Relationships of Several Stability Indices to Convective Weather Events in Northeast Colorado

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ABSTRACT

Seven familiar stability indices were computed from sounding data for each of 83 days of a convection forecasting experiment conducted during the summer of 1985 in northeast Colorado. Observations of convectively driven weather events were collected; the values of the indices were compared against this dataset to examine their performance as predictors of severe weather (large hail, tornadoes, high wind) and significant weather (nonsevere but important from an economic or public safety standpoint). The results of the analysis are

- Benchmark values of the indices that give their typical magnitudes on active days versus quiescent days. These values, compared with those computed in other regions, illustrate the potential fallacy of interpreting the indices in the absence of analogous region-specific reference statistics.
- Rankings that determine which indices worked best in this experiment. The highest ranked indices were the SWEAT index for severe weather and buoyancy for significant weather. Interestingly, SWEAT was the worst of those tested for significant weather.
- Quantitative convection forecasting guidance. The observed relative frequencies of severe and significant convection as functions of the seven indices are presented in graphical form. When used in a forecasting context, these observed relative frequencies can be interpreted as probabilities of severe and/or significant weather. Some of the graphs are clearly bimodal; no explanation for this behavior is offered.

Some of the benefits that would be realized by collecting more data, in this and other regions, are suggested. For example, there is a good possibility that some indices show particular skill for certain types of events (e.g., hail vs high wind, etc.), but the present dataset is too small to clearly establish any such connections.

1. Introduction

Over much of North America, weather forecasting during the summertime is largely a matter of assessing the potential for thunderstorm activity. As an element of routine mesometeorological data analysis, forecasters analyze rawinsonde data to find signatures of thermodynamic characteristics favorable for supporting deep convection.

A number of machine-computable indices have been developed to assist with this task. Their purpose is to provide guidance for forecasting convective weather, but their value as guidance is unclear in the absence of quantitative information about their past performance.

This paper suggests some procedures to provide quantitative information to aid in the interpretation of a given day's set of indices. These procedures are applied to a dataset gathered during a convection forecasting experiment conducted in the vicinity of Denver, Colorado. Thus, the results are specific to northeast Colorado, but the analysis procedures are applicable anywhere.

For the experiment, storm chasers observed and recorded convection-related surface weather events. These observations were the basis for categorizing a given day's weather as severe[1] or significant[2]. By comparing these reports with seven stability indices calculated from the morning rawinsonde observations at Denver, the following information was computed:

- Typical values for each of the indices on quiescent days, significant-weather days, and severe-weather days. These numbers are useful mainly to those who are just becoming familiar with the indices. Charba (1979) and

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[1] The definition for severe weather is that of the National Weather Service: a tornado, or hail at least $\frac{3}{4}$ in. (2 cm) in diameter, or winds causing damage or gusting over 50 kt (26 m s^{-1}).

[2] The definition for significant weather was established for the purposes of this experiment. The attempt was to identify and forecast nonsevere weather events that can nevertheless have serious impact on agriculture, transportation, or public safety, including: hail at least $\frac{1}{4}$ inch (0.6 cm) in diameter, or hail of any size accumulated to a depth of at least 1 in. (2.5 cm), or winds gusting over 35 kt (18 m s^{-1}), or at least 1 in. (2.5 cm) of rain in any 30-min period, or more than 15 lightning strokes per 2000 km^2 in any 5-min period.

Miller (1975), however, present evidence of regional variability in the magnitudes of the indices that imply severe weather, so these results may be of interest to those who know the indices' behavior in other parts of the country.

- Rankings of the indices according to their success as indicators of severe and significant weather. The object is to determine which indices work best in this region.
- The observed relative frequencies of severe and significant weather as functions of each index. In the context of forecasting convection, these relative frequencies are meant to be interpreted as estimates of the probability of severe or significant weather.

