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Influence of atmospheric circulation on the spatial distribution of precipitation in the area of Sofia city

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ABSTRACT

The study aims to reveal spatial distribution of precipitation in the area of Sofia city during the decade 2013 - 2022 and the influence of atmospheric circulation. Statistical methods and cartographic approach are the main tools in this research. The spatial distribution of precipitation is characterized by low amounts (560 mm) in the northern and northeastern parts of Sofia depression and high amounts (760 mm) in the southern part. The main factor for this spatial distribution of precipitation is atmospheric circulation. The relief has a significant modifying effect and affects precipitation through several mechanisms. The most important is the location of mountain slope relative to the main direction of transport of air masses. Leeward slopes receive less precipitation and windward slopes receive more. The second mechanism of influence is anthropogenic relief (high buildings), which is a positive relief form compared to the surrounding plane having respective windward and leeward slopes. This study revealed a third mechanism of relief influence on spatial distribution of precipitation. The large difference in the height of the mountains located south of Sofia creates a significant difference in the air temperature in Sofia depression during a transport of air masses from south and southwest. This is due to the stronger foehn effect of the higher mountain (Vitosha) compared to the foehn effect of the lower mountains (Lyulin, Lozenska Planina), which creates a tongue of higher air temperature northeast of Vitosha, which reaches the southern and southwestern slopes of Stara Planina. The higher temperatures in this tongue create stronger upward air movements, which in turn increase the amount of precipitation. Secondary, but still important factors that affect the spatial distribution of precipitation in Sofia region are the urban heat island and the increased content of aerosols in the air in and over the city.

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1. Introduction

Precipitation is one of the most important elements of climate. It affects all spheres of human life – agriculture, energy, transport, etc. The emergence and development of settlements is directly related to the presence of a water source in the immediate vicinity. On the other hand, precipitation can also have a negative impact. Heavy and intense rainfall can lead to floods that cause significant damage to the economy of a place and claim human lives. In certain places and seasons of the year with lower air temperatures, the precipitation is snow, and when the amounts are high, a significant snow cover forms, which can paralyze life in that area. That is why, the study of precipitation at different spatial and temporal scales is particularly important.

There are a number of new (from this century) studies on precipitation for the entire territory of Bulgaria - Nikolova (2004), Topliyski (2005), Velev (2006), Nojarov (2017a), Nikolova et al. (2021). Other studies refer to different parts of the country such as the Danube Plain (Nikolova and Vassilev 2005), the lower course of the Danube River (Nikolova and Boroneant 2011), southern Bulgaria (Nikolova and Mochurova 2012), the high mountain parts of Bulgaria (Nojarov 2012). On the other hand, there are not many

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studies on precipitation amounts and their spatial distribution in the area of Sofia city (Dimitrov and Stankov 1966; Hristov and Tanev 1978; Blaskova et al. 1983; Nojarov and Vlaskov 2013). Blaskova et al. (1983) have examined the spatial distribution of precipitation over a 12-year period (1954-1965) based on measurements at 25 stations. The lowest precipitation amounts are observed in the northeastern part of Sofia depression, and the highest - in its southern periphery. The central part of Sofia city shows an increase in precipitation. There is also a certain patchiness in its distribution, a fact that was also noted by Dimitrov and Stankov (1966).

Cited above studies on precipitation in and around Sofia city are based on an older period. In view of the changes in climate that have occurred, new research on the subject is needed. The purpose of the article is to reveal spatial distribution of precipitation in the area of Sofia city during the last decade (2013 - 2022). The influence of atmospheric circulation on this distribution is also clarified, since climate changes have a particularly strong impact on atmospheric circulation at global and regional (Bulgaria) scale. Accordingly, the spatial distribution of precipitation during one or another direction of air mass transport can be an important tool for future period's projections. This is due to the fact that projection of the direction of atmospheric transport for a given territory is more reliable and stable compared to the projection of precipitation.

2. Study area

Sofia depression morphostructure is developed upon Sofia graben. It is located between Stara Planina to the north with its sections Chepan, Mala Planina, Sofia Planina and Murgash and the mountains of Srednogorie - Viskyar, Lyulin, Vitosha and Lozenska Planina to the south. Its west-northwest border is defined by the Dragoman watershed ridge, and its east-southeast border - by the Vakarel heights. It includes Sofia depression, the surrounding slopes with an incline of 5° to 12° (from 6° to 10° in Dragoman watershed ridge and Vakarel heights) and the internal to the depression heights - "Tri ushi" - 898 m, "Center "- 770 m, Slivnishki heights - Gradishte peak - 725 m, "Golyamata mogila" - 717 m near Pozharevo, Hrabarsky heights - 755 m and 681 m, "Baba" - 687 m near Doganovo village, "Koriyata" - 687 m near Gorna Malina village, "Golyama Konyovitsa" - 653 m and Simeonovsko height - 650 m.

The upper border of the foothills of Stara Planina reaches 750 m a.s.l., but in Mala Planina, the border drops to 650 m. The upper border of foothills of Srednogorie is higher and reaches 800 m at Lyulin Mountain and 900 m at Vitosha. The lower limit of the foothills is a weakly expressed fold with an incline of 1° to 3° and 550 m altitude.

Within these geomorphological borders, the depression morphostructure occupies an area of 1380 km² - 850 km² foothills and 530 km² depression floor (Kanev 1989). Its average altitude is 530 m.

Several foothill steps can be distinguished in the foothills belt. The karst steps are well expressed in the western part of Sofia depression. In the southern and southwestern parts of the depression, wide steps are developed on poorly consolidated lake sediments in the foothills of Vitosha, Viskyar and Lyulin mountains. There are morphostructural steps in the eastern foothill belt with small depressions embedded in them - Saranska and Dolnokamarska. The internal to the depression heights of volcanogenic and tightly consolidated rocks have had formed the bottom of the Pleistocene Sofia Lake.

