Nat. Hazards Earth Syst. Sci. Discuss., 2, 1837–1865, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/1837/2014/
doi:10.5194/nhessd-2-1837-2014

Natural Hazards
and Earth System
Sciences
Discussions
Open Access

Developing an index for heavy convective rainfall over a Mediterranean coastal area

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Received: 13 December 2013 – Accepted: 18 January 2014 – Published: 25 February 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Heavy convective rainfall incidents that occurred over western coastal Greece and led to flash floods are analyzed with respect to mesoscale analysis for the period from January 2006 to June 2011. The synoptic scale circulation is examined throughout the troposphere along with satellite images, lightning data and synoptic observations of weather stations. Well known instability indices are calculated and tested against synoptic observations. Taking into account the severity of the incidents, the performance of the indices was not as good as expected. Further detailed analysis resulted to the development of a new index that incorporates formalized experience of local weather and modeled knowledge of mechanism of severe thunderstorms. The proposed index named Local Instability Index (LII) is then evaluated and its performance is found to be quite satisfactory.

1 Introduction

Thunderstorms accompanied by heavy rainfall often lead to flash flood events with disastrous consequences on the economy, the environment and in some cases have resulted in fatalities. Although the performance of the numerical weather prediction models have been improved, it is always challenging to further study due to their impacts.

One of the fundamental conditions for a thunderstorm initiation is the existence of an unstable atmosphere. In order to estimate the instability, thermodynamic indices have been created by combining related meteorological parameters (Showalter, 1953; George, 1960; Boyden, 1963; Jefferson, 1963a, b; Miller, 1967; Litynska et al., 1976; Peppler, 1988; Peppler and Lamb, 1989; Jacovides and Yonetani, 1990; Reuter and Aktary, 1993; Tian and Fan, 2013). These indices have not shown always satisfactory results due to local effects that are not well represented or due to limited datasets.

Related studies have been carried out for specific regions of Greece with acceptable results (Dalezios and Papamanolis, 1991; Michalopoulou and Karadana, 1996; Sioutas and Flocas, 2003; Chrysoulakis et al., 2006; Marinaki et al., 2006). The main challenge of these studies was the availability and reliability of observation data as the existing radiosonde network is rather insufficient. It has been shown that the performance of the indices depends on the season or even month, the terrain of the area and the type of the thunderstorms (Michalopoulou and Jacovides, 1987; Prezerakos, 1989; Dalezios and Papamanolis, 1991; Haklander and Van Delden, 2003; **?**).

Western Peloponnese, being washed by the Ionian Sea, is an area that is frequently affected by severe thunderstorms (Maheras and Anagnostopoulou, 2003; Metaxas et al., 1999; Ziakopoulos, 2009; Xoplaki, 2002). However, relevant studies have not been performed so far, mainly due to the luck of radiosondes data. The objective of this study is to examine the thermodynamic environment of severe thunderstorms with respect to heavy rainfall occurring in this area for the period of 1 January 2006 to 30 June 2011. It is proposed an alternative methodological tool for developing a useful and practical index in order to forecast these events without employing radiosondes data, rather other data sources. Using this tool for the examined area, a new index, namely Local Instability Index (LII), was built.

2 Data

The severe thunderstorms with heavy rainfall occurred in the examined area of northwestern Peloponnese (see Fig. 1), more specifically over the hydrological basin defined by the rivers Peiros, Parapeiros, Vergas and Pinios (almost 2500 km^2) of northwestern Peloponnese (MEECC, 2012) during 1 January 2006 to 30 June 2011 were considered. For this purpose, a mesoscale analysis of the atmosphere with 6 h time step for that period was performed with the aid of datasets of dry and dew point temperature at the surface and geopotential height, temperature and humidity at the isobaric surfaces of 850, 700, 500, 300 hPa. The 6 hourly synoptic scale analysis of the atmosphere derived from the archive of Hellenic National Meteorological Service (HNMS) and a re-analysis of 0.125° resolution from the European Centre for Medium-Range Weather Forecasts (ECMWF) with the same time step were also employed (Veremei et al., 2013). Additionally, the surface synoptic observations (SYNOP) derived from the stations of Andravida, Araxos, Pyrgos and Zakynthos (see Fig. 1) were employed and merged in 6 h intervals in order to be compatible with the aforementioned time step (i.e. 00:00–6:00, 06:00–12:00, 12:00–18:00, 18:00–24:00).

Missing merged SYNOP were noticed randomly throughout the available dataset, mainly during night hours, weekends and public holidays, representing a percentage of 2.8 %, 3.1 %, 51.2 %, 29.2 % for the stations Andravida, Araxos, Pyrgos and Zakynthos respectively.

