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CLIMATOLOGICAL ASSESSMENT OF ATMOSPHERIC INSTABILITY INDICES FOR SOUTHEASTERN EUROPE

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Abstract: Atmospheric instability indices are routinely used in operational forecasting for identifying the possibility of convective storm activity. This study focuses on the long- term temporal assessment of Showalter Index, SWEAT Index, K- Index and CAPE at three coastal (Athens, Istanbul and Brindisi) and at one inland station (Sofia) of southeastern Europe. The indices are calculated from daily archived radiosonde observations for a 36-year period, from 1973 to 2008. In order to identify meaningful temporal trends, a two phase methodology is applied. The first step contains the assessment of the monthly, seasonal and yearly averages. The yearly trends of Showalter and SWEAT indices indicate an increase of atmospheric instability mean values for Athens, Brindisi and Sofia after mid 1990s. The second step, which is the primary focus of this study, is the assessment of index extremes. After the selection of index threshold levels, index extremes are studied in terms of threshold exceedences. The analysis reveals long term trends for some combinations of indices and stations.

Keywords: Radiosonde observations, Instability Indices, Showalter, SWEAT, K-Index, CAPE, Climate

1. Introduction

Severe weather phenomena are related to atmospheric instability and include thunderstorms, hailstorms, tornadoes and heavy precipitation. The frequency and the intensity of such events can be modified by climate changes. Regions of atmospheric instability have organized patterns and a change in Earth's climate may lead to a change in the regions of convection and its intensity (Betz et al. 2009). Instability indices are used by forecasters since late 1940s to assess the possibility of convective phenomena and are calculated from the vertical distribution of temperature, humidity and wind from radiosonde observations. In this study the Showalter Index, the Severe Weather Threat Index (SWEAT), the K – Index and the Convective Available Potential Energy (CAPE) are examined as climatological variables based on their long – term temporal statistical trends. The scope of this work is to identify changes in the temporal distribution patterns of atmospheric instability, as this is expressed by instability indices and detect any related long-term climate signals from radiosonde observations.

2. Materials and Methods

The area of study is the Balkans peninsula at the southeastern part of Europe. This work aims to identify temporal changes in routinely used instability indices derived from radiosonde observations from four upper air monitoring stations situated at Athens, Istanbul, Brindisi and Sofia (Fig.1).

Fig. 1. Area of study and location of stations.

Radiosondes are launched twice daily at 00UTC and 12UTC, providing measurements of the vertical distribution of pressure, temperature, relative humidity and wind speed and direction. In this study, archived radiosonde data from January 1973 to December 2008 are used. For the study area, the convective phenomena are better described from the 12UTC radiosonde observations thus the study is limited in the analysis of the instability indices at 12UTC. The overall completeness for each station for 00UTC and 12UTC, along with the missing daily observations at 12UTC are presented in fig. 2.

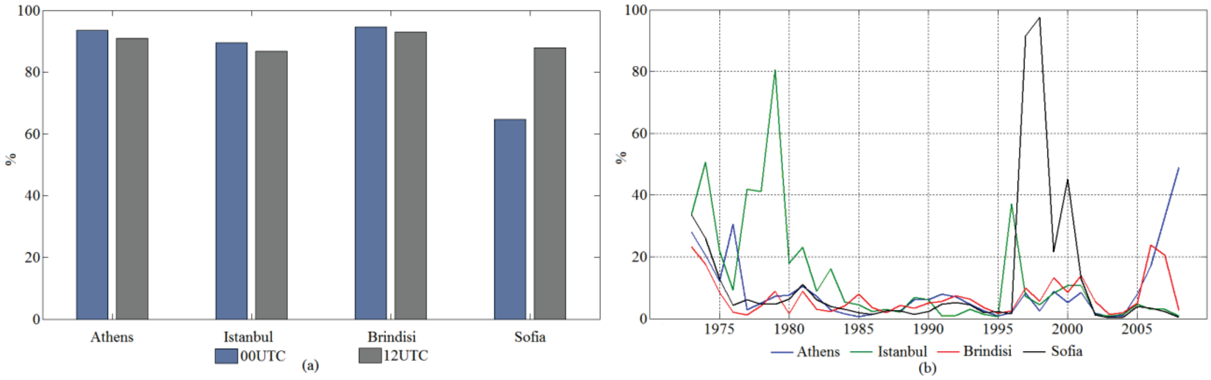

Fig. 2. Dataset completeness at 00UTC and 12UTC (a), and missing daily observations at 12UTC (b).

The overall data availability for all stations at 12UTC is higher than 85%. Limited availability is observed for the Istanbul station for 1979, with missing observations reaching up to 80.5%, for the Sofia station for the period 1997-2000 and for Athens station for 2008. The available data for these years are not included in the study.

3. Instability Indices

Instability indices have been developed to quantify atmospheric instability based on radiosonde observations. Showalter Index (Showalter, 1953) is based on the potential instability concept and it is calculated from the difference of the temperature at 500hPa ($T_{(500\ hPa)}$) and the temperature of an air parcel, lifted from 850hPa to 500hPa ($T'_{(850hPa \rightarrow 500hPa)}$).

$$SSI = T_{(500\ hPa)} - T'_{(850hPa \rightarrow 500hPa)} \quad (^{o}C)$$

The commonly applied thresholds for SSI are:

1<SSI<3: probability of showers and some thunderstorms
-3<SSI<0: unstable, increased possibility of thunderstorms
-6<SSI<-3: very unstable, heavy thunderstorm potential
SSI<-6: extremely unstable, strong thunderstorm potential.

