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Variation of Lightning over the Bulgarian Black Sea Coast

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Abstract. This study examines the annual, seasonal, and monthly lightning density along the Bulgarian Black Sea coastal zone, as a transitional area between land and sea. Seasonal analysis shows that during winter, spring, and summer, lightning density over the coast is higher than over the Black Sea but lower than over land (Bulgaria). In contrast, during autumn, lightning activity reaches its peak over the Black Sea, while the flash densities over the coast and inland areas become approximately equal. To examine regional differences in detail, the Bulgarian coast is divided into four regions —Shabla, Varna, Sunny Beach, and Primorsko. Primorsko, the southernmost region of the Black Sea coast, has the highest flash density, whereas Shabla, the northernmost region, has the lowest. The monthly analysis indicates that July is the month with the highest flash density when examining lightning activity along the entire Bulgarian Black Sea coast. However, when the coast is divided into smaller regions, the maxima occur at different times for each area: Sunny Beach in May, Shabla and Varna in July, and Primorsko in August. These results highlight the pronounced spatial and temporal heterogeneity of lightning activity along the Bulgarian Black Sea coast and emphasize the importance of conducting analyses at finer, local scales to understand the significance of the influence of factors involved in thunderstorm formation within the specific areas and time periods.

1 Introduction

With the development of lightning detection networks and the creation of a database for them, the concept of thunderstorm climatology is increasingly discussed in scientific literature [1, 2, 3]. Lightning activity varies significantly across different geographical locations and is highly variable on all timescales, including annual, seasonal, monthly, and daily. Analyses of the annual global lightning distribution show that, depending on the underlying surface, lightning frequency over continents is typically 1–2 orders of magnitude higher than over oceans [4, 5].

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Detailed regional studies [6, 7, 8] further indicate that, under specific local conditions — such as orographic features, the respective season, and the time of the diurnal cycle — maritime areas can exhibit higher lightning activity than adjacent land regions. This inherent complexity and variability underscore the critical importance of conducting regional-scale studies to better understand and predict localized lightning behavior.

Each coastal zone represents a unique transitional area between land and sea, influenced by specific meteorological dynamics. For these reasons, studying the distribution of lightning over the Bulgarian Black Sea coast is of scientific interest.

The aim of this work is to analyse the temporal distribution of lightning frequency — on annual, seasonal, and monthly scales — specifically within this coastal domain, as well as its corresponding four regions into which it is conditionally divided. The coast has been conventionally divided into four zones, each named after a major city within the respective area, arranged from north to south: Shabla (northernmost), Varna (north-central coast), Sunny Beach (south-central coast), and Primorsko (southernmost). Special attention is given to identifying the periods of highest and lowest lightning frequency within each of these zones, enabling a detailed assessment of both spatial and temporal variability in thunderstorm activity across the region.

2 Data and methodology

The lightning data used in this study spans a 10-year period, from March 2005 to February 2015, and was obtained from the ZEUS lightning detection network (operated by the National Observatory of Athens [9]). The number of recorded lightning flashes was determined for various time intervals—annual, seasonal and monthly—within 0.25° × 0.25° grid cells. Each grid cell was classified based on the underlying surface as either continental (land), coastal, or maritime (sea). Flash density (number of lightning flashes per km²) was calculated by dividing the total number of lightning flashes within a given time period by the area of the corresponding domain or region.

The geographical domains used in the analysis are defined as follows:

- **continental domain** (referred to in this work as Bulgaria): This land area is bounded between longitudes 22.5°E and 28.5°E and latitudes 41.25°N and 44.25°N and is outlined in white in Figure 1.
- **maritime domain** (Black Sea): This includes only the area over the Black Sea (see Figure1), excluding the coastal zone (20–50 km offshore).
- **coastal domain** (Bulgarian Black Sea Coast): This domain represents the entire Bulgarian Black Sea coastal zone, the area where Bulgaria borders the Black Sea. It corresponds to the entire area encompassing all four zones marked with white rectangles in Figure 2.
- **coastal sub-regions:** For more detailed analysis, the coastal domain was further subdivided into four equal-area zones: Shabla (northernmost), Varna (north-central coast), Sunny Beach (south-central coast), and Primorsko (southernmost). These zones are described in Table 1 and illustrated in Figure 2 (individually marked with white rectangles)