The seven sounding indices analyzed here are positive buoyant energy above the level of free convection (or simply "buoyancy") in $J\ kg^{-1}$ (AWSM 1969), precipitable water in centimeters (AWSM 1969), *K* index in Celsius degrees (George 1960), lifted index in Celsius degrees (Galway 1956), the nondimensional SWEAT index (Miller 1975), total totals in Celsius degrees (Miller 1975), and wet-bulb-zero height in meters above ground level (Miller). Following the practice of Miller (1975), Charba (1979), and field forecasters, the units for the various indices will usually be omitted here.

The importance of computing stability indices in the course of analyzing sounding data for thunderstorm potential is well known. Doswell (1982) and Miller (1975) present comprehensive methodologies for operational weather data analysis that emphasize their role in the convection forecasting process. However, there have been relatively few studies of the behavior and the relative effectiveness of the various indices. This is unfortunate, because in addition to providing practical information to field forecasters, these studies invariably result in useful insights into the physical characteristics of thunderstorms and their environments. Stone (1985) discusses the performance of stability indices in the eastern United States 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 shows how performance statistics of stability indices corroborate current understanding of the different processes involved. This paper associates index performance characteristics with various aspects of convection on the high plains east of the Rocky Mountains.

2. The experiment

The Program for Regional Observing and Forecasting Services (PROFS) conducted the 1985 Real-Time (RT85) convection forecasting exercise from mid-May through August 1985 (Haugen 1986). Figure 1 shows the area of forecast responsibility. Forecasters wrote a convection outlook at noon (1800 UTC) each day and experimental warnings as warranted. No forecasts or warnings were disseminated to the public.

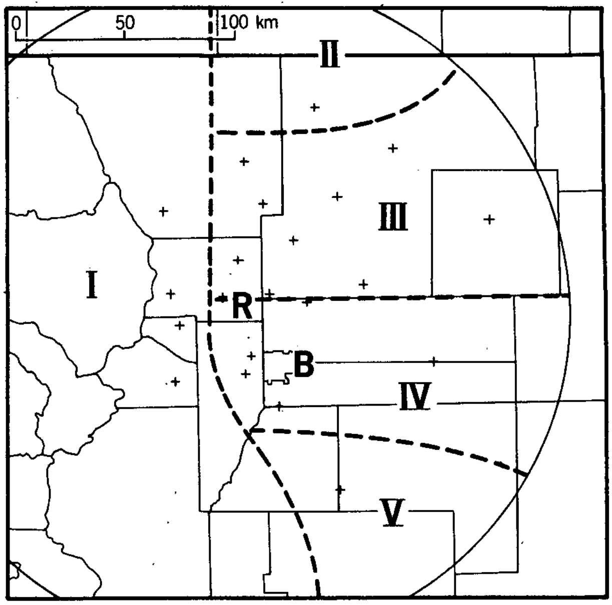

FIG. 1. The area of forecast responsibility is bounded by the circle; this corresponds to the region covered by the radar used for this experiment, located at (R). The radius of the circle is 150 km. The crosses mark the locations of PROFS mesonet sites. The balloons for the morning rawinsondes are launched from the Denver Weather Service Forecast Office (B). The city/county of Denver is the small region west of the forecast office. The eastern boundary of zone I roughly approximates where the mountains meet the plains. The line across the top of the map, cutting through zone II, is the Colorado–Wyoming border. For the daily convection outlook, forecasters issued probabilities of severe and significant weather for each of the five zones in the forecast area. Verification data were collected only for zones II–V.

The RT85 exercise included a substantial effort to collect storm verification data. PROFS deployed as many as five chase teams each day to track and photograph thunderstorms. This dataset was supplemented by reports received by the Denver National Weather Service (NWS) forecast office, which include police reports and observations by Weather Service spotters. The goal of the chase teams was to provide an observation for every thunderstorm in the region, so that it could be known with some confidence whether or not severe weather occurred. This goal is obviously unattainable, but the verification dataset is suitable for this investigation.

The morning [0600 MDT (1200 UTC)] rawinsonde observations taken at the Denver forecast office (Fig. 1) were used to calculate the seven indices every day. Some of the formulae require data at the 850-mb level. In these cases 800-mb data are substituted because the surface pressure in Denver is usually less than 850 mb.

