



Effect of solar activity on the repetitiveness of some meteorological phenomena

Nedeljko Todorović^a, Dragana Vujović^{b,*}

^a Hydrometeorological Service of Serbia, Belgrade, Serbia

^b University of Belgrade, Faculty of Physics, Department of Meteorology, Serbia

Received 4 June 2014; received in revised form 28 July 2014; accepted 9 August 2014

Abstract

In this paper we research the relationship between solar activity and the weather on Earth. This research is based on the assumption that every ejection of magnetic field energy and particles from the Sun (also known as Solar wind) has direct effects on the Earth's weather. The impact of coronal holes and active regions on cold air advection (cold fronts, precipitation, and temperature decrease on the surface and higher layers) in the Belgrade region (Serbia) was analyzed. Some active regions and coronal holes appear to be in a geo-effective position nearly every 27 days, which is the duration of a solar rotation. A similar period of repetitiveness (27–29 days) of the passage of the cold front, and maximum and minimum temperatures measured at surface and at levels of 850 and 500 hPa were detected. We found that 10–12 days after Solar wind velocity starts significantly increasing, we could expect the passage of a cold front. After eight days, the maximum temperatures in the Belgrade region are measured, and it was found that their minimum values appear after 12–16 days. The maximum amount of precipitation occurs 14 days after Solar wind is observed. A recurring period of nearly 27 days of different phases of development for hurricanes Katrina, Rita and Wilma was found. This analysis confirmed that the intervals of time between two occurrences of some particular meteorological parameter correlate well with Solar wind and A index.
© 2014 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Solar activity; Solar wind; Sun–weather relationship; Cold air advection; Repetitiveness; Tropical cyclones

1. Introduction

Active regions and coronal holes can persist on the Sun for a number of rotations. Coronal holes dominate on the corona around and during the minimum of solar activity, while active regions dominate during the maximum of solar activity. The Sun has its rotation period of 27 days, meaning the effects on the Earth caused by a persistent coronal hole will exhibit a 27-day cycle. Coronal holes tend to be geo-effective (i.e. to have effect on the Earth) only when they are located near the solar equator, at a longitude of

around 30° west of the Sun's central meridian, and when they are on the earthward hemisphere of the Sun (<http://www.ips.gov.au/Solar/6/1>). The effect on Earth depends on the heliographic position of the eruptions, as well as the conditions in interplanetary space (Landscheidt, 2000). The effect depends also on solar activity intensity. Tlatov (2014) proposed that in several subsequent double cycles the odd cycles should be weaker than their preceding even cycles.

The main large-scale solar phenomena that affect planetary bodies the most are solar flares, coronal mass ejections (CMEs) and fast Solar winds originating in coronal holes (Mendoza, 2011). They affect our planet at different time intervals, from short time intervals of a solar storm (from a few hours to a few days) to solar cycles taking place over

* Corresponding author. Tel.: +381 64 25 48 048.

E-mail addresses: nedeljko52@yahoo.com (N. Todorović), dvujovic@ff.bg.ac.rs (D. Vujović).

the course of several years (11 or 22 years). The relationship between meteorological phenomena and space weather has been a popular topic of research (Heredia and Elias, 2013; Aslam and Badruddin, in press). Among meteorological phenomena, tropical cyclones have attracted much attention due to their destructive effects. Nyberg et al. (2007) suggested that peaks and trends of major north Atlantic hurricane activity correlate with lower total solar irradiance (i.e. lower solar activity), and vice versa, notably during several periods between 1730 and 2005. Some papers include not only sunspot number but also other solar activity-associated phenomena. Mendoza and Pazos (2009) showed that the highest significant correlations occur between the Atlantic and Pacific hurricanes, and Dst index. The Dst index is a geomagnetic index that measures worldwide magnetic storm levels, and is constructed by averaging the horizontal component of the geomagnetic field from mid-latitude and equatorial magnetograms from four stations. Most importantly, oceans present the highest hurricane-Dst relations during the ascending part of odd solar cycles, and the descending phase of even solar cycles. Conversely, for the ascending part of even cycles and descending part of odd cycles, the relationship is low. Comparing cyclonic activity at middle and subpolar latitudes, the North Atlantic cyclones also show a correlation with solar activity: long-period variations in the cyclonic activity along 1874–1995 indicate oscillations of the surface pressure with periods close to the main periods of solar activity (~ 80 and ~ 11 years, Veretenenko et al., 2007).

At present, there are two primary proposed solar-related mechanisms to account for the relation between space weather and climate: solar and ultraviolet radiation, and solar-modulated energetic particles (Mendoza, 2011). An active Sun warms the lower stratosphere and upper troposphere through ozone absorption of ultraviolet radiation. A warming response to it in the upper troposphere leads to a decrease in convective available potential energy in the atmosphere, leading to a weaker cyclone (Elsner and Jagger, 2008). Shindell et al. (2001) suggested that general circulation models show that changes in the stratosphere, induced by interactions between UV rays and the ozone, may penetrate down to the troposphere, affecting winds and sea level pressure. Increased solar radiation during solar maximum increases sea level pressure, which results in weaker easterly winds and therefore weaker vertical wind shear, in turn promoting more hurricanes (Nyberg et al., 2007). Regarding the role of solar-modulated energetic particles, there is a possible triggering mechanism for condensation and freezing within convective clouds of the cyclone (see review by Tinsley (2000)). The ionization of the upper part of a storm leads to additional latent heat release and additional warming of the cyclone core. The warming of the cyclone core is associated with the lowering of the surface pressure and therefore with the intensification of cyclones (Kavlaikov et al., 2008).

There are no important large active regions with strong magnetic structures at the end of the 11-year solar cycle (so called the quiet Sun). Coronal holes dominating at the end of a cycle are much easier to perceive the influence of. When a coronal hole or an active region is approaching a geo-effective position, slow permanent Solar wind (SW) becomes stronger, and its effects on the Earth can be expected in 2–3 days (Lilensten and Bornarel, 2006). Elsner and Kavlaikov (2001) confirmed a statistically significant relation between initial baroclinity in cyclones (hurricanes) and 11-day average values of Kp index.

