Chapter 2

The Role of Widespread Surface Solar Radiation Trends in Climate Change: Dimming and Brightening

Shabtai Cohen

Department of Environmental Physics and Irrigation, Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, The Volcani Centre, P.O. Box 6,
Bet Dagan 50250, Israel

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Climate Change: Observed Impacts on Planet Earth

1. INTRODUCTION

The flux density and wavelength of electro-magnetic radiation emitted from a body depend on its temperature. On the earth's surface the wavebands that contain the most energy, and are therefore of prime interest in the context of climate influences, are those emitted by the sun and the earth. The calculation of spectral distributions from Planck's law using their approximate temperatures of 5800 and 300 K, for sun and earth, shows that 97% of the energy of solar and >99% of that of terrestrial radiation fall within the wavebands of 0.29–3 and 3–100 μm, respectively. Those wavebands are referred to as short wave (or solar) and long wave (or terrestrial) radiation [1]. The problem with the current ubiquitous, steady increase in atmospheric carbon dioxide concentration stems not from its direct influence on climate, but rather from its absorption of radiation in the long wave band, which decreases long wave radiative losses from the earth. Since its absorption in the solar spectrum is small, CO_2 has a negligible influence on the earth's solar radiation balance.

Global radiation ($E_g\downarrow$) is the total solar radiation falling on a horizontal surface at the earth's surface, that is, at the bottom of the atmosphere (BOA). Precise wide-spread measurements of $E_g\downarrow$ began in the early twentieth century and although it was first assumed that no multi-annual trends in this quantity occurred, by the 1970s there was evidence of significant decreases at some sites. As the evidence for large multi-decadal trends in $E_g\downarrow$ grew, the relationship between decreasing solar radiation (or global dimming) and wide spread decreasing pan evaporation was noticed. The energetic similarity of these changes led to scientific recognition that changes in $E_g\downarrow$ were playing a significant role in climate change. Previous assumptions that other parts of the earth's radiation balance were unchanging, have subsequently come under scrutiny.

This paper provides some background material on solar radiation and reviews some of the work done on the changing $E_g\downarrow$ and its influences on earth's climate.

2. SOLAR RADIATION AND ITS MEASUREMENT

2.1. Top (TOA) and Bottom (BOA) of the Atmosphere Solar Radiation and Atmospheric Transmission

Several of the quantities encountered when studying the earth's short wave radiation balance are easily computed. Understanding these relationships can give the quantitatively minded reader more confidence about solar radiation and its trends.

Black-body radiation is described by the Stefan–Boltzman equation, that is,

$$B = \sigma T^4$$

where B is radiant flux density emitted from a black body of temperature T, and σ is the Stefan–Bolzmann constant, 5.67×10^{-8} $W \cdot m^{-2} \cdot K^{-4}$. Taking the sun's average surface temperature to be 5800 K, calculating solar output for a sphere of solar radius, 6.96×10^8 m, and irradiating a large sphere whose radius is the earth–sun distance, or one astronomical unit (1.5×10^{11} m), the radiant flux density reaching a surface normal to the sun's rays on the earth before it is influenced by the atmosphere, that is, the extra-terrestrial 'solar constant', is 1380 $\mathrm{W{\cdot}m^{-2}}$, which is very close to the currently accepted value of 1366 $\mathrm{W{\cdot}m^{-2}}$ [2]. The latter varies during the year by about 3.3% due to eccentricity of the earth's orbit. As long as the solar surface temperature and composition doesn't change, the yearly average will be constant. In fact, the solar constant has varied by much less than 1% over the past few centuries [3,4]. The ratio of the area of a sphere to that of a circle of the same radius is 4, so the mean solar radiant energy reaching the TOA is 342 $\mathrm{W{\cdot}m^{-2}}$.

TOA (or extra-terrestrial) solar radiation on a plane parallel to the surface varies with the solar zenith angle, that is, the angle between the vertical and the solar vector. Calculation of solar angles and TOA solar radiation is straightforward and given elsewhere [1,5–7]. TOA values are used to compare with BOA measurements in order to determine atmospheric absorption of radiation, for example, atmospheric transmission and turbidity and aerosol optical depth.

2.2. Earth's Albedo and Net TOA Solar Radiation

The earth's planetary albedo depends mostly on cloudiness, but also on land use. There is no scientific theory to indicate that the planetary albedo has been and will remain constant, and a change of 1% in its value can have a large impact on the earth's climate system [8]. Accurate measurements of the albedo began in the 1980s. Satellite observations made continuously during the past twenty years indicate that it is relatively constant at 29 ± 2% [9,10]. These measurements are close to previous estimates of 30 [11] and 31% [12]. However, analyses of earthshine measurements suggest that it may have changed by as much as 5% during the past 15 a [13–15]. The earthshine measurements have met with some criticism [9], but they are based on sound theory. In the future, if additional sites are added to the earthshine observation network, these measurements may gain more acceptance and the differences between the earthshine and satellite measurements will have to be resolved. Taking the current earth albedo to be 29%, the net solar input into the planet is about 243 $\mathrm{W{\cdot}m^{-2}}$ [16].

