Long-term changes in insolation and temperatures at different altitudes

2010 Environ. Res. Lett. 5 024006

(http://iopscience.iop.org/1748-9326/5/2/024006)

IOP Publishing Environmental Research Letters
Environ. Res. Lett. **5** (2010) 024006 (6pp) doi:10.1088/1748-9326/5/2/024006

Long-term changes in insolation and temperatures at different altitudes

E Sanroma[1], **E Palle**[1,2] **and A Sanchez-Lorenzo**[3]

[1] Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain
[2] Instituto de Astrofisica de Canarias, Via Lactea s/n, E38200, La Laguna, Spain
[3] Climate Research Laboratory, Barcelona Science Park, Barcelona, Spain

E-mail: epalle@iac.es

Received 24 February 2010
Accepted for publication 5 May 2010
Published 1 June 2010
Online at stacks.iop.org/ERL/5/024006

Abstract
Over the past few years, ground- and space-based atmospheric measurements have revealed a large inter-decadal variability in the amount of radiation reaching the Earth's surface, also known as global dimming and brightening. However, the underlying physical causes of these changes remain unexplained. Clouds and aerosols, or their interactions, could both be responsible for the insolation changes, which in turn may impact the radiative balance of the planet. Here, making use of the special topology and clean environment of the Canary Islands, we compare trends in sunshine duration and temperature series, as a function of altitude. The temperature dataset is constituted by a series of mean, minimum and maximum temperatures, and daily temperature ranges. We find that the insolation and temperature trends are identical at sea level and at more than 2 km height, but the changes in diurnal temperature range are not, suggesting a possible urban heat effect at the sea level location, as well as a possible different influence of clouds and/or aerosols at different altitudes. We also find that during the summer, especially at the high altitude site, there is a clear correspondence between daytime insolation and nighttime cloud-free atmospheric extinction measurements. This suggests that atmospheric aerosol concentrations are the major contributor to the variations in the flux of solar radiation reaching the ground at high altitude sites over the Canary Islands.

Keywords: sunshine, dimming, brightening, temperature, climate, clouds, aerosols

1. Introduction

The subjects of global dimming and brightening have been analyzed regionally and globally in a large number of publications (e.g. Stanhill and Cohen 2001, Wild *et al* 2005, Wild 2009). Presently, there is wide-spread evidence that large changes in the level of radiation reaching the ground have (and are) occurring over large regions of the globe. It is, however, very difficult to disentangle whether the insolation changes have taken place due to atmospheric aerosol content changes (natural or anthropogenic), cloud changes, or a combination of both (e.g. Khain 2009).

For the study of insolation trends previous to the 1960s, there are very few radiation time series published in the literature (Wild 2009), most especially for Spain where no long-term solar radiation records are available (Sanchez-Lorenzo *et al* 2007, Norris and Wild 2007). Equally, there are few studies of solar radiation tendencies at surface level in tropical areas since most of the series are concentrated at mid-latitude in the Northern Hemisphere, the region where most of the anthropogenic aerosol emissions are concentrated. Some authors have pointed out that the dimming could be a localized (urban) phenomena (e.g. Alpert and Kishcha 2008). Thus, the analysis of insolation time series in a subtropical, 'clean' high altitude site, avoiding urban influences from nearby cities, is important to the global dimming/brightening discussion.

The relative importance of aerosol and/or cloud effects on the dimming/brightening is probably different across the globe, but it could also be different depending on the altitude. In this context, the island of Tenerife offers a good testing site, as we have sunshine duration data for two stations separated by 2300 m height, but only 35 km apart in horizontal distance, and surrounded by the clean environment of the Atlantic ocean. Together with insolation, co-located temperature and atmospheric extinction data are also available. With this idea in mind we have looked for differential changes at these two stations.

