



# Effects of Regional Thermodynamic Parameters on Lightning Flash Density as an Indicator of Convective Activity Over Southwest Iran

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**Abstract**—This study investigated the correlation of thermodynamic parameters with the regional averaged lightning flash density in southwest Iran based on OTD/LIS observations and reanalysis datasets from 1996 to 2014. In addition, the most important parameters and their domains were identified for explaining the lightning density variance using a multiple linear regression model. The results showed that surface sensible heat flux over Syria and Jordan, CAPE over southwest Iran, sea surface temperature over the Arabian Sea, and latent heat flux over Northeastern Europe are the best parameters to predict the lightning density in winter. While in spring, CAPE over southwest Iran, the surface sensible heat flux over northeast Iran and the Arabian Sea, and air surface temperature over the Saudi Arabian Peninsula are the main factors for predicting lightning density. The regression models explain almost 90% and 93% of the lightning variability in winter and spring, respectively. The local effect of CAPE and low-level wind shear on lightning activity is more important in spring than in winter, indicating that the contribution of local lightning-generating convective activity is higher in spring. The correlation coefficient between humidity indices and lightning density showed that western moisture sources have a more important role in providing moisture to convection and lightning in winter than in spring. It is worth noting that the wind speed of jet streams at 300 hPa is positively correlated with lightning activity in winter, although their contribution to the multiple linear regression model is negligible.

**Keywords:** Lightning activity, CAPE, heat flux, surface temperature, multiple linear regression model.

## 1. Introduction

Lightning is a severe meteorological phenomenon that significantly affects ecological systems, atmospheric chemistry, and climate systems (Qie et al.,

2021; Romps et al., 2014). Hence, understanding the causes of its occurrence is important. Lightning occurs due to convective activity (Dayeh et al., 2021) and is strengthened by deep convection (Tinmaker et al., 2015). It has been found to have a strong relationship with thunderstorm activity (Toumi and Makela, 2008; Price, 2013), so it can be applied to track the status of convective cores (Taszarek et al., 2020) and to determine the most convectively active regions of the world (Lavigne et al., 2019).

Synoptic weather systems are a major contributor to lightning (Unnikrishnan et al., 2021). Therefore, lightning activity is strongly dependent on the meteorological process that governs the thermodynamics of a thunderstorm (Dayeh et al., 2021; Qie et al., 2020). Large-scale atmospheric circulations can be affected by the surface air temperature and sea surface temperature, and thus these parameters influence the occurrence and frequency of convection and lightning activity (Qie et al., 2020; Reeve & Toumi, 1999; Tinmaker et al., 2010). Convection is driven by surface heating since the surface heat fluxes can provide the energy needed to destabilize the atmospheric boundary layer and transfer moisture into the upper troposphere (Li et al., 2020). Water vapor is a necessary ingredient for cloud formation. Also, it affects the development of convection and lightning occurrence by releasing latent heat and increasing the atmospheric instability (Fan et al., 2007). Convective available potential energy (CAPE) is a useful convective activity index representing the atmospheric instability and the energy provided by atmospheric buoyancy (Biswasharma et al., 2021; Siingh et al., 2014). The moist entropy and equivalent potential temperature of the atmospheric boundary layer are increased by positive sensible and latent heat fluxes,

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increasing the CAPE and reducing the convective inhibition (Kirshbaum et al., 2018).

Tinmaker et al. (2021) reported, based on previous studies (Marengo & Espinoza, 2016; Rao et al., 1996), that lightning activity and parameters affecting it such as maximum air temperature, Bowen ratio, rainfall, cloud ice content, and aerosol loadings can be associated with the change in seasons and the variation of atmospheric circulations and lapse rates. Damase et al. (2021) explored the dependence of lightning flash density on monthly mean CAPE, surface air temperature, thermodynamic temperature of the top of the cloud, cloud-top temperature, relative humidity, and specific humidity over the three sections of the Himalayan range. They observed that CAPE and surface air temperature are important in generating instability over that region, and relative humidity of 50–60% at 700 hpa is the most optimal condition for lightning over the Himalayan region. On the other hand, Chate et al. (2017) found that total sensible and latent heat fluxes are a better climatic index for lightning activity than CAPE. Qie et al. (2021) reported that the surface latent heat flux along the west coast of the Indian subcontinent is the most significant contributor, explaining 52% of the lightning variance in the South Asia region. Based on the results of this study, the sea surface temperature in the Arabian Sea, the CAPE over the northwestern Indian subcontinent, and the wind shear along the northwestern coast also are leading contributors in this regard.

The development of convection and occurrence of lightning is greatly dependent on the underlying terrain (Li et al., 2020) because of their differences in thermodynamic and dynamic properties. Many researchers have revealed lightning activity's regional characteristics and significant spatial diversity (Boccippio et al., 2000; Unnikrishnan et al., 2021). In contrast, there are few studies in the literature on lightning and convective activity in the region of interest. Due to the many regional differences, it is essential to understand the factors affecting this phenomenon in the study area. Therefore, the primary goal of this study is to assess the relationship between thermodynamic parameters and lightning as an essential indicator of convective activity. The paper is organized as follows. After a brief description of the

study domains, data, and methods in Sect. 2, an analysis of results is presented in Sect. 3, and conclusions are provided in Sect. 4.

## 2. Material and Methods

### 2.1. Study Area

There are two domains as the study areas in this investigation. The first domain is the southwest of Iran (located between the geographic coordinates 47°E and 52°E; 30°N and 33°N; Fig. 1), where the factors affecting its lightning flash rate variability are assessed. The area includes three provinces: Khuzestan province, Chaharmahal and Bakhtiari province, Kohgiluyeh and Boyer-Ahmad province. Moreover, it has very diverse topography, vegetation, and climate characteristics. The Zagros mountain range covers a large part of this area (maximum altitude about 4300 AMSL). These mountains follow an NW to SE direction and have an important role in the precipitation pattern of this area. The mean temperature varies from warm (25 °C) in the Khuzestan Plain to much colder (12.3 °C) in the Zagros heights, and the mean annual precipitation varies from 100 mm in the southwest of the Khuzestan Plain to > 900 mm in some parts of the Zagros heights (Keikhosravi Kiany et al., 2020). Most of the annual precipitation occurs in cold seasons, and convective systems significantly contribute to the total precipitation.

The second domain is larger, at 10°E–70°E and 0°N–60°N (Fig. 1), where its environmental conditions can affect the lightning flash rate variability of the first domain. The most important components affecting the climate of this region are the Saudi Arabia anticyclone (in the Arabian Sea or southeast of Saudi Arabia), the North Africa and Azores high pressure, Siberian high pressure, Sudan low pressure and the Red Sea convergence zone, and the Mediterranean trough, which play an essential role in convective system formation (Rafati and Karimi, 2017) and lightning occurrence in synoptic scale.