2.3. BOA Radiation

From this brief discussion of TOA solar radiation balance we jump to the situation at the surface below the atmosphere where the solar radiation balance is confounded by atmospheric transmissivity and surface albedo. The former depends mostly on cloudiness and cloud properties, but also on dust and other aerosols. The latter, which has a small influence on downward radiation, depends on surface properties, which are influenced by land use and climate.

As solar radiation traverses the atmosphere it is absorbed and reflected by gases and non-gaseous particles [17]. Ozone is responsible for absorption of most of the UV radiation, that is, the solar radiation at wavelengths below 0.29 μm; at larger wavelengths oxygen and ozone absorption is negligible. Water vapour is a significant absorber in the infra-red portion of the solar spectrum above 0.7 μm. Carbon dioxide absorption of solar radiation is negligible. Aerosols can scatter and reflect some of the radiation back to space. Clouds can reflect most of the radiation back to space. Radiation reflected from the earth's surface can be re-reflected back, and so surface albedo can influence the downward flux. Thus, BOA solar radiation is much less than that at TOA, and is commonly divided into two fluxes: direct radiation coming from a 2.5–5° angle centred in the direction of the sun, and diffuse radiation arriving from the rest of the sky hemisphere above the observer. The total of these two, that is, global radiation ($E_g\downarrow$), is the total solar energy available at the surface.

2.4. Measurement of Surface Radiation

Total short wave 'solar' radiant flux density on a horizontal surface on the earth's surface (BOA), that is, global radiation, $E_g\downarrow$, is measured with a pyranometer. First class pyranometers measure the temperature difference between an exposed optically black surface and either a white surface (in the older instruments) or the lower non-exposed surface using a thermopile. In order to exclude thermal radiation and advection of heat from the surroundings the black surface is covered with two quartz glass domes which transmit radiation between 200 and 4500 nm wavelength, and a temperature correction circuit is incorporated into the instrument. Another type of 'pyranometer' in common use, due to its lower cost, is based on a selenium cell which upon illumination causes an electrical current to flow. The sensor is covered with appropriate filters to measure solar radiation, but the maximum wavelength measured is 1100 nm, so total solar radiation is determined indirectly by assuming that the ratio of the full spectrum to that below 1100 nm is constant. In most outdoor conditions the assumption is good enough for many applications, for example, calculation of crop water requirements, but the non-thermopile pyranometers are not acceptable for first class meteorological measurement.

Frequent cleaning of the dome and yearly calibration of sensors is necessary in order to ensure the reliability of measurements. These and other constraints have led to sparse measurement networks producing reliable data for solar radiation as compared to those measuring air temperature. Most of the networks began to operate during the International Geophysical Year, 1957–1958.

A second widely used surface measure which has been of interest is sunshine duration (SSD), or the amount of time that direct solar radiation exceeds a threshold of 120 $W{\cdot}m^{-2}$, corresponding approximately to direct irradiance at 3° solar elevation under clear sky conditions [1]. This measure has been shown to be highly correlated with global radiation, both on a single day basis as well as for yearly totals [18,19]. Instruments measuring SSD came into use in the nineteenth century, and some of their history has been recently reviewed [20]. Many measurement series dating back to the nineteenth century are available in various forms, and analysis of these has enabled a rough view of variations in solar radiation for more than a century (e.g. [21,22]).

In addition to surface measurements, satellite based sensors have been monitoring earth radiance in different wavebands for more than two decades. Algorithms have been developed to use these measurements to calculate solar radiation at the surface. These measurements have the advantage of spatial averaging over an area several orders of magnitude larger than the few square centimetres measured by the surface based sensors, and the ongoing efforts to improve the reliability and accuracy of the satellite measurements has led to their increased acceptance.

2.5. Comparing $E_g\downarrow$ from Different Sites

When comparing sites it is convenient to consider annual totals of $E_g\downarrow$, since seasonal variations can be large and vary greatly areally. However, $E_g\downarrow$ varies with altitude and latitude. One way to normalize data from different sites is to determine the transmission of a unit atmosphere, which is similar to turbidity [6,23]. Yearly means of $E_g\downarrow$ are converted to atmospheric transmittance, τ_m, by dividing by integrated yearly extraterrestrial solar irradiance on a horizontal surface (S_o) computed for the latitude of the measurements, that is,

$$\tau_m = \frac{\int E_g \downarrow \mathrm{dt}}{\int S_o \downarrow \mathrm{dt}} \tag{1}$$

Transmittance is also an exponential function of the optical thickness of the atmosphere k, and the vertical non-dimensional air mass, m, such that

$$\tau_m = \exp(-km)$$

or

$$k = -\ln(\tau_m)/m \tag{2}$$

For a unit air mass ($m = 1$) Eqn (2) yields

$$\tau_1 = \exp(-k) = \exp(\ln(\tau_m)/m) \tag{3}$$

Values of τ_1, which expresses the yearly average transmittance of a unit atmosphere at the site, are computed for each yearly mean of $E_g\downarrow$, where m is computed from site altitude using a simple altimetric relationship like:

$$m = \exp\frac{-A}{8200} \tag{4}$$

and A is site altitude (m) (after [6]). A second method to normalize data from different sites is multiple regression of $E_g\downarrow$ on time and site parameters, where the influence of altitude is taken as linear, but site latitude (Φ) is taken as $\cos^3(\Phi)$ [23].

