DOI:10.28974/idojaras.2025.1.2

IDŐJÁRÁS

Quarterly Journal of the HungaroMet Hungarian Meteorological Service
Vol. 129, No. 1, January – March, 2025, pp. 15–37

Temporal and spatial analysis of lightning density in Türkiye

İhsan Çiçek[1,*], Necla Türkoğlu[1], Zerrin Demirörs[2], Edanur Gözet[3], Batuhan Ateş Yilmaz[3], and **İlker Alan[2]**

[1]*Ankara University, Faculty of Letters, Department of Geography*

[2]*Türkiye State Meteorological Service*

[3]*Türkiye State Meteorological Service, 11th Regional Directorate*

**Corresponding Author E-mail:* ihsan.cicek@ankara.edu.tr

(Manuscript received in final form June 25, 2024)

Abstract— In this study, a temporal analysis of lightning density was performed on lightning data obtained from the Türkiye State Meteorological Service (TSMS) for the period 2017–2021, with the analysis encompassing hourly, monthly, seasonal, and annual scales. ArcGIS version 10.4.1 was used. When the annual lightning density was evaluated by regions, the highest values were observed in the Inner Aegean, Marmara, Southwest Anatolia, Western Black Sea, and Eastern Anatolia Regions. The Central Anatolia Region has the lowest lightning density. Lightning density is also the highest in late spring, early summer when the ground temperature and, thus, instability is highest. May and June were determined to have the highest lightning density, whereas December, January, and February had the lowest lightning density. Considering lightning activity hourly, the highest number of lightning strikes occurred at noon, while the lowest number occurred at night and during the morning hours. Upon examining the relationship of lightning with latitude and longitude values, it was concluded that the relationship with latitude values was more significant and positive. Lightning changes as a function of altitude: it increases between 30-150 m and 500-1000 m, while it decreases between 150-500 m and above 1000 m.

Key-words: lightning analysis, lightning density, lightning detection network (LINET), convective storms, thunderstorms, Türkiye

1. Introduction

The electrical discharge resulting from ascending and descending air movements between the ground and the atmosphere is called lightning (*Ackerman and Knox*, 2015). Lightning can be defined as an electric spark of more than 1 km (*Dwyer and Uman*, 2013). Lightning usually occurs as an intercloud (IC), cloud-to-cloud (CC), or cloud-to-ground (CG) phenomenon (*Uman,* 1986; *Kiçeci* and *Salamcı* 2020). The cloud-to-cloud lightning event occurs more often than the lightning striking the ground (*Holle and Cooper*, 2016). Positively charged ice crystals gather at the top of the cloud, and negative charges gather at the bottom of the cloud. Lightning is caused by the electric current between positively and negatively charged regions. If electric charges inside clouds are dense enough, they create electric fields that can ionize the air and produce electric sparks that can develop into lightning flashes (*Rupke*, 2002; *Ackerman and Knox*, 2015).

Approximately 40–100 lightning strikes the Earth's surface every second (*Tinmaker et al*., 2019). Lightning flashes originate especially from cumulonimbus (Cb) clouds (*Rupke*, 2002). Cold air and a thick layer of moisture are needed at the upper levels for the formation of cumulonimbus (Cb) clouds. Cb clouds that cause thunderstorms, occur with the warming of the ground, orographic elevation, and dynamic elevation in frontal systems (*TSMS*, 2022a). Lightning and rainfall are associated with severe storms that can damage agriculture, power grids, property, and human life (*Tinmaker et al*., 2017). Atmospheric instability, sufficient moisture content, and a lifting mechanism to bring the moist air parcel to the level of free convection are the necessary elements for the development of lightning and thunderstorms (*Tinmaker et al*., 2010; *Öztopal*, 2017).

Lightning is affected by numerous meteorological variables and is very sensitive to changes in surface temperature. As it can be seen in the studies, there is a positive correlation between lightning activity and surface temperature (*Williams*, 2005). The temperature difference formed due to cold air masses on hot land surfaces increases instability and causes deep convection (*Galanaki et al*., 2018). Hence, lightning density on land is higher during the summer months and at noon and evening when the ground temperature is high (*Pinto* and *Pinto Jr*., 2003; *Holle* and *Cooper*, 2016).

Although the lightning event has generally been observed on land, it also occurs in seas, oceans, and coastal areas (*Turman and Edgar*, 1982; *Orville and Henderson*, 1986). Convection on land is deeper and stronger than convection in the sea, since the land surface warms faster than oceans and seas (*Tinmaker et al*., 2019). Lightning activity over the sea in autumn and winter periods is higher than that over the land, particularly at night (*Manzato et al*., 2022). The seas are colder in the spring than in the autumn. Therefore, stronger vertical atmospheric instability occurs in autumn (*Altaratz et al*., 2003). In the Mediterranean Sea, September, when sea surface temperatures are the highest, is the period with the most intense lightning activity (*Rivas Soriano* and *de Pablo*, 2002).

There is a similarity between the spatial and temporal distribution of lightning and that of tornadoes. In the study conducted by *Bayraktar and Çiçek* (2022), it was determined that 47% of all tornadoes in Türkiye were seen in the Mediterranean Region. In the Mediterranean and Aegean regions, they occur in late autumn and winter; in the Marmara and Black Sea regions, they occur in summer and early autumn; in the inner regions, they usually occur in spring, early summer, and late summer.

The lightning event is often accompanied by hail and heavy rains (*Herring et al.,* 2018; *Williams* and *Guha*, 2019). Due to global warming, the amount of lightning has increased by 12% for every 1°C increase in temperature. In other words, there is a high correlation between the lightning displacement speed and the convective available potential energy (CAPE) value of precipitation. An unstable air mass is characterized by warm, moist air near the surface and cold, dry air aloft. In these conditions, if an air parcel is forced upward, it will continue to rise on its own. CAPE is a measure of atmospheric instability and is directly related to the maximum possible vertical velocity of the updraft. Thus, higher values of CAPE are associated with intense vertical speed and thunderstorm occurrence. Observed CAPE values during a storm often exceed 1000 J kg^{-1} and in extreme cases may exceed 5000 J kg^{-1}. However, there are no CAPE thresholds that can be used to determine the thunderstorm occurrence (*Mazarakis et al*., 2008; *Ziv et al*., 2009; *Romps et al*., 2014; *Galanaki et al*., 2015). Sea surface temperature has a significant effect on precipitation (*Reason and Mulenga*, 1999). The increase in precipitation is associated with an increase in the advection of moisture carried from the seas (*Petersen* and *Rutledge*, 1998). The high temperature difference between cold air currents and warm sea surfaces leads to instability in the atmosphere. The water that evaporates from the warm sea surface forms convective clouds. These clouds can drop large amounts of precipitation in a short time. The terrestrial surface temperatures, sea surface temperatures, and severity of meteorological events increase the summer season (*Bozkurt and Göktürk*, 2009). Studies conducted with long-time data series of sea surface temperatures have proven that if sea surface temperatures increase by 1–2°C, there is an increase in the number of days of lightning events by 20–45 days, (*Yamamoto et al*., 2016). Although high sea surface temperature is not a sufficient factor for convective development, it supports synoptic conditions that may cause deep convection (*Kotroni* and *Lagouvardos*, 2016). In the studies conducted by *Yavuz et al*. (2022) on convective precipitation in the cold season from the Marmara Region, it was stated that atmospheric contents (such as atmospheric instability, a lifting mechanism, and high moisture content) similar to those of the warm season are required. Lower convective available potential energy (CAPE) values have been observed in winter thundersnows compared to summer convective thunderstorms.

Surface temperature is among the basic elements of climate and is affected by geographical location and landforms (*Erol*, 2011). This difference in temperature changes can be associated with latitude and altitude. Previous studies have obtained different results; examining the relationship between lightning density and latitude shows that lightning density is higher in the tropical regions (0°–20° latitudes) than in the temperate regions (20°–40° latitudes). Lightning density is lower at high latitudes (40°–60°) (*Mackerras* and *Darveniza*, 1994). Considering lightning activity in the terrestrial areas of China, the areas where lightning is densest are located at latitudes of 20–30° N, and lightning activity decreases to the north (*Xu et al*., 2022).

The relationship between altitude and temperature is more significant than the relationship between latitude and temperature (*Aydın* and *Karabulut,* 2021). Numerous studies have detected a positive correlation between lightning density and orography. Mountain ranges are places with the highest lightning activity. In these regions, it has been revealed that the effect of topographic elevation, orographic forcing, and the heating of the ground as a result of solar radiation, increases convective activities (*Rivas Soriano* et al., 2001b; *Galanaki et al*., 2015; *Kotroni and Lagouvardos*, 2016; *Saha et al*., 2017; *Xu et al*., 2022). Lightning density in terrestrial and mountainous regions is considerably greater than in seas and coasts (*Zipser* and *Lutz,* 1994; *Rivas Soriano et al.,* 2001a; *Koutroulis et al.,* 2012; *Galanaki et al.,* 2018). This difference is even greater in terms of convection initiation (CI). In studies performed in the Mediterranean, the areas with the densest lightning are mountainous areas (Montenegro's Dinaric Alps and the high mountains of the Balkans), whereas the areas where lightning is observed the least are arid and semi-arid areas (*Galanaki et al*., 2018; *Xu et al*., 2022). The Alps' location closer to the level of free convection (LFC) weakens convective inhibition (CIN) (*Manzato et al*., 2022). The smaller the CIN, the deeper the convection (*Manzato et al.,* 2022; *Kirshbaum et al*., 2018). Mountains act as a barrier that provides an important orographic lift mechanism, increasing the transport of incoming air from the sea to the land. In addition, a stronger uplift of clouds near mountains leads to more developed cloud formations (*Reynolds et al*., 1957; *Takahashi*, 1984; *Altaratz et al*., 2003).

