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# Observed solar dimming in the Wider Caribbean

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RESUMEN

Presentamos los resultados de un estudio del fenómeno de oscurecimiento atenuación-luminosidad en el Gran Caribe. El conjunto de datos, que abarca el periodo 1961-1990, consiste de series de tiempo de radiación global provenientes de 30 estaciones de superficie. Las estaciones están distribuidas por toda la región: tres en Florida, EUA, cinco en el Caribe, tres en México, 17 en Venezuela y una en Honduras. En general, para este periodo los resultados muestran la predominancia del oscurecimiento, registrado en 20 de las estaciones, mientras que la luminosidad fue notada únicamente en los 10 sitios restantes. Las tendencias de asociación fueron estadísticamente significativas, al nivel de 5%, en 21 (70%) del total de 30 estaciones. En particular, 16 de las estaciones en que se registró oscurecimiento y cinco de las que mostraron luminosidad, tuvieron tendencias estadísticamente significativas. Considerando la distribución físico-geográfica de las estaciones, se agruparon en continentales e insulares peninsulares. Las tendencias significativas de las estaciones continentales promediaron –0.72 $Wm^2$ por año y las insulares peninsulares –0.82 $Wm^2$ por año. El oscurecimiento fue más frecuente en las áreas continentales pero más intenso en las insulares peninsulares.

ABSTRACT

We present the results of a study of the dimming-brightening phenomena in the Wider Caribbean. The dataset consisted of time series of global radiation from 30 surface stations covering the period 1961-1990. The stations were distributed over the entire region: three in Florida, USA, five in the Caribbean, three in México 17 Venezuela and one in Honduras. Results showed in general a predominance of the dimming over this period, registered at 20 of the stations, while brightening was only noted at the remaining 10 sites. Associated trends were statistically significant, at 5% level, at 21 of the total 30 stations (70%). In particular 16 of the stations registering dimming and 5 of the ones showing brightening had statistically significant trends. Considering the physico-geographical distribution of the stations they were grouped in continental and insular-peninsular. The significant trends averaged –0.72 $Wm^{-2}$ per year for continental stations and –0.82 $Wm^{-2}$ per year for the insular-peninsular ones. Dimming was more frequent in continental areas, but more intense in the insular peninsular ones.

**Keywords**: Dimming-brightening, global radiation, trends.

## 1. Introduction

Recently reported changes of solar radiation at the earth's surface are a fact accepted by the overwhelming majority of the scientific community. Those changes, called solar dimming-brightening phenomena, have been occurring at least during the second half of the 20th century (e.g., Ohmura and Lang, 1989; Stanhill*,* 2007). Although the debate and the studies has moved on, addressing, for example, the possible causes and mechanisms of such variations of the solar radiation (e.g., Romanou *et al.,* 2007), its possible impact on the hydrological cycle (e.g., Wild *et al.,* 2004, 2008) or on global warming (Wild *et al.,* 2007), there are still regions in the world where these phenomena have been poorly studied. Among these regions is the Wider Caribbean.

Recent studies reveal that the Wider Caribbean climate has undergone a change, at least since 1950. Temperature in the region has been increasing while the precipitation is decreasing. In particular the extreme intra-annual temperature range is decreasing, because the number of very warm days and nights is increasing at the same time that the number of very cool days and nights are decreasing (Peterson *et al.,* 2002). In that context, information on the variation of surface solar radiation, one of the main variables of the climatic system, will contribute to the better understanding of the climate trends in the region.

Here we present the results of an analysis of monthly total global downward solar radiation (Q) for a set of 30 surface stations in the region. The dataset covers the period 1961 to 1990. Linear trends of Q for the individual stations were calculated and its statistical significance evaluated. The results are compared with global and regional trends reported in the literature. A pattern of geographical distribution of the changes of solar radiation at the surface in the region is determined, and possible implications of the particular behaviour of the pattern are discussed.