Showalter index is a measure of convective instability when values are less than zero.

The SWEAT Index assesses severe weather potential and is used to discriminate between ordinary and severe thunderstorms. It incorporates thermodynamic and kinetic effects and is calculated from the following formula (Haklander and Van Delden, 2003):

$$SWEAT = 12T_{d(850hPa)} + 20(TT - 49) + 2WS_{(850hPa)} + WS_{(500hPa)} + 125(S + 0.2)$$

where $T_{d(850hPa)}$: Dew-point temperature at 850hPa (^{o}C), TT: Total Totals Index = ($T_{d(850hPa)} - T_{(500hPa)}$) + ($T_{(850hPa)} - T_{(500hPa)}$) in (^{o}C), $WS_{(850hPa)}$: Wind speed at 850hPa in knots, $WS_{(500hPa)}$: Wind speed at 500hPa in knots and S: S = sin[($WD_{(500hPa)} - WD_{(850hPa)}$], where WD is the wind direction.

The proposed thresholds for SWEAT index are:
SWEAT > 300 : potential of severe thunderstorms
SWEAT > 400 : potential of tornadoes.

George (1960) proposed the K-Index as a measure of thunderstorm potential:

$$K = (T_{(850hPa)} - T_{(500hPa)}) + T_{d(850hPa)} - (T_{(700hPa)} - T_{d(700hPa)})$$

The first term is a lapse rate term, while the second and third are related to the moisture between 850hPa and 700hPa. The critical values for the K-Index are the following:

$$\left.\begin{array}{l} K < 15 : 0\% \\ 15 < K < 20 : 20\% \\ 21 < K < 25 : 20 - 40\% \\ 26 < K < 30 : 40 - 60\% \\ 31 < K < 35 : 60 - 80\% \\ 36 < K < 40 : 80 - 90\% \\ K > 40 : \text{near } 100\% \end{array}\right\} \text{thunderstorm probability}$$

CAPE is the amount of energy of a parcel, lifted from the level of free convection (LFC) to the level of equilibrium – neutral buoyancy (LBN).

$$CAPE = g \int_{LFC}^{LBN} \frac{T_p(z) - T_e(z)}{T_e(z)} dz$$

where $T_p(z)$: the temperature profile of an air parcel lifted moist adiabatically, $T_e(z)$: the temperature profile of the environment and g: the gravity acceleration. The recommended thresholds for CAPE (DeRubertis, 2006) are the following:

CAPE = 0 Jkg^{-1} : stable
1000<CAPE<2500 Jkg^{-1}: moderately unstable
CAPE >2500 Jkg^{-1}: very unstable, possible strong convection.

For the purpose of this study, a two-phase methodology is applied. Firstly, the long-term temporal statistical properties of the indices are examined, based on their mean monthly, seasonal and annual time series. Their trends are examined and subsequently the instability indices extremes are studied, based on the exceedences of a selected set of thresholds. Finally, the temporal distributions of the stability indices threshold exceedences are discussed for each station and index.

4. Results and Discussion

The selected stability indices share the common scope of evaluating the potential for convective storm activity in a region. Their temporal and spatial correlation is examined at each station and for each index, based on the correlation coefficient (Tab. 1 and Tab.2). For every station, the higher correlation is observed among the Showalter and the K-Index, with values ranging from -0.72 for Athens to -0.85 for Sofia, although the two indices are based on different approaches. Showalter relies on the lifted parcel theory while the K-Index is solely based on the lapse rate and mid-level moisture observations. They are negative correlated because Showalter, in contrast with K-Index, decreases with instability increase.

Regarding the spatial correlation of indices for the selected stations (Tab. 2), SWEAT, K-Index and CAPE are uncorrelated for each station pair. Very limited correlation is observed for the Showalter index among the stations of Athens and Istanbul. This fact reflects the local character of the convective phenomena along with the limited spatial representativeness of radiosonde observations.

5.1. Monthly, Annual and Seasonal Patterns

The annual distribution of the monthly averages of the selected indices is calculated in order to identify the seasonality of atmospheric instability (Fig. 3).

As it is expected, a clear annual cycle is observed, with increased instability during the warm period. The Showalter and the K-Index distributions share a common pattern, where Athens, Istanbul and Brindisi stations have comparable value ranges while the Sofia station exhibits a much higher range (higher instability during the summer and lower during winter). For the SWEAT index and for Brindisi station an annual cycle is not evident, while for Sofia station a sharp increase in the mean monthly index value is observed from April to June, where the index reaches its maxima. Athens and Istanbul stations have a common pattern with maximum values during July and August. Each station exhibits a different pattern for CAPE monthly averages. A symmetrical distribution is observed for Sofia with a maximum during June, while the maximum for Brindisi station is observed during August. Athens station exhibits a rather smooth increase reaching its maxima in mid-summer, a trend which is observed for all indices and it is attributed to the dry northern etesian winds. Istanbul station exhibits a sharp increase starting on May and retains high mean monthly CAPE values for all summer months. The coastal stations (Athens, Istanbul and Brindisi) exhibit higher monthly averaged values during autumn compared to spring due to the influence of the warmer sea basin.

