Global dimming:
A new aspect of climate change

G. Stanhill

Institute of Soil, Water and Environmental Sciences, Bet Dagan, Israel

The purpose of this article is to draw attention to a recently observed, little known, and even less understood, element of climate change, and to point out its practical implications and theoretical importance.

Global dimming and the evidence for it

By analogy to the well known concept of global warming, global dimming refers to the currently occurring, widespread and significant reduction in global irradiance, $E_g\downarrow$, that is the flux of solar radiation reaching the earth's surface both in the direct solar beam and in the diffuse radiation scattered by the sky and clouds.

The direct evidence for a reduction in $E_g\downarrow$ stems from the International Geophysical Year of 1957/58 when a global network of radiometer stations was set up to provide accurate and comparable measurements of the earth's radiation balance. At the start of the measurements a variety of radiometers of very different accuracies were used, but since then most measurements of $E_g\downarrow$ have been made with thermopile pyranometers and it is these measurements that have been used in this study. When operated in accordance with the World Meteorological Organization's (WMO's) instructions, these radiometers have an accuracy of 5% and 2% respectively for daily and annual totals (WMO 1997).

Ten years ago an analysis of annual values of $E_g\downarrow$, measured in the global network during the four years 1958, 1965, 1975 and 1985, showed that large and statistically significant reductions had occurred at many sites although with considerable spatial variation; weighted for the land surface of the earth the global decrease averaged 9 W m^{-2} or 5.3% over the 1958–85 period (Stanhill and Moreshet 1992). A more recent analysis of the entire WMO-sponsored World Radiation Data Center database presented the changes on a 2.5° × 2.5° grid scale for the 1964–93 period – significant global dimming had taken place over large regions of Africa, Asia, Europe and North America with the decrease averaging 2% per decade (Gilgen *et al.*1998). Detailed studies describing the reductions in the former Soviet Union, USA, Arctic Circle, Germany and Ireland have been published respectively by Abakumova *et al.* (1996), Liepert and Tegen (2002), Stanhill (1995), Power (2003) and Stanhill (1998).

As is the case with global warming, areas exist in which no significant change has occurred, notably Australia (Stanhill and Kalma 1994). A few areas with significant increases in $E_g\downarrow$ have also been reported, the largest of which appears to be Japan where an overall increase during the last 30 years has taken place. Gilgen *et al.*'s (1998) map of global changes shows increases in only four small areas, one of which was significant.

A review of the published information on secular changes in $E_g\downarrow$ up to 2000 concluded that globally the decrease averaged 0.51 ± 0.05 W m^{-2} annually, equivalent to a reduction of 2.7% per decade, and now totals 20 W m^{-2} – seven times the error of measurement. Decreases in $E_g\downarrow$ were found in all but two of the published results from the 39 individual series of long-term measurements tabulated in the review; at 28 sites the global dimming was statistically significant with an average reduction of 0.55 W m^{-2} per year. Only one of the two increases reported for individual series was statistically significant (Stanhill and Cohen 2001).

The degree of global dimming varied markedly with latitude as shown in Fig. 1 – the maximum decrease, exceeding 1 W m^{-2} per year, occurring in the midlatitudes of the Northern Hemisphere, the earth's most densely populated and industrialised zone. However, significant reductions in $E_g\downarrow$ were found even within the empty polar circles, 0.36 W m^{-2} per year in the Arctic and 0.28 W m^{-2} per year in the Antarctic; both these reductions were based on an analysis of data from all of the pyranometer stations in the two polar regions.

Considerable variation was also found in the degree of global dimming within a given latitudinal zone. This can be seen from a study of the 13 series of measurements in Germany analysed by Power (2003) as well as from the ten long-term (≥30 years) series of pyranometer measurements available from the British Isles presented in Table 1.

Six of the British and Irish long-term series showed statistically significant linear trends, four negative and two positive. Although the average annual global dimming for the British Isles, −2.1 MJ m^{-2} (0.06 W m^{-2}), agrees approximately with the average for the 50–60°N zone (Fig.1) there was considerable spatial variation within the British Isles; the significant reductions were found near the western coasts of Ireland and Wales and the significant increases in south-east England (Table 1).