2. Data analysis

In this study, data from two meteorological stations Izaña (hereafter IZ; 16°30′W; 28°18′N) and Santa Cruz de Tenerife (hereafter SC; 16°15′W; 28°27′N) stations have been used. Both stations are located on the island of Tenerife, in the Canaries archipelago (Spain) and belong to the subtropical regime. IZ is a meteorological and astronomical site located 2371 m above sea level, while SC is located in the major metropolitan area of Tenerife, at sea level in the northern part of the island. The meteorological records used in this paper have been compared to data from several additional stations spread over the island of Tenerife and the neighboring islands, and both are consistent with the averaged climate trends over this region (not shown). The data were collected by the Spanish Agencia Estatal de Meteorologia.

Sunshine duration (or insolation) is defined as the amount of time that direct radiation exceeds a certain threshold, usually taken at 120 $\mathrm{W\,m^{-2}}$, and can be considered as a proxy measure of global radiation (e.g. Stanhill and Cohen 2001, Wild 2009). The records cover the entire 1948–2006 and 1943–2006 periods, for IZ and SC respectively. Here we used relative sunshine duration or sunshine factor, defined as the total measured hours of bright sunshine divided by the length of the period for which the sun lies more than 3° above the horizon (Pallé and Butler 2001), in order to avoid the strong season variation in the length of daylight. Maximum ($T_{\max}$), minimum ($T_{\min}$), and mean (T_{mean}) temperature data are also available over the period 1916–2006 for IZ and 1925–2006 for SC. The daily temperature range (DTR) is derived by subtracting $T_{\min}$ from $T_{\max}$. This temperature dataset extends and updates a previous work that analyzed the Izaña series over the period 1919–1989 (Oñate and Pou 1996).

Some missing monthly mean data have been filled by averaging the monthly value of the two preceding and following years. For a few years, several monthly means were missing, and these years have not been considered in this analysis. Throughout this work, linear trends in the climate time series were calculated, over the whole period for which data are available, and over the common period 1948–2006, by means of least-square linear fitting. Their statistical significance was estimated with the t-student test. Time series anomalies were obtained as deviations to the corresponding annual mean over the full available period. Finally, the relationships between time series were analyzed by means of parametric correlations. Statistical significance in the linear trends and correlation coefficients are considered significant only when at least at the 95% level.

Varela *et al* (2008) demonstrated that remote sensing aerosol measurements provided by TOMS (total ozone mapping spectrograph) are not valid to characterize dust concentrations at high mountain sites, or at least in the Canary Islands, and consequently other more localized parameters, such as the *in situ* atmospheric extinction coefficient, are required. Measurements of atmospheric extinction can be obtained from astronomical observations, and the Canaries observatories are an ideal location, due to the atmospheric stability that places them most of the time above the inversion layer, usually located between 700 and 1500 m height. Thus, as the atmospheric extinction data variability is mainly related to aerosol content, the trends in these observations should be considered as a good proxy of changes in natural and/or anthropogenic aerosol optical depth in the atmosphere.

Table 1. Linear trends for the time series at IZ and SC (na: not available; ns: not significant).

	1916/25–2006		1948–2006		
Variable	SC	IZ	SC	IZ	Units
T_{mean}	0.10	0.13	0.17	0.19	°C/decade
$T_{\max}$	ns	0.14	ns	0.15	°C/decade
$T_{\min}$	0.15	0.13	0.29	0.23	°C/decade
DTR	−0.09	ns	−0.25	ns	°C/decade
Sunshine	na	na	ns	ns	h/decade

Unfortunately, long-term atmospheric extinction records are not available at either of the two stations (IZ and SC). However, regular observations of nighttime atmospheric extinction are kept at the astronomical observatory of El Roque de Los Muchachos (ORM) in the island of La Palma (Guerrero *et al* 1998). Since 1984, the Carlsberg Meridian Telescope (CMT) in La Palma provides nightly values of atmospheric extinction in the V band (visible light, centered at 551 nm) from its observations of about 50 photometric standards per night (King 1985). This observatory is located at exactly the same altitude (2300 m) as IZ, and they are separated by a horizontal distance of 144 km. As the two sites are only separated by ocean, and are located in the island tops, it is reasonable to assume that the long-term atmospheric extinction at both sites will be correlated. Extinction data at ORM are available over the period 1985–2006.

