An Evaluation of Stability Indices for Thunderstorm Prediction in Greater Cyprus

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(Manuscript received 10 September 1989, in final form 27 May 1990)

ABSTRACT

The effectiveness of a number of forecasting indices for non-frontal thunderstorm activity has been investigated for the Greater Cyprus area. The indices include the humidity index (HI), the Pickup index (PI), the K-stability index, the Yonetani index in its original II and modified II_c form, and the Showalter stability index (SSI) for the Mediterranean area. Combinations of some of these indices with information of the flow curvature are also considered.

Two data sets, representative of coastal and inland locations are used to evaluate the accuracy of these indices. Verification statistics indicate that Yonetani's indices II and II_c are more successful than the HI, PI, and K indices in the forecast of air mass thunderstorms. The addition of the flow curvature at 500 hPa improves the effectiveness of most indices and its inclusion should be seriously considered for the Eastern Mediterranean area.

1. Introduction

In the Mediterranean area, severe weather conditions associated with non-frontal (air mass) thunderstorms, adversely affect agricultural activities, civil aviation, marine activities, and water resources. Despite their generally small spatial and temporal scales, these thunderstorms can cause dramatic economic losses in agricultural production. For example, heavy thundershowers which affected Cyprus on the afternoon of 15 February 1988 caused severe damage to property and crops, estimated at about six million dollars (Cyprus Economic Review 1989). In that event, the analysis of rain recorder chart at Larnaca airport indicated that 37 mm of rain fell in 15 min (Cyprus Meteorological Service 1989). Accurate forecasts of thunderstorm activity will conceivably reduce this loss in the Greater Cyprus area. To this end, in this paper, the accuracy of several stability indices for the spring-time growing season of Cyprus is examined.

Convective weather phenomena, and especially intense thunderstorms, occupy a very important part of a Weather Service forecast and warning responsibilities. Many forecasting techniques that utilize tropospheric static stability have been proposed in the literature (See Peppler and Lamb 1989 for a summary) and incorporated into operational weather forecasting practice during the last four decades. Most of these techniques combine thermal and moisture information for the lower and middle troposphere, and are intended to indicate the likelihood of moist convection. Within these indices, there has been a strong emphasis on the relationship between static stability and (a) the "yes/no" occurrence of precipitation as in the development of the MOSPoP statistical forecasting models (Glahn and Lowry 1972; Glahn and Bocchieri 1976; Lowry and Glahn 1976; Peppler and Lamb 1989), and (b) the incidence of thunderstorms and severe weather (Showalter 1953; Means 1952; Galway 1956; Miller 1959; Darkow 1968; Yonetani 1975; Reap and Foster 1979; Stone 1985a, 1985b). The importance of computing stability indices in the course of analyzing sounding data for thunderstorm potential is well known. Miller (1975) and Doswell (1982) present comprehensive methodologies for operational weather data analysis that emphasize their role in the deep convection forecasting process.

Most of the previous research relating stability and various aspects of convection only considered a few stability indices. However, a broad range of stability indices and thermodynamic parameters are now available for use in forecasting non-frontal thunderstorms such as the K-index (Reap and Foster 1979), the Yonetani index (1979), the Pickup index (PI-Pickup 1982), the humidity index (HI) of Litynska et al. (1976), and the ones which combine stability indices with thermodynamic and/or kinematic parameters

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(Michalopoulos and Jacovides 1987; Andersson et al. 1989).

There have not been many studies which compare the effectiveness of the various stability indices. This is unfortunate, because in addition to forecasting, these indices assist in gaining useful insights into the physical characteristics of thunderstorms and their environment. Stone (1985a, 1985b) discussed the performance of stability indices and how they relate to thunderstorm activity of varying intensity. Charba (1979) notes a fundamental difference in the severe weather environment of the Gulf Coast relative to that found in the central plains of the United States and demonstrates how performance statistics of stability indices corroborate current understanding of the different processes involved. Schultz (1989) associates stability indices performance characteristics with various aspects of convection. Andersson et al. (1989) investigate the accuracy of several indices in forecasting thunderstorm activity in the area of Sweden, while Michalopoulos and Jacovides (1987) have tested several indices in forecasting non-frontal thunderstorms in the Mediterranean area. In this study, this test has been extended to include an improved Yonetani index and applied to data from the Cyprus area.

2. Data and techniques used

The annual frequency of non-frontal (air mass) thunderstorms in the Greater Cyprus area is at a maximum in spring and during October (Jacovides and Michalopoulos 1981). This investigation utilizes focuses on the three-month spring period of March, April, and May, with data from two periods, 1970–1974 (340 days) and 1984–1988 (380 days). Data concerning this study were obtained as follows:

a. Upper air data from Acrotiri (see Fig. 1) for the first period and Athalassa (near Nicosia) for the second period (1984–88). Acrotiri station was closed in 1978. Note that the Acrotiri station is on the coast and the characteristic relative humidity at low levels may be affected by the presence of the sea.

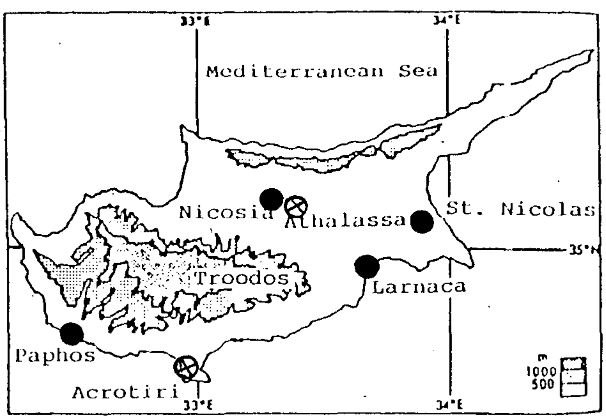

FIG. 1. Topographic map of Cyprus Island and location of surface stations used in the analysis ●. Also, (⊗) shows upper air stations of Acrotiri and Athalassa.

b. Surface data from the stations at Nicosia, St. Nicolas and Paphos. From these stations, we also obtained the time of the beginning and end for each thunderstorm. Surface and 850–500-hPa-analyses for 0000 UTC and 1200 UTC were obtained from the Greek Meteorological Service (EMY).