Table 1. Correlation of indices for each station for the complete dataset

Athens					Istanbul				
	Showalter	SWEAT	K	CAPE		Showalter	SWEAT	K	CAPE
Showalter	1,00	-0,53	-0,72	-0,25	Showalter	1,00	-0,54	-0,76	-0,24
SWEAT	-0,53	1,00	0,39	0,25	SWEAT	-0,54	1,00	0,42	0,21
K	-0,72	0,39	1,00	0,16	K	-0,76	0,42	1,00	0,19
CAPE	-0,25	0,25	0,16	1,00	CAPE	-0,24	0,21	0,19	1,00
Brindisi					Sofia				
	Showalter	SWEAT	K	CAPE		Showalter	SWEAT	K	CAPE
Showalter	1,00	-0,55	-0,76	-0,35	Showalter	1,00	-0,60	-0,85	-0,23
SWEAT	-0,55	1,00	0,36	0,26	SWEAT	-0,60	1,00	0,53	0,29
K	-0,76	0,36	1,00	0,26	K	-0,85	0,53	1,00	0,20
CAPE	-0,35	0,26	0,26	1,00	CAPE	-0,23	0,29	0,20	1,00

Table 2. Spatial correlation of stations for each index for the complete dataset

Showalter					SWEAT				
	Athens	Istanbul	Brindisi	Sofia		Athens	Istanbul	Brindisi	Sofia
Athens	1,00	0,43	0,34	0,39	Athens	1,00	0,22	0,15	0,17
Istanbul	0,43	1,00	0,21	0,39	Istanbul	0,22	1,00	0,11	0,18
Brindisi	0,34	0,21	1,00	0,39	Brindisi	0,15	0,11	1,00	0,16
Sofia	0,39	0,39	0,39	1,00	Sofia	0,17	0,18	0,16	1,00
K Index					CAPE				
	Athens	Istanbul	Brindisi	Sofia		Athens	Istanbul	Brindisi	Sofia
Athens	1,00	0,22	0,15	0,17	Athens	1,00	0,04	0,06	0,05
Istanbul	0,22	1,00	0,11	0,18	Istanbul	0,04	1,00	0,07	0,07
Brindisi	0,15	0,11	1,00	0,16	Brindisi	0,06	0,07	1,00	0,10
Sofia	0,17	0,18	0,16	1,00	Sofia	0,05	0,07	0,10	1,00

The analysis and interpretation of temporal changes and trends in the yearly averaged sequences of indices values (Fig. 4) is used as a descriptive tool to demonstrate long term evolution of index values. These averages should not be compared with thresholds since these thresholds are defined for single soundings. Furthermore, averaged index values tend to dilute the meaning of each index and information related to increased instability, due to the fact that stations record a stable atmosphere on most days (DeRubertis, 2006).

Regarding Showalter index, all stations fall within the same value ranges and remain rather constant until 1993. A decreasing trend is observed for the rest of the studied period for Athens, Brindisi and Sofia. Istanbul station doesn't follow this trend, reaching its yearly averaged maximum at 2003. The sequences of the yearly averaged SWEAT values follow a decreasing trend until 1993 and an increasing trend thereafter. This is more evident at Brindisi and Sofia stations. Athens station exhibits a rapid decrease from 1973 to 1984, remain constant until 1993, with the exception of 1986 - 1987, and an increase to the 1973 levels thereafter. The mean yearly averaged K-Index series imply some long term spatial dependence between Athens and Brindisi stations which follow a similar evolution. Both stations exhibit a decrease until 1986 and 1985 respectively, a sharp increase until 1987 and