The direct evidence for global dimming very briefly outlined above is based on far fewer measurements than are available to study the more widely investigated elements of climate change – temperature and precipitation; not only are the pyranometer measurement series fewer and shorter, but

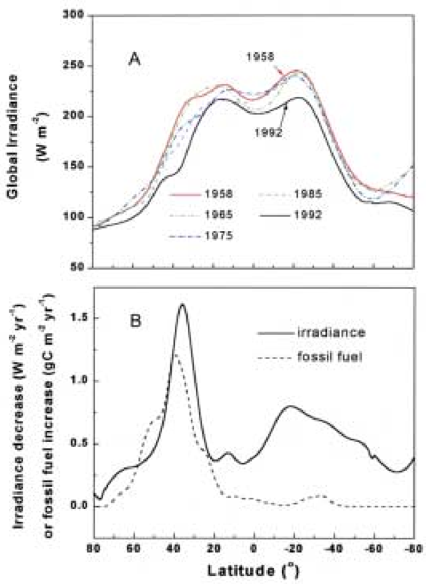

Fig. 1 Latitudinal variation of global dimming, 1958–92 (from Stanhill and Cohen 2001). (gC m^{-2}yr^{-1} is grams of carbon per square metre per year.)

Weather – January 2005, Vol. 60, No. 1

RMetS Royal Meteorological Society

also their spatial coverage is very uneven (Fig. 2). Thus in 1992 over half of the 303 complete years of thermopile pyranometer measurements available were from Europe, a quarter from Asia, and one eighth from Australia and the southern Pacific. Africa and Antarctica each had only four sites with complete years of record and in both these continents the number of sites was less than in 1958 (Stanhill and Cohen 2001).

A further search would almost certainly add to this limited database of pyranometer measurements, and could bring to light the very few records of thermoelectric pyranometer measurements which began in the first third of the last century. The E_g↓ database could also be extended in time and space by the use of indirect and proxy measures of global radiation.

Table 1

Means and trends in annual values of global irradiance in the British Isles (P is probability)

Site	Coordinates	Period	Mean and standard deviation ($W m^{-2}$)		Trend ($W m^{-2}$ $year^{-1}$)	Significance
Lerwick	60.08°N, 1.11°W	1952–2002	89.2	5.07	−0.026	n.s.
Eskdalemuir	55.19°N, 3.12°W	1956–2002	94.1	5.26	−0.058	n.s.
Aldergrove	54.39°N, 6.13°W	1969–2001	103.0	4.40	−0.059	n.s.
Birr	53.05°N, 7.54°W	1971–2002	107.5	6.15	−0.330	P<0.01
Kilkenny	52.40°N, 7.16°W	1969–2002	112.3	7.73	−0.459	P<0.01
Valentia	51.56°N, 10.15°W	1955–2002	115.7	8.02	−0.412	P<0.01
Aberporth	52.08°N, 4.34°W	1959–2002	120.1	5.23	−0.125	P<0.05
Rothamsted	51.48°N, 0.21°W	1958–2000	106.5	7.61	+0.405	P<0.05
East Malling	51.17°N, 0.27°E	1964–2002	113.0	5.83	+0.267	P<0.01
Jersey	49.11°N, 2.11°W	1969–2003	134.0	6.49	+0.078	n.s.

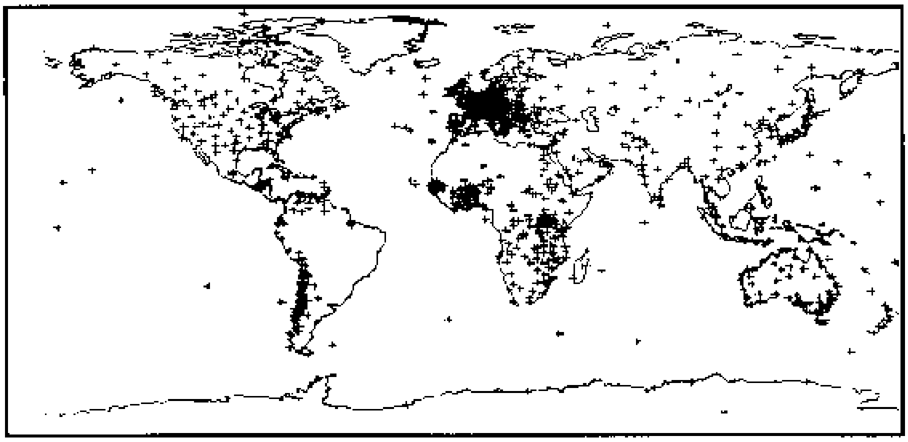

Fig. 2 World map of pyranometer stations

Extending the record

Indirect evidence supporting global dimming can be found in the changes reported for three climatic features known to be positively, closely and causally linked with global radiation, viz. evaporation from water surfaces, diurnal air temperature range and visibility.