Mountains located at mid-latitudes are very sensitive to global warming due to the greenhouse effect (*Rangwala* and *Miller*, 2012). The warming rate is higher in areas with higher altitudes (*Dhital et al*., 2022). In studies carried out in the Mediterranean, June and July are the months with the highest lightning activity (*Manzato et al*., 2022). Concerning the lightning activity of China, whereas lightning density increased with altitude between 1000–2000 m, it decreased between 0–1000 m and above 2000 m altitude. Ninety percent of lightning activity occurred between May and September (*Xu et al*., 2022).

Since lightning bolts and flashes cause NO_x production and forest fires, resulting in significant climatic consequences over long-time scales (*Pinto JR and Pinto*, 2020). Lightning activity is expected to increase in the future (*Williams* and

Guha, 2019). In a warmer future scenario, there will be more water vapor in the atmosphere to release latent heat during condensation. On a global scale, extreme daily precipitation events are predicted to intensify by approximately 7% for every 1°C of global warming (*IPCC*, 2021). This leads to expectations of an increase in storm development and lightning flashes. Furthermore, lightning activity in the future will also depend on the vertical air temperature profile in the troposphere (*Pinto JR et al*, 2013). As *Brooks* (2013) noted, as climate changes, the magnitude of CAPE and shear is also changing. Given that different combinations of CAPE and shear favor the occurrence of different convective phenomena, therefore, this may provide insight into expected future changes in the distribution and nature of convective hazards. For example, if in the coming days both CAPE and shear increase, tornadoes and hailstorms will likely become more common. If low CAPE - high shear days are more frequent, the number of severe convective wind gust events may increase. Preliminary results from climate projections for Europe indicate that an increase in CAPE and a slight increase in shear is expected in the next 100 years. Because of this, the number of unstable, strongly sheared environments is projected to increase as well. As a result, thunderstorms capable of producing severe and extremely severe phenomena may become more frequent.

The objective of the present study is to conduct the temporal and spatial density analyses (simple density) of lightning and lightning flash events that took place between 2017 and 2021 in Türkiye. In this study, both meteorological parameters (ground temperature, moisture content influenced by the sea) and geographical features (latitude-longitude and altitude) were addressed in the spatial analysis of lightning density. Hourly, monthly, seasonal, and annual periods were evaluated in the temporal analysis of lightning density.

1.1. Lightning tracking systems

Lightning detection and tracking systems began to be used in the world in the 1980s. A lighting system is used in almost all European countries. Some of these are low-frequency (LF, 30–300 kHz), while others are very high-frequency (VHF, 30–300 MHz) systems (*Anderson and Klugmann*, 2014). The operating frequency range of the system, which began being used in Belgium in 1992, is very high (VHF, 30–300 MHz). The Lightning Detection Network (LINET) system used in Germany performs detection in the 5–100 kHz range, which is very low and low (VLF/LF) frequencies. The Worldwide Lightning Location Network (WWLLN) tracking system is used in the United States. ZEUS detection system is located in Greece, which works in the low frequency range (VLF, 7–15 kHz) (*Öztopal*, 2017). Lightning detection systems can even monitor lightning events on a global scale. Thus, a reliable lightning database can be created (*Lay et al.,* 2007).

1.2. The lightning detection and tracking system in Türkiye

The lightning detection and tracking system is a remote sensing system that provides meteorological information to detect flash events and make short-term weather forecasts. The lightning detection and tracking system determines the location, type, current intensity, and current direction of lightning. There was a total of 41 passive sensor systems of the lightning detection network LINET installed in Türkiye in 2014, one of which is located in the Turkish Republic of Northern Cyprus. LINET represents a ground-based lightning detection system. LINET sensors consist of electric field sensors and central processing units. The LINET field processor receives signals from the LINET field antenna and the GPS antenna and transmits them to the central processing units. The LINET field antenna is sensitive to electromagnetic waves emitted from lightning. It operates in the VLF range of about 5–100 kHz. The GPS antenna receives signals from GPS satellites (*TSMS*, 2022a). With this system, it is possible to detect the location, current intensity, and current direction of lightning (from cloud to ground or ground to cloud electrical activity) with an accuracy of 200 m.

3.6. Study area and data

The region between 26–45E and 35–43N, where Türkiye is located, was taken as the study area (*Fig. 1*). A data set from 2017 to 2021 of the LINET system described in the previous section was used as study data. This data includes the date and time of the lightning, the latitude and longitude of the place where it occurred, the type of events (IC, CC, or CG), and the event's intensity. In the following study sections, all events will be described as lightning, without distinction.

Fig.1. The Lightning Detection and Tracking System station information

2. Materials and methods

The data utilized in the present study were provided by the Türkiye State Meteorological Service (TSMS). The acquired data cover only cover the time during which events occurred in 2017–2021. Spatially, it involves the latitude and longitude information of the places where the events took place. The coordinate and time information of lightning events was transferred from an MS Excel file to the GIS environment. ArcGIS version 10.4.1 was used as GIS software. The data transferred to the GIS environment was made ready for use in temporal and spatial analysis by creating databases in ArcGIS. The month, day, and time of events were used in the temporal analysis of lightning events, and latitude and longitude information was used in spatial analysis. To conduct spatial density analysis, the data was converted to the ED-1950 Lambert conformal conic projection system.

The aim of the study is to detect and interpret lightning events in terms of time and space. Two tools in ArcGIS 10.4.1 were used to analyze lightning events. These are the point density and total incidence tools. The point density tool counts the vector points within the surrounding pixels and gives them a raster output. Conceptually, a neighbor is defined around the center of each raster cell. The number of points falling in the neighborhood is summed up and divided by the neighbor area. The dot density tool consists of five basic functions: input data, weight value, output data, cell size of the output, and the radius to neighboring points. The purpose of the total incidence tool is to combine multiple points and assign weight values to the combined points (*Özlü et al.*, 2020).

In the study, sea surface temperatures for the period 1970–2022, obtained from TSMS (*TSMS, 2022b*), and Turkey's monthly average temperature data for the period 1991–2020 were used in the temporal and spatial interpretation of lightning (*TSMS*, 2024).

3. Results

3.1. Annual average lightning density

Upon examining the annual average lightning density, it was found that the highest values occur in the Inner Aegean, Marmara, Southwest Anatolia, Western Black Sea, and Eastern Anatolia Regions (25–50 lightning km^{-2} yr^{-1}). Central Anatolia is the region with the lowest lightning density (0.4–1.6 lightning km^{-2} yr^{-1}). It is seen that sufficient moisture content is an essential factor for supporting instability processes.

The Aegean Sea, Mediterranean, Eastern Black Sea, and Southeastern Anatolia are regions where lightning events occur moderately and not very densely (1.6 to 6.5 lightning km^{-2} yr^{-1}) (*Fig. 2*). Denser lightning events occurred in warm seas at low latitudes, such as the Mediterranean and Aegean Seas, providing evidence of the positive relationship between sea surface temperature and lightning density, compared to seas at higher latitudes.

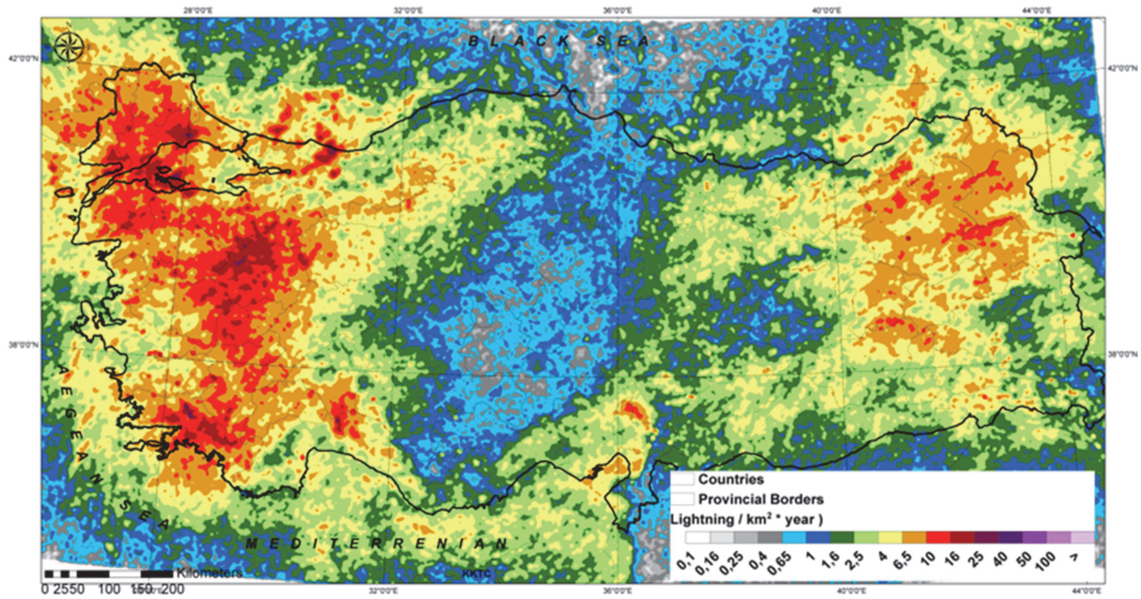

Fig.2. 5-Annual average lightning density (2017–2021).