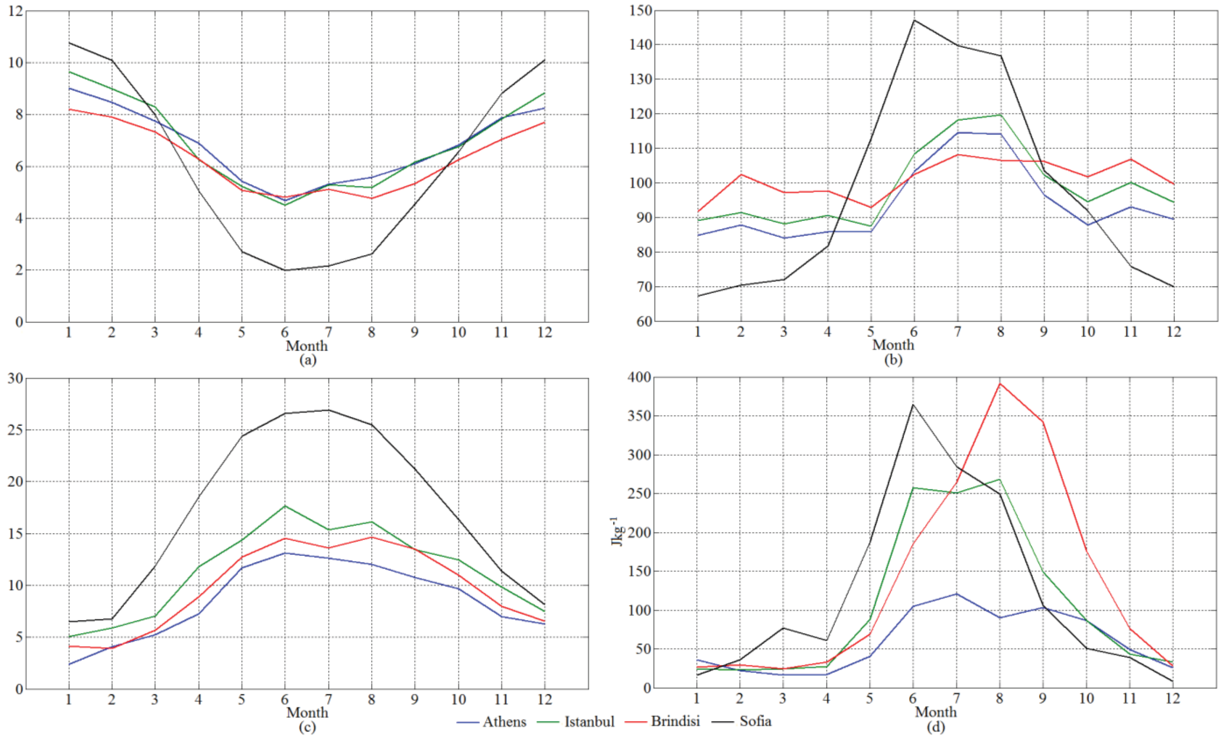

Fig. 3. Annual distribution of monthly averages of Showalter (a), SWEAT (b), K-Index (c) and CAPE (d).

a stable evolution thereafter. Regarding the evolution of the CAPE values, a general decreasing trend until the early 1990s is observed for all stations and a rather stable evolution is exhibited for the rest of the studied period. Especially for the Athens station a similar evolution of CAPE and SWEAT values is observed until 1993. Istanbul station exhibits for all indices an irregular distribution without any meaningful trend.

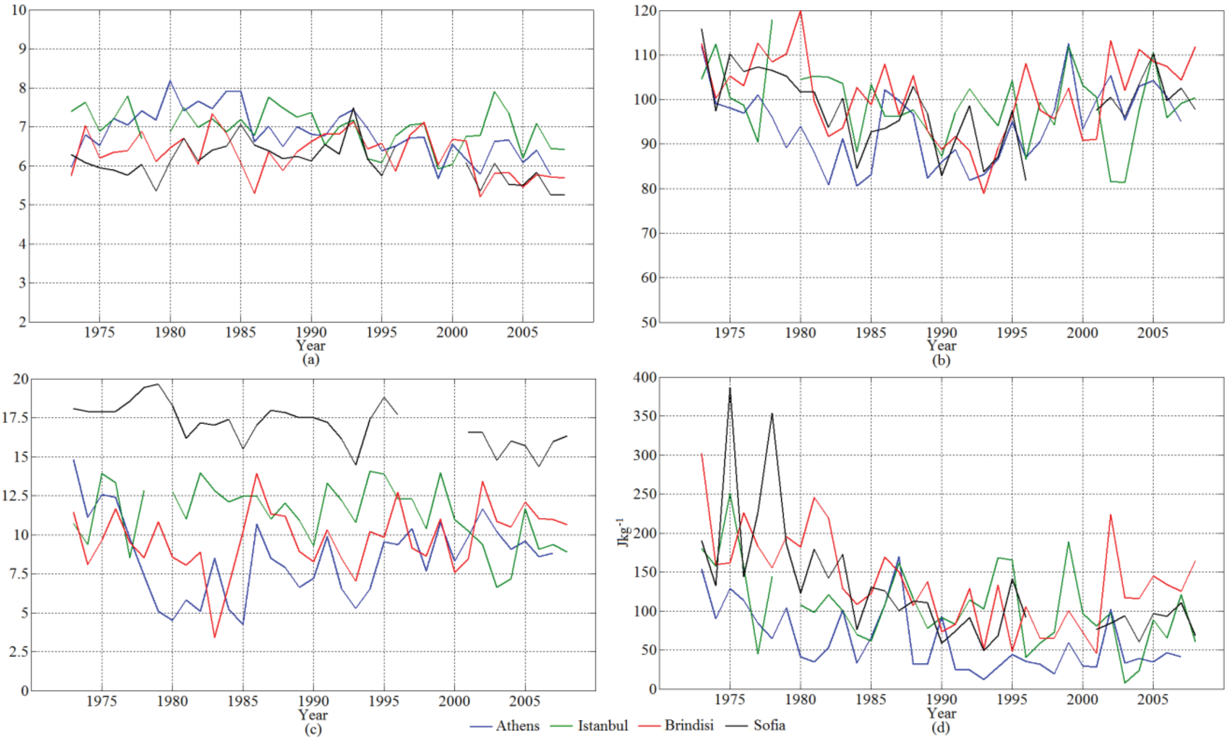

Fig. 4. Yearly averaged distributions of Showalter (a), SWEAT (b), K-Index (c) and CAPE (d).

The seasonal averages of each year are calculated, focusing on the summer months, where increased instability is observed (Fig. 5).