2.6. Archives of Surface Solar Radiation Measurements

Solar radiation data measured by the different national weather services and conforming to WMO standards are collected in various national archives and are available from national weather services. Much of this data has also been collected in two archives – the Global Energy Balance Archive (GEBA) in Zurich, Switzerland [24], and the World Radiation Data Center (WRDC) archive in St. Petersberg, Russia, which was established by the WMO in 1964. GEBA has incorporated much of the data from the WRDC archive after strict quality control filtering, while the WRDC archive should be used with caution.

Data from the US is managed by the National Renewable Energy Laboratory's (NREL) Renewable Resource Data Center (RReDC, at website: www.nrel.gov/rredc). Although solar radiation has been measured in the US for about 75 a, first class long term data is available for only few of the stations in their network.

The World Radiation Monitoring Center (WRMC, http://www.bsrn.awi.de/) archives data from the Baseline Surface Radiation Network (BSRN, [25]), which is a small number of stations (currently about 40) in contrasting climatic zones, covering a latitude range from 80°N to 90°S, where solar and atmospheric radiation is measured with instruments of the highest available accuracy and with high time resolution (1–3 min). The BSRN program began in the late 1990s and is based on voluntary participation of organizations measuring radiation in different countries.

3. TRENDS IN SURFACE SOLAR RADIATION OR GLOBAL DIMMING AND BRIGHTENING

Significant multi-year trends in $E_g\downarrow$ during the first decades that measurements were made were reported by a few scientists during the twentieth century. Many of these decreasing trends, called 'global dimming' [23], were in excess of 1% per decade. They were viewed with considerable scepticism by the scientific community. The reasons for this scepticism are important because they reflect on the way current science is carried out. Here are some possibilities:

a. Previous texts, which were accepted as foundations of climate science, assumed that earth's solar radiation budget was constant on the short term time scale (i.e. hundreds of years [26]), although changes in solar activity and the solar constant were included as possible drivers for long term (i.e. 10^3–10^7 a) climate changes (see Ref. [27] for a review of climate change theories up to the mid 1960s).

b. Climate change science has been dominated by the influence of the ubiquitous and steadily increasing atmospheric greenhouse gases, and especially CO_2. A large effort has been made to establish that this change is large enough to warrant worldwide political action. The magnitude of 'global dimming' was clearly of the same order of magnitude as the greenhouse gas influence. If large changes were occurring un-noticed to the scientific community, how good was our understanding of climate and climate change? That question may have been viewed as a threat to the attempts to harness political action and the unprecedented funding that climate change science was receiving [28].

c. Climate change science has focused on TOA influences (e.g. TOA radiative forcing) and assumed that the distribution of energy within the system is less important.

d. Solar radiation is highly variable spatially and temporally and this high variability has hampered integration of worldwide trends. This is in sharp contrast with greenhouse gases which mix well in the atmosphere and whose rate of increase can be discerned within a few years.

3.1. Global Dimming Reports in the Twentieth Century

Suraqui et al. [29] reported 'severe changes over the years in solar radiation' and issued a call for 'a careful study of incoming radiation at different places throughout the world … to determine the exact kind, order of magnitude and their causes …'. The 'severe changes' referred to emerged from the measurements at the site of the Smithsonian Institution's former solar radiation monitoring station on Mt. St. Katherine in the southern Sinai peninsula (28°31′N, 33°56′E, 2643 m altitude). Measurements using modern radiometers as well as some of the original instruments employed between 1933 and 1937 showed a 12% loss in global radiation during the intervening four decade interval.

Atsumu Ohmura, whose background was in glaciology, and who headed the GEBA archive [24], reported at a conference that solar radiation was decreasing at many sites where it was being measured. His colleagues, who were highly sceptical of his findings, discouraged him from pursuing this, and the report was published (or temporarily buried) in a little known conference proceedings [30]. Russak [31] reported decreasing trends of 0.2–0.6 $W{\cdot}m^{-2}{\cdot}a^{-2}$ for a few stations in northern Europe. Gerald Stanhill, who used solar radiation measurements for determining evaporation and crop water use in arid environments, was intrigued by the decreasing trends in solar radiation that he found in radiation records. Stanhill and Moreshet [32] analyzed data from 45 stations for the years 1958, 1965, 1975 and 1985, and found a statistically significant average worldwide decrease of $E_g{\downarrow}$ totalling 5.3% (or 0.34 $W{\cdot}m^{-2}{\cdot}a^{-2}$) from 1958 to 1985. Decreasing trends of the same order of magnitude were found for sites in Australia [33], Japan [34], the arctic [35], Antarctica [36], Israel [37] and Ireland [38]. The largest decrease, found in Hong Kong, was 1.8 $W{\cdot}m^{-2}{\cdot}a^{-2}$, that is, a decrease in excess of 1% per year [39]. Other groups reported dimming for China [40], the former Soviet Union [41] and Germany [42,43]. Reductions in solar radiation were larger for urban industrial sites, but even at sites remote from pollution $E_g\downarrow$ was usually decreasing at a rapid rate.