## 2. Data and methods

We used Q time series from 30 surface stations located in the region known as the Wider Caribbean (UNEP, 1983). For the purpose of the present study we selected the region delimited by the latitudes 30º N and the Equator, and by the longitudes 110º W and 50º W. Time series were retrieved from two databases, the World Radiation Data Centre (WRDC) located in San Petersburg, Russia (http://wrdc-mgo.nrel.gov/html/get_data-ap.html), and the National Solar Radiation Data Base (NSRDB) in USA (http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/). The time series cover the period 1961-1990 in general. Table I lists the geographical location of the stations, its WMO code, the period covered by its time series, its completeness in percent and the source.

Time series from the NSRDB consisted of monthly averages of daily total values of Q. The time series from the NSRDB report the uncertainty of the variable provided. In our particular case for the four time series from the NSRDB the maximum uncertainty reported was 9%, with 95% of the Q values in the range of uncertainty between 6 and 9%. Thirty seven percent of the data for the four series have been restored by calculations which therefore should be considered with some caution.

Table I. Main features of the time series used in the present study.

| Country | WMO Code | Latitude | Longitude | Filling % | Period | Source |
|---|---|---|---|---|---|---|
| USA (Miami) | 722020 | 25º 47′ | –80º 18′ | 100 | 1961-1990 | NSRDB |
| USA (Key West) | 722010 | 24º 33′ | –81º 45′ | 100 | 1961-1990 | NSRDB |
| USA (West Palm Beach) | 722030 | 26º 41′ | –80º 05′ | 100 | 1961-1990 | NSRDB |
| Cuba (Havana) | 783250 | 23º 10′ | –82º 21′ | 100 | 1961-1990 | WRDC |
| Cuba (Santiago) | 783640 | 20º 30′ | –75º 49′ | 100 | 1961-1990 | WRDC |
| Puerto Rico | 785260 | 18º 26′ | –66º 00′ | 100 | 1961-1990 | NSRDB |
| Honduras | 785010 | 17º 24′ | –83º 56′ | 95 | 1964-1975 | WRDC |
| Martinique | 789250 | 14º 36′ | –61º 00′ | 98 | 1974-1993 | WRDC |
| Barbados | 789550 | 13º 09′ | –59º 37′ | 95 | 1971-1993 | WRDC |
| Guadalupe | 788970 | 16º 16′ | –61º 31′ | 98 | 1973-1993 | WRDC |
| Venezuela | 804050 | 11º 48′ | –66º 11′ | 87 | 1964-1980 | WRDC |
| Venezuela | 804030 | 11º 25′ | –69º 41′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804070 | 10º 34′ | –71º 44′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804100 | 10º 01′ | –69º 19′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804130 | 10º 15′ | –67º 39′ | 96 | 1964-1993 | WRDC |
| Venezuela | 804150 | 10º 36′ | –66º 59′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804160 | 10º 30′ | –66º 53′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804190 | 10º 07′ | –64º 41′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804230 | 10º 35′ | –62º 19′ | 81 | 1964-1993 | WRDC |
| Venezuela | 804350 | 9º 45′ | –63º 11′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804380 | 8º 36′ | –71º 11′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804440 | 8º 09′ | –63º 33′ | 90 | 1964-1993 | WRDC |
| Venezuela | 804470 | 7º 51′ | –72º 27′ | 96 | 1964-1993 | WRDC |
| Venezuela | 804500 | 7º 54′ | –67º 25′ | 94 | 1964-1992 | WRDC |
| Venezuela | 804530 | 7º 18′ | –61º 27′ | 95 | 1964-1993 | WRDC |
| Venezuela | 804570 | 5º 36′ | –67º 30′ | 94 | 1964-1993 | WRDC |
| Venezuela | 804620 | 4º 36′ | –61º 07′ | 90 | 1964-1993 | WRDC |
| México | 762250 | 28º 38′ | –106º 05′ | 82 | 1967-1976 | WRDC |
| México | 762251 | 20º 35′ | –99º 12′ | 93 | 1968-1993 | WRDC |
| México | 762252 | 19º 20′ | –99º 11′ | 98 | 1967-1993 | WRDC |

In the case of the WRDC, data consisted of the daily and monthly sum of Q. This dataset does not report quantitative magnitudes of the uncertainties. From the quality flags we determined that for all time series we used from the WRDC, only 1% of the Q values were restored by calculations.