The evolution of the summer averages shares some common features with the evolution of the yearly averages. Showalter index, for Athens and Brindisi after the early 90's, exhibits a slow decrease, a trend which might be present for the Sofia station but cannot be verified due to the data incompleteness for 1997 – 2000. All of the stations reach their minima (maximum instability) after 2000. The increasing instability after 1993 is observed for the Athens and Brindisi stations at the evolution of the SWEAT index. In contrast with the yearly averages a decreasing trend until the early 90's is observed only for the Sofia station. The yearly evolution of the K-Index summer averages for Athens and Brindisi are similar, with a decreasing trend until 1985 for Brindisi and 1986 for Athens, a sharp increase for both stations until 1987, and a rather stable evolution until 2000, where another sharp increase is observed. Sofia station for the whole study period retains high K-Index values without any significant trend, differentiating from the rest of the stations. Regarding CAPE, the trend of the yearly summer averages is less evident with some sharp increases mainly during 1986-87 and 1995.

5.2. Exceedences assessment

The study of the frequency of the exceedences involves the identification of threshold levels for each index. Threshold values are defined in the literature from index values during days with convective events. These thresholds are not the same with the proposed by the definition of indices (described in the Instability Indices section). In northern Greece the majority of hailstorms occur for K index values ranging from 24.1 to 36, while the 36.8 % and the 25.6% of hail corresponds to Showalter values ranging from 0.1 to 3 and -3.1 to 0 respectively. (Sioutas and Flocas, 2003). In northern Italy severe convective events occur for K index values greater than 30, CAPE values ranging from 700 to 2500 Jkg^{-1} and SWEAT index values ranging from 250 to 300 (Costa et al. 2001). A review of various threshold levels applied in Europe can be found in Siedlecki (2009). This study fo-

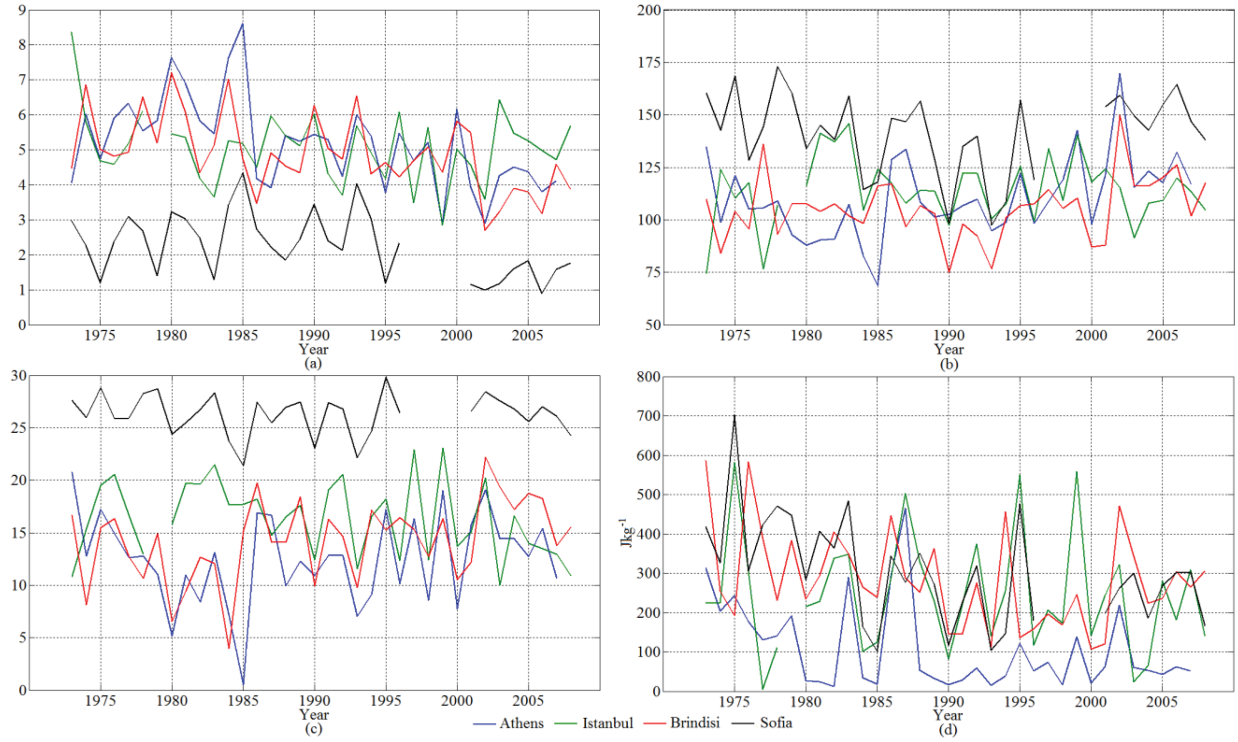

Fig. 5. Annual summer averages of Showalter (a), SWEAT (b), K-Index (c) and CAPE (d).

cuses on index extremes and thus the selected set of thresholds is derived from the assessment of the frequency distributions of the index values along with those proposed by the literature. A uniform strict set of thresholds is selected which corresponds to increased atmospheric instability in the region. Showalter values below 0, describe the left tail of the Showalter values distribution at the four stations while SWEAT values greater than 250, K-Index greater than 30 and CAPE greater than