Lifted index and buoyancy are calculated on the basis of a representative boundary-layer parcel being lifted to its level of free convection. In practice, calculating lifted index and buoyancy in the morning requires a forecast of the afternoon dewpoint and maximum temperature. For this study, the parcel temperature was an average of the three of four highest observed afternoon maximum temperatures measured by the plains stations in the PROFS mesonet (Fig. 1). The dewpoint values coincident with these temperature measurements were averaged for the parcel dewpoint. This average dewpoint was subjectively adjusted by as much as 2°C in some cases. For example, the precipitable water in the morning sounding may have indicated significantly less atmospheric moisture content than was suggested by the average surface dewpoint value, possibly because one or two of the stations involved in the averaging were affected by nearby irrigation. Also, the dewpoint instruments in the PROFS mesonet were prone to cyclic measurement errors, which were evident in time series displays of the dewpoint data. In all cases, the adjustments were done without knowledge of any convective activity on the day in question.

The upper air data were assumed to remain constant after rawinsonde balloon launch time; obviously, this would be a poor assumption in many cases.

TABLE 1. Medians, means, and standard deviations for the indices on quiet-weather days, significant-weather days, and severe-weather days. The first row for each index contains the median values, the second contains the mean values, and the third contains the standard deviations.

	Quiet (48 cases)	Significant (18 cases)	Severe (17 cases)
Buoyancy [J(kg^{-1})]	1140	1140	1650
	1040	1390	1900
	690	511	890
K index (°C)	15.0	17.0	23.5
	11.4	17.6	23.1
	11.7	7.6	5.9
Lifted index (°C)	−3.90	−4.35	−5.00
	−3.42	−4.48	−5.29
	2.08	1.13	1.92
Precipitable water (cm)	1.41	1.67	2.15
	1.41	1.65	2.11
	0.62	0.57	0.52
SWEAT index	55	70	143
	78	84	149
	50	48	63
Total totals (°C)	38.0	40.5	42.0
	37.2	40.6	41.6
	4.8	3.2	3.4
Wet-bulb zero (m AGL)	2090	2310	2580
	2020	2200	2390
	539	417	541

3. Benchmark values

Table 1 gives the mean, median and standard deviation for each index in the three weather categories: quiet, significant and severe. The median is the middle number in an ordered list of values of the index, so there are as many values greater than the median as there are values less than the median. Large differences between the mean and median indicate a tendency for values of the index to cluster on one or the other end of the index's range of variability. Figure 2 shows histograms of the lifted index, which has a fairly symmetric distribution, and the SWEAT index, which is heavily skewed toward one end. Table 1 shows that the mean and median are indeed similar in the case of lifted index, while the differences in the SWEAT statistics are relatively large. Further analysis of the asymmetry in the indices' distributions would be of questionable value to this study. The standard deviation is provided as a measure of the variability of each index.

Miller (1975) calculated median values of the total totals and lifted index for each of four severe weather air mass types. Before comparing the median total totals value for severe weather given in Table 1 with Miller's, the effects of modifying the original formula for total totals as discussed in section 2 must be considered.

The original formula is

$$\text{total totals} = T850 + TD850 - 2T500,$$

where $T850$ is the 850-mb temperature, $TD850$ is the 850-mb dewpoint temperature, and $T500$ is the 500-mb temperature. All temperatures are in Celsius degrees. As stated above, 800-mb temperatures and dewpoints are substituted for the 850-mb values in this study because Denver's surface pressure is usually less than 850-mb. If a parcel at 800 mb is lowered to 850 mb while conserving its mixing ratio and potential temperature, the resultant parcel temperature increases by 5°C, and the dewpoint temperature increases by 1°C. Thus, total totals values calculated using this modification will generally be lower by about 6, and using a value of 48 for comparison with Miller's data is suggested. Miller's results are as follows:

- Type I air masses are associated with severe weather outbreaks in the midwestern United States. In 230 type I soundings, the median value of total totals was 54, and the median lifted index value was −6.
- Type II air masses are typically found along the Gulf Coast. The median values from 38 type II soundings were 54 for total totals and −6 for lifted index.
- Type III air masses correspond to cold-air outbreaks along the West Coast, and over the Great Lakes and the northeastern United States. The median value of total totals in 18 type III soundings was 57, and the median lifted index was −3.
- Type IV air masses are found in the southwest United States and the high plains just east of the Rocky Mountains. This is probably the most common type of air mass among those analyzed for this study. The median value of total totals in 22 type IV soundings was 53, which is substantially greater than that obtained

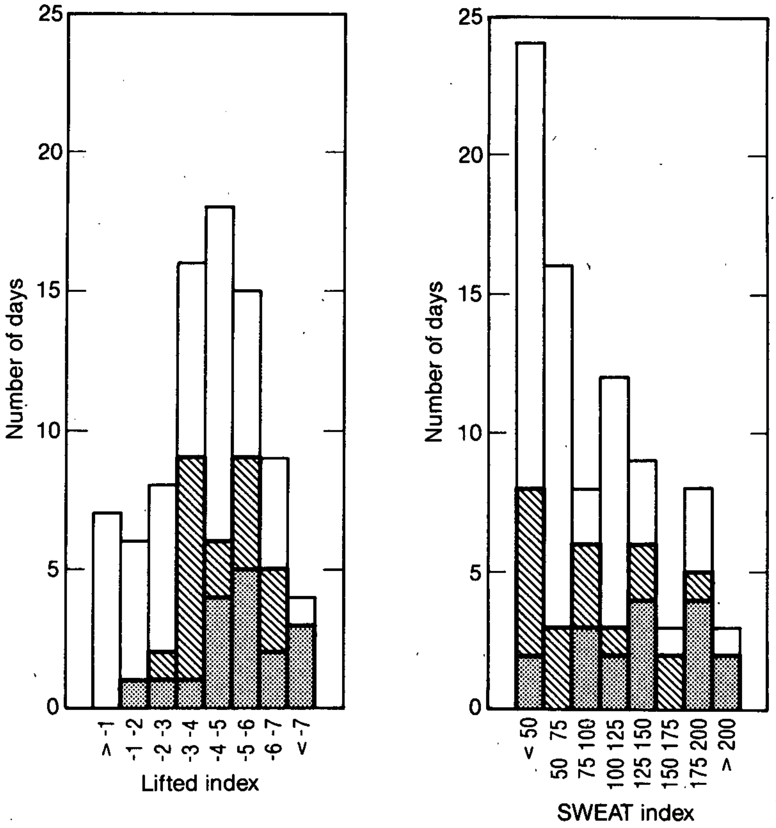

FIG. 2. Histograms for two of the seven tested sounding indices. Stippled units are severe weather days, hatched units are significant-weather days, and clear units are quiet-weather days. The lifted index sample is approximately symmetric. The SWEAT index sample is heavily skewed toward the low end.

here, for unknown reasons. Unfortunately, Miller considered the lifted index an inappropriate measure of potential instability for Type IV soundings because the lower layers are quite dry.

4. Rankings

In situations where the calculated indices, considered separately, give conflicting signals about the potential for severe weather, the forecaster will be interested in some sort of objective ranking of the indices' effectiveness. Several investigators have reported this kind of information.

David and Smith (1971) computed the reduction of variance for each of seven indices (five of which were identical or very similar to indices tested here) used as predictors in linear regression equations for estimating a probability of severe thunderstorms in the vicinity of the 1200 UTC rawinsonde observation for the subsequent 15 h. These statistics were calculated using more 28 000 cases and applied to an area most simply described as the central time zone. The reduction-of-variance values were used to rank the predictors' effectiveness. The SWEAT index scored highest; total totals and *K* index were the two lowest.