For the Dry Temperature, the missing data were classified in three categories. The first category is characterized by observation times at Andravida that there no available observations from the nearby stations, consisting of 9 missing observations. For this category, the Group Method of Data Handling (GMDH) algorithm (Acock and Pachepsky, 2000) was employed with depended variables: the Temperature at 850 hPa (T_{850}) at the same observation time, the 24 h trend of the T_{850} before and after the specific time ($T_{850_0} - T_{850_{-24}}$ and $T_{850_{+24}} - T_{850_0}$), the Dry Temperature of the next and of the previous day at the same time (T_{+24}, T_{-24}), the trends of the Dry Temperature from 30 h before to 6 h before ($T_{-6} - T_{-30}$) and from 6 h after to 30 h after ($T_{+30} - T_{+6}$), the 6 h *Wind Runs* at the same time, before 24 h and after 24 h. The accuracy was found to be as high as 88 %. The second category is characterized by observation times at Andravida that there are available observations for the same time from Araxos station, consisting of 113 missing observations. In this case, the GMDH algorithm was also employed with one more dependent variable, the Dry Temperature T of this nearby station. The accuracy was found up to 90 %.

The third category was characterized by two or more successive missing observations, consisting of 106 cases. In this case, the GMDH algorithm was not selected, but a qualitative approach was employed instead, with the aid of respective values from the nearby weather stations when available, the synoptic analysis and the satellite images from the satellite Meteosat-9 and more specifically a combination of the SEVIRI High Resolution Visible channel and the IR10.8 channel with the aid of the CineSat application.

For the surface relative humidity, the 228 missing merged observations were filled with the aid of a qualitative approach, due the nature of this parameter. The subjective estimation was based on succeeding and preceding observations, on observations of the nearby stations, on the synoptic analysis and on Meteosat-9 images (a combination of the SEVIRI IR3.9, IR10.8 and IR12.0 channels).

The amount of precipitation and the duration of each individual thunderstorm led to their intensity determination.

If a thunderstorm occurs in a 6 h interval in at least one of the weather stations with intensity greater than 5 $\mathrm{mm\,min^{-1}}$ for at least 5 min then this interval is defined as interval of severe thunderstorm.

The lightnings data were available for the period 1 June 2008 to 30 June 2011 refer to an area defined by the points with coordinates A(38.33° N, 20.60° E), B(38.33° N, 21.90° E), C(37.35° N, 21.90° E) and D(37.35° N, 20.60° E) (Fig. 1). Correspondingly, a 6 h intervals being characterized by more than 10 $\mathrm{strokes\,h^{-1}}$, were considered as intervals of severe thunderstorms. These records were fused with the synoptic observations. However there were cases with recorded strokes without recorded thunderstorms from the synoptic observations. The identification of these cases was further verified with the aid of satellite images (Meteosat-9) as derived from the channel combination named *Convection RGB* (WV6.2 – WV7.3, IR3.9 – IR10.8, NIR1.6 and the VIS0.6 channels).

This analysis showed 508 6 h intervals with thunderstorms events over the examined area. 143 cases of these are considered severe being associated with flash flood events. The remaining 365 cases refer either to thunderstorms with no or relatively small amounts of precipitations or thunderstorms associated with frontal activity and were excluded from the subsequent analysis. The 143 severe cases occurred from May to October and thus our study became restricted to these.

Due to limited availability of lightnings data, two distinct sub-periods were used. The first period, from 1 May 2006 to 31 October 2007, that is characterised by luck of the lightnings data. The second one, from 1 June 2008 to 30 June 2011, is considered of higher reliability due to the availability of lightnings data. In the first one, 138 6 h intervals of thunderstorms occurred, including 54 severe thunderstorms. In the second period 370 events of thunderstorms were observed, including 89 severe events.

A set of metadata were aggregated from the first period data i.e.

- Veering and backing of winds at surface, 850, 700, 500, 300 hPa
- Temperature and Humidity 6 h, 12 h and 24 h trends at surface, 850, 700, 500, 300 hPa (i.e. ΔT_{6h} etc)
- Surface Pressure 6 h, 12 h and 24 h trends
- Geopotential Heights trends at 850, 700, 500, 300 hPa
- Thickness for all combinations of the levels surface, 850, 700, 500, 300 hPa
- Components that constitute the Instability Indices KI, HI, TTI and SWEAT (i.e. $(T - \mathrm{Td})_{\mathrm{Levels}}$ or $\sin(\text{wind direction}_{500\mathrm{hPa}} - \text{wind direction}_{850\mathrm{hPa}})$, etc)

3 Methodology

Available data made feasible the calculation of the thermodynamic instability indices KI, HI, TTI and SWEAT. Due to the fact that these indices refer to a specific geographical point, the Andravida surface weather station was chosen as representative of the examined area because this station presented the smallest number of missing data. According to *HeVeS* (Hellenic Verification Scheme) (Petrou et al., 2009) and to *Yule Index* (Marinaki et al., 2006) their performance found to be poor (Dimitrova et al., 2009) and thus of no practical value. This performance could be attributed to the fact that the indices do not take into account the synoptic scale weather patterns nor the local flows. Therefore the development of a new instability index is imperative.