The aim of the research was an establishment of guidelines that could aid in creating a method of long-range weather forecasts based on solar parameters. Attempts were made to find time correlations between particular solar parameters and meteorological parameters. In Section 2 we give a description of the data used. Section 3 gives an analysis of the influence of different coronal holes on the weather in Belgrade. Section 3.1 gives an analysis of the impact of one coronal hole in three successive Sun's rotation. Section 3.2 provides an analysis of the influence of five coronal holes in consecutive Sun's rotations and some particularly strong active regions. The obtained results suggest the existence of a relationship between SW and penetration of cold air in the Belgrade region. If one such principle could apply to a particular area, then it could apply to any region in the world. The time gap of correlations should have different values for the different regions and would be specific to the particular region. As an example, lawfulness of repetitiveness of tropical cyclones at Atlantic in 2005 is given (tropical cyclones Katrina, Rita and Wilma) in the third part of the article.

2. Material and methods

Geomagnetic storms are a natural hazard often causing electrical utility blackouts over a wide geographic area. The question is how these storms influence weather conditions on Earth. The idea was to find a time correlation between energy ejections from Sun, from CH, and active regions in geo-effective position (SW) and the passage of the cold fronts over the Belgrade region. In trying to find the trend, we began by taking the SW data from satellite ACE, and analyzed the time between a strong increase of SW appearance and the passage of a cold front over the Belgrade region. The solar data, i.e. CH, SW, planetary A index and active regions data were taken from www.xlc.com/solar/coronal_holes.html, <http://umtof.umd.edu/pm/flare/>, and <http://www.solen.info/solar>. Surface meteorological data was taken from the Meteorological Observatory in Belgrade ($\varphi = 44^{\circ}48'N$, $\lambda = 20^{\circ}28'E$, $h = 132$ m) and sounding data was taken from the meteorological station Belgrade-Košutnjak station ($\varphi = 44^{\circ}46'N$, $\lambda = 20^{\circ}25'E$, $h = 203$ m). In that way, we acquired surface temperature, pressure, and wind, as well as temperature, pressure, and wind at different heights.

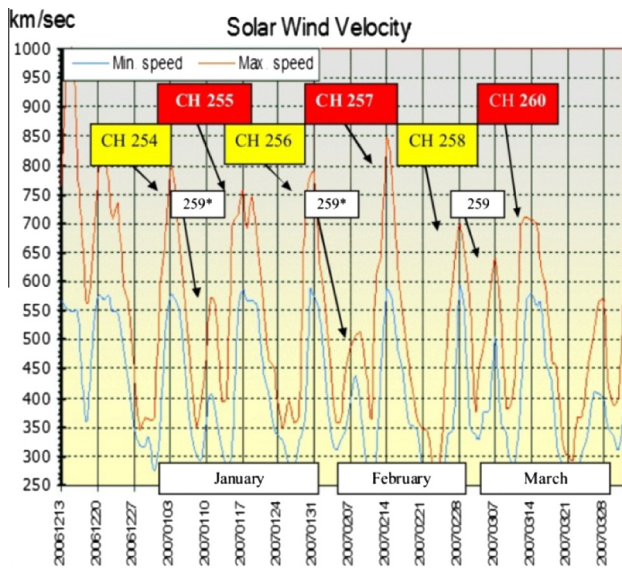


Fig. 1. Coronal holes chronology for the period January–March 2007.

3. Results

3.1. Coronal holes in the period January to March 2007

When a coronal hole (CH) is in geo-effective position, we can study its impact on processes in the atmosphere, and establish the relationship between it and the penetration of cold air in Belgrade. We already have some results in our previous works (Todorović and Vujović, 2007; Stevančević et al., 2008), and in this part of the paper we will give a more comprehensive analysis of CHs and local weather in Belgrade between January and March 2007.

An analysis was conducted taking into consideration that CHs are in geo-effective position every 27 days. CHs are large regions in the corona that are less dense and cooler than surroundings areas. Their magnetic field has an open structure that allows a constant flow of high-density plasma to stream out of the holes. When CHs are in geo-effective position, the impact of the SW on the weather on Earth is more pronounced. In the period between January and March 2007, we followed one CH

in the three consecutive rotations of the Sun. Their marks were CH255, CH257 and CH260. Two of them were strong, and one was light. We analyzed also CHs CH254, CH256 and CH258, as well as CH259* and CH259, that are observed in the period December 2006 – February 2007 (Fig. 1 and Table 1). They cannot be in geo-effective position at the same time due to different heliographic coordinates. For instance, CH254 and CH255 were observed over the course of 14 days, meaning that they were on opposite sides of the Sun. We analyzed CH255 (CH257 and CH260) and CH254 (CH256 and CH258) as our key study.

Fig. 1 shows an approximately 27–28 day repetition of CH. Davydova and Davydov (1996) have similar results of repetition. They concluded that the power spectra of meteorological parameters and geophysical data can typically be observed during the natural solar periods at 13.5 and 27–28 days.

In Figs. 2–4, SW velocity from CH255, CH257, and CH260 are shown. Fig. 2 shows that January 15th is the first day of SW arrival from CH255 from the position of SOHO satellite, i.e. the day of a strong velocity increase. February 12th is the first day of SW arrival from CH257 (Fig. 3), and March 11th is the first day of SW arrival from CH260 (Fig. 4).

Fig. 5 shows maximum surface temperature (t_{max}) and temperatures at levels of 850 hPa (t_{850}) and 500 hPa (t_{500}) in Belgrade in the period January 7th to March 28th, 2007. A trend was noticed: there was a certain period of time that had to pass before the influence of SW could be noticed to have affected the weather on Earth, i.e. before a decrease of temperature occurred. After a few days, a decrease of all temperatures (t_{max} , t_{850} , and t_{500}) was measured in Belgrade (Fig. 5). To find shift in time, we used a lagged correlation because it refers to the correlation between two time series shifted in time relative to one another. One series (SW) have a delayed response of the other series (t_{max} , t_{850} , and t_{500}). The cross-correlation between SW and t_{max} is significantly different from zero at lags $k = 9, 10$ and 11 (Fig. 6). That is in agreement with the results in Table 1 (column 7). The cross-correlation between SW and t_{850} is significantly different from zero at

Table 1
Repetitiveness of the coronal holes and the passage of the cold fronts in Belgrade.