Charba (1979) describes the development of regression equations used in the National Meteorological Center's 2- to 6-h thunderstorm and severe weather probability charts, which are disseminated nationally five times each day. Thirty-seven different predictors were tested, including some calculated from primitive-equation model data. Again, the predictors are ranked according to their contributed reduction of variance in linear regression forecasting equations. The sample data were collected for three spring seasons (mid-March to mid-June) over the continental United States east of the Rocky Mountains. Statistics were calculated separately for severe weather events in the vicinity of the Gulf Coast, and for those elsewhere. In both regions, the highest-ranked predictor was the total totals index, modified by updating with surface observations and model-predicted upper-air temperatures and dewpoints.

Stone (1985) computed point biserial correlation coefficients between six stability indices and two predictands, the occurrence of severe weather, and the occurrence of radar reflectivity values above a given threshold. The data came from the East Coast states during the summer of 1984; there were 373 cases in the sample. An energy index similar to the buoyancy index tested in this paper gave the highest correlations with both predictands.

For this study, the rank sum (Huntsberger and Billingsley 1973, p. 293) is the statistic chosen for the purpose of ranking the indices. It is computed by compiling an ordered list of index values, then averaging the ranks of values (an opposed to the values themselves) from severe weather days, and comparing to the average rank of values from nonsevere weather days.

Consider the example given in Table 2. Precipitable water was measured on 10 days of an (imaginary) experiment, with the presence or lack of severe weather noted. The severe weather values were ranked 1, 2, 4, and 8, for an average rank of 3.75. The nonsevere weather values were ranked 3, 5, 6, 7, 9, and 10, for an average of 6.67. The difference between the two mean ranks is 6.67 − 3.75 = 2.92. In order for this number to be compared to statistics computed over different sized samples, we standardize this value by dividing by the sample size (10), for a final result of 0.292. The range of possible scores is −0.5 to 0.5. A score of 0.5 represents perfect performance, where all the index values on severe weather days are higher than any index value obtained on a nonsevere weather day. A score of 0.0 represents random forecasting, indicating that the predictor knows nothing at all about the predictand.

The rank sum is a nonparametric statistic, and thus has the useful characteristic of being independent of the shapes of the frequency curves that characterize the populations from which the samples were taken. Figure 2 suggests that the indices come from populations whose shapes are markedly different.

This statistic is also independent of how the forecast is expressed. Thus, we can make direct comparisons among the various indices, and we can compare their performance to the human forecasters, whose forecasts were expressed in terms of event probability. We could even have compared them if their forecasts had been expressed in terms such as "probable," "likely," "chance," and "improbable," as long as such terms were ordered so as to represent monotonically increasing (or decreasing) probability of severe weather.

TABLE 2. Ranked values of precipitable water measurements (cm), and whether or not severe weather occurred on those days. These are synthetic data, for illustrative purposes only.

Rank	Value	Severe weather?
1	2.56	yes
2	2.31	yes
3	2.01	no
4	1.78	yes
5	1.70	no
6	1.54	no
7	1.33	no
8	1.32	yes
9	1.19	no
10	0.98	no

TABLE 3. Rank sum scores for the seven sounding indices and the forecasters. Scores are given for severe weather and significant weather.

Type	Rank sum score
Severe Weather	
Forecasters	.322
SWEAT index	.314
Precipitable water	.298
K index	.285
Buoyancy	.253
Total totals	.229
Lifted index	.185
Wet-bulb zero height	.179
Significant Weather	
Forecasters	.302
Buoyancy	.265
Wet-bulb zero height	.216
Total totals	.215
Lifted index	.190
Precipitable water	.184
K index	.154
SWEAT index	.119

Table 3 presents the rank sum statistics for the seven indices, as computed over the sample collected during RT85. The forecasters' convection outlooks (Fig. 1) were also scored for comparison with the indices' scores.[3]

The SWEAT index was particularly good at detecting severe weather conditions and particularly poor at detecting significant weather conditions. Of all the tested indices, only the SWEAT index incorporates information about wind shear. Weisman and Klemp (1982) showed that wind shear is important to the development of rotating updrafts, which are the parent structure to large hail and some tornadoes. Further, strong wind shear "tears apart" the smaller thunderstorms that would be more likely to produce smaller hail and weaker downdrafts, i.e., significant weather events.