A classification of days with and without thunderstorms is based on surface observations. A thunderstorm day is assigned when a thunderstorm occurs at one of the three stations between midnight 0000 UTC and midnight 0000 UTC the next day. There were 50 thunderstorm days during the first period, and 85 thunderstorm days during the second period. Excluded from the study are several periods with missing data and one period associated with cold frontal passage over Greater Cyprus when several of the indices were not representative of thunderstorm potential, as shown by Boyden (1963) and Litynska et al. (1976), and thunderstorms could be classified as "frontal" rather than "air mass."

Table 1 summarizes the techniques treated in this study along with their suggested thresholds for thunderstorm occurrence in the Greater Cyprus environment. The Yonetani's technique development (Yonetani 1979) is summarized in the Appendix.

3. Results and discussion

There exist many different formulas for validating the success of "yes/no" forecasts. In this study, the so-called Yule's index (Meteorological Office 1975) was introduced to determine skill scores because it does not give undue weight either to prefigurance or postagreement. Thus, if we have a table of the following form as Table 2. Yule's index (YI) is defined by

$$\mathrm{YI} = (ad - bc)/[(a + b)(a + c)(c + d)(b + d)]^{1/2} \quad (1)$$

If "occurrence" is denoted by +1 and "non-occurrence" by 0, YI is the linear correlation coefficient between forecast and observed events. By adding 1 to YI, dividing the sum by 2 and multiplying by 100, a value emerges which measures what has been called the "Equivalent Percentage Success" (EPS), where

$$\mathrm{EPS} = 100\,[(\mathrm{YI} + 1)/2].$$

We can also define the following derivatives' scores: the probability of detection (POD) given by POD $= 100a/(a + b)$, the probability of false alarm [also known as the false alarm rate (FAR) given by FAR $= 100c/(c + a)$], and the critical success index (CSI) (also commonly known as the "threat score") given by CSI $= 100a/(a + b + c)$. For perfect forecasts b

TABLE 1. Summary of static stability indices and thermodynamic parameters used. Thresholds given in the "Comments" column are for the occurrence of the non-frontal thunderstorms for the Greater Cyprus environment.

Stability indices thermodynamic parameters	Code in text	Key references	Equation	Explanation	Comments
K	K	Reap & Foster (1979)	$K = (T_{850} - T_{500}) + T_{Dew850} - (T - T_{Dew})_{700}$	T and T_{Dew} are the dry-bulb and dew-point temperatures. Subscripts indicate the pressure level in hPa.	Combination of 850–500-hPa thermal lapse rate, 850 hPa moisture, and measure of thickness of moist layer; Suggested threshold of $K \geqslant +20$ (Peppler and Lamb 1989; Andersson et al. 1989).
Humidity index	HI	Lytinska et al. (1976)	$HI = (T - T_{Dew})_{850} + (T - T_{Dew})_{700} + (T - T_{Dew})_{500}$	Notation as given in K index.	Assesses the degree of saturation at the significant levels 850, 700, and 500 hPa. Suggested threshold for a "yes/no" decision is $HI \leqslant +30$ (Litynska et al. 1976; Michalopoulos and Jacovides 1987).
Potential Wet-Bulb	PI	Pickup (1982)	$PI = \theta_{w500} - \theta_{w850}$	θ_w is the wet-bulb potential temperature (°C or °K). Subscripts indicate the pressure level in hPa.	Assesses potential instability of 850–500-hPa cloud layer; suggested threshold of $PI \leqslant +3°K$ (Pickup 1982; Michalopoulos and Jacovides 1987).
Yonetani	II	Yonetani (1979)	$II = 0.966\Gamma_L + 2.41(\Gamma_U - \Gamma_W) + 9.66\gamma - 15.0.$ RH > 57 $II = 0.966\Gamma_L + 2.41(\Gamma_U - \Gamma_W) + 9.66\gamma - 16.5.$ RH ≤ 57	Γ_L and Γ_U are the lapse rates for 900–850-hPa and 850–500-hPa layers, respectively. RH is the mean relative humidity of the 900–850-hPa layer and Γ_W is the moist adiabatic lapse rate at the 850-hPa temperature. γ = RH/100	Combines information about the lapse rates of the 900–850-hPa and 850–500-hPa layers, with a measure of the mean relative humidity of the 900–850-hPa layer.
Modified Yonetani	II_c	—	$II_c = 0.964\Gamma_L + 2.46(\Gamma_U - \Gamma_W) + 9.64\gamma - 13.0.$ RH > 50 $II_c = 0.964\Gamma_L + 2.46(\Gamma_U - \Gamma_W) + 9.64\gamma - 14.5.$ RH ≤ 50	Notation as given in II index.	Same as II index.
Showalter	SSI	Showalter (1953)	$SSI = T_{500} - T_{P500}$	T_{P500} is the 500-hPa temperature of a parcel lifted dry adiabatically from 850 hPa to its condensation level and moist adiabatically thereafter.	Assesses potential instability of hypothetical 850–500 hPa cloud layer; suggested threshold of $SSI \leqslant +3$ (Peppler and Lamb 1989).