Severe thunderstorms cannot be modeled and consequently predicted analytically nor synthetically (Holton, 2004). The proposed indices for predicting thunderstorms are hypothesis which had been tested for a specific period and consequently it is possible to be disproved and rejected despite the fact that they are successfully tested for a different period. The validation tests for these indices are performed deductively; the proposed index (consisting actually the hypothesis) and its application constrains are considered as the prerequisite knowledge for prediction of the event; if the predicted event is not manifested, the hypothesis is rejected (Trochim, 2000). From a set of proposed indices, the index that is tested more strictly is preferred. It is rational to accept that if there is an effective index, it will be among those who have persisted in criticism and been corroborated.

An index is a successfully tested hypothesis that can be developed from experience, literature or theory, or combination of these (Graham et al., 2010). The index that derives from rich explicatory theoretical framework (content) and a consequently deductive hypothesis, incorporates formalized related experience and has performed successfully through strict validation tests, can be conceived that captures important part of the event behavior.

In order to state and support the effectiveness of the new index, it is suggested to use two different sets of data. The first for building the hypothesis i.e. to find the patterns and the rules that associate the events with the meteorological parameters for the specific period. The second for testing and evaluate the hypothesis according to *Modus Tollens* rule (Lakatos, 1963). It was preferred to use the first sub-period (1 May 2006 to 31 October 2007) for building the hypothesis and the second sub-period (1 June 2008 to 30 June 2011) for testing and evaluation since for the latter sub-period the recorded thunderstorms events are more accurate than the former as explained in the Sect. 2 and the testing of the proposed index (hypothesis) would be more strict.

The factors responsible for forming the Index would be inferentially derived from the theoretical and empirical analysis. Data Mining and Optimization techniques are employed to determine the crucial values of these factors and not the factors themselves, since this would led to an index with poor informative content i.e. relations between the event and parameters with no meteorological meaning.

In this study it was attempted to automatically extract associations rules and patterns between the events and the data and metadata using the software tools: MATLAB and ARMADA for MATLAB. Data Mining techniques such as Principal Components Analysis, Association Rules and Cluster Analysis were applied to data and metadata. However, no useful result was found, mainly due to the sparseness of the phenomena in question.

Thus, in this study, the described methodological tool of *Combined Hypothesis Development* was preferred to be used. The index will have the form of a threshold function that flags or not a warning for an impeded thunderstorm with heavy rainfall. The value of 100 % for the recall of the index will be a major constrain due to the severity of the consequences of the event.

4 Developing the new Local Instability Index (LII)

In this section, the factors accounting for the framework of the index development are depicted and briefly presented along with a specific for the examined area synoptic description.

It is well known that a thunderstorm initiation requires the presence of three ingredients, namely, energy, moisture and lifting mechanism. Using these ingredients as a guidance, a detailed analysis for the factors that were related to thunderstorms events associated with heavy rainfall was conducted.

These mechanisms are closely related with the synoptic scale circulation over the examined area. More specifically, during the period from May to August (5th to 8th month of the year) polar air masses arrive over Mediterranean Sea and as they have crossed the warm continent of Europe, they have become dry and warm (Xoplaki, 2002). At the same time, the eastern Mediterranean region is affected by tropical dry and warm air masses (Rodwell and Hoskins, 2001; Hoskins, 1996). Thus, heat is transferred from the warm lower atmosphere layers to the upper layers of the sea, causing the temperature of the lower atmosphere to be reduced. These conditions enhance the stability of the atmosphere, often associated with temperature inversion and trapping moisture in the lower layers (from the surface to the 3000–5000 ft), inhibiting conditions of any cyclogenesis or depressions passes.

In late summer and especially during September the polar jet stream is shifted to the south. An atmospheric perturbation may interrupt the equatorial flow of the jet, a part of it usually moves southwards causing a northwesterly flow. Consequently, cyclonic conditions are created at the lee side of the Alps (Aebischer and Schär, 1998; Kljun et al., 2000) and the geo-dynamic heights are reduced. The southeastern movement of that part of the jet is usually enhanced by the specific conditions. As the jet gets momentum, it moves further to the south, resulting in further reduction of the geopotential heights and cyclonic conditions over the area of Boot and northern Sidra Sea (Trigo et al., 2001). As a consequence, southwesterly winds gradually prevail over southern Ionian Sea (Brody and Nestor, 1980) enriching even the middle layers of the atmosphere with moisture and reversing the temperature inversion which occurs at the low layers. The examined area is affected by such condition, as the southwestern stream in conjunction with local orography accumulates further moisture in the lower atmosphere, while in the meantime the perturbation has moved eastwards bringing cold and dry air mass in the upper layers. The combination of these conditions can be explosive and cause severe storms.