The geographical distribution of the stations from the standpoint of the areal coverage is highly inhomogeneous. But taking into account that the Wider Caribbean covers 28 continental and island countries in a very particular physico-geographical location the available stations represent the region relatively well. There are 19 stations located in continental areas, a bit more than 60%, and 11 or almost 40% located on islands or peninsulas (hereafter referred to as insular-peninsular areas).

Data completeness was calculated as the total of available months with data divided by the total of months in the period covered by the time series, multiplied by hundred. For the entire set of time series this parameter has a value of 95%, representing a high percentage of available data. Moreover, 23 of the 30 stations, corresponding to around 75%, are more than 95% complete. Only three stations show gaps of 13-18% in its time series.

Because both the WRDC and the NSRDB original datasets report Q values in $Whm^{-2}$ it was necessary to convert those values to $Wm^{-2}$. Usually measured sunshine duration is used for such a purpose. But in our situation sunshine duration was not available for all the stations. We used the theoretical value of sunshine duration considering clear sky for each station and period of the year. In that case the sunshine duration is determined by the sunset and sunrise times. Sunset and sunrises for the 15 day of each month of the year for the geographical location of each individual station were calculated using state of the art software available on line in the Web (Reda and Andreas, 2008).

For each time series monthly values of Q, already converted to $Wm^{-2}$, were used to calculate Q yearly average values. In order to detect the trends, linear regressions of the time series of yearly averages of Q were calculated using the least squares method. The values of the trends are expressed in $Wm^{-2}$ per year. Using the Student t-test the significance of the trend for each time series was calculated. Significant trends over 95 and 99% are reported.

## 3. Results and discussion

Table II summarizes the results of the regression calculations, showing the values of the Q trends, in $Wm^{-2}$ per year, as well as the significance level. Annual trends for each station are compiled in Table IIa for insular-peninsular areas and in Table IIb for continental areas. In general, the signs of the trends of Q for the entire period show that the dimming phenomena predominate in the Wider Caribbean. Negative trends of Q, associated with dimming, were registered at 20 out of the 30 stations representing 67% of the locations. Brightening, corresponding to positive trends of Q, is present at 10 stations (33%). Also with respect to the magnitude of the trends, the dimming is more intense than the brightening with a maximum trend value of –2.98 $Wm^{-2}$ per year against a maximum positive trend of the brightening of 1.33 $Wm^{-2}$ per year.

Table IIa. Annual trends, in $Wm^{-2}$ per year, and the corresponding statistical significance (P) for each station in insular-peninsular areas.

| Station | Trend ($Wm^{-2}$ per year) | P |
|---|---|---|
| Miami | –0.18 | Not significant |
| Key West | 0.10 | Not significant |
| West P. Beach | 0.64 | > 95% |
| Havana | 0.15 | Not significant |
| Santiago | 0.09 | Not significant |
| Puerto Rico | 0.15 | Not significant |
| Honduras | –2.36 | > 99% |
| Martinique | 1.33 | > 99% |
| Barbados | –0.75 | > 99% |
| Guadalupe | –2.05 | > 99% |
| Venezuela (804050) | –1.72 | > 99% |

The average trend for all the 30 stations is –0.57 $Wm^{-2}$ per year, confirming the prevalence of the dimming effect over the Wider Caribbean between 1961 and 1990. The average trend for the Wider Caribbean is in line with the reported trends at more globally distributed sites of –0.51 $Wm^{-2}$ per year (Stanhill and Cohen, 2001). The reduction of Q for the entire Wider Caribbean during the 30 years considered here, –17 $Wm^{-2}$, is lower than the average decrease of Q of –19 $Wm^{-2}$ reported for the entire United States (US), over a shorter period between 1960 and 1980 (Liepert, 2002).

