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Contrast in Lightning Activity over Land and Sea – Further Analyses of Thermodynamic Conditions

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ABSTRACT: The present study is directed to test whether data over Bulgaria (land) and Black Sea (sea) confirms the established in other geographical regions difference in thermodynamic characteristics over land and sea, which may explain the land-ocean contrast in lightning activity. The territory of investigation includes maritime area (western part of the Black Sea – up to 36°E) and continental area (Bulgaria). The necessary temperature and humidity profiles are taken from GFS proximity sounding for the center of each grid box where at least one flash is recorded. Several surface and at higher levels atmospheric data, convective available potential energy (CAPE) and normalize CAPE (NCAPE) (calculated for different layers) are considered. The output of 1-D cloud model with parameterized microphysics is also used. The results indicate that the shapes of CAPE over land and sea are almost similar up to –40°C; only CAPE (–40°C to EL) is indistinguishably more "elegant" over the sea in comparison with a "fat" CAPE (–40°C to EL) over the land. As a result of the difference in temperature and humidity profiles over land and sea, the simulated clouds that developed over land are more vigorous and with significantly larger amount of ice particles (ice crystals and graupel) in comparison to the simulated clouds over sea, which may explain the land-ocean contrast in lightning activity.

INTRODUCTION

The analysis of lightning data shows a predominance of global annual lightning activity over land versus over maritime areas Christian et al. [2003]. More detailed studies revealed that the land-sea lightning contrast has seasonal and diurnal variations [e.g. Petrova et al. 2014, Blakeslee et al. 2014]. The physical reasons for this contrast have not been-definitively established yet. It is

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Rumjana Mitzeva, Faculty of Physics, University of Sofia, Sofia 1164, Bulgaria. Email: rumypm@phys.uni-sofia.bg accepted that the difference in thermodynamic conditions (thermal hypothesis) and/or difference in numbers and size of CCN-IN (aerosol hypothesis) over land and sea may be responsible for difference in lightning activity.

Our previous studies [Mitzeva et al. 2011] showed a significant difference between the mean values of surface temperature, relative humidity and mixing ratio, over the territory of Bulgaria (land) and the Black Sea in the grid boxes where lightning were detected. However the difference between mean values of CAPE over Bulgaria (land) and Black Sea in the grid boxes with lightning were not well pronounced Markova [2013]. This result is in agreement with the results from other authors [see e.g. Lucas et al.1994] that the estimated values of CAPE over land and warm ocean regions show little contrast. Since CAPE depends on both the magnitude of buoyancy and the depth of the integration (from the level of free convection to the equilibrium level) one may assume that environments with similar CAPE may have different degrees of instability if one environment is characterized by tall and thin CAPE and the other by short and wide CAPE. The analyses of Lucas et al. [1994] revealed that the positive area over the ocean is generally “tall and slim” (i.e., CAPE is a result of a small instability, but distributed through a large fraction of the troposphere), while the positive area over the continental regions is “short and fat” (i.e. CAPE is a result of large instability distributed over a shallower depth of the troposphere). Based on this it was concluded that the difference in the CAPE shape over land and sea may explain why oceanic convection has weaker vertical velocities than continental convection for environments with equivalent CAPE. To take into account the shape of CAPE Blanchard [1998] suggested to consider NCAPE which is a normalized CAPE by the depth over which the integration takes place and to consider vertically partition CAPE and NCAPE into multiple layers. However based on Halverson et al. [2002], Williams and Stanfill [2002] concluded that the shape of CAPE might not explain the regional differences in tropical lightning. Based on the theoretical consideration and observations Williams and Stanfill [2002] concluded that due to the higher relative humidity over sea, the cloud base height is systematically lower over the sea than over the land. As a result of this the thermal sizes at cloud base over the sea are smaller and the impact of mixing with the environmental air is higher. As a consequence, the clouds over the sea are with warmer cloud top, smaller depth and lower updraft velocity that are of primary importance to cloud microphysics and electrification.

