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THRESHOLDS OF CAPE AND LIFTED INDEX AT THE DEVELOPMENT OF SUMMER THUNDERSTORMS OVER INLAND AND ALONG THE COAST IN EASTERN BULGARIA

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Боряна Маркова, Румяна Мицева. ПРАГОВИ СТОЙНОСТИ НА CAPE И LIFTED INDEX ЗА РАЗВИТИЕ НА ЛЕТНИ ГРЪМОТЕВИЧНИ ОБЛАЦИ НАД ВЪТРЕШНОСТТА И КРАЙБРЕЖИЕТО НА ИЗТОЧНА БЪЛГАРИЯ

Пресметнати са два индекса на неустойчивост (*CAPE* и *LI*), като са използвани характеристики на околната среда от дни с летни валежи по крайбрежието и във вътрешността на Източна България. Статистическият анализ показва, че средните стойности на *CAPE* и *LI* при гръмотевични облаци са значително по-високи и по-ниски съответно, отколкото за обикновените дъждовни облаци и че разликата между разпределенията и съответните средни стойности на индексите за вътрешността и по крайбрежието са незначителни. С помощта на дискриминантен анализ са установени прагови стойности на *CAPE* и *LI*, които разделят гръмотевичните облаци от обикновените дъждовни (без мълнии) облаци. Резултатите показват, че намерената прагова стойност на *Lifted Index* (*LI*) разделя по-добре гръмотевичните облаци от обикновените дъждовни облаци в сравнение с получения праг за CAPE.

Boryana Markova, Rumjana Mitzeva. THRESHOLDS OF CAPE AND LIFTED INDEX AT THE DEVELOPMENT OF SUMMER THUNDERSTORMS OVER INLAND AND ALONG THE COAST IN EASTERN BULGARIA

CAPE and *Lifted Index*, *LI*, are calculated using environmental conditions for days with summer precipitation along the coast and over inland of eastern Bulgaria. The statistical analysis reveals that the mean values of *CAPE* and *LI* at the development of thunderstorms are significantly higher

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and lower correspondingly than at the development of ordinary precipitating clouds and that the differences between the distribution and corresponding indices over inland and along the coast are insignificant. Using general discriminant analyses the threshold values of *CAPE* and *LI*, which are able to discriminate between thunderstorms and ordinary (without lightning) clouds are established. The results indicate that the thresholds of *LI* have better probability of detection for thunderstorms than the established thresholds for *CAPE*.

Key words: instability indices, thunderstorms, discriminant analyses
PACS numbers**:** 92.60.Pw, 92.60.Qx

1. INTRODUCTION

The use of instability indices to evaluate the state of the atmosphere in relation with the development of convective phenomenon and severe events is already tradition ([1–4] and others). It is known that the ingredients for deep moist convection are instability, moisture inflow and initiating lifting process (e.g. [5, 6]). For the physical representation of the state of the atmosphere the vertically integrated measures of instability such as the Convective Available Potential Energy (*CAPE*) is commonly used (e.g. [7–12]). The other frequently used instability index that predicts the likelihood of thunderstorms is Lifted Index, *LI*. [13] compared the ability of 32 indices proposed over the past 50 years as a predictors for thunderstorm over the Netherlands and established that the best predictors, better than e.g. *CAPE* was *LI*. Usually the threshold values for the corresponding indices above or below which thunderstorms developed are determined. These thresholds however are valid for particular geographical region, season etc.

In [14] the ability of *CAPE*, *LI* and *K*-index to discriminate between ordinary (non-lightning) clouds and thunderstorms in eastern Bulgaria were studied. The results reveal that the higher probability of detection of thunderstorms has Lifted index. The established *LI* threshold ($LI = -2.3$ deg) was able to discriminate correctly ~74 % of cases in accordance to the type of the considered clouds – ordinary precipitating or thunderstorms. However, the results in [14] have to be considered as preliminary, because only data from one year were used and the indices were calculated when the precipitating clouds developed over 5 inland and 6 along the coast stations. One can assume that the environmental conditions along the coast and inland are different at the development of convective clouds over these regions. Thus, in an attempt to search classification functions (threshold values) with higher probability of detection of thunderstorms it is worth to consider separately the inland and coastal cloud cases developed over eastern Bulgaria, using large number of precipitating cases from several years.