The Sofia field is developed along the long axis of the depression. The rivers Iskar, Blato, Lesnovska and several of their smaller tributaries pass through it. There are several swamps formed on the valley bottoms of the rivers Iskar, Blato, Lesnovska, and most of them are dried up. Slivnishtsko and Dragomansko karst swamps are located in the foothills belt. Along the valley of Iskar river, several man-made lakes have been formed as a result of mining activities.

The entire range of terraces along the river valleys can be observed in the depression, and a series of alluvial cones of different ages can be seen in the southern foothills. The depression's threshold near the town of Novi Iskar has an important orographic significance.

Within its administrative boundaries, the Sofia city district has an area of 1311 km^2, of which settlements and urbanized areas occupy 255.81 km², agricultural areas in the depression have an area of 462.80 km², forests - 442.2 km², landscaped areas - 19.27 km², the territories for transport and infrastructure – 88.92 km² and water courses and water areas – 51.60 km². The population of the city of Sofia in the end of 2022 is 1 280 334 (17.5% of the country's population). It is concentrated in the heavily built-up central and southern parts of the depression (Vlaskov and Simeonov 1992). The city is located on the depression's floor (52%) and foothills (48%).

Urban environment creates specific living conditions for people (Vlaskov 2000). Geomorphological characteristics of the depression, built-up area and infrastructure define zones with local microclimatic conditions in the city of Sofia with population exceeding one million (Blaskova et al. 1983).

Based on the available information and the meteorological stations that are used in this study, the south and north boundaries of the studied area are determined by the border between the depression and the corresponding mountains - Lyulin, Vitosha and Lozenska Planina to the south and Stara Planina to the north. The west boundary is generally along the meridian 23.1°E, and the east - along the meridian 23.7°E.

The city of Sofia is located in the subtropical zone (Nojarov 2017b), but its higher altitude determines some specific characteristics of its climate. The average annual air temperature for the period 1991-2020 is 10.9°C (National Institute of Meteorology and Hydrology station), but the current values are around 11.5°C, which is due to the constant rise of air temperature. The average annual amount of precipitation is about 620 mm (NIMH station), however, this amount varies across the territory of Sofia depression as revealed in the present study. The maximum of precipitation is in June and the minimum is in January. Wind speeds are low due to the fact that Sofia depression is a negative landform and therefore it is wind protected. However, in certain synoptic conditions (wind from south-southwest), very high wind speeds can be observed, especially in the southern periphery of the depression, where the foehn effect is strongest. The prevailing wind direction over Sofia depression region at 850 hPa level in the atmosphere for the period 2013–2022 is shown in Fig. 1. Panel A is wind rose representing winter (December, January, and February) months, and panel B is wind rose representing summer (June, July, and August) months. The figure shows the frequency of months (belonging to the relevant season, a total of 30 per season for the studied period) with wind from the 8 directions. Fig. 1A shows that in winter the main wind direction over the city of Sofia is westerly. However, in summer (Fig. 1B), the main wind direction is north-northeasterly. This significant difference is due to the typical atmospheric circulation during these seasons (Nojarov 2021, Nojarov 2023).

3. Data and methods

This study uses data from 10 meteorological stations located in Sofia depression (Table 1). These stations operate both manually and automatically. The research period is 2013 – 2022 and is based on the beginning of the operation of the rain gauge station at the National

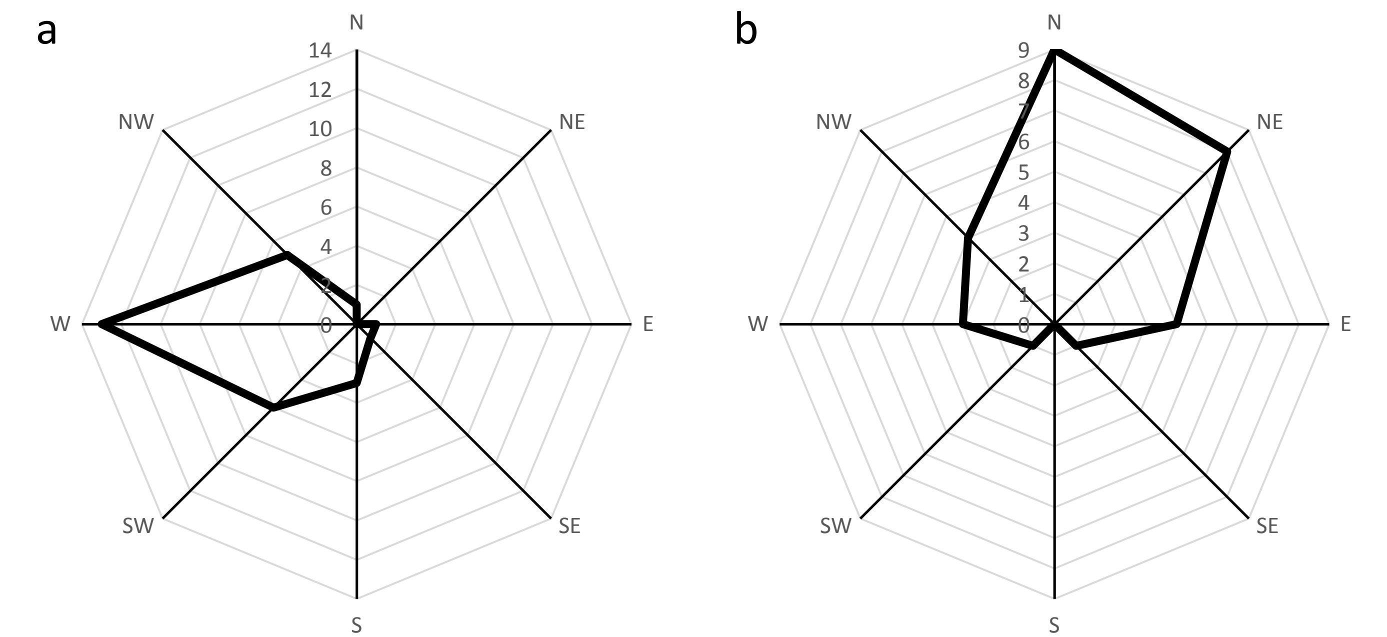

Figure 1. Wind rose for the winter (December, January and February) months (A) and summer (June, July and August) months (B) in the Sofia depression region at 850 hPa level in the atmosphere for the period 2013 – 2022 (number of months per 8 main wind directions).