Gilgen et al. [44] reviewed trends found in the GEBA archive. Their paper, entitled ‘Means and trends of short wave irradiance at the surface estimated from GEBA Data’, included analyses of accuracy and biases, and trends in $E_g\downarrow$ for different regions of the world. The final sentence of the abstract noted that ‘on most continents, shortwave irradiance decreases significantly in large regions, and significant positive trends are observed only in four small regions’.

Stanhill and Cohen [23] tabulated the negative trends for different sites around the world. Of the 30 stations where detailed analyses of trends had been published, at 28 $E_g\downarrow$ had decreased and only at two, Dublin, Ireland and Griffith, Australia, had $E_g\downarrow$ increased (by 0.56 and 0.76 $W{\cdot}m^{-2}{\cdot}a^{-2}$, respectively). They also analysed solar radiation records from the geophysical year, 1958, and the years 1965, 1975, 1985 and 1992. These records were from between 145 (1958) and 303 (1992) stations whose measurements conformed to WMO standards. Average transmittance of a unit atmosphere for the northern hemisphere was 0.52 in 1957 and declined steadily to 0.44 in 1992 while that for the southern hemisphere averaged 0.57 until 1985 and declined between 1985 and 1992 to 0.52. A spline fit to the latitudinal distribution of $E_g\downarrow$ showed that the decrease during the 34 a period had been especially large in the industrialized region of the northern hemisphere with a centre at ~35°N and a width of ~20°. This feature and an analysis of the various possible reasons for the dimming phenomenon, led to the conclusion that particulate aerosols, and especially those from anthropogenic sources, were the cause of the changes. Similar conclusions were drawn at about the same time by Liepert and Lohmann [45].

Many subsequent studies have highlighted similar trends based on data collected from the mid twentieth century and onwards. Trends for individual sites are highly variable, and for some places and some parts of the world no change or increases in solar radiation have been found.

3.2. From Dimming to Brightening

Recent studies [46,47] have found evidence for a reversal in the negative trends in solar radiation, which, for many sites changed to positive trends in the late 1980s and early 1990s. The data sets analysed were from the GEBA archive [46] and, for the first time, long term trends in satellite data from 1983 to 2001 [47]. However, there is an inconsistency between the two studies, since the satellite data show brightening over the oceans and no trend over the land surfaces while the surface GEBA and BSRN measurements are mostly land based and show clear brightening during this period. The reversal in the trend is thought to be related to the decreases in air pollution in Europe and other parts of the western world following legislation that limited air pollution. The positive trend has not led to a full recovery in $E_g\downarrow$ and current levels of solar radiation in most places where dimming took place are still below the values measured during the 1950s. A selection of widespread trends reported for $E_g\downarrow$ is given in Table 2.

A list of the publications on global dimming, brightening and related topics was compiled by M. Roderick at ANU and is kept more or less up to date. It can be found on the web at http://www.rsbs.anu.edu.au/ResearchGroups/EBG/index.php. Several international meetings have been held to discuss these topics (Table 1).

TABLE 1 International meetings held on changing surface solar radiation and related changes in evaporation

Organizing Organization and event	Date	Session title	Location	Reference
AGU/CGU joint assembly	17–18 May 2004	Magnitude and Causes of Decreasing Surface Solar Radiation	Montreal, Canada	[91]
Australian Academy of Science International workshop	22–23 November 2004	Pan evaporation: An example of the detection and attribution of trends in climate variables	Canberra, Australia	[92]
EGU general assembly	15–20 April 2007	Surface Radiation Budget, Radiative Forcings and Climate Change	Vienna, Austria	
AGU fall meeting	10–14 December 2007	Pan Evaporation Trends: Observations, Interpretations, and the Ecohydrological Implications	San Francisco, CA, USA	
Israel Science Foundation international workshop	10–14 February 2008	Global dimming and brightening	Ein Gedi, Israel	[93]
EGU general assembly	13–18 April 2008	Surface Radiation Budget, Radiative Forcings and Climate Change	Vienna, Austria	

TABLE 2 Selected estimates of widespread trends in surface solar radiation from surface measurements and satellite-based estimates. Based on Ref. [94]

Study	Time period	Energy trend per decade/ ($W\cdot m^{-2}$)	Comments
Surface			
[23]	From mid-1950s to 1992	−3	Trend analysis of about 30 sites of various lengths, and data from five years from 1957 to 1992 for >145 stations
[95]	1960–1990	−2	Trend analysis of GEBA and US NREL data sets from 1960 to 1990
[44]	From mid-1950s to 1990	−3	Statistics of the GEBA data set based on about 300 sites of various length
[51]	From mid-1950s to 1990	−1.6	Analysis of GEBA data to constrain the “urbanization” effect. Separation of sparsely populated sites (<0.1 million inhabitants) and
		−4.1	populated sites (>0.1 million inhabitants)
[96]	1977–1990	−2	Trend analysis of five records of the GMD data set from remote sites from South Pole to Barrow, Alaska
[46]	1993–2004	4.7	Trend analysis of 18 BSRN records
[46]	1985–2005	2.2	Decadal change between (1985–1995) and (1995–2005) based on 320 GEBA sites
Satellite			
[47]	1983–2001	1.6	Global. University of Maryland algorithm with ISCCP Clouds – Global average
		2.4	Ocean surfaces
		−0.5	Land surfaces
[97]	1984–2000	2.4	Global. ISCCP Clouds with own RT model
[58]	1984–2000	0.4	Global (ISCCP FD)
		1	Ocean (ISCCP FD)
		−1	Land (ISCCP FD)