1 Coronal hole	2 Geo-effective position date interval	3 Date of a strong increase of SW (SOHO satellite)	4 V_{max} of SW (km s^{-1})	5 t_{max} of SW (in 1000 °C)	6 Cold front passage at Belgrade	7 Interval between columns 3 and 6
CH255	Jan 12th–16th 2007	Jan 15th	756	1050	Jan 25th	10 days
Interval	27 days	28 days			28 days	
CH257	Feb 8th–13th 2007	Feb 12th	844	600	Feb 22nd	10 days
Interval	28 days	27 days			26 days	
CH260	March 9th–11th 2007	March 11th	710	500	March 20th	9 days
CH254	Dec 30th–31st 2006	Jan 1st	794	600	Jan 12th	11 days
Interval	27 days	28 days			28 days	
CH256	Jan 26th–28th 2007	Jan 29th	789	950	Feb 9th	11 days
Interval	27 days	28 days			28 days	
CH258	Feb 22nd–25th 2007	Feb 26th	699	500	March 9th	11 days

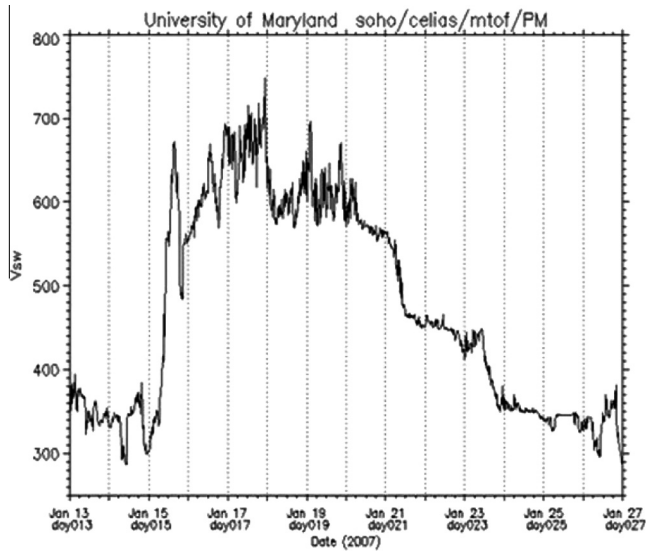


Fig. 2. Solar wind velocity from CH255 (<http://umtof.umd.edu>).

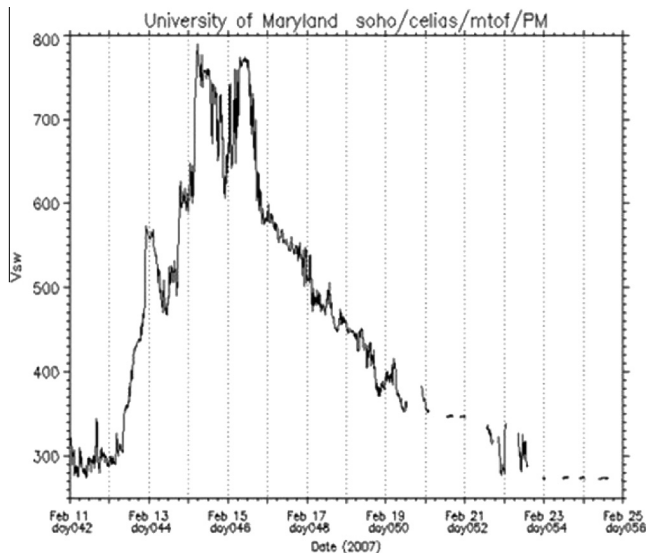


Fig. 3. Solar wind velocity from CH257 (<http://umtof.umd.edu>).

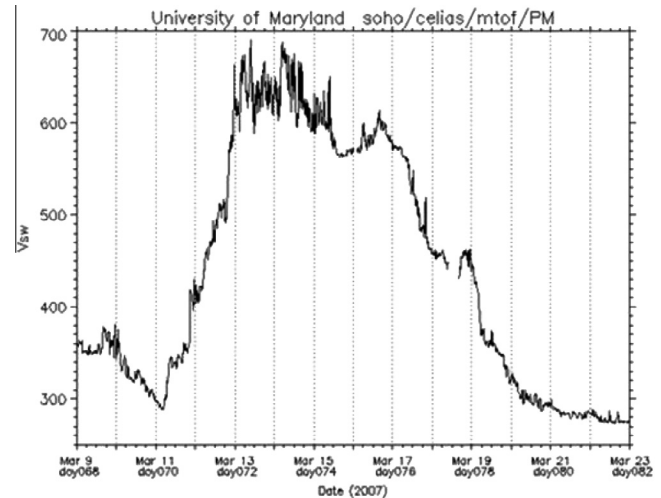


Fig. 4. Solar wind velocity from CH260 (<http://umtof.umd.edu>).

that is period of one Sun's rotation. The period between cold front appearances at Belgrade area is 27–28 days as well.

Table 2 gives the time intervals between a strong increase of SW at the SOHO satellite and minimum and maximum values of temperatures on Earth: the maximum surface temperature (t_{smax}), the temperatures at the level of 850 hPa (t_{850}) and 500 hPa (t_{500}). The average intervals between successive phenomena are 27–28 days. Finally, in Table 3 we give the intervals between the occurrence of Solar wind and resulting cold fronts, t_{smax} , t_{850} , and t_{500} in Belgrade. Eight days after SW is recorded at SOHO satellite, the maximum values of t_{smax} and t_{850} are measured. After nearly 12 days the minimum values of all temperatures are observed.