The present work is a continuation of the study presented in [14]. It is directed to reveal if the distribution and mean values of Convective Available Potential Energy, *CAPE*, and Lifted Index, *LI*, are statistically significant at the development of summer thunderstorms and ordinary (without lightning) precipitating clouds over inland and along the coast in eastern Bulgaria. The task of the study is to obtain threshold values of *CAPE* and *LI*, which can be used as an indication of summer thunderstorms in eastern Bulgaria.

2. DATA AND METHODOLOGY

The environmental conditions of 340 days with precipitation after 1200 UTC from April to September 2006 to 2009 over eleven synoptic stations of the National Institute of Meteorology and Hydrology (NIMH), located in eastern Bulgaria are analyzed. Six of the stations are situated along the coast (Shabla, Kaliakra, Varna, Emine, Burgas and Ahtopol), denoted with triangles in Fig. 1, and five are inland stations (Ruse, Silistra, Razgrad, Dobrich and Karnobat), denoted with circles in Fig. 1. All cases with precipitation after 1200 UTC (1329) are divided into two samples – ordinary (without lightning) precipitating clouds (748) and thunderstorms (581). The information for thunderstorms was taken from synoptic reports in eastern Bulgaria. The both samples are considered separately in two groups based on geographical location – storms developed above the inland (403 ordinary and 353 thunderstorms) and storms developed along the cost (345 ordinary and 228 thunderstorms). The ordinary precipitating clouds and thunderstorms over inland hereafter are denoted as *land or* and *land th*, correspondingly, while along the coast – *coast or* and *coast th*, correspondingly.

The proximity aerological soundings at 1200 UTC close to the stations with detected precipitation, obtained by the numerical model GFS [15], were used to calculate CAPE [16] and Lifted Index [17] (see Table 1). Surface level meteorological data taken from [18], were utilized for processing the data from the soundings.

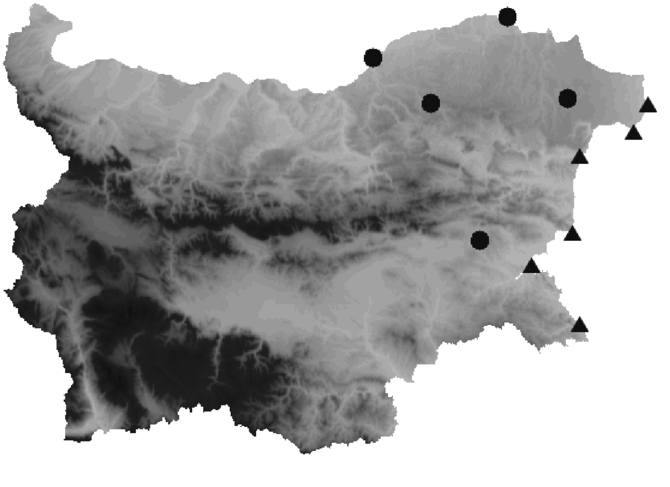


Fig. 1. The location of synoptic stations on the map of Bulgaria. The inland stations are denoted by circles, the stations along the coast are denoted by triangles.

Table 1. Summary of thermodynamic, kinematic parameters and skill scores used: θ is potential temperature [K], θ_e is equivalent potential temperature [K], g is the acceleration of gravity [$m \cdot s^{-2}$], z is height [m], *LFC* – the level of free convection, *EL* – the equilibrium level of the parcel, T_{500} is temperature [°C] at 500 hPa, TP_{500} – temperature of a parcel after it has been lifted pseudo-adiabatically to 500 hPa from its original level, x – the number of correctly classified thunderstorms cases, y – the number of incorrectly classified thunderstorms cases, w – the number of incorrectly classified ordinary clouds cases. Subscripted numbers indicate constant pressure levels.