Throughout September and October (9th and 10th month of the year) and when a southwesterly flow prevails in the upper atmosphere, orographic clouds and precipitation are caused over the western Peloponnese windward areas. The shift of winds at 850 hPa to the southwestern sector favours the occurrence of thunderstorms, occasionally severe.

The factors of energy, moisture and lifting are considered as the independent variables of a *threshold function* that constitute the *Local Instability Index* (LII) requiring a minimum value for the occurrence of severe thunderstorm.

The analysis was carried out every six hours and consequently the Index provides warning values every six hours lasting for the next 12 h. Due to the severity of the phenomena, it is compulsory for the index to predict all or almost all the phenomena and simultaneously maintain a high and practicable precision.

The estimation of the parameters of the proposed Index was based *only* on the data of the period 1 May 2006 to 31 October 2007. In order to determine the crucial values of the parameters, the linear programming (LP)-based branch-and-bound algorithm of the optimization toolbox of MATLAB (R2010a), `bintprog` was used. The precision of LII was the objective function to be maximized. The required parameters were the changing variables of the objective function constrained to rational values. Constrain also was the value of recall, set up to 100 %.

4.1 Energy term

Instability is a prerequisite for air mass thunderstorms and can be partially indicated by the Convective Available Potential Energy (CAPE) (Moncrieff and Miller, 1976). Although CAPE is referring to synoptic scale airmass, it has been shown that CAPE can be used for smaller scale, local weather diagnosis and prediction (Zverev, 1972). CAPE practically defines how strong the updraughts within the thunderstorm potentially are; stronger the updraughts result in heavier rainfalls (Wallace and Hobbs, 2006).

4.1.1 ACAPE term

Using only the data that are available to operational forecasters in their daily duty, the energy term was developed in order to approximate the CAPE. An algorithm in MATLAB was built that accepts the Dry Temperatures (T) and the Dew Point (Td) as inputs from the weather stations of Andravida, Araxos and Pyrgos and calculates a mean T

and Td (Holton, 2004). The Lifted Condensation Level (LCL) was computed and simulating the wet adiabatic finally computed the Temperature (Tp) of the surface parcel would have if would be raised in the levels of 850, 700, 500 and 300 hPa. The Approximated CAPE (ACAPE) is the difference $\mathrm{Tp}-T$ and is referring to the four pressure levels (ACAPE_{850}, ACAPE_{700}, ACAPE_{500} and ACAPE_{300}).

$$\mathrm{ACAPE}_{\mathrm{Level}} = \mathrm{Tp}_{\mathrm{Level}} - T_{\mathrm{Level}} \tag{1}$$

It should be noted that there are a lot of cases of severe thunderstorms with low and sometimes negative CAPE (Curry and Webster, 1999).

Moreover, in the specific case, it can be stated that large amounts of negative ACAPE_{850} is prohibitive for the development of thunderstorm with heavy rainfall (Peppler, 1988). This finding can be modeled by requiring $\mathrm{ACAPE}_{850} \geq -2.5$. At the level of the 700 hPa, the positive energy ($\mathrm{ACAPE}_{700} > 0$) is a prerequisite, especially for the summer period where the geopotential heights are higher and more energy is needed for heavy rainfall to form within the thunderstorm (Bol, 2006). A threshold of 1.5 was noticed for the summer period ($\mathrm{ACAPE}_{700} > 1.5$). For the upper levels, the smaller values of ACAPE show that there is a smaller possibility for thunderstorm development. Thresholds of minus 2 and minus 8 were noted for the levels 500 and 300 hPa respectively. ($\mathrm{ACAPE}_{500} > -2$, $\mathrm{ACAPE}_{300} > -8$).

4.1.2 Thickness term

The thermal properties of the 850 to 500 hPa atmospheric layer are often better represented by the thickness rather than the temperature at a single level (Wallace and Hobbs, 2006). The 850 to 500 hPa thickness is a function of the average temperature and the average moisture content of the air through the specific layer, which are two properties associated with the virtual temperature. Therefore, the specific thickness (between the level z_1 (with pressure p_1) and the level z_2 (with pressure p_2)) is associated with virtual temperature (T_v), as shown below:

$$z_2 - z_1 = -\frac{R_\mathrm{d}\overline{T_\mathrm{v}}}{g} \cdot \ln\left(\frac{p_2}{p_1}\right) \tag{2}$$

The virtual temperature is used for estimating the available convective potential energy and its exclusion may lead to relatively important errors (Doswell and Rasmussen, 1994).

$$\mathrm{CAPE} = \int_{z_\mathrm{EL}}^{z_\mathrm{LFC}} g \cdot \left(\frac{T_\mathrm{v,\,parcel} - T_\mathrm{v,\,env}}{T_\mathrm{v,\,env}}\right) dz \tag{3}$$

where z_LFC and z_EL are the heights of the levels of free convection and equilibrium respectively, $T_\mathrm{v,\,parcel}$ is the virtual temperature of the specific parcel, $T_\mathrm{v,\,env}$ is the virtual temperature of the environment, and g is the acceleration due to gravity.