3.2. Seasonal average lightning density

Since the temperature difference between the ground level and the high level of the atmosphere is small in winter, the atmosphere has a more stable structure. lightning density is very low throughout Türkiye. Lightning on land is only observed in areas close to the coasts in the south and west, and in Southeastern Anatolia because of either high levels or a lack of evaporation to support instability during the winter season and the cold land compared to the seas. Lightning occurs more frequently in the Aegean and Mediterranean coastal areas, where temperatures and sea surface temperatures are higher in winter than in Türkiye in general (*Fig. 3*). While the average sea surface temperature in February for the period of 1970–2022 in the Black Sea is 8.0 °C, it is 15.9 °C in the Mediterranean (Fig. 4). Lightning does not occur on the Black Sea coast as a result of its cold temperature during this period. Concerning the winter averages of lightning events in the last five years, the highest values (4–6 lightning km^{-2} yr^{-1}) occurred in the coastal areas of Southwestern Anatolia (Muğla, İzmir, and Aydın provinces) (*Fig. 3*). The lightning km^{-2} yr^{-1} unit given here expresses the average number of lightning per km^2 in a year obtained from 5-year data.

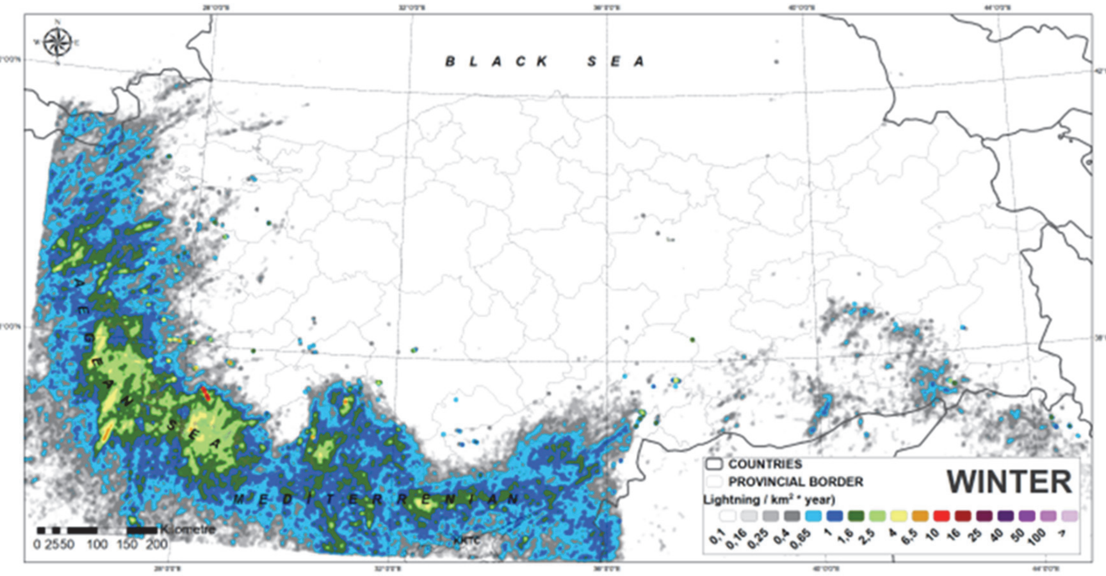

Fig.3. Lightning density during winter (2017–2021).

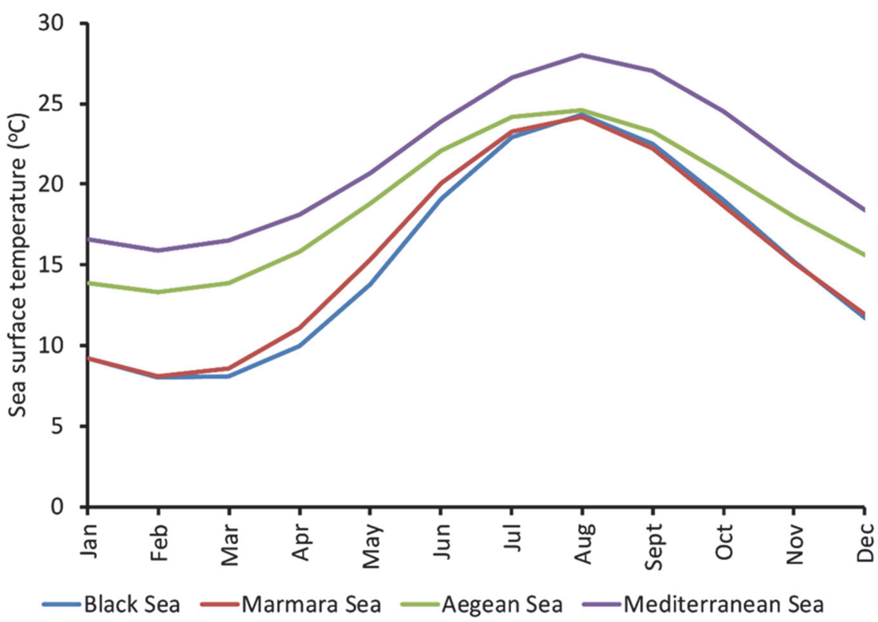

Fig.4. Monthly distribution of sea surface temperature (1970–2022).

Convection is observed with the increasing latent heat transfer as temperatures begin to increase in the spring, and the land warms up faster in the interior of Türkiye. During this season, surface warming, lack of warming in the upper atmosphere, and cold air from the north with jet streams strengthen the instability and increase lightning density. The highest lightning density occurred in the Inner Aegean, western Marmara, and Eastern Anatolia Regions, with a range from 6.5 to 10 lightning events km^{-2} yr^{-1}, and more lightning events were found here than in other regions (*Fig.5*).

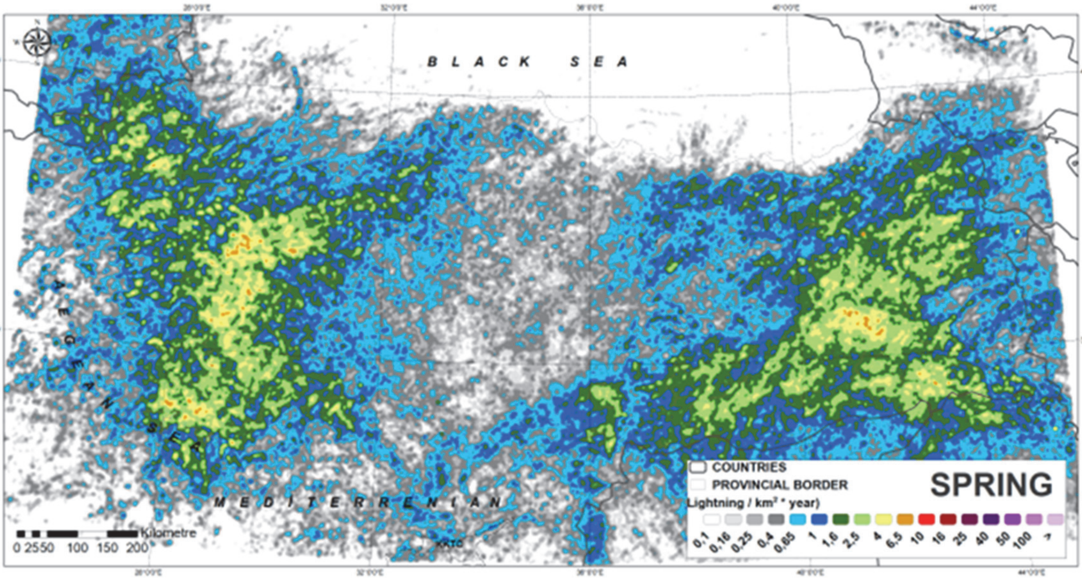

Fig.5. Lightning density during spring (2017–2021).

Summer is the period when instability is the highest, and therefore lightning events are the most frequent. During this period, the Thrace, Western Black Sea, and the inner parts of the Aegean Region are the regions with the highest values (25–40 lightning km^{-2} yr^{-1}). High values are also observed in the Eastern Anatolia Region and Eastern Black Sea Region. The warming of the Black Sea causes lightning density to shift to the north during this period. The higher lightning density in the western and eastern parts of the Black Sea Region reflects the orographic effect. On the other hand, the very low humidity in the Southeastern and Central Anatolian Regions is the factor influencing the low lightning density (*Fig. 6*).