Parameter	Code and units	Equation
Convective Available Potential Energy	*CAPE*, $J \cdot kg^{-1}$	$CAPE = g \int_{LFC}^{EL} \frac{\theta - \theta_e}{\theta_e} dz$
Lifted Index	*LI*, deg	$LI = T_{500} - TP_{500}$
Probability of detection	POD	$POD = \frac{x}{x+y}$
False alarm ratio	FAR	$FAR = \frac{w}{x+w}$

The descriptive statistics (mean, mode, median, etc.) for *CAPE* and *LI* are estimated separately for any of the four samples *land or, land th*, *coast or* and *coast th*. The statistical analyses (*F*- and *t*-test with significance level $\alpha = 0.05$) is performed to establish if there is a statistical significant difference in *CAPE* and *LI* values in the corresponding (for inland and along the coast) considered samples – ordinary precipitating clouds and thunderstorms._

The distributions of the *CAPE* and *LI* in the four samples are considered. The general discriminant analysis [19] is carried out to establish the ability of *CAPE* and Lifted index to classify the clouds as ordinary precipitating cloud or thunderstorm in the samples with clouds developed along the coast and over inland. The probability of detection (*POD*) and false alarm ratio (*FAR*) are calculated [20] for the derived classification functions (see Table 1). From the manner of calculations (given in Table 1) it follows that the probability of detection, *POD* is the ratio of the number of thunderstorms correctly forecasted over the number of actual thunderstorms and that the false alarm ratio, *FAR* is the number of incorrect classified (as thunderstorm) ordinary clouds over the total number of forecasted thunderstorms. For *POD* the best score is 1 and the worst score is 0, while for *FAR* the best score is 0 and the worst score is 1.

The critical values (thresholds) of *CAPE* and *LI* that may separate the studied cases in two groups (ordinary clouds and thunderstorms) are established separately for clouds over inland and along the coast. Using general discriminant analyses [19] the classification function as a combination of *CAPE* and *LI* is obtained.

3. RESULTS

Information for the mean values, mode, median, upper and lower quartile for Convective Available Potential Energy, *CAPE*, for the samples of thunderstorms and ordinary precipitating clouds developed over the inland (*land or* and *land th*) and along the coast (*coast or* and *coast th*) in eastern Bulgaria is given in Table 2. The corresponding information is presented in Table 3 for Lifted Index, *LI*.

Table 2. Descriptive statistics for CAPE calculated at the development of ordinary precipitating clouds over inland (*land or*) and along the coast (*coast or*) and at the development of thunderstorms over inland (*land th*) and along the coast (*coast th*).

	CAPE land or	CAPE land th	CAPE coast or	CAPE coast th
Mean	610	1302.4	542.7	1150
Median	466	1248	378	1189
Mode	40	1248	20	1102
Lower quartile	132.9	845.9	132.5	689.2
Upper quartile	927	1668.6	809.1	1564.0

Table 3. Descriptive statistics for *LI* calculated at the development of ordinary precipitating clouds over inland (*land or*) and along the coast (*coast or*) and at the development of thunderstorms over inland (*land th*) and along the coast (*coast th*).

	LI land or	*LI land th*	*LI coast or*	*LI coast th*
Mean	–0.54	–3.97	–0.57	–3.7
Median	–1.1	–3.9	–0.9	–3.8
Mode	–1.1	–4	–0.7	–3
Lower quartile	–2.8	–5.4	–2.7	–5
Upper quartile	1.8	–2.6	1.4	–2.56

A more detailed review of the information presented in Table 2 and Table 3 reveals that mean values, mode, median, lower and upper quartile of *CAPE*/*LI* at the development of thunderstorms are significantly higher/lower in comparison with the corresponding values of *CAPE*/*LI* at the development of ordinary precipitating clouds in the both samples (inland and along the coast). There is no significant difference in the corresponding *CAPE* and *LI* values calculated at the development of ordinary precipitating clouds along the coast and over inland. The same is valid for *CAPE* and *LI* values at the development of thunderstorms along the coast and over inland. The *CAPE* values of upper quartile and median (Table 2) indicate that according to the study [21], performed for the USA regions, 75% of the studied ordinary precipitating clouds over eastern Bulgaria developed at "marginal instability” (0–1000 J· kg^{-1}) while more than 50% of thunderstorms developed in the interval for “moderate instability” (1000–2500 J· kg^{-1}). The mode and median *LI* values shown in Table 3 revel that according to the classification [21] the higher number of thunderstorms and more than 50% of them developed over eastern Bulgaria when calculated *LI* values are in the interval for “moderate instability” (–3 to –6 deg), while the mode and mediane at the development of ordinary precipitating clouds are in the interval of “marginal instability” ($-3 < LI < 0$ deg).