TABLE 2. A 2 × 2 Contingency Table-Forecast and Observed States.

Forecast observed	Yes	No	Totals
Yes	a	b	$(a + b)$
No	c	d	$(c + d)$
Totals	$(a + c)$	$(b + d)$	$(a + b + c + d)$

$= c = 0$, POD = CSI = EPS = 100, FAR = 0, and YI = +1, i.e., all occurrences of the event are detected and no false alarms are given. For totally wrong forecasts $a = d = 0$, POD = CSI = EPS = 0, FAR = 100, and YI = −1.

The indices POD, FAR, and CSI only provide measures of efficiency of the method when the event occurs and/or is forecast, but do not involve correctly forecast non-occurrences. Yule's index and EPS involve the latter, and hence are better measures if non-occurrences are important. For a thorough discussion of verification parameters the reader is referred to Daan (1984).

Table 3 (as well as Table 5) summarizes the results obtained for each stability-humidity index. One can see from the table that the HI index, although it does not identify atmospheric instability, gives satisfactory results. Therefore, the importance of a deep layer of high relative humidity in the generation of air mass thunderstorms is confirmed. Michalopoulos and Jacovides (1987) augmented this index with the criterion of 500-hPa cyclonic curvature of the flow and improved Yule's index to 0.73 and the EPS scores to 87.0, respectively. This combination dramatically reduced the false alarm rate to 18% (only eight cases), but slightly decreased POD to 72%.

The forecast ability for the K-index, as measured by Yule's scores, is slightly worse than the humidity index. However, the results obtained by this technique agree with the results reported for the Jefferson index by Michalopoulos and Jacovides (1987). Both the K and Jefferson indices are sensitive to mid-level 700 hPa moisture. Therefore, these indices perform similarly as predictors of tropospheric stability (Peppler and Lamb 1989). For the Cyprus area, non-frontal thunderstorms are observed even if the difference $(T - T_{\mathrm{Dew}})_{700}$ is greater than 6°C, i.e., with dry air at the level of 700 hPa (Stefanou, personal communication). Indeed, a number of air mass thunderstorms are observed in the range $6°C < T - T_{\mathrm{Dew}} < 15°C$, for the 0000 UTC soundings. From the definition of K-index (see Table 1), it is obvious that large values in $(T - T_{\mathrm{Dew}})$ result in lower values of the K-index. This is supported by Fig. 2, where the 0000 UTC sounding for the thunderstorm day 14 March 1972 is plotted in combination

TABLE 3. Results obtained and related Yule's index (YI) and equivalent percentage success (EPS) for each index. 1970–1974.

HI ≤ +30

Forecast observed	Yes	No	Totals
Yes	38	12	50
No	43	247	290
Totals	81	259	340

YI = 0.51, EPS = 75.0

PI

Forecast observed	Yes	No	Totals
Yes	43	7	50
No	49	241	290
Totals	92	248	340

YI = 0.55, EPS = 78.0

II

Forecast observed	Yes	No	Totals
Yes	38	12	50
No	29	261	290
Totals	67	273	340

YI = 0.59, EPS = 79.0

$\mathrm{II_c}$

Forecast observed	Yes	No	Totals
Yes	40	10	50
No	26	264	290
Totals	66	274	340

YI = 0.64, EPS = 82.0

K ≥ +20

Forecast observed	Yes	No	Totals
Yes	35	15	50
No	39	251	290
Totals	74	266	340

YI = 0.49, EPS = 74.0

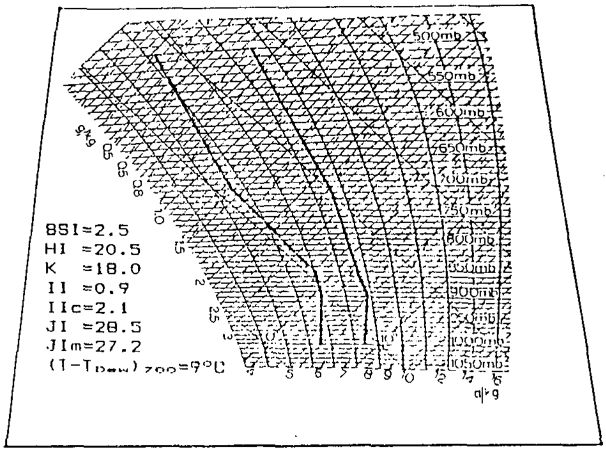

FIG. 2. Tephigram of 14 March 1972 sounding, showing temperature and dew-point (°C). Also, shown are the corresponding values of the various indices used, along with moisture of mid level, 700 hPa, as well as Jefferson indices JI and JI_m.

with the values of several stability indices including the Jefferson index (JI) and modified Jefferson Index (JI_m) (Jefferson 1963a, b; 1966).

If the difference $\theta_{w500} - \theta_{w850}$ is used as a lone thunderstorm predictor, it provides 96% probability of detection (48 out of 50 thunderstorm days). However, the linear correlation coefficient between forecast and observed events is very poor (YI = 0.27), while the EPS is only 64.0. This technique yields a very large false alarm rate, i.e., FAR = 78% with 173 incorrect yes forecasts. However, including 500-hPa curvature flow (Pickup's method), the results are improved drastically so that the verification scores are slightly better than the HI and K indices. Therefore, Pickup's assertion that a kinematic parameter adds valuable information to a thermodynamic index was confirmed.