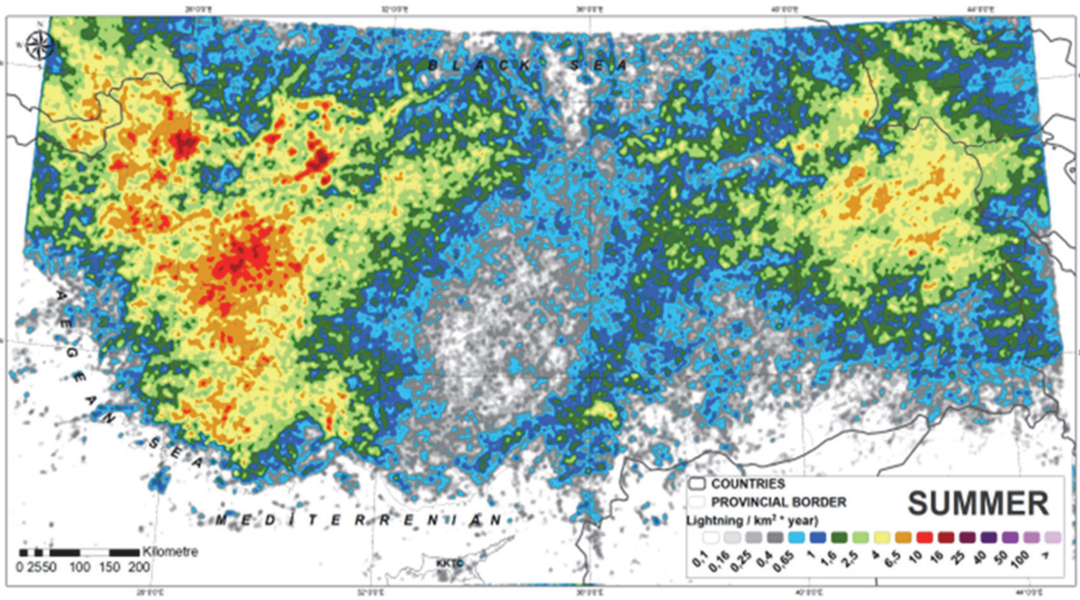

Fig.6. Lightning density during summer (2017–2021).

In autumn, denser lightning events are observed in the Marmara (10–25 lightning km^{-2} yr^{-1}) and Southwest Anatolia Regions, on the Mediterranean coasts (4–6.5 lightning km^{-2} yr^{-1}), and the Eastern Black Sea with the strong orographic effect (*Fig.7*). Due to the rapid cooling of the land, lightning density decreases, especially in the inner regions. Moreover, the cooling of the Black Sea causes a decrease in lightning density on the sea and in the adjacent terrestrial areas (*Fig. 4*). In the Mediterranean Sea, the sea's warmth strengthens the instability on the sea, and, although the lightning density on the sea and the land close to it decreases, it is higher than in Türkiye in general.

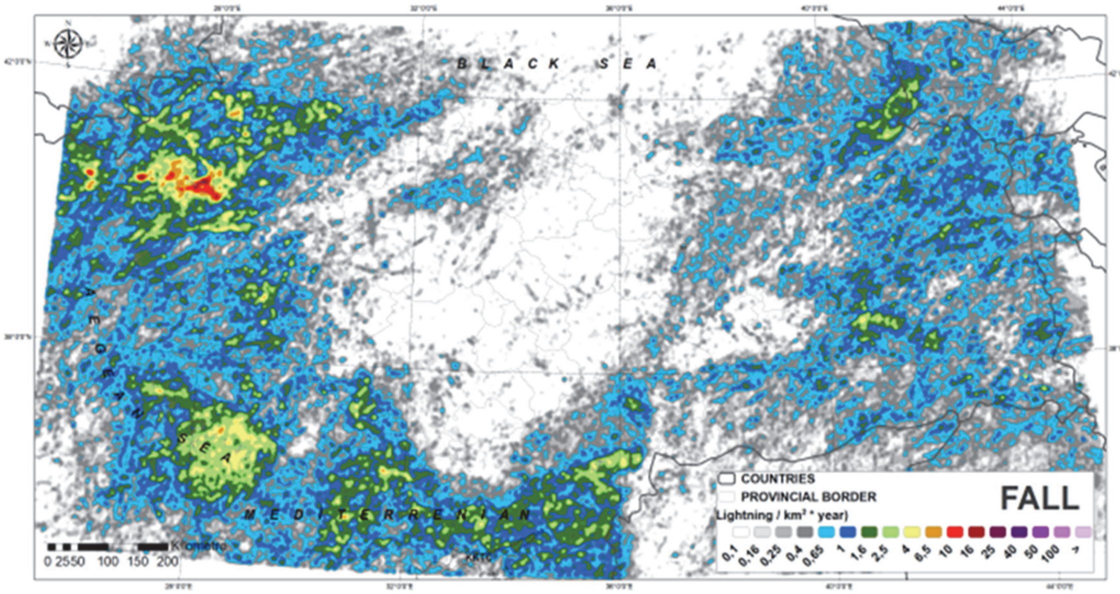

Fig.7. Lightning density during autumn (2017–2021).

3.3. *Monthly average lightning density*

When lightning is average monthly, June (29%) and May (18%) are the months with the most lightning. Almost half (47%) of lightning occurs in these two months. December, January, and February are the months with the least lightning (*Fig. 8*). The annual trend in the number of lightning strikes is related to the annual cycle of surface air temperature. The high surface air temperature during the warm season significantly influences the atmospheric conditions over the land. This single-peak annual lightning density distribution is common at middle latitudes (*Rivas Soriano et al*., 2001b).

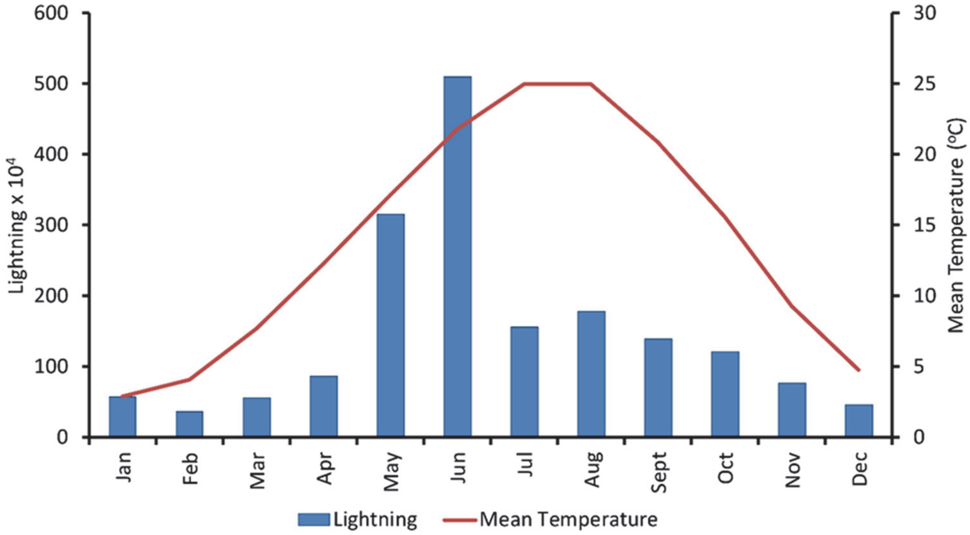

Fig.8. Monthly distribution of lightning (2017–2021) and mean temperature (1991–2020).

It was determined that, considering lightning events by months during the year, lightning events were denser (2.5–4 lightning km^{-2} yr^{-1}) in the Aegean and Mediterranean coastal regions, particularly in Muğla and its surroundings, in January. In February, lightning events intensified in regions like those affected in January. Average sea surface temperatures in February are lower than those in January. The average sea surface temperature in the Aegean Sea (1970–2022) is 13.9 °C in January and 13.3 °C in February. In the same period, it is 16.6°C and 15.9°C in the Mediterranean in January and February, respectively. Hence, relatively fewer lightning events (0.65–1.6 lightning km^{-2} yr^{-1}) occurred compared to January. The areas where lightning events were experienced also expanded with the increasing temperatures in March. In addition to the Aegean and Mediterranean coasts, lightning events intensified in the Southeast Anatolia Region and the west of the Thrace Region, (0.4–1 lightning km^{-2} yr^{-1}). In April, with the warming of the Southeastern Anatolia Region, instability increased, and convective activities were supported, which caused an increase in lightning density (0.65–1.6 lightning km^{-2} yr^{-1}). With the warming of the land in May, lightning density (2.5–4 lightning km^{-2} yr^{-1}) was observed in the inner parts of the Aegean Region, Marmara, and Eastern Anatolia region (*Fig. 8*). With the further increase in ground temperatures in June, lightning density in the same regions also increased (6.5–16 lightning km^{-2} yr^{-1}). In July, lightning density increased over Thrace, Marmara (6.5–16 lightning km^{-2} yr^{-1}), Central Aegean, Eastern Anatolia, and the Eastern Black Sea Region (0.65–1.6 lightning km^{-2} yr^{-1}). Whereas lightning density is high in the west of the Muğla - Sinop line and the east of the Trabzon - Hakkari line on the land in July, it is almost absent in the inner regions.

While high pressure is present in the Black Sea, the Azores high pressure in the Mediterranean reflects stable conditions, causing lightning density to decrease significantly. Lightning events occur predominantly in the Western Black Sea (10–16 lightning km^{-2} yr^{-1}), the Eastern Black Sea, and Eastern Anatolia (2.5–4 lightning km^{-2} yr^{-1}) in August. the Black Sea Region the average sea surface temperature in the Black Sea Region in August is higher than in July. In the Black Sea, during the period 1970–2022, the average sea surface temperature in July was 22.9 °C, while it was 24.3 °C in August (*Fig. 4*). The increase in lightning density in these regions in August can be associated with the increase in sea surface temperatures and the orographic effect. In September, lightning density is high in the following regions: the Marmara Sea (10–16 lightning km^{-2} yr^{-1}), Eastern Black Sea, Mediterranean Region, and Eastern Anatolia Region (0.65–4 lightning km^{-2} yr^{-1}). In October, the sea surface temperatures of the Marmara and Eastern Black Seas start to decrease (*Fig.4*). However, since the sea surface is not cold enough, although lightning density decreases (1.6–4 lightning km^{-2} yr^{-1}), it continues to exhibit its effect. Dense lightning events also occurred in Southeastern Anatolia and the Gulf of Iskenderun. It was found that the lightning events observed in the relatively warmer Aegean and Mediterranean coastal regions in November, were concentrated in the surroundings of Muğla and Hatay (1.6–4 lightning km^{-2} yr^{-1}). Although lightning events were observed in almost the same regions in December, it can be seen that lightning density decreased relatively (1–2.5 lightning km^{-2} yr^{-1}) in comparison with November. Higher sea surface temperatures are associated with higher lightning density in November than in December (*Fig.9*).