3.2. Coronal holes in the period November 2010 to March 2011

A similar analysis was done between November 2010 and March 2011. In this analysis, alongside CH, we included active regions (AR) too, the A index and other meteorological parameters that characterize the passage of the cold front over the Belgrade region. This period represents the end of third year of 24th solar cycles. In that period, the Sun became more active and due to more intense eruptions over the course of unequal time intervals, it was more difficult to find statistically consistent relationships with the events in the lower layers of the atmosphere that eventually determined the natural laws of their repetitiveness. As a basis for our analysis, relative consistency of CH repetition (approximately 27 days of Sun's rotation around its axis), and Solar wind (SW) repetition approximately 10 days after SW appearance of penetration of cold air at Belgrade region was noticed (that is established in the sub-Section 3.1. Other penetrations of cold air are correlated with SW from active regions. The relationship

lags $k = 12$ and 13 (Fig. 6), that is in agreement with results in Table 3 (column 6). Detailed calculations of time periods between a strong increase of SW and the passage of the cold front over Belgrade, as well as the time intervals between their occurrences with the successive Sun's rotation are given in Table 1. Inter-rows denote the time interval between the upper and lower rows. The last column indicates time intervals between the date of a strong increase of SW and the date of the passage of the cold front. The interval for CH255, CH257 and CH260 on average is 9.7 days. For the CH254, CH256 and CH258 the time interval is 11 days. That means if the strong increase of SW is observed at the SOHO satellite, we could expect the passage of the cold front in Belgrade within 10–11 days. The inter-rows show the time interval between CH appearances on the geo-effective position of 27–28 days,

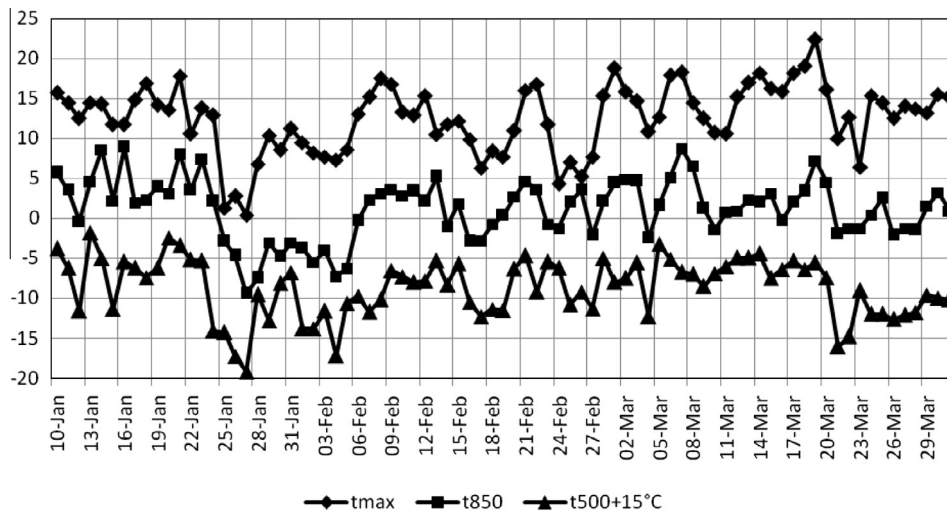


Fig. 5. Daily temperature at Belgrade from January 7th to March 28th, 2007: surface maximum temperature (t_{max}) and temperatures at level $H = 850$ hPa (t_{850} , squares) and $H = 500$ hPa (t_{500} , triangles).

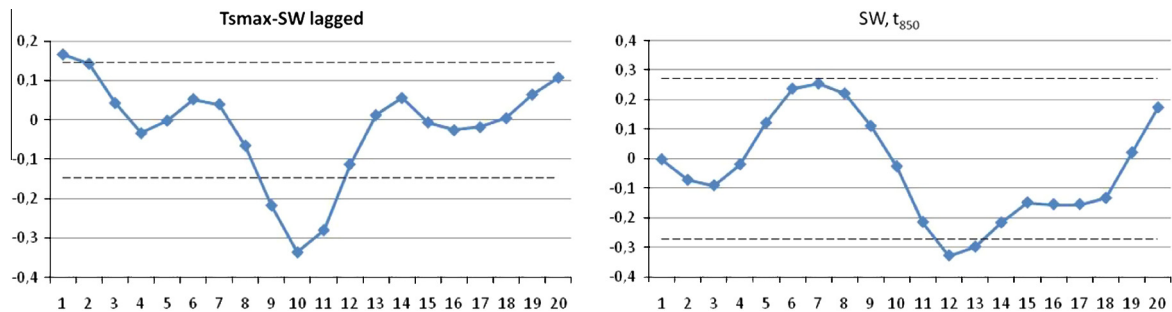


Fig. 6. Cross-correlation for t_{max} , t_{850} and SW time series. Horizontal dashed line is 95% confidence interval.

Table 2

Repetitiveness of the coronal holes, t_{max} , t_{850} , t_{500} and the cold fronts in Belgrade.

1	2	3	4	5	6	7	8	9	10
Coronal hole	Date of a strong increase of SW (SOHO satellite)	Date of maximum value of t_{max}	Date of minimum value of t_{max}	Date of maximum value of t_{850}	Date of minimum value of t_{850}	Date of maximum value of t_{500}	Date of minimum value of t_{500}	Cold front passage at Belgrade	Average interval; columns 2–9 (days)
CH255	Jan 15th	Jan 21th	Jan 27th	Jan 21th	Jan 27th	Jan 20th	Jan 27th	Jan 25th	
Interval	28	32	28	31	28	32	29	28	29.7
CH257	Feb 12th	Feb 22nd	Feb 24th	Feb 21th	Feb 24th	Feb 21th	Feb 25th	Feb 22nd	
Interval	27	25	27	26	25	25	24	26	25.6
CH260	March 11th	March 19th	March 23th	March 19th	March 21th	March 18th	March 21th	March 20th	
Average interval (days)	27.5	28.5	27.5	28.5	26.5	28.5	26.5	27	27.6

between planetary A index and cold air penetration was established in a similar way.

Planetary A index is an approximate, daily average level of geomagnetic activity. Namely, K index is related to the maximum fluctuations of the horizontal components of Earth's magnetic field observed on a magnetometer relative to a quiet day, during a three-hour interval. The relation between K index and magnetometer fluctuations is non-linear.

From a practical point to view, each K index is converted back into a linear scale called the “equivalent three hourly range” a-index and then, finally, the daily A index is merely the average of eight “a” indices. The greater A index yields the greater geomagnetic storm (<http://www.swpc.noaa.gov/info/Kindex.html>).

The analysis was conducted as follows. The date of occurrence of every phenomenon was established. The

Table 3
Time intervals between Solar wind and the cold fronts, t_{smax} , t_{850} , t_{500} in Belgrade.