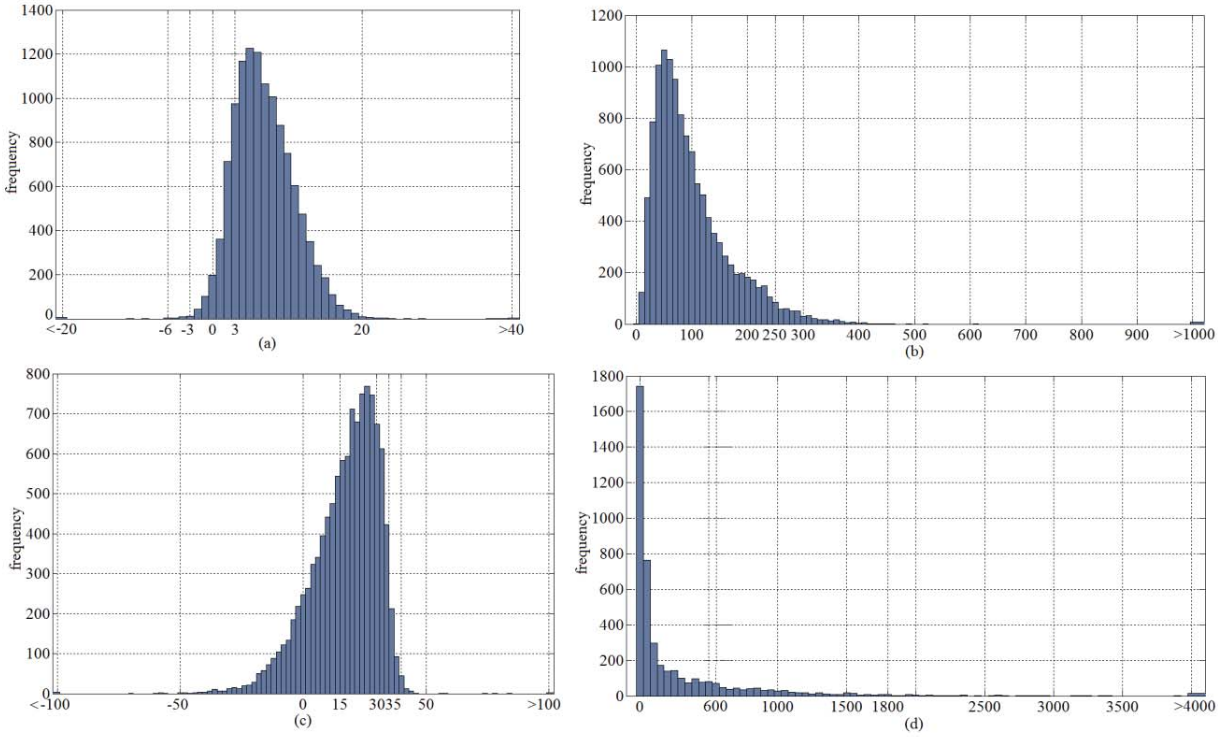

Fig. 6. Frequency distributions of Showalter (a), SWEAT (b), K-Index (c) and CAPE (d) for Sofia station.

600Jkg^1, the right tail of the distributions at the four stations. The frequency distributions for the station of Sofia are illustrated in figure 6. It is noted that for the frequency distribution of CAPE, only values greater than 0 Jkg^{-1} are used.

The numbers of days in which thresholds are exceeded along with the mean index value for these days are presented for each station in table 3. High frequency of thresholds exceedences is noted for the Sofia station for Showalter and K-Index and for Brindisi station for CAPE.

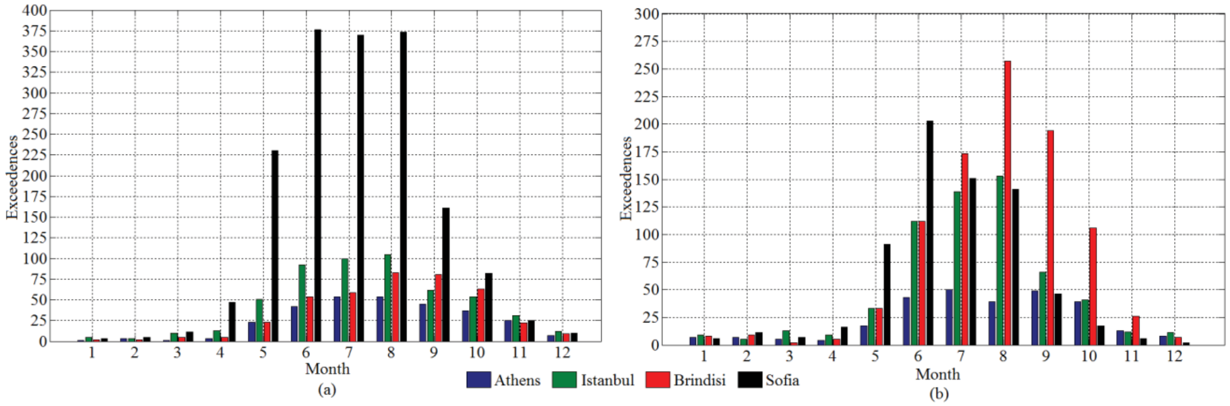

Fig. 7. Monthly frequency of threshold exceedences for K index (a), and CAPE (b).

