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An objective evaluation of two instability indices associated with forecasting convective storms over the North and Central Greece

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Using different methodologies, but the same set of data, two stability indices were derived, with the aim to forecast convective intensities, showers, thundershowers, and hailstorms, over the north and central area of Greece. The indices were derived as analytical expressions of four suitably selected predictor variables, based upon theoretical and statistical arguments.

The objective of this study is to use a statistically acceptable independent set of data in order to objectively evaluate the creditability of both indices. This will be done by examining the behaviour of both indices, and also by performing comparisons between the indices themselves, and the indices against the predictand variable measured in situ by S-band weather radar.

Objektivna evaluacija dva indeksa nestabilnosti povezana s prognoziranjem konvektivnih oluja nad sjevernom i centralnom Grčkom

Koristeći različite metodologije, ali isti niz podataka izvedena su dva indeksa stabilnosti sa ciljem prognoze intenziteta konvektivnih razvoja, pljuskova, olujnih pljuskova i olujne tuče iznad sjevernog i centralnog dijela Grčke. Indeksi su izvedeni kao analitički izrazi za četiri pogodno odabrane varijable prediktora, bazirane na teoretskim i statističkim argumentima.

Predmet ove studije je upotreba statistički prihvatljivog neovisnog niza podataka radi objektivne ocjene pouzdanosti oba indeksa. To će biti učinjeno ispitivanjem ponašanja oba indeksa, zatim usporedbom indeksa međusobno kao i u odnosu na prognoziranu varijablu, koja je mjerena »in situ« jednim vremenskim radarom.

1. Introduction

The knowledge of mesoscale storms is of great importance, since their manifestations are heavy rain, damaging wind and hail, which are so often observed and experienced. Since each storm is unique in many aspects, it is not surprising that researchers, modelers and forecasters have much difficulty in their tasks of studying, understanding and forecasting these mesoscale phenomena. Therefore, the prediction of the occurrence and particularly of the intensities of these storms has been a problem of substantial significance for weather modification scientists, that has defied easy solution.

Forecasting procedures are usually somewhat subjective, and therefore strongly influenced by a person's knowledge and experience. On the other hand, objective techniques mostly based upon the use of the manifestations of the synoptic, dynamic and thermodynamic interactions, which evolve into intense convection in the atmosphere, offer several advantages. They do not require extensive personal experience, they provide the means to synthesize a great amount of data rapidly and effectively, and finally, they can be used in an automated manner.

The objective underlying this study is to use the vertical temperature and moisture structure of the atmosphere, as obtained from the rawinsonde observations, together with manually digitized weather radar data, and form an independent and statistically acceptable set of data, in order to objectively evaluate the creditability of two instability indices. These indices were developed from the same set of data, but under completely different methodologies.

2. Background information

2.1. The Greek National Hail Suppression Program

All the data used in this study were collected during the hail seasons of the Greek National Hail Suppression Program (NHSP). Hence, a brief description of the program is necessary.

The Greek NHSP is the first weather modification program in the modern times of the Greek history. It began in 1984 and was designed as an operational and at the same time as a research, cloud seeding program. The main objectives were to reduce hail damage over three distinct agricultural areas in the northern and central Greece, and simultaneously, to examine and study the thermodynamic, dynamic and microphysical characteristics of the potential hail producing clouds. This randomized cross-over design, being a »piggy-back« venture on the overall operational project, was highly desirable, because it provided the means for monitoring the optimal treatment for the given situation and conditions, and an opportunity to improve the meteorological understandings of the hail process present in this area of Greece (Flueck, 1976). The NHSP was carried out for five consecutive hail seasons, that is, from 1984 up to 1988. The exploratory stage covered the first three years, the confirmatory stage the last two. The relevant background and the overall design were first touched upon in Karacostas (1984). An analysis of the first two years of the exploratory randomized cross-over experiment was presented by Flueck et al. (1986), while an overall picture of the NHSP was fully illustrated by Karacostas (1989, 1990b). Detailed descriptions concerning the operation, data collection and analysis, preliminary evaluation, training procedures of Greek personnel etc, are provided within the interim Reports issued by Atmospheric Incorporated and Intera Technologies.