3. Long-term trends and correlations

The annual mean time series anomalies of T_{mean}, $T_{\max}$, $T_{\min}$, DTR, and sunshine duration, for both SC and IZ, are shown in figure 1. The T_{mean} series of both stations are very similar, and indicate a warming of about 1 °C over the full available period. The trends are statistically significant at the 99% significance level (see table 1). The long-term behavior of the temperature time series are well in line with the worldwide increase in mean air temperature, although the rate of warming over the Canary Islands is nearly twice that of the global mean surface temperatures which have risen by 0.074°/decade over the last century (Trenberth *et al* 2007). A similar warming rate has been observed over inland Spain over the 1901–2005 period (Brunet *et al* 2007). As in global surface temperature, the trends show a non-monotonic increase during the analyzed period, with a slight decrease recorded from the 1960s to the early 1970s. Almost all the warming, however, occurred from the mid-1990s to the present after the pronounced drop in the

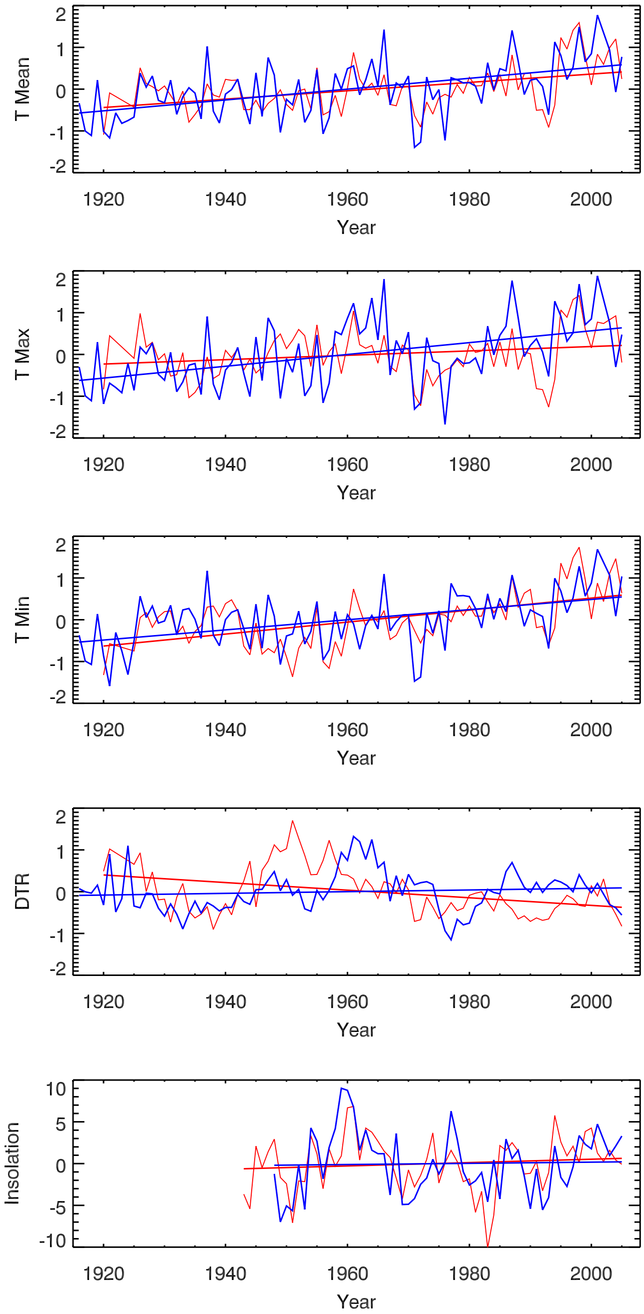

Figure 1. Annual mean time series anomalies of T_{mean}, T_{max}, T_{min}, DTR, and insolation at SC (red) and IZ (blue). The straight lines represent the respective least-squares linear fits to the data. The series are expressed as deviations from the corresponding annual mean over the full available period. The temperatures and insolation anomalies series are expressed as °C and %, respectively.

series in 1992–1994, just after the Pinatubo eruption. The agreement of such local temperature measurements with the world's global mean is perhaps due to the relatively clean environment of the Canaries archipelago, free from strong urban/local or continental anthropogenic aerosol emissions compared to other European sites (Querol *et al* 2004).