Table IIb. Annual trends, in $Wm^{-2}$ per year, and the corresponding statistical significance (P) for each station in continental areas.

| Station | Trend ($Wm^{-2}$ per year) | P |
|---|---|---|
| Venezuela (804030) | –0.80 | > 99 % |
| Venezuela (804070) | –1.03 | > 99 % |
| Venezuela (804100) | –2.98 | > 99 % |
| Venezuela (804130) | 0.43 | > 99 % |
| Venezuela (804150) | –0.65 | > 99 % |
| Venezuela (804160) | –0.63 | > 99 % |
| Venezuela (804190) | –0.81 | > 99 % |
| Venezuela (804230) | 1.04 | > 99 % |
| Venezuela (804350) | –0.73 | > 99 % |
| Venezuela (804380) | –0.74 | > 99 % |
| Venezuela (804440) | –0.64 | > 99 % |
| Venezuela (804470) | –0.12 | Not significant |
| Venezuela (804500) | –2.16 | > 99 % |
| Venezuela (804530) | –0.64 | > 99 % |
| Venezuela (804570) | 0.24 | > 95 % |
| Venezuela (804620) | –0.74 | > 99 % |
| México (762250) | –1.34 | Not significant |
| México (762251) | –0.12 | Not significant |
| México (762252) | 0.04 | Not significant |

The statistical tests of the significance showed that Q trends are significant at least at the 95% level in 21 of the stations, representing 70% of all the time series. From the 20 stations reporting dimming a total of 16 showed trends statistically significant at least at the 95%, while for the 10 stations registering brightening five trends were statistically significant over the 95% significance level. Taking into account only the significant trends, 76% of the time series correspond to dimming and the rest to brightening, reaffirming the preponderance of the dimming process in the region for the period 1961-1990. That is more than 10% higher than the percentage of significant trends reported for the former Soviet Union (FSU) (Abakumova *et al.*, 1996). It is interesting to note that from the nine insignificant trends, eight were in the range between –0.18 and 0.15 $Wm^{-2}$ per year, while the only one outside this range is one station in México with a negative trend of –1.34 $Wm^{-2}$ per year.

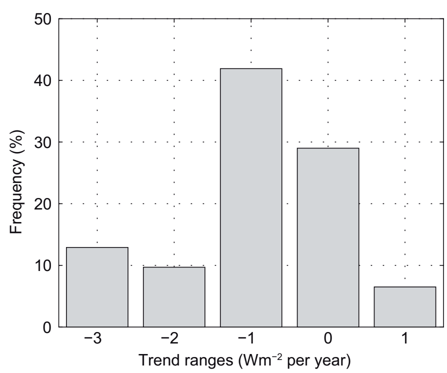


Fig. 1. Frecuencies distribution of Q trends for all stations.

Figure 1 shows the frequency distribution of the trends of Q for all stations. We note that for the same range of absolute values of the trends, the ones with negative sign have higher frequency. In particular there are no positive values of the trends in the range between 2 and 3 $Wm^{-2}$ per year, but there are four negative values (~ 13%) in the range between –2 and –3 $Wm^{-2}$ per year. These features of the trend frequency distribution corroborate again the dominance of the dimming in the region.

In Figure 2 the geographical distribution of the stations and its corresponding trends of Q are depicted. Negative trends are denoted by circles and positive by stars. Significant trends at 5% level of significance are highlighted with a dot in the center of the corresponding symbol. It is noticeable that the trends in some neighbour stations show opposite signs. That is the case, for example, for the station Miami, with a negative trend surrounded by stations with positive trends. Similar behavior has been reported in other regions of the world like Europe (Gilgen *et al.,* 1998) and the FSU between 1960 and 1987 (Abakumova *et al.,* 1996), but has not been further explored in these studies.