Consequently, the 850 to 500 hPa thickness effect on CAPE led us to include this indicator in the LII formation. For practical reasons, the thickness seasonality was subtracted using the moving average. It has been demonstrated that should be less than 0 for the period from May to August and less than 40 for September and October. The ACAPE and the Thickness Term are represented schematically in the Figs. 2 and 3.

Thus, the *Energy Term (ET)* is the conjunction of ACAPE and Thickness Term, i.e.

$$\mathrm{ET} := \mathrm{ACAPE} \wedge \text{Thickness Term}. \tag{4}$$

4.2 Moisture term

According to previous studies (Humphreys, 1926; Showalter and Fulks, 1943; Fawbush et al., 1951; Appleby, 1954; Whitney and Miller, 1956; Miller, 1967; Schaefer, 1986) the low level moisture is a prerequisite for the thunderstorm initiation and development. Usually, low level moisture increases instability as more latent heat is available to the lower atmosphere. In the opposite, when mid-level moisture increases then the atmospheric instability can decrease because moist air is less dense and is therefore less able to evaporate precipitation than the drier air. The evaporation of precipitation at or beneath cloud level causes the air-cooling inside precipitation downdrafts making the air denser and increases instability.

The minimum amount of moisture that was noticed in the recorded events, expressed in relative humidity term, was 60 % at 850 hPA and 40 % at 700 hPA and 120 % for their sum (see Fig. 4). The aforementioned thresholds are insufficient for heavy rainfall. Although, increasing moisture increases the potentiality for heavy rainfall within the thunderstorm, the moisture in the upper levels may decrease the instability (Bol, 2006) and is not taken into account although it was found that the values of the upper levels were associated with the thunderstorms.

4.3 Terrain heating effect and local features

A lifting force is necessary for a rising parcel of air to overcome the convective inhibition which occurs when a layer of warmer air is above a particular region of air, resulting in the cooler air parcel to be hindered from ascending into the atmosphere (Mapes, 2000). Thus, a temperature inversion is created and therefore a stable region of air. The lift mechanism pushes the cooler parcel of air over the inversion contributing to the thunderstorm development. The main sources of a lift mechanism are associated with terrain features, heating and sea breeze.

4.3.1 Terrain heating effect term

A cold air mass with respect to the ground can be heated from it, increasing its instability and vice versa. If an air mass is cooling from the terrain is becoming denser and unfavorable for thunderstorm development (Kessler, 1983). Taking into account the terrain thermal conductivity with respect to heat storage (terrain heat capacity) the terrain heating effect is suggested to be modeled as:

$$\mathrm{THeat} = T_0 - \frac{2T_{-1} + T_{-2}}{3} \quad (5)$$

where T_0, T_{-1}, T_{-2} are the temperature of the terrain on the specific day, 1 day and 2 days before respectively at the same time. The weight factor for the previous day temperature is set to 2 and for the temperature of 2 days before is set to 1. They are decreasing as the effect decreases with time.

The threshold was estimated to Theat = 2 since greater values mean reduced instability. In the cases, where the current is southwesterly, and is consequently supplying to the area, the factor THeat became more ineffective moisture and this can be modeled by subtracting three degrees.

4.3.2 Locality term

Apart from the local influences that were modeled within the aforementioned terms, it can be introduced that the dissolving effect of the easterly downdraft current due to the high mountains on the Eastern parts of the area examined.

4.4 The Local Instability Index (LII)

Summarizing the above terms, the LII can be considered as the conjunction of the ET (Energy Term), MT (Moisture Term), THeat (Terrain Heating Effect Term) and LT (Locality Term):

$$\mathrm{LII} := \mathrm{ET} \wedge \mathrm{MT} \wedge \mathrm{THeat} \wedge \mathrm{LT} \quad (6)$$

5 Calculations, evaluation and discussion

The LII was calculated on the basis of the data of the period 1 May 2006 to 31 October 2007. 88 severe thunderstorms events were predicted. It is important to note that the actual number was 54 and all of them were predicted. Although the importance of 100 % recall is controversial, the risk of neglecting a severe thunderstorm warning may prove hazardous, since injuries or fatalities and damages to structures or to the environment may not be prevented. The LII predicted 1418 no thunderstorm events and the actual number was 1452.