Institute of Geophysics, Geodesy and Geography (NIGGG), Bulgarian Academy of Sciences in April 2012. Thus, the first full year with measurements was 2013. The following stations are also included in the study - National Institute of Meteorology and Hydrology (manual measurement), Automatic Meteorological Station (AMS) Kazichene, AMS Boyana, AMS Lozen, AMS Lyulin, AMS Novi Han, AMS Novi Iskar, AMS Bankya, AMS Orlandovtsi. As can be seen in Table 1, the stations are located at altitudes from 527 m (Novi Iskar) to 754 m (Boyana). Seven of the stations have precipitation measurements during the entire study period. AMS Orlandovtsi has started its operation in May 2014. The stations in Lyulin and Bankya have ended their operation in the end of 2019. The check of the precipitation amounts at other stations has showed that 2020 has average precipitation amounts, 2021 has above average precipitation amounts and 2022 has below average precipitation amounts. Thus, the absence of these three years does not change the average amounts at these two stations, which is the reason for their inclusion in the study. Six of the automatic stations lack data for precipitation amounts in January 2017 due to the fact that air temperature was very low during the entire month and automatic stations that do not have their own heating were not able to successfully measure precipitation. There are no data for the period 06-09.2016, 08.2017 and for the period 02-05.2018 at Lyulin station. There are no data for 11.2022 at Novi Iskar station. The data from all stations were checked for homogeneity using the ratio method. The base stations were the two stations with manual measurements - NIGGG and NIMH. The aforementioned missing months at some automatic stations were removed because they failed the homogeneity test.

Calculation of the direction of air mass transport over the city of Sofia in a given month is based on data from The European Center for Medium-Range Weather Forecasts (ECMWF), ERA5 reanalysis (Copernicus Climate Change Service (C3S) 2017). The resolution of these data is 0.25 x 0.25° (30 x 30 km). The area of Sofia city at this resolution is covered by one grid cell with coordinates of the center 43.75°N, 23.25°E. The data used in this study are for U-wind (west-east direction, west direction is plus sign) and V-wind (south-north direction, south direction is plus sign) at 850 hPa level. This level is the lowest level in the atmosphere, where the movement of air masses is relatively uninfluenced by the earth's surface. U-wind is the projection of the wind vector on the abscissa and V-wind is the projection of the wind vector on the ordinate. Thus, the wind direction angle was calculated using the following formula:

Table 1. List of the 10 meteorological stations used in this study with their coordinates, altitude and period of operation.

Station	Coordinates	Altitude (m.a.s.l.)	Period of operation
NIGGG	42.68°N 23.37°E	576	2013-2022
NIMH	42.65°N 23.38°E	592	2013-2022
Boyana	42.64°N 23.28°E	754	2013-2022
Kazichene	42.66°N 23.46°E	542	2013-2022
Lozen	42.60°N 23.47°E	685	2013-2022
Novi Han	42.61°N 23.59°E	623	2013-2022
Orlandovtsi	42.72°N 23.35°E	530	05.2014-12.2022
Novi Iskar	42.81°N 23.35°E	527	2013-2022
Lyulin	42.71°N 23.25°E	588	01.2013-01.2020
Bankya	42.71°N 23.15°E	665	10.2013-12.2019

$$\alpha = arctan\frac{Vwind}{Uwind}$$

where,

α is the angle of the wind vector with the abscissa of the coordinate system

U_{wind} and V_{wind} are the values as stated above

According to the coordinate system, angle 0° is north direction (corresponds to the positive part of the ordinate), angle 90° is east direction (corresponds to the positive part of the abscissa), angle 180° is south direction (corresponds to the negative part of the ordinate) and angle 270° is west direction (corresponds to the negative part of the abscissa). The actual wind angle is calculated by suitably adding or subtracting the angle α to the abscissa, which, as mentioned above, can have a value of either 90° or 270°.

After obtaining the real direction of the wind at 850 hPa level, the entire circumference of the horizon was divided into 8 sections (directions), according to which the study of the influence of the atmospheric circulation on precipitation amounts in the area of Sofia city was carried out (Fig. 1). North direction includes wind vector angles from 337.5° to 22.5°, northeast direction - from 22.5° to 67.5°, east direction - from 67.5° to 112.5°, southeast direction - from 112.5° to 157.5°, south direction - from 157.5 ° to 202.5°, southwest direction – from 202.5° to 247.5°, west direction – from 247.5° to 292.5° and northwest direction – from 292.5° to 337.5°.

In the next step, the monthly precipitation data of the 10 studied stations were sorted according to the above-mentioned 8 directions of air mass transport. Then, for each direction, for each station, precipitation values of the months that belong to the corresponding direction were averaged. Thus, average monthly precipitation values are obtained for each station for each of the 8 directions of air mass transport.

In order to determine the causes for a certain type of spatial distribution of precipitation, it became necessary to use data for air temperature in the area of Sofia city. Referring to Table 1, two stations had to be excluded - the NIGGG station, where air temperature is not measured, and AMS Lyulin, where, after conducting a homogeneity test using the method of differences, too many months had bad data. AMS Bankya can be included in the study because 2020 has above average air temperature, 2021 has below average air temperature, and 2022 has average air temperature. After checking the homogeneity of air temperature data at the remaining stations, more months had to be removed compared to precipitation data, which has led to the use of four wind directions instead of eight. Thus, the averages are based on a larger sample and are therefore more reliable. Also, in order to avoid the influence of the altitude, the difference between air temperature value for specific month and the average air temperature for the entire studied period was calculated for each station. In this way, the resulting spatial distribution of air temperature is not affected by the altitude of each station.