2.2. Review of previous studies

A statistical objective approach to forecast mesoscale convective storm can be used partly to alleviate the disparity between a lack of understanding and the need for prediction. The objective forecasting of mesoscale convective phenomena has been used for a long time. Endlich and Mancuso (1968) correlated severe thunderstorms and tornadoes with a number of kinematic and thermodynamic parameters. Miller and David (1971) used observational data to forecast thunderstorms through a statistical method. Reap and Foster (1979) developed probability equations for forecasting thunderstorms, severe local storms and tornadoes outbreaks. Andersson et al. (1989) forecasted thunderstorms in southern Sweden by using three thermodynamic indices, and some combinations of them. A synoptic index of convection has been developed by Strong (1979), to predict maximum hail sizes over southern Alberta. A modified version of it has been used over the northern Greece (Rudolf et al. 1987) to forecast potential hailstorms for the Greek National Hail suppression Program (NHSP). Using rawinsonde observations obtained during the 1985 hail season, and applying two different methodologies (Flocas and Karacostas, 1988; Karacostas, 1990a), two thermodynamic instability indices have been developed. Moreover, for the same area of Greece, and using data collected during the NHSP, Dalezios and Papamanolis (1991) calculated several instability indices for operational hail forecasting. The use of thermodynamic indices as a forecasting tool has also been used for the area of Cyprus (Michalopoulou and Jacovides, 1987).

It is obvious that many thermodynamic or instability indices have been used for operational hail forecasting. The main concern of this study is to investigate further the two instability indices developed by Flocas and Karacostas (1988) and Karacostas (1990a); namely the *FK* and the *TK-4*, respectively.

The development of both indices was based upon the analyses and the examinations of the behaviour of 13 thermodynamic and dynamic parameters as potential predictor variables. These were retrieved mainly from rawinsonde measurement of the subsynoptic station of Thessaloniki, during the 1985 hail season of the NHSP. Some of potential predictors are primary measurements, which describe the synoptic and subsynoptic characteristics of the upper atmosphere, and the rest are derived parameters, which describe the instability conditions and other thermodynamic characteristics. From these, four predictor variables were chosen for the development of the two indices. The predictand variable consisted of manually digitized daily values of maximum reflectivity, which were measured by a S-band weather radar being situated at the same location as the rawinsonde station. The 13 potential predictor variables were linearly correlated to the predictand, and the four highest-correlating predictors were chosen for the development of the indices. Detailed descriptions are provided by Flocas and Karacostas (1988) for the *FK* index, and by Karacostas (1990a) for the *TK-4* index.

Although both indices are described through analytical expressions, their development was based upon two different methodologies. The *FK* index, being expressed mathematically by equation:

$$FK = -43.29 - 0.08\,(Dh) + 0.0016\,(EL) - 1.56\,(LI) + 0.57\,(KI), \tag{1}$$

was derived by applying the multiple regression analysis technique to the predictors and the predictand. On the other hand, the *TK-4* index was derived through a linear transformation of the four suitably chosen predictor variables, each weighted according to its linear statistical correlation with the predictand. The *TK-4* index in mathematically expressed by equation:

$$TK\text{-}4 = -3.76 - 0.06(Dh) + 0.0008(EL) - 1.08(LI) + 0.25(KI), \tag{2}$$

where Dh represents the geopotential height falls within 12 hours at the level of 500 hPA. EL signifies the equilibrium level, which is the height where the temperature of a bouyantly rising parcel becomes equal to the temperature of the environment. The lifted index is denoted by LI and it was evaluated by determining the mean mixing ratio in the lower 100 hPa of the sounding, and taking the algebraic difference between the environment temperature and the updraft temperature. Finally, KI indicates the K stability index and it is most useful in determining areas with potential for the development of airmass showers or thunderstorms (George, 1960).

3. Material used and procedure

The evaluation of the two indices, *FK* and *TK-4* is based on a data set which is synthesized from manually digitized radar observations and rawinsonde information. The data were obtained almost simultaneously at the same station, during the 1987–88 hail seasons of the NHSP. They represent the atmospheric characteristics over a subsynoptic scale region of approximately 300 km diameter. The data selected for analyses cover 90 case studies which mostly are not consecutive and thus provide an independent set of data. The predictand sample consists of daily values of maximum reflectivity, made in situ by a S-band weather radar. The maximum reflectivity was chosen as the predictand value,