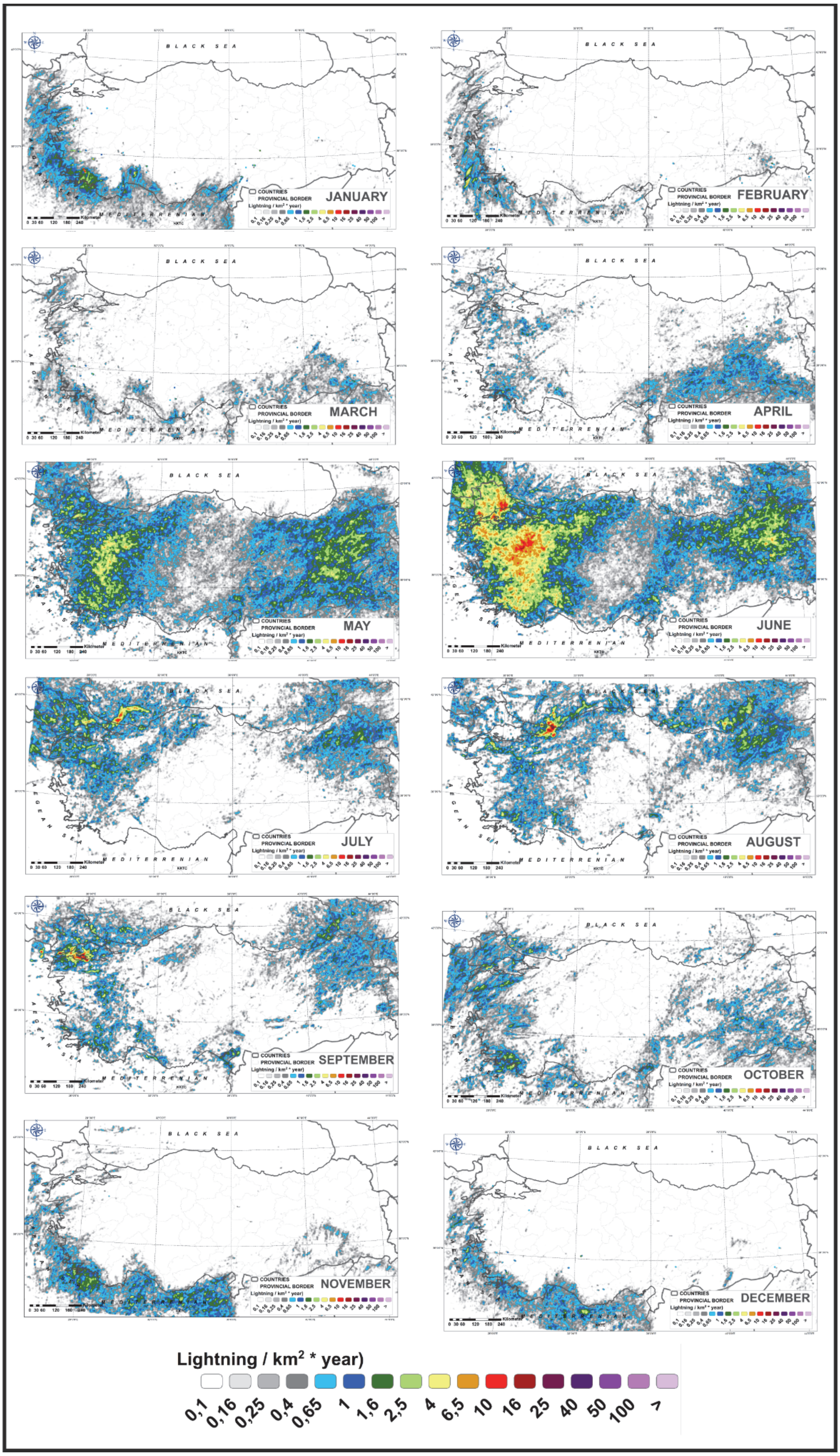

Fig.9. Monthly lightning density (2017–2021).

3.4. Distribution of lightning by the time of day

Upon examining lightning events hourly, the highest number of lightning occurs at noon, whereas the lowest number occurs at night and morning, hours. The period from 11:00 to 15:00 UTC (01:00 to 05:00 national time) is the hottest time of the day. High ground temperature supports convective instability. The period between 19:00–07:00 UTC (22:00–10:00 national time) is when both the ground temperature and instability are at their lowest. Lightning occurs very rarely during this period (*Fig.10*). While lightning density is low in the morning, it increases rapidly after 09:00 UTC (12:00 national time), peaks at 13:00–14:00 UTC (16:00–17:00 national time), and begins to decrease after 14:00 UTC (17:00 national time). The rate of increase from morning to noon is greater than the downward trend from noon to evening. This asymmetrical trend is associated with the rapid warming of the land, the increase in instability at noon, and the continuation of these unstable conditions in the afternoon. This diurnal trend is consistent with the global daily lightning change, in which the peak of lightning activity occurs at noon, and in the afternoon, following the maximum warming of the soil due to solar radiation in land areas (*Galanaki et al.*, 2015).

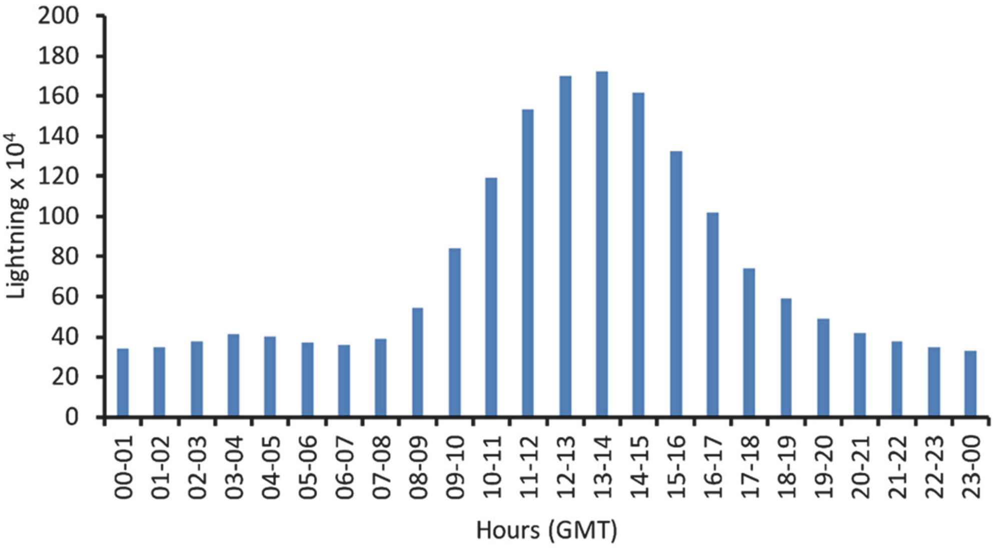

Fig.10. Hourly distribution of lightning (2017–2021).

3.5. The relationship of lightning with latitude and longitude

Considering the relationship between latitude values and lightning density, lightning is positively correlated with latitude, although the correlation is not regular. Lightning intensity increases from the Mediterranean coastline to approximately the peaks of the Taurus Mountains at approximately 37.5N latitude. Lightning intensity decreases in the continental interior, which is roughly between 37.5N and39.5N. Lightning intensity increases again in the high parts of the Black Sea Mountains and in the coastal areas towards the north. Lightning intensity decreases again over the cold, Black Sea (*Fig. 11*).

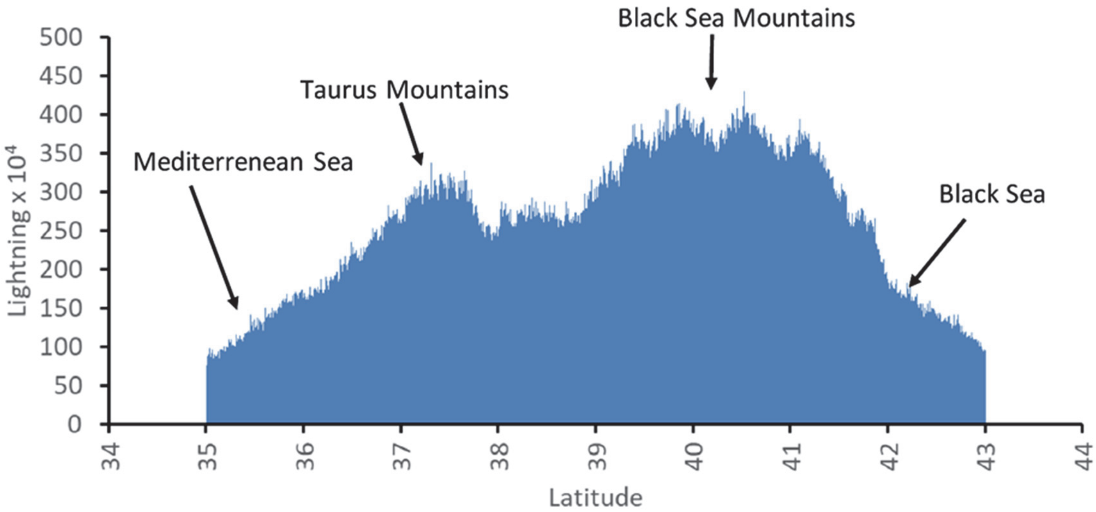

Fig.11. The relationship between latitude and lightning density (2017–2021).