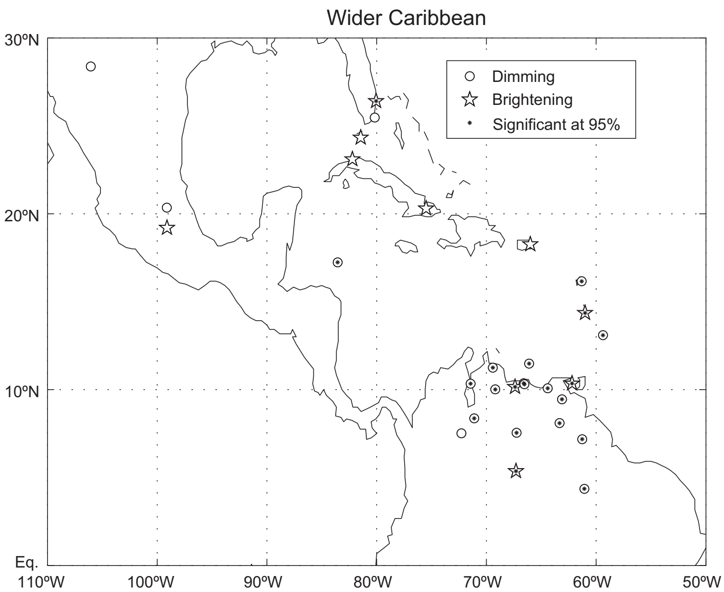


Fig. 2. Geographical distribution of the stations and its corresponding Q trends.

No longitudinal dependency is evident in the trend pattern in Figure 2. The latitudinal distribution shows that north of 15º N, considering the signs of the trends, the brightening predominates and to the south of that latitude the dimming is more frequent. But the average trends of all time series in the northern portion is –0.44 $Wm^{-2}$ per year, while in the southern portion the average trend is –0.64 $Wm^{-2}$ per year, representing dimming in both regions. Moreover, the average of the significant trends of all the time series in the northern portion is –1.26 $Wm^{-2}$ per year, while in the southern portion the average of the significant trend is –0.69 $Wm^{-2}$ per year. It is evident that both in the northern and southern region of the Wider Caribbean the negative trends predominate with differences only in magnitude. Those results do not suggest a conclusive latitudinal pattern.

Considering the complex geographical structure of the Wider Caribbean and the scarcity of the sampling it is more feasible to divide the region in continental and insular-peninsular areas. With

Table III. Number of trends cases showing dimming (negative values) and brightening (positive values) for continental and insular-peninsular areas.

| Station type | Cases | Dimming | | Brightening | |
|---|---|---|---|---|---|
| | | Total | Significant | Total | Significant |
| Continental | 19 | 15 | 12 | 4 | 3 |
| Insular-peninsular | 11 | 5 | 4 | 6 | 2 |
| Total | 30 | 20 | 16 | 10 | 5 |

this approach it is possible to establish a geographically more consistent pattern. Table III reports the number of dimming and brightening cases grouped in continental and insular-peninsular areas.

Regarding the sign of the trends, dimming clearly predominates in the continental areas with negative trends in 15 of the 19 stations, for almost 80% of the cases. For the continental areas the average of the positive trends is 0.44 $Wm^{-2}$ per year and the average of the negative ones is –0.94 $Wm^{-2}$ per year. That is, the dimming also has higher magnitudes than the brightening. The average value of the trend for all the continental stations is –0.65 $Wm^{-2}$ per year. The significance of the trends for the continental areas also confirms the prevalence of the dimming phenomena in these areas. The average value of the significant trends for all continental stations is –0.72 $Wm^{-2}$ per year, higher than the value of –0.51 $Wm^{-2}$ per year derived from globally distributed stations by Stanhill and Cohen (2001). The average value of the significant trends for the Wider Caribbean represents a decrease of –22 $Wm^{-2}$ for the 30 years of data analyzed. For a 20 years period the decrease in the Wider Caribbean was –14 $Wm^{-2}$, lower than the –19 $Wm^{-2}$ decrease reported for the US between 1960 and 1980 (Liepert, 2002).