In all the prior studies of stability indices cited above, only David and Smith (1971) evaluate the SWEAT

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[3] Although the forecasters were not required to give an overall probability that severe weather would occur anywhere in zones II through V (verification data were not collected in zone I), that number can be estimated by subtracting from 1.0 the probability that severe weather will not happen in any zone. For example, if the forecaster had issued a 20% probability of severe weather for zone II, 30% probability for zone III, 40% probability for zone IV and 50% probability for zone V, the overall forecasted probability would be $1.0 - [(1 - .2)(1 - .3)(1 - .4)(1 - .5)]$, or 83.2%.

index as a predictor of severe weather. In that study, the SWEAT index ranks highest by a large margin.

Buoyancy and lifted index are conceptually similar indices. Both include in their respective formulae the afternoon maximum temperature and dewpoint observations, then produce a quantity resulting from lifting that surface parcel to its level of free convection. The lifted index is the difference between the temperature of the lifted parcel at 500 mb and the 500-mb temperature in the sounding. Buoyancy is proportional to the integrated difference between the temperature of the lifted parcel and the sounding between the level of free convection and the equilibrium level. Thus, buoyancy incorporates more information, and on that basis alone should outperform the lifted index. This is borne out by the results shown in Table 3, as well as those presented by David and Smith (1971) and Stone (1985). It should be noted that the formulations for buoyancy used in those studies are similar, but not identical, to that used here.

It does not necessarily follow that lifted index is not a useful quantity. Buoyancy is difficult to calculate by hand (without the use of a computer), whereas lifted index is easily estimated using graphical techniques familiar to every forecaster. Thus, the lifted index can be used in the absence of a computer to monitor the hour-to-hour progress of potential instability during the course of an afternoon.

Two other parameters, *K* index and total totals, are designed to assess stability based only on the morning sounding. The *K* index worked better for severe weather; total totals worked better for significant weather. Charba (1979) reports a different result: total totals ranked higher as a predictor of severe weather than *K* index. It may not be valid to compare these results, for two reasons. Charba uses model-forecast temperatures and dewpoints in the formulations of the indices, and his study applies to a different area.

The rankings also indicate that the amount of precipitable water is well connected to the presence of vigorous convection. The morning skies are normally clear in this region, and there are terrain irregularities that provide elevated heat sources to trigger convection. Dry thermodynamic instability is therefore abundant in a climatological sense. Moisture, on the other hand, is not. Only one day during RT85 had precipitable water over 3 cm, whereas in Florida, for example, precipitable water values over 4 cm are not uncommon.