This study uses mainly statistical methods (Wilks 2006). The level of statistical significance for all calculations is $p < 0.05$. Spearman's rank correlation was used in order to establish the relationships between atmospheric circulation (expressed by U-wind and V-wind) and precipitation in the area of Sofia city. The advantage of this correlation is that it does not depend on the type of statistical distribution of the variables. The research also uses the cartographic approach to data interpretation. The main interpolation method is kriging.

4. Results and discussion

Fig. 2 shows spatial distribution of annual precipitation amounts in Sofia city area for the period 2013 - 2022. In general, precipitation increases in the direction from northeast to south-southwest. At the southwestern foothills of Stara Planina, the values are around 560 mm, while at the northern foothills of Vitosha they are around 760 mm. A similar spatial distribution of precipitation was established by Blaskova et al. (1983) for the period 1954 – 1965. It could be concluded that this distribution of precipitation is stable over time, regardless of the fact that the study periods are relatively short - 12 years in the older study and 10 years in the present study. Approximately the same spatial distribution was obtained for a period of 1 year by Nojarov and Vlaskov (2013). The difference between the lowest and the highest values is about 200 mm (30%), which indicates a relatively large variability of precipitation within Sofia depression. That is why there is a need for a detailed approach in the study of precipitation in this area, which will lead to better planning and implementation of measures to prevent adverse and dangerous precipitation related phenomena. The other thing that stands out in the figure is the relative increase in precipitation along the axis center-north of Sofia city, based on the data from Orlandovtsi station. The increased amounts in this AMS are also confirmed by AMS Banishora, located a little further south of Orlandovtsi. It is not included here due to the fact that it has a short measurement period. Blaskova et al. (1983), and Dimitrov and Stankov (1966) have found the presence of an island with increased precipitation in the central and northern parts of Sofia city. It largely coincides with the area of increased precipitation seen in Fig. 2. The explanation of this island given in the previous two studies is based on two phenomena characteristic of any big city. First, a so-called heat island is formed within the city, associated with greater energy consumption. This higher temperature leads to stronger upward movements of the air, leading to an increase in precipitation. The other phenomenon is greater air pollution in and over the city, leading to increased aerosol content. Aerosols, in turn, are condensation nuclei for the formation of droplets in the air and this favors increased precipitation over the respective area. These two processes are fully valid in the recent study period as well. However, Fig. 2 also shows something different. In the 1950s and 1960s, city parts such as Mladost and Lyulin did not exist. In the study of Dimitrov and Stankov (1966), the NIMH station in Mladost is considered to be outside the city. Currently, this station (as well as other stations) is within the city limits. According to the above-mentioned two phenomena, an increase in precipitation amounts should also be observed in these stations. However, this is not exactly the case referring to Fig. 2. There is obviously another cause for the observed increase in precipitation in the central and northern parts of Sofia city. Clarification of this cause will be sought through the influence of atmospheric circulation, which is suggested as a possible factor by Dimitrov and Stankov (1966), who cite Godev (1965), who points out the important role of orography in modifying air flows and hence precipitation.

The influence of atmospheric circulation is checked using Spearman correlation between monthly precipitation amounts at the stations and U-wind and V-wind at 850 hPa level for the period 2013 - 2022. The results are shown in Table 2. Correlation coefficients between U-wind (west-east direction) and precipitation at the ten studied stations are of different sign and they are not statistically significant. This means that the zonal direction of transport of air masses does not have a significant influence on precipitation in the area of Sofia city. Correlation coefficients between V-wind and precipitation are positive for all stations, and at three of them (Boyana, Orlandovtsi and Novi Iskar) they are statistically significant. Overall, these results show higher precipitation amounts when the transport of air masses is from south and lower precipitation amounts when the transport of air masses is from north, i.e. the meridional transport of air masses has more significant effect on precipitation in the studied territory compared to the zonal one during the period 2013 - 2022.

The spatial distribution of precipitation in the area of Sofia city, based on the direction of air mass transport, is shown in the following figures. The results are for monthly precipitation amounts averaged for the months with the respective transport of air masses. Fig. 3A shows spatial distribution of precipitation when

