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Determination of diurnal daylight courses for a central European region

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ABSTRACT

The diurnal course of daylight (exterior illuminance) during winter and summer in a central European town, Bratislava, Slovakia, is studied. By using multivariate statistical methods (Factor and Cluster Analysis), the most significant types of the diurnal variations of illuminance are determined. The database used consists of mean 5-min values of global horizontal illuminance for the 14-year period 1994–2007. Two sets of data (sunrise-noon, noon-sunset) are utilized for each season, consisting of the anomalies of the semi-diurnal courses of illuminance with respect to the mean semi-diurnal course on each calendar day of the year. For winter, six typical semi-diurnal courses for sunrise-noon and nine for noon-sunrise are found, and for summer, six for sunrise-noon and seven for noon-sunset. For each type of semi-diurnal course, the most representative day is selected. Finally, for a verification of the results the atmospheric circulation patterns near the surface and at the 500-hPa level, the distribution of precipitation over Europe as well as the meteorological observations are presented, for these days.

The purpose of the present study is to achieve an objective determination of the main diurnal daylight courses observed in a central European region. The results can be useful to engineers for a rational use of daylight in buildings, which may significantly contribute towards energy saving.

1. Introduction

Research on the climatology of daylight (exterior illuminance) has received increased interest during the 21st century (Li et al., 2010; Mayhoub and Carter, 2011; Darula, 2011; Kittler et al., 2012; Oteiza and Perez-Burgos, 2012; Petržala and Kómar, 2015; Lopez-Besora et al., 2016; Mardaljevic and Christoffersen, 2017; prEN 17037, 2017) as it can serve engineers and architects for predetermination of daylight availability, improving the energy status of buildings and producing more energy-efficient and healthy buildings. Nevertheless, studies on daylight variability, based on global and/or diffuse horizontal illuminance data, are still rather limited mainly due to the small number of available ground measurements.

Illuminance presents regular diurnal and intra-annual variations due to the movement of the Earth about its axis and around the Sun but also irregularities due to local weather conditions. Darula and Kittler (2004) studied the diurnal courses of illuminance in Bratislava, Slovakia and divided these into four types: clear, cloudy, overcast, and dynamic. Also, Darula et al. (2004) calculated the frequency of these types for Bratislava, Slovakia and Athens, Greece. Furthermore, Markou et al. (2009) and Lytra et al. (2014, 2016) studied statistically the daylight climatology in Athens and Bratislava, respectively.

In the present work, a detailed study of the diurnal variation of daylight in central Europe, for winter and summer, based on measurements from Bratislava, Slovakia, is carried out. It aims at a better understanding of the temporal variations of illuminance due to the prevailing weather conditions and it defines the most characteristic diurnal courses of illuminance for the area. This is achieved primarily by objectively grouping semi-diurnal courses (sunrise-noon and noon-sunset) of global horizontal illuminance using the multivariate statistical methods Factor Analysis (FA) and Cluster Analysis (CA) and secondarily by validating the results of grouping, utilizing meteorological observations of cloudiness, visibility and precipitation (http://www.weatherbase.com/) and the corresponding atmospheric circulation patterns at the surface and at the 500-hPa level. The synoptic maps and the hourly observations of some representative semi-days will be presented and discussed.

The objective determination of the main types of the diurnal variation of illuminance in central Europe, based on multivariate statistical methods, comprises the main novelty of the present work. The methodology used can also be applied elsewhere provided that, at least, 5 or 10 min measurements of exterior illuminance are available.

The paper is organized as follows: the data base is first described along with the methods used for the analysis; next, the revealed types of semi-diurnal courses (sunrise-noon and noon–sunset) of illuminance anomalies are presented and discussed for winter and summer; for the

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most interesting cases, the findings are verified by the synoptic patterns of the representative day; finally, the results are summarized in the conclusions section.

2. Data and methodology

The data used are one-minute values of global horizontal illuminance for the 14-year period 1994–2007, recorded at the Bratislava CIE IDMP (International Daylight Measurement Programme) station (48.17°N, 17.08°E, alt. 195 m). At first, the quality of the data was tested by using the Quality Control Tests adopted by the Comission Internationale de l' Éclairage (CIE, 1994; Bartzokas et al., 2005). The data base was found reliable as 94% of the data passed the tests. Then, from the one-minute values, five-minute average values were calculated. Next, each day was divided in two parts: from sunrise to noon (S–N) and from noon to sunset (N–S) (True Solar Time, TST); thus two independent data sets were created from the available database. Note that as Bratislava is located approximately 2° eastwards of the 15°E meridian, the 12:00 TST (solar noon) is at 11:52 Local Standard Time (LST; GMT + 1) plus or minus a few minutes because of the equation of time. For a common consideration of all the days of the year, the separation of each day to two semi-days was set at 11:50 LST. Only semi-days with at least 90% availability of the 5-min values were used. Since the day length is not constant during the year, only days longer up to +10% of that on winter solstice (22 December – minimum day length) and shorter down to -10% of that on summer solstice (21 June – maximum day length) were considered. In this way, a new "winter" (26 November – 6 February) and a new "summer" (2 May – 8 August) were formed and the whole study was carried out for these two "seasons". The application of all the above criteria and restrictions resulted in 1970 semi-days for winter and 2772 for summer. The difference is due on the one hand to the longer day length at the summer solstice and consequently to the longer 10% length and on the other hand to the faster rate in day length change around the winter solstice than around the summer one.