The Consistency Table of LII for the specific period is shown in the Table 1 and its performance is described as follows:

- Precision = (the number of the thunderstorms that occurred from those that had been forecasted/the number of the latter) = 61 %
- Recall = (the number of the thunderstorms that forecasted from those that had been occurred/the number of the latter) = 100 %
- Fall-out = (the number of the cases with no thunderstorms from those that had not been forecasted/the number of the latter) = 98 %

The weighted harmonic mean of precision and recall, the traditional F-measure or balanced F-score is:

$$F = 2 \cdot \frac{\text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}} \tag{7}$$

resulting in $F = 76\,\%$ and the most adequate measure for the case of severe phenomena the $F_{1.2}$ that weights recall as 1,2 times much as precision is:

$$F_{1.2} = (1 + 1.2^2) \cdot \frac{\text{Precision} \cdot \text{Recall}}{1.2^2\text{Precision} + \text{Recall}} \tag{8}$$

resulting in $F_{1.2} = 79\,\%$ (total performance)

The LII was then calculated for the second period 1 June 2008 to 30 June 2011. 163 severe thunderstorms were predicted. During this period the actual number was 89 and LII predicted all of them. The LII predicted 2165 no thunderstorm events and the actual number was 2239. The Consistency Table of the LII for the specific period is shown in the Table 2 and its performance is: Precision = 55 %, Recall = 100 %, Fall-out = 97 % The balanced F-score is: $F = 71\,\%$ and the weighted F-score i.e. the total performance is: $F_{1.2} = 75\,\%$

The performance of LII per month is illustrated in Table 3.

It is demonstrated that the LII had performed very well for the months May, June, September and October, when unstable weather conditions are more likely to occur. In these cases, most of the thunderstorm events took place during noon or afternoon when the terrain heating effect is stronger. The lower levels of the atmosphere were moist enough and the CAPE was suitable. During July and August of the specific period, only two thunderstorm with heavy rainfall events occurred. This was expected as the atmosphere in the region is generally stable for these months, as was previously explained. Although the performance of LII for July and August is rather low, its use is still beneficial, taking into account the severity of the events and that the *recall* of the LII is 100 %.

6 Conclusions

This study presents an alternative methodological tool for the prediction of severe thunderstorms occurring over a specific area. The northwestern Peloponnese was chosen to illustrate the proposed tool because many thunderstorms with heavy rainfall have occurred with disastrous impacts.

The parameters used were constrained to those that are easily available to operational forecasters while performing their everyday duties. The statistical correlations of the parameters with the observations were examined. In the cases that the correlations were not justified by the relative theory, the respective parameters were neglected. Then, the Local Instability Index (LII) was inferentially drawn by using them. The LII is a threshold function that consists of the low level moisture, a practical approximation of the CAPE, the terrain heating effect and a formalized operational experience. It was

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found that the LII has satisfactory total performance (75 %) over northwestern Peloponnese region for the period from 1 June 2008 to 30 June 2011 and predicted all the thunderstorms with heavy rainfall events (recall = 100 %).

The future challenge for further development and optimization of this tool is to experiment the LII for a longer period and for hydrological basins all around Greece since in case of good performance, the LII would be at the disposal of operational forecasters of HNMC.

Acknowledgements. We would like to thank the HNMC operational forecasters for their help.

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Table 1. LII – Consistency table for the period 1 May 2006 to 31 Oct 2007.

	Observation	
LII	54 (Correct result)	34 (Unexpected Result)
	0 (Missing result)	1418 (Correct absent of result)

Table 2. LII – Consistency table for the period 1 Jun 2008 to 30 Jun 2011.

	Observation	
LII	89 (Correct result)	74 (Unexpected Result)
	0 (Missing result)	2165 (Correct absent of result)

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Table 3. LII – Monthly performance for the period 1 Jun 2008 to 30 Jun 2011.

	LII	Actual	Precision	Recall	F	$F_{1.2}$
May	17	6	0.35	1.00	0.52	0.57
Jun	23	7	0.30	1.00	0.47	0.52
Jul	10	**1**	0,10	1.00	0.18	**0.21**
Aug	11	**1**	0.09	1.00	0.17	**0.20**
Sep	51	34	0.67	1.00	0.80	0.83
Oct	51	40	0.78	1.00	0.88	0.90

Fig. 1. Map of examined area. The locations of the stations are displayed. The points A, B, C, D define the area of lightning data.