Table 3. Number of days in which stability index thresholds are exceeded and mean index value

	Showalter < 0		SWEAT > 250		K Index > 30		CAPE > 600Jkg^{-1}	
	Days	Mean	Days	Mean	Days	mean	days	mean
Athens	266	-2,23	186	360,7	295	43,97	281	1379
Istanbul	393	-2,41	323	338	538	39,73	603	1294
Brindisi	373	-2,19	453	333,4	408	42,86	932	1232
Sofia	1242	-1,83	373	340,6	1693	38,16	697	1313

The number of daily exceedences in Athens is much lower compared to the rest of the stations. The differences in the number of days among the compared stations partly results from an application of uniform threshold levels in conjunction with the different atmospheric conditions at the four stations. Furthermore, especially in an extreme value analysis, the quality of the radiosonde data is of great importance. Although as atmospheric instability increases so does the likelihood of severe weather, the threshold exceedences should not be interpreted as an occurrence of convective phenomena. A statistical analysis of the occurrence of thunderstorms in Athens (611 cases reported at Helliniko station by the Global Surface Summary of the Day database of NCDC) results to a wide range of index values with many cases where the values of indices from the 12UTC radiosonde do not favor convective phenomena.

The monthly frequencies of threshold exceedences for each station for K-Index and CAPE are illustrated in figure 7. The majority of the exceedences are observed as expected during the summer months. Furthermore, for the stations of Athens, Istanbul and Brindisi and during transitional periods, the autumn exceedences are more frequent than in spring. For these stations the maximum of the threshold exceedences is observed during August or July, while for Sofia station the maximum

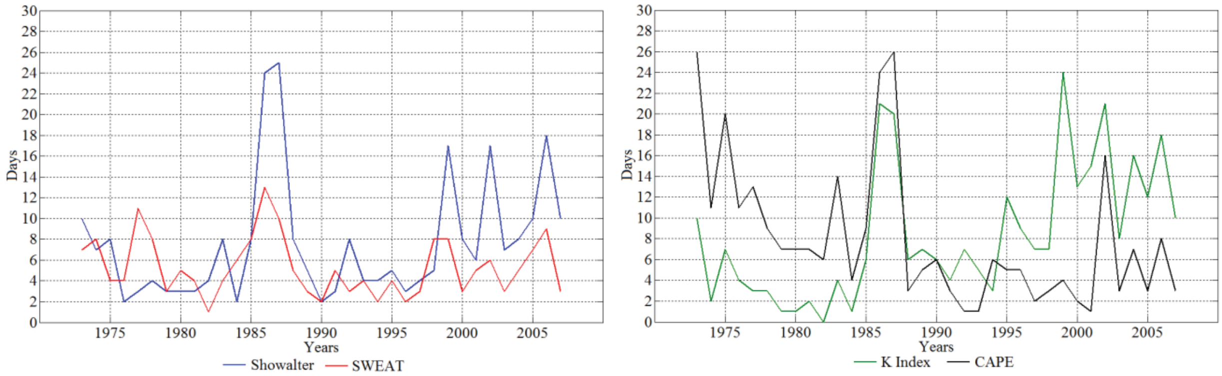

Fig. 8. Yearly threshold exceedences at Athens.

is observed earlier in the summer, during June or even in May.

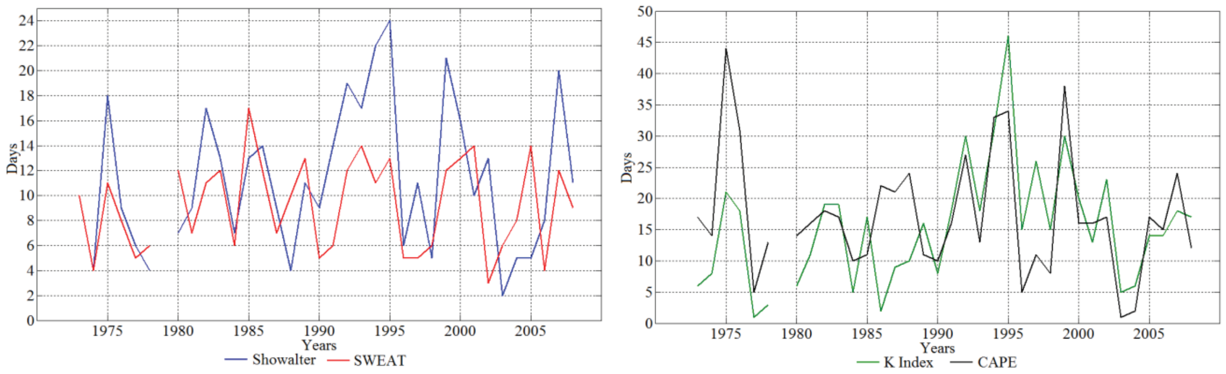

Fig. 9. Yearly threshold exceedences at Istanbul.

