\downarrow$ at sites in Israel distant from local sources of pollution, as shown in this study as well as in Jordan (Alsaad, 1990), and in addition, the low level of $K\downarrow$ measured in Cyprus during the last decade.

The mean annual value measured at Athalassa, Cyprus (33°24′E, 35°10′N, 162 m MSL) for the period 1984–1993 was 6.169 GJ m^{-2} (personal communication, Hadjioannon, 1995). This value is both absolutely, and relative to the extraterrestrial flux, less than that measured for the same period at Bet Dagan, 370 km SSE downwind; this despite the similar cloud cover, 3.0 oktas compared with 3.1, and the much lower levels of industrial and urban activity in Cyprus than in Israel.

5. Conclusions

Two forty year long series of global irradiance measurements in Israel, from Bet Dagan in the central coastal plain and Jerusalem in the central hill region, show similar and statistically highly significant linear decreases averaging 28 MJ m^{-2} per year. When all 130 station-years of $K\downarrow$ measurements made between 1954 and 1994 were pooled, an even greater reduction of 20%, equivalent to -1.02 W m^{-2} annually, was found, four times greater than the estimated error of measurement. The decrease in atmospheric transmissivity was greater under cloud- covered than clear sky conditions, in winter than in summer, and in the northern section of the Jordan Rift Valley.

On the average, global irradiance was 0.50 GJ m^{-2} yr^{-1} greater at Jerusalem than at Bet Dagan with no evidence for a time trend in the difference: spatial differences of $K\downarrow$ within Israel were greater in winter than summer. This was also the case for the differences in $K\downarrow$ measured between 1989–1992 at seven pyranometer stations throughout the country. The range in mean annual values of $K\downarrow$ between the maximum measured in the southern Aravah north of the Red Sea and the minimum measured in the northern Jordan Rift Valley was 1.4 GJ m^{-2} yr^{-1}. Expressed as the standard deviation this spatial variation was 0.48 GJ m^{-2}, 7% of the mean. The range in $K\downarrow$ measured within the greater Tel Aviv connurbation (100 km^2 in area) was much smaller: 7%.

The reasons for the long-term reduction of global irradiance in Israel are not clear. Changes in the extent of cloud cover can be excluded as analysis of 4 long-term observation series showed that *decreases* of varying sizes and significances had occurred in all cases. Increased atmospheric absorption due to pollutants emitted in Israel and in the upwind regions of SE Europe was considered the most likely cause.

The agricultural, climatological, hydrological and visual significance of the decreases in solar irradiance documented in this study indicates the need to monitor this parameter and to intensify research into its causes.

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