Table. 1 Geographical coordinates of the four regions (with dimensions 0.5° × 0.5°), into which the Bulgarian Black Sea coast is conditionally divided

Name of a region	Centre coordinates of the 0.5° × 0.5° region
Shabla	28.50° E 43.50° N
Varna	28.00° E 43.25° N
Sunny Beach	27.75° E 42.75° N
Primorsko	27.75° E 42.25° N

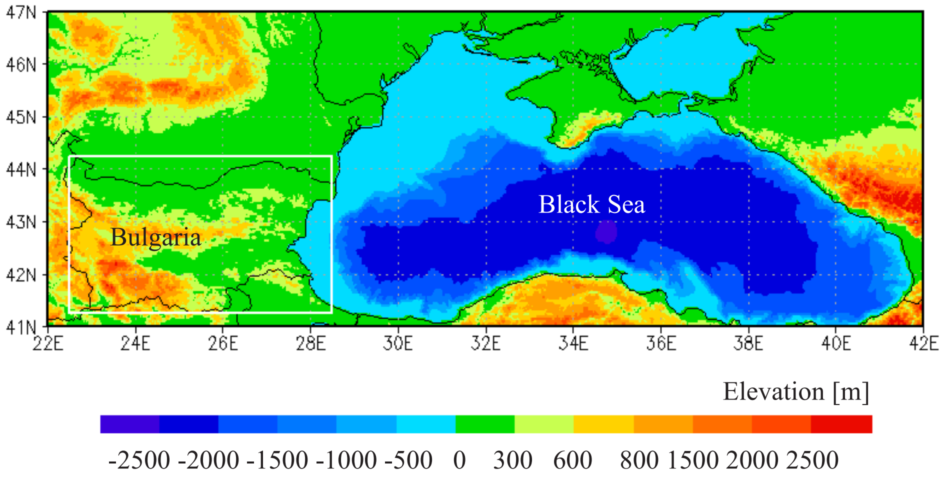


Fig. 1. Topographic map of the investigated areas: the continental domain, including only the land area outlined by the white line (referred to in this work as Bulgaria), and the maritime domain, which corresponds to the Black Sea.

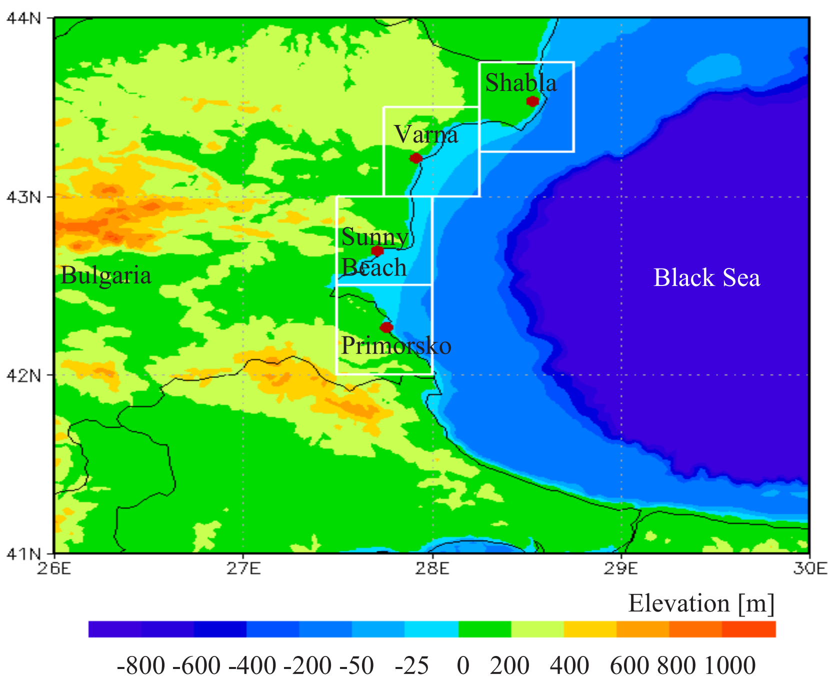


Fig. 2. The Bulgarian Black Sea coast, divided into four regions, each named after a major town — Shabla, Varna, Sunny Beach, and Primorsko — shown with white rectangles. Red dots indicate the locations of the respective towns.