Concerning the relationship between longitude values and lightning density, the region between 26°E and 32°E longitudes facilitate the movement of the humid air of the Aegean Sea to reach the inner parts due to the east-west direction of the mountains. It is the area with the most intense lightning activity in Türkiye because of the sufficient moisture content and high ground temperature found between these longitudes. Previous studies have proven that mountain ranges and elevated areas support convective activities with the effect of orographic forcing, and high summer temperatures. The area between 39E and 44E longitudes is the region of Türkiye with the highest altitude. Lightning activity is also very high in this area. The region between 32E and 39E longitudes is very deficient in terms of moisture content. This should be related to soil moisture and vegetation. Soil moisture was revealed to increase summer convective precipitation efficiency under weak synoptic-scale forcing due to the presence of large sensible heat fluxes in forest areas. As sensible heat fluxes increase the potential to enhance convection and soil moisture abnormalities, they can change boundary layer properties (*Schär et al.*, 1999). This situation should be effective in reducing lightning density in the interior parts, between 32–39E longitudes with poor vegetation and low soil moisture. The longitudinal distribution is mostly related to altitude and vegetation. Lightning density increases as altitude increases, from the low parts in the west to Inner West Anatolia. Lightning density decreases in Central Anatolia because of altitude and insufficient humidity, while lightning density increases with altitude toward Eastern Anatolia (*Fig.12*).

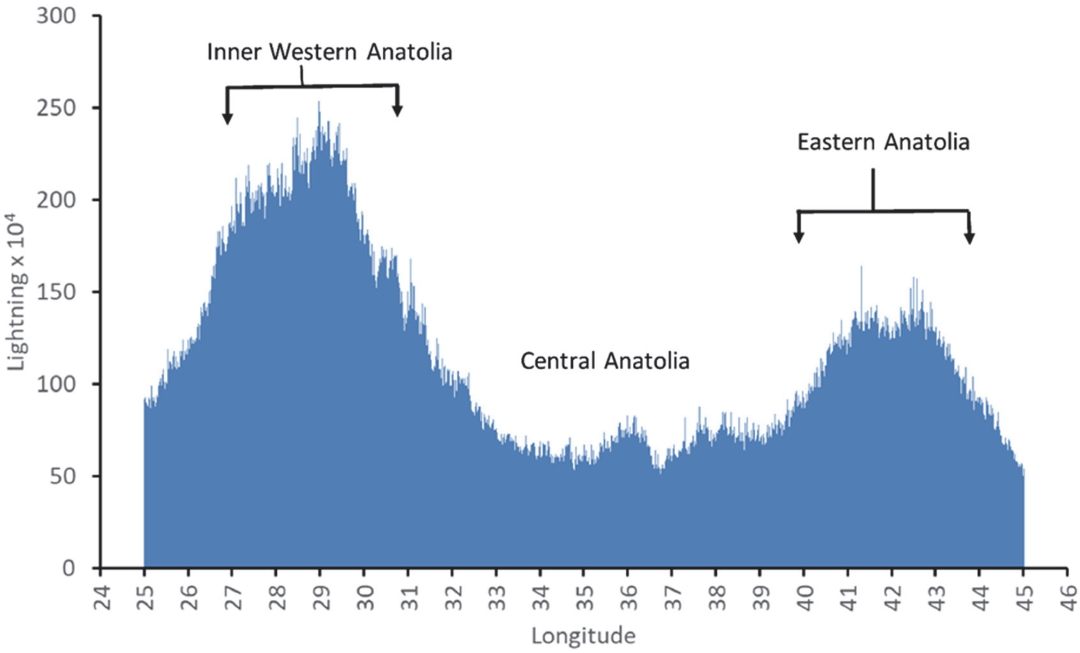

Fig.12. The relationship between longitude and lightning (2017–2021).

3.6. Relationship between lightning and altitude

The relationship between altitude and lightning is examined in two different ways in the present section. Approximately 4×10^6 lightning events were recorded at sea level between 2017 and 2021. Of lightning strikes, 22.5% ($\approx 9\times10^5$ lightning strikes) occurred over the sea. Considering the relationship between altitude and lightning, it becomes difficult to see the trend across different altitudes when sea level is included (*Fig. 13a*). For this reason, the lightning occurring over the sea was subtracted from the total number of lightning strikes, and hence, the relationship between lightning and the elevation in the terrestrial area was predicted. When the relationship is examined without including lightning at sea level, it is seen that lightning increases as a function of altitude between 30–150 m, and 500–1000 m, and decreases as a function of altitude between 150–500 m and above 1000 m. Lightning activity is negligible at 3000 m and above (*Fig.13b*).

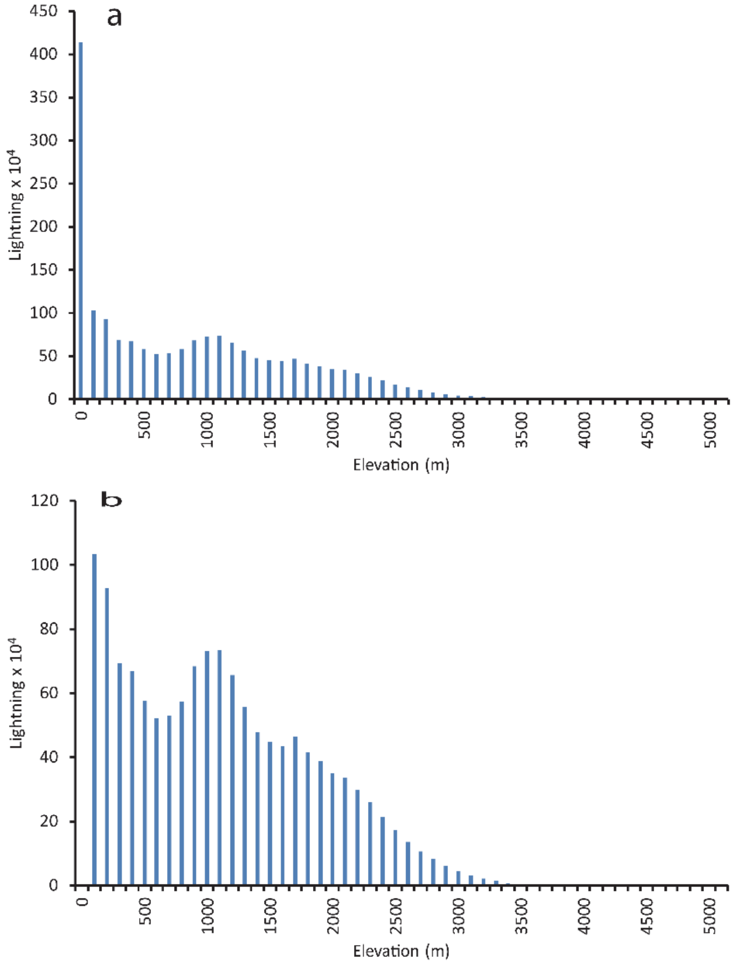

Fig.13. The relationship between lightning and altitude between 2017 and 2021 (a) when sea level is included, (b) when sea level is not included.

4. Discussion and conclusion

In the present study, the annual, monthly, seasonal, and hourly densities of lightning data for 5 years (2017–2021) were calculated. Considering the annual lightning density by regions, the highest values were observed in the Inner Aegean, Marmara, Southwestern Anatolia, Western Black Sea, and Eastern Anatolia Regions. Lightning density in these regions is related to their proximity to the sea, orography, and vegetation type. It was determined that the high level of low-pressure activity on the sea in the Mediterranean basin, especially during the cold period, increases lightning density in the sea and coastal areas. Additionally, the topography and forests increase lightning density with forest influences particularly notable in the warm period (*Kotroni and Lagouvardos*, 2008; *Galanaki et al*., 2015; *Xu et al*., 2022). The Central Anatolia Region is the region with the lowest lightning density. Poor vegetation cover and low soil moisture are factors that should be taken into consideration in this situation. A study from Greece found that lightning efficiency on bare ground surfaces was very low throughout the year, with the lowest values in the summer months (*Kotroni and Lagouvardos*, 2008). Furthermore, low soil moisture in the inner parts weakens convective development (*Schär et al*., 1999). The Aegean Sea, the Mediterranean, the Eastern Black Sea, and the Southeastern Anatolia Region are regions where lightning events occur moderately.