The Box and Whiskers plot demonstrates the above differences for the mean *CAPE* (Fig. 2a) and *LI* (Fig. 2b) values. It is seen that the mean of *CAPE*/*LI* values at the development of thunderstorms are noticeable higher/lower in comparison with *CAPE*/*LI* values at the development of ordinary precipitating clouds. The difference between mean *CAPE*/*LI* values at the development of corresponding type of clouds (ordinary precipitating and thunderstorm) along the coast and over inland is very small. The statistical analysis (*t*- and *F*-tests with a significance level $\alpha = 0.05$) also confirms that there is a well pronounced statistically significant difference between the corresponding mean *CAPE*/*LI* values at the development of thunderstorms and at the development of ordinary precipitating clouds, while the differences in the corresponding mean *CAPE*/*LI* values at the development of the studied clouds over inland and coast are statistically insignificant.

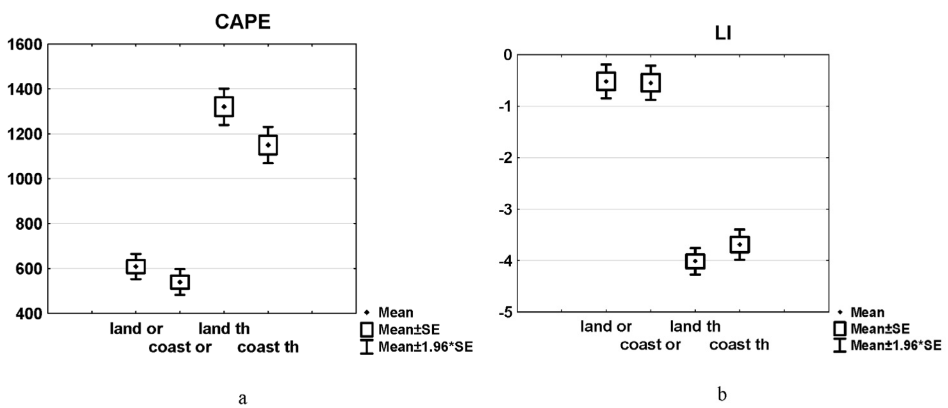
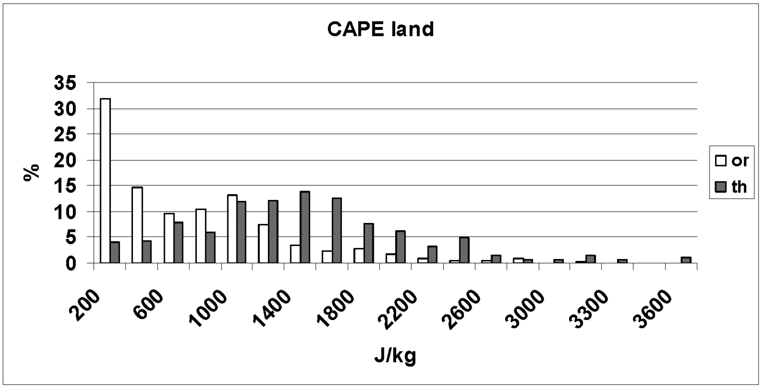
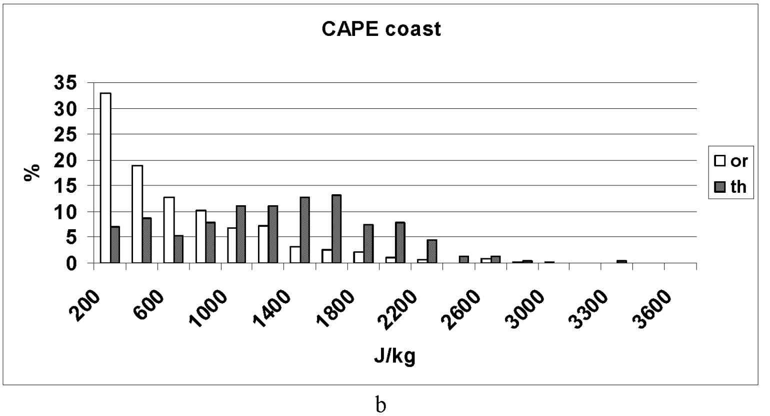


Fig. 2. Box and Whiskers plot of: a) *CAPE*, and b) *LI*, for ordinary precipitating clouds developed over inland and along the coast (*land or and coast or*) and thunderstorms, developed over inland and along the coast (*land th and coast th*).