The present study is a continuation of the work presented in Mitzeva et al. [2011] and is focused to test whether the data over Bulgaria (land) and the Black Sea (sea) confirms i) the established by Lucas et al. [1994] and Blanchard et al. [2010] difference in the shape of CAPE over land and sea; ii) the anticipated by Williams and Stanfill [2002] impact of surface conditions on cloud base height and in turn on cloud microphysics and dynamics that are strongly related to cloud electrifications. It is worthy to note that our work is directed to establish if there is a difference in various thermodynamic characteristics of the environment over land and sea when thunderstorms developed and not to answer the question why the locations of lightning detection over land are more abundant than over sea.

DATA AND METHODOLOGY OF STUDY

In the present study the territory of investigation includes maritime area (western part of the Black Sea – up to 36°E) and continental area (Bulgaria). Our previous study [Mitzeva at al. 2011] revealed that during summer over Bulgaria, the maximum of flash density is in the 3-hours afternoon time interval centred at 1200 UTC. The results also showed that the difference between land-sea lightning activities is largest in these afternoon hours. For this reasons the analyses of environmental conditions are carried out for the above mentioned afternoon interval (herein it is denoted by 1200 UTC).

The information about lightning for 74 days during the summer of 2006 (JJA) is provided from the ZEUS network operated by the National Observatory of Athens (NOA). The number of recorded flashes has been calculated for each grid box (0.25x0.25 degrees) in the 3-hours afternoon time interval (1200 UTC). Additionally each grid box is characterized as continental or maritime depending on the surface cover of the area it represents. It is worth mentioning that for the analyzed afternoon period the number of grid boxes where lightning was detected over Bulgaria are 1031 and over the western part of the Black Sea - 164, although the analyzed maritime area is ~ 2,4 times larger than the continental area. After the exclusion of the grid boxes with calculated CAPE < 250 J kg^{-1} (based on the established by Boorman et al. [2010] threshold) the number of boxes over Bulgaria and Black Sea is reduced to 916 and 160 correspondingly.

The necessary temperature and humidity profiles at 1200 UTC are taken from proximity sounding for the center of each grid box where at least one flash is recorded. The proximity soundings are obtained by the numerical model GFS (http://ready.arl.noaa.gov/). Several surface and at higher levels atmospheric data, CAPE and NCAPE (calculated for different layers) are considered (see Appendix A).

The output of 1-D cloud model with parameterized microphysics is also used. A short description of the numerical model is given in Appendix B. The list of analyzed microphysical and thermodynamic in-cloud characteristics (obtained by model simulations) is also presented in Appendix A.

The mean values, medians, and 10th, 25th, 75th and 90th percentiles of the corresponding parameters in the environment as well the values of some in-cloud characteristics (obtained by the simulation with 1-D model) over sea and land where lightning were detected are compared and discussed.

RESULTS

In Table 1 the mean CAPE and mean NCAPE calculated for different layers (over land and sea) are given together with the corresponding mean depth of the CAPE calculations. When –40°C isotherm is above EL (in 16% of the soundings over land and in 11% of the soundings over sea), the corresponding soundings do not contribute to the calculations of mean CAPE (−40°C to EL), mean DH (−40°C to EL), and mean NCAPE (−40°C to EL).

Table 1. The means CAPE, DH, and NCAPE over land and sea calculated for different layers with the ratio of corresponding mean values. Note that in some columns ratio is land/sea and in others - sea/land.

		LFC to EL		LFC to 0°C		0°C to EL		0°C to −40°C		−40°C to EL	
		mean	Ratio (sea/land)	mean	Ratio (sea/land)	mean	Ratio (land/sea)	mean	Ratio (sea/land)	mean	Ratio (land/sea)
CAPE	land	1178	1.05	112	1.58	1066	1.01	906	1.09	192	2.60
	sea	1235		176		1057		992		74	
DH	land	8142	1.10	1398	1.65	6744	1.02	5796	1.03	1305	1.50
	sea	8933		2300		6633		5998		869	
NCAPE	land	0.14	(land/sea) 1.08	0.07	1	0.15	1	0.16	1	0.11	1.57
	sea	0.13		0.07		0.15		0.16		0.07	