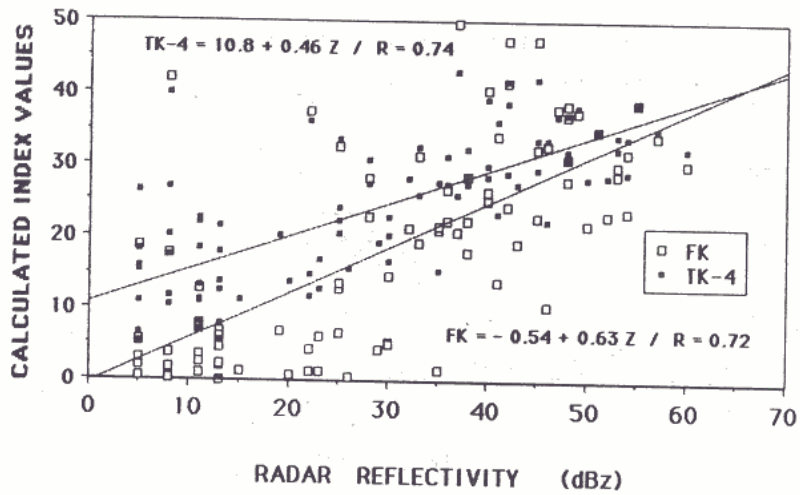

Figure 1. Scatter diagram of the calculated values of both indices as a function of the measured weather radar reflectivity for the 90 case studies. The linear regression lines are also drawn, together with the mathematical expressions of those and the linear correlation coefficients.

since it could initially describe the existence of a convective activity, and at the same time its intensity.

Using this set of data, the values of the two indices have been calculated and are indicated in the scatter diagram on Figure 1 as a function of the measured weather radar reflectivity for the 90 case studies. The linear regression lines are also drawn in the figure, together with their mathematical expressions and the linear correlation coefficients. The *FK*-index line shows an underestimation in the area of low reflectivities, while the *TK-4* index line displays an overestimation in the same area. This is concluded from the examination of the y-intercepts of both regression lines. Besides, the *TK-4* index line has smaller slope, resulting thus in better estimation in the mid-area of radar reflectivities, and in an underestimation in the area of high reflectivities. These characteristics seem to negatively affect the correlation coefficient values [$R(FK)$ = 0.72 and $R(TK\text{-}4)$ = 0.74].

Figure 2 demonstrates the close relation existing between the two indices: *FK* and *TK-4*. The solid line represents their quadratic regression line. The mathematical expression is also presented in the figure, together with the linear regression equation. It is worth to mention that the correlation coefficients between these two indices are very high, whether the indices are correlated linearly of quadratically (95% and 98%). Such a close relationship was expected, since the analytical expressions were obtained from the same set of data, using different, but consistently applied and correctly executed methodologies.

The calculated values of the two indices, together with the actual measurements of the weather radar maximum reflectivities, were distributed into four

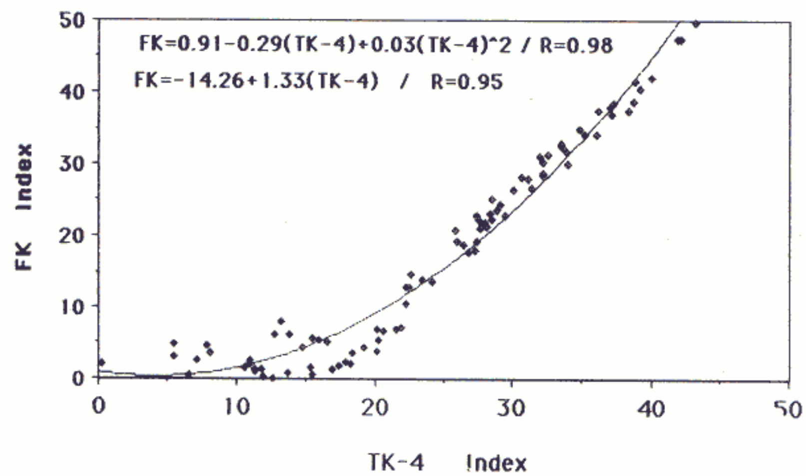

Figure 2. The scatter diagram between the *FK* and the *TK-4* indices. The solid line represents the quadratic regression line. The mathematical expressions of the linear and quadratic regression lines are also depicted, together with the corresponding correlation coefficients.

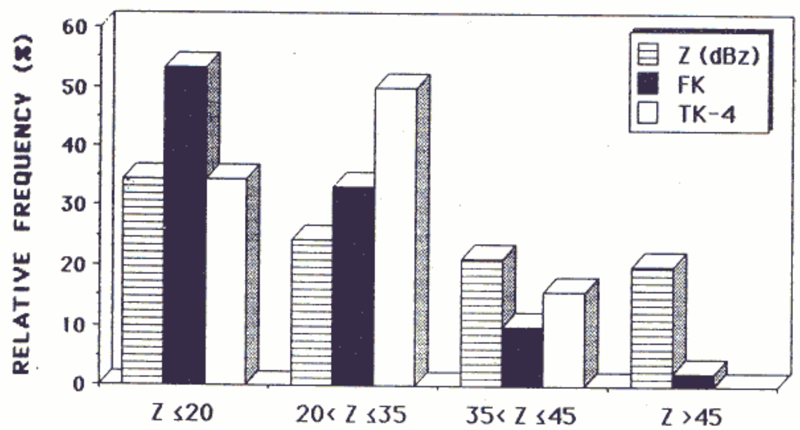

Figure 3. Percent relative frequency distribution functions of the actual weather radar measurements, and the calculated-forecasted values of the indices *FK* and *TK-4*.