Notes*: GMD – Global monitoring division of NOAA, ISCCP FD – International Satellite Cloud Climatology Project result data sets.*

3.3. $E_g\downarrow$ Prior to the 1950s

Little is known about $E_g\downarrow$ prior to the 1950s and since temperature changes then are well documented, such information could be valuable for understanding the influences of $E_g\downarrow$ on climate. Stanhill and Cohen [18,19] used SSD data as proxies for $E_g\downarrow$ based on recent simultaneous measurements of both measures, in order to deduce trends of $E_g\downarrow$ from 1891 to 1987 for the US and from 1890 to 2004 for Japan. SSD was found to be well correlated with $E_g\downarrow$ and therefore can serve as a proxy. The data from the US and Japan were from 106 and 65 stations with at least 70 and 35 a of data each, respectively. In the US mean SSD increased from 1891 to the 1930s and then decreased until the mid-1940s. In Japan a similar increase was observed from 1900 to the mid-1940s. This was followed by a decline until the late 1950s. Palle and Butler [22] found a decrease in SSD for four stations in Ireland for the period from 1890 to the 1940s. Sanchez-Lorenzo et al. [48] analysed SSD for the Iberian Peninsula for 1931–2004 and found a dimming trend from the 1950s to the early 1980s followed by brightening, but the early data (1931–1950) showed no clear trend. Thus, it is possible to obtain estimates of $E_g\downarrow$ for the first half of the twentieth century and many SSD data sets exist, but more work is needed to understand this period.

3.4. Regional Changes

The areal extent of the changes in global radiation and their global impact has been the subject of much debate and some investigation. Significant rates of dimming and brightening have been observed at many sites remote from major sources of air pollution, for example the polar regions [35,36], and the largest trends have been observed in heavily polluted regions (e.g. Hong Kong [39], India [49] and China [50]), suggesting a significant relationship between pollution rates and global radiation trends. Alpert et al. [51] found that dimming from the 1950s to the 1980s averaged 0.41 $W{\cdot}m^{-2}{\cdot}a^{-2}$ for highly populated sites while for sparsely populated sites, that is, populations $<0.1 \times 10^6$ dimming was only 0.16 $W{\cdot}m^{-2}{\cdot}a^{-2}$. In equatorial locations with low population density there were slightly increasing trends. Since most of the globe is sparsely populated this implies that the spatially averaged changes in $E_g\downarrow$ are significant, but smaller than those obtained by averaging the data, which may be biased toward population centres. However, to date no model has been developed to integrate population density and its influence on $E_g\downarrow$ with the worldwide grid of $E_g\downarrow$ in order to update the estimates of dimming and brightening, and current estimates revolve around those given in Table 2. Trends observed from satellites are for wide regions ([47]; Table 2) and it is encouraging that those trends are similar to those computed by averaging data from surface stations.

3.5. Cloud Trends and their Influence on $E_g\downarrow$

Changes in cloudiness during parts of the dimming and brightening periods were studied by Joel Norris [52]. The data was from both surface data sets and satellite observations. The surface set, which was divided into 10° × 10° cells, was from the Extended Edited Cloud Report Archive (EECRA), and included ground based cloud observations from land stations (1971–1996) and ship reports (1952–1997). These showed that zonal mean upper-level cloud cover at low and middle latitudes decreased by 1.5%-sky-cover between 1971 and 1996 over land and by about 1%-sky-cover between 1951 and 1997 over ocean. The upper level data were closely related to satellite (ISCCP) estimates for an overlapping period. Estimates of the cloud cover influence on solar radiation showed that between 1952 and 1997 over mid-latitude oceans cloud changes decreased $E_g\downarrow$ by about 1 $\mathrm{W{\cdot}m^2}$, and over northern mid-latitude land areas cloud changes increased $E_g\downarrow$ slightly. For low-latitude land and ocean regions cloud changes increased $E_g\downarrow$ from the 1980s to the mid-1990s. These changes in cloudiness are relatively small, and although they probably played a significant part in global dimming and brightening, they could not be considered to be major players. Similar conclusions, that is, that cloud trend influences on short wave radiative forcing could not account for most of the global dimming and brightening, were made by Norris and Wild [53], who subtracted the estimated cloud cover influence on solar radiation from surface $E_g\downarrow$ data in the GEBA archive and found that dimming and brightening trends in the residual $E_g\downarrow$ were unchanged.