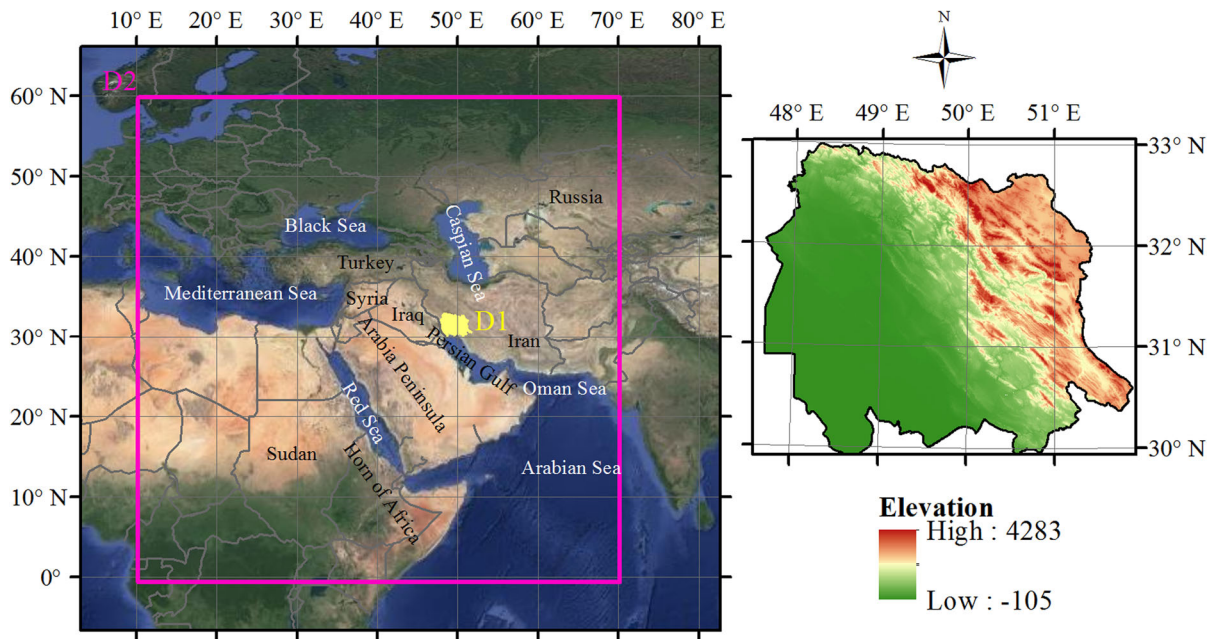


Figure 1

Two domains of the study area: domain 1 (southwest Iran) with yellow and domain 2 with magenta rectangle on the left. Digital elevation model (DEM) of southwest Iran on the right

## 2.2. Data

The use of lightning data from space is a good substitute in areas where there are no ground-based networks (Christian, 2003) like southwest Iran. Lightning data is stabilized by the Optical Transient Detector (OTD) (Christian, 2003). With the launch of the Tropical Rainfall Measuring Mission (TRMM), lightning detection has become conceivable using the Lightning Imaging Sensor (LIS), and since then, further studies have been done on storm structures (ZIPSER et al., 2006). LIS is an instrument that acquires total lightning (cloud-to-ground and intra-cloud) by measuring radiant energy emitted by lightning during day and night (Abreu et al., 2020). LIS/OTD gridded lightning climatology products are available from the Global Hydrology Resource Center (GHRC), and details on these products have been provided by Cecil et al. (2014). The low-resolution monthly time series (LRMTS) and high-resolution monthly climatology (HRMC) were used in this study. The LRMTS presents the smoothed monthly lightning flash rate, with a grid resolution of  $2.5^\circ \times 2.5^\circ$ . A 99-day boxcar moving average for the

LIS and a 111-day boxcar moving average for the OTD are applied to scale flash counts and view times. These averaging periods are chosen to allow LIS and OTD to progress through the diurnal cycle at a given location twice. Also, a  $7.5^\circ \times 7.5^\circ$  boxcar moving average and a low-pass digital filter are applied to both flash rate and view time (Cecil et al., 2014). Smoothing is necessary for results to be robust. The LRMTS has a precise merging of the LIS and OTD flash rates because the combined data are more weighted toward the LIS, which has a greater detection efficiency. This product is considerably recommended for time series analysis. The HRMC has data binned as  $1 \text{ day} \times 0.5^\circ \times 0.5^\circ$  at first. A  $2.5^\circ \times 2.5^\circ$ , a 31-day boxcar moving average, and then a low-pass digital filter are applied, respectively, in the next steps. Following smoothing, the daily average flash rate is extracted from the middle of each month. The units of both products are flashes  $\text{day}^{-1} \text{ km}^{-2}$  (Cecil et al., 2014).

Reanalysis datasets including 2 m air temperature, sea surface temperature (SST), convective available potential energy (CAPE), surface sensible

heat flux, surface latent heat flux, specific humidity at 1000 and 700 hPa, total column water vapor, and U and V components of wind at 850, 700, and 300 hPa were obtained from the ERA5 monthly averaged data on single levels and pressure levels (<https://cds.climate.copernicus.eu>) for the period 1995–2014. ERA5 is the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate and weather that replaces the ERA-Interim reanalysis.

### 2.3. Methodological Procedures

This study determined the relationship between the mean regional lightning flash rate in southwest Iran and thermodynamic parameters in each grid of domain 2 in Fig. 1. The selected parameters included the surface air temperature, sea surface temperature, convective available potential energy, surface sensible heat flux, surface latent heat flux, Bowen ratio (the ratio of the sensible heat fluxes to latent heat fluxes), specific humidity at 1000 and 700 hPa, total column water vapor, low-level vertical wind shear, and wind speed at 300 hPa.

Low-level vertical wind shear was calculated from zonal and meridional wind fields at 850 and 700 hPa based on Wang et al. (2018) as follows:

$$\text{shear} = \sqrt{(U_{850} - U_{700})^2 + (V_{850} - V_{700})^2}.$$

After identifying the dominant regions with the most robust relationship between thermodynamic parameters and lightning flash rate, a multiple linear regression was used to determine the most important parameters to predict lightning flash rate variability. The regional averaged lightning flash rate (LFD) is defined as:

$$LFD(t) = \sum_{i=1}^m biX(t) + r$$

where  $X(t)$  is the averaged thermodynamic variables over the selected regions,  $bi$  is the regression coefficient, and  $r$  is the residuals.

We used part and partial correlations (Morrison, 1976) and the variance inflation factor (VIF) to assess the collinearity problem, as follows:

$$VIF = 1/(1 - R^2)$$

where  $R^2$  is the coefficient of determination of the regression equation. A variance inflation factor greater than 2 is usually considered problematic. The collinearity diagnostics confirm that there are serious problems with multicollinearity. We try to fix the collinearity problem by using z scores of the variables and the forward stepwise method. This is to include only the most useful variables in the model.