The results presented in Fig. 3a and Fig. 3b reveal that there is a pronounced difference in the distribution of *CAPE* values at the development of thunderstorms and ordinary precipitating clouds. The higher percentage of ordinary precipitating clouds developed at very low *CAPE* values ($CAPE \leq 200$ J· kg^{-1}), while the mode of CAPE at thunderstorm developed over inland and along the coast is above 1000 J· kg^{-1}.



a



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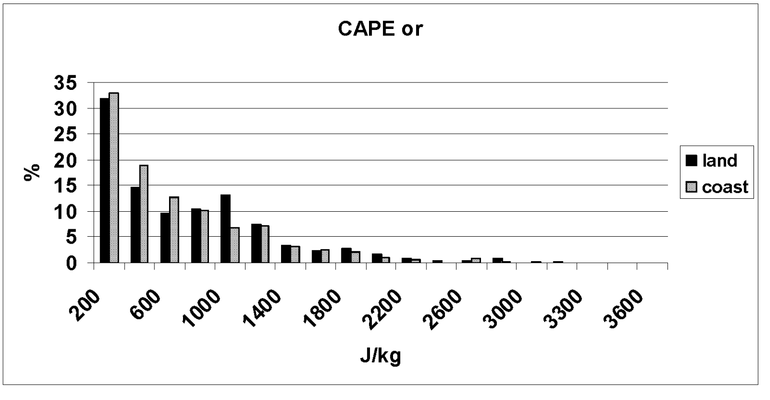

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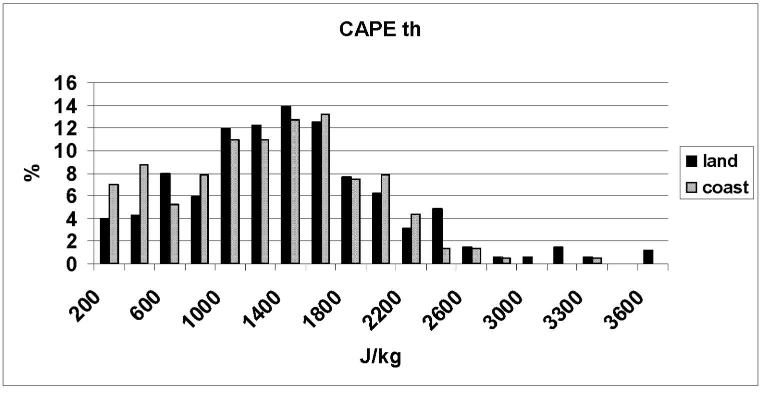
Fig. 3. Frequency distribution of *CAPE* values (in percentages) at the development of: a) ordinary precipitating clouds (white columns) and at thunderstorms (hatch columns) for inland; b) ordinary precipitating clouds (white columns) and at thunderstorms (hatch columns) for coast; c) ordinary precipitating clouds, developed over inland (black columns) and along the coast (hatch columns);