4. THE CAUSES OF DIMMING AND BRIGHTENING

Dimming and brightening are related to aerosol loading of the atmosphere and the influences of aerosols on atmospheric transmittance. The influence of natural aerosols from volcanic eruptions can be seen in the sharp declines in $E_g\downarrow$ for the year or two following the eruptions of El Chichon in 1983 and Pinatubo in 1991 [54]. Stanhill and Cohen [23] reviewed the possible causes for dimming in the context of a simplified expression:

$$E_g\downarrow = E_o \exp\left[-\left(\tau_r + \tau_g + \tau_w + \tau_a + \tau_c\right)\right] \qquad (5)$$

where $E_g\downarrow$ is estimated from the extraterrestrial irradiance at the top of the atmosphere, E_o, modified by a chain of five transmissivities τ which quantify the solar scattering and absorbing properties of the different components of the atmosphere. These include τ_r, representing Rayleigh scattering; τ_g, permanent gas absorption; τ_w, absorption by water vapour; and τ_a and τ_c, the absorption and scattering by the aerosols and cloud components, respectively. The only factor whose known changes and influence on global radiation are large enough to cause changes of the magnitude observed is aerosol loading. Aerosol influences on radiation include direct effects, that is, absorption, reflection and scattering of radiation by aerosols, and indirect effects, referring to aerosol mediated changes in cloud albedo (the Twomey effect), rain suppression (the Albrecht effect), and cloud lifetime. The large changes in $E_g\downarrow$ can be pinned to some extent on anthropogenic pollution, as suggested by the large dimming in urban mega-cities and the industrialised zone of the Northern Hemisphere. The connection between dimming and aerosols has been clearly demonstrated (e.g. [55]), and known changes in aerosol loading of the atmosphere are well correlated with the transition from dimming to brightening in the 1980s [56].

Prior to the twenty-first century scientists studying aerosols had suspected that aerosol influences on climate were far larger than was being acknowledged and Satheesh and Ramanathan [57] demonstrated the large radiative forcing that can be caused by aerosols. As the evidence for worldwide dimming of a magnitude of several percent has mounted scientists who were studying aerosol influences have begun to implement the full extent of aerosol influences in models of earth's climate (e.g. [58,59]).

5. THE INFLUENCE OF SOLAR RADIATION CHANGES (DIMMING AND BRIGHTENING) ON CLIMATE

5.1. The Evaporation Conundrum

Potential evaporation rates in many places in the world decreased during the second half of the twentieth century. As with solar radiation measurements, a major client for these measurements is the agricultural community, where evaporation rates are used to determine irrigation scheduling and application rates. Measurement of evaporation is usually done with an evaporimeter of the evaporation pan type, for example, the US class-A pan and Russian GGI-3000 pan [60]. Specifications of pan size, deployment and exposure are given in the previous reference. Networks of pans have been established in many parts of the world.

Evaporation of water requires large quantities of energy. Therefore, one model of evaporation is the energy budget of the evaporating surface, that is,

$$R_n = \lambda E + C + G \quad \text{and} \quad \lambda E = R_n - C - G \tag{6}$$

where R_n is net radiation absorbed by the surface, λ is the latent heat of vaporisation, E is the evaporative flux, C is convective heat transfer with the environment and G is surface heat flux and/or energy storage. For annual totals, heat flux and energy storage can usually be ignored and evaporation depends only on net radiation and convection.

Evaporation from a wet surface (i.e. potential evaporation) can also be viewed as a diffusion process where water vapour is transported from the surface to the surrounding air, that is,

$$\lambda E = \rho c_{\mathrm{p}}[e_{\mathrm{s}}(T_{\mathrm{s}}) - e_{\mathrm{a}}]/(\gamma r) = \frac{\rho c_{\mathrm{p}}}{\gamma(r_{\mathrm{a}} + r_{\mathrm{s}})}[e_{\mathrm{s}}(T_{\mathrm{s}}) - e_{\mathrm{a}}] \tag{7}$$

where ρ and c_{p} are air density and heat capacity, respectively, $e_{\mathrm{s}}(T_{\mathrm{s}})$ and e_{a} are water vapour pressure in air for saturation at surface temperature (T_{s}) and ambient conditions, respectively, and γ is the psychrometric constant. r is the resistance to vapour transport from the wet surface to the point of interest in the air where humidity is measured, which in turn can be separated into a bulk surface resistance (r_{s}) and boundary-layer aerodynamic resistance (r_{a}). This second description of evaporation emphasises that it is influenced not only by radiation, but also by aerodynamic parameters like air temperature, humidity and wind speed, as well as surface parameters like roughness. Viewing both the energy budget and diffusion models of evaporation together, it is clear that climate factors determine the partitioning of radiative energy absorbed by a surface between the energy dissipation processes, that is, evaporation and convection.

The two approaches [Eqns (6) and (7)] can be used to solve for evaporation from a wet surface with few assumptions, giving the Penman equation [61], that is,

$$\lambda E = \frac{\Delta}{\gamma^* + \Delta}(R_{\mathrm{n}} - G) + \frac{\rho c_{\mathrm{p}}}{r_{\mathrm{a}}(\gamma^* + \Delta)}[e_{\mathrm{s}}(T_{\mathrm{a}}) - e_{\mathrm{a}}] \tag{8}$$

where T_{a} is air temperature, Δ is the slope of the relationship between saturation vapour pressure and temperature, and γ^* is a bulk psychrometric constant which depends on surface properties. The expression ($e_{\mathrm{s}}(T_{\mathrm{a}}) - e_{\mathrm{a}}$) is the air vapour pressure deficit (VPD), which is a function of temperature and humidity. Thus, evaporation from a wet surface can be partitioned between radiative and aerodynamic influences on evaporation, where the radiative term (the left hand part of the Penman equation) is dominated by solar radiation and the aerodynamic term (the right hand part) depends on air temperature, humidity and wind speed. When analysing changes in potential (pan) evaporation Eqn (8) can help to determine which climatic factor has caused the change.