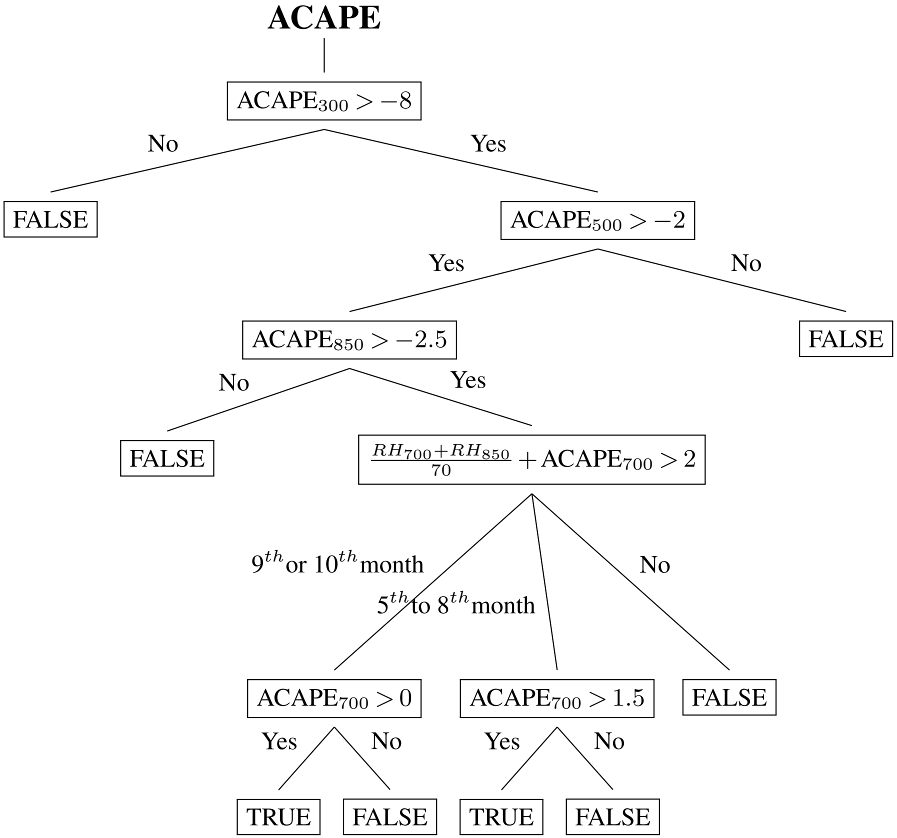

Fig. 2. Schematic diagram of ACAPE.

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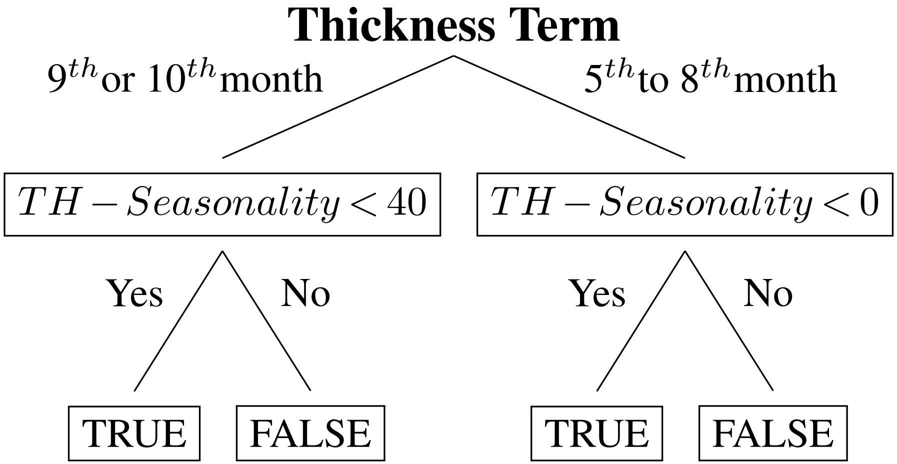

Fig. 3. Schematic diagram of the thickness term.

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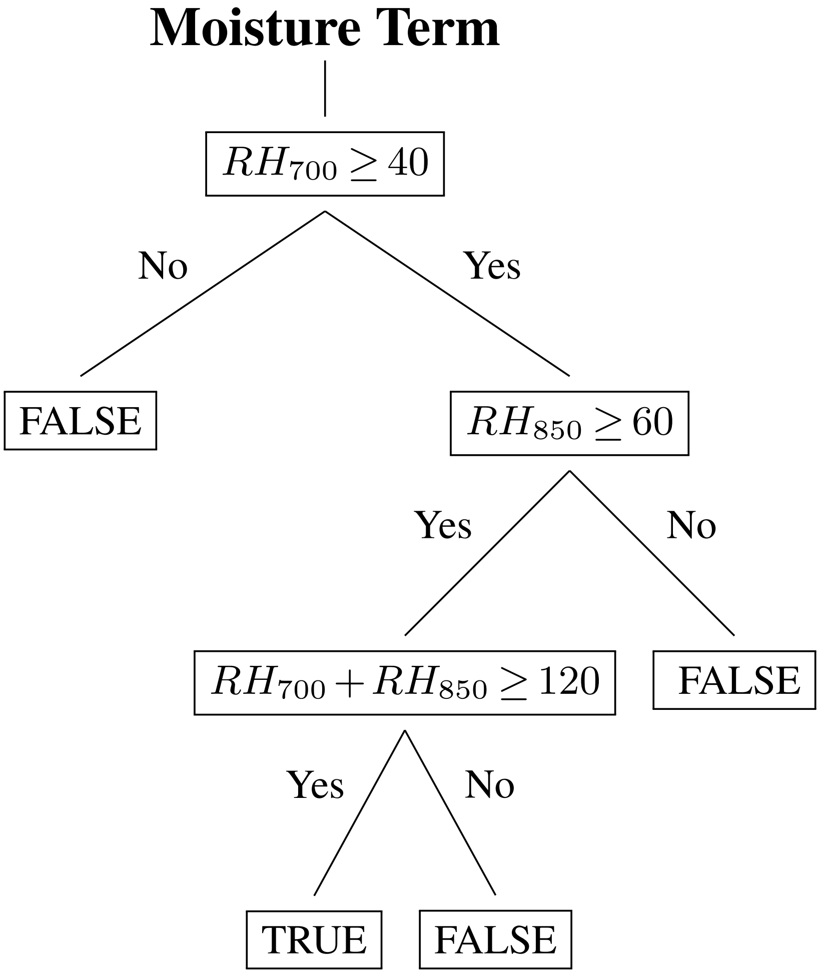