### 3. Results and Discussion

The monthly climatological distribution of lightning activity from 1995 to 2014 is shown in Fig. 2. The highest lightning activity is in May ( $0.035 \text{ flash km}^{-2} \text{ day}^{-1}$ ) and in December ( $0.028 \text{ flash km}^{-2} \text{ day}^{-1}$ ); in contrast, the lowest lightning activity is in July to October ( $0.002\text{--}0.003 \text{ flash km}^{-2} \text{ day}^{-1}$ ). The mean flash rate is equal to 0.019, 0.021, 0.007, and 0.006 flashes  $\text{km}^{-2} \text{ day}^{-1}$  in winter (December, January, and February), spring (March, April, and May), summer (Jun, July, and August), and autumn (September, October, and November), respectively. Therefore, its activity is much higher in spring and winter than in summer and autumn (Fig. 3). Spring and winter are convectively active periods in the region of interest, and this is largely consistent with the seasonal climatological distribution of convective system activity in southwest Iran (Rafati and Karimi, 2017). Figure 4a, d shows the 700 hPa mean geopotential height and mean wind over the study area in

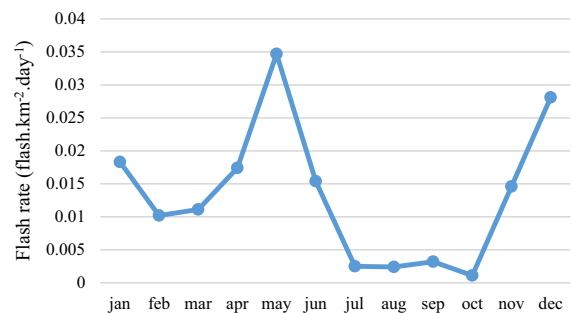


Figure 2  
The mean monthly lightning density over southwest Iran during 1996–2014

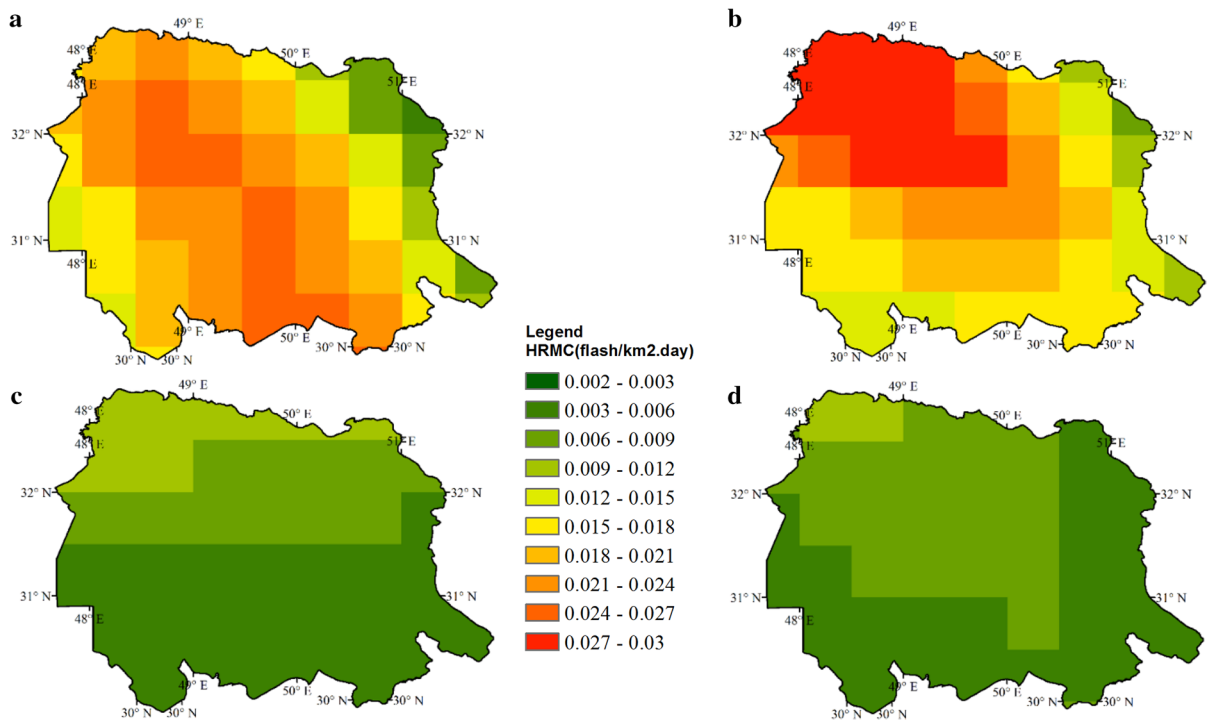


Figure 3

Spatial distribution of the seasonal mean of lightning flash rate during 1996–2014: **a** winter, **b** spring, **c** summer, **d** autumn

the four seasons. In summer and autumn, the subtropical high located over the study area causes the lower occurrence of convective systems and lightning. Also, as can be implied from Fig. 3a, c, d, flash density is enhanced where the mean flow is upslope and decreased where the mean flow is downslope in winter, spring, and autumn. However, the terrain gradient has little effect on the flash density in summer, since the summer mean flow is weak (Fig. 3c).

The summer and autumn were excluded from the study due to low lightning density, while spring and winter were selected to assess the significant meteorological factors to predict seasonal lightning variability.

The spatial distribution of correlation coefficients between each potential factor and the lightning flash rate is presented for winter and spring (Figs. 5, 6, 7, 8, 9, 10). The differences between spring and winter are among our favorite topics in this study.

Among the humidity variables, the specific humidity at 1000 and 700 hPa and total column water vapor were selected in this study. A similar pattern

was observed in the correlation coefficient between humidity and lightning density (Fig. 5). In other words, a positive correlation coefficient was seen over two separate centers for all three variables in winter; the first center is located over the eastern Mediterranean to the east of Iran, and the second center is located over the Horn of Africa. At the same time, there is a relatively integrated center in spring, from the Horn of Africa to the west of Iran along the Red Sea convergence zone. Figure 6 shows the most frequent 850 hPa flow pattern, which causes convective system development. Moist and warm air was advected by the anticyclone located over the Arabian Sea (Saudi Arabia anticyclone). Moisture transfer occurred from the Arabian Sea to the Sudan low pressure, the Red Sea convergence zone, and southwest Iran. The rate of moisture transfer depends on the strength of the anticyclone and wind speed. This can explain why lightning over southwest Iran would be correlated positively with moisture over the Horn of Africa and the Red Sea convergence zone.