The increase in T_{max} and T_{min} at IZ has been practically of the same order, but in SC, while the increase in T_{min} is similar to that of IZ, T_{max} shows a non-significant trend three times smaller. The T_{max} time series has a clearer decrease than the T_{min} from the 1960s to the early 1970s, also showing a more pronounced drop in the series during 1992–1994, especially in SC.

The DTR data differ strongly for both stations because of their different variation in T_{max} (table 1). For the high mountain station, IZ, the DTR has no statistically significant trend over the full period 1916–2006 nor over the 1948–2006 subperiod. Still, the record also shows a broad anomaly in DTR which had its maximum during 1961, and a shallower minimum during the late 1970s. At the urban station, SC, there is a significant diurnal temperature range decrease over the whole period 1924–2006 and 1948–2006 subperiod although the decrease is more notable over the period 1950s–1990s. The SC record also shows a maximum in DTR in 1951, due to a strong decrease in the minimum temperature. In any case, the decrease in DTR between the 1950s and the 1980s seems to be present at both stations, as is the case for the mean DTR over the globe (Vose *et al* 2005, Wild *et al* 2007).

Over the reduced period in which data are available (mid-1940s to 2006), sunshine duration has increased at both stations, but the overall trends are not statistically significant. However, both time series show a general decrease in sunlight reaching the ground from 1960 to about mid-1980s, which is in accordance with the wide-spread period of reduced insolation know as the *global dimming* (Stanhill and Cohen 2001). In fact, linear trends for the subperiod 1960–1985 show statistically significant decrease of $-2.5\%/\mathrm{decade}$ and $-3.9\%/\mathrm{decade}$ at IZ and SC series, respectively. Following again the global patterns (Pallé *et al* 2004, Wild *et al* 2005), insolation trends in SC and IZ show a recovery of the dimming (or brightening) from the 1990s until 2000. Then, in the final years of the series a stabilization or slight decrease can be detected, in agreement with recent evidence that suggest less pronounced brightening beyond the year 2000 at numerous locations around the world (Pallé *et al* 2009, Wild *et al* 2009). However, in IZ the insolation increase (of $-2.8\%/\mathrm{decade}$) is only statistically significant during the subperiod 1985–2006. Prior to 1960 the data indicate a period of brightening, which has also been hinted at by several authors before over different European sites (Ohmura 2006, Sanchez-Lorenzo *et al* 2007, 2008). However, it should be noted that there is a large decadal variability comparable in amplitude to the dimming and brightening, and an insufficient number of years to be able to establish more statistically robust conclusions on the early trends.

Despite being located at different altitudes, both stations show a similar inter-annual variability with significant correlations at the 99% confidence level regarding the insolation and temperature series (table 2), especially in T_{mean} and T_{min}, which is also consistent with the averaged insolation and temperature patterns for the Canaries archipelago as a whole (not shown). The correlation between sunshine data at the two stations, although highly statistically significant, is only 0.6, indicating that there must be some real differences in the optical properties of the atmosphere at the two sites, presumably associated with different elevations or urbanization degree.

Table 2. Correlation coefficients and statistical significance between the different variables studied in this paper. Correlations are calculated using the de-seasonalized monthly mean time series during the maximum available period in which data are available for each pair. If the significance does not reach the 95% significance level, it is considered non-significant. In the top sub-panel the same variables for the two stations are correlated. In the lower panel several pairs of variables measured at the same station (IZ or SC) are correlated.