Although, the Yonetani index II is designed for use on the Kanto Plain in Japan, it proved to be very successful for the observed thunderstorms. As in the case of the Showalter index, the Yonetani index is affected only by the moisture of the low-level parcel and not the moisture of the mid-tropospheric environment. This is probably the reason for the better correlation with occurrence, because a deep, moist layer in the atmosphere is more likely to result in many convective elements (Yonetani 1975).

In order to tailor the Yonetani index for the Greater Cyprus environment, the procedure of Yonetani (1979) is followed closely, as discussed in the Appendix. For this purpose, an independent data set obtained from the upper air station of Nicosia airport was used, which was restricted to three years 1967–1969 and included 45 thunderstorm days. By this modification of the index, significant improvements were observed with FAR dropping to 39%. However, even this value of FAR is still higher than the one determined by Michalopoulos and Jacovides (1987) with the same data set for a combination of the HI and 500-hPa flow curvature information which gave a FAR of 18%.

In Tables 4 and 5, the results obtained using the same techniques and the second data set are summarized together with Yule's index and EPS. The results acquired by these techniques were quite successful for the Greater Cyprus area. Specifically, the Yonetani indices II and II_c were significantly more accurate than the other techniques. These indices provide probability of detection 89% and 93%, respectively, which are equivalent or better than those obtained by PI, HI, and K indices. The Yonetani II and II_c indices also yield a low FAR, so that the probability of false alarm corresponds to 39% and 33%, respectively. In addition, the correlation coefficients between forecast and observed events (i.e., Yule's index) are improved over those of the first data set: 0.71 for the modified Yonetani index and 0.65 for the unmodified one, while the corresponding EPS are 86 and 82, respectively. It is possible that the improvement of these indices indicates that the upper air station of Athalassa is more representative of the Greater Cyprus environment than the Acrotiri observations. This is supported by the improvement of K-index verification scores within the second data set.

The Showalter stability index (SSI) was not found to be a successful predictor for air mass thunderstorms in Greater Cyprus by Michalopoulos and Jacovides (1987). However, since both the Yonetani Index and the SSI evaluate the atmospheric stability, an intercomparison of their success on the second data set from the upper air station of Athalassa seems relevant. Thus in Table 4, results obtained by SSI index are included. It is important to note that the verification statistics for the SSI index were substantially improved over those reported by Michalopoulos and Jacovides (1987). The results evaluated by this index are similar to those obtained by HI, PI, and K indices.

The statistics of the techniques used for both data sets are summarized in Table 5. By most measures of success, the Yonetani indices II and II_c perform best, although PI index has the highest probability of detection (86 and 93 for the first and second data sets, respectively). Unlike the K-index, which was not particularly successful, the Yonetani indices II, II_c, and Showalter indices are affected only by the moisture of the parcel (rooted as low-levels) and not the mid-tropospheric environmental moisture. This appears to be the primary reason for the relative success of these indices.

Correlation coefficients, like YI, do not provide a complete evaluation of the performance of the various stability parameters. To investigate further, histograms of thunderstorm percentage frequency of occurrence vs. index values are shown in Fig. 3 for each of the six stability parameters based on 0000 UTC data. Stability values that are exactly on an interval ending point are

TABLE 4. Results obtained and related Yule's index (YI) and equivalent percentage success (EPS) for each index, 1984–1988.

HI ≤ +30

Forecast observed	Yes	No	Totals
Yes	72	13	85
No	69	226	295
Totals	141	239	380

YI = 0.53, EPS = 77.0

PI

Forecast observed	Yes	No	Totals
Yes	79	6	85
No	83	212	295
Totals	162	218	380

YI = 0.55, EPS = 77.0

II

Forecast observed	Yes	No	Totals
Yes	76	9	85
No	49	246	295
Totals	125	255	380

YI = 0.65, EPS = 82.0

II_c

Forecast observed	Yes	No	Totals
Yes	79	6	85
No	40	255	295
Totals	119	261	380

YI = 0.71, EPS = 86.0

SSI ≤ +3

Forecast observed	Yes	No	Totals
Yes	69	16	85
No	63	232	295
Totals	132	248	380

YI = 0.52, EPS = 76.0

K ≥ +20

Forecast observed	Yes	No	Totals
Yes	72	13	85
No	54	241	295
Totals	126	254	380

YI = 0.59, EPS = 79.0

counted in the interval to the right, except for the critical thresholds. The sample of histograms includes both data sets, except for the case of the SSI.

Comparing the performance of various indices, one notes that the superior performance of the Yonetani and modified Yonetani index is explained by the large difference of frequency of occurrence at the threshold value, an indication of the discriminating power of the

TABLE 5. Comparative verification scores for the indices used.

Index	Threshold	POD	FAR	CSI	YI	EPS
	1970–1974 Data set					
HI	+30	76	53	41	0.51	75.0
K	+20	70	53	39	0.49	74.0
PI	+3	86	53	43	0.55	78.0
II	—	76	43	48	0.59	79.0
II_c	—	80	39	53	0.64	82.0
SSI	+3	—	—	—	—	—
II + Cyclonically curved flow at 500 hPa		68	32	52	0.63	81.0
II_c + Cyclonically curved flow at 500 hPa		74	24	59	0.70	85.0
	1984–1988 Data set					
HI	+30	85	49	47	0.53	77.0
K	+20	85	43	52	0.59	79.0
PI	+3	93	51	47	0.55	77.0
II	—	89	39	57	0.65	82.0
II_c	—	93	33	63	0.71	85.0
SSI	+3	81	48	47	0.52	76.0
II + Cyclonically curved flow at 500 hPa		76	23	63	0.70	85.0
II_c + Cyclonically curved flow at 500 hPa		80	18	68	0.76	88.0