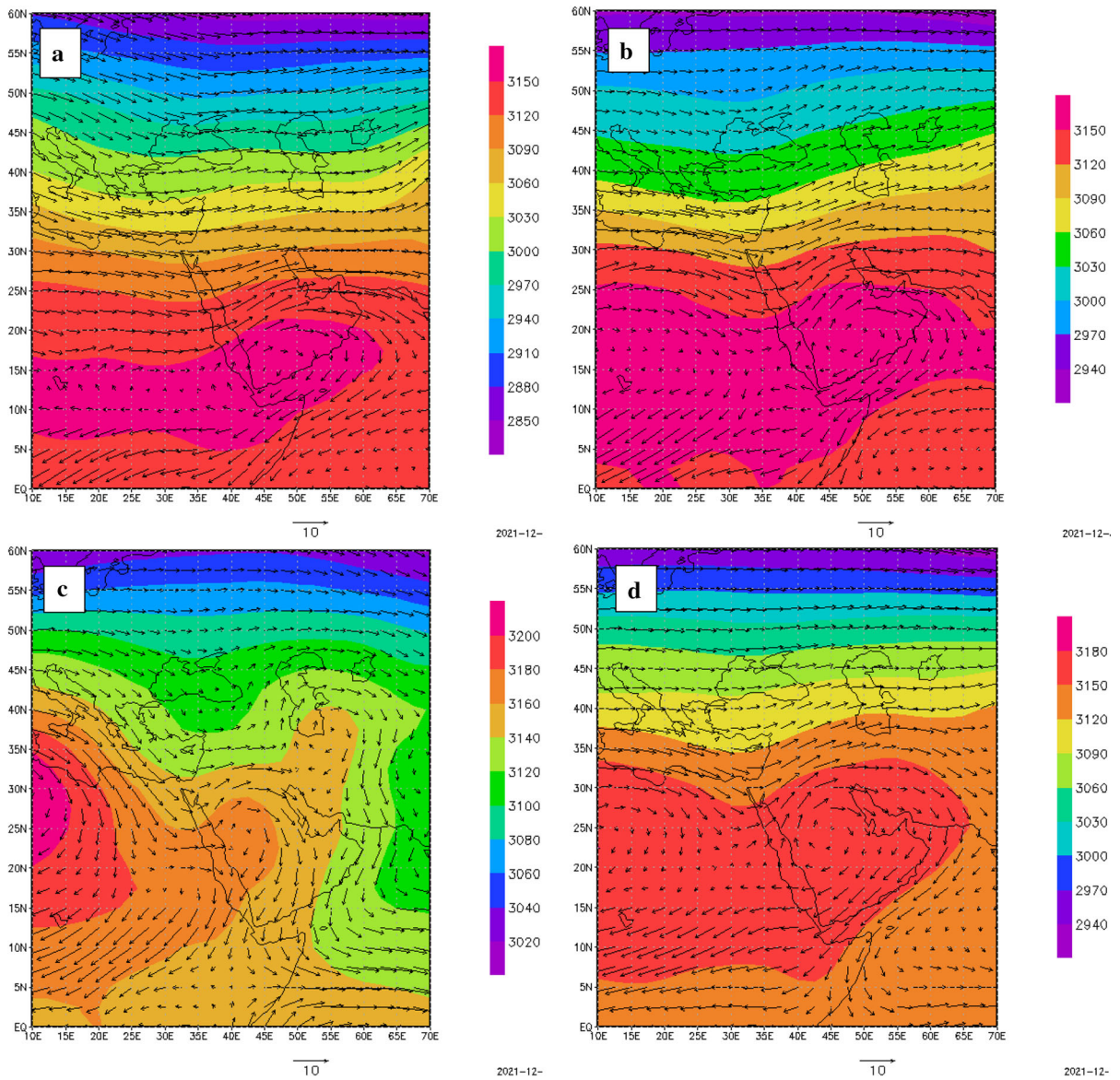


Figure 4 The mean geopotential height and mean wind at 700 hPa during 1981–2010: a winter, b spring, c summer, d autumn

The different spatial distributions of the correlation coefficient of these parameters with lightning activity in spring and winter show that the moisture sources for convection and lightning activity are somewhat different in the two seasons, so that the Mediterranean Sea plays a more critical role in the winter. The second important point is that total column water vapor strongly correlates with lightning

density, while the specific humidity at 1000 hPa shows the weakest correlation.

The correlation between surface air temperature and lightning density is more robust and is also significant in the broader area in winter. In winter, lightning flash density is positively correlated with surface air temperature over Northeast Africa, the Horn of Africa, and the south of the Arabian Peninsula (Fig. 7a). Also, it is negatively correlated with