3 Results

3.1 Annual and seasonal lightning distribution over the maritime, coastal and continental domains

The spatial distribution of lightning activity (expressed as the number of flashes per 0.25° × 0.25° grid cell) over a 10-year period across Bulgaria, the Bulgarian Black Sea coast, and the Black Sea is presented in Figure 3 (left panel). The right panel of Figure 3 illustrates the corresponding annual flash density across three zones: the maritime area (the Black Sea), the coastal region (the Bulgarian Black Sea coast), and the land area (the territory of Bulgaria). Analysis of the results (Figure 3) indicates that the annual lightning frequency in the coastal region is higher than that observed over the sea surface, but lower than that over land. This trend aligns with the general understanding that land surfaces, due to stronger surface heating, promote more vigorous convection and consequently higher lightning activity compared to the sea [10].

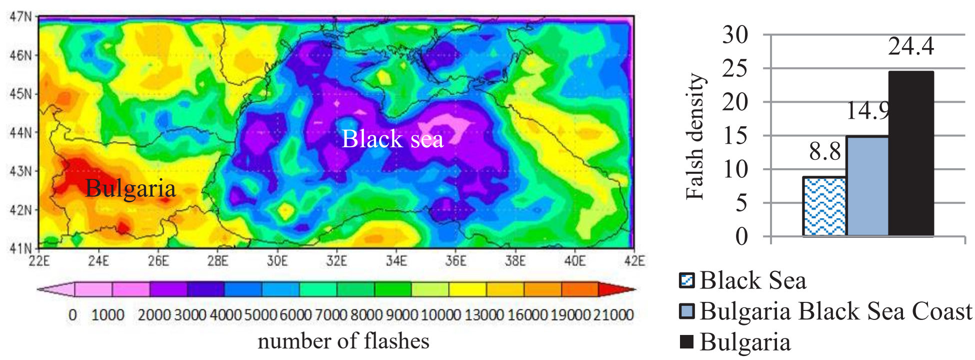
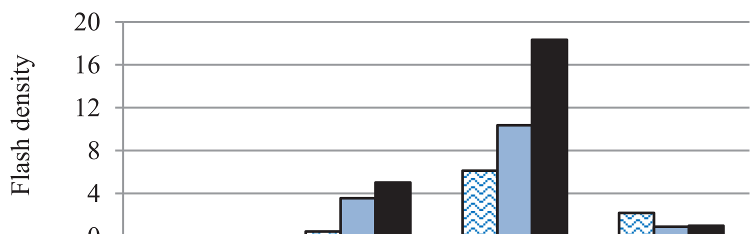


Fig. 3. Left panel: Spatial distribution of lightning flashes (total number of flashes per 0.25° × 0.25° grid cell over the period March 2005 – February 2015) across the investigated areas. Right panel: Corresponding annual flash density (flashes per km^2) for a 10-year period across three domains — maritime (Black Sea), coastal (Bulgarian Black Sea coast) and continental (territory of Bulgaria).



	WINTER	SPRING	SUMMER	AUTUMN
Black Sea	0.0287	0.453	6.122	2.204
Bulgarian Black Sea Coast	0.0288	3.577	10.358	0.895
Bulgaria	0.0442	5.030	18.350	1.002

Fig. 4. Seasonal flash density (flashes per km²) over the Black Sea (pattern-filled columns), the Bulgarian Black Sea coast (blue columns), and Bulgaria (black columns) during winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

The seasonal flash density over the Black Sea (pattern-filled columns), the Bulgarian Black Sea coast (blue columns), and Bulgaria (black columns) during the 10-year study period is shown in Figure 4. During winter, spring and summer, lightning activity over the coastal zone follows the annual trend - being higher than over the sea but lower than over land. However, in autumn, a different pattern is observed: the highest flash density occurs over the Black Sea, while the flash densities over the coast and land areas become approximately equal. This seasonal shift suggests that sea surface temperatures and associated convective processes play a role during the autumn months [11,12,13].