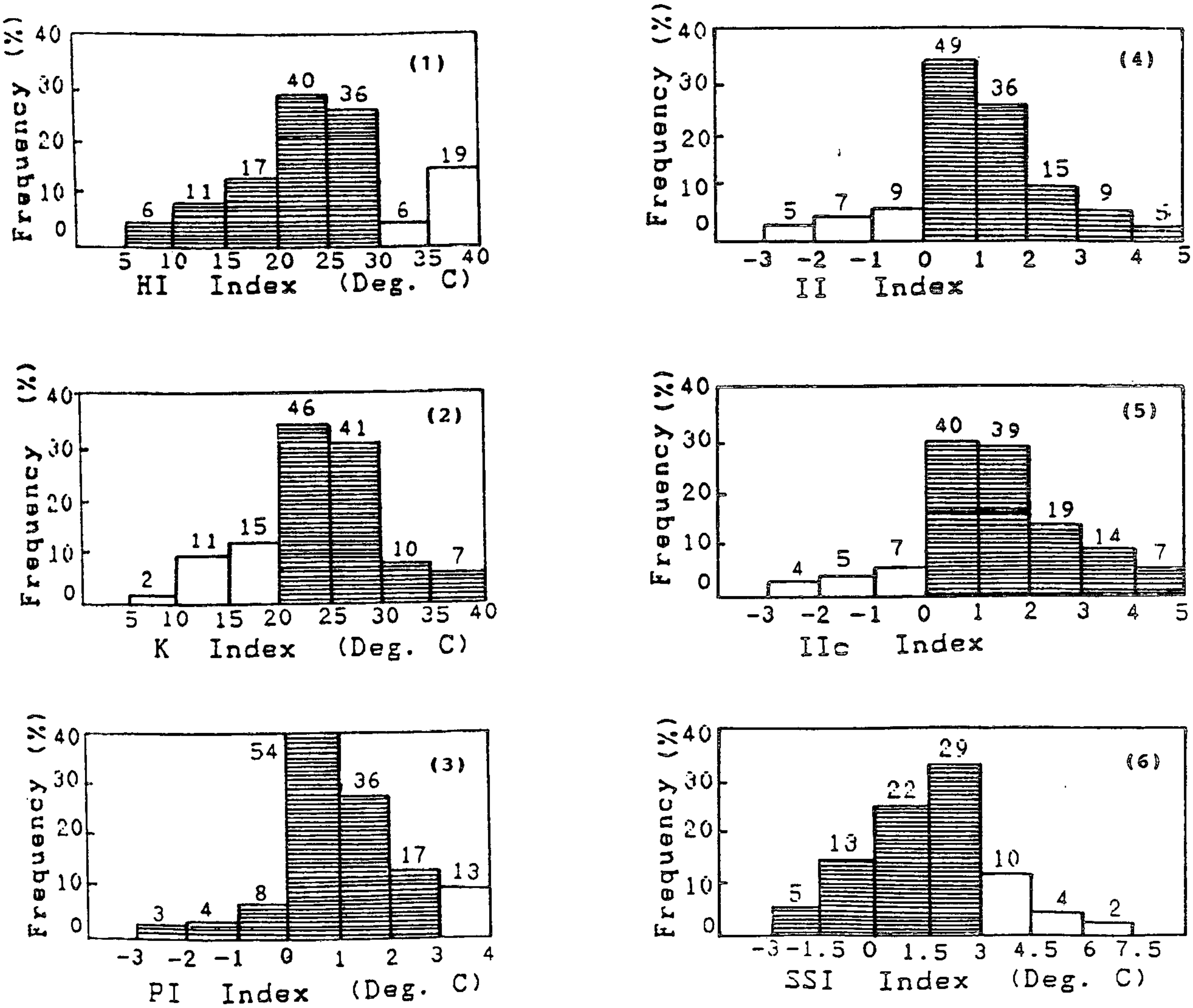

FIG. 3. Histograms of thunderstorm percentage frequency of thunderstorm days vs. stability indices values. Number above each bar is number of cases in the interval. Unshaded bars refer to thunderstorm days outside threshold values.

index. This is demonstrated even more starkly in Fig. 4, where the relative frequency of false alarm forecasts are plotted vs. index values.

In this study, only non-frontal thunderstorms are included. Some indices may be better in forecasting air mass thunderstorms, while others may better treat the environment for severe weather systems. Up to this point in the study, only "pure" thermodynamic indices have been considered. However, some researchers in forecasting verification prefer to combine various indices to improve skill scores. Michalopoulos and Jacovides (1987) combined the HI, with a requirement of cyclonically curved flow at 500 hPa to improve the verification statistics of the HI by a substantial margin. Some results of the effect of combining Yonetani's index with a requirement of cyclonically curved flow at 500 hPa are shown in Table 5. The combined index reduced the false alarm rates by about 50% and improved the correlation coefficients between forecast and observed events. However, this combination slightly decreased the probability of detection. As can be seen from summary of these statistics in Table 5, improvements are obtained by this combination in the YI values as well.