Analysis of measurements from the several hundred evaporation pan stations which make up the US and former Soviet Union national networks showed reductions in the evaporation occurring during the last 35 years (Peterson *et al.* 1995); similar results have been reported from the smaller Indian (Chattopadhyay and Hulme 1997) and Australian (Roderick and Farquhar 2004) evaporation pan networks. The close link between evaporation and E_g↓ results from the fact that solar energy supplies the latent heat needed to change water from its liquid to its gaseous state, and it has been shown that reductions in evaporation, for example those recorded in north-west Russia, can be fully accounted for by those observed in E_g↓ (Roderick and Farquhar 2002). Comparable results from China were reported for the 1954–93 period when the reduction in potential evaporation, calculated by Penman's equation to average 2.1% per decade, was explained by global dimming based on reductions of sunshine duration measured at 60 climate stations (Thomas 2000).

The diurnal temperature range (DTR) is so closely linked with E_g↓ that it is often used as a proxy measure for calculating global radiation (Bristow and Campbell 1984; Thornton and Running 1999). The physical basis for this linkage is that part of the solar energy absorbed at the earth's surface is convected into the lower atmosphere where it raises the daytime maximum temperature above the night-time minimum. A second factor which controls DTR is the degree of surface wetness which determines the partitioning of solar heating between convective and latent heat fluxes; DTR is greatest at non-evaporating desert sites and least at mid-ocean island sites. This effect of surface wetness has been allowed for by including a rainfall term in the equations used to calculate E_g↓ from DTR.

A striking example of a wide-scale, man-induced change in DTR was provided by the 11 September terrorist attacks in New York and Washington when commercial air traffic in the USA was grounded for three days. During this period DTR was 1.8 degC above the climatological normal, almost certainly as a result in the observed reduction in contrail-induced cirrus cloud cover which presumably led to an increase in E_g↓ (Travis *et al.* 2002). Another man-made climate change experiment occurs each year in Israel on the Day of Atonement when road traffic ceases. Measurements between 1965 and 2003 at the Israel Meteorological Services Observatory at Bet Dagan, close to two major traffic interchanges, show that DTR increased by an average of 0.3 degC while E_g↓ increased by an average of 9.72 $W m^{-2}$ as compared with the values measured seven days before and after the fast day.

An analysis of trends in the global maximum and minimum air temperatures shows that the earth's DTR fell by 0.84 degC during the twentieth century (Easterling *et al.* 1997). Using this figure with Bristow and Campbell's (1984) relationship for a moist surface yields a global dimming of 13.6 $W m^{-2}$ for this same period.

A third indirect measure of global dimming is the decline in visibility that has taken place during the last century. Visibility, quantified as visual range – the horizontal distance at which an observer can clearly discern an object against a contrasting background – was one of the first climatological parameters to be observed. An example of its reduction is available from an analysis of the observations made at Lod Airport in the central coastal plain of Israel between 1940 and 1970; during this period visual range during the summer months decreased by an average of 0.8 km per year (Manes *et al.* 1974). Currently, visibility is often measured instrumentally and Fig. 3 presents an example of such automatically observed and analysed measurements used to monitor the effects of air pollution on visibility at the Shenandoah Blue Ridge National Park in Virginia, USA. At this site, once famous for its magnificent views, the annual visual range now averages 40 km (Fig. 3(a)); whereas under completely clean air conditions, now occurring during less