3.2 Regional lightning distribution along the Bulgarian Black Sea coast: Shabla, Varna, Sunny Beach, and Primorsko

The annual distribution of lightning is shown in Figure 5 – upper panel, which presents the flash density (number of flashes per km²) across the four Bulgarian coastal regions: Shabla, Varna, Sunny Beach, and Primorsko. A regional analysis reveals that the Primorsko region, located at the southernmost part of the Bulgarian Black Sea coast, has the highest annual flash density. This is followed by the Varna and Sunny Beach regions. In contrast, the Shabla region, situated at the northernmost end of the coastline, exhibits the lowest annual lightning activity.

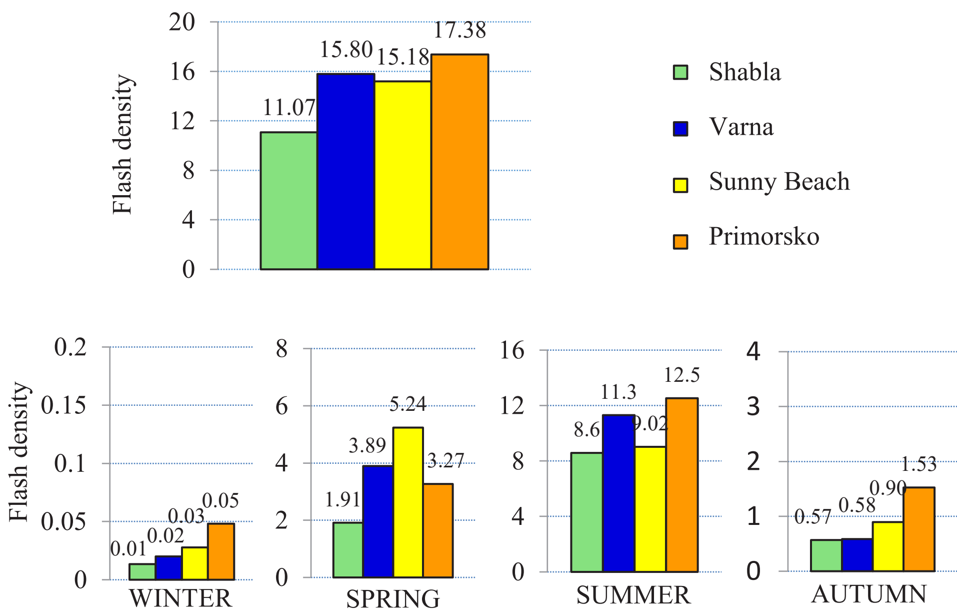


Fig. 5. Lightning flash density (flashes/km²) across four coastal regions along the Bulgarian Black Sea coast — Shabla (green columns), Varna (blue columns), Sunny Beach (yellow columns), and Primorsko (orange columns). Upper panel: Annual flash density for the period March 2005–February 2015. Lower panel: Seasonal flash density for the same regions.

The seasonal flash densities across the same four regions are presented in Figure 5 – lower panel. The analysis shows that, in general, the highest lightning activity occurs in the southernmost region (Primorsko) during the winter, summer, and autumn seasons. During the summer months, the flash density in the Varna region approaches that of Primorsko, indicating a strong regional similarity in peak summer thunderstorm activity. It is worth noting that the seasonal pattern differs in spring, when Sunny Beach records the highest lightning frequency, followed by Varna, Primorsko, and finally Shabla. Across all seasons, Shabla, located at the northernmost part of the Bulgarian Black Sea coast, consistently records the lowest thunderstorm activity.

In Figure 6 (upper panel), the monthly distribution of lightning (flash density) along the entire Bulgarian Black Sea coast is presented. The results indicate that July exhibits the highest lightning density, while December shows the lowest. A closer examination of the monthly lightning distribution across individual coastal regions (Figure 6, lower panel) reveals that the months with peak lightning activity vary by region. Sunny Beach reaches its maximum in May, Shabla and Varna peak in July, and Primorsko in August. These results highlight the spatial and temporal heterogeneity of lightning activity along the Bulgarian Black Sea coast and underscore the importance of conducting detailed regional and monthly analyses to better understand the patterns and driving factors of coastal thunderstorm activity.