In the case of the insular-peninsular areas both phenomena show almost the same number of cases, with only one more case of brightening but with a smaller number of significant trends than for the dimming. That is both dimming and brightening has been taking place in these areas. To consider only islands, we excluded the three stations located in the peninsula of Florida, but the balance between the numbers of stations with dimming and brightening remains similar. The average positive trend for the insular-peninsular areas is 0.41 $Wm^{-2}$ per year and the average of the negatives is –1.41 $Wm^{-2}$ per year. It is noticeable that the average magnitude of the brightening is almost the same both for the continental and insular-peninsular areas. Also it is noteworthy that the average magnitude of the dimming is more than three times the magnitude of the brightening. Also the magnitude at those sites showing dimming is higher in the insular-peninsular than in the continental areas. In that sense the average value of the trends for all the insular-peninsular stations is –0.42 $Wm^{-2}$ per year, almost half of the magnitude obtained for the continental areas. This average of the significant trends for all the insular-peninsular stations represents a decrease of the order of –16 $Wm^{-2}$ over the 30 years, of similar magnitude to the values derived from averages over globally distributed stations (Stanhill and Cohen, 2001) and stations within the US (Liepert, 2002). Considering only the statistical significant trends in this area the average trend reach the value of –0.82 $Wm^{-2}$ per year.

There are clear differences in the character and magnitudes of the trends between continental and insular-peninsular areas. The sign of the trends reveal that the dimming is more frequent (80%) in continental areas, while in the island-peninsular region both dimming and brightening have the same frequency. Regarding the magnitudes, brightening have the same magnitude in both regions but dimming is more intense (–1.41 $Wm^{-2}$ per year vs –0.94 $Wm^{-2}$ per year) in island-peninsular regions. This pattern could be associated with the physico-geographical characteristics of the Wider Caribbean. A possible explanation may be related to the different patterns of local cloudiness and pollution affecting islands and peninsulas with respect to continental regions. In the particular case of pollution, considering the effect of urbanization (Alpert *et al.,* 2005), the most populated cities and great industrial activity in the region of the Wider Caribbean are located in the continental areas, contributing to the enhancement of the dimming in the continental areas with respect to the insular-peninsular areas. However, also the remote and sparsely populated insular-peninsular area still show predominantly significant dimming, in contrast to the findings in Alpert *et al.* (2005) that dimming is only present in highly urbanized areas. More research is necessary in this subject, analyzing jointly the behaviour of cloudiness and aerosols together with the solar radiation.

## 4. Conclusions

Considering the former results as a whole, we can conclude that in the Wider Caribbean region, for the 30 years period between 1961 and 1990, solar dimming has been occurring as in many places around the world. The sign of the linear trends and the average of the significant trends for the region support this conclusion. 70% of the significant trends are negative and their average, –0.75 $Wm^{-2}$ per year, is higher than the average trend reported from globally distributed stations and similar to the trend derived for the neighbour US. Cases of brightening have been found at a few sites during the period studied. The coexistence of such opposite trends is an indication of the complex mechanisms associated with the solar dimming-brightening phenomena, as has been pointed out by several authors (e. g., Wild *et al.,* 2005; Stanhill, 2007). No longitudinal or latitudinal pattern of the dimming-brightening is evident.

A geographically complex pattern has been found considering continental and insular-peninsular areas. The dimming is more frequent (80%) in continental areas, while both dimming and brightening have the same frequency in the island-peninsular region. Simultaneously, brightening has the same magnitude in both regions, but dimming is more intense in island-peninsular regions.

The average decline of Q during the period 1961-1990 for the whole Wider Caribbean, considering the significant trends only, was –23 $Wm^{-2}$. For the continental areas the average decline was –22 $Wm^{-2}$ while for the island-peninsular areas it was –25 $Wm^{-2}$. Overall dimming has also been dominant at the more remote locations, thus supporting the existence of this phenomenon not only in urbanized areas. In case that solar dimming had been effective in masking greenhouse warming (Wild *et al.*, 2007), with dimming being more frequent in continental than in insular-peninsular areas, these latter areas could have been more vulnerable to the direct greenhouse warming than the temperature records for the Caribbean showed.

A number of cases of increase of Q were detected, coexisting with the predominant dimming, denoting the complexity of the causes and mechanisms of the dimming both globally and in the Wider Caribbean in particular. Further research is necessary to understand these phenomena.

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