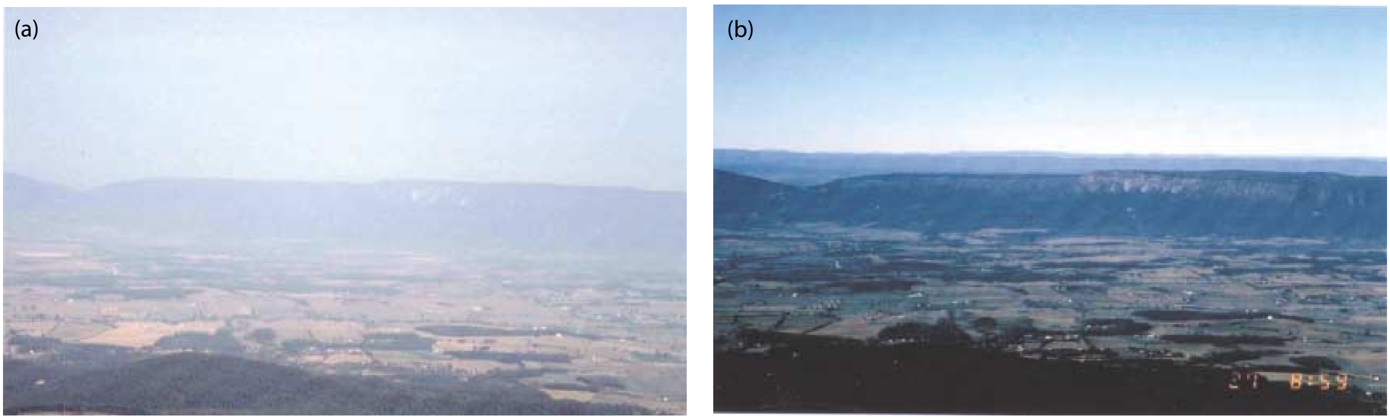

Fig. 3 Effects of pollution-induced regional haze on visibility as monitored at the Skyland site, Shenandoah National Park, Virginia, USA: (a) visual range 40 km, cumulative annual frequency of occurrence 55%, and (b) visual range 250 km, cumulative annual frequency of occurrence <1%

than 1% of the year, visual range reaches 250 km – the limit of human capability (Fig. 3(b)).

The reduction in visibility in this and many other US national parks was so obvious that legislation was eventually enacted mandating the monitoring of visibility and air pollution so that the sources of pollution could be identified and controlled. The results of this monitoring at many national park sites can be seen at http://vista.cira.colostate.Edu from which these illustrations were taken.

As visibility is linearly and inversely related to atmospheric turbidity (Linacre 1992), it should be possible to exploit the many long time-series of visibility observations at land and at sea to calculate values of $E_g\downarrow$ normalised to extraterrestrial irradiance, and so reconstruct past patterns of changes in solar radiation. A more direct proxy measure of solar irradiance – sunshine duration – has been widely measured during the previous century and these measurements have frequently and successfully been used to estimate $E_g\downarrow$, although usually for periods shorter than a year (Lineacre 1992).

In the UK the Campbell–Stokes sunshine recorder was adopted as the official station network instrument in 1880, and is only now being replaced by a fully automatic electronic instrument which removes the subjective element in the assessment of sunshine duration, important under intermittently cloudy conditions. A score of sunshine-duration series more than a century long are available from the British Isles, and a similar number from sites in Europe and British overseas territories.

The US and Japanese meteorological services adopted a different instrument – the Jordan photographic sunshine recorder – for their station networks in the 1890s. In the USA two changes of instrumentation followed but these had little effect on the results, and more than 100 series of at least 70 years' duration are available for analysis. In Japan the Jordan sunshine recorder remained in use until 1986 when it was replaced by a fully automatic electronic recorder – 43 series with more than 70 years of sunshine-duration measurements are available for study. Similar long-term series from China, Taiwan and Korea exist in more limited numbers.

Examination of the US, Japanese and Campbell–Stokes databases shows that in each case annual values of sunshine duration are highly correlated with global radiation sums measured with thermopile pyranometers; more than three quarters of the interannual variation in $E_g\downarrow$ can be accounted for by the interannual variations in sunshine duration. Although the slope of the relationships, *i.e.* the change in $E_g\downarrow$ attributable to a 1-hour change in sunshine duration, was approximately the same for each of the three datasets, the slopes at individual sites within each dataset varied, largely latitudinally, so that caution is needed before using sunshine duration as a proxy measure of global radiation at a specific site.

Causes and consequences of global dimming

Although the cause of the reduction in $E_g\downarrow$ is not fully known and certainly cannot as yet be quantitatively explained, currently the most probable reason is a change in the transmissivity of the earth's atmosphere. An alternative explanation, that the flux of solar radiation reaching the top of the earth's atmosphere has decreased, can be eliminated as recent research indicates that this flux has slightly *increased* over the last century (Foukal 2002). Another possible cause, an increase in the solar radiation reflected to space from the earth and its atmosphere, is under study. First results show small changes insufficient to explain global dimming.

Reduced atmospheric transmissivity could have resulted from changes in the short-wave radiative properties of the sky and/or of the clouds, as well as from an increase in cloud cover. These changes could be the outcome, either directly or indirectly, of greater concentrations of aerosols in the atmosphere. The direct effect relates to the increased short-wave absorption by aerosols under both clear and overcast sky conditions, while an indirect effect refers to the role of aerosols as cloud condensation nuclei leading to increased cloud cover.