1 Coronal hole	2 SW/ Cold front (days)	3 SW/Date of maximum value of t_{smax} (days)	4 SW/Date of minimum value of t_{smax} (days)	5 SW/Date of maximum value of t_{850} (days)	6 SW/Date of minimum value of t_{850} (days)	7 SW/Date of maximum value of t_{500} (days)	8 SW/Date of minimum value of t_{500} (days)	9 Average interval; columns 2–8 (days)
CH255	10	6	12	6	12	5	12	9.0
CH257	10	10	12	9	12	9	13	10.6
CH260	9	8	12	9	10	7	10	9.1
Average interval (days)	9.7	8.0	12.0	8.0	11.3	7.0	11.7	9.7

Table 4
Helioparameters: coronal holes (CH), active regions (AR), maximum values of Solar wind speed (V_{max} of SW), planetary A index, and corresponding dates, were recorded. In the spacing between the rows, an interval between their consecutive occurrences is given (the interval of repetitiveness).

1 CH + AR	2 V_{max} of SW (km s^{-1})	3 SW (ACE)	4 $A_{\text{index,max}}$	5 Date of $A_{\text{index,max}}$	Average interval; columns 3 and 5 (days)
1 CH427+11123 Interval	828	12.11.2010 32	27	12.11.2010 33	32.5
2 CH430 Interval	757	14.12.2010 25	27	15.12.2010 22	23.5
3 CH432 Interval	690	08.01.2011 28	48	06.01.2011 29	28.5
4 CH435 Interval	617	05.02.2011 25	67	04.02.2011 25	25.0
5 CH438 Average interval (days)	713	02.03.2011 27.5	67	01.03.2011 27.2	27.4

Table 5
Meteorological data for the same CH and AR as is in the Table 4: dates when cold fronts passed over Belgrade, the dates of maximum (before cold front passing) and minimum (after cold front passing) temperature at levels of 500 and 850 hPa. In the spacing between the rows, the number of days between their consecutive occurrences is given (the interval of repetitiveness).

	6 CF	7 $t_{\text{max},500}$	8 $t_{\text{min},500}$	9 $t_{\text{max},850}$	10 $t_{\text{min},850}$
1	22.11.2010 33	22.11.2010 32	25.11.2010 33	22.11.2010 32	24.11.2010 35
2	25.12.2010 26	24.12.2010 24	27.12.2010 28	24.12.2010 25	28.12.2010 28
3	20.01.2011 28	17.01.2011 29	24.01.2011 29	18.01.2011 25	25.01.2011 29
4	17.02.2011 29	15.02.2011 30	22.02.2011 27	12.02.2011 33	23.02.2011 29
5	18.03.2011 Average interval (days)	17.03.2011 28.7	21.03.2011 29.2	17.03.2011 28.7	21.03.2011 30.2

date of the passage of the cold front was the date after that a significant drop in temperature occurred. In some cases, weakly expressed cold fronts passed by several days before and after the dominant cold front's passing. In the case of the cold front of 20 February 2011, the front did not pass directly over Belgrade. Nevertheless, due to expressed cyclonic circulation with a center located over the Mediterranean, the effect of feeding of cold air exists, and the advection of cold air is recorded as a cold front passes. Besides the cold front, the dates of appearance

of highest maximum temperature (before any cold front passing) and the lowest minimum temperature (after any cold front passing), the maximum and minimum temperature at isosurfaces of 500 and 850 hPa, the maximum and minimum of tropopause height and the dates with the maximum precipitation amount are determined. Additionally, the maximum speed of SW is taken into consideration. The maximum value of planetary A index and the date when it was measured are also given. After that, the time period before the re-appearance of any one

Table 6

Meteorological data: the dates of maximum (t_{max} , before cold front passing) and the minimum maximum ($t_{\text{max(min)}}$, after cold front passing) surface temperature, the maximum ($h_{\text{tp, max}}$) and minimum tropopause height ($h_{\text{tp, min}}$) and the dates that had experienced maximum precipitation (RR_{max}). In the spacing between the rows, the number of days between their consecutive occurrences is given (the interval of repetitiveness).

	11 t_{max}	12 $t_{\text{max(min)}}$	13 $h_{\text{tp, max}}$	14 $h_{\text{tp, min}}$	15 RR_{max}	Average interval; columns 6 (Table 5) to 15 (Table 6) (days)
1	21.11.2010	27.11.2010	22.11.2010	25.11.2010	23.11.2010	
	32	34	30	31	34	32.6
2	23.12.2010	30.12.2010	22.12.2010	25.12.2010	27.12.2010	
	25	24	26	31	26	26.3
3	17.01.2011	23.01.2011	17.01.2011	26.01.2011	22.01.2011	
	25	33	29	27	29	28.3
4	11.02.2011	25.02.2011	15.02.2011	22.02.2011	20.02.2011	
	30	23	27	24	29	28.1
5	13.03.2011	20.03.2011	14.03.2011	18.03.2011	21.03.2011	
Average interval (days)	28	28.5	28	28.2	29.7	28.8

particular parameter is calculated. Over this observed period, CHs and active regions (ARs), strictly speaking, had not had time to display repetitive trends, as pertains to of the Sun's rotation, and their appearances in geo-effective position. However, the time before the re-appearance of one particular solar or meteorological parameter indicated that its repetitiveness has an approximate value of one axial rotation of the Sun. Ultimately, the intervals between the date of SW recording, values of A index, the date of the passage of the cold front, the date on which maximum precipitation occurred, the date with the lowest maximum daily temperature, and the date with minimum temperature at 500 hPa are calculated. The results are given in Tables 4–8.

Time intervals between two consecutive appearances of a particular parameter are in basic agreement with the repeatability of SW and the A index (in average 27.5 days for SW, 27.2 days for A index, Table 4). These intervals for the cold front (CF) are 29.0 days, for date with maximum temperature at 500 hPa ($t_{\text{max,500}}$) 28.7 days, for date with minimum temperature at 500 hPa ($t_{\text{min,500}}$) 29.2 days, for date with maximum temperature at 850 hPa ($t_{\text{max,850}}$) 28.7 and for date with minimum temperature at 850 hPa ($t_{\text{min,850}}$) 30.2 days (Table 5). Therefore, roughly speaking, the time intervals between the re-appearance for all considered variables are 29 days.