Fig. 4. Schematic diagram of the moisture term.

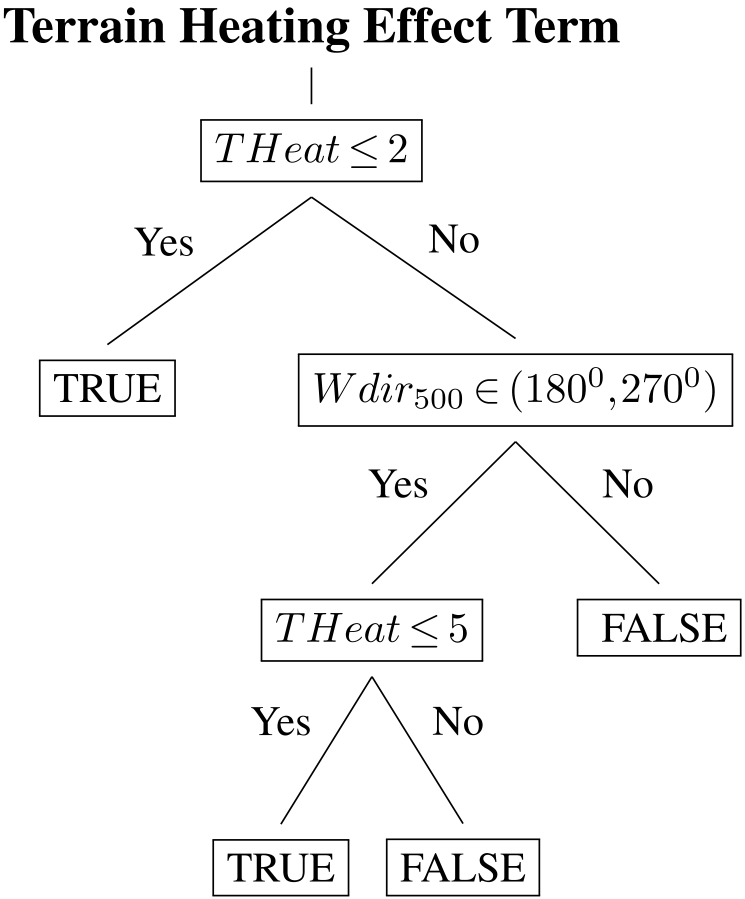

Fig. 5. Schematic diagram of the terrain heating effect term.

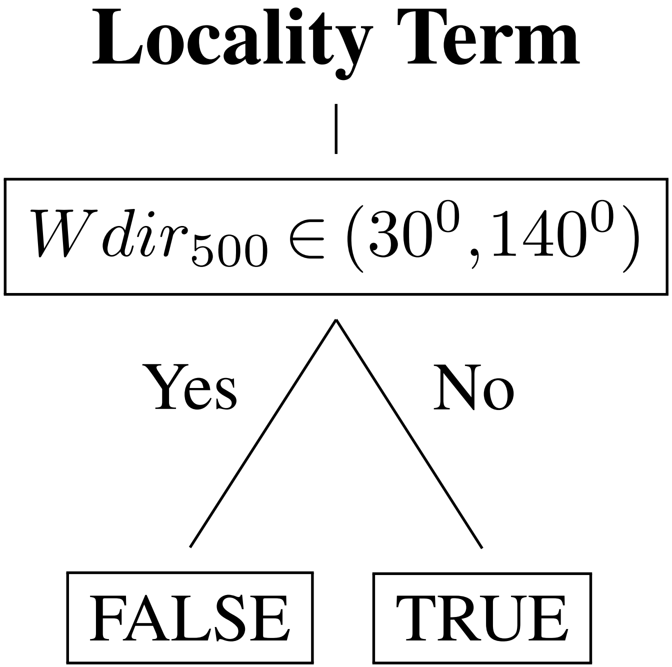

Fig. 6. Schematic diagram of the locality term.

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