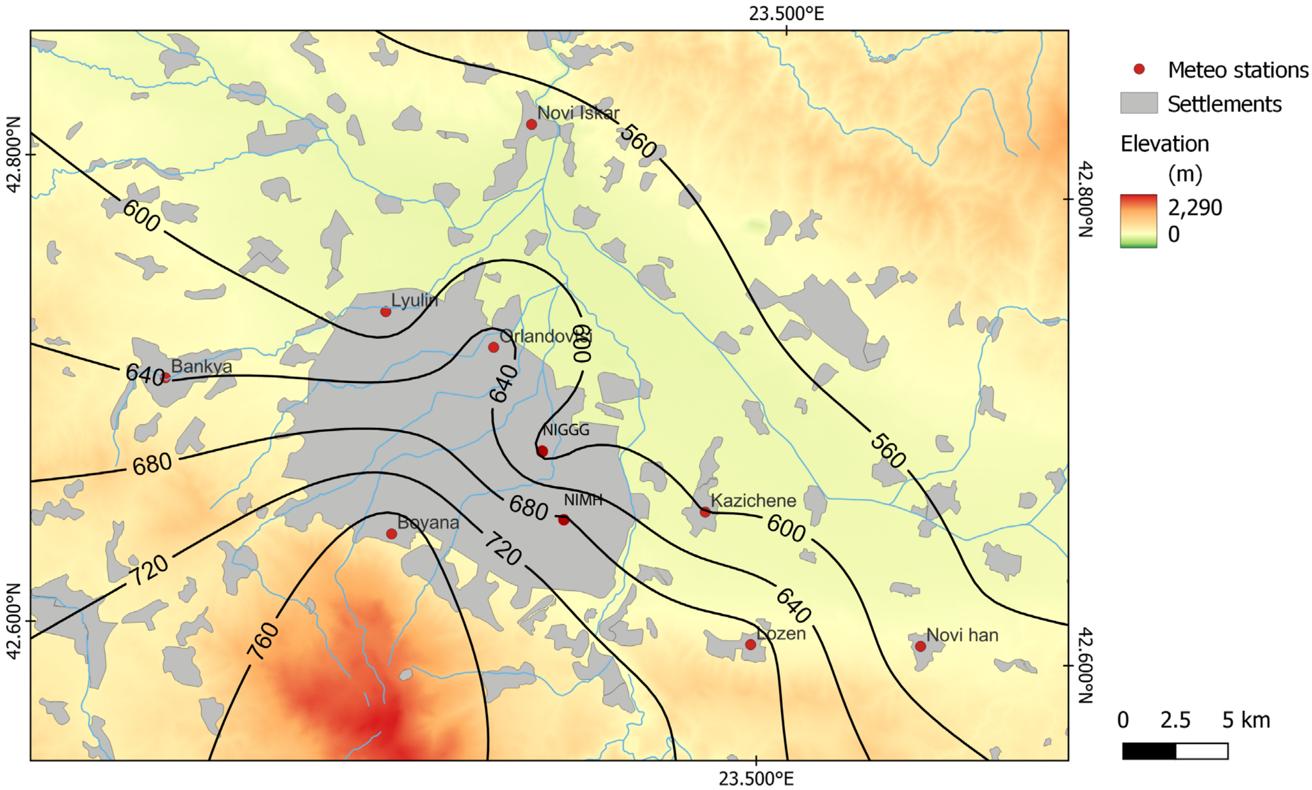

Figure 2. Spatial distribution of annual precipitation amounts (in mm) in the area of Sofia city for the period 2013 - 2022.

Table 2. Spearman's correlation coefficients between the monthly precipitation amounts at the 10 stations and U-wind and V-wind at 850 hPa level for the period 2013 – 2022.

Precipitation at station	U-wind 850 hPa	V-wind 850 hPa
NIGGG	0.03	0.12
NIMH	-0.01	0.06
Boyana	0.10	0.22
Kazichene	-0.01	0.08
Lozen	0.08	0.12
Novi Han	-0.02	0.11
Orlandovtsi	0.13	0.22
Novi Iskar	0.04	0.19
Lyulin	0.09	0.12
Bankya	0.06	0.16

the transport is from north. In general, precipitation increases from north to south from about 45 mm to about 60 mm. The orography can be considered as the main factor, and accordingly the windward slopes (the northern slope of Vitosha) receive more precipitation compared to the leeward slopes (the southern slope of Stara Planina). There is also an increase in the northern part of Sofia. This may be due to the fact that this part of the city is also a kind of windward slope, because the urban environment with its high buildings is a positive relief form compared to the plain part of Sofia depression located to the north.

Fig. 3B shows spatial distribution of precipitation in Sofia region during the transport of air masses from northeast. This distribution is largely similar to that in Fig. 3A (transport from north). The lowest precipitation amounts (about 48 mm) are observed in the northern part of Sofia depression, and the highest - in the southern part along the northern slope of Vitosha (about 63 mm). There is also a relative increase in precipitation in the northern part of Sofia (AMS Orlandovtsi). The causes for this spatial distribution are the same as those mentioned for the transport of air masses from north, with a leading role of orography. The two directions of transport - from north and northeast - do not have significant differences in terms of the positive relief forms surrounding Sofia depression. Precipitation amounts in the studied territory are approximately the same for both directions of transport.

The results for spatial distribution of precipitation when the transport of air masses is from east are shown in Fig. 3C. Precipitation generally increases in the direction from northwest to southeast. In the northwestern part of the city of Sofia, precipitation is about 40 mm, and in the southern and southeastern parts it reaches a little over 55 mm. Generally, there is less precipitation when the transport of air masses is from east compared to north and northeast directions. The higher precipitation in the southern and southeastern parts of Sofia can be explained by orographic reinforcement, because the corresponding slopes of Vitosha still appear windward in terms of air mass transport from east.

The spatial distribution of precipitation in the region of Sofia city during the southeast transport of air masses is shown in Fig. 3D. A relatively uniform increase in precipitation is observed in the direction from northeast (about 60 mm) to southwest (about 75 mm). This distribution is similar to that observed when the transport of air masses is from north and northeast. However, during this direction of transport the precipitation amounts are higher. Another difference