The average number of days between two consecutive appearances of the surface maximum temperature, t_{max} , before crossing the cold front is 28 days. The lowest surface maximum temperature, $t_{\text{max(min)}}$, after the cold front pass, reappears, on average, after 28.5 days. For the maximum height of tropopause, $h_{\text{tp, max}}$, this number is 28 days, for the minimum height of the tropopause ($h_{\text{tp, min}}$) 28.2 days, and for the maximum precipitation (RR_{max}) 29.7 days (Table 6). The values between rows in Table 6 are the number of days between their re-appearance (repetitiveness). Average recurrence intervals of SW and $A_{\text{index, max}}$ are 27.4 days (Table 4), whereas for meteorological parameters they are 28.8 days (Tables 5 and 6).

In Table 7, the number of days between the dates of different recorded parameters is shown. The time interval from the moment when a strong increase of SW is recorded, to the moment of the passage of the cold front over the Belgrade region, on average, is 12.2 days. Exactly the same number of days is recorded between the maximum of planetary A index and the passage of the cold front. From the moment when a strong increase of SW appeared until the maximum precipitation (RR_{max}) appeared in Belgrade, 14.2 days would pass, on average. From SW to $t_{\text{max(min)}}$ were 16.2 days, and from SW to recorded $t_{\text{min,500}}$ passed 14.8 days. If we take out the exception of the fifth case with CH438, after SW registration, the lawfulness of occurrence of meteorological parameters over Belgrade, primarily the passage of the cold front over Belgrade and the appearance of days with maximum precipitation would be more noticeable.

A similar analysis is conducted also for recorded ARs in that period (Tables 8–11). In Table 8, the characteristics of three ARs, 11127, 11158 and 11166, along with the maximum value of A index is shown. In December 2010 and January 2011 there was not a significant influence of ARs on weather in the Belgrade region. In Table 9 the dates of the passing of the cold front over Belgrade, the dates of observed maximum ($t_{\text{max,500}}$ and $t_{\text{max,850}}$, before front passing) and minimum temperatures ($t_{\text{min,500}}$ and $t_{\text{min,850}}$, after front passing) at isobaric levels of 500 and 850 hPa at the period of before mentioned ARs are given. Similarly, in Table 10 the dates of maximum surface temperature (t_{max} , before the passage of the cold front), minimum of the maximum surface temperature ($t_{\text{max(min)}}$ after the passage of the cold front), maximum ($h_{\text{tp, max}}$) and minimum height of tropopause ($h_{\text{tp, min}}$) and maximum precipitation (RR_{max}) are given. The conducted analysis shows similar values as in Table 7: SW – CF 12.3 days, $A_{\text{index, max}}$ – CF 13.3 days, SW – RR_{max} 13.3 days, SW – $t_{\text{max(min)}}$ 15.7 days and SW – $t_{\text{min,500}}$ 16.7 days (Table 11). In these examples, the analysis confirmed the basic relationship – the time correlation between SW and cold air advection over Belgrade.

Table 7

Number of days between the dates of occurrences of the different parameters.

	SW – CF	$A_{\text{index,max}} - \text{CF}$	SW – RR_{max}	SW – $t_{\text{smax(min)}}$	SW – $t_{\text{min,500}}$	Average interval (days)
1	10	10	10	12	10	10.4
2	11	10	13	16	13	14.6
3	12	11	14	15	16	13.6
4	12	13	15	20	16	15.2
5	16	17	19	18	19	17.8
Average value (days)	12.2	12.2	14.2	16.2	14.8	13.9

Table 8

Helioparameters: active regions (AR), maximum velocity of SW (km s^{-1}), the maximum of planetary A index and the corresponding recorded dates.

	AR	V_{max} of SW (km s^{-1})	SW (ACE)	$A_{\text{index,max}}$	Date of $A_{\text{index,max}}$
6	11127	520	27.11.2010	67	27.11.2010
7	11158	644	18.02.2011	39	18.02.2011
8	11166	576	14.03.2011	94	11.03.2011

Table 9

Meteorological data: dates of cold front passing Belgrade, dates of maximum temperature (before front passing) and minimum temperature (after front passing) at levels of 500 and 850 hPa.

AR	CF	$t_{\text{max,500}}$	$t_{\text{min,500}}$	$t_{\text{max,850}}$	$t_{\text{min,850}}$
6	09.12.2010	06.12.2010	14.12.2010	08.12.2010	15.12.2010
7	01.03.2011	02.03.2011	07.03.2011	28.02.2011	08.03.2011
8	28.03.2011	24.03.2011	30.03.2011	25.03.2011	29.03.2011

Table 10

Meteorological data: dates of maximum surface temperature (t_{smax} , before the passage of the cold front), minimum of the maximum surface temperature ($t_{\text{smax(min)}}$ after the passage of the cold front), maximum ($h_{\text{tp,max}}$) and minimum height of tropopause ($h_{\text{tp,min}}$) and maximum precipitation (RR).

AR	t_{smax}	$t_{\text{smax(min)}}$	$h_{\text{tp,max}}$	$h_{\text{tp,min}}$	RR_{max}
6	08.12.2010	17.12.2010	06.12.2010	15.12.2010	09.12.2010
7	28.02.2011	02.03.2011	02.03.2011	07.03.2011	03.03.2011
8	25.03.2011	29.03.2011	24.03.2011	29.03.2011	29.03.2011

Table 11

Number of days between dates when particular events are registered.

AR	SW – CF	$A_{\text{index,max}} - \text{CF}$	SW – RR_{max}	SW – $t_{\text{smax(min)}}$	SW – $t_{\text{min,500}}$	Average interval (days)
11127	12	12	12	20	17	14.6
11158	11	11	13	12	17	12.8
11166	14	17	15	15	16	15.4
Average (days)	12.3	13.3	13.3	15.7	16.7	14.3

3.3. Repetitiveness of tropical cyclones (hurricanes) during the 2005 season over the Atlantic Ocean

As we already mentioned, if we find some period of repetitiveness in a small region, it should be likely that the same or similar periods of repetition be valid for larger areas as well. To show this, we tried to track CHs impact on hurricane development.