The analysis of the results (Table 1) shows that there is no significant difference in the mean total CAPE (LFC to EL) over land and sea, as well between the corresponding mean NCAPE (LFC to EL) and mean depth DH (LFC to EL). The established insignificantly higher (only with 8%) mean NCAPE (LFC to EL) over the land indicates that CAPE over the see is indistinguishably “slimmer” than CAPE over the land. There is also a not pronounced difference in the mean CAPE (0°C to −40°C), DH (0°C to −40°C) and NCAPE (0°C to −40°C) over the sea and the land. Taking into account the importance of the zone between 0°C and −40°C in clouds for the non-inductive charging of hydrometeors, this result was unexpected for us. A significant difference is established between land and sea of mean CAPE calculated between LFC and 0°C and between −40°C and EL. The results show that the mean CAPE (LFC to 0°C) over the sea is approximately 1.6 times higher than over the land, while the mean CAPE (–40°C to EL) over land has more than 2.6 times higher value than over sea. The analysis also reveals that the higher mean CAPE (LFC to 0°C) over sea in comparison with over land is due to the larger depth from LFC to zero isotherm over the sea. However the larger values of mean CAPE (–40°C to EL) over land results from both larger depth of integration and greater instability in the layer (–40°C to EL) over the land than over the sea. The equal values of NCAPE (LFC to 0°C) over land and sea indicate that the shapes of mean CAPE (LFC to 0°C), i.e. below zero isotherm are similar, while the significant higher value (~ 60%) of mean NCAPE (–40°C to EL) over land indicates that in this layers CAPE is a little bit more “elegant” over sea in comparison with a “fat” CAPE over land.

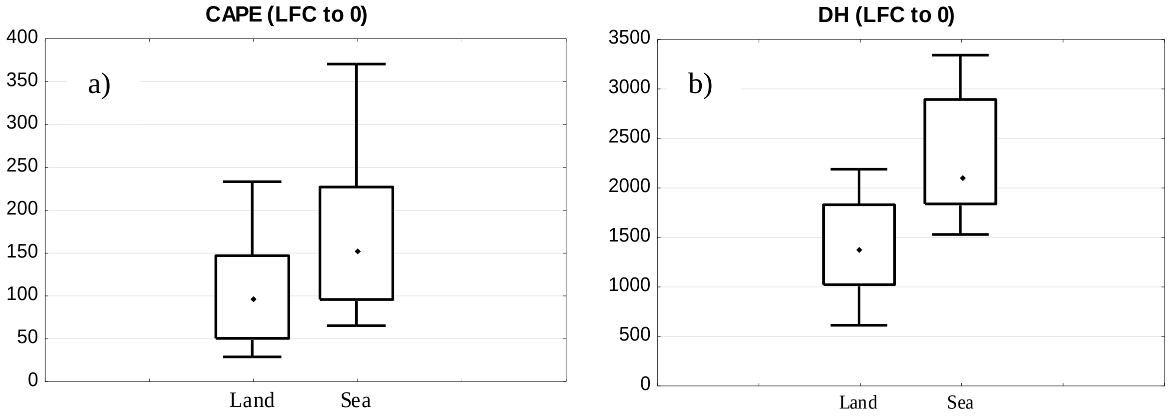

Fig. 1 Box and whiskers plot of the a) CAPE (LFC to 0°C) and b) DH (LFC to 0°C) over land and sea. The boundary of the box closest to zero indicates the 25th percentile, a dot within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles.

The Box and whiskers plots presented in Fig. 1 and Fig. 2 give an additional information for the differences in the medians, lower (10% and 25%) and upper (75% and 90%) percentiles of the corresponding CAPE and depth of integrations over land and sea. Although the plots show that there is a significant overlap in the corresponding values of both samples (land and sea) the distinctions in the considered depths are well pronounced. Fig. 1b shows that in 90% of the boxes over sea the depths between LFC and 0°C, DH (LFC to 0°C) are between 1500 m and 3329 m, while in more than 50% of the boxes over land DH (LFC to 0°C) < 1500 m. There is also a visible difference between DH (–40°C to EL) over land and sea (Fig. 2b) - in more than 90% of the grid boxes over sea DH (–40°C to EL) < 1251 m, while over land, more than 50% of DH (–40°C to EL) >1338 m.