Considering the seasonal lightning density, a relatively higher density of lightning was observed in spring with the warming of the land in comparison with autumn. Although the overall atmosphere is more stable during the winter season, the Aegean and Mediterranean Seas experience a higher frequency of lightning, which, despite being among periods of lowest overall lightning activity, still experiences significant lightning density is the highest in summer, when the surface temperature and, accordingly, instability is the highest. Terrestrial convection is higher in spring and summer. Therefore, denser lightning events occur over the seas in autumn, while the lightning density is higher over the Inner Aegean and Eastern Anatolia Regions during autumn. In winter, it is concentrated in this area because the Mediterranean is warmer. Whereas the dynamic high-pressure system dominating the summer months in the Mediterranean prevents convection and reduces lightning density despite the warm sea surface, the warming of the Black Sea in summer causes lightning density to increase during this period. Summer is the season with the lowest lightning density in the Mediterranean and the highest lightning density in the Black Sea. Upon examining lightning activity hourly, lightning density is the highest at noon and the lowest at night and in the morning hours. These findings are consistent with the results of the study conducted by *Holt et al.* (2001) and *Defer et al.* (2005). Lightning activity in Europe occurs predominantly over land during summer, while during winter, thunderstorms are usually located over the Mediterranean Sea. During spring, the geographical distribution of lightning activity is more spread, while during autumn, the lightning is mainly observed over the sea (*Holt et al*., 2001; *Defer et al*., 2005).

The monthly variation of lightning follows a course with a single maximum, and 29% of the annual lightning strikes occur in June, and 18% in May. Of the annual number of lightning strikes, 47% occur in these two months. Increased lightning activity in late spring and early summer is consistent with the annual temperature trend at mid-latitudes. These findings are similar to the monthly distribution of lightning strikes in the Iberian Peninsula by *Rivas Soriano et al*. (2001b). On the Iberian Peninsula, the monthly variation shows a single peak: about 79% of all lightning events were observed between the months May and September. The number of lightning occurrences increases from April to June, and the sharp decrease after October marks the end of the storm period. This single-peak distribution is related to the annual cycle for the surface air temperature. The high surface air temperature during the warm season supplies an appropriate thermodynamic atmospheric background for convection (*Rivas Soriano et al.,* 2001b). According to lightning climatology studies for parts of western and central Europe, thunderstorm high season falls in summertime and extends from May to August with a peak in July. However, some thunderstorms also occur in the transitional months: March/April and September/October. They are the least likely during wintertime from November to February (*Taszarek et al*., 2017).

Altaratz et al. (2003) carried out a study in the Eastern Mediterranean, and contrary to what is known, the annual average lightning density is higher over the sea than on land. Larger frequencies of ground flashes were detected over the sea than over land during the study period. This is probably due to the large heat and humidity fluxes from the sea surface, which destabilize the colder air above and drive cloud convection. The annual distribution shows that during midwinter (December–January–February), there is higher flash density over the sea, while during autumn and spring, the flash density is similar over the sea and terrestrial regions. However, lightning events on seas in Türkiye over a 5-year period constitute about 22.5% of all lightning, which is consistent with the study by *Altaratz et al*. (2003). It supports the findings of *Williams and Stanfill* (2002) and *Kotroni and Lagouvardos* (2008), indicating that the difference in thermal properties of land compared to sea surfaces explains why considerably more lightning is observed on land than on sea.

Concerning the relationship between altitude and lightning, while lightning increases with altitude in the ranges of 30–150 m and 500–1000 m, it decreases in the ranges of 150–500 m and above 1000 m. This result is consistent with the findings of the lightning activity study in China by *Xu et al*. (2022) *and Galanaki et al.* (2015), indicating that 67% of lightning occurs at altitudes lower than 600 m in winter.

Upon examining the relationship between latitude and longitude values and lightning, a more significant result was obtained regarding latitude. There is a positive relationship between latitude and lightning. Considering the relationship between longitude values and lightning, it can be interpreted that there is a significant decrease in lightning activity, at longitudes 30–35E, in the Central Anatolia Region, where humidity is low. Lightning activity increases as the degree of longitude increases with sufficient moisture content in terrestrial areas together with the orographic effect.

Availability Statement: The data that supports the findings of this study are available from TSMS. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of TSMS.

References

Ackerman S.A. and *Knox J.A.,* 2015: Meteorology: Understanding the Atmosphere. 4th Edition, Jones & Bartlett Learning, Burlington, 244–271.

Altaratz O., Levin Z., Yair Y., and *Ziv B.,* 2003: Lightning activity over land and sea on the Eastern coast of the Mediterranean. *Month. Weather Rev. 131*, 2060–2070. https://doi.org/10.1175/1520-0493(2003)131<2060:LAOLAS>2.0.CO;2

*Anderson G.*and *Klugmann D.,* 2014: A European lightning density analysis using 5 years of ATDnet data. *Nat. Hazards Earth Syst. Sci.14*, 815–829. https://doi.org/10.5194/nhess-14-815-2014

Aydın K. and *Karabulut M.,* 2021: Temperature relationships with elevation and latitude in Turkey. *J. Soc. Sci. 53*, 501–519. https://doi.org/10.29228/SOBIDER.51986

Bayraktar Ö.S. and *Çiçek, İ.,* 2022:. Türkiye'de hortum olayları. *J. Soc. Humanities Sci. Res. 9*(86), 1604–1616. http://dx.doi.org/10.26450/jshsr.3202)

Bozkurt D. and *Göktürk O.M.,* 2009 Artan deniz suyu sıcaklıkları yağmur ve rüzgârı hırçınlaştırırken aşırı yağışlar, seller, fırtınalar *Bilim ve Teknik*, 55–57. https://services.tubitak.gov.tr/edergi/yazi.pdf;jsessionid=dCK1nYJMtkWV6qeWh2DmyvdY?dergiKodu=4&cilt=42&sayi=646&sayfa=54&yaziid=28542

Brooks, H.E., 2013:. Severe thunderstorms and climate change. *Atmos. Res. 123*, 129–138. https://doi.org/10.1016/j.atmosres.2012.04.002

Defer E., Lagouvardos H., and *Kotroni V.,* 2005: Lightning activity in the eastern Mediterranean region. *J. Geophys. Res. 110*, D24210, https://doi.org/10.1029/2004JD005710

Dhital Y., Tang J., Pokharel A., Tang G., and *Rai M.,* 2022: Impact of aerosol concentration on elevation-dependent warming pattern in the mountains of Nepal. *Atmos. Sci. Lett. 23*(10). https://doi.org/10.1002/asl.1101

Dwyer J.R. and *Uman M.A.*, 2013: The physics of lightning. *Physics Rep. 534*, 147–241. http://doi.org/10.1016/j.physrep.2013.09.004

Erol O., 2011: Genel Klimatoloji (10th Edition). Çantay Press, İstanbul ISBN: 9789757206316

Herring S.C., Christidis N., Hoell A., Kossin J.P., Schreck III C.J., and *Scott P.A.,* 2018: Explaining extreme event of 2016 from a climate perspective. *Bull. Amer.Meteorol.Soc. 99*(1)-S1-S6. http://doi.org/10.1175/BAMS-D-17-0284.1

Holle R.L. and *Cooper M.A.* 2016: Lightning occurrence and social vulnerability, In: (Ed. *Coleman J.S.M.*) Atmospheric Hazards, Case Studies in Modeling, Communication,and Societal Impact. Published by ExLi4EvA, 3–19, ISBN-10 9789535125150

Galanaki V., Vassiliki K., Konstantinos L., and *Athanassios A.,* 2015: A ten-year analysis of lightning activity over the Eastern Mediterranean. *Atmos. Res. 166*, 213–222, https://doi.org/10.1016/j.atmosres.2015.07.008

Galanaki E., Lagouvardos K., Kotronia V., Flaounasa E., and *Argirioub A.,* 2018: Thunderstorm climatology in the Mediterranean using cloud-to-ground lightning observations. *Atmos. Res. 207*.136–144. https://doi.org/10.1016/j.atmosres.2018.03.004

Holt M.A., Hardaker P.J., and *McLelland G.P.*, 2001: A lightning climatology for Europe and the UK, 1990–99, *Weather 56*, 290– 296.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [*Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou* (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press. http://doi.org/10.1017/9781009157896

Kiçeci E.C., and *Salamcı E.,* 2020: Aircraft–lightning interaction. *Eur. J. Sci Technol*, Special Issue, 177–187. http://doi.org/10.31590/ejosat.araconf23

Kirshbaum D.J., Adler B., Kalthoff N., Barthlott C., and *Serafin S.,* 2018: Moist orographic convection: Physical mechanisms and links to surface-exchange processes. *Atmosphere 9*, 80. https://doi.org/10.3390/atmos9030080

Kotroni V. and *Lagouvardos K.,* 2008: Lightning occurrence in relation with elevation, terrain slope, and vegetation cover in the Mediterranean. *J. Geophys. Res. 113*, D21118, http://doi.org/10.1029/2008JD010605

Kotroni V. and *Lagouvardos K.,* 2016: Lightning in the Mediterranean and its relation with sea-surface temperature. *Environ. Res. Lett. 11*(3). http://dx.doi.org/10.1088/1748-9326/11/3/034006

Koutroulis A.G., Grillakis M.G., Tsanis I.K., Kotroni V., and *Lagouvardos, K.,* 2012: Lightning activity, rainfall and flash flooding – occasional or interrelated events? A case study in the island of Crete. *Nat. Hazards Earth Syst. Sci. 12*, 881–891. https://doi.org/10.5194/nhess-12-881-2012

Lay E.H., Jacobson A.R., Holzworth R.H., Rodger C.J., and *Dowden R.L.,* 2007: Local time variation in land/ocean lightning flash density as measured by the world wide lightning location network. *J.Geophys. Res. 112*, D13111. https://doi.org/10.1029/2006JD007944