The record number of tropical cyclones in the Atlantic Ocean was observed during the 2005 season. Three of them, Katrina, Rita and Wilma, were the strongest and

had catastrophic consequences: deaths, injuries, and material damage. In another example, we analyzed repetitiveness of tropical cyclones in correlation with the parameters of SW. Such strong hurricanes could be a consequence of high-energy regions on the Sun. These regions last for a longer period of time, and were recorded to appear in geo-effective position over the course of several rotations of the Sun. We analyzed the interval of repetition between CH, AR and hurricane stage development, which is characterized by minimum pressure at the center of the hurricane and by maximum wind. The data was

Table 12
Solar wind parameters.

	1 CH + AR		2 V_{\max} of SW (km s ⁻¹)	3 SW (ACE)
1	CH183, S583	Katrina	556	21.08. 17 h
Interval				24 days 22 h
2	S583	Rita	787	15.09. 15 h
Interval				25 days 9 h
3	CH192, S583	Wilma	624	11.10. 00 h
Average (days)				25 days 3 h

Table 13
Characteristic of the studied hurricanes.

		4 P_{\min} (mb)	5 V_{\max} (kt)	6 Date of P_{\min} and V_{\max}	7 Origin longitude (°N)	8 Origin latitude (°E)
1	Katrina	902	150	28.08. 18 h	75.1	23.1
Interval				24 days 12 h	5.2	2.2
2	Rita	897	155	22.09. 6 h	69.9	21.3
Interval				27 days 6 h	8.6	3.7
3	Wilma	882	160	19.10. 12 h	78.5	17.6
Average (days)				25 days 21 h		

Table 14
Hurricane stage development (TD-tropical depression, TS-tropical storm, H-hurricane).

	Hurricane	9 TD	10 TS	11 H	12 TS	13 TD
1	Katrina	23.08. 18 h	24.08. 12 h	26.08. 00 h	30.08. 00 h	30.08. 12 h
Interval		25 days 6 h	26 days 6 h	25 day 12 h	25 days 18 h	26 days 18 h
2	Rita	18.09. 00 h	19.09. 18 h	20.09. 12 h	24.09. 18 h	25.09. 06 h
Interval		28 days 18 h	29 days 00 h	28 day 00 h	31 days 6 h	31 days 18 h
3	Wilma	15.10. 18 h	17.10. 18 h	18.10. 12 h	26.10. 00 h	27.10. 00 h
Average (days)		27 days 0 h	27 days 15 h	26 days 18 h	28 days 12 h	29 days 08 h

Table 15
Time interval between the dates of a strong increase of Solar wind and the phases of hurricane development (TD-tropical depression, TS-tropical storm, H-hurricane).

	SW (ACE) – TD	SW (ACE) – TS	SW (ACE) – H	SW (ACE) – date of P
1	2 day 1 h	2 days 19 h	4 days 7 h	7 days 1 h
2	2 days 9 h	4 days 3 h	4 days 21 h	6 days 12 h
3	4 days 18 h	6 days 6 h	7 days 12 h	7 days 12 h
Average (days)	3 days 1 h	4 days 9 h	5 days 13 h	7 days 0 h

downloaded from www.nhc.noaa.gov, from the Tropical Cyclone Report of the National Hurricane Center. The results are shown in Tables 12–15.

The time of recurrence between spotted high-energy regions on the Sun is approximately 25 days (Table 12), and it accounts for maximum values of velocity and minimum values of pressure is nearly 26 days (Table 13).

The period between hurricane Katrina and hurricane Rita during the stage of tropical depression (TD) was 25 days and 6 h and during the stage of development (i.e. stage of tropical storms, TS) was 26 days and 6 h (Table 14). It could be concluded that the time interval between the stages of Katrina and Rita's development is

slightly reduced, and between Rita and Wilma slightly increased, due to the fact that the velocity of SW in the case of Hurricane Rita (Table 12, column 2) is considerably greater. Likewise, locations of their TD formation are at nearly the same geographic coordinate, and that is in accordance to the assumption that TD are a consequence of the Sun's high-energy regions; after one rotation of the Sun, they find themselves at approximately same geoeffective position. There is a shift, and it favors this hypothesis, because the position of TD origin is closer to the equator for nearly as much as the Sun ostensibly moves toward the Equator. The average interval between different phases in the development of tropical cyclones is

27–29 days (Table 14). Table 15 gives the time intervals between the dates of monitoring a strong increase of SW at ACE satellite and a particular phase in tropical cyclone development. In the three analyzed cases here, the phase of TD occurred after 3 days, on average (2 to 4 days), while the phase of hurricanes appeared for approximately 5 days (4 to 7 days), and the minimum pressure in the hurricane for 7 days, after SW observation at ACE satellite. That means that there is a correlation between SW and tropical cyclone development, and that this correlation could be useful in forecasting hurricane development. Proposed mechanism of this relation is, therefore, the mechanism of energetic particles. Nevertheless, it is not straightforward, due to the complexity of this relationship. This requires further research and establishment of more exact correlation between space weather and the characteristics and development of tropical cyclones.

4. Discussion and conclusion

Solar wind velocities and temperatures from coronal holes CH255, CH257, CH260 and CH254, CH256, CH258 show different kinetic energy that consequently yield different occurrences in the Earth's atmosphere. The energy of Solar wind and interplanetary magnetic field that penetrate the Earth's atmosphere is never the same. In addition, cyclone trajectory and life cycles, cold air streams and movement of cold air fronts are never the same. However, there are situations when, based on the state of the Sun, certain weather patterns could be expected in the Earth's atmosphere. That means if our hypothesis about a direct relationship between Solar wind and cyclone circulation can be proceed, we could establish weather patterns that could be similar, depending on the occurrence of coronal holes. That could be the basis of long-range weather forecast, as one of the authors already advocates (Radovanović et al., 2005).

We found for the Belgrade region, a cycle of 27–29 days for the passage of the cold front, and maximum and minimum temperatures measured at surface (precisely at 2 m) and at levels of 850 and 500 hPa. This established a cycle of 27–29 days between observation of coronal holes and cold air advection over the Belgrade region, although it is not uniquely determined (because of different space weather and meteorological parameters). Nevertheless, it is possible to yield approximate forecasts for the date, intensity and lifetime of a significant cold air advection over the course of the subsequent two to three rotations of the Sun (e.g. the 27-day rotation of the Sun could be regarded as a meteorological month) in situations when there are dominant coronal holes visible on the Sun's surface.