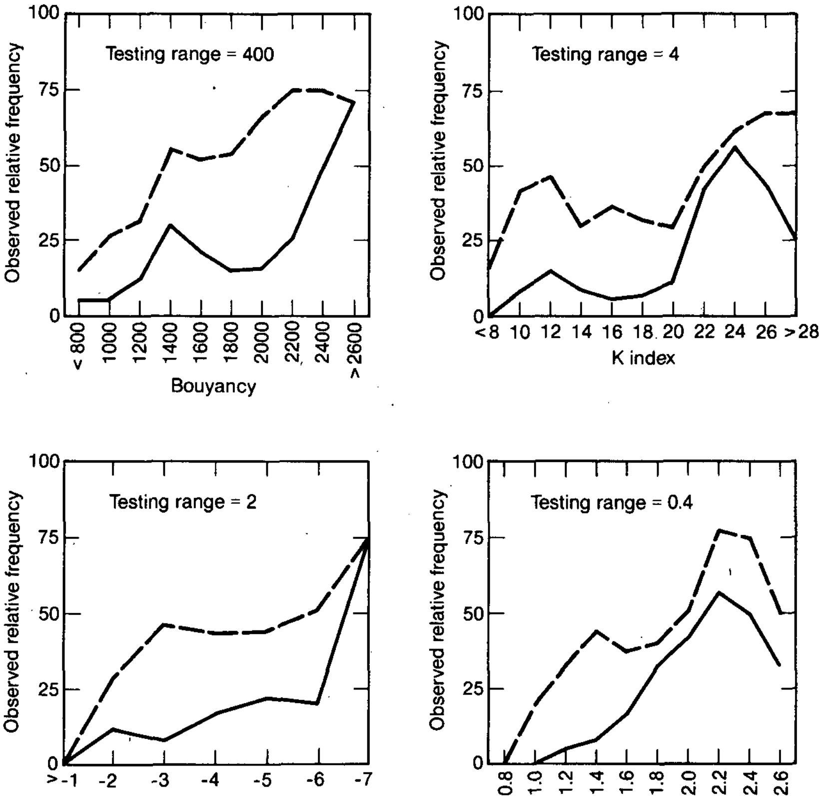

FIG. 3. Observed relative frequencies of severe weather (solid lines) and significant weather (dashed lines) as functions of the seven indices. The testing ranges, together with the midpoint values (plotted on the abscissae), determine the upper and lower limits of index values included in the computations of relative frequencies.

Precipitable water would probably not fare as well as a stand-alone forecasting parameter in more humid climates; this hypothesis remains to be tested.

Table 3 suggests that the wet-bulb zero height fares quite well as a significant weather indicator, but rather poorly as a predictor of severe weather. Case-by-case examination of the dataset shows that the good performance in significant weather situations was almost entirely the result of high values on days with surface high-wind events. Wet-bulb zero values are highest on warm, dry days. These days are conducive to high-based thunderstorms (Brown et al. 1982), which can produce strong surface winds from downdrafts. Thus, although there is a satisfactory physical connection between high values of this index and the occurrence of wind gust events, the available evidence can provide only tentative conclusions until more data are available.

5. Relative frequencies

The charts in Fig. 3 show the relative frequencies of severe and significant weather, as observed during the RT85 experiment, as functions of each sounding index. Individual points along a given curve represent the percentage of convective weather days among those days when the index was within the testing range (given in the upper-left corner of each chart) centered on the value given on the abscissa. Thus, severe weather occurred on about 50% of the days when the SWEAT index was in the range 160 to 200, which centers on 180. Note that adjacent intervals overlap by one-half of the testing range. This has the desired effect of smoothing the curves somewhat.

In a forecasting application, the charts provide an empirically derived estimate of the probability of severe or significant weather implied by a given index observation. For example, the implied probability of significant weather on a day when the precipitable water measurement is 2.4 cm is about 75%. As noted in section 2, lifted index and buoyancy include observed afternoon temperatures and dewpoints in their computations. In practice then, the probability estimates are only valid to the extent that the afternoon temperatures and dewpoints have been forecast accurately.

Charba (1977) presents similar charts of the relative frequency of severe thunderstorms vs several indices. In one of his charts, depicting the performance of the total totals in the Gulf Coast region, he points out that the observed relative frequency of severe weather actually drops off with extreme values of the index, but offers no explanation. There are weak suggestions of this phenomenon in some of the curves in Fig. 3 and