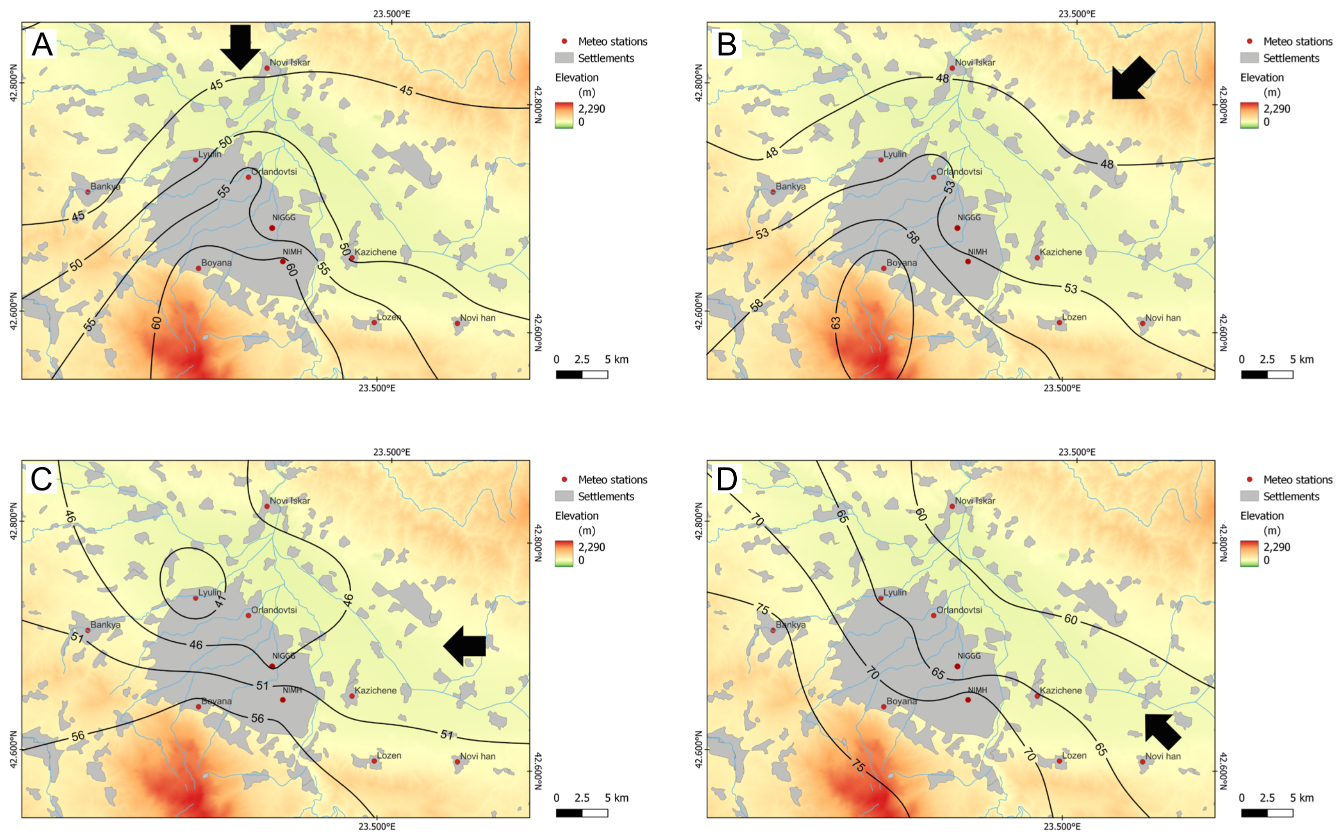

Figure 3. Spatial distribution of monthly precipitation amounts (in mm) in the area of Sofia city when the transport of air masses is from north (A), northeast (B), east (C) and southeast (D) for the period 2013 – 2022.

is that there is no increase in precipitation in the northern part of Sofia, but an increase in precipitation is observed in the southeastern part of the city (NIMH). This means that the specificity of the city, which makes it a positive relief form compared to the surrounding space, also plays its role in this type of transport. However, the main factor for this type of spatial distribution of precipitation is atmospheric circulation. The transport of air masses from southeast is characteristic mostly for the autumn season. The precipitation in most cases is along a warm front of Mediterranean cyclones. It lasts longer and accumulates larger amounts of precipitation. These cyclones in most cases pass south of Bulgaria. Considering their trajectory, there is more precipitation in the southern parts of Sofia depression compared to the northern parts, which largely explains the spatial distribution observed in Fig. 3D. The transport of air masses from north and northeast is typical for the summer season, when precipitation is unevenly distributed and the orography plays a leading role.

The spatial distribution of precipitation during the transport of air masses from south is shown in Fig. 4A. In general, precipitation increases from northeast (about 40 mm) to south-southwest (about 65 mm). This range is greater compared to the ranges observed in the previously discussed directions of air mass transport. The average values are comparable to the values for the previous directions, except for the southeast direction. The cause for this spatial distribution is mainly atmospheric circulation. The transport of air masses from south is typical for the cold half of the year (Fig. 1). During this period, precipitation is mainly due to Mediterranean cyclones passing south of Bulgaria. Accordingly, the precipitation is higher in the southern part of Sofia depression compared to the northern part.

The spatial distribution of precipitation when the transport of air masses is from southwest is shown in Fig. 4B. Similarly to the southern transport, the precipitation increases from northeast (about 45 mm) to south-southwest (about 65 mm). Precipitation amounts during this transport are almost the same as during the transport from south, but they have a smaller range. Southwesterly transport is typical for the cold half of the year (October-April). In this case, once again, the atmospheric circulation is the main factor for the spatial distribution of precipitation in the area of Sofia city. Precipitation is along warm fronts of Mediterranean cyclones, which pass mainly to the south of Bulgaria. Accordingly, more precipitation is observed in the southern parts of Sofia depression than in its northern parts.

A characteristic feature can be observed in the spatial distribution of precipitation in Sofia region, both in the case of southern and southwestern transports of air masses. Along southwest - northeast direction (Boyana - Novi Iskar) there is a very well defined tongue with increased precipitation, which passes centrally through the city. The causes for its existence cannot be either atmospheric circulation (in a broad sense, as set as a factor for the general spatial distribution of precipitation), nor urban heat island, which does not cover the parts north of Sofia city, nor increased content of aerosols over the city, because the tongue also includes non-urban parts, nor the orography contrast city-surrounding plain territory. Table 2 shows that Boyana, Orlandovtsi and Novi Iskar stations have a statistically significant correlation coefficient between V-wind and precipitation. These stations form the axis of this tongue, which means that the transport along south-north direction has a significant influence and probably causes the observed deviation in the spatial distribution of precipitation. In a