The probability that cloud absorption is an important cause of global dimming is supported by a number of studies which have shown that greater reductions in $E_g\downarrow$ occur in years of, and at sites and seasons with, greater cloud cover (Liepert and Kukla 1997; Power 2003; Stanhill 1998).

Aerosol concentrations during the last century have increased alongside those of CO_2 and the other gases radiatively active in the long-wave bands, the generally accepted cause of global warming. Thus global dimming and global warming can be attributed to changes in the short- and long-wave radiative properties of the atmosphere, both to a major extent having been brought about by the combustion of fossil fuels.

Despite, or perhaps because of, their common origin, global dimming poses a problem to the current consensus explanation of global warming – how can a significant decrease in solar heating of the earth's surface be reconciled with an increase in its surface temperature? Not only are the changes in opposite directions, but also their timings and locations do not coincide.

This major question centres around the magnitude of aerosol-induced short-wave cooling, often referred to as negative radiative forcing. The short-wave cooling needed to bring the measured global warming since the industrial era, 0.6 ± 0.2 degC, into agreement with the amount calculated from current models of climate change, is $-2.4\,\mathrm{W\,m^{-2}}$. The latest Intergovernmental Panel on Climate Change (IPCC) report gives this same value as the consensus estimate of negative short-wave radiative forcing on the basis of atmospheric radiative transfer models but emphasises the many uncertainties in these estimates (IPCC 2001). Whatever the accuracy of this mean estimate of negative short-wave radiative forcing it is only one tenth of the measured global decrease in $E_g\downarrow$ between 1958 and 1992, ~20 W m^{-2}, reported in this study (Stanhill and Cohen 2001).

The practical consequences of global dimming of the magnitudes documented are likely to be very widespread as it is solar energy that drives the earth's life-sustaining air, water and carbon cycles. The clearest and easiest way to demonstrate the effect of global dimming, that on the hydrological cycle, has already been noted – the reduction of evaporation from water and land surfaces with a non-limiting water supply, *i.e.* under potential evaporation conditions.

Further consequences for the hydrological cycle could follow any changes in atmospheric circulation resulting from different patterns of solar heating at the earth's surface; changes in circulation patterns would affect precipitation as well as evaporation. Changes in atmospheric circulation are of course a major cause as well as a consequence of local climate change with all the practical implications that this involves.

The effects of global dimming on the carbon cycle could also be widespread. Lower intensities of solar radiation in the photosynthetically active wavebands can be expected to have an adverse effect on carbon assimilation by plant communities, and hence agricultural and forestry production. However, where and when water and not light is the factor limiting plant growth the opposite situation could arise, and plant production could be unaffected or even enhanced by global dimming in cases where this leads to a reduction in plant water stress. Other practical consequences of global dimming include the reduction in the economic potential of solar energy to serve as an alternative, non-polluting and renewable source of energy as well as the adverse effects on visibility illustrated in Fig. 3.

The future of global dimming

The theoretical and practical significance of the changes in solar irradiance at the earth's surface briefly outlined are such as to justify further studies to answer the question, "Where has all the sunshine gone?". Hopefully, such studies will eventually lead to a quantitative understanding of global dimming which would allow it to be incorporated into current models of climate change and reconciled with global warming. Another important goal is to prepare an extensive, long-term database of $E_g\downarrow$ to verify model predictions and estimate the consequences of the changes in solar radiation.

A verified and theoretically based explanation of global dimming is needed to establish that the restrictions to fossil-fuel combustion proposed in the Kyoto Protocol on Climate Change are indeed essential. Substantiation of the currently most plausible explanation of global dimming – enhanced cloud absorption of solar radiation due to the indirect aerosol effect – would provide a strong additional argument for reducing the use of fossil fuels. As these represent the non-renewable photosynthetic harvest of solar energy from the distant past, their conservation could, perhaps ironically, help to restore solar radiation to its former levels.

Acknowledgements

I wish to thank the many colleagues, in particular S. Moreshet and S. Cohen, who have contributed to much of the work described, as well as Kath Phelps of Hort Research International, Tony Pallot of JerseyMet and Dave Yeoman of IACR, Rothamsted, who respectively supplied the data for East Malling, Jersey, and Rothamsted presented in Table 1.