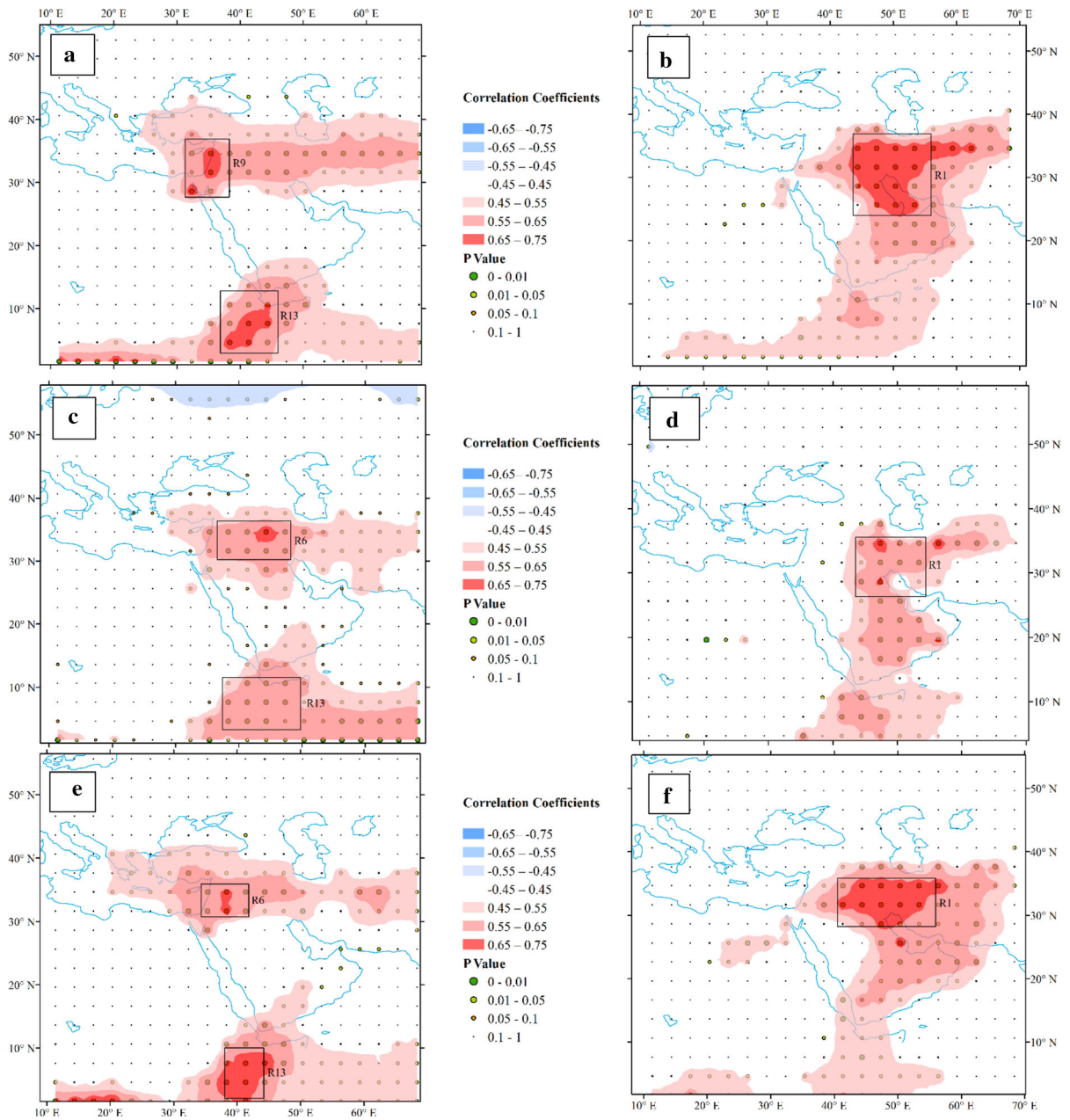


Figure 5

Correlation coefficients (above the 95% confidence level) between the regional averaged flash density over southwest Iran and **a** total column water vapor in winter, **b** total column water vapor in spring, **c** specific humidity at 1000 hPa in winter, **d** specific humidity at 1000 hPa in spring, **e** specific humidity at 700 hPa in winter, and **f** specific humidity at 700 hPa in spring (1996–2014)

surface air temperature over Russia, where cold air advection can increase instability in the area and cause higher convective activity and lightning occurrence. While in spring, it is positively correlated

over a very small area in the south of the Arabian Peninsula. Also, there is a negative correlation coefficient area around the Caspian Sea (Fig. 7b). This can be explained by flow patterns that create

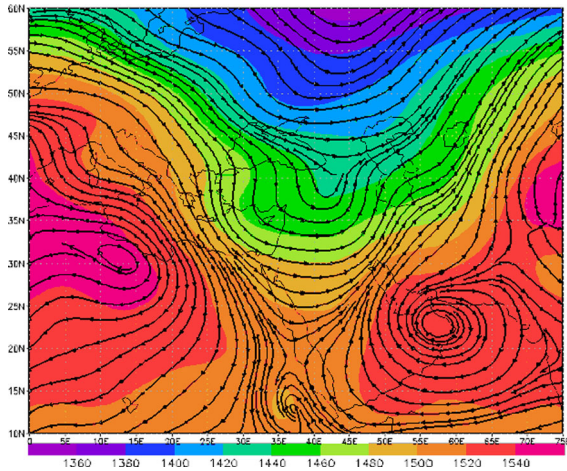


Figure 6

The most frequent 850 hPa pattern [geopotential height (m) and streamlines] which induced convective system development (Rafati and Karimi, 2017)

convective systems. Based on the results of a previous study (Rafati and Karimi, 2017), moist and warm air is advected by the anticyclone located in the Arabian Sea or southeast of Saudi Arabia. Cold air is advected either by the Azores high pressure or Siberian high pressure. At times, local high pressure that forms in the north of Iran, the north and south of the Mediterranean Sea, or the Black Sea is responsible for this advection. The result of these flows pattern is spreading of the Sudan low pressure toward southwest Iran. It provides the conditions for the formation of convective systems and the occurrence of lightning. Also, the important effect of North Africa surface air temperature was found on lightning activity over northwest South Asia and the Indian summer monsoon (Rizou et al., 2015; Qie et al., 2020). It is consistent with our results in winter.

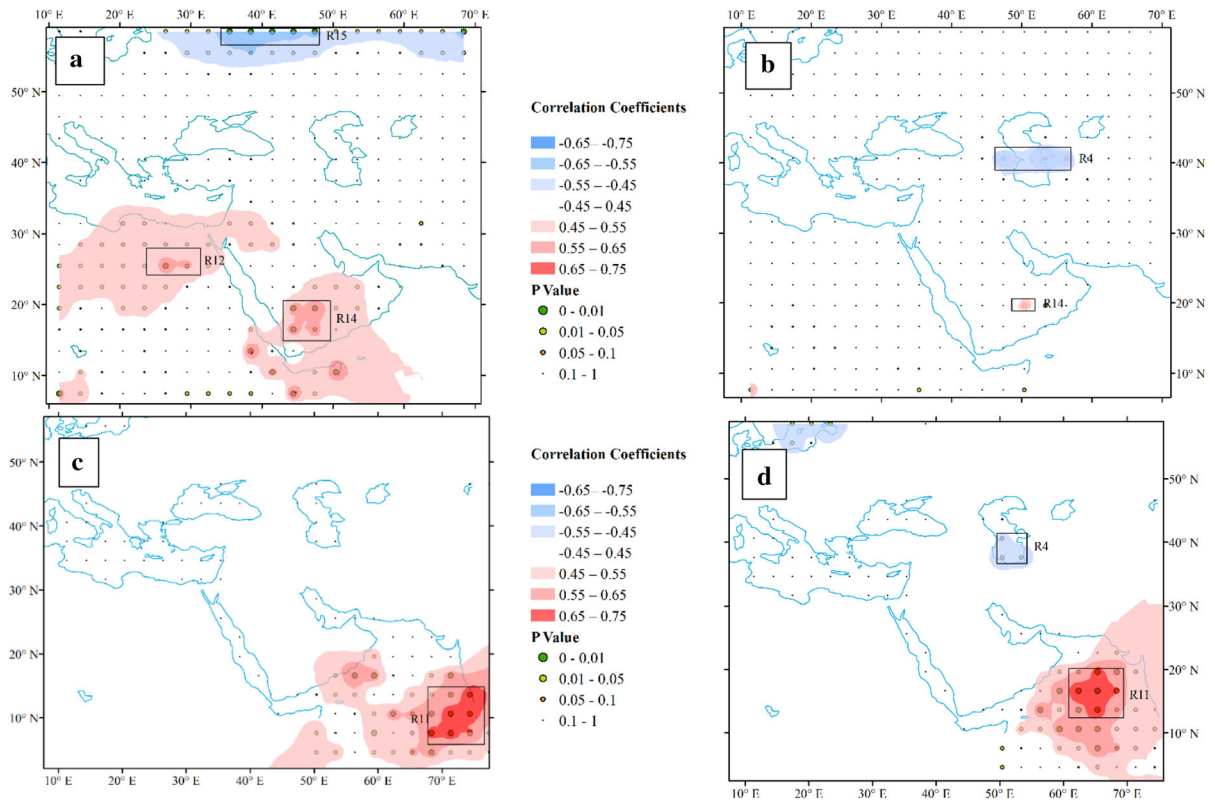


Figure 7

The correlation coefficients (above the 95% confidence level) between the regional averaged flash density over southwest Iran and **a** surface air temperature in winter, **b** surface air temperature in spring, **c** sea surface temperature in winter, and **d** sea surface temperature in spring (1996–2014)