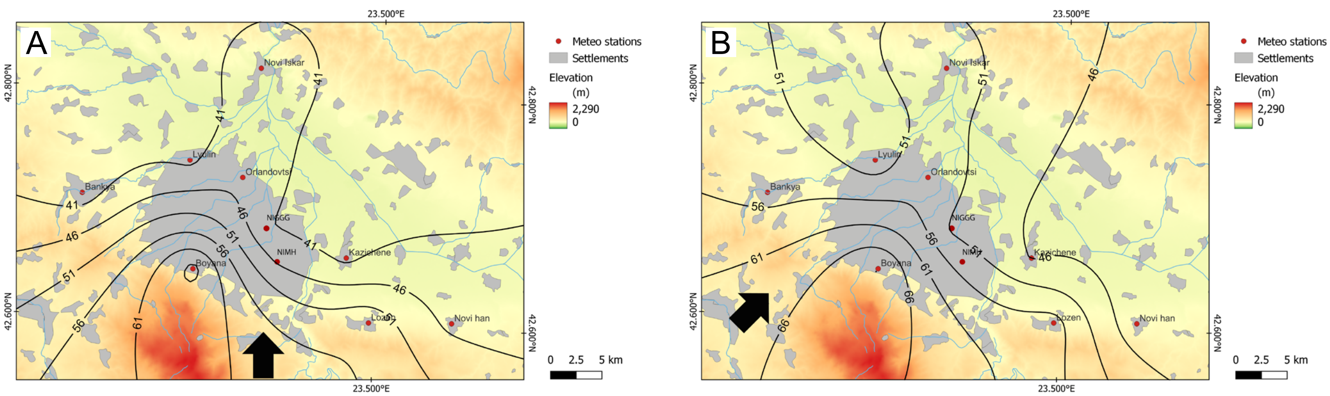

Figure 4. Spatial distribution of monthly precipitation amounts (in mm) in the area of Sofia city when the transport of air masses is from south (A) and southwest (B) for the period 2013 – 2022.

case of southern and southwestern transport in the area of Sofia city, the so-called foehn effect is observed, which leads to an increase of air temperature. There are several mountains of different heights south and southwest of Sofia depression. One of the mountains (Vitosha - highest peak 2290 m) is relatively high, while the others (Lyulin – highest peak 1256 m, Plana – highest peak 1337 m, Lozenska Planina – highest peak 1190 m) are relatively low. The difference between the highest peaks of these mountains is about 1000 m, which is a significant value. All other things being equal, the warming of the air due to the foehn effect will be greater when the air passes a higher obstacle. In other words, the air temperature north and northeast of Vitosha is expected to be higher than the air temperature north and northeast of, for example, Lyulin or Lozenska Planina. The monthly deviations from the mean air temperature for the entire studied period at eight of the stations were used to test this hypothesis, as described in the Data and Methods section. The results are obtained by averaging over a wider southwesterly transport that includes 850 hPa level wind vector angles from 180° to 270°. Thus, the sample has a sufficiently large number of cases in order to obtain reliable results. Spatial distribution of deviations of air temperature in the region of Sofia city in conditions of southwest transport are shown in Fig. 5. As already mentioned above, this type of transport is typical mainly for the cold half of the year, which explains the negative air temperature values. The figure clearly shows the positive temperature deviations (higher values) immediately northeast of Vitosha, forming a characteristic tongue that passes through the center of the city and reaches the southwestern slope of Stara Planina. This confirms the hypothesis that the foehn effect northeast of Vitosha is stronger compared to that northeast of Lyulin or Lozenska Planina. Relatively warmer air along the Boyana-Orlandovtsi-Novi Iskar axis leads to stronger upward movements, which in turn leads to an increase in precipitation. This explains the tongue of increased precipitation northeast of Vitosha observed in Fig. 4A-B and indicates another mechanism of interaction between orography and atmospheric circulation that can significantly influence precipitation in regions with varied relief.

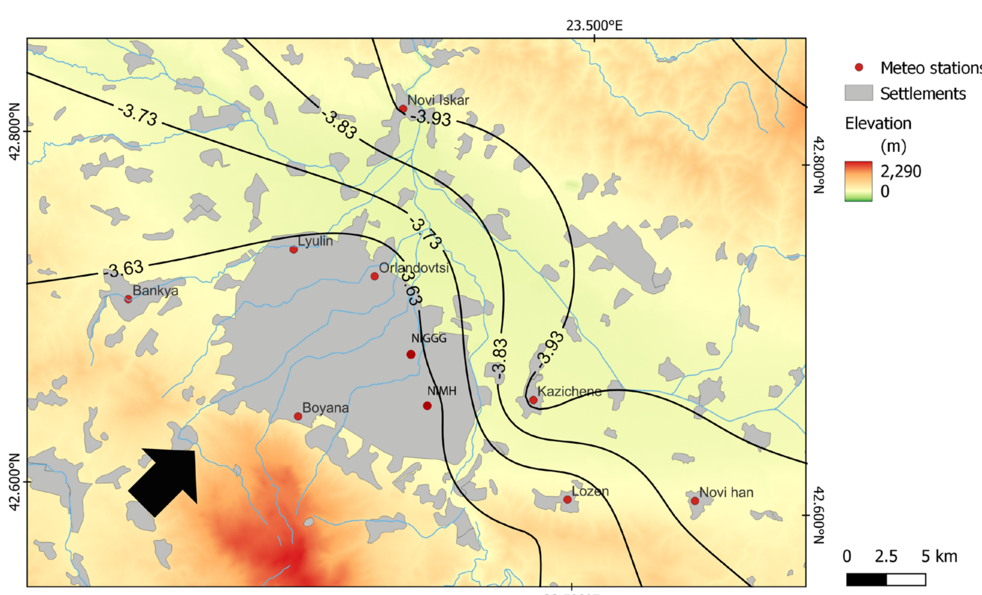

Figure 5. Spatial distribution of monthly deviations of air temperature (in °C) from the average air temperature for the entire period 2013 – 2022 in the area of Sofia city when the transport of air masses is from southwest (wind direction at 850 hPa level between 180° and 270°).