Correlations	r	P (%)
Sunshine SC–IZ	0.60	99.9
T_{mean} SC–IZ	0.60	99.9
T_{max} SC–IZ	0.47	99.5
T_{min} SC–IZ	0.62	99.5
DTR SC–IZ	0.20	—
Sunshine T_{mean} IZ	0.40	99.5
Sunshine T_{max} IZ	0.43	99.5
Sunshine T_{min} IZ	0.34	99.5
Sunshine DTR IZ	0.26	—
Sunshine T_{mean} SC	0.23	—
Sunshine T_{max} SC	0.18	—
Sunshine T_{min} SC	0.19	—
Sunshine DTR SC	−0.08	—

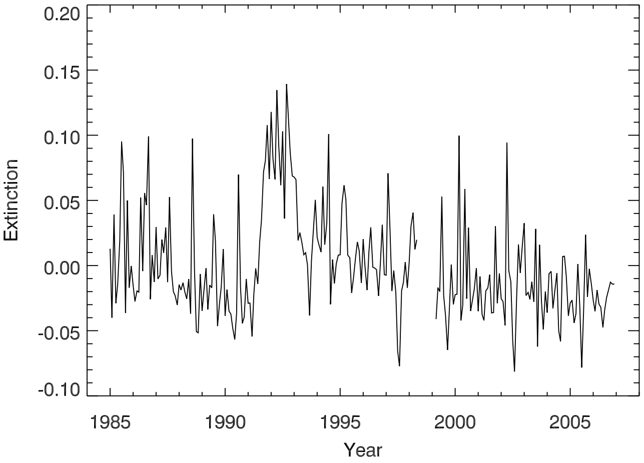

Figure 2. Monthly mean extinction anomalies at ORM, in the island of La Palma. The spike in the record, in 1992, is due to the atmospheric aerosol loading from the Pinatubo eruption. The volcanic eruption of El Chichon in Mexico in 1982 is probably the cause of the decrease in insolation at the beginning of the record. Because El Chichon is at a similar latitude to the Canary Islands, it is likely to have had a large impact on the surface irradiance at these sites. It is unfortunate that the extinction records begin in 1985 so the relative impacts of El Chichon and Mount Pinatubo cannot be determined.

4. Extinction measurements and the possible role of aerosols

The atmospheric extinction at the ORM has significantly decreased throughout the studied period, as can be inferred from figure 2. The decreasing rate is of −9.03%/decade, significant at the 99% level. This trend agrees with the reported significant decreases in global and regional optical thickness of tropospheric aerosols from 1990 to the present (Mishchenko *et al* 2007). The increase in atmospheric transparency during the last two decades is also consistent with the detected increase in insolation and temperatures over the Canary Islands since the mid-1980s. In fact, global and regional reductions in anthropogenic aerosols have been suggested as one of the contributing factors to the recent brightening and the strong warming recorded since the 1980s (e.g. Wild *et al* 2007, Ruckstuhl *et al* 2008).

In figure 2, a strong peak in atmospheric extinction in the early 1990s is readily observable, due to the large amounts of aerosols injected into the atmosphere by the Mount Pinatubo eruption (June 1991). The clear drop in the temperature series over the Canary Islands in 1992 and 1993 is probably related to this volcanic eruption, via a reduction in the incoming solar radiation and the consequent surface cooling. If the years 1992 and 1993 (the most affected by the eruption) are removed, the trend in the mean atmospheric extinction is equally significant.

The inter-annual variability in sunshine duration is mainly determined by changes in clouds; however, its significant correlation with the extinction measurements in IZ ($r = -0.48$; $P > 95\%$) point toward a possible dominating role for aerosol in the detected dimming and brightening. This possible influence should be more evident during the dry and cloudless summer season (defined as June, July, and August in this paper) in IZ (García-Herrera *et al* 2001), when more than 82% of the days are considered as cloud-free conditions over the 1971–2000 period (MMA 2002). In order to check this possibility, figure 3(a) shows the summer sunshine duration series in IZ, together with a low pass filter for a better visualization of decadal variability. The evolution is very similar to the annual one (figure 1), but the dimming (1960–1980s) and brightening (1980s–2006) periods are more clearly observed during the summer season. Equally, in agreement with all monthly anomaly series, the mean summer extinction series show a strong significant decrease during the 1985–2006 period (not shown) of −20.4%/decade. Finally, the correlation coefficient between the insolation and extinction at IZ using the summer mean values (figure 3(b)) shows a highly significant correlation ($r = -0.84$; $P > 99\%$), increasing the strength of the relationship in comparison to when all months are considered.