This led to a more careful examination of the synoptic conditions under which air mass thunderstorms occur in the Greater Cyprus area. In most of the cases, non-frontal thunderstorms were accompanied either by a trough or by a closed-low at 500-hPa level. Figure 5 depicts a typical form of the synoptic systems at 500 hPa that usually exist over the Greater Cyprus area during air mass thunderstorm formation. Few thunderstorms are associated with a weak ridge at 500 hPa or with neutral conditions. This led to an investigation of the existence of cyclonically curved flow at 500 hPa as a lone thunderstorm predictor which provided quite

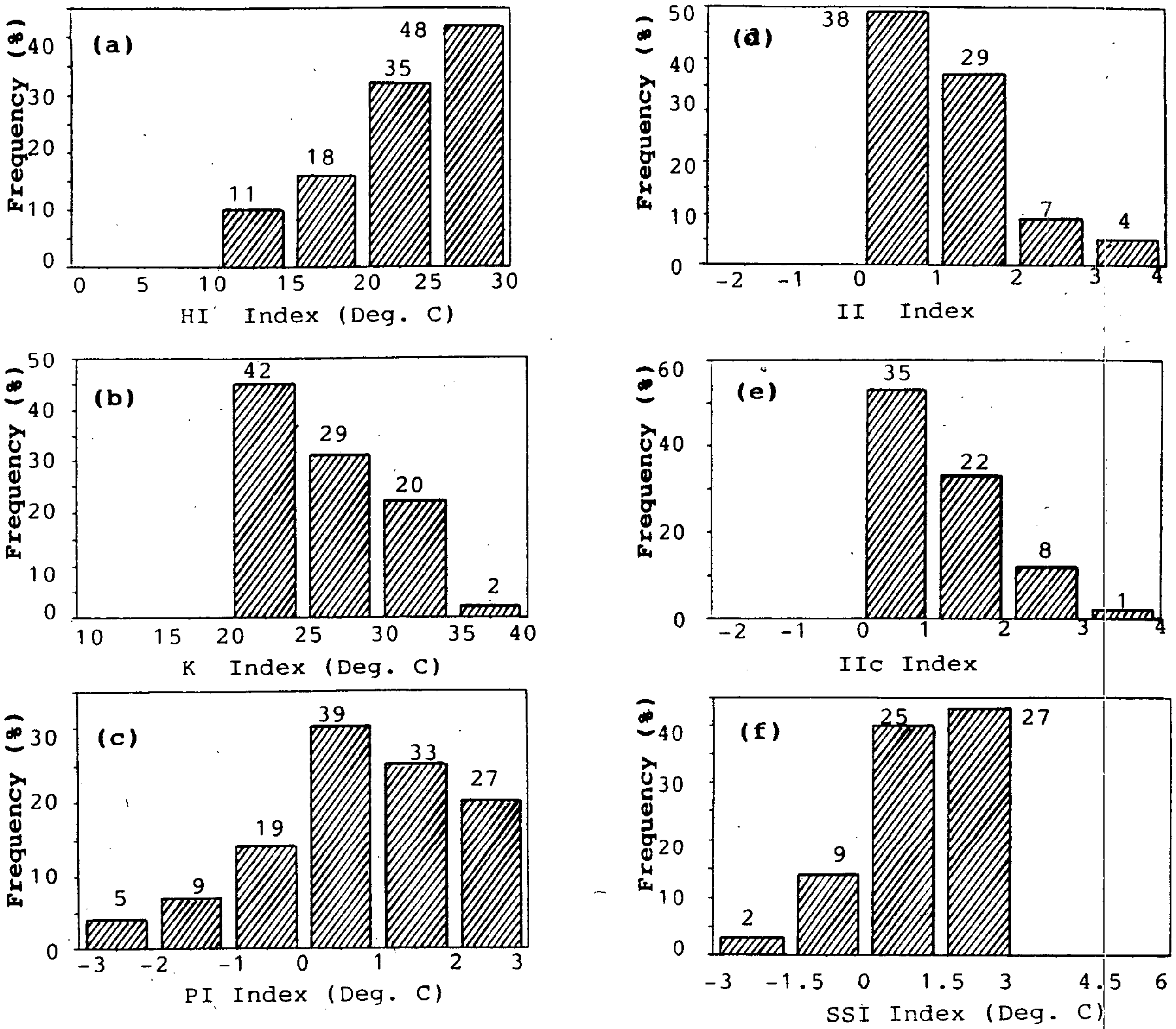

FIG. 4. Histograms of false alarm forecasts frequency vs. index values. Number above each bar is number of cases in the interval.

successful results. For these cases, the POD = 94% (47 out of 50 thunderstorm days), YI = 0.67, with EPS = 83.0, FAR = 44%, and CSI = 54%.

In addition, for most of the thunderstorm days, the lower layers were less stable than the upper ones. This observation is another characteristic of the non-frontal thunderstorm environment. The results obtained agree with Yonetani's (1975) study for the area of Kanto Plain in Japan. Potential instability is observed in 73% of the thunderstorm days for the layer 1000–700 hPa, and only 11% of the time for the layer 700–500 hPa. This agrees with the results reported by Jacovides and Michalopoulos (1981) for the same area.

Andersson et al. (1989) studied several thermodynamic indices for forecasting air mass thunderstorms in Sweden during the summer. Using the K-index, they found a correlation coefficient between forecast and observed events of about YI = 0.44, while POD = 93%, and FAR = 63%. Using a modified K-index in combination with a cyclonically curved flow at 500 hPa improved the statistics only slightly. Their FAR remained high with the modified K-index, which is unlike this case, where the kinematic parameter lowered the false alarm rate substantially. In general, prediction statistics were comparable. But the best results from this study, i.e., the Yonetani II and II_c indices, were better than those reported by Andersson et al. (1989).