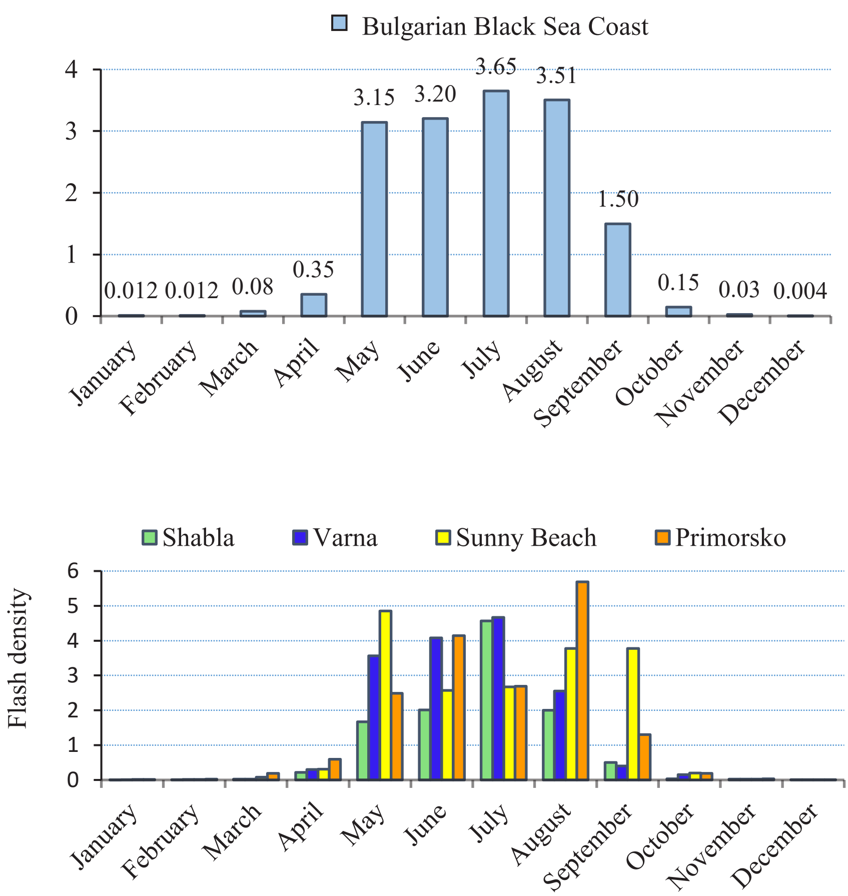


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Fig. 6. Monthly flash density (flashes per km²): upper panel – over the Bulgarian Black Sea coast; lower panel – by regions: Shabla (green columns), Varna (blue columns), Sunny Beach (yellow columns), Primorsko (orange columns).

4 Summary

The detailed analysis of lightning activity over the Bulgarian Black Sea coast confirms the importance of conducting studies at smaller, local scales, particularly in transitional coastal zones where localized meteorological processes can influence thunderstorm development.

The results show that the annual flash density along the Bulgarian coastline is higher than over the adjacent open waters of the Black Sea but lower than over inland regions of Bulgaria. Clear spatial differences are observed:

- Primorsko, located in the south, exhibits the highest flash density.
- Shabla, in the north, records the lowest lightning activity.
- Varna and Sunny Beach present intermediate values.

Moreover, monthly and seasonal variability reveals marked temporal heterogeneity. While July marks the overall peak of lightning activity, regional maxima vary:

- Sunny Beach peaks early in May;
- Shabla and Varna peak in July;
- Primorsko reaches its maximum in August.

Of particular note is the fact that only during spring does Sunny Beach exhibit the highest flash density, unlike the other three seasons where the peaks occur over Primorsko. This suggests that local topography and the corresponding mesoscale dynamics for specific seasons with maximum thunderstorm activity in a given area should be carefully considered.

These results highlight the need to analyze lightning activity at finer spatial scales and over shorter time intervals, enabling more precise assessments and a clearer understanding of lightning frequency and distribution within specific regions. This provides a valuable foundation for future studies focused on the formation of thunderclouds characteristic of specific areas, especially due to the fact that they are associated with various severe weather phenomena, such as heavy rainfall, strong winds, hail, and others.

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