Thus, it seems very plausible that an increase in the summer atmospheric transparency over the Canaries, or aerosol loading decrease, is related to the recent brightening period since 1985 up to the present. Note that aerosol particle size can greatly influence the scattering of light in the atmosphere, thus a change in observed extinction may be due to either a change in the total concentration of aerosols, a change in the size distribution, or both. Unfortunately, no aerosol loading estimations are available for the period previous to 1985, and consequently we cannot confirm the cause of the dimming period. On the other hand, due to the cloudless summer conditions over IZ, it is clear that the strong decrease in sunshine duration should not be due to trends in cloud cover. Thus, changes in natural and/or anthropogenic aerosols concentrations are the most plausible cause.

Moreover, according to our results, the temperature and insolation series in IZ are significantly correlated (table 2). While the overall increase in temperature, affecting by equal amounts the maximum and minimum temperatures, is probably due to the greenhouse gas forcing, the decadal

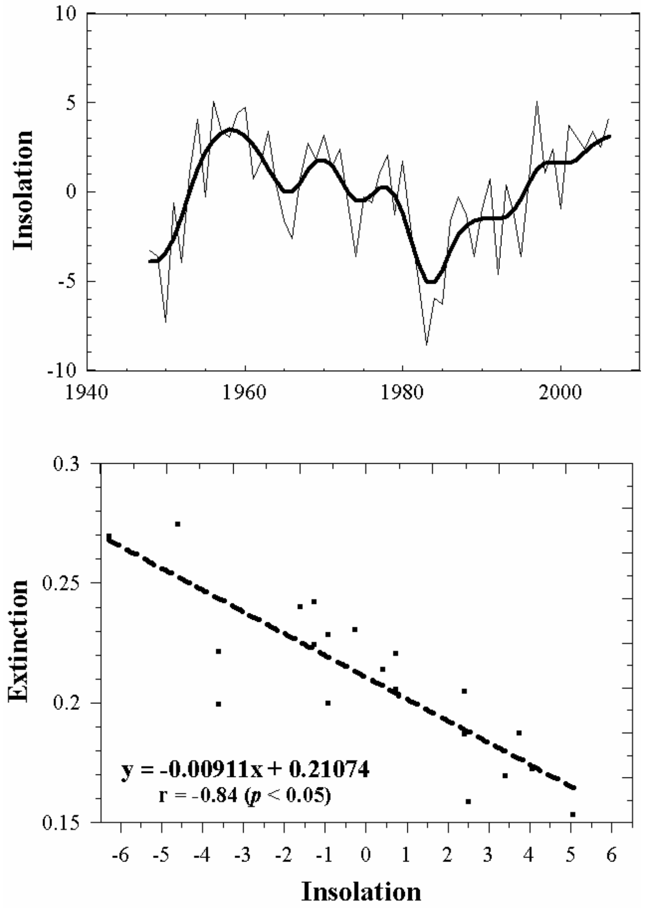

Figure 3. Top: summer insolation series at IZ (thin line), plotted together with a low pass filter (thick line). The series are expressed as deviations from to the corresponding annual mean over the full available period. Bottom: relationship between extinction measurements and insolation anomalies where each point is the summer mean during the 1985–2006 period. The linear regression model fit is indicated in the plot (dashed line), together with the linear regression equation and the coefficient of correlation.

variability suggests that changes in temperature series, especially maximum temperatures, may be partially affected by changes in insolation, especially in IZ. In this greenhouse gas dominated scenario, no significant century-scale trends in DTR have occurred, but a large decadal variability is present due to the changes in anthropogenic aerosol concentrations during the second half of the 20th century (Wild 2009).