We observed that, in two different cases (for three and five successive rotations of the Sun), if the arrival of Solar wind is observed at the satellite, we could expect the passage of the cold front over the Belgrade region 10–12 days after said observation. Eight days after SW is recorded at

the satellite, the maximum values of the maximum surface temperature and the temperature at the level of 850 hPa are measured. After nearly 12 days, the minimum values of these temperatures are observed, including the minimum temperature at the level of 500 hPa. The minimum value of the maximum surface temperature at Belgrade region appears after 12–16 days after observed Solar wind. The maximum amount of precipitation occurs 14 days after Solar wind is observed.

The relationship between repetitiveness of coronal holes and active regions, and advection of cold air over Belgrade are not unambiguously determined, due to the influence of many of solar and meteorological parameters. Nevertheless, the analysis shows that it is possible to forecast the dates, intensity and duration of particular advections of cold air on the basis of solar parameters. Our analysis showed that there is clear time correlation between solar and meteorological parameters.

In addition, we analyzed the period from Solar wind appearance to the different stages of the development of hurricanes in the example of three hurricanes over the Atlantic. The data shows that after 2–4 days after Solar wind is measured, the tropical depression stage occurred, after in average 4 days the tropical storm occurred and hurricane phase occurred after nearly 5 days. However, this relationship is very complex and requires further research to establish a more accurate correlation between certain parameters of Solar wind and characteristics of tropical cyclones.

This analysis confirmed that intervals of time between two appearances of some particular meteorological parameter are in good correlation with Solar wind and A index. In addition, the number of days between the dates analyzed shows a time correlation between solar and meteorological parameters. The results in all three cases support this. Determining the repeatability of weather patterns gives us space to confirm the hypothesis that processes in the Earth's atmosphere are a consequence of the Sun's activity.

Every particular meteorological synoptic situation, depth, speed and the trajectory of cyclone with belonging frontal systems govern when cold air advection will appear. Furthermore, many different helioparameters that are not explicitly considered here, such as temperature and velocity of the Solar wind, the duration of particle flow, the energetic structure of particles, the chemical composition of Solar wind, the characteristics of accompanying magnetic fields, all play an important role in that analysis. However, because of the complexity of the process, it is very difficult assign the relevance of particular parameter due to their overlapping. Our intention in further research is to analyze how repetitiveness of different meteorological parameters depends on different characteristic of Solar wind.

Acknowledgment

The Serbian Ministry of Education and Science partly supported this study under Grant 176013.

References

- Aslam, O.P.M., Badruddin, in press. Study of the influence of solar variability on a regional (Indian) climate: 1901–2007. *J. Adv. Space Res.* <<http://dx.doi.org/10.1016/j.asr.2014.06.019>>.
- Davydova, Y.I., Davydov, V.V., 1996. Solar periods and meteorological parameters of the Earth's atmosphere. *Geomag. Aeron.* 35 (6), 857–859.
- Elsner, J.B., Kavvakov, S.P., 2001. Hurricane intensity changes associated with geomagnetic variation. *Atmos. Sci. Lett.* 2, 86–93.
- Elsner, J.B., Jagger, T.H., 2008. United States and Caribbean tropical cyclone activity related to the solar cycle. *Geophys. Res. Lett.* 35, L18075.
- Heredia, T., Elias, A.G., 2013. A study of possible solar and geomagnetic effects on the precipitation over northwestern Argentina. *J. Adv. Space Res.* 51, 1883–1892.
- Kavvakov, S., Pérez-Peraza, J., Elsner, J.B., 2008. A statistical link between tropical cyclone intensification and major geomagnetic disturbances. *Geofísica Internacional* 47, 207–213.
- Lilensten, J., Bornarel, J., 2006. *Space Weather, Environment and Societies*. Springer, Dordrecht.
- Mendoza, B., 2011. The effects of space weather on hurricane activity, recent hurricane research – Climate, dynamics, and societal impacts, Anthony Lupo (Ed.), ISBN: 978-953-307-238-8, InTech. doi: 10.5772/14070. Available from: <<http://www.intechopen.com/books/recent-hurricane-research-climate-dynamics-and-societal-impacts/the-effects-of-space-weather-on-hurricane-activity>>.
- Mendoza, B., Pazos, M., 2009. A 22-yr Hurricane cycle and its relation to geomagnetic activity. *J. Atm. Solar-Terr. Phys.* 71 (17–18), 2047–2054.
- Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., Halimeda Kilbourne, K., Quinn, T.M., 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* 447, 698–702.
- Radovanović, M., Lukić, V., Todorović, N., 2005. Heliocentric electromagnetic long-term weather forecast and its applicable significance. Collection of papers of Geographical Institute “Jovan Cvijić”, No. 54, pp. 5–18.
- Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., Waple, A., 2001. Solar forcing of regional climate change during the Maunder minimum. *Science* 294, 2149–2152.
- Stevančević, M., Todorović, N., Radovanović, M., Ducić, V., Milenković, M., 2008. Belgrade School of Meteorology, 1, 199–209, Belgrade, 260 pp, (in Serbian).
- Tinsley, B.A., 2000. Influence of solar wind on the global electric circuit, and inferred effects on cloud microphysics, temperature and dynamics in the troposphere. *Space Sci. Rev.* 94, 231–258.
- Tlatov, A.G., in press. The change of the solar cyclicity mode. *J. Adv. Space Res.*, <<http://dx.doi.org/10.1016/j.asr.2014.06.024>>.
- Todorović, N., Vujović, D., 2007. The relationship between coronal holes and cold air advection in Belgrade region. In: 8th European Conference on Applications of Meteorology, San Lorenzo de El Escorial, Spain, 1–5 October 2007, Abstracts, 4, EMS2007-A-00440.
- Veretenenko, S.V., Dergachev, V.A., Dmitriyev, P.V., 2007. Solar activity and cosmic ray variations as a factor of intensity of cyclonic processes at midlatitudes. *J. Geomag. Aeron.* 47, 399–406.
- Landscheidt, T., 2000. Solar wind near Earth: indicator of variations in global temperature. European Space Agency Special Publication 463, 497–500, www.nasa.gov <<http://www.dxlc.com/solar/http://umtof.umd.edu/pm/http://www.solen.info/solarwww.nhc.noaa.gov>>.