Mackerras D. and *Darveniza M.,* 1994: Latitudinal variation of lightning occurrence characteristics. *J. Geophys. Res. 99*, 10,813–10,821. https://doi.org/10.1029/94JD00018

Manzato A., Serafin S., Miglietta M.M., Kirshbaum D., and *Schulz W.,* 2022: A Pan-Alpine climatology of lightning and convective initiation. *Month. Weather Rev. 150*, 2213–2230, https://doi.org/10.1175/MWR-D-21-0149.1

Mazarakis N., Kotroni V., Lagouvardos K., and *Argiriou A.,* 2008: Storms and lightning activity in Greece during the warm periods of 2003–06. *J. Appl. Meteorol. Climatol. 47*, 3089–3098, https://doi.org/10.1175/2008JAMC1798.1

Orville R.E. and *Henderson R.W.,* 1986: Global distribution of midnight lightning: September 1977 to August 1978. *Month. Weather Rev. 114*, 2640–2653. https://doi.org/10.1175/1520-0493(1986)114<2640:GDOMLS>2.0.CO;2

Öztopal, A., 2017: Türkiye'nin yıldırım ve şimşek gözlemlerinin incelenmesi *Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi. 19* (56), 304–313. https://doi.org/10.21205/deufmd.2017195634

Özlü T., Haybat H . and *Zerenoğlu H.,* 2020: Trafik kazalarının zamansal ve mekânsal incelenmesi: Eskişehir şehir örneği. *Int. J. Geogr. Geogr. Educat. (IGGE) 43*, 136–158. https://doi.org/10.32003/igge.746447

Petersen W.A. and *Rutledge S.A.,* 1998: On the relationship between cloud-to-ground lightning and convective rainfall. *J. Geophys. Res. 103*, D112, 14025–14040. https://doi.org/10.1029/97JD02064

Pinto I.R.C.A., and *Pinto Jr O.,* 2003: Cloud to-ground lightning distribution in Brazil. *J. Atmos. Solar-Terrest.l Phys. 65*, 733–737. https://doi.org/10.1016/S1364-6826(03)00076-2

Pinto Jr O., Pinto I.R.C.A., and *Neto O.,* 2013: Lightning enhancement in the Amazon region due to urban activity. *Amer. J. Climate Change 2*(4), 270–274. http://doi.org/10.4236/ajcc.2013.24026

Pinto Jr O. and *Pinto I.R.C.A.,* 2020 Lightning changes in response to global warming in Rio de Janeiro, Brazil. *Amer. J. Climate Change 9*(3), 266–273. https://doi.org/10.4236/ajcc.2020.93017

Rangwala, I. and *Miller, J.R.,* 2012: Climate change in mountains: a review of elevation-dependent warming and its possible causes. *Climatic Change 114*, 527–547. https://doi.org/10.1007/s10584-012-0419-3

Reason C.J.C. and *Mulenga H.,* 1999: Relations between South African rainfall and SST anomalies in the southwest India Ocean. *Int. J. Climatol. 19*, 1651–1673. https://doi.org/10.1002/(SICI)1097-0088(199912)19:15<1651::AID-JOC439>3.0.CO;2-U

Reynolds S.E, Brook M., and *Gourley M.F.,* 1957: Thunderstorms charge separation. *J. Atmos. Sci. 14*, 426–436. https://doi.org/10.1175/1520-0469(1957)014<0426:TCS>2.0.CO;2

Rivas Soriano L., de Pablo F., Diez E.G., 2001a: Relationship between convective precipitation and cloud-to-ground lightning in the Iberian Peninsula. *Monthly Weather Review,* 129:12, 2998–3003. https://doi.org/10.1175/1520-0493(2001)129%3C2998:RBCPAC%3E2.0.CO;2

Rivas Soriano L., de Pablo F., Diez, E.G., 2001b: Cloud-to-ground lightning activity in the Iberian Peninsula: 1992-94. *Journal of Geophysical Research,* 106:D11, 11,891-11,901. https://doi.org/10.1029/2001JD900055

Rivas Soriano L. and *de Pablo F.,* 2002: Maritime cloud-to-ground lightning: The western Mediterranean Sea. *J. Geophys. Res. 107*, D21. https://doi.org/10.1029/2002JD00221

Romps D.M., Seeley J.T., Vollaro D, and *Molinari J.,* 2014: Projected increase in lightning strikes in the United States due to global warming. *Science 346*, 851–854. https://doi.org/10.1126/science.1259100

Rupke E., 2002: Lightning direct effects handbook. Lightning Technologies Inc., AGATE-WP3.1-031027-043-Design Guideline https://agate.niar.wichita.edu/Lightning/AGATE-Handbook-Rev-E.pdf

Saha U., Siingh D., Kamra A.K., Galanaki E., Maitra A., Singh R.P., Singh A.K., Chakraborty S., and *Singh R.,* 2017: On the association of lightning activity and projected change in climate. *Atmos. Res. 183*, 173–190. https://doi.org/10.1016/j.atmosres.2016.09.001

Schär C., Lüthi D., Beyerle U., and *Heise E.,* 1999: The soil–precipitation feedback: a process study with a regional climate model. *J. Climate 12*, 722–741. https://doi.org/10.1175/1520-0442(1999)012<0722:TSPFAP>2.0.CO;2

Takahashi T., 1984: Thunderstorm electrification—A numerical study. *J. Atmos. Sci. 41*, 2541–2558. https://doi.org/10.1175/1520-0469(1984)041<2541:TENS>2.0.CO;2

Taszarek M., Brooks H.E., and *Czernecki B.,* 2017: Sounding-Derived Parameters Associated with Convective Hazards in Europe. *Month. Weather Rev. 145*, 1511–1528. https://doi.org/10.1175/MWR-D-16-0384.1

Tinmaker M.I.R, Ali K., and *Beig G.,* 2010: Relationship between lightning activity over Peninsular India and sea surface temperature. *J. Appl. Meteorol. Climatol. 49*, 828–835. https://doi.org/10.1175/2009JAMC2199.1

Tinmaker M.I.R., Aslam M.Y., and *Chate D.M.,* 2017: Association of rainfall and stability index with lightning parameter over the Indo-Gangetic Plains. *Amer. J. Climate Change 6*, 443–454. https://doi.org/10.4236/ajcc.2017.63023

Tinmaker M.I.R., Ghude S.D., and *Chate D.M.,* 2019: Land-sea contrasts for climatic lightning activity over Indian region. *Theor. Appl. Climatol. 138*, 931–940. https://doi.org/10.1007/s00704-019-02862-4

TSMS (Türkiye State Meteorological Service), 2022a: https://www.mgm.gov.tr/genel/meteorolojiyegir.aspx?s=17 accessed October 25 2022

TSMS (Türkiye State Meteorological Service), 2022b: https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=K accessed February 02 2024

TSMS (Türkiye State Meteorological Service), 2024: https://www.mgm.gov.tr/veridegerlendirme/sicaklik-analizi.aspx

Turman B.N. and *Edgar B.C.,* 1982: Global lightning distributions at dawn and dusk. *J. Geophys. Res. 87*, 1191–1206. https://doi.org/10.1029/JC087iC02p01191

Uman M.A,. 1986: All About Lightning. Dover Publications N.Y. 99:173; ISBN- 2-486-25237-x

Williams E., 2005: Lightning and climate: a review. *Atmos. Res. 76*, 272–287. https://doi.org/10.1016/j.atmosres.2004.11.014

Williams E. and *Guha A.,* 2019: Lightning and climate change. In Proceedings of the International Seminar on Lightning Protection. São Paulo: Institute of Energy and Environment of the University of São Paulo ISBN: 9781728118925

Williams E. and *Stanfill S.,* 2002: The physical origin of the land-ocean contrast in lightning activity. *Comptes Rendus Physique 3*, 1277–1292. https://doi.org/10.1016/S1631-0705(02)01407-X

Xu M., Qie X., Pang W., Shi G., Liang L., Sun Z., Yuan Z., Zhu K., and *Zhao P.,* 2022: Lightning climatology across the Chinese continent from 2010 to 2020. *Atmos. Res. 275*. https://doi.org/10.1016/j.atmosres.2022.106251

Yamamotu K., Nakashima T., Sumi S., and *Ametani A.,* 2016: About 100 years survey of the surface temperatures of Japan sea and lightning days along the coast. 33rd International Conference on Lightning Protection (ICLP). https://doi.org/10.1109/ICLP.2016.7791346

Yavuz V., Lupo A.R., Fox N.I., and *Deniz A.,* 2022: A long-term analysis of thundersnow events over the Marmara Region, Turkey. *Nat. Hazards 114*, 367–387. https://doi.org/10.1007/s11069-022-05393-w

Zipser E.J. and *Lutz K.R.*, 1994: The Vertical profile of radar reflectivity of convective cells: A strong indicator of storm intensity and lightning probability? *Month. Weather Rev. 122*, 1751–1759. https://doi.org/10.1175/1520-0493(1994)122<1751:TVPORR>2.0.CO;2

Ziv B., Saaroni H., Yair Y., Ganot M., Baharad A., and *Isasrachi D.,* 2009: Atmospheric factors governing winter thunderstorms in the coastal region of the eastern Mediterranean. *Theor. Appl. Climatol. 95*, 301–310. https://doi.org/10.1007/s00704-008-0008-6