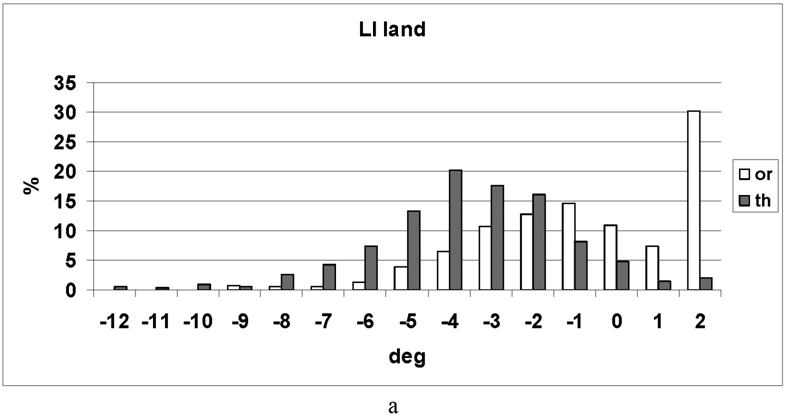


d

Fig. 3. Frequency distribution of *CAPE* values (in percentages) at the development of : d) thunderstorm clouds developed over inland (black columns) and along the coast (hatch columns).

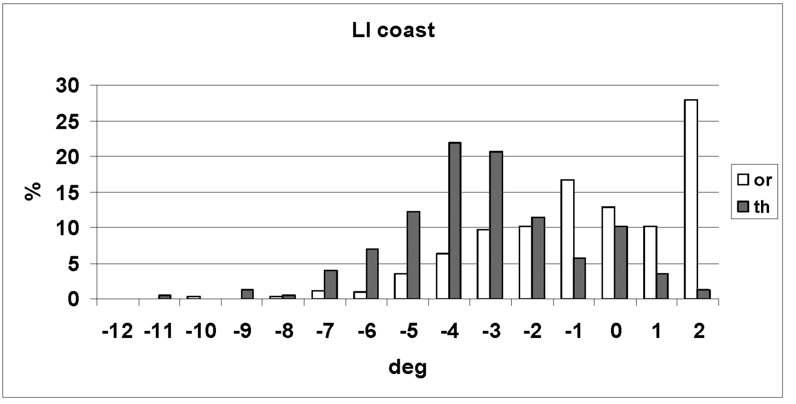
There is no significant difference in the shape of *CAPE* distributions at the development of corresponding type of clouds developed along the coast and over the inland (see Fig. 3c for ordinary clouds and Fig. 3d for thunderstorm).

The results presented in Fig. 4a and Fig. 4b also reveal that there is a pronounced difference in the distribution of LI values at the development of thunderstorms and ordinary precipitating clouds. The higher percentage of ordinary precipitating clouds developed at positive values of LI, while the mode of LI at thunderstorm development over inland and along the coast is ~ -4 deg.



a

Fig. 4. Frequency distribution of *LI* values (in percentages) at the development of: a) ordinary precipitating clouds (white columns) and at thunderstorms (hatch columns) for inland;



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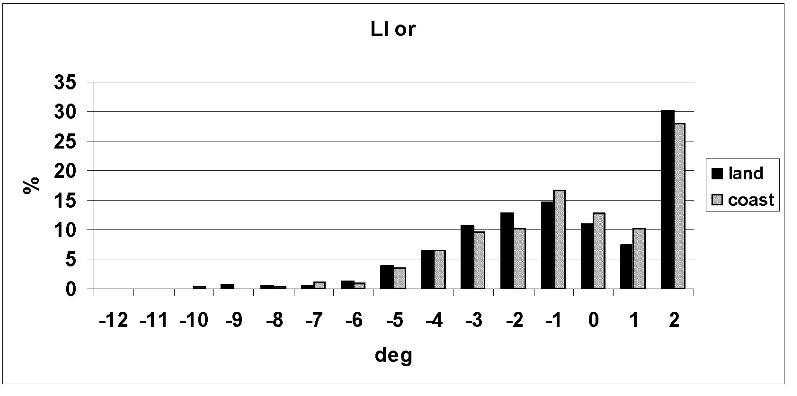

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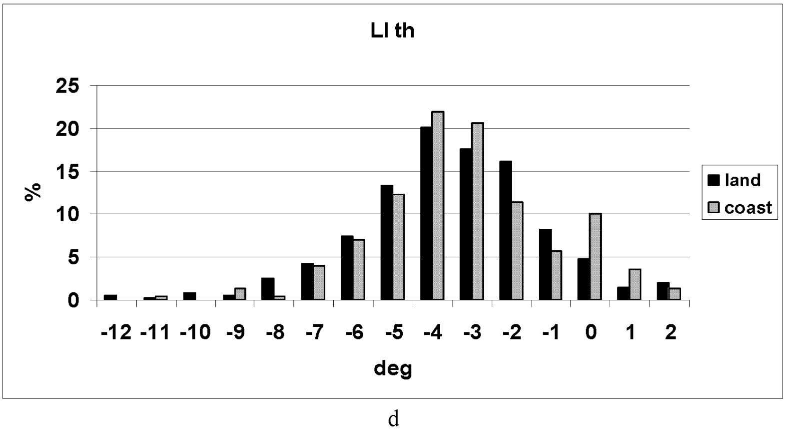