Widespread reductions in pan evaporation during the second half of the twentieth century were first reported for the former Soviet Union and much of the northern hemisphere [62,63]. These reports were considered evidence of global warming, which was thought to be increasing regional evaporation but decreasing pan evaporation due to a feedback influence of increasing regional humidity on local (or pan) potential evaporation [64] (see below). However, Stanhill and Cohen [23] considered decreasing evaporation to be evidence for decreasing solar radiation and Cohen et al. [65] showed that in Israel's arid conditions the overwhelming influence on evaporation is solar radiation. A full analysis of environmental factors showed that decreasing solar radiation was decreasing potential evaporation rates. Qian et al. [50] found a striking correspondence between decreasing $E_{\mathrm{g}}\downarrow$ and pan evaporation in China.

Two Australian biologists, Roderick and Farquhar [66], analysed worldwide changes in temperature and humidity and their relationship to evaporation rates. If regional evaporation were increasing and causing local pan evaporation to decrease then VPD should be decreasing [see Eqn (8)]. However, there was no evidence that this was occurring worldwide. Daily minimum temperatures are closely related to the daily dew point temperature and air vapour pressure (e_a), since excess humidity precipitates as dew when the air is coolest in the early morning. Saturation vapour pressure (e_s) increases exponentially with increasing temperature, so if average and minimum temperatures increase at the same rates, VPD will increase and this should increase evaporation rates. However, worldwide minimum temperatures are increasing much faster than average temperatures and Roderick and Farquhar reasoned that this might be stabilizing VPD, as observed in climate data from the US. This implied that the aerodynamic term in the Penman equation [Eqn (8)] was stable; and if evaporation was decreasing it would have to be caused by decreasing net radiation, which is dominated by solar radiation. Roderick and Farquhar continued to develop a rigorous estimate of the evaporative equivalent to solar radiation. For a first order analysis the evaporative equivalent of radiative energy is expressed by λ, whose value is $\sim$2.4 $\text{MJ}\cdot\text{kg}^{-1}$ and 1 kg of water will cover a surface area of 1 m^2 to a depth of 1 mm. For the region of the FSU where both radiation and evaporation trends were available, solar radiation, which was in the range of 3000–4000 $\text{MJ}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$, had declined by $\sim$9% or 315 $\text{MJ}\cdot\text{m}^{-2}$ in three decades, which is equivalent to 131 mm of water. This is similar to the average reported evaporation reduction during that period, $\sim$111 mm of water. Thus, the reported reductions in evaporation rates matched those for solar radiation, and the pan evaporation data set corroborated the reported dimming trends in $E_g\downarrow$. Roderick and Farquhar's analysis [66] convinced many scientists that dimming was real and was having a significant impact on earth's climate.

Evaporation at most sites in Australia has decreased significantly during the period on record, with no signs of recovery during the 'brightening' era [67]. The climate parameters that could be causing this were investigated by Roderick et al. [68] using a physical model similar to Eqn (8). They found that the primary cause for the reduction in evaporation in Australia was decreasing wind speed with some regional contributions from decreasing solar radiation.

The question as to whether changes in pan evaporation are similar or opposite to changes in regional evaporation involves the 'complementary' hypothesis [69], which hypothesises that when regional evaporation changes, air humidity changes in the same direction, and a feedback occurs which has an opposite effect on local evaporation. The hypothesis [70] considers the sum of regional and local (e.g. pan) evaporation to be equal to a constant value, making them 'complementary'. For example, in the Tibetian plateau, $E_g\downarrow$ and pan evaporation decreased from 1966 to 2003 [71], yet regional evaporation increased [72].

Since global radiation influences both local and regional evaporation similarly, when global radiation changes the constant of the complementary equation may also change. Nevertheless, when significant changes in air temperature occur, especially if accompanied by changes in wind speed, which have also been noted for many sites, changes in pan evaporation cannot be taken as unambiguous evidence for dimming, brightening or warming [73].

5.2. Soil Moisture Trends

Another line of evidence for changes in regional evaporation rates has come from the study of soil moisture data from an extensive network of stations in the Ukraine where plant available soil moisture for the top 1 m of soil is determined gravimetrically every 10 days from April to October at 141 stations from fields with either winter or spring cereals. The data, from 1958 to 2002 [74], shows that soil moisture increased until approximately 1980 and then levelled off. No trends in rainfall were observed for this region while air temperature increased slightly. As noted above, one of the first reports of dimming was from this region during the period in question [41]. The observed changes in soil moisture were opposite to the predictions that global warming would lead to soil desiccation [75,76]. Thus, Robock and Li [74] concluded that the changes in soil moisture were evidence of dimming and its reduction of regional evaporation rates. Subsequent modelling with a sophisticated land surface model, which included a decreasing trend of solar radiation along with increasing CO_2 and global warming, demonstrated similar increases in soil moisture [77].