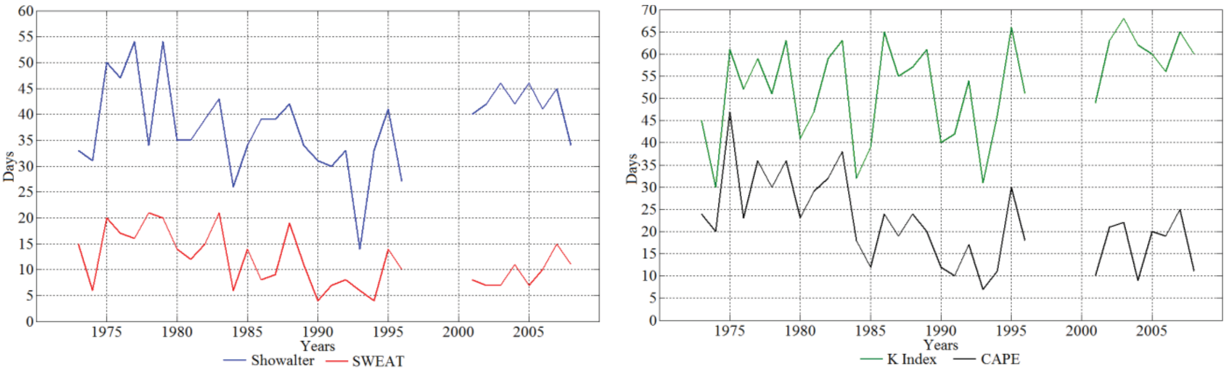

Fig. 10. Yearly threshold exceedences at Brindisi.

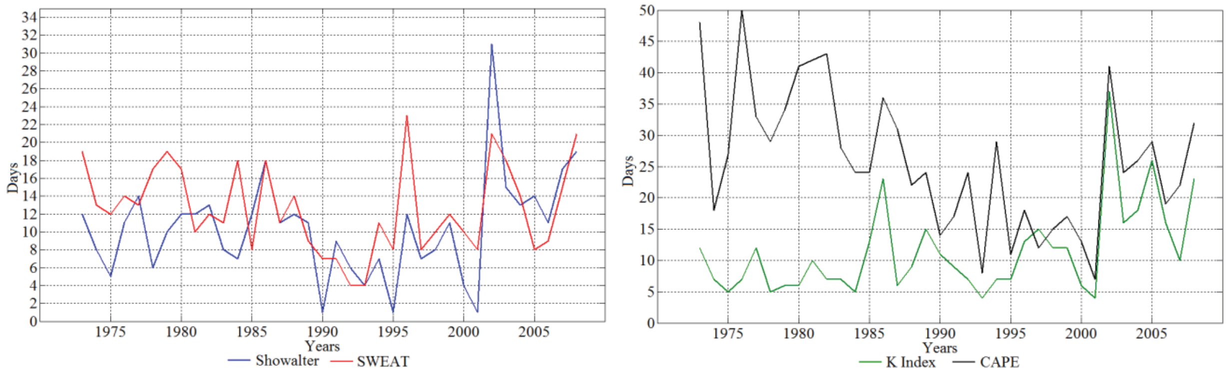

Fig. 11. Yearly threshold exceedences at Sofia.

The yearly evolution of the exceedences of all indices at Athens, Istanbul, Brindisi and Sofia are presented in figures 8, 9, 10 and 11 respectively.

In Athens, for all indices and during 1986 and 1987 an increase in threshold exceedences is observed. Regarding the Showalter and the K indices, an increasing trend is observed after 1995. SWEAT index threshold exceedences for the whole period don't have any meaningful trend and CAPE threshold exceedences after a gradual increase until 1995 (with the exemption of 1986-1987 period), exhibit a slow increase during the last decade.

The evolution of threshold exceedences for Istanbul station doesn't indicate any noticeable trend for any of the studied indices. Regarding Brindisi station and for all indices an increase in the number of threshold exceedences is observed after 2000. After a sharp increase during 2002, the threshold exceedences remain relatively high compared to the rest of the studied period. While the exceedences of Showalter, SWEAT and K-Index until 2001 remain relatively stable, the CAPE threshold exceedences have a decreasing trend until 2001.

Sofia station's threshold exceedences are examined in two time frames, due to the incompleteness of the dataset for 1997-2000. Before 1997 a decreasing trend is observed for the exceedences of Showalter and CAPE thresholds, while a relatively stable evolution is observed for SWEAT and K-Index. For the 2001 – 2008 time frame the threshold exceedences of Showalter and K-Index have higher values compared to late 90's and a relatively stable distribution.

6. Conclusions

In this study atmospheric instability indices are calculated and treated as climatological variables in order to identify any climatological temporal changes from 1973 to 2008 at four stations in Southeastern Europe. An increasing instability trend is identified after mid 1990s for the yearly averages of Showalter and SWEAT indices at Athens, Brindisi and Sofia. This trend is also evident for the annual summer averages of Showalter index at Athens and Brindisi. The yearly averages of CAPE index for all stations exhibit a decreasing trend until the early 1990s and a stable evolution for the rest of the studied period. K-Index yearly and annual summer averages follow a similar evolution at Athens and Brindisi with a decreasing trend until 1985, a sharp increase until 1987 and a stable development thereafter. Regarding the frequency of index extremes and after applying a uniform strict group of thresholds, which results to increased atmospheric instability, a temporal assessment of threshold exceedences is carried out. Threshold exceedences are observed mainly during the warm period and an increased frequency of autumn exceedences compared to spring is observed for the coastal stations. Athens station exceedences are much smaller compared to other stations and an increasing instability trend after 1993 is evident for Showalter and SWEAT threshold exceedences. Istanbul exceedences do not impose any significant trend, while in Brindisi an increased number of exceedences is observed after 2000 for all indices. Sofia station shows an increase compared to 90's values in the number of exceedences for Showalter and CAPE for the time frame 2001 - 2008. Further research is proposed in identifying different threshold levels for every station and identifying changes in the instability patterns and their intensity in relation to climate change.

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