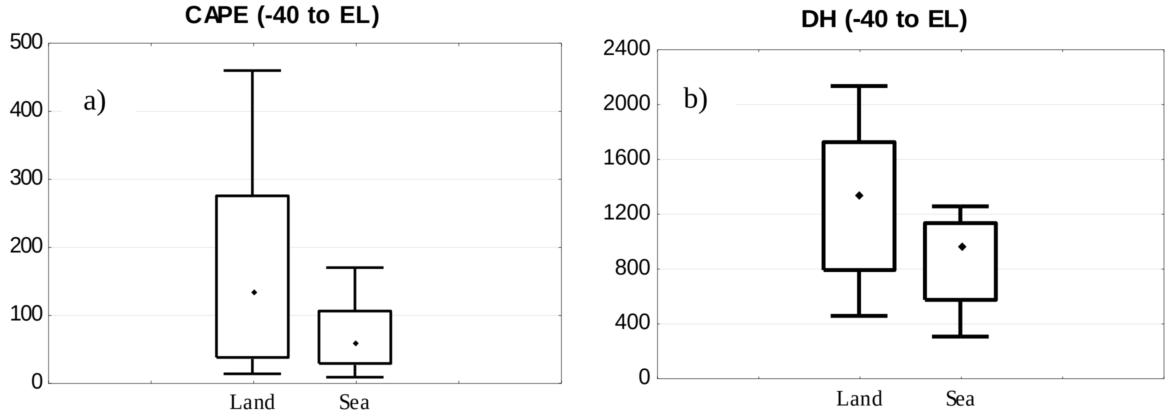

Fig. 2 Same as in Fig. 1 but for a) CAPE (–40°C to EL) and b) DH (–40°C to EL) over land and sea.

Although the contribution of CAPE (–40°C to EL) to the total CAPE (LFC to EL) is small (~ 16% over land and ~6% over sea) one can assume that the higher values of CAPE (–40°C to EL) and DH (–40°C to EL) over land may contribute to higher flash rate. The reasons for this speculation are the recent laboratory study by Avilla et al. [2011] (showing that significant charge is also transferred at very low temperatures) and the established in Mitzeva et al. [2012] higher mean values of cloud depth above –40°C in thunderstorms with high flash rate in comparison with this depth in thunderstorms with low flash rate.

The mean surface temperature Tsfc over sea is about 1.4° colder than over land, which is approximately 6% lower over sea than over land. The difference between relative humidity RH in the environment over land and sea is more pronounced - the mean relative humidity over sea is 79%, while over land - 58%. As a result of this the mean lifting condensation level, LCL (AGL) over land is 2.5 times higher than over sea. The box and whiskers plot (Fig.3b) shows that in 50% of the grid boxes over sea the calculated LCL are lower than 500 m AGL, while in

Table 2. The mean values of surface temperature, T_{sfc}, relative humidity, RH and lifted condensation level, LCL over land and sea with the ratio of corresponding mean values.

		mean	Ratio	
			sea/land	land/sea
Tsfc (^{0}C)	land	22.73		1.67
	sea	21.36		
RH (%)	land	58	1.37	
	sea	79		
LCL (m)	land	1232		2.47
	sea	499		

90% of the grid boxes over land the LCL are above 500 m AGL.