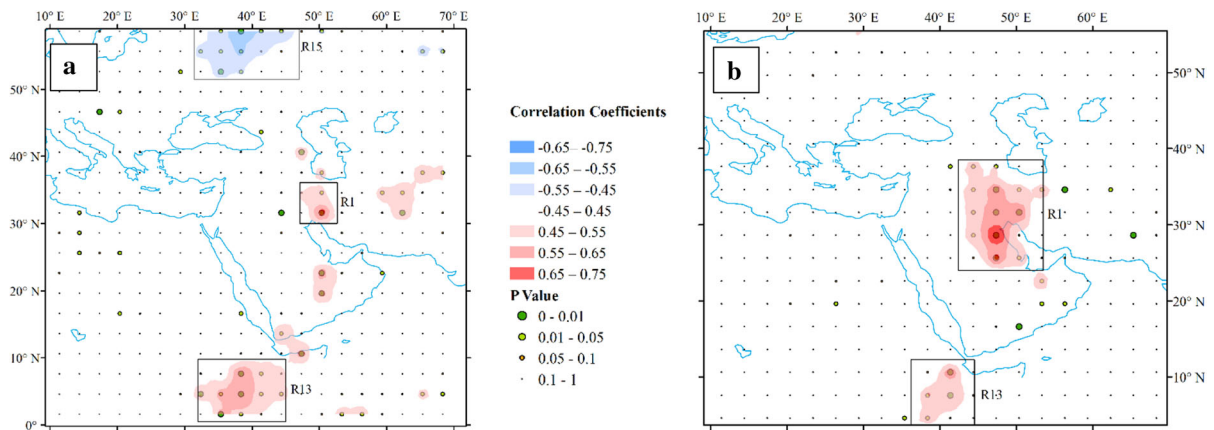


Figure 8

Correlation coefficients (above the 95% confidence level) between the regional averaged flash density over southwest Iran and CAPE time series (1996–2014) in **a** winter and **b** spring

However, its correlation with lightning activity in spring is nonsignificant.

The lightning density also positively correlates with the sea surface temperature over the Arabian Sea in both seasons (Fig. 7c, d), where the source of warm and humid air mass is for the study area. This is consistent with previous studies (Jaramillo et al., 2018; Qie et al., 2020) indicating that convective activity is severely affected by the tropical sea surface temperature. Of course, the center of maximum positive correlation coefficient over the Arabian Sea varies in spring and winter. A weak negative correlation center is also seen over the Caspian Sea, similar to surface air temperature in spring. SST shows insignificant correlations with the lightning density over the Mediterranean Sea, Black Sea, Oman Sea, Red Sea, and the Persian Gulf in both seasons.

As shown in Fig. 8, the lightning flash rate over southwest Iran is positively correlated with the CAPE over the same area in spring and winter. However, the correlation coefficient is more robust, and the area with a significant correlation coefficient is wider in spring. Therefore, the local effect of CAPE on lightning activity in southwestern Iran seems to be greater in spring than in winter. The second area whose CAPE is positively correlated with lightning density is the Horn of Africa in both seasons, although the correlation is more robust in winter. Also, the correlation is significant in some centers

along the Red Sea convergence zone in winter (Fig. 8a), because the occurrence of convective systems in southwest Iran depends on the configuration of the Sudan low pressure (Rafati and Karimi, 2017). Most of the convective systems were initiated in the Red Sea convergence zone and then arrived in southwest Iran. This indicates that the contribution of the nonlocal convective activity causing lightning is higher in winter than in spring.

The correlation of sensible and latent heat fluxes with lightning activity is shown in Fig. 9. The lightning flash rate is negatively correlated with sensible heat flux over Syria and Jordan, and northeast Africa in winter (Fig. 9a). In other words, the lightning flash rate decreases in southwest Iran with increasing upward sensible heat flux in these areas. Also, it decreases with increasing sensible heat flux in northeast Europe, where the sensible heat flux is positive (downward). It is negatively correlated over the northwest and northeast of Iran in spring.

In contrast, the lightning flash rate is positively correlated over the Arabian Sea (Fig. 9b), which confirms the seasonal differences in the influence of the thermodynamic parameters between land and ocean on lightning activity. In general, the negative correlation between lightning density and sensible heat flux is somewhat more robust in spring. Comparing the spatial correlation distribution of the latent and sensible heat fluxes, as expected, the type of