distinct classes. The percent relative frequency distribution of these, as a function of the four classes, is illustrated in Figure 3. The classes were chosen in such a way as to provide a distinction among the cases: (i) with absolutely no convection at all (ii) with some light convection and isolated light rain showers, (iii) with scattered rain showers, isolated thunderstorms and potential hail development, and (iv) with heavy rain showers, numerous thunderstorms, and very high potential for hail formation. From Figure 3 it becomes apparent that the actual radar measurements are almost uniformly distributed within the four classes. On the other hand, the calculated forecasted values of the *FK* and *TK-4* indices seem to follow an exponential decay function and the skewed normal distribution, respectively. This heterogeneity results in discrepancies of the order of 15 to 20 %, particularly in the low and high reflectivity values.

A direct verification of the forecasting potentiality of both indices is provided through the contingency tables. Table 1 provides the information needed for the verification of both indices. The values in the parentheses correspond to the cases forecasted by the *TK-4* index. Table 1 shows that the forecasts of the *FK* and *TK-4* indices were correct only to the level of 43 % and 49 % respectively, within the same class. However, within one class, the forecasting scores become as high as 81 % and 86 %, respectively. Although the percentages are relatively small, particularly for the cases within a class, they seem to be a bit higher than those encountered for the Convective Day Category (CDC) index, which was used during the Greek NHSP (Rudolf et al., 1987). It is worth mentioning that the *FK* and *TK-4* indices are simpler and easier to be applied than the CDC.

Table 1. Contingency table for forecasting through the indices FK and TK-4.

z/*FK* (*TK-4*)	$z \leq 20$	$20 < z \leq 35$	$35 < z \leq 45$	$z < 45$	
$z \leq 20$	30(25)	0 (5)	1 (1)	0 (0)	31
$20 < z \leq 35$	14 (8)	7 (13)	1 (1)	0 (0)	22
$35 < z \leq 45$	3 (0)	11 (13)	2 (6)	3 (0)	19
$z > 45$	1 (0)	12 (12)	5 (6)	0 (0)	18
	48 (33)	30 (43)	9 (14)	3 (0)	90

Table 2. Verification of the forecast of the FK and TK-4 indices.

z / Index	$z < 35$	$z \geq 35$	
$z < 35$	51	2	53
$z \geq 35$	25	12	37
	76	14	90

Since the 35 dBz radar reflectivity value is a critical one for the operations of the Greek NHSP, it is important to investigate the performance of the *FK* and *TK-4* indices with respect to this value. For this purpose, the two-by-two contingency Table 2 was constructed. It is also used for the calculation of the tetrachoric correlation coefficient, as described by Panofsky and Brier (1968). Although the numerical value of the tetrachoric correlation coefficient is not completely comparable with that of an ordinary correlation coefficient, the resulting 77 % for both indices against the actual weather radar measurements provides the ground for *FK* and *TK-4* to be considered as acceptable aids for operational hail suppression programs. Moreover, the cases within a class, as they are distributed in Table 2, suggest a level of successful forecast of the order of 70 %.

4. Summary and concluding remarks

The indices *FK* and *TK-4* were developed to provide the means to forecast convective intensities, showers, thundershowers, and hailstorms over the north and central area of Greece. They were obtained from four reasonable and suitably selected predictor variables, with the aim to blend: synoptic scale information with sub-synoptic and mesoscale instability parameters, moisture, and trigger mechanisms.

A statistically acceptable set of data, being synthesized from 90 case studies of manually digitized weather radar observations and rawinsonde information obtained almost simultaneously at the same station during the 1987–88 operation seasons of the NHSP, was used for the evaluation of these two indices.

Examining the behaviour of both indices, it appeared that they provide a rather high correlation coefficient, indicating thus the acceptability of the applied methodologies. In addition, equation (2) appeared to be more stable than equation (1). Maybe that could justify the larger discrepancies observed for the *FK* index. The verification percentages encountered for *FK* and *TK-4* were relatively low for the cases within a class. Considering the cases within one class, verification percentages were acceptable. However, this should not encourage forecasters to use instability indices as the main forecasting tool, but rather as an aid. The main forecast would thus be reinforced in the advantages of the objective forecasting technique, providing the means to synthesize a great amount of data rapidly, effectively, and in an automated manner.

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