In SC, the change in minimum temperature is consistent with the slow build up of the greenhouse effect; however, the behavior of the maximum temperature is not so easily explained. The continuous decrease of DTR in the 1980s and 1990s could be explained by either local atmospheric phenomena (such as an increase in low clouds) or by an increase in aerosol concentrations at low altitudes. The aerosols could be either produced locally or transported from the Sahara region, and could be dampening the increase in maximum temperatures in SC (Makowski *et al* 2008). Unfortunately we do not have low altitude aerosol content or atmospheric extinction data, as is the case for the IZ station.

On the other hand, Sperling *et al* (2004) observed a significant upward trend in the summer relative humidity over SC, below the trade wind inversion, whereas no significant changes are detected above the trade wind inversion at the IZ station. Thus, an increase in low level cloud cover and moisture (with more latent cooling at the surface) is expected at the SC station. In fact, there is recent evidence of poleward expansion of the Hadley circulation since the late 1970s (e.g. Hu and Fu 2007), and consequently northern windward slopes of the Canary Islands should register an intensification in trade wind circulation.

Thus, an increase in the advection of wet and humid fresh air is expected, which condenses at low levels, under the inversion layer, developing a layer of low thin clouds (cloud sea). Over the inversion layer the intensification of the Hadley cell has an opposite effect, and the air is dry and clear. This scenario is consistent with the non-significant increase in $T_{\max}$ and decrease in DTR during the second half of the 20th century detected in SC.

5. Discussion and conclusions

According to our results, the role of aerosol and/or cloud changes seems to dominate the decadal variability in insolation and DTR over the Canary Islands. The two insolation series, located at different altitudes, show a similar inter-annual and decadal variability of sunshine duration. This similarity suggests that the trends in global aerosol content/properties during recent decades may play an important role in modulating the insolation. This fact is more evident at the IZ station, which shows a good agreement between insolation and aerosol optical depth estimations from atmospheric extinction measurements, especially during the summer season when cloud-free conditions are dominant. On the other hand, the two temperature series show clear disagreements in $T_{\max}$ and DTR variables, which are probably related to differences in the aerosol/cloud interactions with altitude and/or as a result of changes in atmospheric circulation (e.g. intensification in the Hadley circulation), with a different climate response in the two stations due to the orography.

Further research is needed in order to overcome present uncertainties, with special emphasis on the characterization of the major changes in atmospheric circulation patterns along the year and trends in cloudiness parameters (e.g. total and low cloud cover, cloud types, and optical thickness). Also, in order to confirm the possible brightening detected before the dimming period, a digitalization of early sunshine measurements for the Canary Islands, currently in analog format, should be performed.

Acknowledgments

Research by Esther Sanroma was supported by a summer student grant from IAC. Arturo Sanchez-Lorenzo was supported by the Spanish Ministry of Science and Innovation (MICINN) project NUCLIEREX (CGL2007-62664).

References

Alpert P and Kishcha P 2008 Quantification of the effect of urbanization on solar dimming *Geophys. Res. Lett.* **35** 8

Brunet M, Jones P D, Sigró J, Saladié O, Moberg A, Della-Marta P M, Lister D, Walther A and López D 2007 Temporal and spatial temperature variability and change over Spain during 1850–2005 *J. Geophys. Res.* **112** D12117

García-Herrera R, Gallego D, Hernández Martín E, Gimeno L and Ribera P 2001 Influence of the North Atlantic oscillation on the canary islands precipitation *J. Clim.* **14** 3889–903

Guerrero M A, García-López R J, Corradia R L M, Jiménez A, Fuensalida J J, Rodríguez-Espinosa J M, Alonso A, Centurion M and Prada F 1998 Extinction over the Canarian Observatories: the limited influence of Saharan dust *New Astron. Rev.* **42** 529–32

Hu Y and Fu Q 2007 Observed poleward expansion of the Hadley circulation since 1979 *Atmos. Chem. Phys.* **7** 5229–36

Khain A P 2009 Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review *Environ. Res. Lett.* **4** 015004