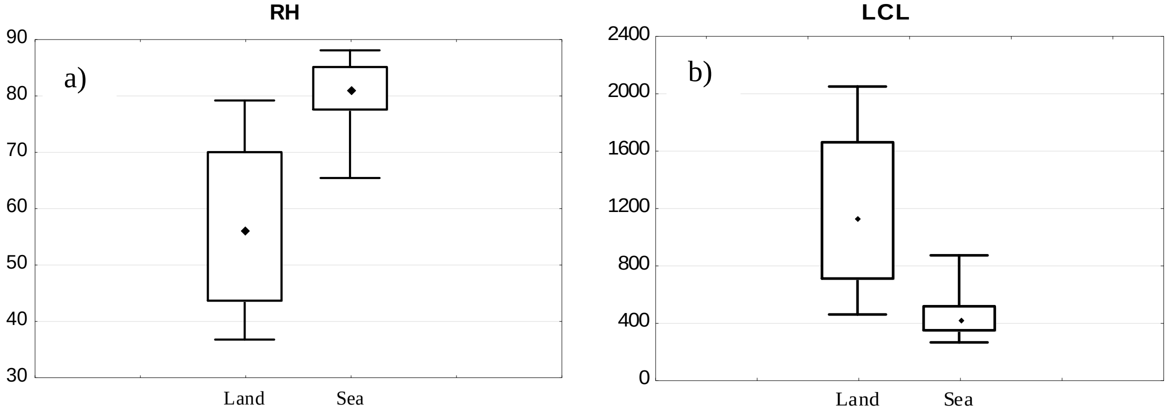

Fig. 3 Same as in Fig.1 but for a) relative humidity, RH and b) lifted condensation level LCL over land and sea.

Table 3. The mean values of the simulated by 1–D model updraft velocity W_{max} [m/s], cloud depth $DH_{top-LCL}$ [m], maximum liquid water content (cloud and precipitating drops) S_{max} [gm^{-3}], maximum ice content (ice crystals and graupel), $S_{f\ max}$ [gm^{-3}], and amount of total fallout liquid water of ascending thermal Sum S_r [gm^{-3}] over land and sea. The ratio of corresponding land/sea mean values are given in last column.

		mean	Ratio (land/sea)
W_{max}	land	18.17	2.19
	sea	8.29	
$DH_{top-LCL}$	land	7429	2.26
	sea	3323	
S_{max}	land	3.5	1.58
	sea	2.2	
$S_{f\ max}$	land	0.8	13.6
	sea	0.05	
Sum S_r	land	0.56	Ratio (sea/land) 2.9
	sea	1.65	

For the simulations of clouds by 1-D model (see Appendix B) using environmental conditions at the center of grid box over Bulgaria (land) where lightning were detected the updraft velocity and radius of the thermal at cloud base was fixed to be Wo=5 m/s and Ro=5 km respectively. These values were chosen because they were the most appropriate [Andreev and Mitzeva 1976] to simulate the maximum cloud top height of 56 precipitating powerful convective clouds in the western part of the Thracian lowland. The same initial values were also used by Mitzeva [1988] for the calculation of in-cloud characteristics with the same model and which were able to determine satisfactorily the type of precipitation (rain or hail) in the Thracian lowland.

Based on the similarity theory for point sources of buoyancy it is reasonable to assume similar to Williams and Stanfill [2002] that as an average the size of the ascending thermals at cloud base (LCL) over land are significantly larger than over the sea since the mean LCL over land is 2.5 higher than over sea. The observations also confirmed the concept that boundary layer thermals are broader in more continental conditions in comparison to oceanic conditions. A summary of the land–ocean contrast in updraft velocity, presented in Fig. 9 in Williams and Stanfill [2002] (based on observations in Jorgenson and LeMone [1989] and Lucas et al. [1994]) revealed that the updraft velocity at cloud base is approximately 2 times lower over oceans in comparison with over continents. For this reason our simulations with 1-D cloud using environmental conditions for the grid boxes over the Black Sea were performed with R_0= 2.5 km and W_0= 3 m/s.

In Table 3 the mean values of some simulated by 1-D cloud model characteristics using environmental conditions in the grid boxes over Bulgaria (land) and over the Black Sea (sea) are presented. It is worth noting that the simulated values of liquid and solid mass of hydrometeors by 1-D models are rather underestimated. That is why the results of model simulations have to be considered only qualitatively in relation with the difference between dynamics and microphysics of clouds, which developed over sea and over land.