Stone (1985b) has computed point biserial correlation coefficients between various thermodynamic indices and the occurrence or non-occurrence of radar echoes above different reflectivity thresholds. Among his indices were the K and SSI indices. The highest

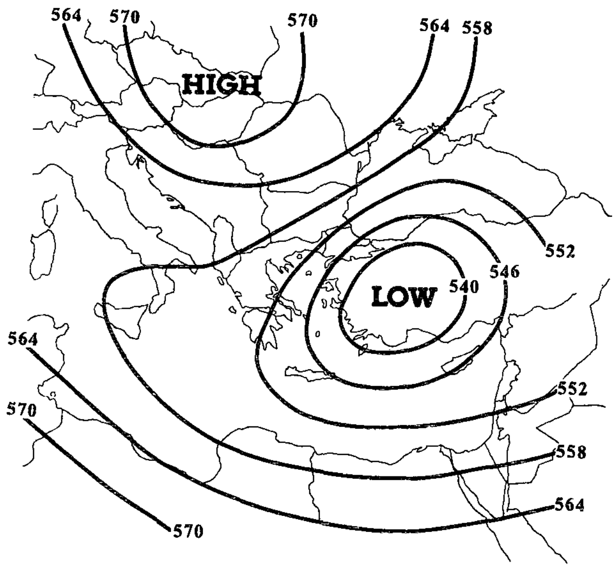

FIG. 5. 500 hPa analysis for 0000 UTC 14 March 1972. Values in geopotential meters.

correlations were found for the occurrence of reflectivity above 41 dBz, which corresponds to the lowest level associated with thunderstorms. The correlation, for the periods 1800–2400 and 0000–0600 UTC, was 0.53 and 0.53, respectively, and was reached with the K index. For the SSI, the correlation was found to be 0.58 and 0.52, respectively. Since Stone's correlations can be compared to our YI values, they are also seen to be comparable with our results, especially for the K and SSI indices.

4. Conclusions

The principal conclusions of this investigation are:

a. On days with air mass thunderstorms, the Yonetani stability index (II) and a modified version of the index (II_c) provide useful assistance to the forecasters. The success of the indices suggests that the interaction between a convective cloud and its subcloud layer is essential for the cloud development.

b. From the point of view of the general forecast, i.e., greater values of Yule's index and EPS, the original and modified Yonetani indices were more accurate than the PI, HI, and K indices, although the difference from Pickup's method was small.

c. A comparison of the skill scores for two independent data sets in Tables 3, 4, and 5, shows that better scores were found for the 1984–1988 dataset. The results suggest that the upper air station of Athalassa (used in the 1984–88 study) is more representative of the air mass thunderstorm environment than Acrotiri which is located near the coast. This assertion was supported by results from the SSI and K indices which dramatically improved from the ones from the 1970–74 period.

d. Both histograms in Figs. 3 and 4, should be useful to the forecaster, because they provide an idea of the probability of occurrence of non-frontal thunderstorms for various ranges of the different stability indices, and the discriminating power of each index, with Yonetani's index clearly being best.

e. The introduction of kinematic parameters, i.e., cyclonic curvature at 500 hPa, in forecasting seem to be justified. Their combination with HI and Yonetani's II, II_c, indices were most successful. However, when using such combined indices, one may choose less restrictive thresholds for each index. The combination of various stability indices and other methods for improving thunderstorm probability forecasts by using combinations of techniques are currently being tested by the authors for the entire Eastern Mediterranean. Information from numerical forecasts, such as the relative vorticity (a measure of the baroclinicity) and amount of accumulated sub-grid-scale precipitation, may be important in these efforts.

Acknowledgements. The authors are very grateful to the Head of the Forecasting Branch of the Meteorological Service of Cyprus, Dr. L. Stefanou for providing data for the upper air station at Athalassa and for the useful discussions and comments during the preparation of this manuscript. We also gratefully acknowledge Prof. D. P. Lalas of Wayne State University for his help in the course of the work. Also, the authors gratefully acknowledge the useful comments and suggestions received from several anonymous referees. Finally, we are grateful to the National Center for Disaster Prevention, Japan, for providing publication support.

APPENDIX

Scientific Motivation of the Yonetani Index and Procedure Developing the Index

Essential factors for the development of convective clouds include: (1) a sufficient supply of moist air in low layers and (2) large positive buoyancy within the cloud. As for item (1), moist air will be more easily supplied when temperature lapse rate is large and/or water content is larger in the lower layer. The potential buoyancy within the atmosphere can be estimated by the difference between temperature lapse rate and moist adiabatic lapse rate in the cloud layer. Therefore, three elements, temperature lapse rate in the lower layer, relative humidity at the lower levels, and the excess of the temperature lapse rate over the moist adiabatic lapse rate in the upper layer should be larger on days when thunderstorms occur than on non-thunderstorm days. We might also expect a critical relationship to exist between these elements on days when thunderstorms are observed.

Figure A1 shows that a "negative correlation" exists between the lapse rate of the 900–850-hPa layer, Γ_L, and the excess of the temperature lapse rate of the 850–500-hPa layer over the moist adiabatic lapse rate at the 850-hPa temperature, $(\Gamma_U - \Gamma_W)$, when the mean relative humidity at the 900-hPa- and 850-hPa levels, RH, was almost the same on air mass thunderstorm days in the northern Kanto Plain, Japan (Yonetani 1979). Because the height of cloud base is usually somewhere between 1000 and 1500 m, the 850-hPa level is chosen as the boundary of upper and lower layer here. The equations which best divide thunderstorm days from non thunderstorm days determined by visual inspection are written as:

$$\Gamma_L + 2.5\,(\Gamma_U - \Gamma_W) - 6.5 = 0$$

when RH is almost 90%,

and

$$\Gamma_L + 2.5\,(\Gamma_U - \Gamma_W) - 7.5 = 0$$

when RH is almost 80%. (A1)

Figure A2 shows the relation between Γ_L and RH when $(\Gamma_U - \Gamma_W)$ is almost 1.5 (upper) and 1.0 (lower). If the critical relation between Γ_L and RH exists, it should be consistent with Eq. (A1); in other words, it should contain points of $(\Gamma_L = 2.75, \text{RH} = 90)$ and $(\Gamma_L = 3.75, \text{RH} = 80)$ when $(\Gamma_U - \Gamma_W) = 1.5$ and $(\Gamma_L = 4.0, \text{RH} = 90)$ and $(\Gamma_L = 5.0, \text{RH} = 80)$ when $(\Gamma_U - \Gamma_W) = 1.0$, which are obtained from Eq. (A1). The straight lines in Fig. A2 are drawn so that they fulfill the above conditions, respectively. It is clear that these two lines give a critical relation.