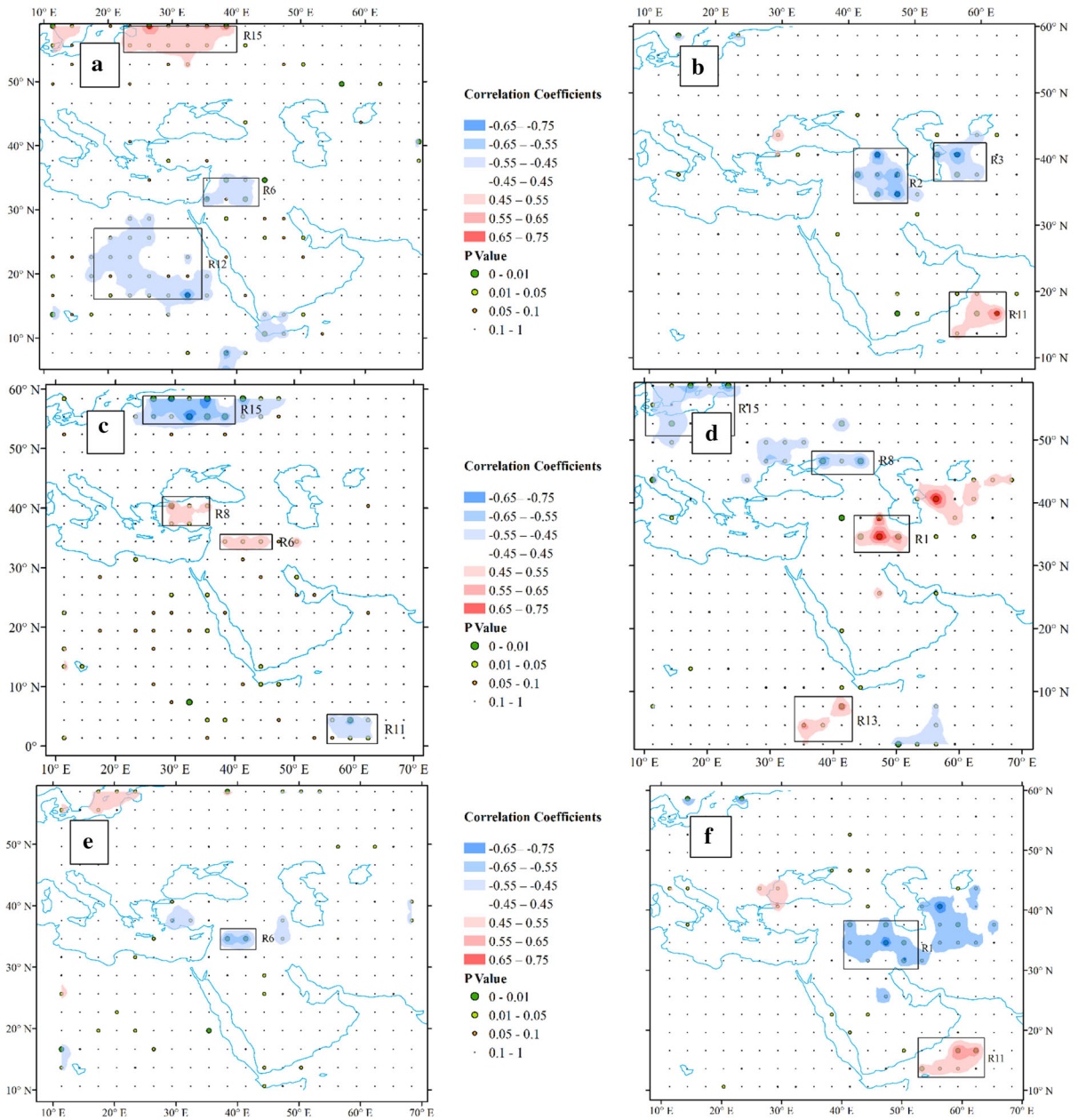


Figure 9

The correlation coefficients (above the 95% confidence level) between the regional averaged flash density over southwest Iran and **a** sensible heat flux in winter, **b** sensible heat flux in spring, **c** latent heat flux in winter, **d** latent heat flux in spring, **e** Bowen ratio in winter, and **f** Bowen ratio in spring (1996–2014)

relationship in these two variables is the opposite; in other words, in areas where there is a negative correlation between lightning density and sensible heat flux, a positive correlation is often observed between lightning density and latent heat flux and vice versa.

Since increased latent heat fluxes generally imply smaller sensible heat fluxes for given solar energy input, lightning density over southwest Iran increases with increasing latent heat flux over Iraq, Syria, and western Turkey, while it decreases with increasing

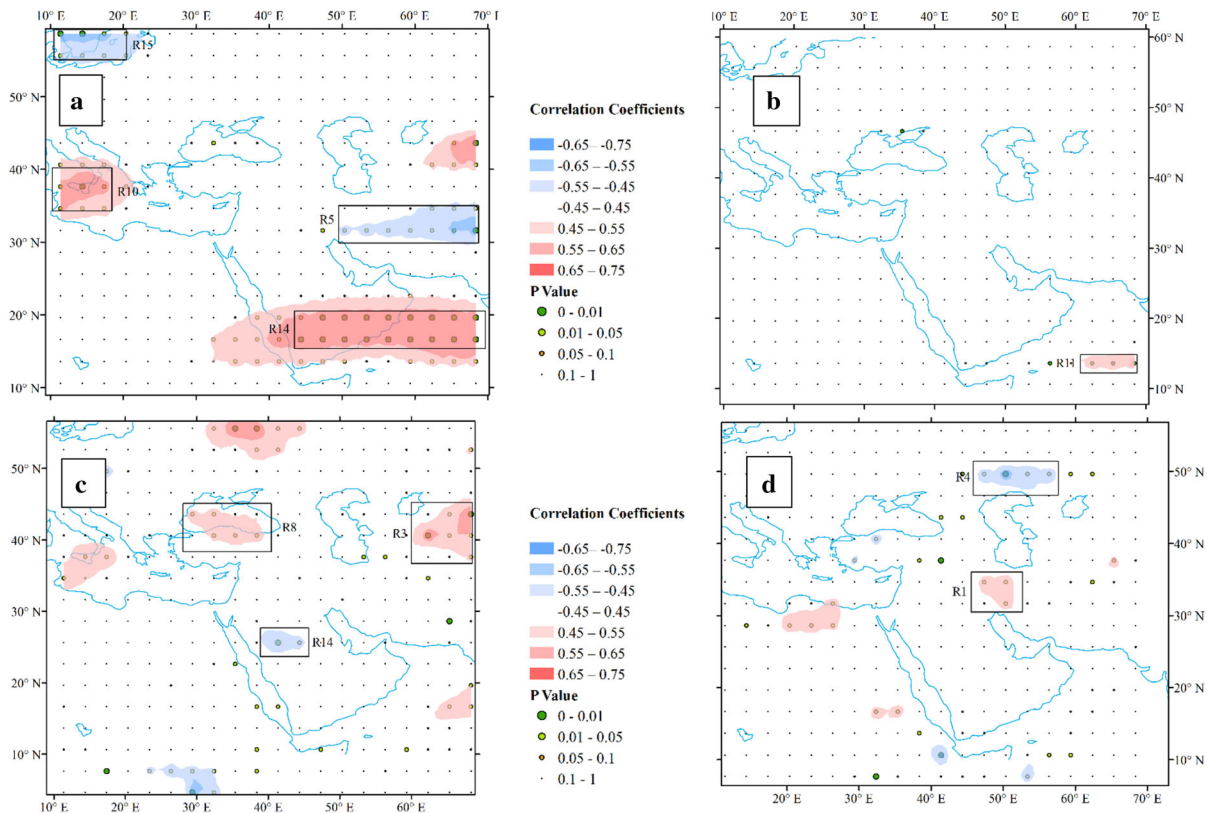


Figure 10

The correlation coefficients (above the 95% confidence level) between the regional averaged flash density over southwest Iran and **a** wind speed at 300 hPa in winter, **b** wind speed at 300 hPa in spring, **c** low-level wind shear in winter, and **d** low-level wind shear in spring (1996–2014)

latent heat flux over northeast Europe and the Arabian Sea in winter (Fig. 9c). In spring, the most robust positive relationship is observed over the west of Iran (Fig. 9d). The local effects of sensible and latent heat flux are generally more significant in spring than in winter, as is CAPE.

An optimal combination of sensible and latent heat flux is required to create sufficient dry and moist static destabilization (Kirshbaum et al., 2018). Also, Tinmaker et al. (2021) showed a strong correlation between lightning flashes and the Bowen ratio ( $R = 0.95$ ) over the Indian region for both dry and wet seasons. Hence, this study also assessed the Bowen ratio and lightning density correlation. The significant correlation coefficient between Bowen ratio and lightning density can be seen in wider areas in spring than in winter. There is a negative correlation in the northern half of Iran and a positive

correlation in the Arabian Sea and west of the Black Sea in spring (Fig. 9f). This means that the convection and lightning activity increases in southwestern Iran by decreasing the ratio of sensible heat flux to latent heat flux over northern Iran and increasing it over the Arabian Sea and west of the Black Sea.

The correlation map of lightning density and wind speed at 300 hPa shows that the lightning density is positively correlated to the strength of the subtropical jet and polar front jet in winter (Fig. 10a), while this relationship is not observed clearly in spring (Fig. 10b). As shown in Fig. 10c, d, wind shear local effect on lightning is only observed in spring. This confirms that convections formed in winter are primarily nonlocal and formed under synoptic-scale factors, while the contribution of local convection causing lightning is higher in spring.