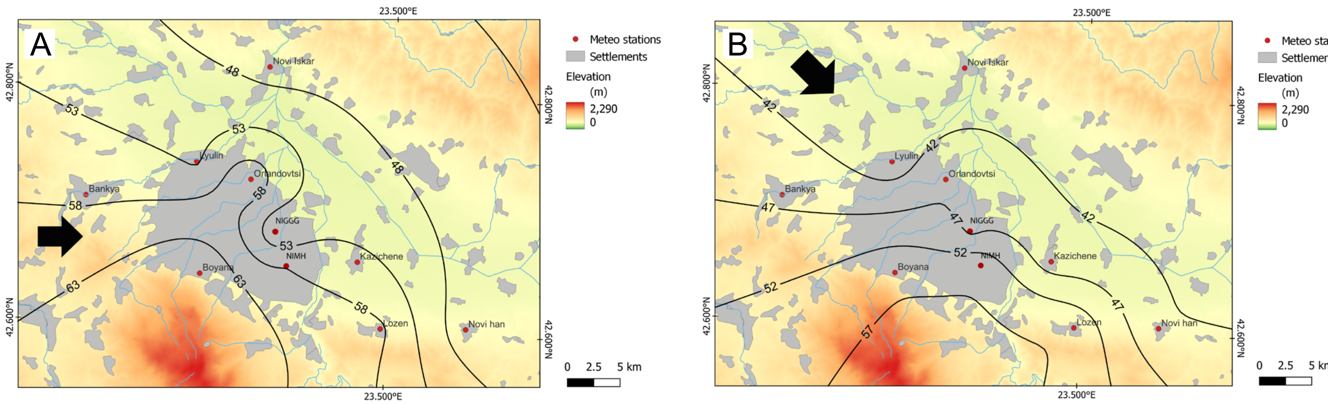

Figure 6. Spatial distribution of monthly precipitation amounts (in mm) in the area of Sofia city when the transport of air masses is from west (A) and northwest (B) for the period 2013 – 2022.

The spatial distribution of precipitation in the area of Sofia city when the transport of air masses is from west is shown in Fig. 6A. Precipitation amounts increase from northeast (about 48 mm) to southwest (about 63 mm). The months with such a transport are predominantly during the cold half of the year, which means that atmospheric circulation has a leading role. Precipitation mainly occurs along warm fronts of Mediterranean cyclones that pass south of Bulgaria. Accordingly, the precipitation in the southern part of Sofia depression is more compared to the northern part. The figure shows the presence of a smaller tongue with increased precipitation that reaches the northern part of the city (Orlandovtsi). The causes are similar to those valid for the southerly and southwesterly transports, because the westerly direction, as defined in the section Data and Methods, includes wind vectors with values less than 270°, i.e. there are some cases of air heating as a result of the foehn effect caused by the mountains south of Sofia. However, it is weaker and does not reach the northern part of Sofia depression.

The spatial distribution of precipitation in the area of Sofia city when the transport of air masses is from northwest is shown in Fig. 6B. Precipitation amounts increase from northwest (about 40 mm) to southeast (about 57 mm). Orography plays a major role for precipitation amounts during this direction of transport. The northwestern part of Sofia depression, which is leeward, has less precipitation. On the other hand, the windward part (the southeastern districts of Sofia, the village of Lozen) receives higher precipitation amounts. It should also be noted that this transport of air masses, together with the easterly one, is characterized by a relatively low precipitation amounts in the studied area. The spatial configuration of Sofia depression, which longitudinal axis has a northwest-southeast direction in the western part and a west-east direction in the eastern part, is important for this phenomenon. The best conditions for a rain shadow in the studied territory are created during the transport of air masses from northwest and east.

5. Conclusion

The spatial distribution of precipitation in the region of Sofia city is characterized by low amounts in the northern and northeastern parts of Sofia depression and high amounts in the southern part. The difference in precipitation is about 200 mm, which requires a differentiated approach in the study, planning and organization of various measures related to dangerous natural phenomena as a result of, for example, intense precipitation. The territory of Sofia depression is large enough to have its own specifics in its different parts in terms of precipitation. The main factor for the spatial distribution of precipitation is atmospheric circulation (Nojarov 2013; Nojarov 2017a). The relief in the certain territory has a significant modifying effect on this spatial distribution. There are several mechanisms through which relief affects precipitation. The most important is the location of mountain slope relative to the main direction of transport of air masses. Leeward slopes receive less precipitation and windward slopes receive more. In Sofia depression, in most cases the southern and southwestern slope of Stara Planina is leeward, and the northern slopes of Lyulin, Vitosha, and Lozenska Planina are windward. The second mechanism of influence is the anthropogenic relief (high buildings), which is a positive relief form compared to the surrounding plane. A typical example is the northern part of Sofia, which borders to the north the flat Sofia field, and when the transport of air masses is from the northern quarter, it is similar to a windward slope with the corresponding higher precipitation. This study also revealed a third mechanism of relief influence on the spatial distribution of precipitation. The large difference in the height of the mountains located south of Sofia creates a significant difference in the air temperature in Sofia depression during a transport of air masses from south and southwest. This is due to the stronger foehn effect of the higher mountain (Vitosha) compared to the foehn effect of the lower mountains (Lyulin, Lozenska Planina), which creates a tongue of higher air temperature northeast of Vitosha, which reaches the southern and southwestern slopes of Stara Planina. The higher temperatures in this tongue create stronger upward air movements, which in turn increase the amount of precipitation. Secondary, but still important factors that affect the spatial distribution of precipitation in Sofia region are the urban heat island and the increased content of aerosols in the air in and over the city.

Revealing the spatial distribution of precipitation in the area of Sofia city, based on the direction of the prevailing atmospheric transport, is important also from another point of view. The long-term projection of changes in atmospheric circulation over a given area in connection with, for example, global warming, is more reliable compared to the projection of precipitation amounts over a given territory. As noted above, precipitation depends on many local factors, while atmospheric circulation depends more on global factors. Recent studies (Nojarov 2021, 2023) show a statistically significant trend of increasing of the transport of air masses from northeast in Bulgaria in summer. This is valid also for Sofia region.

In this regard, the spatial distribution of precipitation, characteristic of the northeast transport, will become more and more frequent in Sofia depression. This facilitates the long-term planning of measures related to possible dangerous precipitation processes during such a direction of transport.

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PN: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Review and Editing, Visualization, Supervision; PN and VV: Writing - Original Draft; PN, VV and YV: Resources, Data Curation; VV: Project administration, Funding Acquisition; YV: Software, Validation

Conflict of interest

The authors have declared that no competing interests exist.

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