Next, each semi-diurnal course of global horizontal illuminance was converted to a semi-diurnal variation of anomalies from the mean semi-diurnal course for the same calendar day over the 14-year period by calculating the differences for each 5-min value. Because of the lack of a very long database, the mean semi-diurnal variation of illuminance for each calendar day was estimated not only from the 14 days of the same date but also from ± 5 days around it (11 days per year × 14 years = 154 days). Finally, in order to have the same day-length for all the days of each "season" (necessary for the application of FA and CA), a few 5-min values after sunrise and before sunset were omitted. As a result, the day-length was defined from 08:20 to 15:50 LST for winter (solstice day length) and from 05:05 to 18:50 LST for summer (first and last day of "summer").

Thus, two matrices of semi-diurnal courses of the anomalies of global horizontal illuminance (S–N and N–S) were created for both "seasons", "winter" (W) and "summer" (S). In particular, the dimensions of the four matrices are: 985 rows (number of semi-days) × 42 columns (number of 5-min values) (W, S–N), 985 × 48 (W, N–S), 1386 × 81 (S, S–N), and 1386 × 84 (S, N–S). The difference in the two semi-day lengths, S–N and N–S, in both "seasons", must be due to local topography.

In order to reduce the dimensionality of the created anomaly matrices, the FA with Varimax rotation (Ritchman, 1986) was applied. Since in this work FA is used as a dimension-reduction tool only, the resulting factor score time-series are not presented. Then, the K-Means technique of CA was applied to the new matrices, which consist of the factor scores time-series, in order to group days presenting similar diurnal variation of illuminance anomalies in homogeneous clusters. The K-Means technique begins by using the values of the first *k* cases in the data file as temporary estimates of the *k* cluster means, where *k* is the desired number of clusters. An iterative process is used to find the final cluster centres. This process continues until no further changes occur in the centres. An objective methodology for selecting the optimum number of clusters, followed by many authors, is the so-called 'jump' method proposed by Sugar and James (2003); it is based on distortion, a quantity that measures the average distance between each observation and its closest cluster centre, and was adopted in this work.

Finally, for each cluster the most representative day was selected by using the least square error method. Namely, the sum of square differences between the 5-min anomalies of each semi-day and the corresponding 5-min ones of the mean semi-day of each group was calculated, and for each group the semi-day with the least sum of those differences was selected.

For the rest of the meteorological data (cloudiness, visibility, precipitation), hourly observations were used and in cases of lack of hourly data, three observations per day (7-14-21 LST) from three stations in the greater Bratislava area (Mlynska dolina, Koliba, and airport of Bratislava) were used (Slovak Hydro-meteorological Institute, SHI). The distances of the three stations from the CIE IDMP station are approximately 5, 4 and 11 km, respectively. Finally, the synoptic maps used are available in the web page: http://www.wetterzentrale.de/de/reanalysis.php?map=1&model=cfsr&var=1.

3. Results

3.1. Winter

For the defined winter period (26 November – 6 February), the application of FA led to 4 Factors for S–N and 4 Factors for N–S explaining approximately 90% of the total variance. As it was mentioned above, the FA was used as a dimension-reduction tool only and, therefore, its results are not presented. Then, the application of CA to the factor scores matrices of the two semi-diurnal variations of illuminance, S–N and N–S, yielded 6 and 9 Clusters, respectively.

The mean diurnal course of illuminance anomalies of the semi-days for each cluster along with the course of the anomalies of its representative semi-day are presented for S–N and N–S.

3.1.1. Sunrise-Noon

Cluster 1 comprises 84 out of the 985 winter semi-days (i.e. 8.5%) and is characterized by positive values of anomalies of global horizontal illuminance (Fig. 1a) for all 5-min intervals from sunrise to noon. This finding does not necessarily indicate that the semi-days of Cluster 1 are characterized by clear sky conditions since the average cloudiness for December-January in Bratislava is 75%. It simply indicates that, for the days of Cluster 1, cloudiness, in average, is somewhat lower than usually, especially around 09:00 LST, when maximum illuminance anomalies are found (approximately +5 klux). This conclusion is confirmed from the meteorological observations (http://www.weatherbase.com/) for the most representative semi-day of this cluster (29 December 2004) and from the corresponding synoptic maps of sea level pressure and 500-hPa height (Fig. 2a) for 06-UTC and the 06-12 UTC precipitation (Fig. 2b). The observations reveal mostly cloudy sky, especially around noon (negative anomalies after 10:50 in Fig. 1a), and the weather maps show the domination of a barometric col (saddle) at the surface and a trough at 500 hPa over central Europe, without rain over Bratislava.

Cluster 2 (61 semi-days - 6.3%) is characterized by positive anomalies from sunrise until around 11:00 LST and then almost zero values until noon (Fig. 1b). This means that Cluster 2 contains semi-days with sky conditions clearer than usually in the morning, especially from 9:30 LST to 10:10 LST, and similar to the ones of the mean semi-day from 10:45 LST to noon. The meteorological observations of the most representative semi-day (8 January 2007) of Cluster 2 indicate clear-sky conditions after 9:30 LST (meteorological maps are not presented).

Cluster 3 (Fig. 1c), which contains most cases (492 semi-days -