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Fig. 4. Frequency distribution of *LI* values (in percentages) at the development of: b) ordinary precipitating clouds (white columns) and at thunderstorms (hatch columns) for coastal; c) ordinary precipitating clouds developed over inland (black columns) and along the coast (hatch columns);d) thunderstorm clouds developed over inland (black columns) and along the coast (hatch columns)

There is no significant difference in the shape of *LI* distribution for ordinary clouds (Fig. 4c) and thunderstorms (Fig. 4d) developed along the coast and over the inland.

Although there is not statistically significant difference between the corresponding *CAPE* and *LI* values at clouds (thunderstorms or ordinary) developed along the coast and over the inland the general discriminant analyses [19] is carried out separately for both samples (inland and along the coast) to determine the thresholds values of *CAPE* and *LI* which discriminate thunderstorms from ordinary precipitating clouds in eastern Bulgaria. The obtained thresholds of *CAPE* and *LI*, the percentage of correctly classified cases (*th* or *or*) and calculated skill scores *POD* and *FAR* are presented in Table 4 and Table 5, respectively. It is worth noting that the percentage correctly classified thunderstorms give the same information as the probability of detection *POD*. The false alarm ratio however differs from percentage of incorrect classified ordinary thunderstorms.

Table 4. Threshold of *CAPE* for the type of clouds, the percentage of correctly classified cases, and skill scores *POD* and *FAR*

Stations	Threshold, *CAPE*, $J \cdot kg^{-1}$	Correct classification %			*POD*	*FAR*
		Total	*th*	*or*		
Land	953	72.9	67.7	77.4	0.68	0.28
Coast	826	72.8	68.4	75.7	0.68	0.35

Table 5. Threshold of *LI* for the type of clouds, the percentage of correctly classified cases, and skill scores *POD* and *FAR*.

Stations	Threshold, *Li*, deg	Correct classification %			*POD*	*FAR*
		Total	*th*	*or*		
Land	-2.2	72.9	81.3	65.5	0.81	0.33
Coast	-2.1	73.8	78.5	70.7	0.79	0.36

The results in Table 4 show that 68.4% of thunderstorms along the coast and 67.7% of thunderstorms over inland developed at *CAPE* values higher than the determined corresponding thresholds 953 $J \cdot kg^{-1}$ and 826 $J \cdot kg^{-1}$. Thus, using the determined *CAPE* thresholds values, the probability of detection (*POD*) of thunderstorm is 0.68, with false alarm ratio *FAR* = 0.28 (for clouds over inland) and *FAR* = 0.35 (for clouds along the coast). According to results in Table 5 – 81.3% of thunderstorms over inland and 78.5% of thunderstorm along the coast developed at *LI* values lower than the determined *LI* thresholds. The probability of detection of thunderstorm using *LI* threshold values is 0.81 and 0.79 for thunderstorm developed over inland and along the coast *FAR* is 0.33 and 0.36 correspondingly.

In an attempt to obtain better discrimination between the ordinary precipitating clouds and thunderstorms general discriminant analyses [19] with combination of *CAPE* and Lifted index are carried out. The obtained classification functions $F(th,or)$ for clouds developed along the coast and over the inland stations are presented in Table 6. At $F(th,or) > 0$ the case is classified as thunderstorm; at $F(th,or) \leq 0$ the case is classified as ordinary cloud. The percentage of correctly classified cases in accordance to the type of the clouds (*or* or *th*), the *POD* and *FAR* values indicate that the combination of *CAPE* and *LI* values does not improve the classification ability of the single use of the determined *LI* threshold.