King D L 1985 Atmospheric Extinction at the Roque de los Muchachos Observatory *RGO/La Palma Technical Note no 31*

Makowski K, Wild M and Ohmura A 2008 Diurnal temperature range over Europe between 1950 and 2005 *Atmos. Chem. Phys.* **8** 6483–98

Mishchenko M I, Geogdzhayev I V, Rossow W B, Cairns B, Carlson B E, Lacis A A, Liu L and Travis L D 2007 Long-term satellite record reveals likely recent aerosol trend *Science* **315** 1543

MMA 2002 Valores normales y estadisticos de observatorios meteorologicos principales (1971–2000) *Spanish Meteorological Office Report* (six volumes)

Norris J R and Wild M 2007 Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar 'dimming', and solar 'brightening' *J. Geophys. Res.* **112** D8

Ohmura A 2006 Observed long-term variations of solar irradiance at the earth's surface *Space Sci. Rev.* **125** 111–28

Oñate J J and Pou A 1996 Temperature variations in Spain since 1901: a preliminary analysis *Int. J. Climatol.* **16** 805–15

Pallé E and Butler C J 2001 Sunshine records from Ireland, cloud factors and possible links to solar activity and climate *Int. J. Climatol.* **21** 709–29

Pallé E, Goode P R, Montañés-Rodriguez P and Koonin S E 2004 Changes in the Earth's reflectance over the past two decades *Science* **304** 1299–301

Pallé E, Goode P R and Montañés-Rodriguez P 2009 Interannual variations in Earth's reflectance 1999–2007 *J. Geophys. Res.* **114** D00D03

Querol X *et al* 2004 Speciation and origin of PM10 and PM2.5 in selected European cities *Atmos. Environ.* **38** 6547–55

Ruckstuhl C *et al* 2008 Aerosol and cloud effects on solar brightening and the recent rapid warming *Geophys. Res. Lett.* **35** L12708

Sanchez-Lorenzo A, Brunetti M, Calbó J and Martin-Vide J 2007 Recent spatial and temporal variability and trends of sunshine duration over the Iberian Peninsula from a homogenized data set *J. Geophys. Res.* **112** D20115

Sanchez-Lorenzo A, Calbó J and Martin-Vide J 2008 Spatial and temporal trends in sunshine duration over Western Europe (1938–2004) *J. Clim.* **21** 6089–98

Sperling F N, Washington R and Whittaker R J 2004 Future climate change of the subtropical north Atlantic: implications for the cloud forests of Tenerife *Clim. Change* **65** 103–23

Stanhill G and Cohen S 2001 Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences *Agricult. Forest Meteorol.* **107** 255–78

Trenberth K E *et al* 2007 Observations: surface and atmospheric climate change *Climate Change 2007—The Physical Science Basis: Working Group I contribution to the Fourth Assessment Report of the IPCC* ed S Solomon, D Qin, M Manning, Z Chen, M C Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press)

Varela A M, Bertolin C, Muñoz-Tuñon C, Ortolani S and Fuensalida J J 2008 Astronomical site selection: on the use of satellite data for aerosol content monitoring *Mon. Not. R. Astron. Soc.* **391** 507–20

Vose R S, Easterling D R and Gleason B 2005 Maximum and minimum temperature trends for the globe: an update through 2004 *Geophys. Res. Lett.* **32** L23822

Wild M 2009 Global dimming and brightening: a review *J. Geophys. Res.* **114** D00D16

Wild M, Gilgen H, Roesch A, Ohmura A, Long C and Dutton E G 2005 From dimming to brightening: trends in solar radiation inferred from surface observations *Science* **308** 847–50

Wild M, Ohmura A and Makowski K 2007 Impact of global dimming and brightening on global warming *Geophys. Res. Lett.* **34** L04702

Wild M, Trussel B, Ohmura A, Long C N, Konig-Langlo G, Dutton E G and Tsvetkov A 2009 Global dimming and brightening: an update beyond 2000 *J. Geophys. Res.* **114** D00D13