References

Abakumova, G. M., Feigelson, E. M., Bussak, V. and Stadnik, V. V. (1996) Evaluation of long term changes in radiation, cloudiness and surface temperature on the territory of the former Soviet Union. *J. Clim.*, **9,** pp. 1319–1327

Bristow, K. L. and Campbell, G. S. (1984) On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agric. For. Meteorol.,* **31,** pp. 159–166

Chattopadhyay, N. and Hulme, M. (1997) Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agric. For. Meteorol.,* **87,** pp. 55–73

Easterling, D. R., Horton, B., Jones, P. D., Peterson, T. C., Karl, T. R., Parker, D. R., Salinger, M. J., Razuvayev, V., Plummer, N., Jameson, P. and Folland, C. K. (1997) Maximum and minimum temperature trends for the globe. *Science*, **277,** pp. 364–367

Foukal, P. (2002) A comparison of variable solar and ultraviolet irradiances in the 20th century. *Geophys. Res. Lett.*, **29,** doi: 10.1029/2002GLO15474

Gilgen, H., Wild, M. and Ohmura, A. (1998) Means and trends of short wave irradiance at the surface estimated from global energy balance archive data. *J. Clim.,* **11,** pp. 2042–2061

IPCC (2001) *Climate change 2001: The scientific basis*. Cambridge University Press, Cambridge

Liepert, B. G. and Kukla, G. J. (1997) Decline in global solar radiation with increased horizontal visibility in Germany between 1964 and 1990. *J. Clim.*, **10,** pp. 2391–2401

Liepert, B. G. and Tegen, I. (2002) Multidecadal solar radiation trends in the United States and Germany and direct tropospheric forcing. *J. Geophys. Res.*, **107,** D12,10.1029/2001JD00760

Linacre, E. (1992) *Climate data and resources.* Routledge, London

Manes, A., Rindsberger, M., Guetta, D. and Teitelman, A. (1974) Long term trends in visibility at the Ben Gurion (Lod) airport area. *Isr. J. Earth Sci.*, **23,** pp. 1–7

Peterson, T. C., Golubev, V. S. and Groisman, P. Y. (1995) Evaporation losing its strength. *Nature*, **377,** pp. 687–688

Power, H. C. (2003) Trends in solar radiation over Germany and an assessment of the role of aerosols and sunshine duration. *Theor. Appl. Climatol.,* **76,** pp. 47–63

Roderick, M. L. and Farquhar, G. D. (2002) The cause of decreased pan evaporation over the past 50 years. *Science*, **298,** pp. 1410–1411

—— (2004) Changes in Australian pan evaporation from 1970 to 2002. *Int. J. Climatol.,* **24,** pp. 1077–1090

Stanhill, G. (1995) Global irradiance, air pollution and temperature changes in the Arctic. *Phil. Trans. R. Soc., A*, **352,** pp. 247–258

—— (1998) Long term trends in, and spatial variation of, solar irradiances in Ireland. *Int. J. Climatol.*, **18,** pp. 1015–1030

Stanhill, G. and Cohen, S. (2001) Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion on its probable causes and possible agricultural consequences. *Agric. For. Meteorol.*, **107,** pp. 255–278

Stanhill, G. and Kalma, J. D. (1994) Secular variation of global irradiance in Australia. *Aust. Meteorol. Mag.*, **43,** pp. 81–86

Stanhill, G. and Moreshet, S. (1992) Global radiation climate change: the world network. *Clim. Change,* **21,** pp. 57–75

Thomas, A. (2000) Spatial and temporal characteristics of potential evapotranspiration trends over China. *Int. J. Climatol.,* **20,** pp. 381–396

Thornton, P. E. and Running, S. W. (1999) An improved algorithm for estimating incident solar radiation from measurements of temperature, humidity and precipitation. *Agric. For. Meteorol.*, **93,** pp. 211–228

Travis, D. J., Carleton, A. M. and Lauristen, R. (2002) Jet contrails and climate: anomalous increases in U.S. diurnal temperature range for September 11–14, 2001. *Nature,* **418,** p. 601

WMO (1997) Measurement of radiation. In: *Guide to meteorological instruments and methods of observation*, 6th edition. World Meteorological Organization, Geneva, p. 7-9

Correspondence to: G. Stanhill, Institute of Soil, Water and Environmental Sciences, Volcani Center, POB 6, Bet Dagan, Israel 50250.

e-mail: Gerald@agri.gov.il

doi: 10.1256/wea.210.03