5.3. The Hydrological Cycle

Regional evaporation rates are a central part of the hydrological cycle, and so the question as to whether decreases in pan evaporation indicate decreasing or increasing regional evaporation is of great importance. An increasing hydrological cycle with increased regional evaporation would lead to increased rainfall rates. However, it would also increase cloudiness whose feedback influence would cause a decrease in $E_g\downarrow$. As noted above, cloud changes have been relatively small.

Prior to the twenty-first century, it was assumed that global warming would enhance evaporation and lead to an enhancement (or spinning up) of the hydrological cycle. Ramanathan et al. [49] evaluated the influences of anthropogenic aerosols on solar and thermal radiation balances, atmospheric temperature profiles and climate. They found that ‘aerosols enhance scattering and absorption of solar radiation and produce brighter clouds that are less efficient at releasing precipitation. These in turn lead to large reductions in the amount of solar irradiance reaching Earth’s surface, a corresponding increase in solar heating of the atmosphere, changes in the atmospheric temperature structure, suppression of rainfall, and less efficient removal of pollutants. Thus, these aerosol effects can lead to a weaker hydrological cycle'. A case in point is the Indian sub-continent where anthropogenic aerosol 'brown clouds' can reduce $E_g\downarrow$ by more than 10% and change the regional hydrological cycle. In particular, dark aerosols absorb solar radiation and cause enhanced atmospheric warming and decreased $E_g\downarrow$, which decreases surface temperatures and evaporation rates. Together, these enhance atmospheric stability and spin down the hydrological cycle [78].

Liepert et al. [79] and Wild et al. [80] also considered that a reduction of $E_g\downarrow$ and related reductions in evaporation rates could be 'spinning down' the hydrological cycle. They argued that reductions in surface solar radiation were only partly offset by enhanced down-welling longwave radiation from the warmer and moister atmosphere and that the radiative imbalance at the surface leads to weaker latent and sensible heat fluxes and hence to reductions in evaporation and precipitation despite global warming. This is in line with experimental evidence of the influence of aerosols on climate [81].

5.4. Daily Temperature Range (DTR)

$E_g\downarrow$ is directly related to maximum mid-day temperatures since it heats the surface. The same factors that reduce $E_g\downarrow$, that is, clouds, haze and aerosols, increase downwelling long-wave radiation at night leading to higher night-time, or minimum daily temperatures. Therefore, it is no surprise that $E_g\downarrow$ is significantly correlated with daily temperature range (DTR, [82]). Various episodes of temperature changes that correspond to sudden changes in atmospheric aerosol loading have been reported. One dramatic demonstration of the influence of aerosol on DTR was shown by Travis et al. [83], who studied climate data for the period of the World Trade Centre tragedy in September 2001. During the three days that air traffic in the US was grounded there were no atmospheric contrails, leading to increased $E_g\downarrow$ and an increase of ~1 °C in DTR. Stanhill and Moreshet [34] found an average 18% increase in $E_g\downarrow$ during Yom Kippur (the Day of Atonement) in Israel, which is a one day Jewish holiday in the fall when industries close and car use is minimal. Analysis of data from 1963–2003 shows that average daily total DTR increased on Yom Kippur by 0.31 °C (Stanhill and Cohen, unpublished data). Robock and Mass [84] and Mass and Robock [85] showed that tropospheric aerosol loading from the 1980 Mt. St. Helens volcanic eruption strongly reduced the diurnal temperature range for several days in the region with the volcanic dust, and surface temperature effects under smoke from forest fires was correlated with a reduction in daytime temperatures [86,87].

Global surface temperatures have been increasing since the beginning of the industrial era. As noted by Roderick and Farquhar [66] minimum temperatures have been increasing faster than maximum temperatures and thus DTR has been decreasing. This may also be related to decreasing surface radiation.

Wild et al. [88] used DTR to analyse the influence of changes in $E_g\downarrow$ on global temperatures. They contend that global dimming masked global warming until the 1980s and that during the global brightening era the accelerating temperature increases demonstrate the full (unmasked) global warming that is caused by greenhouse gases.

5.5. Wind Speed and the Monsoon System

Another mechanism for the influence of changes in $E_g\downarrow$ on climate is sea warming and its influence on wind speed and the monsoon rain system [89]. Xu et al. [90] showed that wind speeds over China have decreased because of dimming. This is related to the increased atmospheric stability caused by aerosol mediated warming of the atmosphere as surface radiation decreases. Thus, aerosols over China changed the land-ocean temperature contrast, affecting monsoon winds.

6. CONCLUSIONS

Global radiation $E_g\downarrow$ decreased significantly (i.e. dimming) from the beginning of widespread measurements in the 1950s to the late 1980s over large parts of the globe and then partly recovered (i.e. brightening) in many places. The areal extent of these changes is not certain because of the large spatial variability, but the mean trends are evident in satellite estimates of global radiation. The trends are apparently caused by anthropogenic aerosols which reduce surface short wave radiation directly and indirectly through their influence on cloud properties. Changes in $E_g\downarrow$ have played a part in regional and global changes in DTR (positively correlated) as well as soil moisture (negatively correlated) and potential evaporation rates (positively correlated), but in some cases potential evaporation has changed due to other factors. Dimming may have offset global warming between the 1950s and 1980s while the more recent brightening may have unmasked the full extent of global warming, as seen in the accelerated temperature increase since the early 1990s.

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