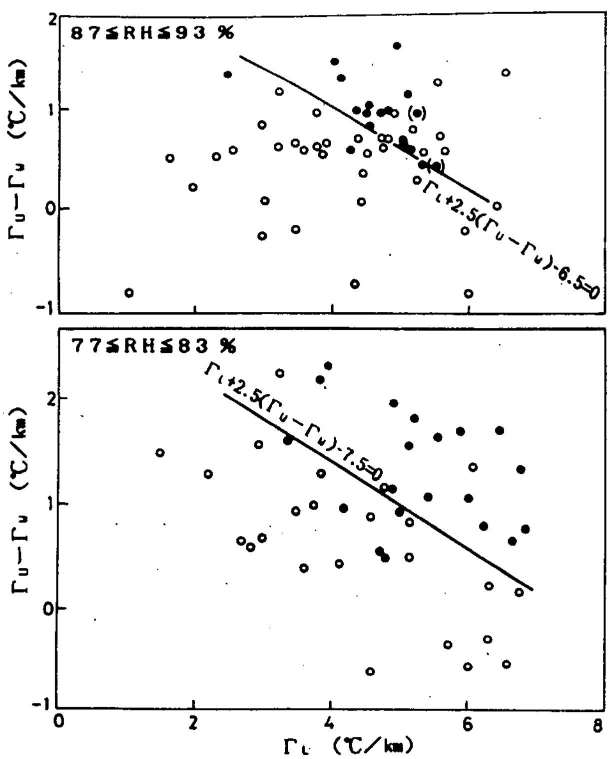

FIG. A1. Relation between Γ_L and $(\Gamma_U - \Gamma_W)$ on air mass thunderstorm days (black circles) and other days (white). Parenthetic circles are on frontal thunderstorm days. (From Yonetani 1979.)

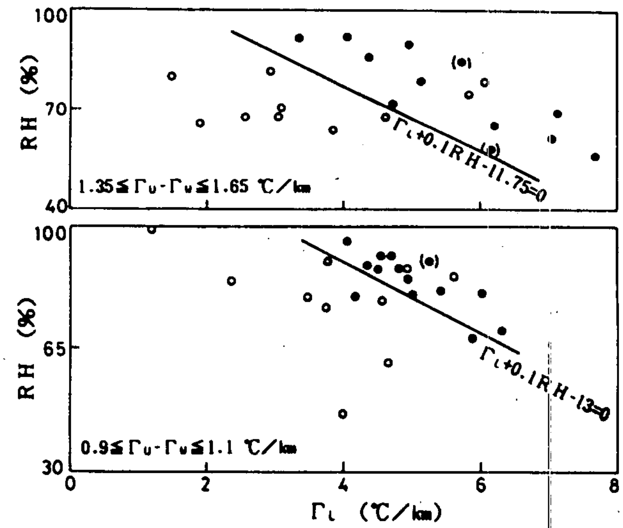

FIG. A2. As in Fig. A1, but for relation between Γ_L and RH. (From Yonetani 1979.)

Figures A1 and A2 show that there is a relationship between Γ_L, $(\Gamma_U - \Gamma_W)$, and RH on air mass thunderstorm days in the northern Kanto Plain, Japan and that it can be presented by a linear equation. Because Eq. (A1) shows that the decrease of 10 of RH causes the decrease of 1.0 of the constant, the relation is written as,

$$f(\Gamma_L, \Gamma_U - \Gamma_W, \text{RH}/100) = \Gamma_L + 2.5(\Gamma_U - \Gamma_W) + 10(\text{RH}/100) - 15.5 > 0. \quad \text{(A2)}$$

Geometry shows that the distance from a point (x_0, y_0, z_0) to a plane $Ax + By + Cz + D = 0$ is $[\text{Abs}(Ax_0 + By_0 + Cz_0 + D)]/[A^2 + B^2 + C^2]^{1/2}$. Referring to this, a stability index is defined as

$$\text{II}' = 0.966\Gamma_L + 2.41(\Gamma_U - \Gamma_W) + 9.66(\text{RH}/100) - 15.0. \quad \text{(A3)}$$

The absolute value of II′ corresponds to the length from a point $(\Gamma_L, \Gamma_U - \Gamma_W, \text{RH}/100)$ to the plane $f(\Gamma_L, \Gamma_U - \Gamma_W, \text{RH}/100) = 0$; and II′ is positive only when the three parameters satisfy Eq. (A2).

More precise analysis showed that $\text{II}' > 1.5$ when thunderstorms occurred and $\text{RH} \leqslant 57$. Because of this, the stability index is newly defined as

$$\text{II} = \begin{cases} \text{II}' & \text{for RH} > 57 \\ \text{II}' - 1.5 & \text{for RH} \leqslant 57. \end{cases} \quad \text{(A4)}$$

When $\text{II} > 0$ indicates non-frontal thunderstorms are likely, a negative value indicates a thunderstorm should not be expected.

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