Table 6. Classification functions F(th,or) for the type of clouds, and the percentage of correctly classified cases - thunderstorm th or ordinary or, using combination of CAPE and LI, and skill scores POD and FAR.

Indices	Function	Correct classification %			POD	FAR
		Total	*th*	*or*		
Land *CAPE, LI*	$F(th,or) = -0.3264\ LI + 0.0004\ CAPE - 1.1399$	72.4	77.9	67.5	0.78	0.32
Coast *CAPE, LI*	$F(th,or) = -0.2650\ LI + 0.0007\ CAPE - 1.1917$	73.6	75.0	72.8	0.75	0.36

Due to the insignificant difference between *LI* and *CAPE* thresholds for thunderstorm development over inland station and along the coast we suggest that it is reasonable in the future not to consider separately the data from inland stations and stations along the coast. For this reason the threshold of *LI* and *CAPE* values, which are able to discriminate correctly high percentage of thunderstorms from ordinary (non-lightning) precipitating clouds developed over eastern Bulgaria are determined. Their values are given in Table 7.

Table 7. Threshold of *CAPE* and *LI* values for the type of clouds, using data from all stations; the percentage of correctly classified cases and skill scores *POD* and *FAR*.

Index	Thresholds	Correct classification %			*POD*	*FAR*
		Total	*th*	*or*		
CAPE	891 $J \cdot kg^{-1}$	72.5	68.3	75.7	0.68	0.31
LI	–2.2 deg	73.2	79.9	68.1	0.80	0.34

The results show that the percentage of correctly classified clouds as thunderstorms or ordinary precipitating clouds, as well as the calculated correspondingly false alarm ratio (*FAR*) using the determined threshold of *CAPE* (891 J· kg^{-1}) or *LI* (–2.2 deg) are approximately one and the same. However the calculated *POD* at the use of *LI* threshold is significantly higher (*POD* = 0.8) in comparison with calculated *POD* at the use of *CAPE* threshold (*POD* = 0.68). Based on this one can conclude that the established LI threshold values has a better probability of detection of thunderstorms developed in eastern Bulgaria than the established *CAPE* thresholds. It is worth also to be mentioned that the both determined thresholds are in the upper limit of the interval of "marginal instability" assign for the USA regions [21]. The significantly lower *CAPE* thresholds and higher *LI* thresholds at the development of thunderstorms over eastern Bulgaria is in accordance to other studies for thunderstorms developed over Europe. For example the analyses in [13] indicates that the established by them $LI < -0.4$ °C as a threshold is the best predictor (among the thresholds of 32 others instability indices) for thunderstorms over Netherlands. The studies of [22] and [23] reveal that more than 50% of different types of severe convective storms in Europe developed at $CAPE \leq 500$ J· kg^{-1}.

4. SUMMARY

CAPE and Lifted index are calculated using environmental conditions of 340 days with precipitation over eastern Bulgaria from April-September 2006 to 2009. The data at the surface necessary for the calculations of the both instability indices are taken from 11 synoptic stations of the National Institute of Meteorology and Hydrology (NIMH) located in eastern Bulgaria. Five of the stations are situated along the coast and six are inland stations. Proximity sounding at 1200 UTC for these stations close to the location of the storms development was used for the calculations of *CAPE* and *LI*. For the statistical analyses the cases have been divided in two samples – ordinary (without lightning) precipitating clouds and thunderstorms. The both samples have been considered separately in two groups based on geographical location – storms developed above the inland and storms developed along the cost.

The main result from the study is that the differences between the distribution and mean values of *CAPE* and *LI* over inland and along the coast are statistically insignificant, thus the separation of the summer clouds developed over eastern Bulgaria based on different geographical locations (inland and along the coast) is not required. The statistical analyses shows that the mean values of *CAPE* and *LI* at the development of thunderstorms are significantly higher and lower correspondingly than at the development of ordinary precipitating clouds. The established thresholds of *CAPE* and *LI* classified correctly ~ 73% of the studied clouds according to their type – thunderstorms or ordinary (non-lightning) clouds. The results however reveal that the thresholds of Lifted index has higher probability of detection of thunderstorm (*POD* = 0.80) than the established threshold for *CAPE* (*POD* = 0.68).

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