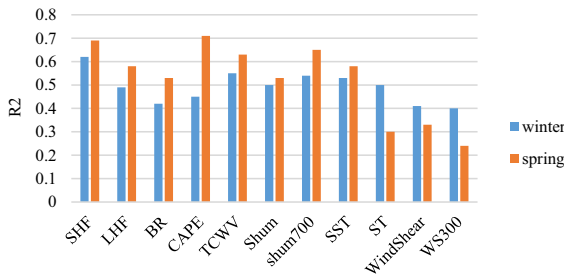


Figure 11

The coefficients of determination of the independent variables using univariate linear regression models to predict lightning flash rate in winter and spring

A multiple linear regression model was used to determine the main factor in predicting lightning variability. The regional mean of the factors was entered into the regression model. We entered different variables of the factors over different regions (shown with rectangles in Figs. 5, 6, 7, 8, 9, 10) to develop and improve the regression model. Before analyzing the results of multivariate linear regression, the univariate linear regression results are presented for comparison.

Figure 11 shows the coefficient of determination of the independent variables using univariate linear regression models to predict lightning flash density. CAPE (71%), sensible heat flux (SHF) (69%), and specific humidity at 700 hPa (65%) have the highest coefficients of determination, respectively, in spring. Thus, these parameters show the most single-factor contribution to the lightning activity variance. Sensible heat flux (62%), total column water vapor

(55%), and specific humidity at 700 hPa (54%) have the highest coefficients of determination, respectively, in winter. In general, the coefficient of determination of the studied variables is higher in spring than winter (except for surface temperature [ST], low-level wind shear, and wind speed at 300 hPa).

Table 1 shows multiple linear regression results for spring and winter. The surface sensible heat flux over Syria and Jordan (SHF6), CAPE over southwest Iran (CAPE1), sea surface temperature over the Arabian Sea (SST11), and latent heat flux over Northeastern Europe (LHF15) were respectively found to play the most crucial role in predicting the seasonal lightning variability in winter. While in spring, CAPE over southwest Iran (CAPE1), the surface sensible heat flux over northeast Iran (SHF3) and the Arabian Sea (SHF11), and surface temperature over the Saudi Arabian Peninsula (ST14) are respectively the most important factors in predicting lightning flash density. Other variables were excluded from the models because they are highly correlated with these parameters, and their partial and part correlations drop sharply from the zero-order correlation. Thus, much of their variance is explained by other variables. The tolerance or percentage of the variance in the model that cannot be explained by the other predictors is shown in Table 1 and are greater than 53% for variables accepted in the model. In addition, the variance inflation factor is not greater than 2 in any of these variables, indicating that there

Table 1

Results of the multiple linear regression model to predict lightning density in winter and spring

Model	Coefficient	Significance	Correlations			Collinearity statistics		R <sup>2</sup>	
			Zero-order	Partial	Part	Tolerance	VIF		
Winter	Constant	-5.47E-14						0.898	
	SHF6	0.357	0.007	0.79	0.644	0.268	0.566		1.765
	CAPE1	0.192	0.111	0.674	0.414	0.145	0.571		1.751
	SST11	0.375	0.004	0.728	0.683	0.299	0.635		1.575
	LHF15	0.308	0.018	0.697	0.581	0.228	0.547		1.83
Spring	Constant	3.06E-14						0.93	
	CAPE1	0.412	0.001	0.841	0.751	0.301	0.531		1.882
	SHF3	0.314	0.005	0.769	0.681	0.246	0.611		1.637
	SHF11	-0.292	0.012	-0.788	-0.629	-0.214	0.537		1.864
	ST14	0.211	0.019	0.529	0.595	0.196	0.863		1.159

is no multicollinearity problem. The regression models explain almost 90% and 93% ( $R^2$  in Table 1) of the lightning variability in winter and spring, respectively.

#### 4. Conclusions

In this study, the relation of thermodynamic parameters over a region from 10° E to 70° E and 0° N to 60° N was investigated with the regional averaged lightning density time series in southwest Iran based on OTD/LIS observations and reanalysis datasets from 1996 to 2014. In addition, the most critical parameters and their domains were identified for explaining the lightning density variance in the study area using a multiple linear regression model.

The results showed that surface sensible heat flux over Syria and Jordan, CAPE over southwest Iran, sea surface temperature over the Arabian Sea, and latent heat flux over Northeastern Europe are the best parameters to predict the seasonal lightning activity in winter. While in spring, CAPE over southwest Iran, the surface sensible heat flux over northeast Iran and the Arabian Sea, and surface temperature over the Saudi Arabian Peninsula are the main factors for predicting lightning density. The regression models explain almost 90% and 93% of the lightning variability in winter and spring, respectively. Sensible and latent heat fluxes are important factors explaining convection and lightning density variability in both seasons, but the domain of the highest correlation is different in spring and winter. Sensible heat flux over Syria and Jordan, northeastern Africa in winter, and over the northwest and northeast Iran in spring are negatively correlated with convection and lightning activity in southwestern Iran. In other words, lightning activity increases over southwest Iran with decreasing sensible heat flux because of increasing latent heat flux in these areas. It was found that the Bowen ratio explained a lower percentage of lightning variance in comparison with latent and sensible heat flux and was therefore excluded from the regression model. Another important parameter for explaining the variance in lightning activity is CAPE, especially in spring. The local effect of CAPE on lightning activity over southwest Iran is more

important in spring than in winter, indicating that the contribution of local convection to lightning is more important in spring. This conclusion was also confirmed by wind shear since its local effect on lightning is only observed in spring. Therefore, it can be said that nonlocal systems and synoptic-scale factors play an essential role in forming convection and lightning-generating systems in winter. This is consistent with results reported by Rafati and Karimi (2017) on mesoscale convective systems.

The extent of the region whose temperature has a significant correlation with lightning activity is much smaller in spring than in winter. Nevertheless, the contribution of this variable was significant in the spring model, unlike the winter model. The lightning density also shows a positive correlation with the sea surface temperature over the Arabian Sea in both seasons, where the source of warm and humid air mass is for the study area. SST does not play a significant role in the lightning activity in other water resources in the area. The correlation coefficient between humidity indices and lightning density showed that western moisture sources (such as the Mediterranean Sea) have a more important role in providing moisture to convection and lightning in winter than in spring. Also, the most important moisture index for determining the variability of lightning activity is the total column water vapor over the Eastern Mediterranean in winter and the specific humidity at 700 hPa over West Iran in spring. It is worth noting that there is a significant positive correlation between lightning activity and wind speeds at 300 hPa in winter, especially with the subtropical jet stream (from the southern half of the Red Sea to the northern Arabian Sea) and the polar front jet stream (Western Mediterranean). However, their contribution to the multiple linear regression model is negligible because it does not independently explain a significant percentage of the lightning variance (low tolerance).

In general, these results are essential for improving knowledge and understanding about the main regional parameters to predict convection and lightning activity for future studies in subtropical regions.

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### Data availability

Lightning products are available from the Global Hydrology Resource Center (GHRC) at <https://ghrc.nsstc.nasa.gov>, and Reanalysis datasets (ERA5) are available from the European Centre for Medium-Range Weather Forecasts (ECMWF) at <https://cds.climate.copernicus.eu>.

### Declarations

**Conflict of interest** The authors have not disclosed any competing interests.

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