The results show that as an average, the simulated by 1-D model clouds are more vigorous – the mean depth, $DH_{top\text{-}LCL}$ and mean maximum updraft velocity W_{max} are more than 2 times higher over the land than over the sea. The box and whiskers plots in Fig. 4 reveal that 50% of thermals ascending in continental conditions (Bulgaria) have a maximum updraft higher than 16.5 m/s, while in 50% of the simulated clouds using environmental conditions over the Black Sea, W_{max} < 8 m/s. There is also a significant difference in the simulated cloud depth $DH_{top\text{-}LCL}$ – 50% of simulated clouds over the land are with $DH_{top\text{-}LCL}$ > 9 km, while over the sea $DH_{top\text{-}LCL}$ < 4 km.

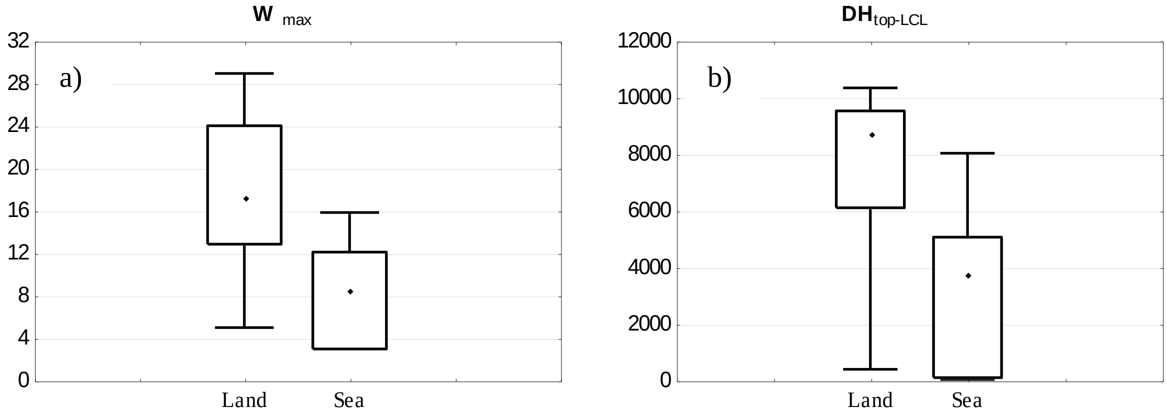

Fig. 4 Same as in Fig. 1 however for a) maximum vertical velocity, W_{max} and b) the cloud depth $DH_{top\text{-}LCL}$ over land and sea.

Due to the lower values of updtraft velocity in clouds, developed over the sea, the mean sum of liquid fallout, Sum S_r is almost three times larger than Sum S_r of clouds developed over the land (sea also box and whiskers plot in Fig. 5a). As a result the mean maximum liquid water content S_{max} in the updraft of clouds (simulated by ascending thermal) developed over the land is ~1.6 times higher than simulated S_{max} in the clouds developed in maritime environment. The most remarkable differences (over land and sea) is between simulated mean maximum values of ice particles mass $S_{f\ max}$ – more than 13 times mean $S_{f\ max}$ is larger in the simulated clouds over the land than over the sea. The box and whiskers plot presented in Fig. 5b illustrates this significant differences – the amount of solid particles is significantly lower in the simulated clouds developed over the Black Sea in comparison with the simulated clouds over Bulgaria.