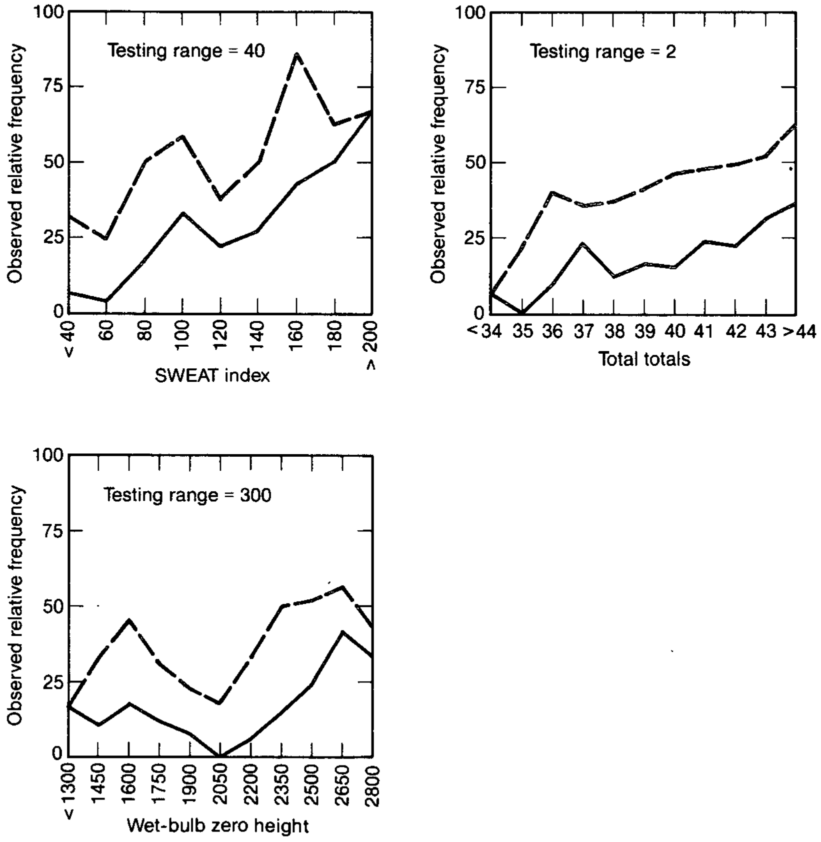

FIG. 3. (*Continued*)

in other presentations of the same dataset given in Schultz and LeFebvre (1986). On some days during RT85, forecasters (including the author) noted evidence in the data and in sky observations that extreme midtropospheric instability caused convection to occur too early, before the boundary layer had a chance to build up the heat and moisture required to support strong convection. Also, too much atmospheric water vapor sometimes resulted in cloudiness that shut off surface heating. These kinds of events may explain the falloff of severe weather frequency with extreme values of the predictors.

With one exception (severe weather vs precipitable water), all of the charts in Fig. 3 show a relative maximum somewhere in the low end of the range. It is especially pronounced in the charts for SWEAT, wet-bulb zero height, and K. The dataset was examined to determine if there were a few days where all the indices were low that nevertheless had active convective weather. In most of the charts, perhaps five such "anomalous" case days would be sufficient to produce the local maxima. There was only one such day. No physical explanation for the curves' behavior is offered here.

It should be noted that, if the tendency for the frequency of thunderstorms to fall off with extreme values of the indices is a physical reality, or if the index performance is truly bimodal and not an artifact of the small sample size, then the rank-sum procedure used in section 4 is not a valid method for ranking the indices, since it is based on the assumption that the probability of severe weather correlates monotonically with the magnitude of the index.

6. Summary and conclusions

Seven indices computed from sounding data are used as predictors of severe and significant convective weather in the vicinity of Denver, Colorado. Their performance is analyzed for the purpose of providing forecasters with information to aid in the interpretation of a given day's set of indices.

Benchmark values for each index on severe weather days, significant-weather days, and quiet days are given. The only known dataset against which any of these benchmarks might be compared is that of Miller (1975). In the cases of both lifted index and total totals, the magnitudes associated with severe weather are somewhat lower than those reported by Miller.

The indices are then ranked according to how well their magnitudes associated with the presence of severe and significant weather during RT85. The SWEAT index was the best predictor of severe weather in northeast Colorado, probably because it is the only one of the tested indices that incorporates information about wind shear. Buoyancy was the best predictor of significant weather. Stone (1985) and David and Smith (1971) report similar success by these two indices.

The observed relative frequencies of severe and significant weather are plotted against each index. In the forecasting context, these frequencies can be interpreted as probabilities of severe or significant weather. The possibility that the frequency of severe weather drops off with extreme values of some indices, first observed by Charba (1977), is also suggested in some of these plots.

There is growing evidence that suggests the need for regionally specific studies of the performance and behavior of sounding indices for forecasting convection. It would be inappropriate to expect any single index to work best in all locations, or to expect that any index works best for all types of severe weather (wind, large hail, and tornadoes). The latter notion was not emphasized in this paper because of the small sample size, but the prospects for investigating event-type specificity in the indices certainly is a motivation for additional data collection.

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