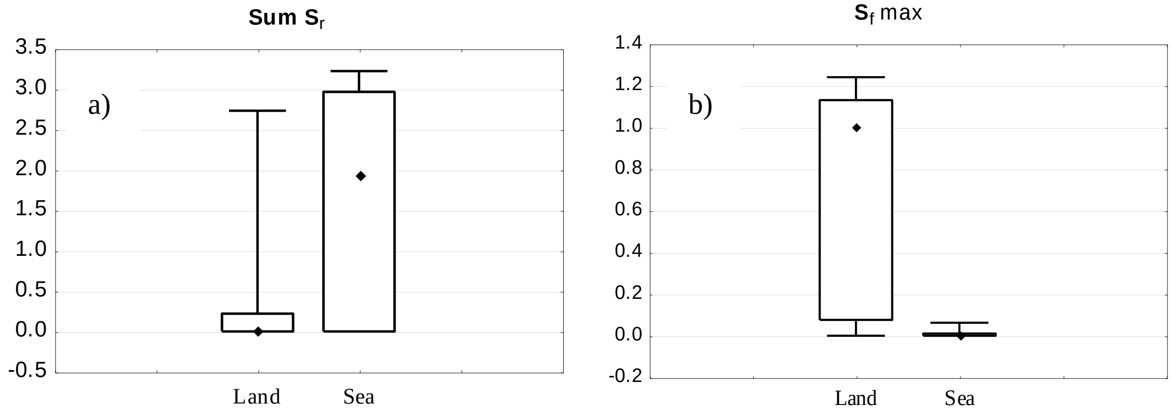

Fig. 5 Same as in Fig. 1 however for a) sum of liquid fallout Sum S_r and b) mass of maximum solid particles in the ascending thermals S_f max.

In the scientific community there is a general consensus that the non-inductive mechanism plays the major role in the electrification of thunderstorms, culminating in lightning. Since laboratory studies shows that the magnitude of the charge transfer per collision increases rapidly with increasing velocity of impact and (especially) the size of ice particles, it is reasonable to assume that the established here higher updraft velocity, depth and larger ice particle amount in simulated clouds which developed over land may explain the higher lightning activity over land in comparison with lightning activity over the sea.

CONCLUSION

Proximity soundings in grid boxes (0.25x0.25 degrees) with detected flashes are used to test whether data over Bulgaria (961 boxes) and the Black sea (160 boxes) confirm i) the established difference in the shape of CAPE over ocean and land in other geographical regions; ii) the ability of the difference in temperature and humidity over land and sea to explain the land-ocean contrast in lightning activity.

Our results show that there is no significant difference in the mean CAPE (LFC to 0°C) and mean NCAPE (0°C to −40°C) over land and sea, i.e. as an average the shapes of CAPE over land and sea are similar up to −40°C. It is established that the mean CAPE (LFC to 0°C) over sea is larger than over land, however it results from larger depth of integration below zero isotherm over the sea. The higher mean CAPE (−40°C to EL) over land results from both larger depth of integration and greater instability in the layer (−40°C to EL) over the land than over the sea. As a result the CAPE in the layers above −40°C is more “elegant” over the sea in comparison with a “fat” CAPE over the land. One can speculate that the thicker warm part with positive area over the sea and higher values of CAPE (−40°C to EL) and NCAPE (−40°C to EL) can contribute to some extent to the explanation of the higher lightning activity over land. However the contribution of CAPE (LFC to 0°C) and CAPE (−40°C to EL) to the total CAPE (LFC to EL) is rather small. Additionally taking into account that no significant difference is established in the mean values of CAPE and NCAPE over land and sea in the so called charging zone (0°C to −40°C), one can conclude that the CAPE and its shape can not explain the land-ocean contrast in lightning activity.

Our study supports the traditional thermal hypothesis that the difference in temperature and humidity over land and sea may explain the difference in lightning activity. The analyses show that the warmer and dryer surface over land leads to significantly higher mean cloud base height (LCL) over Bulgaria than over the Black sea. As a consequence of this we assume (based on the similarity theory for point sources of buoyancy) that the thermals sizes at cloud bases over land are larger and thus the updrafts are more protected from the mixing with environmental air. The simulated clouds using environmental conditions (temperature and humidity profiles) over the land are more vigorous and with significantly larger amount of ice particles (ice crystals and graupel) in comparison to the simulated clouds over the sea. Since the magnitude of the charge transfer per collision increases rapidly with increasing the size and concentration of ice particles and their impact velocity, it is reasonable to assume that the established here higher updraft velocity, depth and larger ice particle amount in simulated clouds which developed over land may explain the higher lightning activity over land in comparison with lightning activity over sea.

APPENDIX A
LIST OF SYMBOLS

Table A.1. List of symbols used for environmental characteristics.

CAPE, J kg^{-1}	Convective available potential energy $CAPE = g \int_{LFC}^{EL} \frac{T_i - T_e}{T_e} dz$ where g- acceleration due to gravity, T_i- the temperature of the rising parcel, T_e - the temperature of the environment	NCAPE, J kg^{-1}m^{-1}	Normalized CAPE (=CAPE/DH)
LFC, m	Level of free convection	T_{sfc}	surface temperature
EL, m	Equilibrium level	RH, %	Surface relative humidity
DH, m	Layer depth	LCL, m	Lifted condensation

Table A.2. – List of symbols used for model output.

Variables simulated by the 1-D model			
W_{max}, ms^{-1}	Maximum vertical velocity	$DH_{top-LCL}$, m	Cloud depth (cloud top-LCL)
S_c, g m^{-3}	LWC due to cloud droplets	S_{cf}, g m^{-3}	Mass of ice crystals
S_p, g m^{-3}	LWC of rain drops	S_{pf}, g m^{-3}	Mass of precipitating ice particles
S max, g m^{-3}	S max = (S_C + S_P) max	S_f max g m^{-3}	S_f max =(S_{cf} + S_{pf})max
S_r	Liquid fallout of an ascending thermal	S_{rf}, g m^{-3}	Precipitating ice particles fallout of ascending thermal
Sum S_r	Total liquid fallout during the the thermal ascent		

APPENDIX B
NUMERICAL CLOUD MODEL

A one-dimensional Lagrangian parcel model with parameterization of microphysical processes [Andreev 1976] is used in this study for the calculations of several in-cloud characteristics. The model uses bulk microphysical parameterisations with five classes of water substance - water vapor, cloud water, rain, cloud ice, and precipitating ice. The cloud droplets and ice crystals are assumed to be monodisperse and have negligible fall velocities and so move upward with the air in the ascending thermal. A Marshall–Palmer type size distribution is assumed for raindrops and graupel. In the model cloud, droplets are formed by condensation. Raindrops form by autoconversion of the cloud droplets and grow by collision and coalescence with cloud drops [Kessler 1969]. Below 0°C, ice crystals originate by heterogeneous freezing at the expense of cloud droplets, the concentration being given by Fletcher [1962]. Homogeneous freezing occurs below −40°C. Precipitating ice (graupel) forms by the freezing of raindrops [Bigg 1953], the contact nucleation of drops by ice crystals [Cotton 1972] and conversion of ice crystals [Hsie et al. 1980]. Ice crystals grow by deposition of water vapor while precipitating ice grows by coalescence with cloud and raindrops. Precipitation fallout is calculated in the same manner as in Cotton [1972] and comprises that portion of the raindrops S_r and graupel S_{rf} having terminal velocities greater than the updraught speed. The ascent of the thermal is driven by the buoyancy force reduced by entrainment and the weight of the hydrometeors present. The thermal entrains air from the cloudless local environment, which is unchanged throughout the simulation. The entrainment is parameterized as in Mason and Jonas [1974], with the entrainment rate inversely proportional to the radius of the ascending thermals [Stomell 1947]. The temperature in the rising thermal changes due to cooling, entrainment of environmental air and heat released by the microphysical processes. The differential equations, describing the dynamical and microphysical processes are integrated numerically by the Runge–Kutta method with height step dZ=5 m. The simulations are carried out for the thermal ascending from the cloud base to the height of zero velocity. It is assumed that the cloud base height coincides with the lifting condensation level (LCL). LCL is calculated using surface temperature and profiles of temperature and humidity from the aerological sounding for 1200 UTC obtained by GFS model http://ready.arl.noaa.gov/. The updraft velocity and radius of the thermal at cloud base is fixed to be Wo=5 m/s and Ro=5 km respectively at the simulations for the grid boxes over the land (Bulgaria) and to Wo=3 m/s and Ro=2.5 km. at the simulations for the grid boxes over the sea.

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